The Energy Frontier: in the Search for New Physics

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Outline

- **Introduction: Physics Landscape**
  - The Forces of Nature and the fundamental Particles
  - The Standard Model
  - Open Questions
  - Models of New Physics
    - ⋆ Supersymmetry
    - ⋆ Extra dimensional theories
    - ...
- **The Energy Frontier in this and the Next Decade**
  - The role of the Tevatron at Fermilab in shaping the next decade
    - ⋆ Precision Measurements
    - ⋆ Discovery of new particles or new bosonic or fermionic (SUSY) dimensions
  - The Large Hadron Collider (LHC) at CERN:
    Largest Potential in Direct Searches for New Particles
  - A Linear Collider (LC), somewhere in the world:
    Precision measurements testing Properties of New particles
    - ⋆ Particle masses ⋆ Couplings ⋆ Branching ratios ⋆ Spin ⋆ Parity
- **Outlook**

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)

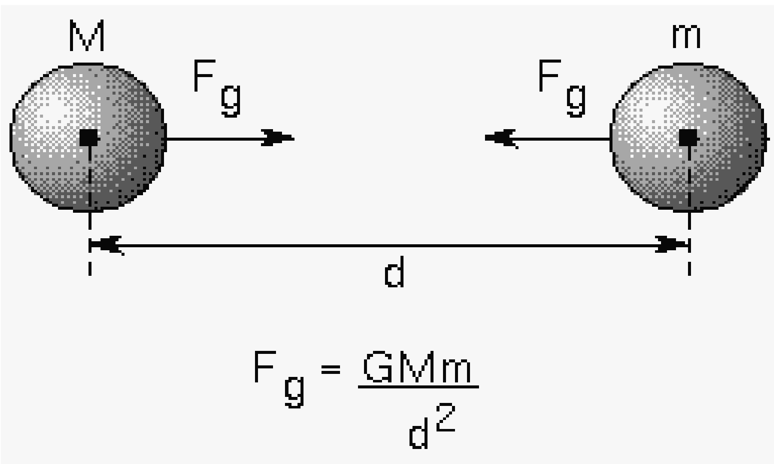
⟶ How do they get mass?

⟶ How do we test the mechanism for the origin of mass?

Gravitational and electromagnetic interactions

- Gravity

Attractive force between



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

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

- Electromagnetism

Attracts particles of opposite charge

forces within atoms and

between atoms (residual em.i.)

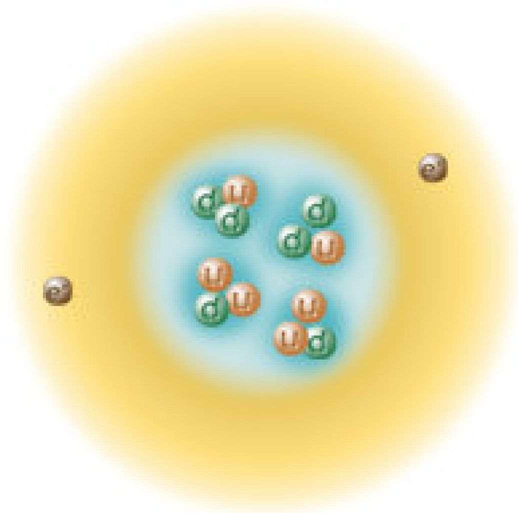
Electrons interact with protons

via quantum of e.m. energy

$\longrightarrow$ the photons $\quad s_\gamma = 1$, $\; m_\gamma = 0$

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 → uud **formed by three quarks, bound together by**
n → udd **the gluons of the strong interactions**

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

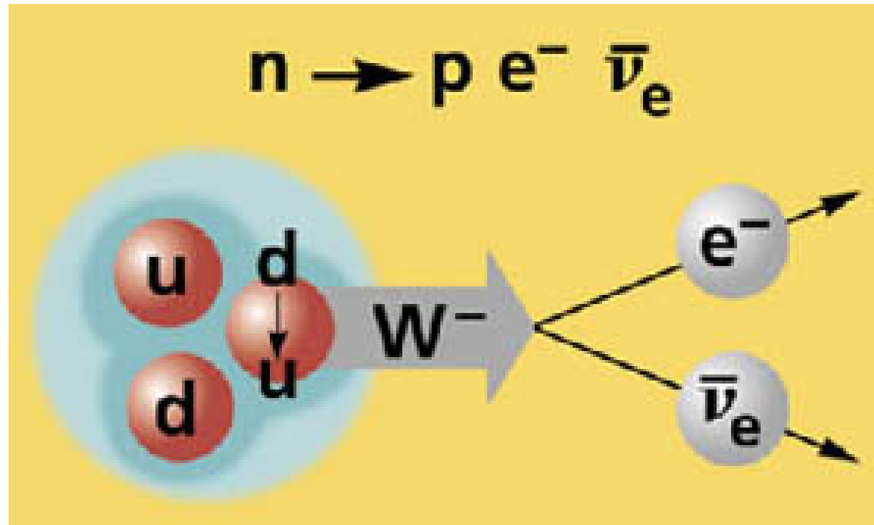
Very strong at large distances $\longrightarrow$ confinement ≡ no free color particles

Weak Interactions

Observation of beta decay

⇓

demanded a
novel interpretation



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

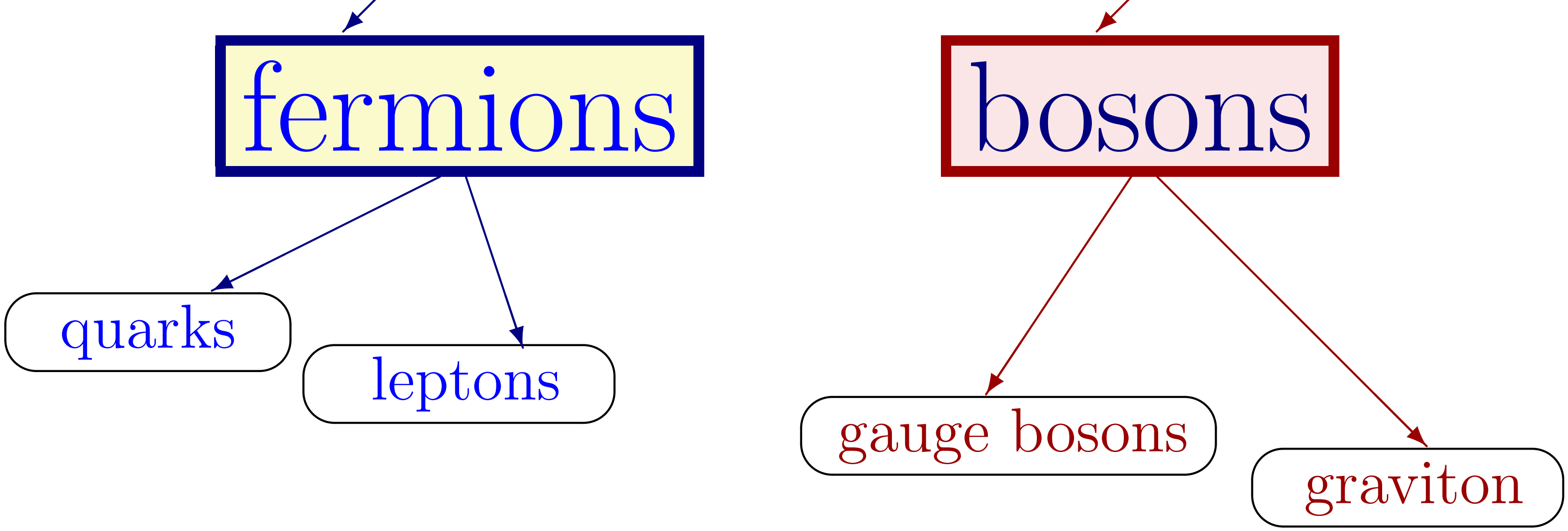
gauge bosons: W and Z

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.

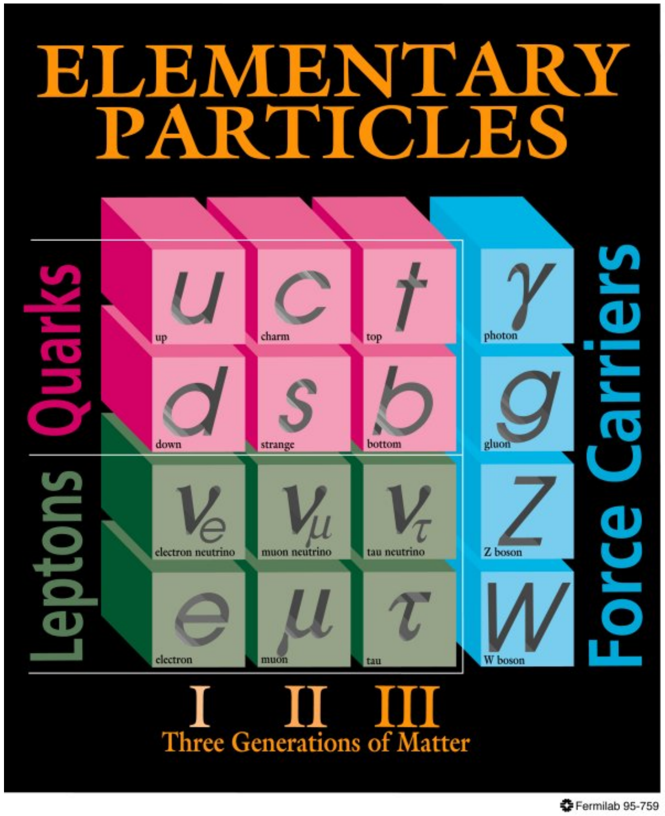


The Standard Model

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_μ's and B_μ

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

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

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

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

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

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

  $\Longrightarrow$ 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.

The Origin of Mass of the Fundamental Particles

or The Quest for ElectroWeak Symmetry Breaking (EWSB):

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

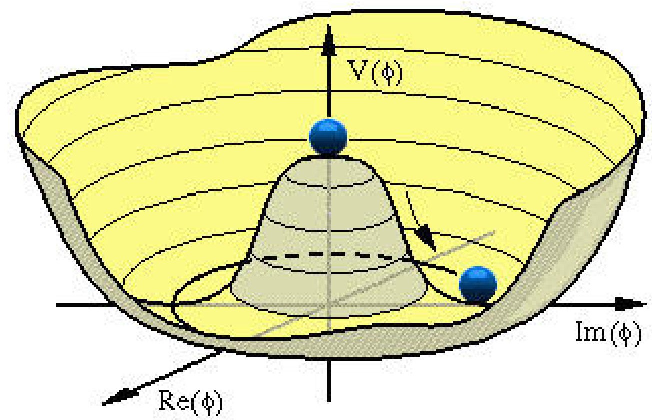
- **We know EWSB occurs at the TeV scale**

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

In the Standard Model

Introduce a self-interacting complex scalar doublet $\Longrightarrow$ 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:

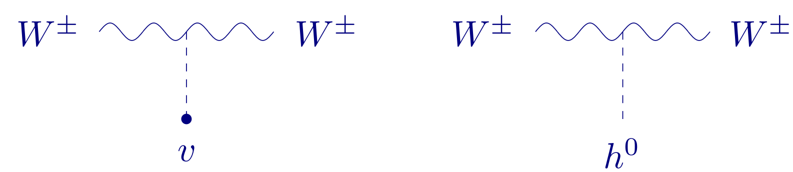
$$V(\phi) = -m^2\phi^2 + \frac{\lambda}{2}\phi^4$$

Higgs vacuum condensate $v \Longrightarrow$ 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

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

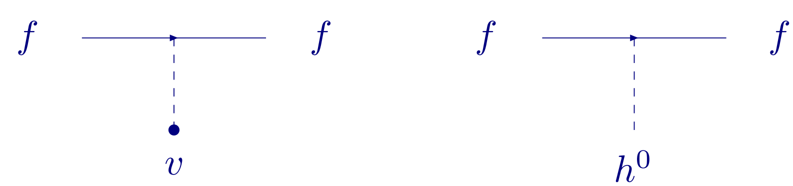


Higgs neutral under strong and electromagnetic interactions $\Longrightarrow \quad m_\gamma = 0 \quad m_g = 0$

exact symmetry $SU(3)_C \times SU(2)_L \times U(1)_Y \quad \Longrightarrow \quad SU(3)_C \times U(1)_{em}$

⋆ mass to fermions via Yukawa interactions

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



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

$\longrightarrow$ no direct evidence for the Higgs

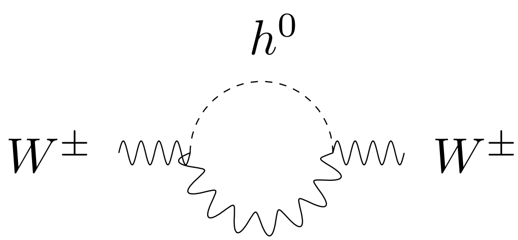
- Direct Higgs search at the Large Electron Positron Collider – LEP

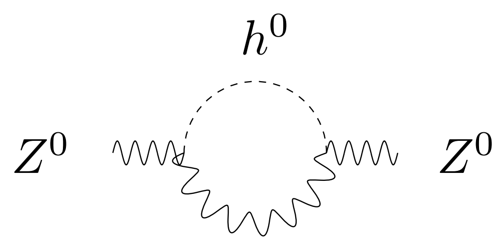
$$e^+e^- \xrightarrow{Z^*} H_{\rm SM}Z \qquad\qquad m_H > 114.6 \text{ GeV at } 95\% \text{ C.L.}$$

(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.

$$m_H < 260 \text{ GeV at } 95\% \text{ C.L.}$$

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

$\Longrightarrow$ 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!

$$m^2 = v^2 \lambda = m^2(\Lambda_{eff}) + \Delta m^2 \qquad \Delta m^2 \propto \frac{\sum_i (-1)^{2s} n_i \, g_{hii}^2}{16\pi^2} \Lambda_{eff}^2$$

To explain $v \simeq \mathcal{O}(m_W)$, either $\Lambda_{eff} \leq 1$ TeV
or 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 far below M_{Pl}

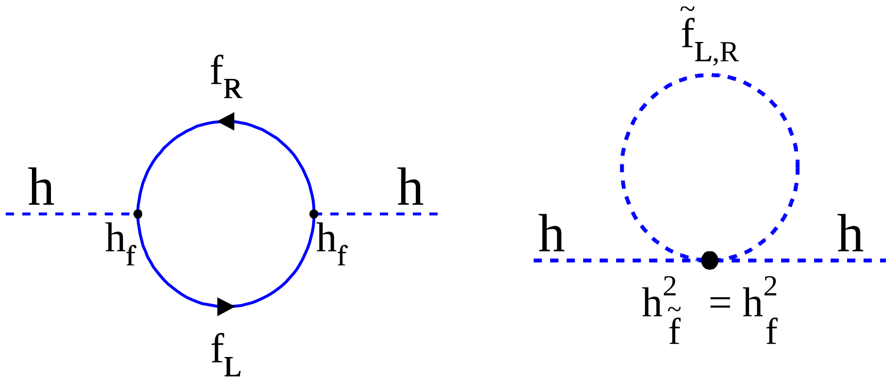
Will history repeat itself? Take SM and double the particle spectrum

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.



$$\Delta m^2 \propto g^2_{\phi f \bar{f}} [m^2_f - m^2_{\tilde{f}}] \ln(\Lambda^2_{eff}/m^2_\phi)$$

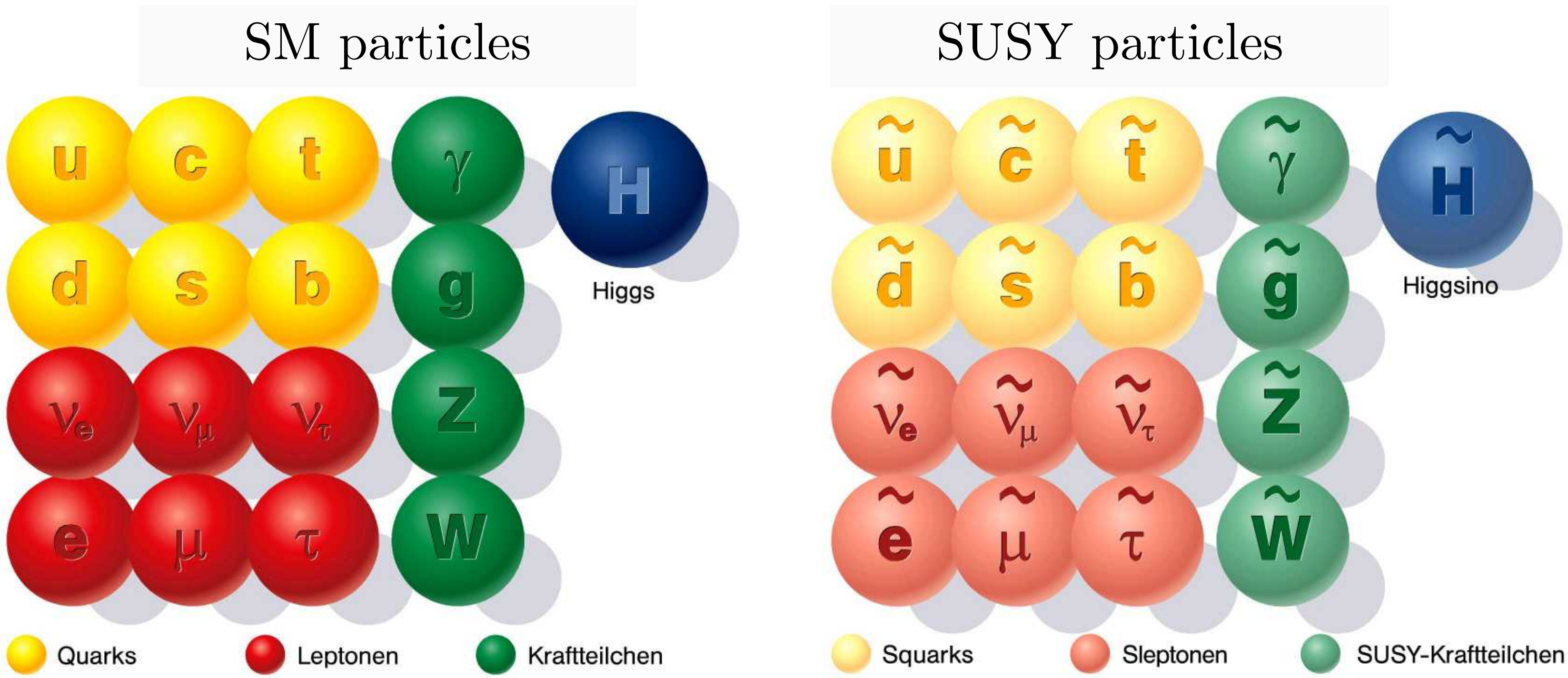
No SUSY particle, degenerate in mass with its SM partner, ever been seen.

$\Longrightarrow$ SUSY must be a broken symmetry.

- In low-energy SUSY: quadratic sensitivity to Λ_{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 $\Longrightarrow$ **Glimpse of Planck scale Physics**

Higgs and Supersymmetry

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

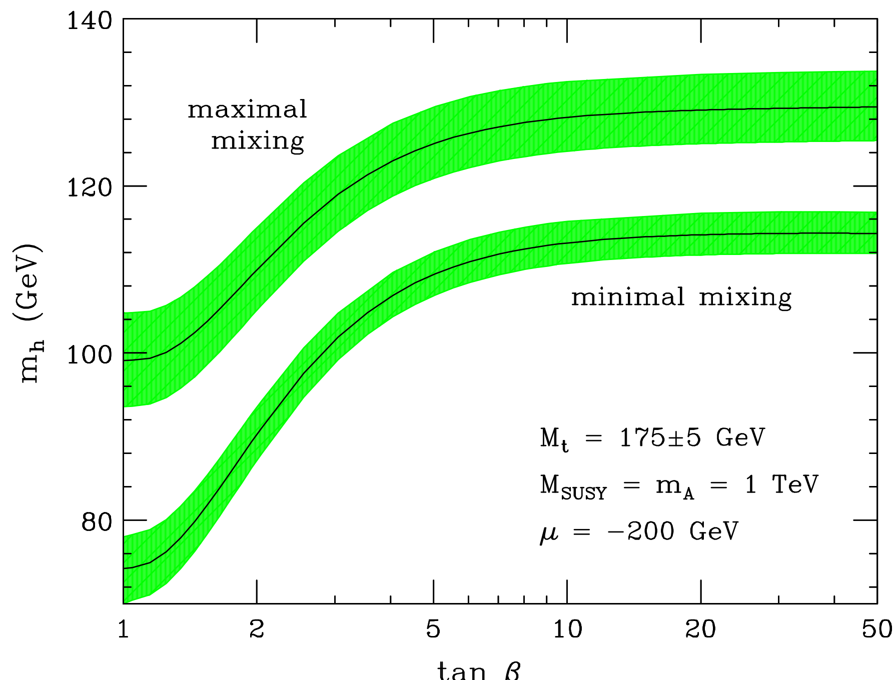
MSSM: simplest extension

- 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.

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



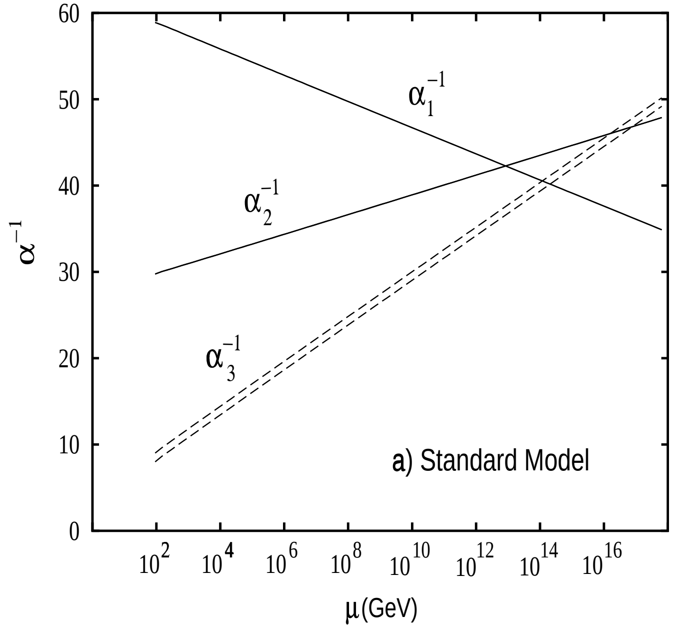
M.C. & H.Haber

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**

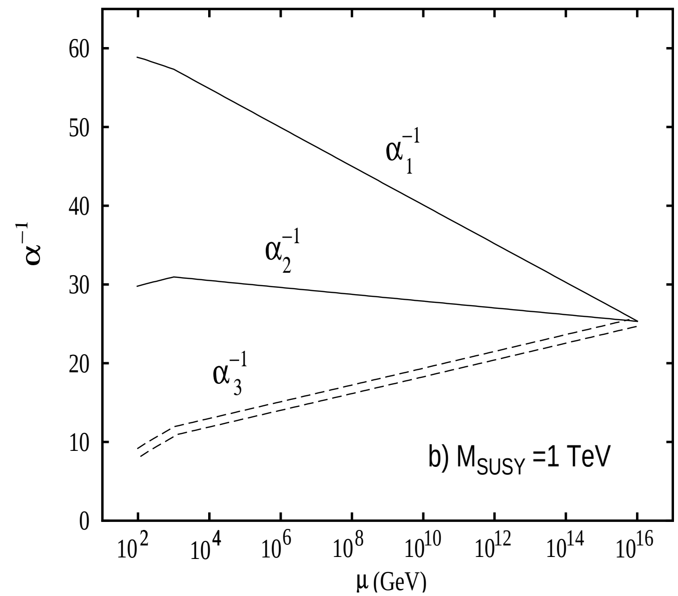
SM:

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:

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

The difference provides $\quad \Omega_{CDM} h^2 = 0.1126^{+0.161}_{-0.0181}$

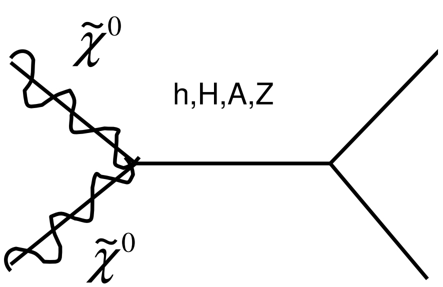
<u>What is dark matter?</u> (SM has no potential candidate)

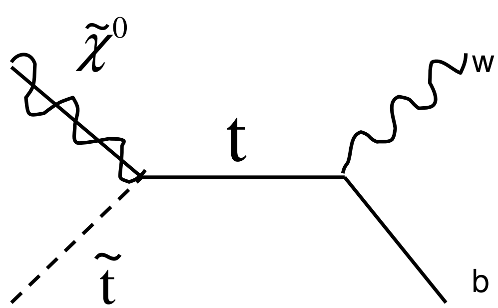
SUSY with R-parity conservation – a discrete symmetry: $R_P = (-1)^{3B+L+2S}$

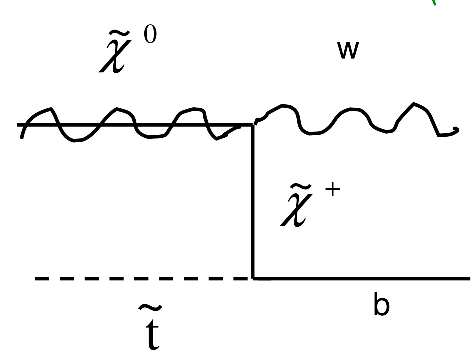
$\Longrightarrow$ naturally provides a stable dark matter candidate: the lightest $\tilde{\chi}_1^0$

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

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







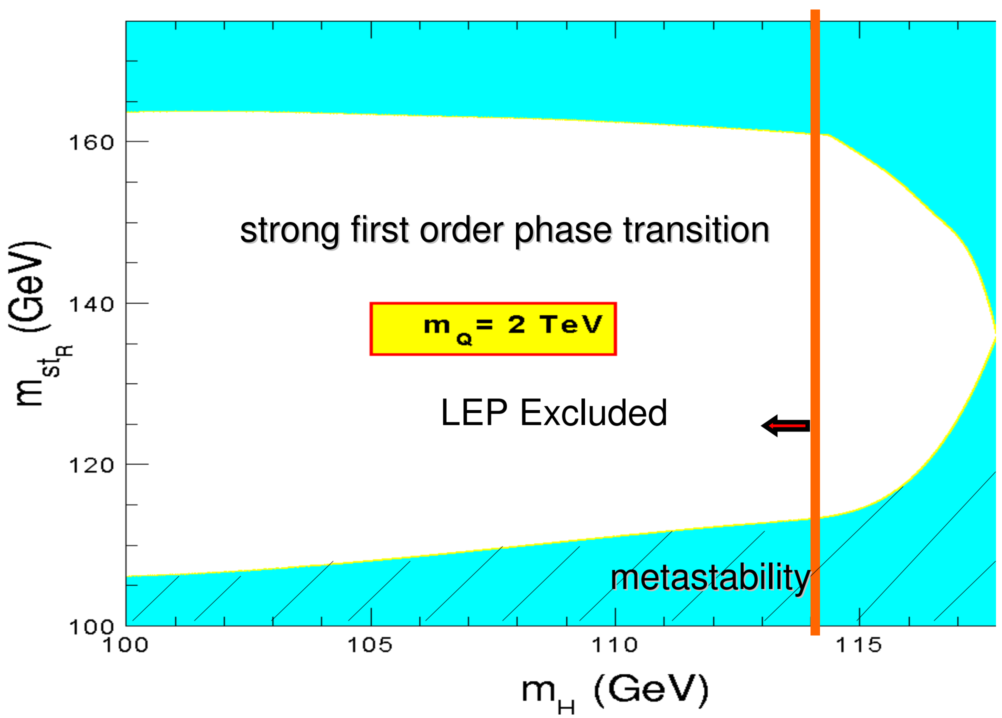
⋆ **Provides a solution to the Matter–Anti-matter Asymmetry**

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

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



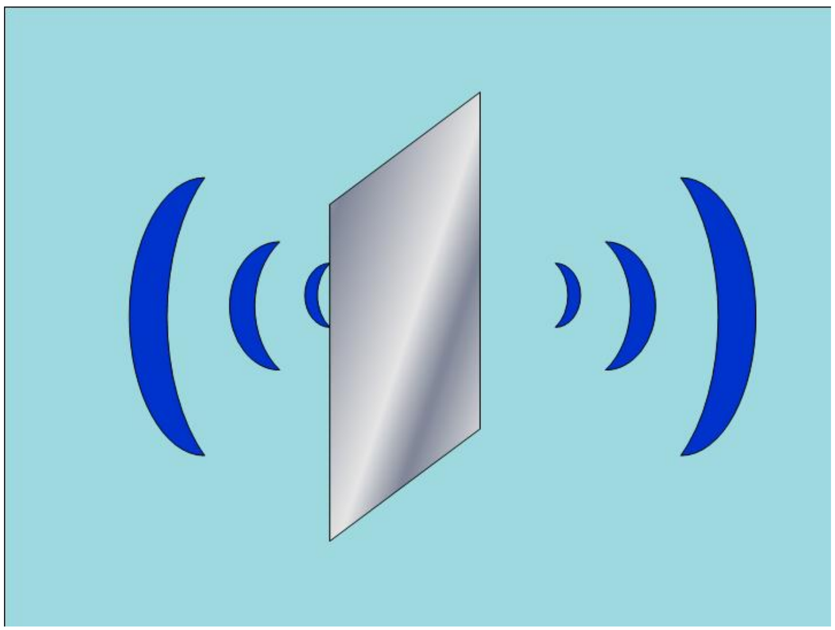
Electroweak Baryogenesis: *only testable model of baryon asymmetry generation*

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 $\Longrightarrow$ fundamental scale, pushed down to ew. scale by geometry

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



$k = 0$ (flat)

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

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

this lowers the fundamental Planck scale,

$\Longrightarrow$ depending on the size & number of ED.

$M_{Pl}^{\text{fund.}} \simeq 1$ TeV $\Longrightarrow$ R= 1 mm, 10^{-12} cm

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:

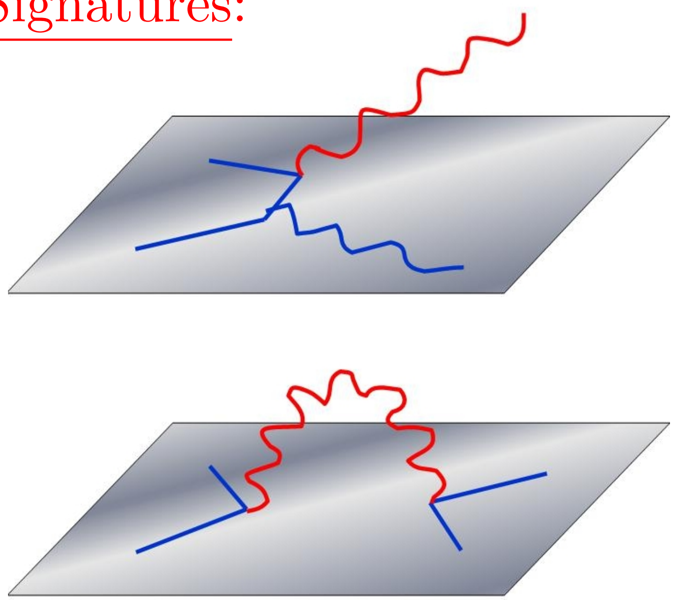
Kaluza Klein (KK) excited states with the same quantum numbers as the graviton and/or the SM particles

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

imbalance between measured energies and momentum in 4-D

= momentum in the extra dimensions

Signatures:



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

$1/R \simeq 10^{-2}$ GeV $(d=6)$;
$1/R \simeq 10^{-4}$ eV $(d=2)$;

(a) emission of KK graviton states: $G_n \Leftrightarrow \not{E}_T$
(gravitons appear as continuous mass distribution)

(b) graviton exchange $2 \to 2$ 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.

Servant & Tait

Universal Extra Dimensions:

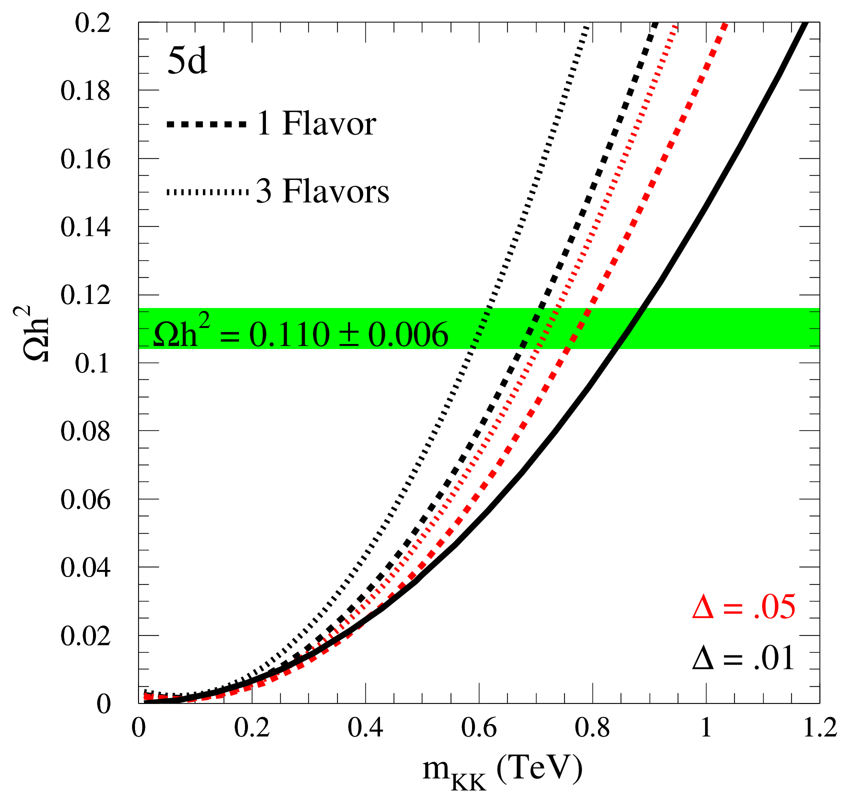
All fields in the bulk – no wall or branes

⟹ momentum conserved in ED.

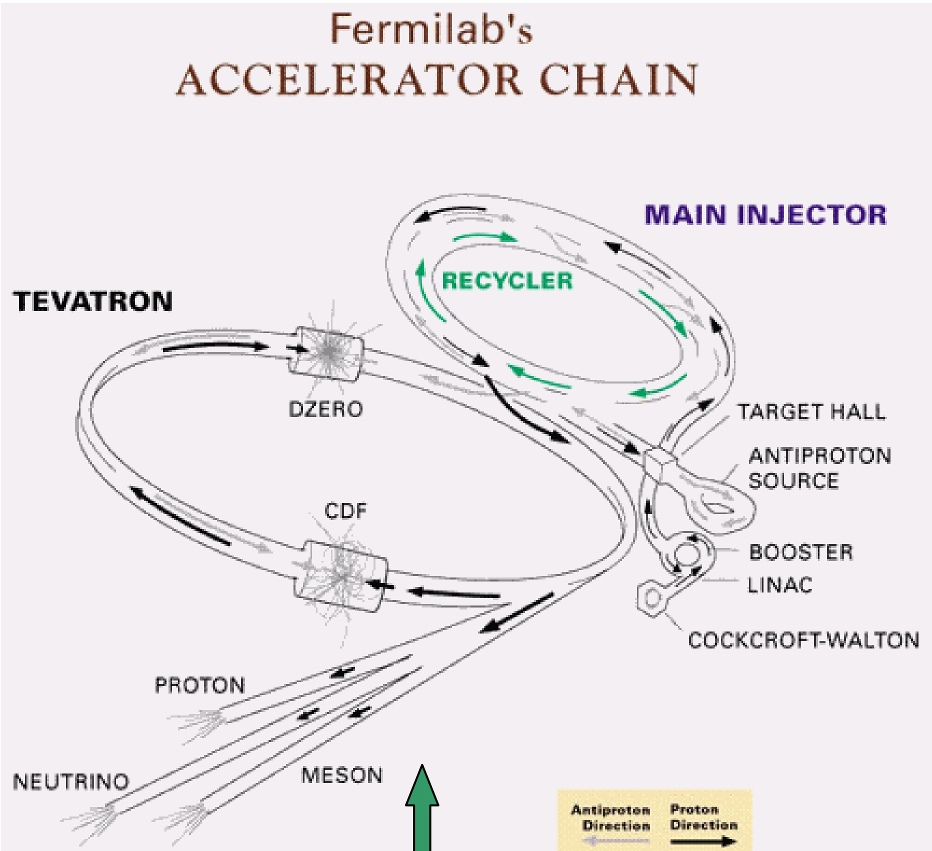
- KK modes produced by pairs
- no big corrections to EW observables

- Lightest Kaluza-Klein Particle (LKP)

  ⟶ **good dark matter candidate**

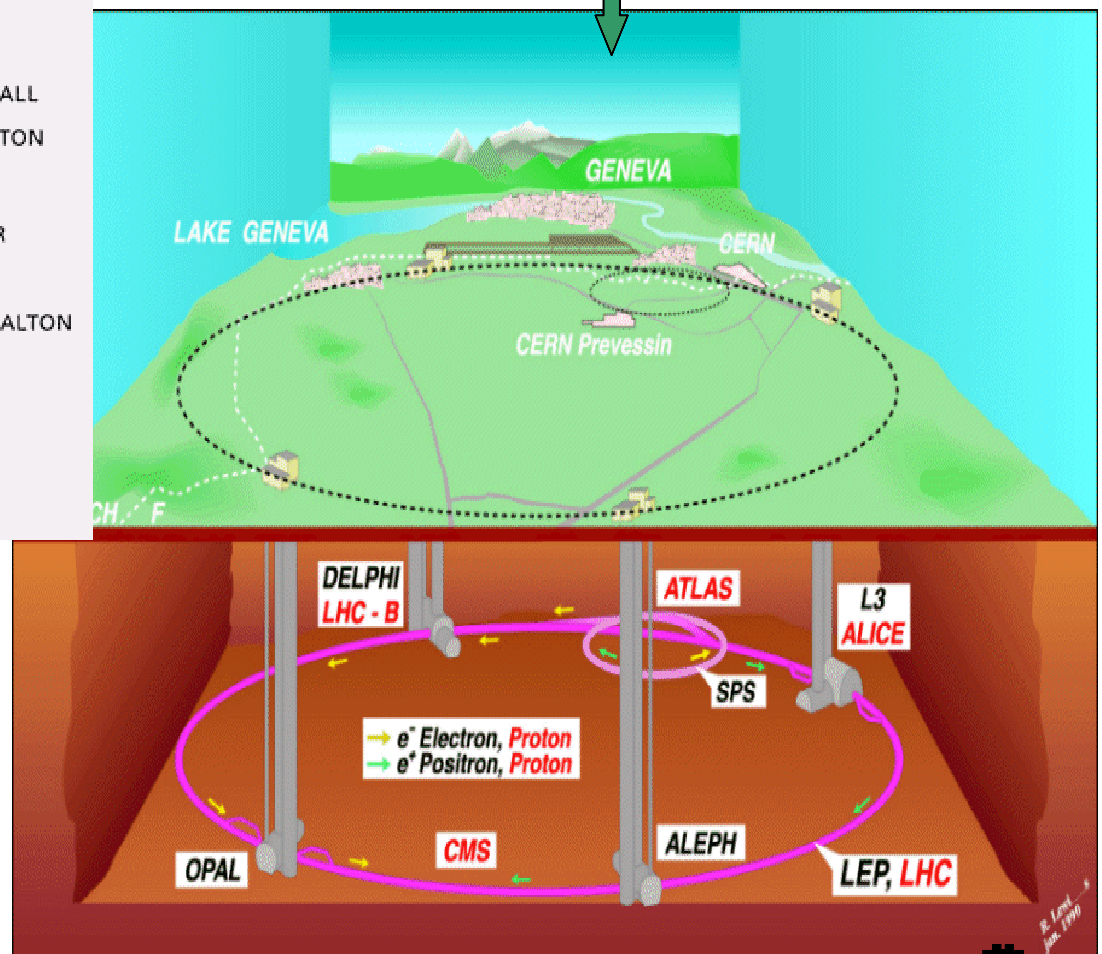


Searching for New Physics



Large Hadron Collider (LHC) at CERN

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



The Tevatron at Fermilab

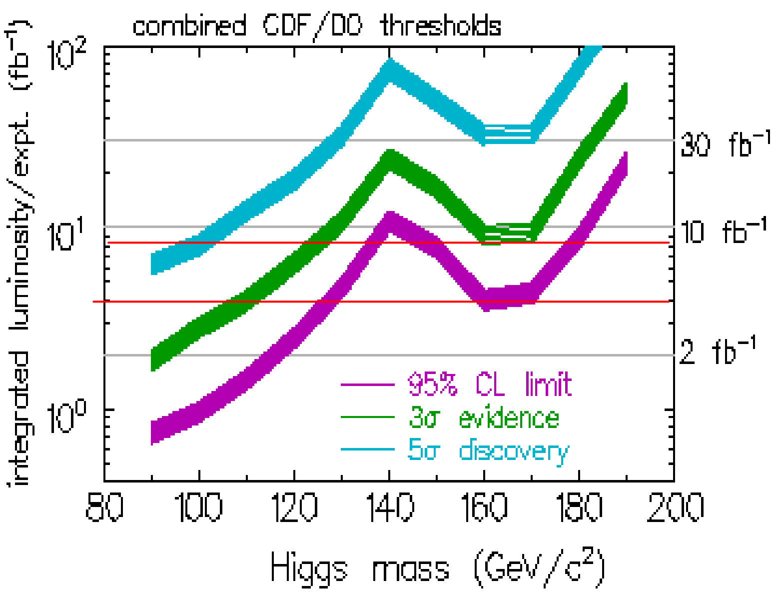
$p\bar{p}$ at $\sqrt{s} = 2$ TeV (2001 - 2009)

What will we know by the End of this Decade?

after the first run period of LHC → 10-30 fb-1 of data

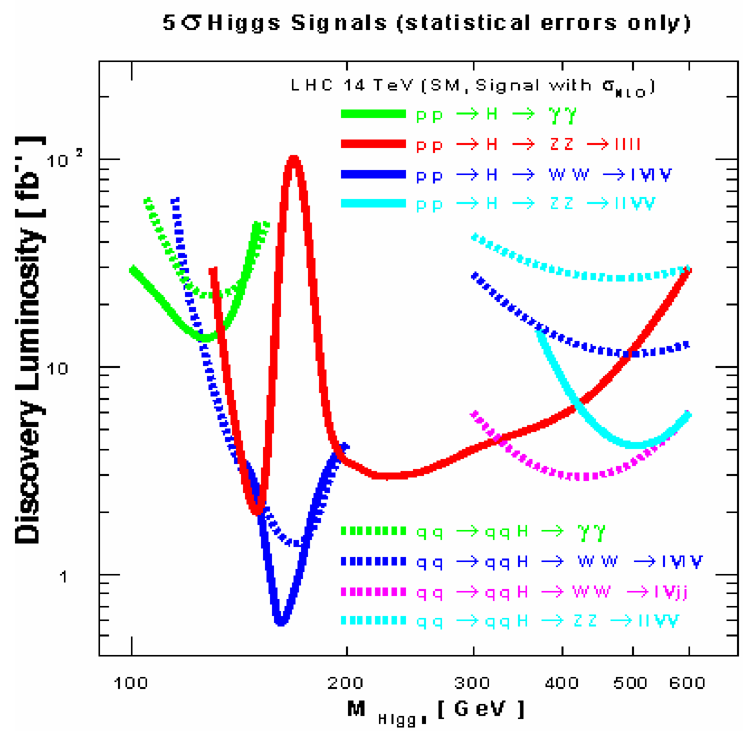
•Tevatron can search for a Higgs in parts of the mass range preferred by precision data

$$p\bar{p} \to V\,H \to Vb\bar{b} \quad \text{with } V = W, Z$$



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

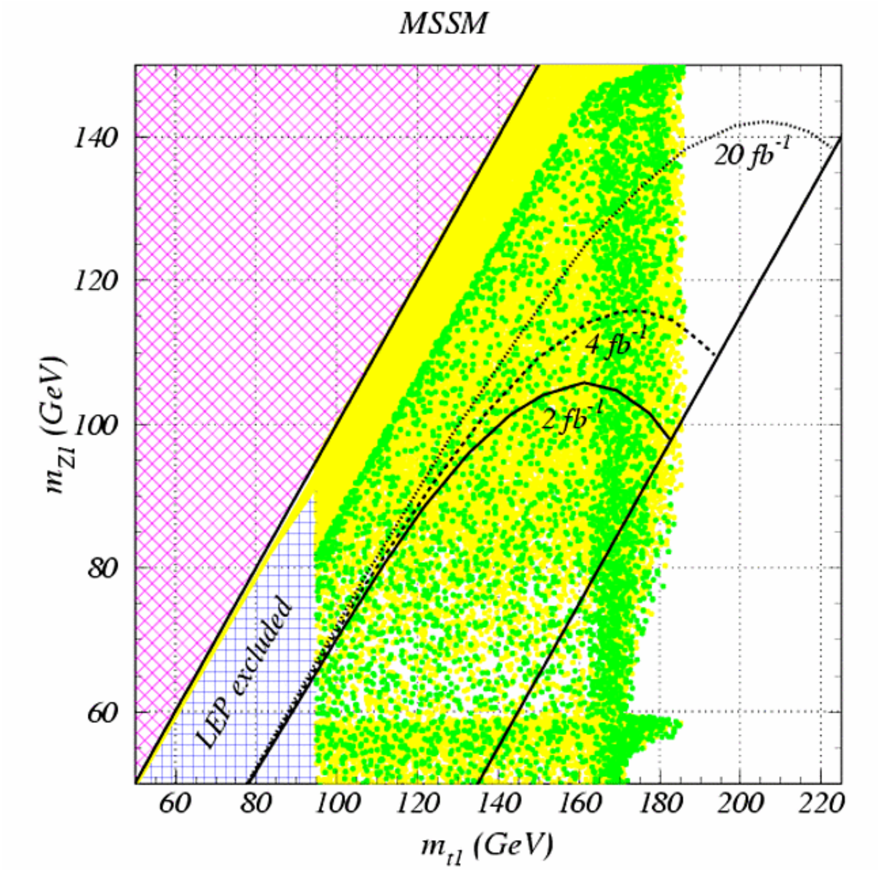
• LHC can search for a Higgs via many channels, already in the first few years



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

Tevatron Run II reach for stops
probes Dark Matter and Baryogenesis at the Electroweak scale!

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



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

If stop-neutralino mass difference is below 30 GeV:

- $\longrightarrow$ trigger on $\not{E}_T$ crucial
- $\longrightarrow$ co-annihilation region difficult at Tevatron or any hadron collider

Balazs, M.C. & Wagner

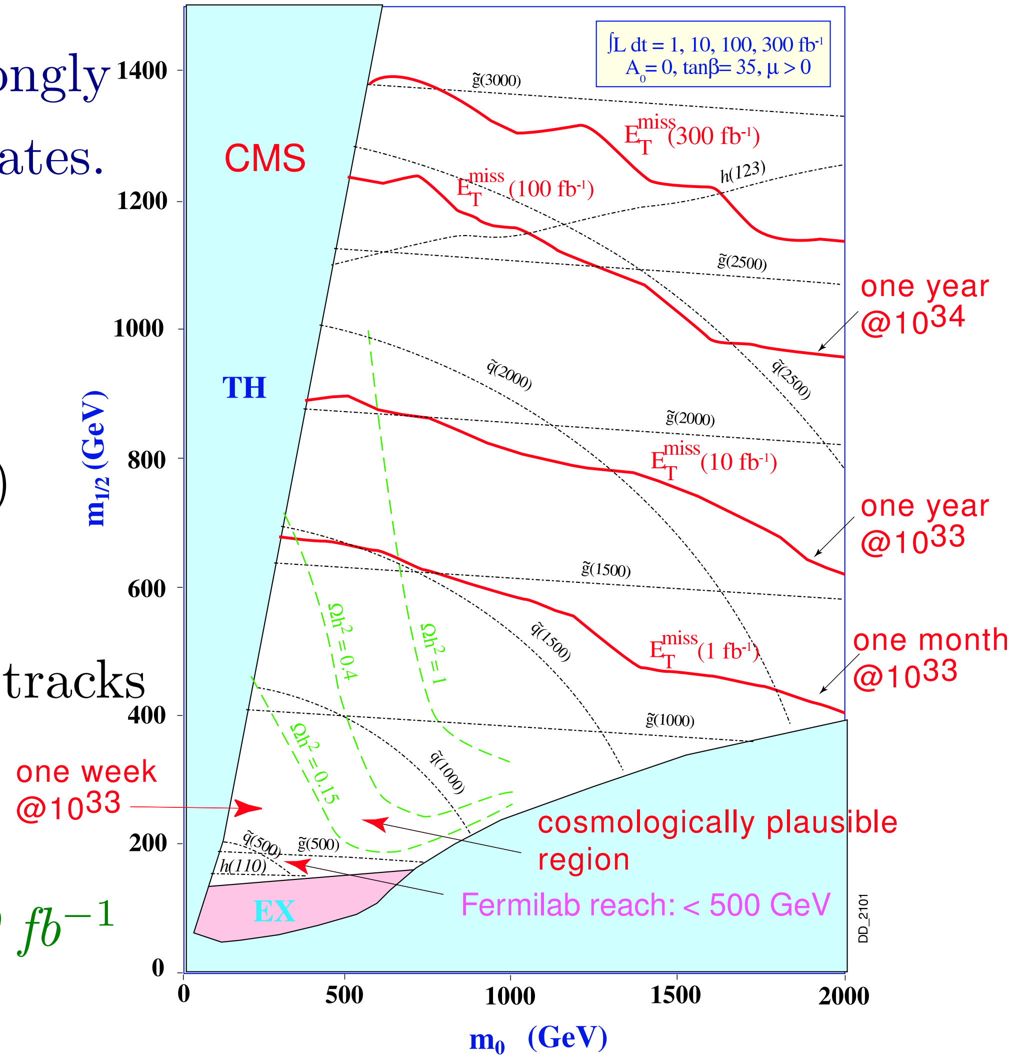
A definite test of this scenario at the LC

SUSY at the LHC

Supersymmetric particles, especially strongly interacting ones, are produced at large rates.

- most likely types of signatures:
  - ‘mSUGRA’ type – high E_T jets and $\not{E}_T$ (maybe leptons)
  - ‘GMSB’ type – hard photons & $\not{E}_T$; heavily ionizing tracks

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



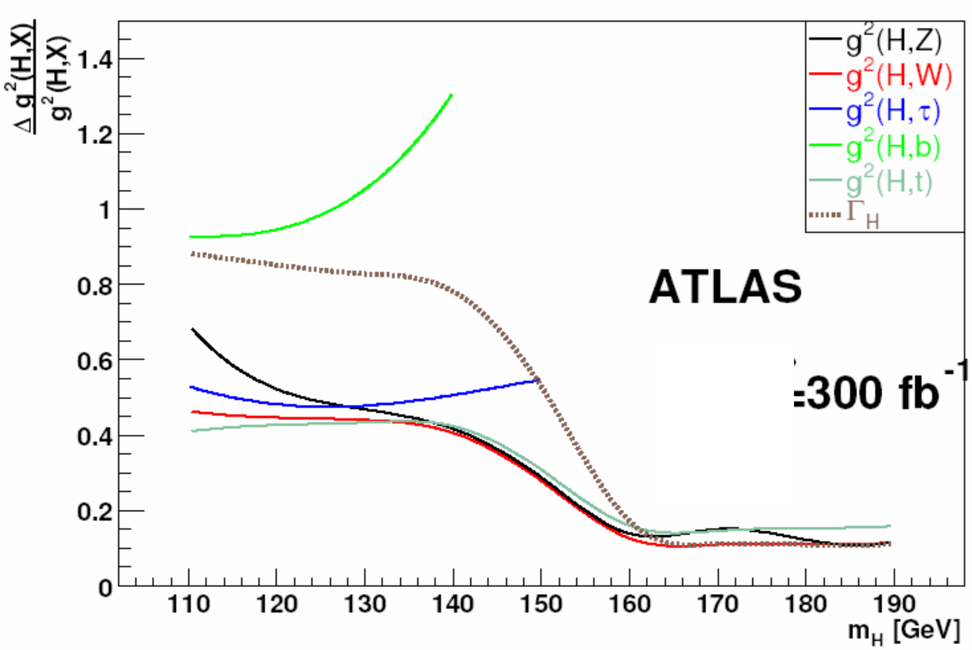
If low-energy SUSY is there, we expect to see some of its signature(s) by the end of this decade.

The Energy Frontier in the next Decade

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

Many production and decay processes accessible:

- start precision measurements of Higgs couplings to bosons and fermions

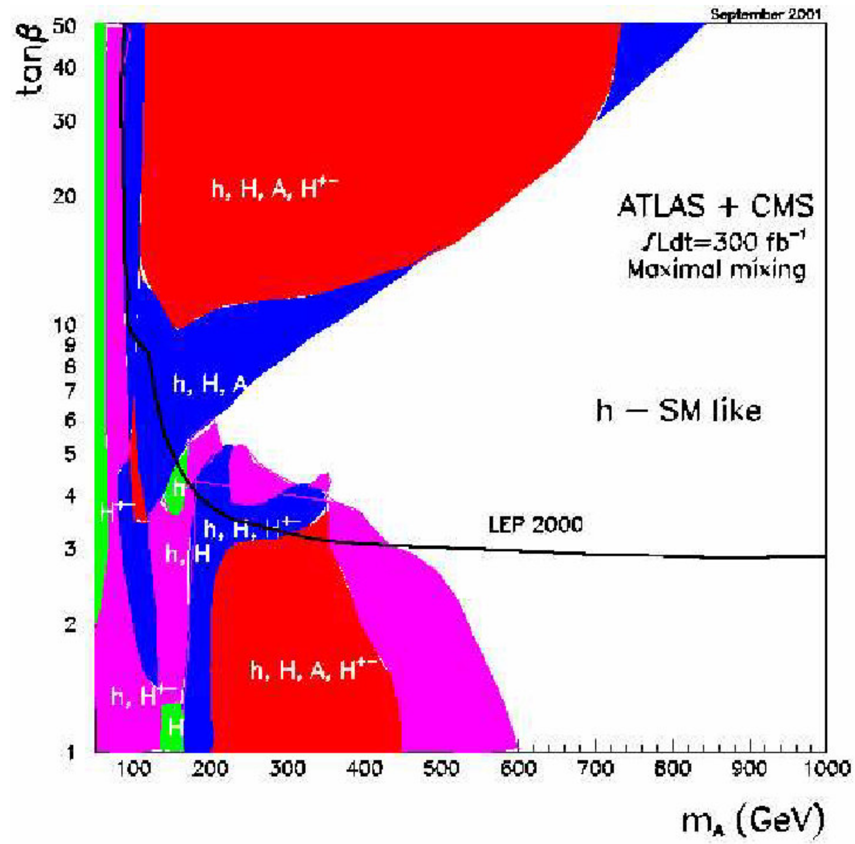


from $\sigma(XX \to H_{SM}) \times BR(H_{SM} \to YY)$

which implies meas. partial and total widths

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

- better coverage of h, H, A and $H^{\pm}$ but still regions where only h is visible



Higgs Physics → LHC will have a great shot at it!

Extra Dimensions

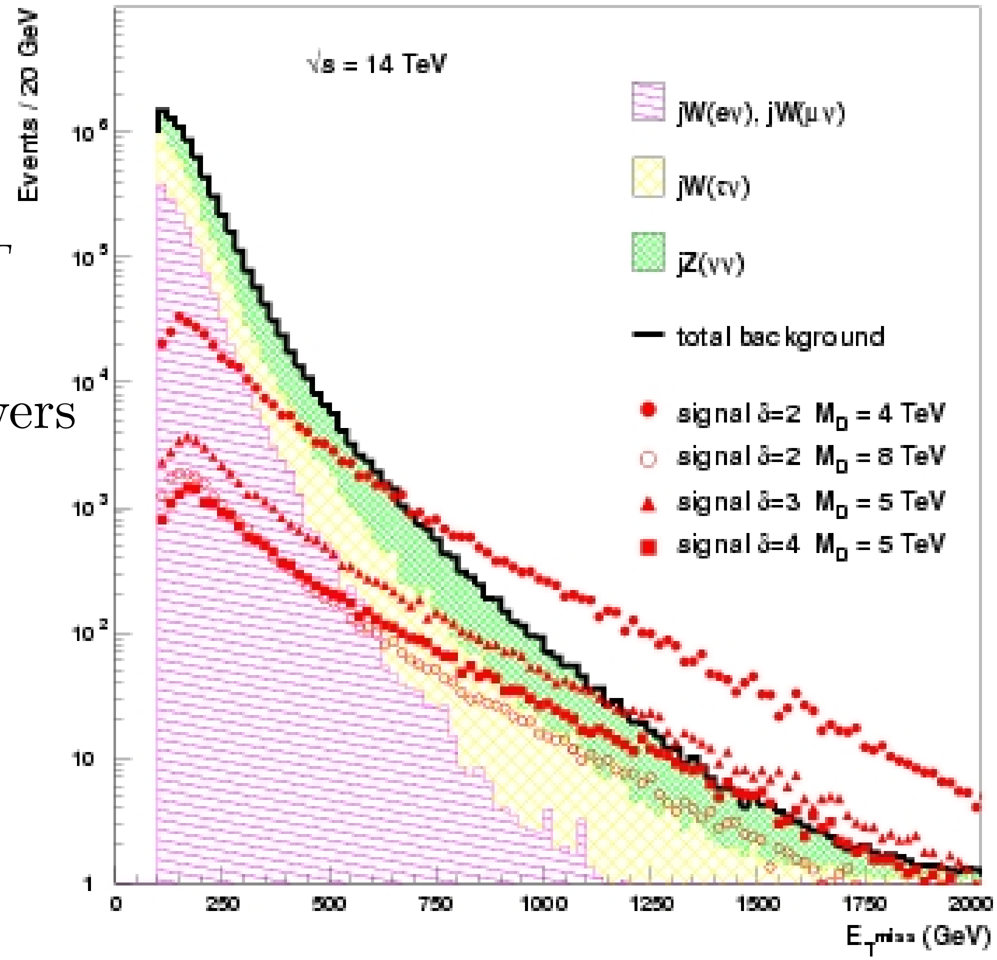
- emission of KK graviton states

$$p\bar{p} \to g\,G_N \;(G_N \to \not{E}_T) \longrightarrow \text{jet}+\not{E}_T$$

cross section summed over full KK towers

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

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)

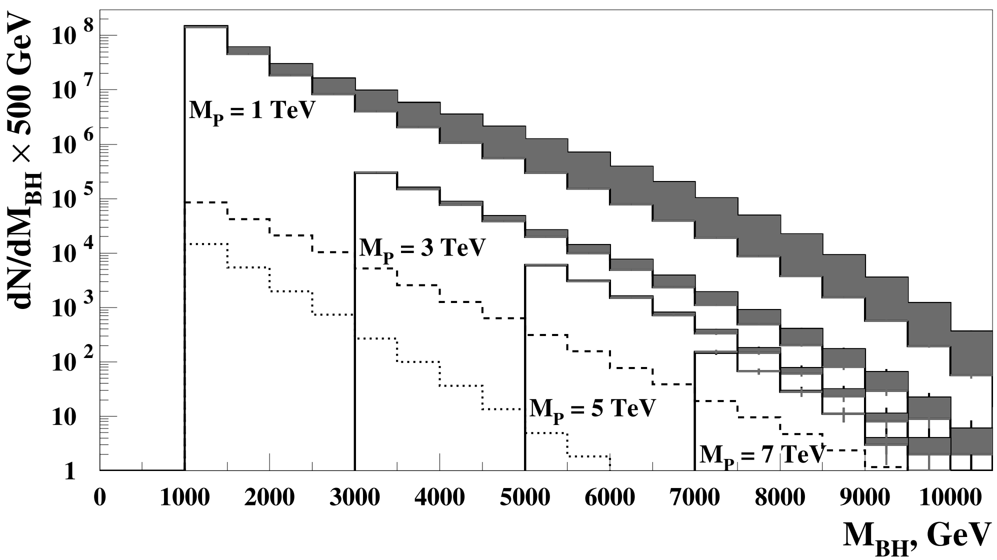
Exciting Possibility: **TeV-scale Production of Black Holes**

For $M_{BH} \gg M_{\rm Pl}^{\rm fund} \Longrightarrow$ 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 $\Longrightarrow$ BH forms

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

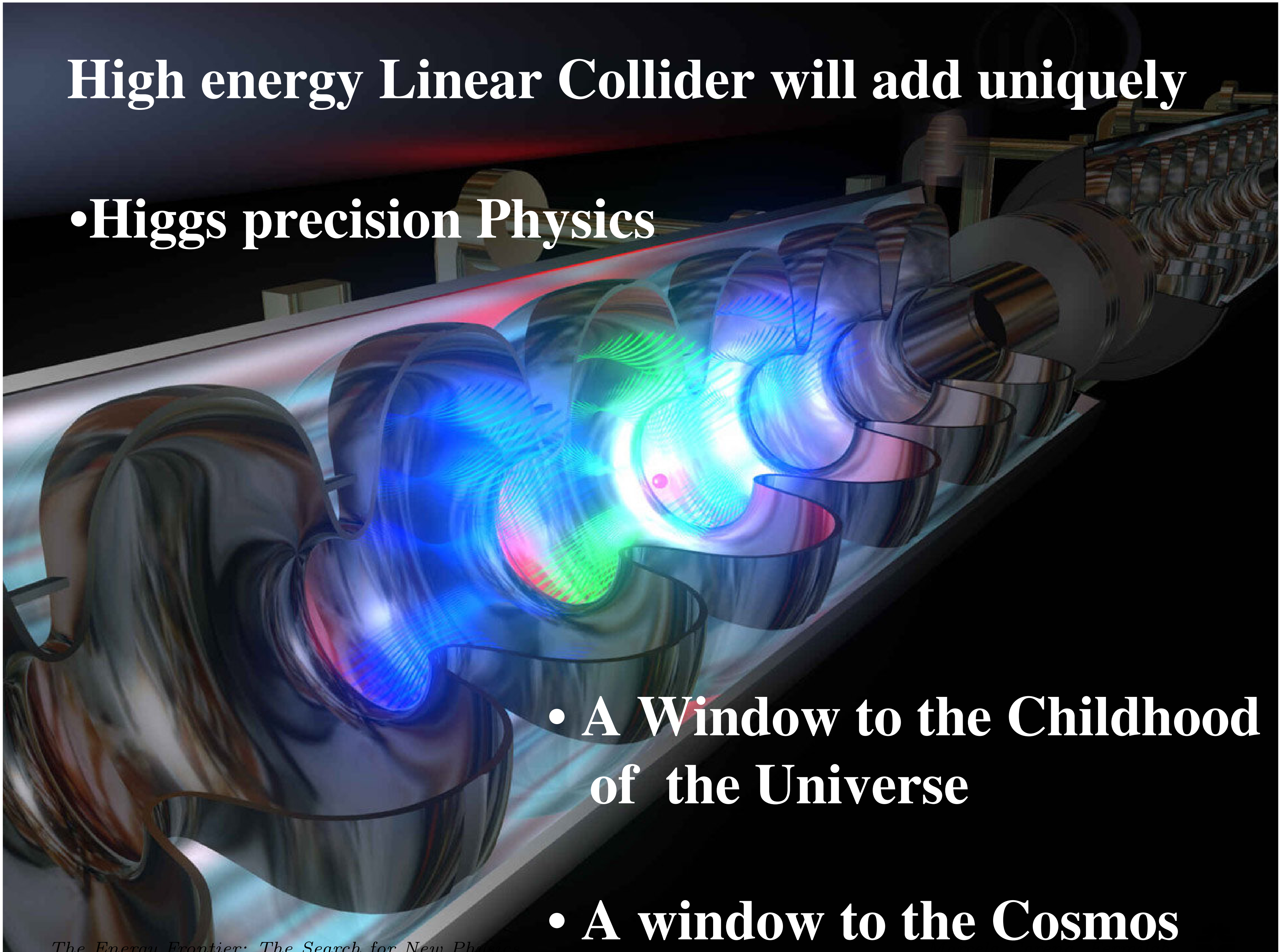


- Signal: sprays of SM particles in equal abundances

$\longrightarrow$ 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
The Energy Frontier: The Search for New Ph

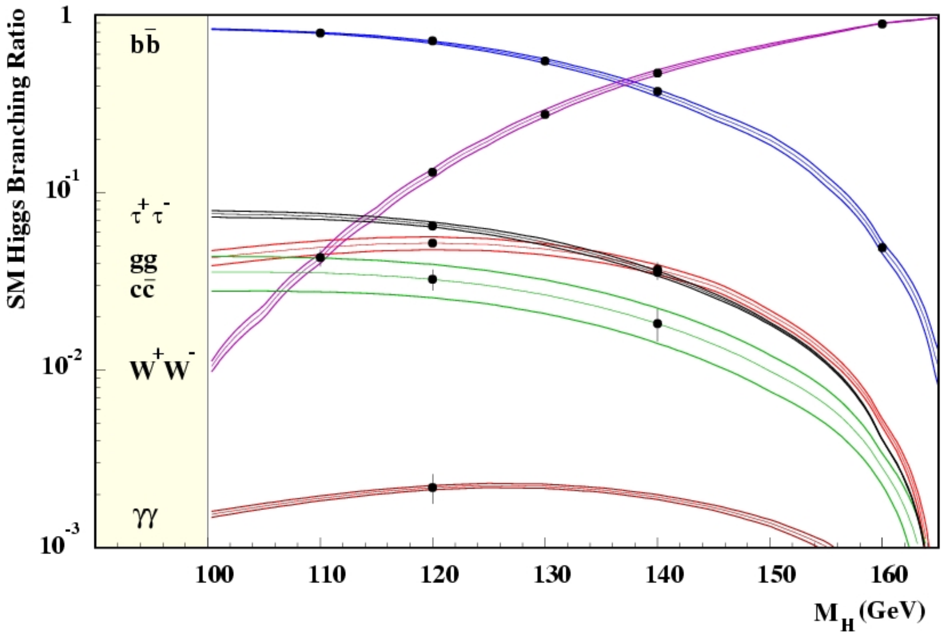
Higgs Physics at a LC

Production mainly through:

$e^+e^- \to Z\,H_{SM}$

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

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



measure most Br's with 3–10% accuracy

HZZ coupling measured from σ_{ZH} independently of Higgs decay modes!

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

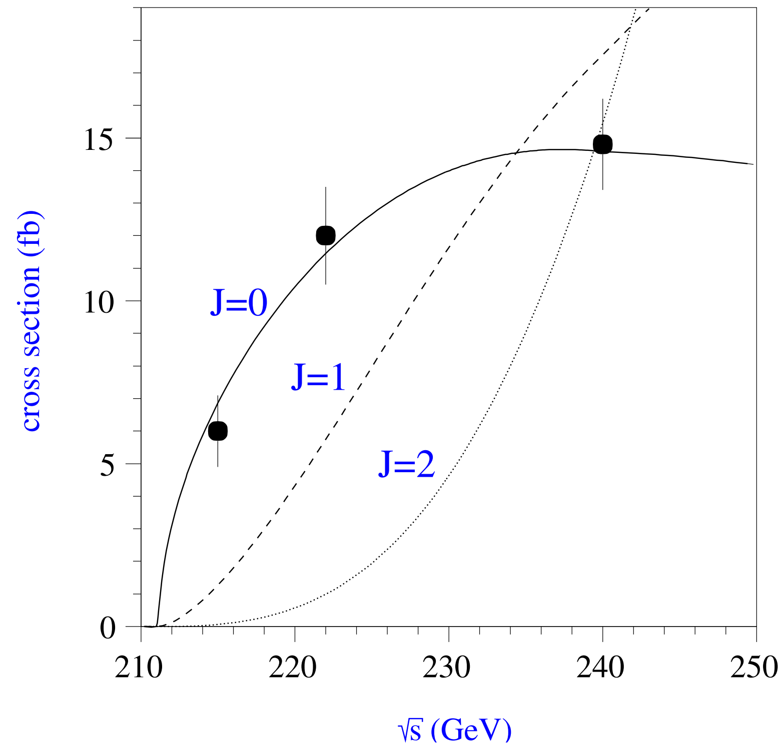
$\Longrightarrow$ disentangle different Higgs models

- Precision Measurement of Higgs Mass

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

- Higgs quantum numbers: spin and parity
  - threshold dependence of excitation curve
  - angular distributions

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



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

Supersymmetry

(a) Measurements of SUSY particles masses

$\Longrightarrow$ sleptons, charginos, neutralinos
with an accuracy of 1% or less

If any visible SUSY particle produced,
$\longrightarrow \delta M_{\tilde{\chi}_1^0} \sim 1\% \Longrightarrow$ important for LHC meas.

(b) Measurement of SUSY parameters

- $\tilde{\chi}_i^{\pm}, \tilde{\chi}_i^0$ production & decay
  $\longrightarrow$ param. of mixing mass matrix to 1%
  $\longrightarrow$ determine composition in terms of
  SUSY partners of γ, Z, W, H
- slepton and squark mixing angles
  from cross sections with polarized beams

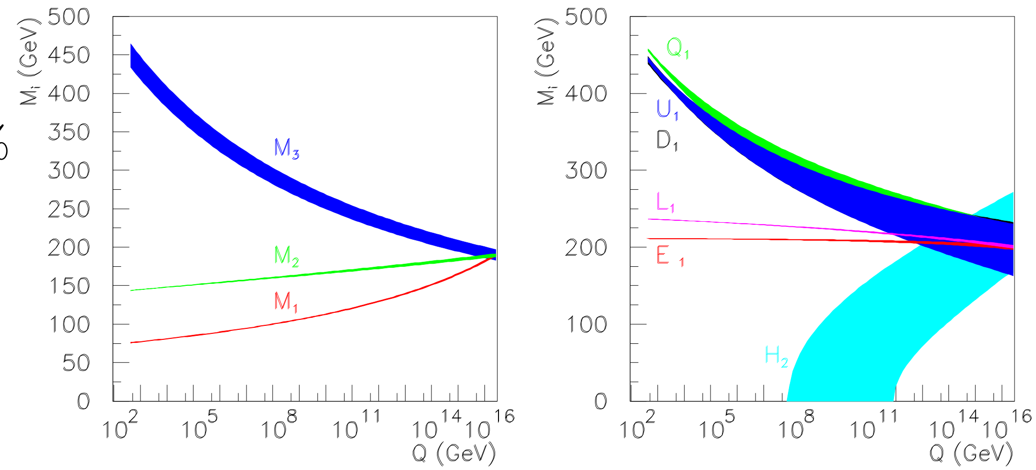
(c) Spin of SUSY particles:

Simplicity of production reactions allows spin determination from angular distributions

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

$\Longrightarrow$ 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 $\Omega_{\rm DM}$.

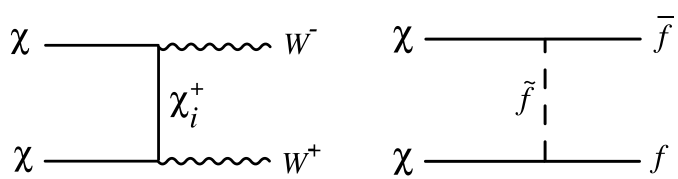
$\Rightarrow$ A coincidence or DM provides fundamental motivation for new particles at EW scale.

$\star$ Understanding what DM is made of demands Collider & Astrophysical/Cosmological input.

- If the LSP is found to be a stable neutralino

$\rightarrow$ accurate meas. of $\tilde{\chi}^0_1$ mass & composition

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



$\Longrightarrow$ <u>determined thermal relic density</u> assuming standard evolution of the universe

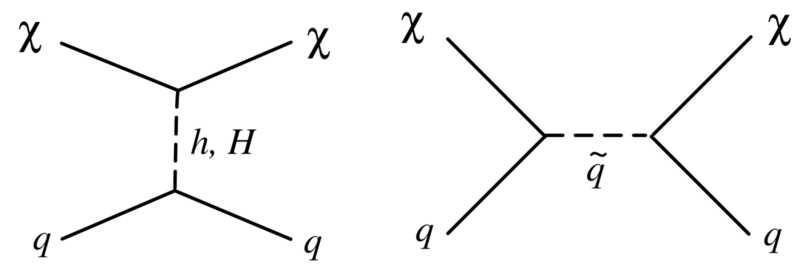
- comparing this result with $\Omega_{\rm DM}$ from Astrophysical/Cosmological input

$\Longrightarrow$ new insights into history of our universe

- <u>Dark Matter Detection</u>:

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

$\longrightarrow$ input from both collider and conventional DM experiments



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

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

$\Longrightarrow$ LC will provide important info about DM halo densities and velocity distributions.

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

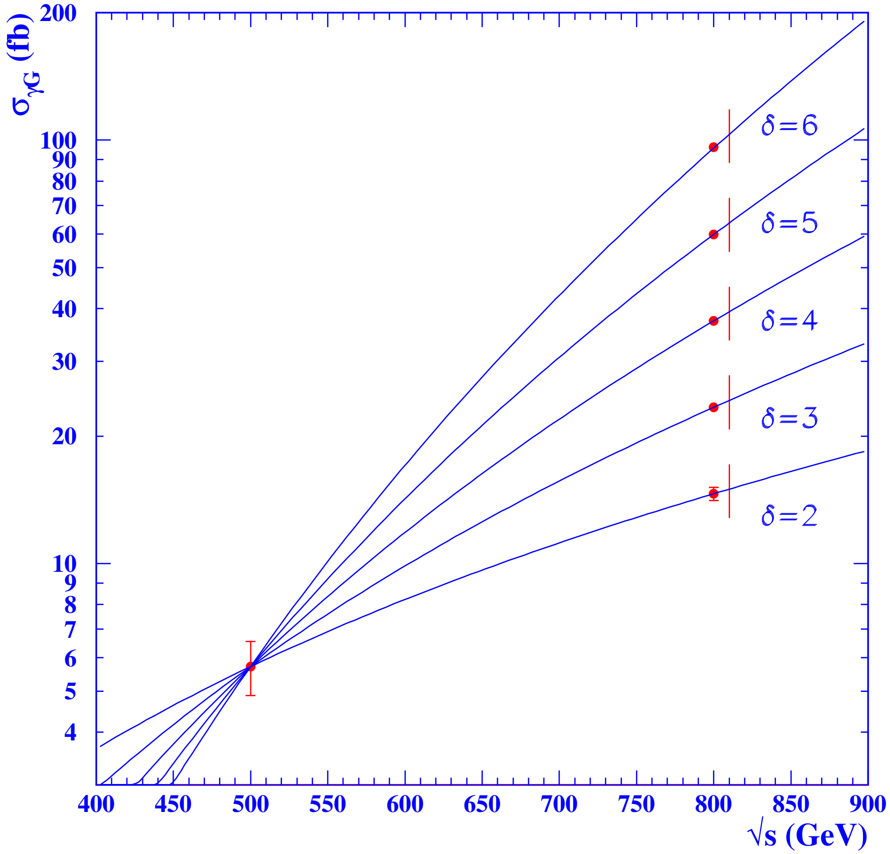
We need to test the SM at higher energies and answer the questions which lie beyond it: gravity, dark matter, baryogenesis, unification of forces.

Extra Dimensions

Flat ED:

graviton emission: $e^+e^- \to \gamma\, G_N$

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



graviton exchange in 2 → 2 processes:

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

What Can We Learn from the Tevatron?

– Precision measurements:

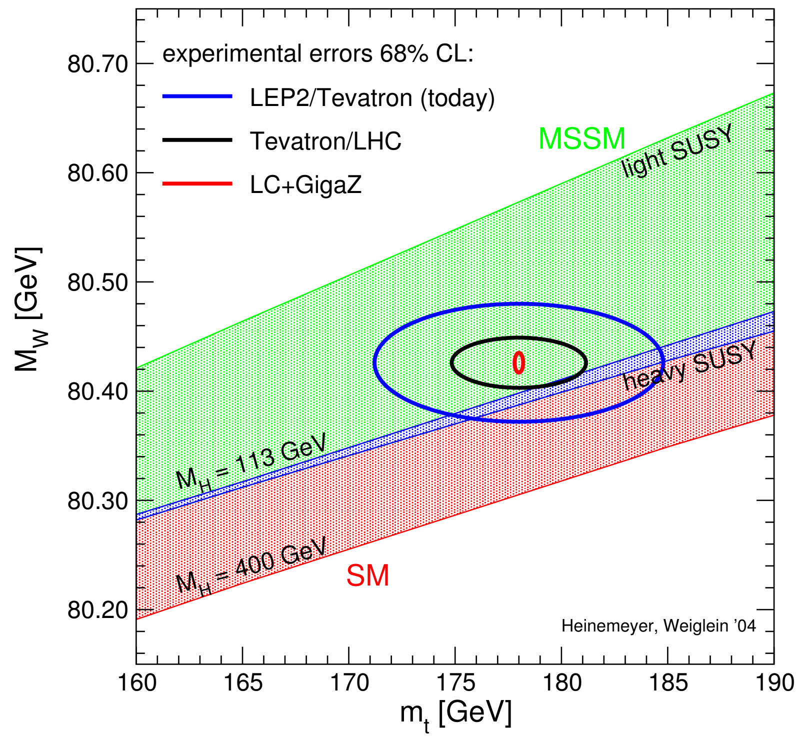
- top quark mass: $\delta M_t \simeq 3$ GeV with 2 fb^{-1}
- W mass: $\delta M_W \simeq 30$ MeV with 2 fb^{-1}

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, νN
- SM relationship for M_t–M_W–M_H
  $\Longrightarrow$ crucial information on M_H

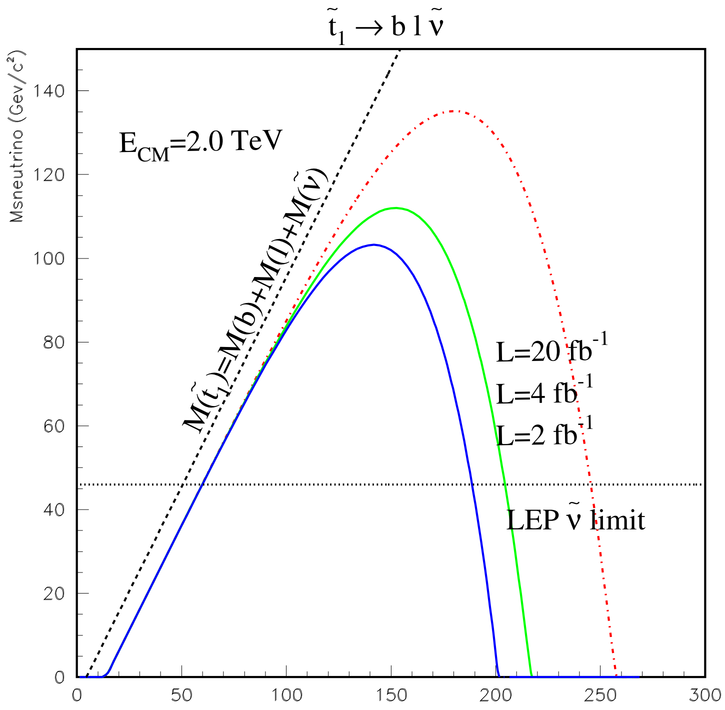
$\Longrightarrow$ A light SM Higgs Boson strongly favored by data



Stop and Sbottom Searches

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

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



Demina, Lykken, Matchev & Nomerotski

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

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

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

$m_{\tilde{b}_1} \leq 230$ GeV in $\tilde{b}_1 \to b\tilde{\chi}_1^0$

generic squark & gluinos: 350–450 GeV

New Studies: jets + photons + $\not{E}_T$ with 4 fb^{-1} M.C., Choudhury, Logan, Diaz & Wagner

$\longrightarrow$ possible signature of gauge-mediated scenarios

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

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

What can we learn from the Tevatron?

Precision measurements:

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

This is crucial to learn more about where to look for the Higgs, in which mass range: a light SM Higgs strongly favoured by data

Search for SUSY particles well beyond the LEP reach

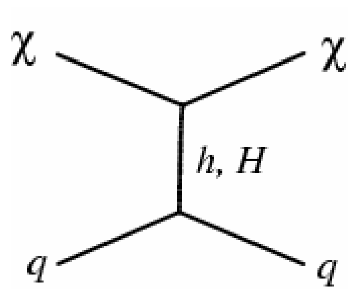
- good chances to find quark superpartners below 300 – 500 GeV
- gauge bosons and Higgs superpartners below 150 - 300 GeV

More about the Tevatron: John Womersley's Colloquium in 2 weeks!

Direct Dark Matter Detection:
complementarity to colliders searches

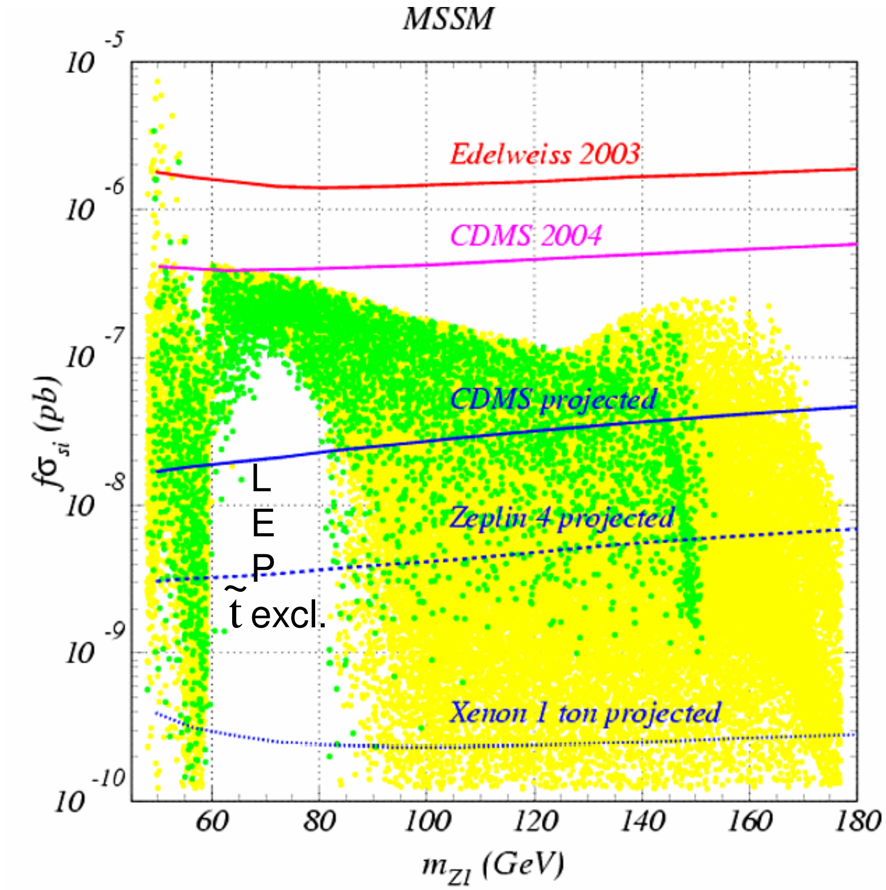
$\not{E}_T$ at colliders → important evidence of DM candidate,
but, stability of LSP on DM time scales cannot be chekced at colliders

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



→ upper bounds on Spin independent cross sections

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



small σ_{si} for large μ : co-annihilation regions

Balazs, MC, Wagner '04

Higgs Physics

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

$$\sigma(e^+e^- \to Z\phi) \Longrightarrow g_{\phi ZZ}$$

This is the most powerful feature unique to the LC.

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

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

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

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

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

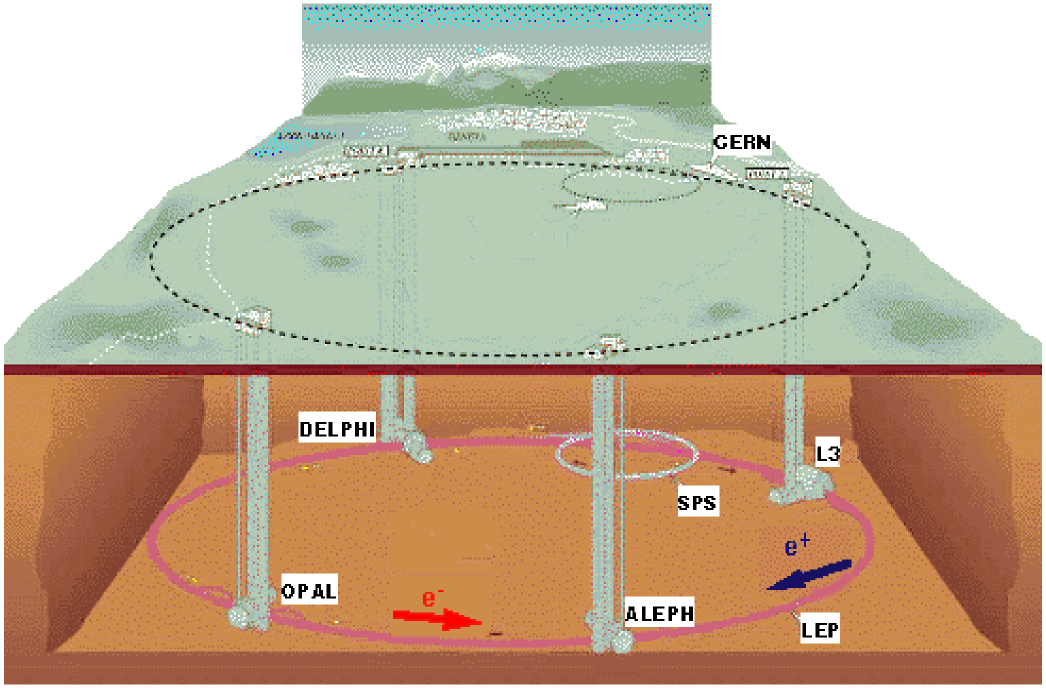
The Search for the Higgs Boson

If the Higgs Boson is created , it will decay rapidely into other particles

- **The past: The Large Electron Positron Collider - LEP**

At LEP energies mainly

$$e^+e^- \xrightarrow{Z^*} H_{SM} Z$$



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

and

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

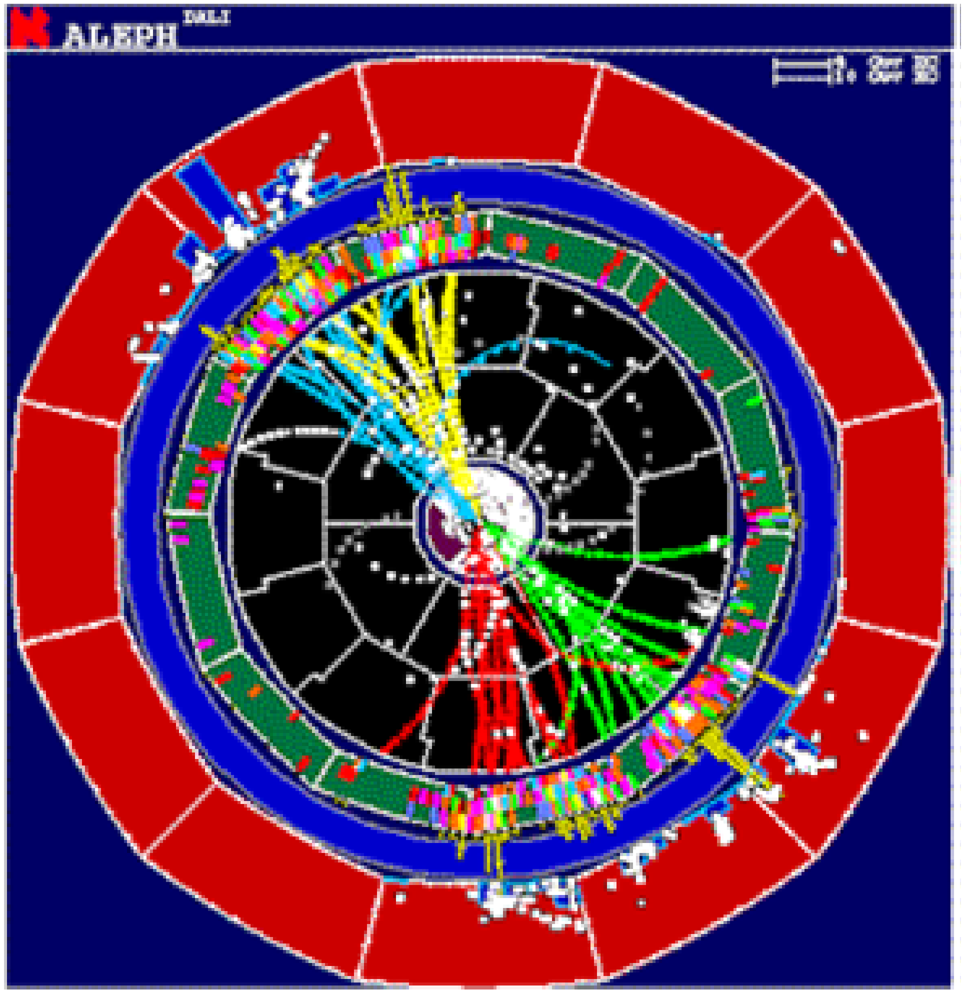
In case of SUSY Higgs one can also search for $e^+e^- \xrightarrow{Z^*} hZ, HZ, Ah, AH$

Radiative corrections can have important impact on Higgs Branching ratios

Example: main decay mode $h \rightarrow b\bar{b}$ strongly suppressed in some MSSM regions

Higgs Particle Search at LEP (Aleph detector)

Higgs candidate with mass of about 114 +- 3 GeV and three identified b quarks



SM Higgs Boson 95% C.L. limit

$$m_{H_{SM}} > 114.6\,GeV$$

But, tantalizing hint of a Higgs with mass about 115 – 116 GeV (just at the edge of LEP reach)