Hiding the Higgs with Lepton Jets

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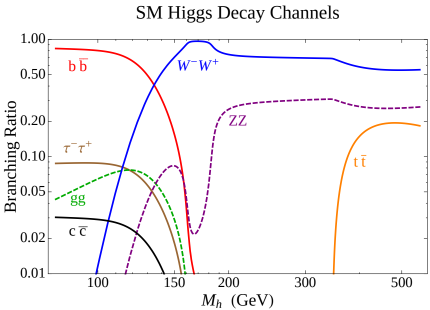
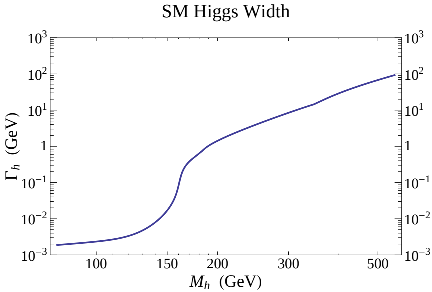
1002.2952

Talk Outline

Higgs Decays in the SM

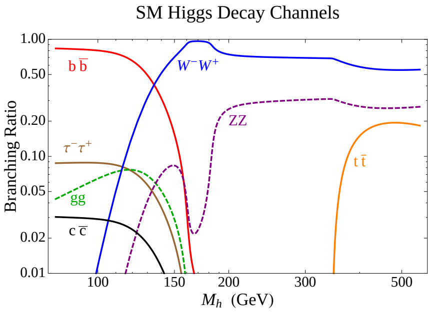


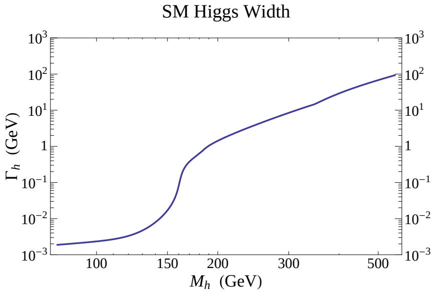


The LEP constraint on the SM Higgs, $m_h \gtrsim 114.4$ GeV, implies

- that the Higgs is heavy.

Higgs Decays in the SM





The LEP constraint on the SM Higgs, $m_h \gtrsim 114.4$ GeV, implies

- that the Higgs is heavy.
- or, that the Higgs decays exotically! Note that the SM Higgs width is tiny below the W^-W^+ threshold.

Hiding the Higgs

A **Hidden Higgs** is light and has been produced at LEP, but was missed because of exotic decays.

There are a couple of reasons to find this scenario appealing.

1. The precision electroweak fit favors a light Higgs, $m_h \sim 87 \pm^{35}_{26}$ GeV.
2. A heavy Higgs leads to the SUSY fine tuning problem.

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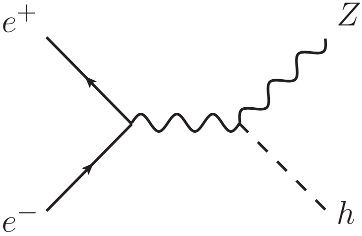
2. A heavy Higgs leads to the SUSY fine tuning problem.

   And most interestingly to me,

3. Its fun to think of dynamical alternatives to the standard scenario! By pondering exotic Higgs decays that would have been missed, we can learn to think more inclusively about new physics at colliders.

Higgstrahlung at LEP

The most important constraints on a light Higgs come from LEP.



The LEP experiments each collected $\sim$ 400 pb^{-1} at $\sqrt{s} = 195 - 209$ GeV.

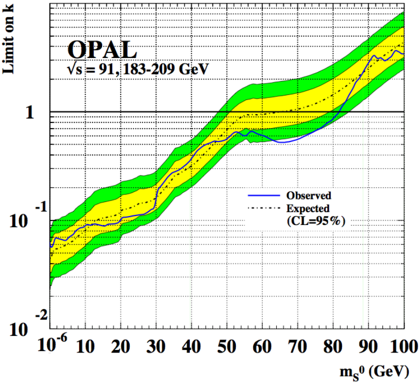
At these energies, a 100 GeV Higgs has $\sigma_{hZ} \sim 0.2 - 0.3\ \mathrm{pb}$.

Therefore, if the Higgs is light, LEP has produced $\sim \mathcal{O}(100)$ Higgstrahlung events.

LEP Higgs Constraints

1. model independent limit,

$$m_h \gtrsim 82 \text{ GeV}$$



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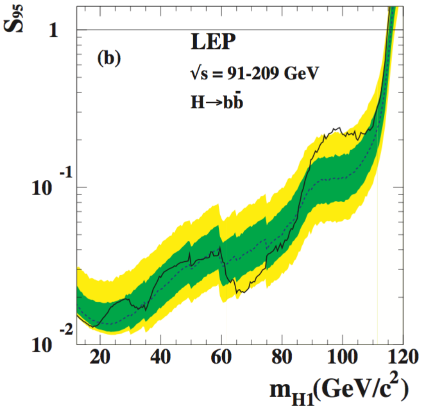
2. $h \to b\bar{b}$ limit,

$$m_h \gtrsim 115 \text{ GeV}$$

If $m_h \sim 100$ GeV, then $\mathrm{Br}_{h\to b\bar{b}} \lesssim 0.2$



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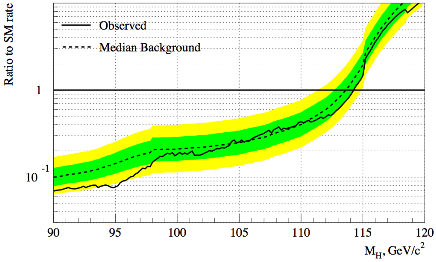
If $m_h \sim 100$ GeV, then $\mathrm{Br}_{h \to b\bar{b}} \lesssim 0.2$

3. $h \to \not{E}_T$ limit,

$$m_h \gtrsim 114 \text{ GeV}$$

If $m_h \sim 100$ GeV, then $\mathrm{Br}_{h \to \not{E}_T} \lesssim 0.15$



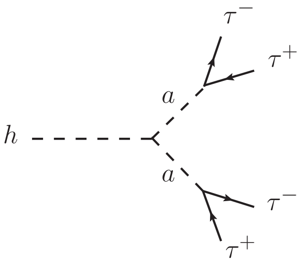
Hiding the Higgs in the NMSSM

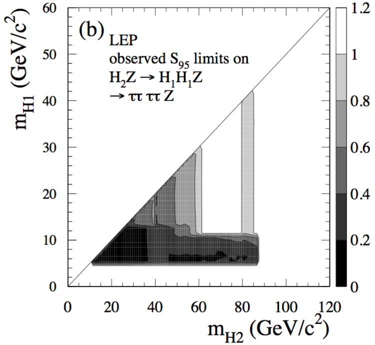
A well known* example of a Hidden Higgs can occur in the NMSSM.

$$W \supset \lambda S H_u H_d + \kappa S^3$$

There are two new Higgses beyond the MSSM, $S = (s, a)$. The pseudoscalar a is naturally light in the R and PQ symmetric limits.

For $m_a \lesssim 2m_b$ the dominant Higgs decay can be $h \to 2a \to 4\tau$, which as of this summer was only constrained to $m_h \gtrsim 85$ GeV.

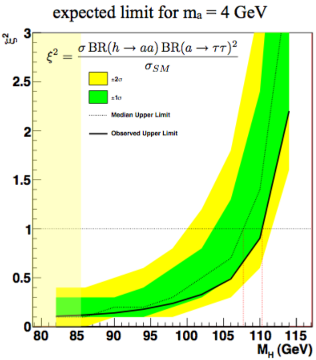


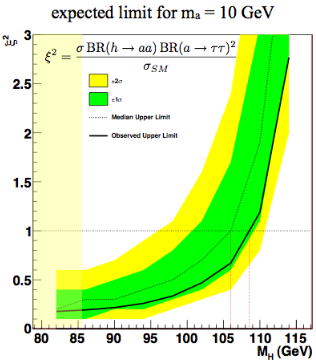


* R. Dermisek and J. Gunion, **0502105**

Aleph Search For $h \longrightarrow 4\tau$

- A group* at (mostly) NYU has just resurrected the ALEPH analysis pipeline and searched for $h \rightarrow 2a \rightarrow 4\tau$.
- They look for two "τ jets" each of which are required to have 2 or 4 tracks.
- The new limit is $m_h \gtrsim 110$ GeV.





*K. Cranmer's talk, **20 Years of Aleph Data, CERN, Nov. 3 2009**, also with J. Beacham, I. Yavin, P. Spagnolo

Other Hidden Models

There remain a couple of proposals that are nearly unconstrained.

They involve the higgs decaying to more SM states than usual, resulting in final states which have been mostly overlooked.

- **RPV MSSM:** $h \longrightarrow 6j$.
  L. M. Carpenter, D. E. Kaplan, E.-J. Rhee, **0607204**
- **Burried Higgs** and **Charming Higgs:** $h \longrightarrow 4j$.
  B. Bellazzini, C. Csaki, A. Falkowski, A. Weiler, **0906.3026, 0910.3210**

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- **Higgs to Lepton Jets**.

A Light Hidden Sector

Higgs decays provide an opportunity to probe the light spectrum, which may include a new light hidden sector.

- **Hidden Valleys**: Light hidden sectors can dramatically modify collider physics.

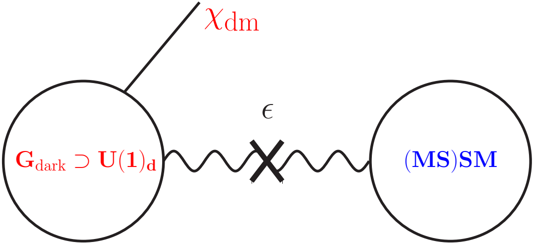
  M. Strassler and K. Zurek **0604261**, M. Strassler **0607160**

- **Dark Sector**: Dark matter may be charged under a light hidden sector as an explanation of the leptonic cosmic ray anomalies.

  N. Arkani-Hamed, D. Finkbeiner, T. Slatyer, and N. Weiner, **0810.0713**
  N. Arkani-Hamed and N. Weiner, **0810.0714**

The Dark Sector

The dark sector setup:



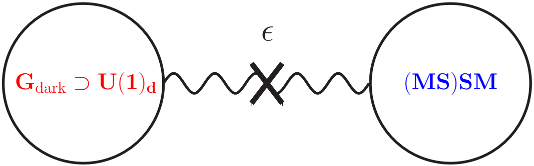
where G_d is broken at the GeV scale.

Our sector talks to their sector through the kinetic mixing portal:

$$\mathcal{L} \supset \frac{\epsilon}{2} b_{\mu\nu} B^{\mu\nu} \qquad \epsilon \lesssim 10^{-3}$$

The Dark Sector

For the rest of this talk we can ignore dark matter...



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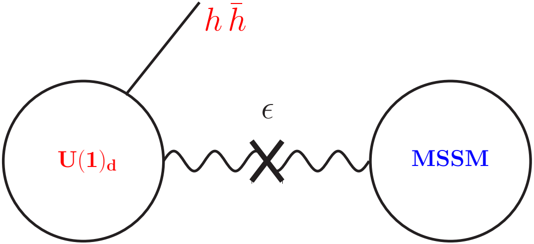
And we'll focus on the simplest case,



C. Cheung, LT. Wang, JTR, and I. Yavin, **0902.3246**

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The Kinetic Mixing Portal

With kinetic mixing, we have the Lagrangian,

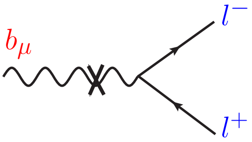
$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4} b_{\mu\nu} b^{\mu\nu} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{\epsilon}{2} \cos\theta_W \, b^{\mu\nu} F_{\mu\nu}$$

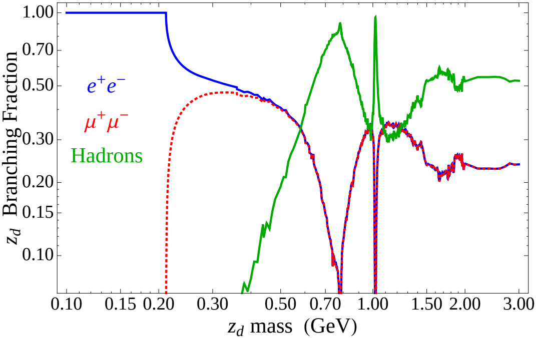
$$V \supset \frac{1}{2} m_b^2 b^2 + b_\mu J_b^\mu + A_\mu J_{\text{EM}}^\mu$$

We remove the kinetic mixing by shifting our massless photon,

$$A_\mu \to A_\mu + \epsilon \cos\theta_W \, b_\mu$$

The hidden photon couples to the electromagnetic current, $\epsilon b_\mu J_{\text{EM}}^\mu$





Decaying to the Hidden Sector

Supersymmetric kinetic mixing includes gaugino mixing:

$$\mathcal{L}_{\text{gaugino}} \supset -2i\epsilon\, \lambda_{\tilde{b}}\, \bar{\sigma}^{\mu}\partial_{\mu}\, \lambda_{\tilde{B}} + \text{h.c.}$$

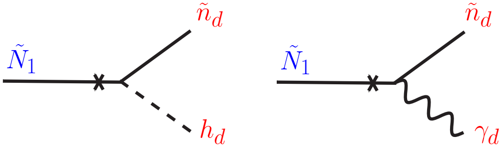
We remove the mixing by shifting the lighter gaugino:

$$\lambda_{\tilde{b}} \to \lambda_{\tilde{b}} + \epsilon\, \lambda_{\tilde{B}}$$

And we have the new interaction:

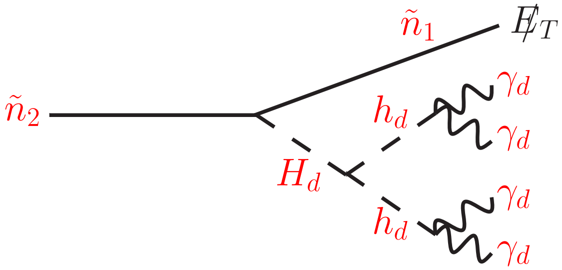
$$V \supset \epsilon\, \lambda_{\tilde{B}}\, \tilde{J}_b$$

This means that SM neutralinos can decay into the hidden sector,



Lepton Jets

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



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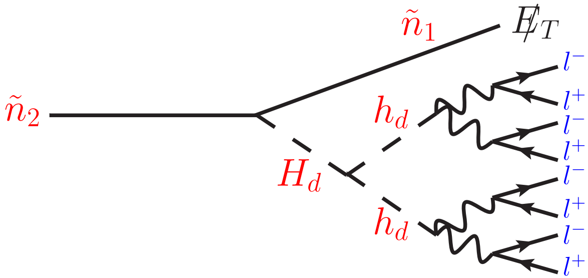

The hidden photons decay back to the SM through the kinetic mixing. The lepton jet can include missing energy.

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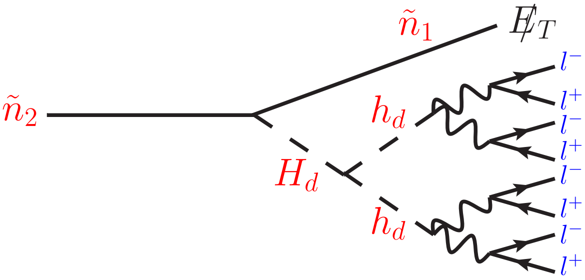


The hidden photons decay back to the SM through the kinetic mixing. The lepton jet can include missing energy.

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

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

Higgs Decays to the Hidden Sector

It is possible that the Higgs decays into the hidden sector with a large branching fraction.

- **Higgs $\rightarrow$ Hidden Sector $\rightarrow$ Displaced Vertices**
  M. Strassler and K. Zurek, **0605193**.

- **Higgs $\rightarrow$ Hidden Sector $\rightarrow$** $l^+l^-l^+l^-$
  S. Gopalakrishnaa, S. Jungb, J. D. Wells, **0801.3456**

Higgs Decay Channels

We focus on decay channels where the hidden sector remains naturally light, and the lepton jets are fully leptonic, $m_{\gamma_d} \lesssim 500$ MeV.

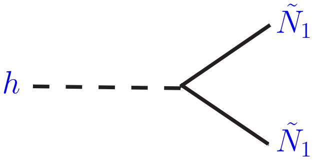
This means that the Higgs should not couple directly to the hidden sector, and we now show three scenarios where the Higgs decays into weak-scale states that subsequently decay into the hidden sector.

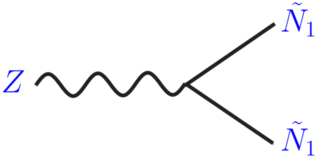
1. Neutralino Channel
2. Sneutrino Channel
3. Singlet Channel

Neutralino Channel

One possibility, is that the Higgs decays to a pair of light MSSM neutralinos, $h \to 2\,\tilde{N}_1$, which then decay into the hidden sector.

If $m_{\tilde{N}_1} < m_Z/2$ then the Z also decays to neutralinos.





This is consistent with the LEP I measurement of Γ_Z if $\mathrm{Br}_{Z\to 2\tilde{N}_1} < 10^{-3}$.

This is possible, with h dominantly decaying to neutralinos, for $\tilde{N}_1$ mostly bino, because,

$$\Gamma_{h\to 2\tilde{N}_1} \sim (\theta_{\tilde{B}\tilde{H}})^2 \quad \text{and} \quad \Gamma_{Z\to 2\tilde{N}_1} \sim (\theta_{\tilde{B}\tilde{H}})^4$$

Sneutrino Channel

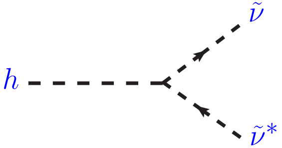
The higgs can also decay to sneutrinos, through the D-term,

$$D_1 = \frac{g_1}{2}\left(|H_u|^2 - |H_d|^2 - |\tilde{\nu}_i|^2 + \ldots\right)$$
$$D_2^a = \frac{g_2}{2}\left(H_u T^a H_u^* + H_d T^a H_d^* + \tilde{L}_i T^a \tilde{L}_i^*\right)$$

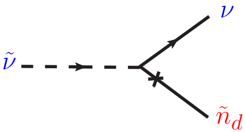
$$V \supset \frac{1}{2}D_1^2 + \frac{1}{2}D_2^2$$

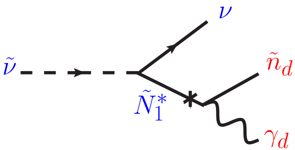
In order to be consistent with Γ_Z, $m_Z/2 < m_{\tilde{\nu}} < m_h/2$.
The resulting decay rate dominates over $h \to b\bar{b}$,

$$\Gamma_{h\to 2\,\tilde{\nu}_i} \sim \frac{m_Z^4 \sin(\alpha+\beta)^2}{16\pi v^2 m_h}$$



The $\tilde{\nu}$ decays to the hidden sector through the kinetic mixing.





Singlet Channel

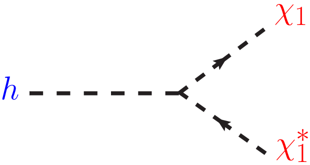
Higgs decays can also be induced by the F-term of a singlet.

For example, consider the NMSSM, where S couples to χ and $\bar{\chi}$ with hidden sector charge ± 2.

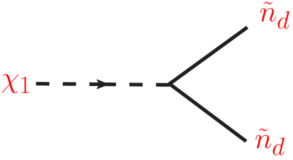
$$W \supset S\,H_u H_d + S\,\chi\bar{\chi} + \chi\bar{h}^2 + \bar{\chi}h^2$$

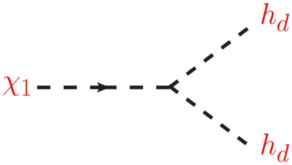
$\langle S \rangle$ gives a weak scale mass to χ and $\bar{\chi}$.

$$V \supset |F_S|^2 = |H_u H_d + \chi\bar{\chi}|^2$$



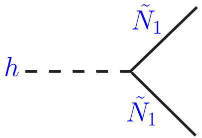
The last two operators of the superpotential cause χ to decay into the light scalars and fermions.





Sample Decay

An example Higgs decay might look like:



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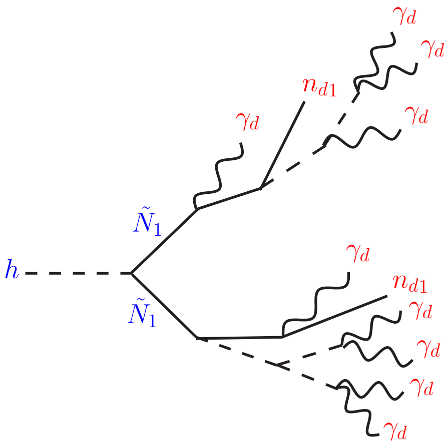

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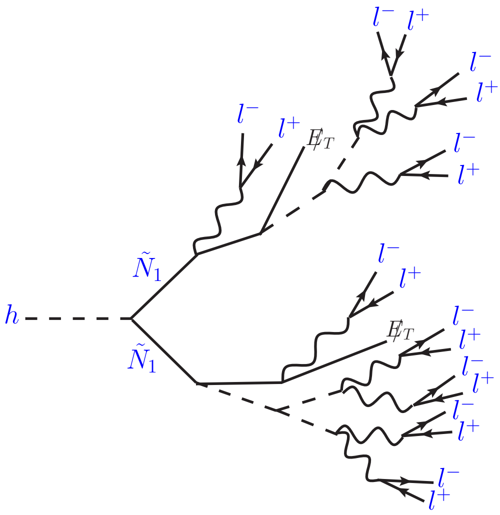


The Higgs can produce lots of leptons together with missing energy, even in the simplest $U(1)_d$ model.

Hiding the Higgs with Leptons?

How can this final state possibly hide a light Higgs?!

Of course there were no dedicated searches since this is a new idea.

At LEP:

- Track counts were used to identify hadronic events, and events with many leptons could have been grouped with the QCD background.
- At LEP-2 its easy to miss the 100 events without the right dedicated search.

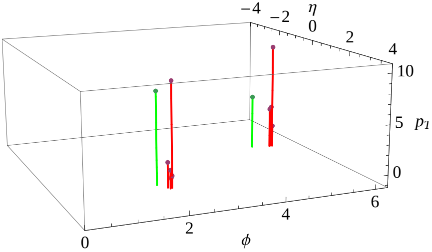
At the Tevatron:

- Searches that look for leptons impose strong isolation requirements and we'll see that lepton jets do not produce isolated leptons.
- The QCD jet background is 10^6 times bigger than the Higgstrahlung cross-section.

Lepton Jet Monte Carlo

We've simulated $h \longrightarrow$ Lepton Jets to estimate the sensitivity of some existing LEP and Tevatron searches, using,

1. Madgraph for Higgs production and decay.
2. BRIDGE for hidden sector cascade.
3. SlowJet (our Mathematica code) for event analysis.



Caution: We do not simulate the detectors. The efficiency to reconstruct nearby tracks and leptons is important for setting real limits, and this requires full detector simulation.

Some Constraining Searches

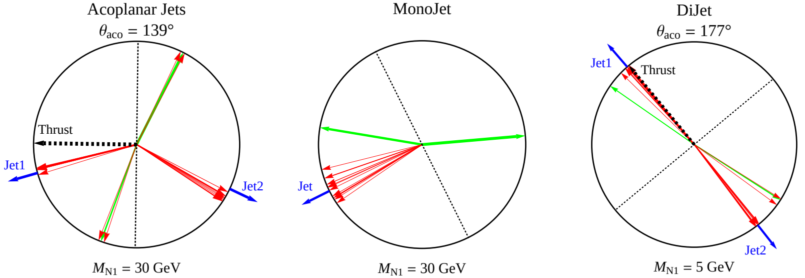
In our paper we report signal efficiencies for 15 searches. Here I focus on the ones we find to be most constraining,

1. LEP I: Acoplanar Jets and Monojets (ALEPH)
   Phys. Lett. B 313, 299 (1993), Phys. Lett. B 334, 244 (1994)
2. LEP II: $h \to \not{E}_T$ (OPAL)
   0707.0373
3. LEP II: $h \to WW^*$ (ALEPH)
   0605079
4. LEP II: New NMSSM Hidden Higgs Search (ALEPH), $h \to 4\tau$
   K. Cranmer, talk at **20 Years of ALEPH Data**, *CERN, Nov. 3, 2009*
5. Tevatron: NMSSM Hidden Higgs Search (D0), $h \to 4\mu, 2\mu\, 2\tau$
   0905.3381

We will use these searches to determine the patterns of observables (topology, multiplicities, MET) that are least constrained. After learning this, it is straightforward to pick explicit models.

LEP I: Monojets and Acoplanar Jets

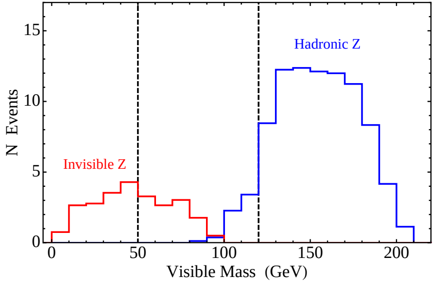
- LEP I produced ~ 20 million Z's, constraining the $\tilde{N}_1$ channel. With $\mathrm{Br}_{Z\to 2\tilde{N}_1} \sim 10^{-4} - 10^{-3}$ there were 500-5000 lepton jet events per detector!
- ALEPH searched for acoplanar jets and monojets. Lepton jet events with these topologies must be suppressed by $\sim 10^{-3}$.



- The model is safe if the neutralino is light, $m_{\tilde{N}_1} \lesssim 5$ GeV. Then, the neutralinos are boosted and all events consist of two back-to-back *Neutralino Jets*, faking hadronic Z's.

LEP II: Invisible Higgs Search

- At LEP II, each detector searched for an invisible Higgs produced with a hadronic Z.
- These searches can constrain lepton jets if they have too much $\not{E}_T$. They're also sensitive to ($h \to$ lepton jets) produced with an invisible Z.
- OPAL selects a wide window in visible mass around the Z, $50\ \mathrm{GeV} < M_{\mathrm{vis}} < 120\ \mathrm{GeV}$.



- We find that some missing energy helps to evade this search, and the least constrained models have $\not{E}_T \sim 50$ GeV.

LEP II: $h \to WW^*$

- ALEPH searched for $h \to WW^*$, which is predicted to dominate in fermiophobic models.
- They do a topological search, with mutually exclusive categories covering each decay mode of the Z, W, and W^*.

Class and topology	Targeted Channel	(BR)
1: Fully-Hadronic	**No leptonic decay**	**(0.422)**
1a: 6 jets	$q\bar{q}\,q\bar{q}\,q\bar{q}$	(0.328)
1b: 4 jets and E_{miss}	$\nu\bar{\nu}\,q\bar{q}\,q\bar{q}$	(0.094)
2: Two-Hard-Leptons	**Z leptonic decays**	**(0.054)**
2a: plus jets	$\ell^+\ell^-\,q\bar{q}\,q\bar{q}$	(0.032)
2t: plus jets and E_{miss}	$\ell^+\ell^-\,\tau\nu\,q\bar{q}$	(0.003)
2b: plus jets and 1 soft lepton	$\ell^+\ell^-\,q\bar{q}\,\ell\nu$	(0.010)
2c: plus jets and 1 hard lepton	$\ell^+\ell^-\,\ell\nu\,q\bar{q}$	(0.007)
2d: plus 1 hard lepton and 1 track	$\ell^+\ell^-\,\ell\nu\,\ell\nu$	(0.003)
3: One-Hard-Lepton (and E_{miss})	**W leptonic decays**	**(0.171)**
3a: plus jets	$q\bar{q}\,\ell\nu\,q\bar{q}$	(0.101)
3b: plus jets and 1 soft lepton	$q\bar{q}\,\ell\nu\,\ell\nu$	(0.031)
3c: plus 1 track and M_{miss}	$\nu\bar{\nu}\,\ell\nu\,\ell\nu$	(0.029)
3d: plus jets and M_{miss}	$\nu\bar{\nu}\,\ell\nu\,q\bar{q}$	(0.008)
4: One-Soft-Lepton	**W* leptonic decays**	**(0.130)**
4a: plus jets	$q\bar{q}\,q\bar{q}\,\ell\nu$	(0.101)
4b: plus jets and M_{miss}	$\nu\bar{\nu}\,q\bar{q}\,\ell\nu$	(0.029)

Subclass	Selection Criteria							
	E_{ℓ_1}	E_{ℓ_2}	E_{ℓ_3}	D_{14}	$M_{\mathrm{tot}}/\sqrt{s}$	M_{miss}	E_{had}	N_{ch}
1a	< 25			< 13		< 60		
1b	< 25			< 13		> 60		
2a	> 25	> 20	< 8				> 60	
2t	> 25	> 20	< 8				< 60	
2b	> 25	> 20	> 8				> 60	
2c	> 25	> 20	> 8				< 60	> 4
2d	> 25	> 20	> 8				< 60	$= 4$
3a	> 25	< 10			> 0.4	< 95		
3b	> 25	$[10, 20]$			> 0.4	< 95		
3c	> 25	$[10, 20]$			< 0.4	> 95		
3d	> 25	< 10			< 0.4	> 95		
4a	< 25			> 13	> 0.6			
4b	< 25			> 13	< 0.6			

LEP II: $h \to WW^*$

- ALEPH searched for $h \to WW^*$, which is predicted to dominate in fermiophobic models.
- They do a topological search, with mutually exclusive categories covering each decay mode of the Z, W, and W^*.

Class and topology	Targeted Channel	(BR)
1: Fully-Hadronic	**No leptonic decay**	**(0.422)**
1a: 6 jets	$q\bar{q}\,q\bar{q}\,q\bar{q}$	(0.328)
1b: 4 jets and E_{miss}	$\nu\bar{\nu}\,q\bar{q}\,q\bar{q}$	(0.094)
2: Two-Hard-Leptons	**Z leptonic decays**	**(0.054)**
2a: plus jets	$\ell^+\ell^-\,q\bar{q}\,q\bar{q}$	(0.032)
2t: plus jets and E_{miss}	$\ell^+\ell^-\,\tau\nu\,q\bar{q}$	(0.003)
2b: plus jets and 1 soft lepton	$\ell^+\ell^-\,q\bar{q}\,\ell\nu$	(0.010)
2c: plus jets and 1 hard lepton	$\ell^+\ell^-\,\ell\nu\,q\bar{q}$	(0.007)
2d: plus 1 hard lepton and 1 track	$\ell^+\ell^-\,\ell\nu\,\ell\nu$	(0.003)
3: One-Hard-Lepton (and E_{miss})	**W leptonic decays**	**(0.171)**
3a: plus jets	$q\bar{q}\,\ell\nu\,q\bar{q}$	(0.101)
3b: plus jets and 1 soft lepton	$q\bar{q}\,\ell\nu\,\ell\nu$	(0.031)
3c: plus 1 track and M_{miss}	$\nu\bar{\nu}\,\ell\nu\,\ell\nu$	(0.029)
3d: plus jets and M_{miss}	$\nu\bar{\nu}\,\ell\nu\,q\bar{q}$	(0.008)
4: One-Soft-Lepton	**W* leptonic decays**	**(0.130)**
4a: plus jets	$q\bar{q}\,q\bar{q}\,\ell\nu$	(0.101)
4b: plus jets and M_{miss}	$\nu\bar{\nu}\,q\bar{q}\,\ell\nu$	(0.029)

Subclass	Selection Criteria							
	E_{ℓ_1}	E_{ℓ_2}	E_{ℓ_3}	D_{14}	$M_{\text{tot}}/\sqrt{s}$	M_{miss}	E_{had}	N_{ch}
1a	< 25			< 13		< 60		
1b	< 25			< 13		> 60		
2a	> 25	> 20	< 8				> 60	
2t	> 25	> 20	< 8				< 60	
2b	> 25	> 20	> 8				> 60	
2c	> 25	> 20	> 8				< 60	> 4
2d	> 25	> 20	> 8				< 60	$= 4$
3a	> 25	< 10			> 0.4	< 95		
3b	> 25	[10, 20]			> 0.4	< 95		
3c	> 25	[10, 20]			< 0.4	> 95		
3d	> 25	< 10			< 0.4	> 95		
4a	< 25			> 13	> 0.6			
4b	< 25			> 13	< 0.6			

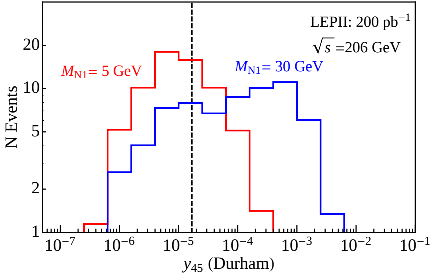
- We find that **2c** is most constraining for our scenario. This category looks for 2 hard leptons, one softer lepton, and at least two additional tracks, and has very low SM background.

LEP II: $h \longrightarrow WW^*$

- **2c** requires two leptons with E_T above 25 and 20 GeV.
- The leptons in lepton jets are softer than this, but this category is sensitive to a leptonic Z produced with lepton jets.
- They're interested in the topology, $ZWW^* \rightarrow l^- l^+ \nu \, l \, j \, j$, with 5 well-separated objects.

They cut on $y_{45} > 2 \times 10^{-5}$ using Durham where,

$$y_{ij} = \frac{2\,\mathrm{Min}(E_i^2, E_j^2)(1 - \cos\theta_{ij})}{E^2_{\mathrm{vis}}}$$



We find that this search strongly constrains models where the topology has more than 2 lepton jets, whereas $h \rightarrow 2$ Lepton Jets is safe.

New ALEPH Search For $h \to 4\tau$

- The new ALEPH search for a Hidden Higgs in the NMSSM, discussed above, is also sensitive to lepton jets.

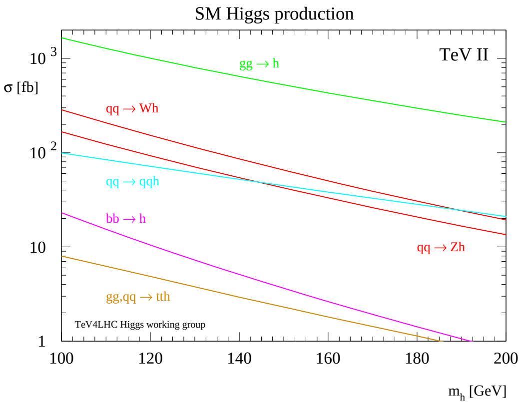
- They look at events consistent with an invisible or leptonic Z, and they require the rest of the event to reconstruct as two jets using the JADE algorithm.

- Each jet must have exactly 2 or 4 tracks. Their signal is $\tau^+\tau^-$ with 1 and 3-pronged τ's.

- This search is sensitive to $h \to$ Lepton Jets when the lepton jets are sparse, and not sensitive to models where the lepton jets have more than 4 tracks.

Tevatron

The Tevatron is also a good place to look for $h \longrightarrow$ Lepton Jets.



We simulate the three dominant channels for a light Higgs: gluon fusion and Higgstrahlung with a W or Z.

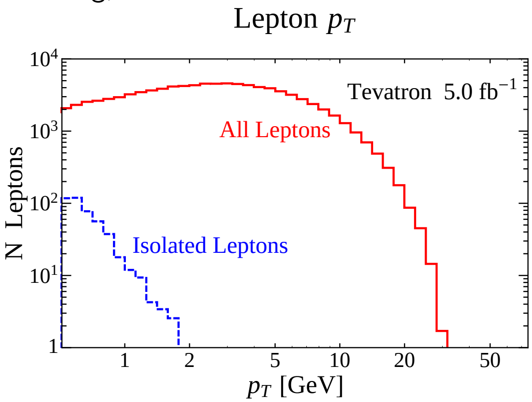
With 5 fb^{-1}, a 100 GeV higgs has been produced $\sim$ 10500 times.

Tevatron Trilepton Searches

Trilepton searches are not sensitive to lepton jets because they demand well-isolated leptons.

The isolation definitions usually use cones of $\Delta R < 0.4$ and demand at least one of the following,

1. **Total Isolation**: from all other leptons, tracks, and jets.
2. **Track Isolation**: $\Sigma_{\text{track}}\, p_T < p_T^{\max}$
3. **Calorimeter Isolation** $\Sigma\, E$ or $\Sigma\, E_T < E^{\max}$



The isolated leptons produced by lepton jets are too soft to be detected by trilepton searches.

D0 Search for $h \to 4\mu, 2\mu\, 2\tau$

- In 2009, D0 performed a search for the NMSSM process $h \to 2a \to 4\mu, 2\mu\, 2\tau$.
- They looked for muons accompanied by a nearby track within $\Delta R < 1$. The pair must be isolated in the tracker and calorimeter.
- This search is sensitive to lepton jets that include muons, $m_{\gamma_d} > 2m_\mu$.
- Lepton jets with more than 2 leptons spoil the isolation definition and are safe. Lepton jets with exactly 2μ must be suppressed by $\sim 10^{-3}$.

How Existing Searches Constrain the Hidden Sector

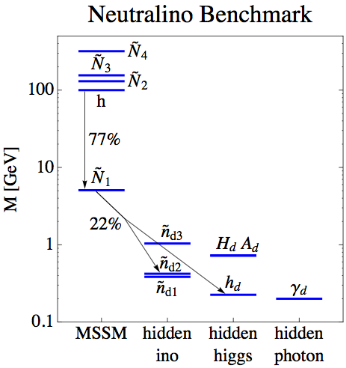
To summarize, we have identified the characteristics of hidden sector cascades such that $h \to$ Lepton Jets is the least constrained.

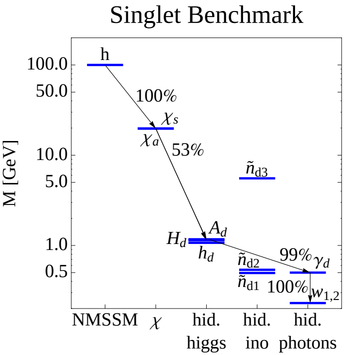
1. Lots of leptons, $n_{\rm lep} > 4$, per lepton jet.
2. Some (but not too much) missing energy, $\not{E}_T \sim 50$ GeV.
3. A 2-lepton-jet topology.
4. Either no muons, $m_{\gamma_d} < 2\mu$, or enough leptons per lepton jet such that 2μ lepton jets are suppressed by 10^{-3}.

We're led to the topology $h \to 2\,LJ + \not{E}_T$. This is constrained by an OPAL search for $h \to 2j + \not{E}_T$ (hep-ex/**0209026**), which sets a 2σ limit of $m_h \simeq 100$ GeV.

Benchmark Models

We have picked benchmark models for the neutralino and singlet channels that satisfy the above searches by 2σ.



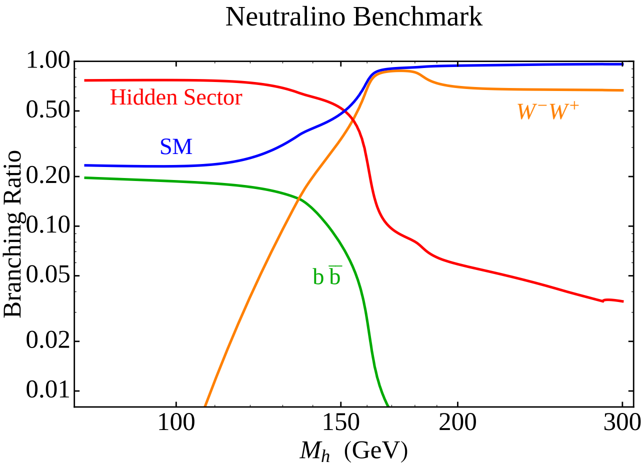


For both benchmarks, $m_h = 100$ GeV, and the singlet benchmark includes muons.

The sneutrino channel has more difficulty accommodating a 100 GeV Higgs, because of the irreducible MET carried by neutrinos, and the additional production channel, $e^- e^+ \to Z^* \to \tilde{\nu}\tilde{\nu}^*$.

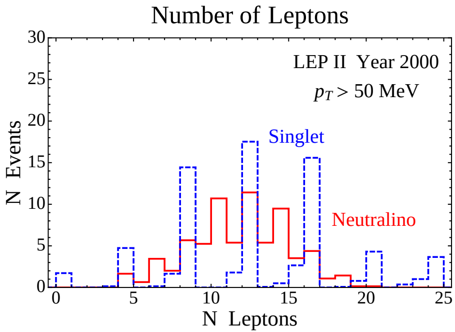
Benchmark Branching Fractions

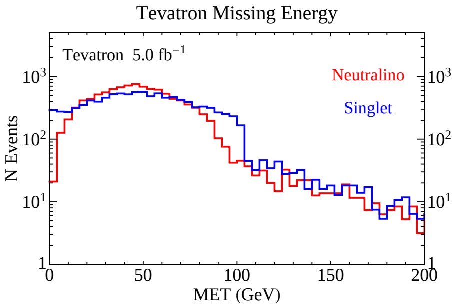
For each model, the Higgs dominantly decays to the hidden sector for $m_h = 100$ GeV.



The branching ratio to $b\bar{b}$ is below the LEP limit of 20% for a 100 GeV Higgs.

Benchmark Lepton Count and Missing Energy





Strategies for Future Searches

Dedicated searches at LEP I, LEP II, and the Tevatron should be able to discover, or rule out, a light Higgs decaying to lepton jets.

The challenge is to differentiate lepton jets from QCD jets. There are two complimentary approaches:

1. Develop a set of cuts that select for lepton jets and not QCD jets, and look for some events. D0 is making great progress on this front right now!

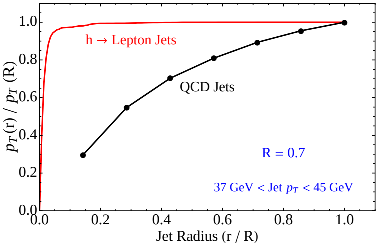
2. Look for deviations from the SM in distributions that are sensitive to the differences between lepton jets and QCD jets.

It is probably best to combine these approaches.

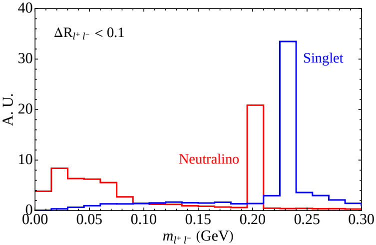
Some Properties of Lepton Jets

Some properties of our benchmarks:

- Lepton jets are much narrower than QCD jets



- Lepton/track pair invariant masses are spiked at the hidden photon mass(es).



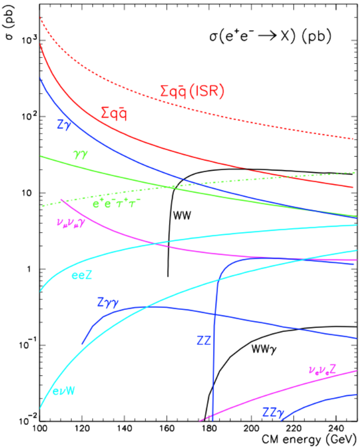
- The ECAL/HCAL ratio is larger for lepton jets than QCD jets.

Conclusions

- The Higgs may be hiding below 114 GeV if it decays exotically.
- A GeV-scale hidden sector can produce lepton jets, and the Higgs can dominantly decay to lepton jets and be light, $m_h \lesssim 100$ GeV.
- The models that are least constrained are all electron, have many electrons per Higgs decay, some missing energy, and a 2-lepton-jet topology.
- There could be 20000 lepton jet events at LEP I, 100 lepton jet events at LEP II, and 10000 lepton jet events at the Tevatron awaiting discovery.
- With 1 fb^{-1} at 7 TeV, the LHC is about to produce 15000 light Higgses!

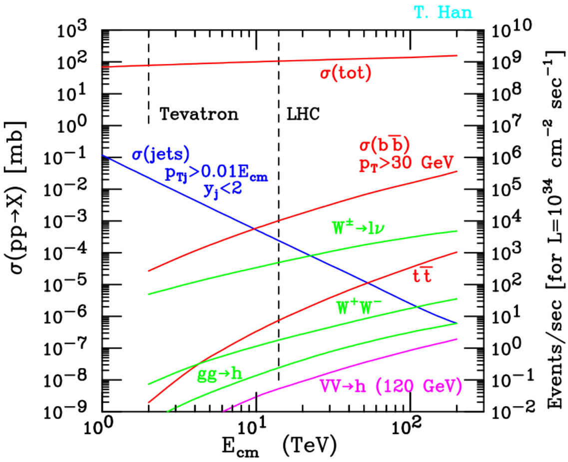
Backup Slides

LEP II Cross-Sections and Luminosities



E_{CM} (GeV)	183	189	192	196	200	202	205	207
$\int \mathcal{L}\, dt$ (pb^{-1})	56.82	174.21	28.93	79.83	86.30	41.90	81.41	133.21

Hadron Collider Cross-Sections



$m_h = 120$ GeV

Search Efficiencies

LEP-1 searches							
Search	Ref.	Obs.	Bckg.	Neutr.	Sneutr.	Singlet	Max.
Monojets	[40]	3	2.8	< 1	0	0	6.6
Acoplanar	[39]	0	0.2	< 1	0	0	3.8
LEP-2 searches							
Search	Ref.	Obs.	Bckg.	Neutr.	Sneutr.	Singlet	Max.
$H \to 4\tau$	[10]	2	5.09	1	**8**	1	5.0
$H \to \not{E}$	[34]	8	11	2	5	3	7.5
$H \to WW^{*}$2c	[50]	0	0.3	2	< 1	2	3.8
$H \to WW^{*}$2t	[50]	1	1.2	1	1	3	5.0
6l	[53]	1	1.1	< 1	4	< 1	5.0
$2j + \not{E}$ (OPAL)	[54]	13	19.8	8	**35**	7	7.8
$2j + \not{E}$ (ALEPH)	[55]	19	15.9	7	3	1	14.5
$2j + 2l + \not{E}$	[55]	5	3	2	4	5	9.0
Tevatron searches							
Search	Ref.	Obs.	Bckg.	Neutr.	Sneutr.	Singlet	Max.
Dark photon	[56]	7	8	~ 1	< 1	< 1	7.9
$H \to 4\mu$	[57]	2	2.2	0	0	2	5.8
Unified 3l	[42]	1	1.47	< 1	< 1	< 1	3.7
Low p_T 3l	[43]	1	0.4	< 1	< 1	< 1	5.4
Like-sign 2l	[41]	13	7.8	1	< 1	< 1	14.7

Table 1: A compilation of relevant searches for constraining the Higgs-to-lepton jet events.