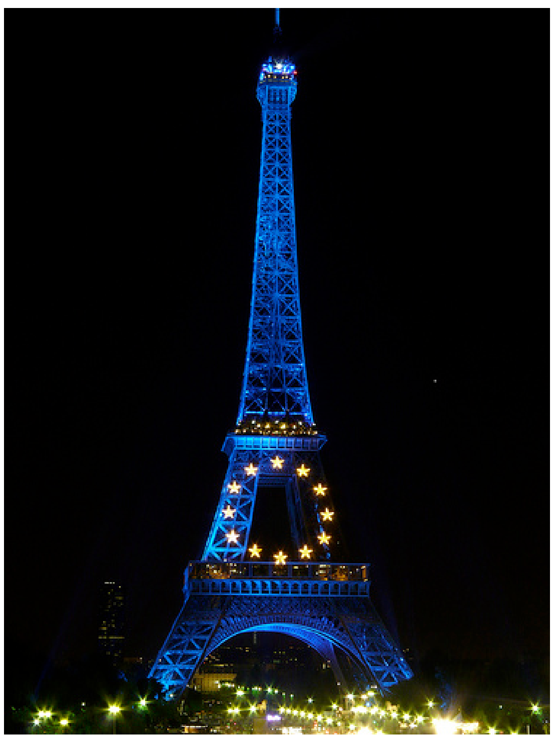
Beyond the Standard Model Physics

Marcela Carena
Theoretical Physics Department, Fermilab
Department Physics and Enrico Fermi Institute, University of Chicago



10 - 25 years of D0-France
Paris, October 13-14, 2008

Outline

The Standard Model Paradigm and what it fails to explain

Models of New Physics to explain:

The (dynamical) origin of EWSB, the hierarchy problem

** Supersymmetry ** Strong Dynamics

** Extra Dimensions ** Higgs SM extensions

Many possibilities:

SM-like fundamental scalar Higgs, Composite Higgs,

NO HIGGS, Higgs as a Pseudo Nambu-Goldstone boson

The origin of Dark Matter in models of New Physics

Flavour Physics in BSM scenarios

New physics signatures at the energy frontier

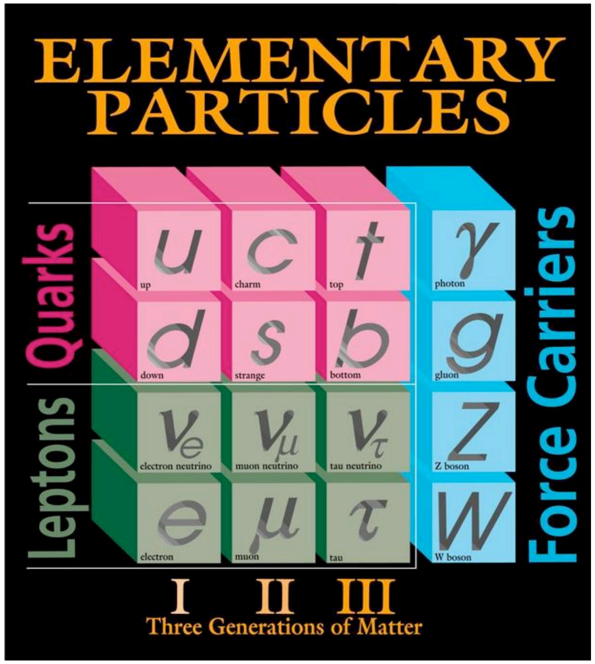
Patrice Verdier's Talk

Karl Jacobs' Talk

Standard Model

explains data collected in the past several years and

describes processes up to energies of $\approx$ 100 GeV



However, it is only an effective theory. At least Gravity should be included at $M_{Pl} = 10^{19}$ GeV

Many open questions

Origin of Mass of fundamental particles

Generation of big hierarchy of scales $M_{Pl}/M_Z = 10^{17}$, $M_Z/M_\nu = 10^{12}$

Generation of hierarchies of fermion masses

Neutrinos: are they encoding a secret message?

Connection of electroweak and strong interactions with gravity

Explanation of matter-antimatter asymmetry of the universe

Dark matter

Dark energy

Collider Experiments: **Tevatron, LHC**, a future lepton collider
our most robust handle to reveal the new physics to answer these questions

EWSB occurs at the TeV scale:

new phenomena should lie in the TeV range or below, at the reach of LHC

The Quest of 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

Standard Model, Supersymmetry ==> examples of weak EWSB

** strong interaction dynamics among new fermions (mediated perhaps by gauge interactions, in possible connection with warped extra dimension)

Technicolor, Top-condensation/Top-color, Higgsless models, Gauge-Higgs Unification, Little Higgs models,....

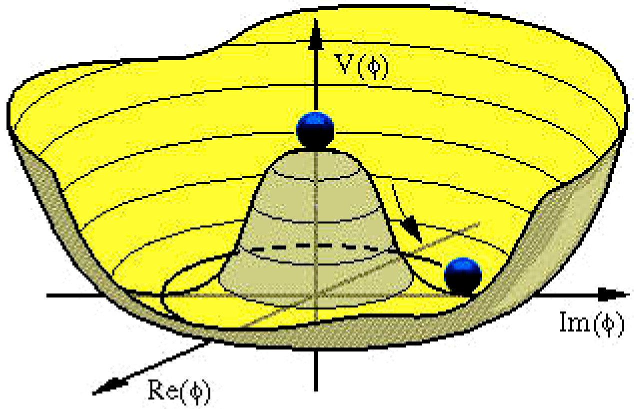
These mechanisms generate new particles with clear experimental signatures

precision measurements strongly constrain

the existence of new particles at the TeV scale

EWSB in the SM: The Higgs Mechanism

A self interacting complex scalar doublet with no trivial quantum numbers under $SU(2)_L \times U(1)_Y$



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

$$V(\Phi) = \mu^2 \Phi^+\Phi + \frac{\lambda}{2}\left(\Phi^+\Phi\right)^2 \qquad \mu^2 < 0$$

Higgs vacuum condensate v ==> scale of EWSB

$SU(3)_C \times SU(2)_L \times U(1)_Y$ ==> $SU(3)_C \times U(1)_{em}$

Higgs gives mass to W,Z and SM fermions: $M_V^2 = g_{\phi VV}\, \mathrm{v}/2$ $\quad m_f = \mathrm{h_f}\ \mathrm{v}$

- One extra physical state -- Higgs Boson -- left in the spectrum

Associated to the SM EWSB mechanism: The Hierarchy problem

$$\text{Why v} \ll M_{Pl}\,?$$

Quantum corrections to $\mu^2 \rightarrow \mu^2 = \mu^2(\Lambda_{eff}) - \alpha\Lambda_{eff}^2$ *diverge quadratically with the scale at which the SM is superseded by New physics*

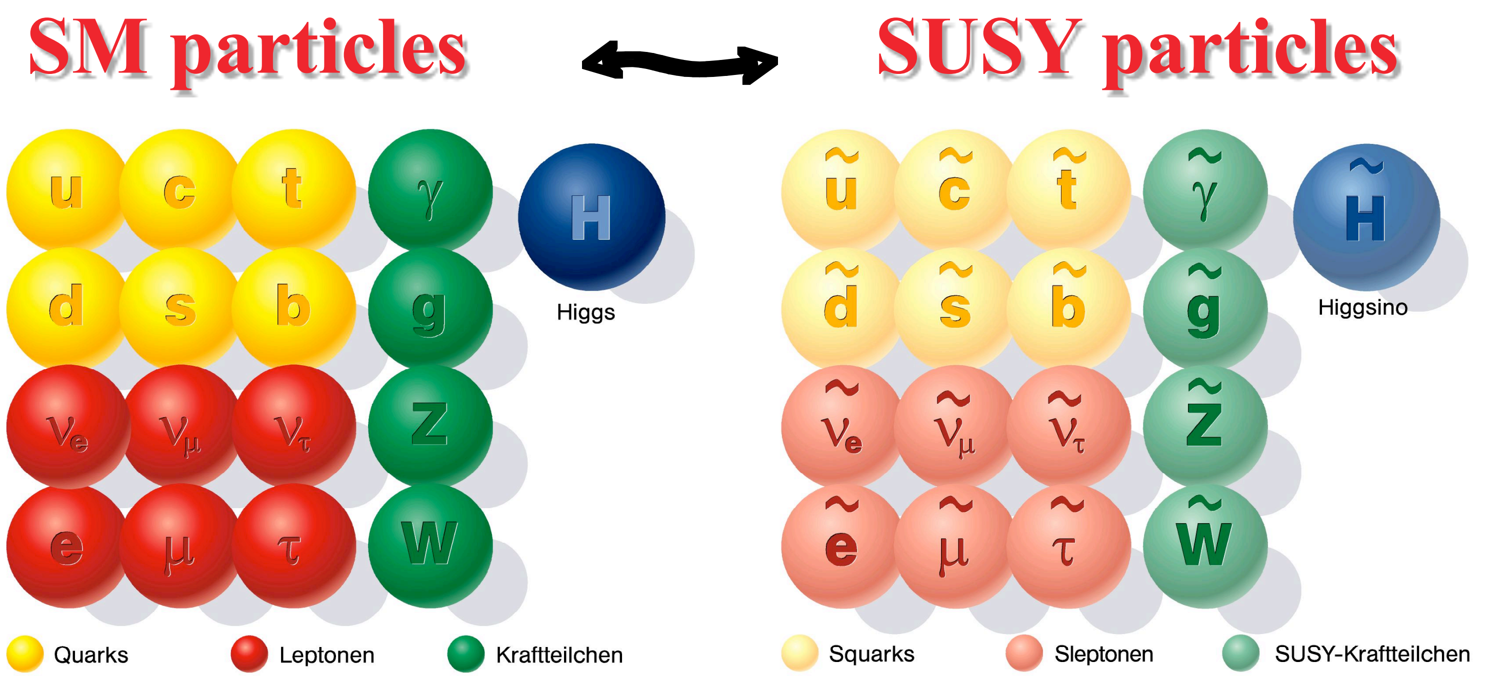
New Physics at the TeV scale or extreme fine tuning

A new Symmetry in Nature? SUPERSYMMETRY

Fermion-Boson Symmetry:

For every fermion there is a boson with equal mass and couplings

Couplings of SUSY particles equal to couplings of SM particles



Contains a good Dark matter candidate

Provides a solution to the hierarchy problem and generates EWSB radiatively

Is consistent with gauge coupling unification

No SUSY partner degenerate in mass with its SM particle has been observed

SUSY solution to the hierarchy Problem

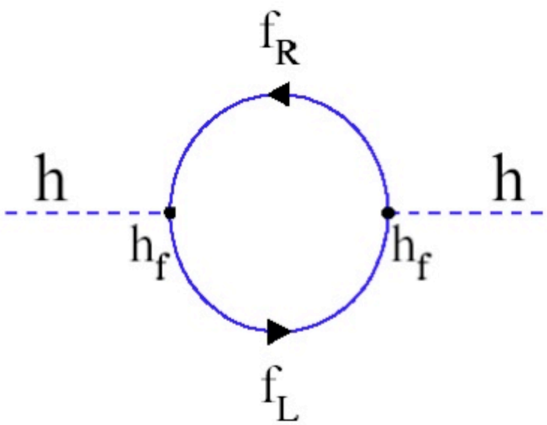
Self energy of an elementary scalar related by SUSY to the self energy of a fermion

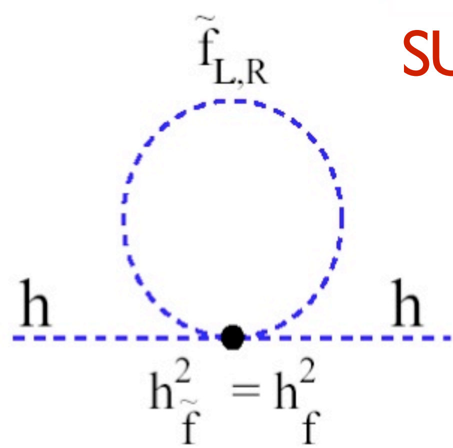
Cancellation of quadratic divergences in Higgs mass quantum corrections has to do with SUSY relation between couplings and bosonic and fermionic degrees of freedom

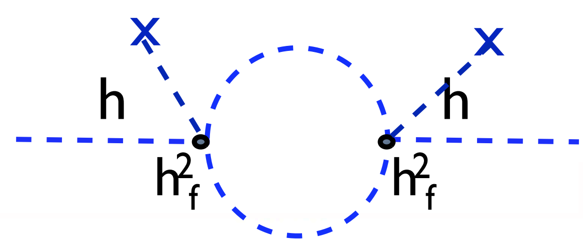
$$\Delta\mu^2 \approx g^2_{hf\tilde{f}}[m_f^2 - m_{\tilde{f}}^2]\ln(\Lambda^2_{eff} / m_h^2)$$

not with the exact equality of fermion and scalar masses

SUSY must be broken in nature







In low energy SUSY: quadratic sensitivity to Λ_{eff} replaced by quadratic sensitivity to SUSY breaking scale

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

The Minimal SUSY extension of the Standard Model (MSSM)

Names		spin 0	spin 1/2	$SU(3)_C,\ SU(2)_L,\ U(1)_Y$
squarks, quarks	Q	$(\widetilde{u}_L\ \ \widetilde{d}_L)$	$(u_L\ \ d_L)$	$(\,\mathbf{3},\ \mathbf{2}\,,\ \frac{1}{6})$
($\times 3$ families)	U	$\widetilde{u}^*_R$	$(u^C)_L$	$(\,\overline{\mathbf{3}},\ \mathbf{1},\ -\frac{2}{3})$
	D	$\widetilde{d}^*_R$	$(d^C)_L$	$(\,\overline{\mathbf{3}},\ \mathbf{1},\ \frac{1}{3})$
sleptons, leptons	L	$(\widetilde{\nu}\ \ \widetilde{e}_L)$	$(\nu\ \ e_L)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ -\frac{1}{2})$
($\times 3$ families)	E	$\widetilde{e}^*_R$	$(e^C)_L$	$(\,\mathbf{1},\ \mathbf{1},\ 1)$
Higgs, higgsinos	?			

Matter Superfields

Names	spin 1/2	spin 1	$SU(3)_C,\ SU(2)_L,\ U(1)_Y$
gluino, gluon	$\widetilde{g}$	g	$(\,\mathbf{8},\ \mathbf{1}\,,\ 0)$
winos, W bosons	$\widetilde{W}^{\pm}\ \ \widetilde{W}^0$	$W^{\pm}\ \ W^0$	$(\,\mathbf{1},\ \mathbf{3}\,,\ 0)$
bino, B boson	$\widetilde{B}^0$	B^0	$(\,\mathbf{1},\ \mathbf{1}\,,\ 0)$

Gauge Superfields

The winos and bino are not mass eigenstates, they mix with each other and with the Higgs superpartners, called higgsinos, of the same charge

The Higgs Sector: two Higgs fields with opposite hypercharges

2 Higgs doublets necessary to give mass to both up and down quarks and leptons in a gauge/SUSY invariant way

2 Higgsino doublets necessary for anomaly cancellation

Names		spin 0	spin 1/2	$SU(3)_C, SU(2)_L, U(1)_Y$
Higgs, higgsinos	H_u	$(H_u^+ \quad H_u^0)$	$(\widetilde{H}_u^+ \quad \widetilde{H}_u^0)$	$(\mathbf{1}, \mathbf{2}, +\frac{1}{2})$
	H_d	$(H_d^0 \quad H_d^-)$	$(\widetilde{H}_d^0 \quad \widetilde{H}_d^-)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$

- Both Higgs fields acquire v.e.v. New parameter, $\tan\beta = v_2/v_1$.

Both Higgs fields contribute to the superpotential and give masses to up and down/lepton sectors, respectively

$H_1 \equiv H_d$
$H_2 \equiv H_u$

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

With two Higgs doublets, a mass term may be written $\delta P[\phi] = \mu H_1 H_2$

Interesting to observe:

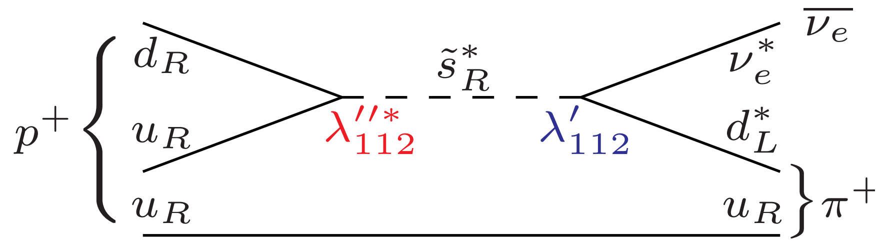
The quantum numbers of H_1 are the same as those of the lepton superfield L.
One can add terms in the superpotential replacing H_1 by L

Dangerous Baryon and Lepton Number Violating Interactions

$$P[\Phi]_{new} \rightarrow \begin{cases} P_{\Delta L=1} = \frac{1}{2}\lambda_{ijk} L_i L_j E_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \mu'_i L_i H_u \\ P_{\Delta B=1} = \frac{1}{2}\lambda''_{ijk} \bar{U}_i \bar{D}_j D_k \end{cases}$$

If both types of couplings were present, and of order 1, then the proton would decay in a tiny fraction of a second through diagrams like this:

Proton Decay



One cannot require B and L conservation since they are already known to be violated at the quantum level in the SM.

Instead, one postulates a new discrete symmetry called **R-parity.**

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

All SM particles have $P_R = 1$

All Supersymmetric partners have $P_R = -1$

Important Consequences of R-Parity Conservation

Since SUSY partners are R-parity odd (have $P_R = -1$)

every interaction vertex must contain an even number of SUSY particles

- All Yukawa couplings induced by $P(\Phi)_{new}$ are forbidden (have and odd number of SUSY particles)

- The Lightest SUSY Particle (LSP) must be absolutely stable

If electrically neutral, interacts only weakly with ordinary matter

LSP (usually the lightest neutralino) is a good Dark Matter candidate

- LSP annihilation cross section usually too small ==> too much relic density: Cosmological data excludes many SUSY models

- In collider experiments SUSY particles can only be produced in even numbers (usually in pairs)

- Each sparticle eventually decays into a state that contains an LSP ==> Missing Energy Signal at colliders

Soft Supersymmetry Breaking:

Give different masses to SM particles and their superpartners,
but preserves the structure of couplings of the theory

Gaugino masses, squark/slepton squared mass terms and trilinear/biliniar terms prop. to scalar superpotential do not spoil cancellation of quadratic divergences

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

Trilinear terms are proportional to the Yukawa couplings

induce L-R mixing in the sfermion sector once the Higgs acquire v.e.v.

→ mixing proportional to fermion masses: relevant for 3rd generation

B → SUSY breaking parameter to be determined from condition of proper EWSB

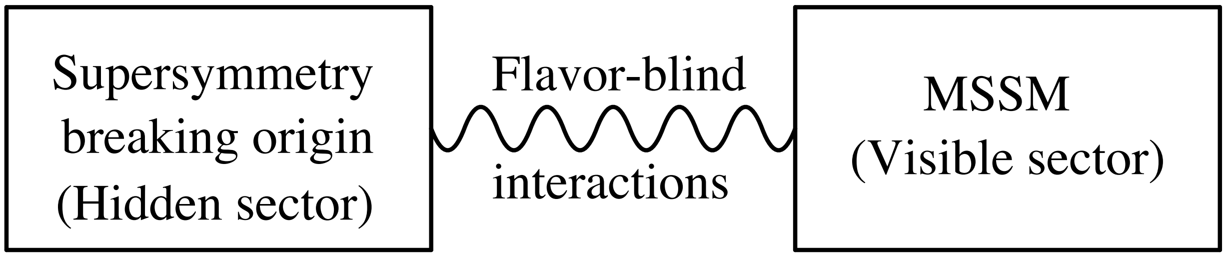
MSSM: 105 new parameters not present in the SM

Most of what we do not really know about SUSY is expressed by the question:
"How is SUSY broken?"

Understanding the origins of Spontaneous SUSY breaking:

Soft SUSY breaking terms arise indirectly,

not through treel level, renormalizable couplings to the SUSY breaking sector



Spontaneous SUSY breaking occurs in a Hidden sector of particles, with none or tiny direct couplings to the MSSM particles, when some components of the hidden sector acquire a vev $< F > \neq 0$

One can think of Messengers mediating some interactions that transmit SUSY breaking effects indirectly from the hidden sector to the MSSM

If the mediating interactions are flavor blind (gravity/ordinary gauge interactions), the MSSM soft SUSY breaking terms will also be flavor independent (favored experimentally)

Many alternatives: Gravity-type; Gauge; Extra Dimensional mediated, ...
$\Longrightarrow$ different boundary conditions at an specific SUSY breaking scale

EWSB IN SUSY: radiatively generated

mSUGRA (CMSSM) example:

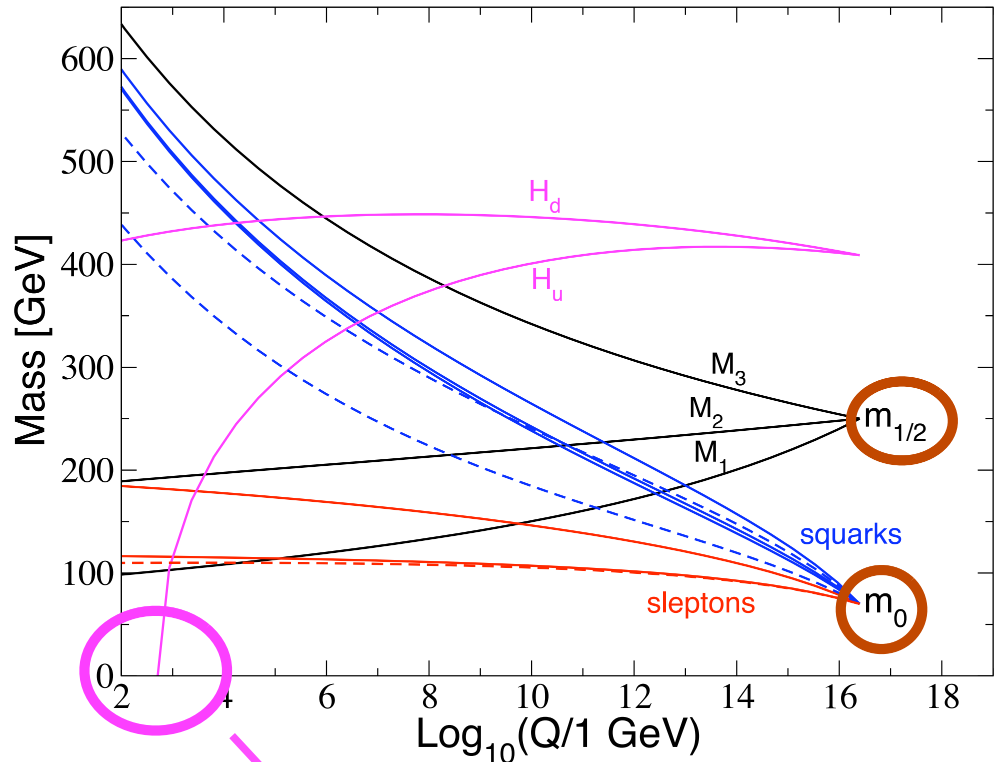
Renormalization group running of the soft SUSY breaking parameters starting with common values m_0 and $M_{1/2}$ for sfermion and guagino masses, respectively

Gaugino masses M_1, M_2, M_3

Slepton masses (dashed=stau)

Squark masses (dashed=stop)

Higgs: $(m^2_{H_u} + \mu^2)^{1/2}$, $(m^2_{H_d} + \mu^2)^{1/2}$



Electroweak symmetry breaking occurs because $m^2_{H_u} + \mu^2$ runs negative near the electroweak scale. This is due directly to the large top quark Yukawa coupling.

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 + $\tilde{G}$

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

Superpartner masses proportional to their gauge couplings.

- Signatures:

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

⋆ 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

The specific pattern of SUSY sparticle masses depend on the SUSY breaking scenario. The crucial question is how much can we learn about it from collider and astroparticle physics experiments

The SUSY Particles of the MSSM

Names	Spin	P_R	Mass Eigenstates	Gauge Eigenstates
Higgs bosons	0	$+1$	$h^0\ H^0\ A^0\ H^\pm$	$H_u^0\ H_d^0\ H_u^+\ H_d^-$
squarks	0	-1	$\widetilde{u}_L\ \widetilde{u}_R\ \widetilde{d}_L\ \widetilde{d}_R$	" "
			$\widetilde{s}_L\ \widetilde{s}_R\ \widetilde{c}_L\ \widetilde{c}_R$	" "
			$\widetilde{t}_1\ \widetilde{t}_2\ \widetilde{b}_1\ \widetilde{b}_2$	$\widetilde{t}_L\ \widetilde{t}_R\ \widetilde{b}_L\ \widetilde{b}_R$
sleptons	0	-1	$\widetilde{e}_L\ \widetilde{e}_R\ \widetilde{\nu}_e$	" "
			$\widetilde{\mu}_L\ \widetilde{\mu}_R\ \widetilde{\nu}_\mu$	" "
			$\widetilde{\tau}_1\ \widetilde{\tau}_2\ \widetilde{\nu}_\tau$	$\widetilde{\tau}_L\ \widetilde{\tau}_R\ \widetilde{\nu}_\tau$
neutralinos	$1/2$	-1	$\widetilde{N}_1\ \widetilde{N}_2\ \widetilde{N}_3\ \widetilde{N}_4$	$\widetilde{B}^0\ \widetilde{W}^0\ \widetilde{H}_u^0\ \widetilde{H}_d^0$
charginos	$1/2$	-1	$\widetilde{C}_1^\pm\ \widetilde{C}_2^\pm$	$\widetilde{W}^\pm\ \widetilde{H}_u^+\ \widetilde{H}_d^-$
gluino	$1/2$	-1	$\widetilde{g}$	" "

MSSM Higgs Sector

→ 2 CP-even h, H with mixing angle α with mixing angle β
1 CP-odd A and a charged pair $H^{\pm}$

$$m_A^2 = m_1^2 + m_2^2 = m_{H_1}^2 + m_{H_2}^2 + 2\mu^2$$

Soft SUSY breaking Higgs mass parameters ($m_{H_1}^2 + m_{H_2}^2$)

$$m_{H^\pm}^2 = m_A^2 + M_W^2 \qquad m_H^2 \simeq m_A^2$$

$$m_h^2 \simeq M_Z^2 cos^2 2\beta + \frac{3m_t^4}{4\pi^2 v^2}\left[log\left(\frac{M_{SUSY}^2}{m_t^2}\right) + \frac{X_t^2}{M_{SUSY}^2}\left(1 - \frac{X_t^2}{12M_{SUSY}^2}\right)\right]$$

Important corrections due to incomplete cancellation of particles and sparticles contributions. Mainly top and stops loops and also sbottom loops for tanb >10

after the Higgs acquires v.e.v., the stop mass matrix reads

$$M_{\tilde{t}}^2 \simeq \begin{bmatrix} m_{Q_3}^2 + m_t^2 & m_t(A_t - \mu^*/\tan\beta) \\ m_t(A_t^* - \mu/\tan\beta) & m_{U_3}^2 + m_t^2 \end{bmatrix}$$

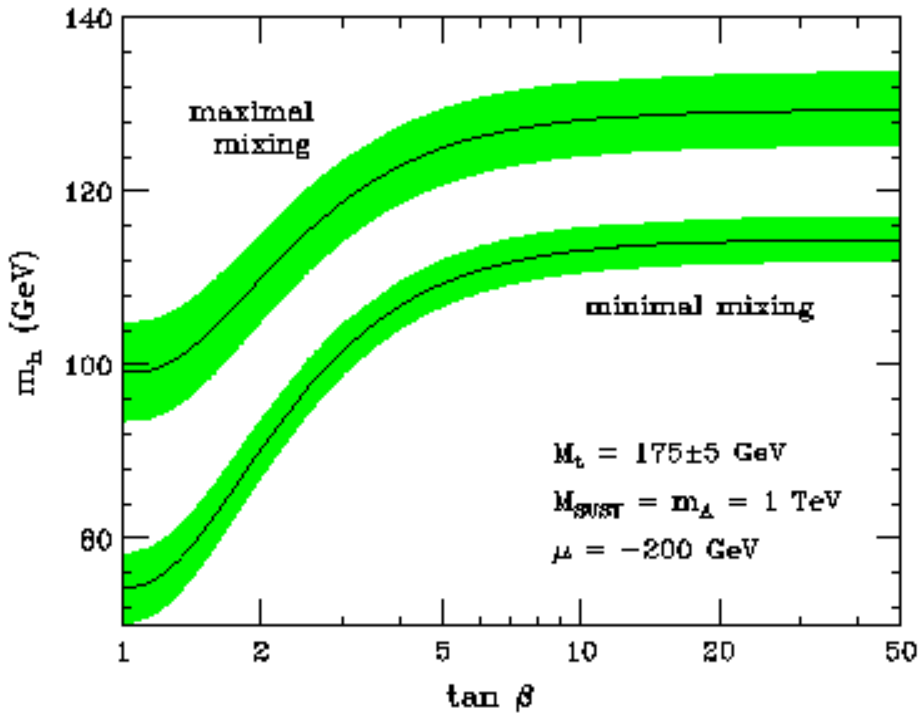
Dependence on SUSY breaking parameters through the stop sector:

$M_{SUSY} \to$ averaged stop mass and stop mixing $: X_t = A_t - \mu/\tan\beta$

and $m_{H_i}^2$

Effect of Quantum Corrections on the Lightest Higgs Mass

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

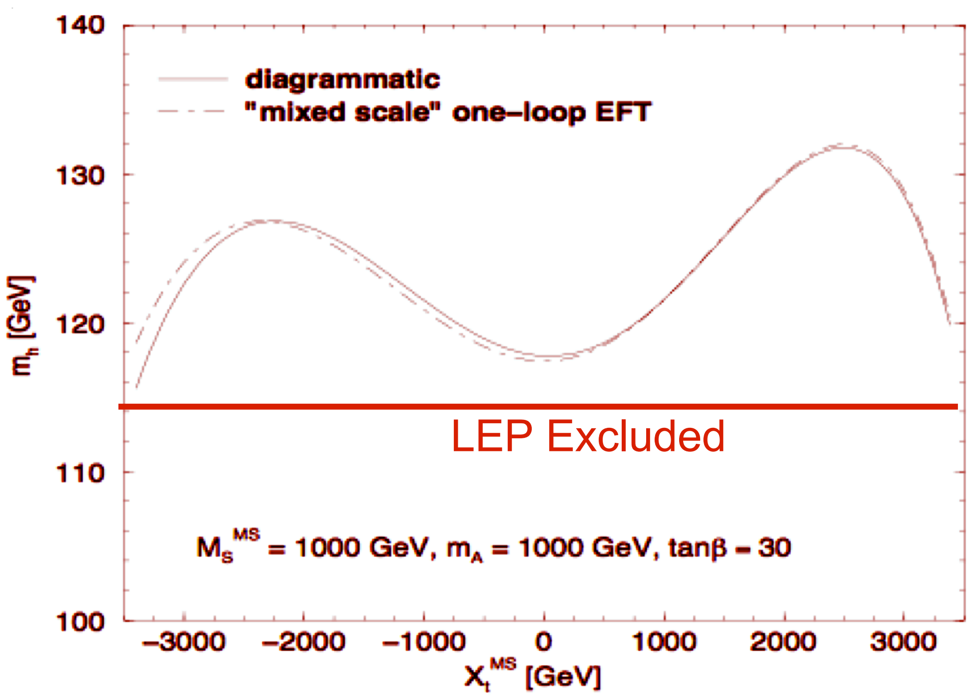


After 2 -loop corrections

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

stringent test of the MSSM

$$M_S = 1 \rightarrow 2 \text{ TeV} \Longrightarrow \Delta m_h \simeq 2 - 5 \text{ GeV}$$
$$\Delta m_t = 1 \text{ GeV} \Longrightarrow \Delta m_h \sim 1 \text{ GeV}$$



MSSM Higgs couplings to gauge bosons and fermions

At tree level: Higgs interactions are **flavor diagonal**

$$\mathrm{hZZ,\ hWW,\ ZHA,\ WH^{\pm}H} \longrightarrow \sin(\beta-\alpha)$$
$$\mathrm{HZZ,\ HWW,\ ZhA,\ WH^{\pm}h} \longrightarrow \cos(\beta-\alpha)$$

Normalized to SM values

$$\mathrm{(h,H,A)}\ u\bar{u} \longrightarrow \cos\alpha/\sin\beta,\quad \sin\alpha/\sin\beta,\quad 1/\tan\beta$$
$$\mathrm{(h,H,A)}\ d\bar{d}/l^+l^- \longrightarrow -\sin\alpha/\cos\beta,\quad \cos\alpha/\cos\beta,\quad \tan\beta$$

$$H^- t\bar{b} \propto [m_t \cot\beta P_R + m_b \tan\beta P_L] V_{tb} \qquad H^- \tau^+ \nu_\tau \propto m_\tau \tan\beta P_L$$

(tanb enhanced)

Quantum corrections to the couplings can be significant:

Vertex corrections to Higgs fermion Yukawa couplings through SUSY particle loops can induce **important flavor changing neutral and charged currents**

Probe the Higgs sector via indirect Higgs searches in rare B meson decays

Depending on SUSY spectrum, radiative corrections to the Higgs couplings can change Higgs searches in a very crucial manner, and open new opportunities

The search for SUSY at Colliders

Depending on the mediation mechanism

and the associated scale of SUSY breaking :

Different initial conditions for the Soft SUSY breaking parameters

↓

Different mass hierarchies among the SUSY particles

Different type of final signatures

large missing $E_{T,}$ energetic and isolated taus or photons, displaced photons,

slow, highly ionazing tracks, long lived gluons, high ET jets,

same sign dileptons. multileptons, ...

Need to overcome large QCD backgrounds and extract a NP signature

Patrice Verdier's Talk

The search for a light Stop at Hadron Colliders

If a SM-like Higgs with mass below 125 GeV is found

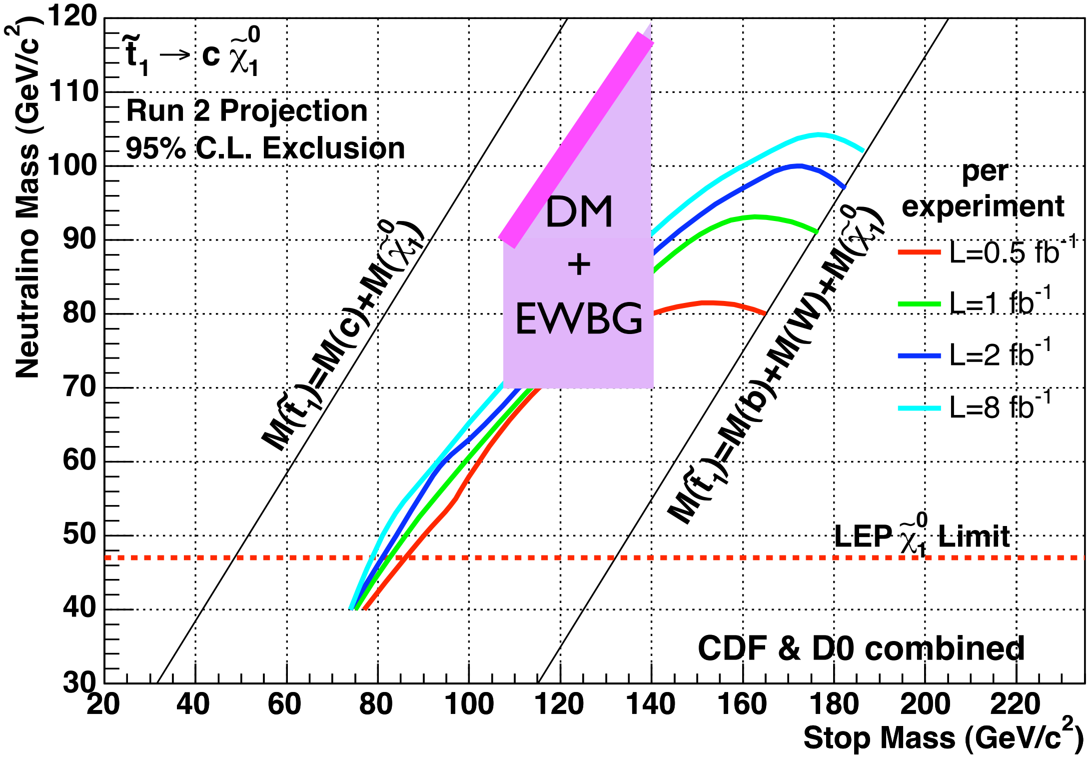
→ light stops will be the next probe of EWBG

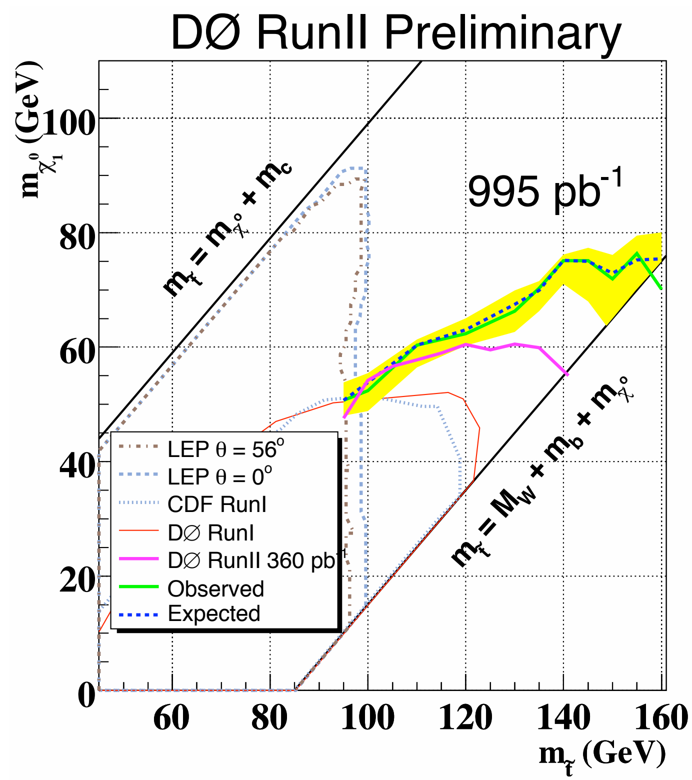
Light Stop models with Neutralino LSP Dark Matter → $\not{E}_T$ signal

→ dominant decay $\tilde{t}_1 \rightarrow c\,\tilde{\chi}_1^0$

For small Stop-Neutralino mass difference: co-annihilation region $\Delta_{m_{\tilde{t}\tilde{\chi}}} < 30$ GeV

→ excellent agreement with WMAP data





Very Challenging for Hadron colliders

Light Stops at the LHC

Kraml, Raklev '06

Same-sign tops in gluino decays

$$pp \to \tilde{g}\tilde{g} \to tt\ \tilde{t}_1^*\tilde{t}_1^*, \qquad t \to bl^+ \bar{\nu}_1 \qquad \tilde{t}_1^* \to c\tilde{\chi}_1^0$$

Signal: 2 SS leptons, 2 SS bottoms, jets plus Missing Energy

Stops with masses ~ 120 – 160 GeV at LHC reach if gluino masses up to ~ 900 GeV

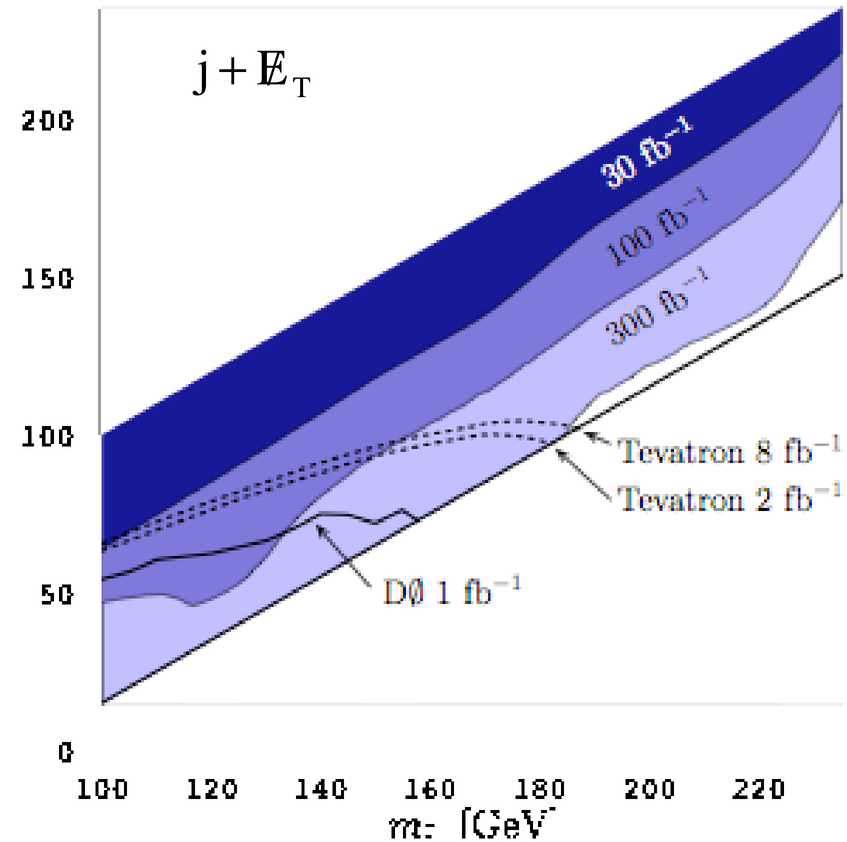
Mass measurements from distributions, but not enough
Independent distributions to get absolute masses

Stop pair production in association with a hard photon or a hard jet

Signal: Photon or Jet + Missing Energy

In co-annihilation region:
minimal activity associated with stop decays

MC, Freitas, Wagner, arXiv0808.2298



MSSM Higgs Boson Searches at colliders

Karl Jacob's Talk

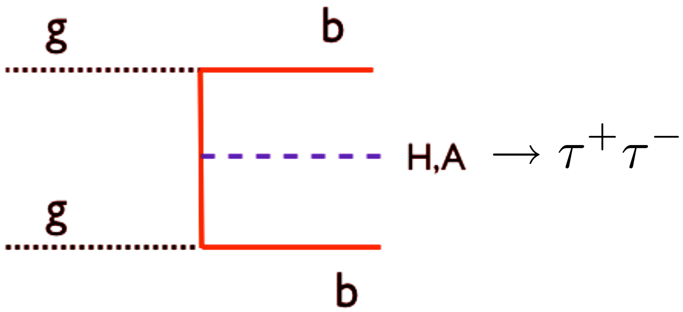
1) Search for a SM-like Higgs responsible for EWSB
must have SM-like couplings to W-Z gauge bosons
and most probably SM-like couplings to the top-quark

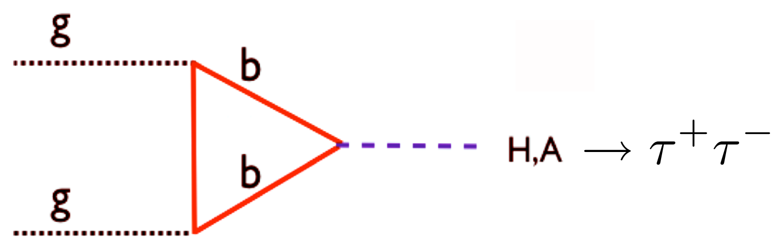
Results as expected for a SM-like Higgs of mass below ~ 135 GeV
hence in the $q\bar{q}H \to \tau^+\tau^-$ and $H \to \gamma\gamma$ channels

2) Search for the non-SM-like neutral Higgs bosons A and H
they have $\tan\beta$ enhanced couplings to the bottom quarks

Higgs searches at colliders

Non-Standard MSSM Higgs searches in inclusive $\tau^+\tau^-$ decays





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

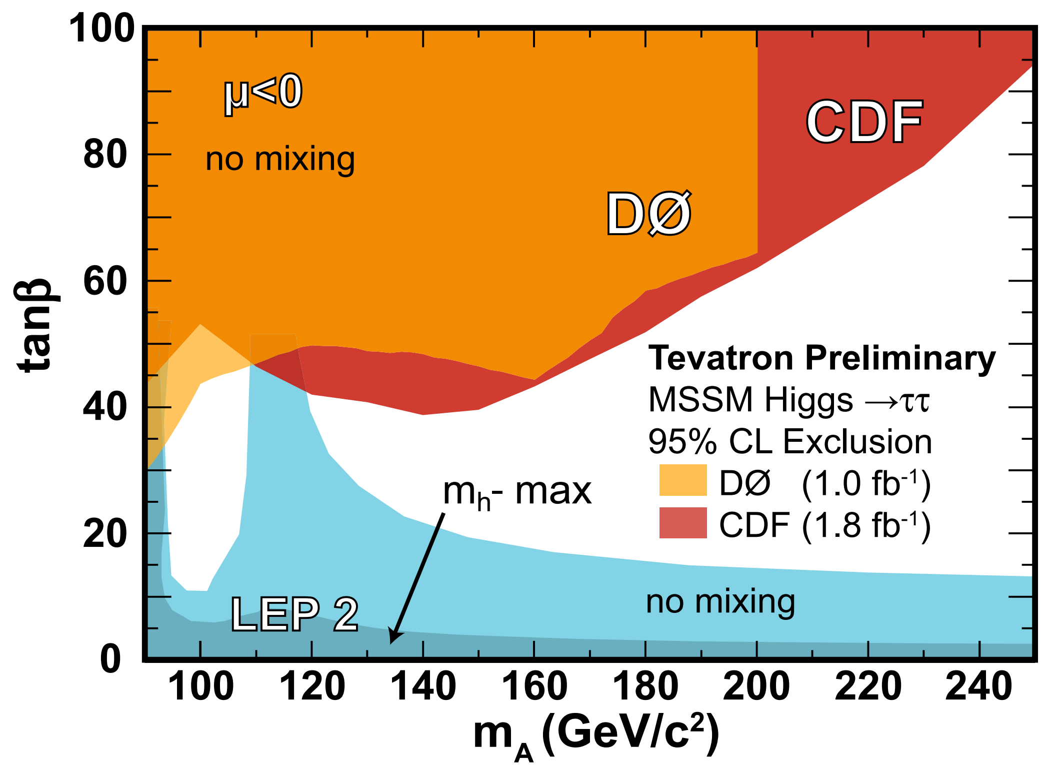
M. C., Heinemeyer, Wagner,Weiglein '05

Important reach for large tanb, small m_A

• Weaker dependence on SUSY parameters via radiative corrections

Also possible to look for bbA/H with A/H decays to bb ==> 4 b's final state BUT, strong dependence SUSY spectrum via radiative corrections and less sensitivity (at the Tevatron)

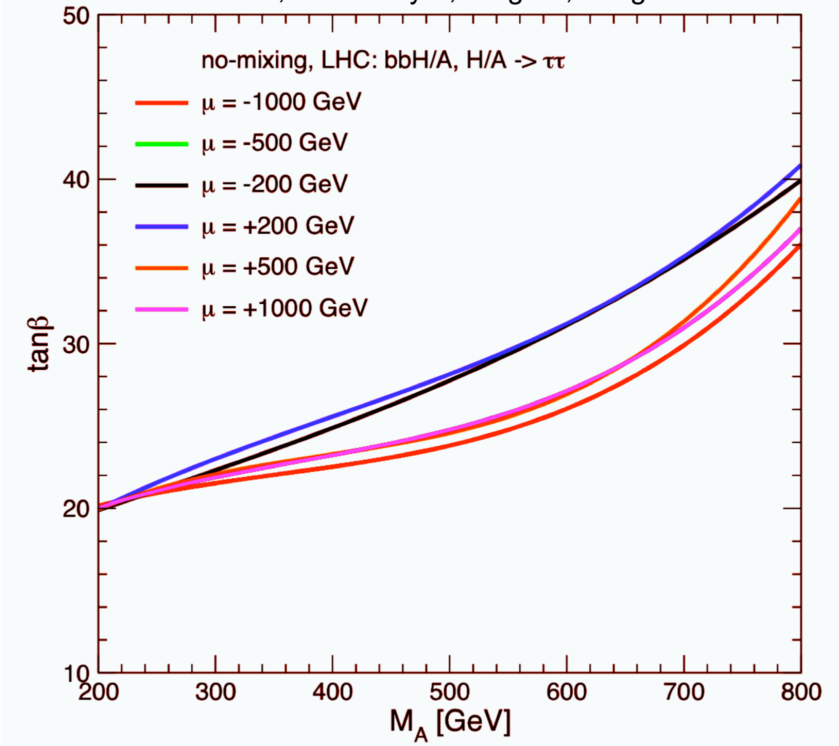
A/H Higgs searches at the Tevatron: The state of the art



Searches for Non-Standard Neutral Higgs bosons at the LHC

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

M.C, Heinemeyer, Wagner, Weiglein



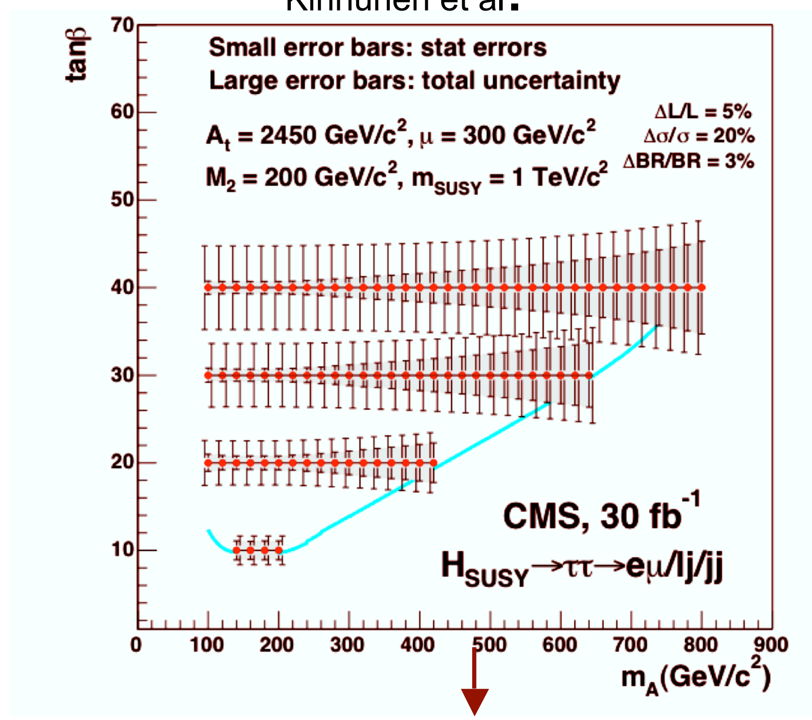
- Enhancement of Hbb and Abb couplings by factor $\tan\beta$ compared with SM Higgs.

  ==> large production cross section

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

  (with different decay modes of tau leptons)

Kinnunen et al.



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

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

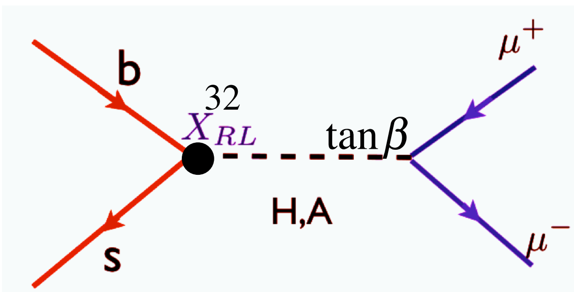
Robustness of results under variations of SUSY space ==>handle on tan beta

Indirect A/H Higgs searches through rare B meson decays

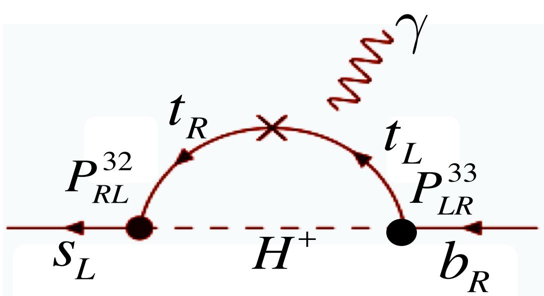
Important Flavor Changing effects: in Minimal Flavor Violation (MFV) scenarios

1) tree level ==> charged Higgs induced via V_{CKM}

2) tan beta enhanced loop corrections both in the neutral and charged Higgs sectors



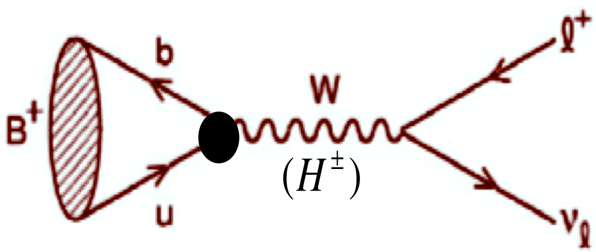
$$BR(B_S \to \mu^+\mu^-)^{SUSY} \propto \frac{|\mu A_t|^2 \tan\beta^6}{m_A^4}$$



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

Δ_b and ϵ_0^3 are vertex corrections to Higgs-fermion couplings depending on the squark mass Matrix structure

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



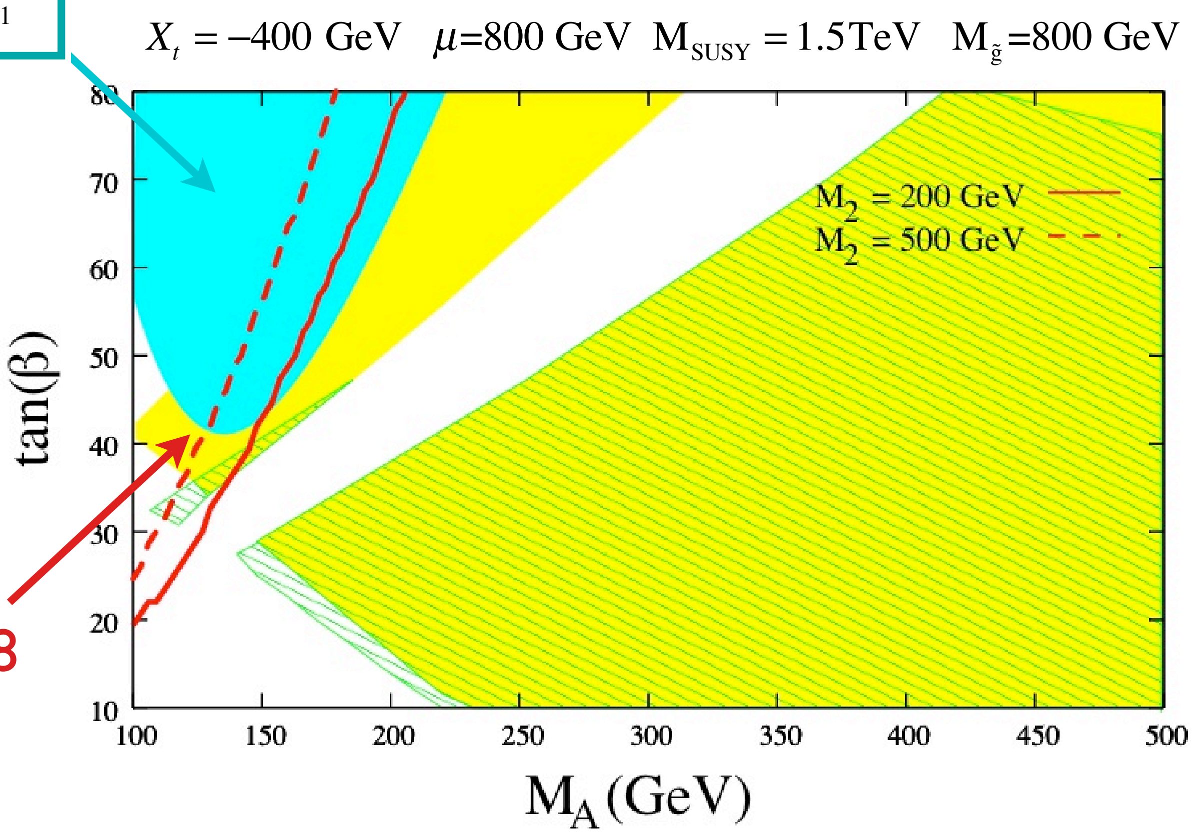
$$\frac{\mathrm{BR}(B_u \to \tau\nu)^{MSSM}}{\mathrm{BR}(B_u \to \tau\nu)^{SM}} = \left[1 - \left(\frac{m_B^2}{m_{H^\pm}^2}\right)\frac{\tan\beta^2}{(1+\varepsilon_0^3 \tan\beta)}\right]^2$$

The interplay among B physics, Higgs Physics and DM in the MSSM

H/A inclusive production, B observables and DM spin-independent cross section all depend on m_A and $\tan\beta$

M.C., Menon Papaqui, Szynkman, Wagner
M.C. Menon, Wagner

$p\bar{p} \to H/A \to \tau^+\tau^-$
excluded : 1.8 fb^{-1}



CDMS 2008
Excluded

Effects of the ~~SUSY~~ scale in MFV models

GREEN (hatched) region:
Allowed in low energy ~~SUSY~~: M = M_{SUSY}

YELLOW region:
Allowed in high energy ~~SUSY~~: M = M_{GUT}

If low energy SUSY is realized in nature, the interplay among these three types of experimental data would be crucial in pinning down the SUSY particle spectrum and, possibly, gain some information about SUSY breaking

EWSB and Strong Interaction Dynamics

New Strong Dynamics at the TeV scale:

EWS broken by critically strong new interactions

Analogy with QCD: scale of EWSB is exponentially separated from M_{Planck} by running of coupling

No Higgs boson: e.g. *QCD-like Technicolor theories, Higgsless 5D models*

Composite Higgs Boson: a strong interaction postulated as an attractive four fermion interaction which forms a quark condensate (bound state boson)

e.g. *Topcolor theories* (gauging of Top condensation)
Top seesaw mechanism (top-vector-like singlet condensate)
Top condensation from Warped ED KK gluons

Pseudo-Nambu Goldstone Higgs Boson:

**associated to a global symmetry partly broken by gauge/yukawa interactions.

Little Higgs Models (valid up to scale of tens of TeV)

** *Gauge Higgs Unification Models* (associated with Warped ED)

EWSB and Strong Interaction Dynamics

Flavour:

Technicolor-like models require many different flavor scales
Extended technicolor to give masses to fermions, but induce FCNC or too small top quark mass ==> Topcolor assisted Technicolor

Precision electroweak bounds:
heavier Higgs vs new fermions/gauge bosons contributions
strongly contrains these scenarios

These theories require a UV completion

What about the connection between theories of strong dynamics and the existence of extra dimensions of space?

Warped Extra Dimension: Elegant solution to the Hierarchy Problem

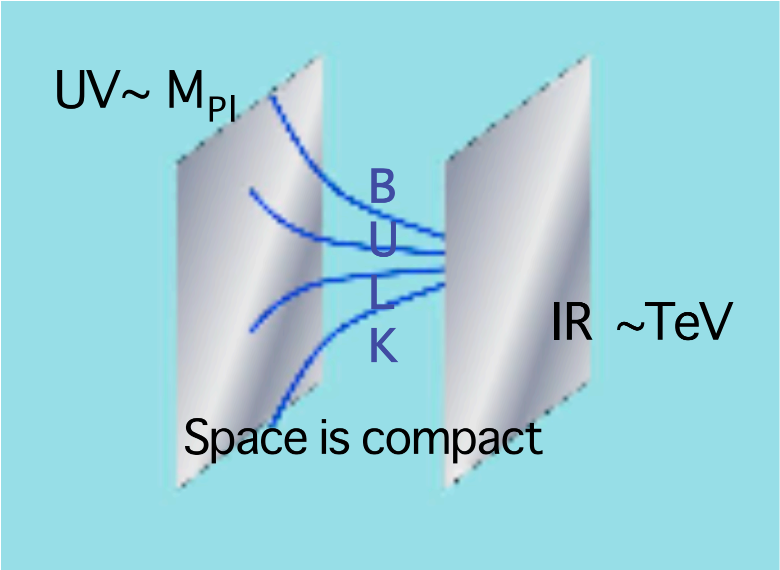
All fundamental parameters at the Planck scale, and yet, due to the curvature of the extra-dimensional metric and the Higgs field localization, the Higgs v.e.v. is naturally of order of the TeV scale

Metric: $ds^2 = e^{-2k|y|}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$ k the AdS curvature

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: $M_{Pl}^{fund.}$

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



Assuming fundamental scales all of same order:

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

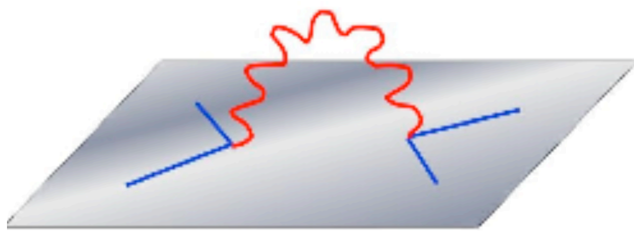
Solution to the hierarchy problem:
Higgs field lives on the TeV brane

with kL~30

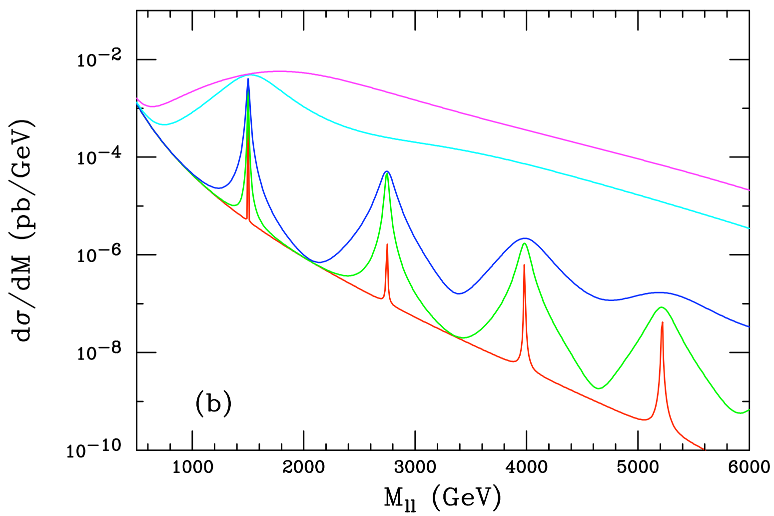
$$\mathrm{v} \sim \tilde{\mathrm{k}} \equiv \mathrm{k\ e}^{-\mathrm{kL}} \approx M_{Pl}\ \mathrm{e}^{-\mathrm{kL}} \sim \mathrm{TeV}$$

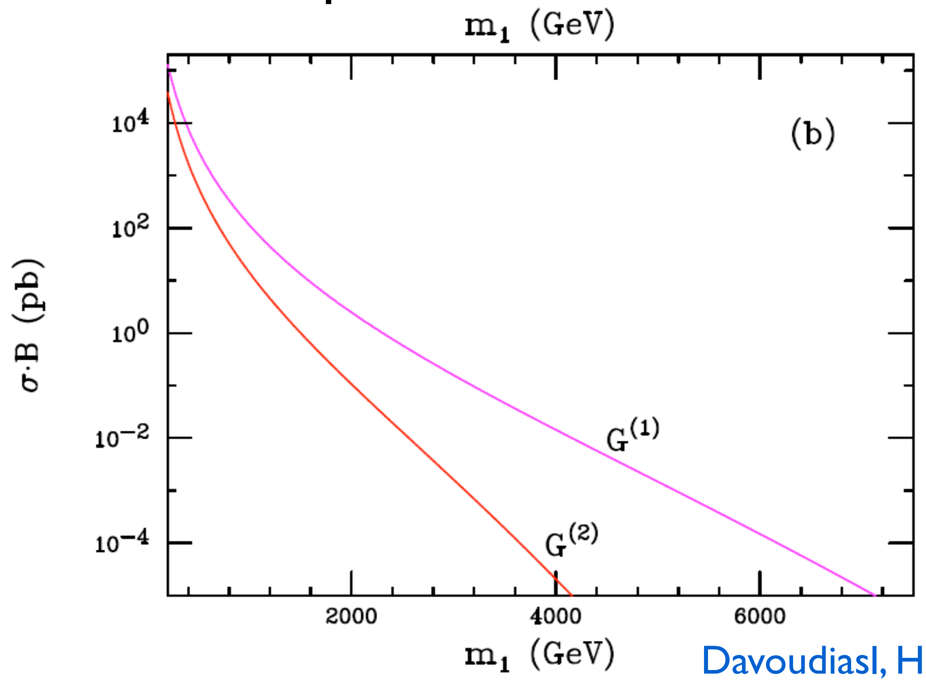
Collider Signatures of Warped ED

If only Gravity propagates in the Warped Extra dimension



KK Gravitons, with masses of the order of the TeV scale and couplings of order 1/TeV to SM particles





Davoudiasl, Hewett, Rizzo

Produced as resonances $pp \to G_N \to e^+e^-$ or contribute to fermion pair production

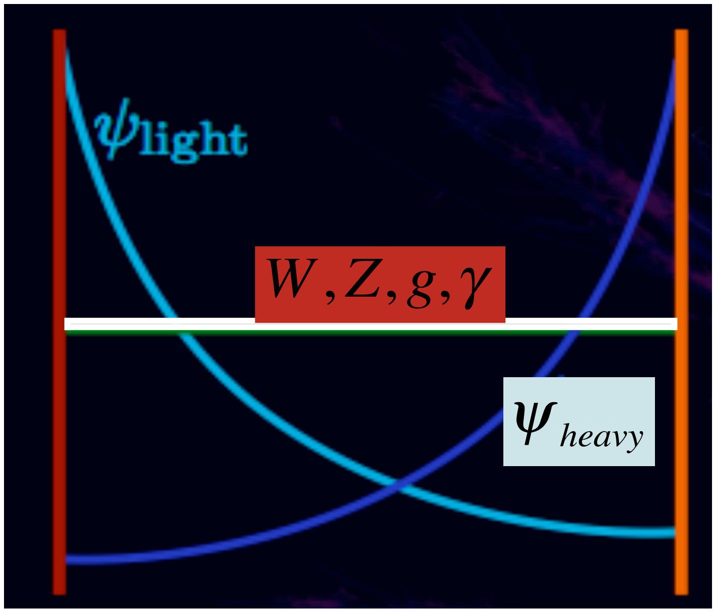
Use angular distributions to determine spin 2 of the resonance

If SM particles propagate in the bulk ==> lower production cross section for KK Graviton (due to light quark & gluon profiles) and main decay to top pairs

Not such a promising signature

Warped Extra dimensions with Matter in the bulk

- Allowing gauge fields and matter to propagate in the bulk
  $\Rightarrow$ models of EWSB, flavor, GUTs, etc.
- Bulk Randall-Sundrum models: several possibilities for model building



UV brane

IR brane
Higgs + KK modes

Higgs or Higgsless (b.c. EWSB)

Hierarchical fermion masses from localization
[masses depend on overlap with Higgs/TeV scale]
FCNC and higher dimensional operators
suppressed for the light fermion families

KK modes localize towards the IR for
* Weak bosons, Gluons, Fermions
* As well as gravitons

Large corrections to the SM gauge boson masses and couplings due to Higgs induced mixing ==> strong EW constraints on the spectrum

$$\tilde{k} \geq 1.5 \text{ TeV} \Rightarrow \text{KK gauge boson masses} > 3\text{TeV}$$

Strong Dynamics at the TeV scale from AdS_5 models of EWSB

Gauge-Higgs Unification models

If there is a Higgs: what is its dynamical origin ?
Or why is it localized towards the TeV brane ?

- Gauge field in 5D has scalar A_5
- To extract H from A_5 need to enlarge SM gauge symmetry.

Gauge sector enlarged in the bulk: SU(2)$_L$ x SU(2)$_R$~S0(4) ==> SO(5)
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

Contino, Nomura, Pomarol 03
Agashe, Contino, Da Rold, Pomarol 05-06

* No tree-level Higgs Potential ==> Induced at one-loop level
* Dynamical EWSB: driven by the top Yukawa

Medina, Shah, Wagner 07

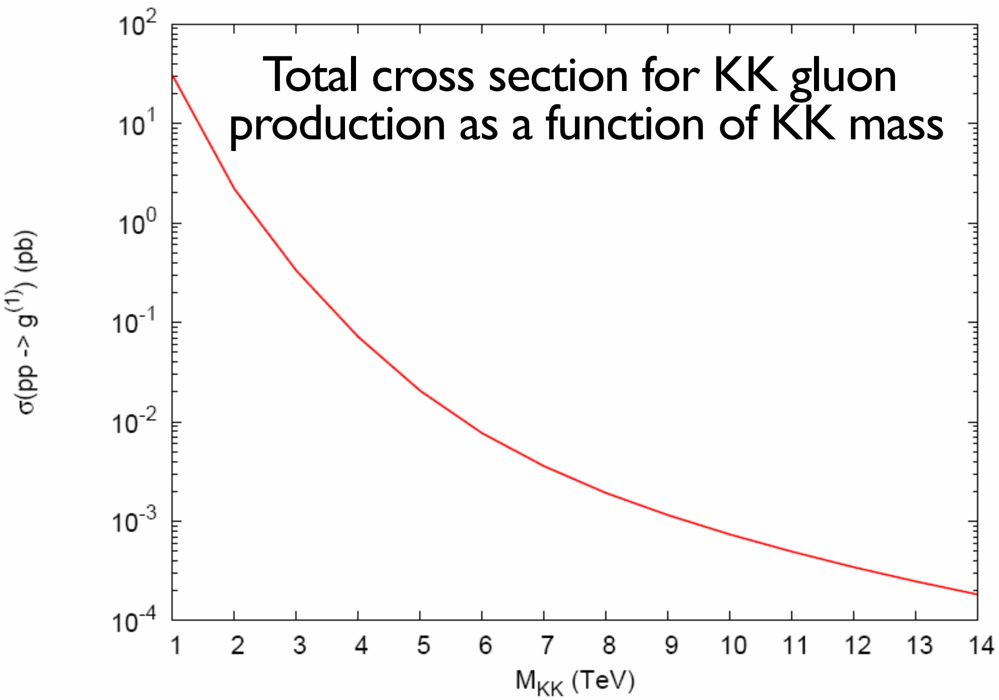
Spectrum:

KK gauge boson's of few TeV,
KK fermions as light as 500 GeV, some with exotic charges.
Enhancement of Higgs signals

Search for KK gluons at the LHC

L. Randall, B. Lillie, L.T. Wang
Agashe, Belyaev, Krupovnickas, Perez, Virzi

- Gluon KK modes are localized towards the IR brane, but its wave function is flat in the bulk, away from IR brane
- This leads to couplings of gluon KK mode with all light fermions of about a fifth of the strong gauge coupling. Equality of couplings of light fermions serves to cancel FCNC



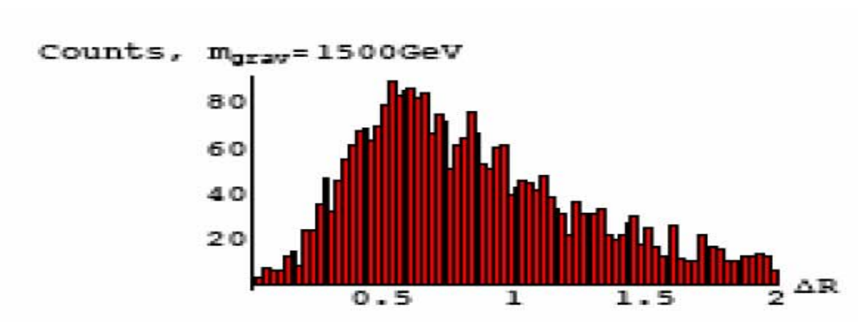
Resulting cross sections still sizable, for KK gluons up to about 4 TeV.

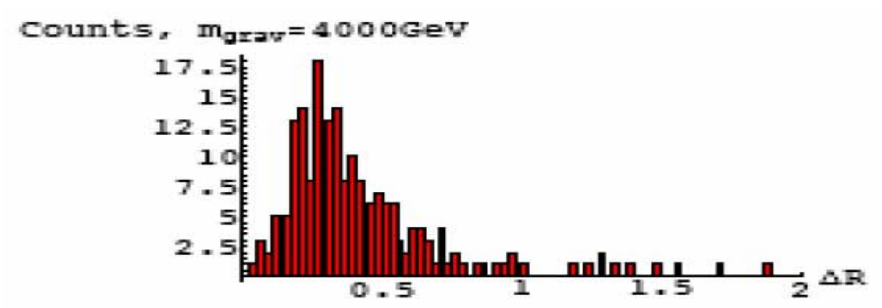
Dominant decay mode of the KK gluon is into third generation quarks, in particular into the right-handed top quark in the simplest models.

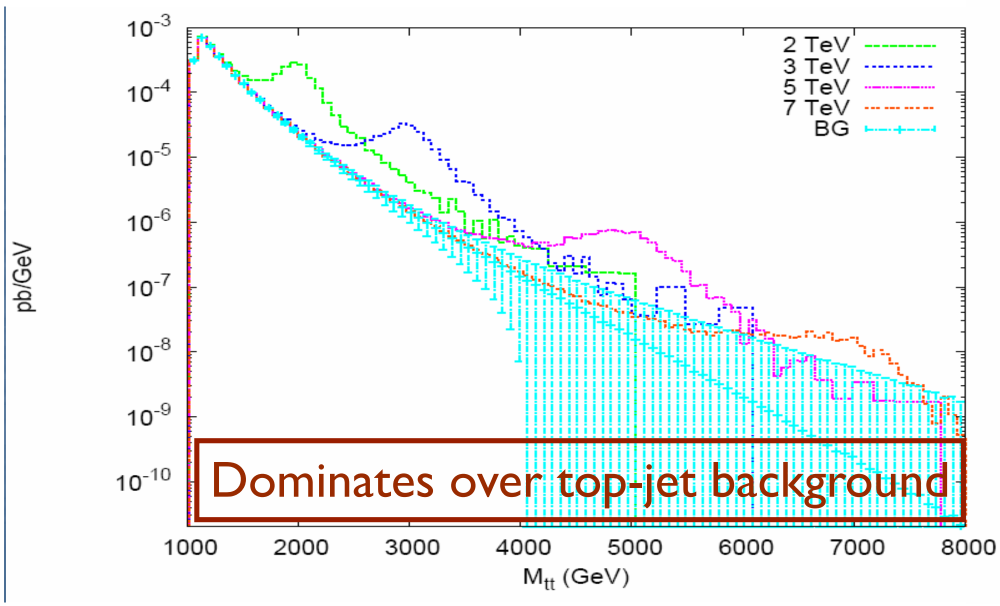
Realistic models may imply a very different L-R hierarchy of KK gluon-top couplings

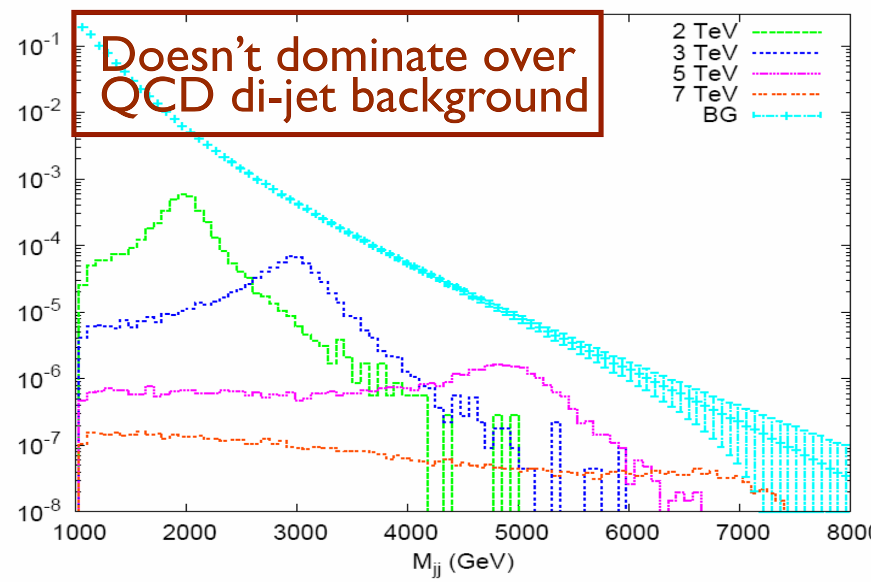
KK gluon decay properties

For heavier KK gluons, top quarks from their decays become more boosted.
The W's and b's are no longer isolated and the top looks more like a massive jet.
This can be seen from the angular separation of the top decay products









** Reach up to a few TeV KK gluons but efficient energetic top jet ID required

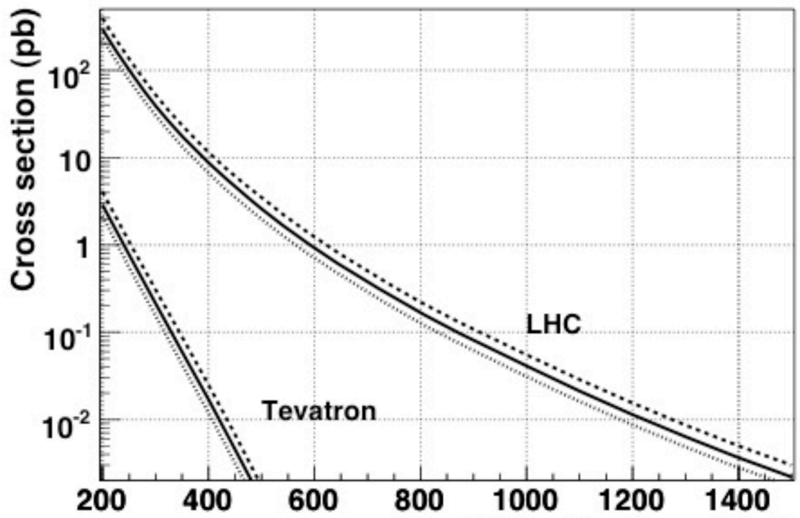
** For sufficiently large KK gluon mass top must be treated as a massive jet and require the jet invariant mass to be close to the top

Fermion KK Spectrum and collider searches (just QCD)

Third generation KK quark excitations
may have mass below 1 TeV

q'	Q	$m_{q'}$ (GeV)	decay
q_1	2/3	369	$q_1 \to Zt$, (20%) $q_1 \to Ht$, (60%) $q_1 \to Wb$, (20%)
q_2	2/3	373	$q_2 \to Zt$, (9%) $q_2 \to Ht$, (70%) $q_2 \to Wb$, (21%)
u_2	2/3	504	$u_2 \to Zt$, (13%) $u_2 \to Ht$, (40%) $u_2 \to Wb$, (41%) $u_2 \to Zq_1$, (1.5%) $u_2 \to Wq'^{d_3}$, (2.5%) $u_2 \to W\chi_2^{u_3}$, (2.%)
$\chi_2^{u_3}$	5/3	369	$\chi_2^{u_3} \to Wt$, (100%)
q'^{d_3}	−1/3	369	$q_2'^{d_3} \to Wt$, (100%)

$\bar{q}' q'$ Production



-- Light KK quark singlet u_2, a **solid** prediction of the model (<==> T parameter)

KK Fermion Signatures from Warped Space at the LHC

3rd. generation KK fermions with masses ~1TeV accessible at the LHC with ~ 100 fb^{-1}

$$pp \to t\bar{t}' \to W^+ b W^- \bar{b} \text{ with one W decaying leptonically}$$

Aguilar-Saavedra '05; Skiba, Tucker-Smith'07; Holdom'07

For smaller masses ~500 GeV < 10 fb^{-1} suffice + observation in Higgs decays viable

Exotic quantum numbers of the KK fermions ==> spectacular new signatures

Quarks with charge 5/3 and -1/3 have similar decay channels:

$$pp \to q'\bar{q}' \to W^+W^-t\bar{t} \to W^+W^+W^-W^-b\bar{b}$$

Non-negligible BR of KK fermion of Q= 2/3 decaying into KK fermion of Q= -1/3

==> $$pp \to u_{2/3}\bar{u}_{2/3} \to W^+ d_{-1/3} W^- \bar{d}_{1/3} \to 4W + t\bar{t} \to 6W + b\bar{b}$$

Channels with 4 or even 6 W's may allow early discovery of q'

MC, Ponton, Santiago, Wagner '07

Dennis, Ünel, Servant, Tseng '07

KK fermions in the decay of KK gluons

- In simple Gauge-Higgs unification models, consistency with precision measurements demands the presence of light KK right handed top quark states.

M.C., E. Ponton, J. Santiago and C. Wagner

- The KK gluon may decay into these additional KK modes, which are strongly coupled to it and decay mostly into weak gauge bosons and third generation quarks,

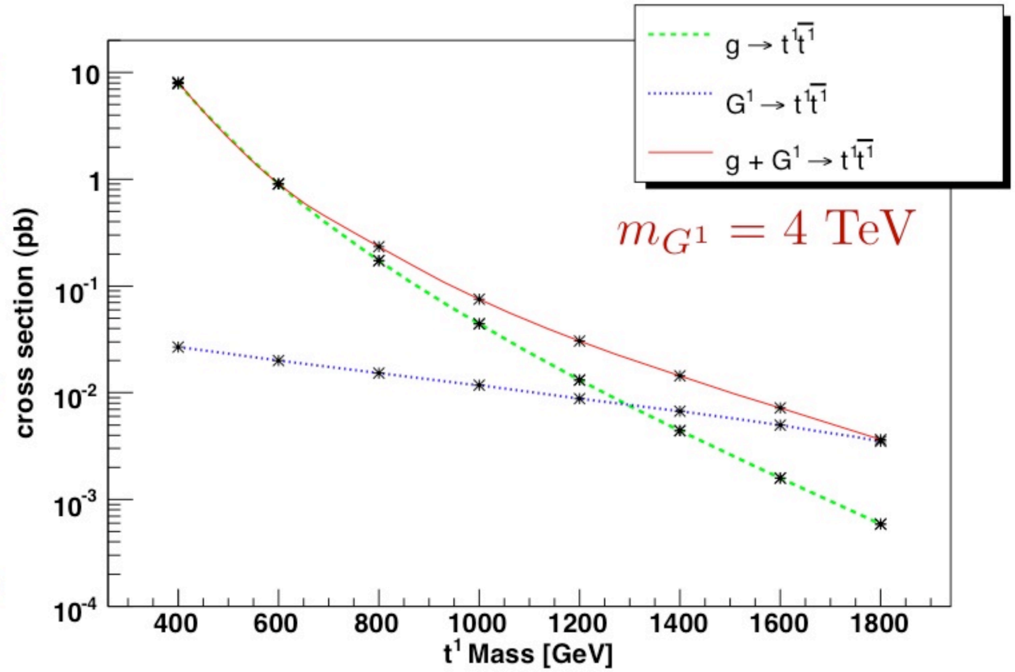
$$\Gamma(t^1 \to Wb) = 2\,\Gamma(t^1 \to tZ) = 2\,\Gamma(t^1 \to Ht)$$

- Fermion KK modes enhance the width of KK gluon and reduces the branching ratio of its decay into top quarks

Gluon KK search becomes very difficult, but search for fermion KK modes still possible, due to constructive interference of contributions to the gluon and KK gluon induced production cross section.

Reach of t^1 up to masses of about 1.5 TeV may be achieved.

Single t^1 production may be used as a complementary channel.



M.C., A. Medina, B. Panes, N. Shah and C. Wagner

The search for the SM Higgs from Warped Space at the LHC

New possibilities for early discoveries:

Recent results: $pp \to T\bar{T} \to W^+bH\bar{t}/HtW^-\bar{b} \to W^+bW^-\bar{b}H$

$pp \to T\bar{T} \to HtH\bar{t} \to W^+bW^-\bar{b}HH$

Aguilar-Saavedra'06

T is a vector-like "singlet" $\Rightarrow BR(T \to Ht) \approx 25\%$

as the SM $t\bar{t}H$ process ==> only channel to search for H to bb at LHC
shown recently to need at least 60 fb^{-1}

Kinematics and high b jet multiplicity, plus m_T mass reconstruction help against tt+nj background

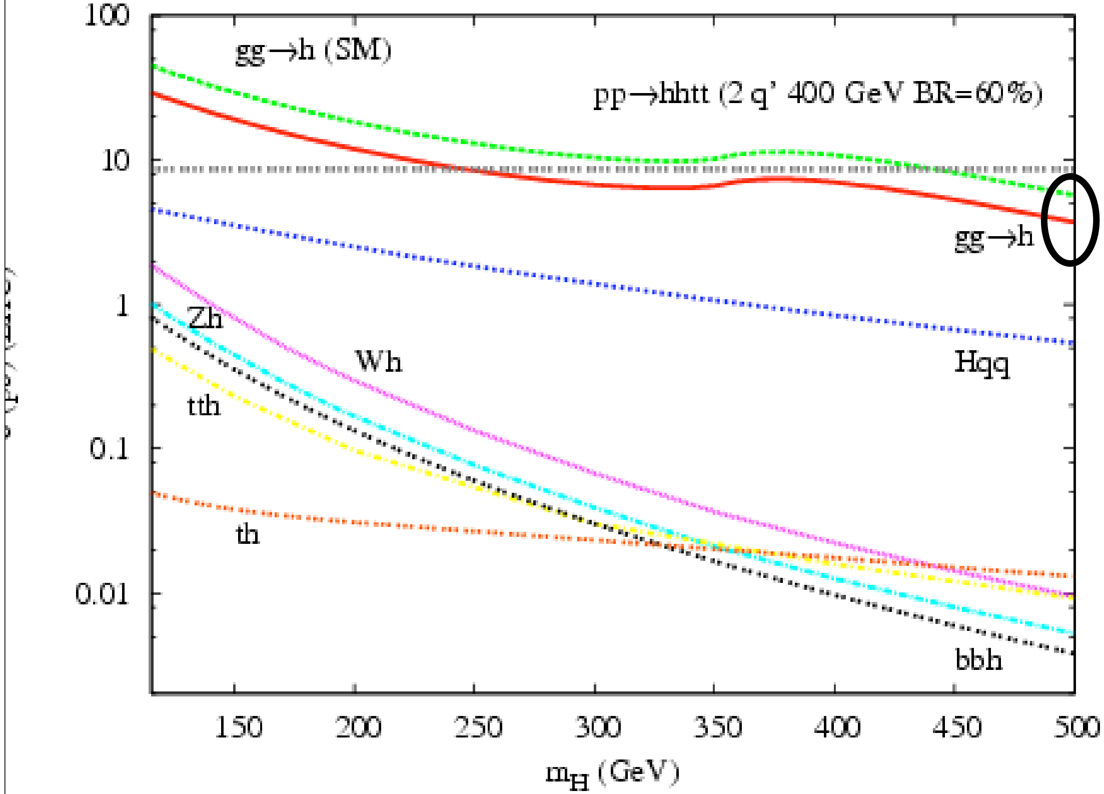
5σ discovery for m_T=500 GeV and m_H=115 GeV with 8 fb^{-1}

Gauge-Higgs Unification models:

multiplicity of KK 3.generation fermion doublets with same mass
+ enhanced BR(t'--> Ht) ~ 40 --70 % ==> Very promising! →

Interesting new possibilities for Higgs searches at the LHC

New Higgs production mechanism mediated by q' pair production



Gluon fusion production reduced up to a factor 0.65

Top mixing with KK modes ==> reduced top Yukawa

Major enhancement of Higgs production by new mechanism associated with q'

(for Mq' ~ 400 - 500 GeV)

$$\sigma(p\bar{p} \rightarrow q'\bar{q}' \rightarrow 2H2j) \sim \sigma(gg \rightarrow H)$$

light 3. generation KK fermions are a solid prediction of the model tied to the mechanism of top quark mass generation

Sizeable enhancement of inclusive Higgs signal. Some backgrounds (WW/ZZ +jets) enhanced

New channels may allow to explore different mass regions

$$p\bar{p} \rightarrow q'\bar{q}' \rightarrow 2H + 2j \rightarrow 4b + 2j$$
$$p\bar{p} \rightarrow q'\bar{q}' \rightarrow 2H + 2j \rightarrow 2b + 2W + 2j$$
$$p\bar{p} \rightarrow q'\bar{q}' \rightarrow 2H + 2j \rightarrow 4W + 2j$$

EWSB from Top Condensation via Radion Stabilization

Bai, M.C, Ponton

- Strong interactions responsible for fermion condensation related to the 5D SU(3)c QCD interactions: Gluon KK modes

- Relaxation of the radion field to the minimum of the potential energy ensures that the fermion closest to the IR brane condenses ($g_{4F} > g_{4F}^c$)
  * strength of the fermion KK gluon coupling depends on fermion localization

- Condensation involves the top quark ==> Topcolor
  To reproduce the top quark mass, a TopSeesaw mechanism is necessary,
  ==> condensate: $< \bar{t}_L \chi_R >$
  With χ_R a linear combination of the top quark and a new vector-like fermion singlet

- Physics that leads to top condensation automatically induces a potential that stabilizes the distance between the UV and IR branes
  ==> the electroweak-Planck hierarchy determined dynamically and the KK scale predicted to be about 35 TeV

Spectrum:

A heavy (composite) SM-like Higgs with mass of about 500 GeV

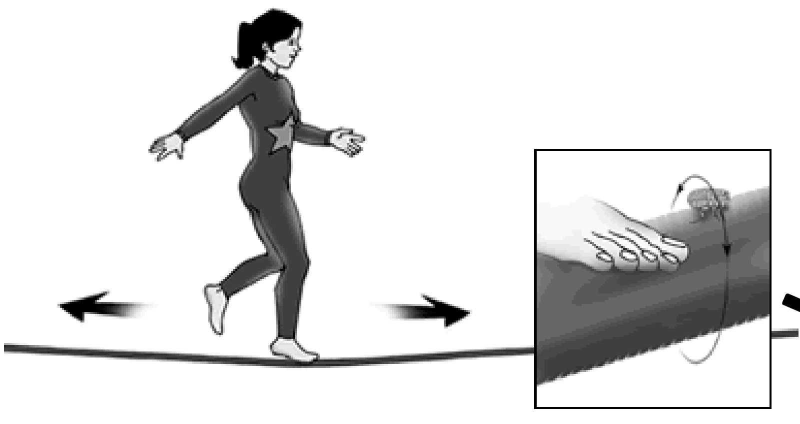
A vector-like "singlet" quark with mass ~1.6 - 3 TeV,
and large mixing with the left top quark via condensation mechanism

Single heavy quark production at LHC with decays into Higgs and gauge bosons plus third generation quarks
Previous studies show sensitivity in the 2 TeV range

A radion with mass a few GeV very weakly coupled to SM particles

KK scale is in the 30 TeV range (No KK excitations accessible at LHC)

Are there Large Extra Dimensions of space?



ED are a prediction of Strings

Can stabilize the Higgs mass

Can provide a DM candidate

each point in space would have additional dimension attached to it

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

Gravity flux in flat ED Newton's law modified: $M_{Pl}^2 = (M_{Pl}^{\mathrm{fund.}})^{2+d}\, R^d$

This lowers the fundamental Planck scale dep. on size & number of ED

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

Solution to Hierarchy problem <==> New problem: Why R so large?

If SM propagates in the ED ==> Universal Extra Dimensions (UED)

, they should be quite small: $R \leq 10^{-17}$ cm $\approx 1/$ TeV

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

As a particle moves in the ED its kinetic energy is converted to a group of massive particles in our 4D world

SM particles + gravitons + tower of new particles:

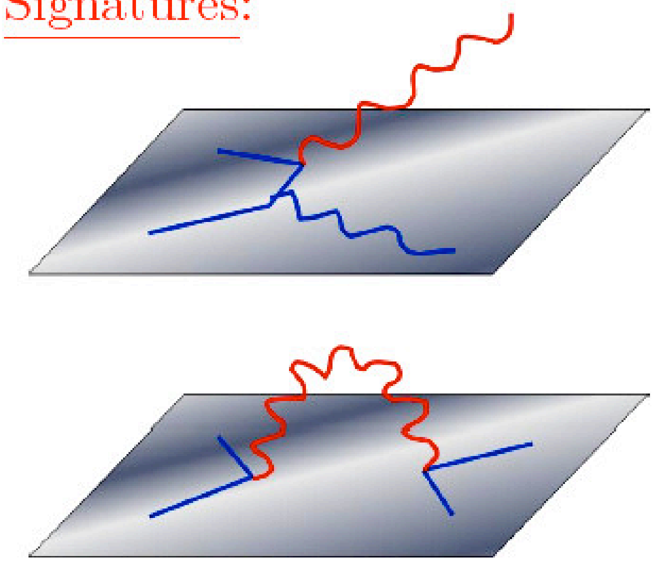
Kaluza Klein (KK) excited states with the same quantum numbers

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

= momentum in the extra dimensions

Signatures:



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

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

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

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

Measuring the masses and behaviour of the new particles would tell us how the ED look like, how many they are.

Extra Dimensions

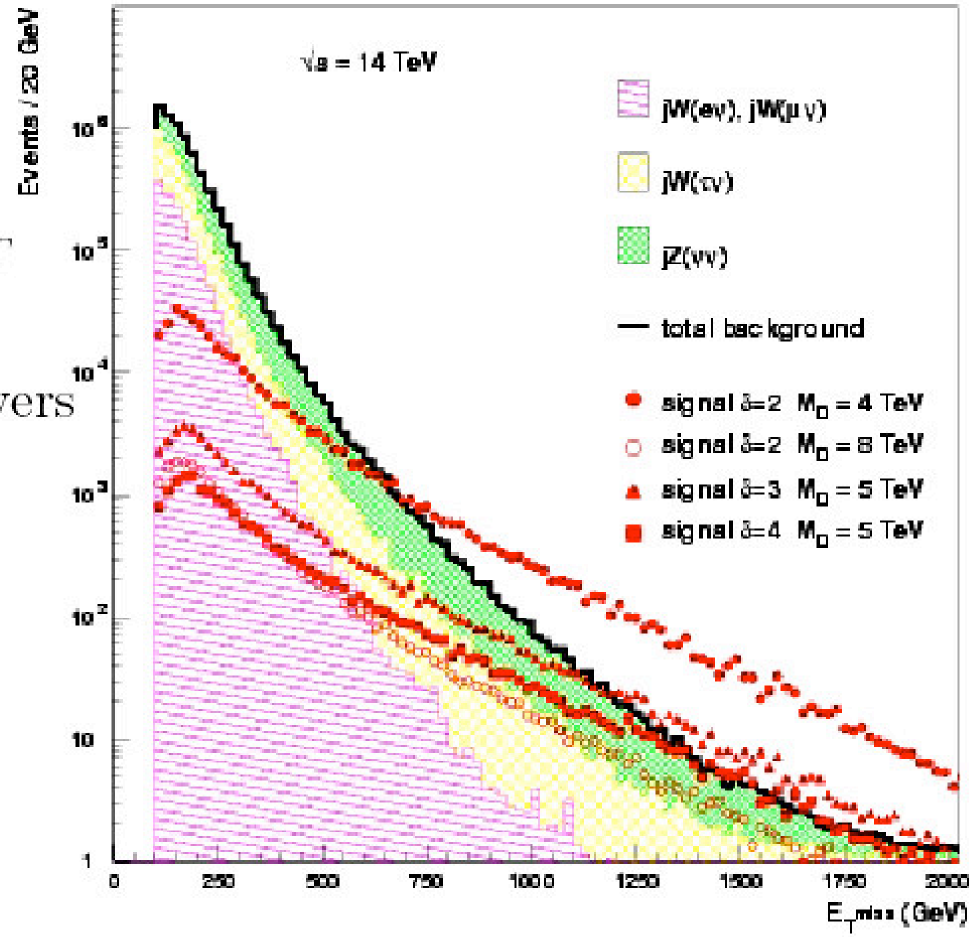
- emission of KK graviton states

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

cross section summed over full KK towers

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

Emitted graviton appears as a continuous mass distribution.



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

Outlook

The SM must be superceded by a more fundamental theory at the TeV scale

Supersymmetry and some (warped) ED inspired, strong dynamics models

may offer elegant solutions to many of the SM unsolved mysteries :

The hierarchy problem

Radiative Generation of EWSB

The existence of a DM candidate

To provide such solutions at least some new particles are expected at the LHC reach, and
A SM-like Higgs (composite or not) is expected to be there as well.

We are about to enter an exciting era in which findings both in particle physics and cosmology

will further revolutionize our understanding of nature

EXTRAS

SUSY Lagrangian

$$\mathcal{L}_{\rm SUSY} = (\mathcal{D}_\mu A_i)^\dagger \mathcal{D} A_i + \left(\frac{i}{2}\bar{\psi}_i\bar{\sigma}^\mu\mathcal{D}_\mu\psi_i + \text{h.c.}\right)$$
$$- \frac{1}{4}(G^a_{\mu\nu})^2 + \left(\frac{i}{2}\bar{\lambda}^a\bar{\sigma}^\mu\mathcal{D}_\mu\lambda^a + \text{h.c.}\right)$$
$$- \left(\frac{1}{2}\frac{\partial^2 P(A)}{\partial A_i \partial A_j}\psi_i\psi_j - i\sqrt{2}gA_i^* T_a \psi_i \lambda^a + h.c.\right) - V_{scalar}$$

SM fermion superpartners + Higgs

SM fermions + Higgsinos

Gauginos

Yukawa interactions

Novel gaugino-scalar-fermion interaction

Gauge bosons in covariant derivatives and in $G_{\mu\nu}$

$$V_{scalar} = \sum_i \left|\frac{\partial P(A)}{\partial A_i}\right|^2 + \frac{1}{2}\sum_a \left(g\sum_i A_i^* T^a A_i\right)^2$$

Quartic couplings governed by gauge couplings crucial for Higgs sector

The Superpotential: $P(A) = \frac{m_{ij}}{2}A_iA_j + \frac{\lambda_{ijk}}{6}A_iA_jA_k$

The superpotential parameters determine the matter field masses and give equal masses to fermions and scalars when the Higgs acquires a v.e.v

$$m_f^2 = m_s^2 = \lambda_{ffh}^2 \, \text{v}^2$$

SUSY Particle Mass Eigenstates

Gaugino/Higgsino Mixing: similar to gauge boson mixing with Goldstone modes after spontaneous EWSB, gauginos mix with the Higgsinos of equal charge

The chargino eigenstates are two Dirac, charged fermions with masses:

$$m^2_{\tilde{\chi}^\pm_{1,2}} = \frac{1}{2}\left[|M_2|^2 + |\mu|^2 + 2m_W^2 \mp \sqrt{(|M_2|^2 + |\mu|^2 + 2m_W^2)^2 - 4|\mu M_2 - m_W^2 \sin 2\beta|^2}\right].$$

- If μ is large, the lightest chargino is a Wino, with mass M_2, and its interactions to fermion and sfermions are governed by gauge couplings.
- If M_2 is large, the lightest chargino is a Higgsino, with mass μ, and the interactions are governed by Yukawa couplings.

The neutralino eigenstates are four Majorana fermions with masses that depend on $M_1 \quad M_2 \quad \mu \quad \tan\beta$

- If the theory proceeds from a GUT, there is a relation between M_2 and M_1, $M_2 \simeq \alpha_2(M_Z)/\alpha_1(M_Z) M_1 \simeq 2M_1$.
- So, if μ is large, the lightest neutralino is a Bino (superpartner of the hypercharge gauge boson) and its interactions are governed by g_1.

The gluino masses are given by the Soft SUSY breaking parameter M_3

The squark and slepton masses are determined by the soft SUSY breaking parameters: m_{Q_i} m_{U_i} m_{D_i} m_{L_i} m_{E_i}

with i= family indices 1-3

Example: the Stop Sector

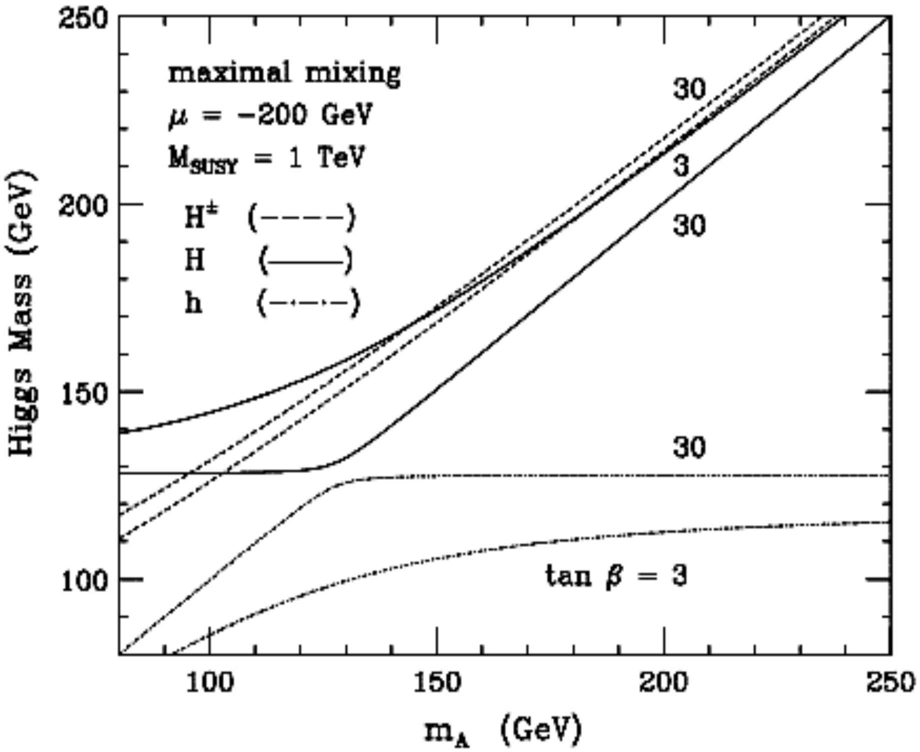
- Once the Higgs acquires a v.e.v., the mass matrix is

$$M_{\tilde{t}}^2 \simeq \begin{bmatrix} m_{Q_3}^2 + m_t^2 & m_t(A_t - \mu^*/\tan\beta) \\ m_t(A_t^* - \mu/\tan\beta) & m_{U_3}^2 + m_t^2 \end{bmatrix}$$

Only for the 3rd generation the Left-Right mixing effects are relevant since they are proportional to the quark masses

In the Sbottom/Stau sectors, the mixing is proportional to: $\mathbf{m_{b.\tau}(A_{b,\tau}} - \mu\tan\beta)$ and becomes relevant for large $\tan\beta$

MSSM Higgs Masses as a function of M_A



$$m_H^2 \cos^2(\beta-\alpha) + m_h^2 \sin^2(\beta-\alpha) = [m_h^{max}(\tan\beta)]^2$$

- $\cos^2(\beta-\alpha) \to 1$ for large $\tan\beta$, low m_A
  $\Longrightarrow$ H has SM-like couplings to W,Z
- $\sin^2(\beta-\alpha) \to 1$ for large m_A
  $\Longrightarrow$ h has SM-like couplings to W,Z

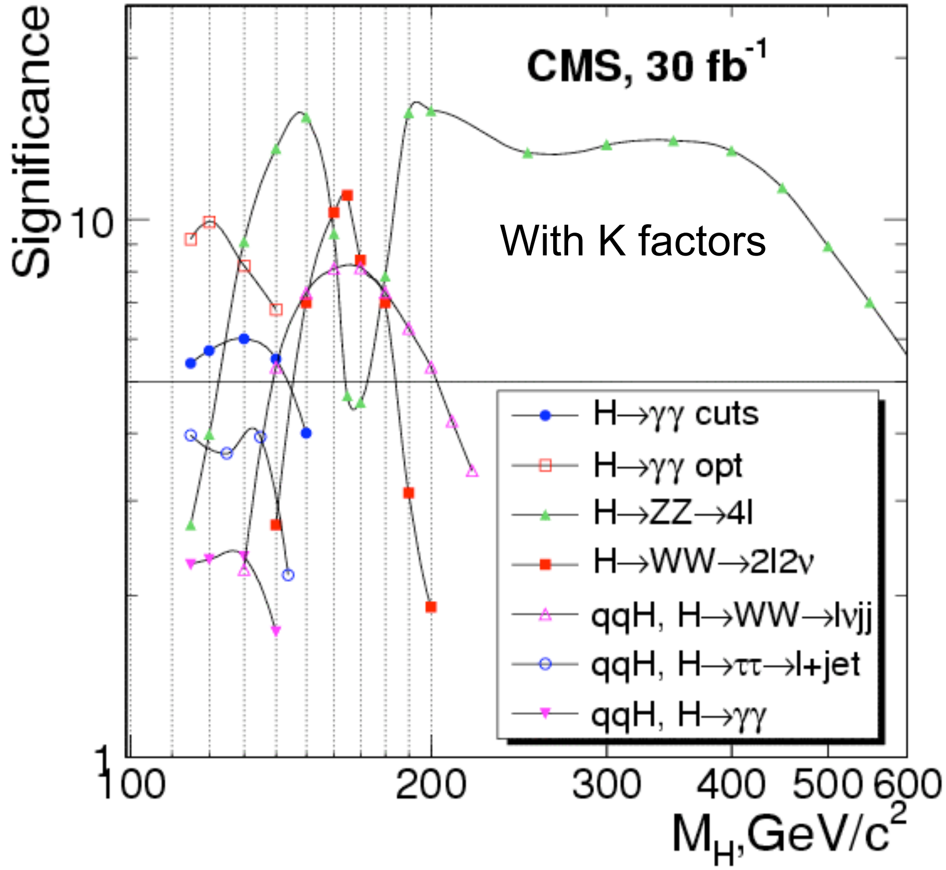
for large $\tan\beta$:
always one CP-even Higgs with SM-like couplings to W,Z
and mass below $m_h^{max} \le 135$ GeV

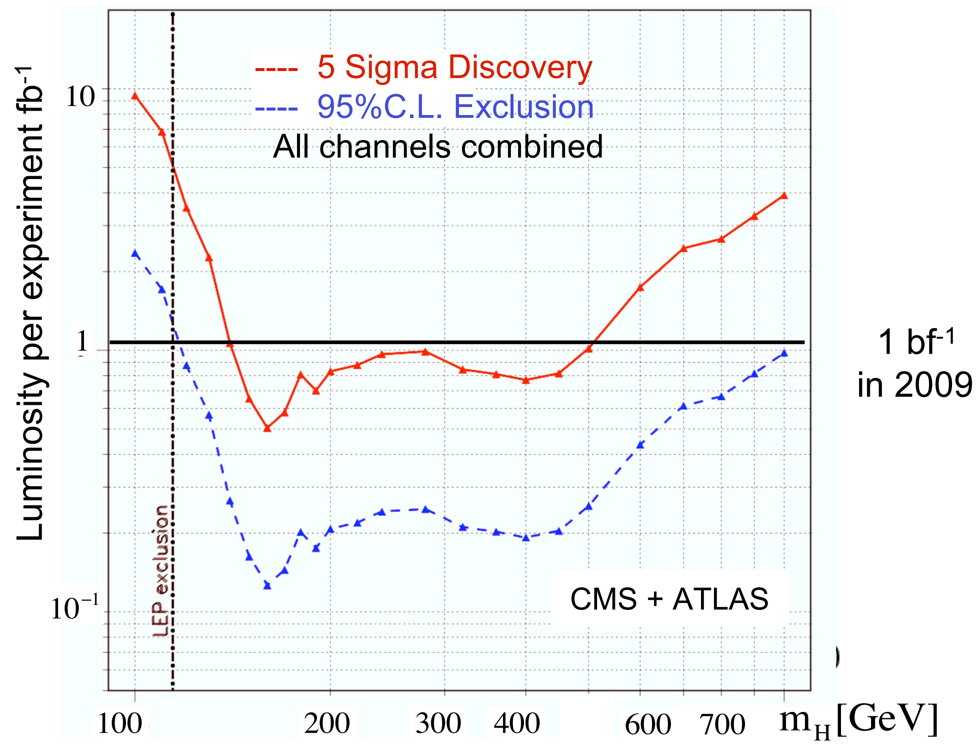
↓

if $m_A > m_h^{max}$ $\rightarrow$ $m_h \simeq m_h^{max}$ and $m_H \simeq m_A$
if $m_A < m_h^{max}$ $\rightarrow$ $m_h \simeq m_A$ and $m_H \simeq m_h^{max}$

m_A nearly degenerate with m_h or m_H

LHC Discovery Potential of a SM Higgs





- **Low mass range** $m_{H_{SM}}$ < 200 GeV

$$H \to \gamma\gamma, \tau\tau, bb, WW, ZZ$$

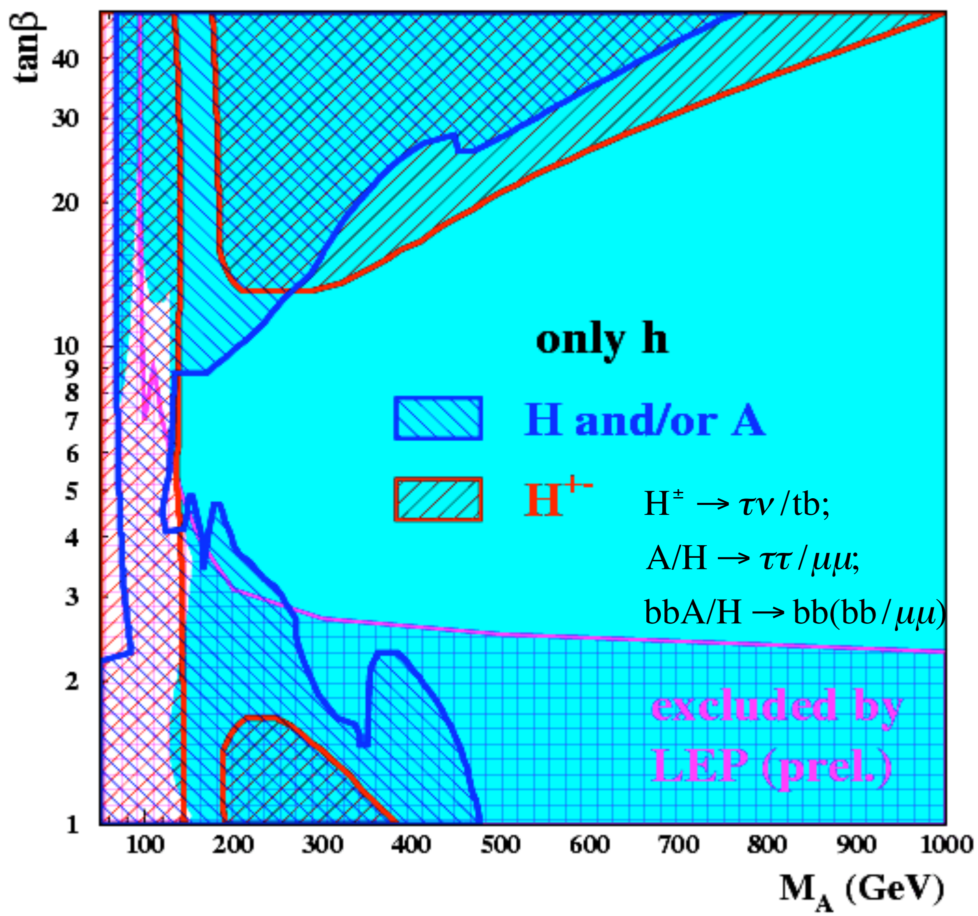
- **High mass range** $m_{H_{SM}}$ > 200 GeV

$$H \to WW,\ ZZ$$

A SM Higgs cannot escape detection at the LHC

Many Higgs production and decay processes accesible with full LHC potential

ATLAS and CMS with 300fb-1



Still regions where only a SM-like Higgs is visible

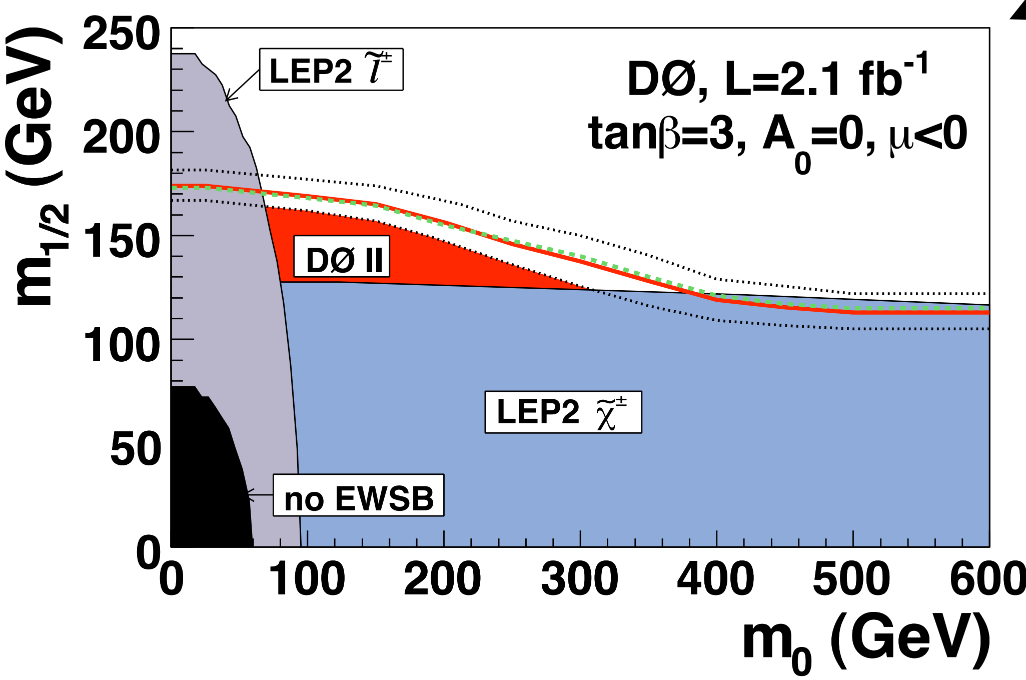
Squark and Gluino Searches

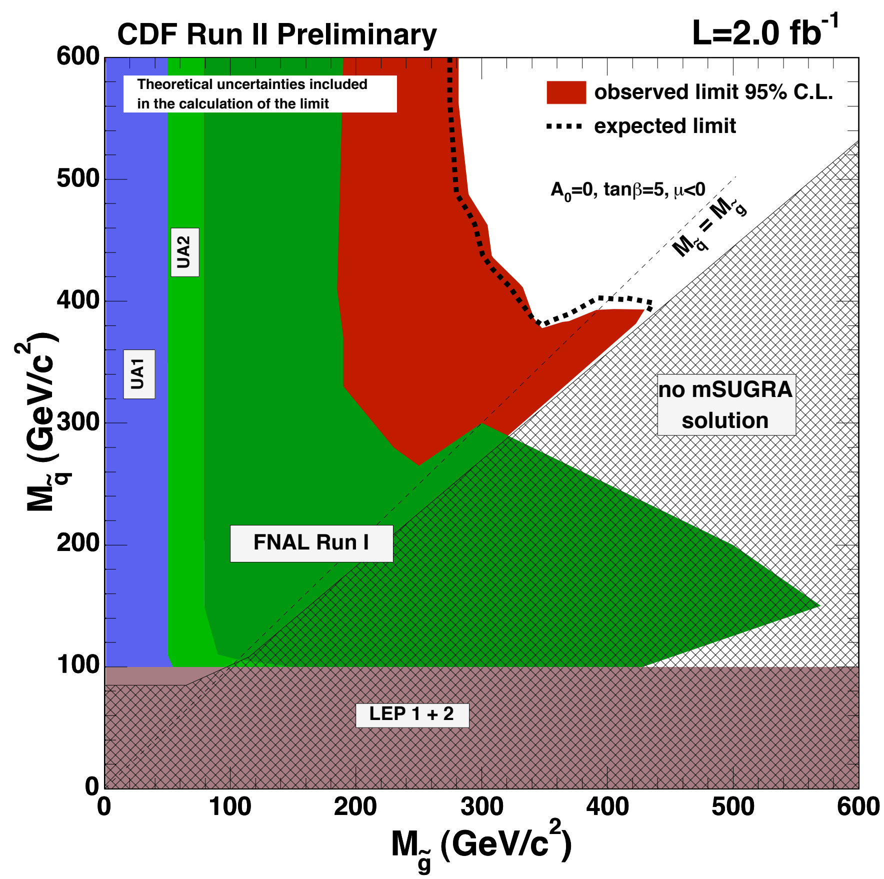
strong interacting particles are produced at large rates at hadron colliders

- most likely types of signatures:
  - ‘mSUGRA’ type – high E_T jets and $\not{E}_T$ (maybe lepton

At the Tevatron

no evidence for squarks or gluinos up to masses of ~ 300-400 GeV





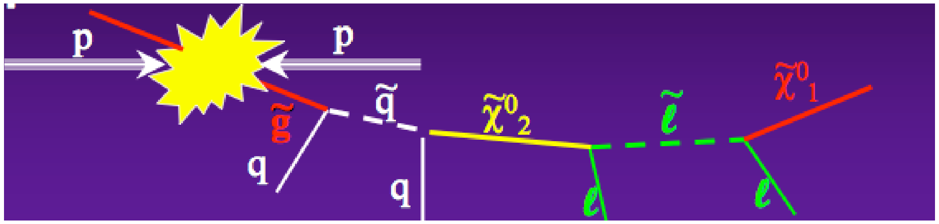
At low energy: $m_{\tilde{q}}^2 \simeq m_0^2 + 6M_{1/2}$

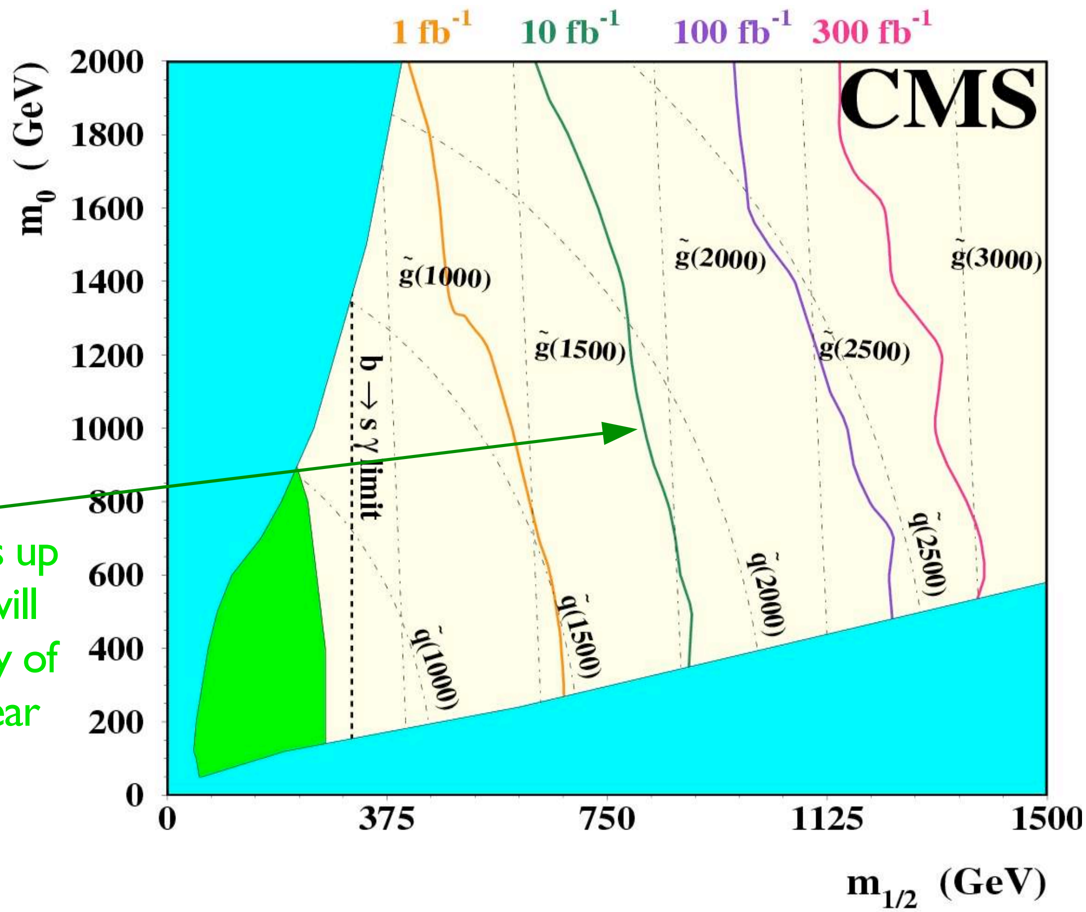
$$m_{\tilde{g}}^2 \simeq 2.5M_{1/2}$$

MET signals at the LHC

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

Typical SUSY event at LHC





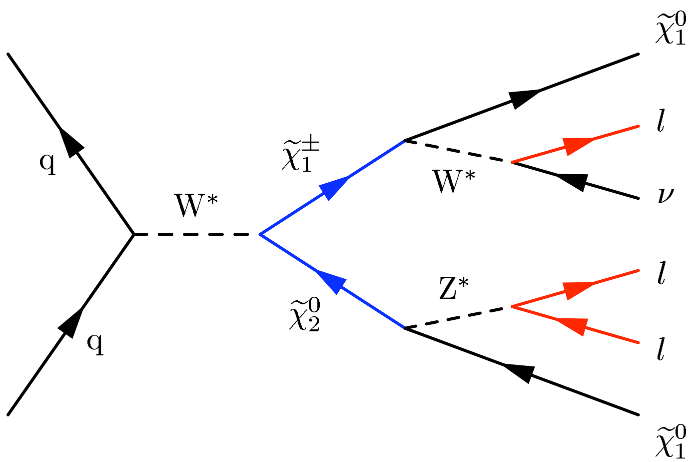
Once the LHC is up and running, it will deliver luminosity of 10 fb^{-1} in one year

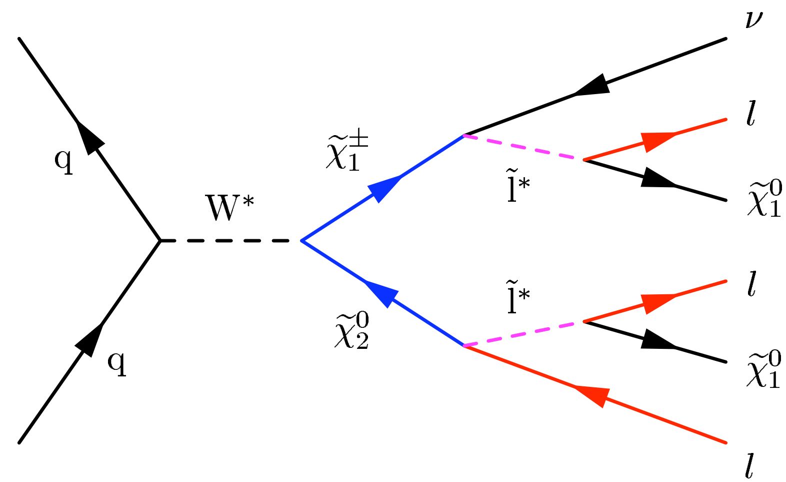
If low energy SUSY exists, we expect to see some of its signatures at LHC

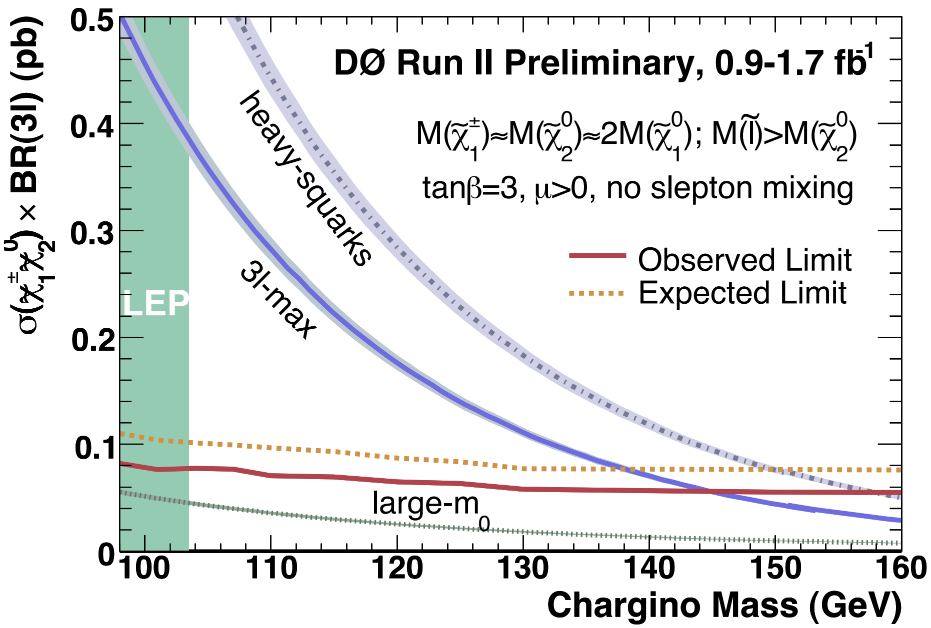
reach: $M_{\tilde{q}}$ *and* $M_{\tilde{g}}$ *up to to* ~ 2 *TeV with 10* fb^{-1}

Chargino/Neutralino Searches

Tri-lepton + lots of MET







No evidence at the Tevatron

At LHC, dilepton and trilepton signatures can be very powerful.

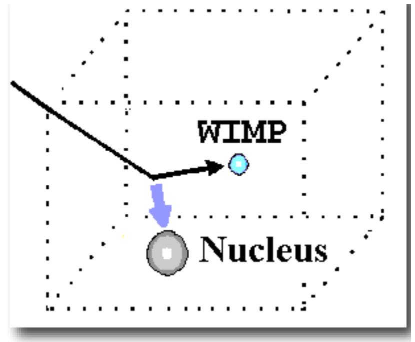
We might be able to infer masses of SUSY particles or mass combinations using kinematic endpoints

mass determination with 10% accuracy

Indirect Higgs Searches through Direct Dark Matter Searches

Direct DM experiments: WIMPs elastically scatter off nuclei in target; observe nuclei recoils

CDMS, XENON, COUPP, others

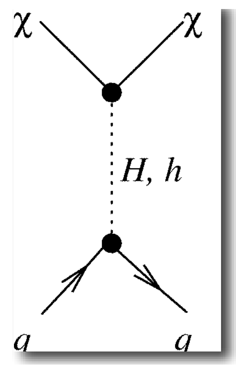


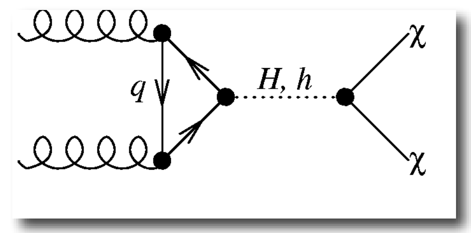
Sensitive mainly to spin-independent elastic scattering cross section ⟶ $\sigma_{SI} \leq 10^{-8}\, pb$

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

↓

tan β enhanced couplings for H





$$\sigma_{\chi N} \sim \frac{g_1^2 g_2^2 |N_{11}|^2 |N_{13}|^2\, m_N^4}{4\pi m_W^2 \cos^2\beta\, m_H^4} \left(f_{T_s} + \frac{2}{27} f_{TG} \right)^2, \quad (m_{\tilde{q}}\,\text{large}, \cos\alpha \approx 1).$$

Smaller μ values imply larger Higgsino component, N_{13}, of the LSP $\Rightarrow$ larger σ_{SI}

Dark Mater in Universal Extra Dimensions

5D UED has a Z_2 symmetry (KK-parity):
lightest KK mode stable and a good DM candidate

- 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.

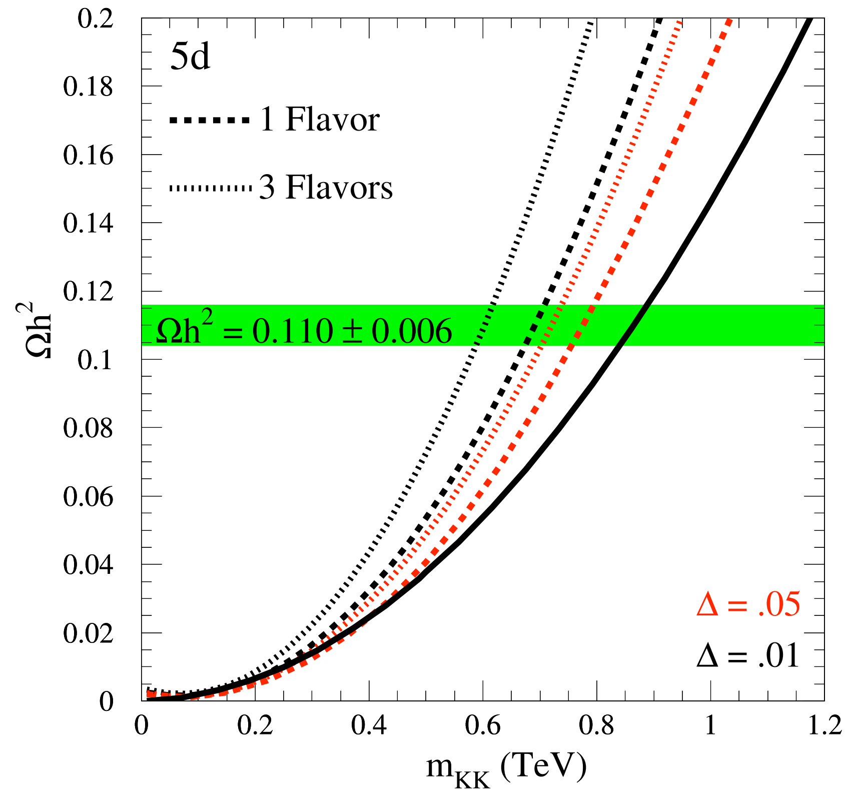
- KK modes produced by pairs

- no big corrections to EW observables

- Lightest Kaluza-Klein Particle (LKP)

$\longrightarrow$ **good dark matter candidate**

Tait, Servant



Enhancing the potential of early Higgs discoveries

- H--> Z Z decay channel

$$B \equiv BR(H \to ZZ) \sim 0.02 - 0.25$$

for $m_H \sim 120 - 200$ GeV

$$\sigma(H \to ZZ)_{incl.} \approx 2\sigma(q\bar{q}')B(2-B) + \sigma(gg \to H)B$$

Enhancement of the inclusive H -> ZZ channel on the order of a few

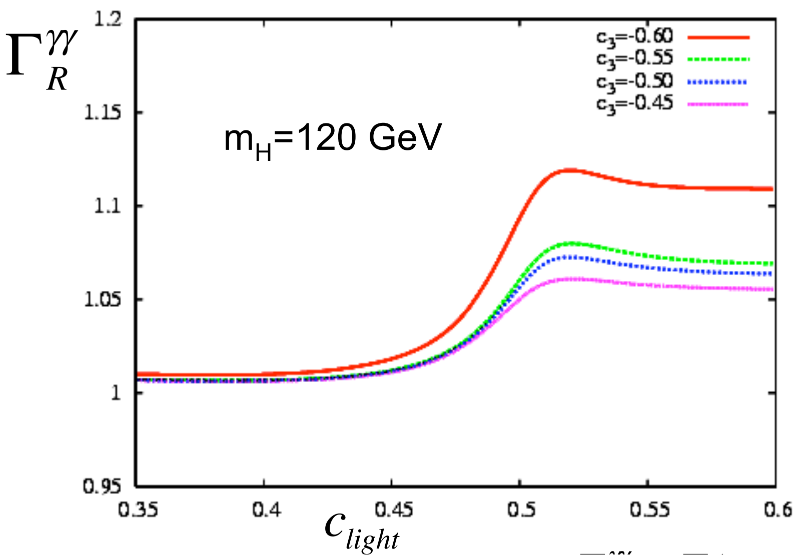
Also, larger background due to new KK quarks decaying to Z+j

Probably Higgs mass reconstruction sufficiently precise to cut this background

- $H \to \gamma\gamma$ decay rate slightly enhanced + advantage of enhanced production.

  Backgrounds in this channel are not increased by other q' decay modes

$$\Gamma_R^{\gamma\gamma} \equiv \Gamma(H \to \gamma\gamma)/\Gamma(H \to \gamma\gamma)_{SM}$$



If 3 generations of light KK fermions are present ==> many sources of enhancement of Higgs production mediated by these light new fermions

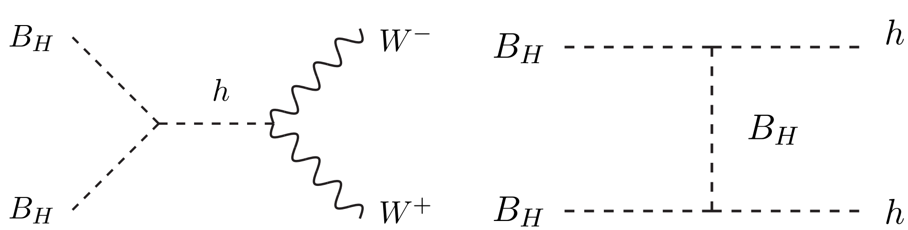
Discovering the Higgs boson from KK fermions decays implies the discovery of the KK fermions

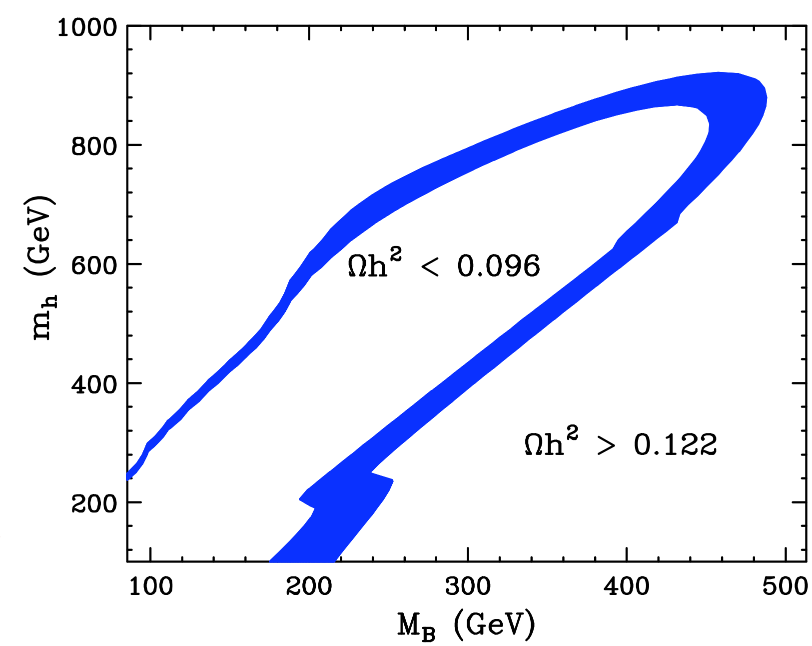
Dark Mater in Universal Extra Dimensions

6D UED also has KK-parity. 4D- KK particles are labeled by 2 positive integers (j,k) Particles are odd under KK parity if j+k is odd. The lightest odd mode (1,0) is stable

One loop corrections to masses in 6DSM ⟶ LKP is a linear combination of the electrically neutral spin-0 adjoint of the EW gauge group ==> "spinless photon" B_H

Main annihilation channels into WW, ZZ and hh (t-pairs for light M_B)





Observed relic density thermally generated for M_B < 500 GeV

Extra Dimensions

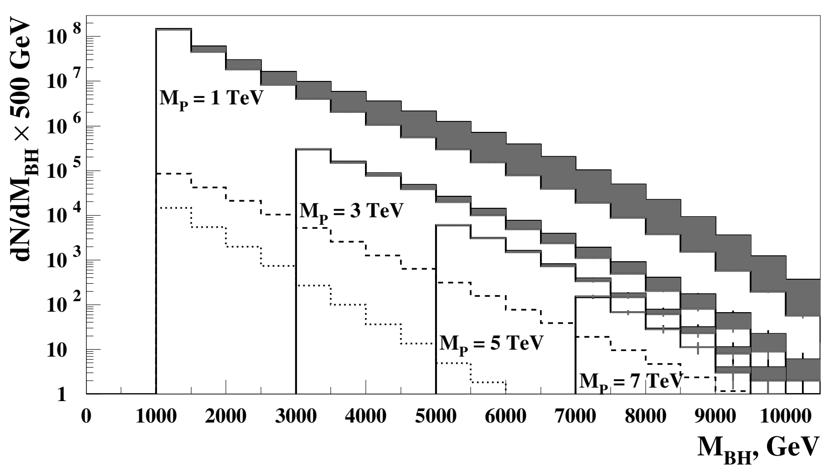
Exciting Possibility: **TeV-scale Production of Black Holes**

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

- Two partons with center of mass energy: $\sqrt{\hat{s}} \equiv M_{BH}$ moving in opposite direction
If impact parameter smaller than the Schwarzschild radius $\Longrightarrow$ BH forms

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

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