# Additional Scalar Boson Search at FCC-ee

presented by
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# Motivation for Additional Scalar Boson Search at FCC-ee

- Additional scalar bosons required by many BSM theories:
  - Extended Higgs sector:
    additional singlet, 2HDM(required by MSSM), triplet, etc.
  - Potential Dark Matter candidates.
- Physics opportunities at FCC-ee
  - The FCC-ee program projected to start with a 4-year run around the Z-pole, producing $\mathcal{L}_{\text{int}}$ = 150 ab$^{-1}$ of data, or about $3 \times 10^{12}$ Z-bosons.
    c.f. the entire LEP program produced only $5 \times 10^{6}$ Z-bosons.
  - **Great sensitivity** for light scalar bosons coupled to the Z, via the Higgs-strahlung-like channel.
  - For charged decays of Z, we can look at the recoil mass spectrum of the Z-decay products to conduct a **decay-mode independent** search of the scalar boson. This can be supplemented by a decay-mode dependent search later.
- Complementing the LHC results (e.g. $m_{\mu\mu} < 25$ GeV).

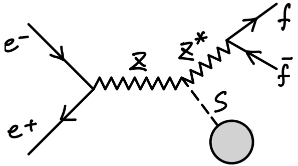



Figure: The Bjorken process for production of a scalar boson at FCC-ee.

# The OPAL Analysis

- A similar analysis[1] was done by the OPAL Collaboration at LEP, in search for the SM Higgs.
- For LEP1 run from 1989-95, they accumulated $115.4\,\text{pb}^{-1}$ of data at $\sqrt{s} = 91.2$ GeV.
- Looked at three channels: $Z \to e^+e^-$, $Z \to \mu^+\mu^-$, and $Z \to \nu\bar{\nu}$ with $S^0 \to e^+e^-$ or $\gamma$.
- For the charged lepton channel, the recoil mass is calculated by

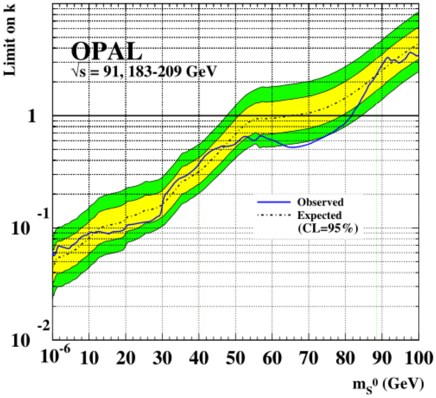
$$m_{\text{rec}}^2 = (\sqrt{s} - E_{ll})^2 - p_{ll}^2.$$

- Main backgrounds: 2-fermion and 4-fermion.
- Placed limit on $k$ where

$$k = \frac{\sigma_{S^0 Z^0}}{\sigma_{H^0_{\text{SM}} Z^0}} \text{ with } m_{H^0_{\text{SM}}} = m_{S^0}$$

[1] Eur. Phys. J. C **27**, 311 (2003)

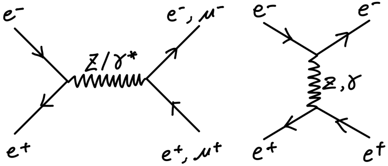
# The OPAL Result



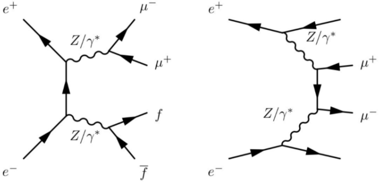

- We will go through a similar analysis and compare our results with the OPAL baseline.
- Our study will eventually give numbers on FCC-ee's potential to discover or exclude possible BSM scalar bosons coupling to the Z-boson, over a wide mass range.

# The Backgrounds

2-fermion backgrounds (examples)




4-fermion backgrounds (examples)




- The 2-fermion background has large cross-section, but can be largely cut away by selecting on the modified acoplanarity:

$$\alpha = \frac{1}{2}(\sin\theta_1 + \sin\theta_2)|\pi - \phi_{\text{open}}|$$

$\alpha = 0$ for back-to-back lepton pair.

- The 4-fermion background has cross section comparable with the SM Higgs-strahlung, but can also be greatly suppressed by cutting on $\alpha$.
- Other cuts can also be applied to further improve the results...

# Generation and Detector Simulation

- Signal + Background samples generated by Whizard with ISR and no BES.
- Hadronization and FSR simulated in Pythia8 .
- Used this ILD Delphes datacard for detector simulation.
  - Tweaked photon RECO efficiency: 95 % for $E_\gamma > 10$ GeV $\rightarrow$ 95 % for $E_\gamma >$ **1 GeV**.
  - Delphes simulation does not include photon conversion.
  - The photon RECO efficiency affects the photon and conversion veto performance on the 2-fermion background. Understanding the impact of the efficiency on the results will be included in our future studies.
- The end products are ROOT files written in Delphes format.

# Table of Monte Carlo Samples

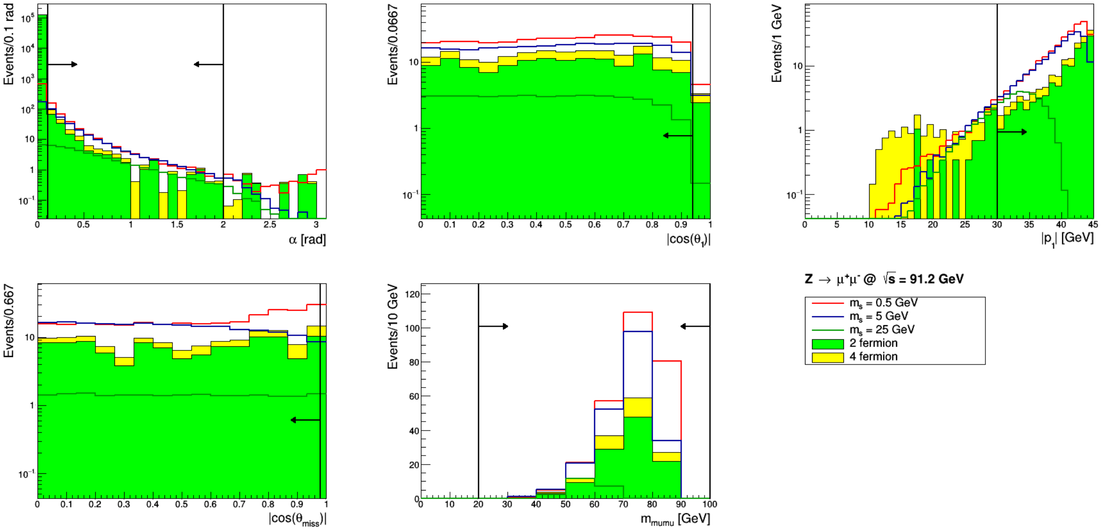
| Category | Sample Name | Channels | $\sqrt{s}$ [GeV] | # of Evts | Cross Section [pb] | Gen-level cuts |
|---|---|---|---|---|---|---|
| Signals | eeZS_p5 | $Z \to l^+l^-$ $S$ inclusive | 91 | $3 \times 10^5$ | 37.276 | $m_{ll} > 20$ GeV |
| | eeZS_2 | | | $3 \times 10^5$ | 27.510 | |
| | eeZS_5 | | | $3 \times 10^5$ | 17.027 | |
| | eeZS_10 | | | $2.5 \times 10^5$ | 7.856 | |
| | eeZS_15 | | | $3 \times 10^5$ | 5.748 | |
| | eeZS_25 | | | $3 \times 10^5$ | 2.291 | |
| 2-fermion | ee2fermion_mutau | $2\mu$ or $2\tau$ | 91 | $1 \times 10^6$ | 3013.049 | $m_{ll} > 20$ GeV |
| 4-fermion | ee4lepton_muon | $2\mu$ + $2l$ | 91 | $1 \times 10^5$ | 11.339 | $m_{ll} > 20$ GeV |
| | ee4lepquark | $2\mu$ + $2q$ | | $8.8 \times 10^5$ | 1.019 | $m_{ll} > 20$ GeV $m_{qq} > 300$ MeV |

- We are completing the sample set by generating more channels for the backgrounds and more samples at higher $\sqrt{s}$. Higher Statistics is also desirable in some cases.
- For now, we focus on the $Z \to \mu^+\mu^-$ channel at $\sqrt{s} = 91$ GeV.

# Cutflow for the Muon Channel at $\sqrt{s} = 91$ GeV

- Starting from the Delphes files, we apply the "**pre-selection**" cuts:
  - **Photon Veto**: All RECO photons should have E $<$ 1 GeV.
  - We look for all possible final state $e/\mu$ pairs with **opposite charge**.
  - If $>$ 1 pair found, we select the pair with the **highest sum of momentum** $|\vec{p}_1| + |\vec{p}_2|$.
- For each event passing the photon veto, we have selected one pair of leptons ($e^+e^-$ or $\mu^+\mu^-$). We store their kinematic variables in `TNtuple` trees to save disk space and processing time. Then we cut on these variables.
  - **Modified Acoplanarity**: $0.11 < \alpha = \frac{1}{2}(\sin\theta_1 + \sin\theta_2)|\pi - \phi_{\text{open}}| < 2$
  - **Forward Angles**: $|\cos\theta_1| < 0.94$ AND $|\cos\theta_2| < 0.94$
  - **Momentum**: $|\vec{p}_1| > 30$ GeV AND $|\vec{p}_2| > 20$ GeV
  - **Missing Momentum Angle**: $|\cos\theta_{p_{\text{miss}}}| < 0.98$ for $|\vec{p}_{\text{miss}}| > 2$ GeV
  - **Invariant Mass**: $20$ GeV $< m_{ll} < 100$ GeV

# Cutflow Plots



# Cutflow Table

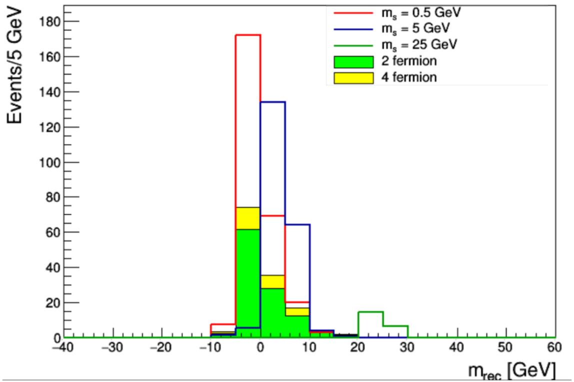
Number of events in this table is normalized to the LEP1 luminosity of $115.4\,\text{pb}^{-1}$.

| Cut | $m_s = 0.5$ GeV | $m_s = 5$ GeV | $m_s = 25$ GeV | 2-fermion | 4-fermion | Signal Efficiency (5 GeV) |
|---|---|---|---|---|---|---|
| Generation "Truth" | 1437.23 | 645.38 | 87.20 | 174181.16 | 1308.52 | 100% |
| Preselection | 1009.79 | 432.79 | 48.05 | 128053.11 | 540.43 | 67.1% |
| Alpha | 316.23 | 246.49 | 40.01 | 139.78 | 50.10 | 38.2% |
| Forward Angle | 302.67 | 236.26 | 39.47 | 133.52 | 48.39 | 36.6% |
| Momentum | 273.66 | 210.61 | 21.12 | 110.92 | 28.21 | 32.6% |
| $p_{\text{miss}}$ Angle | 273.61 | 210.58 | 21.11 | 110.92 | 28.19 | 32.6% |
| Invariant Mass | 273.61 | 210.58 | 21.11 | 110.92 | 28.19 | 32.6% |
| **OPAL Final Result** | – | – | – | 17.0 | 35.4 | 35.0% |

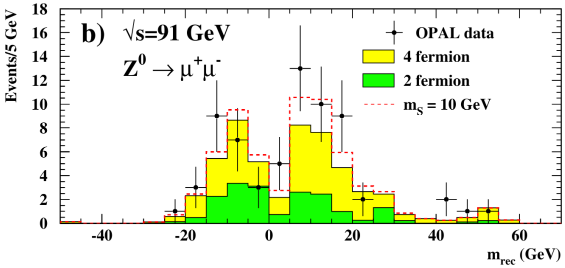
- The last 2 cuts are there to reduce backgrounds that we have not simulated yet.
- Comparing with OPAL, the 2f bkg is large due to low photon RECO efficiency.
  the 4f bkg is small due to incomplete sample set.
- The signal efficiencies agree within 10%.

# Recoil Mass Plots

## Our Analysis




## OPAL

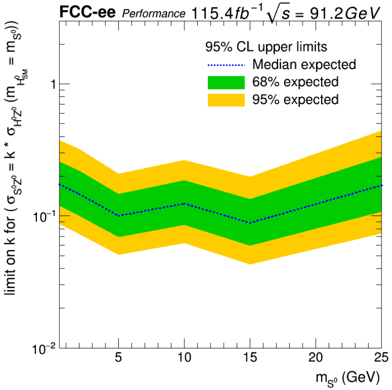



2-fermion background peaking at 0 GeV recoil mass in our plot is indicative of insufficient photon veto.

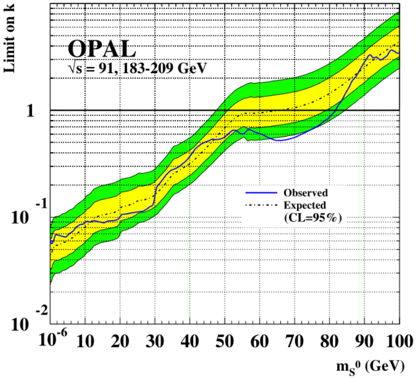
We then feed these recoil mass histograms to Combine, a statistics tool used by CMS, to extract limits on $k = \frac{\sigma_{S^0 Z^0}}{\sigma_{H^0_{\text{SM}} Z^0}}$ with $m_{H^0_{\text{SM}}} = m_{S^0}$.

# Limit Plots

Our Analysis




OPAL $\mathcal{L}_{\text{int}} = 777.4\,\text{fb}^{-1}$




- Not an apple-to-apple comparison yet: we only have muon channel at LEP1 energy.
- However, we can already observe that the sensitivity on the lower mass side is compromised by the large 2f resulting from the photon RECO efficiency, along with un-optimized cuts.

# What's Next

- Optimize the cuts, both manually and by incorporating ML techniques.
- Include the electron channel at $\sqrt{s} = 91$ GeV, overcoming challenges in generation.
- Study the impact of photon and conversion reconstruction.
- Investigate higher mass regions by studying larger $\sqrt{s}$ datasets.

# Summary

For the additional scalar boson search at FCC-ee, we have:

- Generated signal + bkg samples for the Bjorken process producing a light scalar boson with SM Higgs coupling.
- Selected lepton pairs from the Z-decay, and applied cuts from the OPAL scalar boson search to suppress the 2f and 4f background.
- Plotted the recoil mass spectrum of the muon channel events passing the cuts, and used Combine to extract limits on $k$.
- Showed that, with many precautions in mind, our analysis gives results comparable to that of OPAL.