LHC Phenomenology: Beyond the Standard Model

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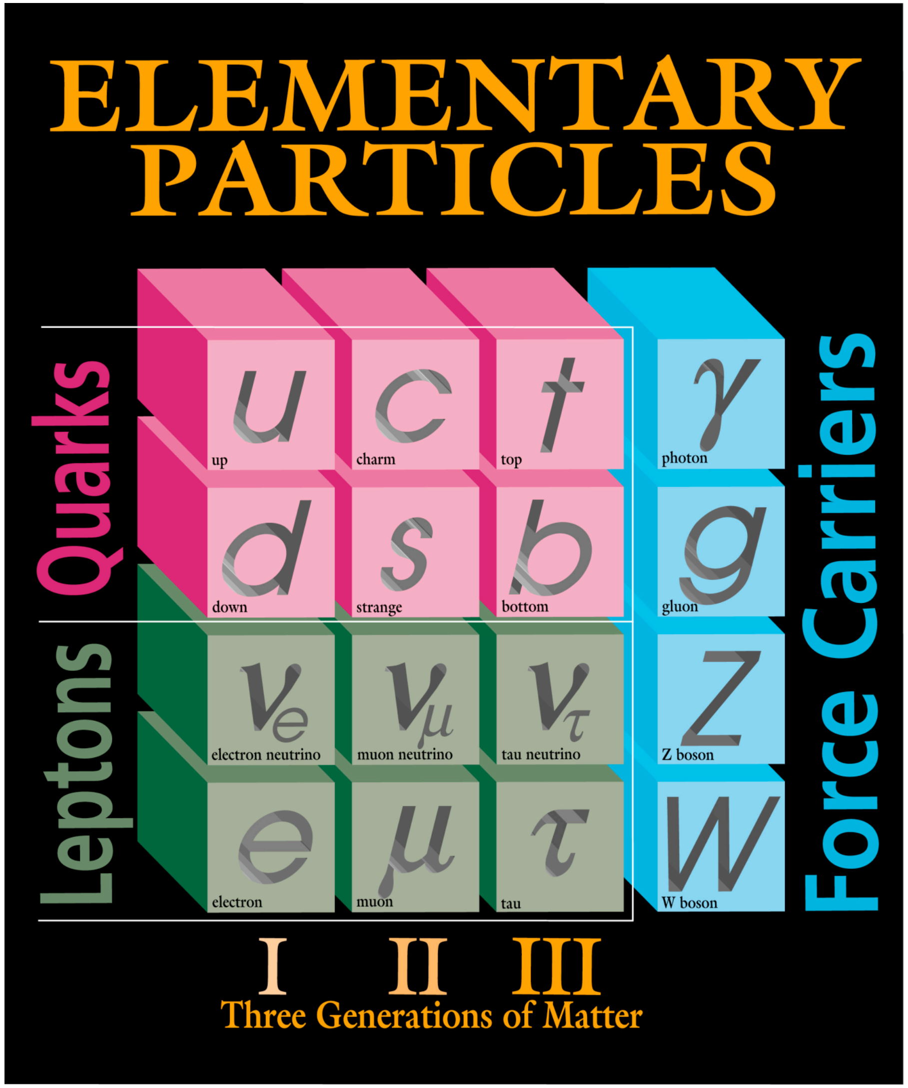
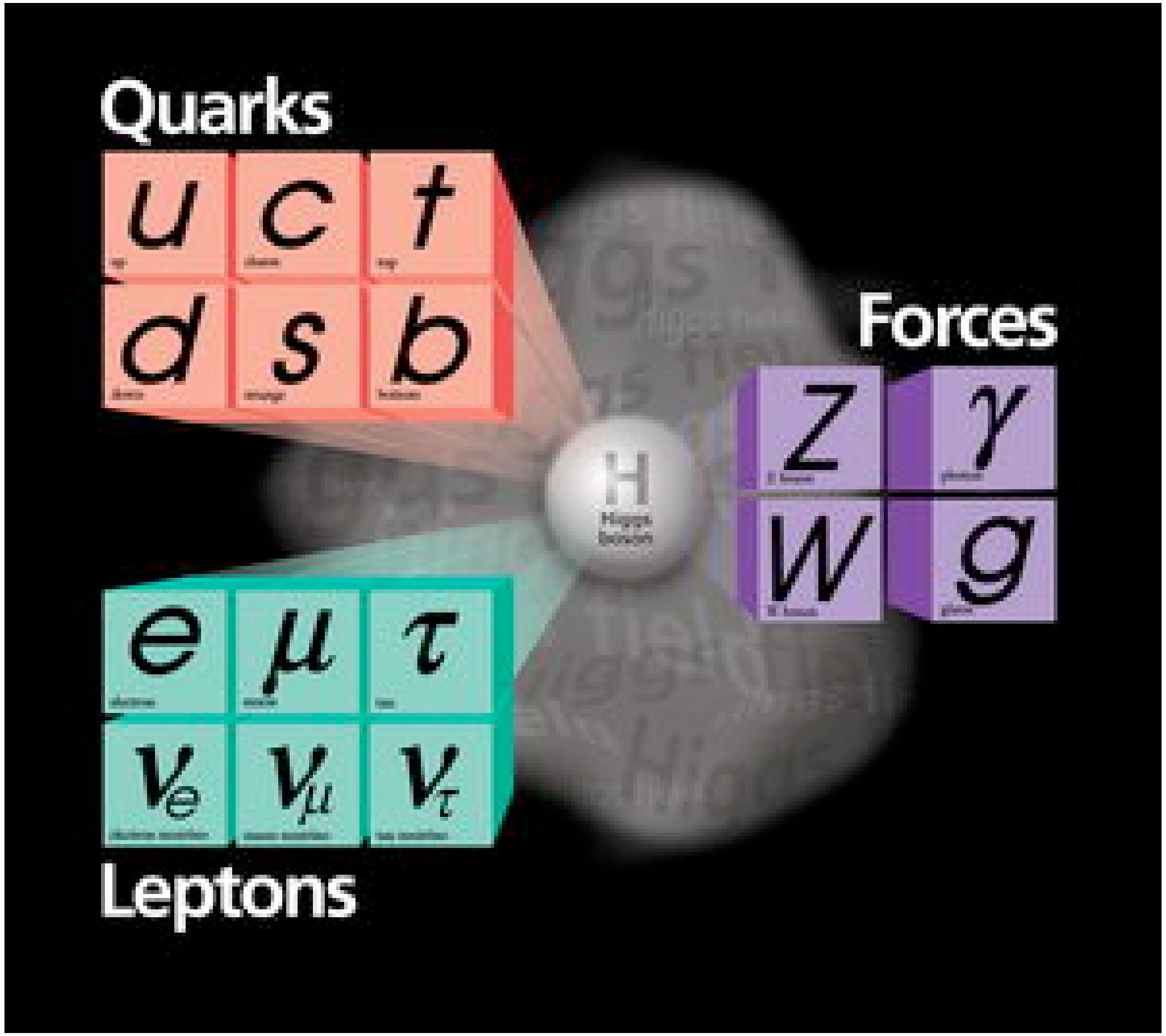
Standard Model



Fermilab 95-759

Problem is that leptons and W,Z have mass.

The Speculative Solution: Higgs Boson



SM Higgs Boson

EWSB accomplished by a single Higgs boson.

$$H = \begin{pmatrix} \frac{1}{\sqrt{2}}(h+v) + i\phi_1 \\ \phi_2 + i\phi_3 \end{pmatrix} \quad \text{where } v = 246\,\text{GeV}$$

$$\{W_T^{\pm}, Z_T^0\} + \{\phi_1, \phi_2, \phi_3\} \Rightarrow \{W_T^{\pm}, W_L^{\pm}, Z_T^0, Z_L^0\}$$

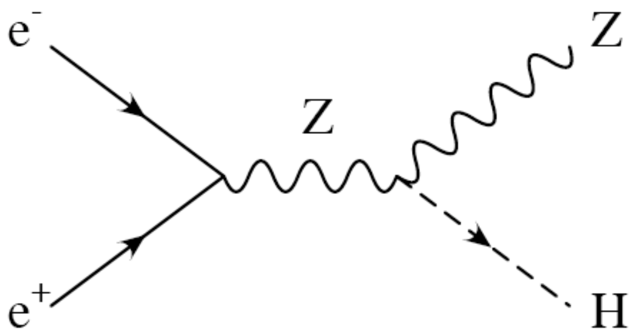
$$L = \left[m_W^2 W^{+\mu} W_\mu^- + \frac{1}{2} m_Z^2 Z^\mu Z_\mu\right] \cdot \left(1 + \frac{h}{v}\right)^2 - m_f \bar{f}_L f_R \left(1 + \frac{h}{v}\right) + h.c.$$

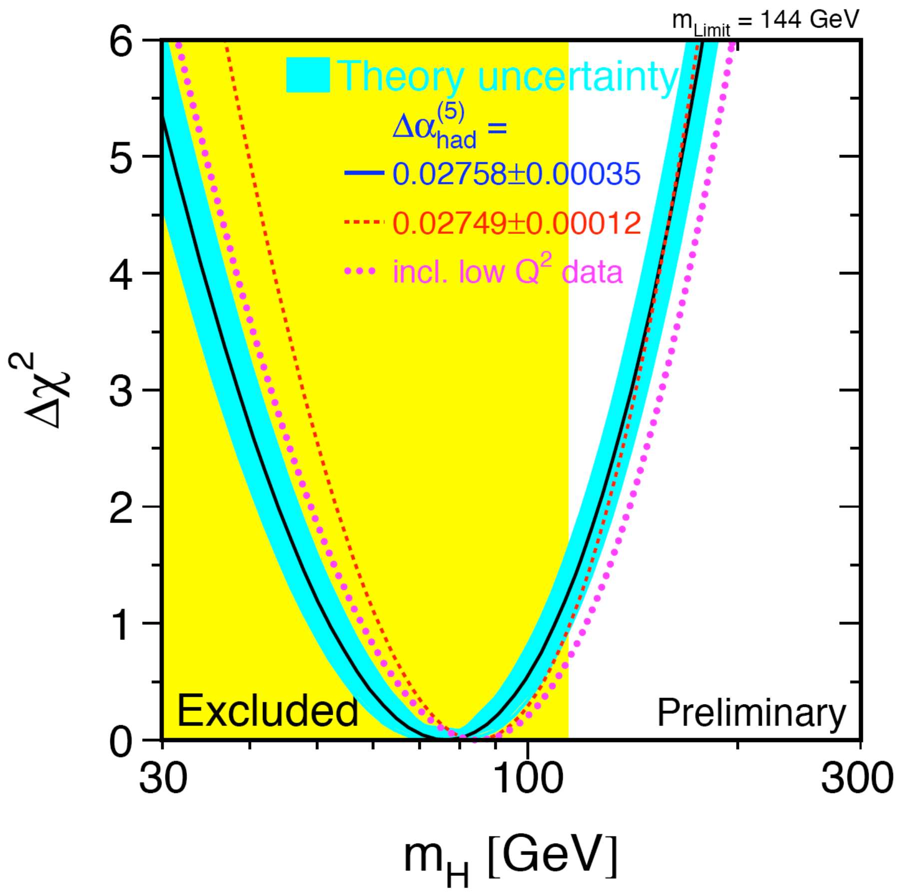
Higgs mass is only free parameter.

Higgs mass limits

Higgs boson mass upper limit (95% CL) from precision Electroweak is less than 182 GeV.

Lower limit from lack of direct signal at LEP 2 is about 115 GeV.





LEPEWWG

Experiment: 115 GeV < m_h < 180 GeV

Should we believe in the Higgs boson?

The Higgs boson is a speculative particle explanation for elementary particle masses.

Cons:

1. One particle carries all burdens of mass generation?
2. Fundamental scalar not known in nature.
3. Hasn't been found yet.
4. Too simplistic -- dynamics for vev not built in.
5. Idea not stable to quantum corrections.

Pros: Still consistent with experimental facts!

Higgs boson is very special…

The $|H|^2$ operator is the only gauge-invariant, Lorentz invariant relevant operator in the Standard Model.

Other relevant operators include:

Neutrino physics.

$$B_{\mu\nu}, \qquad HL, \quad \nu_R^T i\sigma^2 \nu_R$$

Lorentz Tensor

Lorentz spinor

Lepton #
Not in SM.

Effective Theories

Expectation of Effective Theories:
All operators receive O(1) coefficients unless there is a symmetry principle not to. (corollaries: ‘t Hooft’s naturalness principles.)

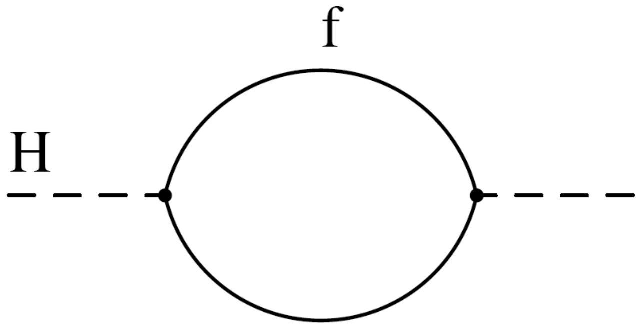
Dimension=4 marginal operators: $\lambda \sim 1$

Dimension<4 relevant operators: $\Lambda^{\#} \sim (M_{pl})^{\#}$

$\Rightarrow$ Higgs mass operator expected to be $(M_{pl})^2|H|^2$ unless there is a principle to forbid it.

Related: Quadratic Sensitivity

A quantum loop is quadratically divergent. Higgs Mass, connected to Higgs vev, is unstable to the Highest mass scales in the theory.



$$m_H^2 \sim \frac{\alpha_f}{4\pi}\Lambda^2 \quad \Rightarrow \quad \Lambda^2 \sim M_{Pl}^2 \, ?$$

Statics and Dynamics of Higgs Mass

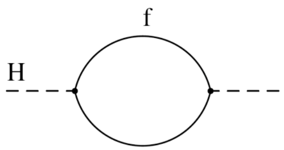
Principle: SUSY, Xdim,
Little Higgs, Compositeness, etc.

$$H^\dagger(m_{EW}^2 + \text{stabilizers} + \cdots)H + \Delta\mathcal{L}[\text{stabilizer dynamics}] + \cdots$$

Top squarks, radion,
T-odd top partners, etc.

Gluinos, KK Gravitons, etc.

SUSY:



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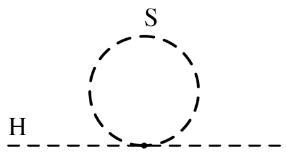


$$m_H^2 \sim \frac{\alpha_f}{4\pi}\Lambda^2 - \frac{\alpha_f}{4\pi}\Lambda^2 \sim 0 + \cdots$$

Minimal Supersymmetric Standard Model

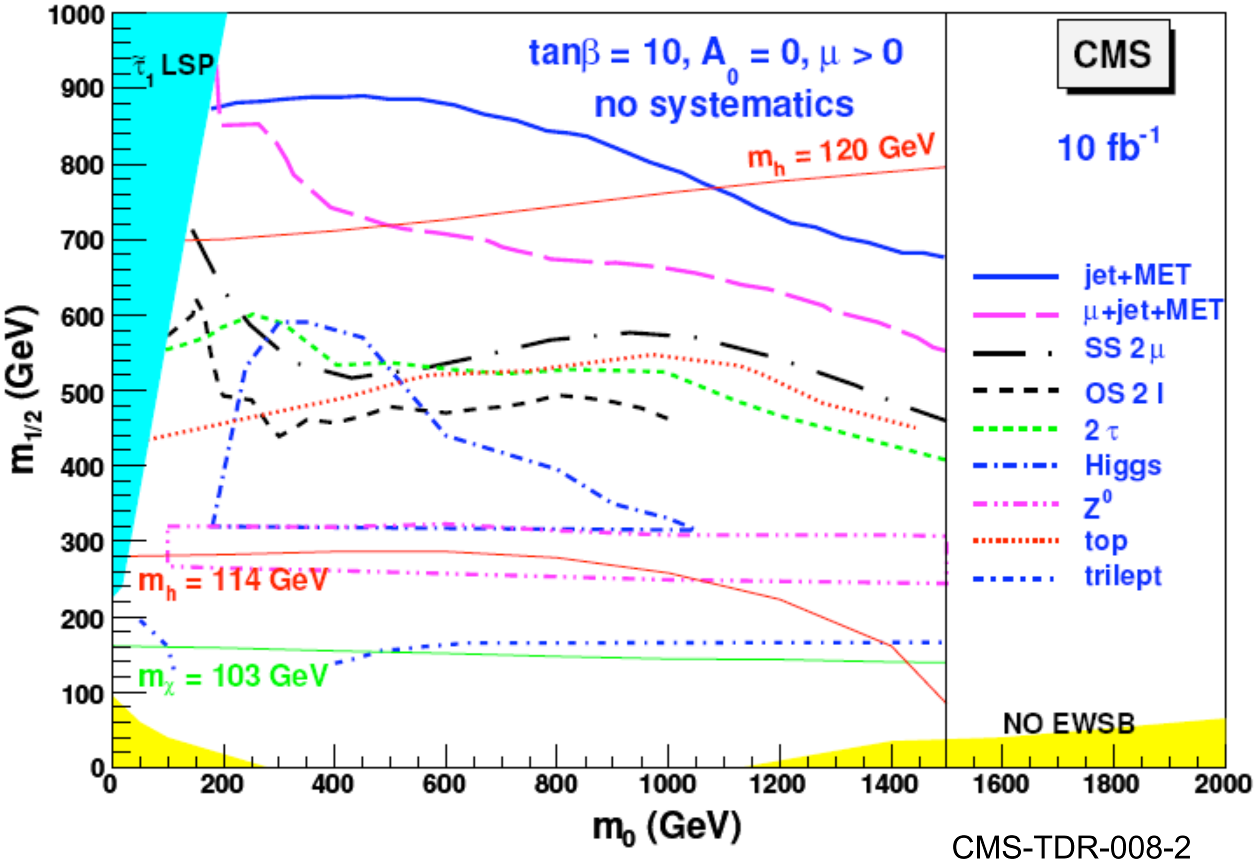
Martin, hep-ph/9709356

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)	$\overline{u}$	$\widetilde{u}_R^*$	$u_R^\dagger$	$(\,\overline{\mathbf{3}},\ \mathbf{1},\ -\frac{2}{3})$
	$\overline{d}$	$\widetilde{d}_R^*$	$d_R^\dagger$	$(\,\overline{\mathbf{3}},\ \mathbf{1},\ \frac{1}{3})$
sleptons, leptons	L	$(\widetilde{\nu} \ \ \widetilde{e}_L)$	$(\nu \ \ e_L)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ -\frac{1}{2})$
($\times 3$ families)	$\overline{e}$	$\widetilde{e}_R^*$	$e_R^\dagger$	$(\,\mathbf{1},\ \mathbf{1},\ 1)$
Higgs, higgsinos	H_u	$(H_u^+ \ \ H_u^0)$	$(\widetilde{H}_u^+ \ \ \widetilde{H}_u^0)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ +\frac{1}{2})$
	H_d	$(H_d^0 \ \ H_d^-)$	$(\widetilde{H}_d^0 \ \ \widetilde{H}_d^-)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ -\frac{1}{2})$

If supersymmetry masses heavy (greater than all the SM masses), 4 Higgses $\{H^+, H^-, A, H\}$ form a heavy, decoupled doublet, and h remains a light field, which behaves just as the Standard Model Higgs boson.

Supersymmetry predicts mass of h field to be less than About 135 GeV. I.e., compatible with data.
Challenge: "Preference" for Higgs mass below expt bound.

LHC Supersymmetry reach



CMS-TDR-008-2

CMSSM

Mbino ~ 0.4 $m_{1/2}$
Mwino ~ 0.8 $m_{1/2}$
Mgluino ~ 2.7 $m_{1/2}$

$Msquark^2 \sim m_0^2 + 5m^2_{1/2}$

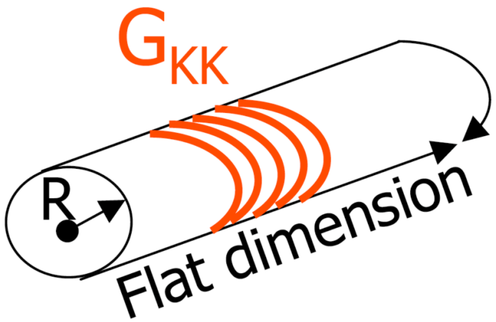
$\tilde{M}_{strong}$ < few TeV

Large Extra Dimensions

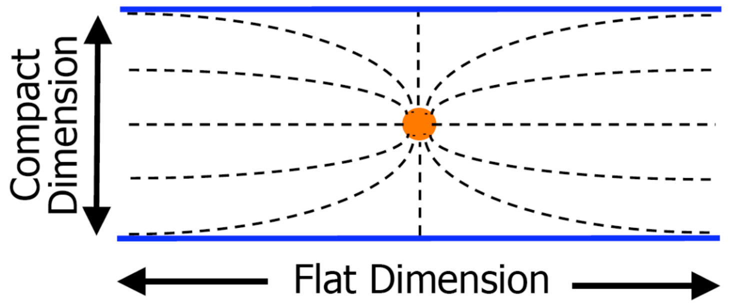
Quadratic divergence ok if no high scales

$$V(r) \sim \frac{1}{V_n M_D^{n+2}} \frac{m_1 m_2}{r} \quad \text{for } r \gg R$$

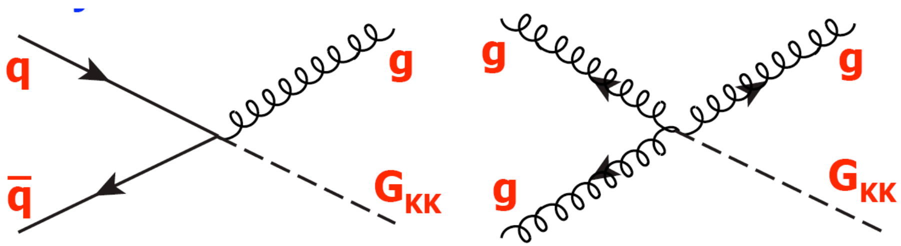
$$M_{Pl}^2 = V_n M_D^{n+2}$$



Extra Dimensions may
Explain large Planck Mass.
(Arkani-Hamed, Dimopoulos, Dvali)

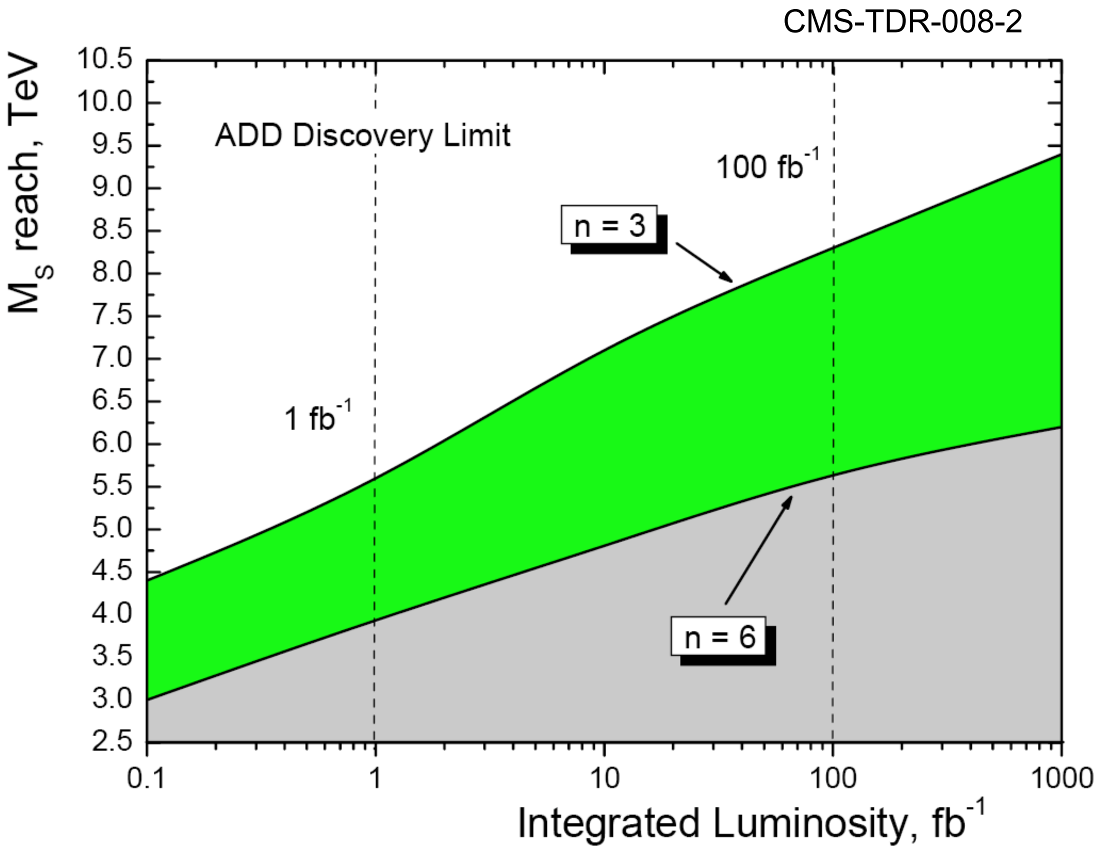


Drawings from Landsberg, 2001



Kaluza-Klein copies of
The graviton accessible
At high-energy colliders.
(Giudice, Rattazzi, JW; Peskin, Perelstein, etc.)

LHC Reach for KK Gravitons



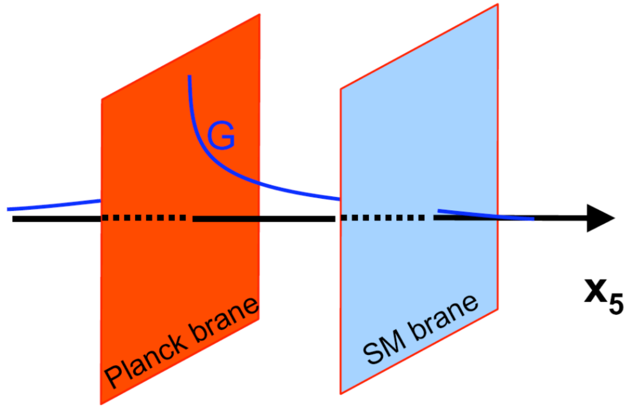
Tevatron/LEP limits:
M_s > 1.5 TeV

LHC expectations:
M_s < ~ 5 TeV
sensitivity

Higgs Implications of Warped Extra Dimensions

$$ds^2 = \exp\left(-2k|y|\right)\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$$ (Randall, Sundrum)

Graviton in warped Xdim space: KK Graviton



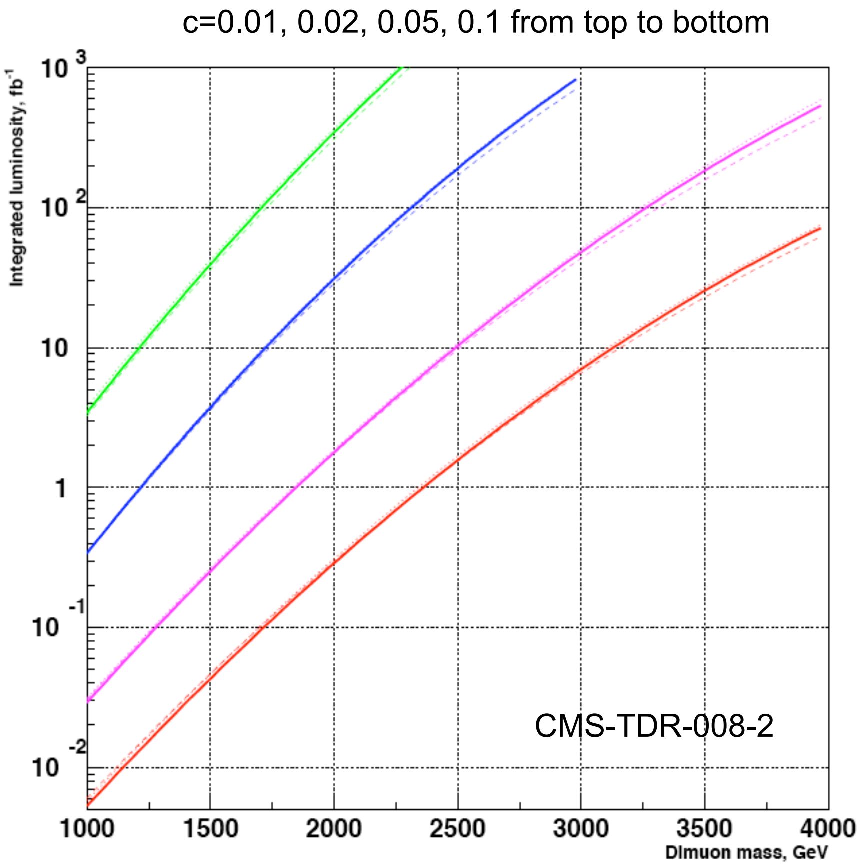
Separation of the two branes at each point is a field T(x) -- Radion Field.

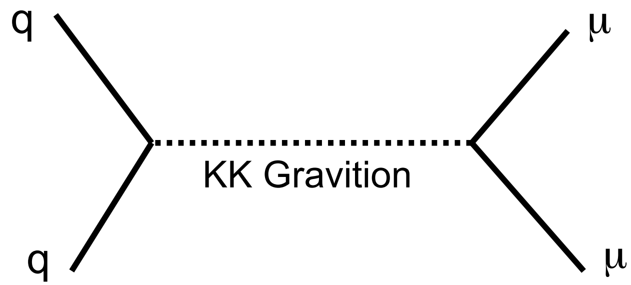
The Radion interacts with SM Particles *almost* identically the same as a Higgs boson, but with universally reduced couplings.

The radion and Higgs can mix through H^*HR gravitational coupling, leading to no eigenstate that interacts with full expected strength.

Giudice, Rattazzi, JDW, '01

KK Graviton Search in RS





Expectations and Opportunities

Data consistent with a rather light Higgs boson.

The entourage of states that protects and supports the Higgs boson should have mass close to it:

$M_{new} \sim$ <H> [175 GeV]

or $(4\pi)^{1/2}$<H> [620 GeV]

or 4π<H> [2.2 TeV]

or ?

LHC in prime real estate to discover the new dynamics -- the entourage the makes the Higgs viable.

dailymail.co.uk

New Opportunities with Higgs Relevant Operator

The $|H|^2$ operator gives us a chance to see states that we could never have otherwise seen before.

Generic couplings of Higgs to SM singlets, hidden sectors, etc

$$|\Phi_{hid}|^2|H|^2$$ (Generic coupling)

$$X^{\mu\nu}B_{\mu\nu}$$ (Possible coupling with extra $U(1)_{hid}$)

Recall: Challenges of being sensitive to New Physics

The Standard Model matter and gauge states saturate dimensionality of the lagrangian.

$$\mathcal{L} = i\bar{\psi}\gamma^\mu D_\mu \psi + \frac{1}{4} W^{a,\mu\nu} W^a_{\mu\nu} + \cdots$$

Any new states coupled in may come with a large suppression scale:

$$\mathcal{L} = \frac{1}{\Lambda^{\#}} \mathcal{O}_{SM} \mathcal{O}_{hid}$$

Simple, Non-Trivial Hidden World

Probably simplest theory is a Hidden-Sector Abelian Higgs Model.

A complex scalar charged under $U(1)_{X}$. The particle spectrum is a physical Higgs boson and an X gauge field.

Lagrangian

Consider the SM lagrangian plus the following:

$$\mathcal{L}_X^{KE} = -\frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu} + \frac{\chi}{2}\hat{X}_{\mu\nu}\hat{B}^{\mu\nu}$$

$$\begin{aligned}\mathcal{L}_\Phi \; = \; & |D_\mu \Phi_{SM}|^2 + |D_\mu \Phi_H|^2 + m_{\Phi_H}^2 |\Phi_H|^2 + m_{\Phi_{SM}}^2 |\Phi_{SM}|^2 \\ & -\lambda |\Phi_{SM}|^4 - \rho |\Phi_H|^4 - \boxed{\kappa |\Phi_{SM}|^2 |\Phi_H|^2} .\end{aligned}$$

Canonical Kinetic Terms

First, we make kinetic terms canonical by

$$\begin{pmatrix} X_\mu \\ Y_\mu \end{pmatrix} = \begin{pmatrix} \sqrt{1-\chi^2} & 0 \\ -\chi & 1 \end{pmatrix} \begin{pmatrix} \hat{X}_\mu \\ \hat{Y}_\mu \end{pmatrix}$$

The covariant derivative is shifted to

$$D_\mu = \partial_\mu + i(g_X Q_X + g' \eta Q_Y) X_\mu + i g' Q_Y B_\mu + i g T^3 W^3_\mu$$

$$\text{where } \eta \equiv \chi / \sqrt{1-\chi^2}$$

Higgs Masses and Mixings

$$\begin{pmatrix} \phi_{SM} \\ \phi_H \end{pmatrix} = \begin{pmatrix} c_h & s_h \\ -s_h & c_h \end{pmatrix} \begin{pmatrix} h \\ H \end{pmatrix}$$

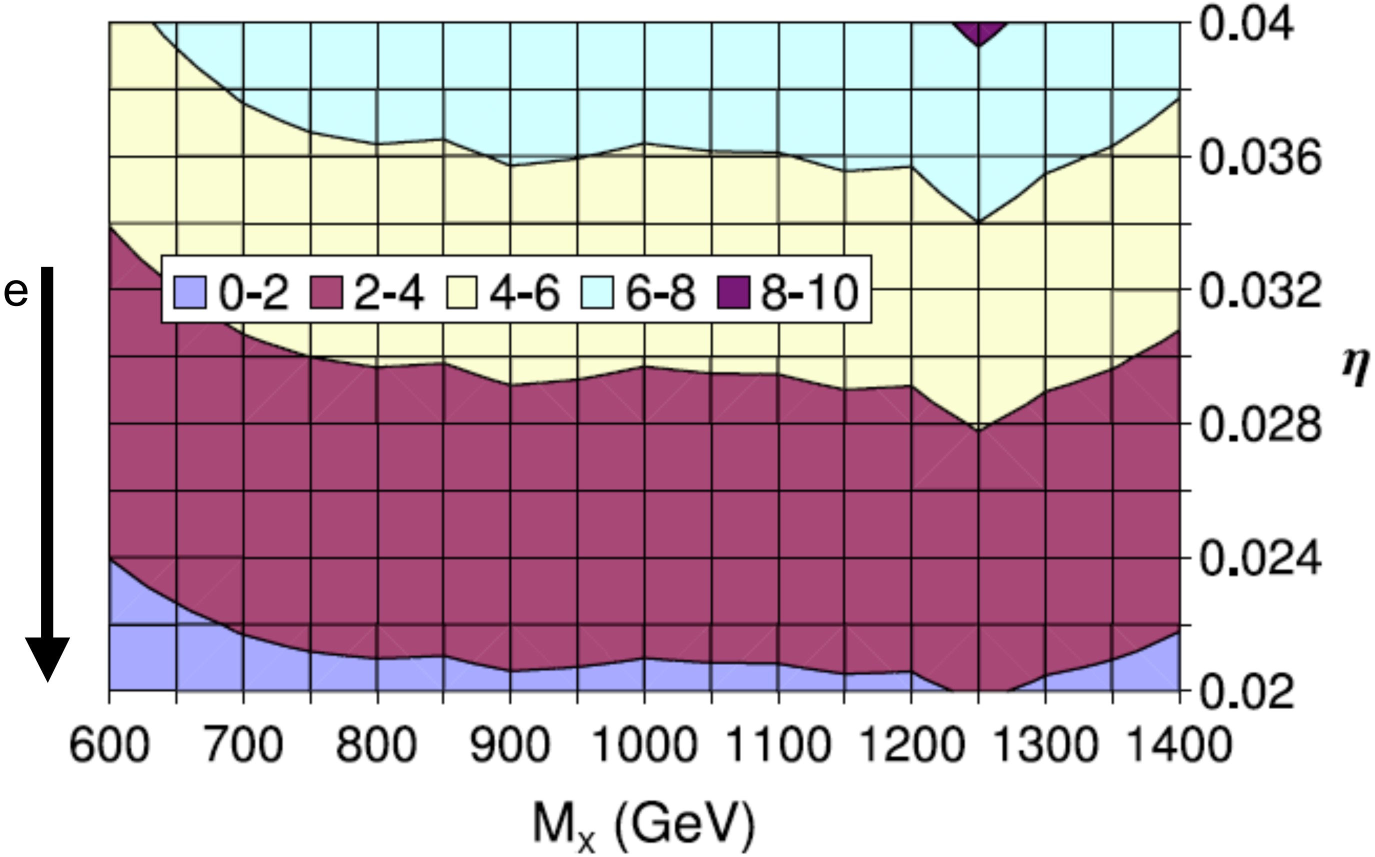
The mixing angle and mass eigenvalues are

$$\tan(2\theta_h) = \frac{\kappa v \xi}{\rho\xi^2 - \lambda v^2}$$

$$M^2_{h,H} = \left(\lambda v^2 + \rho\xi^2\right) \mp \sqrt{(\lambda v^2 - \rho\xi^2)^2 + \kappa^2 v^2 \xi^2}$$

Collider Searches for Z'

Undetectable



Kumar, JW 0606183

Two Paths to LHC Discovery

Within this framework, we studied two ways to find Higgs boson at the LHC:

1) Narrow Trans-TeV Higgs boson signal

2) Heavy Higgs to light Higgs decays

Narrow Trans-TeV Higgs Boson

When the mixing is small, the heavy Higgs has smaller cross-section (bad), but more narrow (good).

	Point A	Point B	Point C
s_ω^2	0.40	0.31	0.1
m_h (GeV)	143	115	120
m_H (GeV)	1100	1140	1100
$\Gamma(H \to hh)$ (GeV)	14.6	4.9	10
$BR(H \to hh)$	0.036	0.015	0.095

Investigate Point C example

Two Signals

1) $$H \to WW \to l\nu jj$$

$$p_T(e,\mu) > 100\,\mathrm{GeV} \quad \text{and} \quad |\eta(e,\mu)| < 2.0$$

$$\text{Missing } E_T > 100\,\mathrm{GeV}$$

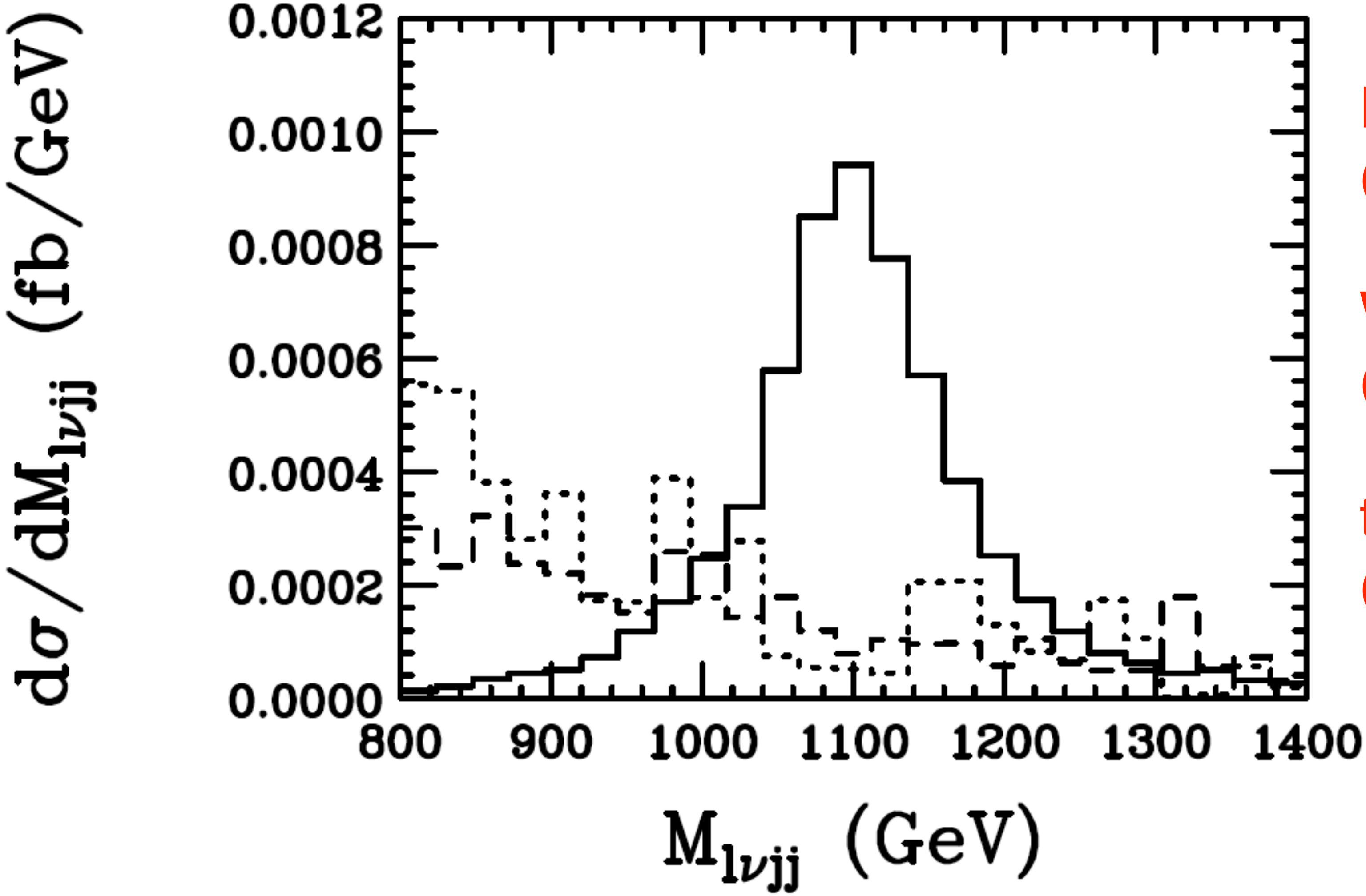
$$p_T(j,j) > 100\,\mathrm{GeV} \quad \text{and} \quad m_{jj} = m_W \pm 20\,\mathrm{GeV}$$

$$\text{“Tagging jets” with } |\eta| > 2.0$$

H->WW->jjlν

Techniques: Atlas & CMS TDRs and Iordanidis, Zeppenfeld, '97

Between 1.0 & 1.3 TeV 13 signal events in 100 fb^{-1} vs. 7.7 bkgd



H->WW (solid)

WWjj (dashed)

ttjj (dotted)

Difference from SUSY heavy Higgs boson

SUSY heavy Higgs has qualitatively different behavior:

ϕ		$g_{\phi\bar{t}t}$	$g_{\phi\bar{b}b}$	$g_{\phi VV}$
SM	H	1	1	1
MSSM	h^o	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\sin(\beta-\alpha)$
	H^o	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos(\beta-\alpha)$
	A^o	$1/\tan\beta$	$\tan\beta$	0

Haber et al. '01

$$HVV: \quad \cos(\beta-\alpha) \to \boxed{0} + \mathcal{O}(m_Z^4/m_A^4)$$

$$H\bar{t}t: \quad \frac{\sin\alpha}{\sin\beta} \to \boxed{\frac{1}{\tan\beta}} + \mathcal{O}(m_Z^2/m_A^2)$$

$$H\bar{b}b: \quad \frac{\cos\alpha}{\cos\beta} \to \boxed{\tan\beta} + \mathcal{O}(m_Z^2/m_A^2)$$

Heavy Higgs decays mostly into tops or bottoms (or susy partners) depending on tanβ.

H decays to lighter Higgses

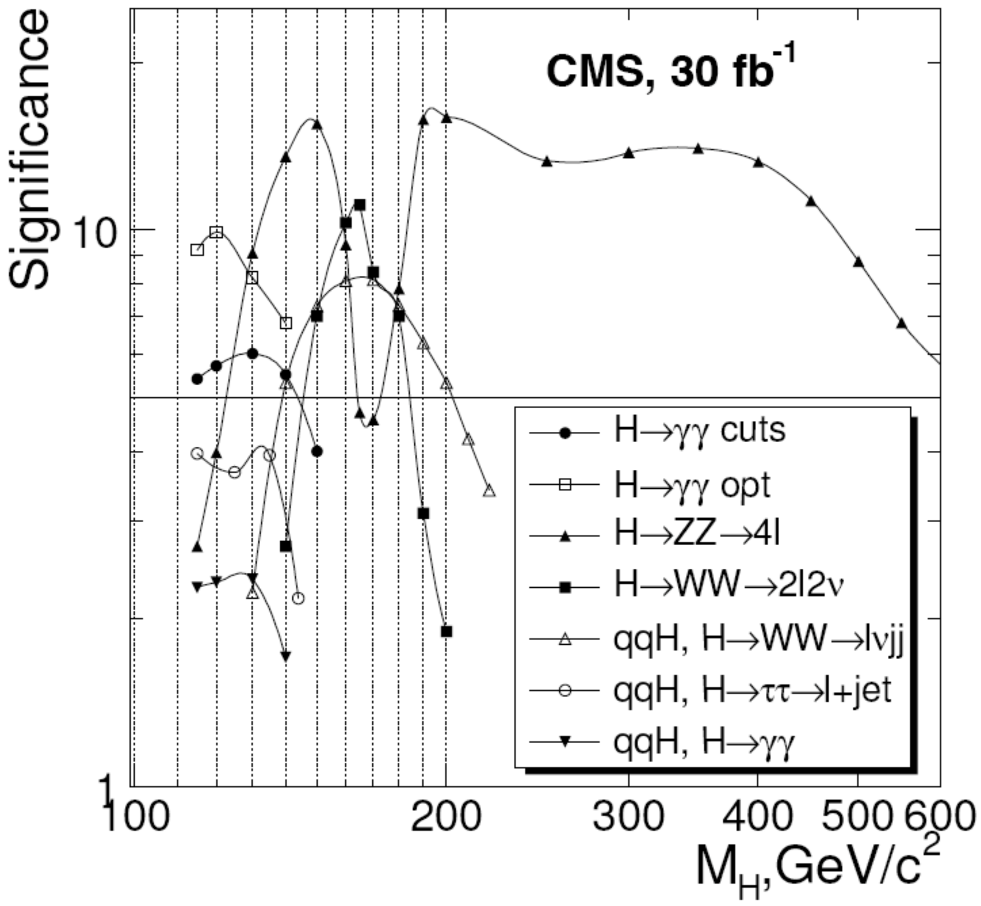
We can also have a heavier Higgs boson decaying into two lighter ones in this scenario.

	Point 1	Point 2	Point 3
s_ω^2	0.5	0.5	0.5
m_h (GeV)	115	175	225
m_H (GeV)	300	500	500
$\Gamma(H \to hh)$ (GeV)	2.1	17	17
$BR(H \to hh)$	0.33	0.33	0.33

Both Higgses suppressed with respect to SM Higgs.

Higgs discovery significances

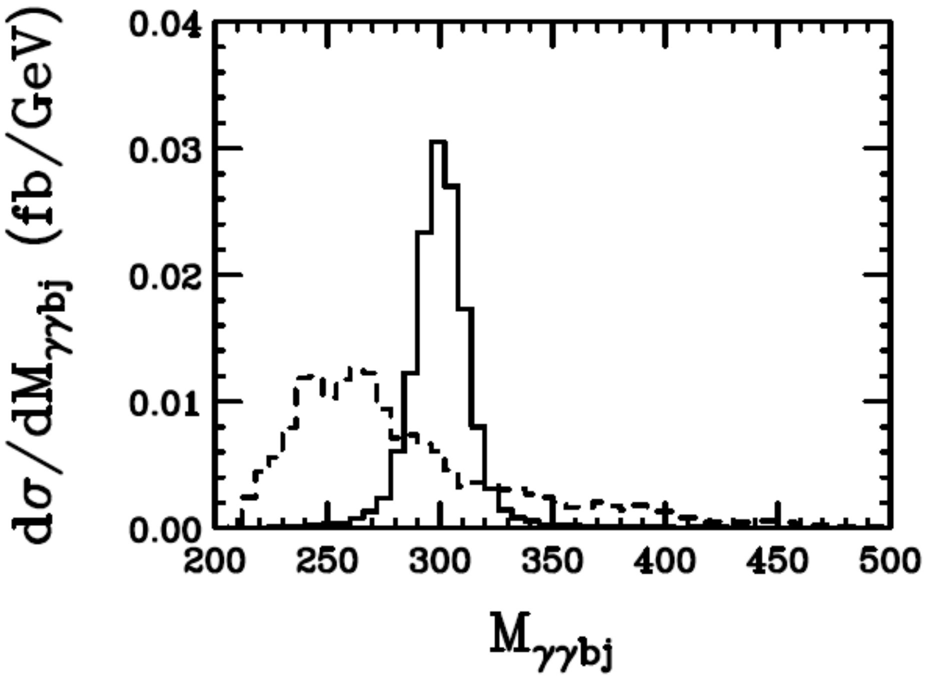
CMS-TDR-008-2



Heavy to Light Higgs rate

Considered discovery mode (Richter-Was et al.):

$$gg \to H \to hh \to \gamma\gamma\bar{b}b$$

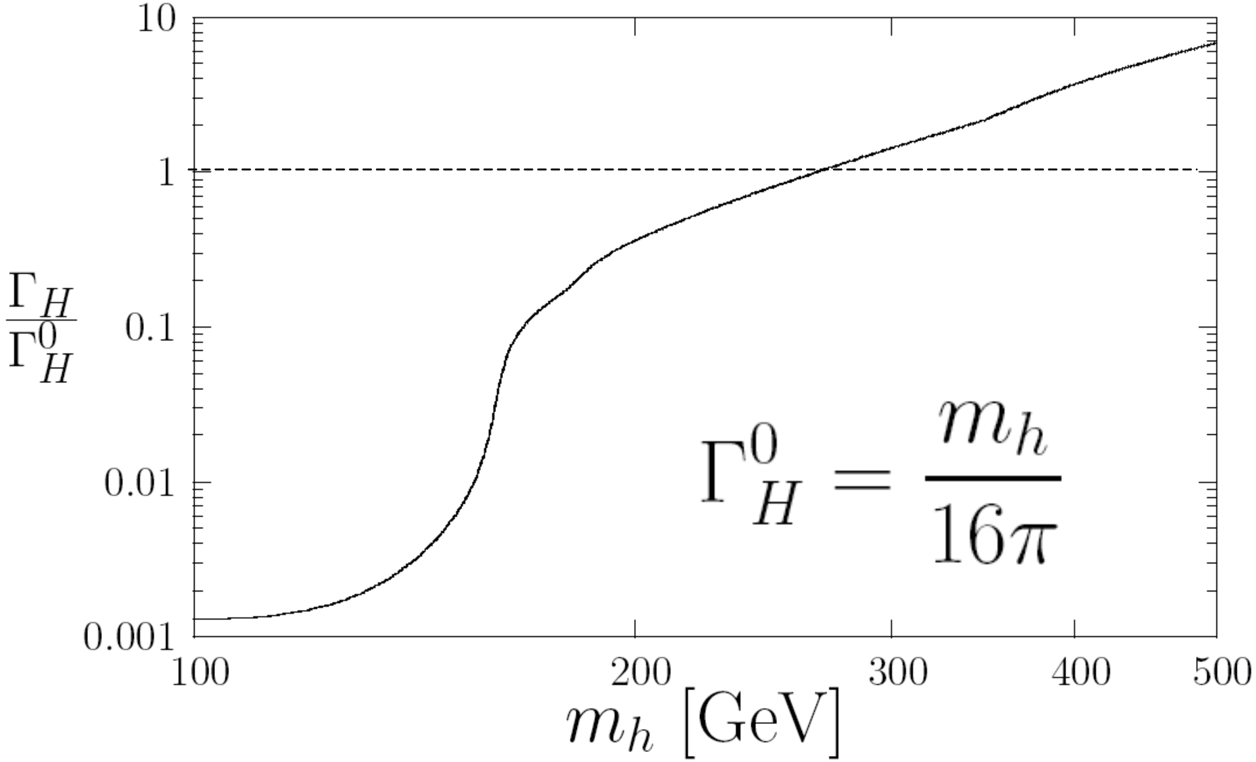


Channel	1 tag	2 tags
$H \to hh$	24	12
$\gamma\gamma bb$	0.4	0.2
$\gamma\gamma bc$	0.15	0.01
$\gamma\gamma bj$	1	0.009
$\gamma\gamma cc$	1.2	0.069
$\gamma\gamma cj$	3.6	0.042
$\gamma\gamma jj$	1.8	0.007
Total background	8.2	0.34

30 fb^{-1} bkgd estimates

Bowen, Cui, JW

Light Higgs accidentally narrow



Light Higgs boson especially susceptible to new decay modes.

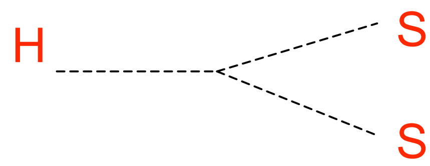
Sources of Invisible Decay

Many ideas lead to invisible Higgs decays -- possible connections to dark matter.

Joshipura et al. '93 ;
Binoth, van der Bij, '97, etc.

Simplest of all is the addition of a real scalar field with Z_2.

$$\mathcal{L} = \frac{M_S^2}{2} S^2 + \lambda S^2 |\Phi_{SM}|^2 + \cdots$$



Example from Abelian Higgs Model with fermions:

$U(1)_X$: $\{\Phi_H, \psi, \bar{\psi}, \chi, \bar{\chi}\} = \{3, -1, 1, -2, 2\}$ leads to

$$\mathcal{L} = y \Phi_H \psi \chi + y' \Phi_H^* \bar{\psi} \bar{\chi} + M_\psi \bar{\psi} \psi + M_\chi \bar{\chi} \chi \cdots$$

Invisible Higgs at LHC

$\not{p}_T$ cut	$m_h = 120$ GeV S/B	$m_h = 120$ GeV S/$\sqrt{\text{B}}$ (10 fb^{-1})	$m_h = 120$ GeV S/$\sqrt{\text{B}}$ (30 fb^{-1})	$m_h = 140$ GeV S/$\sqrt{\text{B}}$ (30 fb^{-1})	$m_h = 160$ GeV S/$\sqrt{\text{B}}$ (30 fb^{-1})
65 GeV	0.22 (0.16)	5.6 (4.9)	9.8 (8.5)	7.1 (6.2)	5.2 (4.5)
75 GeV	0.25 (0.22)	5.7 (5.3)	9.9 (9.1)	7.3 (6.7)	5.4 (5.0)
85 GeV	0.29	5.7	9.8	7.4	5.6
100 GeV	0.33	5.4	9.3	7.3	5.7

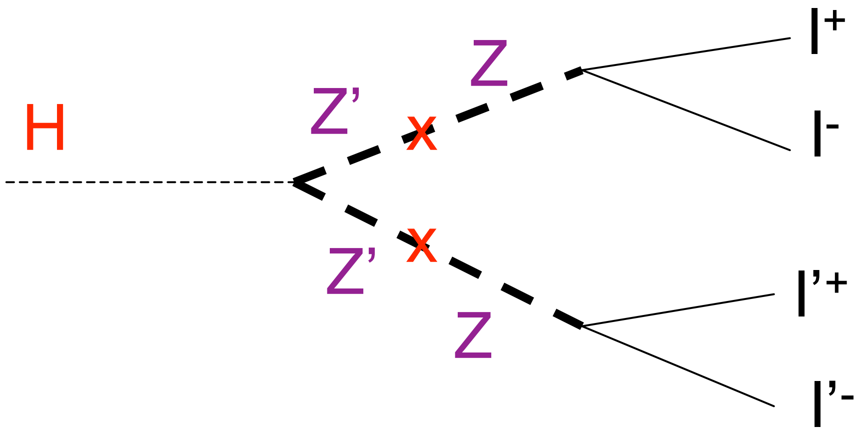
TABLE II: Signal significance for associated $Z(\to \ell^+\ell^-) + h_{inv}$ production at the LHC, combining the ee and $\mu\mu$ channels. The numbers in the parentheses include the estimated Z+jets background discussed in the text.

Davoudiasl, Han, Logan, '05

Light Z’ and Higgs Decays

With tiny kinetic mixing, a very low Z’ mass is possible in this framework. The light Higgs, however, could couple to it well with impunity. This leads to

H->Z’Z’ -> 4 leptons signature



Gopalakrishna, Jung, JW, ‘08

Conclusions

Higgs boson is a unique object that is *especially* sensitive to new physics.

New physics comes from its “viability entourage”: supersymmetry, extra dimensions, etc., all which affect Higgs boson collider phenomenology and add new TeV-scale dynamics.

New physics comes from its gauge- and Lorentz-invariant window to relevant operators, e.g. $|H|^2|\Phi|^2$.

Collider physics alterations can show up very quickly at low luminosity (e.g., Higgs to four lepton decays, light entourage particles), and/or after much time (e.g., hidden sector fields with tiny mixings with the Higgs boson, heavy entourage)