The Mystery of Mass:

- B physics, Direct Dark Matter Detection and Higgs Boson Searches at Colliders -

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Outline

- **Introduction**

  -- The Standard Model (SM) and the quest for electroweak symmetry breaking

  -- The Higgs mechanism and the search for the SM Higgs Boson

- **What does the SM fail to explain?**

  Conceptual issues: * The hierarchy problem * Unification of forces

  Data driven issues: * Dark Matter * Baryonic asymmetry

- **Supersymmetry: a solution to all these problems**

  An extended Higgs sector <==> Flavor changing neutral current effects

- **The search for the Supersymmetric Higgs bosons**

  -- At colliders

  -- Complementarity with B physics and direct Dark Matter searches

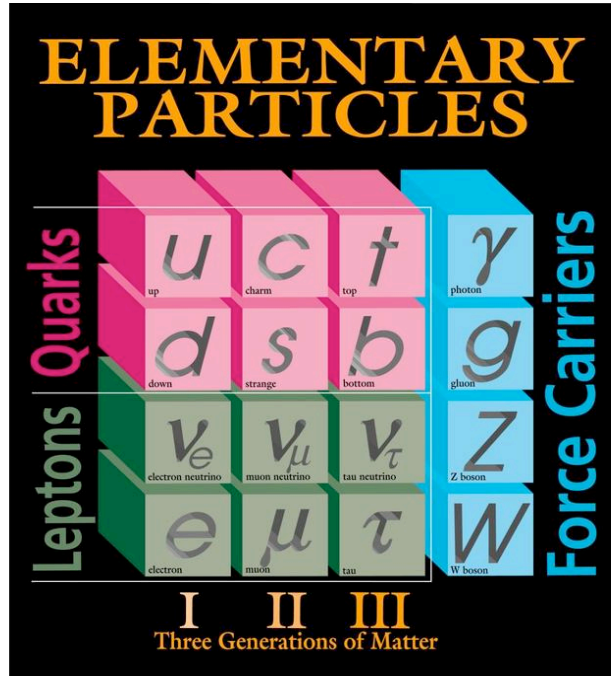
- **Conclusions**

The Standard Model

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

based on a gauge field theory with a symmetry group

$$G = SU(3)_c \times SU(2)_L \times U(1)_Y$$



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

There are neutral and charged mediated interactions:
The charged force carrier -- W boson-- can change the flavor of the quarks: u <==> d

Matter Fields:

3 families of quarks and leptons have very different masses !

$$m_3/m_2 \text{ and } m_2/m_1 \cong \text{ a few tens or hundreds}$$

$m_e \approx 0.5 \;\; 10^{-3} GeV$ $\qquad$ $m_\mu/m_e \approx \mathbf{200}$ $\qquad$ $m_\tau/m_\mu \approx 20$

Largest Hierarchies: $\qquad$ $m_t \approx 175 \text{ GeV}$ $\qquad$ $m_t/m_e > 10^5$

neutrino masses as small as 10^{-10}GeV

Crucial Problem:

- 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 $\mathrm{SU}(2)_L$ gauge bosons?

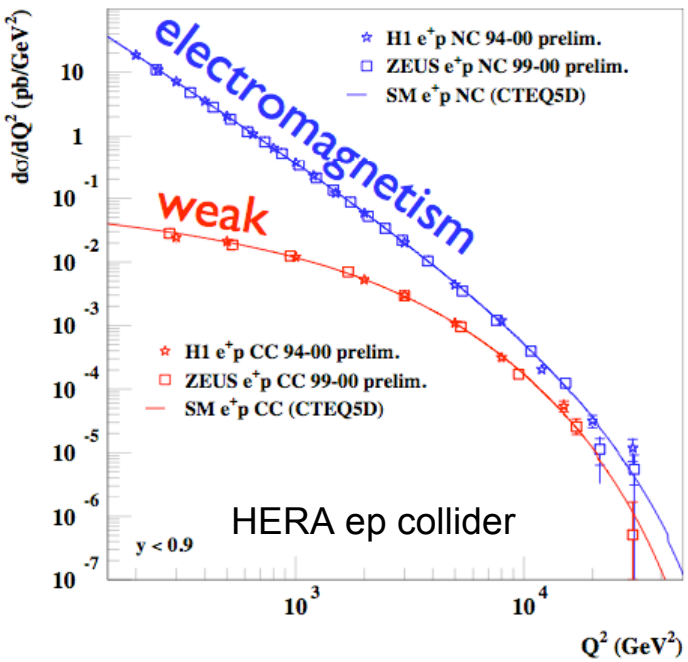
  $m_W = 80.449 \pm 0.034 \text{ GeV}$ $\qquad$ $m_Z = 91.1875 \pm 0.0017 \text{ GeV}$

- A fermion mass term $L = m\,\overline{\psi}\psi = m\,(\overline{\psi_L}\psi_R + \overline{\psi_R}\psi_L)$ 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 Breakdown (EWSB)

- There is a Mystery 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



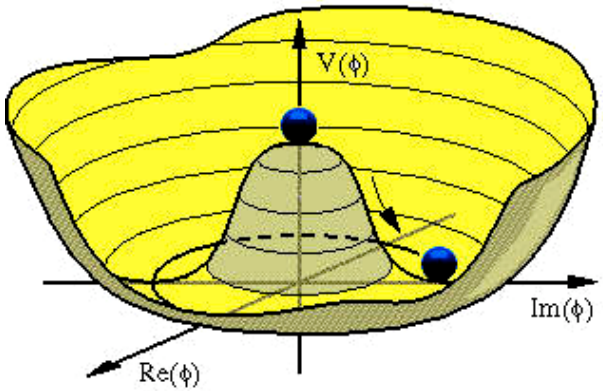
We know that the electromagnetic and weak forces are unified ==> electroweak theory

what breaks the symmetry
==> the Mystery Field

We know EWSB occurs at the electroweak scale
New phenomena associated to the Mystery Field should lie in the TeV range or below
within LHC/ILC reach

In the Standard Model: 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 a 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 V = W,Z

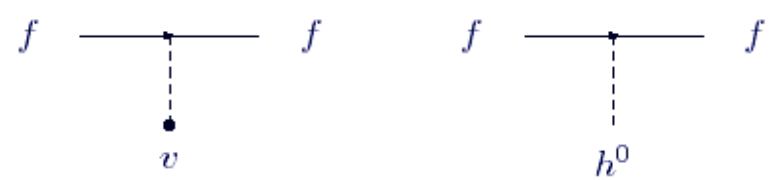
⋆ interaction with gauge fields

$$m_V^2 = g_{\phi\, VV}\; v/2 \quad \longrightarrow v = 174 \text{ GeV}$$

- Higgs neutral under strong and electromagnetic interactions $m_\gamma = 0 \qquad m_g = 0$
exact symmetry $SU(3)_C \times SU(2)_L \times U(1)_Y$ ==> $SU(3)_C \times U(1)_{em}$

⋆ mass to fermions via Yukawa interactions

$$m_f = g_{\phi\, f\bar{f}}\; v$$



- One state left in the spectrum: Higgs Boson with mass: $m_\phi^2 = 2\lambda v^2$

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.

- First evidence of EWSB ==> masses of gauge bosons

Measuring the WWH and ZZH couplings is essential to identify the Higgs as the agent of EWSB without a vacuum expectation value, no such trilinear coupling at tree level

==> we need to detect the Higgs in association with gauge bosons

- The other particle whose mass is related to the source of EWSB is the top quark

-- If there were other particles (Higgs) responsible for the top mass, their v.e.v. will be small (not responsible for W,Z masses) ==> their couplings to the top would need to be too strong --

==> if the theory remains perturbative, the top mass will mainly come from a Higgs with SM-like couplings to W and Z

but will present big mysteries of its own!

The first step is discovery:

Observe one candidate Higgs boson (or more).

Next step: determine its basic properties :

mass, spin, CP quantum numbers;
couplings to boson and fermions, total width;
Higgs self couplings to reconstruct Higgs potential;
possible rare decay modes

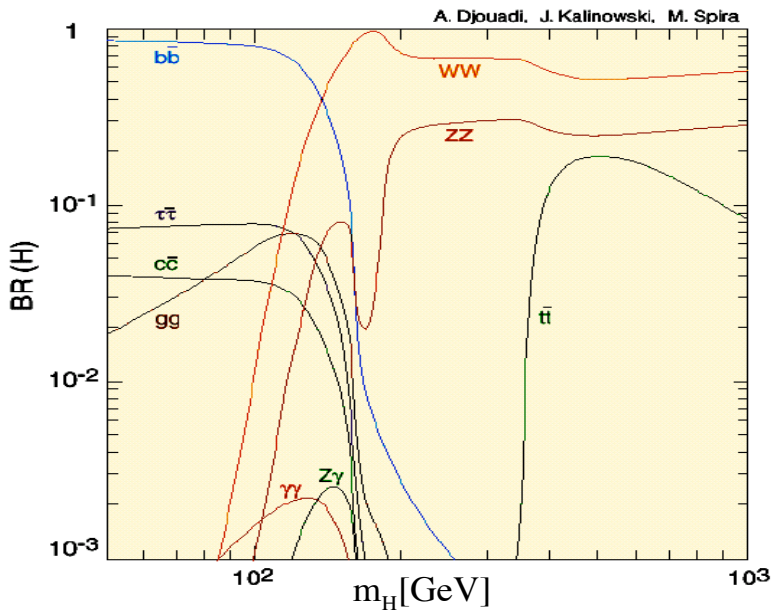
Use precision measurement of basic properties to learn about basic model of nature:

Is this scalar a Higgs boson?
Distinguish between a SM Higgs boson and a SM-like Higgs boson coming from an extended Higgs sector in other models of new physics:
(Supersymmetry, Extra dimensions, Strongly interacting Higgs models …)
Investigate CP violation, beyond the SM, via effects in the Higgs sector

Both the LHC and the ILC will be crucial in establishing the nature of the EWSB mechanism

How do we search for the Higgs?

Through its decays into gauge bosons and fermions



Depending on its mass it will decay into different particles. One can define:

$$BR(h \to XX) \equiv \frac{\Gamma(h \to XX)}{\sum_{\substack{X_i = \\ all\ particles}} \Gamma(h \to X_i X_i)}$$

- Uncertainties due to uncertainties in α_S, m_t, m_b and m_c
- Leading QCD corrections mapped into scale of fermion masses ==> $m_f(m_{H_{SM}})$

- Main decay modes for $O(M_Z) \le m_{H_{SM}} \le 2M_Z$ ==> $h \to b\bar{b}$ and $h \to WW^*, ZZ^*$

- For $m_{H_{SM}} \le 140$ GeV ==> $h \to \tau^+\tau^-$, $c\bar{c}$, gg also important; $h \to \gamma\gamma$ tiny but clean signature

- Above WW, ZZ thresholds, it decays almost exclusively into these particles, with small admixture of $h \to t\bar{t}$ above $t\bar{t}$ threshold

For example, at $m_{H_{SM}} = 120 GeV$: $b\bar{b}$ ~68% ; $c\bar{c}$ ~ 3.1% ; $\tau^+\tau^-$ ~ 6.9% ; gg ~ 7%

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

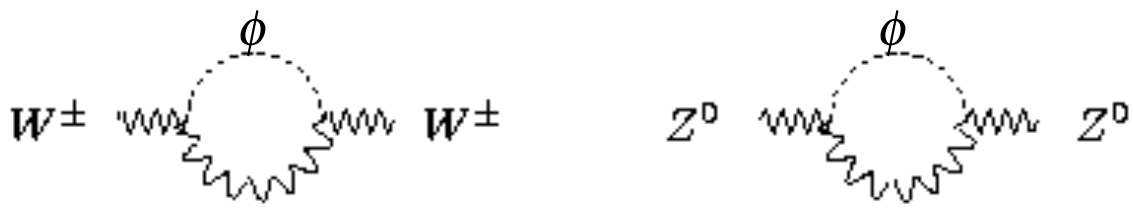
$$e^+e^- \xrightarrow{Z^*} H_{SM} Z \qquad m_{H_{SM}} > 114.6 \text{ GeV at } 95\% \text{ C.L.}$$

with $H_{SM} \to b\bar{b}, \tau^+\tau^-;\ Z \to q\bar{q}, l^+l^-, \nu\bar{\nu}$ final LEP result, 2003

- **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

Although the Higgs boson has not been seen and its mass is unknown, it enters via virtual Higgs production in electroweak observables: particle masses, decay rates,etc



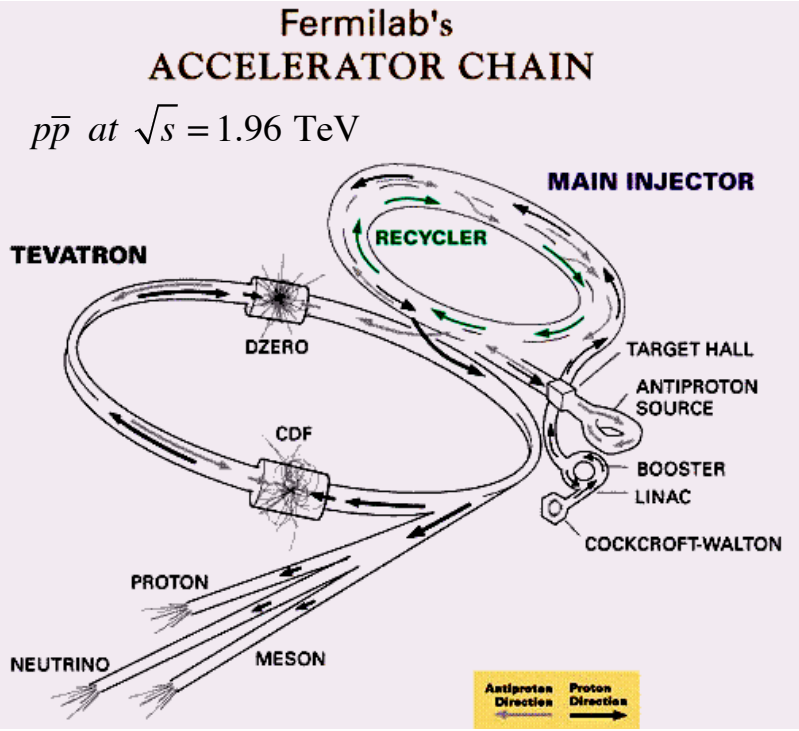
All electroweak parameters have a weak logarithmic dependence on $m_{H_{SM}}$
Nonetheless, preferred value of $m_{H_{SM}}$ can be determined

$$m_{H_{SM}} < 200 \text{ GeV at } 95\ \% \text{ C.L}$$

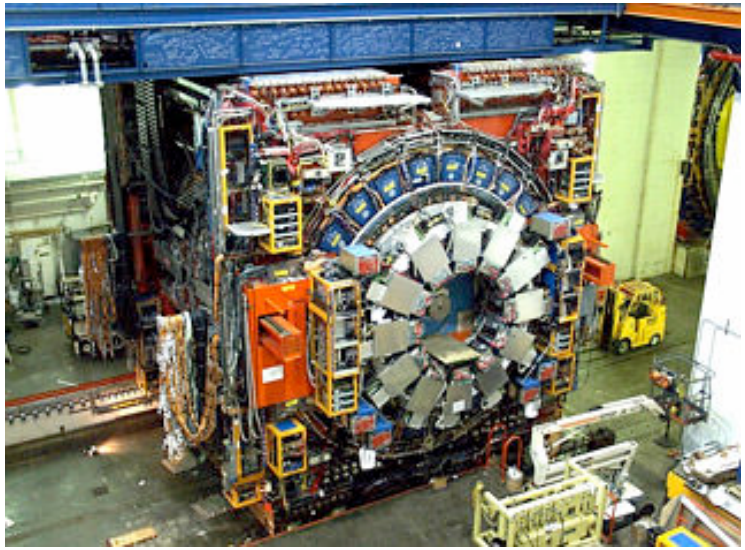
To avoid a light Higgs Boson, must have new phenomena below 1 TeV

The TeVatron at Fermilab (2001-2009)

at present: the highest energy accelerator in the world



- ~4 miles circumference:
  beams of protons-antiprotons colliding to create a shower of new particles: $E = mc^2$
- 2 multi-purpose detectors: D∅ and CDF

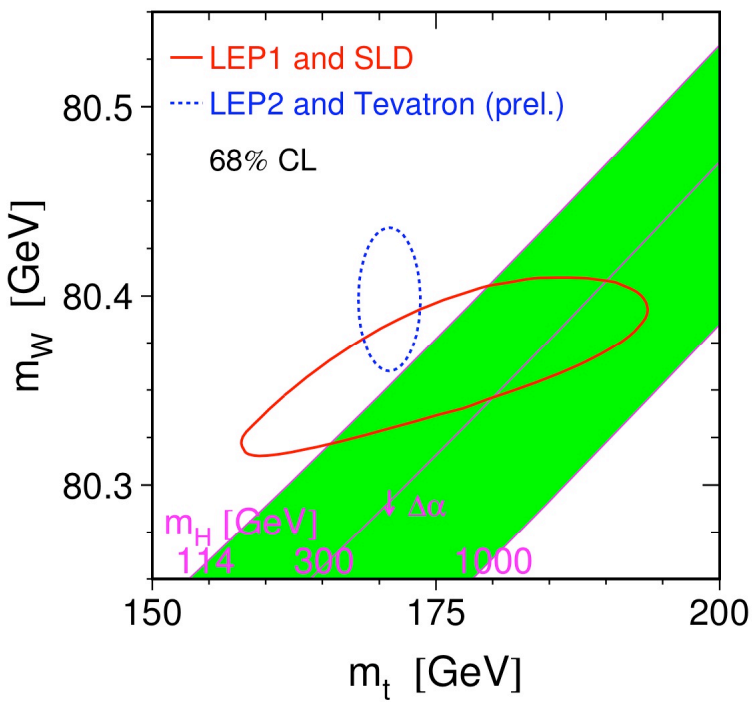


Precise measurements of Mt and Mw

==> 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**

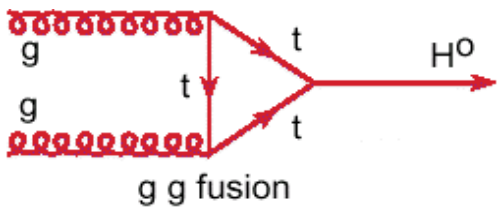
SM correlation for M_t-M_w-$m_{H_{SM}}$



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)

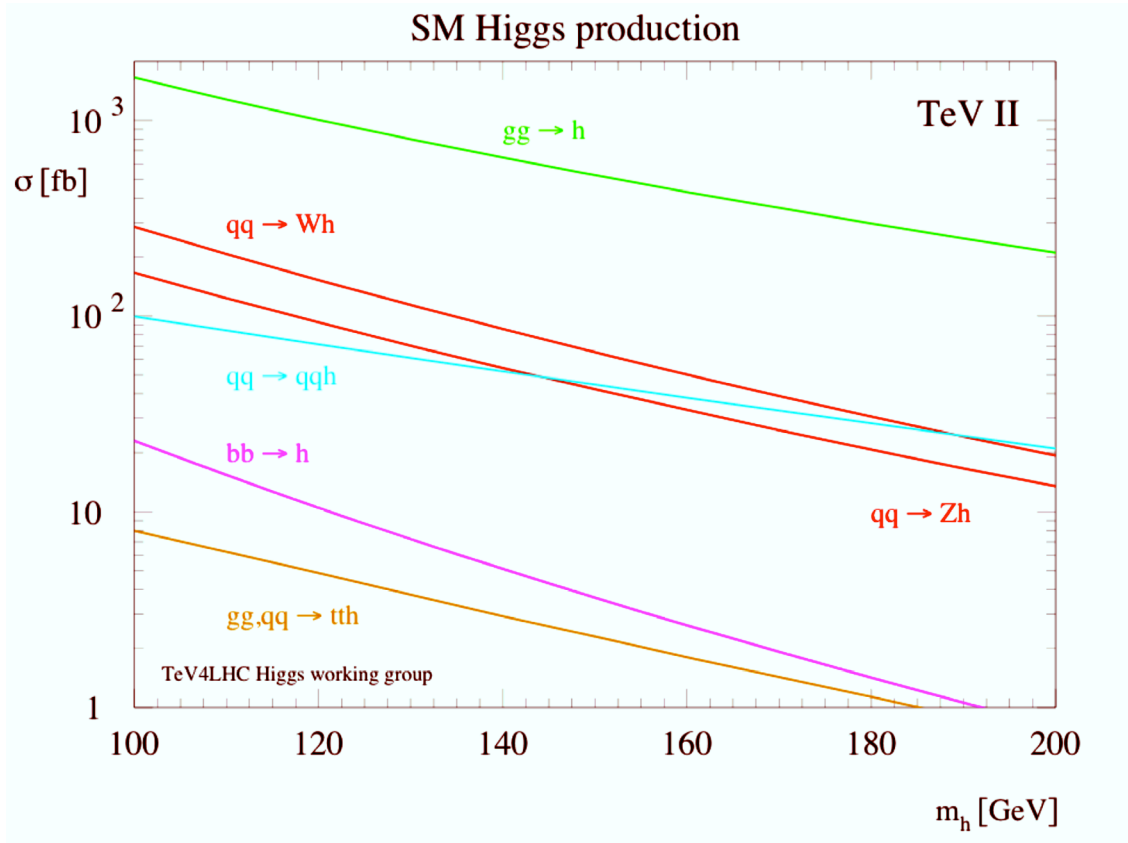
LEPEWWG '07; TEVEWWG '07

SM Higgs Production cross sections at the Tevatron



with $H \rightarrow WW$

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



Much progress recently in computing
NLO and NNLO QCD corrections
http://maltoni.home.cern.ch/maltoni/TeV4LHC/SM.html

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

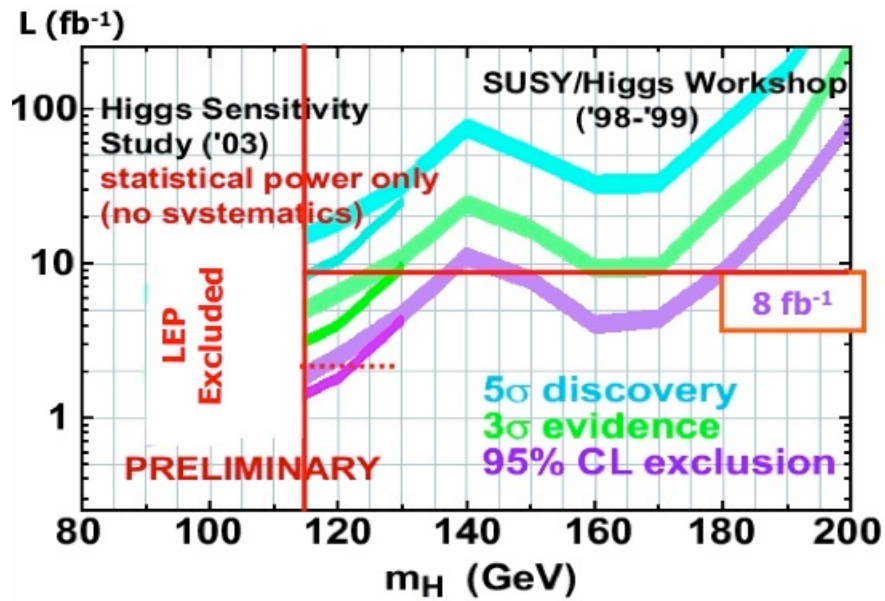
for Zh ==> $Zb\bar{b}$, ZZ, $t\bar{t}$, $W^* \to t\bar{b}$

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

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

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

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

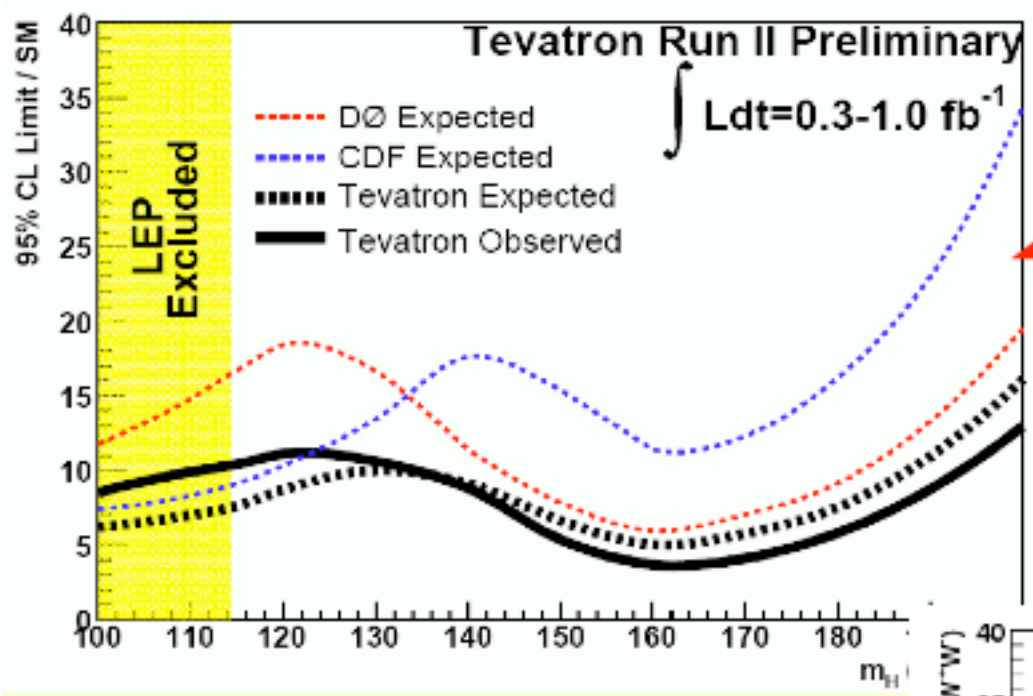


Quite challenging! Evidence of a signal will mean that the Higgs has SM-like couplings to the W and Z

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

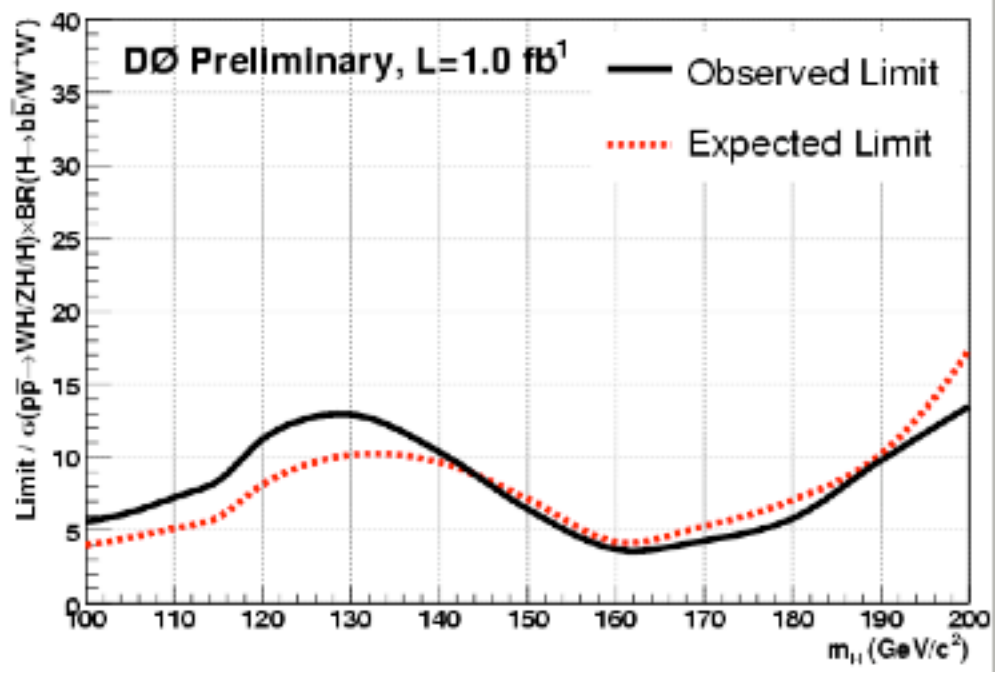
Progress?

Wine & Cheese
April 6th, 2007



ICHEP '06 Combined Results

- Large improvement at low mass: *factor of 3!*
  - Better than luminosity increase alone: sqrt(L_{new}/L_{old}) = 1.7



An Emerging Path...

- Though we're not quite there, we know we're missing pieces
  - Advanced analysis selections (NN,ME) provide factor of ~1.5-1.7 in equivalent luminosity
  - Missing channels (WH→WWW, single-tag for ZH)
  - New channels (taus, H→ZZ, hadronic H→WW) in the pipeline

Ingredient	Equiv Lumi Gain	Xsec Factor MH=115 GeV	Xsec Factor MH=160 GeV
Today with 1fb^{-1}	-	5.9	4.2
Lumi = 2 fb^{-1}	2	4.2	3.0
b-Tag (Shape + LayerØ)	2	3.0	3.0
Multivariate Techniques	1.7	2.3	2.3
Improved mass resolution	1.5	1.8	2.3
New Channels	1.3/1.5	1.6	1.9
Reduced systematics	1.2	1.5	1.7
Two Experiments	2	1.1	1.2

Add another experiment ☺

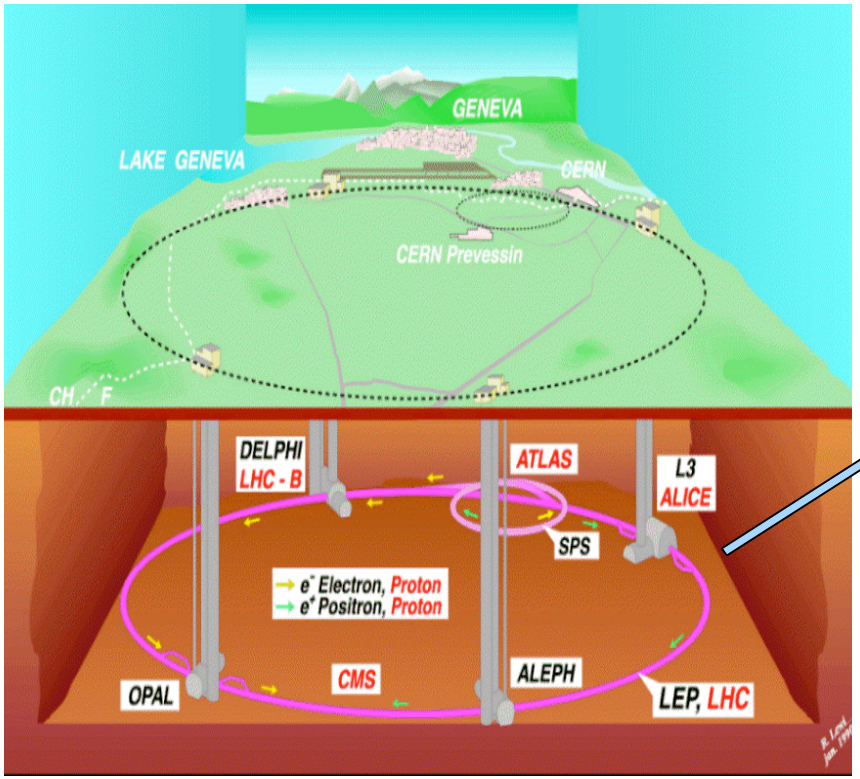
→At 115 GeV need ~2.5 fb^{-1}

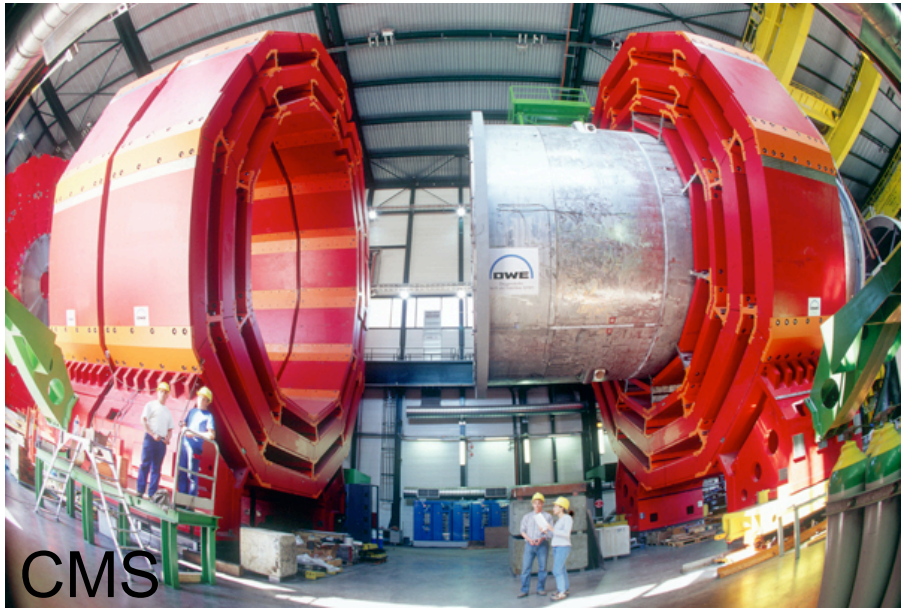
At 160 GeV need ~3 fb^{-1}

The Large Hadron Collider

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

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

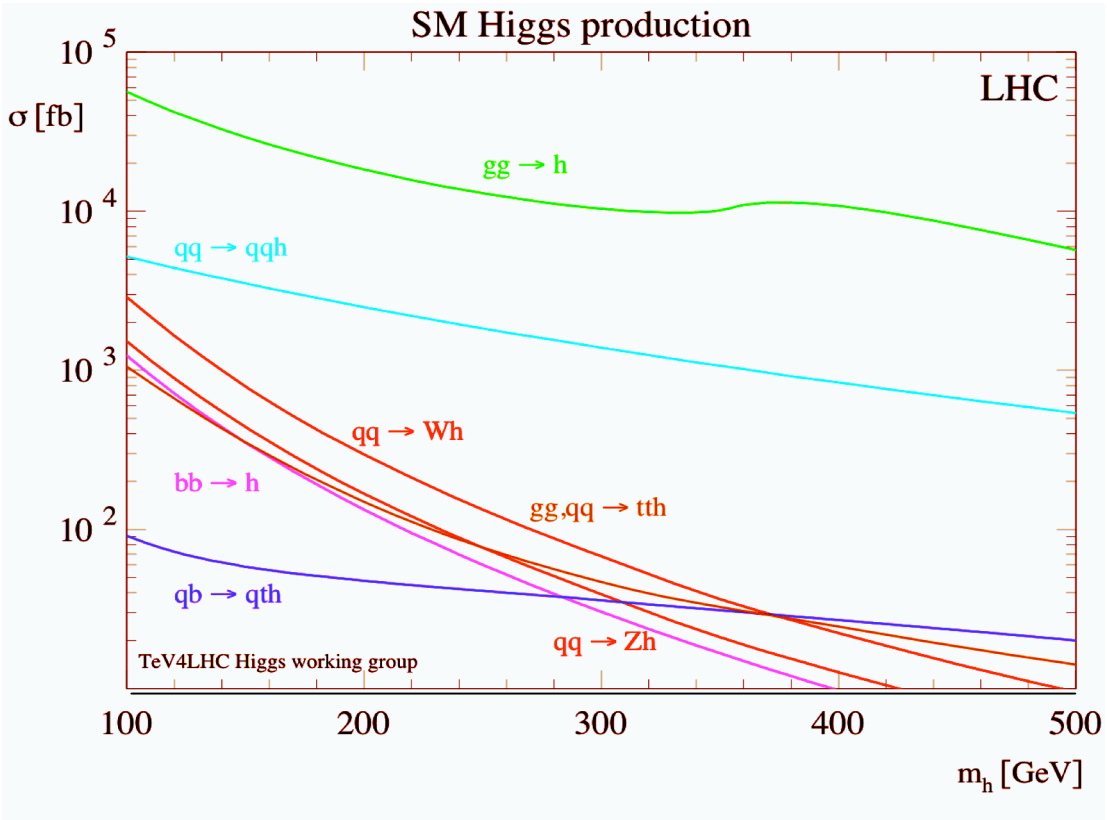




~ a billion proton-proton collisions per second!

2 multi-purpose detectors ATLAS and CMS

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

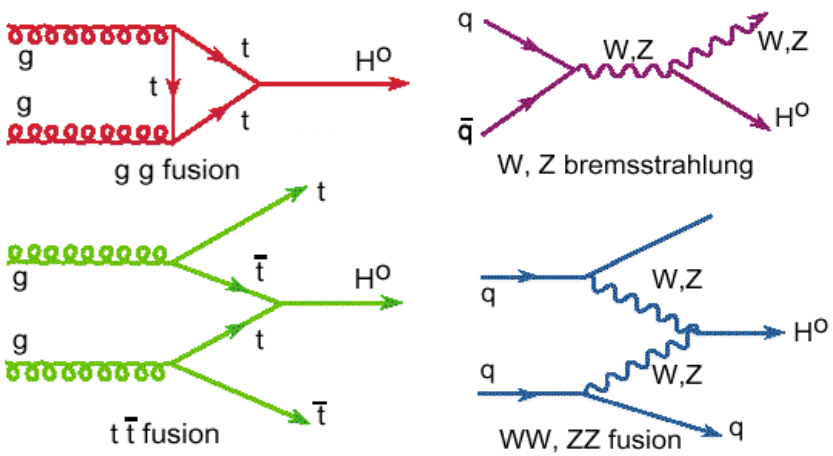
- gluon fusion: dominant production process $\sigma_{gg\to h} \sim 30-15$ pb $(m_h \sim 120-200$ GeV$)$
- vector boson fusion: ==> $\sigma_{qq\to qqh} \sim 6-3$ pb $(m_h \sim 120-200$ GeV$)$

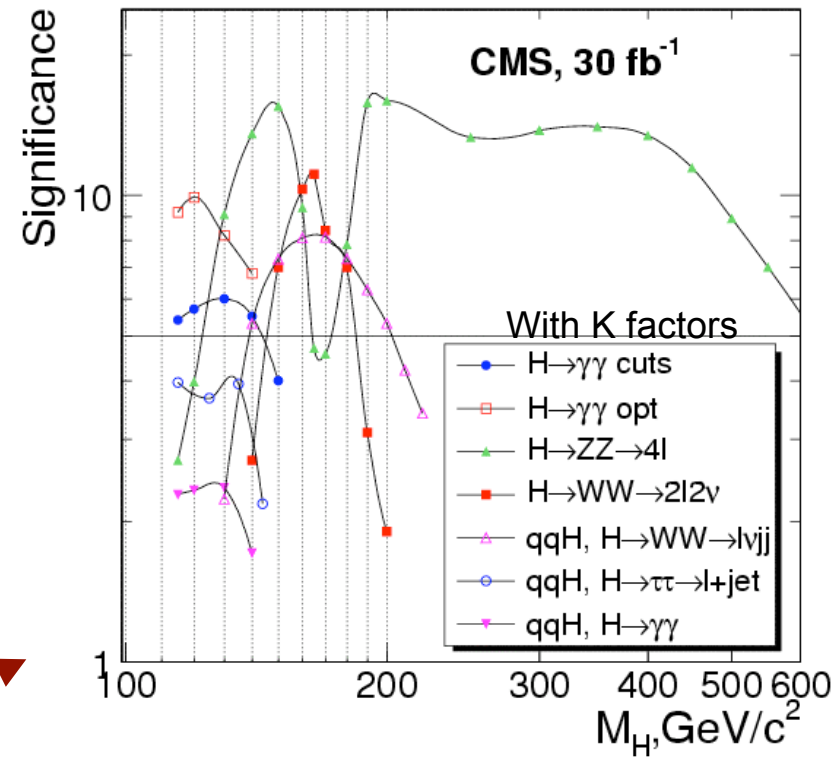
  important tagging of forward jets
- $t\bar{t}$ fusion: $\sigma_{gg,qq\to tth} \sim 0.8-0.2$ pb $(m_h \sim 120-200$ GeV$)$ ==> unique $h \to b\bar{b}$ decay

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

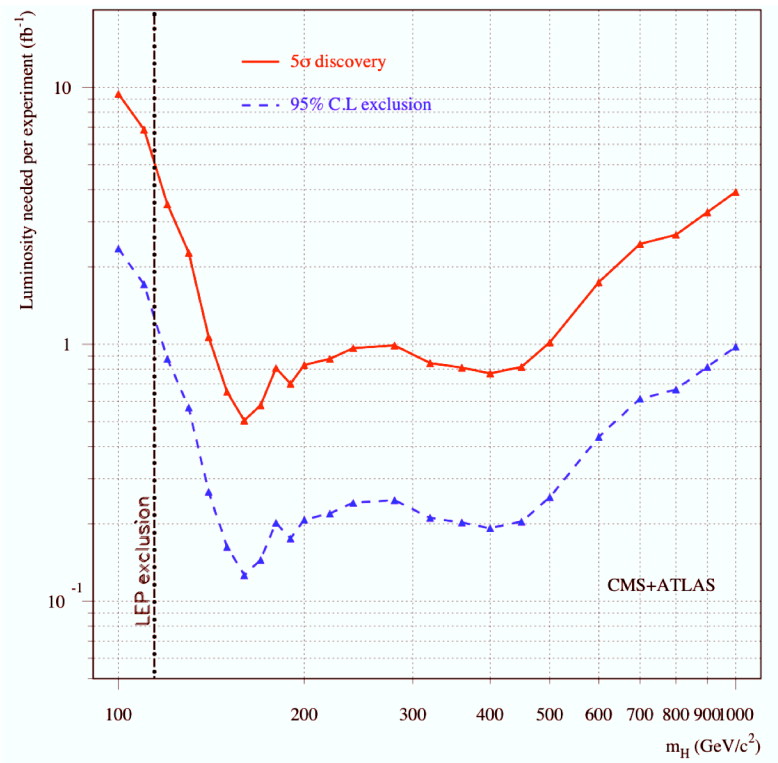
  Inclusive H ==> ZZ==> 4l

- **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

Measuring Higgs Couplings at LHC

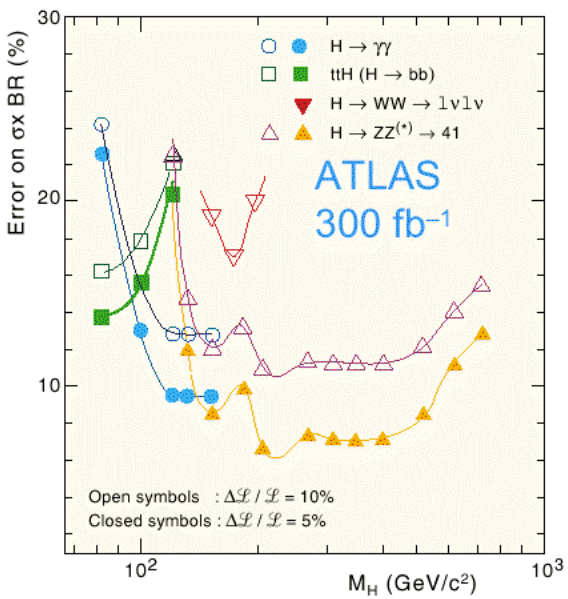
LHC rates for partonic processes are given by

$$\sigma(\mathrm{pp} \to \mathrm{H_{SM}}) \times \mathrm{BR}(\mathrm{H_{SM}} \to \mathrm{YY}) = \frac{\sigma^{SM}}{\Gamma_p^{SM}} \frac{\Gamma_p \Gamma_Y}{\Gamma}$$

Γ_p is the Higgs partial width involving the production couplings and BR $(\mathrm{H_{SM}} \to \mathrm{YY}) = \dfrac{\Gamma_Y(\mathrm{H_{SM}} \to \mathrm{YY})}{\Gamma}$

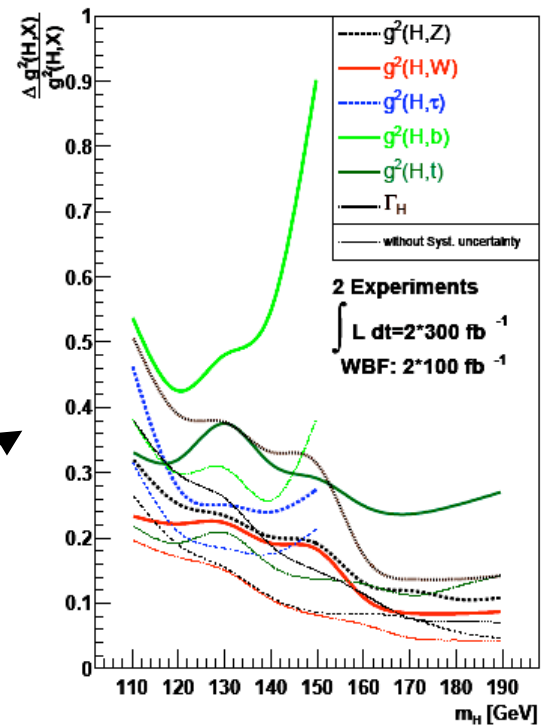
•From precision on $\sigma \times \mathrm{BR}$ ==> determine ratios of decay widths ==> with some mild theoretical assumptions

ratios of couplings



Duehrssen, Heinemeyer, Logan
Rainwater, Weiglein, Zeppenfeld

Precision of 10-40% for Γ_Y
==> 5-20% in the couplings



- **Measuring HWW and HZZ couplings of order one (SM-like) will be evidence of a Higgs responsible for the EWSB ==> WW fusion most relevant channel**

The Standard Model: an effective theory

On its behalf: it works amazingly well !! beyond our wildest expectations.

1. The SM is not valid at energies above $M_{Pl} \approx 10^{19} GeV$ where gravity can no longer be ignored

2. SM neutrinos are massless, but neutrino masses have recently been observed to be very small $m_\upsilon / m_e \leq 10^{-6}$

   Theories with fundamental scales of order $M >> \mathrm{v}$ generate neutrino masses

   $\mathrm{v}^2 / M \longrightarrow M \approx 10^{15} GeV$

3. Quantum corrections can destabilize the Higgs potential or render the Higgs self coupling to infinity (see Appendix)

4. Has inelegant mathematical issues: The hierarchy problem ==> $\mathrm{Why\ v} \ll \mathrm{M_{Pl}}$?

   ==> quantum corrections make it unnatural to have such huge hierarchy

   (see Appendix)

5. **It does not allow for unification of all forces in nature**

6. **It does not explain: Dark Matter**

   The Matter-Antimatter asymmetry

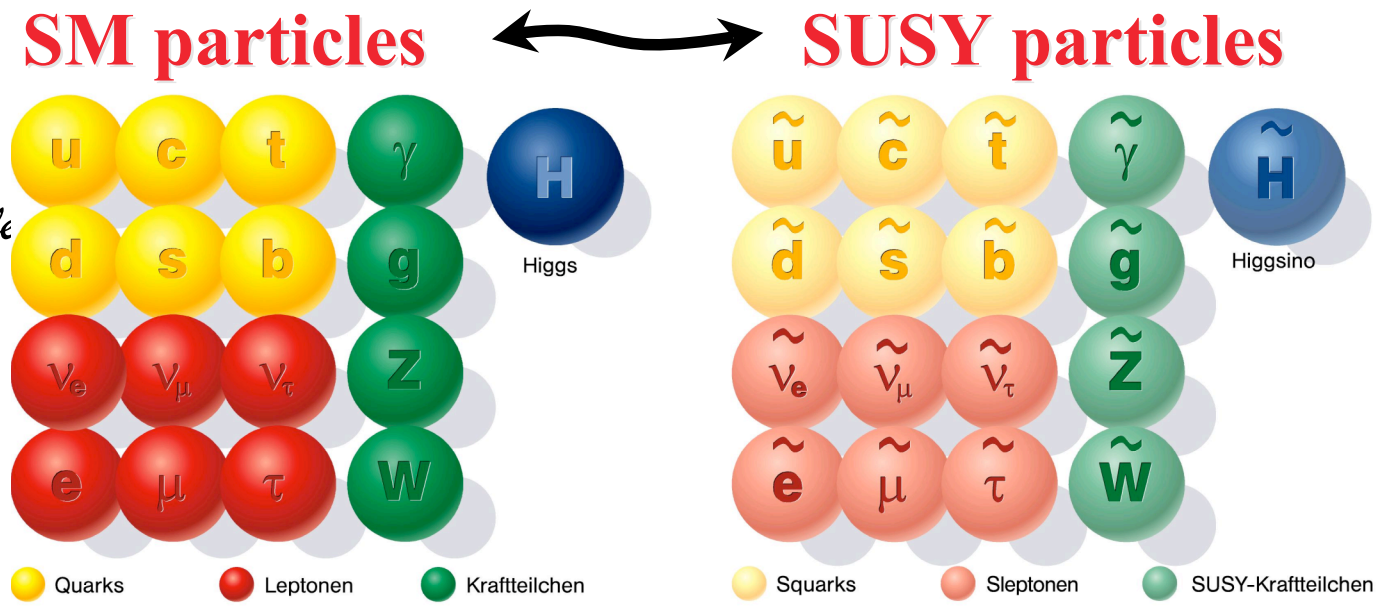
   The fermion mass hierarchies

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

SUSY is an essential part of String Theory



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

-- provides a solution to the Higgs mass stability problem

-- plays a central role in unification of gauge couplings

-- provides a natural candidate for Dark Matter, the neutralino

-- provides a solution to the Matter-Antimatter asymmetry of the Universe

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

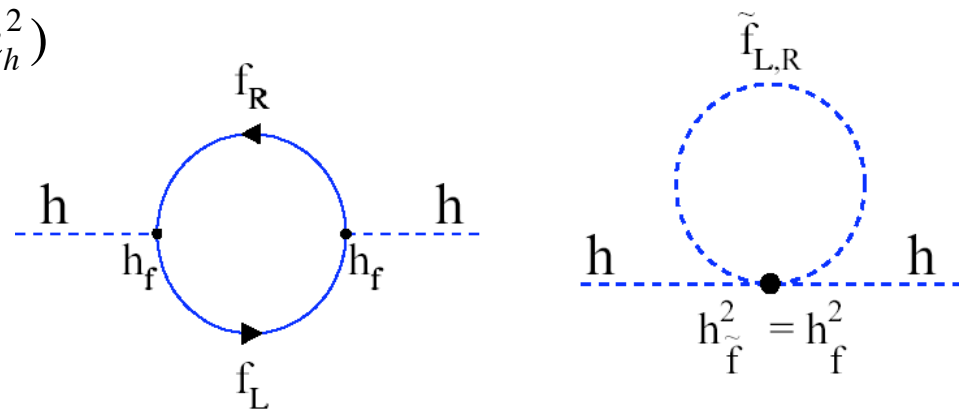
- **Solve hierarchy/naturalness problem**

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

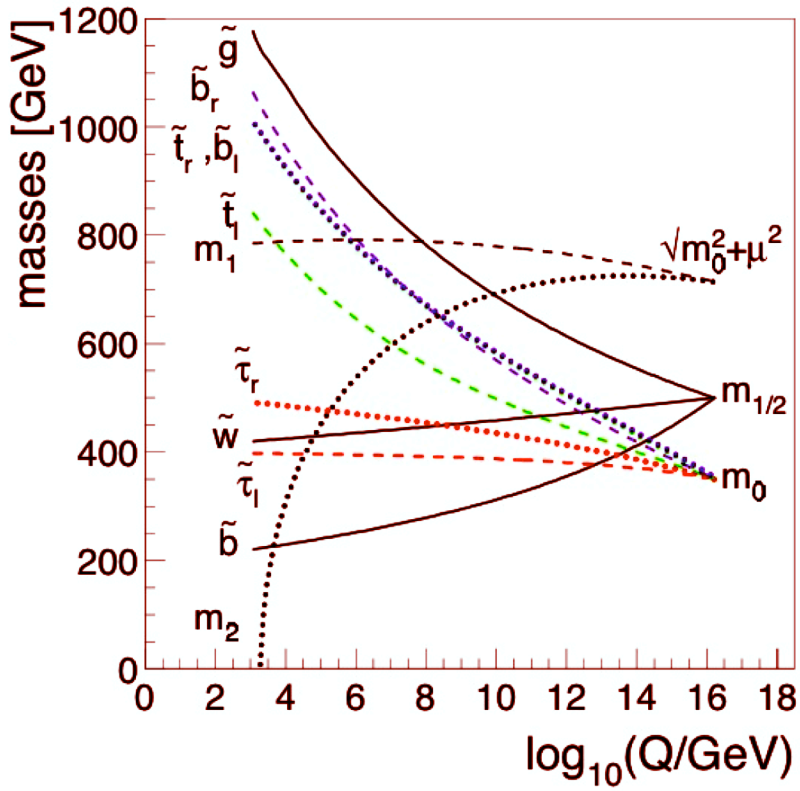
The scale of SUSY breakdown must be of order 1 TeV, if SUSY is associated with scale of electroweak symmetry breakdown

- **EWSB is radiatively generated**

In the evolution of masses from high energy scales

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

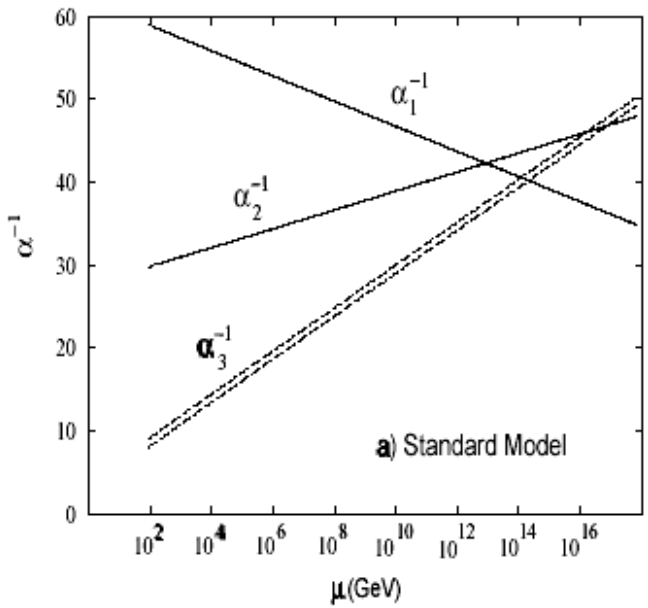
==> important top quark Yukawa effects!



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

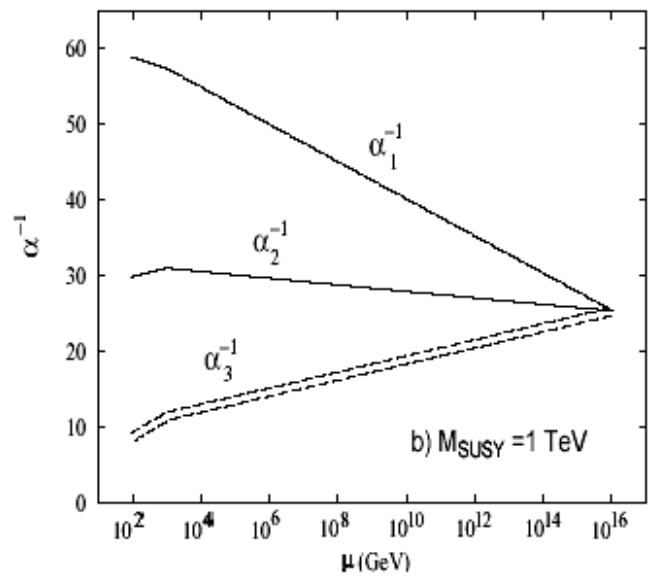
SM:

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.



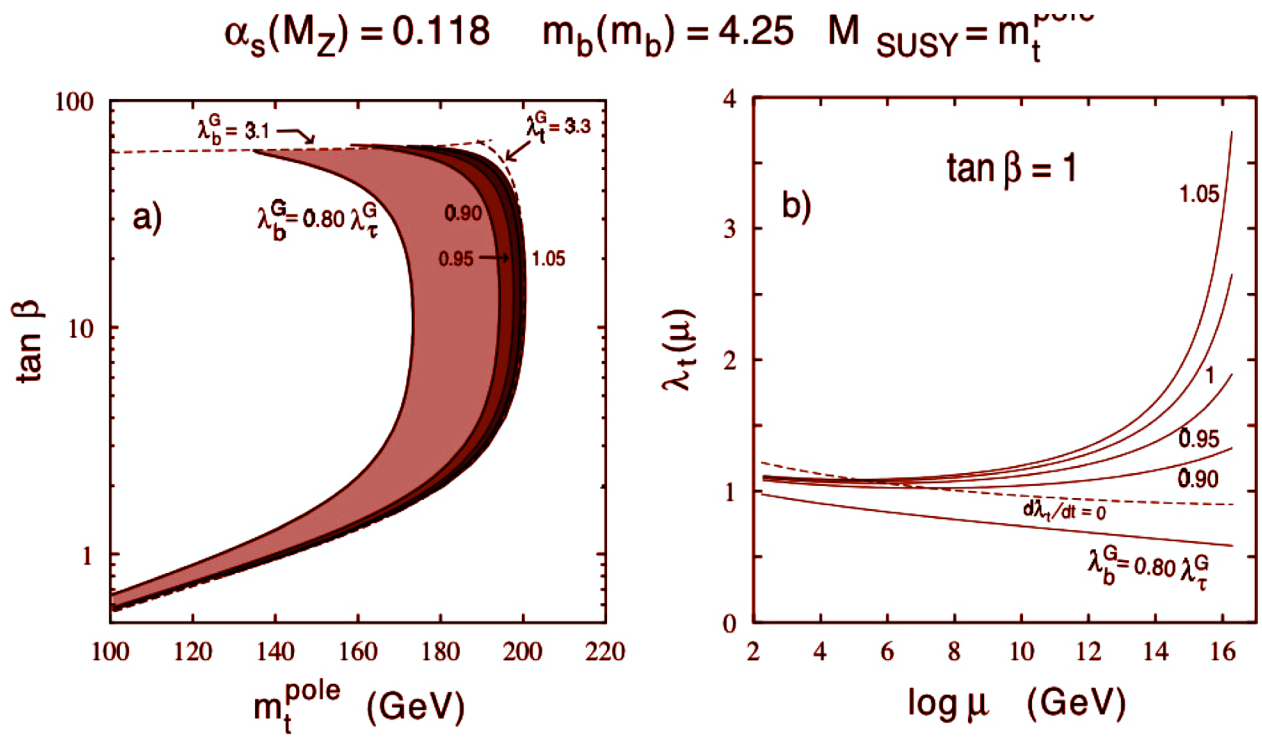
Experimentally, $\alpha_3(M_Z) \simeq 0.118 \pm 0.004$

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

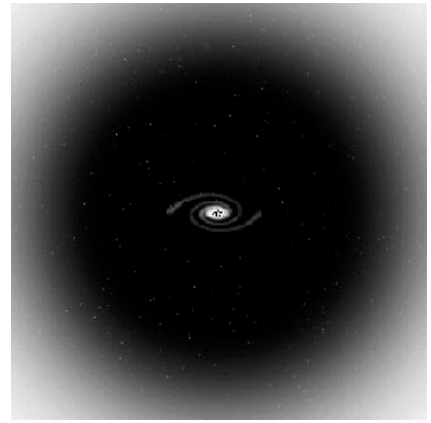
$\longrightarrow$ varying $h_t(m_t)$ prediction $\qquad \tan\beta = v_2/v_1; \quad m_t = h_t v_2$

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

Bardeen, M.C., Pokorski, Wagner

- **Provides a good Dark Matter candidate**

What is Dark Matter?
one of the fundamental open questions
==> demands new physics



- **Most suitable candidates beyond the Standard Model**:

==> Weakly interacting particles (WIMPS) with masses and interaction cross sections of order of the electroweak scale

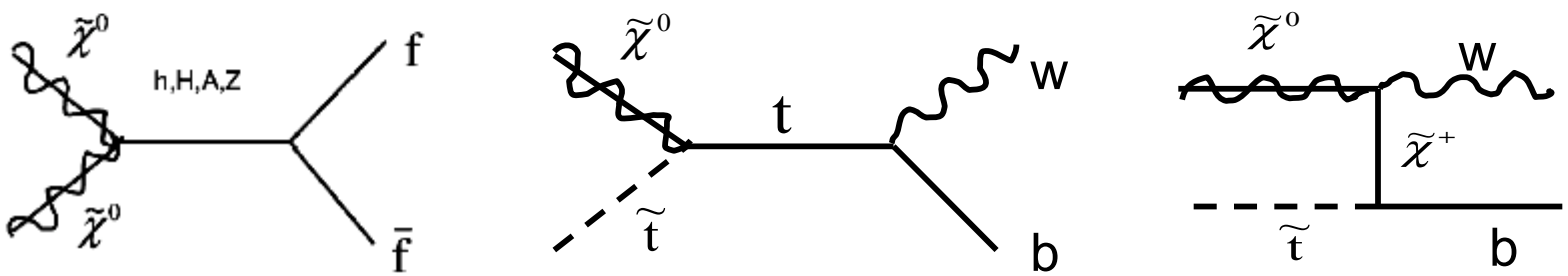
SUSY with R-parity discrete symmetry conserved $R_P = (-1)^{3B+L+2S}$

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

$$\Omega_{CDM} \sim 1 \,/\, \int_0^{x_F} \langle \sigma_A \, v \rangle \, dx \qquad x \equiv \frac{M}{T}$$

$0.089 < \Omega_{CDM} h^2 < 0.131$ WMAP at 3 σ

Many processes contribute to the $\tilde{\chi}_1^0 \, \tilde{\chi}_1^0$ annihilation cross section: $\langle \sigma_A \, v \rangle$



What Happened to the Antimatter?

- Anti-matter is governed by the same interactions as Matter.
- Was produced with same abundance as regular matter at the birth of the universe.
- But....observable Universe is mostly made of Matter $N_B >> N_{\bar{B}}$

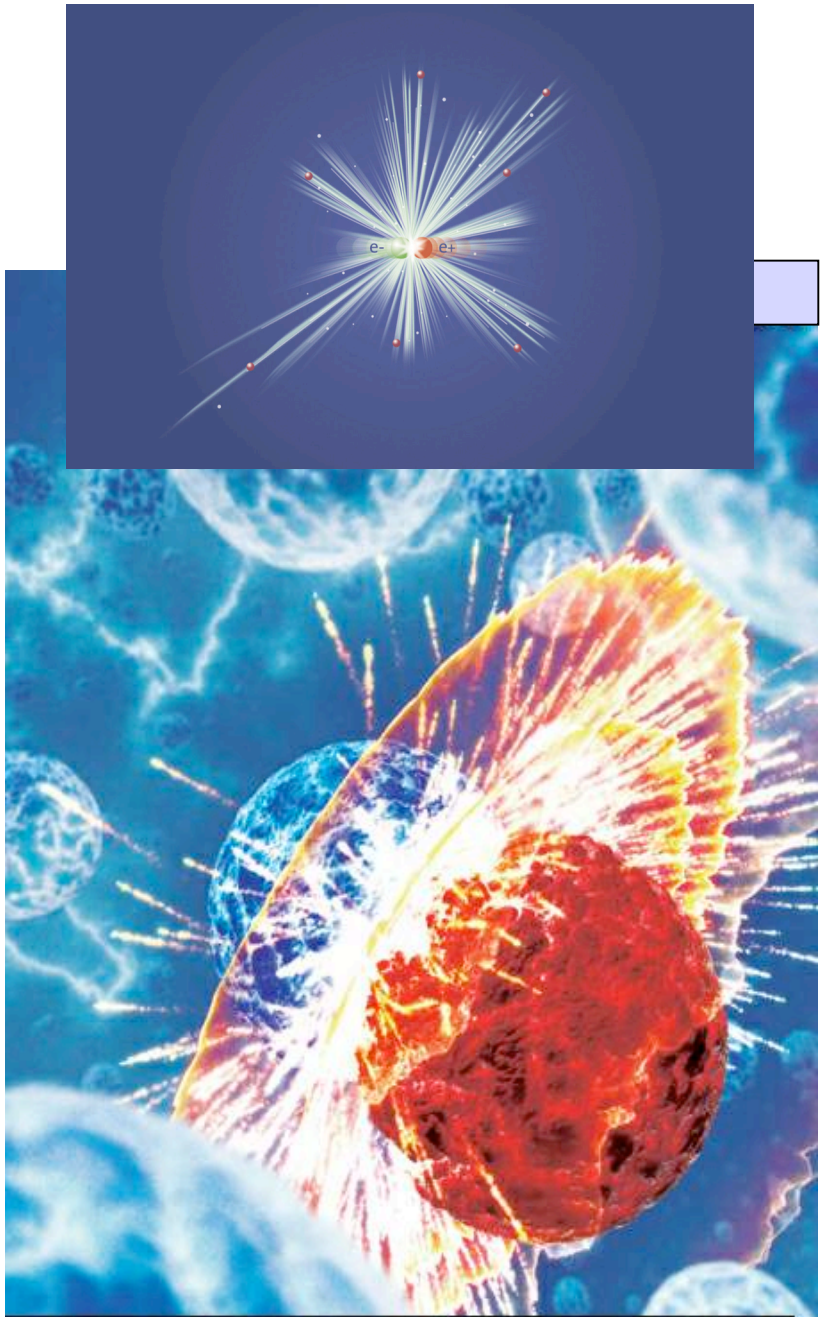
A tiny imbalance should have occurred at some point or it all would have annihilated, leaving only radiation

What generated $\eta = \frac{n_B}{n_\gamma} \approx \left(6^{+0.3}_{-0.2}\right) 10^{-10}$ *?*

To remove preferentially antimatter,
the CP symmetry which transforms
Matter into Antimatter must be violated.

CP-violation is present in the SM but
is insufficient by many orders of magnitude

We search for new sources of CP-violation:
in quarks or neutrinos,
in the Higgs properties, in SUSY.



Baryogenesis at the Electroweak Phase transition

Kuzmin, Rubakov and Shaposhnikov, '85-'87
Cohen, Kaplan and Nelson '93

- 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 $n_B = 0$ at T > Tc, independently

of the source of baryon asymmetry

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

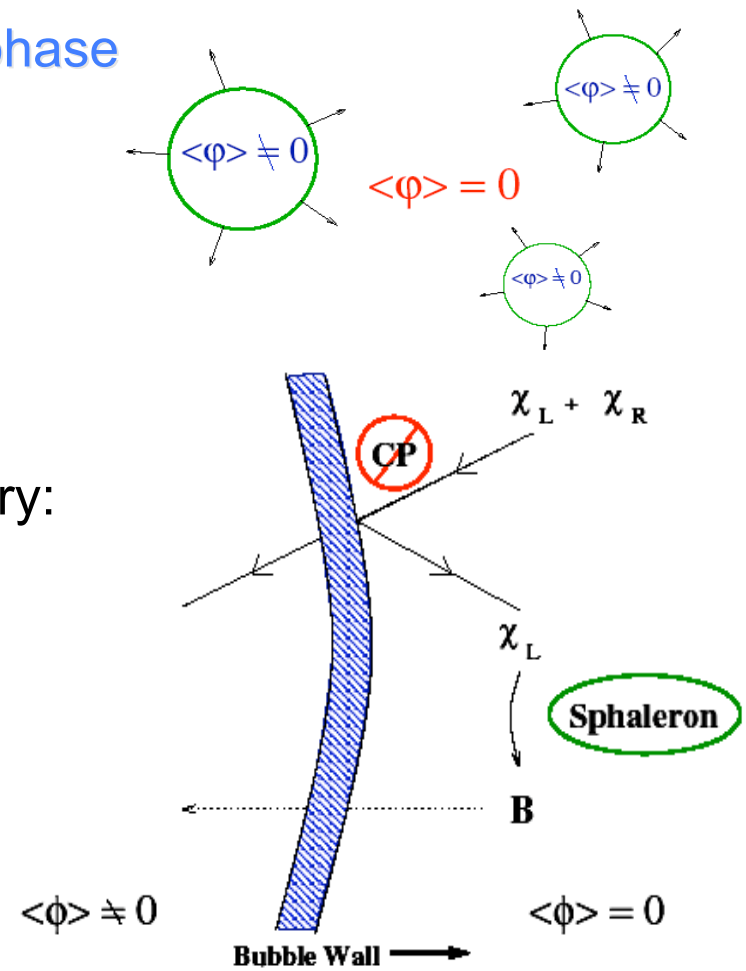
To preserve the generated baryon asymmetry:
strong first order phase transition:

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

Shaposhnikov '86-'88

Baryon number violating processes out of equilibrium in the broken phase

- **In the SM ==> $m_{H_{SM}}$ < 40 GeV**

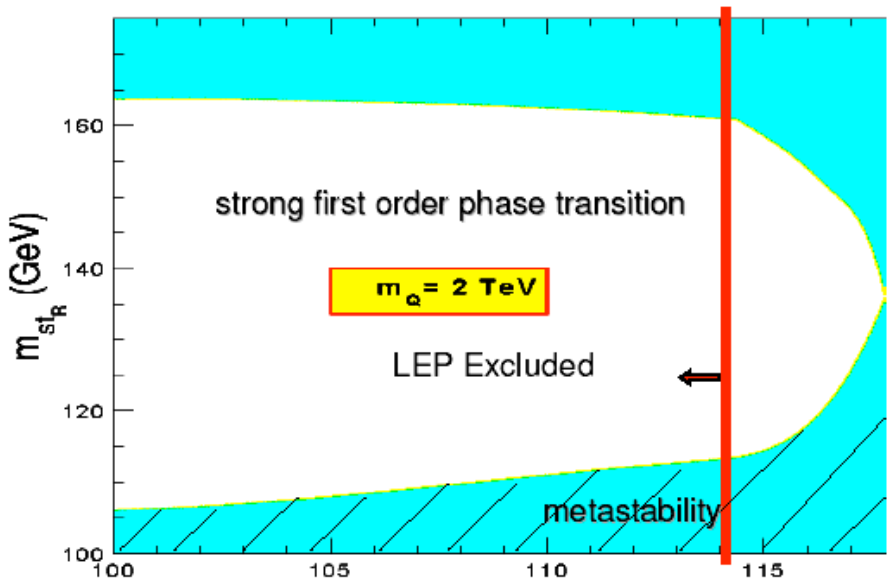


- **Provides a solution to the matter-Antimatter Asymmetry**

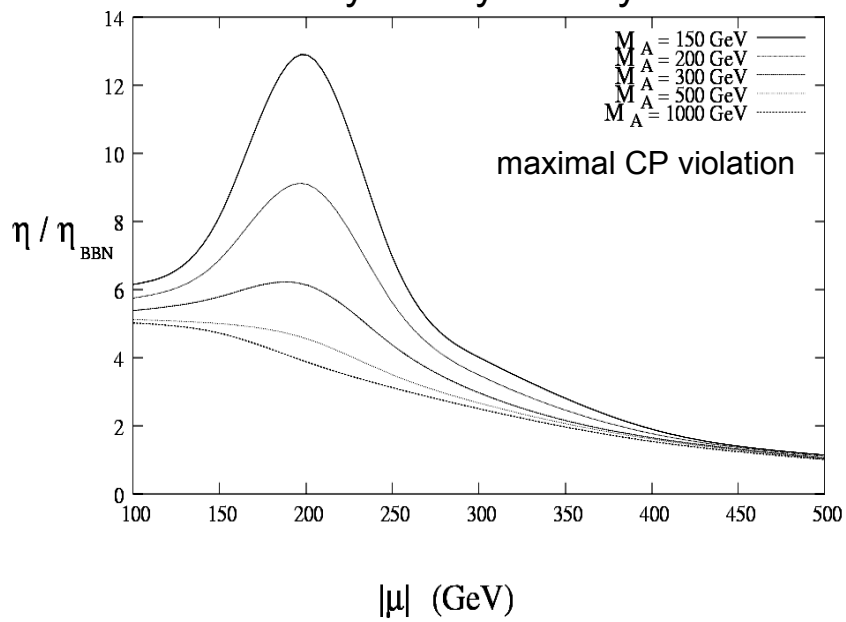
SUSY opens the window for Baryogenesis at the electroweak scale (ruled out in the SM)

- Higgs associated with mass below 120 GeV and SM-like properties
- The lightest stop must have mass below the top quark mass.

M.C., M.Quiros, M.Seco, C.E.M.Wagner



Baryon Asymmetry



If the Higgs is heavier but below 200 GeV ==> heavier stops and gauginos more strongly coupled can do the job as well.

M.C., Quiros , Wagner, Megevand.

Preferred: Gaugino and Higgsino masses of the order of the weak scale and smaller m_A

Resonant enhancement: $M_2 = |\mu|$

Electroweak Baryogenesis: *only testable model of baryon asymmetry generation*

The Connection between Higgs and Flavor Physics

The Flavor Structure in the SM

- In the mass eigenstate basis, the Higgs field interactions are also flavor diagonal

$$\bar{d}_{R,i}(\hat{h}_d^{ij}\ \phi)\ d_{L,j} + h.\ c. \rightarrow \bar{d}_i(m_i + h_i\phi)d_i \qquad \text{with}\ \ m_i = h_i \mathrm{v}$$

Flavor Changing effects arise from charged currents, which mix left-handed up and down quarks: $\bar{u}_{L,i}V_{CKM}^{ij}\gamma_\mu d_{L,j}W_\mu^+ + h.c.$ where $V_{CKM} = U_L^\dagger D_L$

- The CKM matrix is almost the identity ==> Flavor changing transitions suppressed
- The Higgs sector and the neutral gauge interactions do not lead to FCNC

Flavor Beyond the Standard Model

Two Higgs doublet Models: Yukawa interactions ==> $\bar{d}_{R,i}(\hat{h}_{d,1}^{ij}\ \phi_1 + \hat{h}_{d,2}^{ij}\ \phi_2)\ d_{L,j}$

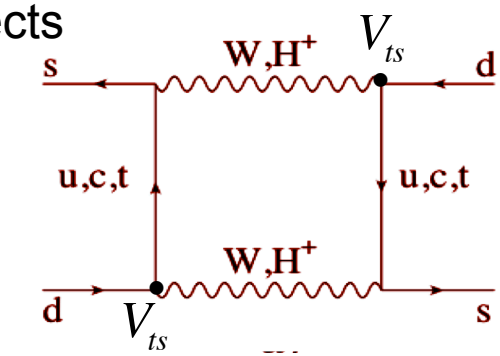
Different v.e.v.'s ==> $\hat{m}_d^{ij} = \hat{h}_{d,1}^{ij}\mathrm{v}_1 + \hat{h}_{d,2}^{ij}\mathrm{v}_2$

Diagonalization of the mass matrix will not give diagonal Yukawa couplings ==> will induce large, usually unacceptable FCNC in the Higgs sector

Solution: Each Higgs doublet couples only to one type of quarks ==> SUSY at tree level

The Flavor Problem in SUSY Theories

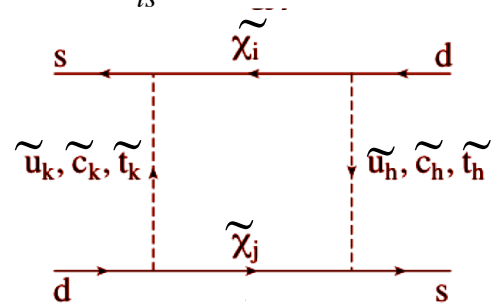
~~SUSY~~ mechanisms ==> can give rise to large FCNC effects



Minimal Flavor Violation

- At tree level: the quarks and squarks diagonalized by the same matrices $\tilde{D}_{L,R} = D_{L,R}; \quad \tilde{U}_{L,R} = U_{L,R}$

Hence, in the quark mass eigenbasis the only FC effects arise from charged currents via V_{CKM} as in SM.



- At loop level: FCNC generated by two main effects:

1) Both Higgs doublets couple to up and down sectors
==> important effects in the B system at large tan beta

Isidori, Retico: Buras et al.

2) Soft ~~SUSY~~ parameters obey Renormalization Group equations:
given their values at the ~~SUSY~~ scale, they change significantly at low energies
==> RG evolution adds terms prop. to $h_d h_d^+$ and $h_u h_u^+$, and h.c.

In both cases the effective coupling governing FCNC processes

$$(X_{FC})_{ij} = (h_u^+ h_u)_{ij} \propto m_t^2 \, \mathrm{V}_{3i}^{\mathrm{CKM}*} \mathrm{V}_{3j}^{\mathrm{CKM}} \qquad \text{for } i \neq j$$

D'Ambrosio, Giudice, Isidori, Strumia

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.

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 $m_A \approx m_H \approx m_{H^{\pm}}$

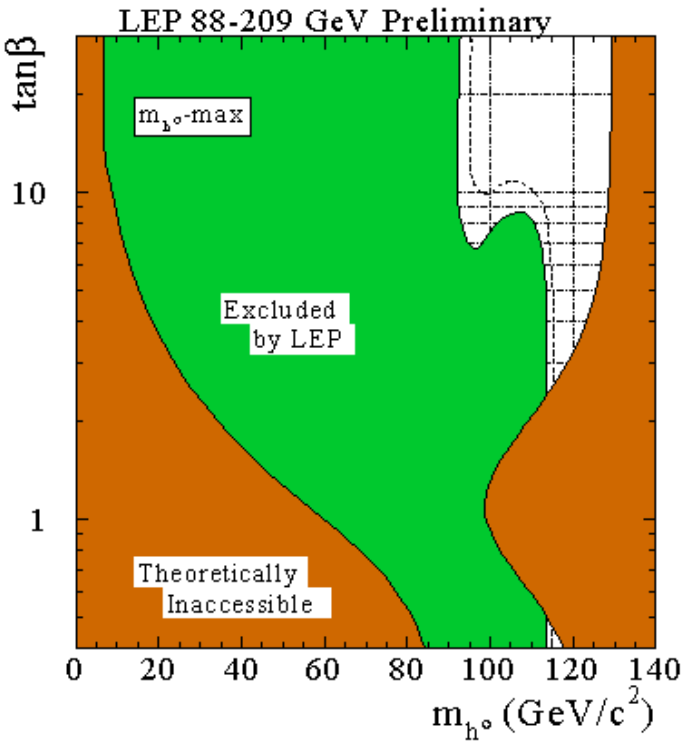
LEP MSSM HIGGS limits: $\longrightarrow$ $m_{H^{\pm}} > 78.6\mathrm{GeV}$

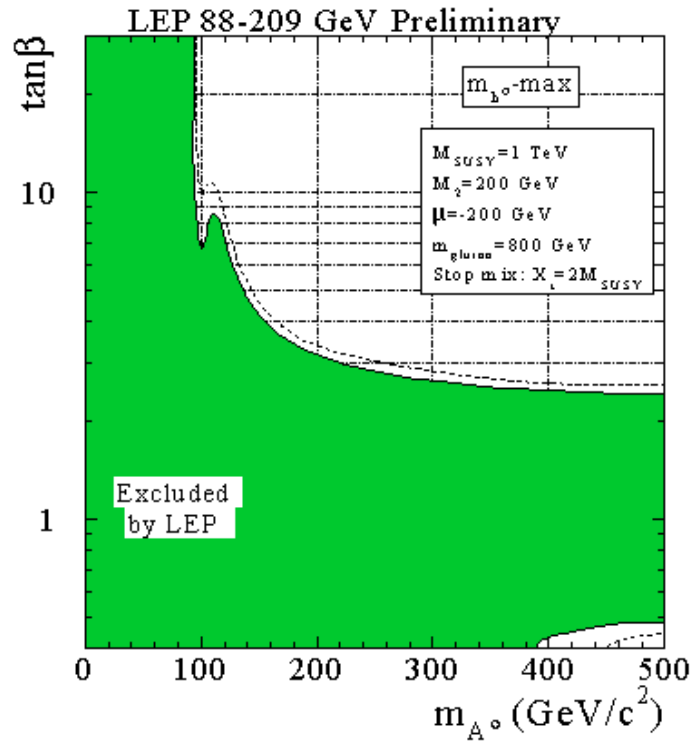
$m_h > 91.0$ GeV; $m_{A,H} > 91.9$ GeV; $m_h^{\mathrm{SM-like}} > 114.6\mathrm{GeV}$

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

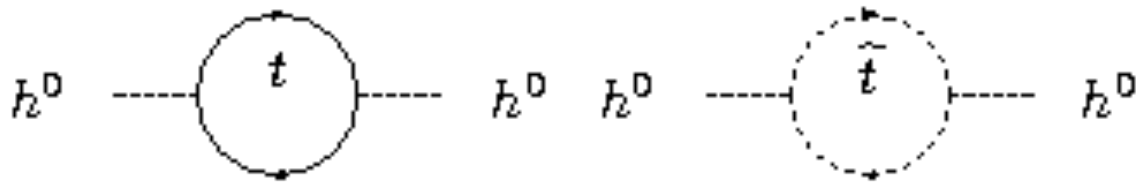
Charged Higgs $m_{H^\pm} > 78.6 GeV$

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



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

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

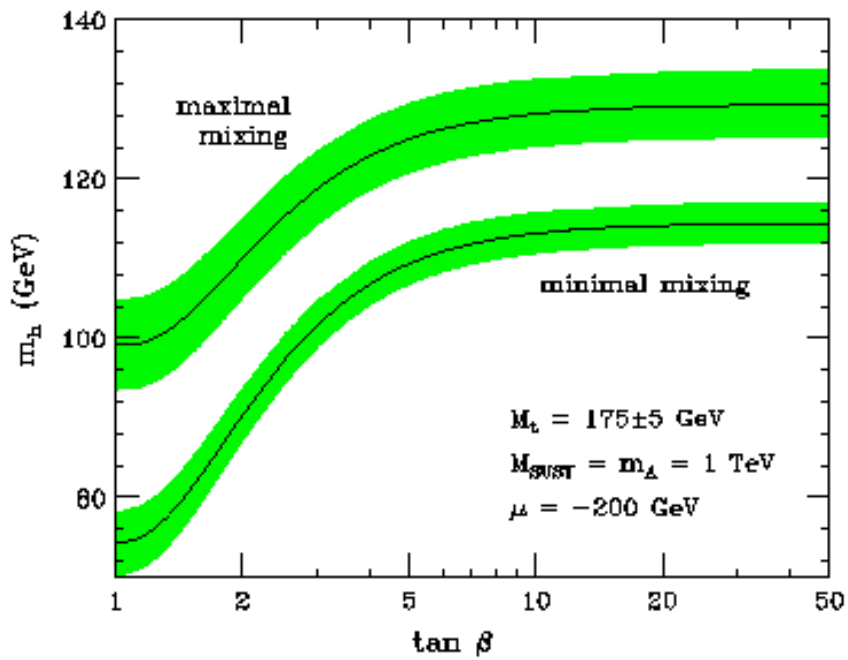
- m_t^4 **enhancement**
- **log sensitivity to stop masses** M_S
- **depend. on stop mass mixing** X_t

After 2 -loop corrections

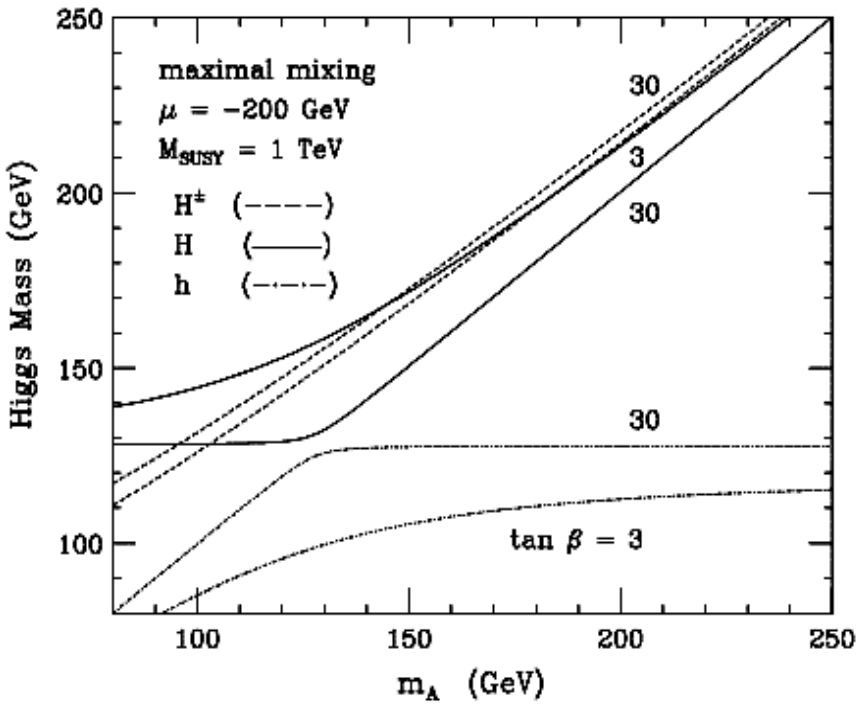
$$m_h \leq 135 \text{ GeV}$$

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 $m_{H^\mp}$)

Radiative Corrections to the Higgs Couplings

1) Through radiative corrections to the CP-even Higgs mass matrix δM_{ij}^2 , which defines the mixing angle α

$$\sin\alpha\cos\alpha = M_{12}^2 / \sqrt{\left(\mathrm{Tr}\, M^2\right)^2 - 4\det M^2}$$

The off diagonal elements are prop. to

M.C. Mrenna, Wagner

$$M_{12}^2 \propto -\left(m_A^2 + m_Z^2\right)\cos\beta\sin\beta + \frac{m_t^4}{16\pi^2 \mathrm{v}^2}\frac{\mu X_t}{M_S^2}\left(\frac{X_t^2}{M_S^2} - 6\right)$$

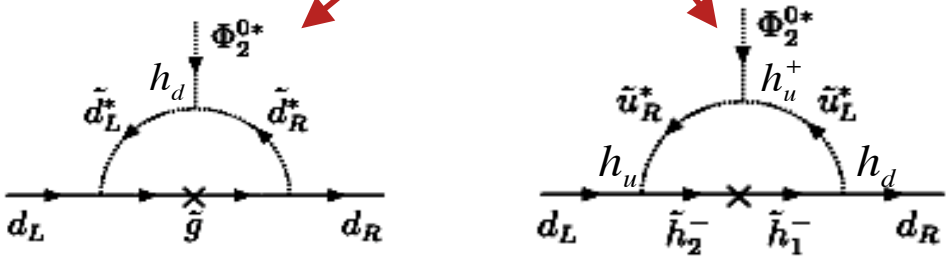
Important effects of rad. correc. on $\sin\alpha$ or $\cos\alpha$ depending on the sign of μX_t and the magnitude of X_t / M_S

===> govern couplings of Higgs to fermions
===> via rad. correc. to $\cos(\beta-\alpha)$ and $\sin(\beta-\alpha)$ governs couplings to vector bosons

When off-diagonal elements vanish, possible for small m_A and large tan beta
===> either $\sin\alpha$ or $\cos\alpha$ vanish ===> strong
suppression of the SM-like Higgs boson coupling to bottom-quarks and tau-leptons

2) Vertex corrections to neutral Higgs-fermion couplings ($\tan\beta$ enhanced)

$$-L_{eff.} = \bar{d}_R^0 \hat{h}_d \left[\phi_1^{0^*} + \phi_2^{0^*} \left(\hat{\varepsilon}_0 + \hat{\varepsilon}_Y \hat{h}_u^+ \hat{h}_u \right) \right] d_L^o + \phi_2^0 \bar{u}_R^0 \hat{h}_u u_L^0 + h.c.$$



ε loop factors intimately connected to the structure of the squark mass matrices.

- **<u>In terms of the quark mass eigenstates</u>** Dedes , Pilaftsis

$h_u = M_u / v_2$

$$-L_{eff} = \frac{1}{v_2}\left(\tan\beta\, \Phi_1^{0^*} - \Phi_2^{0^*}\right) \bar{d}_R M_d \left[V_{CKM}^+ R^{-1} V_{CKM} \right] d_L + \frac{1}{v_2} \Phi_2^{0^*} \bar{d}_R M_d d_L + \Phi_2^0 \bar{u}_R M_u u_L + h.c.$$

and $R = 1 + \varepsilon_0 \tan\beta + \varepsilon_Y \tan\beta |h_u|^2$ ➔ R diagonal with $R^{33} \equiv 1 + \Delta_b$

Dependence on SUSY parameters →

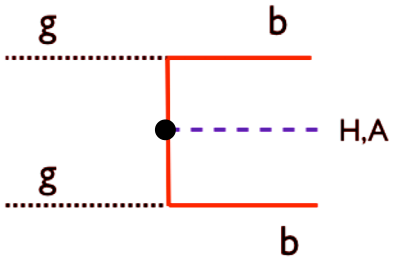
$$\varepsilon_0^i \approx \frac{2\alpha_s}{3\pi} \frac{\mu^* M_{\tilde{g}}^*}{\max\left[m_{\tilde{d}_1^i}^2, m_{\tilde{d}_2^i}^2, M_{\tilde{g}}^2\right]} \qquad \varepsilon_Y \approx \frac{\mu^* A_t^*}{16\pi^2 \max\left[m_{\tilde{t}_1}^2, m_{\tilde{t}_2}^2, \mu^2\right]}$$

Non-Standard Higgs Production at the Tevatron and LHC

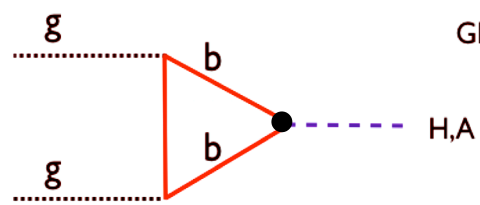
Looking at $V_{CKM} \cong I \Rightarrow$ Flavor Conserving Higgs-fermion couplings

- Important effects on couplings to b quarks and tau-leptons

destroy basic relation
$g_{\mathrm{h,H,Abb}} / g_{h,H,A\,\tau\tau} \propto m_b / m_\tau$



Associated Production



Gluon Fusion

$$\bullet \equiv g_{bbA/H} \approx \frac{m_b \tan\beta}{(1+\Delta_b)\mathrm{v}}$$

- Considering value of running bottom mass and 3 quark colors

$$BR(A \to b\bar{b}) \cong \frac{9}{9+(1+\Delta_b)^2} \Rightarrow \sigma(b\bar{b}A) \times BR(A \to b\bar{b}) \cong \sigma(b\bar{b}A)_{SM} \times \frac{\tan\beta^2}{(1+\Delta_b)^2} \times \frac{9}{(1+\Delta_b)^2+9}$$

$$BR(A \to \tau^+\tau^-) \cong \frac{(1+\Delta_b)^2}{9+(1+\Delta_b)^2} \Rightarrow \sigma(b\bar{b}, gg \to A) \times BR(A \to \tau\tau) \cong \sigma(b\bar{b}, gg \to A)_{SM} \times \frac{\tan\beta^2}{(1+\Delta_b)^2+9}$$

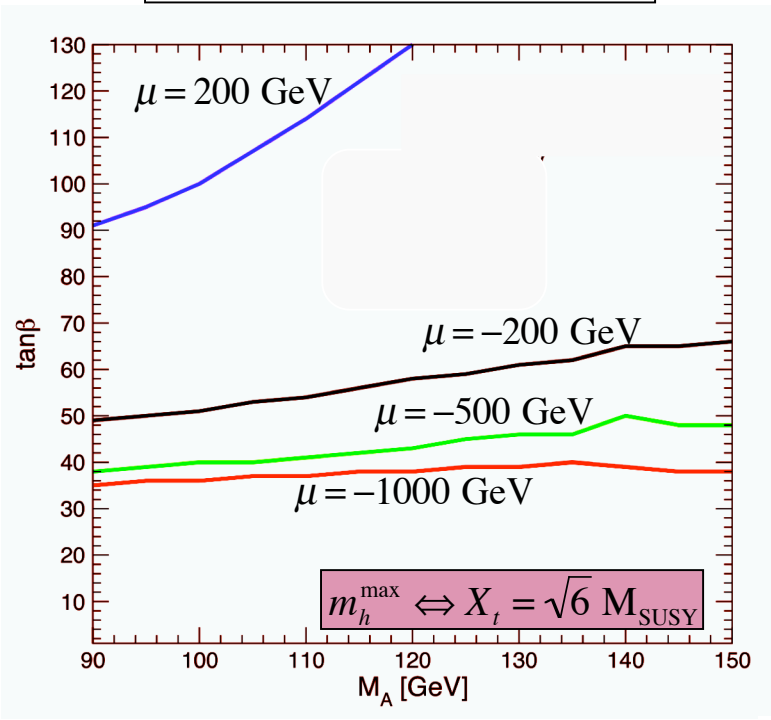
There is a strong dependence on the SUSY parameters in the bb search channel.
This dependence is much weaker in the tau-tau channel

Searches for Non-Standard Higgs bosons at the Tevatron

A) In the bb mode $p\bar{p} \to b\bar{b}\phi, \quad \phi \to b\bar{b}$

==> probe large region of $\tan\beta - m_A$ plane

$\Rightarrow$ based on D0 $\to 260\text{pb}^{-1}$



- Enhanced reach for negative values of μ
- Strong dependence on SUSY parameters

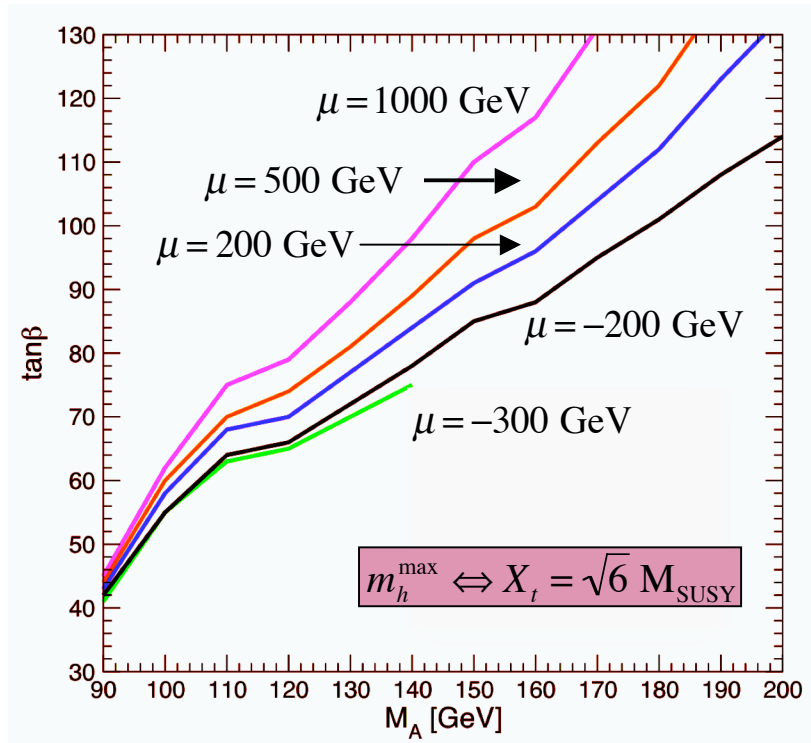
$$\sigma(b\bar{b}\phi)BR\left(\phi \to b\bar{b}\right) \propto 1/\left(1+\Delta_b\right)^2$$

$$\Rightarrow \text{enhanced for } \Delta_b < 0 \;\Leftrightarrow\; \mu < 0 \;\; (\text{if } A_t \text{ and } M_{\tilde{g}} > 0)$$

B) In the tau tau inclusive mode

$p\bar{p} \to X\phi, \quad \phi \to \tau^+\tau^-$

$\Rightarrow$ based on CDF : 310pb^{-1}

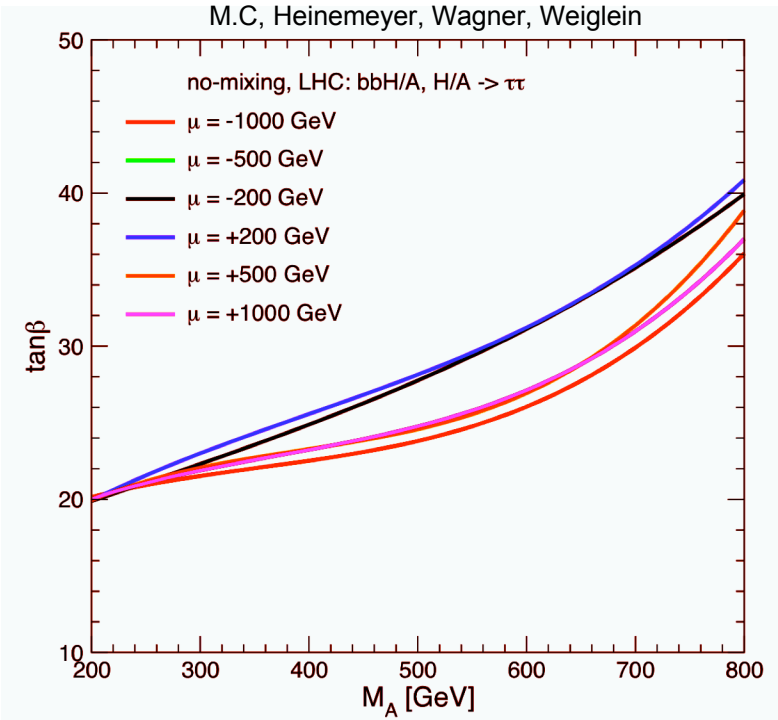


- Important reach for large tanb, small m_A
- Weaker dependence on SUSY parameters via radiative corrections

M. C., Heinemeyer, Wagner,Weiglein '05

Searches for Non-Standard Neutral Higgs bosons at the LHC

$pp \to A/H\,X,\;\; A/H \to \tau^+\tau^-,$ rescaling CMS prospects for 30 fb^{-1} (similar for ATLAS)



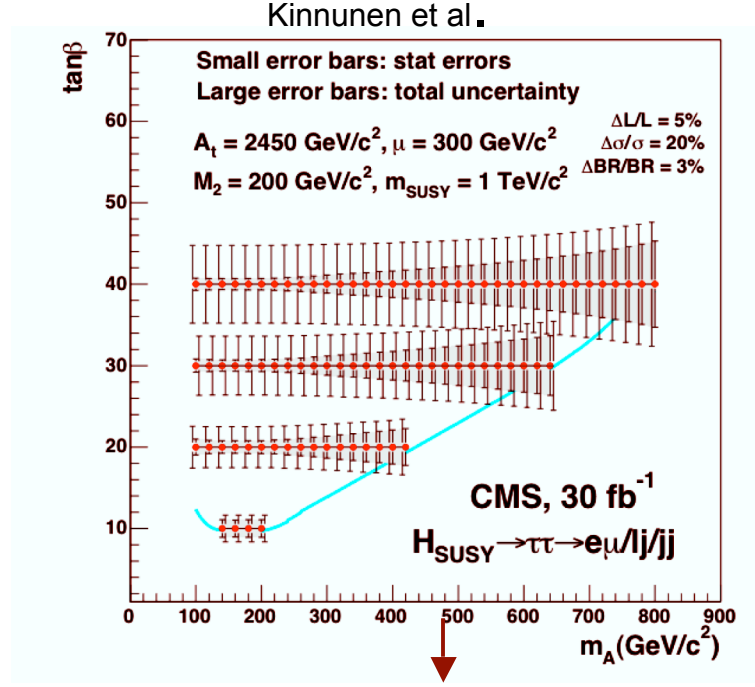
- Enhancement of Hbb and Abb couplings by factor $\tan\beta$ compared with SM Higgs.

  ==> large production cross section

  ==> decay dominated by $A/H \to \tau^+\tau^-$

  (with different decay modes of tau leptons)

Kinnunen et al.



Cancellation of Δ_b effects ==> projections stable under variations of SUSY space ==> $\boxed{\Delta\tan\beta \approx 8}$

main variation ==> $A/H \to \tilde{\chi}_i^0\tilde{\chi}_j^0,\;\; \tilde{\chi}_k^\pm\tilde{\chi}_l^\mp$

Robustness of results under variations of SUSY space ==>handle on tan beta

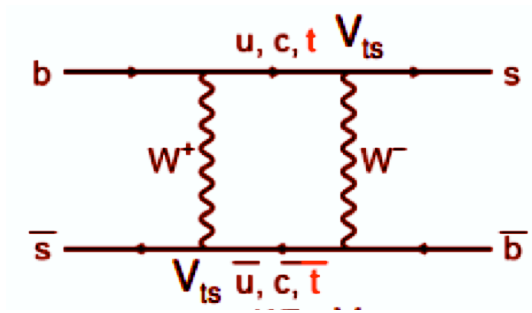
Indirect searches for MSSM Higgs bosons in B meson observables

B-observables: rare B-meson transitions mediated by charged currents involving FC effects

A) Bs mixing

$B_s^0 = (\bar{b}s)$ $\quad \bar{B}_s^0 = (b\bar{s})$

Flavor eigenstates mix via weak interactions →



Mass eigenstates:

$$B_H = pB_s^0 + q\bar{B}_s^0 \qquad B_L = pB_s^0 - q\bar{B}_s^0$$

The B meson mass matrix:

$$M = \begin{bmatrix} M - i\Gamma/2 & M_{12} - i\Gamma_{12}/2 \\ M_{12}^* - i\Gamma_{12}^*/2 & M - i\Gamma/2 \end{bmatrix}$$

$$\Gamma_{12} << M_{12}$$

$$\Delta M_s = M_{B_H} - M_{B_L} = 2\,|M_{12}| = \frac{G_F^2}{6\pi^2}\eta_B m_{B_S} \underbrace{\hat{B}_{B_S} f_{B_S}^2}_{\text{lattice}} M_W^2 S_0(m_t)\,|V_{ts}|^2$$

Short distance QCD corrections

Box-diagram

ΔM_S Direct Measurement and Global CKM Fit

Using ratio: $\frac{\Delta m_s}{\Delta m_d} = \frac{m_{Bs}}{m_{Bd}} \frac{f_{Bs}^2 B_{Bs}}{f_{Bd}^2 B_{Bd}} \frac{|V_{ts}|^2}{|V_{td}|^2}$

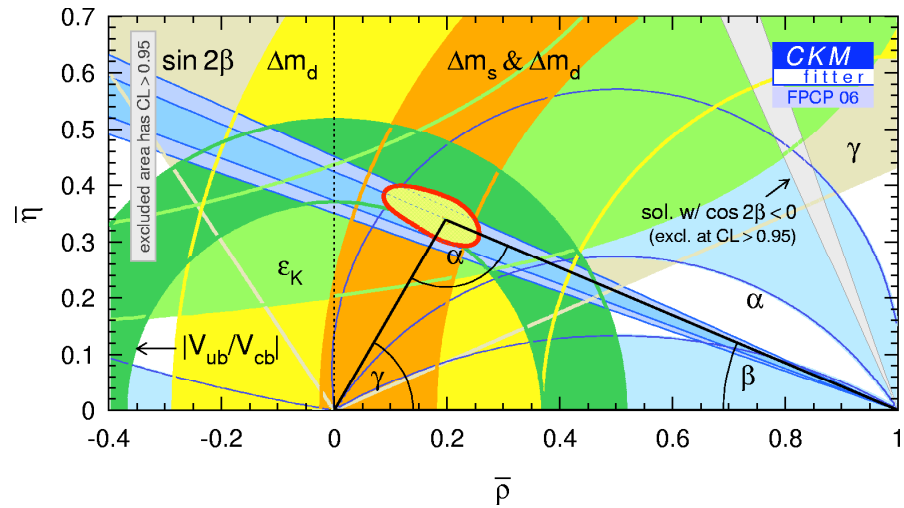
Minimize QCD lattice uncertainty providing a measurement of $|V_{ts}|/|V_{td}|$

CDF: $\Delta M_S = 17.7 \pm 0.10 \pm 0.07\, ps^{-1}$

SM fit :

$$\Delta M_S^{CKM} = 18.9^{+12.2}_{-5.5}\, ps^{-1}$$

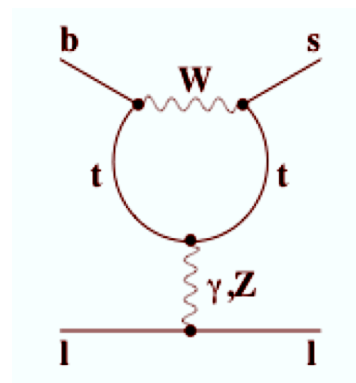
$$\Delta M_S^{UT} = 20.9 \pm 5.2\, ps^{-1}$$



2) Rare decay rate: $B_S \to \mu^+\mu^-$

SM amplitude $\propto V_{ts} \frac{m_\mu}{M_W}$

Initial state $B_S = (\bar{b}s)$



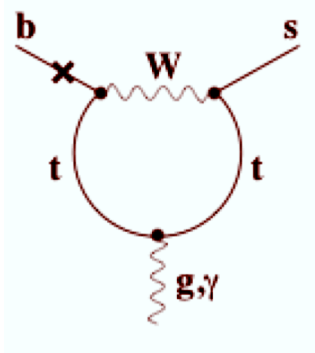
Final state

$$BR(B_s \to \mu^+\mu-)_{SM} \approx (3.8 \pm 1.0) \times 10^{-9}$$

- Present CDF limit: $BR(B_s \to \mu^+\mu^-) < 1.\, 10^{-7}$

A/H Higgs can affect these observables in a relevant way

3) Rare decay rate $B \to X_S \gamma$



$$\mathrm{BR}(B \to X_S \gamma)^{\mathrm{SM}} = (2.98 \pm 0.26) \times 10^{-4}$$

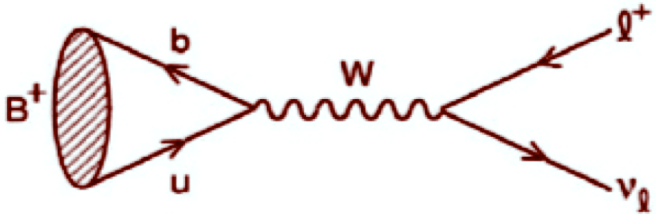
Considering world average measurement,

$$\mathrm{BR}(B \to X_S \gamma)^{\mathrm{exp}} = (3.55 \pm 0.24^{+0.09}_{-0.10}) \times 10^{-4}$$

and large theoretical uncertainty

2 σ allowed range for new physics ==> $\boxed{0.92 \le \frac{\mathrm{BR}(B \to X_S \gamma)^{\mathrm{exp}}}{\mathrm{BR}(B \to X_S \gamma)^{SM}} \le 1.46}$

4) $B_u \to \tau \nu$ transition



$$BR(B_u \to \tau\nu)^{SM} = \frac{G_F^2 m_B m_\tau^2}{8\pi}\left(1 - \frac{m_\tau^2}{m_B^2}\right) f_B^2 |V_{ub}|^2 \tau_B = (0.85 \pm 0.13) \times 10^{-4}$$

Latest result from Belle & Babar ==> $BR(B_u \to \tau\nu)^{\mathrm{exp}} = (1.31 \pm 0.48)\ 10^{-4}$

SUSY charged Higgs can contribute to flavor changing effects and affect in a relevant way the results for these B-meson observables

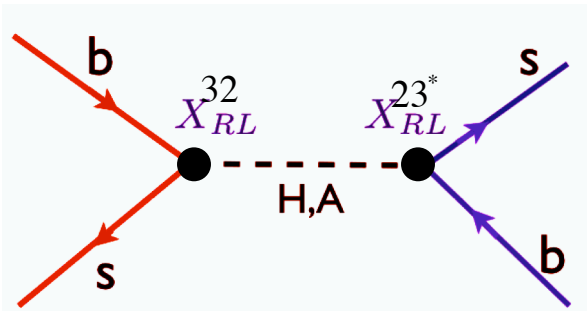
B and Higgs Physics at the Tevatron and the LHC

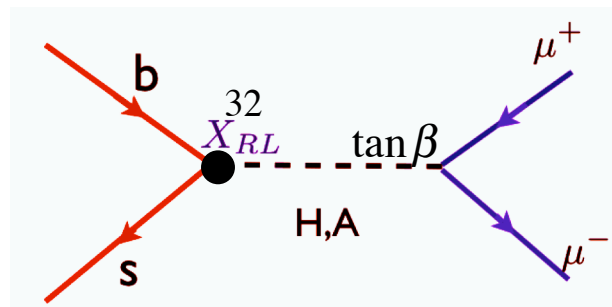
explore complementary regions of SUSY parameter space

Important Flavor Changing effects: 1) tree level ==> charged Higgs induced via V_{CKM}
2) tan beta enhanced loop corrections both in the neutral and charged Higgs sectors

- **Loop-induced Higgs mediated FCNC in the down-quark sector**

Correlation between Bs mixing and $\mathrm{BR}(B_S \to \mu^+\mu^-)$





$$\left(\Delta M_{B_S}\right)^{SUSY} \propto - \frac{X_{RL}^{32} X_{LR}^{32}}{m_A^2}$$

Negative sign with respect to SM

$$BR(B_S \to \mu^+\mu^-)^{SUSY} \propto \frac{\left|X_{RL}^{32}\right|^2 \tan\beta^2}{m_A^4} \propto \frac{\left|\mu A_t\right|^2 \tan\beta^6}{m_A^4}$$

with $$\left(\mathrm{X}_{\mathrm{RL}}^{\mathrm{H/A}}\right)^{ji} \approx -\frac{\bar{m}_{d_j}\, h_t^2\, \varepsilon_Y\, x_{\phi_1}^{H/A} \tan\beta^2}{\mathrm{v}\left(1+\varepsilon_0^{\mathrm{j}} \tan\beta\right)\left(1+\Delta_b\right)} \mathrm{V}_{\mathrm{CKM}}^{3\mathrm{j}^*} \mathrm{V}_{\mathrm{CKM}}^{3\mathrm{i}} \Longrightarrow \frac{\Delta M_{B_S}}{BR(B_S \to \mu^+\mu^-)} \propto \frac{m_A^2}{\tan\beta^2}$$

SUSY contributions strongly correlated

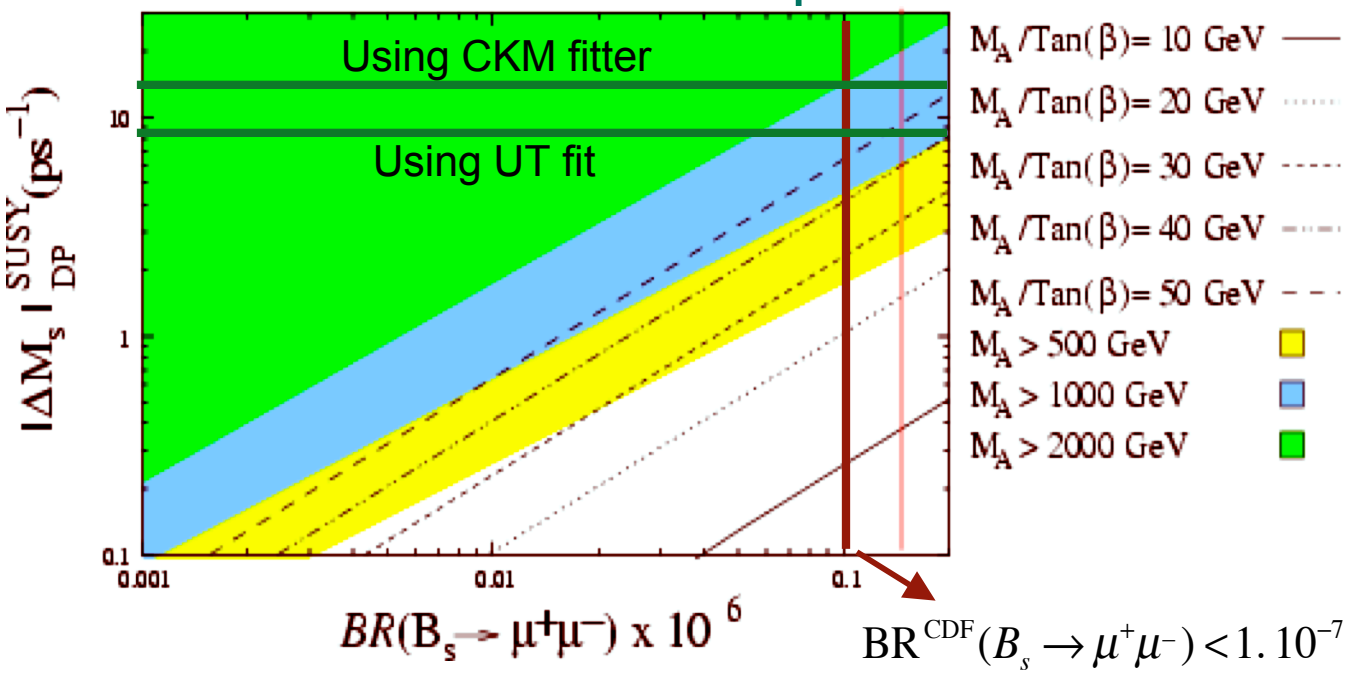
What can we learn from Bs-mixing?

How strong is the bound on $\mathrm{BR}(B_s \to \mu^+\mu-)$?

Upper bound on NP from CDF ==> $\Delta M_S = 17.7 \pm 0.10 \pm 0.07\, ps^{-1}$

$\Delta M_S^{CKM} = 18.9^{+12.2}_{-5.5}\, ps^{-1}$

$\Delta M_S^{UT} = 20.9 \pm 5.2\, ps^{-1}$



$\mathrm{BR}^{CDF}(B_s \to \mu^+\mu^-) < 1.\, 10^{-7}$

$\mathrm{BR}(B_s \to \mu^+\mu-)_{SM}$ of order 10^{-9}

↓

at the reach of LHC(b) with about 10(a few)fb^{-1}

↓

SUSY corrections can enhance it by 2 orders of magnitude.

M. C., Menon, Papaqui, Zsynkman, Wagner 06

For natural values of m_A< 1000 GeV ==> largest contributions at most a few ps-1

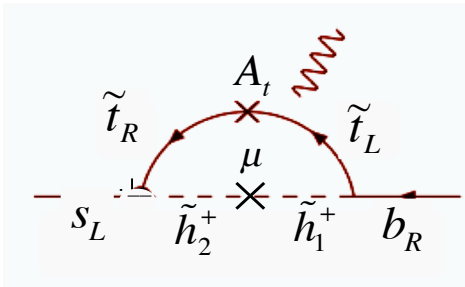
↕

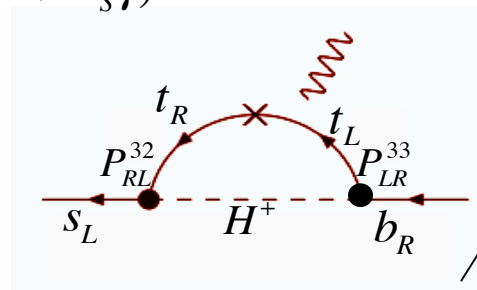
A/H at the reach of the Tevatron or the LHC <==> strong constraints on $|\Delta M_S|^{SUSY}_{DP}$

Flavor Changing in the charged Higgs coupling:

Similar to the neutral Higgs case ==> tanb enhanced SUSY loop corrections

- **Important SUSY contributions to** $BR(B \to X_S \gamma)$





$$\delta h_t \propto h_t \frac{2\alpha_S}{3\pi} \mu^* M_{\tilde{g}}$$

$$A_{\chi^+} \propto \frac{\mu A_t \tan\beta \, m_b}{(1+\Delta_b)} \, h_t^2 f[m_{\tilde{t}_1}, m_{\tilde{t}_2}, \mu] \, V_{ts}$$

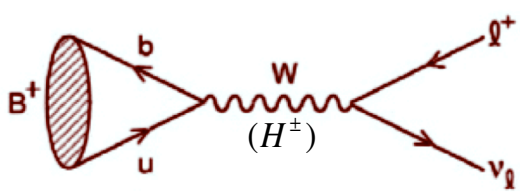
$$A_{H^+} \propto \frac{(h_t - \delta h_t \tan\beta) \, m_b}{(1+\Delta_b)} \, g[m_t, m_{H^+}] \, V_{ts}$$

If At ~0 + large $\mu M_{\tilde{g}} > 0$ ==> NO constraint on tanb-ma plane from $b \to s\gamma$

$$0.92 \leq \mathrm{BR}(B \to X_S\gamma)^{MSSM} / \mathrm{BR}(B \to X_S\gamma)^{SM} \leq 1.46 \quad 2\sigma \text{ range}$$

Becher and Neubert '06

- $B_u \to \tau\nu$ **transition**



In the MSSM ==> charged Higgs contribution interferes destructively with SM one.

$$R_{B_u \to \tau\nu} = \frac{\mathrm{BR}(B_u \to \tau\nu)^{MSSM}}{\mathrm{BR}(B_u \to \tau\nu)^{SM}} = \left[1 - \left(\frac{m_B^2}{m_{H^\pm}^2} \right) \frac{\tan\beta^2}{(1+\Delta_b)} \right]^2$$

Belle + Babar averaged:

$$BR(B_u \to \tau\nu)^{\exp} = (1.31 \pm 0.48) \; 10^{-4}$$

$$\Rightarrow 0.32 \leq R_{B_u \to \tau\nu} \leq 2.77 \quad \text{at } 2\,\sigma$$

Interplay between Higgs and B physics searches in different SUSY scenarios

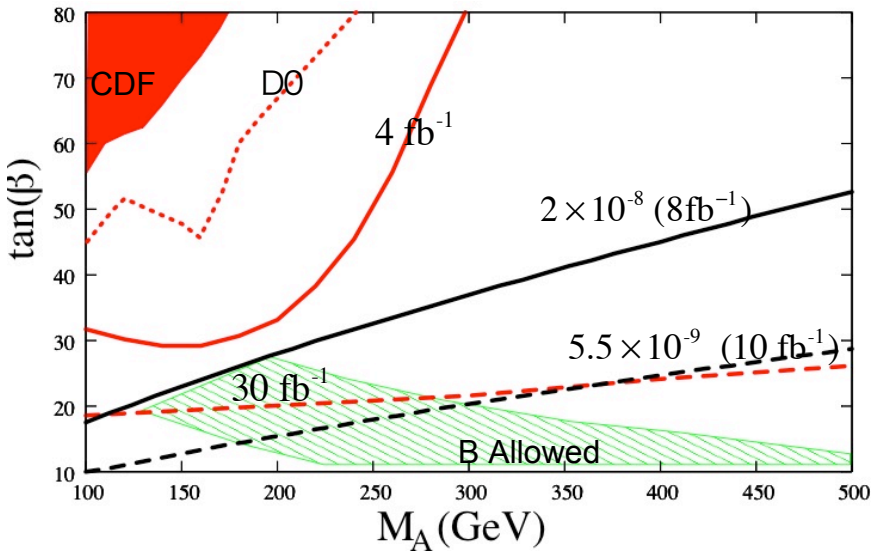
1) Non-SM-like Higgs and B-meson Searches

Large to moderate values of X_t ==> SM like Higgs heavier than 120 GeV

$BR(B_S \to \mu^+\mu^-) \propto |\mu A_t|^2 \Rightarrow$ Experimental bound ==> small μ

Small $\mu < 0$ ==> $\cong$ constant H^+ and enhanced negative $\chi^+ - \tilde{t}$ contributions to $BR(b \to s\gamma)$

M. C. et al. hep-ph/0603106 and hep-ph/0704.1143



Red $p\bar{p}, pp \to H/A \to \tau^+\tau^-$
-- 1 fb^{-1} (CDF and D0 excluded)
-- projected 4 fb^{-1} at the Tevatron
-- projected 30 fb^{-1} at the LHC

black lines: $BR(B_s \to \mu^-\mu^+)$ reach:

Tevatron: 2×10^{-8} (8fb^{-1})

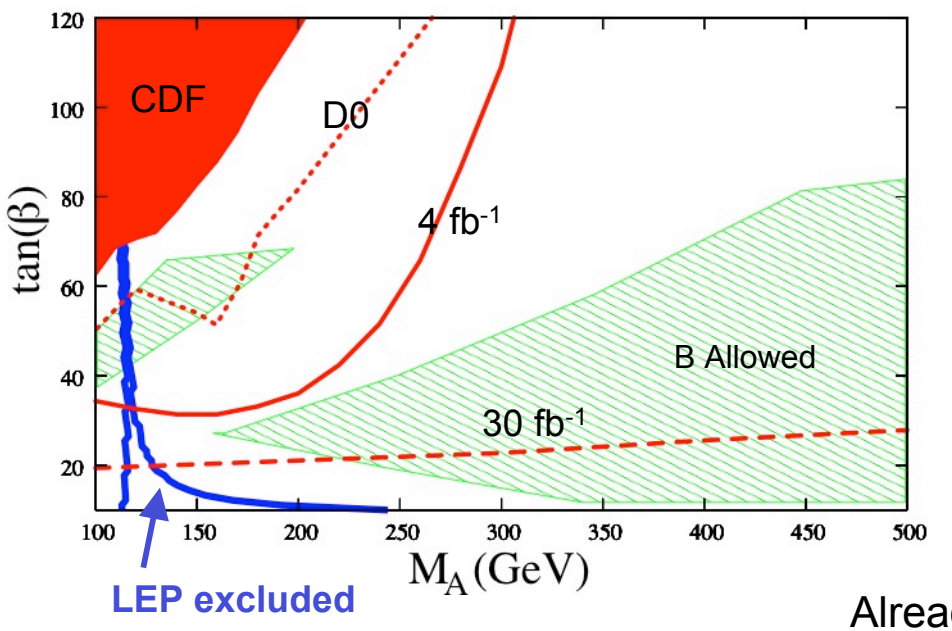
LHC: 5.5×10^{-9} (10 fb^{-1})

Hatched Area: Allowed regions by $BR(B_u \to \tau\nu)$, $BR(b \to s\gamma)$ and $BR(B_S \to \mu^+\mu^-)$

- Sizeable LR stop mixing <==> small/moderate mu
  ==> **B searches more powerful than Non-SM like Higgs searches**

- **Small X_t , sizeable μ ==> No mixing scenario**
  - Interesting region since light SM-like Higgs lighter than 125 GeV
  - **No constraints from** $\mathrm{BR}(B_s \to \mu^+\mu^-)$
  - Mild constraints from $\mathrm{BR}(\mathrm{b} \to \mathrm{s}\gamma)$ if large μ $\mathrm{M}_{\tilde{g}} > 0$
- Important constraint from recent measurement of $\mathrm{BR}(B_u \to \tau\nu)$

M.C., Menon, Wagner



Red: $p\bar{p}, pp \to H/A \to \tau^+\tau^-$
-- 1 fb^{-1} (CDF and D0 excluded)
-- projected 4 fb^{-1} at the Tevatron
-- projected 30 fb^{-1} at the LHC

Green: Allowed by B physics constraints

Blue: LEP Excluded from Higgs searches

↓

Already strong bounds on SM-like Higgs from LEP

==> Non-SM like neutral Higgs searches can cover areas compatible with B physics constraints

Discovery reach for a SM-like MSSM Higgs at the Tevatron

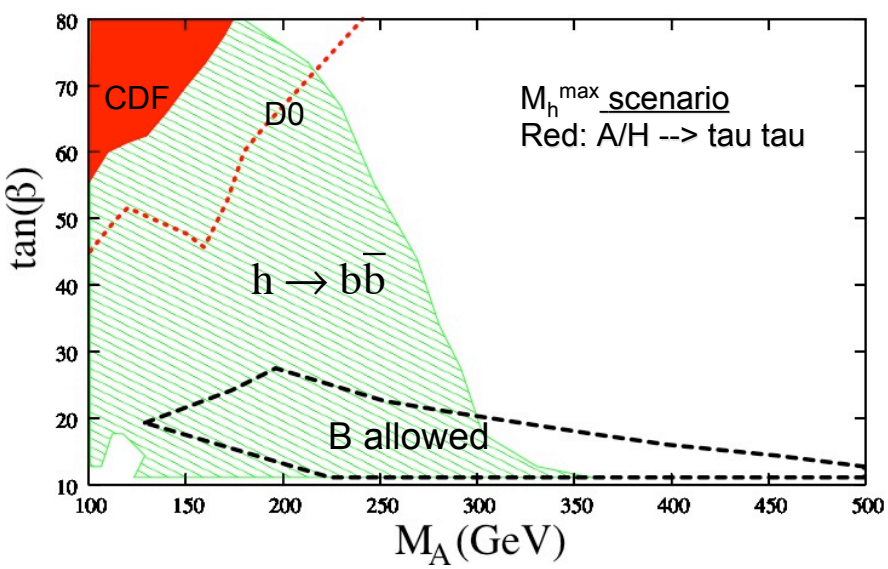
$p\bar{p} \rightarrow W/Z\ h$ with $h \rightarrow b\bar{b}$ with 4 fb^{-1}

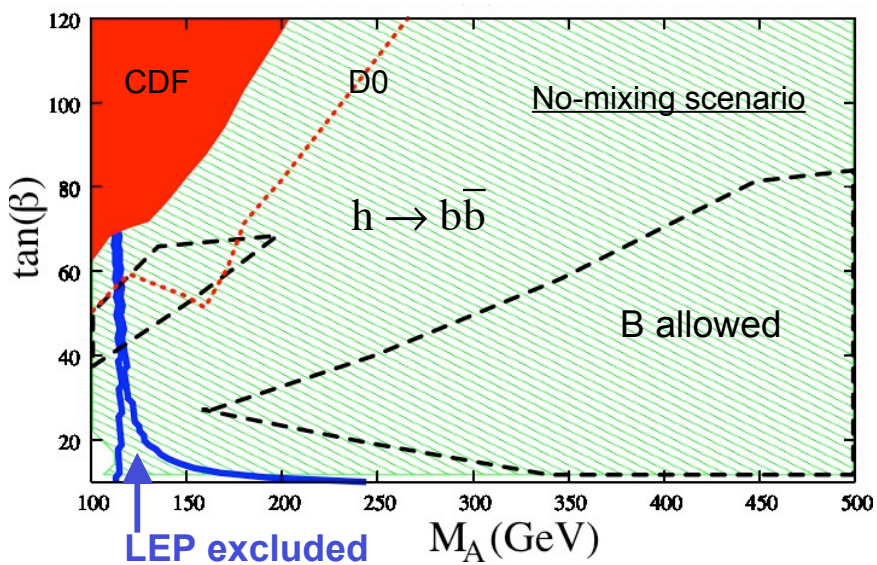
•The m_h^{max} scenario: $M_S = 1$ TeV ; $X_t = 2.4\ M_S$; $m_{\tilde{g}} = -0.8\ M_S$; $M_2 = -\mu = 200$GeV; $A_t = A_b$

-- Maximizes m_h and allows conservative tan beta bounds

-- $g_{hbb}, g_{h\tau\tau}$ enhanced due to $\sin\alpha_{eff}/\cos\beta$ factor for low m_A and intermediate and large tan beta (analogous for H if $m_A < m_h^{max}$)

==> strong suppression of $h \rightarrow \gamma\gamma$





•The No-Mixing scenario: X_t=0, M_S= 2 TeV ==> lightest Higgs mass < 125 GeV

==> similar behavior for Higgs couplings to tau leptons, bottom quarks and photons.

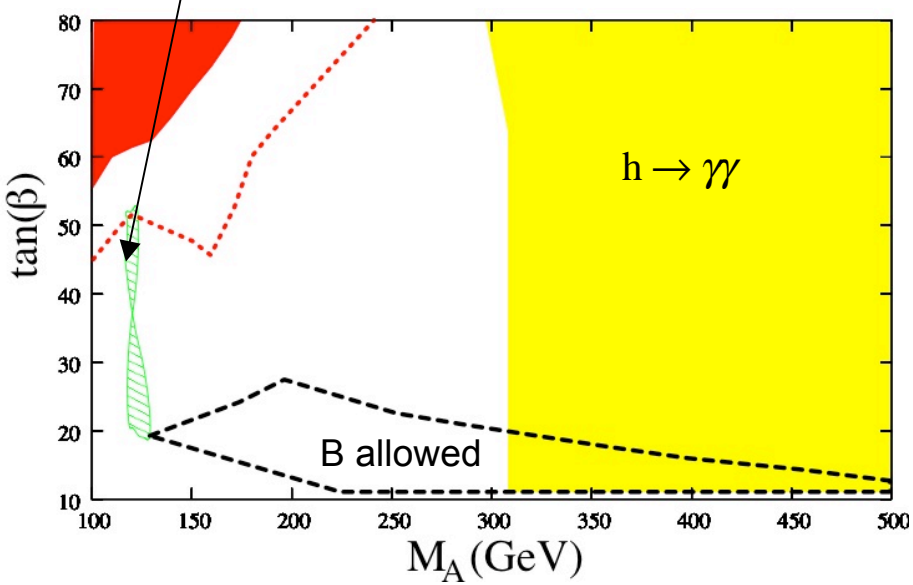
Tevatron may have sensitivity to discover all 3 MSSM neutral Higgs bosons

Discovery reach for SM-like MSSM Higgs at the LHC with 30 fb-1

- The m_h^{max} scenario: $M_S = 1\ \mathrm{TeV}$; $X_t = 2.4\ M_S$; $m_{\tilde{g}} = 0.8\ M_S$; $M_2 = -\mu = 200\mathrm{GeV}$; $A_t = A_b$

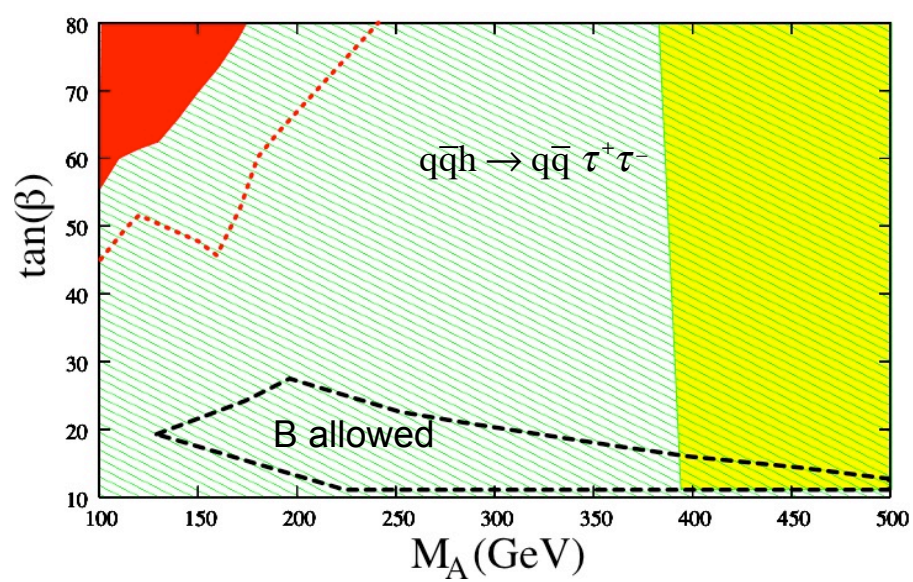
Production and decay channels: $q\bar{q}h \to q\bar{q}\ \tau^+\tau^-$ and $h \to \gamma\gamma$ inclusive

$q\bar{q}h \to q\bar{q}\ \tau^+\tau^-$ CMS Projections



ATLAS Projections

re-evaluating Higgs studies at present



First, full simulation analysis of qqH, H->ττ->l+jet,
Optimized $h \to \gamma\gamma$ Nikitenko, ICHEP 06

CMS can cover small part of B allowed region, with $h \to \gamma\gamma$ and $h \to \tau\tau$;
ATLAS tau tau channel seems to have full coverage with $h \to \tau\tau$

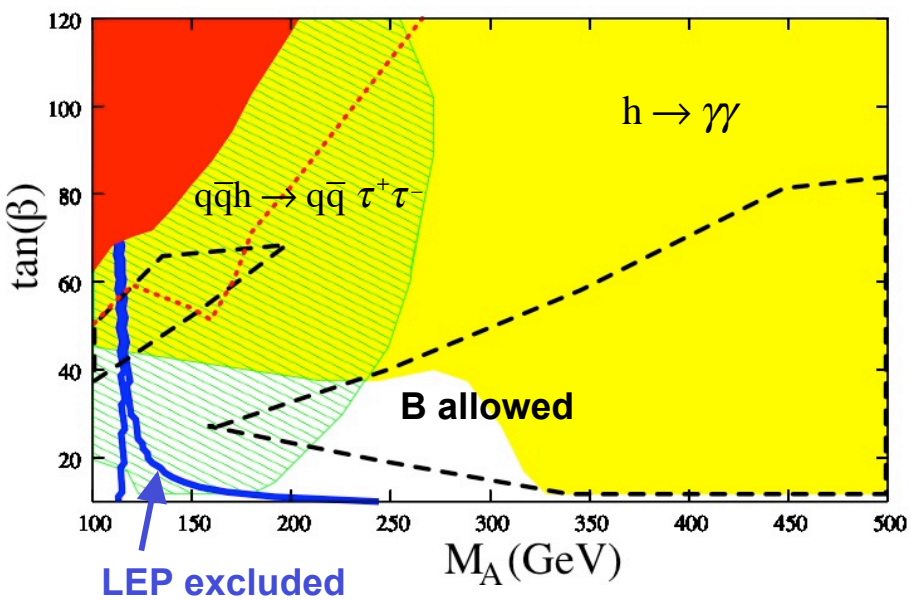
Discovery reach for SM-like MSSM Higgs at the LHC with 30 fb-1

•The No mixing scenario:

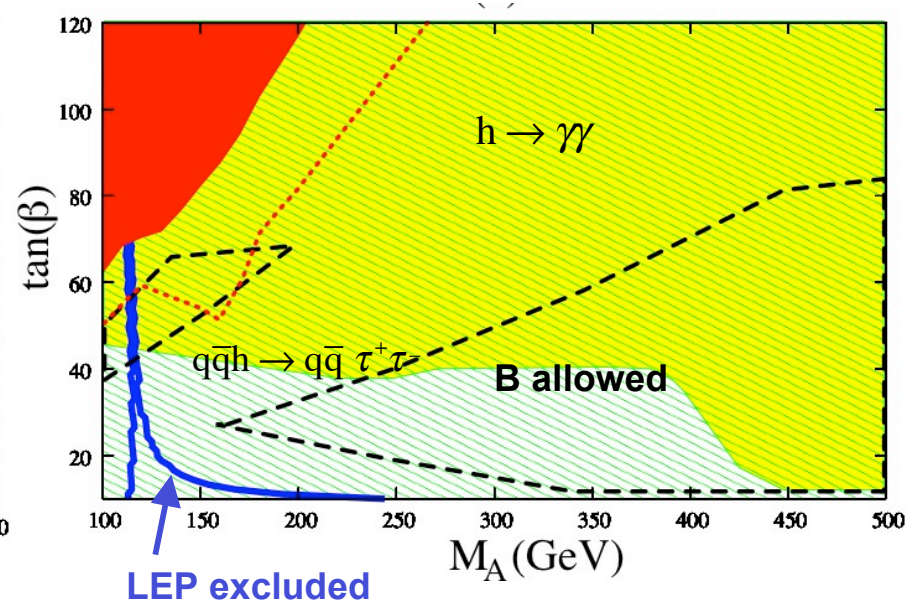
$$M_S = 2\ \text{TeV}\ ;\quad X_t = 0\ ;\ m_{\tilde{g}} = 0.8\ M_S\ ;\ M_2 = 200\text{GeV};\ A_t = A_b;\ \mu = 1.5\ \text{TeV}$$

Production and decay channels: $q\bar{q}h \to q\bar{q}\ \tau^+\tau^-$ and $h \to \gamma\gamma$ inclusive

CMS Projections



ATLAS Projections



SM-like Higgs needs di-tau and di-photon channels to secure discovery with 30 fb^{-1}
some B allowed regions remain uncovered

Prospects for SM–like Higgs searches at Tevatron and LHC for:

- The small $\sin\alpha_{eff.}$ (rad.correc. α) scenario:

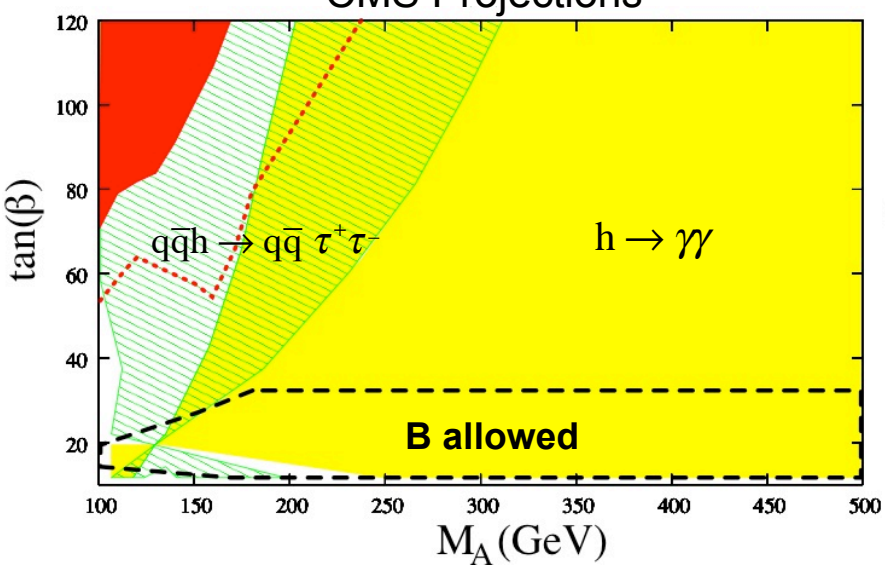
$$M_S = 800\ \text{GeV}\ ;\quad X_t = -\ 1.2\ \text{TeV}\ ;\ \mu = 2.5\ M_s\ ;\ m_{\tilde{g}} = M_2 = 500\text{GeV};\ \ A_t = A_b$$

==> $g_{hbb}, g_{h\tau\tau}$ importantly suppressed for large tan beta and small m_A, and in different ways due to Δ_b corrections

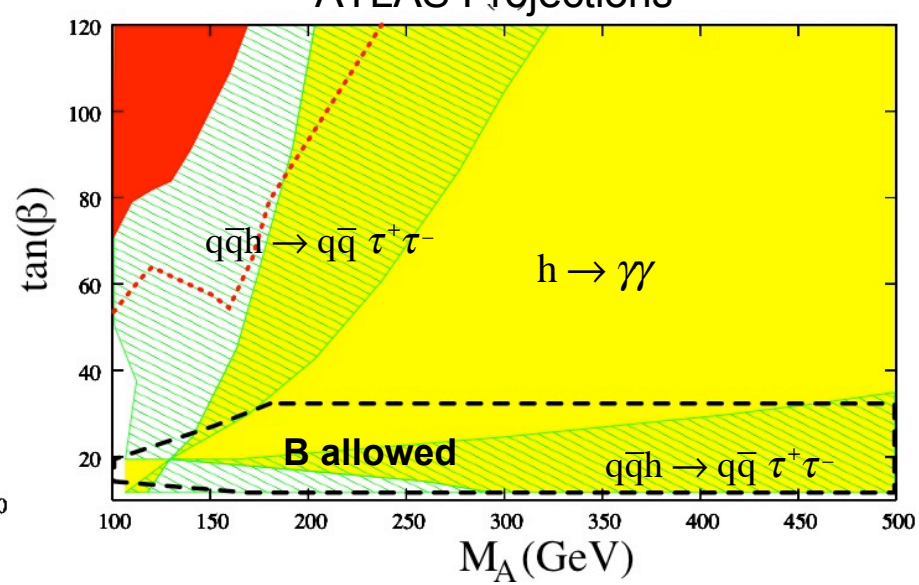
hence, $h \to \gamma\gamma$ channel enhanced with respect to SM

M.C., Menon. Wagner
Hep-ph/0704.1143

CMS Projections



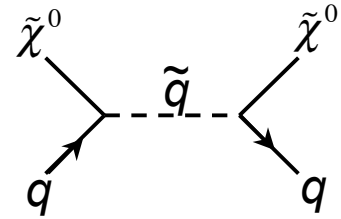
ATLAS Projections

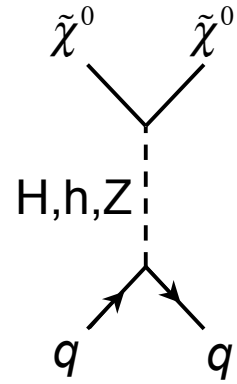


-- The Tevatron has almost no chance due to the suppressed hbb coupling
-- LHC: Complementarity in coverage
-- One can see a SM-like Higgs in the $\gamma\gamma$ channel and not in the $\tau^+\tau^-$channel

Direct Detection of WIMPs

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





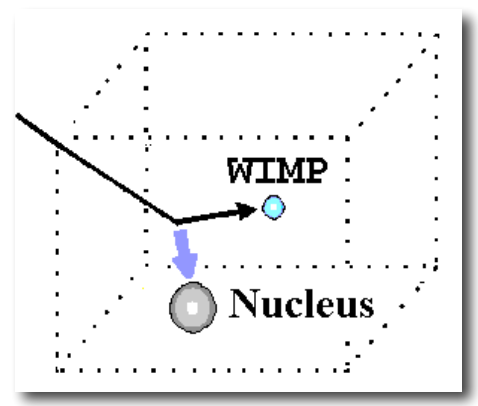
Main Ingredients to calculate signal:
Local density & velocity distribution of WIMPs and $\sigma_{n\chi}$
==> rate per unit time, per unit detector material mass

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

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



<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

Indirect searches for MSSM Higgs bosons via direct Dark Matter experiments

- **Collider experiments will find evidence of DM through $\not{E}_T$ signature**

knowledge of new physics particle masses and couplings will allow to compute DM-annihilation cross sections and elastic scattering WIMP-proton cross sections

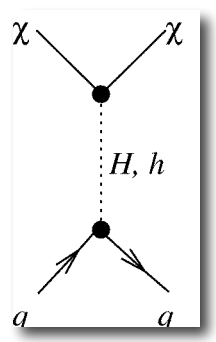
But only Direct Detection Experiments will confirm the existence of Dark Matter particles

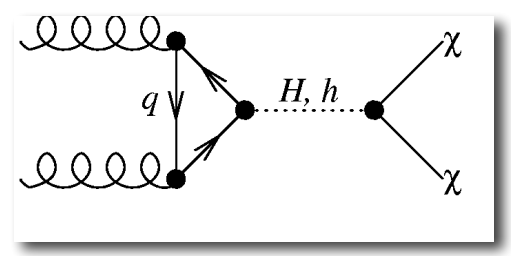
Direct DM experiments: CDMS, ZEPLIN, EDELWEISS, CRESST,WARP,…
sensitive mainly to spin-independent elastic scattering cross section $\longrightarrow \sigma_{SI} \leq 10^{-8}\, pb$

==> dominated by virtual exchange of H and h, coupling to strange quarks and to gluons via bottom loops

$\downarrow$

$\tan\beta$ enhanced couplings for H



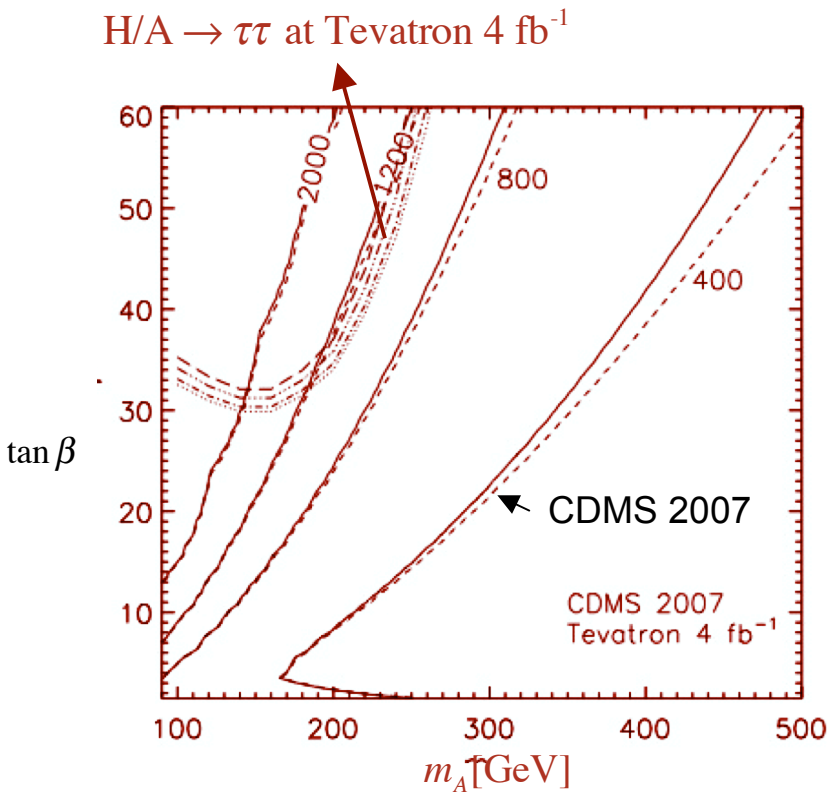


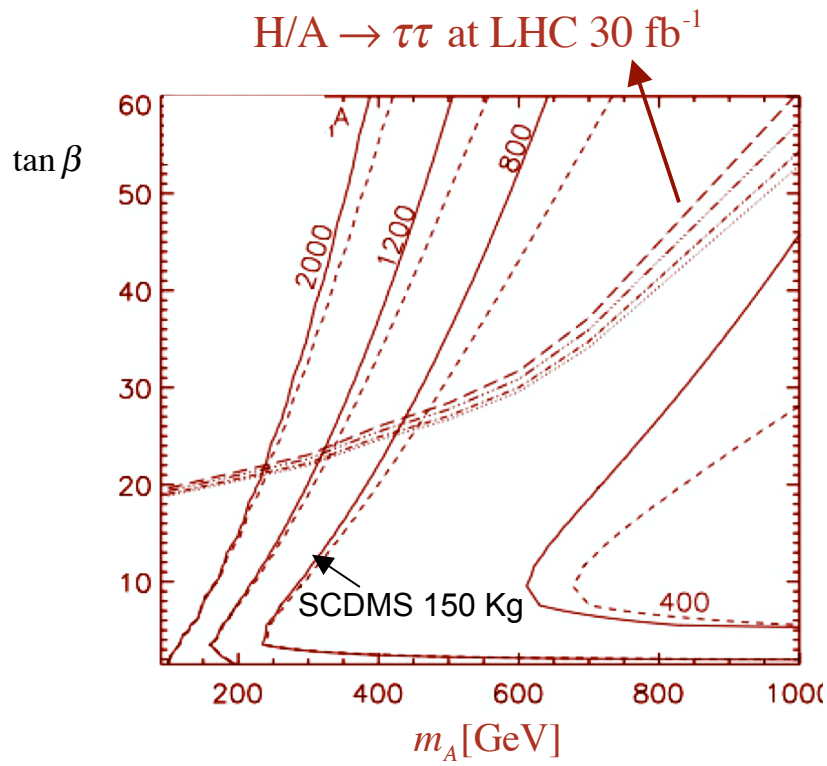
Direct DM searches Vs the Tevatron and LHC H/A searches

Both MSSM Higgs searches and neutralino direct DM searches depend on m_A and $\tan\beta$

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

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

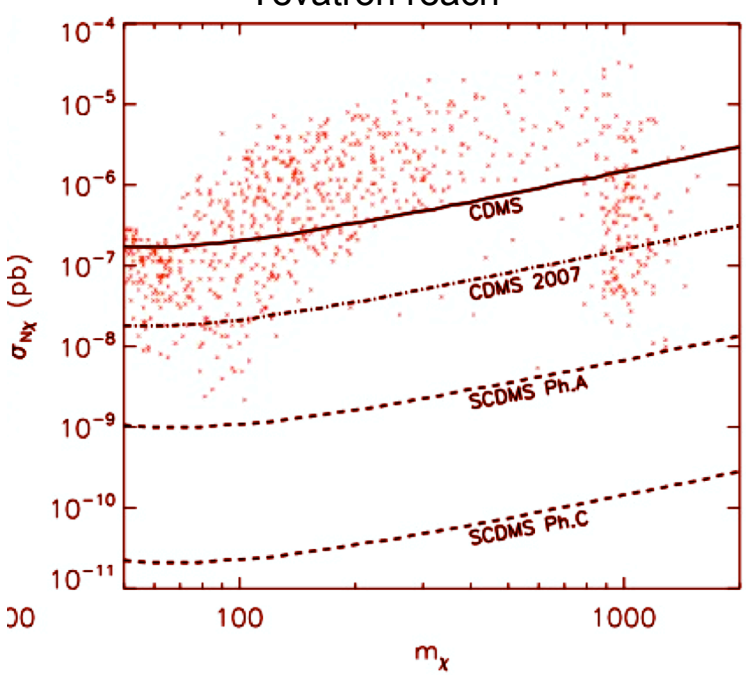
CDMS DM searches Vs the Tevatron and LHC H/A searches

•If the lightest neutralino makes up the DM of the universe

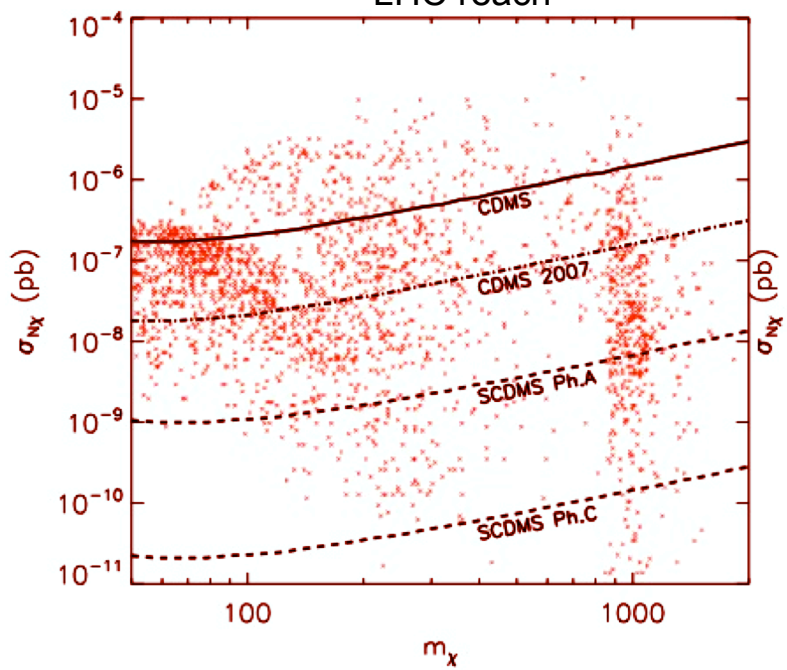
==> Evidence for H/A at the Tevatron (LHC) predict neutralino cross sections typically within the reach of present (future) direct DM detection experiments.

(strong μ dependence)

Tevatron reach



LHC reach



Conclusions

- **Experiments at particle accelerators around the world give us the capability to observe the Higgs particle and thereby test the EWSB mechanism**

-- The Tevatron has the first opportunity for testing the Higgs sector beyond LEP bounds

-- The LHC will test it in many different ways and provide some useful precision measurements

-- Precision tests that can truly reveal the nature of EWSB will only become available at the ILC

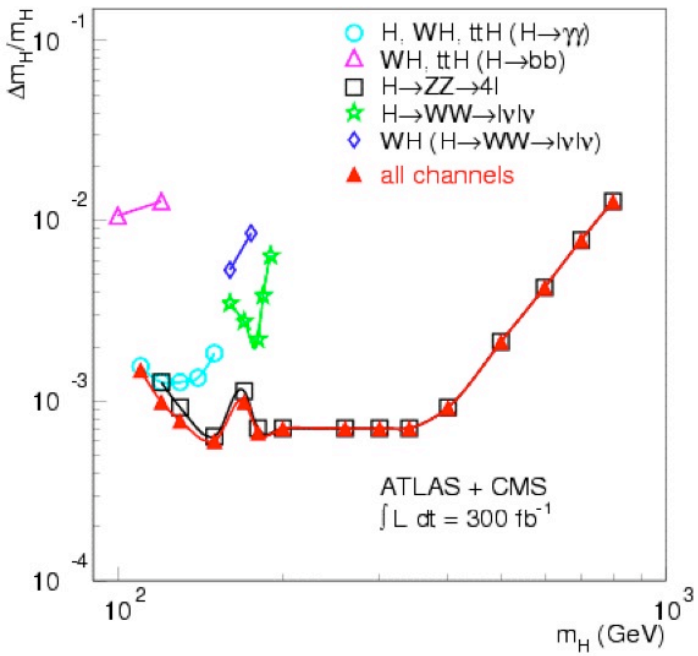
- **There are many reasons to believe that the SM must be superceded by a more fundamental theory at the TeV scale**

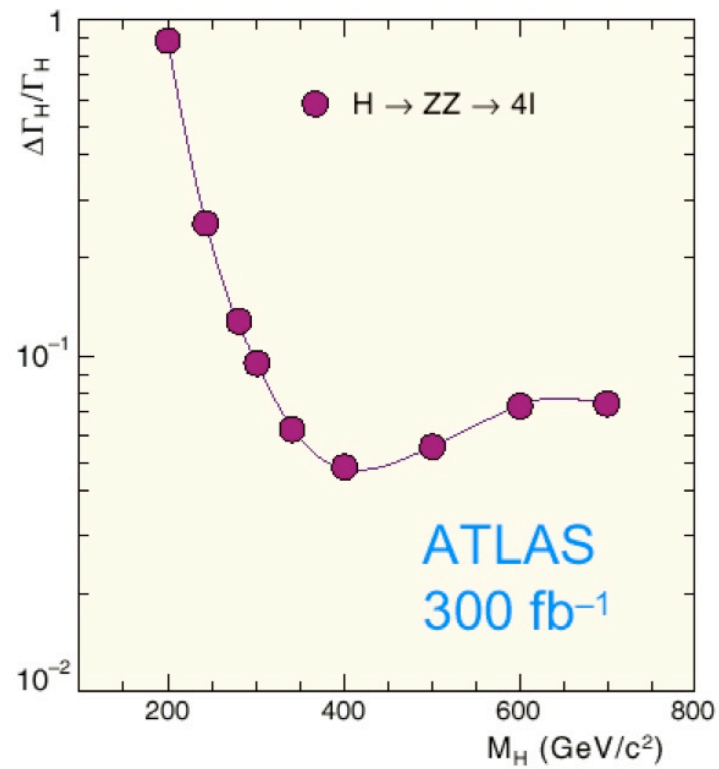
Supersymmetry is the leading candidate

This opens the possibility of a more complex Higgs structure and connects Higgs physics with Flavor physics and Cosmology

We are about to reveal the Mystery of mass and, most probably, arrive at findings which will revolutionize our understanding of nature

Mass and Width Resolution





MSSM Higgs	$\Delta m/m$ (%) 300 fb^{-1}
h, A, H → γγ	0.1–0.4
H → 4 ℓ	0.1–0.4
H/A → μμ	0.1-1.5
h → bb	1–2
H → hh → bb γγ	1-2
A → Zh → bb ℓℓ	1–2
H/A → ττ	1-10

Analysis of indirect widths for mass range below 200 GeV:
10-20% precision

SM Electroweak Baryogenesis fufills the Sakharov conditions

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

Finite Temperature Higgs Potential

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

E receives contributions proportional to the sum of the cube of all light boson particle masses and

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

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

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

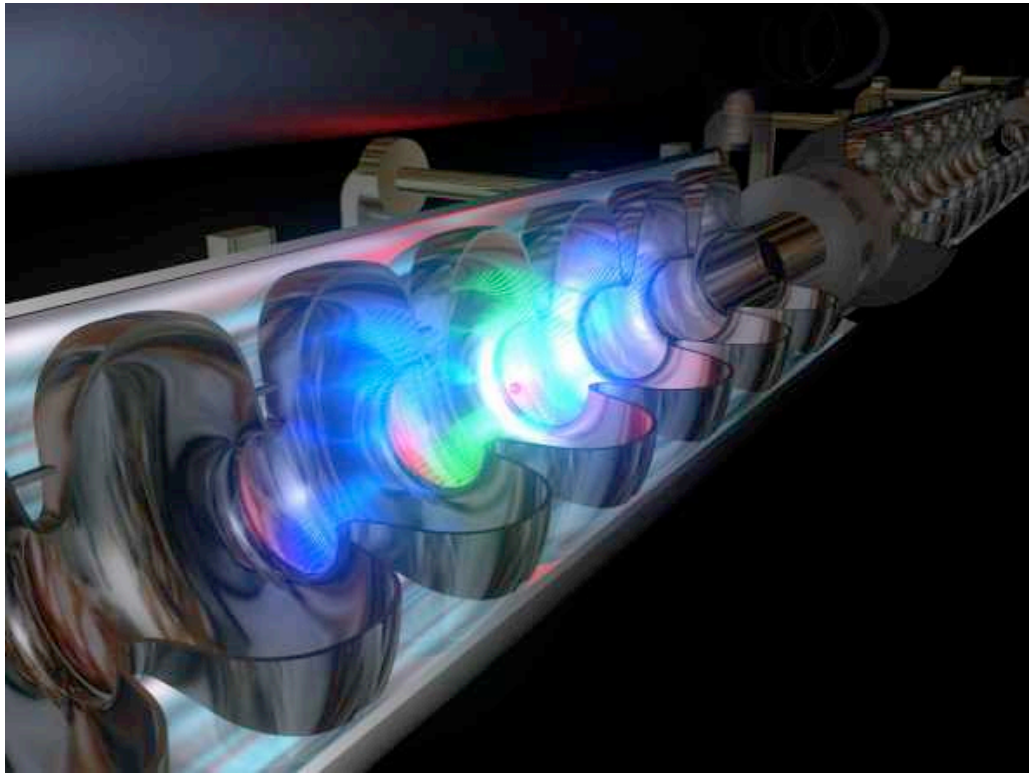
- **Independent Problem: not enough CP violation**

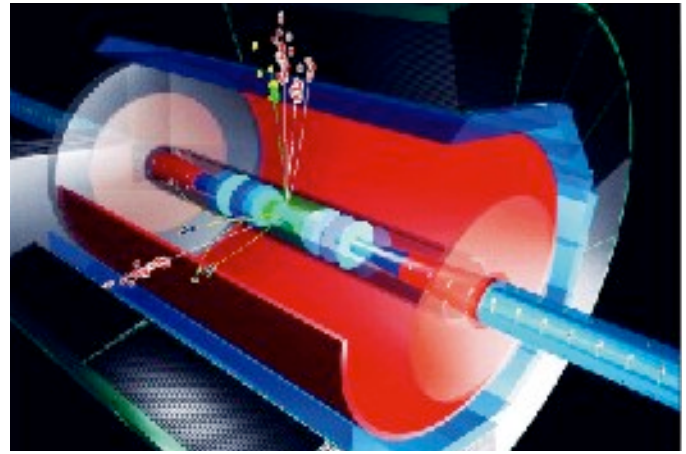
Farrar and Shaposhnikov, Gavela et al., Huet and Satter

Electroweak Baryogenesis in the SM is ruled out

The International Linear Collider (ILC) (2010 →?)

a telescopic view to the highest energies of nature





A proposed international accelerator, colliding electrons against positrons at

$$\sqrt{s} = 500 - 1000 \text{ GeV}$$

Super high-tech machine

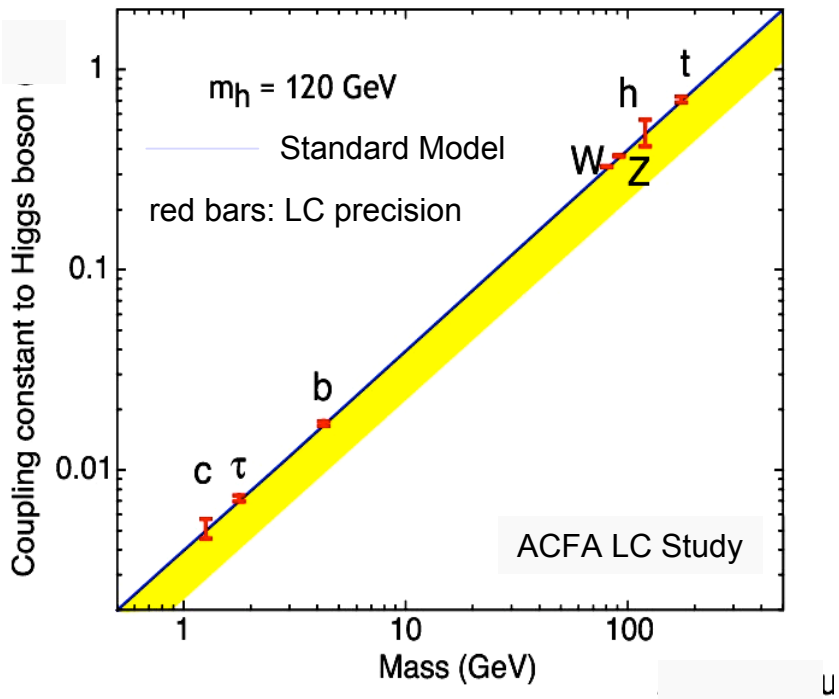
- Accelerate the beam over > 15 km
- Focus the beams to a few nanometers and made them collide

Exploring the Higgs Sector

Unique powerful feature of the ILC

➔ it can observe the Higgs no matter how it decays !

$$e^+e^- \xrightarrow{Z^*} H_{SM} Z$$ Initial beam Energy and Z decay well known



The SM Higgs interactions with particles are proportional to particle masses

Determine if the Higgs is Standard and responsible for mass,

or

if it comes from a more complex theory and has modified properties.

A complex Higgs interacts with other Higgs particles and can be a source of extra Charge-Parity violation

⬇

Explain the Matter-Antimatter imbalance in the universe

SM Higgs at the ILC $\left(\sqrt{s} = 500 \text{ GeV upgradeable to } 1 \text{ TeV}\right)$

Production mainly through:

$$e^+e^- \xrightarrow{Z^*} ZH_{SM}; \quad e^+e^- \to \nu\bar{\nu}W^*W^* \to \nu\bar{\nu}H_{SM};$$

$$e^+e^- \to t\bar{t}H_{SM}$$

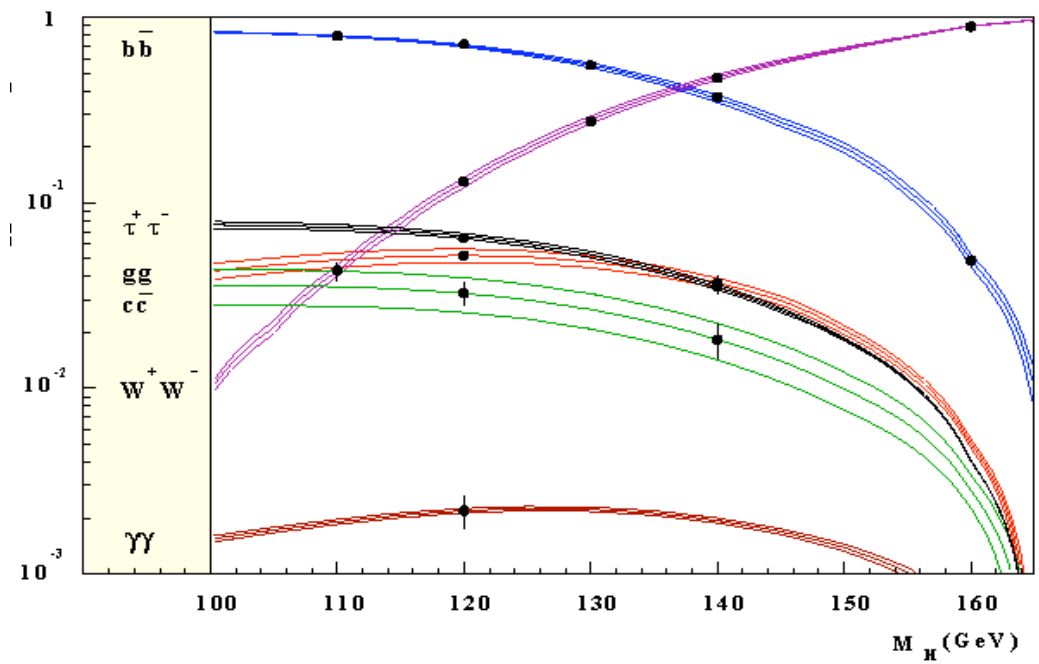
$\sqrt{s} = 350 - 500$ GeV $\Rightarrow$ m_h up to kin. limit $m_h \sim \sqrt{s} - M_Z$ observable

$\sqrt{s} = 800$ GeV $\Rightarrow$ $m_h \sim 650$ GeV observable

low mass, high L

==> g_{Htt} *meas.*

SM Higgs Branching Ratios



Extraction of most BR's with 3-10% accuracy

Extraction of most couplings with 2-4% accuracy

HZZ coupling meas. via σ_{ZH} independent of Higgs decay modes!!

Higgs Decay Width: $\Gamma_{tot} = \Gamma_W / BR(H_{SM} \to WW)$

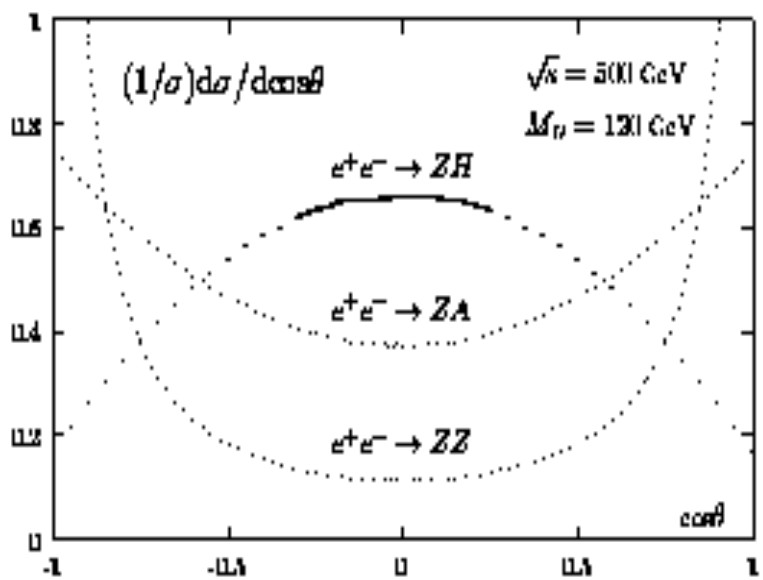
$$\delta\Gamma / \Gamma \approx 6\%$$

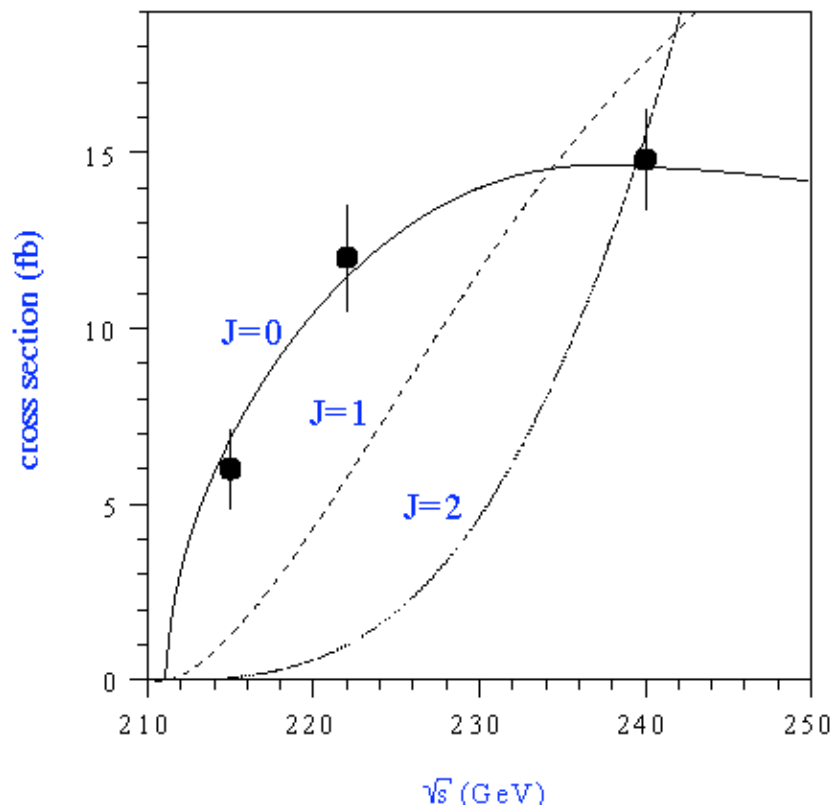
for mass of 120 GeV

Other Important Higgs Properties to measure

- **Spin and Parity:**

from threshold dependence of the excitation curve and angular distributions





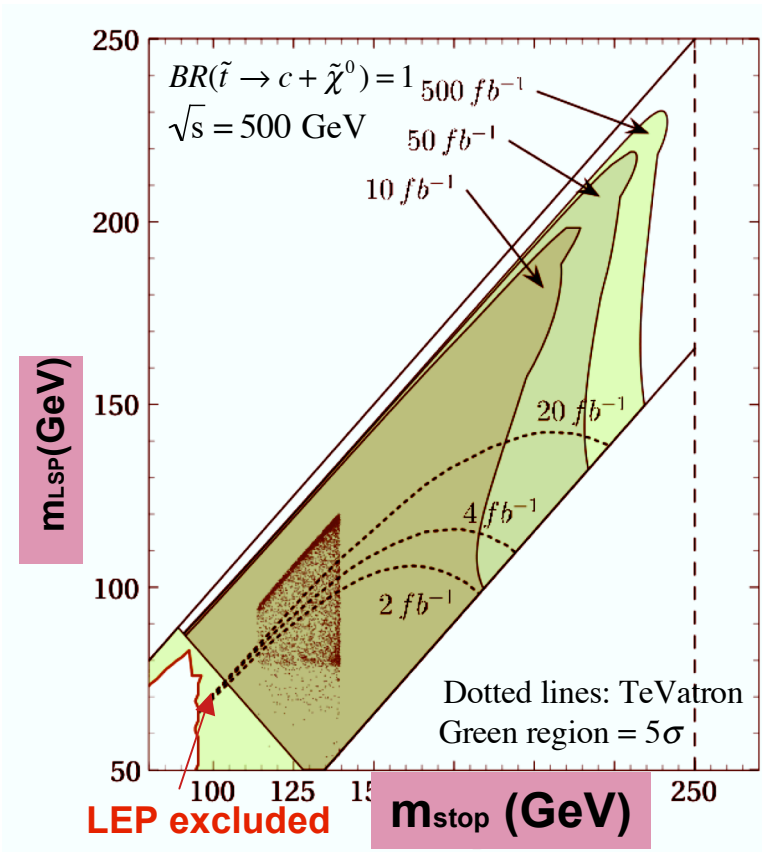
* **Higgs Self Couplings**

* **Invisible Higgs Decays**

* **CP nature of the Higgs Boson**

The Power of ILC: Cosmological Implications

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



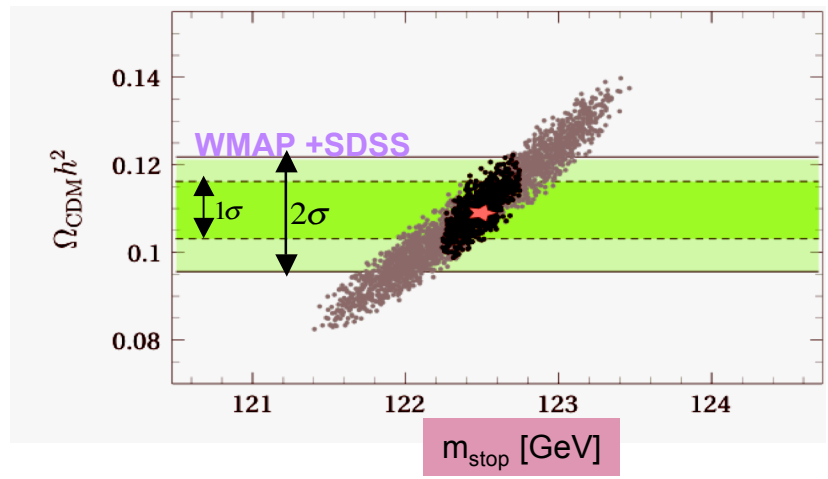
Precise measurement of SUSY parameters

-- 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

EXTRAS

The flavor problem in SUSY Theories

SUSY breaking mechanisms ==> can give rise to large FCNC effects

- Novel sfermion-gaugino-fermion interactions, e.g. for the down sector

$$\bar{d}^i_{L,R}\,\tilde{\lambda}\,\tilde{d}^j_{L,R} \rightarrow \bar{d}_{L,R} D^+_{L,R} \tilde{D}_{L,R} \tilde{\lambda}\,\tilde{d}_{L,R}$$

$$\boxed{\text{recall } V_{CKM} = U_L^+ D_L}$$

where $\tilde{D}_{L,R}$ come from the block diagonalization of the squark mass matrix

$$\left(\tilde{d}^{i\,*}_L\ \tilde{d}^{i\,*}_R\right)\begin{pmatrix} M_Q^2 + \mathrm{v}_1^2 \hat{h}_d^+ \hat{h}_d + D_{\tilde{d}_L} & \mathrm{v}_1\left(A_d^* - \mu \tan\beta\right)\hat{h}_d^+ \\ \mathrm{v}_1 \hat{h}_d\left(A_d - \mu^* \tan\beta\right) & M_D^2 + \mathrm{v}_1^2 \hat{h}_d \hat{h}_d^+ + D_{\tilde{d}_R} \end{pmatrix}\begin{pmatrix} \tilde{d}^i_L \\ \tilde{d}^i_R \end{pmatrix}$$

- The diagonal entries are 3x3 matrices with $M_Q^2,\ M_D^2$ the soft SUSY breaking mass matrices and the rest proportional to the Yukawa or I
- The off-diagonal matrices are proportional to the Yukawa and to the soft SUSY breaking matrices A_d coming from the trilinear interactions of the Higgs doublets with the sfermions

$$\tilde{u}^*_L\left(A_u^* \phi_2 - \mu \phi_1\right)\hat{h}_u^+ \tilde{u}_R + \tilde{d}^*_L\left(A_d^* \phi_1 - \mu \phi_2\right)\hat{h}_d^+ \tilde{d}_R + h.c.$$

B and Higgs Physics at the Tevatron and the LHC

explore complementary regions of SUSY parameter space

Important Flavor Changing effects: 1) tree level ==> charged Higgs induced via
2) tan beta enhanced loop corrections both in the neutral and charged Higgs sectors
==> model dependent ==> assume Minimal Flavor Violation

- Loop-induced Higgs mediated FCNC in the down-quark sector

$$-L_{FCNC} = \bar{d}_R^j \left(X_{RL}^S\right)^{ji} d_L^i \; \phi_S + h.c. \qquad \text{with } i \neq j \quad \phi_S = h, H, A$$

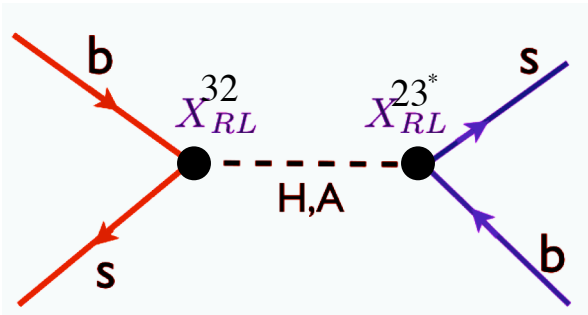
$$\text{and} \quad \left(X_{RL}^S\right)^{ji} = \frac{\overline{m}_{d\,j}\, h_t^2\, \varepsilon_Y \left(x_2^S - x_1^S \tan\beta\right)\tan\beta}{v\left(1+\varepsilon_0^j \tan\beta\right)\left(1+\Delta_b\right)} V_{CKM}^{3j*} V_{CKM}^{3i}$$

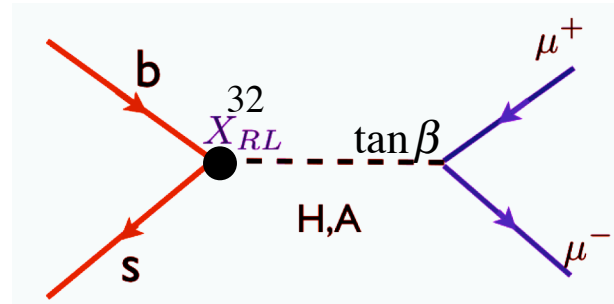
Example: case of universal soft SUSY squark mass parameters

x_1^S, x_2^S are the components of the h, H and A in ϕ_1^0, ϕ_2^0
==> $\tan\beta^2$ enhanced coupling for H/A or h/A, depending on value of m_A

Correlation between Bs mixing and $\mathrm{BR}(B_S \to \mu^+\mu^-)$

due to $\tan\beta$ enhanced Higgs mediated flavor violating effects





$$\left(\Delta M_{B_S}\right)^{SUSY} \propto - \frac{X_{RL}^{32} X_{LR}^{32}}{m_A^2}$$

Negative sign with respect to SM

$$BR(B_S \to \mu^+\mu^-)^{SUSY} \propto \frac{\left|X_{RL}^{32}\right|^2 \tan\beta^2}{m_A^4}$$

- SUSY contributions strongly correlated, and for Minimal Flavor Violation

$$\frac{\Delta M_{B_S}}{BR(B_S \to \mu^+\mu^-)} \propto \frac{m_A^2}{\tan\beta^2}$$

to maximize $\Delta M_{B_S}^{DP}$ for a given value of $\mathrm{BR}(B_S \to \mu^+\mu^-)$ $\Leftrightarrow$ minimize $\tan\beta$ (for fixed m_A)

$\Rightarrow$ choose large, negative values of ε_0 and ε_Y (large implies $\mu \approx M_{\tilde{g}} \approx 2M_{\tilde{q}} \approx \frac{2}{3} A_t$)

Looking at $V_{CKM} \cong I \Rightarrow$ <u>Flavor Conserving Higgs-fermion couplings</u>

$$-L_{eff} = \frac{1}{v_2}\left(\tan\beta\,\Phi_1^{0^*} - \Phi_2^{0^*}\right)\bar{b}_R M_b \frac{1}{R^{33}} b_L + \frac{1}{v_2}\Phi_2^{0^*}\bar{b}_R M_d b_L + h.c.$$

$$R^{33} = 1 + \left(\varepsilon_0^3 + \varepsilon_Y h_t^2\right)\tan\beta \equiv 1 + \Delta_b$$

In terms of h,H and A:

$$\phi_1^0 = -\sin\alpha\, h + \cos\alpha\, H + i\,\sin\beta\ A$$
$$\phi_2^0 = \cos\alpha\, h + \sin\alpha\, H\ -\ i\,\cos\beta\ A$$

Hence:

$$g_{hbb} \approx \frac{-m_b \sin\alpha}{(1+\Delta_b)\, v\, \cos\beta}\left(1 - \Delta_b / \tan\alpha \tan\beta\right)$$

$$g_{Hbb} \approx \frac{m_b \cos\alpha}{(1+\Delta_b)\, v\, \cos\beta}\left(1 - \Delta_b \tan\alpha / \tan\beta\right)$$

$$g_{Abb} \approx \frac{m_b \tan\beta}{(1+\Delta_b) v}$$

M.C. Mrenna, Wagner

destroy basic relation

$g_{h,H,Abb} / g_{h,H,A\,\tau\tau} \propto m_b / m_\tau$

At large $\tan\beta \Rightarrow g_{Hbb} \approx g_{Abb}$

- <u>strong suppression</u> of coupling of h (H) to bottoms if

$\tan\alpha \simeq \Delta_b / \tan\beta \longrightarrow g_{h\,b\bar{b}} \simeq 0$; $g_{h\,\tau\tau} \simeq -\frac{m_\tau}{v}\Delta_b$ (similar for H)

$\Longrightarrow$ main decay modes of SM-like MSSM Higgs: $b\bar{b} \sim 80\%$ $\tau^+\tau^- \sim 7-8\%$

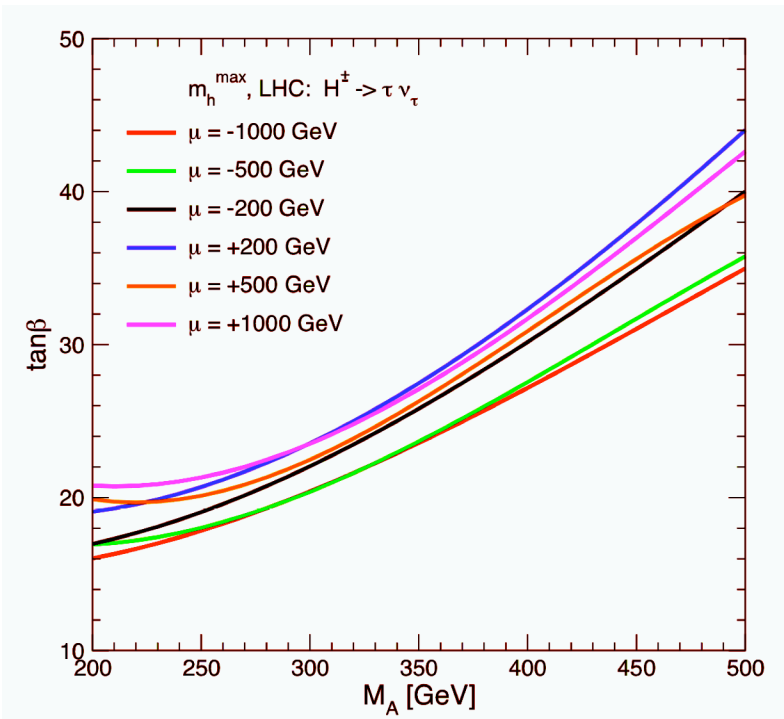
drastically changed $\Longrightarrow$ other decay modes enhanced

Charged Higgs searches at the LHC

- Similarly to the neutral Higgs case, there are tan beta enhanced loop corrections which depend on SUSY parameters

For $m_{H^\pm} > m_t + m_b$ expect $H^\pm \to tb$ decay, however

$$\sigma(gb \to H^\pm t) \times BR(H^\pm \to \tau\nu) \propto \frac{\tan\beta^2}{(1+\Delta_b)^2} \frac{(1+\Delta_b)^2}{(1+\Delta_b)^2 + 9\left(1 - m_t^2/m_{H^\pm}^2\right)^2}$$



Much more robust under radiative corrections

$$\Delta \tan\beta \leq 10$$

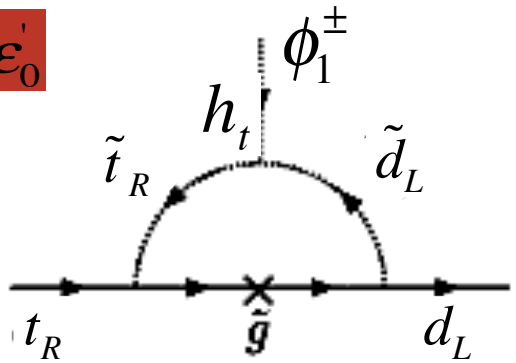
Including variation due to charged Higgs decay into SUSY particles for small mu

M.C., Heinemeyer, Wagner, Weiglein

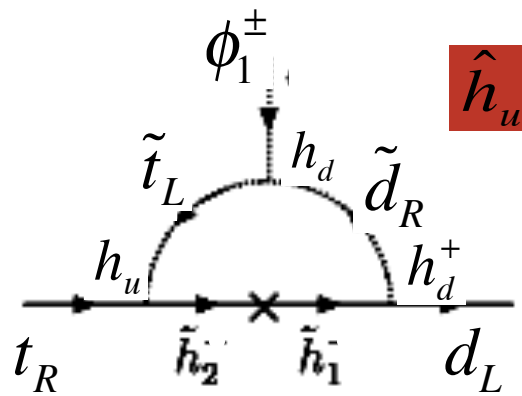
Flavor Changing in the charged Higgs coupling

- Similar to the neutral Higgs case, we have $\tan\beta$ enhanced loop corrections which depend on SUSY parameters

$\hat{h}_u\ \varepsilon_0'$



$\hat{h}_u\ \varepsilon_Y'\hat{h}_d^{+}\hat{h}_d$



$$-L_{eff}^{H^{\pm}} = \bar{u}_R^j\, P_{RL}^{ji}\, d_L^i\, H^+ + \bar{u}_L^j\, P_{LR}^{ji}\, d_R^i\, H^+ + h.c.$$

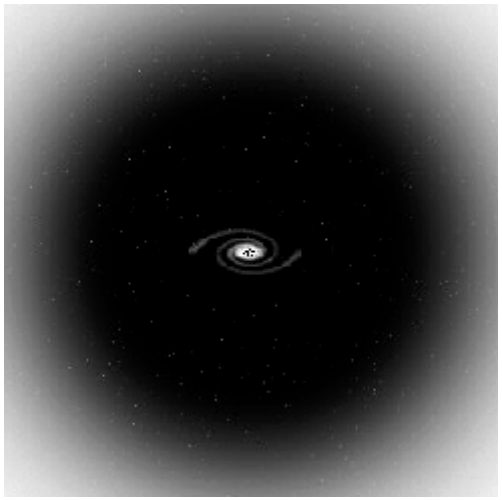
$$P_{RL}^{3i} \approx \frac{\sqrt{2}}{\mathrm{v}}\,\overline{m}_t \cot\beta\, V_{CKM}^{3i}\left(1-\tan\beta\left(\varepsilon_0' - \varepsilon_Y' h_b^2\right)\right)$$

$$P_{LR}^{j3} = \frac{\sqrt{2}}{\mathrm{v}}\frac{\overline{m}_b \tan\beta}{\left(1+\varepsilon_0^{3^*}\tan\beta\right)} V_{CKM}^{j3}$$

$$P_{LR}^{33} = P_{LR}^{j3}(J \to 3,\ \varepsilon_0^{3^*} \to \Delta_b^*)$$

This type of corrections are most important in constraining new physics from $B \to X_S\gamma$ and $B_u \to \tau\nu$

♦ What is Dark Matter (DM)?



Visible matter would not keep the stars in their orbits

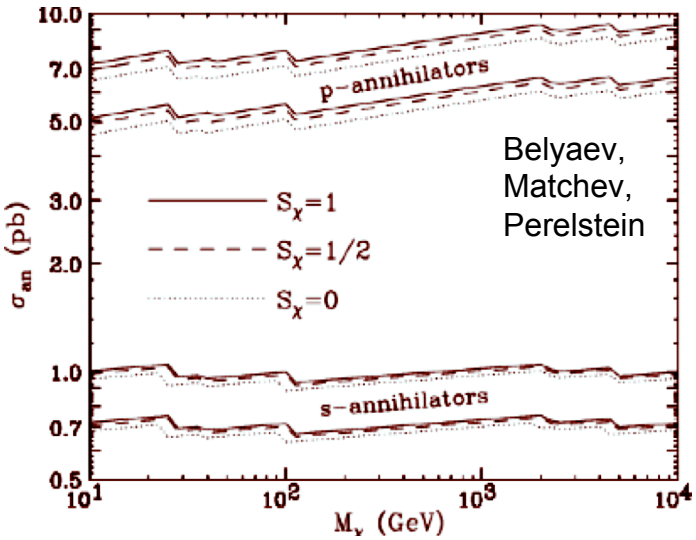
Dark matter holds the universe together. What is it?

Many possible hypothetical candidates:
Most likely WIMPs
➔ with weak interactions & TeV-scale masses
-- in SUSY, Extra Dimensions, many types of particles --

- First, the universe was hot and dense: particles and antiparticles annihilated to form dark matter particles and vice-versa.

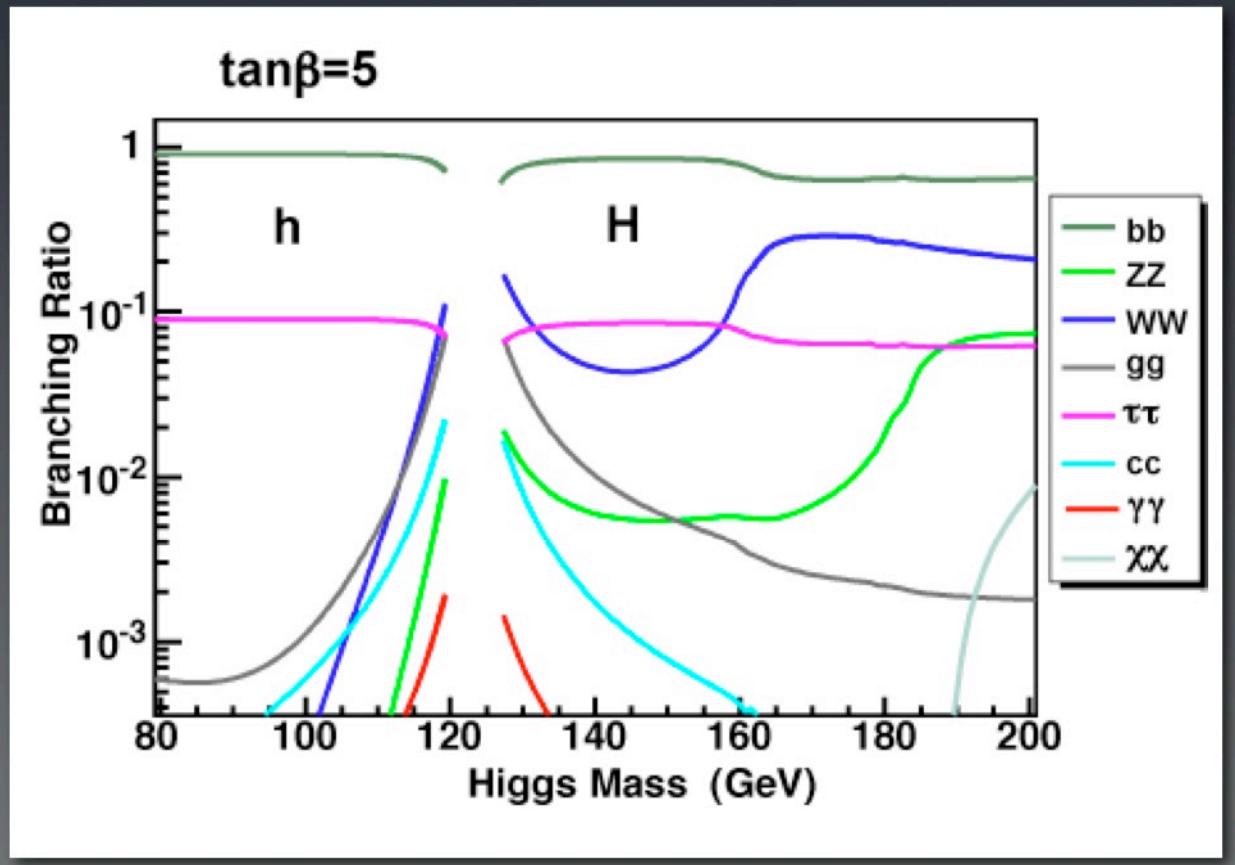
- As the universe expanded and cooled down, encounters between particles became rarer and finally the # of DM particles became a constant.

- The present DM density depends on mass & properties of DM particles: calculations are consistent with $\sigma_{ann.} \approx \text{a few pb}^{-1} \approx \alpha_W^2 / M_W^2$



The challenge is to create Dark Matter in the laboratory to study it!

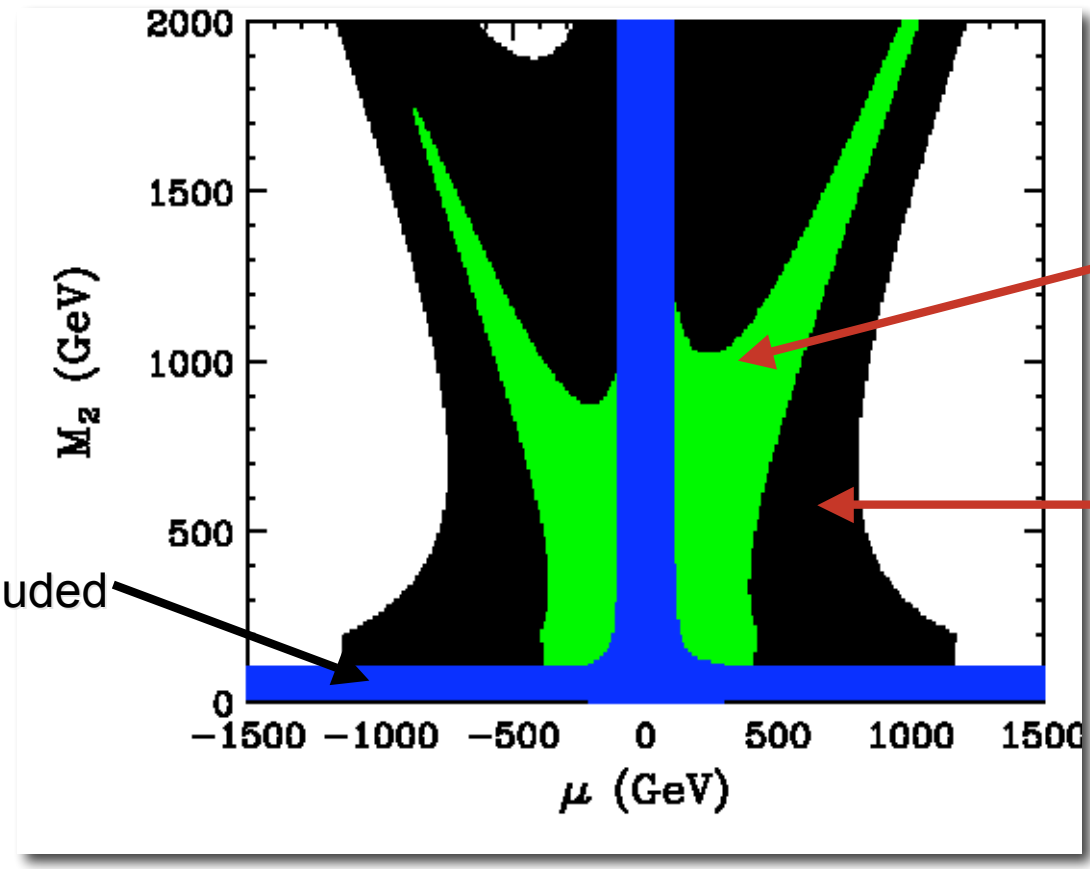
MSSM h, H branching ratios



- bb and ττ BRs stable at ~90% and ~9% respectively
- γγ BR is very m_A-dependent!

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

ILC discoveries will allow us to:

- Solve the Mysteries of Matter at the TeV scale.

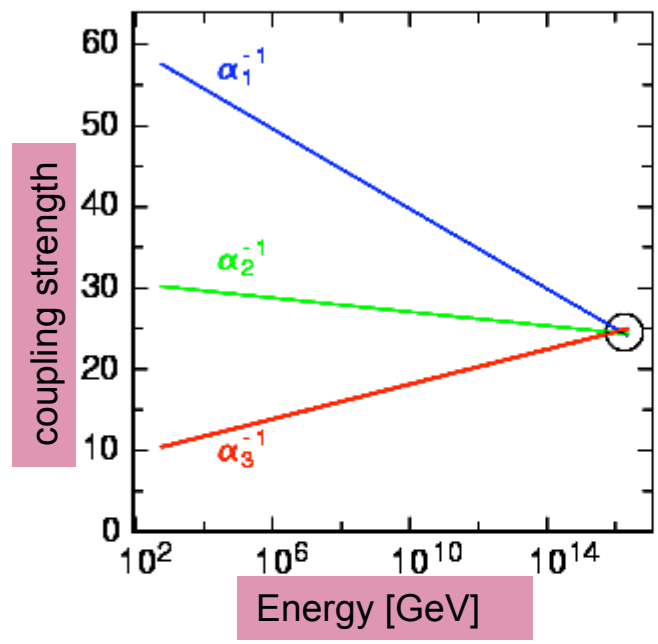
Determine how and why the Higgs works with a minimum of theoretical input
Find Extra source of CP violation

- 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.



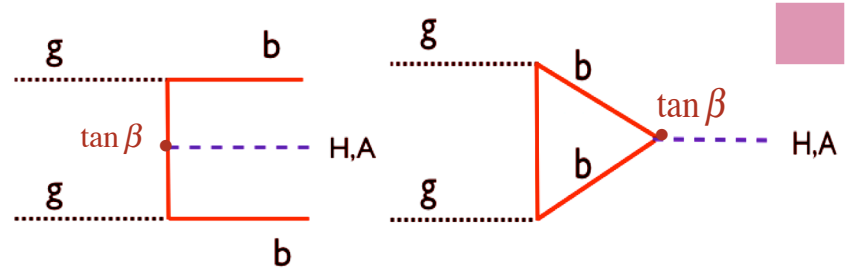
Remarkable high precision➔ Opens the window to explore energies that no accelerator will ever reach directly.

Heavy MSSM Higgs searches at the Tevatron and the LHC

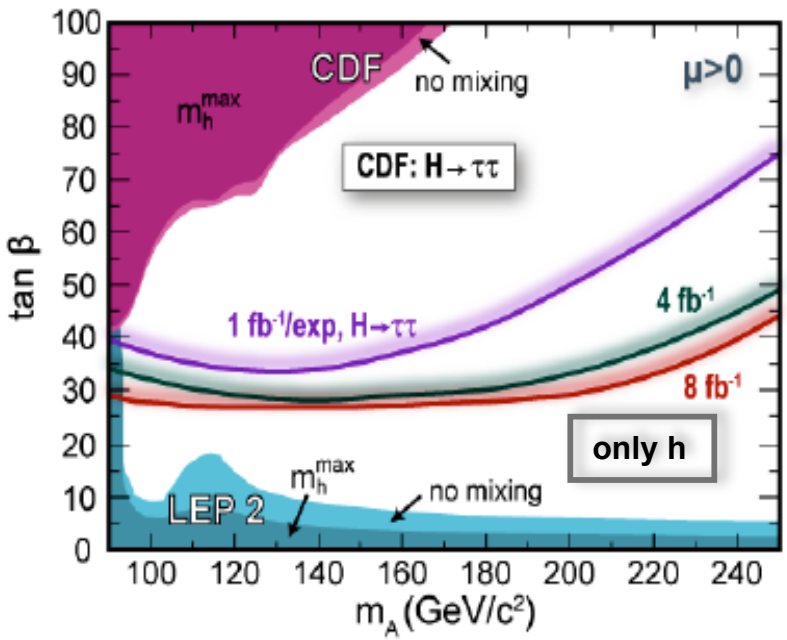
Enhanced couplings to b quarks and tau-leptons
==> enhanced production processes

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

==> robust results under quantum corrections

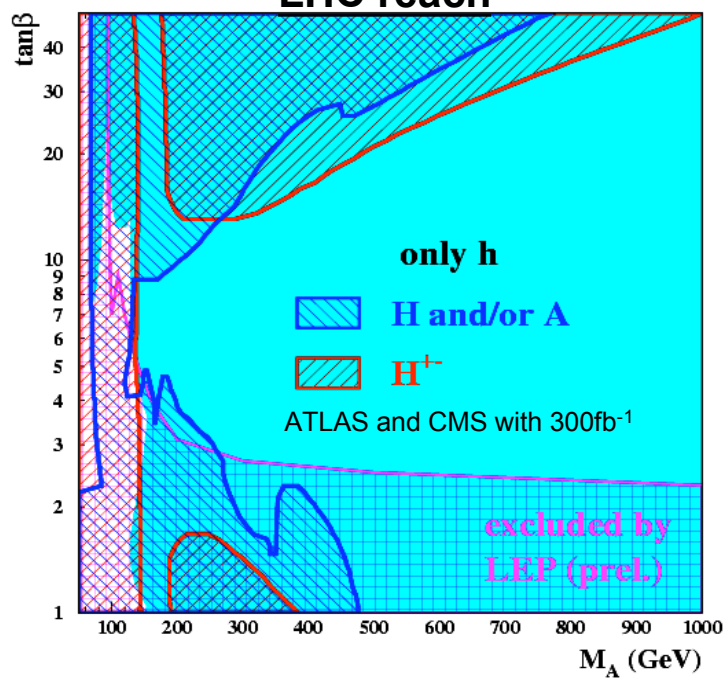


Tevatron reach



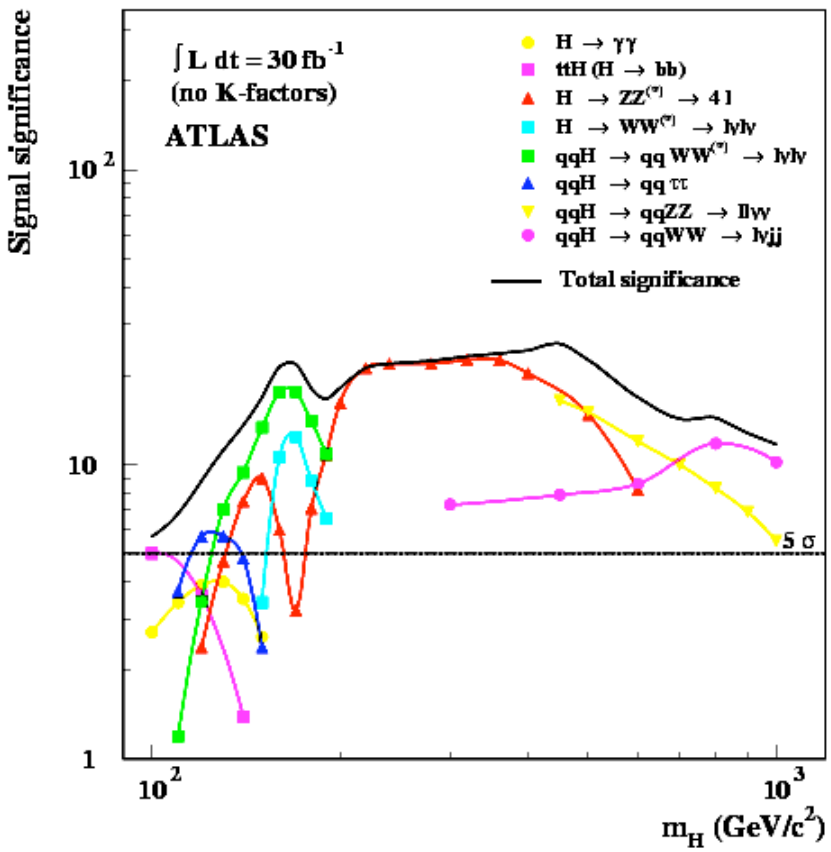
A large region of the full MSSM parameter space can be proved!

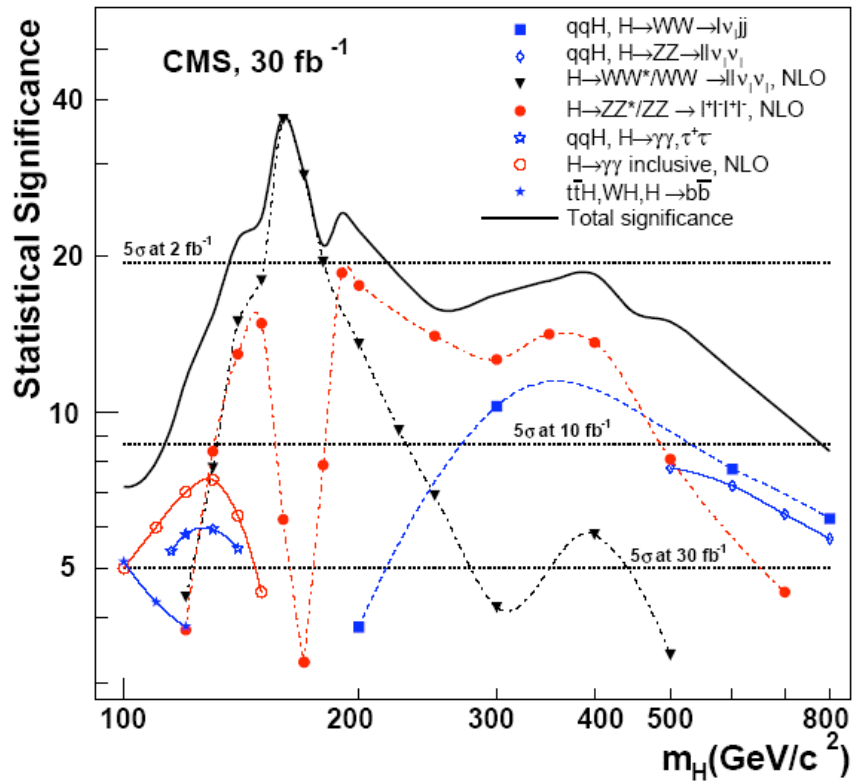
LHC reach



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)

A daring alternative: Warped Extra Dimensions

- Warped extra Dimensions, offer a solution to the hierarchy problem,

  why $v << M_{Pl}$?

  without relying on unnatural cancellations, strong interactions or SUSY.

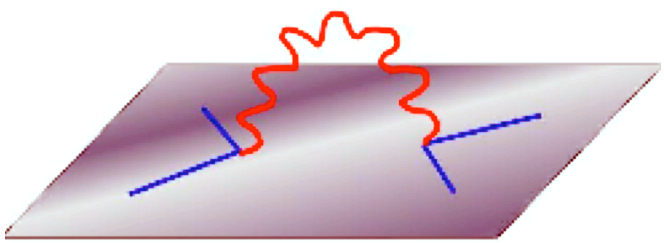
  ⇩

  All fundamental parameters are of the order of the Planck scale, and yet, due to the curvature of the extra-dimensional metric and the localization of the Higgs field, the Higgs v.e.v. is naturally of order of the TeV scale

4-D effective theory:

SM particles + Gravitons + tower of new particles: Kaluza Klein (KK) excited states with same quantum number as a graviton and/or the SM particles

Signatures:



- KK Gravitons, with masses of the order of the weak scale and couplings of order 1/TeV to SM particles → simplest mechanism

- Fermions and gauge boson KK modes of the order of the TeV scale may also exist, (strongly constrained by precision electroweak data.)

KK states produced as resonances or contribute to fermion pair production at colliders

Solution to the Hierarchy Problem

- Space is compact, of size 2 L, with orbifold conditions x, y → x,-y
- Brane at y = 0 (Ultraviolet or Planck Brane)
  Brane at y = L (Infrared or TeV Brane)
- Non-factorizable metric:

$$ds^2 = e^{-2k|y|}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$$

→ solution to 5d Einstein equations

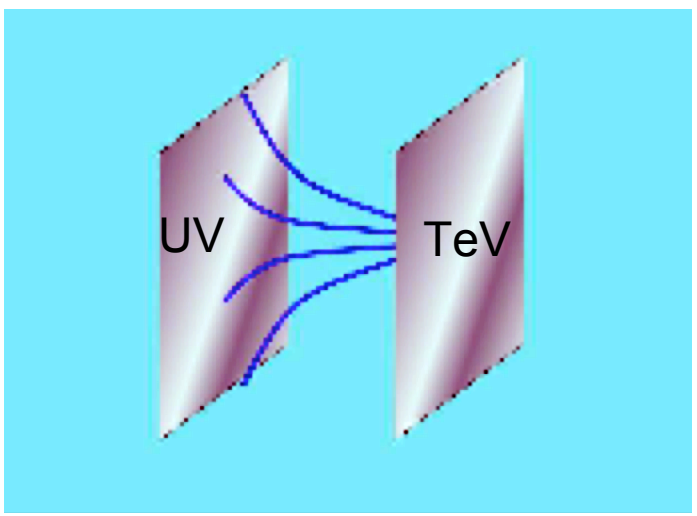
- Newton's law modified: 5d Planck mass relates to M_{Pl}: $M_{Pl}^2 = \frac{(M_{Pl}^{fund.})^3}{2k}(1-e^{-2kL})$

→ Natural energy scale at the UV brane: Fundamental Planck scale $\Rightarrow M_{Pl}^{fund.}$

At the TeV brane, all masses are affected by an exponential warp factor e^{-kL}.

Assuming fundamental scales all of same order:

$$M_{Pl} \approx M_{Pl}^{fund.} \approx \mathrm{v} \approx \mathrm{k}$$



Solution to Hierarchy problem :

Higgs field lives on the TeV brane

with $\tilde{\mathrm{v}} \approx \mathrm{v}\, \mathrm{e}^{-\mathrm{kL}} \approx M_{Pl}\, \mathrm{e}^{-\mathrm{kL}}$

$$kL \approx 30$$

Appendix

- Gauge Theories
- A simple example: the abelian Higgs mechanism
- The Standard Electroweak Lagrangean
- The Higgs Mechanism in the SM
- Fermion Masses and Mixings in the SM
- Running of the Higgs quartic coupling
- The Hierarchy problem of the SM Higgs sector

Gauge Theories ==> definition, structure and rules of construction

Best way to come up with a GT, start from a global symmetry and promote it to a gauge one ==> demand invariance of the Lagrangian under local transformations

$L[\phi, \partial_\mu \phi]$ ==> Invariant under D dimensional continuous group Γ

of transformations: $\boxed{\phi' = U(\theta^A)\phi \quad \text{with A} = 1,2,...,\text{D}}$

θ^A infinitesimal $\rightarrow U(\theta^A) = 1 + ig \sum_{\text{A}} \theta^{\text{A}} T^A$ T^A are the group generators

T^A are matrices indep. of space- time coordinates and normalized such that

$$tr(T^A T^B) = \frac{1}{2}\delta^{AB} \qquad \text{and satify } \left[\text{T}^{\text{A}}, \text{T}^{\text{B}}\right] = iC_{ABC}\text{T}^{\text{C}}$$

For each quantity V^A we define: $V = \sum_A V^A T^A$

If now $\theta^A \to \theta^A(x_\mu) \quad \Rightarrow \quad L[\phi, \partial_\mu \phi]$ is no longer gauge invariant under $U\left[\theta^A\left(x_\mu\right)\right]$ due to derivative terms

Gauge invariance is recovered if ordinary derivative replaced by covariant derivative

$$\mathcal{D}_\mu = \partial_\mu + igV_\mu$$

V_μ^A are a set of D gauge fields in correspondence with the group generators and

$$V_\mu^{'} = UV_\mu U^{-1} - (1/ig)\,(\partial_\mu U)\; U^{-1}$$

As a result, the covariant derivative has the same transformation properties as ϕ

$$(\mathcal{D}_\mu \phi)^{'} = U(\mathcal{D}_\mu \phi)$$

$\Rightarrow \quad L[\phi, D_\mu \phi]$ is invariant under gauge transformations.

In order to construct a gauge invariant kinetic term for the gauge fields V^A we construct the field strength tensor from the commutator of 2 covariant derivatives

$$\left[D_\mu, D_\nu\right]\phi = ig\left\{\partial_\mu V_\nu - \partial_\nu V_\mu + ig\left[V_\mu, V_\nu\right]\right\}\phi \equiv ig\, F_{\mu\nu}\phi$$

which is equivalent to $F^A_{\mu\nu} = \partial_\mu V^A_\mu - \partial_\nu V^A_\mu - gC_{ABC}V^B_\mu V^C_\nu$

==> transforms as a tensor in the adjoint representation $\boxed{F'_{\mu\nu} = UF_{\mu\nu}U^{-1}}$

$$\Rightarrow \text{ invariant quantity: } \mathrm{tr}\,(\mathrm{UF^2U^{-1}}) = \mathrm{tr}\,(\mathrm{UU^{-1}F^2}) = \mathrm{tr}\,(F_{\mu\nu}F^{\mu\nu}) = \frac{1}{2}F^A_{\mu\nu}F^{A\mu\nu}$$

The complete Yang Mills Lagrangian invariant under gauge transformations reads

$$L_{YM} = -\frac{1}{4}F^A_{\mu\nu}F^{A\mu\nu} + L\left(\phi, D_\mu\phi\right)$$

An Abelian theory like QED ==>$U[\theta(x)] = \exp[ie\mathcal{Q}\theta(x)]$ the photon field transforms as

$$V'_\mu = V_\mu - \partial_\mu\theta(x) \quad \text{and} \quad F_{\mu\nu} \quad \text{is linear in } V_\mu$$

In the absence of fermions ==>no self interactions (are free)

Non-Abelian theories like QCD have both linear and quadratic terms in the gauge fields

The origin of mass : the Higgs mechanism

A simple example: the abelian Higgs model [U(1) gauge theory]

$$\mathcal{L} = -\tfrac{1}{4} F_{\mu\nu} F^{\mu\nu} \qquad F_{\mu\nu} = \partial_\nu A_\mu - \partial_\mu A_\nu$$

- Local U(1) gauge invariance ==> Lagrangian invariant under the transformation

$$A_\mu(x) \to A_\mu(x) - \partial_\mu \eta(x) \quad \forall\, \eta$$

- Suppose we add a mass term: $\mathcal{L} = -\tfrac{1}{4} F_{\mu\nu} F^{\mu\nu} + \tfrac{1}{2} m^2 A_\mu A^\mu$

==> this term violates local gauge invariance

- If we extend the model adding a single complex scalar field: $\phi = \tfrac{1}{\sqrt{2}} (\phi_1 + i \phi_2)$

$$\Rightarrow \mathcal{L} = -\tfrac{1}{4} F_{\mu\nu} F^{\mu\nu} + |D_\mu \phi|^2 - V(\phi)$$

with $D_\mu = \partial_\mu - ie A_\mu$ and $V(\phi) = \mu^2 |\phi|^2 + \lambda (|\phi|^2)^2$

==> the most general renormalizable potential allowed by U(1) invariance

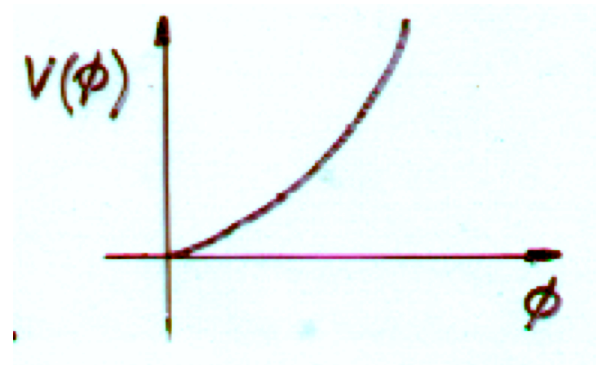
$\mathcal{L}$ ==> inv. under U(1) rotations $\phi \to e^{i\theta} \phi$ and under local transformations

$$A_\mu(x) \to A_\mu(x) - \partial_\mu \eta(x) \qquad \phi(x) \to e^{-ie\eta(x)} \phi(x)$$

Considering $V(\phi) = \mu^2 |\phi|^2 + \lambda \left(|\phi|^2 \right)^2$ assuming $\lambda > 0$ ==> two solutions

i) $\mu^2 > 0$

The potential has the shape ==>



and preserves the symmetry of the Lagrangian.

The state of lower energy is for $\langle \phi \rangle = 0$ ==> vacuum state

$$\partial V / \partial \phi = \mu^2 \phi^+ + 2\lambda |\phi|^2 \phi^+ = 0 \Rightarrow \phi^+ = 0 \text{ sol.}$$

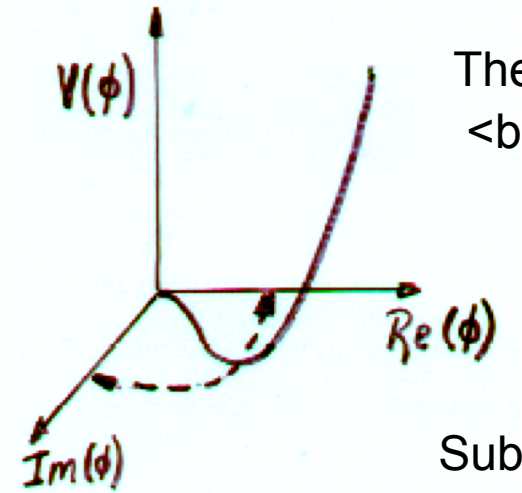
$$\partial^2 V / \partial \phi^2 \big|_{\langle \phi \rangle = 0} = \mu^2 = m_\phi^2$$

The theory is QED with a massless photon and

a charged scalar field ϕ with mass μ

ii) $\mu^2 \equiv -|\mu|^2 < 0$

$$\Rightarrow \partial V/\partial\phi^+ = 0 \longrightarrow \langle\phi\rangle_{min} = |\mu|/\sqrt{2\lambda} \equiv v$$



The direction in which the vacuum is chosen is arbitrary <but one usually chooses it to lie along the real part of ϕ >

It is convenient to write: $\phi = 1/\sqrt{2}\, e^{i\chi/v}\,(v + H)$

χ, H ==> real fields with no v.e.v.'s

Substituting in the Lagrangian:

$$\mathcal{L}_\phi = -1/4\, F_{\mu\nu}F^{\mu\nu} - ev A_\mu \partial^\mu \chi + \frac{e^2 v^2}{2} A_\mu A^\mu$$
$$+ 1/2\,(\partial_\mu H \partial^\mu H + 2\mu^2 H^2) + 1/2\, \partial_\mu \chi \partial^\mu \chi + (H, \chi \text{ interac.})$$

Describes a photon of mass $m_{A_\gamma} = ev$, a scalar field H ==> $m_H^2 = -2\mu^2 \equiv 4\lambda v^2$

and a massless field χ => rotated away by $A'_\mu \equiv A_\mu - 1/ev\, \partial_\mu \chi$

χ is the Goldstone boson "eaten" by the gauge field to give mass to the photon

In the unitary gauge: $A'_\mu \equiv A_\mu - \frac{1}{ev}\partial_\mu \chi$ the particle content is clear

1 massive gauge field A'_μ

1 massive scalar field H

Summarizing:

The spontaneous breakdown of the gauge theory by a non-zero v.e.v

= The Higgs mechanism

==> disappearence of a Goldstone boson which transforms into the longitudinal component of a massive gauge boson

Number of degrees of freedom:

Before Spontaneous Symmetry Breaking (SSB) ==>

1 massless γ = 2

1 complex scalar = 2

4

After SSB ==>

1 massive γ ⟶ 3

1 real scalar ⟶ 1

4

The Standard Model of Electroweak Interactions

Weak interactions seem rather different from QED (based on a U(1) gauge group)

- They are short ranged ==> which requires massive messenger particles

$$r_W = \hbar / M_W c \approx 2.5 \times 10^{-16}\, cm \Leftrightarrow M_W \approx 80 \text{ GeV}$$

very different from the infinite range of the QED force ==> massless photon

==> Hard to think about a unified theory of EW interactions

- They have a chiral structure: in the massless fermion limit only left handed quarks and leptons are coupled to the weak interaction messengers

- They come in two types: charged and neutral current-current interactions
  - -- Charged current interactions mediated by W+- bosons can change flavour: charged leptons into neutrinos; up-type quarks into down-type quarks
  - -- Neutral currents do not allow for flavour changing processes at tree level

Weak interactions are described by a non- Abelian SU(2) chiral gauge group

The electroweak gauge group is the product of 2 groups $SU(2)_W \times U(1)_Y$ and this symmetry is spontaneously broken

The Standard Electroweak Lagrangian

$$L = L_{kin.}^{gauge} + L_{kin.}^{fermions} + L_{Higgs}$$

The chiral SU(2)W x U(1)Y Yang Mills Lagrangian with massless left- and right-handed fermions reads:

$$L_{kin.}^{gauge} + L_{kin.}^{fermions} = -\frac{1}{4}\sum_{A=1}^{3} F_{\mu\nu}^{A} F^{A\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + \overline{\psi}_L i\gamma^\mu D_\mu \psi_L + \overline{\psi}_R i\gamma^\mu D_\mu \psi_R$$

The gauge antisymmetric tensors ==> $B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu \rightarrow U(1)_Y$

$$F_{\mu\nu}^{A} = \partial_\mu W_\nu^A - \partial_\nu W_\nu^A - g\varepsilon_{ABC} W_\mu^B W_\nu^C \rightarrow SU(2)_W$$

3 generators:Pauli matrices

The fermion fields: $\psi_{L,R} = \left[(1 \mp \gamma_5)/2\right]\psi \equiv \mathrm{P}_{\mathrm{L,R}}\ \psi$ $\quad \mathrm{P}_{\mathrm{L,R}}$ are projectors

$$\overline{\psi}_{L,R} = \psi_{L,R}^{+}\gamma_0 = \psi^{+} P_{L,R}\gamma_0 = \overline{\psi}\, P_{R,L}$$

$$\gamma_5^2 = \mathrm{I}; \quad \gamma_5^{+} = \gamma_5$$

Dirac matrices in the chiral/Weyl rep.

$$\gamma^i = \begin{pmatrix} 0 & \sigma^i \\ -\sigma^i & 0 \end{pmatrix} \qquad \gamma^0 = \begin{pmatrix} 0 & \mathrm{I} \\ \mathrm{I} & 0 \end{pmatrix}$$

$$\{\gamma_\mu, \gamma_\nu\} = 2g_{\mu\nu}; \quad g_{\mu\nu} = diag(+,-,-,-)$$

Quantum number assignments for the matter fields

Non-Abelian $SU(2)_W$ ==> chargeless one dim. Singlet (1) representation
charged two dim. Doublet (2) representation

Abelian $U(1)_Y$ ==> only one dimensional representation ==> can give different hypercharges to SU(2) singlets and doublets

Non-Abelian $SU(3)_C$: Singlets ==> Leptons and Triplets ==> Quarks

- Quarks and leptons cannot mix, since weak interactions do not change color, nor left and right handed fields (would violate Lorentz symmetry)

- Charged Currents ==> connect up- and down-type quarks and charged leptons and neutrinos and W+- bosons couple only to left handed fermions

Hence ==> form Left-handed doublets and Right-handed singlets

For one generation of SM particles ==> **seven chiral spinors: $u_{L,R}$, $d_{L,R}$, $e_{L,R}$ and v_L.**
For the moment we will treat neutrinos as massless, we omit the right-handed one.

For the $SU(2)_W$ multiplets: $\mathbf{q}_L = \begin{pmatrix} \mathbf{u}_L \\ \mathbf{d}_L \end{pmatrix}$ $\quad \mathbf{u}_R \quad \mathbf{d}_R \quad \mathbf{l}_L = \begin{pmatrix} \nu_L \\ \mathbf{e}_L \end{pmatrix} \quad \mathbf{e}_R$

For the hypercharges: $\mathbf{q}_L : \frac{1}{3} \quad \mathbf{u}_R : \frac{4}{3} \quad \mathbf{d}_R : -\frac{2}{3} \quad \mathbf{l}_L : -1 \quad \mathbf{e}_R : -2$

We can now write the covariant derivatives

$$D_\mu \psi_L = \left(\partial_\mu + igW_\mu + ig'\frac{1}{2}YB_\mu \right)\psi_L \qquad \text{where } W_\mu = \frac{1}{2}\sigma^A W_\mu^A$$

While the right-handed fields are singlets under $SU(2)_W$, hence do not couple to W's

$$D_\mu \psi_R = \left(\partial_\mu + ig'\frac{1}{2}YB_\mu \right)\psi_R$$

From the explicit form of the Pauli matrices:

$$\sigma^1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \qquad \sigma^2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \qquad \sigma^3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$W_\mu^{1,2}$ mix up- and down-type quarks, while W_μ^3 the same as B_μ, does not.

Writing the interaction part only, in the form current x vector field

$$\Rightarrow \quad L_{\text{int}} = -gJ_{W,\mu}^A W^{A\mu} - g' J_{Y,\mu} B^\mu$$

With the conserved currents:

$$J_{W,\mu}^A = \bar{q}_L \gamma_\mu \frac{1}{2}\sigma^A q_L + \bar{l}_L \gamma_\mu \frac{1}{2}\sigma^A l_L$$

$$J_{Y,\mu} = \frac{1}{6}\bar{q}_L \gamma_\mu q_L - \frac{1}{2}\bar{l}_L \gamma_\mu l_L + \frac{2}{3}\bar{u}_R \gamma_\mu u_R - \frac{1}{3}\bar{d}_R \gamma_\mu d_R - \bar{e}_R \gamma_\mu e_R$$

The Higgs Mechanism

So far:

Gauge bosons are massless, implying long range forces, because a mass term $m^2 W_\mu W^\mu$ would violate gauge invariance

Fermions are massless, again because of gauge invariance

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

Adding a complex scalar field Φ, doublet under $SU(2)_W$ and with Y= 1 with a potential

$$V(\Phi) = \mu^2 \Phi^+ \Phi + \lambda\left(\Phi^+ \Phi\right)^2 \qquad (\lambda > 0)$$

or

$$V(H,\phi_o) = \frac{\mu^2}{2}\left(H^2 + \phi_0^2\right) + \frac{\lambda}{4}\left(H^2 + \phi_0^2\right)^2 \quad \textbf{with} \quad \Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} \phi_1^+ + i\phi_2^+ \\ H + i\phi_0 \end{pmatrix}$$

The Higgs Lagrangian, with the covariant derivative as previously defined

$$L_{Higgs} = \left(D_\mu \Phi\right)^+ D^\mu \Phi - V(\Phi)$$

As in the Abelian simple example, for $\mu^2 < 0$ there is a minimum at $\langle \Phi \rangle_{\min} = \begin{pmatrix} 0 \\ \mathbf{v} \end{pmatrix}$

Minimization condition only fixes the modulus $\Phi^+\Phi$ ==> no fixed direction since

$$V(\Phi) \propto \Phi^+\Phi = \frac{1}{2}\left(\phi_1^2 + \phi_2^2 + H^2 + \phi_0^2\right)$$

Hence,

$$V(H,\phi_0) = -\frac{|\mu|^2}{2}\left(H^2 + \phi_0^2\right) + \frac{\lambda}{4}\left(H^2 + \phi_0^2\right)^2$$

$$\partial V/\partial H = -|\mu|^2 H + \frac{\lambda}{4} 2\left(H^2 + \phi_0^2\right) 2H = 0 \quad \Rightarrow \quad \boxed{\left\langle H^2 \right\rangle_{\min} = \frac{|\mu|^2}{\lambda} = 2\mathbf{v}^2}$$

$$\partial V/\partial \phi_0 = 0 \quad \Rightarrow \quad \langle \phi_0 \rangle = 0$$

and

$$\boxed{m_H^2 = \partial^2 V/\partial H^2 |_{\langle H \rangle_{\min} \langle \phi_0 \rangle_{\min}} = 2|\mu|^2 = 4\lambda \mathbf{v}^2}$$

$$\boxed{m_{\phi_0}^2 = \partial^2 V/\partial \phi_0{}^2 |_{\langle H \rangle_{\min} \langle \phi_0 \rangle_{\min}} = 0 \quad \Rightarrow \quad \textbf{Goldstone Boson}}$$

same for $m_{\phi_1}^2$ **and** $m_{\phi_2}^2 \rightarrow$ **Charged Goldstone bosons**

W and Z gauge boson masses

In the unitary gauge the Higgs Lagrangian becomes

$$H \to \sqrt{2}\mathbf{v} + H$$

$$\langle H \rangle = 0$$

$$L_{Higgs} = \frac{1}{2}\partial_\mu H \partial^\mu H - \frac{1}{2}\underbrace{4\lambda \mathbf{v}^2}_{\mathbf{m_H^2}} H^2 + \sqrt{2}\lambda \mathbf{v} H^3 + \frac{\lambda}{4} H^4$$

$$+\frac{1}{4}\left(\mathbf{v} + \frac{1}{\sqrt{2}}H\right)^2 \begin{pmatrix} W_\mu^1 & W_\mu^2 & W_\mu^3 & B_\mu \end{pmatrix} \begin{pmatrix} g^2 & 0 & 0 & 0 \\ 0 & g^2 & 0 & 0 \\ 0 & 0 & g^2 & -gg' \\ 0 & 0 & -gg' & g'^2 \end{pmatrix} \begin{pmatrix} W^{1\mu} \\ W^{2\mu} \\ W^{3\mu} \\ B^\mu \end{pmatrix}$$

Last term contains the physical photon, W+- and Z bosons boson masses !!

The mass matrix has one zero eigenvalue and three others: g^2, g^2 and $g^2+g'^2$

==> it describes a massless particle, two of equal non-zero mass and one heavier

The massless eigenstate $\to A_\mu = \sin\theta_W W_\mu^3 + \cos\theta_W B_\mu$

The Z boson eigenstate $\to Z_\mu = \cos\theta_W W_\mu^3 - \sin\theta_W B_\mu$

The W boson eigenstate

$$W^\pm = (W_1 \pm W_2)/\sqrt{2}$$

With the Weinberg angle: $\sin\theta_W = g' \Big/ \sqrt{g'^2 + g^2}$ $\cos\theta_W = g \Big/ \sqrt{g'^2 + g^2}$

Summarizing: the theory has the following mass eigenstates:

- Two charged vector boson W+- with mass $M_W^2 = g^2 \mathbf{v}^2/2$
- Two neutral ones with masses $M_Z^2 = \left(g^2 + g'^2\right)\mathbf{v}^2/2 = M_W^2/\cos^2\theta_W$ **and** $M_\gamma = 0$
- One neutral Higgs boson with mass $m_H^2 = 4\lambda \mathbf{v}^2$

The Higgs mechanism and the diagonalization of the vector boson mass matrix ==> rewrite the interaction Lagrangian of fermions and gauge bosons interm of the physical fields, separating into Charged and Neutral Currents: $L_{\text{int}} = L_{CC} + L_{NC}$

$$L_{CC} = -\frac{g}{\sqrt{2}} \sum_{i-1,2,3} \left(\bar{u}_{L_i} \gamma^\mu d_{L_i} + \bar{\nu}_{L_i} \gamma^\mu e_{L_i}\right) W_\mu^+ + h.c.$$

$$\boxed{e = g \sin\theta_W = g' \cos\theta_W}$$

$$L_{NC} = -g\, J_\mu^3\, W^{3\mu} - g' J_{Y,\mu} B^\mu = -e\, J_\mu^{em} A^\mu - \left(e/\sin 2\theta_W\right) J_\mu^Z Z^\mu$$

With the electromagnetic and Z currents:

$$J_\mu^{em} = \sum_{i=u,d,c,s,t,b,e,\mu,\tau} \bar{\psi}_i \gamma_\mu Q_i \psi_i \quad \text{with the electric charge } Q_i = T_i^3 + Y_i/2$$

$$J_\mu^Z = \sum_{\substack{i=u,d,c,s,t,b,\\ e,\mu,\tau,\nu_e,\nu_\mu,\nu_\tau}} \bar{\psi}_i \gamma_\mu \left(v_i - a_i \gamma^5\right) \psi_i \quad \text{where } \psi_i = \psi_{L_i} + \psi_{R_i}$$

About the Neutral Currents:

- The coupling to the photon ==> $Q = T_L^3 + Y/2 = T_R^3 + Y/2$,
  with the weak isospin T_L^3 = +-1/2 for doublets, and T_R^3=0 for singlets
  ==> defines the hypercharge Y assignments to reproduce the known electric charges of quarks and leptons

- The photon couples only vector like, i.e., it does not distinguish chiralities
- The Z boson couples to axial and vector fermion currents differently

==> $a_i = T_L^3$ and $v_i = T_L^3 - 2Q\sin^2\theta_W$ and it couples universally to all families

Number of degrees of freedom

The EWSB reshuffles the degrees of freedom of the theory

Before:

1 complex scalar double	= 4
1 massless SU(2) Wμ	= 6
1 massless U(1) Bμ	= 2
	12

After:

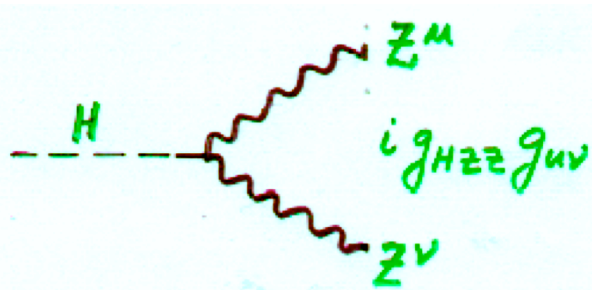
1 charged W+-	= 6
1 massive Z	= 3
1 massless photon	= 2
1 massive scalar	= 1
	12

Higgs neutral under strong and em interactions ==> massless photon and gluons
Massless gauge bosons ==> Exact symmetry:

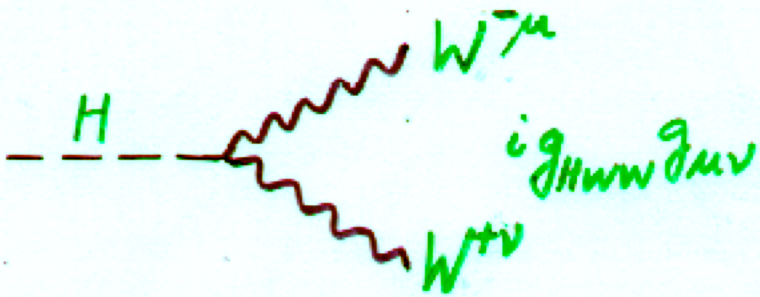
$$SU(3)_C \times SU(2)_W \times U(1)_Y \Rightarrow SU(3)_C \times U(1)_{em}$$

Higgs-Vector Boson Couplings

from $$\mathcal{L}_{H-W/Z} = \left(v + H/\sqrt{2}\right)^2 \left[\frac{g_2^2}{2} W_\mu^+ W^{-\mu} + \frac{g_1^2+g_2^2}{4} Z_\mu Z^\mu\right]$$



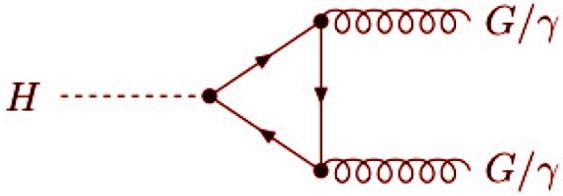
$$i g_{HZZ} g_{\mu\nu} \qquad g_{HZZ} = 2!\,\frac{(g_1^2+g_2^2)}{4}\frac{2v}{\sqrt{2}} = \frac{M_Z^2}{v}\sqrt{2}$$



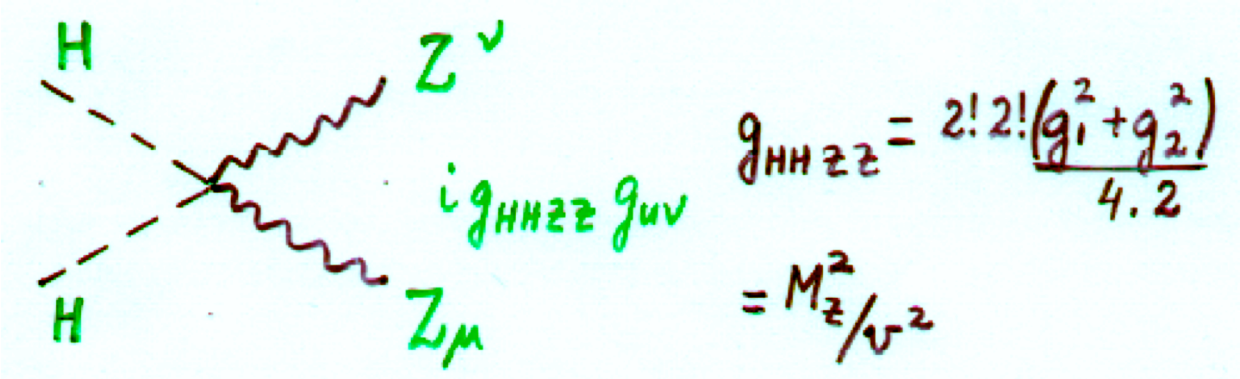
$$i g_{HWW} g_{\mu\nu} \qquad g_{HWW} = \frac{g_2^2}{2} v\sqrt{2} = \frac{M_W^2}{v}\sqrt{2}$$

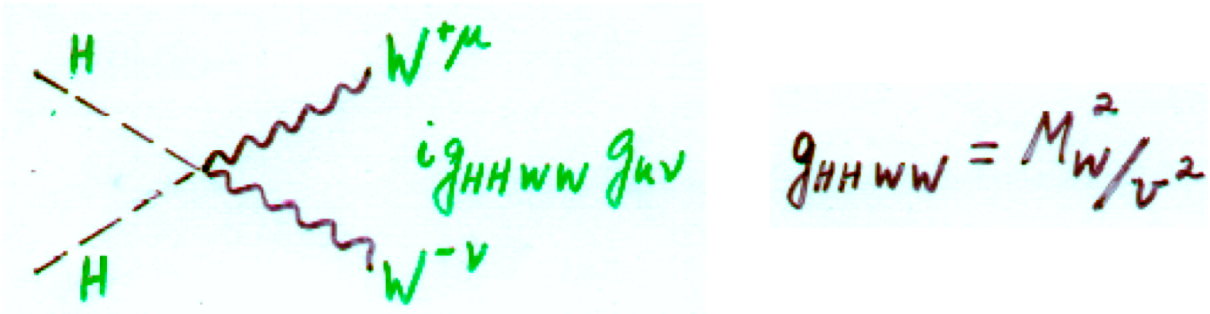
Tree level couplings are proportional to masses.

There are also loop induced couplings into massless gauge bosons ===>



Higgs-Gauge Boson Quartic Couplings :
also proportional to the gauge boson masses





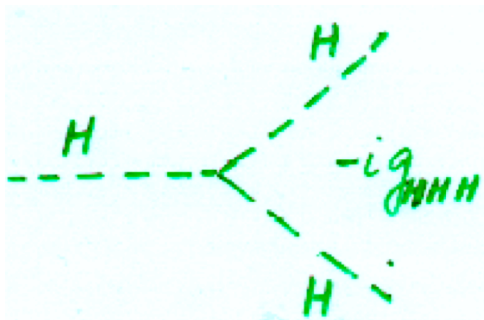
We can relate: $\alpha_i = g_i^2/4\pi$ $\qquad g' \equiv g_1; \quad g \equiv g_2$

$$\alpha_1, \alpha_2 \Leftrightarrow \alpha_{em}, \sin\theta_W^2 \begin{cases} 1/\alpha_{em} = 1/\alpha_1 + 1/\alpha_2 \\ \sin\theta_W^2 = g_1^2/g_1^2 + g_2^2 \end{cases}$$

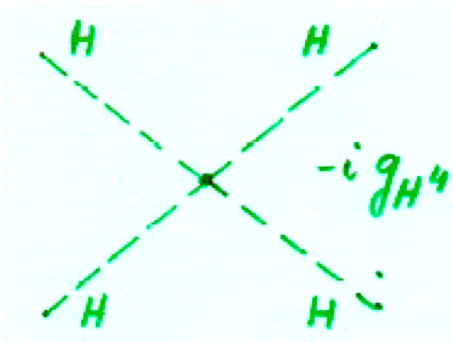
Higgs Self-Interactions

From:

$$V(\phi) = -|\mu|^2/2\, H^2 + \lambda\,(v + H/\sqrt{2})^4$$



$$g_{HHH} = 3!\,\lambda\sqrt{2}\,v = \frac{3\,m_H^2}{\sqrt{2}\,v}$$



$$g_{H^4} = 4!\,\lambda/4 = \frac{m_H^2}{v^2}\cdot 3/2$$

Higgs potential has two free parameters :

$$|\mu| \text{ and } \lambda \;\rightarrow\; \text{trade by } \; v^2 = -|\mu|^2/2\lambda;\; m_H^2 = 4\lambda v^2$$

Fermion Masses and Mixings

Higgs mechanism generates masses also for the fermions through Yukawa couplings of the Higgs doublet to two fermions:

-- Higgs couplings to quark doublets and either up or down-type fermions

-- Higgs couplings to lepton doublet and charged lepton singlets

- Each term is parametrized by a 3x3 matrix in generation space

$$L_{Hf\bar{f}} = -(h_d)_{ij}\bar{q}_{L_i}\Phi d_{R_j} - (h_u)_{ij}\bar{q}_{L_i}\Phi^C u_{R_j} - (h_l)_{ij}\bar{l}_{L_i}\Phi e_{R_j} + h.c$$

recall: $\Phi = \begin{pmatrix} (\phi_1 + i\phi_2)/\sqrt{2} \\ \mathrm{v} + (H + i\phi_0)/\sqrt{2} \end{pmatrix}$ and $\Phi^{\mathrm{C}} = -i\sigma_2\Phi^*$

Once the electroweak symmetry is spontaneously broken $\langle\Phi\rangle = \mathrm{v}$

$$L_{m_f} = (m_d)_{ij}\bar{d}_{L_i} d_{R_j} + (m_u)_{ij}\bar{u}_{L_i} u_{R_j} + (m_e)_{ij}\bar{e}_{L_i} e_{R_j} + h.c$$

with $m_f = h_f \mathrm{v}$ and u_L, d_L and e_L the quark and lepton doublet components

- These mass matrices are not diagonal in the same basis as the charged currents,, but can be diagonalized by bi-unitary transformations

$$V^{u\dagger} m_u \tilde{V}^u = diag(m_u, m_c, m_t)$$
$$V^{d\dagger} m_d \tilde{V}^d = diag(m_d, m_s, m_b)$$
$$V^{e\dagger} m_e \tilde{V}^e = diag(m_e, m_\mu, m_\tau)$$

with unitary matrices V $\rightarrow$ $V^\dagger V = I$

We change the basis from weak eigenstates $(i, j, ...)$ to mass eigenstates $(\alpha, \beta, ...)$

$$u_{Li} = V^u_{i\alpha}\, u_{L\alpha}, \qquad \mathrm{d}_{Li} = V^d_{i\alpha}\, \mathrm{d}_{L\alpha}, \qquad u_{Ri} = \tilde{V}^u_{i\alpha}\, u_{R\alpha}, \qquad \mathrm{d}_{Ri} = \tilde{V}^d_{i\alpha}\, \mathrm{d}_{R\alpha}$$

The up and down matrices V^u and V^d are not identical, hence, the charged current couplings are no longer diagonal

$$L_{CC} = -\frac{g}{\sqrt{2}} V^{CKM}_{\alpha\beta}\ \bar{u}_{L_\alpha} \gamma^\mu d_{L_\beta} W^+_\mu + h.c.$$

with the CKM matrix $V^{CKM}_{\alpha\beta} = V^{u\dagger}_{\alpha i} V^d_{i\beta}$

Due to the unitarity of the transformations,
there is No Flavour mixing in the neutral current

Running of the Higgs quartic coupling

recall: $V(\phi) = -|\mu|^2 \Phi^\dagger\Phi + \lambda\left(\Phi^\dagger\Phi\right)^2$

with $v = 174$ GeV

The quartic coupling determines the Higgs boson mass: $m_h^2 = 4\lambda v^2$ and is not asymptotically free

$$\frac{d\lambda}{d\ln Q^2} = \frac{6}{16\pi^2}\left(\underbrace{\lambda^2 + \lambda h_t^2}_{} - \underbrace{h_t^4}_{}\right) + \text{elw. correc.}$$

•There is the usual situation of non-asymptotic freedom for sufficiently large Q^2

λ becomes too large
(strongly interacting, close to Landau pole)

From requiring perturbative validity of the model up to scale Λ or M_{pl}

$$\lambda^{max}(\Lambda)/4\pi = 1 \Rightarrow m_h^{max} = 2\sqrt{\lambda^{max}}\, v$$

•The part of the β_λ independent of λ can drive $\lambda(Q)$ to negative values ==> destabilizing the electroweak minimum

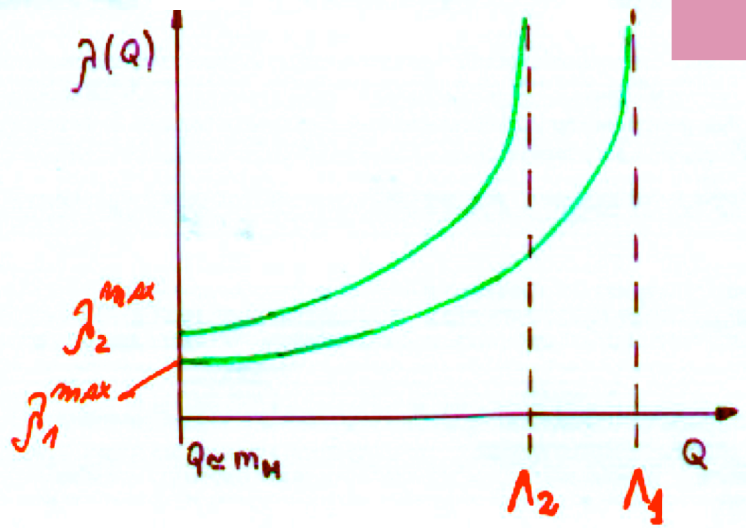
Lower bound on $\lambda(m_h)$ from stability requirement

m_h^{min} strongly dependent on m_t

• $\lambda(Q)$ becomes strongly interacting ($\simeq$ has a Landau pole) at $Q = \Lambda$

$\Longrightarrow$ determines $\lambda^{MAX}(Q \simeq m_H)$

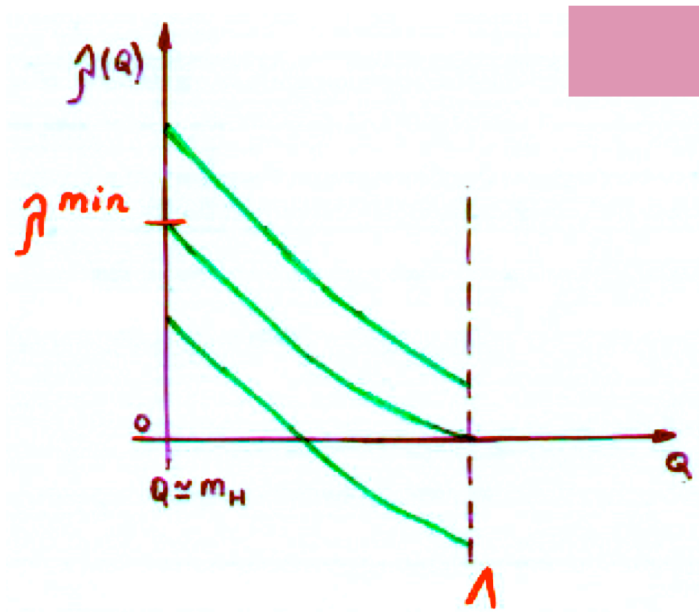
$$m_h^{\max} = 2\sqrt{\lambda^{\max}}\,\mathrm{v} \quad \rightarrow$$



• $\lambda(Q) = 0$ for $Q = \Lambda$

$\Longrightarrow$ determines $\lambda^{min}(Q \simeq m_H)$

$$m_h^{\min} = 2\sqrt{\lambda^{\min}}\,\mathrm{v} \quad \rightarrow$$



Maximum and minimum conditions of the Higgs potential far away from the electroweak minimum

this page only $\lambda \to 2\lambda$

$$V(\phi) \sim -|\mu|^2 \phi^2 + \frac{\lambda(\phi)}{2} \phi^4$$

$$\boxed{\beta_\lambda = d\lambda/d\ln\phi^2 = \phi^2 \cdot d\lambda/d\phi^2}$$

$$\partial V/\partial\phi^2 = -|\mu|^2 + \lambda(\phi)\,\phi^2 + \beta_\lambda/2\;\phi^2$$

$$\partial^2 V/(\partial\phi^2)^2 = \beta_\lambda + \lambda(\phi) + \beta_\lambda/2 + \frac{1}{2}\frac{\partial\beta_\lambda}{\partial\ln\phi^2}$$

$\Rightarrow$ Extreme: $\phi^2\left(\lambda(\phi) + \beta_\lambda/2\right) = |\mu|^2$

if $\phi^2 \sim |\mu|^2 \Rightarrow \phi^2 \simeq |\mu|^2/\lambda(\phi^2)$

if $\phi^2 \gg |\mu|^2 \Rightarrow \lambda(\phi) \sim -\beta_\lambda/2 \to$ h.o. in pert. theory $\Rightarrow \lambda(\phi) \sim 0$

$\partial^2 V/(\partial\phi^2)^2 \sim \beta_\lambda$

Extremes for $\lambda(\phi) \sim 0$

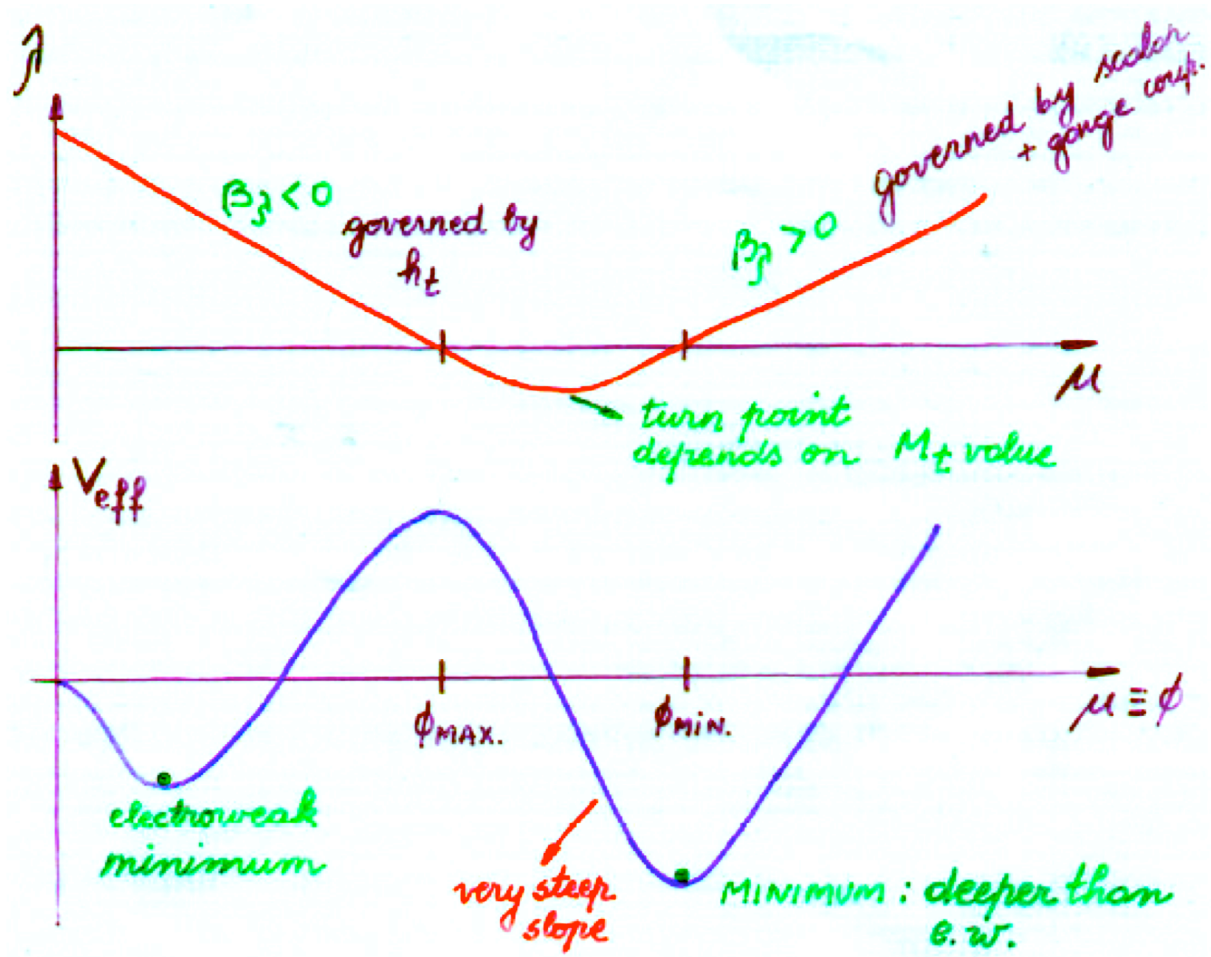
Maximum at $\beta_\lambda < 0$; Minimum at $\beta_\lambda > 0$

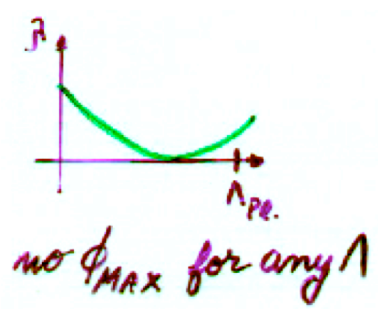
The stability m_h lower bound comes from defining for a given top quark mass the lower value m_h for which

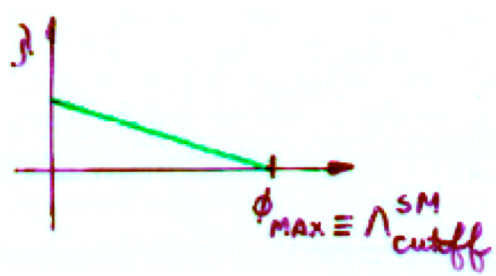
→no Maximum for

$$\phi < \Lambda^{SM}_{cutoff}$$

$$(\equiv \lambda(\phi) \geq 0 \text{ for } \phi < \Lambda^{SM}_{cutoff})$$







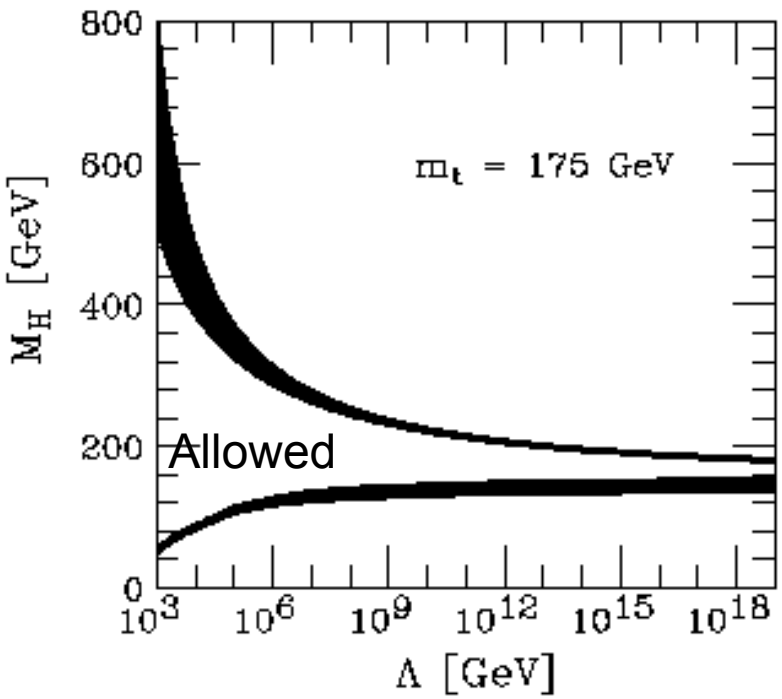
Perturbativity and Stability Bounds

- Higgs potential unstable at large values of the Higgs field $\phi > \Lambda$

if the Higgs mass is too small ⇨ light Higgs $m_h \leq 130$ GeV

prefers new physics at $\Lambda \approx 10^4 - 10^{11} GeV$

- The value of the Higgs self-coupling runs off to infinity at an energy scale above Λ if the Higgs mass is too large.



If SM description valid up to scales

$$\Lambda \approx 10^{13} - 10^{19} GeV$$

then 130 GeV $\leq m_h \leq$ **200 GeV**

The Hierarchy Problem of the SM Higgs Sector

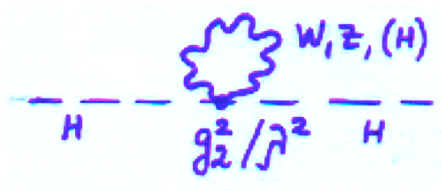
- SM is an effective theory $\Longrightarrow$ low energy quantities (masses, couplings) expected to be given as a function of parameters of the fundamental theory valid at Q> $\Lambda_{eff.}$

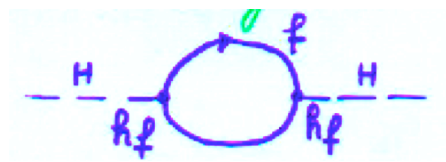
- **low energy dimensionless couplings: receive quantum corrections prop. to log ($\Lambda_{eff.}$)**
- **what about the Higgs potential mass parameter μ?** $\quad v^2 = |\mu|^2 / 2\lambda$

Quantum corrections to μ^2 are quadratically divergent

$$\mu^2 = \mu^2(\Lambda_{eff.}) + \Delta\mu^2 \longrightarrow \Delta\mu^2 \approx \frac{n_W g^2_{hWW} + n_h \lambda^2 - n_f g^2_{hf\bar{f}}}{16\pi^2} \Lambda^2_{eff.}$$

to explain v $\approx O(m_W)$, either
$\Lambda_{eff.} \leq$ 1 TeV or extreme fine tuning
to give cancellation





<u>lesson from history</u>: electron self energy $\longrightarrow$ fluctuations of em fields generate a quadratic divergence but existence of electron antiparticle cancels it, otherwise QED will break down well below M_{Pl}

Will history repeat itself? Take SM and double particle spectrum ==> Supersymmetry