

# The Energy Frontier: in the Search for New Physics

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UCSC Physics Department  
Santa Cruz, May 20, 2004.



## The Forces of Nature

- Why are the four forces in nature so different?
- How do we try to model them?

## The Fundamental Particles

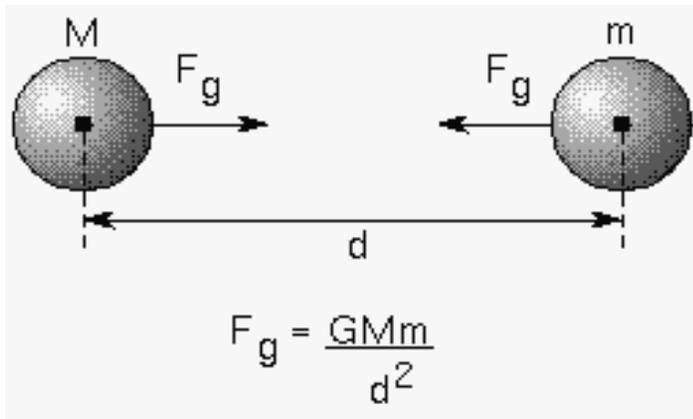
- quarks and leptons (matter), and gauge bosons (force carriers)
- How do they get mass?
- How do we test the mechanism for the origin of mass?



# Gravitational and electromagnetic interactions

- Gravity

Attractive force between  
2 massive objects:



$$G = 1/M_{Pl}^2$$

is very weak unless one of the  
masses is huge, like the earth.

- Electromagnetism

Attracts particle of opposite charge  
forces within atoms and

between atoms (residual em.i.)

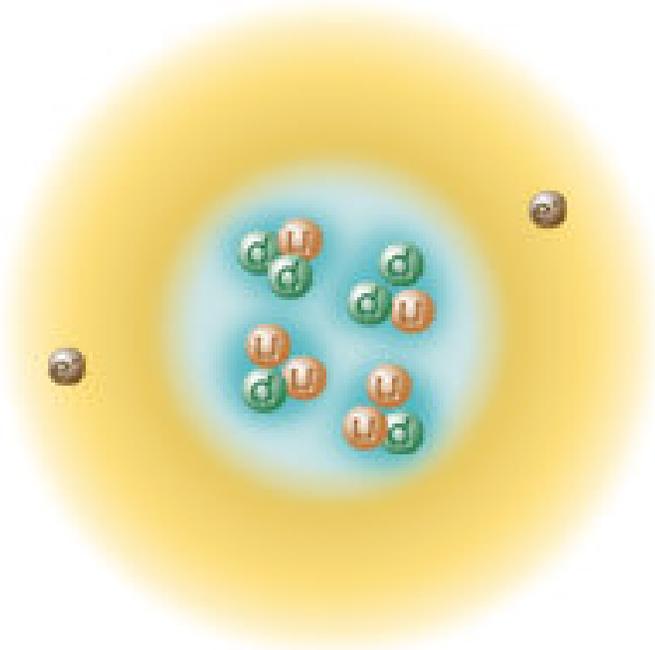
Electrons interact with photons  
via quantum of e.m. energy

→ the photons  $s_\gamma = 1$   
 $m_\gamma = 0$

Modeled by a theory based  
on  $U(1)$  gauge symmetry



# Strong Interactions



Atoms are made from  
protons, neutrons and electrons.

D.I.S. of electrons with protons or  
neutrons at high energies shows that

**protons and neutrons  
are not fundamental**

$p \rightarrow uud$  formed by three quarks, bound together by  
 $n \rightarrow udd$  the gluons of the strong interactions

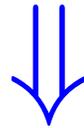
Modeled by a theory based on  $SU(3)_c$  gauge symmetry

Very strong at large distances  $\longrightarrow$  confinement  $\equiv$  no free color particles

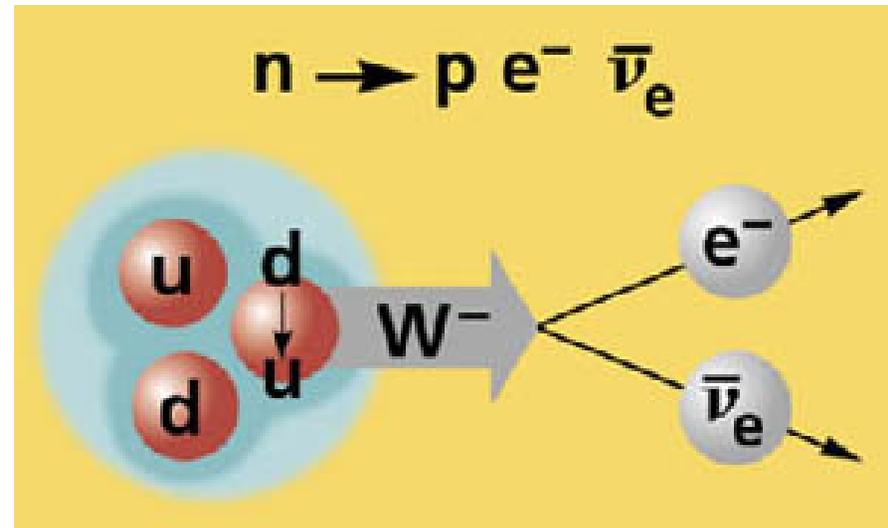


# Weak Interactions

Observation of beta decay



demanded a novel interpretation



Short range forces exist only inside the protons and neutrons, with massive carriers:

gauge bosons:  $W$  and  $Z$

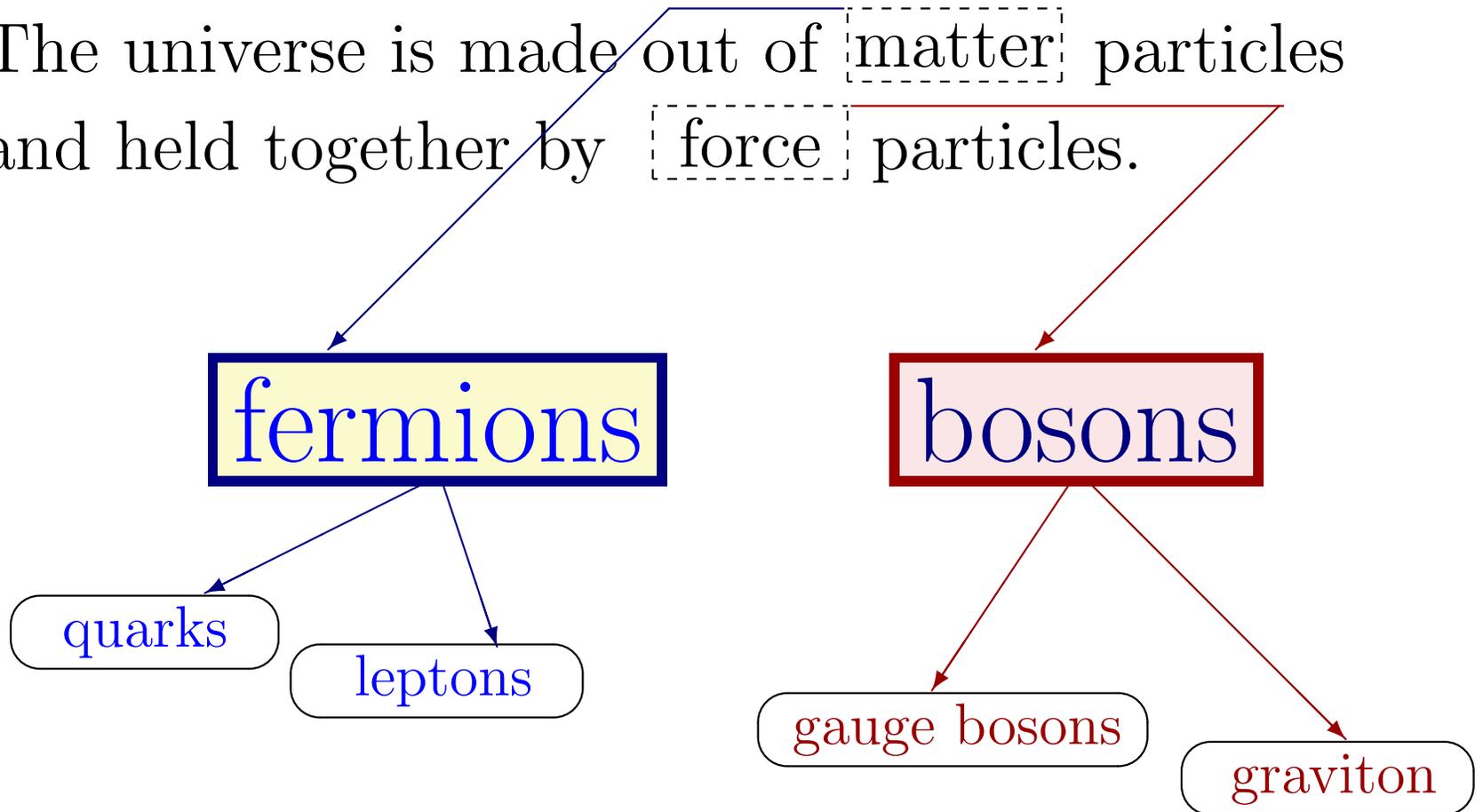
Modeled by  $SU(2)_L$   
gauge symmetry

assigns 2 isospin charges  $\pm \frac{1}{2} \longrightarrow \begin{pmatrix} u \\ d \end{pmatrix}_L, \begin{pmatrix} \nu_L \\ e \end{pmatrix}_L$



# The Complete Picture

The universe is made out of **matter** particles and held together by **force** particles.



# The Standard Model

The universe is made by matter particles: Fermions  
held together by force particles: Gauge bosons, Graviton

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

based on a gauge field theory with a symmetry group

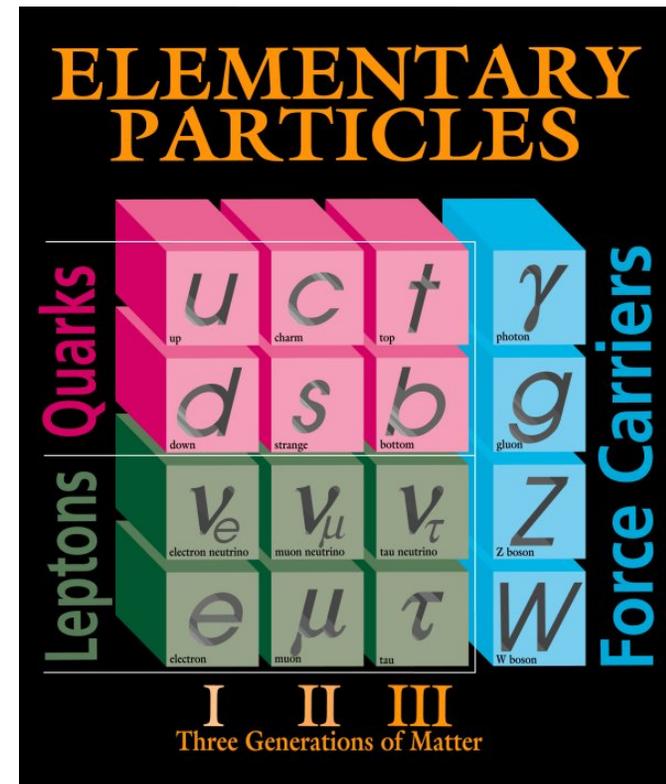
$$G = SU(3)_c \times SU(2)_L \times U(1)_Y$$

12 fundamental gauge fields:

8 gluons, 3  $W_\mu$ 's and  $B_\mu$   
and 3 gauge couplings:  $g_1, g_2, g_3$

The matter fields:

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



Fermilab 95-759



Matter: 3 families of quarks and leptons have the same properties (quantum numbers) under the symmetries of nature

**BUT they have very different masses!**

$m_3/m_2$  and  $m_2/m_1 \simeq$  a few tens or hundreds

$$m_e \approx 0.5 \times 10^{-3} \text{ GeV} \quad \frac{m_\mu}{m_e} \approx 200 \quad \frac{m_\tau}{m_\mu} \approx 20$$

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

neutrino masses as small as  $10^{-10} \text{ GeV}$

### Crucial Problem:

Due to the chiral nature of the model, fermion mass term  $\mathcal{L} = m\bar{\psi}_L\psi_R + h.c.$  is not invariant under gauge group

Also, how to give mass to  $SU(2)_L$  gauge bosons?

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



**Standard Model**  $\longrightarrow$  the pillar of particle physics:

explains data collected in the past several years **and**  
describes physical processes up to energies of  $\approx 100$  GeV.

**However, it is only an effective theory.**

$\longrightarrow$  at least Gravity should be included at  $M_{Pl} = 10^{19}$  GeV

- **Many open questions**

- ★ origin of the mass of fundamental particles

- ★ generation of big hierarchy of scales  $M_{Pl}/m_Z = 10^{17}$ ,  $m_Z/m_\nu = 10^{12}$

- ★ connection of electroweak and strong interactions with gravity

- ★ generation of hierarchies of fermion masses

- ★ explanation of matter-antimatter asymmetry of the universe

- ★ dark matter

$\implies$  crucial to get the complete picture valid up to higher energies,  $M_{Pl}$

- **Collider Experiments:** Tevatron, LHC, LC (TeV reach)

our most robust handle to reveal the new physics  
that should answer these questions.



**EWSB occurs at the TeV scale**

⇒ New Phenomena should lie in the TeV range or below, within LHC/LC reach

## The Quest for EWSB

is the search for the dynamics that generates the Goldstone bosons that are the source of mass for the W and Z.

Two broad classes of theories have been proposed:

- weakly interacting self-coupled elementary (Higgs) scalar dynamics
- strong interaction dynamics among new fermions (mediated perhaps by gauge forces)

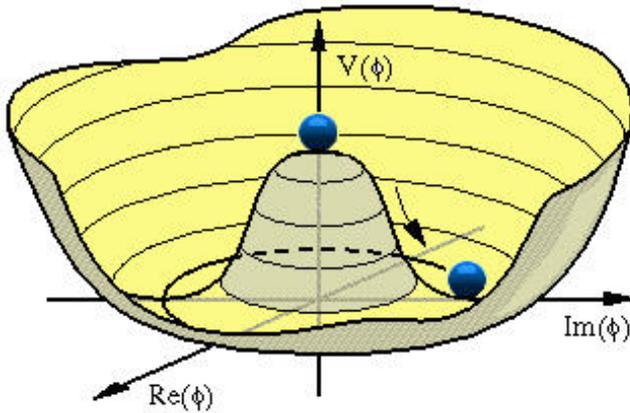
Both mechanisms generate new phenomena with significant experimental consequences.

## Standard Model → example of weak EWSB

Introduce a self-interacting complex scalar doublet ⇒ Higgs with non-trivial quantum numbers under  $SU(2)_L \times U(1)_Y$ .



# The Higgs Mechanism:



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

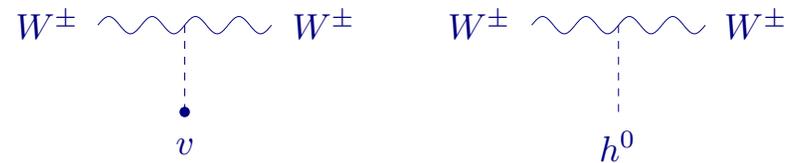
$$V(\phi) = -m^2\phi^2 + \frac{\lambda}{2}\phi^4$$

Higgs vacuum condensate  $v \implies$  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

$$m_V^2 = g_\phi^2 V_V v^2 / 2 \implies v = 174 \text{ GeV}$$



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

★ mass to fermions via Yukawa interactions

$$m_f = \sqrt{2}g_\phi f\bar{f}v$$



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



→ no direct evidence for the Higgs

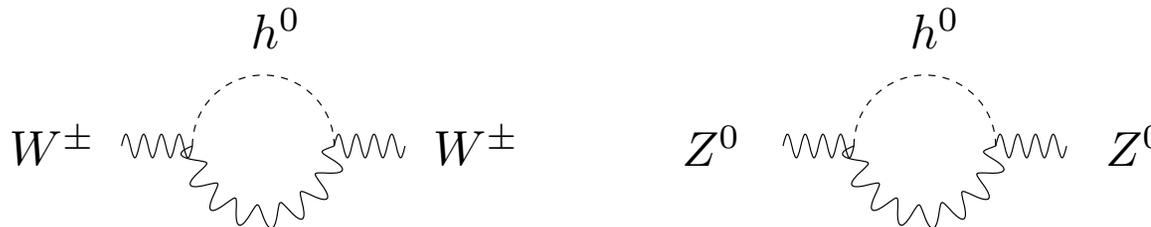
- Direct Higgs search at the Large Electron Positron Collider – LEP

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

(final LEP result, 2003)

- constraints on  $m_H$  from precision tests of the SM (*one part in a thousand!*)  
from CERN, Fermilab, SLAC

Although this Higgs boson has not been seen and its mass is unknown, it enters via loop corrections in electroweak observables: particles masses, decay rates, etc.



All electroweak parameters have at most logarithmic dependence on  $m_H$ .  
However, Standard Model preferred value of  $m_H$  can be determined.

$$m_H < 251 \text{ GeV at 95\% C.L.}$$

To avoid light Higgs boson, must have new phenomena below 1 TeV.



In weakly-coupled approach, SM most probably embedded in a

Supersymmetric theory: fermion-boson symmetry

$\implies$  Solve hierarchy/naturalness problem: Why  $v \ll M_{Pl}$ ?

## In the SM

- Quantum corrections to dimensionless couplings prop. to  $\log(\Lambda_{eff})$   
 $\Lambda_{eff} \longrightarrow$  cutoff scale at which a more fundamental theory supersedes the SM.
- Quantum corrections to Higgs potential mass parameter: quadratically divergent!

$$m^2 = v^2 \lambda = m^2(\Lambda_{eff}) + \Delta m^2 \quad \Delta m^2 \propto \frac{\sum_i n_i g_{hii}^2}{16\pi^2} \Lambda_{eff}^2$$

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

lesson from history: electron self-energy  $\longrightarrow$

fluctuations of em fields generate a quadratic divergence but existence of  
electron anti-particle cancels it, otherwise QED will break down below  $M_{Pl}$

*Will history repeat itself? Take SM and double the particle spectrum*

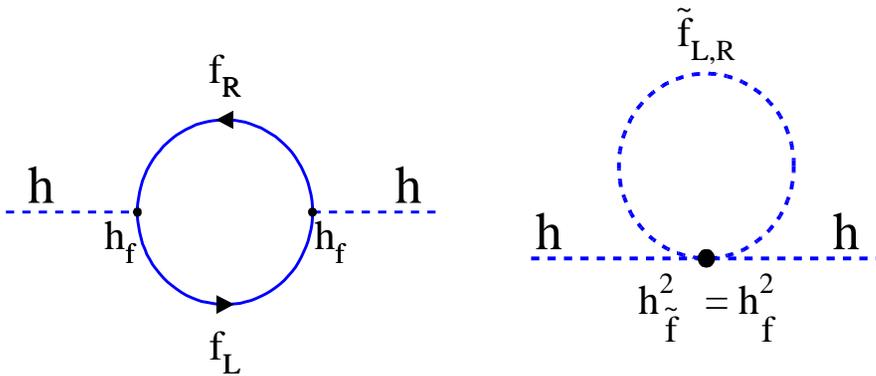
New Fermion-Boson Symmetry: SUPERSYMMETRY (SUSY)



## In Supersymmetry:

for every SM fermion there is a boson with same mass and couplings.

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



$$\Delta m^2 \propto g_{\phi f \bar{f}}^2 [m_f^2 - m_{\tilde{f}}^2] \ln(\Lambda_{eff}^2 / m_\phi^2)$$

No SUSY particle, degenerate in mass with its SM partner, ever been seen.

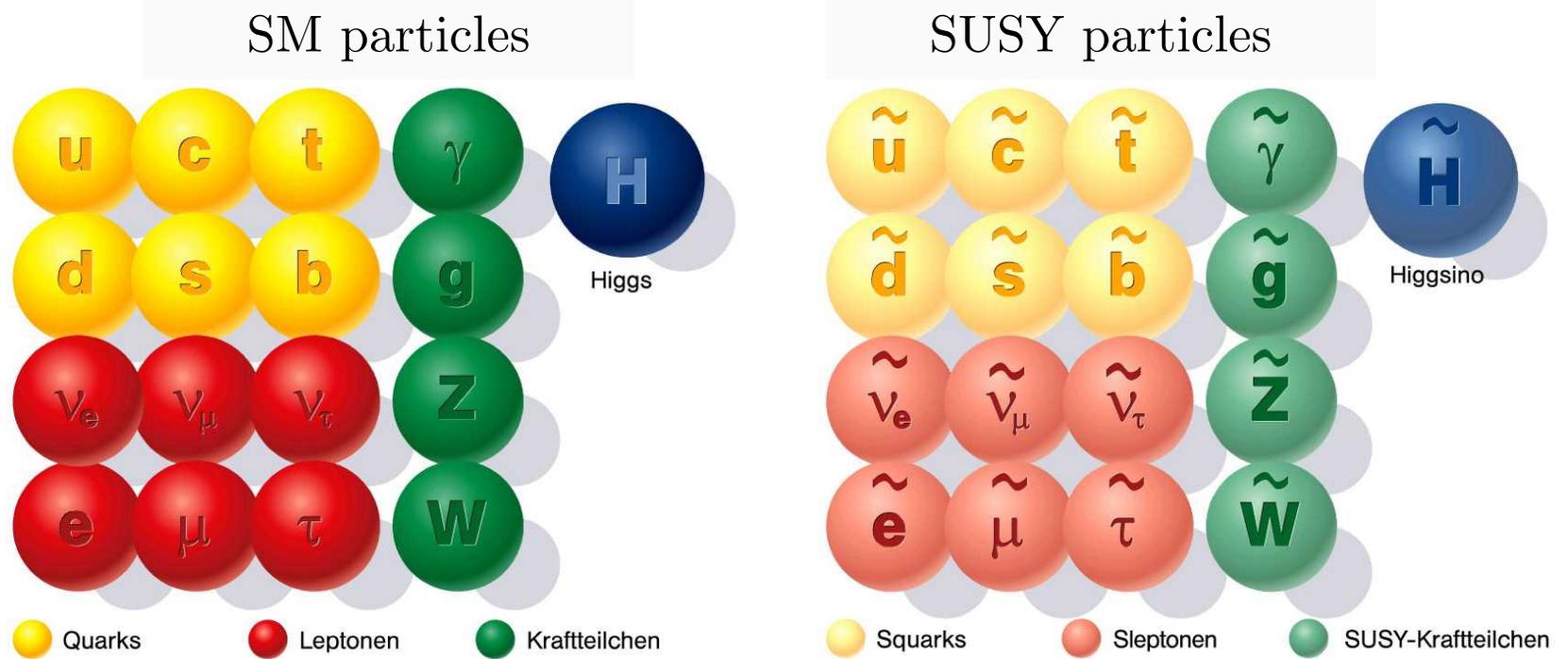
$\implies$  SUSY must be a broken symmetry.

- In low-energy SUSY: quadratic sensitivity to  $\Lambda_{eff}$  is replaced by quadratic sensitivity to SUSY breaking scale.

SUSY breaking scale must be at or below 1 TeV if SUSY is associated with EWSB scale !



# Minimal Supersymmetric Spectrum:



- SUSY associates a complex scalar  $\tilde{f}_{L(R)}$  to each chiral fermion  $f_{L(R)}$
- Minimal model: 2 Higgs doublets  $H_1, H_2$  to generate mass to up and down quarks and leptons, and have an anomaly free Higgsino sector
- SUSY Particle masses  $\longrightarrow$  depend on the mechanism of SUSY breaking  
 TeV SUSY  $\implies$  **Glimpse of Planck scale Physics**



# Higgs and Supersymmetry

SUSY Theories  $\implies$  larger Higgs sector with lightest Higgs  
having (usually) SM-like properties and  $m_h \leq 200$  GeV

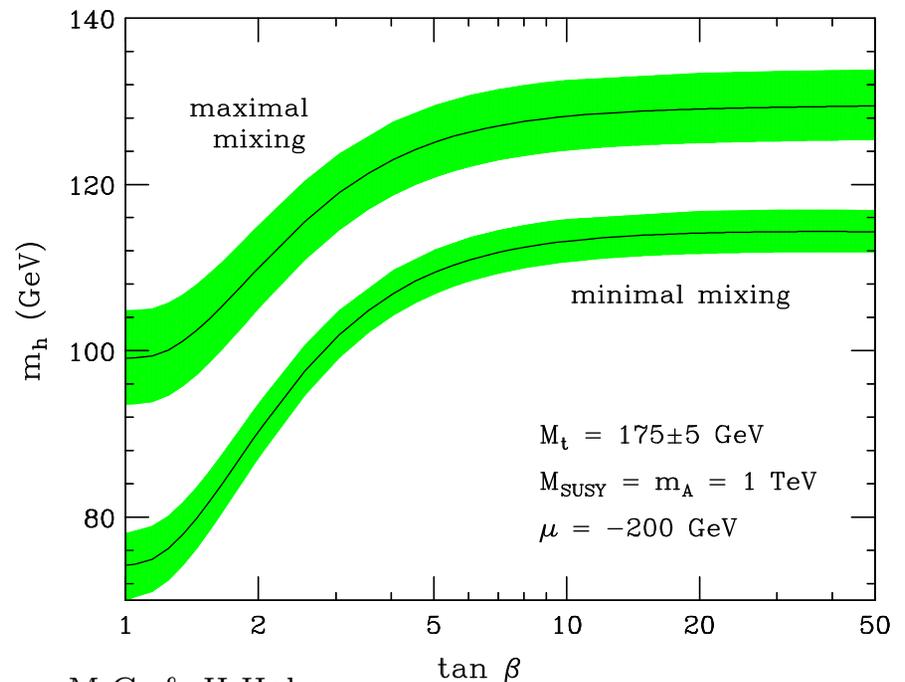
## MSSM: simplest extension

- two neutral scalars acquire vev's:  $v_1, v_2$  with  $\tan \beta = v_2/v_1$
- gauge bosons masses fix  $v^2 = v_1^2 + v_2^2$
- 5 physical states:

2 CP-even  $h, H$       1 CP-odd  $A$       and a charged pair  $H^\pm$

Lightest Higgs: important quantum  
corrections due to incomplete  
cancellation of particles and  
SUSY particle loops.

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



M.C. & H.Haber

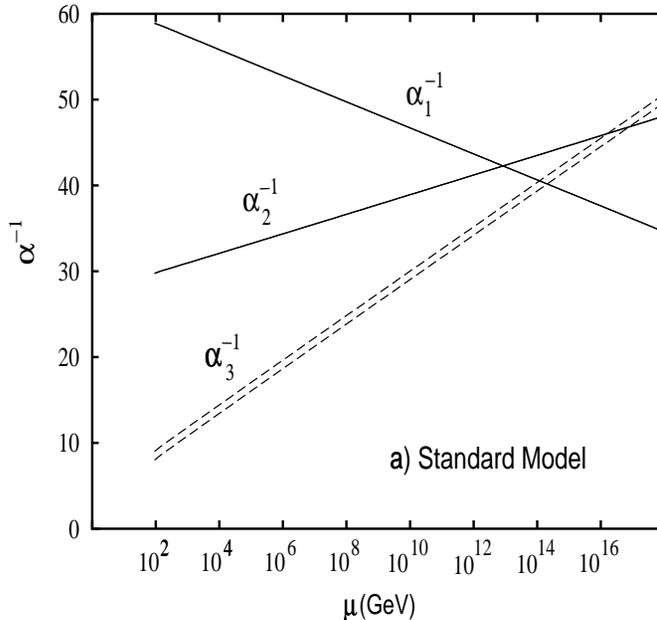


If SUSY exists, many of its most important motivations demand some SUSY particles at the TeV range or below.

★ Allows for the unification of gauge couplings

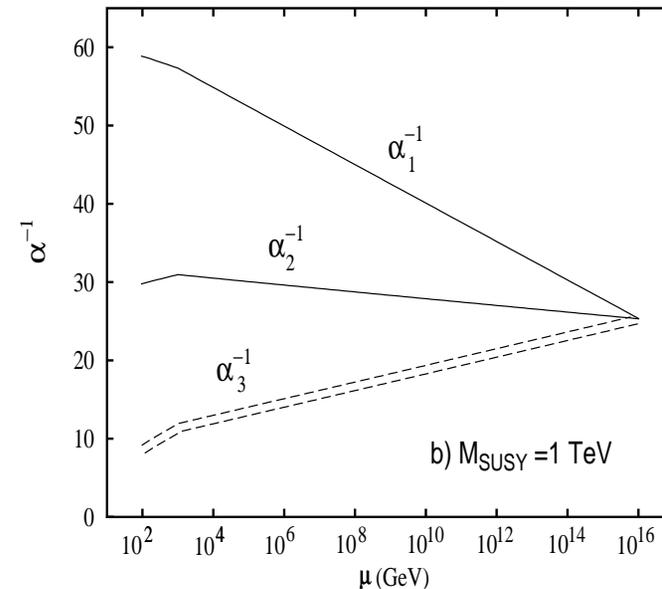
SM:

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!!*



# ★ Provides a good Dark Matter candidate

WMAP satellite measured the CMB and determines:

$$\Omega_M h^2 = 0.135 \pm 0.009 \quad \Omega_B h^2 = 0.0224 \pm 0.0009 \quad \Omega_{CDM} h^2 = 0.71 \pm 0.04$$

What is dark matter? (SM has no potential candidate)

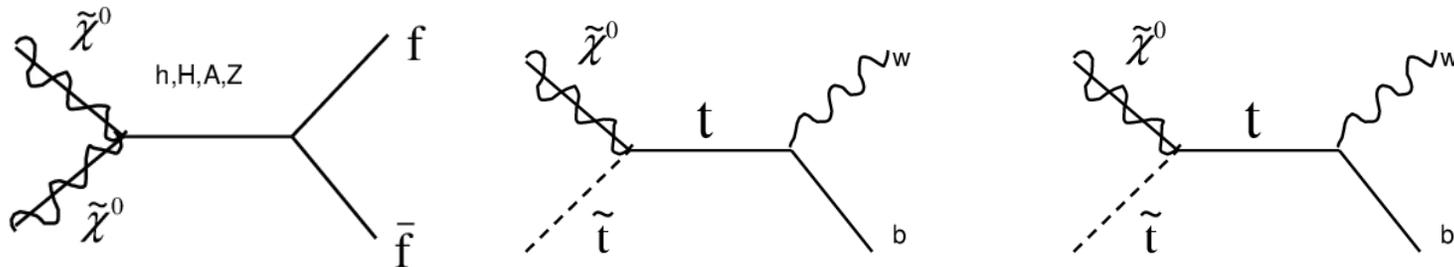
SUSY with  $R$ -parity conservation – a discrete symmetry:

$$R_P = (-1)^{3B+L+2S}$$

⇒ naturally provides a stable dark matter candidate: the lightest  $\tilde{\chi}_1^0$

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

Many processes contribute to the  $\tilde{\chi}_1^0 \tilde{\chi}_1^0$  annihilation cross section:



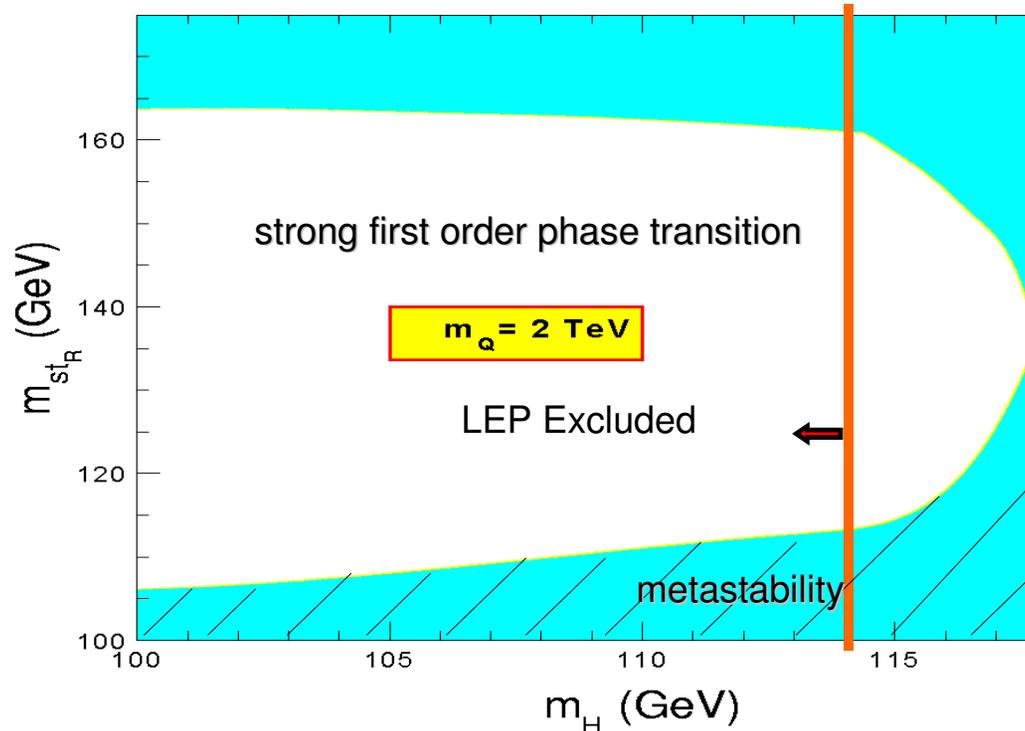
★ Provides a solution to the Matter–Anti-matter Asymmetry

$$\eta = \frac{n_B}{n_\gamma} = 2.6810^{-8} \Omega_B h^2 \simeq 6 \times 10^{-10}$$

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



- Also requires:
  - Gaugino and Higgsino masses on the order of the electroweak scale
  - CP-odd Higgs masses  $< 500$  GeV
  - New CP violating phases which are constrained by EDM's.
- other stop heavy,  $m_{\tilde{t}_L} \simeq 1$  TeV, to respect limit  $m_h \geq 114$  GeV.

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

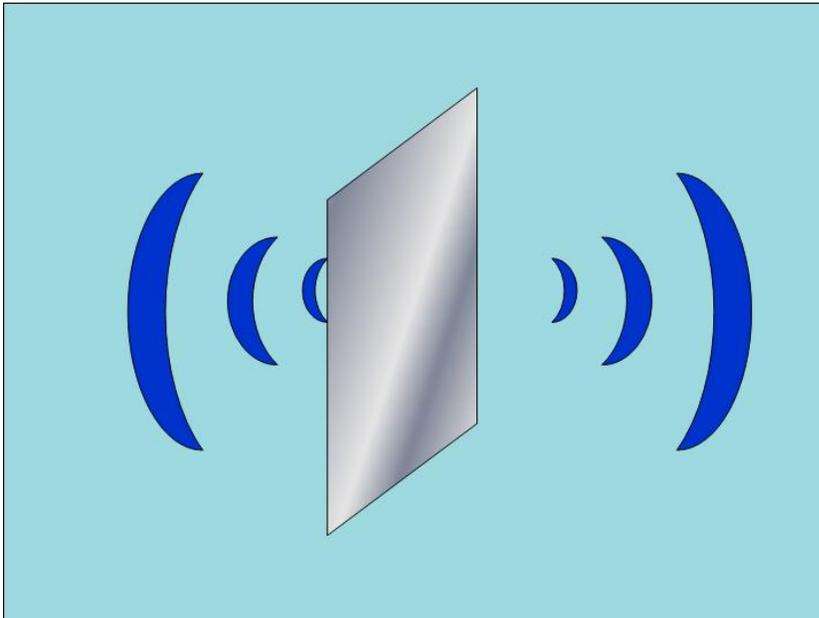


# A daring alternative: Extra Dimensions (ED)

- If seen by SM particles, they should be quite small:  $R \leq 10^{-17}$  cm  $\approx$  1 TeV
- If only seen by gravity  $\longrightarrow$  they can be larger:  $R \leq 0.1$  mm

Gravity in ED  $\implies$  fundamental scale, pushed down to ewk. scale by geometry

Metric:  $ds^2 = e^{-2k|y|} \eta_{\mu\nu} dx^\mu dx^\nu + dy^2 \implies$  Solution to 5d Einstein eqs.



$k = 0$  (flat)

gravity flux in ED  $\implies$  Newton's law modified:

$$M_{Pl}^2 = (M_{Pl}^{\text{fund.}})^{2+d} R^d$$

this lowers the fundamental Planck scale,  
 $\implies$  depending on the size & number of ED.

$$M_{Pl}^{\text{fund.}} \simeq 1 \text{ TeV} \implies R = 1 \text{ mm}, 10^{-12} \text{ cm} \\ \text{if } d = 2, 6$$



# How can we probe ED from our 4D wall (brane)?

4-D effective theory:

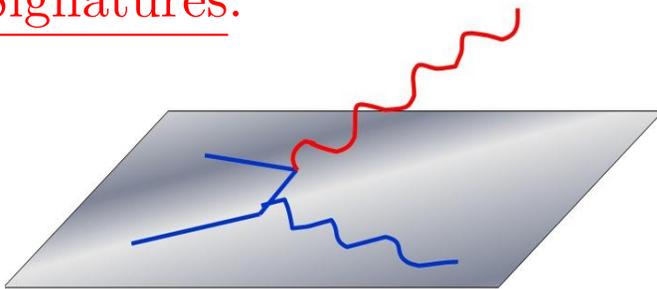
SM particles + gravitons + tower of new particles:

Kaluza Klein (KK) excited states with the same quantum numbers as the graviton and/or the SM particles

mass of the KK modes  $\implies E^2 - \vec{p}^2 = p_d^2 = \sum_{i=1,d} \frac{n_i^2}{R^2} = M_{G_{\vec{n}}}^2$

imbalance between measured energies and momentum in 4-D  
= momentum in the extra dimensions

## Signatures:

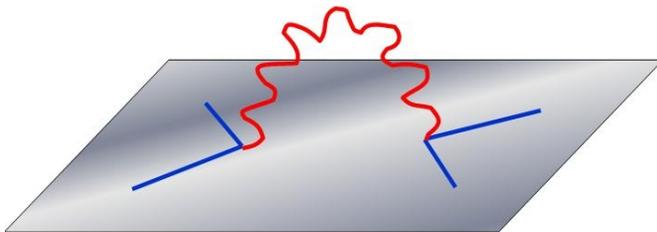


- coupling of gravitons to matter with  $1/M_{Pl}$  strength

$$R^{-1} \simeq 10^{-2} \text{ GeV} \quad (d = 6);$$

$$1/R \simeq 10^{-4} \text{ eV} \quad (d = 2);$$

- (a) emission of KK graviton states:  $G_n \leftrightarrow \cancel{E}_T$   
(gravitons appear as continuous mass distribution)



- (b) graviton exchange  $2 \rightarrow 2$  scattering  
deviations from SM cross sections



# SM fields propagating in ED

⇒ TeV-scale Extra dimensions

- Gauge bosons and/or fermions in the bulk

⇒ new particles may be within reach of LHC.

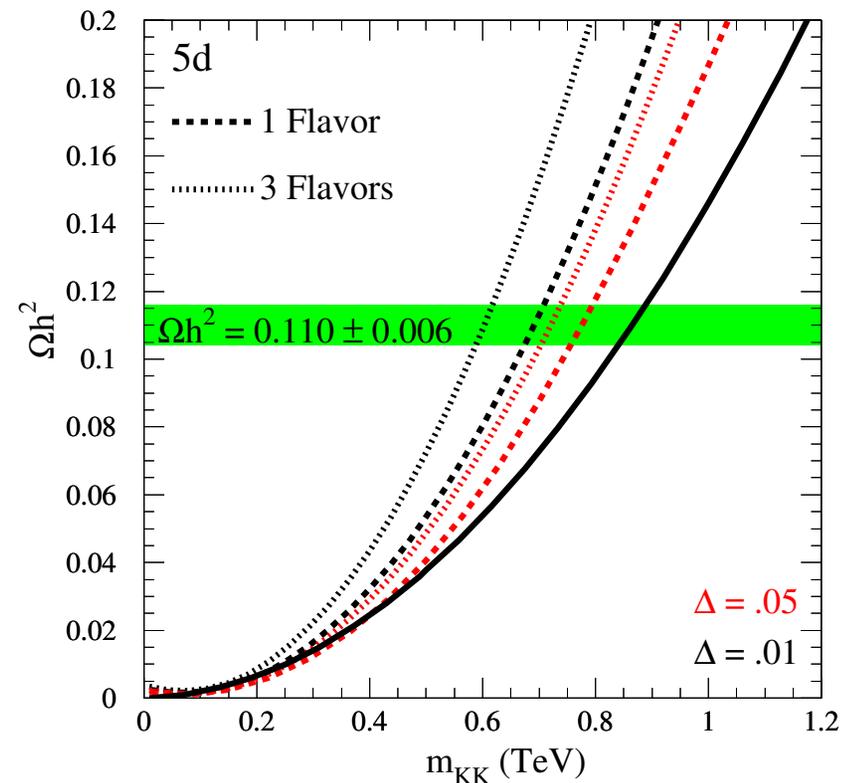
## Universal Extra Dimensions:

All fields in the bulk – no wall or branes

⇒ momentum conserved in ED.

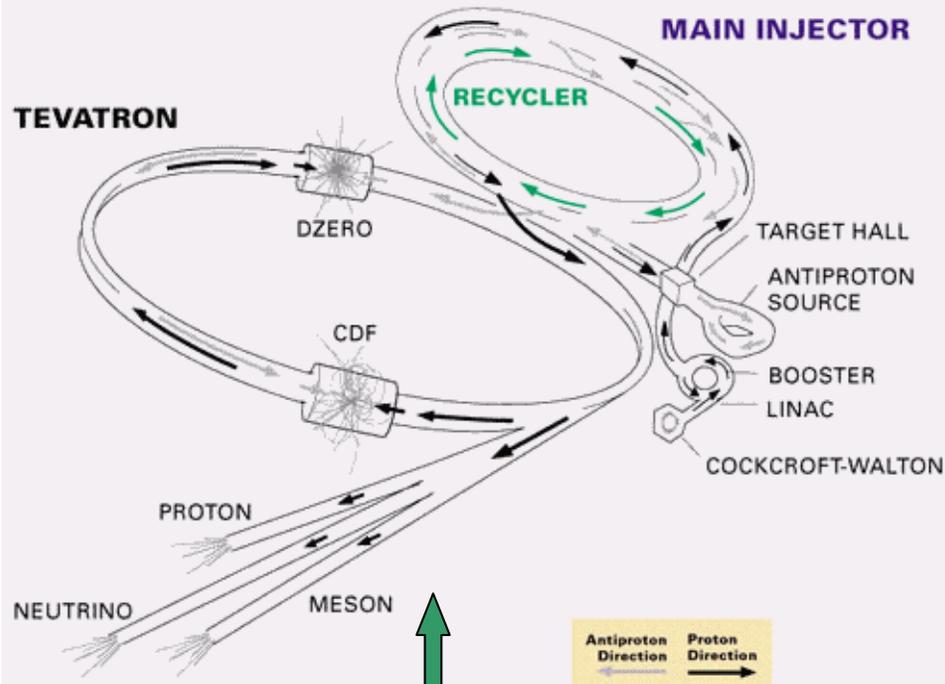
- KK modes produced by pairs
- no big corrections to EW observables
- Lightest Kaluza-Klein Particle (LKP)  
→ good dark matter candidate

Servant & Tait



# Searching for New Physics

## Fermilab's ACCELERATOR CHAIN

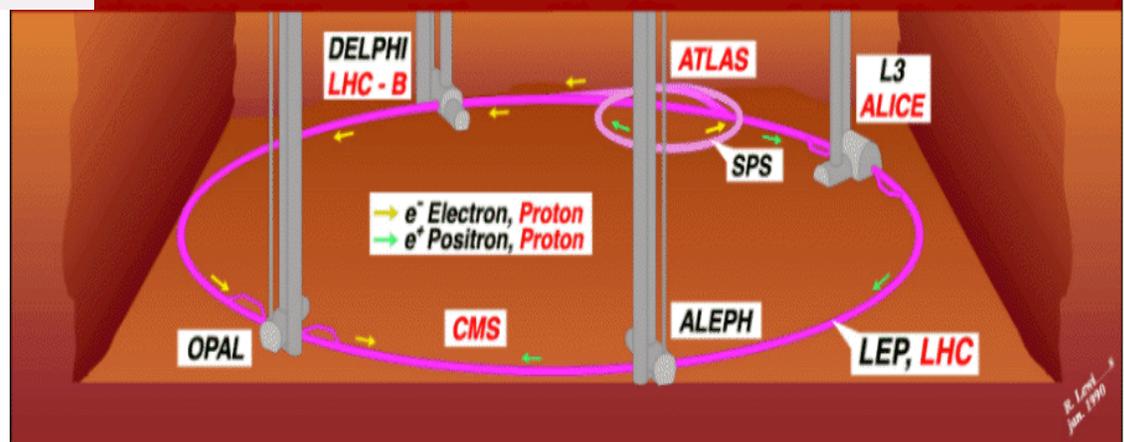


## The Tevatron at Fermilab

$p\bar{p}$  at  $\sqrt{s} = 2 \text{ TeV}$  (2001 - 2009)

## Large Hadron Collider (LHC) at CERN

$pp$  at  $\sqrt{s} = 14 \text{ TeV}$  (2007/8 - 2015/20)



# What Can We Learn from the Tevatron?

## – Precision measurements:

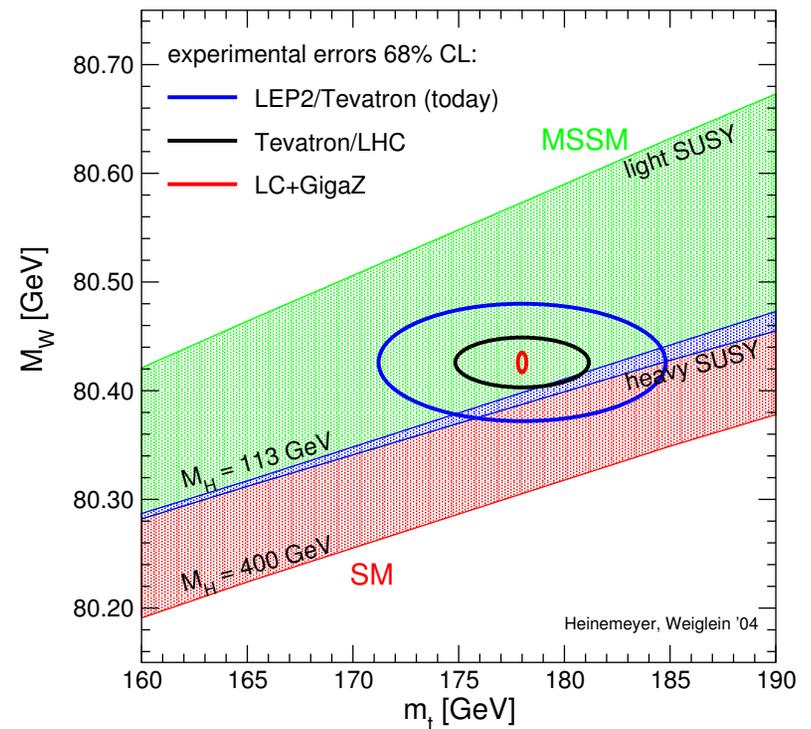
- top quark mass:  $\delta M_t \simeq 3 \text{ GeV}$  with  $2 \text{ fb}^{-1}$
- $W$  mass:  $\delta M_W \simeq 30 \text{ MeV}$  with  $2 \text{ fb}^{-1}$

high precision for  $M_t$  is important to  
exploit precision on  $M_W$  in context of electroweak precision measurements

## $M_t$ – $M_W$ – $M_H$ Correlation

- direct  $M_t$  and  $M_W$  measurements from LEP and the Tevatron
- Indirect  $M_t$  and  $M_W$  determination from SM fit to precision data – LEP, SLD,  $\nu N$
- SM relationship for  $M_t$ – $M_W$ – $M_H$   
 $\implies$  crucial information on  $M_H$

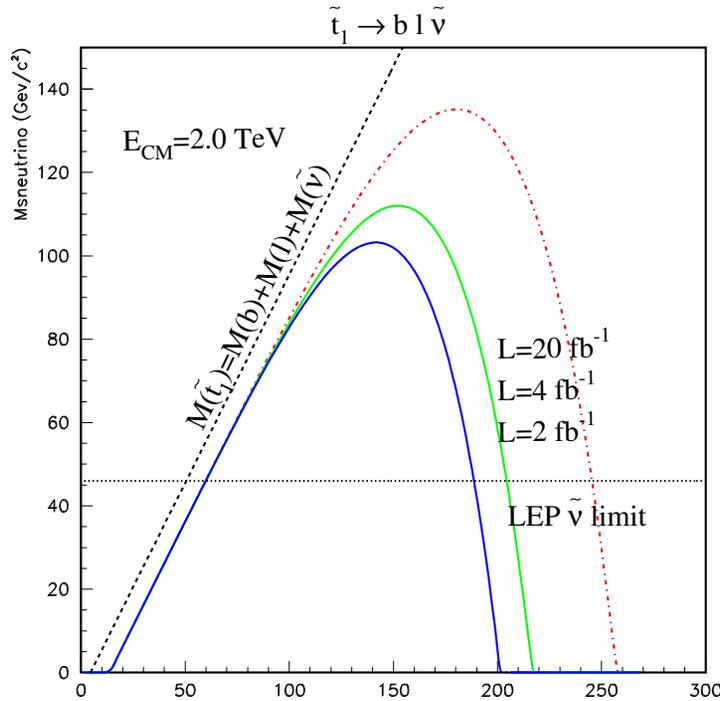
$\implies$  A light SM Higgs Boson strongly favored by data



# Stop and Sbottom Searches

In many models (MSUGRA, extended Gauge- and Anomaly-Mediated)

→  $\tilde{t}$ 's and  $\tilde{b}$ 's can be quite light



Demina, Lykken, Matchev & Nomerotski

prospects: with  $\int \mathcal{L} dt = 4 \text{ fb}^{-1}$

$$m_{\tilde{t}_1} \leq 200/210 \text{ GeV} \quad \text{in } \tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm / \tilde{t}_1 \rightarrow bl\tilde{\nu}$$

$$m_{\tilde{t}_1} \leq 180 \text{ GeV} \quad \text{in } \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$$

$$m_{\tilde{b}_1} \leq 230 \text{ GeV} \quad \text{in } \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$$

generic squark & gluinos: 350–450 GeV

New Studies: jets + photons +  $\cancel{E}_T$  with  $4 \text{ fb}^{-1}$  M.C., Choudhury, Logan, Diaz & Wagner

→ possible signature of gauge-mediated scenarios

In the cases  $\tilde{t} \rightarrow c\gamma\tilde{G}$  and  $\tilde{t} \rightarrow bW\gamma\tilde{G}$ , sensitivity up to  $m_{\tilde{t}_1} \leq 300 \text{ GeV}$

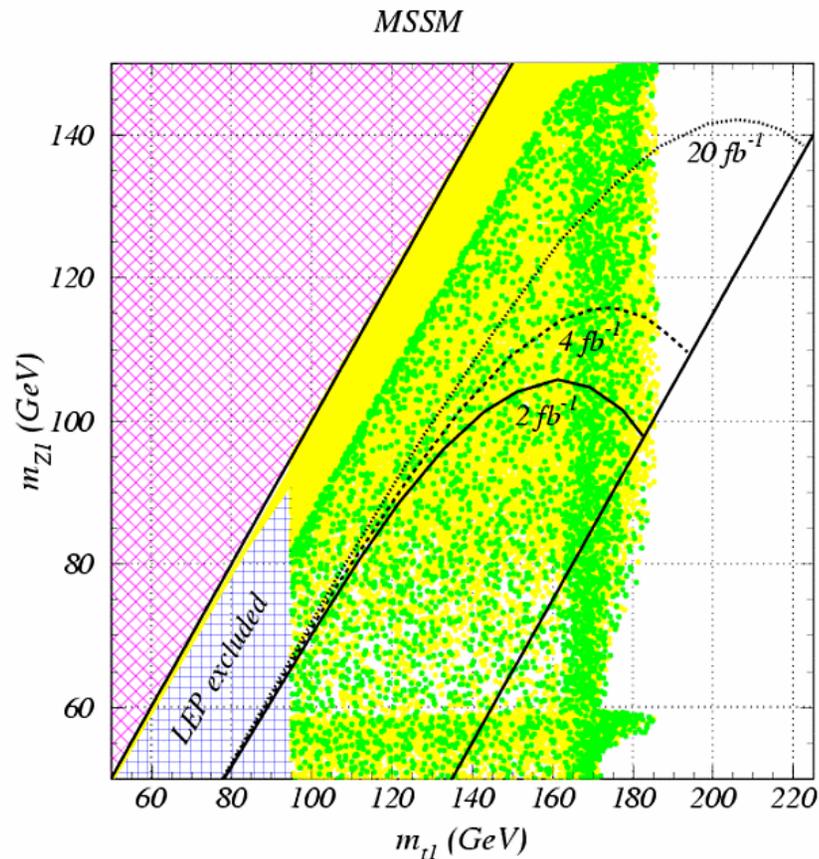
For generic squark production,  $\tilde{q} \rightarrow q\gamma\tilde{G}$ , sensitivity up to  $m_{\tilde{q}} \leq 400 \text{ GeV}$



## Tevatron Run II reach for stops

probes Dark Matter and Baryogenesis at the Electroweak scale!

Dots show scan over SUSY space with neutralino relic density compatible with WMAP observations  $0.095 \leq \Omega_{CDM} h^2 \leq 0.129$  and with electroweak Baryogenesis



Balazs, M.C. & Wagner

Lines show reach at the Tevatron for different total luminosities for dominant decay mode  $\tilde{t}_1 \rightarrow c \tilde{\chi}$ .

If stop-neutralino mass difference is below 30 GeV:

- trigger on  $\cancel{E}_T$  crucial
- co-annihilation region difficult at Tevatron or any hadron collider

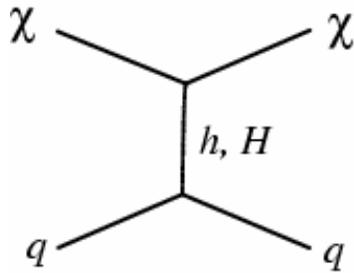
*A definite test of this scenario at the LC*



# Direct Dark Matter Detection: complementarity to colliders searches

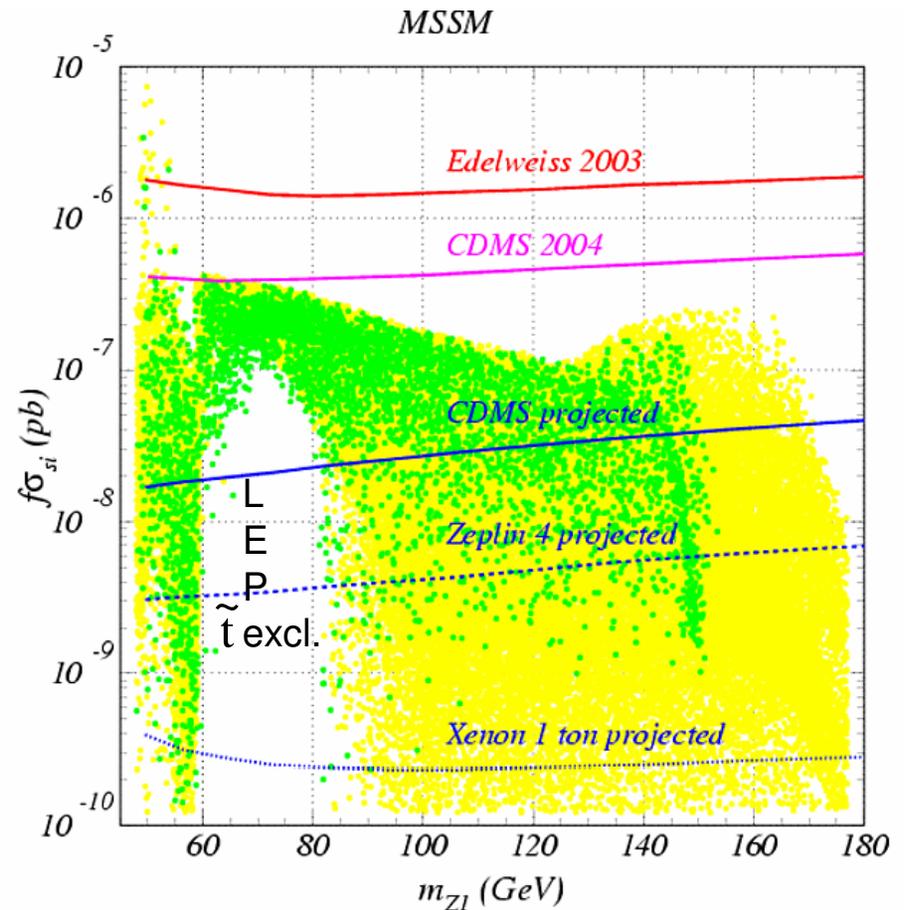
$\cancel{E}_T$  at colliders  $\longrightarrow$  important evidence of DM candidate,  
but, stability of LSP on DM time scales cannot be checked at colliders

☀ Neutralino DM is searched for in  
neutralino-nucleon scattering exp.  
detecting elastic recoil off nuclei



$\longrightarrow$  upper bounds on  
Spin independent cross sections

Next few years:  $\sigma_{SI} \approx 10^{-8}$  pb  
Ultimate goal:  $\sigma_{SI} \approx 10^{-10}$  pb



small  $\sigma_{SI}$  for large  $\mu$  : co-annihilation regions

Balazs, MC, Wagner '04



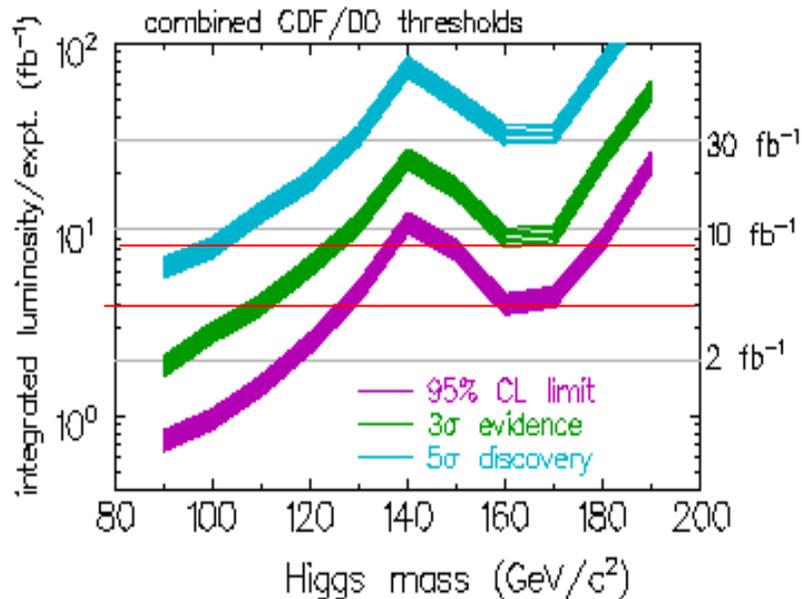
# What will we know by the End of this Decade?

after the first run period of LHC → 10-30 fb<sup>-1</sup> of data

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

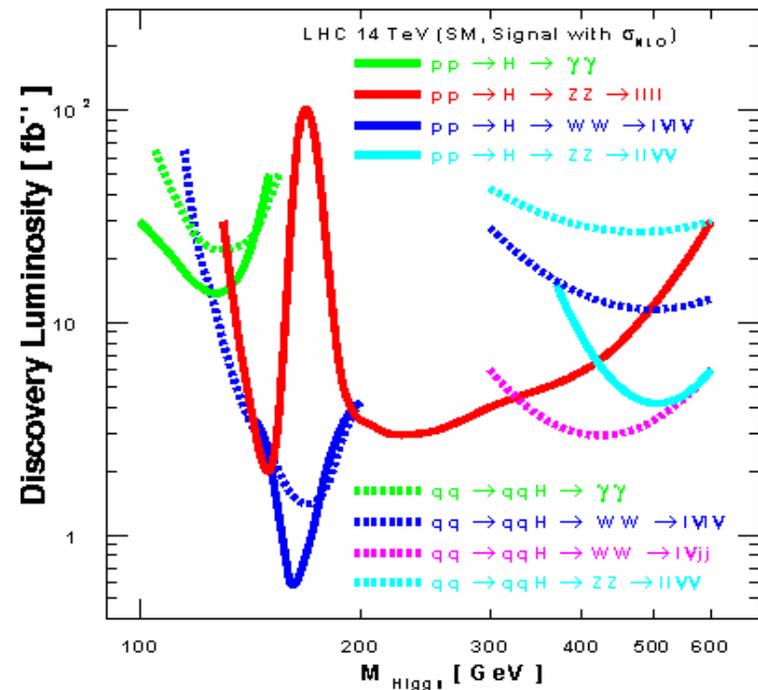
• LHC can search for a Higgs via many channels, already in the first few years

$p\bar{p} \rightarrow V H \rightarrow V b\bar{b}$  with  $V = W, Z$



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

5σ Higgs Signals (statistical errors only)



**If the SM Higgs exists:  
It will be discovered at LHC !**

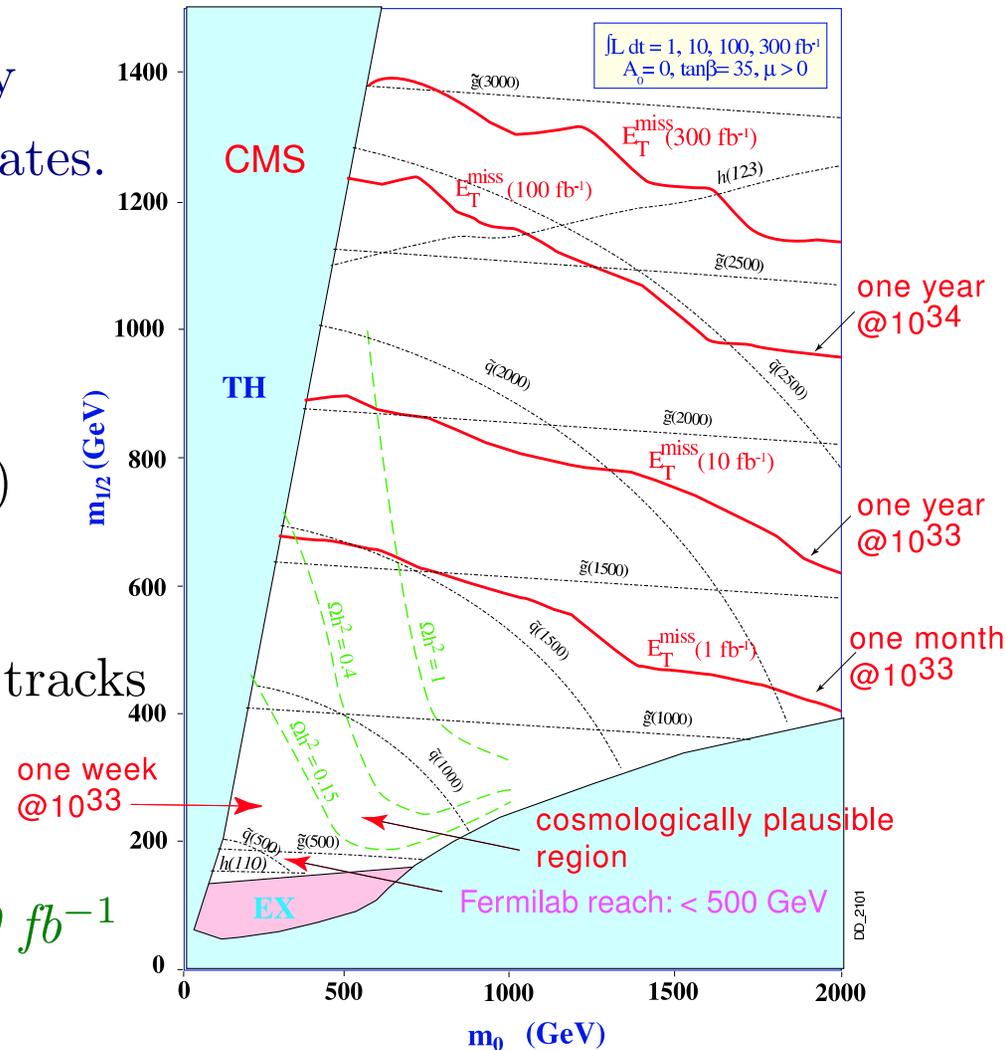


# SUSY

LHC: SUSY particles, especially strongly interacting ones, are produced at large rates.

- most likely types of signatures:
  - ‘mSUGRA’ type – high  $E_T$  jets and  $\cancel{E}_T$  (maybe leptons)
  - ‘GMSB’ type – hard photons &  $\cancel{E}_T$ ; heavily ionizing tracks

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



If low-energy SUSY is there, we expect to see some of its signature(s) by the end of this decade.

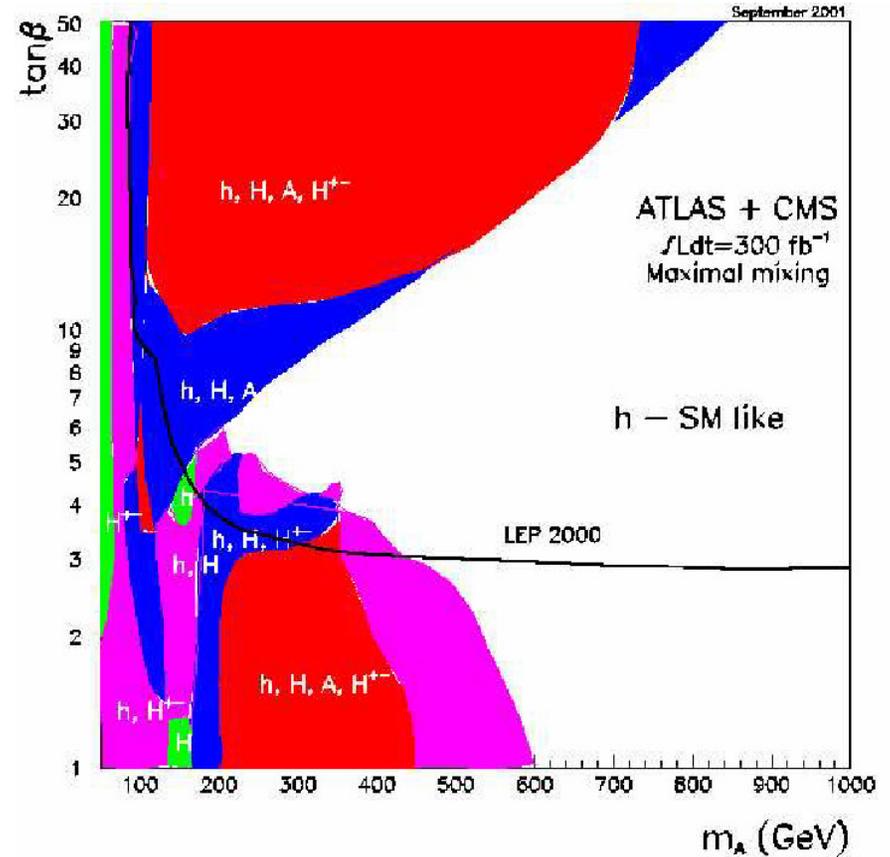
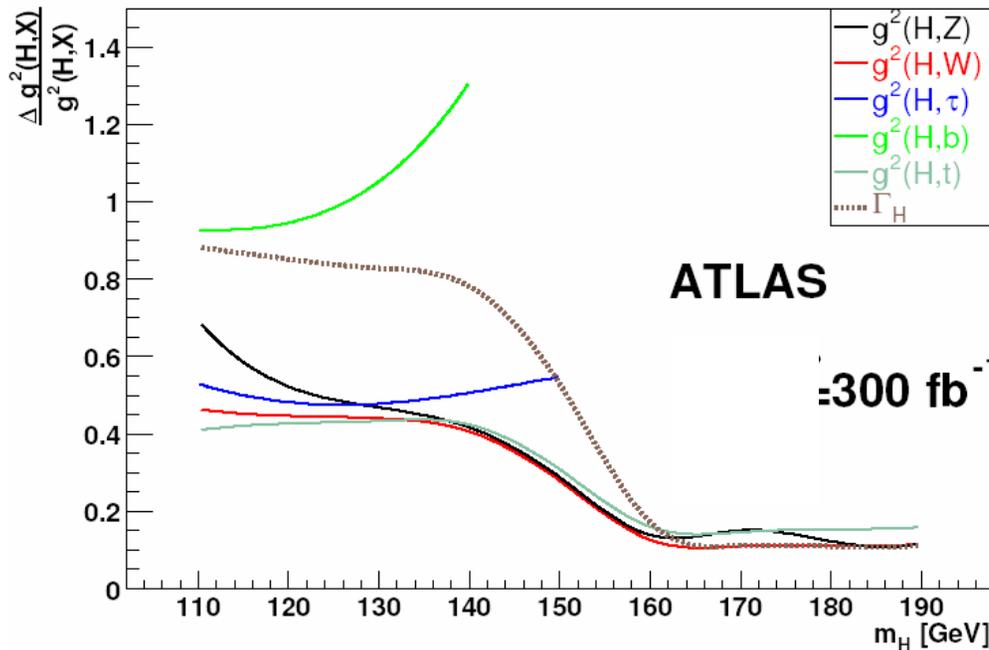


# The Energy Frontier in the next Decade

LHC: high luminosity up to  $300\text{fb}^{-1}$

Many production and decay processes accessible:

- start precision measurements of Higgs couplings to bosons and fermions
- better coverage of  $h, H, A$  and  $H^\pm$  but still regions where only  $h$  is visible



from  $\sigma(\text{XX} \rightarrow H_{\text{SM}}) \times \text{BR}(H_{\text{SM}} \rightarrow \text{YY})$   
 which implies meas. partial and total widths

$$\text{BR}(H_{\text{SM}} \rightarrow \text{YY}) = \frac{\Gamma(H_{\text{SM}} \rightarrow \text{YY})}{\Gamma_{\text{tot}}}$$

**Higgs Physics**  $\rightarrow$  LHC will have a great shot at it!



# Extra Dimensions

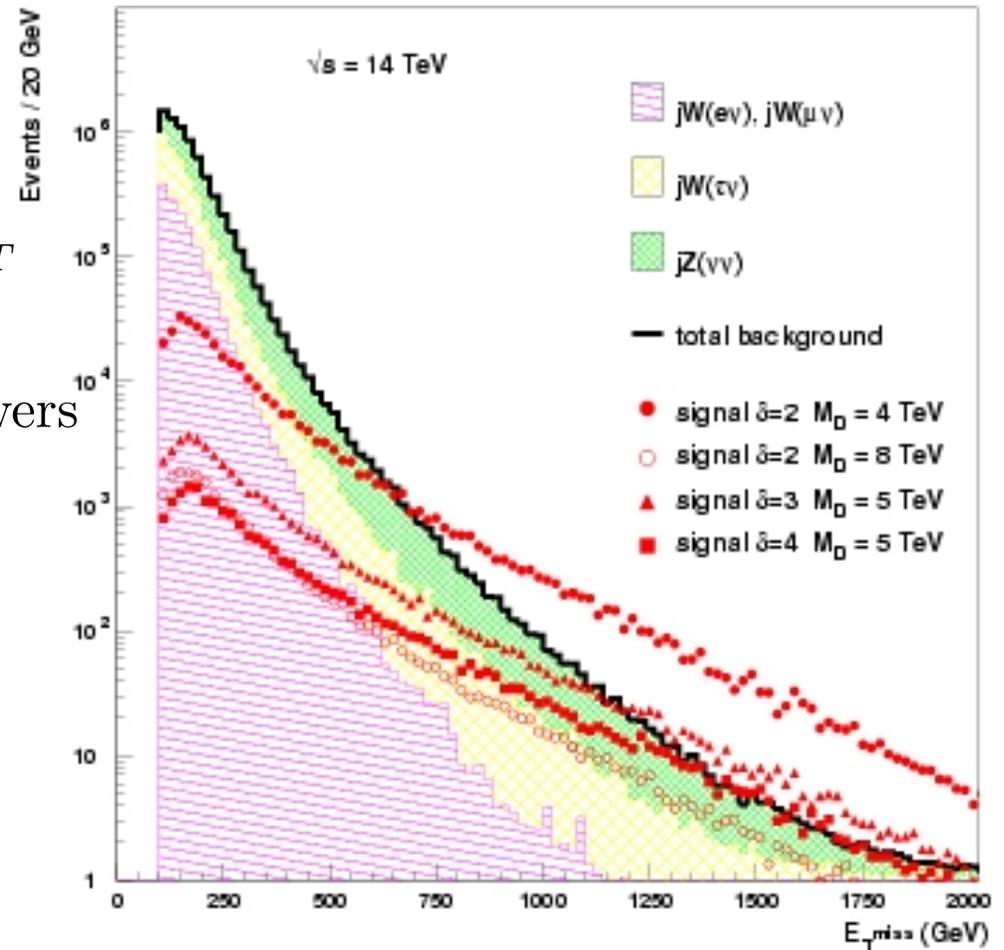
- emission of KK graviton states

$$p\bar{p} \rightarrow g G_N (G_N \rightarrow \cancel{E}_T) \longrightarrow \text{jet} + \cancel{E}_T$$

cross section summed over full KK towers

$$\implies \sigma/\sigma_{SM} \propto (\sqrt{s}/M_{\text{Pl}}^{\text{fund}})^{2+d}$$

Emitted graviton appears as a continuous mass distribution.



Discovery reach for fundamental Planck scales on the order of 5–10 TeV  
(depending on  $d = 4, 3, 2$ )



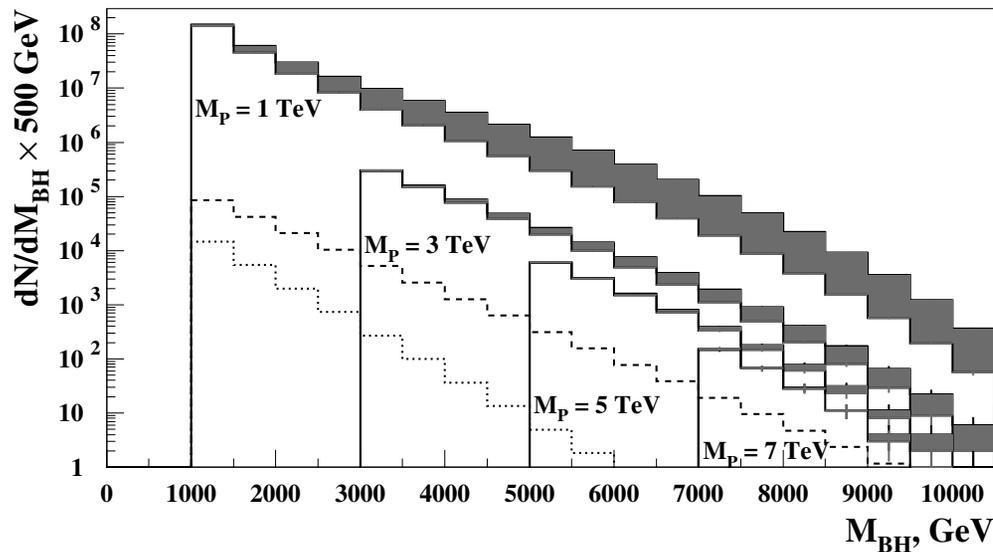
## Exciting Possibility: TeV-scale Production of Black Holes

For  $M_{BH} \gg M_{Pl}^{\text{fund}} \implies$  BH properties understood:

- Two partons with center of mass energy:  $\sqrt{\hat{s}} \equiv M_{BH}$   
moving in opposite direction.

If impact parameter smaller than the Schwarzschild radius  $\implies$  BH forms

- If  $M_{Pl}^{\text{fund}} \sim 1 \text{ TeV} \implies$  more than  $10^7$  BH per year at the LHC !!



- Signal: sprays of SM particles  
in equal abundances  
 $\longrightarrow$  look for hard, prompt leptons  
and photons

**May be the first signal of  
TeV-scale Quantum Gravity!**

- At LHC, limited space for trans-Planckian region



# High energy Linear Collider will add uniquely

- Higgs precision Physics

- A Window to the Childhood of the Universe

- A window to the Cosmos



# Higgs Physics

- If kinematically accessible, LC can observe Higgs bosons independent of their decay patterns using the Z recoil mass method.

$$\sigma(e^+e^- \rightarrow Z\phi) \implies g_{\phi ZZ}$$

*This is the most powerful feature unique to the LC.*

- W boson fusion:  $\sigma(\phi\nu_e\bar{\nu}_e) \implies g_{\phi WW}$

ratio  $\frac{g_{\phi WW}}{g_{\phi ZZ}}$  tests SU(2) symmetry

- $\sigma(e^+e^- \rightarrow \phi t\bar{t}) \implies g_{\phi t\bar{t}}$  direct measure of Yukawa coupling

- Higgs Decay Width: from cross sections + observed decay modes

$$\Gamma_H = \Gamma_W / Br(\phi \rightarrow WW)$$



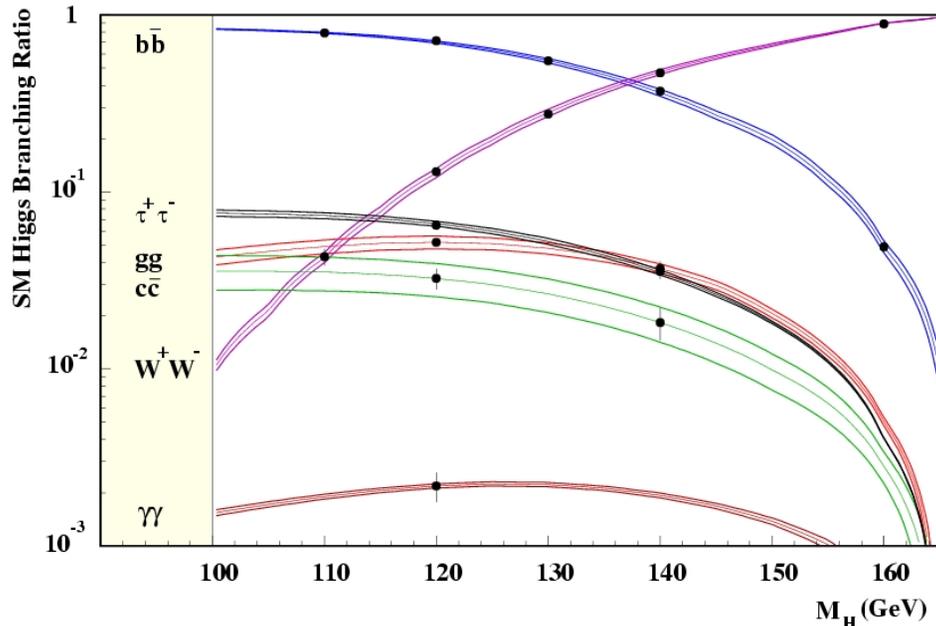
# Higgs Physics at a LC

Production mainly through:

$$e^+e^- \rightarrow Z H_{SM}$$

$$e^+e^- \rightarrow \nu\bar{\nu} WW^* \rightarrow \nu\bar{\nu} H_{SM}$$

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



measure most  $Br$ 's with 3–10% accuracy

$HZZ$  coupling measured from  $\sigma_{ZH}$  independently of Higgs decay modes!

width  $\delta\Gamma/\Gamma \sim 6\%$  for  $m_H \sim 120$  GeV

$\Rightarrow$  disentangle different Higgs models

• Precision Measurement of Higgs Mass

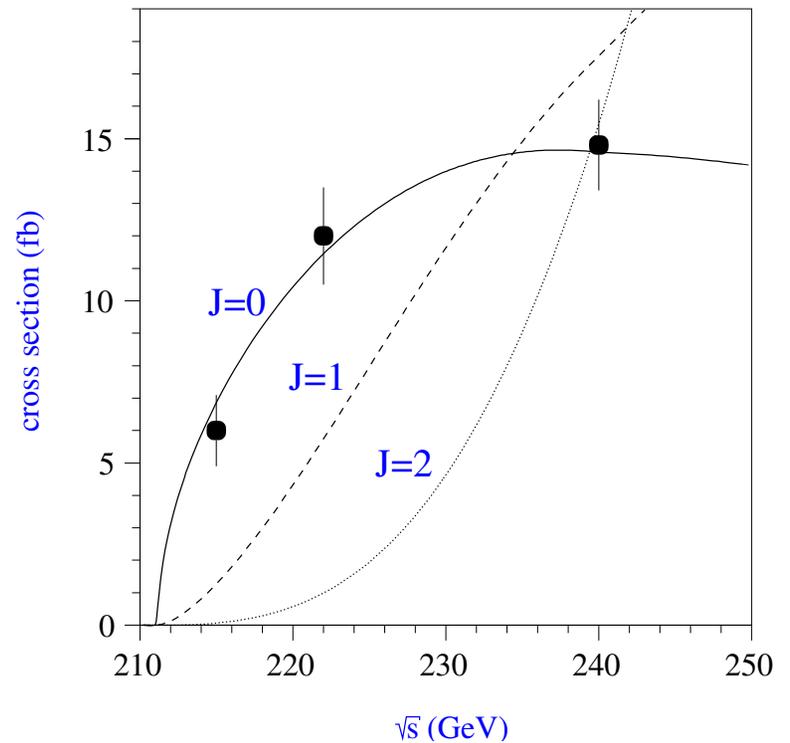
$$\delta m_h \sim 50 \text{ MeV (LHC: 100-150 MeV)}$$

• Higgs quantum numbers: spin and parity

■ threshold dependence of excitation curve

■ angular distributions

$$e^+e^- \rightarrow Z\phi; \quad e^+e^- \rightarrow f\bar{f}\phi$$



One can determine unambiguously spin & parity of the particle produced.



# Supersymmetry

## (a) Measurements of SUSY particles masses

⇒ sleptons, charginos, neutralinos

with an accuracy of 1% or less

If any visible SUSY particle produced,

→  $\delta M_{\tilde{\chi}_1^0} \sim 1\%$  ⇒ important for LHC meas.

## (b) Measurement of SUSY parameters

■  $\tilde{\chi}_i^\pm, \tilde{\chi}_i^0$  production & decay

→ param. of mixing mass matrix to 1%

→ determine composition in terms of

SUSY partners of  $\gamma, Z, W, H$

■ slepton and squark mixing angles

from cross sections with polarized beams

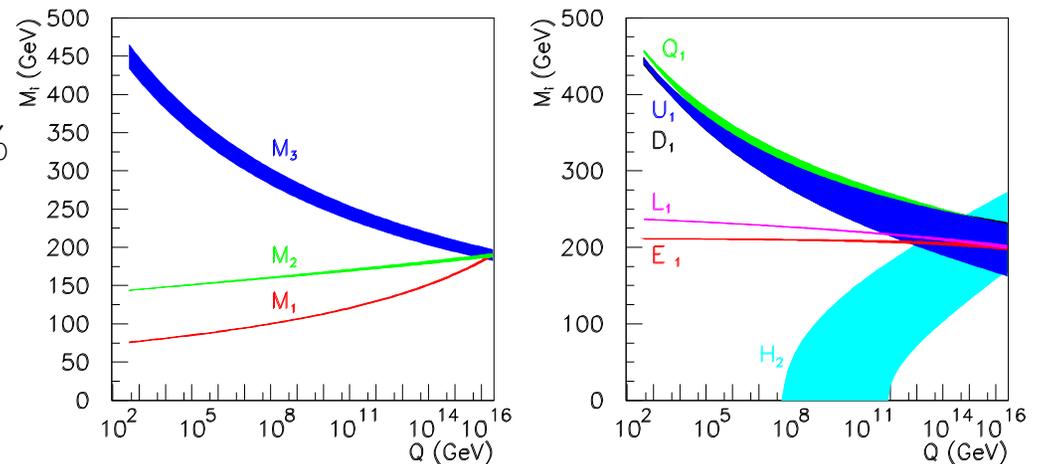
## (c) Spin of SUSY particles:

Simplicity of production reactions allows spin determination from angular distributions

Precise SUSY measurements at LC  
+ LHC input on gluinos/squarks

⇒ allow for precise extrapolation of  
SUSY parameters at high energies

Test type of SUSY theory at high energies.



**TeV scale Physics can provide our first  
glimpse of the Planck scale regime!!**



# Linear Collider and the Cosmos

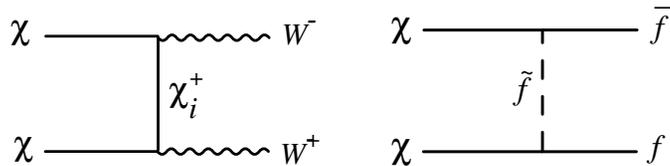
- Weak-interacting particles with weak-scale masses naturally provide  $\Omega_{\text{DM}}$ .

⇒ A coincidence or DM provides fundamental motivation for new particles at EW scale.

★ Understanding what DM is made of demands Collider & Astrophysical/Cosmological input.

- If the LSP is found to be a stable neutralino  
→ accurate meas. of  $\tilde{\chi}_1^0$  mass & composition

⇒ Comput. of  $\tilde{\chi}_1^0 \tilde{\chi}_1^0$  annih. cross section



⇒ determined thermal relic density  
assuming standard evolution of the universe

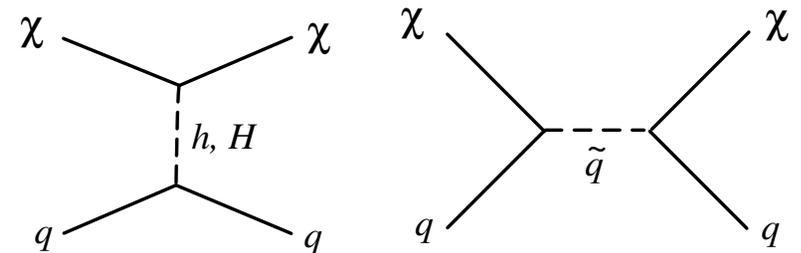
- comparing this result with  $\Omega_{\text{DM}}$  from Astrophysical/Cosmological input

⇒ new insights into history of our universe

## Dark Matter Detection:

- Direct: depends on  $\tilde{\chi}_1^0 N$  scattering

→ input from both collider and conventional DM experiments



- Indirect: through annih. decay products  
( $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow \gamma$ 's in galactic center,  $e^+$ 's in halo, anti-protons,  $\nu$ 's in centers of Earth & Sun)

⇒  $\tilde{\chi}_1^0 N$  scattering not necessarily in one-to-one correspondence with DM detection rates

⇒ LC will provide important info about DM halo densities and velocity distributions.



# Extra Dimensions

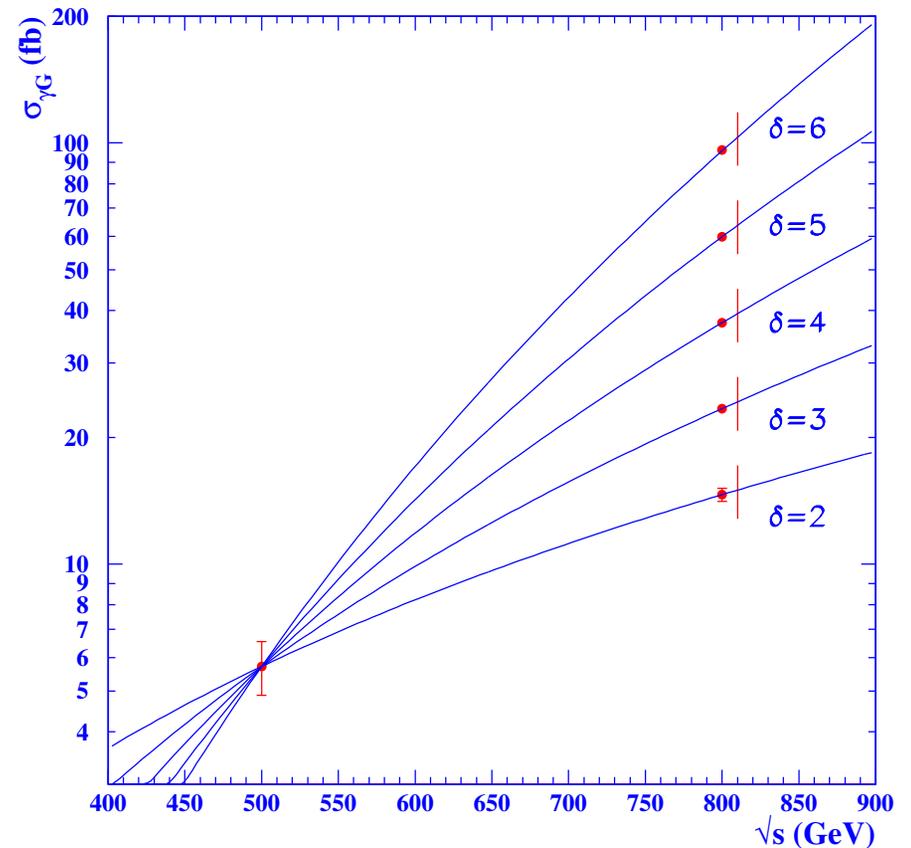
## Flat ED:

graviton emission:  $e^+e^- \rightarrow \gamma G_N$

- if signal observed, reach on  $M_{\text{Pl}}^{\text{fund}}$  is comparable to LHC if the beams are partially polarized.
- varying  $\sqrt{s}$  one can determine values of fundamental parameters:  $M_{\text{Pl}}^{\text{fund}}$  &  $\delta$

graviton exchange in  $2 \rightarrow 2$  processes:

- deviations for  $e^+e^- \rightarrow f\bar{f}$  or new decays with  $hh$  or  $\gamma\gamma$
- ability to determine spin-2 nature



# Conclusions

Theoretical arguments suggest that the SM must be superseded by a more fundamental theory at the TeV-scale:

**SUPERSYMMETRY** is a leading candidate.

The observation of a Higgs particle tests the EWSB mechanism.

- The Tevatron will have the first opportunity for testing the Higgs sector beyond the LEP bounds, and search for new physics.
- The LHC will be a sure window onto new physics –  
If Higgs & SUSY are there, we will find them.
- Precision tests will only be truly available at a future  $e^+e^-$  Linear Collider
  - unique capabilities which complement LHC, opening the window to Planck-scale physics
  - unique connection with cosmology

*We need to test the SM at higher energies and answer the questions which lie beyond it: gravity, dark matter, baryogenesis, unification of forces.*

