A Short Review of Supersymmetry and Extra Dimensions

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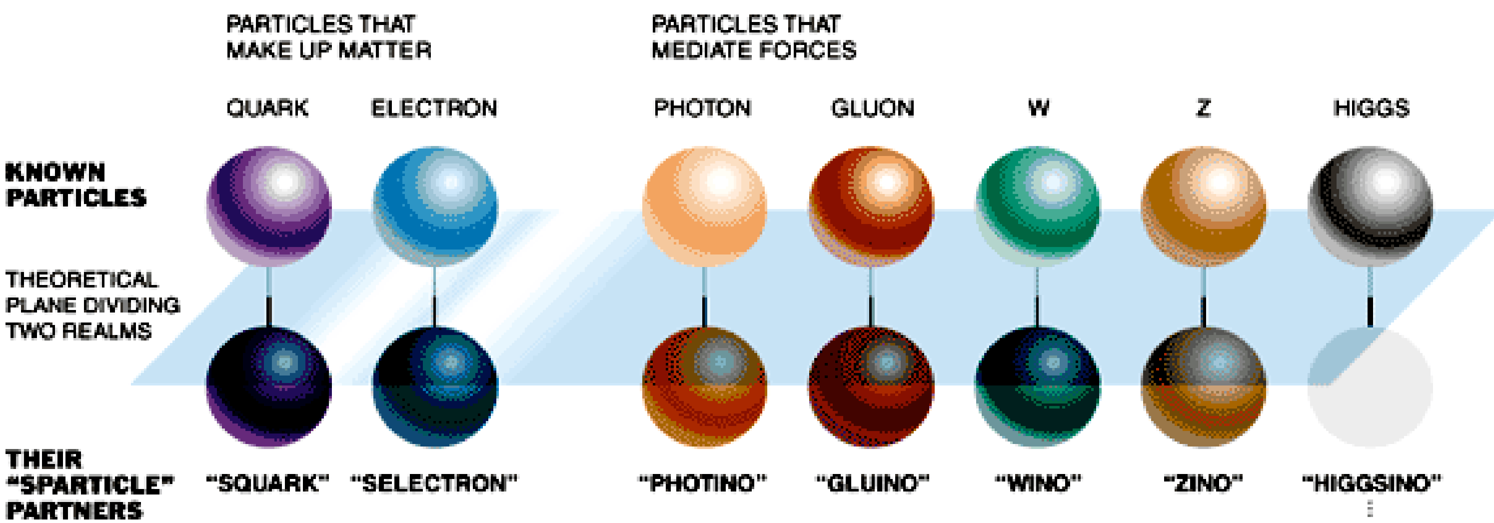
Physics Beyond the SM: Supersymmetry

fermions ⟷ **bosons**



Photino, Zino and Neutral Higgsino: Neutralinos

Charged Wino, charged Higgsino: Charginos

No new dimensionless couplings. Couplings of supersymmetric particles equal to couplings of Standard Model ones.
Two Higgs doublets necessary. Ratio of vacuum expectation values denoted by $\tan\beta$

Minimal Supersymmetric Standard Model

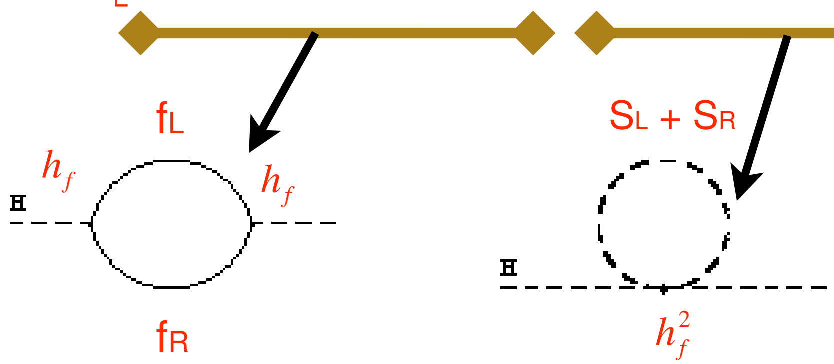
SM particle	SUSY partner	G_{SM}
$(\mathrm{S}=1/2)$	$(\mathrm{S}=0)$	
$Q=(t,b)_L$	$(\tilde{t},\tilde{b})_L$	(3,2,1/6)
$L=(\nu,l)_L$	$(\tilde{\nu},\tilde{l})_L$	(1,2,-1/2)
$U=\left(t^C\right)_L$	$\tilde{t}^*_R$	($\bar{3}$,1,-2/3)
$D=\left(b^C\right)_L$	$\tilde{b}^*_R$	($\bar{3}$,1,1/3)
$E=\left(l^C\right)_L$	$\tilde{l}^*_R$	(1,1,1)
$(\mathrm{S}=1)$	$(\mathrm{S}=1/2)$	
B_μ	$\tilde{B}$	(1,1,0)
W_μ	$\tilde{W}$	(1,3,0)
g_μ	$\tilde{g}$	(8,1,0)

Higgs Mass Parameter Corrections

Quadratic Divergent contributions:

One loop corrections to the Higgs mass parameter cancel if the couplings of scalars and fermions are equal to each other

$$\delta m_H^2 = \frac{N_C h_f^2}{16\pi^2}\left[-2\Lambda^2 + 3m_f^2\log\left(\frac{\Lambda^2}{m_f^2}\right) + 2\Lambda^2 - 2m_s^2\log\left(\frac{\Lambda^2}{m_s^2}\right)\right]$$



(If the masses proceed from the v.e.v. of H, there is another diagram that ensures also the cancellation of the log term. Observe that the fermion and scalar masses are the same in this case, equal to h_f v.)

Supersymmetry is a symmetry that ensures the equality of these couplings

The Higgs Sector : Two Higgs Doublets with opposite hypercharge

- Anomalies cancel automatically, since the fermions of the second Higgs superfield act as the vector mirrors of the ones of the first one.
- Use the second Higgs doublet to construct masses for the down quarks and leptons.

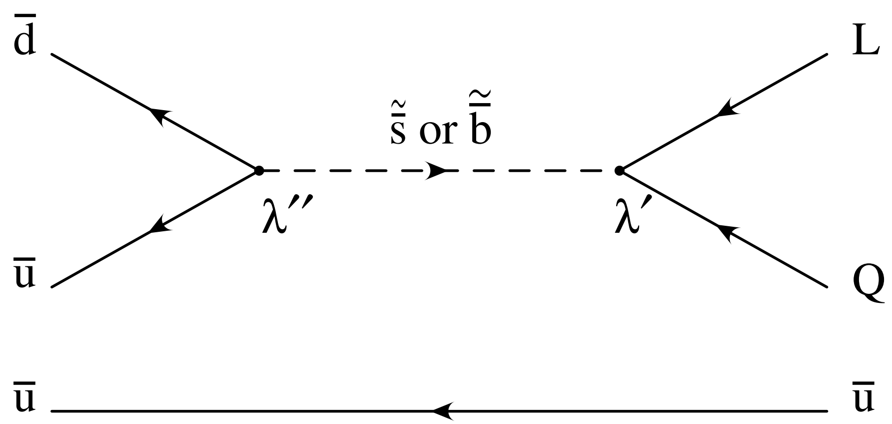
$$P[\Phi] = h_u QUH_2 + h_d QDH_1 + h_l LEH_1$$

- Once these two Higgs doublets are introduced, a mass term may be written

$$\delta P[\Phi] = \mu H_1 H_2$$

- μ is only renormalized by wave functions of H_1 and H_2.

Proton Decay



In Supersymmetry, Baryon and Lepton Number conservation is not guaranteed at the renormalizable level, making proton decay possible.

- Both lepton and baryon number violating couplings involved.
- Proton: Lightest baryon. Lighter fermions: Leptons

R-Parity

- A solution to the proton decay problem is to introduce a discrete symmetry, called R-Parity. In the language of component fields,

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

- All Standard Model particles have $R_P = 1$.
- All supersymmetric partners have $R_P = -1$.
- All interactions with odd number of supersymmetric particles, like the Yukawa couplings **inducing proton decay are forbidden.**
- Supersymmetric particles should be produced in pairs.
- The lightest supersymmetric particle is stable.
- Good dark matter candidate. Missing energy at colliders.

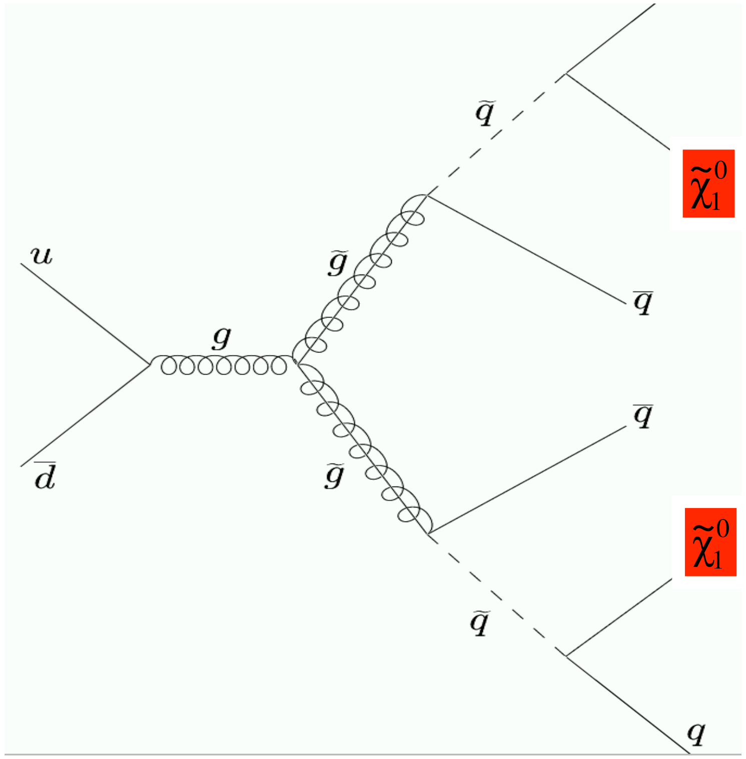
Preservation of R-Parity:

Supersymmetry at colliders

Gluino production and decay: Missing Energy Signature

Supersymmetric Particles tend to be heavier if they carry color charges.

Charge-less particles tend to be the lightest ones.



Possibility of observing DM candidate due to presence of color particles.

If just weakly interacting particles, DM observation at LHC would be difficult.

➢ **Lightest supersymmetric particle = Excellent Cold dark matter candidate.**

Soft Supersymmetry Breaking Terms

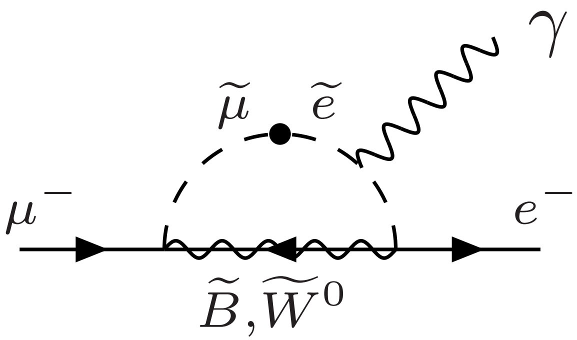
$$\mathcal{L}_{soft} = -\frac{1}{2}(M_3\tilde{g}\tilde{g} + M_2\tilde{W}\tilde{W} + M_1\tilde{B}\tilde{B})$$
$$-m_Q^2\tilde{Q}^\dagger\tilde{Q} - m_U^2\tilde{U}^\dagger\tilde{U} - m_D^2\tilde{D}^\dagger\tilde{D} - m_L^2\tilde{L}^\dagger\tilde{L} - m_E^2\tilde{E}^\dagger\tilde{E}$$
$$-m_{H_1}^2 H_1^* H_1 - m_{H_2}^2 H_2^* H_2 - (\mu B H_1 H_2 + cc.)$$
$$-(A_u h_u \tilde{U}\tilde{Q}H_2 + A_d h_d \tilde{D}\tilde{Q}H_1 + A_l h_l \tilde{E}\tilde{L}H_1) + c.c.$$

All gauge invariant mass terms allowed in the theory. These terms do not affect the condition of cancellation of quadratic divergences, which depend on equality of couplings and not masses.

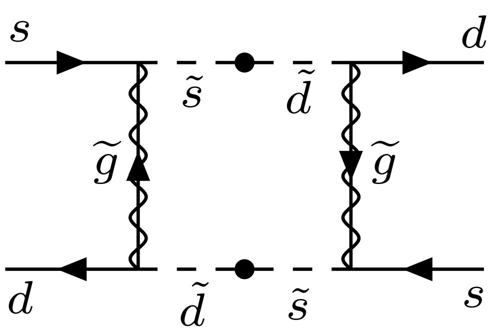
All terms can be, in principle, matrices in flavor space, inducing mixing between squarks and sleptons of different flavors : Plenty of new, free parameters. Is there a guiding principle ?

SUSY Breaking and Flavour Changing Neutral Currents

- Two particularly constraining examples of flavor changing neutral currents induced by off-diagonal soft supersymmetry breaking parameters
- Contribution to the mixing in the Kaon sector, as well as to the rate of decay of a muon into an electron and a photon.
- While the second is in good agreement with the SM predictions, the first one has never been observed.
- Rate of these processes suppressed as a power of supersymmetric particle masses and they become negligible if relevant masses are heavier than 10 TeV



$\mu^- \to e^- \gamma$



$K^0 \leftrightarrow \overline{K^0}$

Low Energy Supersymmetry requires reduced flavor dependence. Preference towards flavor independent SUSY breaking schemes.

Minimal Supergravity Model

- The simplest possibility is the case in which all scalar masses are **universal** and flavor independent at a certain scale.
- In the minimal supergravity model, for example, one assumes that all scalars acquire a common mass m_0^2 at the Grand Unification scale
- In addition, since gauginos belong to the same adjoint representation, one assumes that all gauginos acquire a common mass $M_{1/2}$ at the GUT scale
- These two parameters must be complemented with a value of the parameter μ at M_{GUT}.
- For the Higgs sector it is assumed that $m_i^2 = |\mu|^2 + m_{H_i}^2$, with $m_{H_i} = m_0$.
- Finally, all the trilinear parameters A_{ijk} are assume to take a common value A_0.

Renormalization Group Evolution

- One interesting thing is that the gaugino masses evolve in the same way as the gauge couplings:
  $d(M_i/\alpha_i)/dt = 0,\qquad \frac{dM_i}{dt} = -b_i \alpha_i M_i/4\pi,\qquad d\alpha_i/dt = -b_i \alpha_i^2/4\pi$
  $t \equiv \ln(M_{GUT}^2/Q^2)$
- The scalar fields masses evolve in a more complicated way.
  $4\pi dm_i^2/dt = +C_a^i 4M_a^2 \alpha_a - |Y_{ijk}|^2[(m_i^2 + m_j^2 + m_k^2 + A_{ijk}^2)]/4\pi$
- There is a positive contribution coming from the gaugino masses and a negative contribution proportional to the Yukawa couplings.
- Colored particles are affected by positive, strongly coupled corrections and tend to be the heaviest ones.
- Weakly interacting particles tend to be lighter, particular those affected by large Yukawas.
- There scalar field H_2 is both weakly interacting and couples with the top quark Yukawa. Its mass naturally becomes negative.

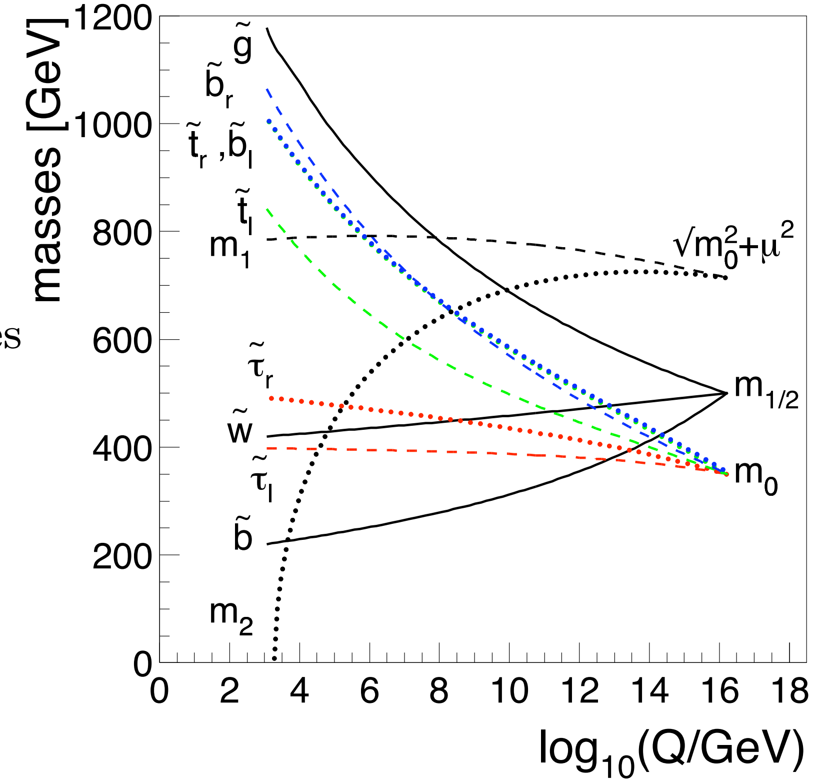
⋆ Solve hierarchy/naturalness problem by having $\Delta m^2 \simeq \mathcal{O}(v^2)$

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

⋆ EWSB is radiatively generated

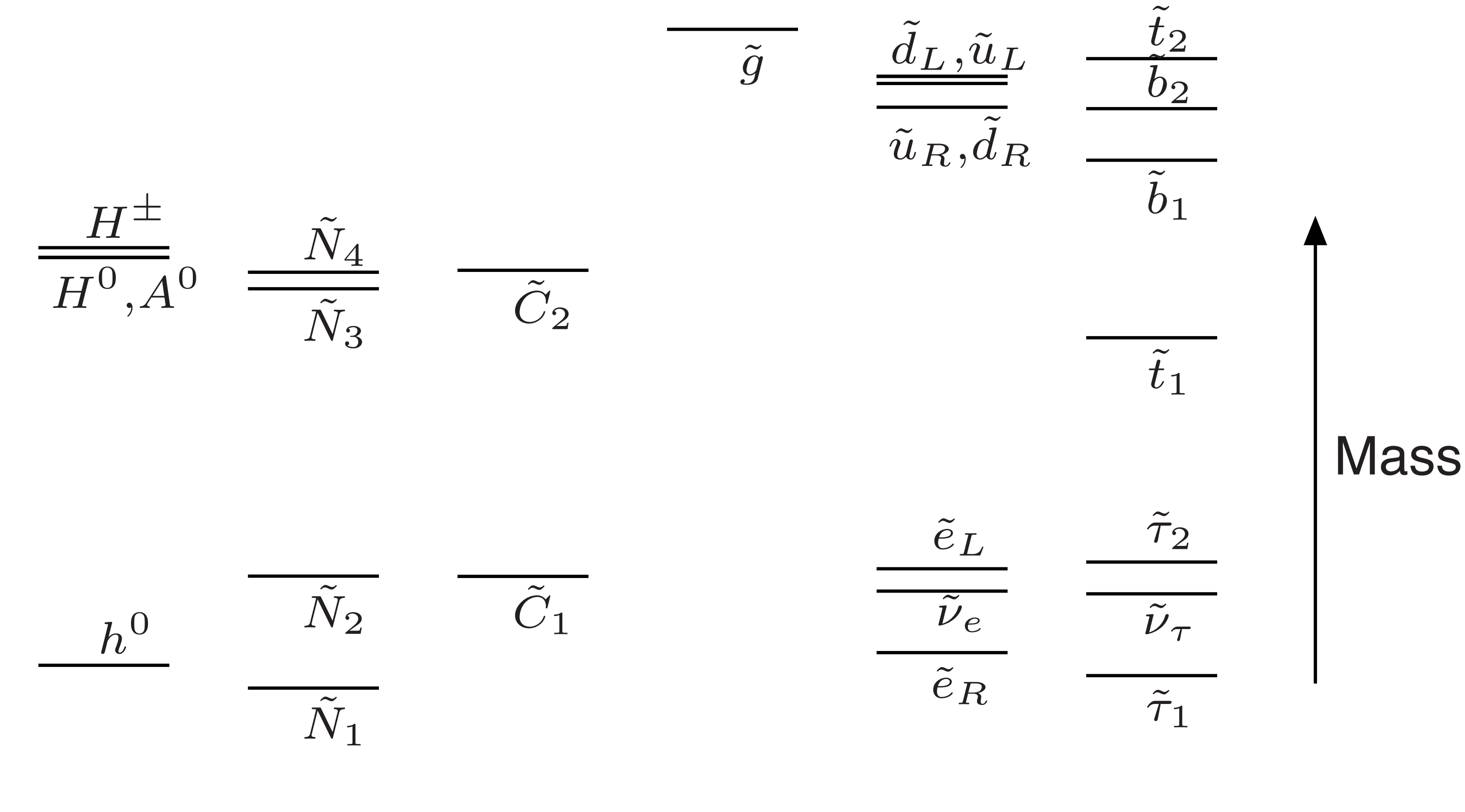
In the evolution of masses from high energy scales
$\longrightarrow$ a negative Higgs mass parameter is induced
via radiative corrections

$\Longrightarrow$ *important top quark effects!*



Resulting MSSM Spectrum:

Typical for MSUGRA models with $M_{\frac{1}{2}} > m_0$.



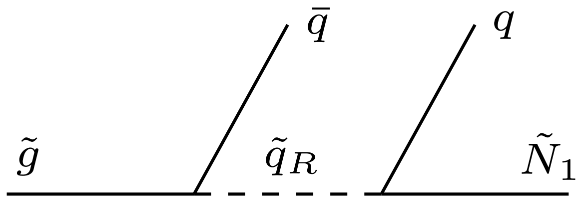
Neutralino is the LSP.
The lightest squark is the stop.

The Gluino is the heaviest sparticle
The lightest slepton is the stau.

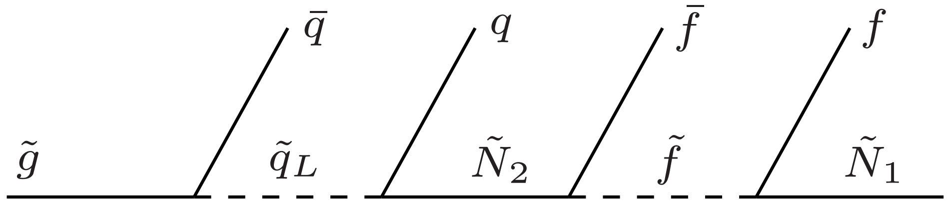
Gluino Decays:

The gluino can only decay through squarks, either on-shell (if allowed) or virtual.

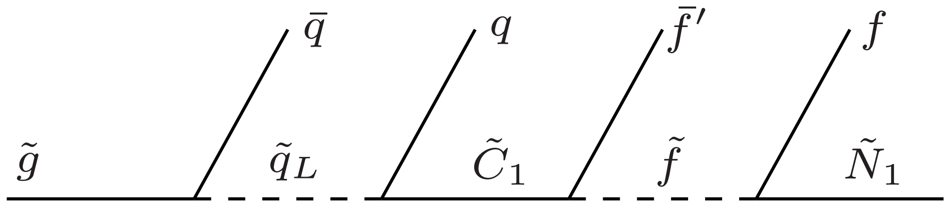
For example:



$jj + \not{E}$ or $t\bar{t} + \not{E}$



$jjjj + \not{E}$ or $t\bar{t}jj + \not{E}$ or
$jj\ell^+\ell^- + \not{E}$



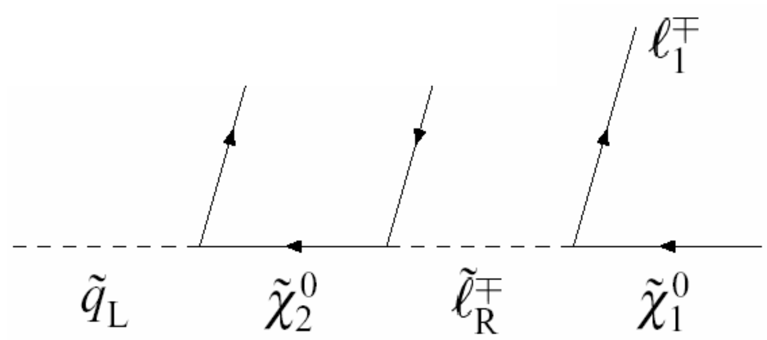
$jjjj + \not{E}$ or $t\bar{t}jj + \not{E}$ or
$jj\ell^\pm + \not{E}$

Because $m_{\tilde{t}_1} \ll$ other squark masses, top quarks can appear in these decays.

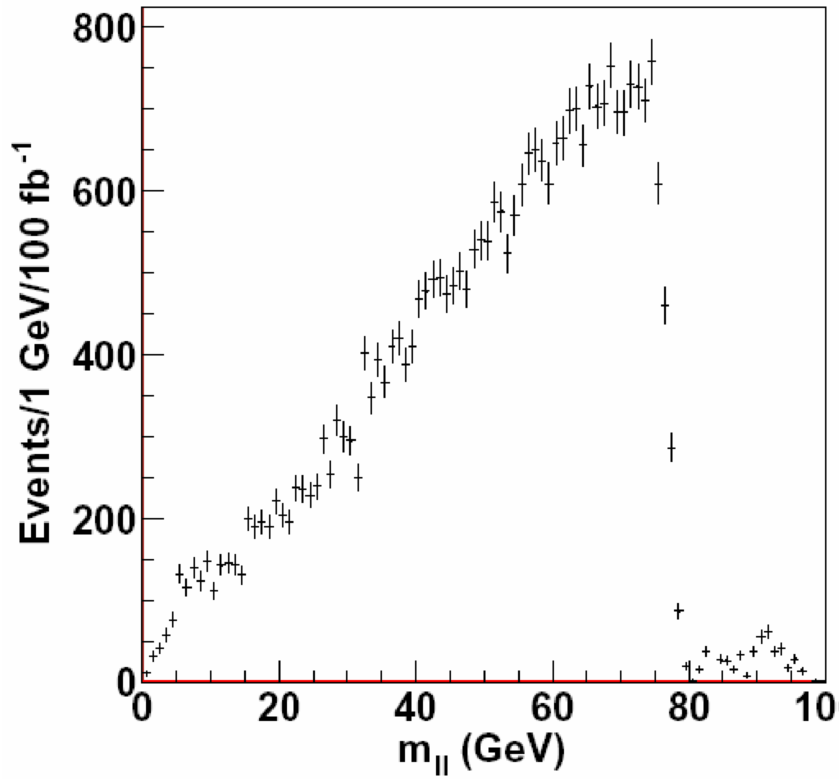
The possible signatures of gluinos and squarks are numerous and complicated
due to cascade decays

Searches at the LHC

By studying the kinematic distributions of the decay products one can determine the masses of produced particles, including the LSP.



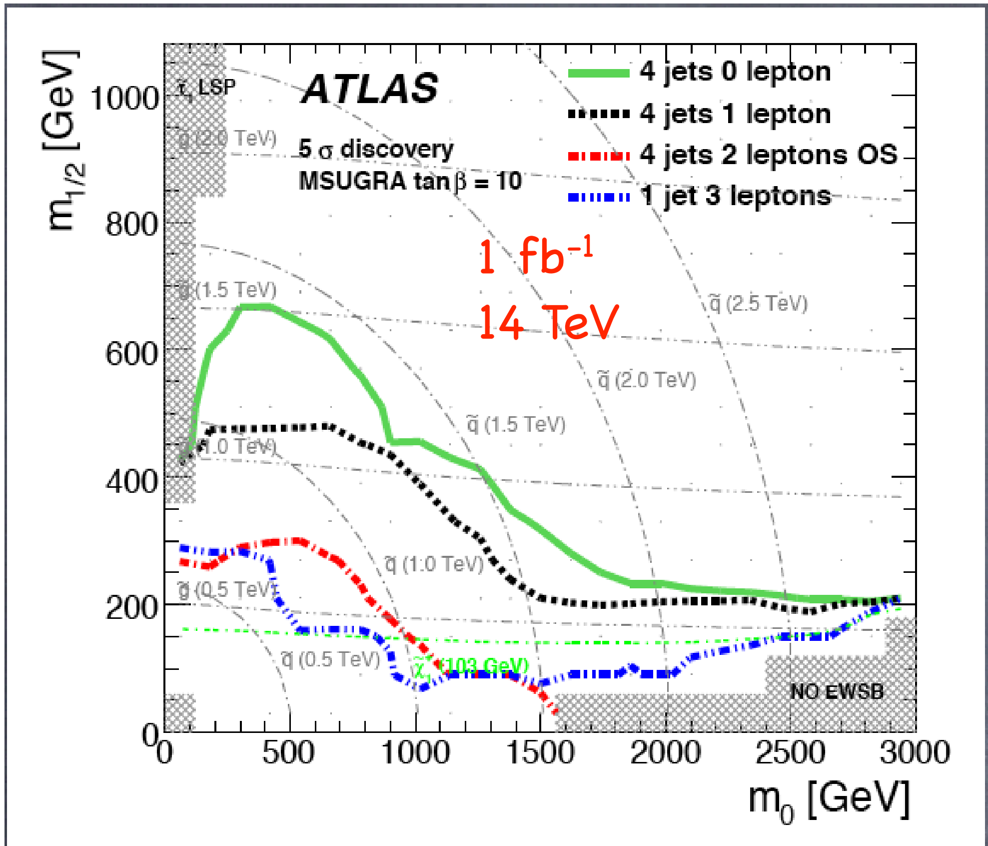
$$
\begin{aligned}
(m^2_{ll})^{\rm edge} &= \frac{(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{l}_R})(m^2_{\tilde{l}_R} - m^2_{\tilde{\chi}^0_1})}{m^2_{\tilde{l}_R}} \\
(m^2_{qll})^{\rm edge} &= \frac{(m^2_{\tilde{q}_L} - m^2_{\tilde{\chi}^0_2})(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{\chi}^0_1})}{m^2_{\tilde{\chi}^0_2}} \\
(m^2_{ql})^{\rm edge}_{\rm min} &= \frac{(m^2_{\tilde{q}_L} - m^2_{\tilde{\chi}^0_2})(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{l}_R})}{m^2_{\tilde{\chi}^0_2}} \\
(m^2_{ql})^{\rm edge}_{\rm max} &= \frac{(m^2_{\tilde{q}_L} - m^2_{\tilde{\chi}^0_2})(m^2_{\tilde{l}_R} - m^2_{\tilde{\chi}^0_1})}{m^2_{\tilde{l}_R}} \\
(m^2_{qll})^{\rm thres} &= [(m^2_{\tilde{q}_L} + m^2_{\tilde{\chi}^0_2})(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{l}_R})(m^2_{\tilde{l}_R} - m^2_{\tilde{\chi}^0_1}) \\
&\quad -(m^2_{\tilde{q}_L} - m^2_{\tilde{\chi}^0_2})\sqrt{(m^2_{\tilde{\chi}^0_2} + m^2_{\tilde{l}_R})^2(m^2_{\tilde{l}_R} + m^2_{\tilde{\chi}^0_1})^2 - 16 m^2_{\tilde{\chi}^0_2} m^4_{\tilde{l}_R} m^2_{\tilde{\chi}^0_1}} \\
&\quad +2m^2_{\tilde{l}_R}(m^2_{\tilde{q}_L} - m^2_{\tilde{\chi}^0_2})(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{\chi}^0_1})]/(4m^2_{\tilde{l}_R} m^2_{\tilde{\chi}^0_2})
\end{aligned}
$$

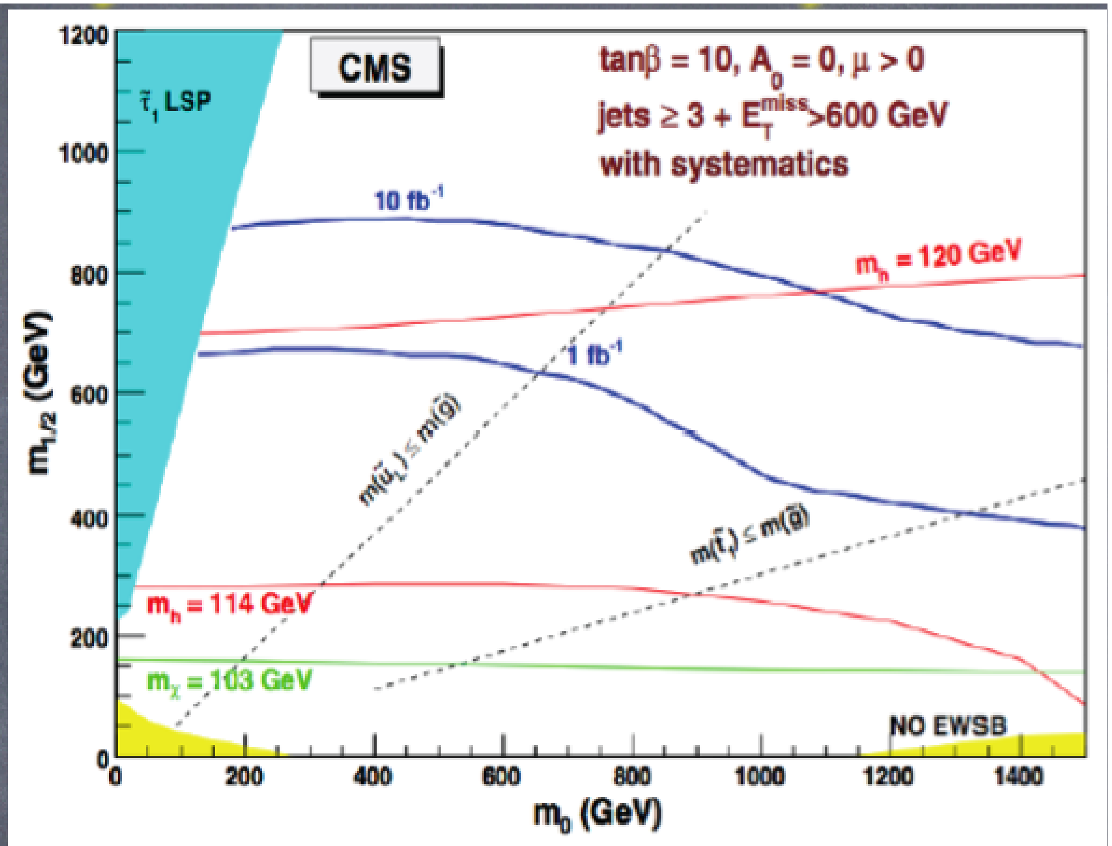


Weiglein et al. (2004)

SUSY LHC Reach at 14 TeV and 1/fb

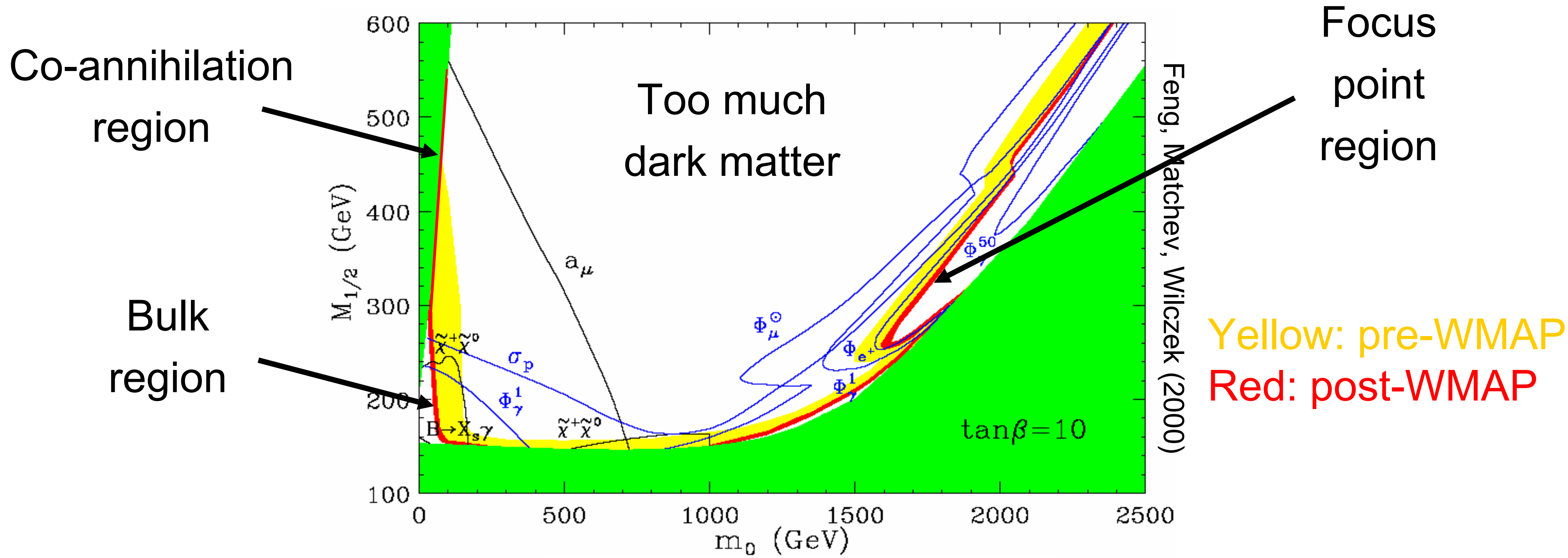
Squark and Gluino Masses up to 1.5 TeV





Dark Matter density strongly restricts viable models:

-- CMSSM example --



Ellis, Olive et al., Baer, Balazs et al

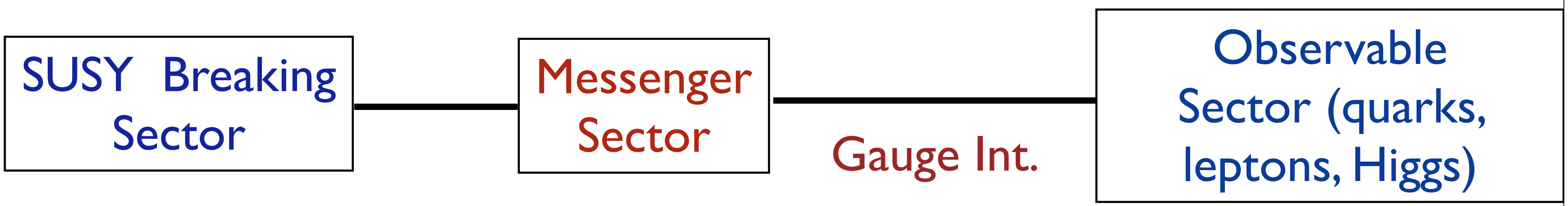
If stops, as required by electroweak baryogenesis, are very light, can contribute to coannihilation channels $m_{\tilde{\chi}_1^0} < m_{\tilde{t}} < m_{top}$

EWBG facilitates agreement with DM relic density

Carena, Balazs, Menon, Morrissey, C.W.'05

Gauge Mediated SUSY Breaking

- Supersymmetry breaking is transmitted to the observable sector via (flavor blind) gauge interactions



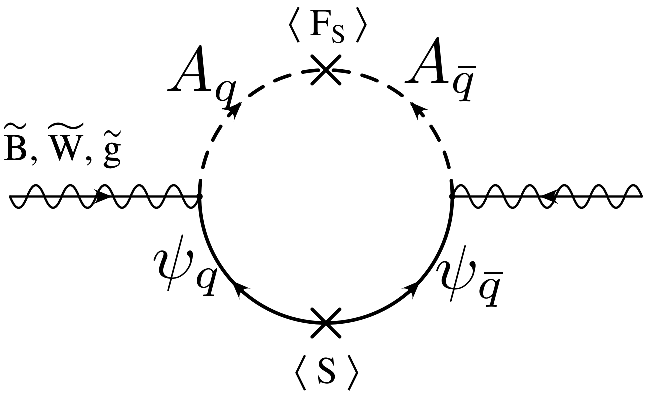
- Messenger sector in complete representations of SU(5) and vector-like.

- Minimal model: One $(5, \bar{5}) \equiv (3, 2) + (\bar{3}, \bar{2})$

$$W = \lambda \; S \; 3 \; \bar{3} + \gamma \; S \; 2 \; \bar{2}, \qquad < S >= S + F_S \theta^2,$$

with S a singlet field parametrizing SUSY breaking and the messenger mass

Integrating the messenger sector gives mass to gauginos at one-loop

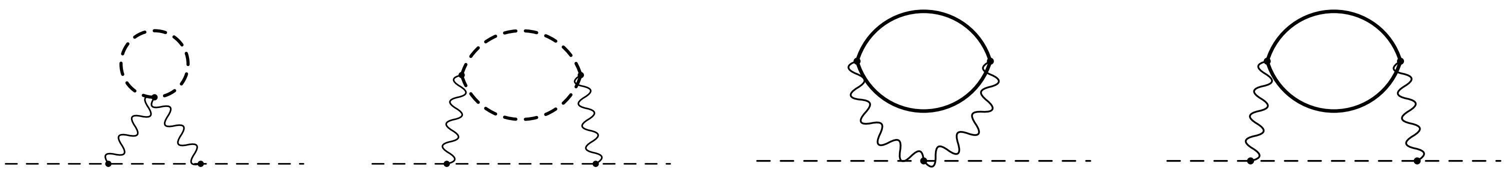


$$M_a = \frac{\alpha_a}{4\pi}\Lambda, \qquad \text{where} \qquad \Lambda \equiv \frac{\langle F_S \rangle}{\langle S \rangle}.$$

Gauge bosons do not get contributions since they are protected by gauge invariance ==> successful SUSY breakdown

Scalar superpartner masses are generated at two-loops

$$m^2_{A_i} = 2\Lambda^2 \left[\left(\frac{\alpha_3}{4\pi} \right)^2 C_3^{A_i} + \left(\frac{\alpha_2}{4\pi} \right)^2 C_2^{A_i} + \left(\frac{\alpha_1}{4\pi} \right)^2 C_1^{A_i} \right]$$



Minimal GMSB model can be generalized by putting N copies of the messenger sector. All expressions above multiplied by N

Spectrum of Sparticles (Minimal Gauge Mediation)

- Gaugino masses fulfill the standard unification relations,

$$M_i \propto \frac{\alpha_i}{4\pi}\frac{F_S}{S}, \qquad \frac{M_i}{M_j} = \frac{\alpha_i}{\alpha_j}$$

- Scalar masses at the messenger scale are also governed by their color structure. For instance,

$$m_{\tilde{q},H} \propto \frac{\alpha_{3,2}}{4\pi}\frac{F_S}{S},$$

- This implies that, independently of the messenger scale, there are large negative corrections to the Higgs mass parameter, triggering EWSB
- The requirement of a weak scale spectrum demands

$$\Lambda \equiv \frac{F_S}{S} = \mathcal{O}(10^5 \text{ GeV})$$

- The scale of SUSY breaking has important consequences, for instance it determines the gravitino mass and interactions (and therefore the nature of the LSP). Lightest superpartner tends to be a Bino.

The Gravitino

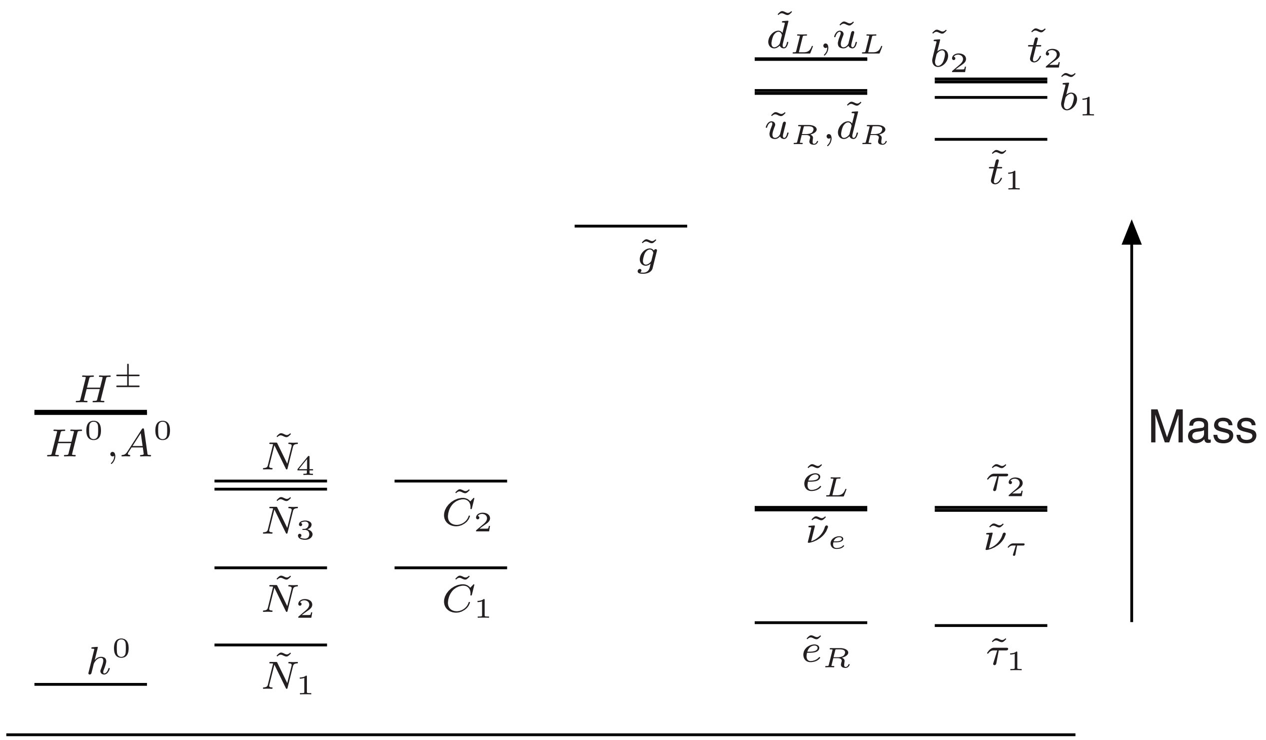
- When standard symmetries are broken spontaneously, a massless **Goldstone** boson appears for every broken generator.
- If the symmetry is local, these bosons are absorbed into the longitudinal components of the gauge bosons, which become massive.
- The same is true in supersymmetry. But now, a massless fermion appears, called the Goldstino.
- In the case of local supersymmetry, this Goldstino is absorbed into the Gravitino, which acquires mass $m_{\tilde{G}} = F/M_{Pl}$, with F the order parameter of SUSY breaking.
- The coupling of the Goldstino (gravitino) to matter is proportional to $1/F = 1/(m_{\tilde{G}} M_{Pl})$, and couples particles with their superpartners.

If the messenger scale is significanly lower than the Planck scale, the gravitino is the LSP !

$$m_{\tilde{G}} = F/M_{Pl} \ll \quad m_{\rm soft} \sim \frac{\alpha_a}{4\pi} \frac{\langle F \rangle}{M_{\rm mess}}$$

A sample sparticle mass spectrum for Minimal GMSB

with $N = 1$, $\Lambda = 150$ TeV, $M_{\rm mess} = 300$ TeV, $\tan\beta = 15$, sign(μ) = +1



The NLSP is a neutralino, which can decay to the nearly massless Goldstino/gravitino by: $\tilde{N}_1 \to \gamma \tilde{G}$. This decay can be prompt, or with a macroscopic decay length.

Interesting: The NLSP does not need to be neutral, can be the stau/slepton

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

$$m_{\tilde{G}} \sim \frac{F}{M_{Pl}} \simeq 10^{-6} - 10^{-9}\text{GeV}$$

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

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

- Signatures: The NLSP (Standard SUSY particle) decays

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

$\star$ NLSP can have prompt decays:

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

$\star$ 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)

Important remarks

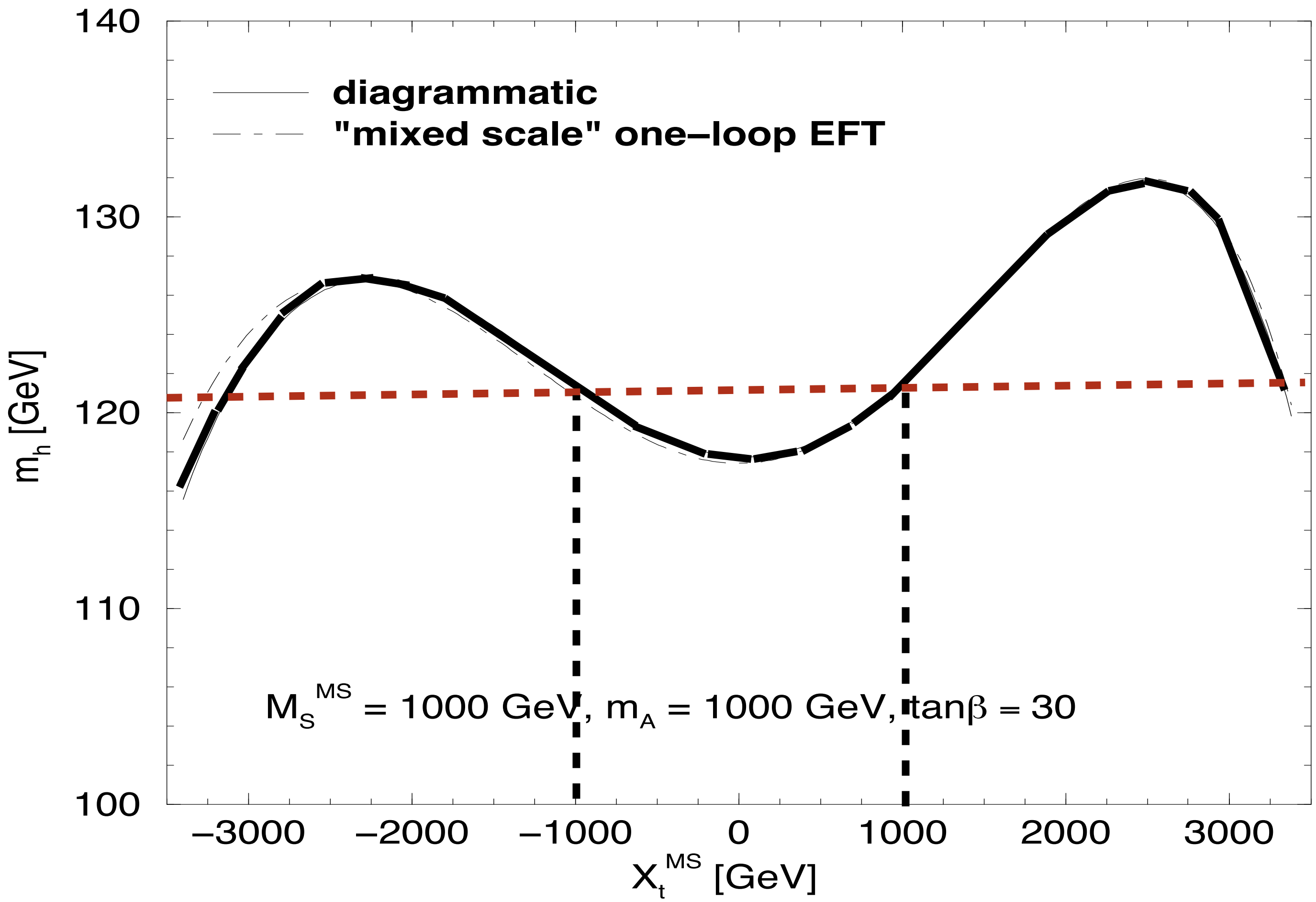
- I have presented only some simple, representative models. By no means should the particularly predictions of these models be considered general.
- For instance, the relation between the gaugino masses may be different from the one presented above, leading to different phenomenology. Anomaly mediation, in which the gaugino masses are proportional to the beta functions is an example.
- There may also be extended gauge symmetries that can affect the dynamics, particle content and RG evolution of parameters, as well as extra chiral fields, for instance singlets. An example will be presented below.
- The exact dynamics at the weak scale and the origin and nature of supersymmetry breaking is still unknown. We expect experiments to guide us in that direction. Marcela Carena will discuss some of these subjects. Collider signatures will be presented later.

Standard Model-like Higgs Mass

Long list of two-loop computations: Carena, Degrassi, Ellis, Espinosa, Haber, Harlander, Heinemeyer, Hempfling, Hoang, Hollik, Hahn, Martin, Pilaftsis, Quiros, Ridolfi, Rzehak, Slavich, C.W., Weiglein, Zhang, Zwirner

Carena, Haber, Heinemeyer, Hollik, Weiglein, C.W.'00

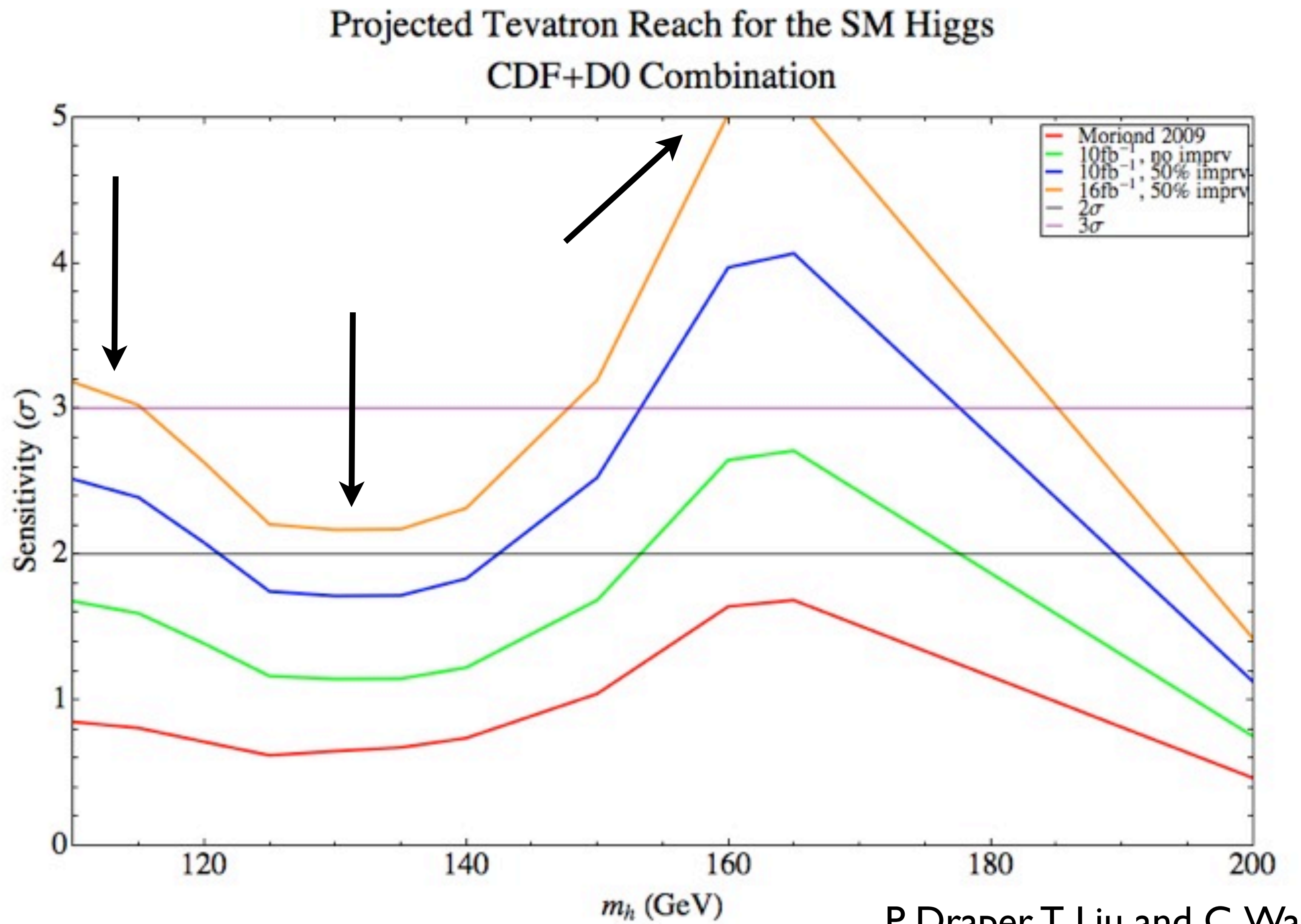
Leading m_t^4 approximation at $O(\alpha\,\alpha_s)$



For natural values of the stop mixing, the Higgs remains lighter than 120 GeV

$$X_t = A_t - \mu/\tan\beta, \qquad X_t = 0 : \text{ No mixing;} \qquad X_t = \sqrt{6} M_S : \text{ Max. Mixing}$$

Prospects for SM Higgs Searches at the Tevatron

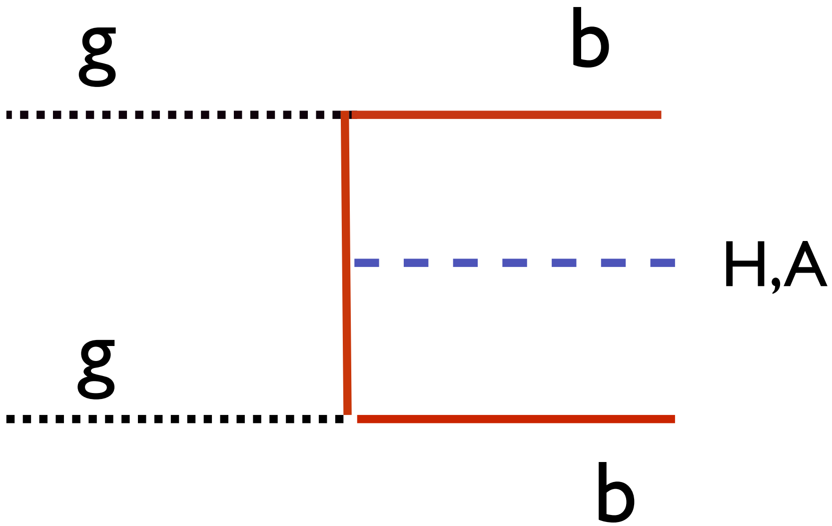


P. Draper, T. Liu and C. Wagner'09

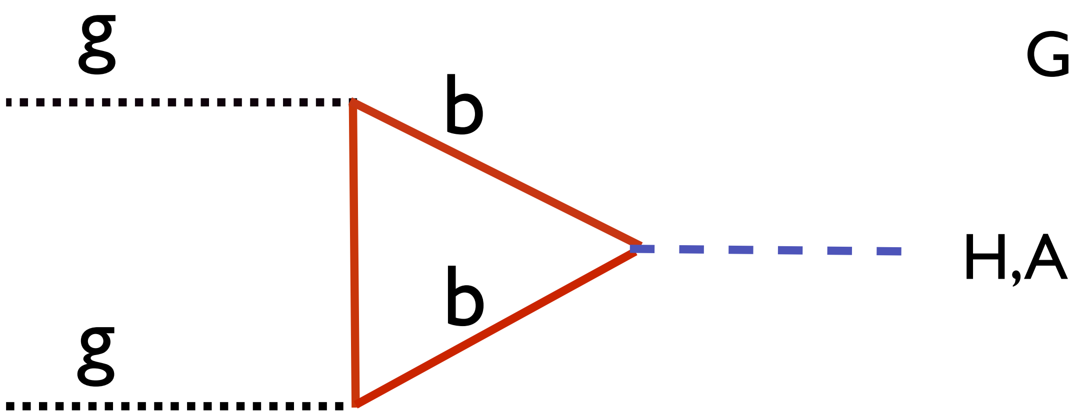
CDF+D0 multi-channel combination. WH->bb dominates at 115 GeV, gg->H->WW dominates at 160 GeV. Both contribute in intermediate range.

Non-Standard Higgs Production

QCD: S. Dawson, C.B. Jackson, L. Reina, D.Wackeroth, hep-ph/0603112



Associated Production

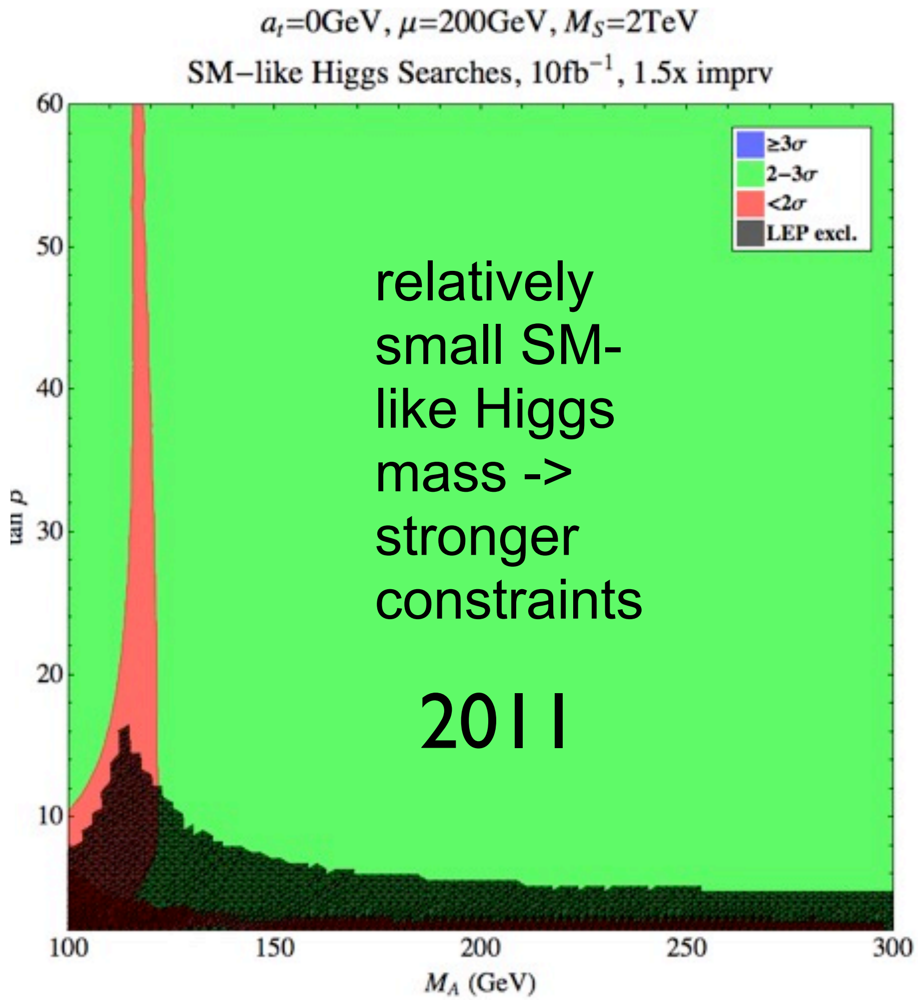


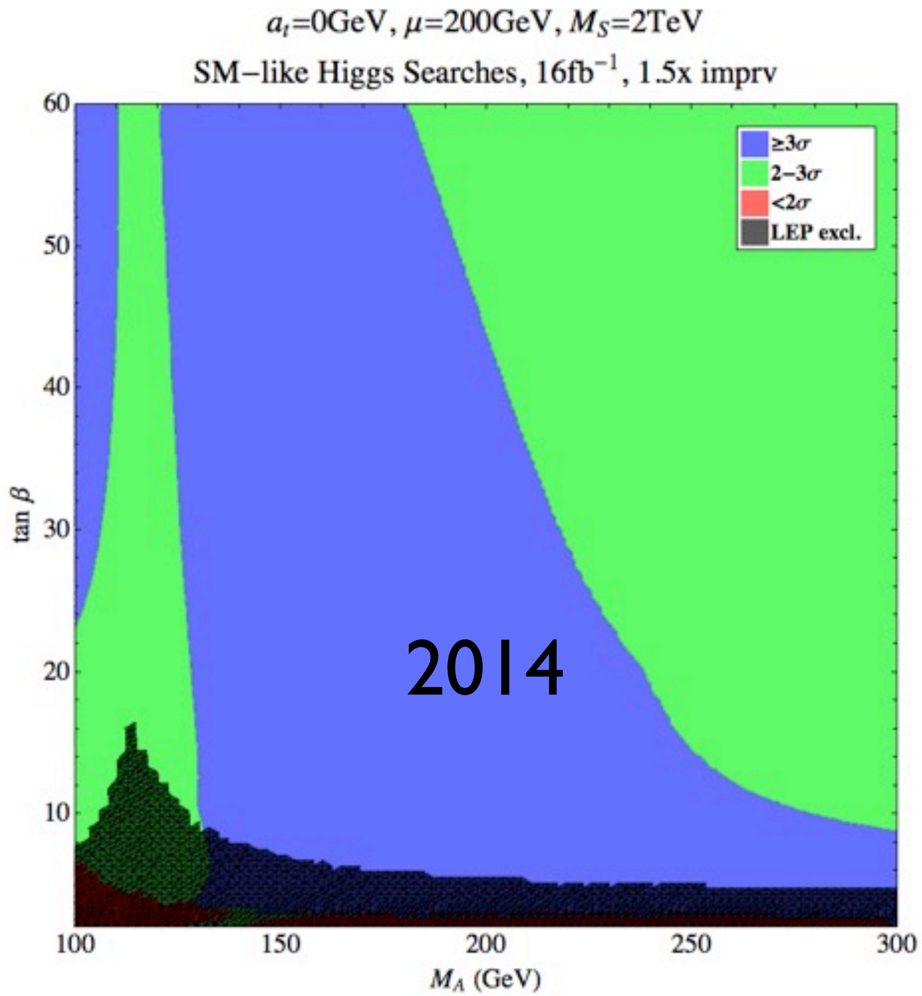
Gluon Fusion

$$g_{Abb} \simeq g_{Hbb} \simeq \frac{m_b \tan\beta}{(1+\Delta_b)v}, \qquad g_{A\tau\tau} \simeq g_{H\tau\tau} \simeq \frac{m_\tau \tan\beta}{v}$$

Minimal Mixing Scenario (SM-like Higgs mass below 120 GeV)

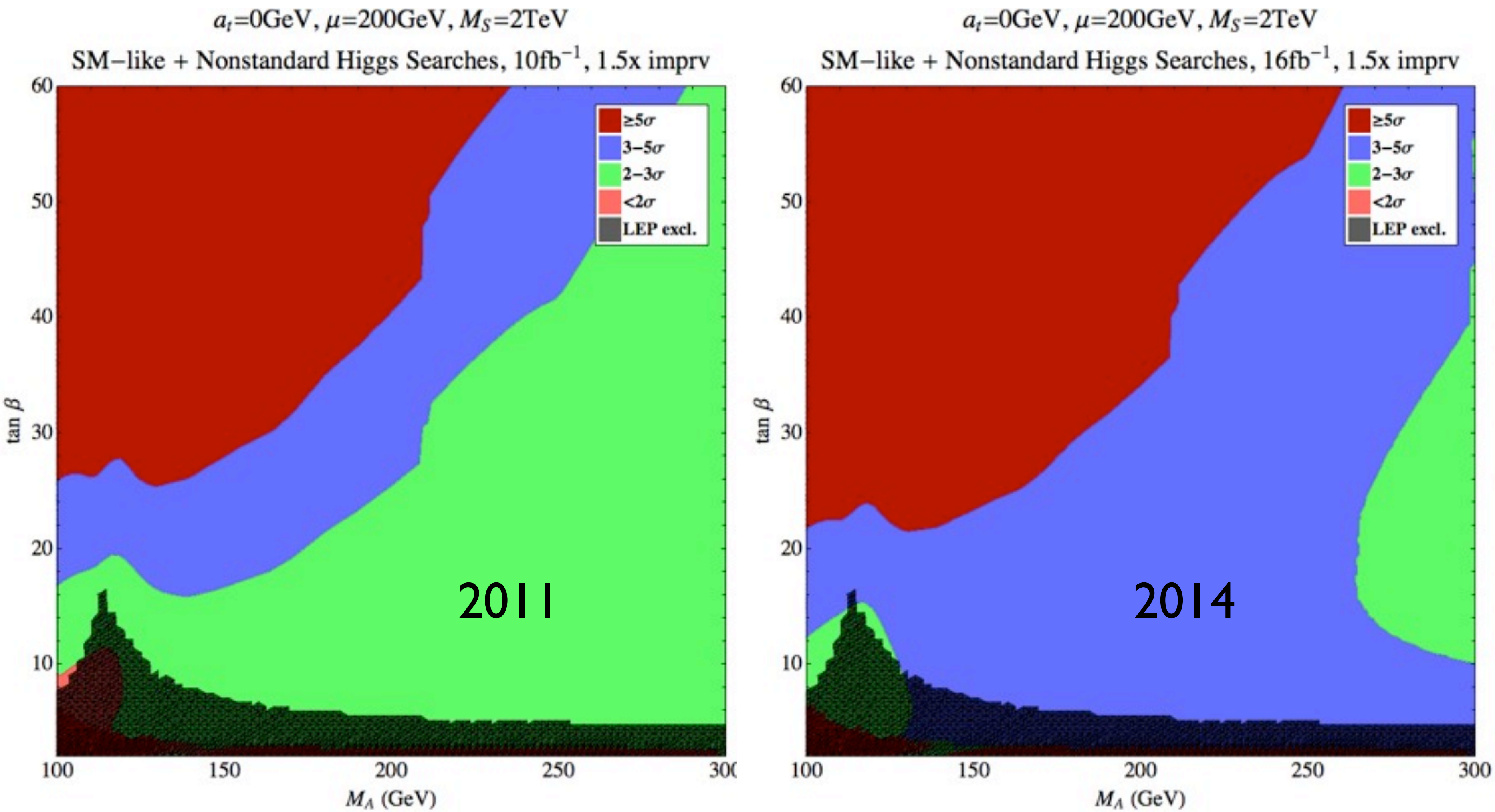
P. Draper, T. Liu and C.W. ’09 + M. Carena’10





Even with only SM channels and 2011 run, 2 sigma sensitivity is achieved in most parameter space. Evidence may be achieved with further running.

Combination with Non-Standard Higgs channels



Combination enlarges the region where evidence may be achieved in a considerable way

Singlet Extensions of the MSSM

- Models in which the mu-term is forbidden by some symmetry but include singlets with couplings

$$P[\Phi] = \lambda S H_1 H_2$$

may lead to a natural explanation of the origin of mu.

Since S is a singlet, its mass is driven naturally to small values by Yukawa interactions, leading to a v.e.v. that generates the mu-term.

They don't spoil unification and they can lead to an increase of the SM-like Higgs boson mass

$$m_h^2 = M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \text{loop corr.}$$

They also include an additional CP-even and CP-odd Higgs bosons. The CP-odd component may become light in models in which trilinear soft breaking terms of the singlet are suppressed (Dobrescu et al., Dermisek et al)

Such light scalars would couple to the SM-like Higgs boson and may induce additional, exotic decays. Neutralinos are also light in certain examples (nMSSM) inducing invisible decays of the SM-like Higgs (Menon, Morrissey, C.W.)

Phenomenological Properties of Extra Dimensions

Extra Dimensions

- Extra dimensional scenarios can address some of these open questions
- I will talk about three possible implementations:
- Large extra dimensions: Only gravity propagate into them. They solve the hierarchy problem by lowering the fundamental Planck scale
- Universal Extra Dimensions: All fields propagate into them. The compactification radius should be at least of the order of the (inverse) TeV scale, in order to avoid phenomenological problems
- Warped extra dimensions: Non-trivial extra dimensional metric. All fundamental parameters are of the order of the Planck scale. Weak scale is obtained by exponentially small warp factor.

Large Extra Dimensions

Lowering the Planck Scale

- Idea: We live in a four dimensional wall, but there are extra dimensions and only gravity can penetrate into them.
- Problem: If gravity can penetrate intro the extra dimensions, Newton law will be modified

$$\vec{F} = \frac{m_1 m_2 \hat{r}}{\left(M_{Pl}^{\rm fund}\right)^{2+d} r^{2+d}}$$

- $M_{Pl}^{\rm fund}$ = Fundamental Planck Scale. Behaviour valid for $r \ll R$. For $r \gg R$, instead

$$\vec{F} = \frac{m_1 m_2 \hat{r}}{\left(M_{Pl}^{\rm fund}\right)^{2+d} r^2 R^d}$$

- Hence,

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

Arkani-Hamed, Dimopoulos, Dvali'98

Size of flat Extra Dimensions

- Let's assume that the fundamental Planck scale is of the order of 1 TeV, to solve the hierarchy problem.

$$M_{Pl}^2 = (1\text{TeV})^{2+d} R^d$$

- Then, the value of R is given by

$$R = 10^{32/d} 10^{-17} \text{cm}$$

- For $d = 1$ we get $R = 10^{15}$ cm $\rightarrow$ Excluded
- For $d = 2$ we get $R \simeq 1$ mm $\rightarrow$ Would demand somewhat larger fundamental Planck scale
- For $d = 6$ we get $R \simeq 10^{-12}$ cm.
- The scenario is allowed for $d \geq 2$

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

Flat case ($k = 0$) : 4-D effective theory:

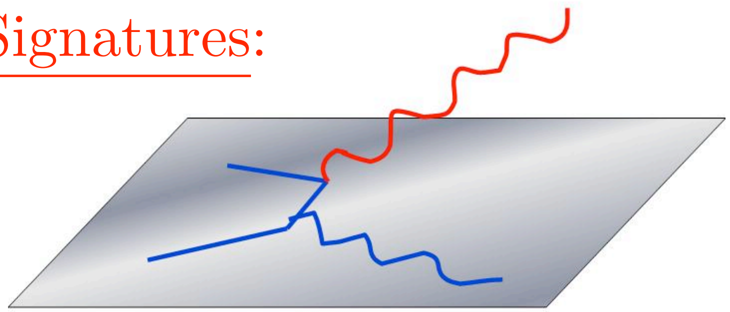
SM particles + gravitons + tower of new particles:

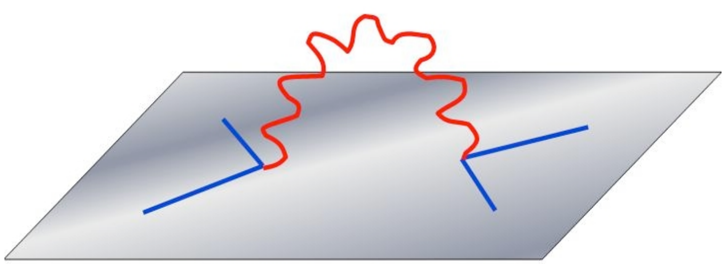
Kaluza Klein (KK) excited states with the same quantum numbers as the graviton and/or the SM particles

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

imbalance between measured energies and momentum in 4-D

Signatures:





- Coupling of gravitons to matter with $1/M_{Pl}$ strength
  $R^{-1} \simeq 10^{-2}$ 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 distribu

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

Han, Lykken, Zhang ; Giudice, Rattazzi, Wells'99

Effective Cross Sections

- Let us consider the emission of gravitons in the collision of electrons and positrons (protons and antiprotons).
- Final state will be γ + Missing energy (jets + Missing Energy)
- Each graviton extremely weakly coupled but cross section will be given by the sum of the individual KK graviton production cross section, scaling with N_{KK}.
- Again, the effective gravitational constant appears and we get

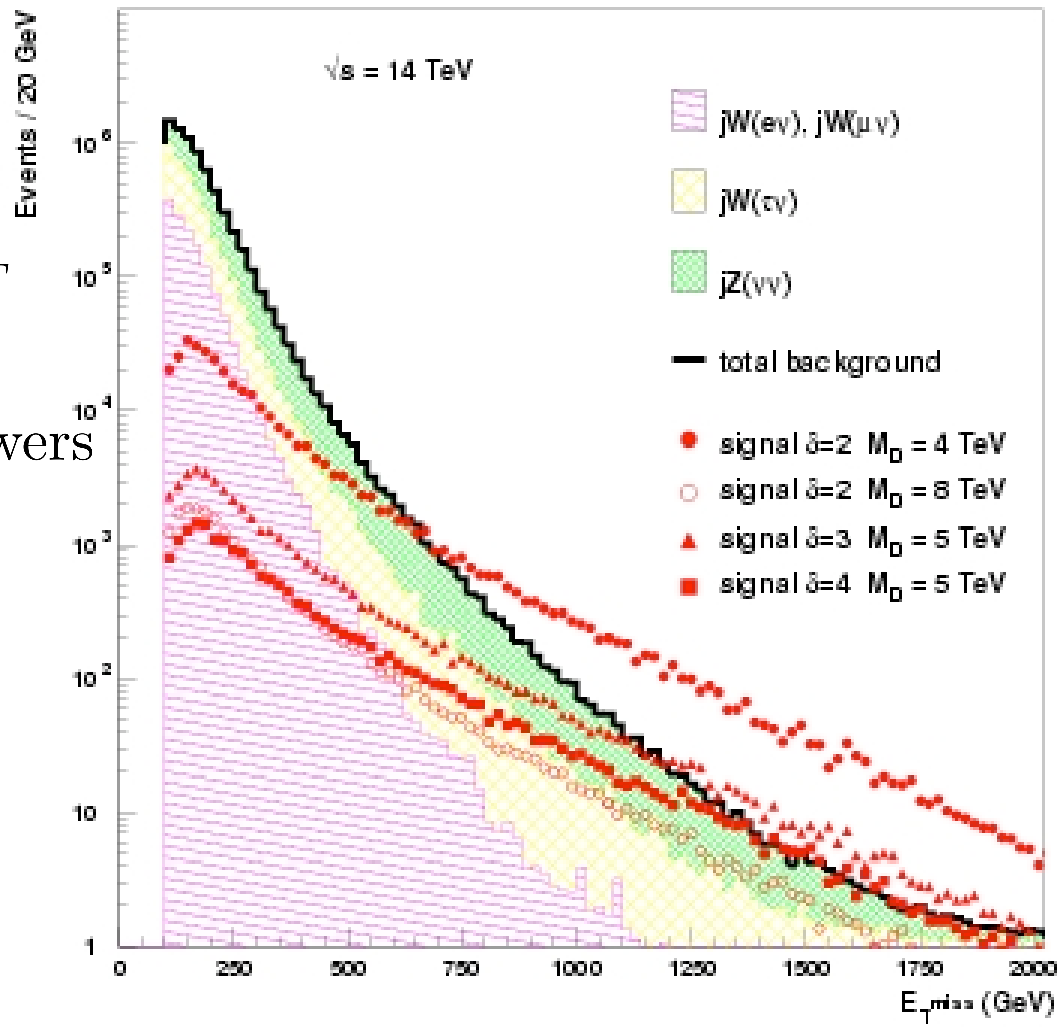
$$\sigma \simeq \frac{1}{M_{Pl}^2}(E^d R^d)$$

$$\sigma \simeq \frac{1}{s}\left(\frac{\sqrt{s}}{M_{Pl}^{\text{fund}}}\right)^{2+d}$$

Flat 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)

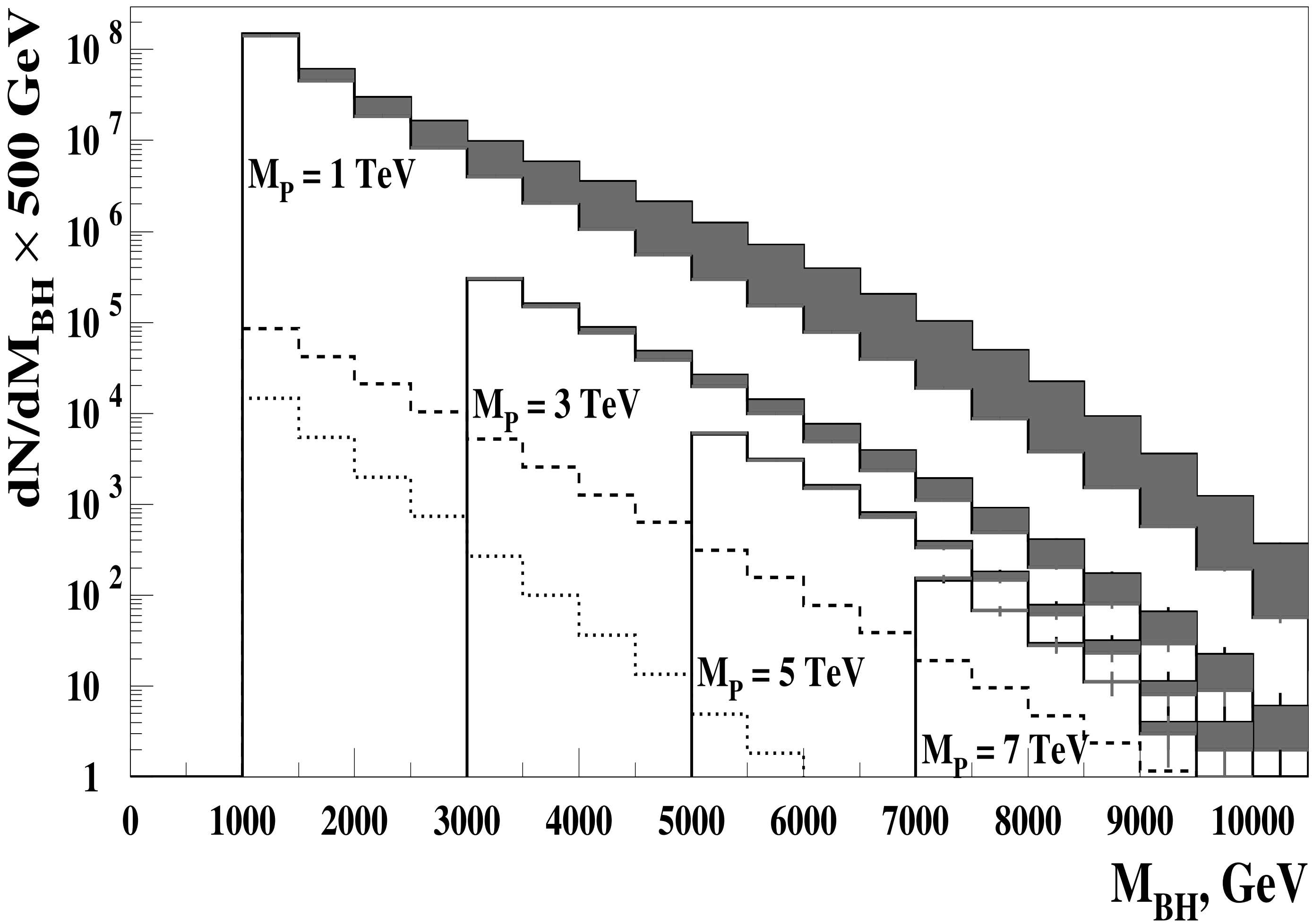
Black Hole Production ?

- Two partons with center of mass energy $\sqrt{s} = M_{BH}$, with $M_{BH} > M_{Pl}^{fund}$ collide with a impact parameter that may be smaller than the Schwarzschild radius.

$$R_S \simeq \frac{1}{M_{Pl}^{fund}} \left(\frac{M_{BH}}{M_{Pl}^{fund}} \right)^{\frac{1}{d+1}}$$

- Under these conditions, a blackhole may form
- If $M_{Pl}^{fund} \simeq 1$ TeV $\rightarrow$ more than 10^7 BH per year at the LHC (assuming that a black hole will be formed whenever two partons have energies above M_{Pl}^{fund}).
- Decay dictaded by blackhole radiation, with a temperature of order $1/R_S$. Signal is a spray of SM particles in equal abundances: hard leptons and photons.
- At LHC, limited space for trans-Planckian region and quantum gravity.

Black Hole production at the LHC



Dimopoulos and Lansberg; Thomas and Giddings '01

Sensitivity up to $M_{Pl}^{\rm fund} \simeq 5 - 10$ TeV for 100 fb^{-1}.

Universal Extra Dimensions

Universal Extra Dimensions

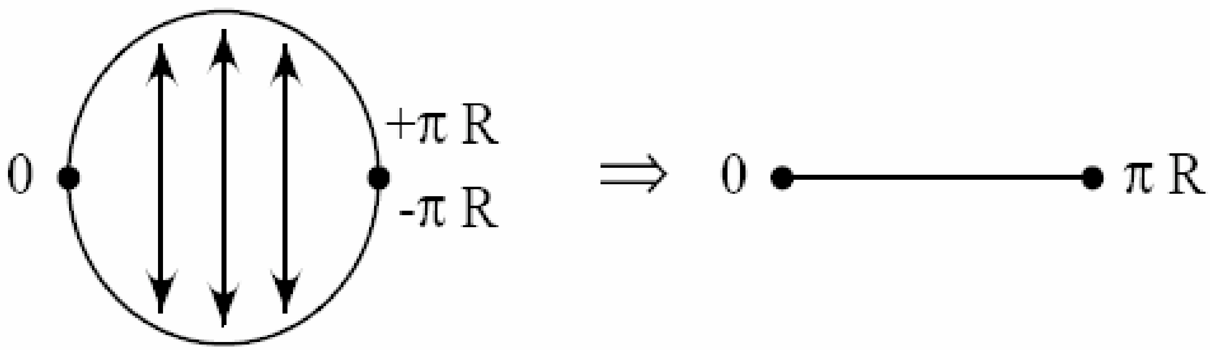
Appelquist, Cheng, Dobrescu'01

Most natural extension of four dimensional description:

- All particles live in all dimensions, including quarks, leptons, Higgs bosons, gauge bosons and gravitons.
- Universality implies a translational invariance along the extra dimension, and thus conservation of the component of momentum in the that direction.
- This implies that a KK state with $n \neq 0$, carrying non-zero momentum in the extra dimension, cannot decay into standard, zero modes.
- The lightest KK particle is stable, being a good dark matter candidate.

Orbifold

- Massless 5d spinors have 4 components, leading to mirror fermions at low energies.
- If extra dimension is compactified in a circle, no standard chiral theory may be obtained.
- Chiral theories may be obtained by invoking orbifold boundary conditions, projecting out unwanted degrees of freedom.
- Fold the extra dimension, identifying y with $-y$

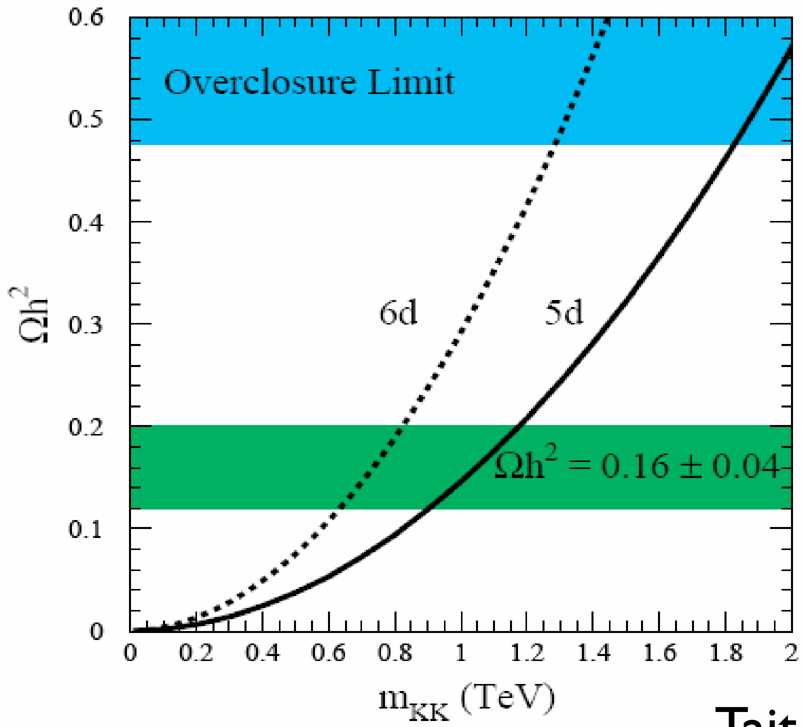


- Boundary Conditions:
  $\Psi(-y) = \gamma_5 \Psi(y)$
  $V_\mu(-y) = V_\mu(y), V_5(-y) = -V_5(y)$

KK Parity

- Conservation of KK number is broken to conservation of KK parity: $(-1)^n$.
- KK-parity requires odd KK modes to couple in pairs:
- The lightest first-level KK mode is stable.
- First level KK modes must be pair-produced.
- The Lightest Kaluza-Klein Particle plays a crucial role in phenomenology, similar to the LSP of SUSY:
- All relic KK particles decay to LKPs.
- Any first level KK particle produced in a collider decays to zero modes and an LKP.
- KK parity is also present with boundary fields, provided the same fields live on both boundaries.

Relic Density: Results



Tait, Servant'02

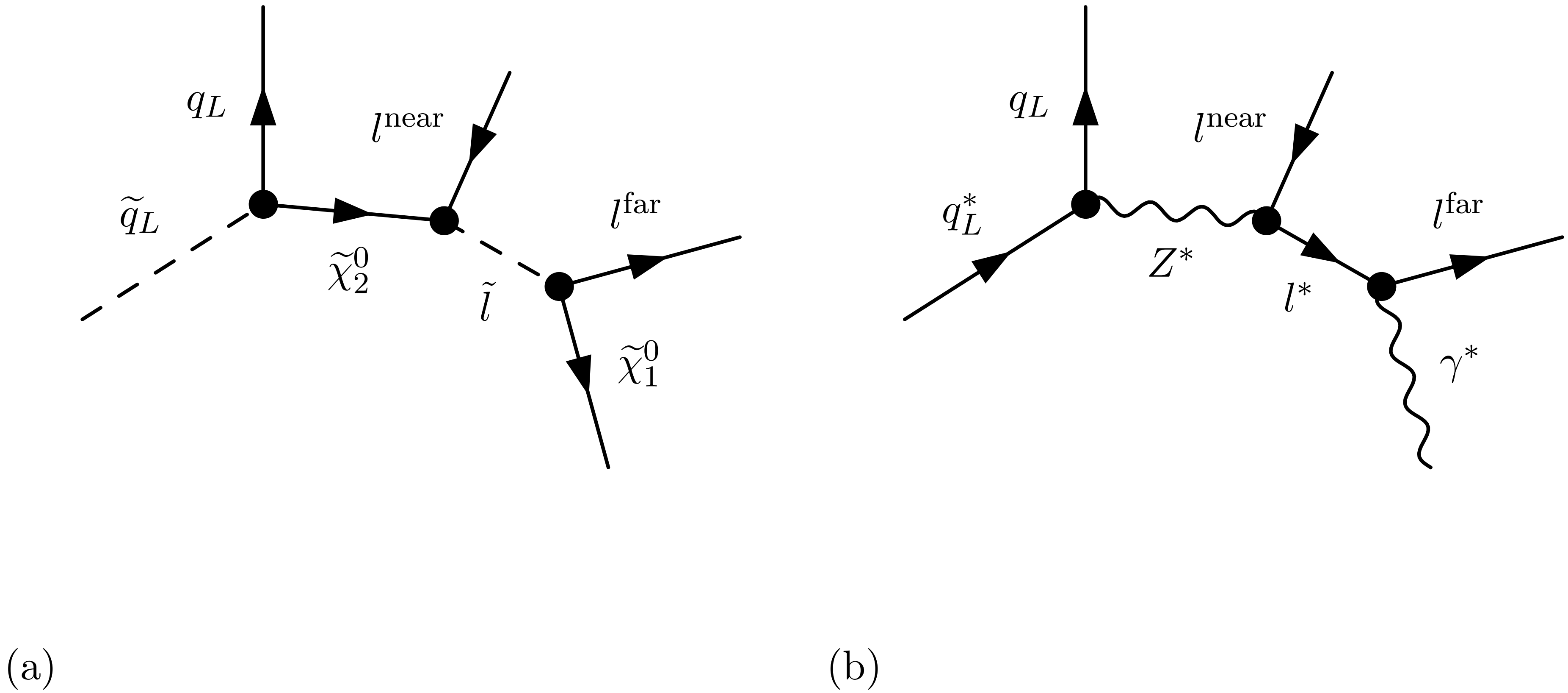
Universal extra dimensions of the order of 500 GeV–1 TeV preferred for the LKP to be a good dark matter candidate

Coannihilation and Graviton effects may modify this picture

Matchev and Kong'06; Feng, Rajamaran, Takayama'03; Shah & Wagner'06

Decay Chains are similar to the ones in SUSY

Difficult to differentiate between the two. Cross sections are larger for UED, but this can be compensated by a somewhat larger mass spectrum.



Warped Extra Dimensions

Warped Extra Dimensions

Randall, Sundrum'99

Solution to the Hierarchy Problem

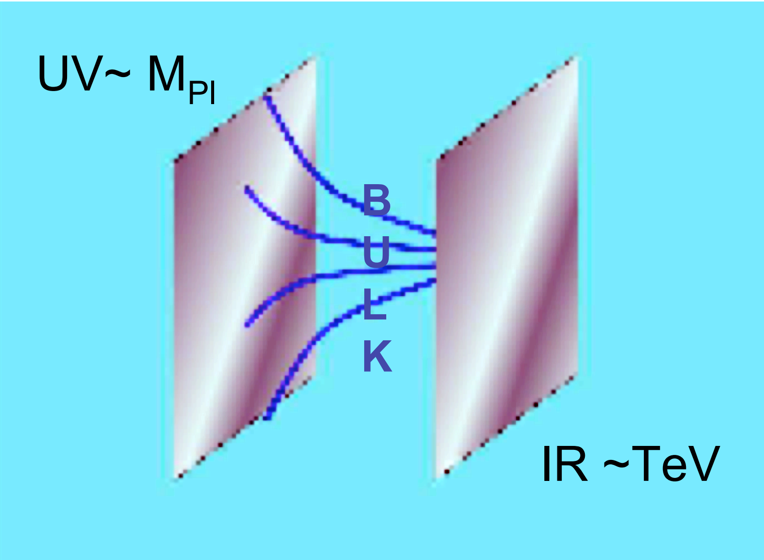
- Space is compact, of size 2 L, with orbifold conditions x, y → x,-y
- Brane at y = 0 (Ultraviolet or Planck Brane)

  Brane at y = L (Infrared or TeV Brane)

- Non-factorizable metric: $ds^2 = e^{-2k|y|}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$ solution to 5d Einstein equations
- Newton's law modified: 5d Planck mass relates to M_{Pl}: $M_{Pl}^2 = \frac{(M_{Pl}^{fund.})^3}{2k}(1 - e^{-2kL})$

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

At the TeV brane, all masses are affected by an exponential warp factor: $e^{-kL} << 1$



Assuming fundamental scales all of same order:

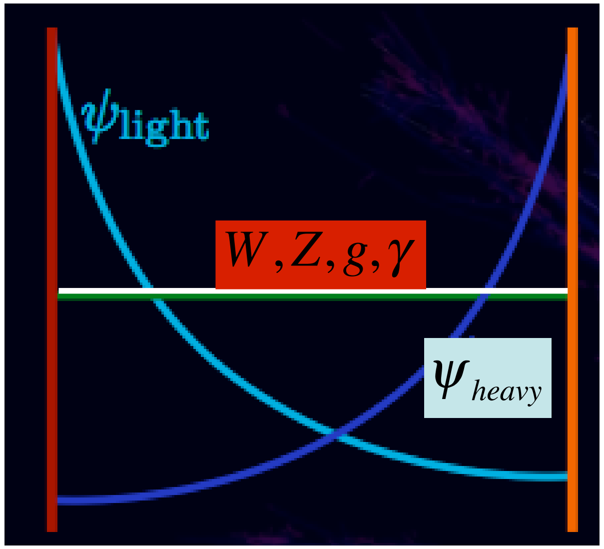
$$M_{Pl} \approx M_{Pl}^{fund.} \approx \mathrm{k}$$

Solution to Hierarchy problem :

Higgs field lives on the TeV brane

$$\mathrm{v} \sim \tilde{\mathrm{k}} \equiv \mathrm{k\,e^{-kL}} \approx M_{Pl}\,\mathrm{e^{-kL}} \sim \mathrm{TeV}$$

with kL ~30



UV brane

IR brane
Higgs + KK modes

Hierarchical fermion masses from localization

FCNC and higher dimensional operators
suppressed for the light fermion families

Many KK excitations of bulk SM fields
==> rich phenomenology

All KK mode masses are quantized in units of $\pi\ k\ \exp(-kL)$,

$$m_n = (x_1 + (n-1)\pi) k \exp(-kL)$$

where $x_1 \simeq 2.5$ for gauge bosons and 3.8 for gravitons. For even fermions, it depends on the localization, but it is similar to gauge bosons.
In general, it depends on localization and on brane terms.

- Since all KK modes tend to be localized towards the IR brane, and the heavy SM fermions should also be localized towards this brane, KK glons couple strongly to top quarks.

KK Gravitons at the LHC

- 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.
- One can rewrite the warp factor and the massive graviton couplings in terms of mass parameters as:

Graviton Coupling strength

E/Λ_π

$$\exp(-kL) = \frac{m_n}{kx_n}$$

$$\Lambda_\pi \simeq \frac{\bar{M}_{Pl} m_1}{kx_1}$$

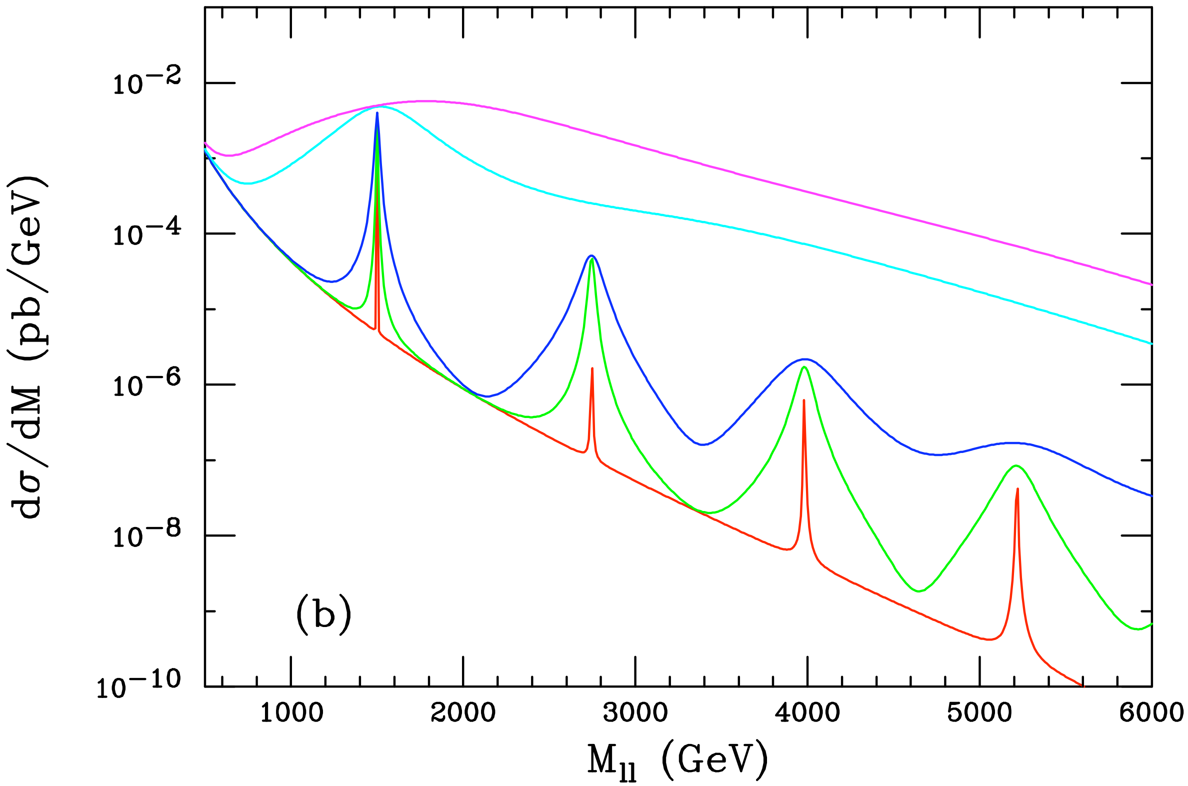
with $x_1 \simeq 3.8$, $x_n \simeq x_1 + (n-1)\pi$.

- Calling $\eta = k/\bar{M}_{Pl}$, one gets that the graviton width is

$$\Gamma(G^n) \simeq m_1 \eta^2 \frac{x_n^3}{x_1}$$

• Warped Extra Dimensions

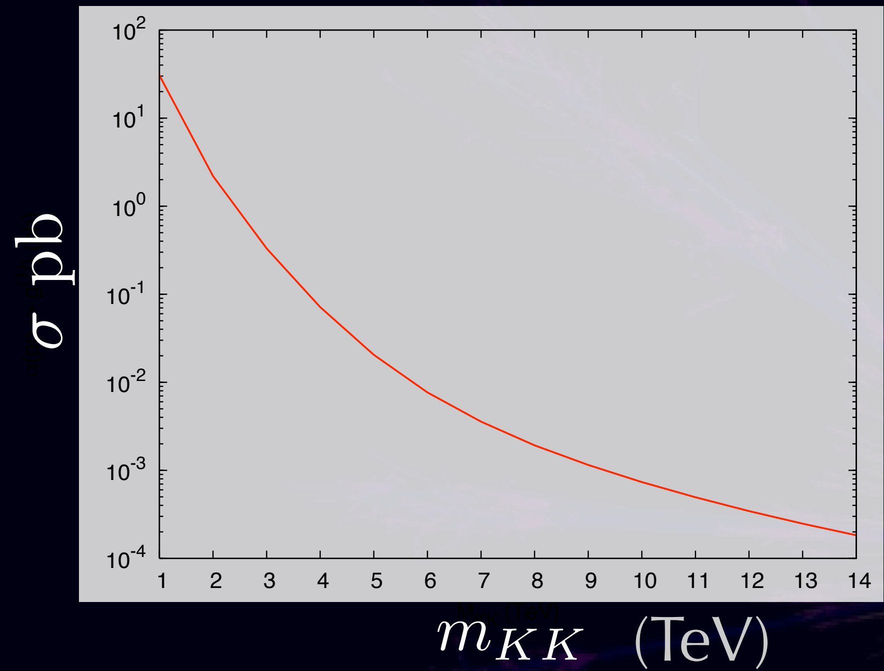
Narrow graviton resonances: $pp \to G_N \to e^+e^-$



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

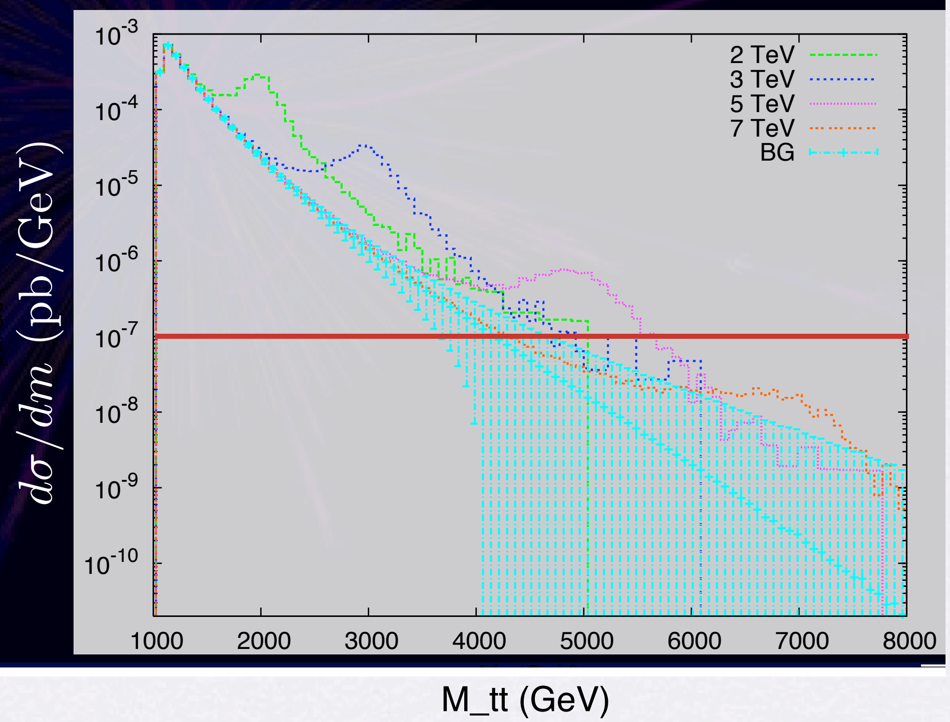
B. Lillie, L. Randall, L. Wang hep-ph/0701166

Top pairs from KK gluons



Cross-section at LHC reasonable, limited by small coupling to light fermions, and lack of glue-glue coupling

- Nice signal above SM top production
  - PDF and stat. errors shown, assuming $100 fb^{-1}$
- Width/Mass ~17%



More realistic reach estimates

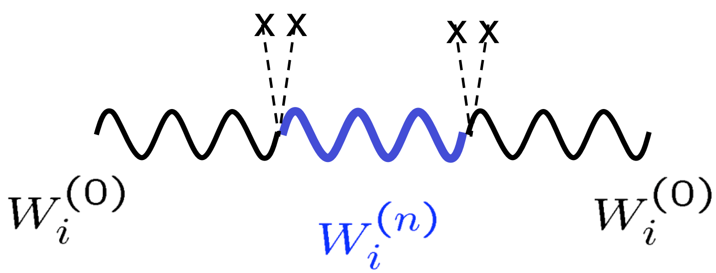
- When heavy gluon KK modes decay into top-quarks, tops are heavily boosted
- Reach depends on proper top quark identification and control of backgrounds.
- KK gluons decaying dominantly into right-handed top quarks may be discovered up to masses of 4 TeV. (Agashe et al'07, U. Baur, L. Ohr'08)
- Measurement of the inclusive top cross section may provide information on the particular RS model, and, in particular of the size of the IR brane kinetic terms. (Lillie, Tait, Shu'07).

Models with Custodial Symmetries

Effects of KK modes of the gauge bosons on Z pole observables

<u>SM in the bulk</u>

- Large mixing with Z and W zero modes through Higgs



Large corrections to the M_z/M_w ratio (T parameter)

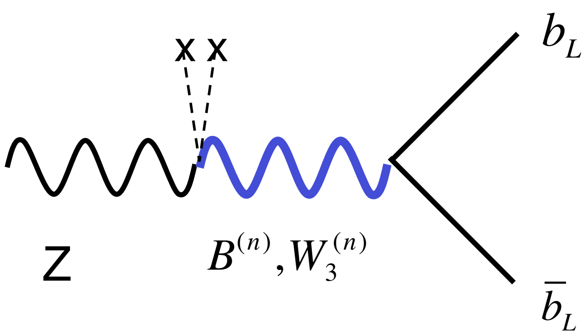
$$\Downarrow$$

$$M_{KK} \geq 5-10 \ \text{TeV}$$

- Top and bottom zero modes localized closer to the IR brane

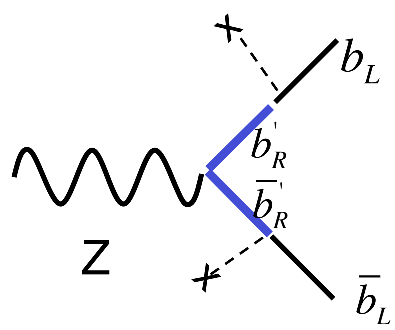
Large gauge and Yukawa couplings to Gauge Bosons and fermion KK modes

Large corrections to the Zbb coupling



$$\Downarrow$$

$$M_{KK} \gtrsim 7-8 \,\text{TeV}$$



Csaki et al'02; Hewett et al'02, Pomarol et al'02

How to obtain a phenomenologically interesting theory?

1) Extend SM bulk gauge symmetry to a custodial symmetry

$SU(2)_L \times SU(2)_R$

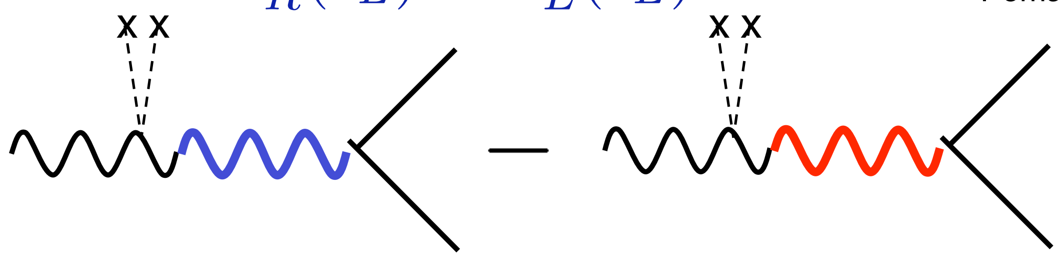
Agashe, Delgado, May, Sundrum ‘03

$T \propto$  ~ 0

2) The custodial symmetry together with a discrete L $\leftrightarrow$ R symmetry and a specific bidoublet structure of the fermions under $SU(2)_L \times SU(2)_R$

$$T^3_R(b_L) = T^3_L(b_L)$$

Agashe, Contino, DaRold, Pomarol ‘06

$\delta g_{b_L} \propto$  ~ 0

==> reduce tree level contributions to the T parameter and the Zbb coupling that allow for lightest KK gauge bosons with $M_{KK} \sim 3$ TeV

How light can the KK modes be?

Corrections to the M_z/M_w ratio and the Zbb coupling:

At tree level:

- T and Zbb protected by custodial symmetry only broken by b.c. at UV brane:
  - Governed by KK gauge boson mixing with gauge bosons
  - mixing with fermion KK modes affecting Zbb naturally reduced by bidoublet structure
- Contributions to S are less model dependent and always positive

$$S \simeq 0.15 \left(\frac{1.5\text{TeV}}{\tilde{k}}\right)^2$$

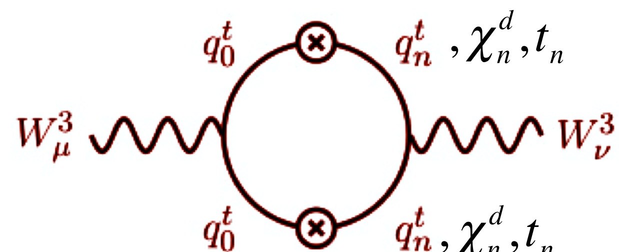
At loop level:

- One loop corrections are important

Quantum corrections are calculable (finite)

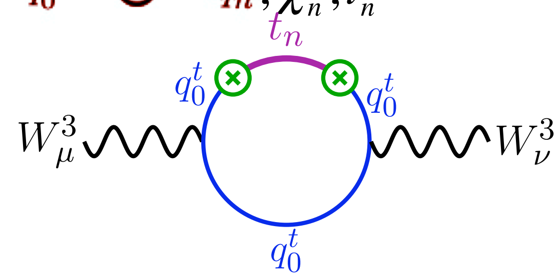
-- Bidoublets contribute negatively to T

– Singlets contribute positively to T (need singlets)



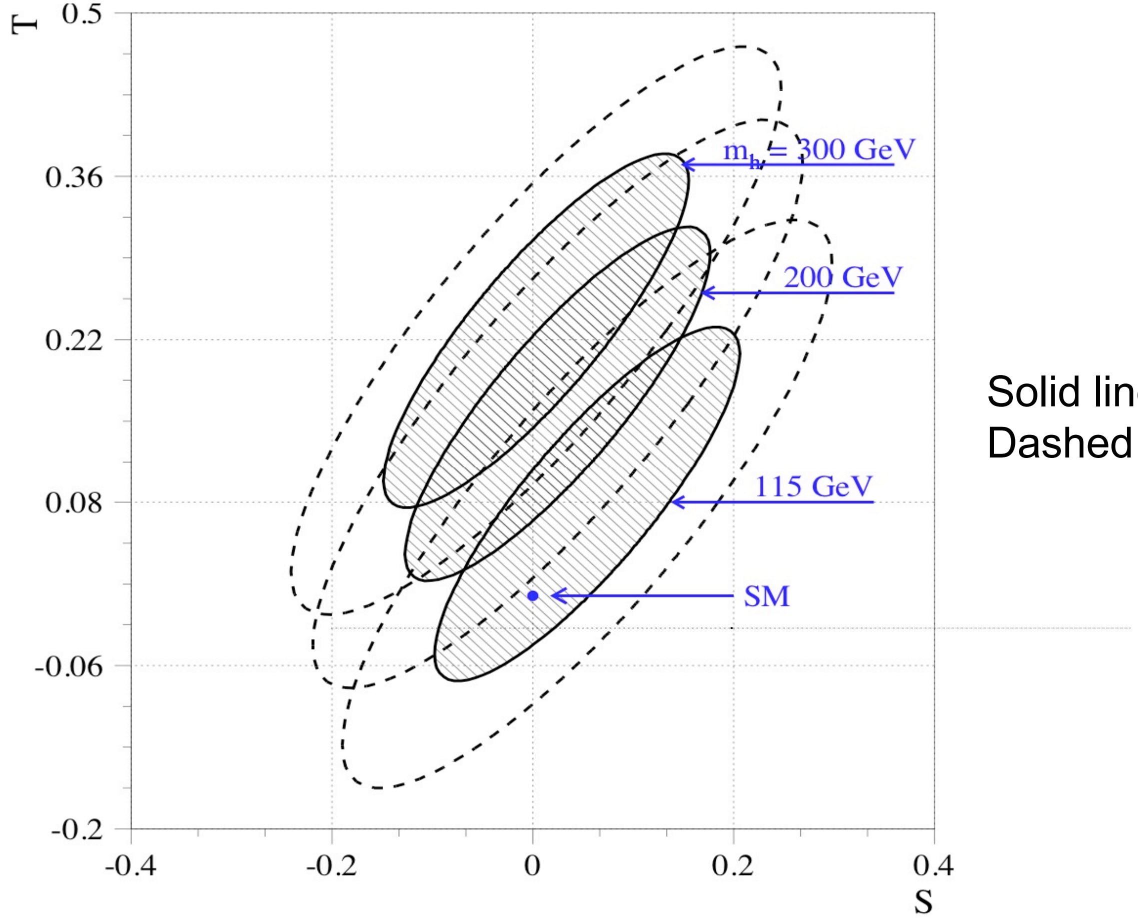
– Vector like contributions to S are small and positive

– Large positive T leads to large positive $\delta g_{bL} \equiv \delta_{Zbb}$



M. Carena, E. Ponton, J. Santiago, C.W., 06-07

T-S fit to Electroweak Precision observables



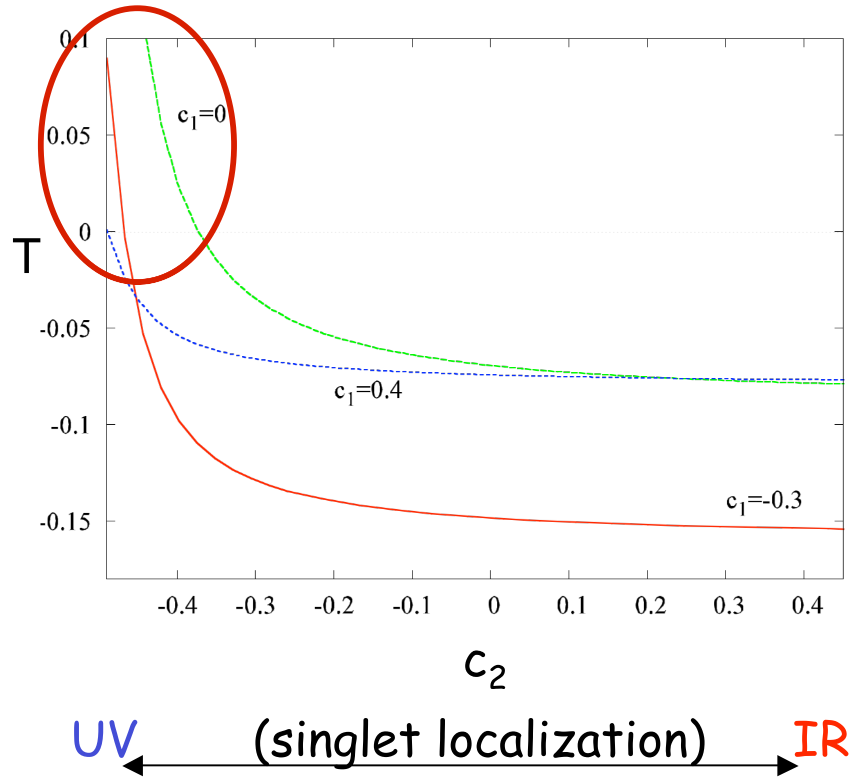
Solid lines: 68% C.L
Dashed lines: 95% C.L. contours

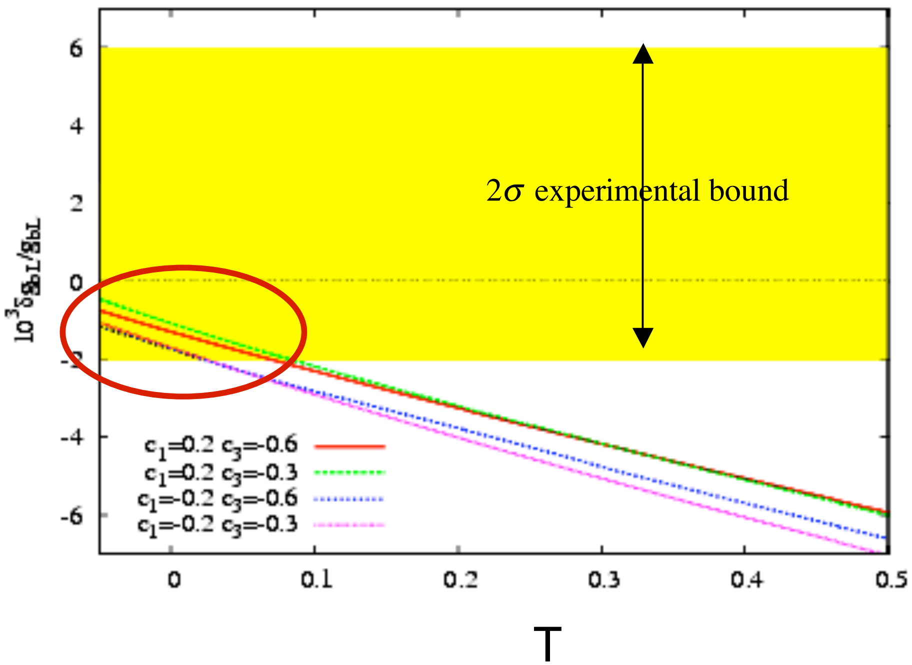
For mh ~ 120 GeV: Positive S ~ 0.1 <==> positive T

Correlation between corrections to T and Zbb

T has negative values in most of the parameter space. Positive values require: RH top "almost flat" and LH top/bottom near the IR

M.~Carena, E.~Ponton, J.~Santiago and C.~E.~M.~Wagner,
Nucl.Phys.B759:202-227,2006 and hep-ph/0701055





c_2 : Right-handed top bulk mass

Positive T leads to deviations from allowed experimental values of Zbb

Gauge Higgs Unification

Manton'79, Hosotani'83

- Idea: Can we get the Higgs from the scalar, five dimensional component, of the gauge fields
- Problem: The quantum numbers of the gauge fields we discussed so far do not allow such a possibility
- Can we extend the gauge symmetry to realize such a possibility
- New symmetry must be broken on both branes (Dirichlet)
- Scalars acquire Neumann boundary conditions in such a case and present zero modes (Higgs bosons)

Higgs From Gauge Fields in Warped Extra Dimensions

Contino, Da Rold, Pomarol'06

Bulk gauge symm: $SU(3)_c \times SO(5) \times U(1)_X \longrightarrow SO(5) \supset SU(2)_L \times SU(2)_R$

UV: $SU(2)_L \times U(1)_Y$ IR: $SO(4) \times U(1)_X \simeq SU(2)_L \times SU(2)_R \times U(1)_X$

Extra gauge bosons have the quantum numbers of the Higgs

$$SO(5)/SO(4) \longrightarrow A_\mu^{\hat{a}}(-,-) \quad A_5^{\hat{a}}(+,+)$$

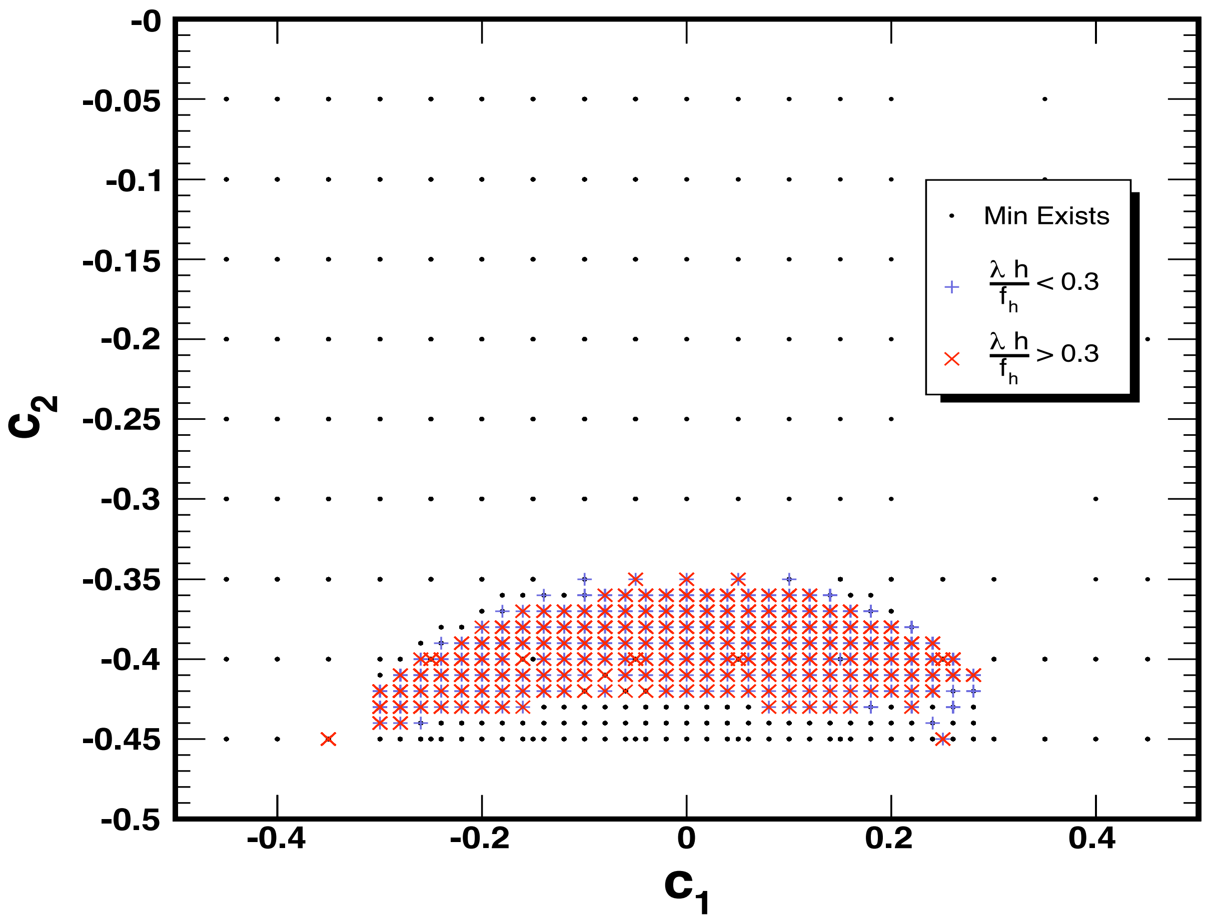
Identify with H

No tree-level Higgs potential $\longrightarrow$ induced at one-loop (calculable)

Coleman-Weinberg potential has been computed for the model considered here by A. Medina, N. Shah, C.W. , Phys. Rev. D 76: 095010 (2007)

- EWSB minima in large regions of parameter space
- Can be consistent with Z, W, top masses and Higgs LEP bound

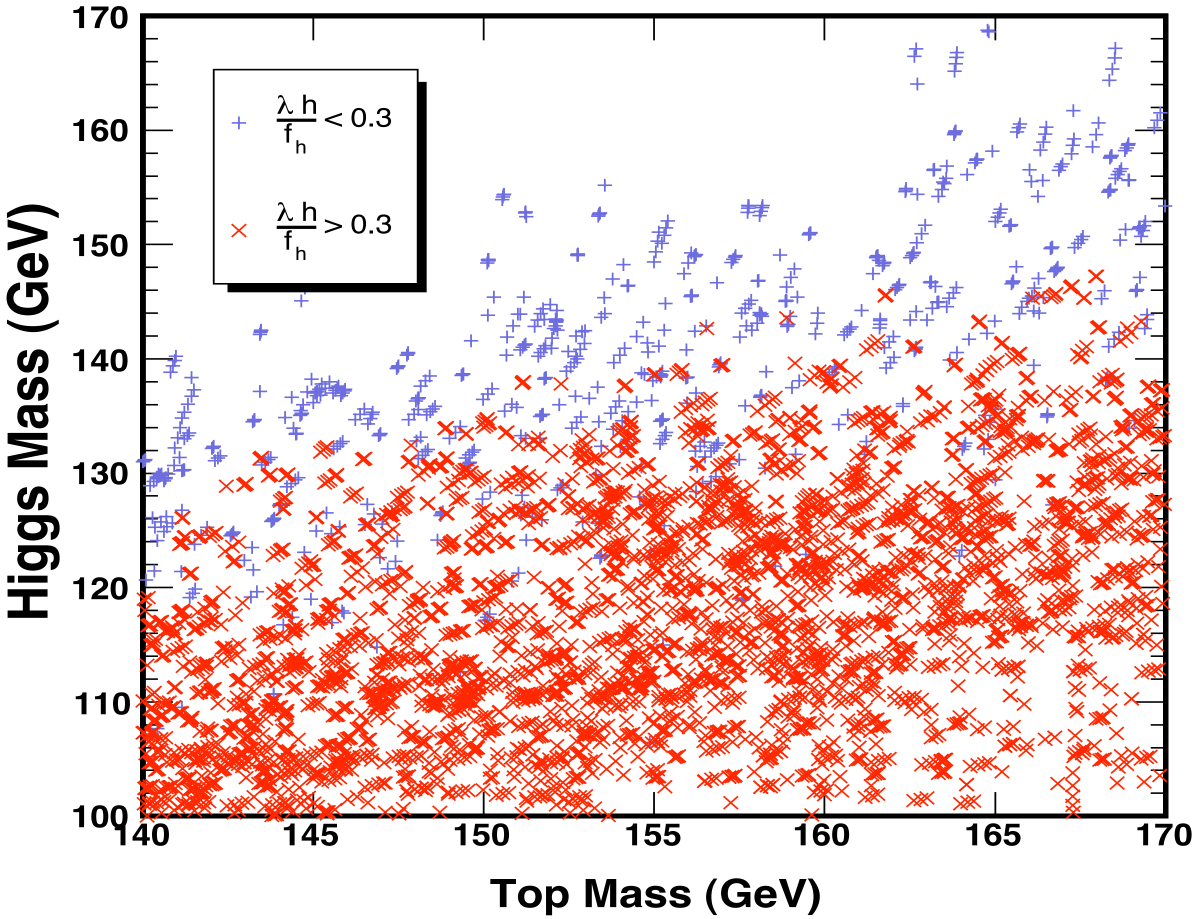
Values of c_2 and c_1 leading to consistent values of the gauge boson and third generation masses



A. Medina, N. Shah, C.W. , Phys. Rev. D 76: 095010 (2007)

Consitent with values necessary for a good agreement with precision electroweak measurements

Blue points: Couplings of Higgs SM-like (linear regime)
Good agreement with precision measurements

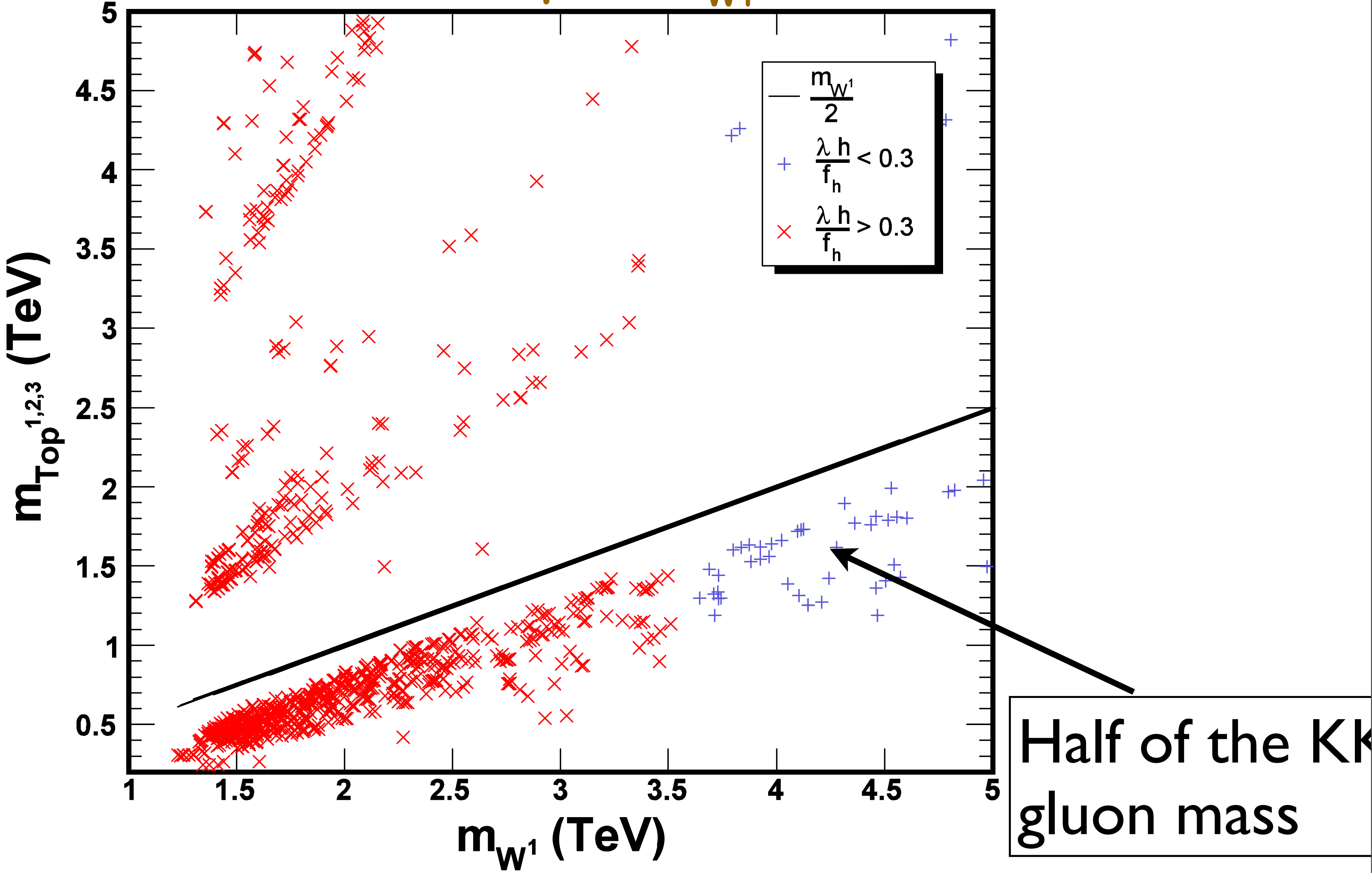


Medina, Shah, Wagner '07

In the linear regime, Higgs mass is predicted to be between the current experimental limit and 160 GeV

First few KK mode of the Top vs. m_{W1}

Medina, Shah, Wagner '07



In these models KK gluons are strongly coupled to KK tops and KK tops provide their dominant decay branching ratio

Gauge-Higgs Unification: Collider Phenomenology

- t^1 production cross section through QCD alone and through QCD+G^1 for M_{G1}=4 TeV.

M. Carena, A. Medina, B. Panes, N. Shah, C.W. '08

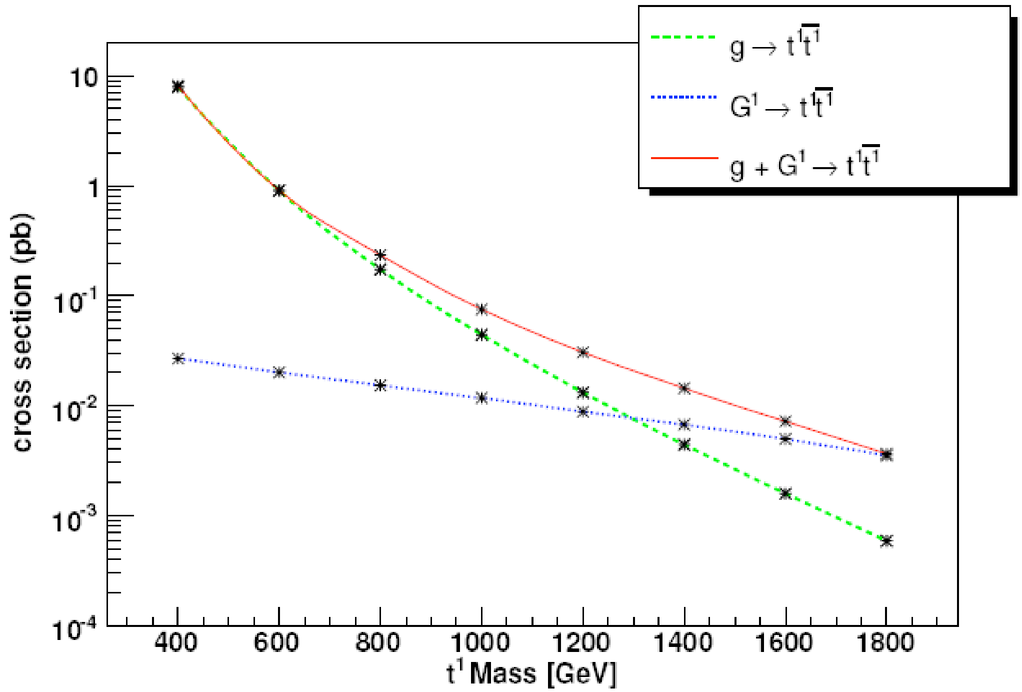
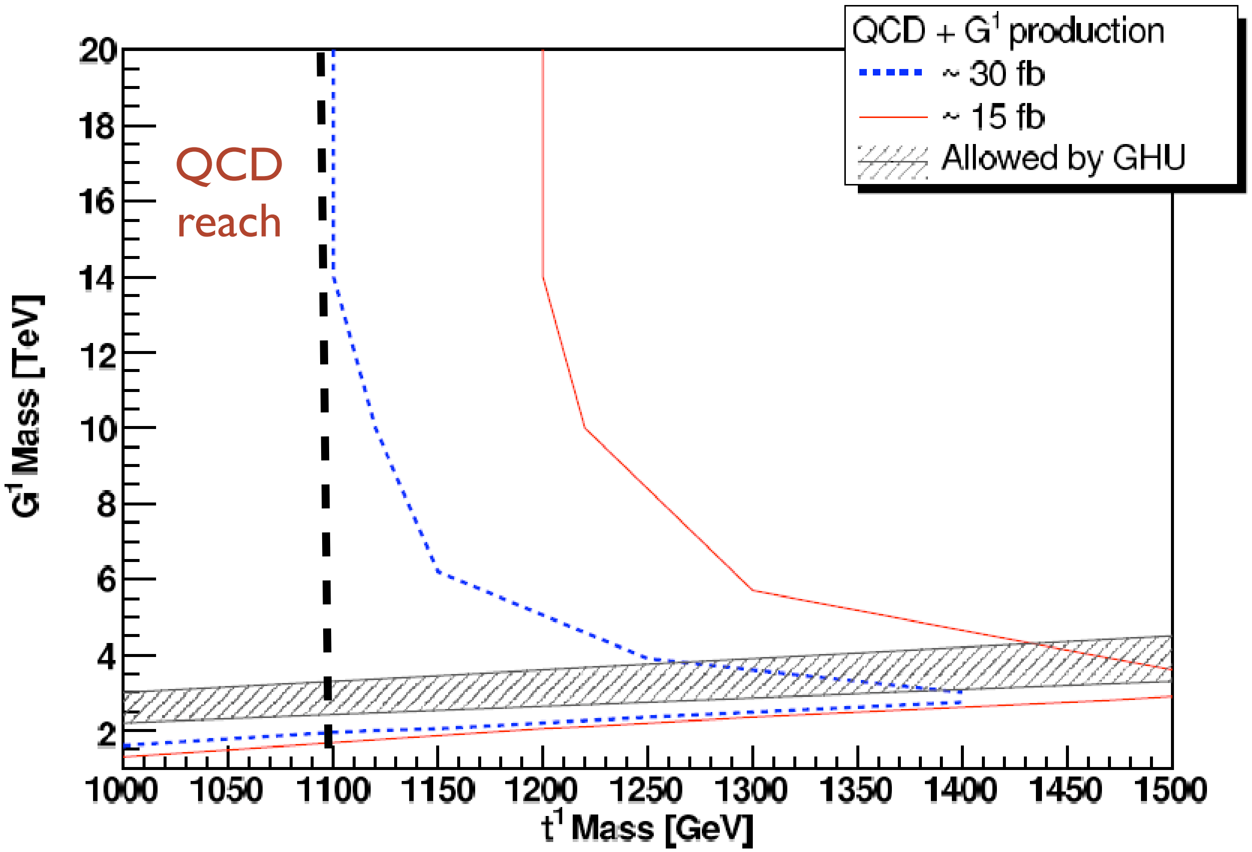


Figure 5: Cross section for M_{G^1} = 4.0 TeV with couplings $g_{G^1\bar{t}^1{}_L t^1_L}/g_s(\tilde{k}) = -5.18$ and $g_{G^1\bar{t}^1{}_R t^1_R}/g_s(\tilde{k}) = -2.77$.

Notice that for $M_{t1} \approx$ 1.5 TeV, G^1-induced production contributes in a significant amount to the t production cross section.

LHC Discovery Reach

- First KK mode of the top decays mostly into W and bottom-quarks
- Two points were explored, on the blue and red lines. In the first the KK top may be discovered with 100 inverse fb, in the second with 300 inverse fb.



M. Carena, A. Medina, B. Panes, N. Shah, C.W. '08

Figure 20: Curves of constant cross section for QCD in addition of G^1 decay, in (m_{G^1}, m_{t^1}) plane.

Dark Matter

- Dark Matter may be included by extending the model to include a new Z_2 discrete symmetry which affects certain states

- New symmetry relates the localization of new odd states with the new ones

- KK gauge bosons, odd under this symmetry may provide a dark matter candidate

  Panico, Ponton, Santiago, Serone; Agashe, Falkowski,Low, Servant'08

- Lepton sector of the model: Neutrino masses may be generated by a five dimensional generation of the See-Saw mechanism. Odd Neutrinos, mostly right-handed, can also provide alternative dark matter candidates.

  Carena, Medina, Shah, Wagner'09

- Such model predicts a direct dark matter detection rate only an order of magnitude below the present limits and therefore soon testable at XENON and CDMS.

Physics Beyond the Standard Model : The LHC ERA

- The current decade will see the completion of the Tevatron and the full development of the LHC program, which will provide detailed information of physics at the TeV scale.
- Origin of fermion and gauge boson masses (electroweak symmetry breaking dynamics) expected to be revealed by these experiments.
- Missing energy signatures at the LHC may reveal the presence of a dark matter candidate which may be the first evidence of a world of new particles. Direct and indirect detection experiments will reach maturity, and the Dark Energy equation of state may be determined.
- Tevatron, LHCb and super B-factories will provide accurate information on flavor physics, leading possibly to complementary information on new physics.
- Search for charged lepton number violation and neutrino double beta decay experiments could reveal nature of neutrinos, and new dynamics at the TeV scale. Neutrino oscillation experiments may lead to the observation of CP-violation or other surprises.
- The next years can mark the termination of the Standard Model Dictatorship and the beginning of a genuine new era in physics, similar to the one that led to the successful SMs of particle physics and cosmology, which arguably started about 100 years ago.

Conclusions I

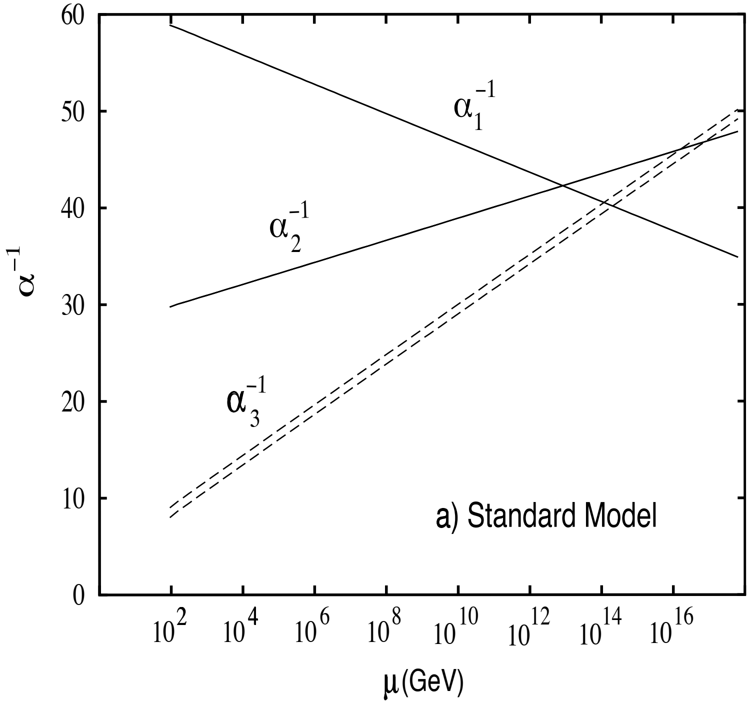
- Low energy supersymmetry provides a perturbative consistent ultraviolet completion of the Standard Model, which may be extrapolated up to energies of order of the GUT or Planck scales.
- The minimal SUSY extensions of the SM lead naturally to the breakdown of the electroweak symmetry, relating the weak scale to the supersymmetry breaking scale
- It is consistent with unification of couplings, leads to a natural dark matter candidate and can help in realizing the mechanism of electroweak baryogenesis
- Missing energy is, in general, a signature of this class of models. If the SUSY breaking scale is small, the gravitino may be the LSP, leading to interesting collider signatures, including not only missing energy but displaced vertices.
- Under the assumption of perturbative unification, it leads to a Higgs, with SM couplings to the gauge bosons and a mass smaller than 135 GeV.
- The extended Higgs structure may lead to rich signatures at hadron colliders, as well as an impact on flavor physics.

Conclusions II

- Extra Dimensions present an exciting alternative scenario for physics beyond the standard model
- If large extra dimensions exist, they may provide a test of quantum gravity effects at the weak scale
- Universal extra dimensions lead to a scenario with similar signatures and properties of supersymmetry, including Dark Matter and Missing Energy signatures.
- Warped extra dimensions with SM fields propagating in the extra dimension, lead to a solution of the hierarchy problem, to interesting approach to the flavor problem and to possible exciting signatures at the LHC. Gauge Higgs unification may be realized and dark matter may be incorporated.

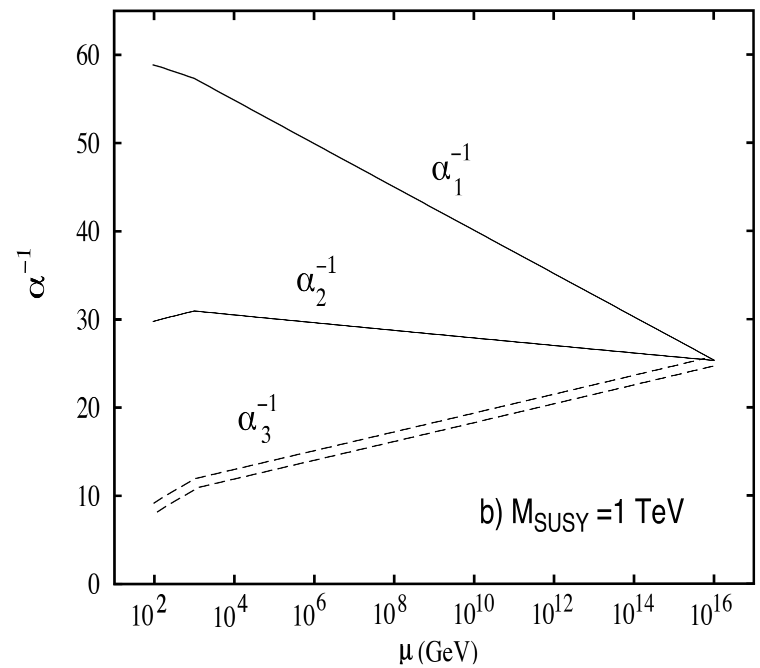
SM:

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, Carena, Pokorski & C.W.

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!!

Threshold Corrections

- The unification prediction depends strongly on the supersymmetry particle mass spectrum,

$$\alpha_3(M_Z) \simeq 0.127 - \alpha_3^2(M_Z)\ln\left(\frac{T_{SUSY}}{M_Z}\right)$$

- The threshold scale does not correspond to any particular particle scale but it may be approximated by

$$T_{SUSY} \simeq |\mu|\left(\frac{M_2}{M_3}\right)^{3/2}$$

where Mi are the SU(2) and SU(3) gaugino masses.

- Naive unification may be obtained for threshold scales of the order of 1 TeV, which are easier to obtain for a smaller ratio of the wino and gluino masses than what the simplest models predict.

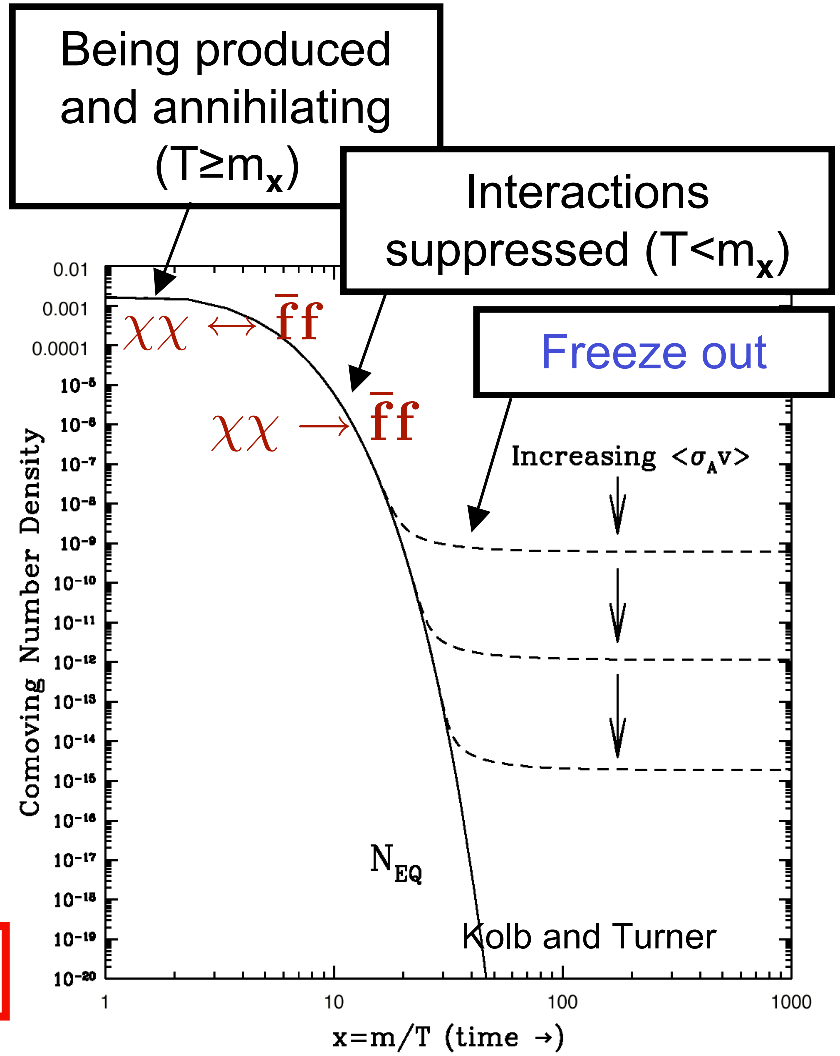
Cosmology data ↔ Dark Matter ↔ New physics at the EW scale

Evolution of the Dark Matter Density

- Heavy particle initially in thermal equilibrium
- Annihilation stops when number density drops

$$H > \Gamma_A \approx n_\chi < \sigma_A \mathrm{v} >$$

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



- Leaves a relic abundance:

$$\Omega_{DM} h^2 \approx \ < \sigma_A \mathrm{v}>^{-1}$$

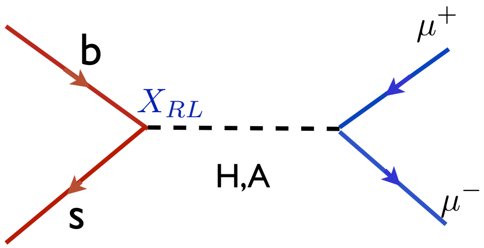
If m_x and σ_A determined by electroweak physics,

$\sigma_A \approx k\alpha_W^2 / \mathrm{m}_X^2 \approx$ a few pb then Ω_{DM} h^2~0.1 for m_x~0.1-1 TeV

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

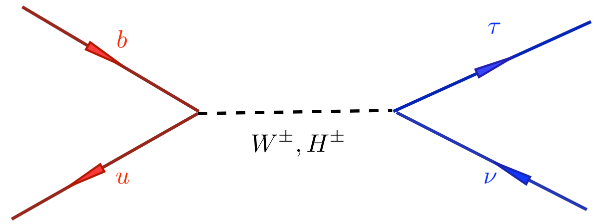
Flavor Higgs induced effects

- The same corrections to the couplings induced FCNC in the neutral Higgs sector, which combined with charged Higgs induced contributions, lead to important flavor effects induced by the Higgs sector at large values of $\tan\beta$



$B_s \to \mu^+\mu^-$

$\left(g_{A\mu\mu} = \frac{m_\mu \tan\beta}{v} \right)$



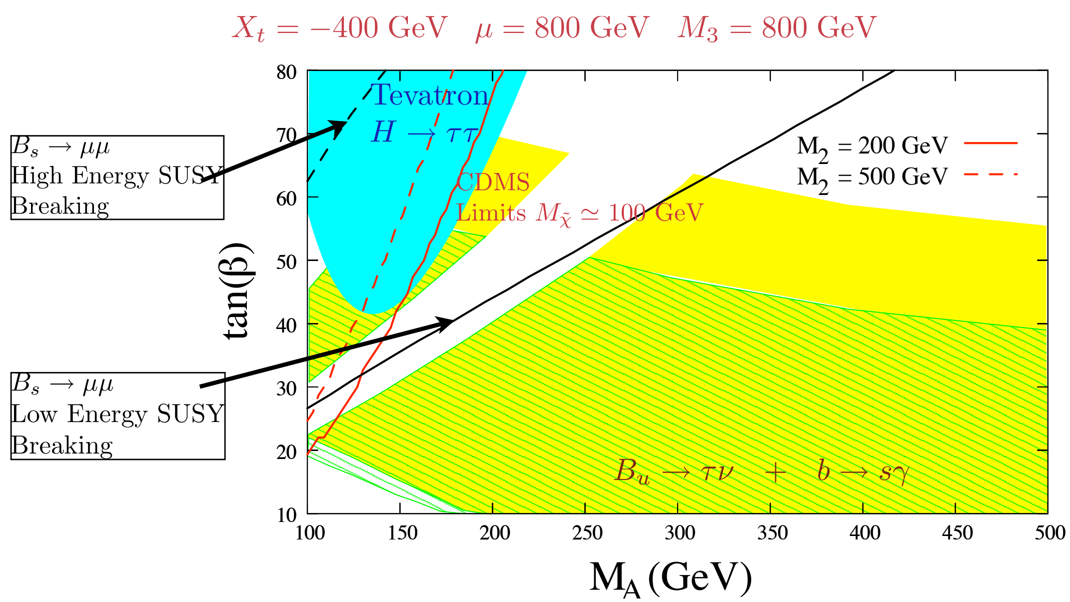
$$X_{RL} \propto \frac{\left(E_t h_t^2 + E_{g,3} - E_{g,(1,2)}\right)\tan^2\beta}{\left(1 + E_{g,(1,2)}\tan\beta\right)\left(1+\Delta_b\right)}$$

Babu, Kolda'00, Buras et al'02, Dedes, Pilaftsis'03...

In models with flavor independent high energy supersymmetry breaking, flavor violating gluino couplings are induced at low energies and cannot be ignored.

Very relevant constraints come also from b to s gamma, which receives SUSY contributions from charged Higgs, chargino and gluino loops.

Direct dark matter detection may also become relevant.



M. Carena, A. Menon, C.W.

The Randall-Sundrum Model of Warped Space:

==> elegant solution to the hierarchy problem

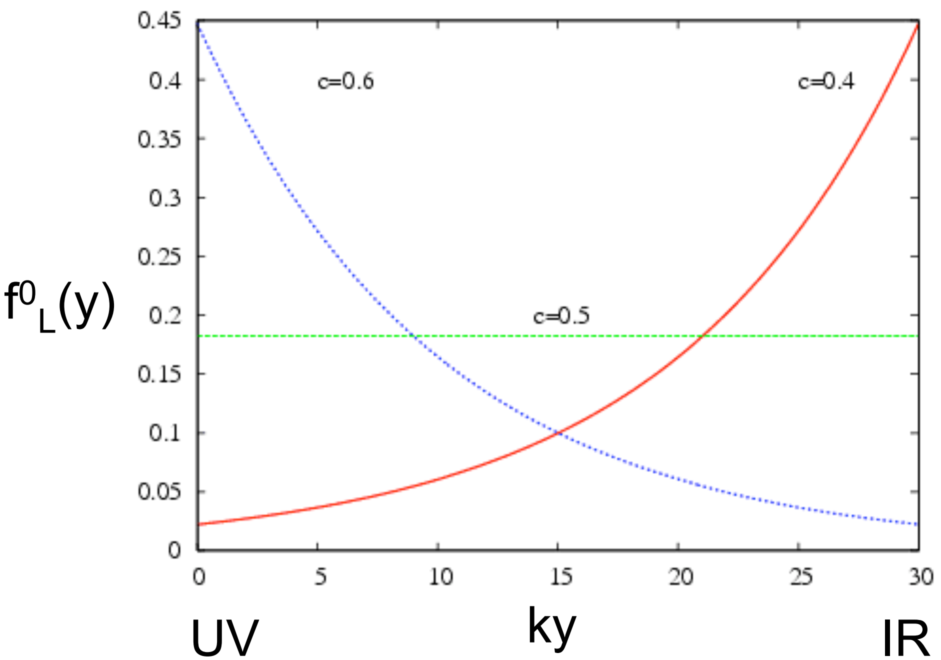
RS With Bulk Fermions and Gauge bosons:

- Higgs field must be located in the IR brane, but SM fields may live in the bulk.
- Fermions in the bulk: ==> suggestive theory of flavor

-- SM fermion masses related to the size of their zero mode wave function at the IR

Localization determined from bulk mass term: $L_m = c_f k \bar{\Psi}\Psi$

$\Downarrow$



KK mode expansion:

$$\Psi_{L,R}(x,y) = e^{3ky/2} \sum_n \psi^n_{L,R}(x) f^n_{L.R}(y)$$

Boundary conditions for f(y) at the branes (UV, IR) = (+,+) ==> zero mode

If b.c. (-,+), (+,-) or (-,-) ==> no zero mode

-- The KK spectrum is defined in units of $\tilde{k} = ke^{-kL}$ of factors that depend on c_f and is localized towards the IR brane