The Energy Frontier:
in the Search for New Physics

Marcela Carena

Theoretical Physics Dept.

Fermilab

Texas A&M University

College Station, October 23, 2003.

Outline

- **Introduction: Physics Landscape $\Longrightarrow$ Certainties and Unknowns**

– The Standard Model – Open Questions

– Models of New Physics

⋆ Supersymmetry ⋆ Models of Strong Dynamics

⋆ Little Higgs Models ⋆ 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 Standard Model

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

SM $\Longrightarrow$ **Quantum field theory that successfully describes how all known fundamental particles interact via the strong, weak and electromagnetic forces** $\Longrightarrow$ based on a gauge field theory with a symmetry group

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

- Strong Interactions:

protons and nucleons formed by quarks, bound together by gluons (force carriers) $m_g = 0$
Very strong at large distances $\longrightarrow$ confinement: no free color particles.

- Electromagnetic Interactions:

electrons interact with protons via quantum of electromagnetic energy: Photon
Long range force $\longrightarrow$ $m_\gamma = 0$

- Weak Interactions:

Short range force inside the protons and neutrons $\longrightarrow$ massive carriers W, Z bosons:
$m_Z \simeq 80.5$ GeV, $m_W \simeq 91.2$ GeV

Origin of mass of Z, W $\leftrightarrow$ spontaneous ElectroWeak Symmetry Breaking (EWSB);
$SU(2)_L \times U(1)_Y \rightarrow U(1)_{em}$

Similar to Superconductivity

Standard Model Particles

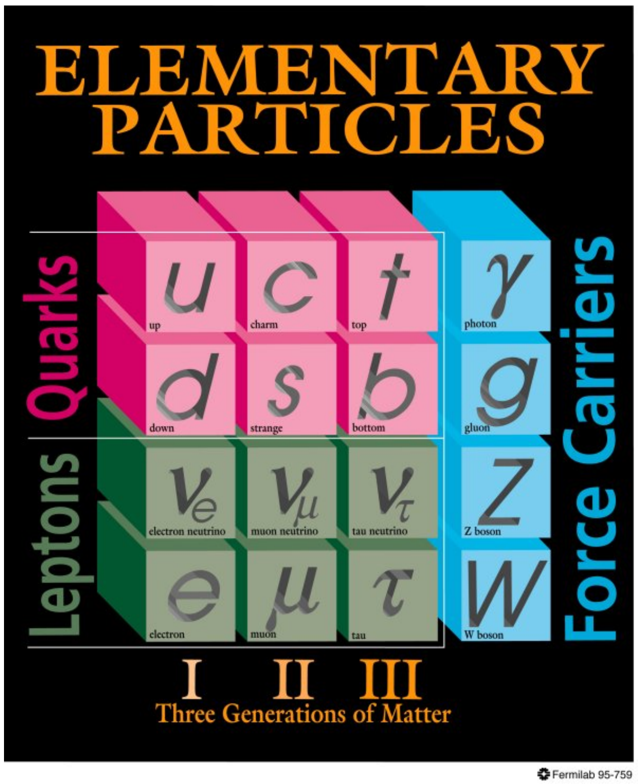
There are 12 fundamental gauge fields:

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 same quantum numbers under gauge groups



But very different masses!

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

$m_e = 0.5\ 10^{-3}$ GeV, $\frac{m_\mu}{m_e} \simeq 200$, $\frac{m_\tau}{m_\mu} \simeq 20$

Largest hierarchies

$m_t \simeq 175$ GeV $\qquad m_t/m_e \propto 10^5$

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

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	<1×10^{-8}	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

Quarks spin = 1/2

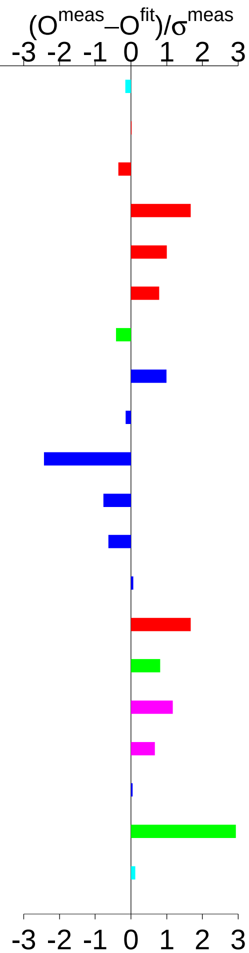
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

Precision Tests of the SM

- The SM has been tested with very high precision (one part in a thousand) at experiments around the world: CERN, Fermilab, SLAC

Winter 2003

	Measurement	Pull
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-0.16
m_Z [GeV]	91.1875 ± 0.0021	0.02
Γ_Z [GeV]	2.4952 ± 0.0023	-0.36
σ^0_{had} [nb]	41.540 ± 0.037	1.67
R_l	20.767 ± 0.025	1.01
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.79
$A_l(P_\tau)$	0.1465 ± 0.0032	-0.42
R_b	0.21644 ± 0.00065	0.99
R_c	0.1718 ± 0.0031	-0.15
$A^{0,b}_{fb}$	0.0995 ± 0.0017	-2.43
$A^{0,c}_{fb}$	0.0713 ± 0.0036	-0.78
A_b	0.922 ± 0.020	-0.64
A_c	0.670 ± 0.026	0.07
A_l(SLD)	0.1513 ± 0.0021	1.67
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.82
m_W [GeV]	80.426 ± 0.034	1.17
Γ_W [GeV]	2.139 ± 0.069	0.67
m_t [GeV]	174.3 ± 5.1	0.05
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	2.94
Q_W(Cs)	-72.83 ± 0.49	0.12



• Standard Model $\Longrightarrow$ the pillar of particle physics that explains data collected in the past several years and provides description of physical processes up to energies of $\approx$ 100 GeV.

However, it is only an effective theory.
$\rightarrow$ 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

EWSB occurs at the TeV scale

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

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:

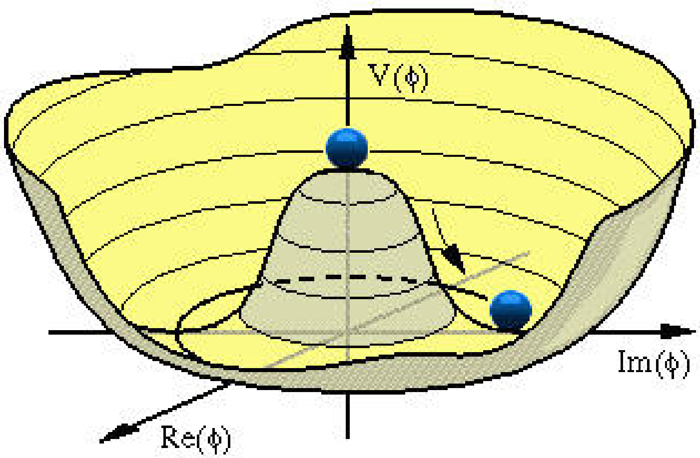
- weakly interacting self-coupled elementary (Higgs) scalar dynamics
- strong interaction dynamics among new fermions (mediated perhaps by gauge forces)

Both mechanisms generate new phenomena with significant experimental consequences

Standard Model $\rightarrow$ example of weak EWSB

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 nonzero 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

  ⋆ Interactions with gauge fields: $g^2_{\phi\ VV}\phi^2 V^2_\mu \quad \longrightarrow m^2_V = g^2_{\phi\ VV} v^2/2 \quad \longrightarrow v$= 174 GeV

  ⋆ Mass to fermions via Yukawa interactions: $g_{\phi\ f\bar{f}}\Phi\bar{\psi}_L\psi_R \Longrightarrow m_f = \sqrt{2} g_{\phi\ f\bar{f}} v$

- one extra physical state left in the spectrum ≡ HIGGS Boson with mass $m^2_\phi = 2\lambda v^2$

Present Data → no direct evidence of Higgs [$m_h > 114.4$ GeV (LEP2)]

but, electroweak observables depend logarithmically on m_ϕ via quantum corrections

– SM with weakly coupled Higgs is in excellent agreement with precision EW data

$m_{H_{SM}} \leq 210$ GeV at 95 % C.L.

In weakly coupled approach, SM most probably embedded in Supersymmetric theory

fermion-boson symmetry $\Longrightarrow$ Stabilization of 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!

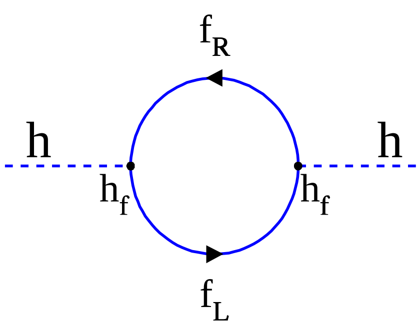
$$m^2 = v^2\lambda = m^2(\Lambda_{eff}) + \alpha\Lambda_{eff}^2$$

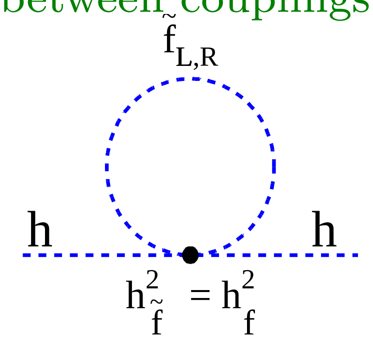
To explain $v \simeq \mathcal{O}(m_W)$, either $\Lambda_{eff} \leq 1$ TeV or extreme fine tuning to give cancellation

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 and bosonic and fermionic degrees of freedom





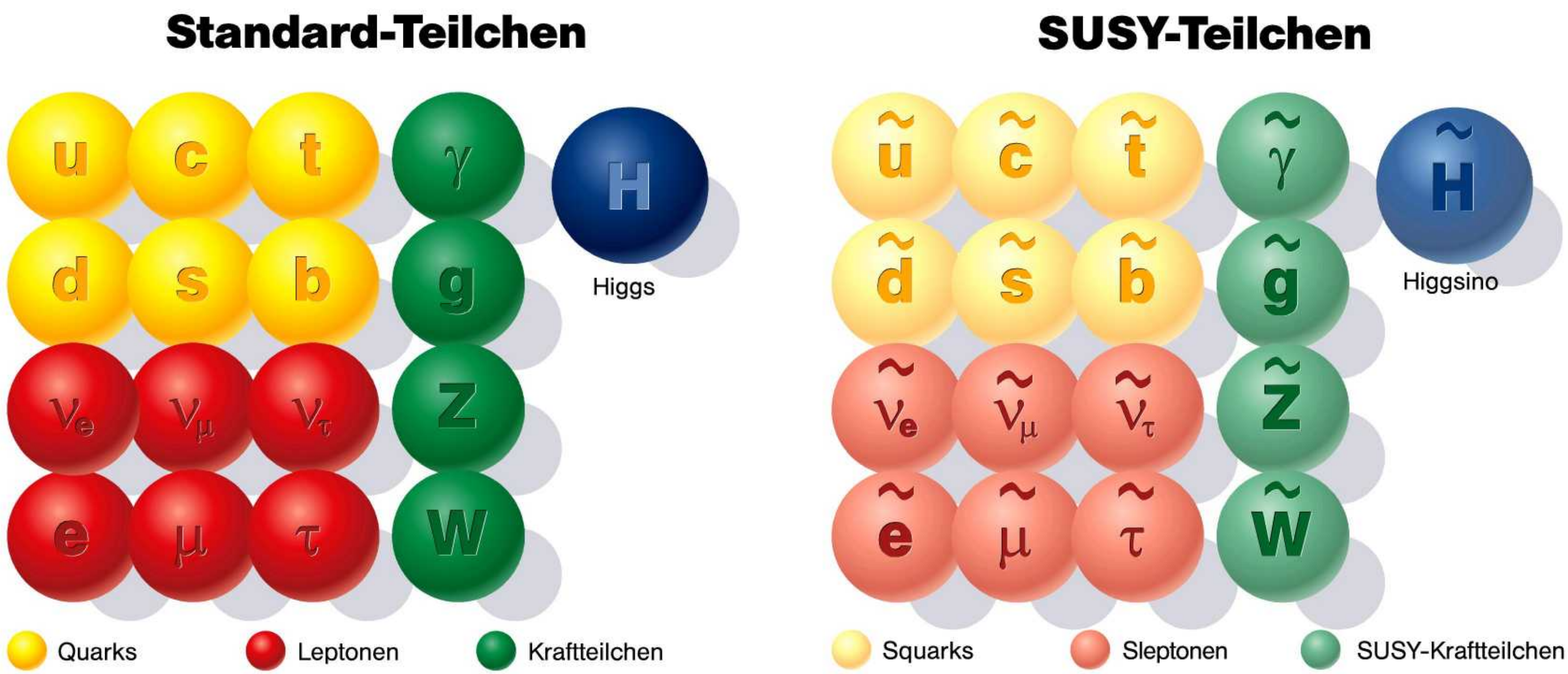
$$\Delta m^2 \propto g^2_{\phi f\bar{f}}[m_f^2 - m_{\tilde{f}}^2]\ln(\Lambda^2_{eff}/m^2_\phi)$$

No SUSY particle, degenerate in mass with its SM partner, has 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

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 specific mechanism of SUSY breaking

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

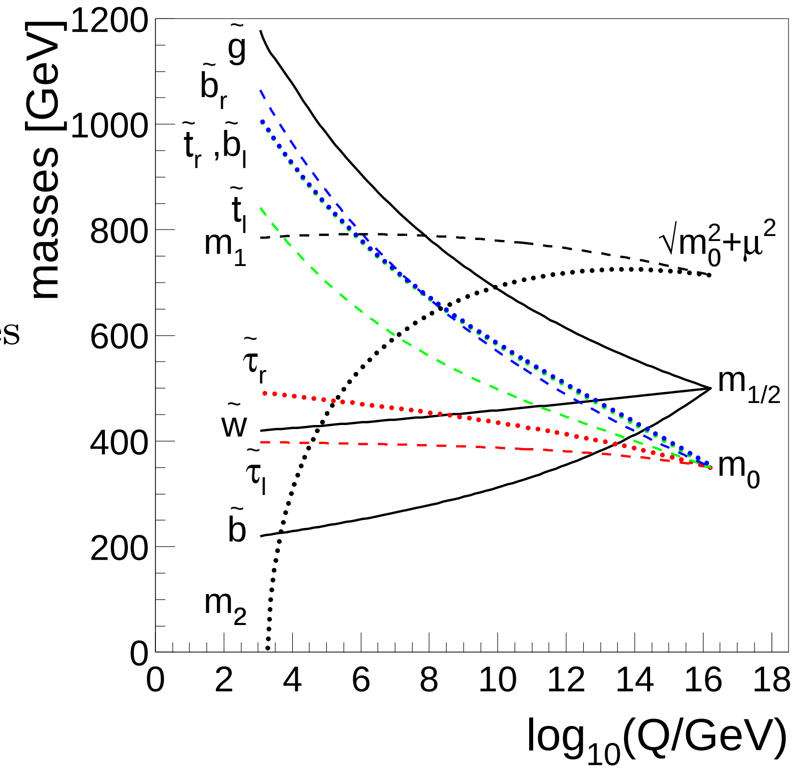
⋆ Solve hierarchy/naturalness problem by having $\Delta m^2 \simeq \mathcal{O}(v^2)$

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

⋆ EWSB is radiatively generated

In the evolution of masses from high energy scales
$\longrightarrow$ a negative Higgs mass parameter is induced
via radiative corrections

$\Longrightarrow$ *important top quark effects!*



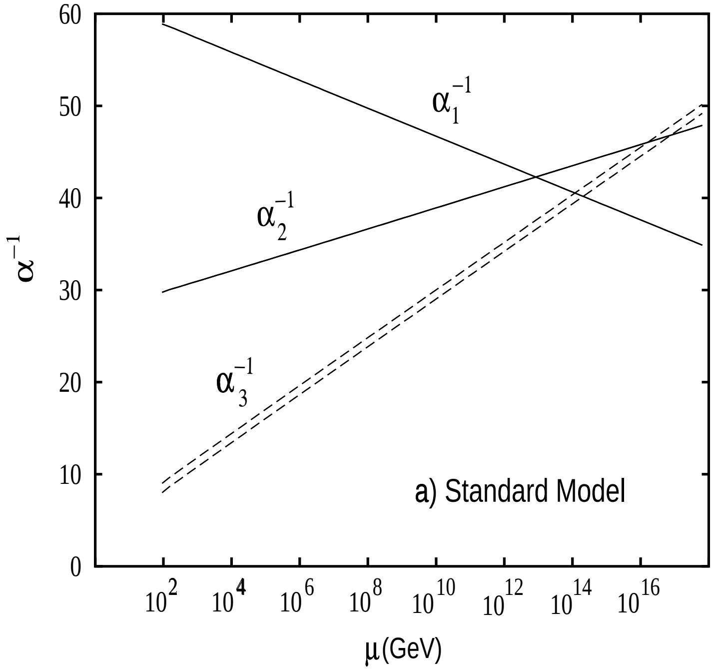
⋆ Play central role in unification of gauge couplings

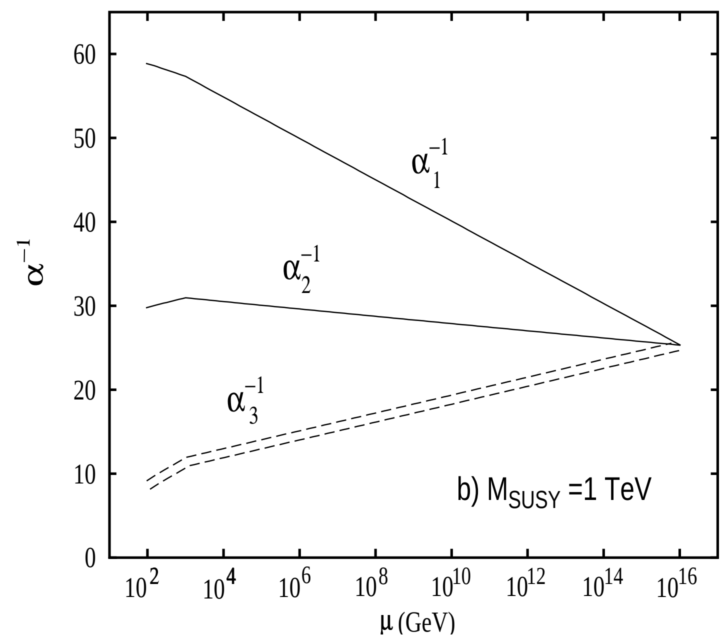
SM:

All 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





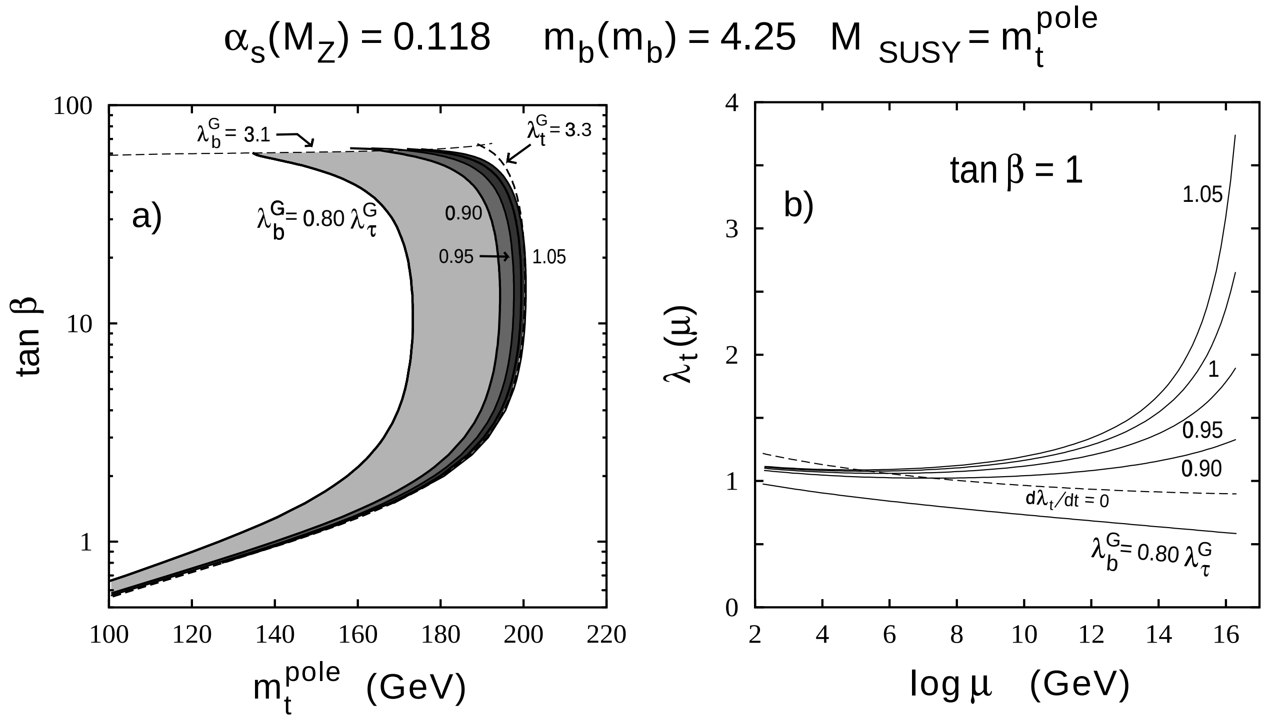
Experimentally, $\alpha_3(M_Z) \simeq 0.118 \pm 0.004$

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

Bardeen, M.C., Pokorski & Wagner

Remarkable agreement between Theory and Experiment!!

⋆ Large value of m_t can be understood as a result from quasi infrared fixed point of top-Higgs Yukawa coupling.



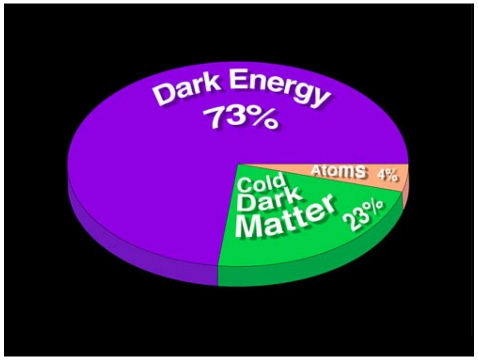
fixing m_b and α_s while varying $h_b(M_{GUT})$ and $h_\tau(M_{GUT})$ away from exact unification

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

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

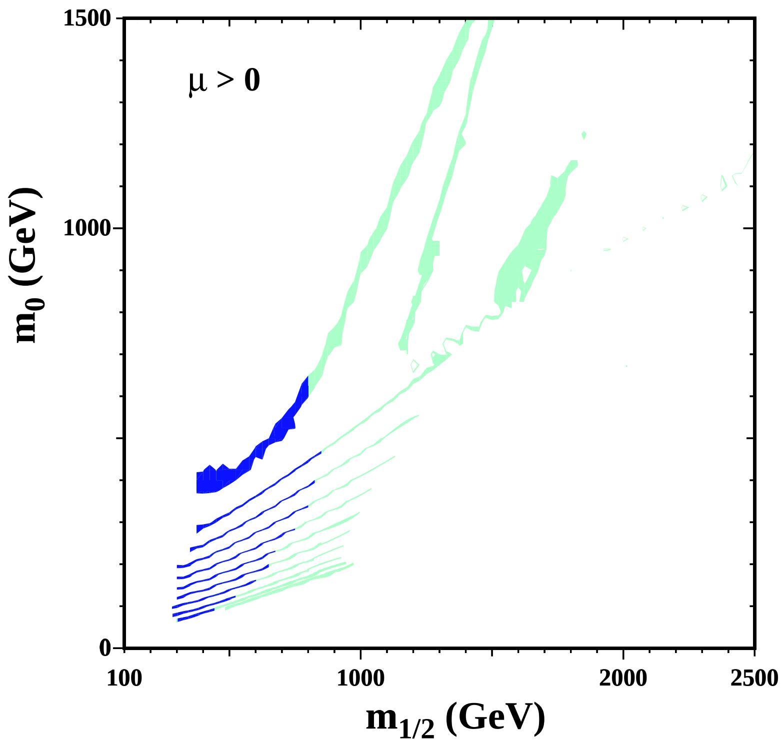
Bardeen, M.C., Pokorski, Wagner

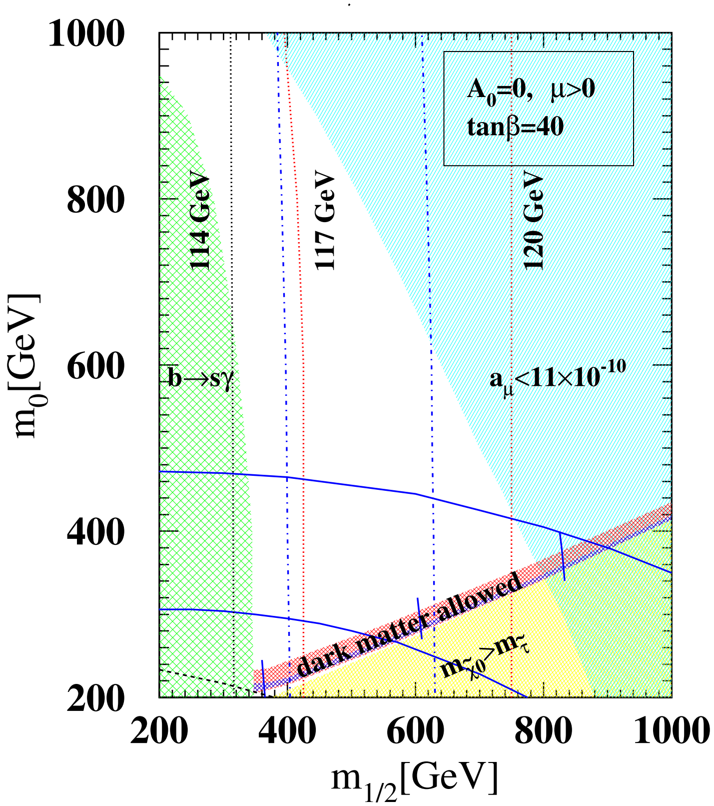
⋆ Provides a good dark matter candidate ⟶



Present WMAP satellite data has confirmed with great accuracy the cold-dark matter density of the universe: $0.094 \leq \Omega_{CDM} h^2 \leq 0.13$

→ SUSY dark matter candidate is likely to be the lightest neutralino with mass possibly below 500 GeV and almost degenerate with the stau





⋆ Provides a possible solution to the observed baryon asymmetry

Baryogenesis at the electroweak phase transition:

⋆ Start with B=L=0
⋆ CP violating sources $\Longrightarrow$ create chiral baryon-antibaryon asymmetry in the symm. phase
⋆ Net Baryon number diffusse in the broken phase
⋆ Strong first order phase transition $\Longrightarrow$ baryon number violating processes are out of equilibrium in the broken phase $\Longrightarrow$ preserve the generated baryon asymmetry

In the SM:

- **EW Baryogenesis** demands a Higgs mass below 40 GeV
  $\Longrightarrow$ **ruled out by experiment**
- Independent problem: not enough CP violation

In Supersymmetry: both problems solve

- New bosonic degrees of freedom with coupling of order one to the Higgs
  $\Longrightarrow$ sufficiently strong first order phase transition with a Higgs mass up to 120 GeV
- New sources of CP violation from the sfermion sector

– Another interesting feature: Allows natural introduction of gravity
SUSY algebra naturally includes coordinate trasformations
$\Longrightarrow$ Local SUSY $\leftrightarrow$ SuperGravity

Higgs and Supersymmetry

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

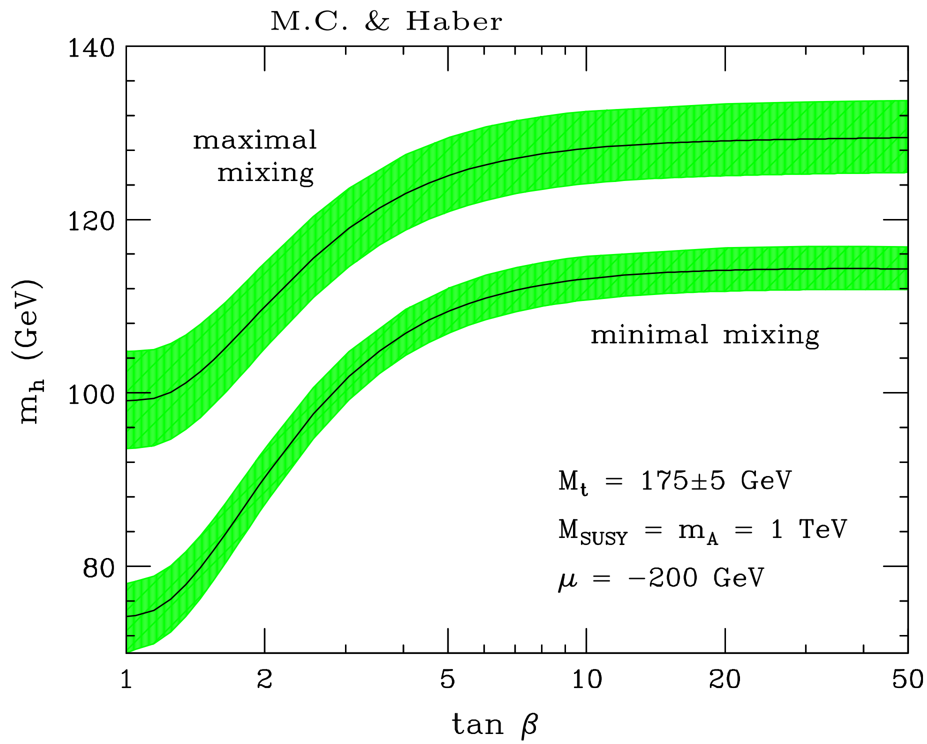
MSSM: simplest extension

- two neutral scalars acquire vacuum expectation values: 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

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



The mechanism of SUSY breaking is not well understood.

$\Downarrow$

Different SUSY breaking scenarios $\longrightarrow$ crucially different patterns of low energy spectrum –production and decays–

- Important to develop a comprehensive search strategy to explore the main signals in different SUSY breaking scenarios.

SUGRA Scenarios

Supersymmetric particles odd under a discrete symmetry: R-parity: $R_p = (-1)^{3B+L+2S}$
$\rightarrow$ naturally avoids too fast proton decay

- If R-parity Conserved: Lightest Supersymmetric Particle (LSP) Stable
  $\Longrightarrow$ lots of $\not{E}_T \rightarrow$ distinctive SUSY signature

- LSP Stable $\Longrightarrow$ good Dark Matter candidate.

Best candidate: Neutralino $\Longrightarrow$ SUSY partner of the neutral Higgs or gauge bosons

- Strongly interacting particles (due to RG effects) tend to be heavier than weakly interacting ones.

Gauge-Mediated Low-energy SUSY Breaking Scenarios

- Special feature $\longrightarrow$ LSP: light (gravitino) Goldstino:

$$m_{\tilde{G}} \sim 10^{-6} - 10^{-9}\text{GeV}$$

If R-parity conserved, heavy particles cascade to lighter ones and

NLSP $\longrightarrow$ SM partner + $\tilde{G}$

$$e.g., \; \tilde{\chi}_1^0 \rightarrow (h, Z, \gamma)\, \tilde{G}; \qquad \tilde{\ell}^{\pm} \rightarrow \ell^{\pm}\, \tilde{G}; \qquad \tilde{q} \rightarrow q\, \tilde{G}$$

Superpartner masses proportional to their gauge couplings.

- Signatures:

decay length $\quad L \sim 10^{-2}\text{cm} \left(\frac{m_{\tilde{G}}}{10^{-9}\text{GeV}}\right)^2 \times \left(\frac{100\text{GeV}}{M_{\text{NLSP}}}\right)^5$

⋆ NLSP can have prompt decays:

Signature of SUSY pair: 2 hard photons, (H's, Z's) + $\not{E}_T$ from $\tilde{G}$

⋆ macroscopic decay length but within the detector:

displaced photons; high ionizing track with a kink to a minimum ionizing track

(smoking gun of low energy SUSY)

⋆ decay well outside the detector: $\not{E}_T$ like SUGRA

Strongly Coupled EWSB Dynamics

(a) Models which do not require a Higgs Boson

$\Longrightarrow$ Strong interactions at the TeV scale: Technicolor,

- New gauge interaction which is asymp. free and becomes strong at scales of order 1 TeV

$\rightarrow$ new fermions (technifermions) feel this interaction and form condensates $\rightarrow$ EWSB

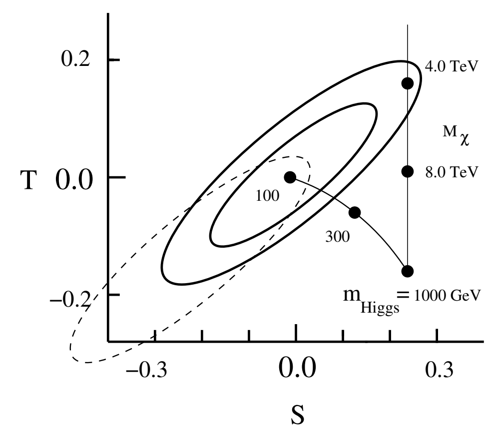
Robust prediction:

vector resonance with mass $\leq$ 2 TeV (to unitarize the $W_L^- W_L^+ \rightarrow W_L^- W_L^+$ amplitude)

(b) Strong interactions above TeV scale give rise to bound states

$\Longrightarrow$ Composite Higgs Models

Top-condendate models: effective four-Fermi interactions that induce bound states with the same quantum numbers than a Higgs, and condensation of such bound state $\rightarrow$ EWSB



Top quark seesaw theory:

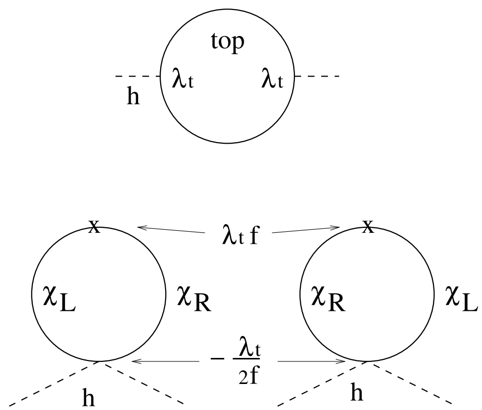
- Higgs is a bound state of left-handed top and right-handed component of a new vector-like fermion: $m_H \simeq 500$ GeV.
- New contributions from additional quarks bring agreement with precision electroweak measurements.

(c) Little Higgs Models:

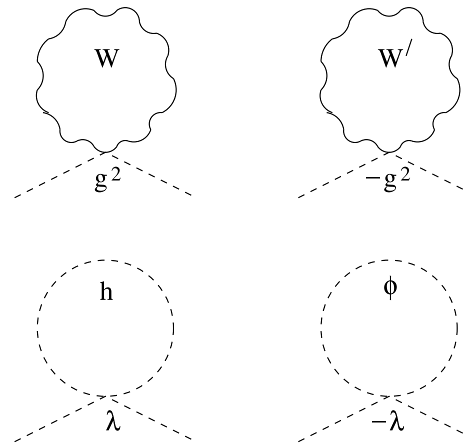
• Higgs is a pseudo-Goldstone boson from a spontaneous global symmetry breaking at scale 10–30 TeV. $\Longrightarrow$ New Dynamics needed above that scale.

• Global symmetry explicitly broken by gauge and Yukawa interactions, however, no single int. breaks all the symmetries, hence protecting the Higgs mass
Higgs acquires mass only radiatively at the electroweak scale.

• Non-linearly realized symmetry yields cancellation of quadratically divergent quantum corrections between fields of the same spin.



A fermion loop cancels a fermion loop.



The gauge and Higgs loops are cancelled by diagrams with new bosons in loops.

Cancellation of quadratic divergences works at one loop.
$\Longrightarrow$ new fermionic partners for SM quarks and leptons and new gauge boson partners for SM gauge fields at the TeV scale.

- LHC should discover some of them;
- LC: precision measurement of heavy gauge boson couplings to fermions via polarized cross sections and asymmetries.

Many possible Signatures of strongly coupled EWSB:

• Strong WW scattering • Anomalous gauge couplings

• Extra scalars → composites of underlying strongly coupled fermions

• Extra Fermions • Heavy vector bosons

• Extended Higgs sector at TeV scale or below → mixing can bring the SM-like Higgs down to 200 GeV.

No compelling model exists that can be called the Standard Model of Strongly coupled EWSB

Why is it so difficult?

⋆ The mechanism of fermion mass generation is ackward (not simple as in the simplest Higgs model) and it is distinct from the gauge bosons mass generation mechanism

⋆ In most models, the energy scale associated with the flavor dynamics is rather close to the scale of EWSB ⟶ need to address the origin of EWSB and flavor in the same overall picture

⋆ No clear connection to fundamental physics at high energy. Gauge coupling unification must be regarded as accidental.

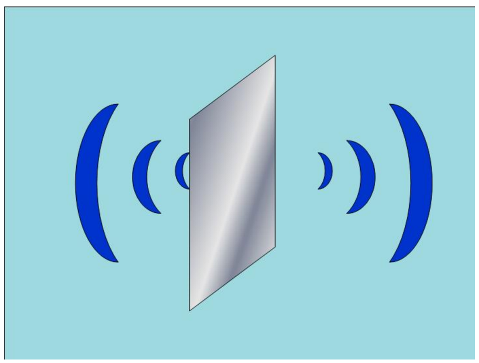
⋆ Strongly-coupled systems are hard to treat theoretically ⟹ explicit computations are often very difficult

A daring alternative: Extra Dimensions (ED)

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

Gravity in ED $\Longrightarrow$ fundamental scale, pushed down to electroweak 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)

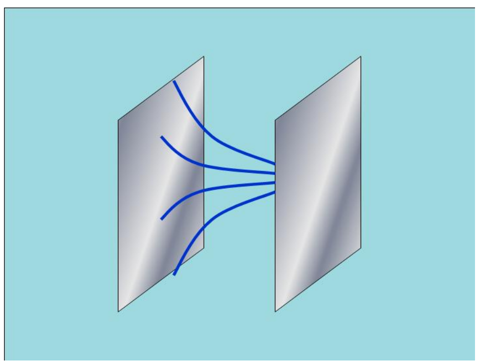
gravity flux in ED $\Longrightarrow$ Newton's law modified:

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

this lowers the fundamental Planck scale,

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

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



k≠0 (warped ED)

$$M_{Pl}^2 = \frac{(M_{Pl}^{\rm fund.})^3}{2k}(1 - e^{-2kL})$$

fundamental scales: $M_{Pl} \sim M_{Pl}^{\rm fund.} \sim v \sim k$

$\Longrightarrow$ Physical Higgs v.e.v. suppressed by e^{-kL}

$\Longrightarrow$ $\tilde{v} = v\, e^{-kL} \simeq m_Z$ if $kL \approx 34$

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

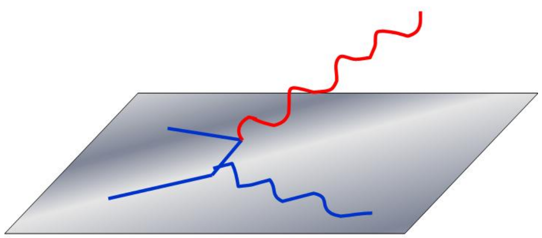
4-D effective theory:

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 $\Longrightarrow E^2 - \vec{p}^{\,2} = p_d^2 = \sum_n (m_{KK}^{(n)})^2$

imbalance between measured energies and momentum in 4-D = momentum in ED

Signatures



9

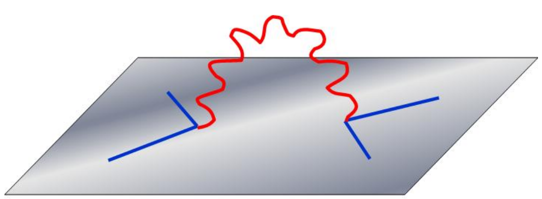
flat

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

$M_{G_1} \simeq 10^{-2}$ GeV ($d = 6$); $M_{G_1} \simeq 10^{-4}$ eV ($d = 2$);

(a) Emission of KK graviton tower states: $G_n \Longleftrightarrow \not{E}_T$
(emitted gravitons appear as continuous mass distribution)

(b) Graviton exchange in $2 \rightarrow 2$ scattering – deviations for SM cross sections or new decays



8

warped

- Graviton KK modes have 1/TeV coupling strength to SM fields and masses starting with a few hundred GeV.

KK graviton states produced as resonances or may contribute to $f\bar{f}$ production.

SM fields propagating in ED

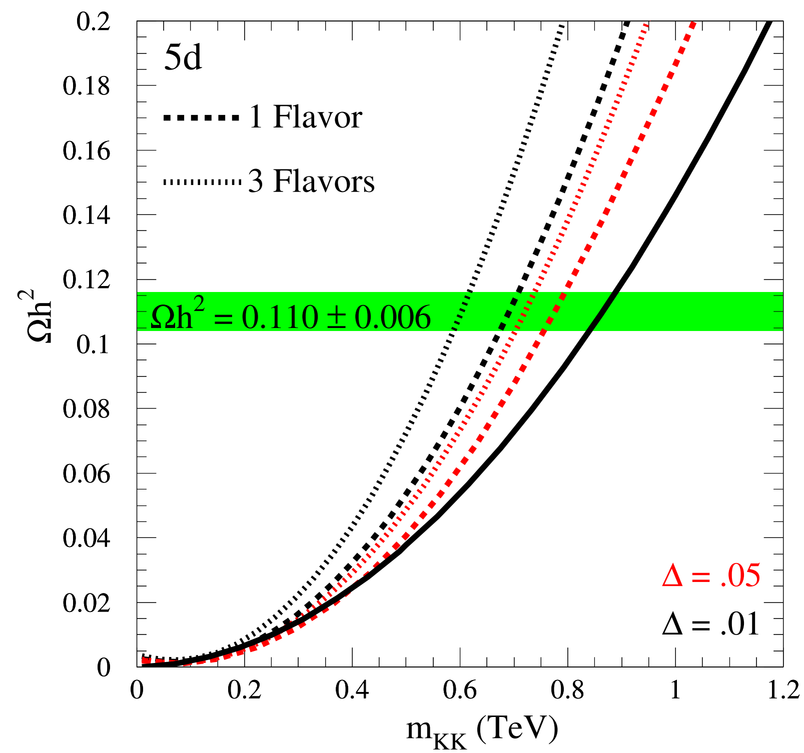
$\Longrightarrow$ TeV-scale Extra dimensions or warped extra dimensions

- Gauge bosons and/or fermions in the bulk

$\Longrightarrow$ new particles may be within reach of LHC.

Universal Extra Dimensions (flat ED):

All fields in the bulk – no wall or branes
$\Longrightarrow$ momentum conserved in ED.



- KK modes produced by pairs

- no big corrections to EW observables

- Lightest Kaluza-Klein Particle (LKP)
  $\longrightarrow$ **good dark matter candidate**

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}

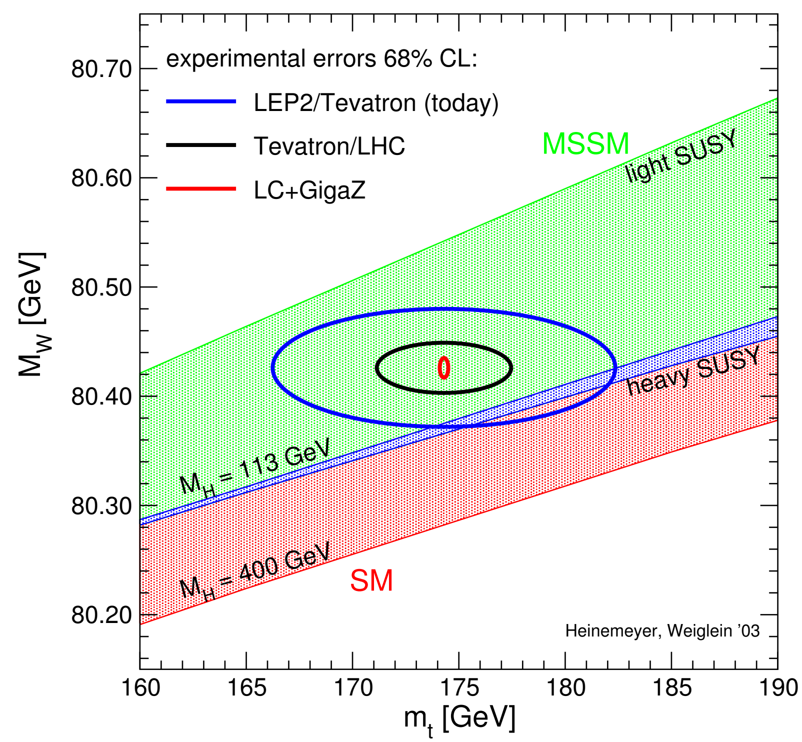
high precision for M_t is important to

$\Longrightarrow$ exploit precision on M_W in the context of electroweak precision measurements

M_t–M_W–M_H Correlation

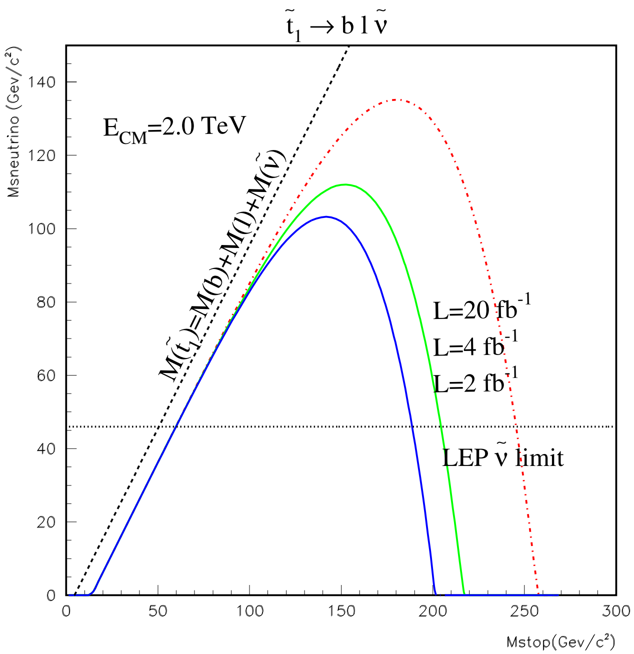
- direct M_t and M_W measurements from LEP and the Tevatron
- Indirect M_t and M_W determination from SM fit to precision data (LEP, SLD, νN)
- SM relationship for M_t–M_W–M_H $\Longrightarrow$ crucial information on M_H

$\Longrightarrow$ 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



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

$m_{\tilde{t}_1} \leq$	200/210	in $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^{\pm} / \tilde{t}_1 \rightarrow bl\tilde{\nu}$
$m_{\tilde{t}_1} \leq$	180	in $\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$
$m_{\tilde{b}_1} \leq$	230	in $\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$

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

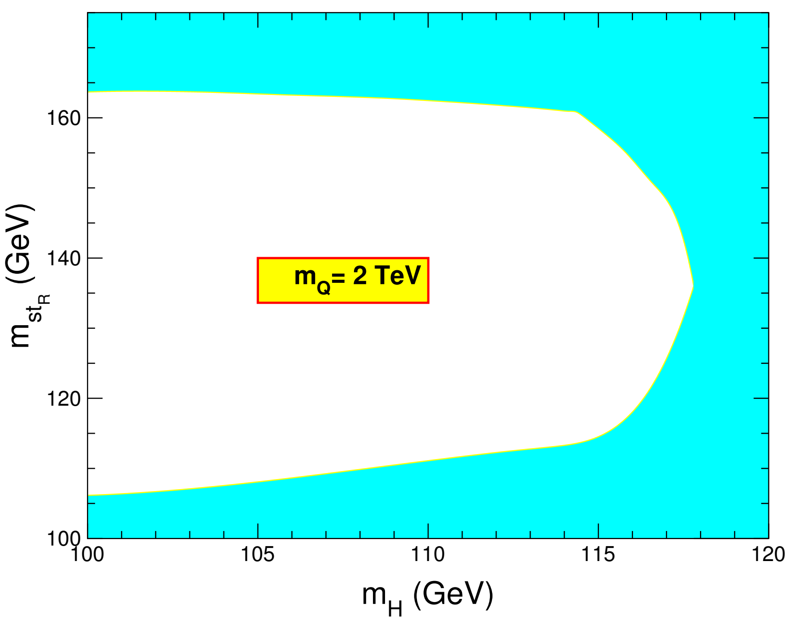
In the cases $\tilde{t} \rightarrow c\gamma\tilde{G}$ and $\tilde{t} \rightarrow bW\gamma\tilde{G}$, sensitivity up to $m_{\tilde{t}_1} \leq 300$ GeV

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

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

• To preserve baryon asymmetry generated at the EW phase transition light stop $m_{\tilde{t}_R} \leq M_t$ and an MSSM Higgs boson with $m_h \leq 120$ GeV are required
$\Longrightarrow$ Higgs associated with electroweak symmetry breakdown has SM-like properties

• Other stop needs to be heavy, $m_{\tilde{t}_L} \simeq 1$ TeV, to induce a Higgs mass above the current experimental limit, $m_h \geq 114$ GeV



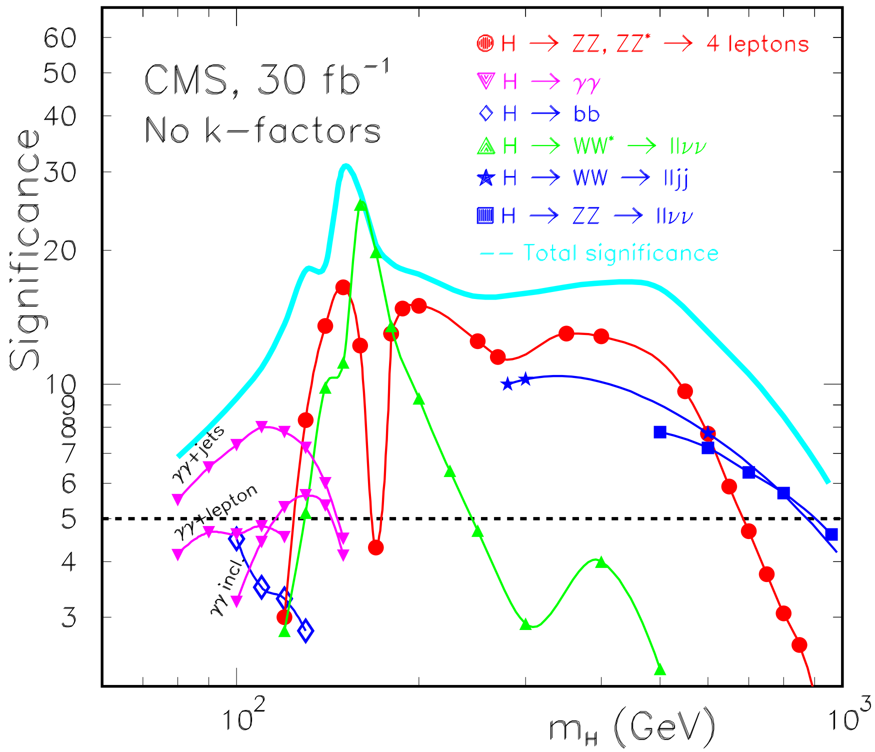
M.C., Quiros & Wagner

A definite test of this scenario at the LHC: Higgs and Stops searches.

What Will We Know by the End of the Decade?

After the first run period of the LHC $\longrightarrow$ 10–30 fb^{-1} collected

– *If the SM Higgs exists, it will be discovered at the LHC.*



mass regions –

- m_H in the range $2\,M_Z$ – 600 GeV
  best channel is $H \to ZZ \to 4\ell$
- $m_H > 600$ GeV
  $H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$ and
  $H \to WW \to \ell\nu JJ$
  more demanding :
- $m_H < 2\,M_Z$ (esp. below 130 GeV)

need combination of three channels:

$H \to \gamma\gamma$, $\quad H\,t\bar{t} \to b\bar{b}\,t\bar{t}$,

$q\bar{q}\,H \to q\bar{q}\,\tau^+\tau^-/WW^*$

to achieve 5σ discovery with 10 fb^{-1} ($\sim$ 1 yr)

- Higgs Bosons in the Minimal Supersymmetric Extension of the Standard Model (MSSM)

– many different channels for H, A & $H^\pm$

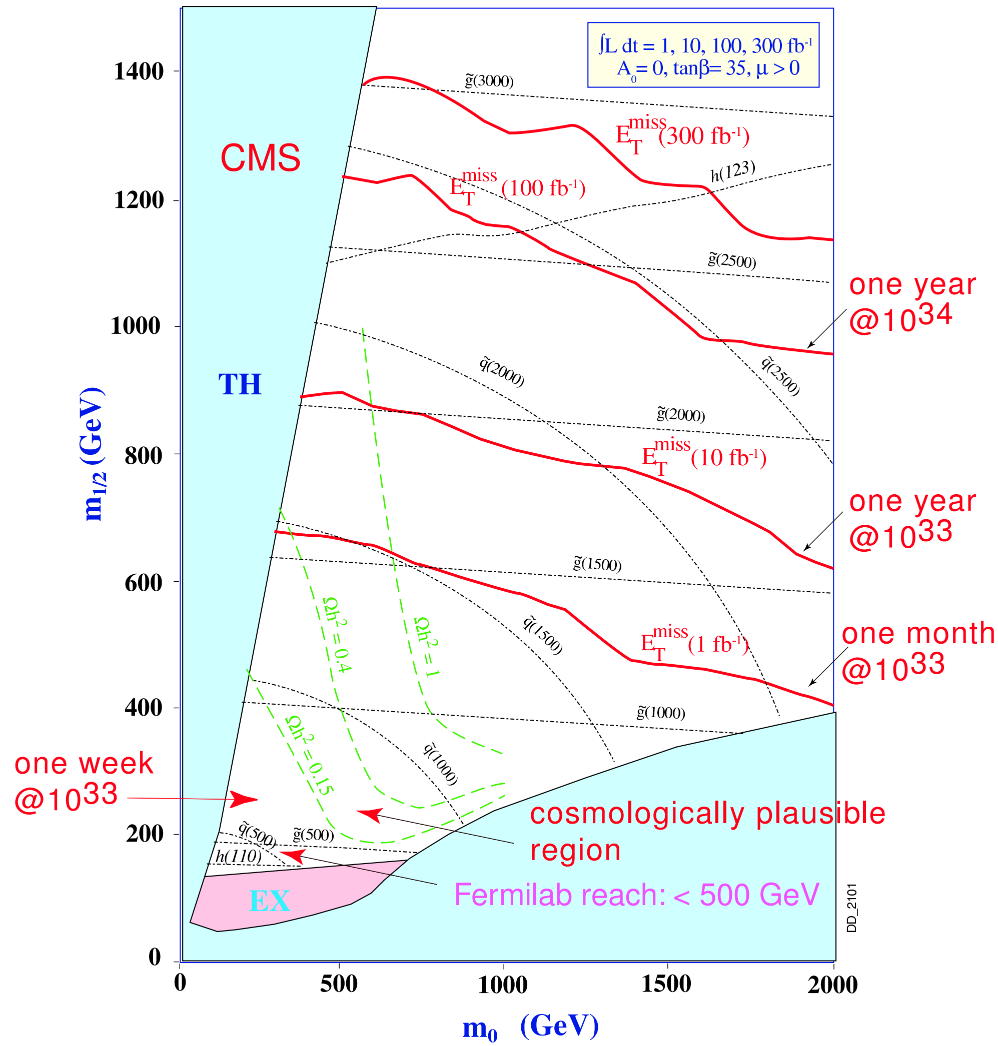
– but full coverage assured only for h

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 $\not{E}_T$ (maybe leptons)
  - ‘GMSB’ type – hard photons & $\not{E}_T$; heavily ionizing tracks

reach: $M_{\tilde{q}}$ and $M_{\tilde{g}}$ up to ∼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 During the Next Decade

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

Continue Exploration of Higgs Physics

- Mass:

δm_H to 0.1% (leptonic & $\gamma\gamma$ modes)

1% ($b\bar{b}$ final states)

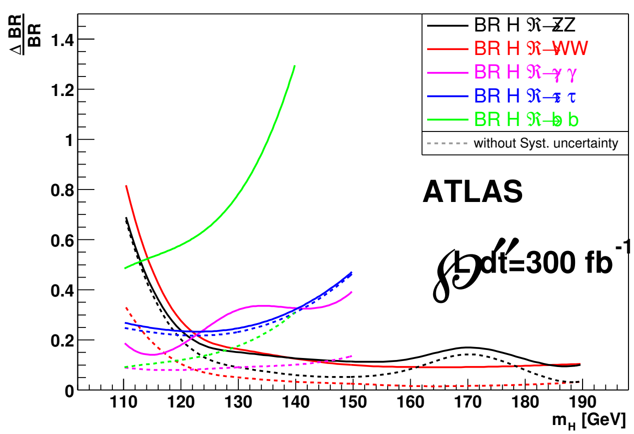
- Couplings

$\delta g^2/g^2$ ~20% for $H \to Z, W, \tau, t$ ($m_h > 150$ GeV)

- Branching Ratios

$\delta Br(H \to ZZ)/Br \sim$ 10–20% ($m_H > 125$ GeV)

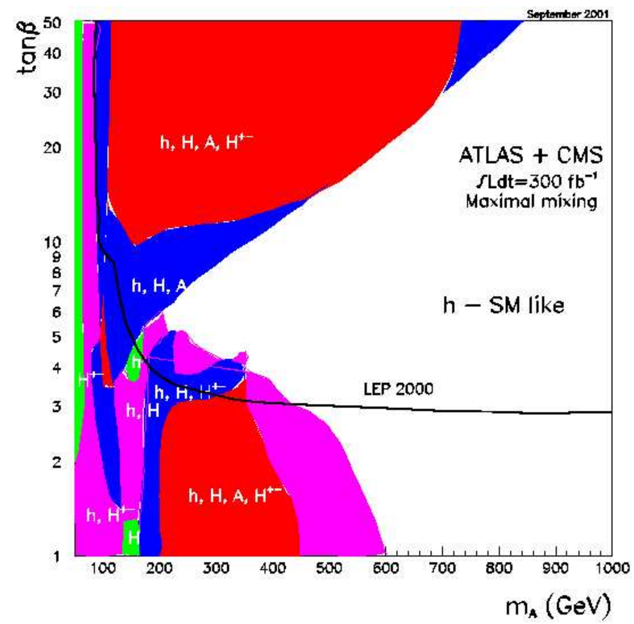
$\delta Br(H \to b\bar{b})/Br \sim$ 50% ($m_H \sim 120$ GeV)



MSSM Higgs

- higher luminosity allows access to many additional channels

$\longrightarrow$ better coverage of H, A, $H^{\pm}$, h



- still some regions where only h is visible
- some prospects to cover part of this region with Higgs decay in SUSY particles

Higgs Physics $\longrightarrow$ LHC will have a great shot at it.

Extra Dimensions

- Flat Extra Dimensions

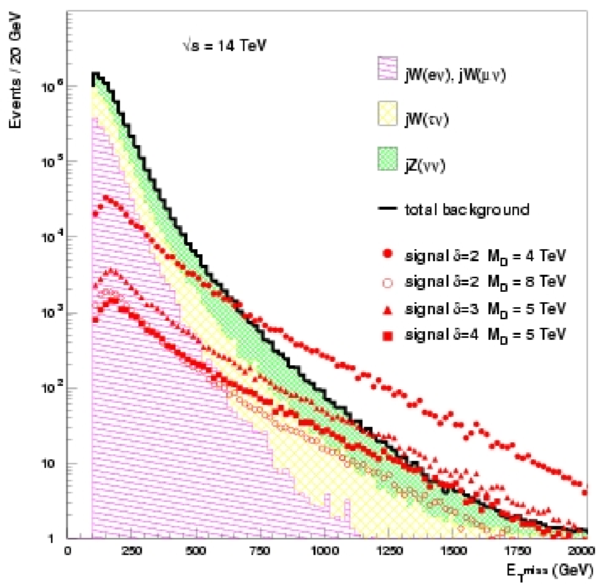
– emission of KK graviton tower states

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

cross section summed over full KK towers

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

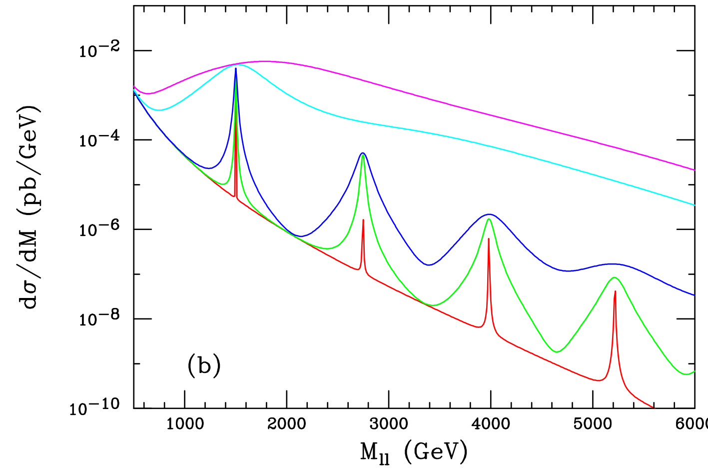
emitted graviton appears as a continuous mass distribution



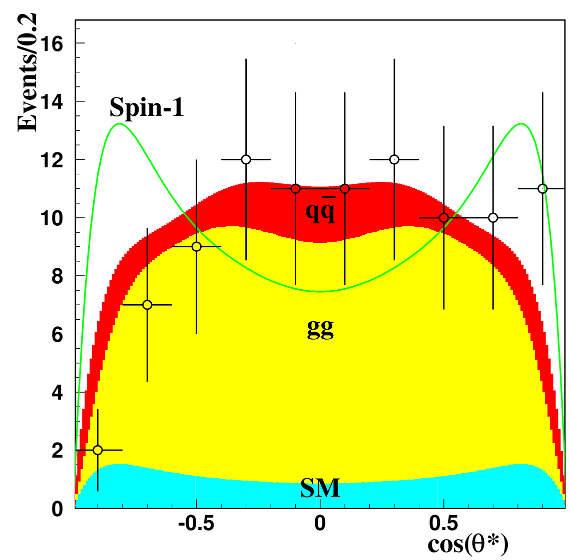
Discovery reach for fundamental Planck scales in the order of 5-10 TeV (depending on $d =$ 4,3,2)

- Warped Extra Dimensions

narrow graviton resonances: $pp \to G_N \to e^+e^-$



from top to bottom: $k/M_{Pl} = 1, 0.5, 0.1, 0.05, 0.01$



⋆ angular distributions reveal spin of resonance

Extra Dimensions

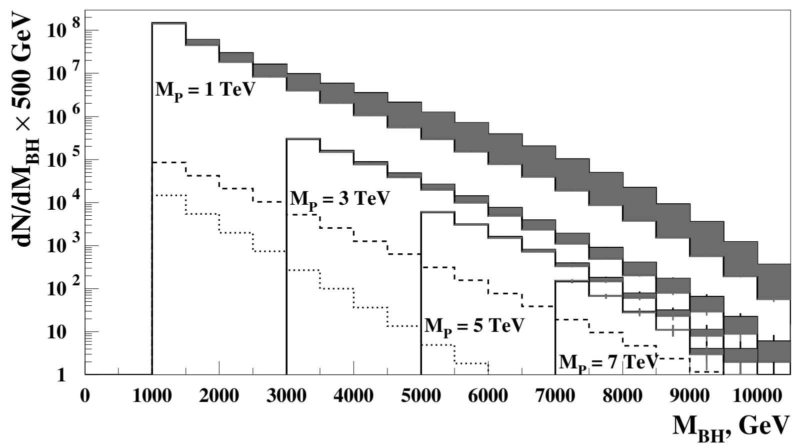
Exciting Possibility: **TeV-scale Production of Black Holes**

If $M_{BH} \gg M_{\text{Pl}}^{\text{fund}} \Longrightarrow$ 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 $M_{\text{Pl}}^{\text{fund}} \sim 1$ 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 & photons;



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

- At LHC, limited space for trans-Planckian region and quantum gravity pollution
- At a VLHC ($\sqrt{s} \geq 100$ TeV), perfect conditions

High Energy Lepton Colliders

- High Luminosity LHC –

  - New information on Higgs and Supersymmetry.
  - explore our ideas of space and time.
  - uncover other new particles & interactions

a LC will add uniquely to this program.

- High precision Higgs physics
- A window to the Childhood of the Universe (GUT Physics)
- 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.

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

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

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

- Accuracy on Branching Ratios $\delta Br/Br$

LC typical precision $\sim$ 2–10%
  for $m_H \sim$ 110–150 GeV

LHC $\longrightarrow$ 10–50% in same mass range
  10–20% if $m_H > 150$ GeV

- Accuracy on couplings $\delta g/g$

LC typical precision $\rightarrow$ 1–5%
  for $m_H \sim$ 110–150 GeV

LHC $\longrightarrow$ 15–25% in same mass range
  5–10% if $m_H > 150$ GeV

Super-LHC with 3000 fb^{-1} will improve precision by about a factor 2.

Prec. Meas. of Br's & Γ's

- distinguish MSSM/SM Higgs
- indir. evidence for m_A beyond kin. reach
- info on SUSY vertex corr. to bottom Yuk. coupl.

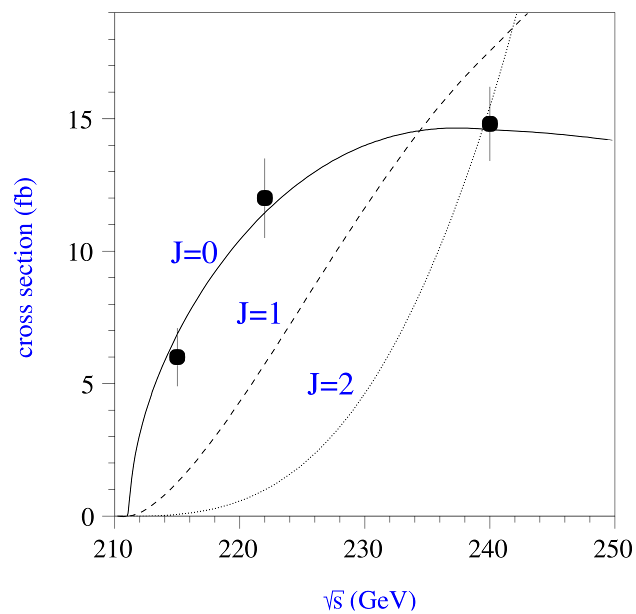
- Precision Measurement of Higgs Mass

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

- Higgs quantum numbers: spin and parity

- threshold dependence of excitation curve
- angular distributions

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



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

Supersymmetry

(a) Measurements of SUSY particles masses

$\Longrightarrow$ 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

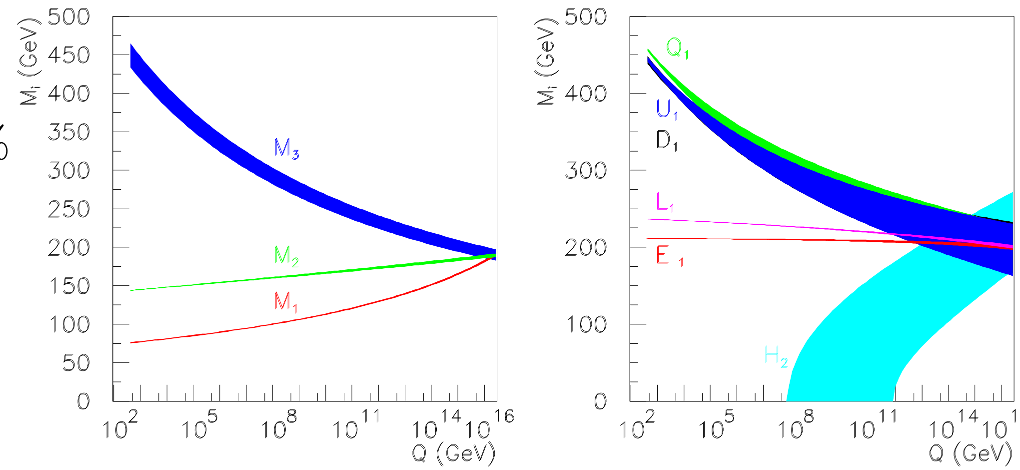
(c) Spin of SUSY particles:

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 $\Omega_{\rm DM}$.

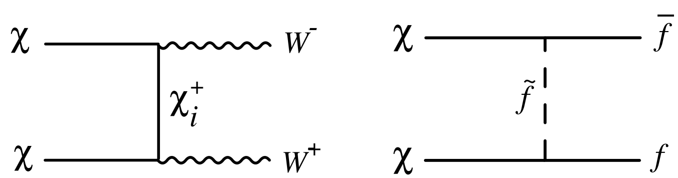
$\Rightarrow$ A coincidence or DM provides fundamental motivation for new particles at EW scale.

$\star$ 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 $\tilde{\chi}_1^0$ mass & composition

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



$\Longrightarrow$ determined thermal relic density assuming SM evolution of the universe

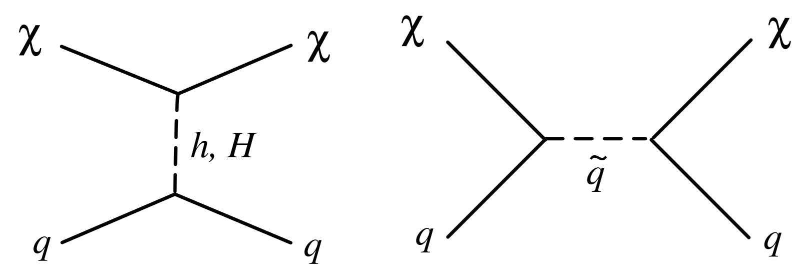
- comparing this result with $\Omega_{\rm DM}$ from Astrophysical/Cosmological input

$\Longrightarrow$ new insights into history of our universe

- Dark Matter Detection:

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

$\longrightarrow$ 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, ν's in centers of Earth & Sun)

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

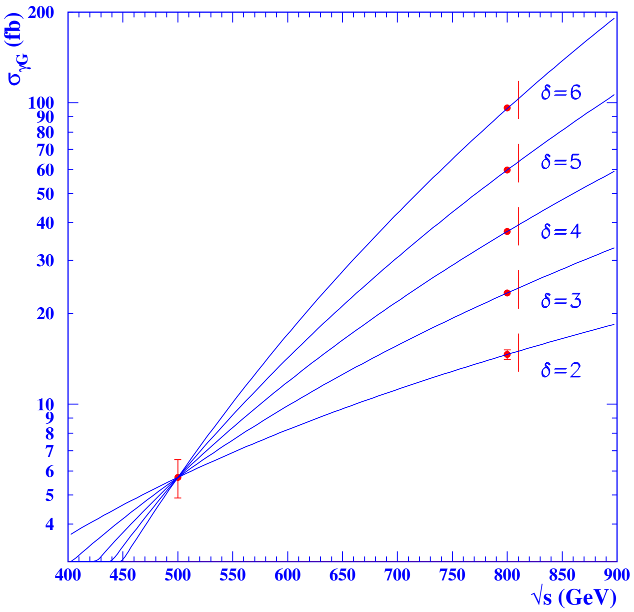
$\Longrightarrow$ LC will provide important info about DM halo densities and velocity distributions.

Extra Dimensions

Flat ED:

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

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

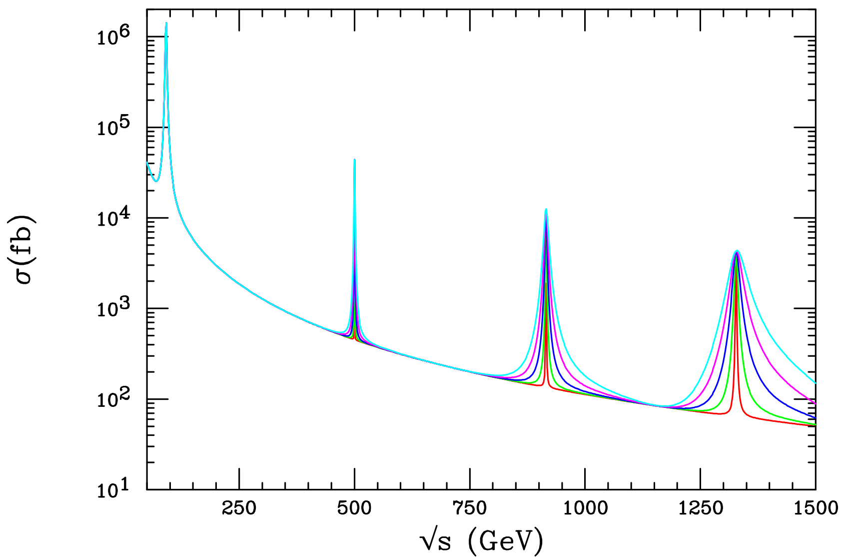


graviton exchange in $2 \to 2$ processes:

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

Warped ED:

- Given sufficient center-of-mass energy, KK graviton states produced as resonances:



$\sigma(e^+e^- \to \mu^+\mu^-)$ as a function of $\sqrt{s}$, including KK graviton exchange, $m_1 = 500$ GeV, $k/M_{Pl} = 0.01$–0.05 range.

Energy Frontier – Outlook

By the End of This Decade

– Tevatron

- will have measured M_t, M_W to unprecedented accuracy $\longrightarrow$ indirect constraints on $M_{H_{\rm SM}}$
- If Nature is kind, discovery of new particles.

– LHC

- If Higgs & SUSY are there, we will find out.
- If Nature is kind, we will know exactly which type of SUSY is there.

In the Next Decade

– LHC: A *sure* window to new physics:

- Higgs
- SUSY
- New Dimensions
- New Particles & Interactions

– LC

- unique capabilities which complement LHC – opening the window to Planck scale physics
- unique connection with Cosmology

Great Challenges $\Longleftrightarrow$ *Great Discoveries*

$\Longrightarrow$ **Shed light on most of the fundamental open questions of Physics and Cosmology!**

extras

More on Top Physics (explore hints for NP)

• top electroweak and strong interactions

– accurate measurement of $\sigma_{t\bar{t}}$ (10 %)

$\Longrightarrow$ precision test of SM QCD; or if $\sigma_{t\bar{t}} > \sigma_{t\bar{t}}^{SM}$ $\Longrightarrow$ non-SM prod. mechanism

Search for $t\bar{t}$ resonances in the invariant mass ($M_{t\bar{t}}$) spectrum:

$\rightarrow$ resonant topcolor Z', multiscale technicolor...

– measurement of CKM matrix element $|V_{tb}|$ (10 %):

best via measurement of $\Gamma(t \rightarrow bW)$ in single top production

• test SM production mechanisms and decays or find hints for new physics

– probe EW top couplings via W polarization in top decays

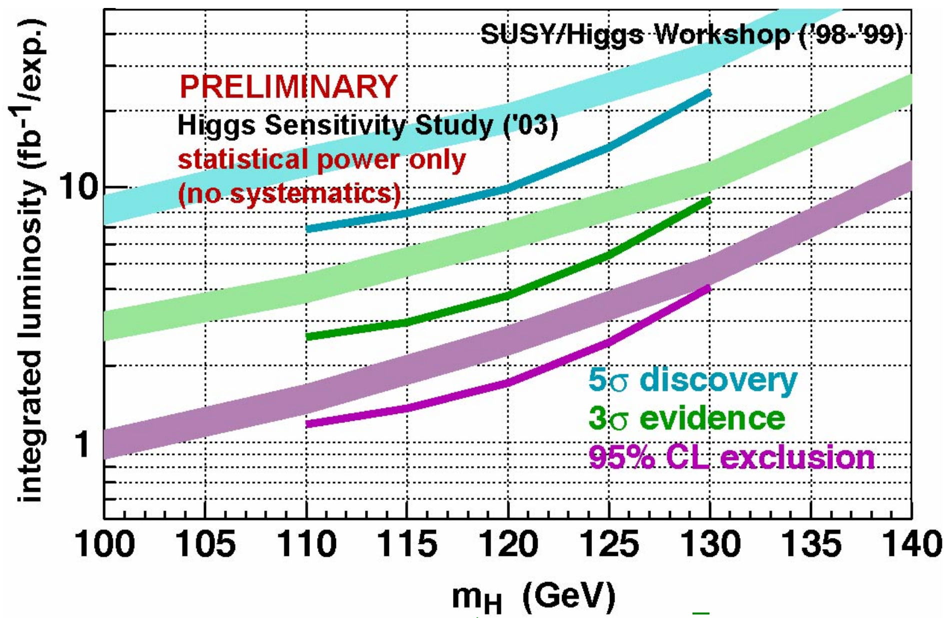
– search for anomalously large rare top decays: $t \rightarrow c\gamma$, ...

and non-SM decays: $t \rightarrow H^{\pm}b$, $t \rightarrow \tilde{t}\tilde{\chi}$ ...

Tevatron Higgs Searches

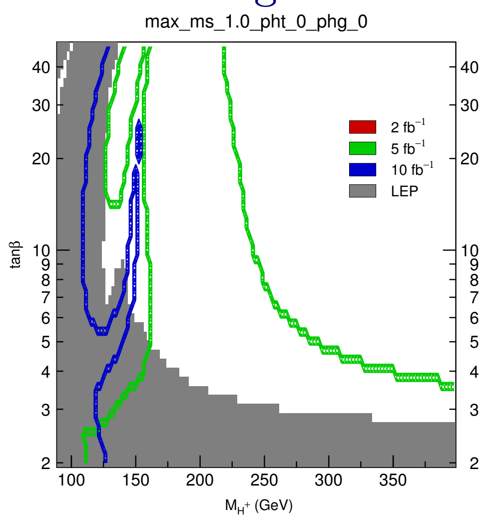
⋆ recent results from CDF+DØ

Higgs Sensitivity Studies:

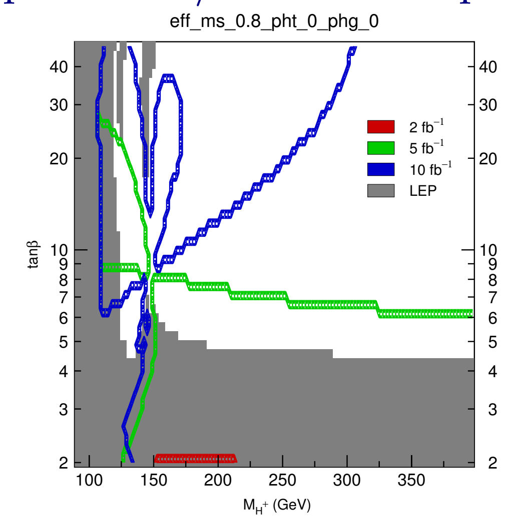


What regions of MSSM parameter space can be excluded? $p\bar{p} \to Vh/VH \to Vb\bar{b}$:

max. mixing scenario:



suppressed $h/H \to b\bar{b}$ couplings:



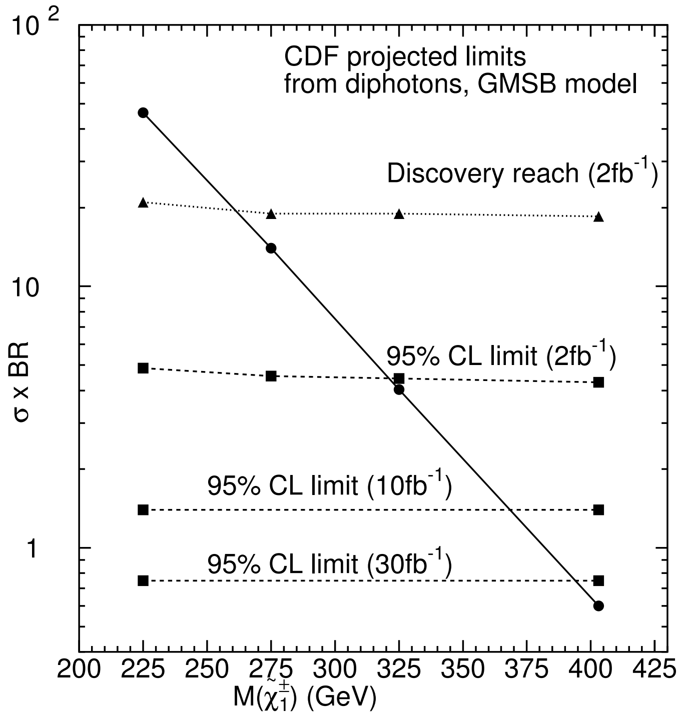
M.C., Mrenna, Wagner

Gauge-Mediated Tevatron Reach

- Bino-like NLSP: $\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$

  Signal: $\gamma\gamma X \not{E}_T$

  $X = \ell$'s and/or jets



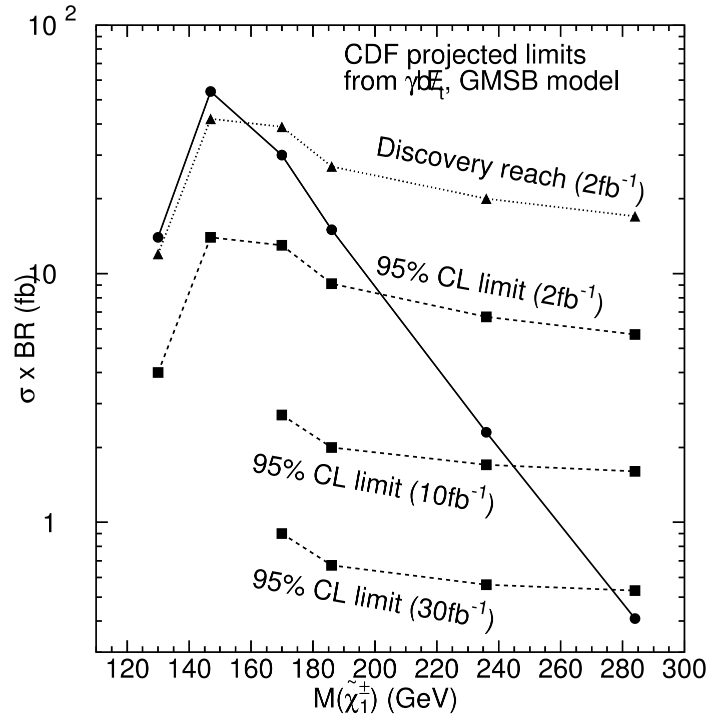
$M_{\tilde{\chi}^{\pm}} \sim 325$ GeV *(exclusion)* &

~ 260 GeV *(discovery)*

- Higgsino-like NLSP: $\tilde{\chi}_1^0 \rightarrow (h, Z, \gamma)\tilde{G}$

  Signal: γ b $\not{E}_T X$

  diboson signatures $(Z \rightarrow \ell\ell/\mathrm{jj};\ h \rightarrow b\bar{b})\not{E}_T$



$M_{\tilde{\chi}_1^{\pm}}$ sensitivity ~ 200 GeV for 2 fb^{-1}

Tevatron Searches for KK Gravitons

Flat ED

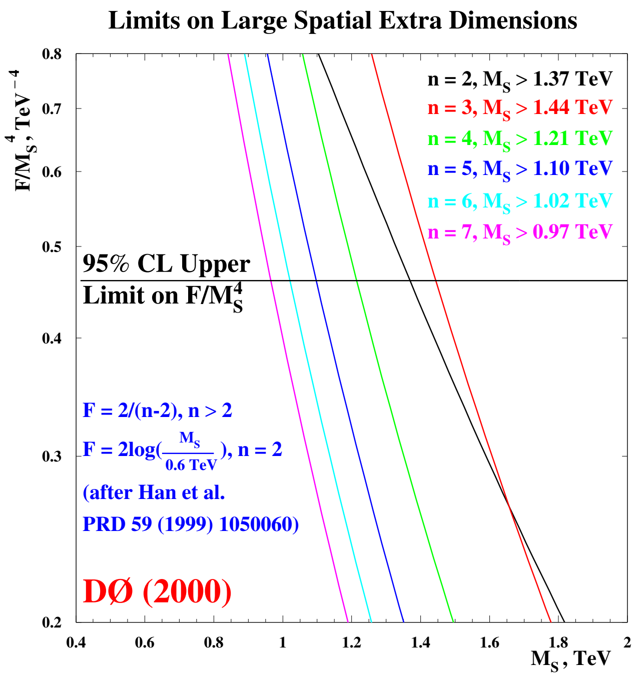
⋆ direct: $p\bar{p} \rightarrow$ jets $+ \not{E}_T$

$n = 2 \quad M_{\rm Pl}^{\rm fund} > 1.5$ TeV

$n = 6 \quad > 0.8$ TeV

at 95% CL

⋆ Drell-Yan and di-photons

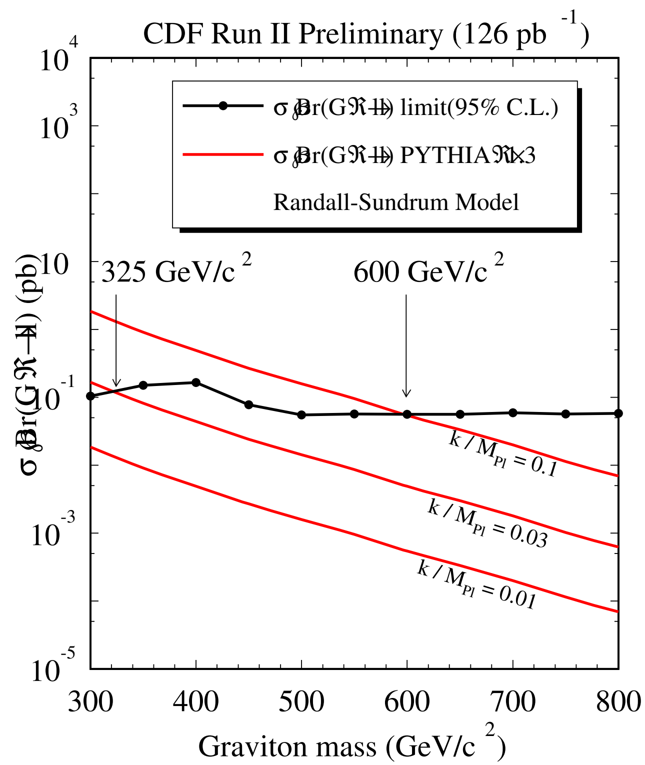


Run 2:

$M_{\rm Pl}^{\rm fund}$ sensitivity $\approx$ 1.3–2.5 TeV

Warped ED

⋆ $p\bar{p} \rightarrow \ell^+\ell^- \qquad \ell = e$ and μ



$\longrightarrow$ with 2 fb^{-1},

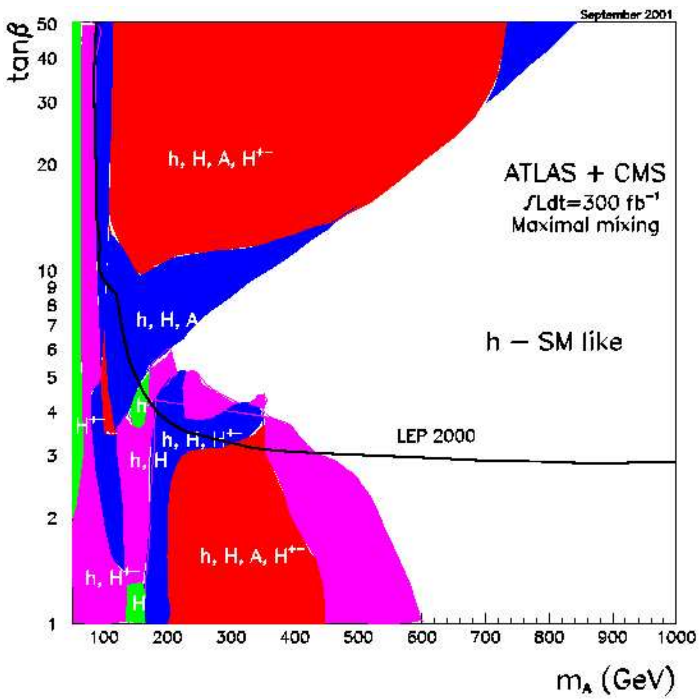
expected reach is in the few TeV range

SUSY after a high luminosity run

– MSSM Higgs:

access to many additional channels

$\longrightarrow$ better coverage of H, A, $H^{\pm}$, h



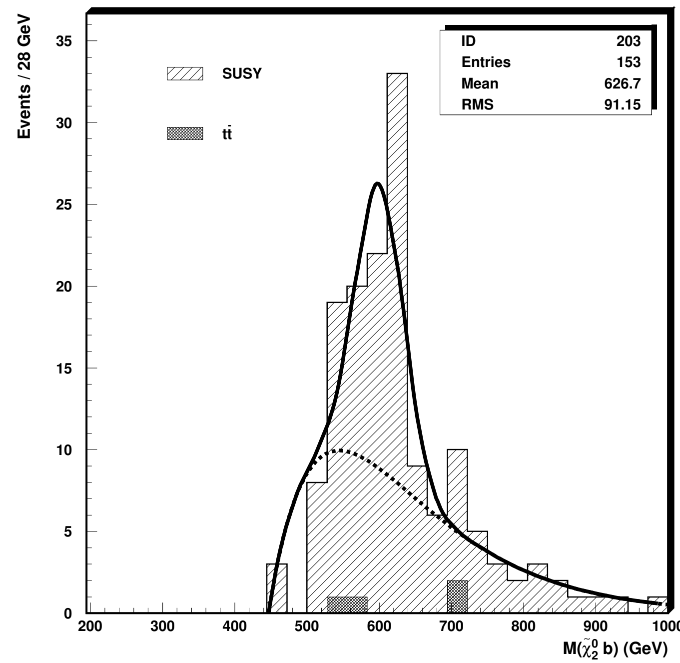
• still some regions where only h is visible

• some prospects to cover part of this region with Higgs decay in SUSY particles

LHC will have a great shot at Higgs Physics.

In some cases, one can reconstruct decay chains.

ex: $\tilde{g} \to \tilde{b}b$; $\tilde{b} \to b\tilde{\chi}_2^0$; $\tilde{\chi}_2^0 \to \tilde{\ell}_R^{\pm}\ell^{\mp}$; $\tilde{\ell}^{\pm} \to \ell^{\pm}\tilde{\chi}_1^0$;



Directly measure $M_{\tilde{b}}$ and $M_{\tilde{g}}$ to 10%

High $\tan\beta$ demands high luminosity.

If SUSY is there, depending on the signal, info about mass patterns will enable us to constrain models of SUSY breaking

SUSY after a high luminosity run

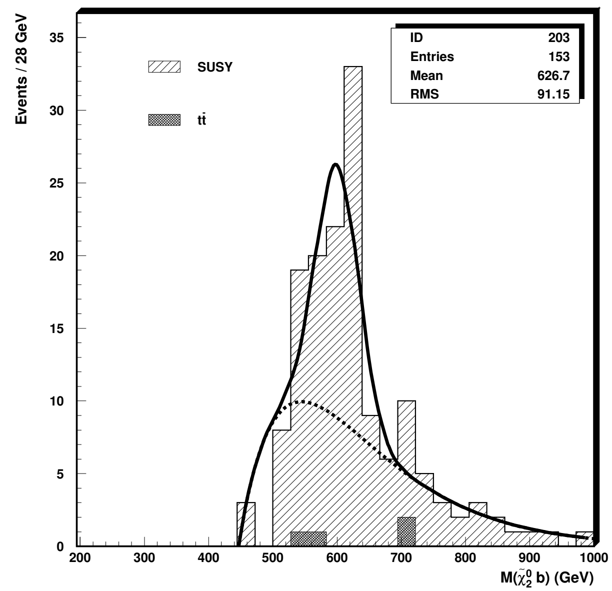
• estimation of SUSY mass scale, $M_{\rm SUSY}$, from the jets+$\not\!\!E_T$ signal

• $M_{\rm SUSY}^{\rm eff} = (M_{\rm SUSY} - M_{\tilde\chi}^2/M_{\rm SUSY})$
takes into account a heavy LSP – reduces the number and p_T of observed jets

• a precision of 10 (30)% can be obtained on $M_{\rm SUSY}^{\rm eff}$ after 100 fb^{-1}

– use correlation between $M_{\rm SUSY}^{\rm eff}$ and $\sigma_{\rm SUSY}$ to discriminate different models

In some cases, can reconstruct decay chains.
ex: $\tilde g \to \tilde b b$; $\tilde b \to b\tilde\chi_2^0$; $\tilde\chi_2^0 \to \tilde\ell_R^\pm \ell^\mp$; $\tilde\ell^\pm \to \ell^\pm \tilde\chi_1^0$;



Directly measure $M_{\tilde b}$ and $M_{\tilde g}$ to 10%
High $\tan\beta$ requires high luminosity.

If SUSY is there, depending on the signal, info about mass patterns will enable us to constrain models of SUSY breaking

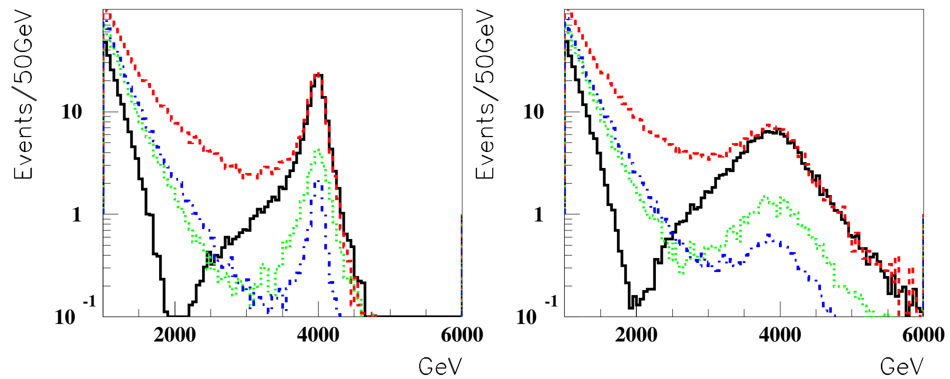
KK Excitations of Gauge Bosons

γ/Z excitations in TeV scale extra dimensions –

- detect peak in $\ell^+\ell^-$ invariant mass for $M_{\rm Pl}^{\rm fund} < 5.8$ TeV (100 fb^{-1})

no peak $\Longrightarrow M_{\rm Pl}^{\rm fund} > 12$ TeV (300 fb^{-1})

study lepton angular distributions $\Longrightarrow$ distinguish KK excitations & alternatives



$M_{e^+e^-}$ $M_{\mu^+\mu^-}$

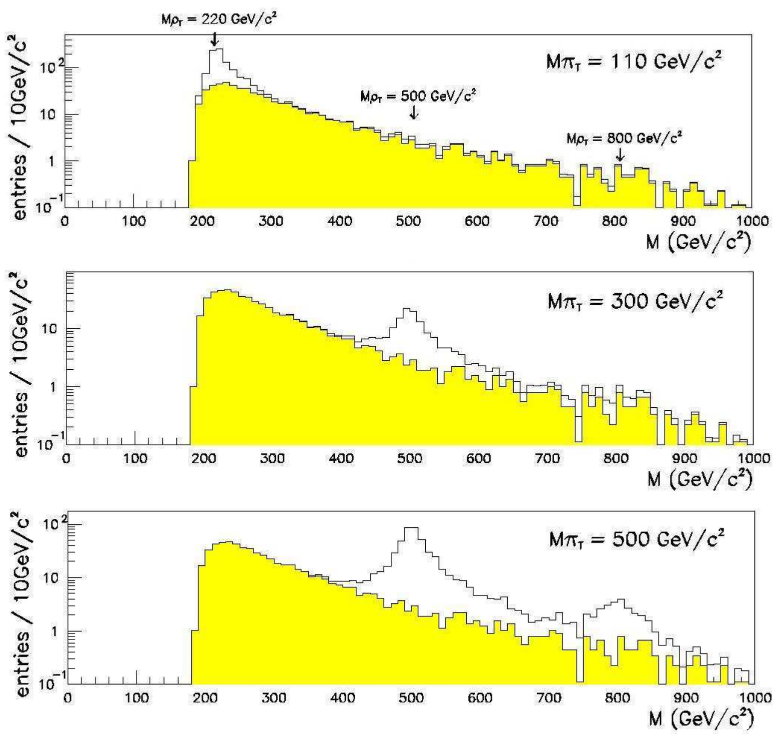
Strong Dynamics

– Technicolor-type models

$\Rightarrow$ detect ρ_T up to the TeV range

best channel:

$$\rho_T^\pm \to W^\pm Z \to \ell^\pm \nu \ell^+ \ell^-$$



ATLAS, 30 fb^{-1}

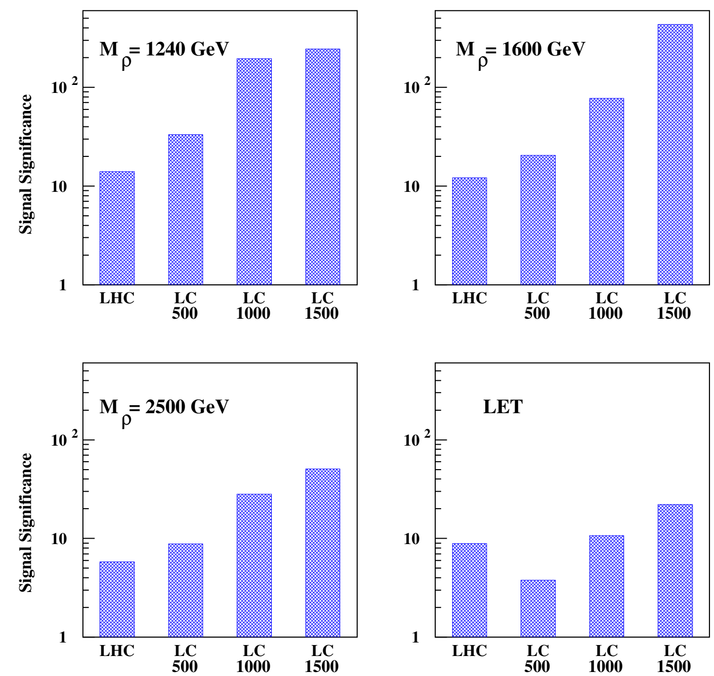
– Strongly Coupled Vector Boson Scattering

(strongly coupled resonances)

- LC $\longrightarrow e^+e^- \to \nu\bar{\nu}W^+W^-/ZZ$

  LHC, 300 fb^{-1}: bump in W^+W^- scattering

  (LET $\to$ enhancement in σ_{SM})



Latest ATLAS study shows sensitivity to longitudinal gauge vector boson scattering only for SLHC luminosities (~ 3000 fb^{-1})

Extra Dimensions

– emission of KK graviton tower states

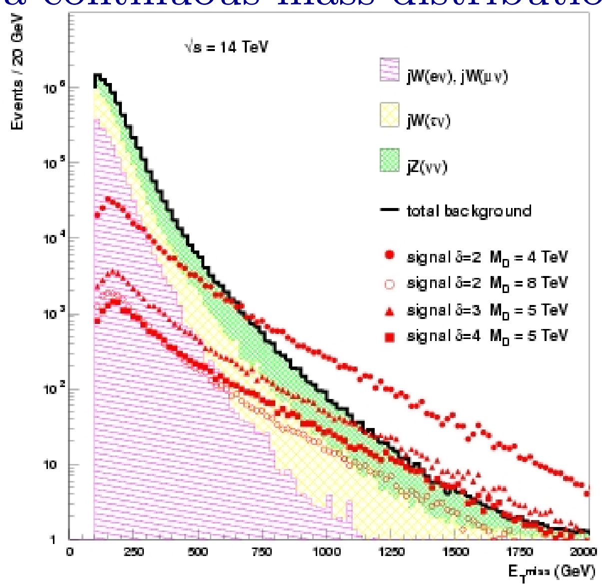
• $p\bar{p} \to g\, G_N \;\; (G_N \to \not{E}_T) \longrightarrow \text{jet}+\not{E}_T$

cross section summed over full KK towers

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

emitted graviton appears as

a continuous mass distribution



Discovery reach for

fundamental Planck scales

in the order of 5-10 TeV

(depending on d= 4,3,2)

Exciting Possibility:

TeV-scale Production of Black Holes

If $M_{BH} \gg M_{\rm Pl}^{\rm fund} \Longrightarrow$ BH prop. understood:

• two partons: $\sqrt{\hat{s}} \equiv M_{BH}$ moving in oppo. dir:

if impact parameter smaller than

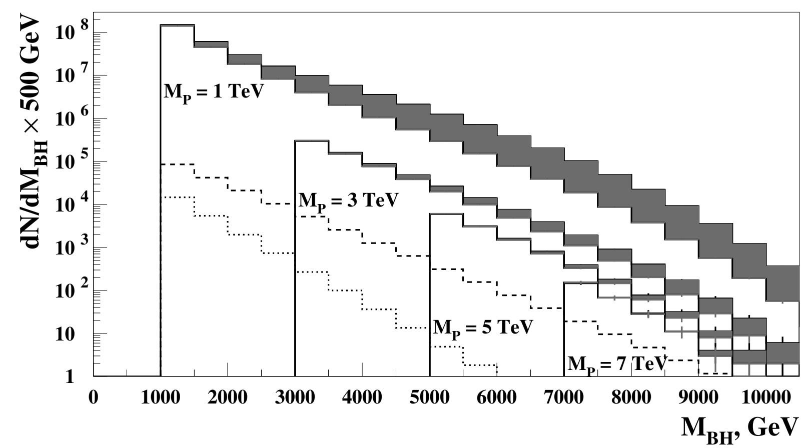
Schwarzschild radius $\Longrightarrow$ BH forms

• $M_{\rm Pl}^{\rm fund} \sim 1$ 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 & photons;

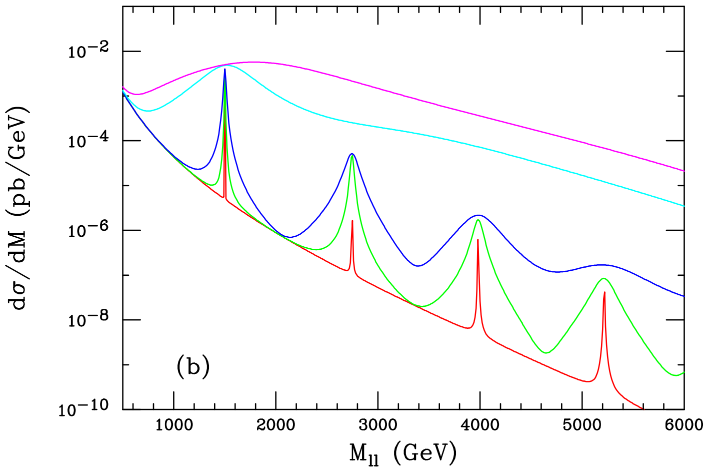


May be the first signal ofTeV-scale Quantum Gravity!

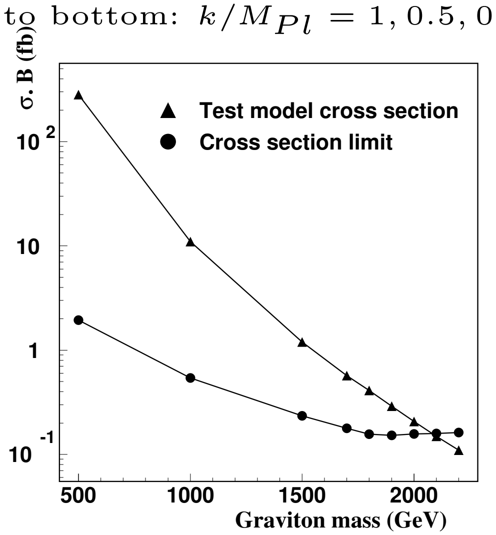
• Warped Extra Dimensions

Narrow Graviton Resonances

$pp \to G_N \to e^+e^-$



from top to bottom: $k/M_{Pl} = 1, 0.5, 0.1, 0.05, 0.01$



ATLAS, 100 fb^{-1}

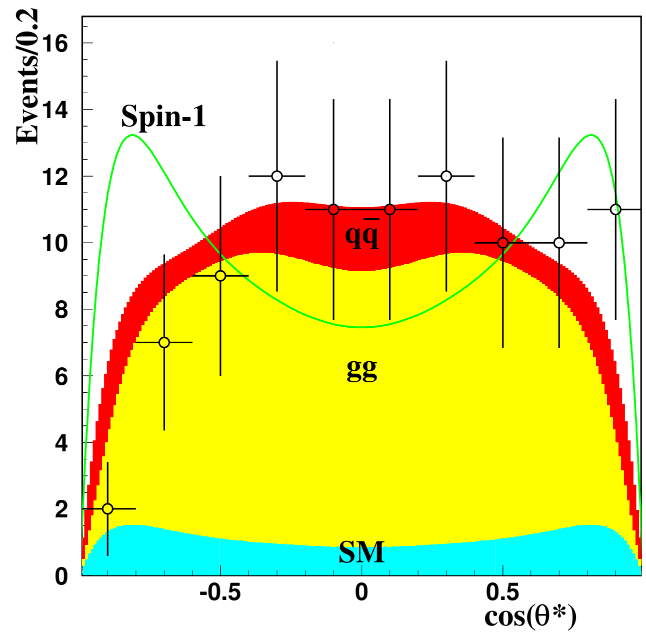
smallest detectable $\sigma \times Br$

Probe up to $M_{\tilde{g}} \sim 2100$ GeV

– to demonstrate that the resonance is a graviton and not another exotic object (spin-1 Z', ...)

$\Longrightarrow$ use angular distributions

to determine the spin of the resonance



construct a likelihood function to quantify angular distribution information

$\Longrightarrow$ spin can be determined with 90% CL for $M_G \sim 1700$ GeV (100 fb^{-1})

⋆ SM Fields in the Bulk

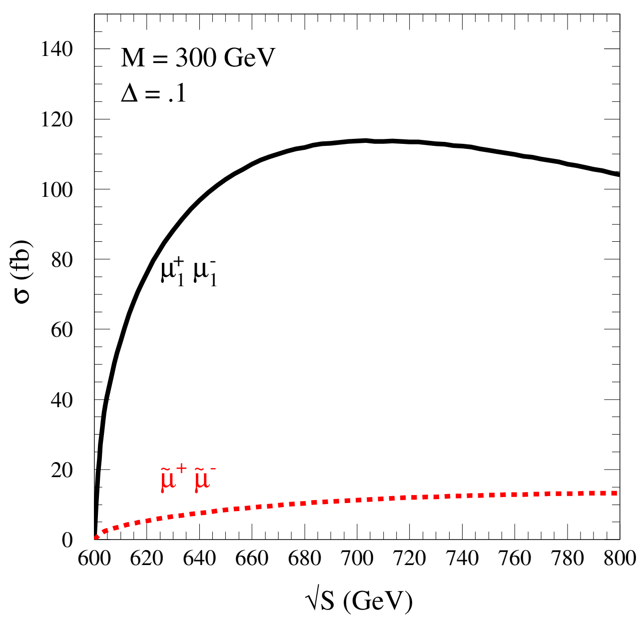
- Universal Extra Dimensions (UED)

Important property: Spectrum of 1st KK excitations can mimic a SUSY spectrum, though particles have different spin

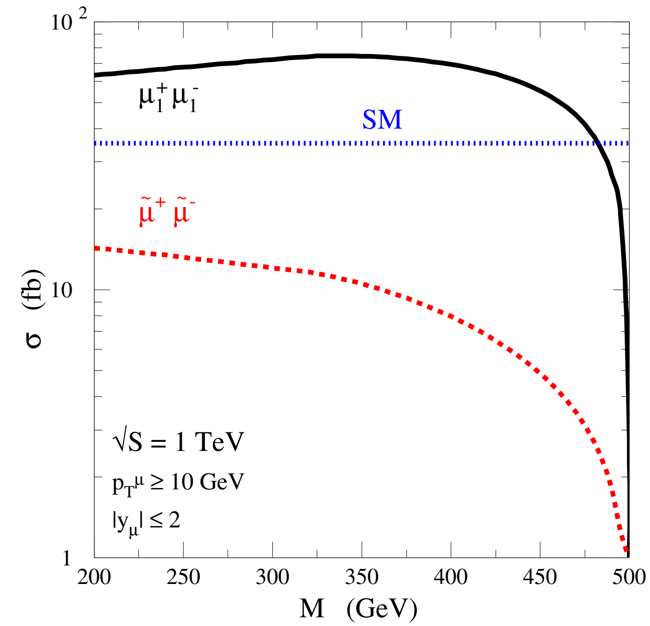
LC has the unique opportunity of distinguishing SUSY from UED: examine p- versus s-wave production

Comparison of cross section production for smuon pairs Vs first KK mode muon pairs.

(Tait et al. in prep.)



$e^+e^- \to \mu_1^+\mu_1^-(\tilde{\mu}^+\tilde{\mu}^-)$ as a function of $\sqrt{s}$, for $M = 300$ GeV.



$e^+e^- \to \mu_1^+\mu_1^-(\tilde{\mu}^+\tilde{\mu}^-)$, as a function of M, at a 1 TeV LC

Top Seesaw Model

• Extended SM fermion content: a vector pair of quarks, $\chi_{L,R}$ with the same quantum numbers as t_R

• The dynamics of the model yields mixing between the right & left-handed top & heavy quark components. $\Longrightarrow$ the left mixing has a direct influence on the interaction of the physical top with the weak bosons:

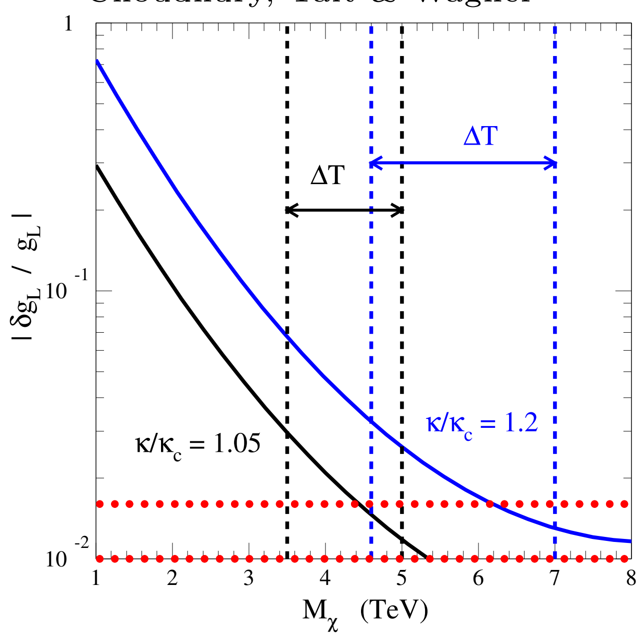
- Modification of left-handed top coupling with $s_L \simeq \mu_{t\chi}/m_{\chi\chi}$

$$\frac{\delta g_L}{g_L} = \frac{s_L^2}{1 - 4\sin^2\theta_W/3}.$$

$m_{\chi\chi} \longrightarrow$ heavy quark mass constrained by EW data $\longrightarrow$ 3.8–7 TeV

$\mu_{t\chi} \sim 700$ GeV to reproduce physical m_t

Choudhury, Tait & Wagner



• A LC can test the Top Seesaw model via accurate determination of top-vector boson couplings at the level of 1.5%.

• It can also measure directly the heavy Higgs associated to this model and hence determine a range of acceptable χ masses.