Strange Quark as a probe for new physics in the Higgs sector

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Matthew Basso (University of Toronto), On behalf of the authors of the associated Snowmass 2021 paper and the ILD Concept Group
Overview

- Broad interest in studying the light quark Yukawa couplings at future lepton colliders as a portal to BSM physics
  - See recent ECFA seminar on physics with light quarks
- Goal of this study: assess the sensitivity of Higgs to strange couplings at the ILC and to study detector design enabling strange jet tagging
  - Strange jet tagging capabilities strongly depend on particle identification (PID)
  - Submitted as part of the Snowmass 2021 proceedings: 2203.07535

Strange quark as a probe for new physics in the Higgs sector

Measurement prospects for Higgs to strange

- $h(125) \to ss$: extremely challenging (BR $\sim 1E-4$) unless enhanced relative to SM expectations
  - Is the Yukawa coupling universal between generations?
- $H^\pm \to cs$: some BSM models allow for the 1\textsuperscript{st} and 2\textsuperscript{nd} generation fermion masses to be an additional source of EW symmetry breaking
  - Results in “SM” and “heavy” Higgs doublets
  - Predicts an enhancement to Higgs cross section
  - Charged heavy Higgs can undergo flavour violating decays (e.g., $cs$) – \textbf{slc-tagging at future detectors can help...}

\[ \text{Charged heavy Higgs branching ratios. Taken from Fig. 6 of 1610.02398.} \]
...one such proposed detector

- The International Large Detector (ILD)
  - 3 double-layer pixel detectors for vertexing
  - 2 double-layer pixel detectors, time projection chamber (TPC), and 1 double-layer strip detector for tracking
    - Low material of TPC assists in low-$p$ tracking
  - Forward tracking detector provides tracking acceptance starting at $\theta = 4.8^\circ$
  - High granularity sampling calorimeters for particle flow reconstruction
    - Precise EM/hadronic design still under study
  - Tracking/calorimetry contained in 3.5 (4) T field

ILD detector quadrant. Taken from Fig. 5.1 of 2003.01116.
Developing a jet flavour tagger

- Developed a recurrent neural network for tagging jets by flavour, trained on ILD-reconstructed ($Z\rightarrow\nu\nu$(h$\rightarrow qq/gg$)) samples
  - Architecture in Backup

- The tagger utilizes per-jet inputs and inputs for the 10 leading constituents in each jet
  - Includes 4-vector information and existing (LCFIPlus) jet tagger scores
  - Additionally use truth-based PID inputs for the jet's constituents: electron, muon, proton, pion, or kaon (includes $K^{\pm}$, $K_{s}^{0}$, and $\Lambda^{0}$)

The tagger has 5 output nodes for gluon, light (u/d), strange, charm, and bottom jets. Pictured here is the strange node (others are in the Backup).
Standard Model $h(125) \rightarrow ss$ analysis

- Analysis measuring $Zh(125) \rightarrow ss$ at $\sqrt{s} = 250$ GeV using 900 fb$^{-1}$ of data from the ILC’s first 10 years of operation

- Performed in two channels based on the decay of the $Z$, $Z \rightarrow \nu\nu$ and $Z \rightarrow ll$, each with their own dedicated selections
  - Leading backgrounds include $Z \rightarrow qq$ and semileptonic $ZlZl$
  - Full set of selections and backgrounds in Backup (also cutflows and plotted cutflows)
Constituting a fit for $\kappa_s$

- A signal discriminant is constructed using the sum of the strange scores for the leading and subleading jets – yields a 2-bin fit
- Fit a simple likelihood with uncorrelated background uncertainties
  - Assumes uncertainties are dominated by data statistics
Constructing a fit for $\kappa_s$

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A signal discriminant is constructed using the sum of the strange scores for the leading and subleading jets – yields a 2-bin fit

Fit a simple likelihood with uncorrelated background uncertainties
  - Assumes uncertainties are dominated by data statistics
Combined limits on $\kappa_s$

- Combined 95% upper limit on the Higgs-strange Yukawa coupling modifier, $\kappa_s$, is found to be **6.74**
  - Competitive with indirect searches ([1905.03764](https://arxiv.org/abs/1905.03764))
- Uncertainty on $h \rightarrow gg$ rate could be significant
  - Assigning ±100% uncertainty affects the $Z \rightarrow ll$ channel, where the absolute uncertainty is comparable to the counting uncertainty in data
  - Could be mitigated by an explicit cut on gluon jet output node (see an example in Backup)
Constraining 2 Higgs doublet models

- Spontaneous flavour violating (SFV) 2HDMs allow for large Higgs-strange/light couplings
  - See 1908.11376, for instance
  - Can manifest as a modification of the SM Higgs-strange Yukawa coupling, due to mixing of the SM/BSM Higgs doublets
- Higgs to strange analyses at future lepton colliders stand to set some of the strongest limits on such models
  - Will improve even more when including the full ILC dataset and additional channels (e.g., $(Z\rightarrow qq)h$)

\[\text{Dashed line := HL-LHC.}\]
Particle identification is important!

- We can study the effect of having truth PID only up to certain particle momenta (0, 10, 20, 30, ∞ GeV)
- With no PID, there is no capacity for separating strange and light jets
  - At 80% light rejection, there is ~50% improvement in strange efficiency going from PID < 10 GeV to PID < 30 GeV
- PID is essential for analyses studying strangeness (and specifically >10 GeV)
Leading particles in jets of different flavours

- Same conclusion maybe be drawn when studying the leading particles in jets
  - Strange hadrons are most often the leading particles in strange jets
  - The leading particle typically has momentum $\sim 15$ GeV
Detector proposal for high momentum PID

• Ring imaging Cherenkov (RICH) detectors: use the angle of emitted Cherenkov cones which, coupled with momenta measurements, yield particle masses
  - Used by DELPHI, SLD, LHCb...

• We are proposing the use of a compact gaseous RICH detector at future colliders
  - Also utilizes silicon photomultipliers (SiPMs)
  - Benefits include: \(\pi/K\) separation up to \(\sim 30\) GeV, low material budget, low radial extent, ...

\[
\cos(\theta_c) = 1 / (\beta \times n(\lambda))
\]
\(\theta_c := \) Cherenkov angle
\(\beta := v/c\)
\(n := \) refraction index
Compact gaseous RICH for ILD/SiD detectors

Pure $\text{C}_4\text{F}_{10}$ at 1 bar (boiling point -1.9 °C at 1 bar) for radiator, ~flat refraction index in wavelength

Low-mass carbon-composite structure

Material $\sim 0.05 \times X_0$

Small radial extent (helps reduce cost of the calorimeters)

SiPM imaging plane – broad quantum efficiency in wavelength, $<100$ ps timing resolution

Focusing mirrors made of Be with Cr/Al/MgF$_2$ coating, ~flat reflectivity in wavelength
Separation power for pions/kaons

- Achievable separation power for pions/kaons depends strongly on Cherenkov angle resolution
  - e.g., for our proposed RICH, resolutions >5 mrad degrade the performance significantly

- Different sources which contribute to the total resolution are enumerated in the Backup
  - Particularly important is the magnetic smearing effect...

Separation power = \[ \frac{|\theta_\pi - \theta_K|}{\sigma_\theta \times \sqrt{N_{pe}}} \]

- \( \theta_\pi(K) \) = Cherenkov angle for pions (kaons)
- \( \sigma_\theta \) = Cherenkov angle resolution
- \( N_{pe} \) = number of photoelectrons per ring
Magnetic smearing effect

- Cherenkov cones spiral in the magnetic field of the solenoid, leading to smeared images with elliptical shapes
  - Calculations assume 5 T (comes from SiD design: 0911.0006)
  - \(~2 \text{ mrad}~\) contribution to the total resolution (<5 mrad)
- For a 50% improvement in SiPM photon detection efficiency, the radiator length may be reduced to 10-15 cm, reducing magnetic smearing

The dip angle \(\theta_{\text{dip}}\) corresponds to the angle between particle momentum and component perpendicular to the field.
Performance versus other PID methods

Cherenkov angle resolution = 5 mrad

Expected p/K separation

PID separation (# of signals)

Momentum [GeV/c]

Cherenkov angle

Compact gaseous RICH

3σ
Summary and next steps

- Presented our studies towards strange tagging at future lepton colliders
  - Direct measurements of $h(125)\rightarrow ss$ at future colliders can provide competitive avenues for studying the extended Higgs sector – but PID is a necessary ingredient!
  - RICH detectors can offer $>3\sigma$ pion/kaon separation up to $\sim30$ GeV
    - Cluster counting in TPCs is also a powerful option (ILD: 1902.05519)
  - Ongoing: expanding to the full ILC luminosity, including $H^{\pm}\rightarrow cs$, and testing a modified ParticleNet (1902.08570) neural network for multiclassification
- Strange tagging broadly applicable to other measurements: $Z\rightarrow ss$, $e^+e^-\rightarrow ss$, $W\rightarrow cs$, ...
  - Prospect studies at the ILC and the FCC-ee are already examining at these channels
Questions?
Backup
Jet flavour tagger architecture

- Neural network architecture:
  - *Multiclassifer* (5 output classes: gluon, light, strange, charm, or bottom)
  - 3-layer recurrent neural network using Gated Recurrent Units (GRUs) for particle-level inputs
  - Concatenated with jet-level inputs and fed into a 3-layer MultiLayer Perceptron (MLP)
  - Similar architecture applied for strange tagging at *hadron* colliders (2011.10736)
Jet flavour tagger output nodes

**Bottom**

**Charm**

**Gluon**

**Strange**

**Light**
Confusion matrix for jet flavour tagger
Leading strange hadron momentum for varying cuts on jet flavour tagger

Strange score > 0.0
Strange score > 0.4
Strange score > 0.7

Cutting tighter on the strange output node selects jets with leading strange hadrons with higher momenta
MC samples and selections for $h \to ss$ analysis

Table 2: MC processes considered in the $h \to ss$ analysis, including raw statistics and cross sections. N.B. the samples were generated at $\sqrt{s} = 250$ GeV and the cross sections assume 100% LH-polarised electron beams and 100% RH-polarised positron beams. The cross sections include the corresponding BRs for the indicated decays. In the non-Higgs processes, "#f" denotes the number (#) of fermions (f) in the final state. In $Z \to (\ell\bar{\ell}) h \to (other)$, "other" denotes any non-hadronic SM decay. The $Z \to (\ell\bar{\ell}) h \to (u\bar{d}d\bar{d})$ processes, while having 0 raw events, have cross sections which are much smaller than that of $Z \to (\ell\bar{\ell}) h \to (s\bar{s})$. Accordingly, they may be safely excluded from the analysis but are highlighted here for posterity. The ZZ/WW process covers the interference of ZZ and WW final states, e.g., $u\bar{d}d\bar{d}$ or $c\bar{c}s\bar{s}$.

<table>
<thead>
<tr>
<th>Process name</th>
<th>Raw events [a.u.]</th>
<th>LR cross section [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z(\to \nu\bar{\nu})h(\to s\bar{s})$</td>
<td>500,000</td>
<td>0.021</td>
</tr>
<tr>
<td>$Z(\to \nu\bar{\nu})h(\to b\bar{b})$</td>
<td>500,000</td>
<td>58.1</td>
</tr>
<tr>
<td>$Z(\to \nu\bar{\nu})h(\to c\bar{c})$</td>
<td>499,800</td>
<td>2.9</td>
</tr>
<tr>
<td>$Z(\to \nu\bar{\nu})h(\to u\bar{u})$</td>
<td>1 $\times$ 10$^{-5}$</td>
<td></td>
</tr>
<tr>
<td>$Z(\to \nu\bar{\nu})h(\to d\bar{d})$</td>
<td>500,000</td>
<td>5 $\times$ 10$^{-5}$</td>
</tr>
<tr>
<td>$Z(\to \nu\bar{\nu})h(\to gg)$</td>
<td>499,800</td>
<td>8.6</td>
</tr>
<tr>
<td>$Z(\to \ell\bar{\ell})h(\to s\bar{s})$</td>
<td>373</td>
<td>0.011</td>
</tr>
<tr>
<td>$Z(\to \ell\bar{\ell})h(\to b\bar{b})$</td>
<td>872,380</td>
<td>29.8</td>
</tr>
<tr>
<td>$Z(\to \ell\bar{\ell})h(\to c\bar{c})$</td>
<td>43,334</td>
<td>1.5</td>
</tr>
<tr>
<td>$Z(\to \ell\bar{\ell})h(\to u\bar{u})$</td>
<td>0</td>
<td>6 $\times$ 10$^{-6}$</td>
</tr>
<tr>
<td>$Z(\to \ell\bar{\ell})h(\to d\bar{d})$</td>
<td>0</td>
<td>3 $\times$ 10$^{-5}$</td>
</tr>
<tr>
<td>$Z(\to \ell\bar{\ell})h(\to gg)$</td>
<td>123,225</td>
<td>4.4</td>
</tr>
<tr>
<td>$Z(\to \ell\bar{\ell})h(\to other)$</td>
<td>460,688</td>
<td>15.9</td>
</tr>
</tbody>
</table>

2f Z hadronic: 25,354,400, 127,965
4f ZZ hadronic: 7,699,000, 1,405
4f WW hadronic: 14,790,600, 14,866
4f ZZ/WW hadronic: 18,494,200, 12,389
2f Z leptonic: 24,500,000, 21,214
4f ZZ semileptonic: 4,199,600, 838
4f single Z semileptonic: 6,999,600, 1,423

Table 3: Kinematic selections for $Z \to \nu\bar{\nu}$ and $Z \to \ell\bar{\ell}$ channels of the $h \to ss$ analysis. The selections are grouped into categories serving specific purposes.

<table>
<thead>
<tr>
<th>Category</th>
<th>Selection</th>
<th>$Z \to \nu\bar{\nu}$</th>
<th>$Z \to \ell\bar{\ell}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Object counting</td>
<td>Number of leptons, $N_{\text{leptons}}$</td>
<td>≥ 0</td>
<td>≥ 2</td>
</tr>
<tr>
<td>Number of jets, $N_{\text{jets}}$</td>
<td>≥ 2</td>
<td>≥ 2</td>
<td></td>
</tr>
<tr>
<td>Leading 2 leptons are SFOS$^a$</td>
<td>–</td>
<td>True</td>
<td></td>
</tr>
</tbody>
</table>

2f Z rejection
- Leading jet momentum, $p_{\text{jet}}$ | $[0, 110]$ GeV | $[60, 105]$ GeV |
- Subleading jet momentum, $p_{\text{jet}}$ | $[30, 80]$ GeV | $[55, 75]$ GeV |
- Dijet energy, $E_{\text{jj}}$ | $[125, 155]$ GeV | $[130, 150]$ GeV |
- Missing mass, $M_{\text{miss}}$ | $[75, 120]$ GeV | – |
- Dijet/missing-#p$^2$ angular separation, $\Delta R_{\text{jj,miss}}$ | $[3, 4.6]$ | $> 1.25$ rad |
- Dijet azimuthal separation, $\Delta \phi_{\text{jj}}$ | – | $> 1.75$ rad |
- Leading lepton momentum, $p_{\ell}$ | – | $[40, 50]$ GeV |
- Subleading lepton momentum, $p_{\ell}$ | – | $[20, 60]$ GeV |
- Dilepton mass, $M_{\ell\ell}$ | – | $[80, 100]$ GeV |
- Dilepton energy, $E_{\ell\ell}$ | – | $[85, 115]$ GeV |
- Recoil mass, $M_{\text{reco}}$ | – | $[122, 155]$ GeV |

4f ZV rejection
- Leading jet LCFIPos BTag score, score$_{b}^{\text{pos}}$ | $< 0.20$ | $< 0.20$ |
- Subleading jet LCFIPos BTag score, score$_{b}^{\text{pos}}$ | $< 0.20$ | $< 0.20$ |
- Leading jet LCFIPos CTag score, score$_{c}^{\text{pos}}$ | $< 0.35$ | $< 0.3$ |
- Subleading jet LCFIPos CTag score, score$_{c}^{\text{pos}}$ | $< 0.35$ | $< 0.35$ |

4f VV rejection
- 2 $\to$ 3 jet transition variable, $g_{23}^{\text{ZZ}}$ | 0.010 | 0.005 |
- 3 $\to$ 4 jet transition variable, $g_{34}^{\text{ZZ}}$ | 0.002 | 0.005 |

h $\to gg$ rejection
- Number of PFOs in event, $N_{\text{PFO}}^{\text{event}}$ | $[30, 60]$ | $[20, 80]$ |
- Number of PFOs in leading jet, $N_{\text{PFO}}^{\text{leading}}$ | $[10, 40]$ | $[5, 40]$ |
- Number of PFOs in subleading jet, $N_{\text{PFO}}^{\text{subleading}}$ | $[9, 37]$ | $[5, 40]$ |
**Cutflows for $h \to ss$ analysis**

### $Z\to \nu\nu$ channel

| $\mathcal{L}$ Preliminary, $\mathcal{L} = 900 \times 2 \sqrt{s} = 250 \text{ fb}^{-1}$, $\mathcal{F}_{\nu\nu}$, $\mathcal{F}_{\nu\nu}$ | $|\mathcal{H}| - 0.8 \mathcal{H}$ (in cm) | $|\mathcal{H}| + 0.8 \mathcal{H}$ (in cm) | $(|\mathcal{H}| - 0.8 \mathcal{H})^2$ (in cm) | $(|\mathcal{H}| + 0.8 \mathcal{H})^2$ (in cm) | $(|\mathcal{H}| - 0.8 \mathcal{H})^2 + (|\mathcal{H}| + 0.8 \mathcal{H})^2$ (in cm) | $(|\mathcal{H}| - 0.8 \mathcal{H})^2 - (|\mathcal{H}| + 0.8 \mathcal{H})^2$ (in cm) |
|---------------------------------------------------------------|-----------------|-----------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| No cut                                                  | $18.98 \pm 0.30$ | $18.68 \pm 0.30$ | $3678 \pm 65$                   | $3678 \pm 65$                   | $7356 \pm 130$                   | $0$                              |
| No leptons                                             | $18.60 \pm 0.30$ | $18.21 \pm 0.30$ | $3663 \pm 65$                   | $3663 \pm 65$                   | $7326 \pm 130$                   | $0$                              |
| No b-tag                                               | $18.60 \pm 0.30$ | $18.41 \pm 0.30$ | $3678 \pm 65$                   | $3678 \pm 65$                   | $7356 \pm 130$                   | $0$                              |
| No $p_T$ jets                                          | $18.60 \pm 0.30$ | $18.41 \pm 0.30$ | $3678 \pm 65$                   | $3678 \pm 65$                   | $7356 \pm 130$                   | $0$                              |
| No $p_T$ jets                                          | $18.02 \pm 0.25$ | $17.64 \pm 0.25$ | $3678 \pm 65$                   | $3678 \pm 65$                   | $7356 \pm 130$                   | $0$                              |
| No $p_T$ jets                                          | $18.02 \pm 0.25$ | $17.64 \pm 0.25$ | $3678 \pm 65$                   | $3678 \pm 65$                   | $7356 \pm 130$                   | $0$                              |
| No $p_T$ jets                                          | $18.02 \pm 0.25$ | $17.64 \pm 0.25$ | $3678 \pm 65$                   | $3678 \pm 65$                   | $7356 \pm 130$                   | $0$                              |

### $Z\to \ell\ell$ channel

| $\mathcal{L}$ Preliminary, $\mathcal{L} = 900 \times 2 \sqrt{s} = 250 \text{ fb}^{-1}$, $\mathcal{F}_{\ell\ell}$, $\mathcal{F}_{\ell\ell}$ | $|\mathcal{H}| - 0.8 \mathcal{H}$ (in cm) | $|\mathcal{H}| + 0.8 \mathcal{H}$ (in cm) | $(|\mathcal{H}| - 0.8 \mathcal{H})^2$ (in cm) | $(|\mathcal{H}| + 0.8 \mathcal{H})^2$ (in cm) | $(|\mathcal{H}| - 0.8 \mathcal{H})^2 + (|\mathcal{H}| + 0.8 \mathcal{H})^2$ (in cm) | $(|\mathcal{H}| - 0.8 \mathcal{H})^2 - (|\mathcal{H}| + 0.8 \mathcal{H})^2$ (in cm) |
|---------------------------------------------------------------|-----------------|-----------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| No cut                                                  | $18.00 \pm 0.30$ | $18.70 \pm 0.30$ | $3678 \pm 65$                   | $3678 \pm 65$                   | $7356 \pm 130$                   | $0$                              |
| No leptons                                             | $18.60 \pm 0.30$ | $18.41 \pm 0.30$ | $3678 \pm 65$                   | $3678 \pm 65$                   | $7356 \pm 130$                   | $0$                              |
| No b-tag                                               | $18.60 \pm 0.30$ | $18.41 \pm 0.30$ | $3678 \pm 65$                   | $3678 \pm 65$                   | $7356 \pm 130$                   | $0$                              |
| No $p_T$ jets                                          | $18.60 \pm 0.30$ | $18.41 \pm 0.30$ | $3678 \pm 65$                   | $3678 \pm 65$                   | $7356 \pm 130$                   | $0$                              |
| No $p_T$ jets                                          | $18.02 \pm 0.25$ | $17.64 \pm 0.25$ | $3678 \pm 65$                   | $3678 \pm 65$                   | $7356 \pm 130$                   | $0$                              |
| No $p_T$ jets                                          | $18.02 \pm 0.25$ | $17.64 \pm 0.25$ | $3678 \pm 65$                   | $3678 \pm 65$                   | $7356 \pm 130$                   | $0$                              |
| No $p_T$ jets                                          | $18.02 \pm 0.25$ | $17.64 \pm 0.25$ | $3678 \pm 65$                   | $3678 \pm 65$                   | $7356 \pm 130$                   | $0$                              |
Cutflows for $h\rightarrow ss$ analysis: $Z\rightarrow \nu\nu$ channel

**ILD Preliminary, $\mathcal{L} = 900 \text{ fb}^{-1}, \sqrt{s} = 250 \text{ GeV}, P(e^-, e^+) = (-80\%, +30\%)$**

- (h $\rightarrow ss)(Z \rightarrow \ell\ell/\nu\nu)$
- (h $\rightarrow gg)(Z \rightarrow \ell\ell/\nu\nu)$
- (h $\rightarrow u\bar{u}/d\bar{d})(Z \rightarrow \ell\ell/\nu\nu)$
- (h $\rightarrow c\bar{c})(Z \rightarrow \ell\ell/\nu\nu)$
- (h $\rightarrow b\bar{b})(Z \rightarrow \ell\ell/\nu\nu)$
- (h $\rightarrow$ other)(Z $\rightarrow \ell\ell$)
- 2f Z hadr.
- 4f ZZ hadr.
- 4f WW hadr.
- 4f ZZ/WW hadr.
- 2f Z lept.
- 4f ZZ semilept.
- 4f ZZ semilept.
- 4f single Z semilept.

2022/05/05
Cutflows for $h\to ss$ analysis: $Z\to ll$ channel

**ILD Preliminary, $\mathcal{L} = 900$ fb$^{-1}$, $\sqrt{s} = 250$ GeV, $P(e^-, e^+) = (-80\%, +30\%)$**

- (h → s$\bar{s}$)(Z → $\ell\bar{\ell}$/νν)
- (h → gg)(Z → $\ell\bar{\ell}$/νν)
- (h → u$\bar{u}$/d$\bar{d}$)(Z → $\ell\bar{\ell}$/νν)
- (h → c$\bar{c}$)(Z → $\ell\bar{\ell}$/νν)
- (h → b$\bar{b}$)(Z → $\ell\bar{\ell}$/νν)
- (h → other)(Z → $\ell\bar{\ell}$)
- 2f Z hadr.
- 4f ZZ hadr.
- 4f WW hadr.
- 4f ZZ/WW hadr.
- 2f Z lept.
- 4f ZZ semilept.
- 4f single Z semilept.
Cutflow discussion

The cutflow for the $Z \rightarrow \nu \bar{\nu}$ channel is shown in Table 4. Histograms of the variables included as part of this channel’s selections (showing the evolution of the yields as each selection is applied) are shown in Figs. 8 through 11. From Table 4, we see the signal efficiency for our selections is 14% while our background efficiency is 0.005%. Even with the high background rejection, $Z \rightarrow q\bar{q}$ is still highly dominant with $\sim 4,200$ events compared to the $\sim 2$ events expected for $h \rightarrow s\bar{s}$. Therefore, improvements to the sensitivity of the analysis are expected to be accompanied by improved rejection of $Z \rightarrow q\bar{q}$. The $h \rightarrow gg$ process is the dominant Higgs background with $\sim 110$ events.

The cutflow for the $Z \rightarrow \ell\bar{\ell}$ channel is shown in Table 5. Histograms of the variables included as part of this channel’s selections (showing the evolution of the yields as each selection is applied) are shown in Figs. 12 through 16. From Table 5, the hadronic backgrounds are almost entirely removed by cutting on the number of leptons. The signal efficiency for our selections is 6% while our background efficiency is 0.001%. The $4f$ single $Z$ and $ZZ$ backgrounds are the dominant backgrounds, with $\sim 800$ events compared to the $\sim 1$ events expected for $h \rightarrow s\bar{s}$. As with the $Z \rightarrow \nu \bar{\nu}$ channel, the $h \rightarrow gg$ process is the dominant Higgs background with $\sim 100$ events.
Alternative discriminants: sum of strange scores minus sum of gluon scores

\[ Z \rightarrow \nu \nu \text{ channel} \]

\[ Z \rightarrow ll \text{ channel} \]

Provides slightly stronger separation of \( h \rightarrow ss \) from \( h \rightarrow gg \), but limits should be explicitly computed to confirm.
Limit plots on $\kappa_s$ from $h\to ss$ analysis

**Z$\to\nu\nu$ channel**

**Z$\to ll$ channel**
Limits on $\kappa_s$ when PID is absent

Compared to 6.74 with full PID
RICH: estimated performance for different particle types and momenta

![Graph of C4F10: Number of detected photons](image1)

![Graph of C4F10: Cherenkov angle](image2)
Figure 27: (a) A schematic diagram of the helix trajectory and Cherenkov cone. Notice that cones move in 3D. A simple program was implemented: step through the magnetic field, radiate Cherenkov photons when $100 < r < 125$ cm, reflect them from a spherical mirror, and find their intersection with a detector plane. (b) Ray tracing model for the simulation of three dip angles.
RICH: Cherenkov rings for varying dip angle

\[ \Delta \theta_c = \theta_c(\text{pion}) - \theta_c(\text{Kaon}) = 6.1 \text{ mrad} \]

\[ \theta_{\text{dip}} = 4^\circ \]
\[ P = 20 \text{ GeV/c} \]
\[ B = 5 \text{ Tesla} \]

\[ \theta_{\text{dip}} = 50^\circ \]
\[ P = 20 \text{ GeV/c} \]
\[ B = 5 \text{ Tesla} \]

\[ \text{st.dev. (pion)} = 1.1 \text{ mrad} \]

\[ \text{st.dev. (pion)} = 2.2 \text{ mrad} \]
RICH: Cherenkov rings for varying momentum

Δθ_c = θ_c(pion) - θ_c(Kaon) = 31.5 mrad
θ_dip = 4°
P = 10 GeV/c
B = 5 Tesla
st.dev. (pion) = 2.25 mrad

Δθ_c = θ_c(pion) - θ_c(Kaon) = 2.4 mrad
θ_dip = 4°
P = 30 GeV/c
B = 5 Tesla
st.dev. (pion) = 1.1 mrad
## RICH: contributions to the Cherenkov angle resolution

Table 6: Various contributions to the Cherenkov angle resolution.

<table>
<thead>
<tr>
<th>Single photon error source</th>
<th>SiD/ILD RICH detector [mrad]</th>
<th>SLD CRID detector [mrad]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chromatic error</td>
<td>~0.9</td>
<td>~0.4</td>
</tr>
<tr>
<td>Pixel size error (1–3 mm²)</td>
<td>0.8–2.3</td>
<td>~0.5</td>
</tr>
<tr>
<td>Smearing effect due to magnetic field</td>
<td>1.5–2.5</td>
<td>~0.5</td>
</tr>
<tr>
<td>Mirror alignment</td>
<td>&lt; 1</td>
<td>~1</td>
</tr>
<tr>
<td>Tracking angular error</td>
<td>&lt; 1</td>
<td>~0.8 [93, 94]</td>
</tr>
<tr>
<td>Other systematics errors</td>
<td>a few mrad</td>
<td>a few mrad</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>&lt; 5</strong></td>
<td><strong>~4.3</strong></td>
</tr>
</tbody>
</table>