Hidden Higgs

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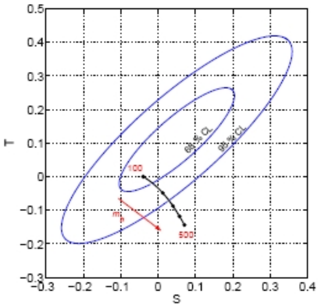
Outline

Based on AA,Ruderman,Volansky,Zupan [1002.xxxx]

What do we know about Higgs?

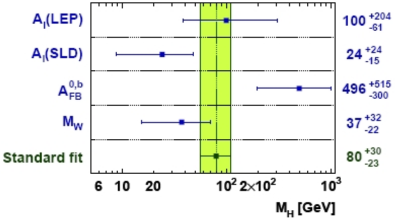
- The Higgs boson is predicted by many theories of electroweak symmetry breaking
- Higgs is the *simplest* mean to unitarize the scattering amplitude of longitudinally polarized W and Z bosons
- A *light* Higgs boson is strongly suggested by electroweak precision observables



- *Hints* that there exists a light scalar field with the coupling $\sim m_V V_\mu V_\mu h$ to the W and Z gauge bosons
- *But* there is no experimental input as to Higgs width or its coupling to SM fermions!

Tension for the SM Higgs

- Experimental: tension between the LEP limit $m_h > 114.4\,\mathrm{GeV}$ and the electroweak fit $m_h = 80^{+30}_{-23}$ (Gfitter)
  - Leptonic observables and W mass alone prefer a very light Higgs, of order 60 GeV!
  - Only the $Z \to bb$ forward-backward asymmetry pushes the Higgs mass toward larger values

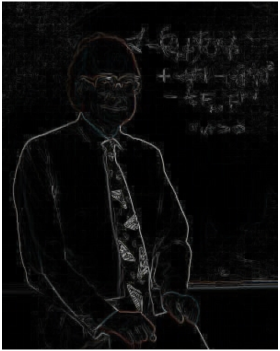


- Mixed: If tau data instead of electron data used for $\Delta\alpha_{had}$ in the electroweak fit, the best fit Higgs mass further decreases Passera,Marciano,Sirlin [1001.4528]
- Theoretical: In many extensions of the SM, in particular in the MSSM or simplest little Higgs theories, $m_{Higgs} \approx m_Z$ preferred by naturalness, while $m_{Higgs} \geq 115$ GeV leads to the *little hierarchy problem*

There is some tension within the minimal Higgs paradigm, which prompts searching for alternatives

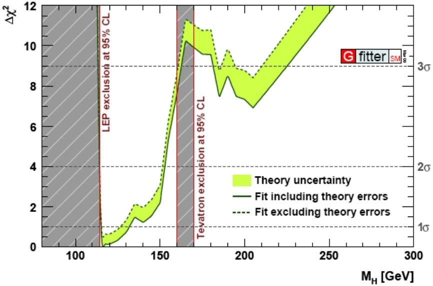
So maybe Higgs IS lighter than 115 GeV?

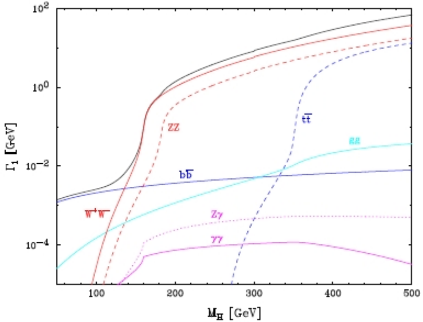
- One possibility: suppressed coupling to Z boson, so that it was not produced at LEP. But then electroweak fit is not improved even if Higgs is light
- More exciting possibility: Higgs was copiously produced at LEP, but it escaped our attention.



Recall the Standard Model Higgs

- LEP constrained $m_{Higgs} > 114.4$ GeV by looking for $H \to b\bar{b}$ decay





- SM Higgs couples to mass
- For a light Higgs, the couplings to the relevant SM states are tiny, e.g. $y_b \sim m_b/v_{EW} \sim 0.02$
- Branching ratios for various Higgs decays can easily be altered by new physics when Higgs below WW threshold

Summary of Higgs limits beyond the SM

Assuming SM production cross section, and $BR(H \to xx) = 1$

Decay Channel	**Limit**
$h \to \not{E}$	114 GeV
$h \to \tau\bar{\tau}$	115 GeV
$h \to jj$	113 GeV
$h \to WW^*$ or ZZ^*	110 GeV
$h \to AA \to 4b, 4\tau$	110 GeV
$h \to AA \to 4c, 4g$	86 GeV
$h \to$ anything	82 GeV

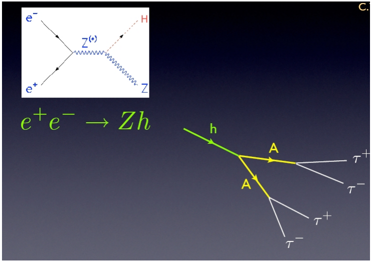
see Chang,Dermisek,Gunion,Weiner [0801.4554] for review

- Invisible and two-body decay channels very well constrained
- Constraints on four- and more body decay channels typically not much better than the model independent OPAL constraint, with the exception of the 4b and 4τ channels
- Typically, the multiparticle channels are weakly constrained not because of fundamental reasons but because nobody bothered to look

Hidden Higgs in NMSSM

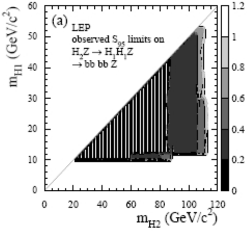
Best known example of Hidden Higgs: NMSSM near R-symmetric or PQ-symmetric limit

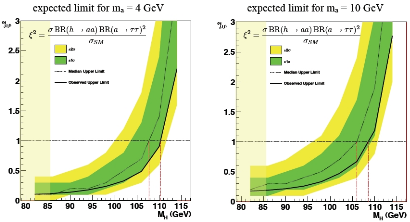
- NMSSM: $W = \lambda S H_u H_d + \kappa S^3$, $V_{soft} = A_\lambda \lambda S H_u H_d + A_\kappa \kappa S^3 + m_S^2 |S|^2$
- Two CP-odd Higgses $A_{1,2}$: one in S, one in $H_{u,d}$, that mix due to EW breaking. The A_1 mass for large $\tan\beta$ is $m_{A1}^2 \sim \kappa A_\kappa \mu/\lambda$. It is light if e.g. $A_\kappa \sim$ GeV
- A_1 has sizable coupling to Higgs via potential, so cascade decay $h \to AA \to 4f$ may easily dominate



Non-standard Higgs decays in NMSSM

- Much as Higgs, pseudoscalar A_1 couples more strongly to heavier SM particles
- For $m_{A1} > 2m_b$ the dominant decay of A_1 is into 2 b quarks Dobrescu,Landsberg,Matchev [hep-ph/0008192] Dermisek,Gunion [hep-ph/0502105] . Constrained by LEP [hep-ex/0602042]





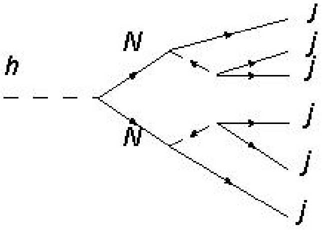
- For $2m_\tau < m_{A1} < 2m_b$ dominant decay into 2 tau leptons Dermisek,Gunion [hep-ph/0611142] . Constrained by Cranmer et al [20 years of ALEPH]
- For event lighter A_1, it decays to a pair of gluons; because the 2 gluons are very collimated this case is probably covered by $H \to 2j$ analysis

Other Hidden Higgs models

- The window for Hidden Higgs within the NMSSM seems to be closing
- Nevertheless, a neat example of a complicated but finally fruitful theory-experiment interaction
- Other realizations of Hidden Higgs are still alive
  - ↯ $H \to 6j$ in R-parity violating MSSM Carpenter,Kaplan,Rhee [hep-ph/0607204]
  - ↯ $H \to 4j$ (Buried Higgs) in SUSY Little Higgs Bellazzini,Csaki,AA,Weiler [0906.3026]
  - ↯ $H \to$ lepton jets in MSSM+light hidden sector AA,Ruderman,Volansky,Zupan [0902.xxxx]

Higgs to 6 jets

- Higgs can cascade decay into 6 quarks within the R-parity violating MSSM
- First, Higgs decays into the lightest MSSM neutralino. A large branching fraction requires
  - $m_{N1} < m_{Higgs}/2 \sim 50\,\mathrm{GeV}$ (not excluded by experiment if N_1 is mostly bino)
  - N_1 has some (at least 20 percent) higgsino component
- The lightest neutralino can decay into 3 quarks via an off-shell squark, $N_1 \to q\tilde{q} \to qqq$, if the R-parity violating operator $U^c D^c D^c$ is present in the superpotential
- No bounds on the Higgs mass, except the model independent bound of 82 GeV



Buried Higgs

- Higgs can cascade decay into four light colored objects within little SUSY (supersymmetric little Higgs models)
- The MSSM extended to include $SU(3)$ global symmetry spontaneously broken to $SU(2)$ at the scale $f \gtrsim v_{EW}$
- Instead of Higgs doublets $H_{u,d}$, Higgs triplets $\mathcal{H}_{u,d}$
- 5 Goldstone bosons from $SU(3) \to SU(2)$ breaking, 3 of which get eaten by W and Z after EW breaking

Two physical pGB scalars h and η embedded in the triplets as

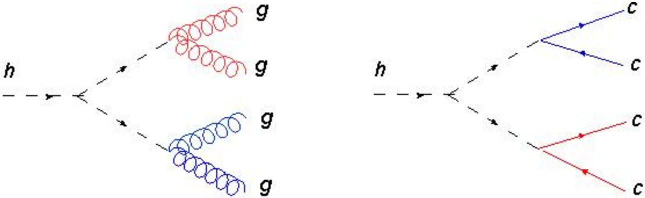
$$\mathcal{H}_u \approx f \sin\beta \begin{pmatrix} 0 \\ \sin((\tilde{v}+h)/f) \\ e^{i\eta/f}\cos((\tilde{v}+h)/f) \end{pmatrix} \qquad \mathcal{H}_d^T \approx f \cos\beta \begin{pmatrix} 0 \\ \sin((\tilde{v}+h)/f) \\ e^{-i\eta/f}\cos((\tilde{v}+h)/f) \end{pmatrix}.$$

- The pGB scalar h identified with the SM Higgs boson
- The pGB pseudoscalar η is a new singlet

Buried Higgs

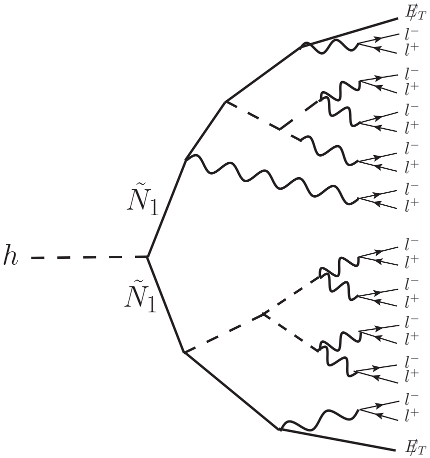
- ϟ Singlet pseudoscalar η is naturally light, thanks to global symmetry protection,
- ϟ lives in the 3rd component of the triplet and does not couple to W or Z.
- ϟ has derivative couplings to the Higgs, $\sim f^{-1}h(\partial_\mu\eta)^2$
- ϟ couples to SM fermions via their mixing with heavy partner fermions

- Higgs decays dominantly to a pair of PGB pseudoscalars η as long as the scale f is not too large, $f \lesssim 400\,\mathrm{GeV}$
- Couplings of η to SM fermions depend on fermion representations under global SU(3), masses of heavy fermionic partners of SM fermions, etc.
- Several phenomenologically distinct realizations of Hidden Higgs
  - Gluophilic Higgs, $h \to 4j$ when $\eta \to gg$ dominates
  - Charming Higgs, $h \to 4c$ when $\eta \to cc$ dominates
- In most cases, the standard discovery mode $h \to \gamma\gamma$ is strongly suppressed



Higgs to lepton jets

- AA,Ruderman,Volansky,Zupan [1002.xxxx] proposal: Higgs decays into lepton jets and missing energy, in the MSSM + light hidden sector



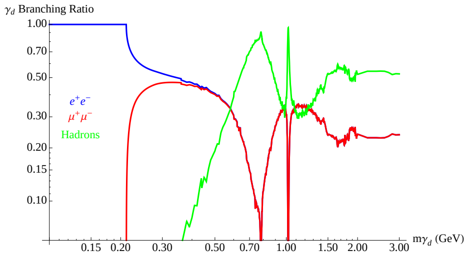
Could this have been missed at LEP???

Hypercharge Portal

- Astrophysical observations, especially the PAMELA cosmic ray positron excess, hint at existence of a light, GeV scale hidden sector
- One possibility is that it contains a hidden massive photon z_μ that mixes kinetically with the SM hypercharge,

$$\epsilon z_{\mu\nu} B_{\mu\nu} \qquad \epsilon \leq 10^{-3}$$

- As a result, the hidden photon can decay into a pair of charged kinematically available SM states: electrons, muons, pions,...



Bino Portals

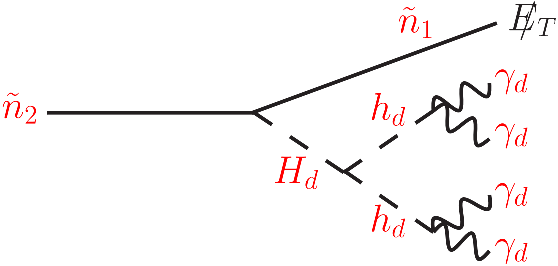
Going into hidden sector via MSSM bino

$$-i\epsilon\tilde{b}^\dagger\bar{\sigma}_\mu\partial_\mu\tilde{B} - i\epsilon\tilde{B}^\dagger\bar{\sigma}_\mu\partial_\mu\tilde{b}$$

- Induces dark bino shift $\tilde{b} \to \tilde{b} + \epsilon\tilde{B}$, that leads visible bino mili-coupling to hidden sector
$$\epsilon\sqrt{2}g_d\tilde{B}\left(h_u^\dagger\tilde{h}_u - h_d^\dagger\tilde{h}_d\right)$$
- Effects of bino mass mixing resulting from the shift are down by another m_z/m_Z and can be neglected
- The lightest SM superpartner is no longer stable but decays into hidden sector!

Lepton Jets

When a hidden sector state is produced, it cascade decays through hidden sector interactions.



$$c\tau \sim 10^{-5}\left(\frac{10^{-3}}{\epsilon}\right)^2 \qquad \theta \sim \frac{m_{\gamma_d}}{p_T}$$

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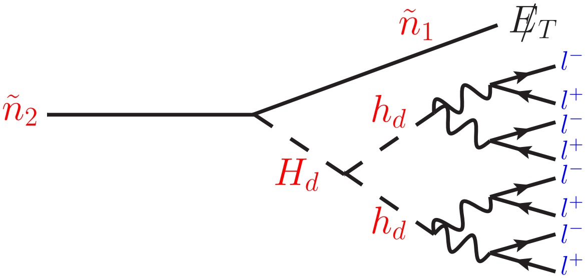
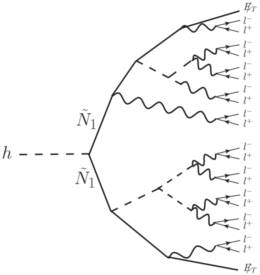


The last step can be prompt, and the decay products are all very boosted and collimated.

$$c\tau \sim 10^{-5}\left(\frac{10^{-3}}{\epsilon}\right)^2 \qquad \theta \sim \frac{m_{\gamma_d}}{p_T}$$

Higgs to lepton jets

- It is difficult to arrange Higgs decaying directly into hidden sector without fine tuning
- But it's easy to arrange Higgs decaying first into superpartners or new singlets,
- We studied three scenarios,
  - Neutralino channel, $H \to \tilde{N}_1 \tilde{N}_1 \to \ldots$
  - Sneutrino channel, $H \to \tilde{\nu}\tilde{\nu} \to \ldots$
  - Singlet channel, $H \to \chi\bar{\chi} \to \ldots$



Neutralino Channel

- In the MSSM the lightest Higgs boson can decay into neutralinos when $m_N < m_h/2$

$$g_{h11} h \tilde{N}_1 \tilde{N}_1 + \text{h.c.} \qquad g_{h11} = \frac{1}{2}\left(g c_W - g' c_B\right)\left(s_\gamma c_U - c_\gamma c_D\right)$$

$$H_u^0 = (s_\beta v + s_\gamma h + \ldots)/\sqrt{2},\ H_d^0 = (c_\beta v + c_\gamma h + \ldots)/\sqrt{2}$$

$$\Gamma(h \to \tilde{N}_1 \tilde{N}_1) \approx \frac{g_{h11}^2 m_h}{4\pi}$$

- A large branching fraction only when neutralino is *mixture* of bino/wino and higgsino
- A light neutralino has to be mostly bino to evade detection at LEP
- Branching fraction into neutralinos is above 75% when $c_{U,D} \gtrsim 1/5$
- That implies $BR(Z \to \tilde{N}_1 \tilde{N}_1) \sim 10^{-3} - 10^{-4}$, so that $m_{N1} < m_Z/2$ NOT excluded by Z width

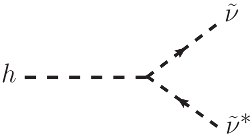
Sneutrino Channel

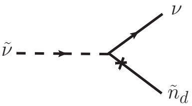
- In the MSSM the lightest Higgs boson can decay into left-handed sneutrinos when $m_{\tilde{\nu}} < m_h/2$

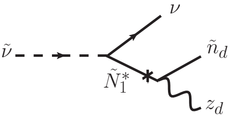
$$-\frac{m_Z^2}{v}\cos(\beta+\gamma)h\tilde{\nu}^\dagger\tilde{\nu}$$

$$\Gamma(h\to\tilde{\nu}\tilde{\nu}) \approx \frac{m_Z^4}{16\pi m_h v^2}\cos^2(\beta+\gamma)$$

- Branching fraction is large, typically $\sim 100\%$
- However, $BR(Z\to\tilde{\nu}\tilde{\nu}) \sim 10^{-2}$ when kinematically allowed, so Z width constrains $m_{\tilde{\nu}} > m_Z/2$

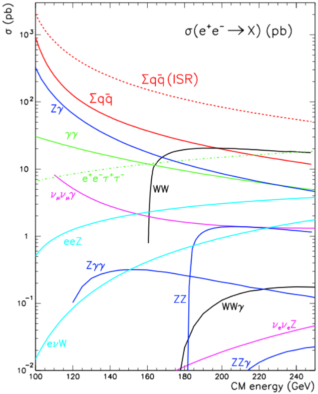






How could this have been missed at LEP?

- LEP experiments each collected $\sim\ 400\mathrm{pb}^{-1}$ at $\sqrt{s} = 195 - 209$ GeV.
- At these energies, a 100 GeV Higgs has $\sigma_{hZ} \sim 0.2 - 0.3\mathrm{pb}$ corresponding to $\sim O(100)$ events per experiment.
- Backgrounds much larger, so not obvious it would have been seen without dedicated analysis
- Many multilepton searches restricted to *isolated* leptons - not sensitive to our signal



Constraints

A list of most constraining searches

- LEP1 monojet and acoplanar dijet searches **Phys. Lett. B 334, 244 (1994), Phys. Lett. B 313, 299 (1993)**
- OPAL invisible Higgs search **arXiv:0707.0373 [hep-ex]**
- ALEPH Higgs to WW* search **arXiv:hep-ex/0605079**
- ALEPH Higgs to 4 tau search, *K. Cranmer, talk at 20 years of ALEPH data, CERN, Nov. 3 2009*
- D0 NMSSM Hidden Higgs search **arXiv:0905.3381 [hep-ex]**

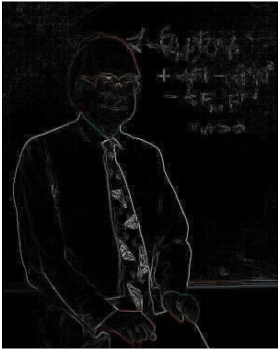
Typical SUSY searches (e.g. trilepton searches) are less constraining because they require isolated leptons

- We have found benchmark point that are consistent with all LEP and Tevatron searches published so far
- Experiment favors a scenario with two-lepton-jet topology and a large number $(5-20)$ of tracks per jet

Uncovering Hidden Higgs

For $m_{Higgs} \sim 100$ GeV,

- Roughly 100 Higgs events per experiment at LEP2
- Roughly 10000 Higgs events per experiment at Tevatron
- Often also hidden SUSY events at LEP1, LEP2, Tevatron



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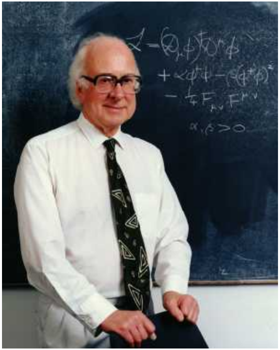

Just look carefully, and you'll see

Summary

- LEP and Tevatron experiments may have missed a light Higgs if it has non-standard decays
- The gaps can be easily filled by dedicated analysis
- ☺ Ongoing ALEPH, L3 and Tevatron analyses
- ☺ LHC strategies to discover Higgs decaying into light jets or lepton jets in preparation
- A light Higgs could solve the SUSY little hierarchy problem, and improve electroweak fits
- Even if Higgs is heavier than 115 GeV, it is conceivable that non-standard Higgs decay show up at the LHC, as the leading or subleading channel. So better be prepared
- Even if Higgs is completely standard, this kind of scenarios allow the experimentalists to patch up gaps in their sensitivity
- ☻ New interesting theoretical idea still being born