Measuring $ZH \rightarrow qqWW^* \rightarrow qqql\nu$ at ILC

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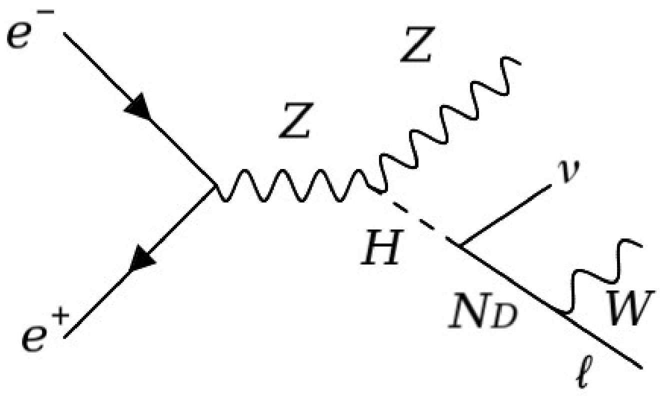
Image source: Sterile Neutrino Contraints

Main goal

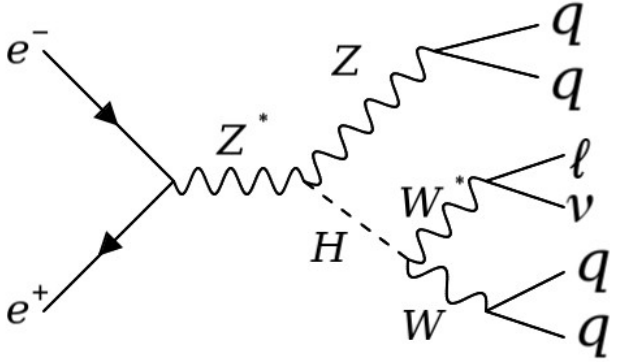
- Hypothesized dark sector model with a weak-like force
  - Can explain matter-antimatter asymmetry
  - Heavy dark neutrinos
    - My focus: $m_Z < m_{N_D} < m_H$
    - Higgs decay product

- **Goal: Investigate the sensitivity of ILC for detecting the dark neutrino**



$H \to WW^*$

- $H \to WW^* \to Wl\nu$ likely largest background
- No simulated samples of the dark neutrino model yet
- $H \to WW^*$ interesting to study on its own



Conclusion:

- Use $H \to WW^* \to qql\nu$ as a pseudosignal
- **$H \to WW^* \to qql\nu$ main focus of presentation**
- For now, only study $Z \to qq$

Cut method

1. Dataset: MC-2020 full simulation data, 1000 fb^{-1} each for (+0.8, -0.3) and (-0.8, +0.3), iLCSoft v02-02
   - Signal: qqh_ww (only $W^* \rightarrow l\nu$, $W \rightarrow qq$)
   - Background: 2f, 4f, 6f

2. Pre-selection

3. Cuts

4. MVA cuts

Pre-selection

- Enforce four jets with Durham clustering
- Require at least one isolated lepton (neural network)
  - Muon: lepton finder output > 0.7
  - Electron: lepton finder output > 0.5
- Pair jets to Z and W to minimize

$$\chi^2 = \left(\frac{m_W - m_{12,jet}}{\Delta m_{W,jet}}\right)^2 + \left(\frac{m_Z - m_{34,jet}}{\Delta m_{Z,jet}}\right)^2$$

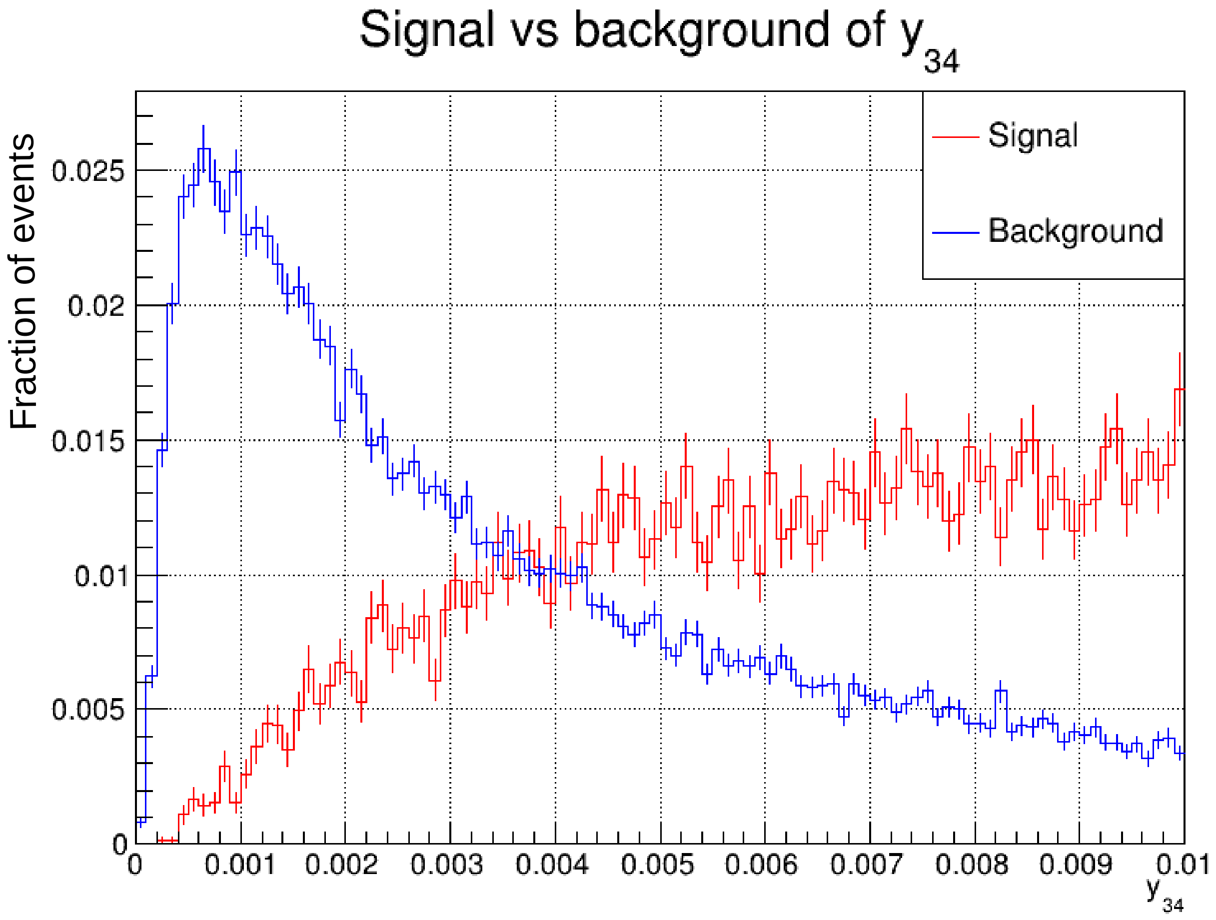
- Mass resolution calculated by pairing jets based on whether a jet contains the most energy from MC W or MC Z

Cuts

- Separate cuts for eLpR, eRpL beam (1000 fb^{-1} each)
- Main backgrounds: hadronic and semileptonic decays

- Missing energy, lepton energy (semileptonic)
- Isolated lepton finder output value (hadronic)
- 4-jet invariant mass (semileptonic + hadronic)
- Jet distance $y_{4\rightarrow 3}$ (semileptonic)
- Number of particles in smallest jet (semileptonic)
- Missing momentum (semileptonic + hadronic)

Example distribution

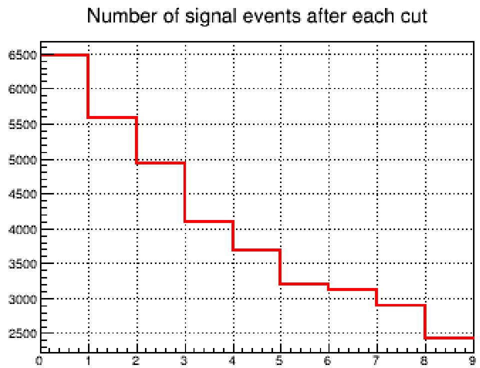


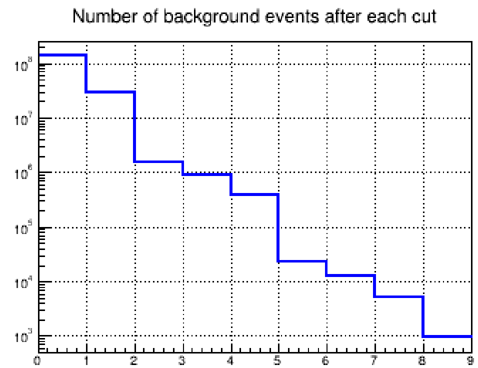
Machine learning

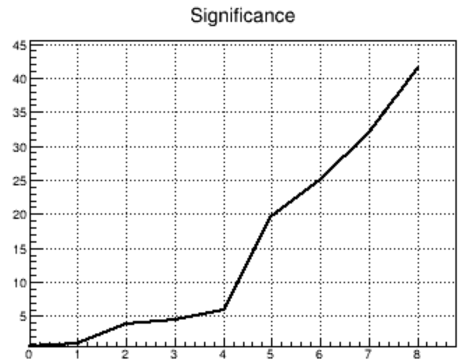
- Boosted decision tree (TMVA)
- 100 trees, 4 nodes at most, optimize significance
- Weighted events
- Input parameters:
  - Lepton energy, missing energy
  - 4-jet combined momentum
  - Angle between isolated lepton and closest jet, lepton $\cos(\theta)$, missing momentum $\cos(\theta)$, Z boson $\cos(\theta)$, W boson $\cos(\theta)$ in H rest frame
  - Higgs mass, Z mass, W mass

Cut table – eLpR beam

	Total signal	Total background	Significance	2f_l	2f_h	4f_l	4f_sl	4f_h	6f
No cuts	6472	136651487	0.55	12982897	77324421	10379315	19163106	16800470	1278
Pre-selection	5583	30106102	1.02	7366002	1606336	7651845	13260215	220833	872
elep/50. + emis/90. < 1.	4930	1556237	3.95	75113	265900	857303	209602	147613	705
0.8 < mvalep	4101	877321	4.37	54525	41290	623639	138607	18676	585
(180. < mvis) && (mvis < 225.)	3695	386614	5.91	34476	21865	237881	82092	9918	383
0.007 < y34	3201	23318	19.66	160	2109	406	13519	6778	346
2 < min_n	3126	12464	25.04	4	1223	7	4376	6541	314
(10. < mis.P()) && (mis.P() < 50.)	2896	5327	31.93	2	564	4	2207	2449	102
MVA cut	2420	981	41.50	1	73	2	570	304	31

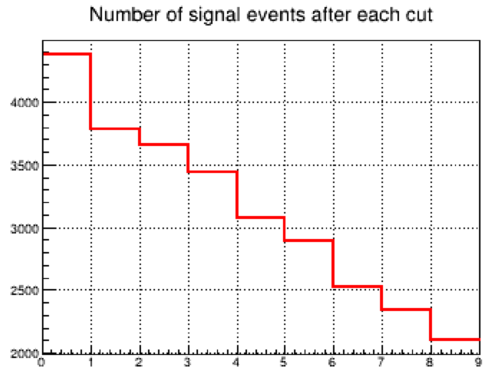


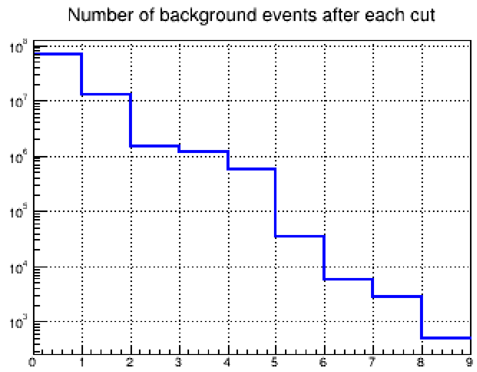


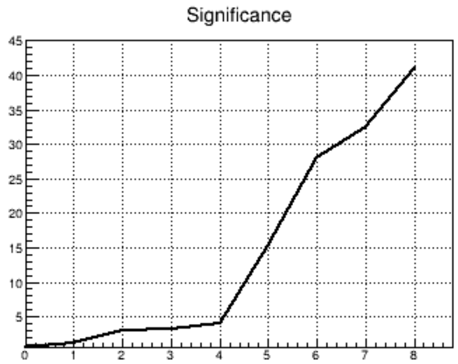


Cut table – eRpL beam

	Total signal	Total background	Significance	2f_l	2f_h	4f_l	4f_sl	4f_h	6f
No cuts	4376	66511092	0.54	10314870	45672588	6114301	2839022	1570051	260
Pre-selection	3778	12547917	1.07	5696748	979693	4109167	1739683	22431	194
elep/60. + emis/100. < 1.	3661	1518141	2.97	99987	189804	1016886	193442	17855	167
0.6 < mvalep	3435	1206227	3.12	88826	62401	890288	159199	5357	156
(160. < mvis) && (mvis < 220.)	3071	559413	4.10	63936	33233	359843	99486	2819	96
0.004 < y34	2896	33799	15.12	565	6575	2378	21820	2369	93
4 < min_n	2527	5638	27.97	0	1775	0	1881	1910	71
(10. < mis.P()) && (mis.P() < 50.)	2344	2852	32.52	0	879	0	1049	902	23
MVA cut	2100	510	41.11	0	94	0	245	162	9







Significance

- eLpR + eRpL combined significance: **58σ**
- Previous study of ZH→qqWW*→qqqqlν at ILC (H. Ono): 36σ
  - Both **W*→lν** and W*→qq were used
- Previous study of H→WW* significance, with all decay modes: 61σ
- **Major improvement** of significance compared to previous studies

Future work

- Begin analyzing dark neutrino model
- Signal sample generation ongoing
  - Heavy neutrino model for Whizard
- Check that the samples have reasonable outputs
- Apply further cuts to reduce $ZH \rightarrow qqWW^* \rightarrow qqql\nu$ background
  - Helicity angle
  - Mass resonance at dark neutrino mass

Image source: Symmetry Magazine

Techincal details

- Use ROOT::RDataFrame in Jupyter notebook

  Simplifies:

  - Making and analyzing cuts
  - Defining new variables
  - Running the code in parallel
  - Visualize the filtered data
  - Exploratory data analysis

```
ROOT::RDataFrame df("myTree", file);
auto h = df.Filter("y > 2").Histo1D("x");
h->Draw()
```