New Signatures from Warped Space

- an alternative to Supersymmetry -

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Outline

- **Introduction**
  -- Why go Beyond the Standard Model (SM)
  -- The wonders of extra spatial dimensions

- **Warped extra dimensions**
  -- A solution to the hierarchy problem
  -- A theory of flavor

- **The stringent tests from precision electroweak observables**
  -- Corrections to Z and W boson self energies from mixing with their KK modes
  -- Large corrections to gauge couplings of heavy fermions ==> Zbb coupling

  ==> custodial symmetry to the rescue!

- **The search for the messengers of the extra dimension at colliders**
  -- Light new KK quarks
  -- new Higgs physics opportunities
  -- exotic decay channels
  -- KK gauge bosons within LHC reach

- **Conclusions**

Why go beyond the Standard Model ?

The SM with a weakly coupled fundamental Higgs explains data quite well,

however, it is only an effective theory ==> Gravity should be included at $M_{Pl} = 10^{19}$ GeV

and it fails to address several important questions:

- **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
⋆ The mystery of Dark Matter
⋆ The mystery of Dark Energy

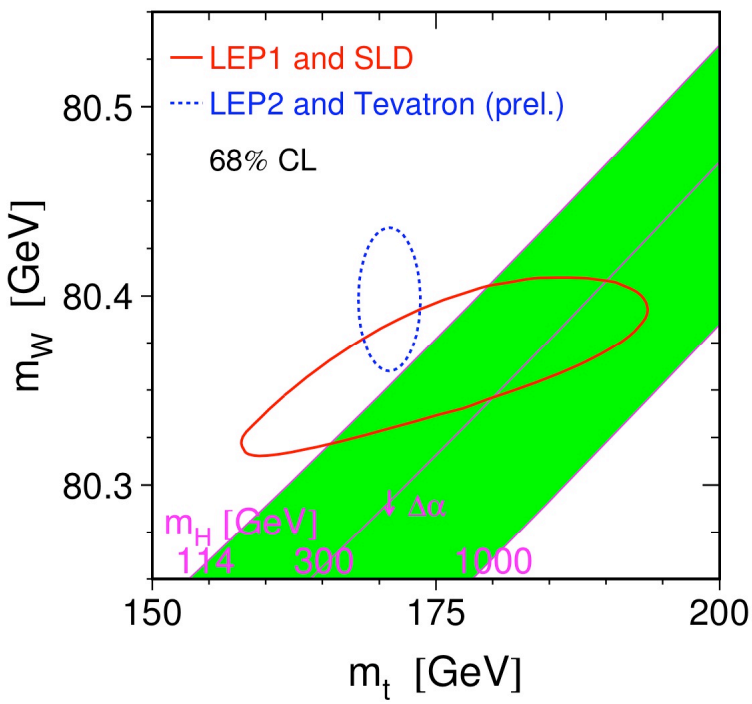
The Big Hierarchy problem is the reason we expect new physics at the TeV scale
==> within the reach of the **Tevatron, LHC, ILC**

Precise measurements of Mt and Mw

==> an indirect search for the SM Higgs

- **Precision measurements of the top quark and W boson masses may exclude the SM at/above the TeV scale**

SM correlation for M_t-M_w-$m_{H_{SM}}$



New CDF/D0 top mass (170.9 ± 1.8 GeV) plus the newest combined LEP and Tevatron measurement of the W mass (80.398 ± 0.025 GeV)

LEPEEWG '07; TEVEWWG '07

Several SM extensions provide an understanding of the hierarchy between M_{Pl} and the electroweak scale

-- Supersymmetry

-- Extra dimensions

-- Strong Coupling Dynamics

-- Little Higgs Models

Supersymmetry ===> My Prime Choice !

Based on a new symmetry between fermions and bosons
is the most mature theory BSM and can fit data extremely well

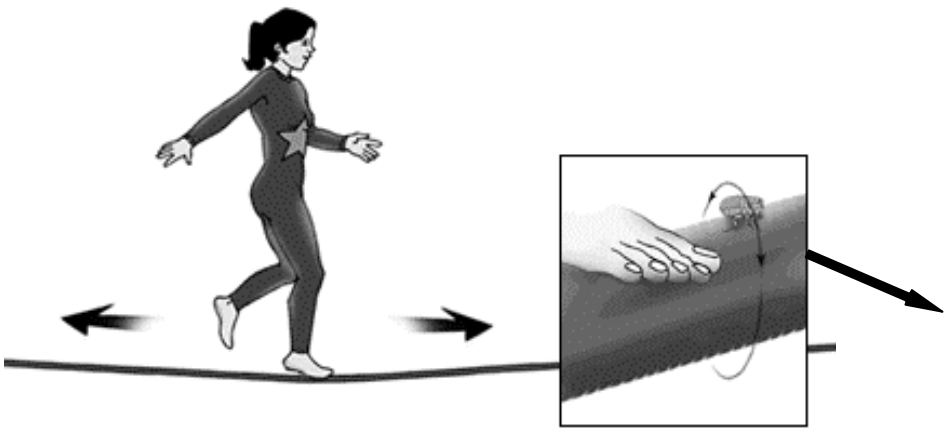
Not only provides a solution to the Higgs mass stability problem, but it also:

Allows for Unification of gauge couplings
Provides a natural candidate for Dark Matter
Provides a solution to the matter-antimatter asymmetry of the Universe
Is an essential part of string theory

However, no SUSY partner has been detected so far ==> SUSY must be broken

SUSY signatures at the electroweak scale expected, to stabilize Higgs quantum corrections and answer some of the fundamental questions in physics
the LHC will tell…

Are there Extra Dimensions (ED) 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

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

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

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

Gravity flux in ED ➔ Newton's law modified: $M_{Pl}^2 = (M_{Pl}^{\text{fund.}})^{2+d}\, R^d$ for k=0

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

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

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

How can we probe ED from our 4D brane?

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

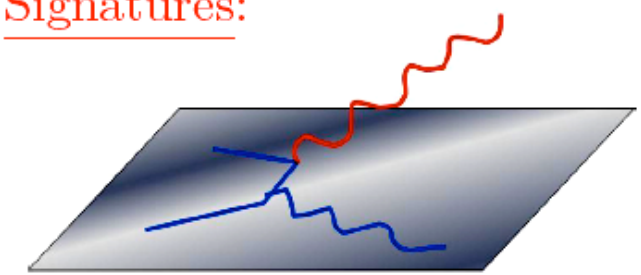
SM particles + gravitons + tower of new particles:

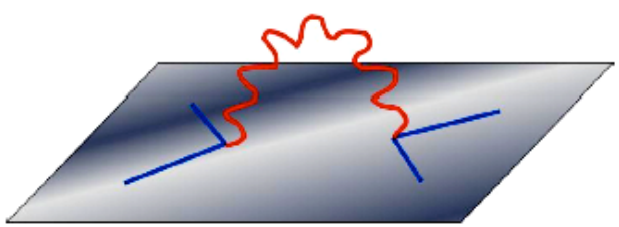
Kaluza Klein (KK) excited states with the same quantum numbers

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 ED

Signatures:





Flat space

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

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

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

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

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

A daring alternative: Warped Extra Dimensions

- Warped extra Dimensions, offer a novel solution to the hierarchy problem, without relying on unnatural cancellations, strong interactions or SUSY

==> an exponential "warp" factor in the space-time metric

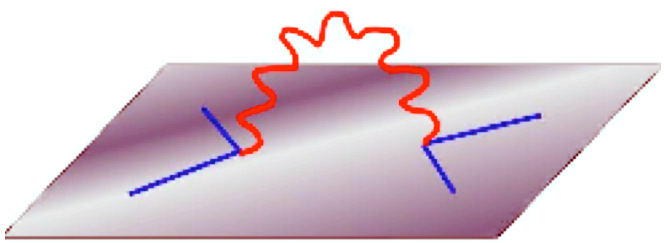
All fundamental parameters are of the order of the Planck scale, and yet, due to the curvature of the extra-dimensional metric and the localization of the Higgs field, the Higgs v.e.v. is naturally of order of the TeV scale

Randall, Sundrum'99

4-D effective theory:

SM particles + Gravitons + tower of new particles: Kaluza Klein (KK) excited states with same quantum number as a graviton and/or the SM particles

Signatures:



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

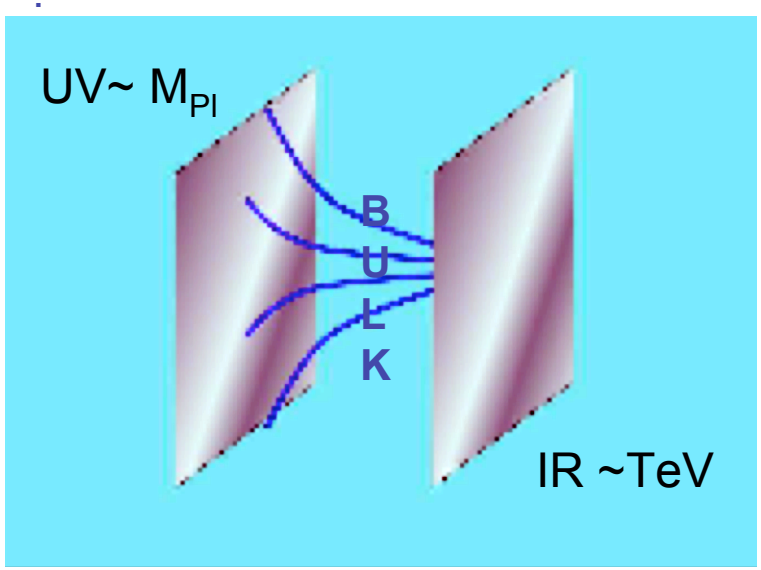
- Fermions and gauge boson KK modes of the order of the TeV scale may also exist, (strongly constrained by precision electroweak data.)

KK states produced as resonances or contribute to fermion pair production at colliders

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

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

with kL ~30

The Randall-Sundrum Model of Warped Space:

==> elegant solution to the hierarchy problem

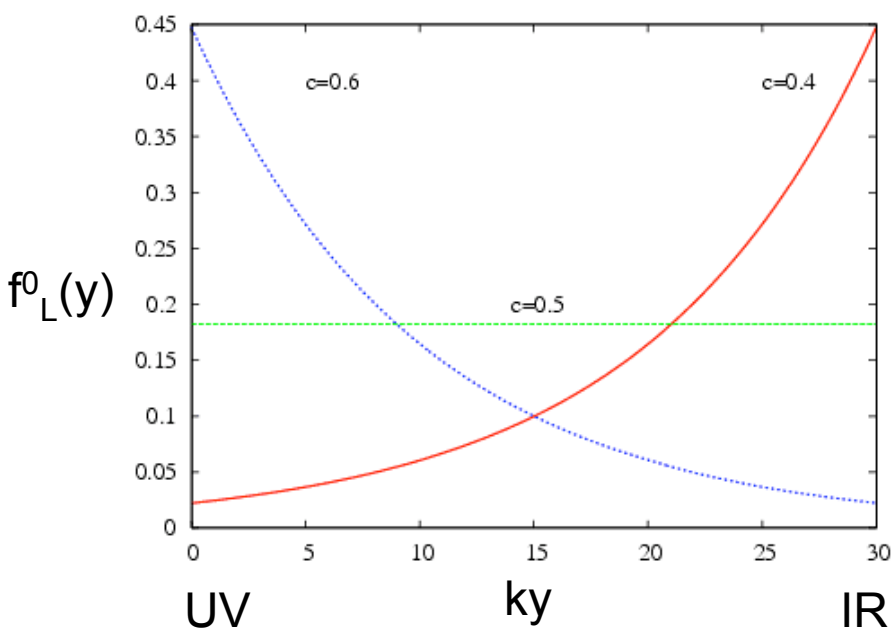
RS With Bulk Fermions and Gauge bosons:

- 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:

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

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

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

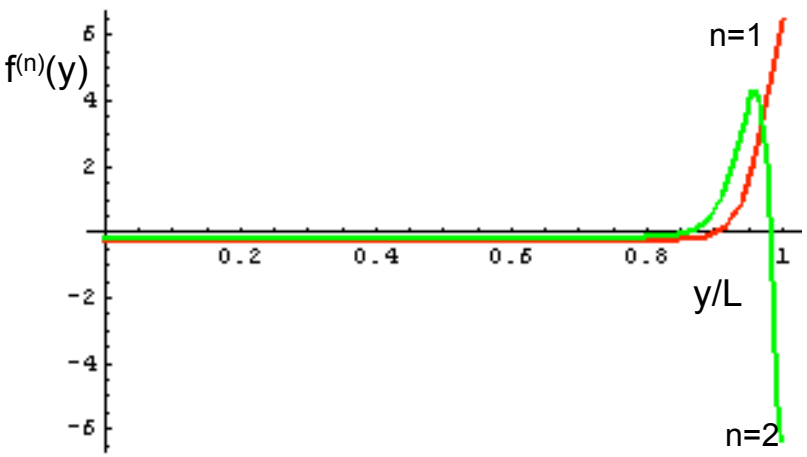
-- The KK spectrum is defined in units of $\tilde{k} = ke^{-kL}$ of factors that depend on c_f and is localized towards the IR brane

The Gauge bosons in the bulk

- If fermions in the bulk, since they are charged under SM interactions
  ==> gauge fields in the bulk as well

KK mode decomposition: $$A^{\lambda}(x,y) = \sum_n A_n^{\lambda}(x) f^n(y)$$

- KK masses are quantized in units of $\tilde{k} = ke^{-kL}$ of factors 2.5, 5.6, 8.7…



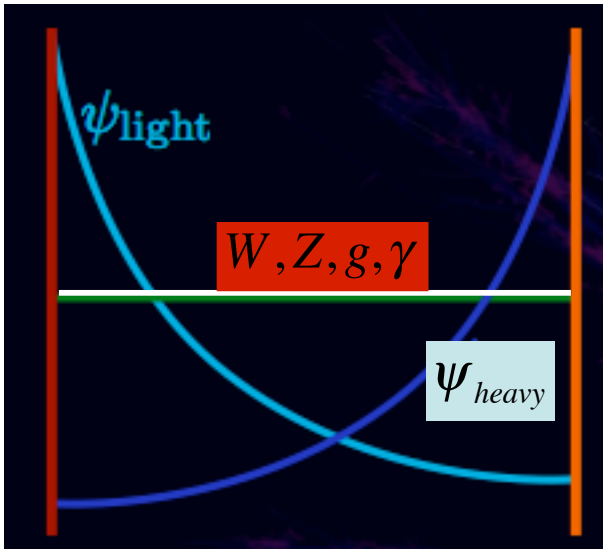
==> KK gauge bosons also localized towards the IR brane

Strong KK boson couplings to fields localized in the IR brane

$$f^n(L) \approx \sqrt{2kL} f^0(L)$$

$$f^0(L) = \text{constant gauge coupling}$$

- SM (zero mode) gauge bosons have flat wave functions
  ==> couple to SM and KK fermions equally : gauge invariance



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

Does the original RS model pass the test of precision measurements and allow for new excitations of SM particles at the reach of the LHC?

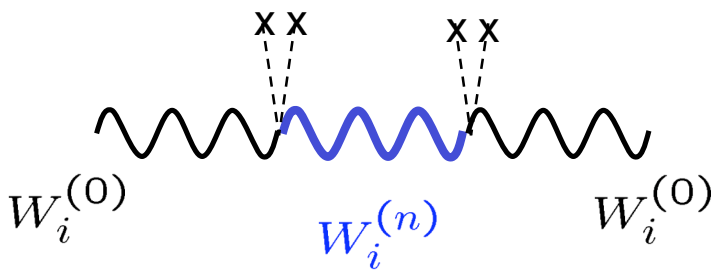
All KK modes are localized towards the IR brane ==> large corrections to SM gauge boson masses and couplings due to mixing induced by the Higgs

Stringent bounds on the scale of new physics $\Lambda_{NP} \geq 10 \ \ \mathrm{TeV}$

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

SM in the bulk

- Large mixing with Z and W zero modes through Higgs



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

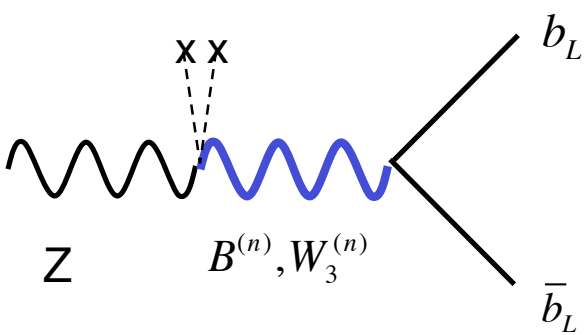
$$\Downarrow$$

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

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

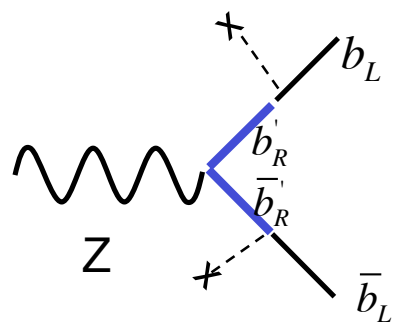
Large gauge and Yukawa couplings to Gauge Bosons and fermion KK modes

Large corrections to the Zbb coupling



$$\Downarrow$$

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

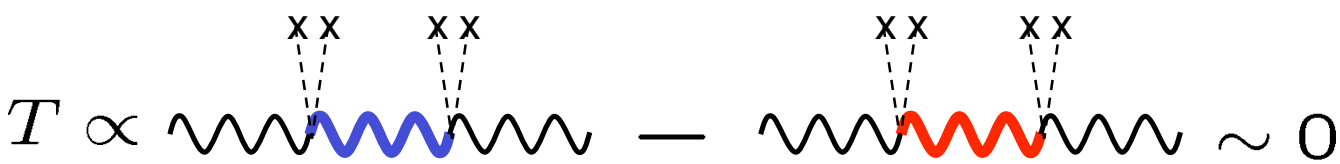


How to obtain a phenomenologically interesting theory?

1) Extend SM bulk gauge symmetry to a custodial symmetry

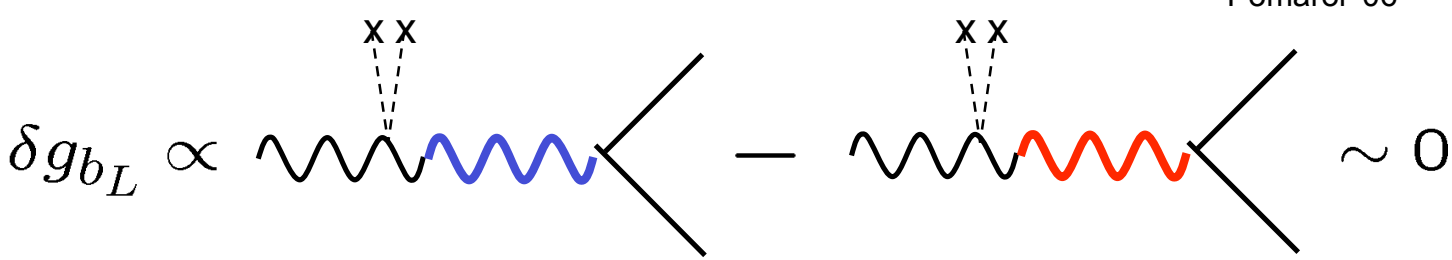
$SU(2)_L \times SU(2)_R$

Agashe, Delgado, May, Sundrum '03



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

Agashe, Contino, DaRold, Pomarol '06



==> 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

The model

The gauge sector:

Bulk gauge symmetry : $SU(2)_L$ x $SU(2)_R$ x $U(1)_X$ x P_{LR}

Broken by Boundary conditions to $SU(2)_L$ x $U(1)_Y$ in the UV

$$W^a_{L\mu} \sim (+,+) \qquad B_\mu \sim (+,+)$$

$$W^b_{R\mu} \sim (-,+) \qquad Z'_\mu \sim (-,+)$$

$a = 1,2,3, \quad b = 1,2$

B_μ and Z'_μ are orthogonal l.c. of $W^3_{R\mu}$ and X_μ

(+,+) zero modes
==> Unbroken gauge symmetries

(-,+); (+,-); (-,-) no zero modes
==> broken gauge symmetries

Hypercharge : $\frac{Y}{2} = T^3_R + Q_X$ Electric charge: $Q = T^3_L + T^3_R + Q_X$

P_{LR} symmetry ==> $g_L = g_R$

Fermion Quantum Numbers

$$\boxed{T_R^3(b_L) = T_L^3(b_L)} \quad \Leftrightarrow$$

The simplest option is bidoublets under $SU(2)_L \times SU(2)_R$

$$\begin{array}{cc} & SU(2)_R \\ SU(2)_L & \begin{pmatrix} \chi_L^u(-+) & t_L(+,+) \\ \chi_L^d(-+) & b_L(+,+) \end{pmatrix}_X \end{array} \sim (2,2)_{2/3} \sim \begin{array}{c} U(1)_Q \\ \begin{pmatrix} 5/3 & 2/3 \\ 2/3 & -1/3 \end{pmatrix} \end{array}$$

$$t_R(+,+) \sim (1,1)_{2/3} \quad \text{with} \quad Q = 2/3$$

The Higgs is also a bidoublet with $Q_X = 0$

How light can the KK modes be?

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

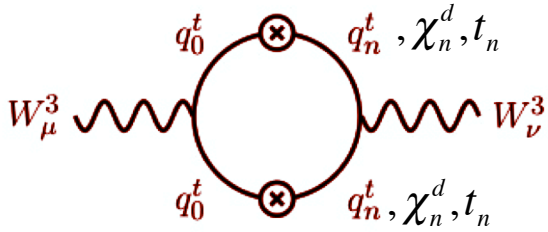
At tree level:

- 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

At loop level:

- One loop corrections are important

Quantum corrections are calculable (finite)



-- Bidoublets contribute negatively to T

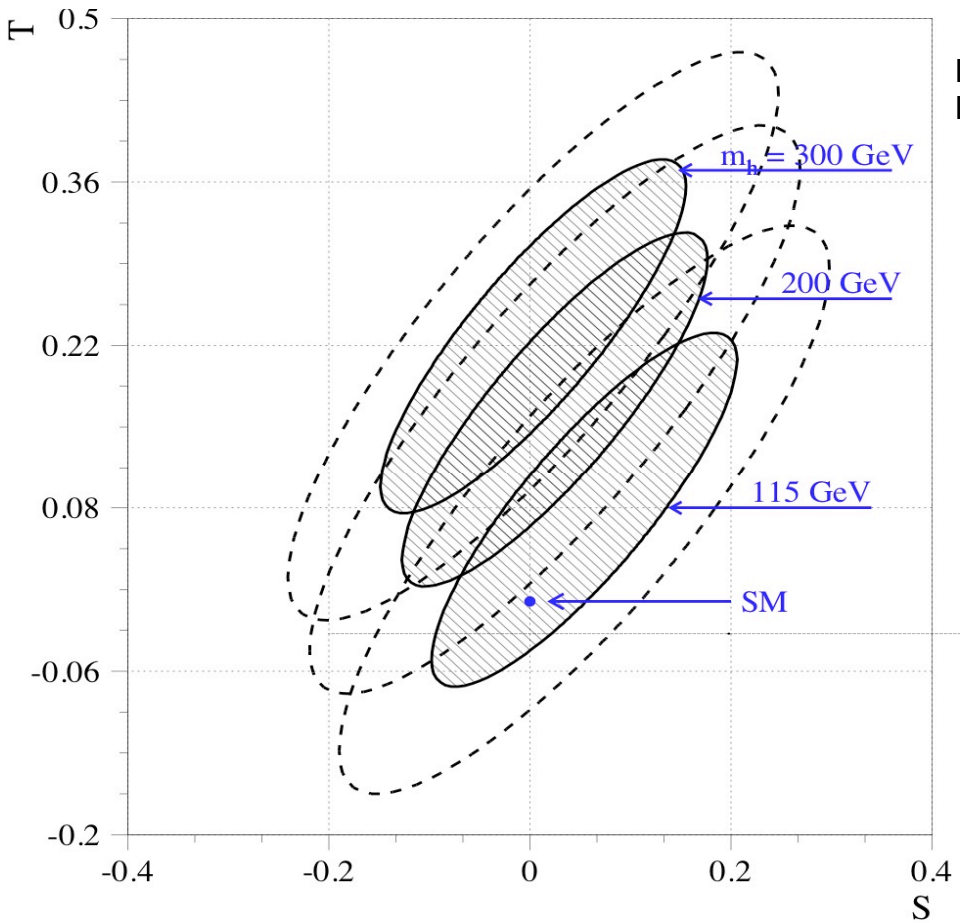
– Singlets contribute positively to T (need singlets)

– Vector like contributions to S are small and positive

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

M.C, Ponton, Santiago, Wagner, '06-'07

T-S fit to Electroweak Precision observables



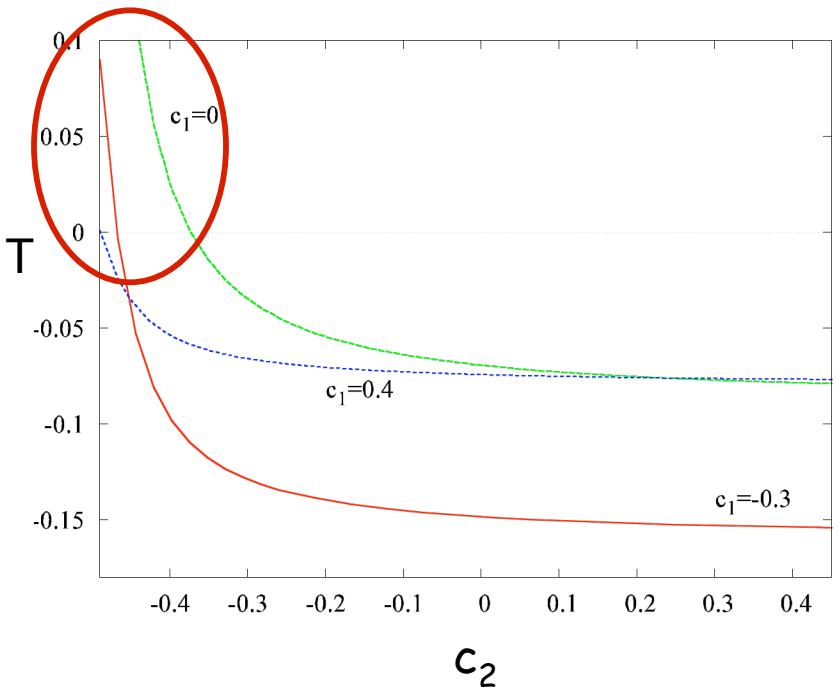
M.C, Delgado, Ponton, Tait and Wagner
LEPEWWG T-S global fit

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

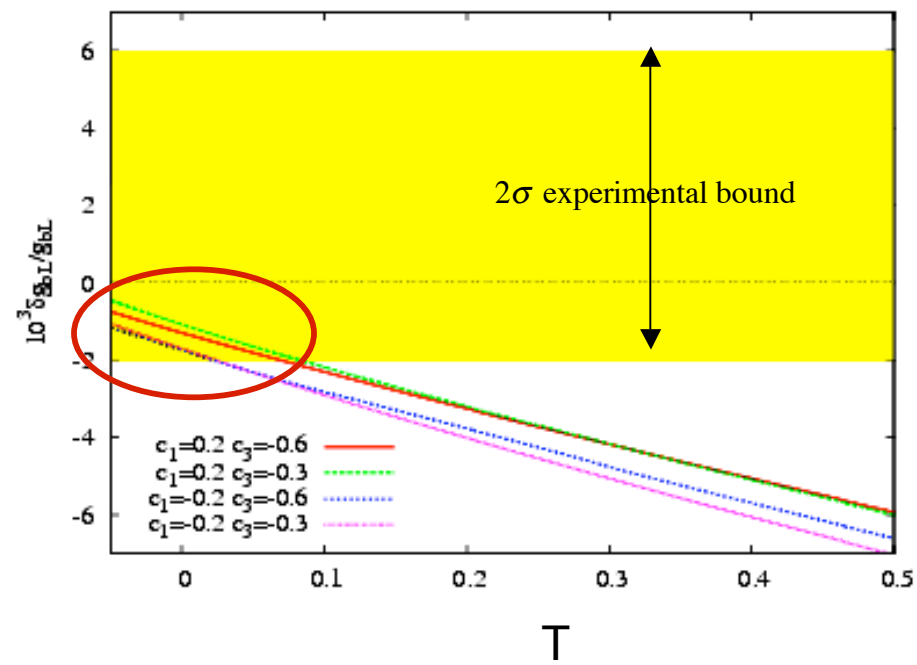
For mh ~ 120 GeV: Positive S ~ 0.1 <==> positive T

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



UV ← (singlet localization) → IR



Positive T leads to large deviations from allowed experimental values of Zbb

Global fit to Electroweak Observables

- Compute tree level effects based on the effective lagrangian up to dimension six operators, by integrating out heavy gauge boson (and fermions).

Han, Skiba '06

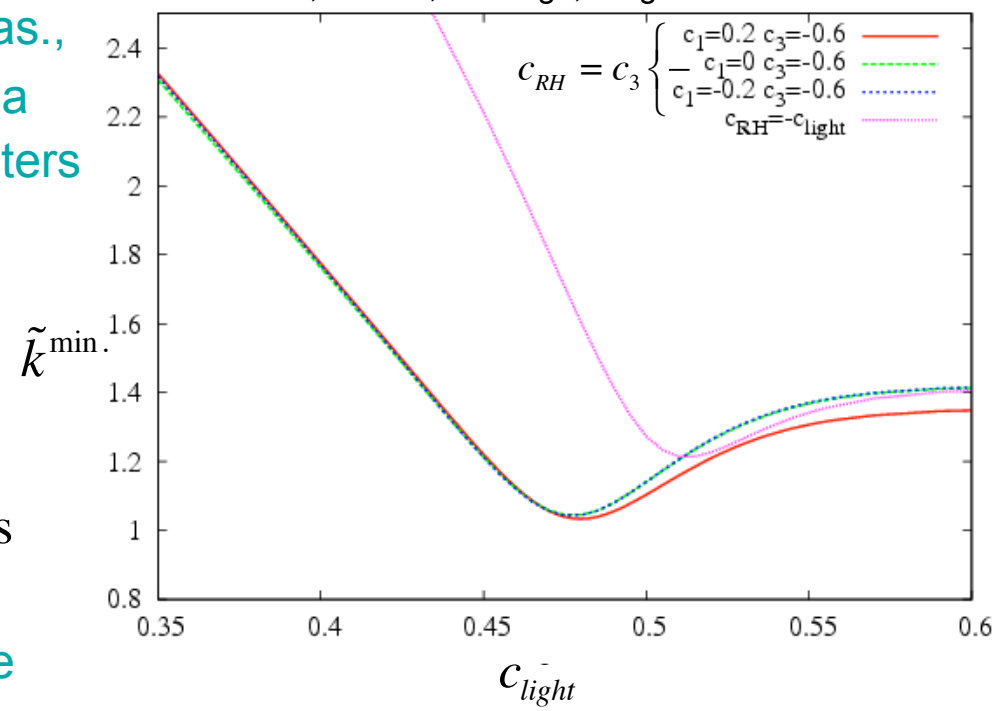
- Add leading one--loop effects on T and S parameter and Zbb coupling

- Perform a χ^2 fit to low-energy meas., LEP1, SLD, LEP2 and Tevatron as a function of the fundamental parameters of the theory: $\tilde{k} = ke^{-kL}$ and the fermion localization parameters:

$$c_1, c_2, c_3 \Leftrightarrow t_L, t_R, b_R$$

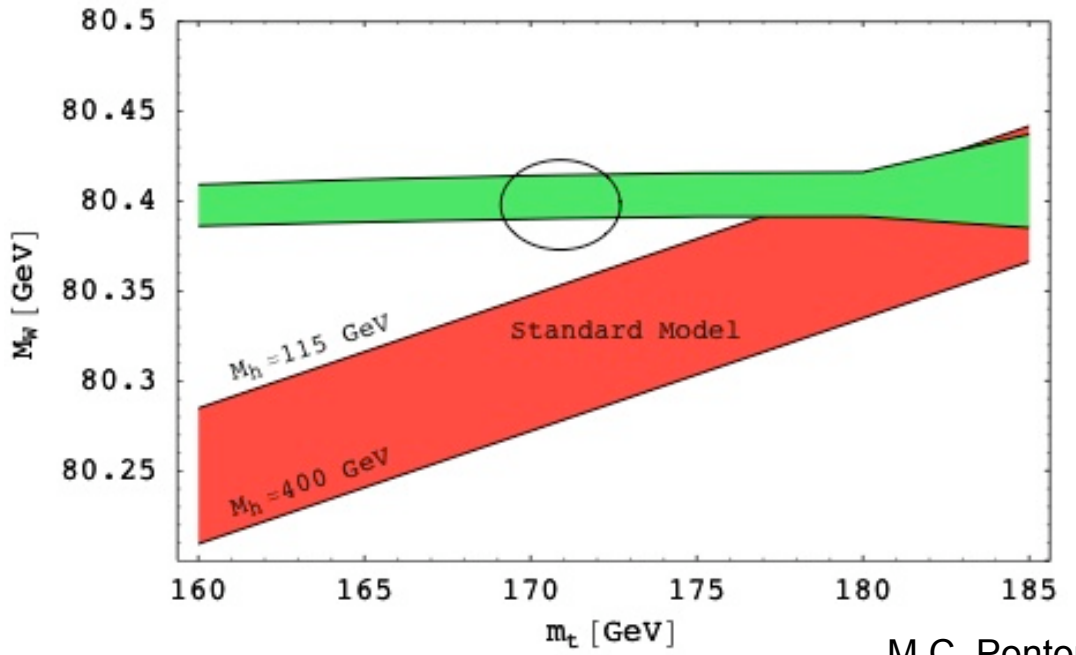
$$c_{light}, c_{RH} \Leftrightarrow \text{LH and RH light fermions}$$

M.C, Ponton, Santiago, Wagner '07



- To reduce number of parameters we optimize with respect to c_2 and c_{RH} and obtain 2 sigma lower bound on $\tilde{k}$ → $\tilde{k} \geq 1.2 \text{ TeV} \Leftrightarrow m_{KK}^{gauge} \geq 3 \text{ TeV}$

How well does the model fit M_{top} and M_W?



M.C, Ponton, Santiago, Wagner
in preparation

68% C.L. values based on new CDF/D0 top mass (170.9 ± 1.8 GeV)
plus the newest combined LEP and Tevatron
measurement of the W mass (80.398 ± 0.025 GeV)

Green: Obtained by using lower bound on $\tilde{k}$ from a 2 sigma fit to Electroweak observables, scanning over fermion localization parameters, for the Higgs mass 120 GeV

Fermion Spectrum

KK excitations of the first two quark families with mass below 1 TeV

All bidoublets of $SU(2)_L \times SU(2)_R$

Electric charge, typical masses and decay channels

q'	Q	$m_{q'}$ (GeV)	decay
q_1^1	$2/3$	$\sim 200 - 500$	$q_1^1 \to Zu, \quad (100\%)$
q_1^2	$2/3$	$\sim 200 - 500$	$q_1^2 \to Zc, \quad (100\%)$
q_2^1	$2/3$	$\sim 200 - 500$	$q_2^1 \to Hu, \quad (100\%)$
q_2^2	$2/3$	$\sim 200 - 500$	$q_2^2 \to Hc, \quad (100\%)$
$\chi_2^{u_1}$	$5/3$	$\sim 200 - 500$	$\chi_2^{u_1} \to Wu, \quad (100\%)$
$\chi_2^{u_2}$	$5/3$	$\sim 200 - 500$	$\chi_2^{u_2} \to Wc, \quad (100\%)$
q'^{d_1}	$-1/3$	$\sim 200 - 500$	$q'^{d_1} \to Wu, \quad (100\%)$
q'^{d_2}	$-1/3$	$\sim 200 - 500$	$q'^{d_2} \to Wc, \quad (100\%)$

Light 1st and 2nd generation KK quarks: a **possible** prediction of the model

Fermion Spectrum (continued)

KK quark excitations of the third generation with mass below 1 TeV

	q'	Q	$m_{q'}$ (GeV)	decay
Mainly Bidoublet	q_1	$2/3$	369	$q_1 \to Zt$, (20%) $q_1 \to Ht$, (60%) $q_1 \to Wb$, (20%)
Mixture of Bidoublet + Singlet	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.%)
Bidoublet	$\chi_2^{u_3}$	$5/3$	369	$\chi_2^{u_3} \to Wt$, (100%)
Bidoublet	q'^{d_3}	$-1/3$	369	$q_2'^{d_3} \to Wt$, (100%)

Light 3rd generation KK quarks: a **solid** prediction of the model

Signatures from Warped Space at the Tevatron

- Searches for new quarks
  - Ongoing searches for heavy quarks decaying to W/Z +j apply directly

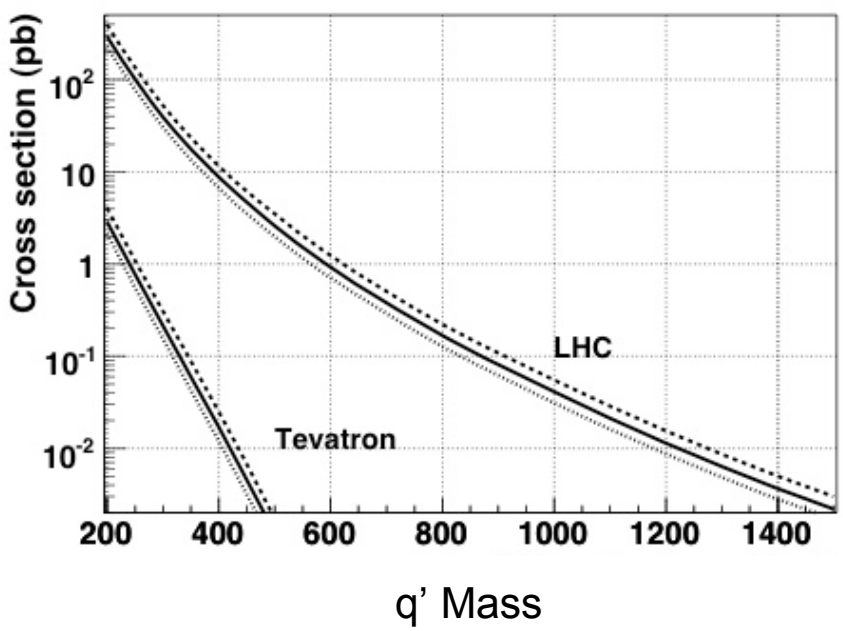
$p\bar{p} \to q'\bar{q}' \to 2W + 2j$ in lepton plus jets events, (CDF note 8495)

==> examine W+j mass spectrum distributions and compare with a fourth gen. q'

$p\bar{p} \to q'\bar{q}' \to 2Z + 2j$ in events with 2 leptons + >3 energetic jets (CDF note 8590)

==> look at the tails of the jet energy distribution for an excess over SM

- sensitivity to this signal relatively large since multiple new quarks contribute factor 4(2) in the production cross section with subsequent exclusive decay into W+j (Z+j)

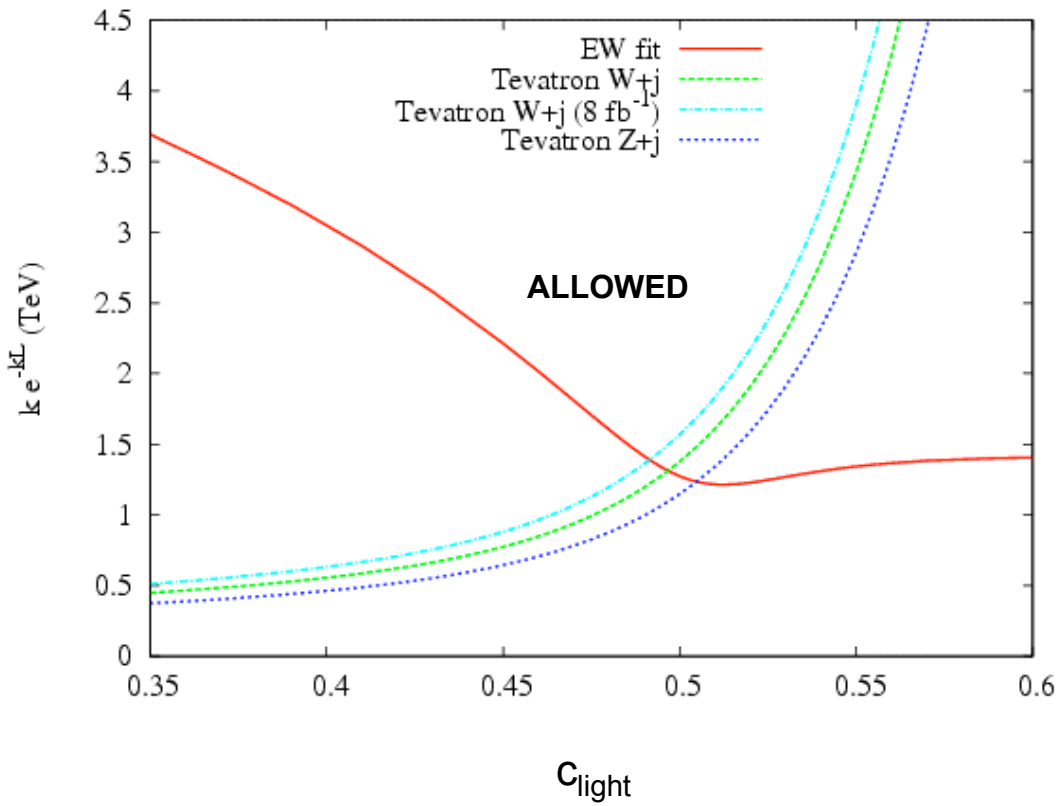


Tevatron lower bounds on KK quarks of 1. and 2. generations

$$m_q \geq \begin{cases} 325\ (410)\ \text{GeV}, & W+j \text{ with } 0.76 \text{ (projected 8) fb}^{-1} \\ 300\ \text{GeV}, & Z+j \quad \text{with } 1.1 \text{ fb}^{-1} \end{cases}$$

M.C, Ponton, Santiago, Wagner '07

Combined lower limit on $\tilde{k}$ from EW fit and ==> direct Tevatron searches



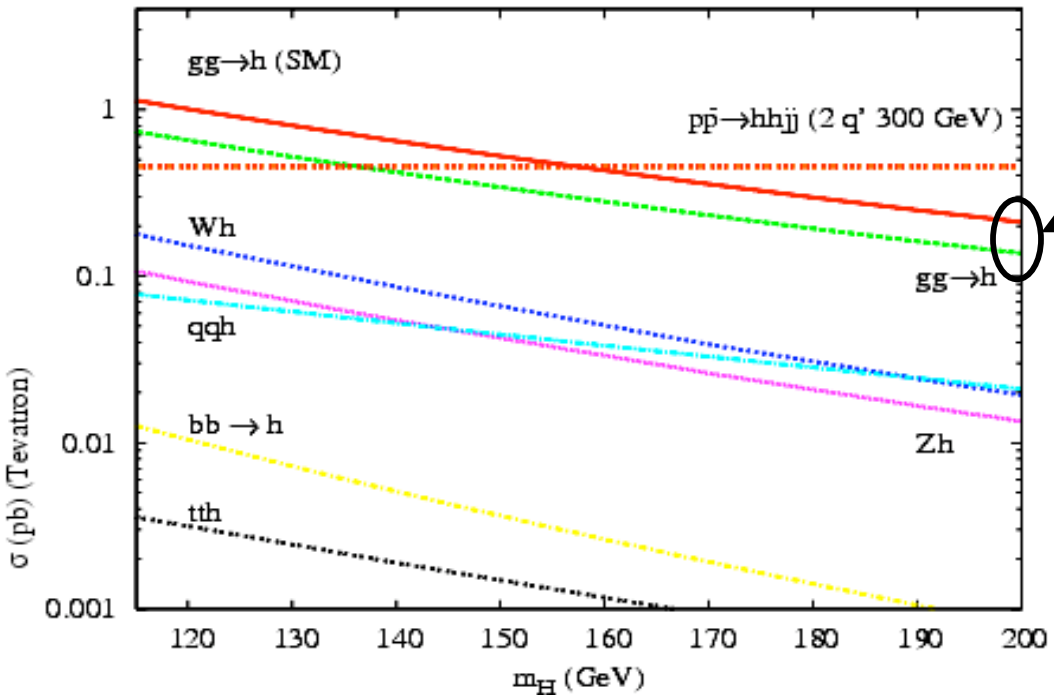
If KK modes of light quarks exist, Tevatron searches eliminate the possibility of strong localization of such KK quarks towards the UV brane

Interesting new possibilities for Higgs searches at the Tevatron

- New Higgs production mechanism mediated by q' pair production

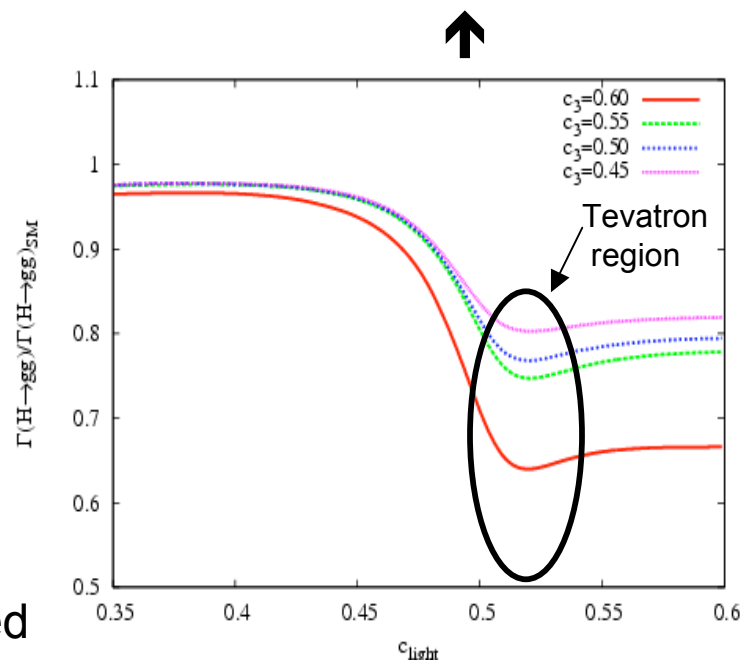
$$\sigma(p\bar{p} \to q'\bar{q}' \to 2H2j) \sim \sigma(gg \to H)$$

$\Rightarrow$ Light Higgs
Mq' ~ 300 GeV



Top mixing with KK modes

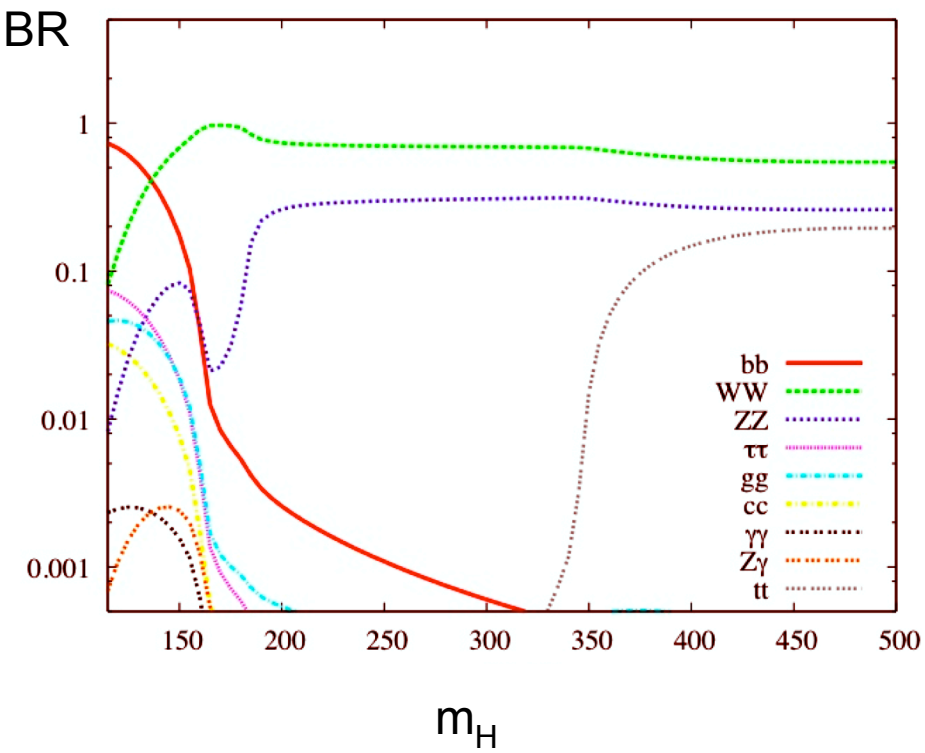
==> reduced top Yukawa



Sizeable enhancement of inclusive Higgs signal

Also some backgrounds (WW/ZZ +jets) enhanced by other light KK quarks decays

Higgs has SM-like decay BR's



New channels may allow to explore different mass regions

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

(too tiny)

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

(2b+4j+lepton + missing E_T)

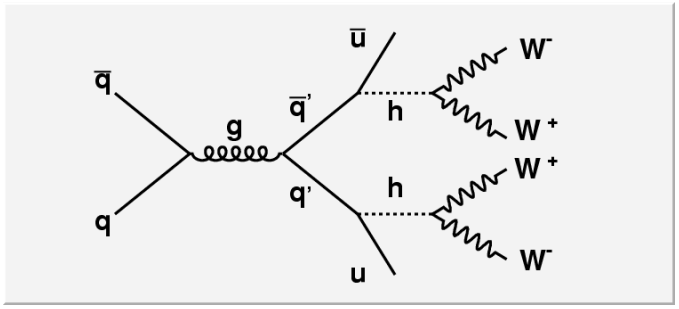
$$p\bar{p} \to q'\bar{q}' \to 2H + 2j \to 4W + 2j$$

(see below)

Most available New physics studies at CDF and D0 are rather model dependent and apply cuts which tend to eliminate the KK quark signals.

One example that almost works: LS dileptons: SUSY vs q' (M_H=170 GeV)

M.C, Ponton, Santiago, Wagner: work in progress



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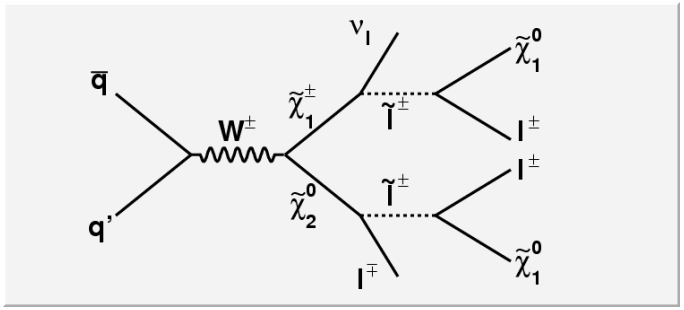
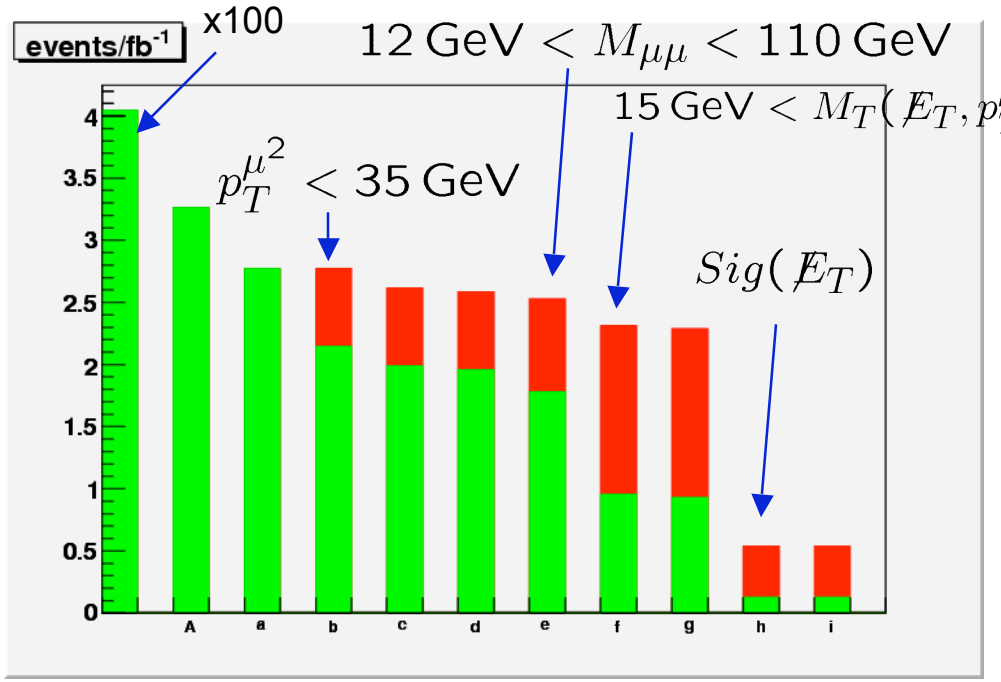


D0 Note 5126-CONF (1fb^{-1})



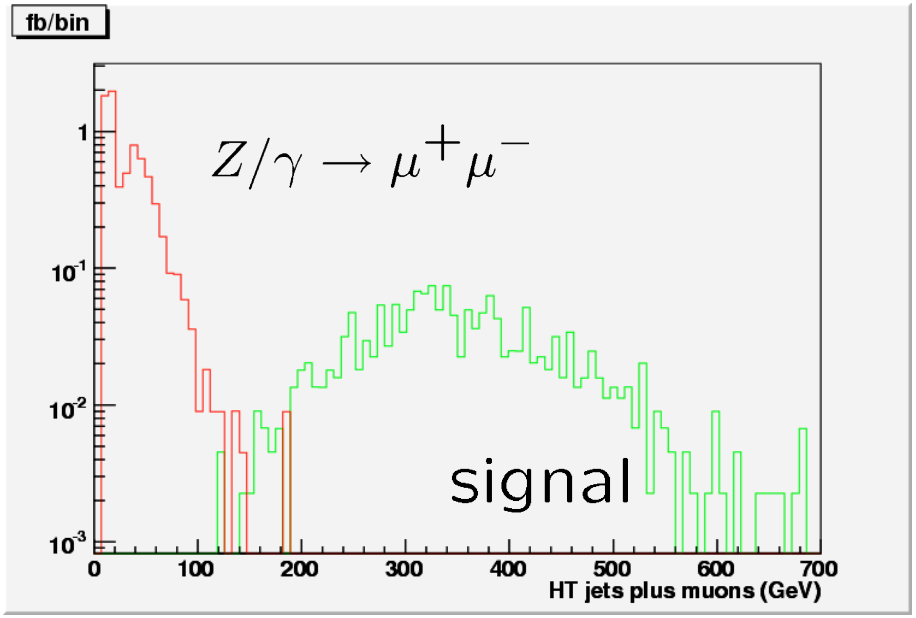
	sum	data
selection $\mathcal{B}$	14922±981	15234
$M_{\mu^\pm\mu^\mp} \in [25-65]$ GeV/c^2 (a)	3479±232	3569
$p_T^{\mu^2} < 35$ GeV/c (b)	3479±232	3358
$p_T^{\mu^2} > 8$ GeV/c (c)	8.9±1.8	10
$p_T^{\mu^1} > 13$ GeV/c (d)	6.5±1.4	6
$M_{\mu^\pm\mu^\pm} \in [12-110]$ GeV/c^2 (e)	4.9±1.2	2
$M_T(\not{E}_T, p_T^{\mu^2}) \in [15-65]$ GeV/c^2 (f)	2.9±0.8	2
$\not{E}_T > 10$ GeV (g)	2.3±0.7	1
Sig($\not{E}_T$) > 12 GeV$^{1/2}$ (h)	1.7±0.6	1
$\not{E}_T \times p_T^{\mu^2} > 160$ GeV^2/c (i)	1.1±0.4	1

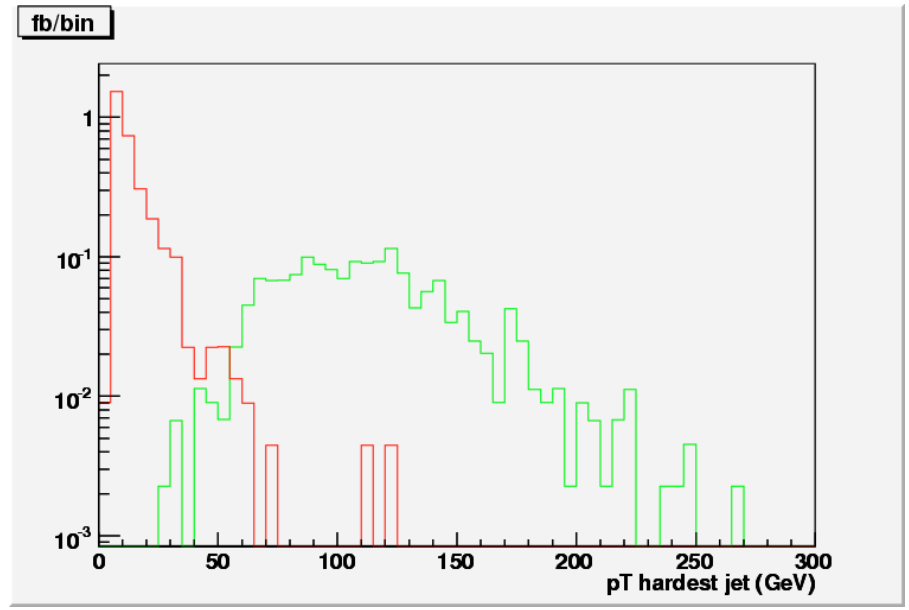
Simulations using MG/ME+Pythia+PGS4

Main backgrounds considered

$\mathrm{QCD}, WZ, ZZ, Z/\gamma + \mathrm{jet(s)}$ and $W + \mathrm{jet(s)}$

Possible alternative cuts? signal is harder than backgrounds





Optimize the analysis for our signal, and include new cuts to achieve a similarly small background level without losing too much signal.

Our signal gives about 5 events in 2 fb-1 for MH = 170 GeV
===> could exclude this if no signal is present

KK quarks searches are complementary to Higgs searches from KK quark decays

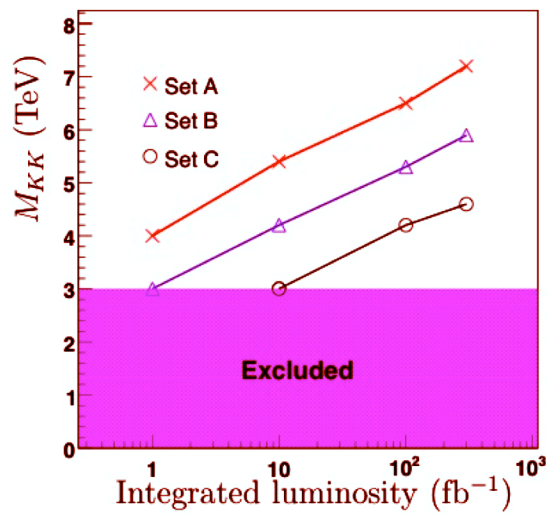
Gauge Boson Signatures from Warped Space at the LHC

- KK excitations of the Z gauge bosons and photons accessible via Drell-Yan processes

$$pp \to \gamma^{(n)} / Z^{(n)} \to l^+ l^-$$

up to masses

$$M_{Z^{(1)},\gamma^{(1)}} \sim 6 \text{ TeV}$$



Ledroit, Moreau, Morel '07

Based on ATLAS physics analysis framework and tools

Sets A,B,C define sets of c parameters, different from those in our model

- KK gluons decaying predominantly to top pairs $q\bar{q} \to g^{(1)} \to t\bar{t}$

==> must efficiently identify energetic tops:

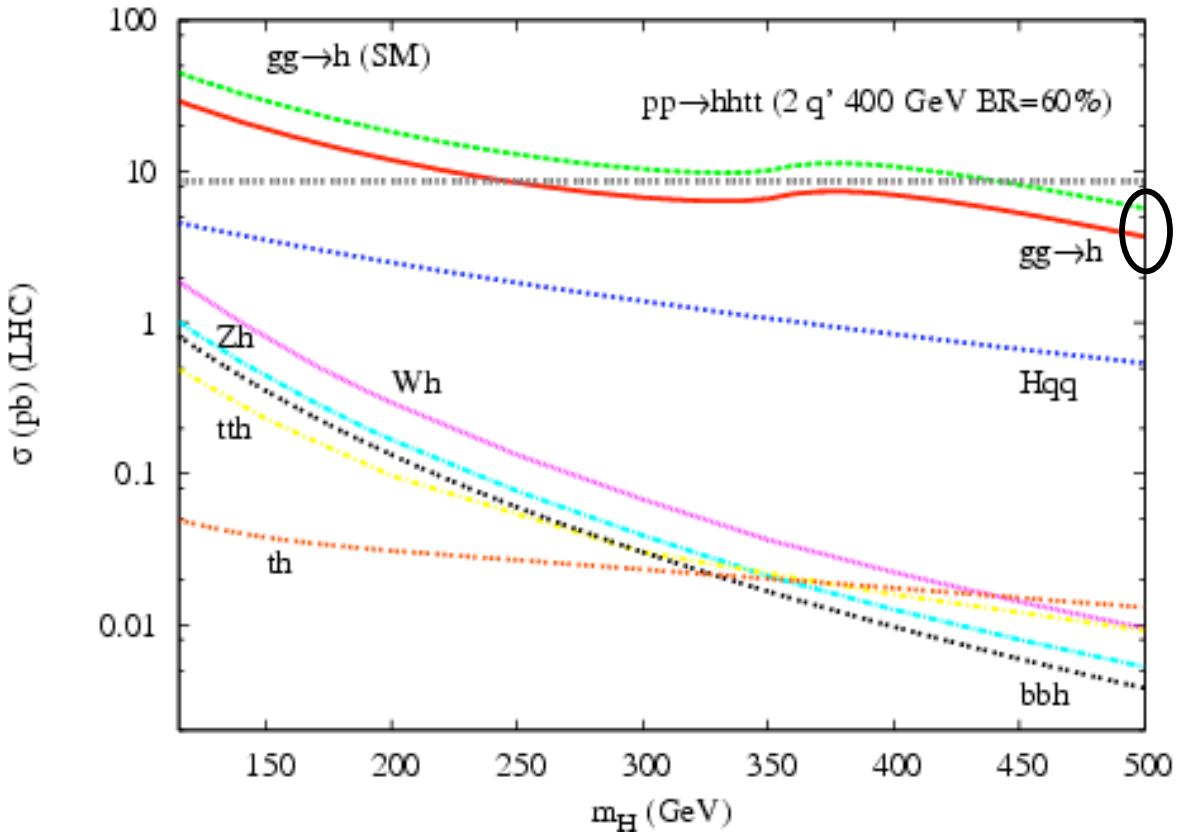
gain detailed information from *top jets* to improve fake jet efficiencies

$$M_{g(1)} \sim 4 - 5 \text{ TeV}, \; 100 \text{ fb}^{-1}$$

Agashe, Belyaev, Krupovnickas, Perez, Virzi'06

Lillie, Randall, Wang'07

Higgs production at the LHC



Gluon fusion production reduced up to a factor 0.65

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

(for Mq' ~ 400 - 500 GeV)

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

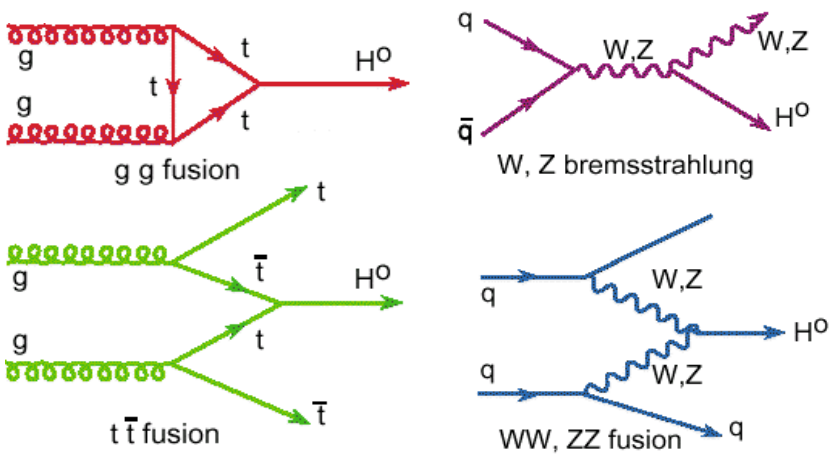
- *Important distinction:*

-- light 1. and 2. generation KK quarks can be avoided by changing boundary conditions

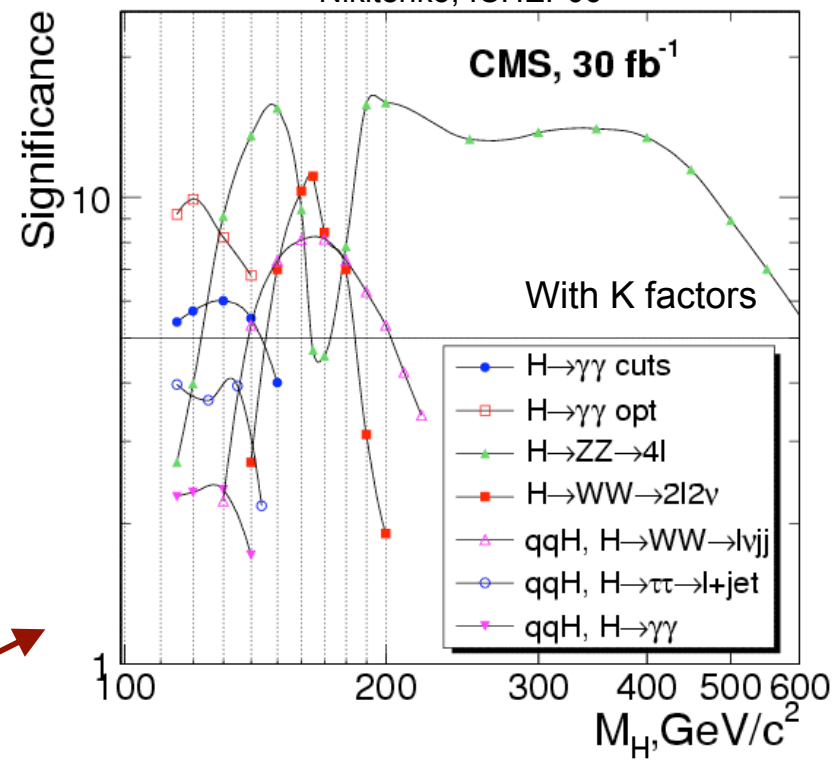
-- light 3. generation KK fermions are a solid prediction of the model tied to the mechanism of top quark mass generation

The search for SM Higgs at the LHC

Higgs Production processes



Nikitenko, ICHEP06



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

Production DECAY	Inclusive	VBF	WH/ZH	ttH
$H \rightarrow \gamma\gamma$	YES	YES	YES	YES
$H \rightarrow bb$	✖		YES	YES
$H \rightarrow \tau\tau$	✖	YES		
$H \rightarrow WW^*$	YES	YES	YES	
$H \rightarrow ZZ^*, Z \rightarrow l^+l^-$	YES			

- **Intermediate mass range**

  200 GeV < $m_{H_{SM}}$ < 700 GeV

  Inclusive H ==> ZZ==> 4l

- **Large mass range**: $m_{H_{SM}}$ > 700 GeV

  VBF with H ==> WW ==> lν jj

  ZZ ==> ll νν

The search for the SM Higgs from Warped Space

New possibilities for early discoveries: $\sigma(pp \to q'\bar{q}' \to HHjj) > 10\sigma(pp \to t\bar{t}H)$

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

$\boxed{pp \to T\bar{T} \to HtH\bar{t} \to W^+bW^-\bar{b}HH}$ Aguilar-Saavedra'06

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

Both channels contribute to the same final state $l\nu b\bar{b}b\bar{b}jj$ (or same plus 2 jets)

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}

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

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

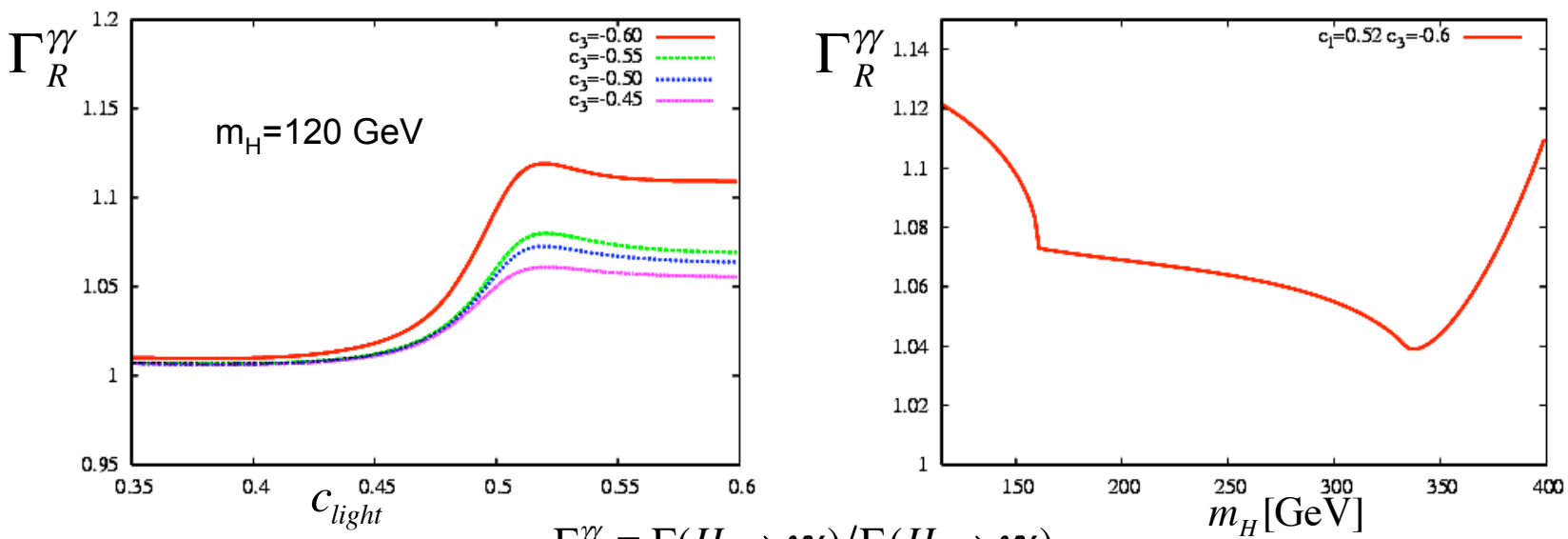
$$\sigma(H \to ZZ)_{incl.} \approx 2\sigma(q\bar{q}')B(2-B) + \sigma(gg \to H)B$$

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



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

Other possibilities for an early discovery for low-mass Higgs

- $pp \to q'\bar{q}' \to HHjj \to bb\tau\tau jj$ with leptonic τ decays

Under study

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

-- Background also enhanced by other decays of the same or other new fermions --

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

Different significances for Higgs discovery than for KK fermion observation, due to different background/signal classification

KK Fermion Signatures from Warped Space at the LHC

- 3 generation KK fermions with masses ~1TeV can be discovered at the LHC with high luminosities ~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 + observability 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:

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

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'

Dennis, Ünel, Servant, Tseng '07

- More interesting phenomenology under study:

MC, Ponton, Santiago, Wagner '07

-- Single KK fermion production,

-- Deviations from Wtb coupling of ~ 10% (within the reach of LHC)

Conclusions

There are many reasons to believe that the SM must be superceded by a more fundamental theory at the TeV scale

Supersymmetry is the leading candidate, but

Theories of Extra dimensions offer a very intriguing alternative

- Custodial protection of T and Zbb: new opportunities for warped space models
- Quantum corrections calculable and relevant:
  - -- Fix some features of the model (t_L, b_L near IR brane)
  - – Help accomodate new M_{top}, M_W measurements when fitting precision EW data
- Very rich,interesting and new phenomenology
  - – Light (2-3 TeV) gauge boson KK modes
  - – Light (~ 0.4 -- 1 TeV) quarks, some with exotic charges
  - – Spectacular signatures: multigauge bosons, LS leptons, ...
  - – Major enhancement of Higgs signals

At the LHC, we expect to make discoveries which will revolutionize our understanding of nature

EXTRAS

The complete model

Bulk gauge symmetry : $SO(5) \times U(1)_X \times P_{LR}$

Broken by boundary conditions to

$SU(2)_L \times SU(2)_R \times U(1)_X \times P_{LR}$ in the IR brane

and

$SU(2)_L \times U(1)_Y$ in the UV brane

The complete quark sector ==> 3 SO(5) multiplets

$$\xi^i_{1L} \sim Q^i_{1L} = \begin{pmatrix} \chi^{u_i}_{1L}(-,+) & q^{u_i}_L(+,+) \\ \chi^{d_i}_{1L}(-,+) & q^{d_i}_L(+,+) \end{pmatrix} \oplus u'^i_L(-,+) \,, \quad \xi^i_{2R} \sim Q^i_{2R} = \begin{pmatrix} \chi^{u_i}_{2R}(+,-) & q'^{u_i}_R(+,-) \\ \chi^{d_i}_{2R}(+,-) & q'^{d_i}_R(+,-) \end{pmatrix} \oplus u^i_R(+,+) \,,$$

$$\xi^i_{3R} \sim T^i_{1R} = \begin{pmatrix} \psi'^i_R(-,+) \\ U'^i_R(-,+) \\ D'^i_R(-,+) \end{pmatrix} \oplus T^i_{2R} = \begin{pmatrix} \psi''^i_R(-,+) \\ U''^i_R(-,+) \\ D^i_R(+,+) \end{pmatrix} \oplus Q^i_{3R} = \begin{pmatrix} \chi^{u_i}_{3R}(-,+) & q''^{u_i}_R(-,+) \\ \chi^{d_i}_{3R}(-,+) & q''^{d_i}_R(-,+) \end{pmatrix} ,$$

In the absence of mixing among multiplets, the SM fermions arise as zero modes of fields with (+,+) b.c. The remaining b.c. are chosen to preserve the $SU(2)_L \times SU(2)_R$ in the IR brane and to allow for mass mixing terms in the IR to obtain fermion masses after EWSB.

The Higgs Sector

A) A fundamental scalar field living in the IR brane

B) A model of gauge-Higgs unification

- Bulk gauge symmetry $SO(5) \times U(1)_X$ broken to $SO(4) \times U(1)_X$ on the IR and to the SM on the UV
- A5 along $SO(5)/SO(4)$ has a zero mode with the Higgs quantum numbers exponentially localized towards the IR brane
- Calculable Higgs potential
  - Solution to the little hierarchy problem

Contino, Nomura, Pomarol NPB (03)

Agashe, Contino, Da Rold, Pomarol (05-06)

- Yukawa couplings through gauge couplings: fermion masses and mixings from non-trivial b.c.

- Bidoublet embedding:

$$\underset{SO(5)}{5} = \underset{(SU(2)_L, SU(2)_R)}{(2,2) \oplus (1,1)}$$

A model of gauge-Higgs unification

- Bulk gauge symmetry $SO(5) \times U(1)_X$ broken to $SO(4) \times U(1)_X$ on the IR and to the SM on the UV
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Custodial protection of Zbb

- Fermion coupling to Z at zero momentum

$$\frac{g}{\cos\theta_W}[Q_L^3 - Q\sin^2\theta_W]Z_\mu\bar{\psi}\gamma^\mu\psi$$

- Q_L^3 can be protected by a subgroup of the custodial symmetry

$$U(1)_L \times U(1)_R \times P_{LR} \to U(1)_V \times P_{LR}$$

$$\left.\begin{array}{r} U(1)_V \Rightarrow \delta Q_L^3 + \delta Q_R^3 = 0 \\ P_{LR} \Rightarrow \delta Q_L^3 = \delta Q_R^3 \end{array}\right\} \Rightarrow \delta Q_L^3 = 0$$

$$\boxed{\frac{\delta g_f}{g_f} = \frac{e^2}{s^2c^2}\left[G^f_{++} - \frac{c^2 T_R^3 \frac{g_R^2}{g_L^2} + s^2 T_L^3 - s^2 Q}{T_L^3 - s^2 Q} G^f_{-+}\right] = \frac{e^2}{s^2c^2}\left[G^f_{++} - G^f_{-+}\right]}$$

Observables used in the global fit

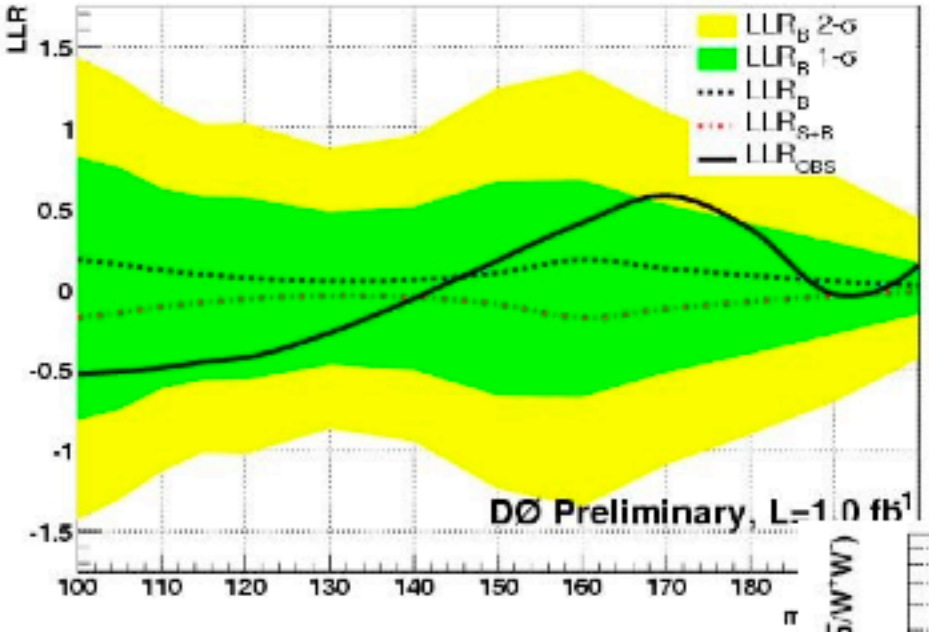
Bottom considered independently

	Standard Notation	Measurement	Reference
Atomic parity violation	$Q_W(Cs)$	Weak charge in Cs	[21]
	$Q_W(Tl)$	Weak charge in Tl	[22]
DIS	g_L^2, g_R^2	ν_μ-nucleon scattering from NuTeV	[23]
	R^ν	ν_μ-nucleon scattering from CDHS and CHARM	[24, 25]
	κ	ν_μ-nucleon scattering from CCFR	[26]
	$g_V^{\nu e}, g_A^{\nu e}$	ν-e scattering from CHARM II	[27]
Z-pole	Γ_Z	Total Z width	[20]
	σ_h^0	e^+e^- hadronic cross section at Z pole	[20]
	$R_f^0(f = e, \mu, \tau, b, c)$	Ratios of decay rates	[20]
	$A_{FB}^{0,f}(f = e, \mu, \tau, b, c)$	Forward-backward asymmetries	[20]
	$\sin^2\theta_{eff}^{lept}(Q_{FB})$	Hadronic charge asymmetry	[20]
	$A_f(f = e, \mu, \tau, b, c)$	Polarized asymmetries	[20]
Fermion pair production at LEP2	$\sigma_f(f = q, \mu, \tau)$	Total cross sections for $e^+e^- \to f\overline{f}$	[20]
	$A_{FB}^f(f = \mu, \tau)$	Forward-backward asymmetries for $e^+e^- \to f\overline{f}$	[20]
	$d\sigma_e/d\cos\theta$	Differential cross section for $e^+e^- \to e^+e^-$	[28]
W pair	$d\sigma_W/d\cos\theta$	Differential cross section for $e^+e^- \to W^+W^-$	[29]
	M_W	W mass	[20, 30]

TABLE I: Relevant measurements

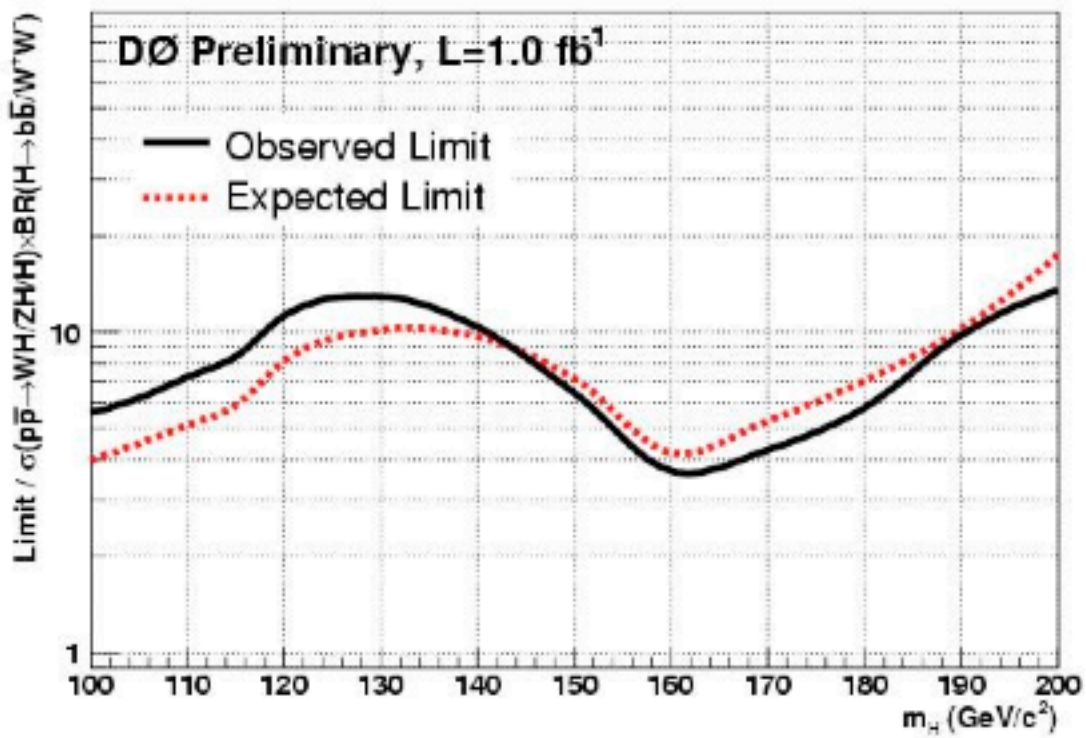
Combined SM Limits

Wine & Cheese
April 6th, 2007



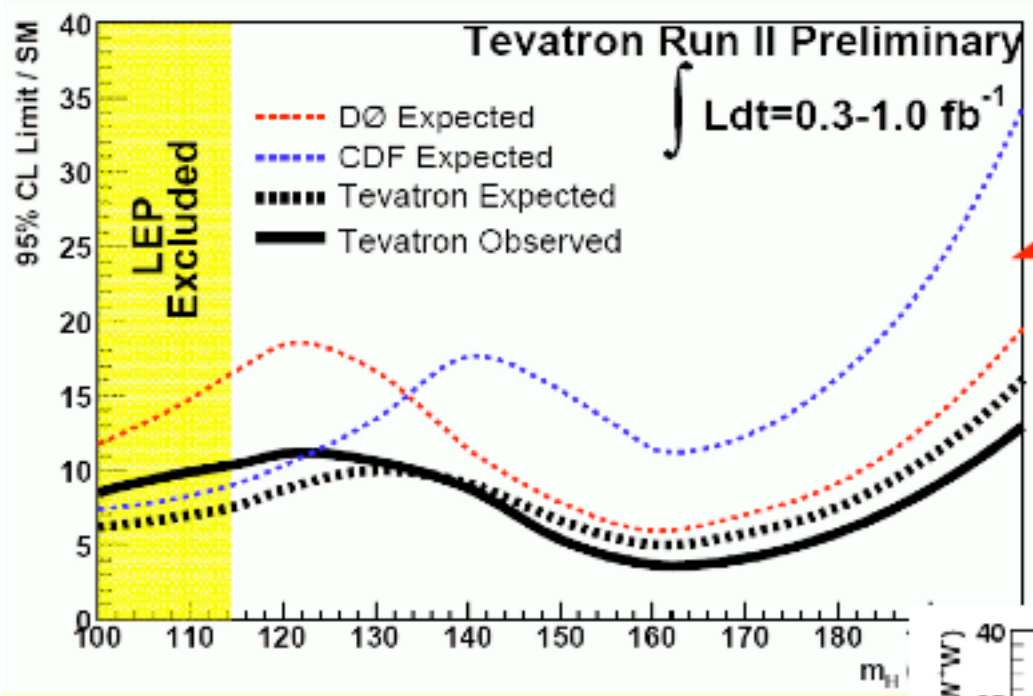
- Combination includes:
  - WH (m_H=100-150 GeV)
  - ZH (m_H=100-150 GeV)
  - H→WW (m_H=120-200 GeV)

- Limit ratios:
  - observed (expected)
  - 8.4 (5.9) @ m_H = 115 GeV
  - 3.7 (4.2) @ m_H = 160 GeV



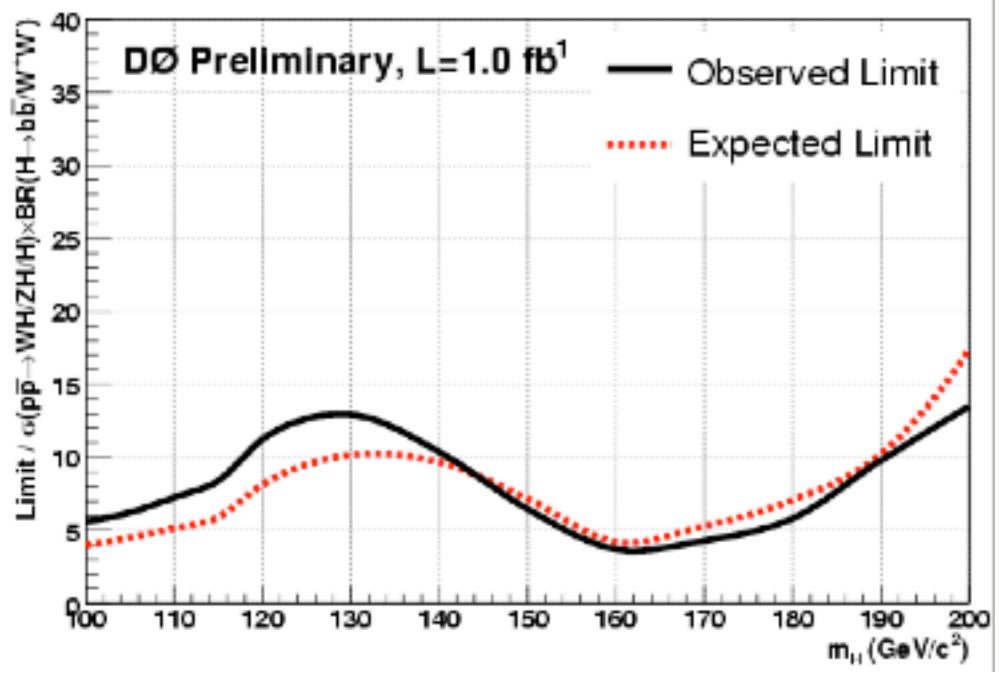
Progress?

Wine & Cheese
April 6th, 2007



ICHEP '06 Combined Results

- Large improvement at low mass: *factor of 3!*
  - Better than luminosity increase alone: sqrt(L_{new}/L_{old}) = 1.7



An Emerging Path...

- Though we're not quite there, we know we're missing pieces
  - Advanced analysis selections (NN,ME) provide factor of ~1.5-1.7 in equivalent luminosity
  - Missing channels (WH→WWW, single-tag for ZH)
  - New channels (taus, H→ZZ, hadronic H→WW) in the pipeline

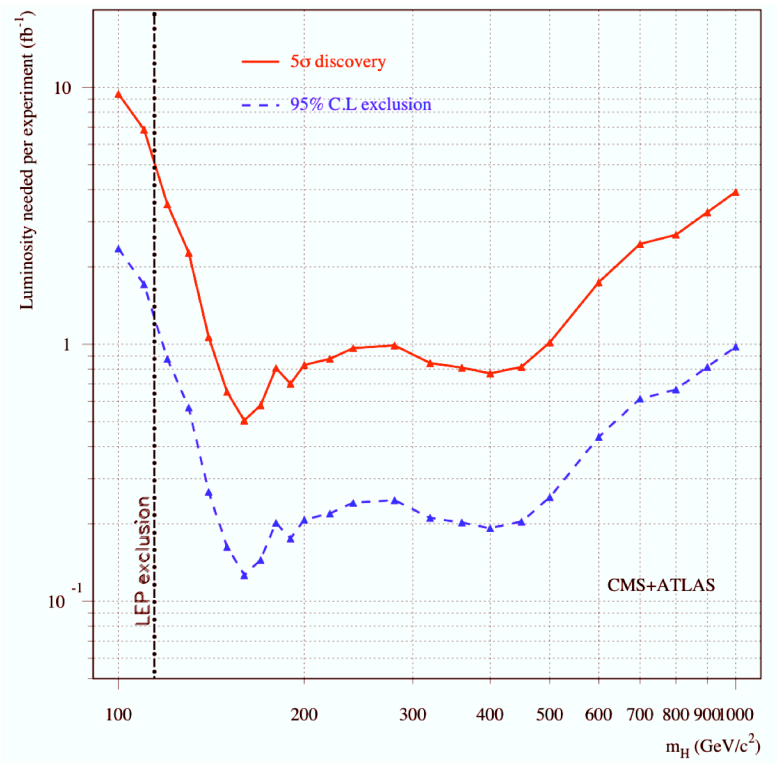
Ingredient	Equiv Lumi Gain	Xsec Factor MH=115 GeV	Xsec Factor MH=160 GeV
Today with 1fb^{-1}	-	5.9	4.2
Lumi = 2 fb^{-1}	2	4.2	3.0
b-Tag (Shape + LayerØ)	2	3.0	3.0
Multivariate Techniques	1.7	2.3	2.3
Improved mass resolution	1.5	1.8	2.3
New Channels	1.3/1.5	1.6	1.9
Reduced systematics	1.2	1.5	1.7
Two Experiments	2	1.1	1.2

Add another experiment ☺

→At 115 GeV need ~2.5 fb^{-1}

At 160 GeV need ~3 fb^{-1}

The LHC potential ==> a SM Higgs cannot escape discovery!



Total sensitivity combining all channels plus two experiments

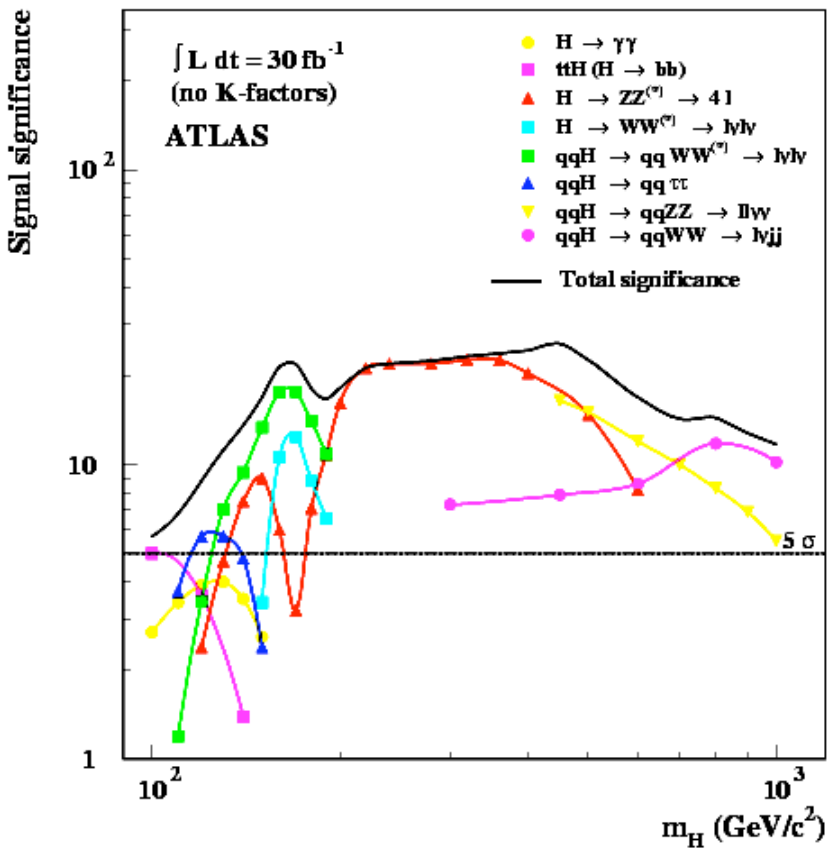
5 σ discovery possible over the entire SM Higgs mass range of interest with 5 fb-1 (~ 2010)

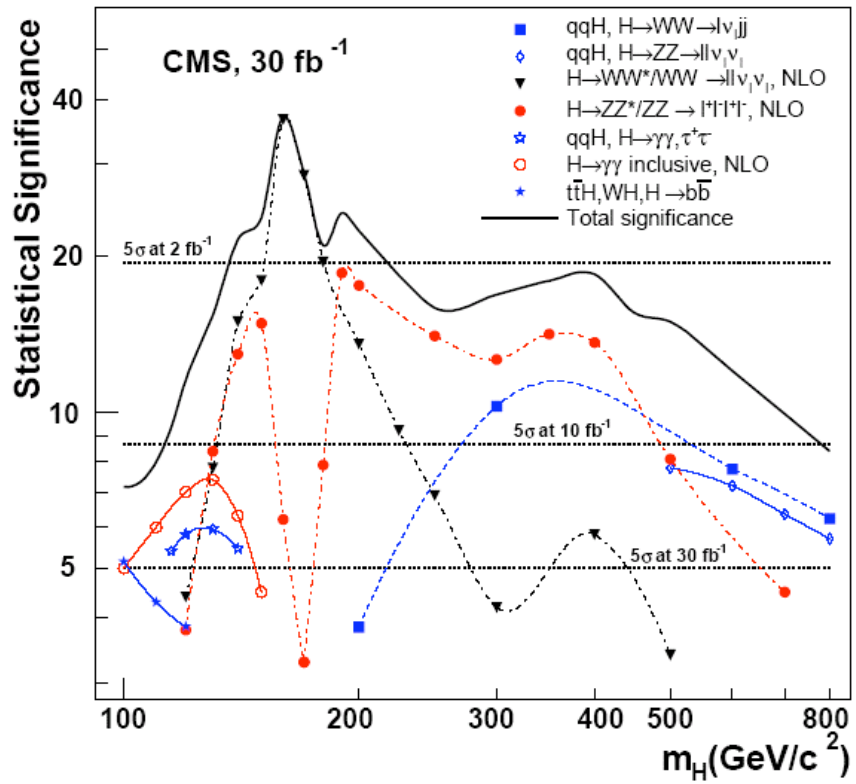
==> For $m_{H_{SM}}$~120 GeV combination of many different channels necessary, hence, requires a good understanding of the detectors.
==> The Tevatron may explore such region

Higgs mass resolution: 0.1 to 1%, combining most channels for maximal luminosity 300 fb^{-1} (~2015) and both experiments, using H ==>ZZ ==> 4l or H ==> gamma gamma

Total Width resolution: 5-8 % for $m_{H_{SM}}$ > 300 GeV, ATLAS 300 fb^{-1}, H ==> ZZ ==> 4l

Measure Higgs Couplings with 5-20 % accuracy (maximal luminosity, both exp.)
Measuring SM-like Higgs couplings to W and Z bosons of order one will be evidence of the Higgs responsible for the EWSB ==> WW fusion most relevant channel


Signal significance
∫L dt = 30 fb-1
(no K-factors)
ATLAS
H → γγ
ttH (H → bb)
H → ZZ(*) → 4 l
H → WW(*) → lνlν
qqH → qq WW(*) → lνlν
qqH → qq ττ
qqH → qqZZ → llνν
qqH → qqWW → lνjj
Total significance
5 σ
10 2
10
1
10 2
10 3
m_H (GeV/c2)


Statistical Significance
CMS, 30 fb -1
qqH, H→WW→lνjjj
qqH, H→ZZ→llνlνl
H→WW*/WW →llνlνl, NLO
H→ZZ*/ZZ → l+l-l+l-, NLO
qqH, H→γγ,τ+τ-
H→γγ inclusive, NLO
tt̄H,WH,H →bb̄
Total significance
5σ at 2 fb-1
5σ at 10 fb-1
5σ at 30 fb-1
40
20
10
5
100
200
300
400
500
800
mH(GeV/c 2)

Measuring Higgs Couplings at LHC

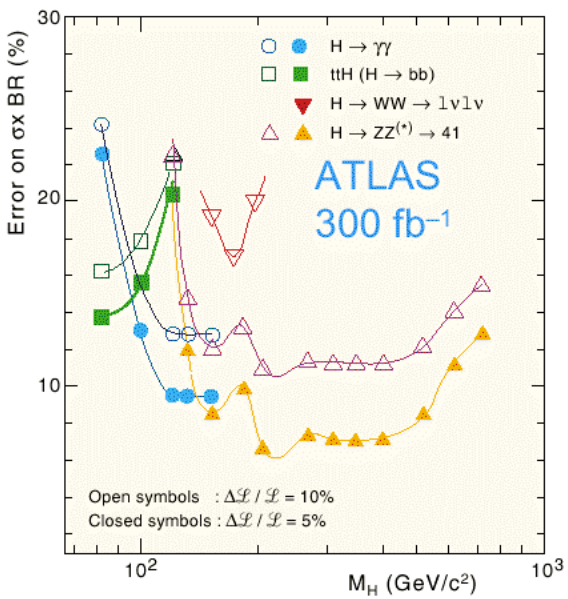
LHC rates for partonic processes are given by

$$\sigma(\mathrm{pp} \to \mathrm{H_{SM}}) \times \mathrm{BR}(\mathrm{H_{SM}} \to \mathrm{YY}) = \frac{\sigma^{SM}}{\Gamma_p^{SM}} \frac{\Gamma_p \Gamma_Y}{\Gamma}$$

Γ_p is the Higgs partial width involving the production couplings and BR $(\mathrm{H_{SM}} \to \mathrm{YY}) = \dfrac{\Gamma_Y(\mathrm{H_{SM}} \to \mathrm{YY})}{\Gamma}$

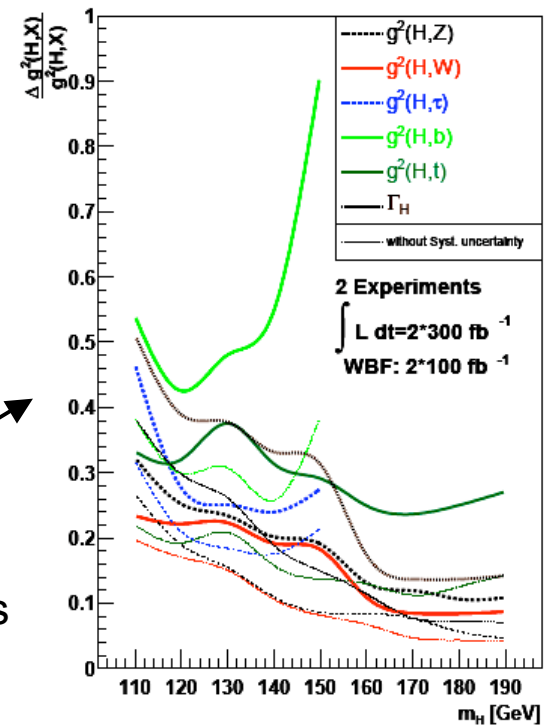
•From precision on $\sigma \times \mathrm{BR}$ ==> determine ratios of decay widths ==> with some mild theoretical assumptions

ratios of couplings



Duehrssen, Heinemeyer, Logan
Rainwater, Weiglein, Zeppenfeld

Precision of 10-40% for Γ_Y
==> 5-20% in the couplings



- **Measuring HWW and HZZ couplings of order one (SM-like) will be evidence of a Higgs responsible for the EWSB**
  ==> WW fusion most relevant channel

The Hierarchy/naturalness problem of the SM: Why $v \ll M_{Pl}$?

- Quantum corrections to dimensionless couplings prop. to $\log(\Lambda_{eff})$

$\Lambda_{eff} \longrightarrow$ cutoff scale at which a more fundamental theory supersedes the SM.

- Quantum corrections to Higgs potential mass parameter: quadratically divergent!

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

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

The Higgs is expected to have a mass of about 10^{19} GeV but a 200 GeV Higgs is necessary to solve the mass puzzle of the SM.

lesson from history: electron self-energy $\longrightarrow$
fluctuations of em fields generate a quadratic divergence but existence of electron anti-particle cancels it, otherwise QED will break far below M_{Pl}

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

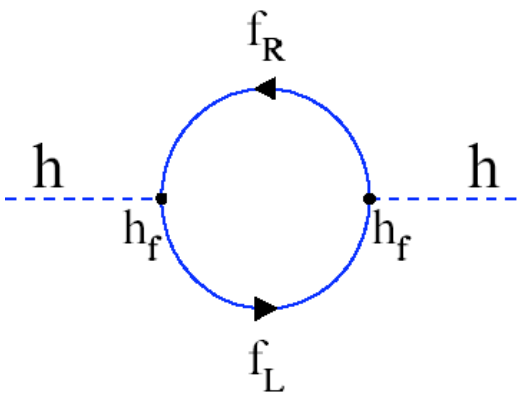
New Physics at the TeV scale is needed to stabilize the Higgs mass quantum corrections and to answer the fundamental questions of particle physics

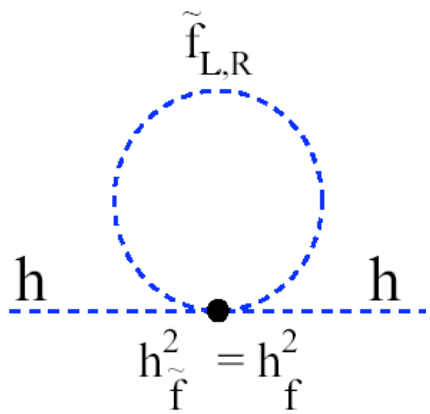
For every fermion there is a boson of equal mass and couplings

Self energy of an elementary scalar related by SUSY to the self energy of a fermion → only log dependence on fundamental high energy scale!

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

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





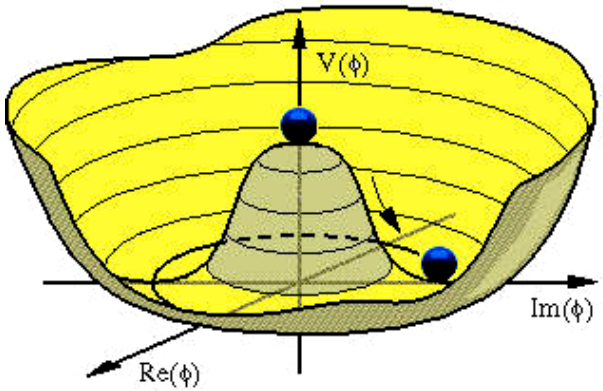
SUSY must be broken in nature: no SUSY partner, degenerate in mass with its SM particle has been seen

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

In the Standard Model: 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 a non-zero value to minimize its energy:

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

Higgs vacuum condensate $v \Longrightarrow$ scale of EWSB

- Spontaneous breakdown of the symmetry generates 3 massless Goldstone bosons which are absorbed to give mass to $V = W, Z$

  ⋆ interaction with gauge fields

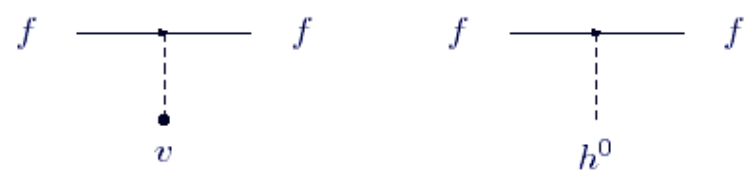
  $m_V^2 = g_{\phi\ VV}\ v/2 \quad \longrightarrow v = 174$ GeV

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

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

⋆ mass to fermions via Yukawa interactions

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



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

- **Direct Higgs search at the Large Electron-Positron collider** (LEP)

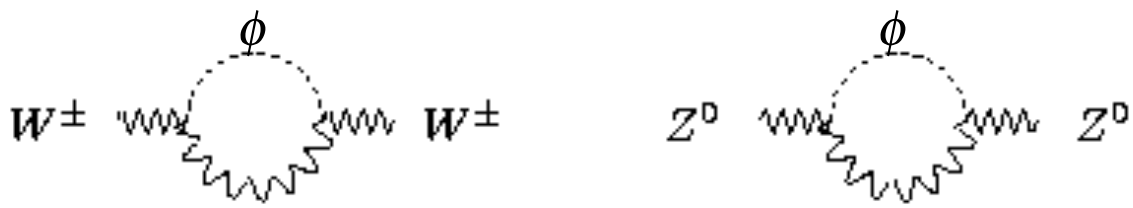
$$e^+e^- \xrightarrow{Z^*} H_{SM} Z \qquad m_{H_{SM}} > 114.6 \text{ GeV at } 95\% \text{ C.L.}$$

with $H_{SM} \to b\bar{b}, \tau^+\tau^-;\ Z \to q\bar{q}, l^+l^-, \nu\bar{\nu}$ final LEP result, 2003

- **Indirect constraints on $m_{H_{SM}}$ from precision tests of the SM**

accuracy at the per mille level from experiments at CERN, Fermilab and SLAC

Although the Higgs boson has not been seen and its mass is unknown, it enters via virtual Higgs production in electroweak observables: particle masses, decay rates,etc



All electroweak parameters have a weak logarithmic dependence on $m_{H_{SM}}$
Nonetheless, preferred value of $m_{H_{SM}}$ can be determined

$$m_{H_{SM}} < 200 \text{ GeV at } 95\ \% \text{ C.L}$$

To avoid a light Higgs Boson, must have new phenomena below 1 TeV