Exotic Higgs Decays to LLPs: Incorporating Hadronic & Invisible Z Decays to Signal

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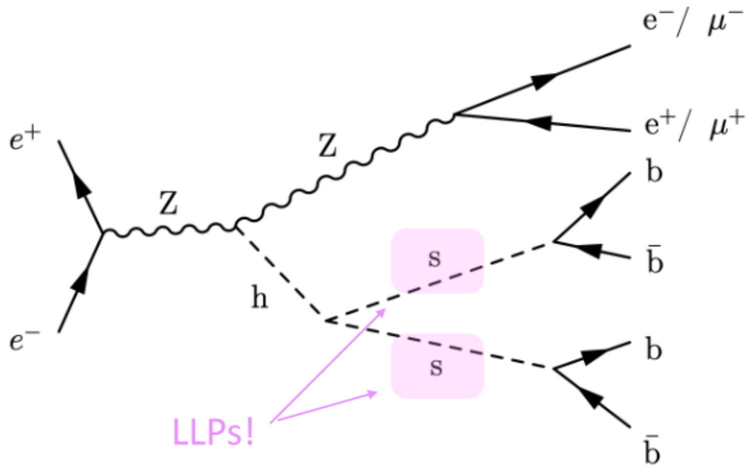
Based on work by Magdalena Vande Voorde, Giulia Ripellino, Axel Gallén, Rebeca Gonzalez Suarez

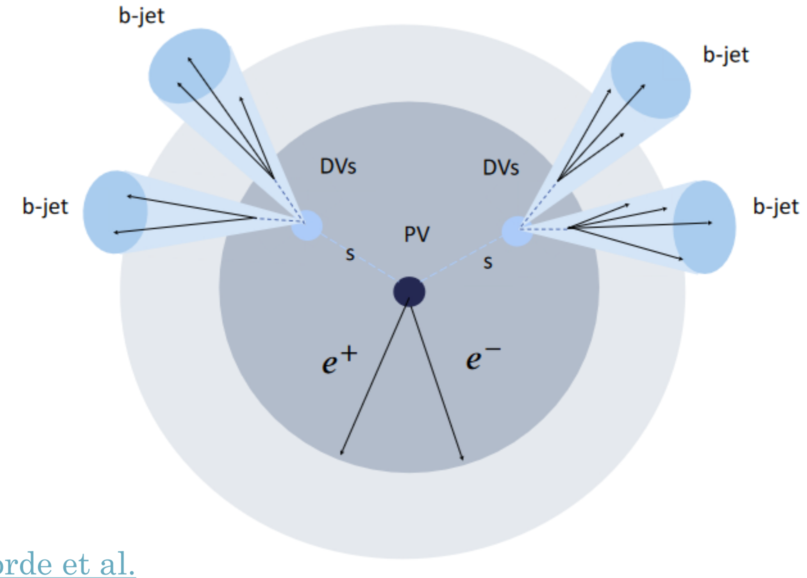
Original Analysis Signal Process

- Targeting **240 GeV, *Zh* production** stage w/ signal process:

$$e^+e^- \rightarrow Z\,h \text{ with } Z \rightarrow e^+e^- \text{ or } \mu^+\mu^- \text{ and } h \rightarrow ss \rightarrow b\bar{b}b\bar{b}$$

- This provides following experimental signatures:
  - **Reconstructed Z boson** from e^+e^- or $\mu^+\mu^-$ pairs
  - **Displaced vertices** from b pairs from long-lived scalar decay





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Path to Increasing Signal Statistics

- Branching fraction of $Z \rightarrow e^+e^-$ or $\mu^+\mu^-$ only ~6.7% of Z decay modes, significantly limiting our signal statistics and maximum sensitivity
- Incorporating $Z \rightarrow \nu\bar{\nu}$ (~20% branching frac.) & $Z \rightarrow q\bar{q}$ ($q = u, d, s, c, b,$ ~70%) to signal would greatly increase sensitivity
- Generated new samples with MadGraph 3.5.4 & Winter 2023 IDEA card at the 6 original signal points now with $Z \rightarrow q\bar{q}$ & $Z \rightarrow \nu\bar{\nu}$
  - New samples (and their reco. script outputs) available: /eos/experiment/fcc/ee/analyses/case-studies/bsm/LLPs/exoticHiggsSamplesCLD/
  - To maintain background rejection & signal sensitivity, wanted to replace first two of the originally used cuts, but retain final displaced vertex cut

Mass of Scalar m_S [GeV]	Mixing angle $\sin\theta$	Mean proper lifetime $c\tau$ [mm]
20	1×10^{-5}	3.4
20	1×10^{-6}	341.7
20	1×10^{-7}	34167.0
60	1×10^{-5}	0.9
60	1×10^{-6}	87.7
60	1×10^{-7}	8769.1

6 signal points varying scalar mass, mixing angle, influencing mean decay time

	Selection
Pre-selection	≥ 2 oppositely charged electrons or muons
Z boson tag	$70 < m_{ll} < 110$ GeV
Multiplicity of DVs	n_DVs ≥ 2

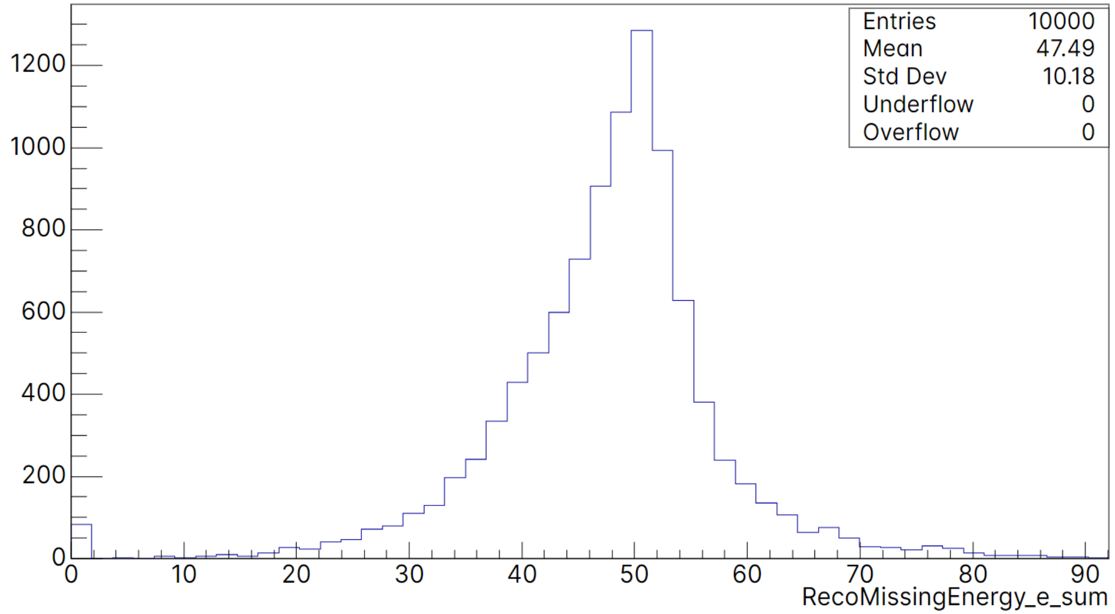
Cut flow used in original analysis

Strategy & Results for $Z \to \nu\bar{\nu}$

Backgrounds and Missing Energy Cut

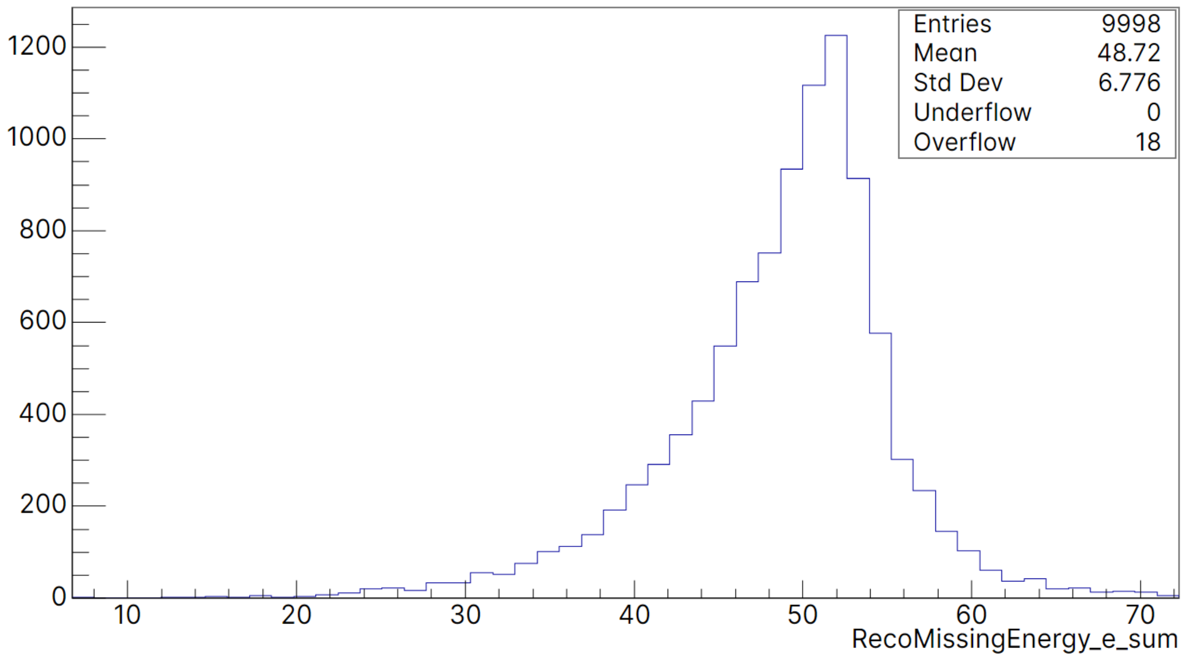
- Chose ZZ, WW, ZH ($Z \rightarrow \nu\bar{\nu}, H \rightarrow bb$) and ZH ($Z \rightarrow \nu\bar{\nu}, H \rightarrow WW$) as first order backgrounds
  - Since for our backgrounds ~10 – 50 events (out of 100,000) would pass DV cut, some level of initial background rejection is required
  - Found that the best way to do this was cutting on energy from 'MissingET' branch
- Despite confusion as to whether this was total or transverse missing energy per each event, it still proved helpful in rejecting background

Signal Missing Energy Distributions



Missing Energy (GeV)

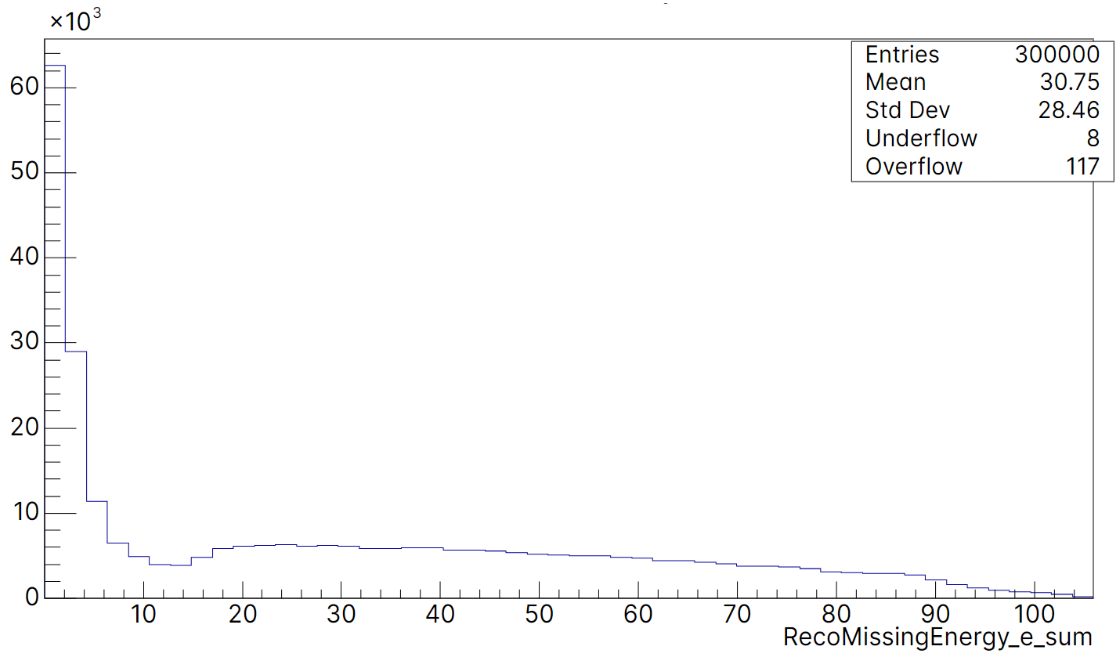
$m_s = 20 \text{ GeV}, \sin(\theta) = 10^{-6}$



Missing Energy (GeV)

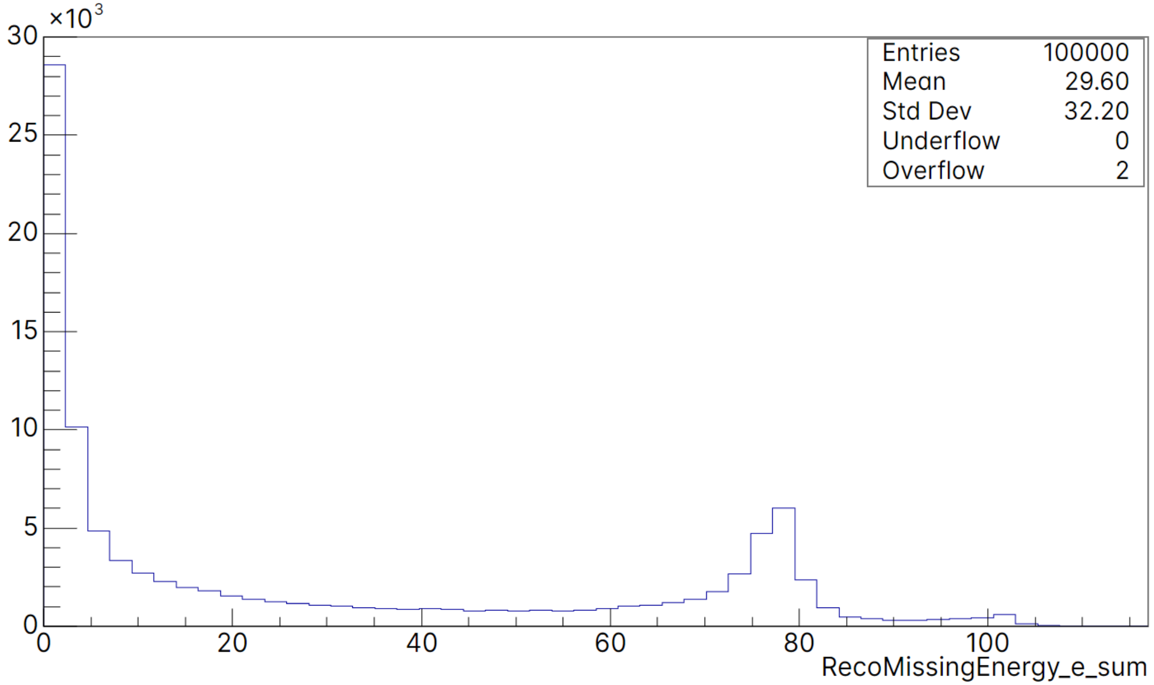
$m_s = 60 \text{ GeV}, \sin(\theta) = 10^{-6}$

Background Missing Energy Distributions



Missing Energy (GeV)

$e^+e^- \rightarrow WW$



Missing Energy (GeV)

$e^+e^- \rightarrow ZZ$

Note: ZH backgrounds look more similar to signals

Cut Efficiencies

- After some optimization, settled on cut of 30 $GeV < MET < 70\ GeV$, and again retained $N_{DV} \geq 2$ cut
- This yielded the following efficiencies:

Signal:	20 GeV, 1e-5	20 GeV, 1e-6	20 GeV, 1e-7	60 GeV, 1e-5	60 GeV, 1e-6	60 GeV, 1e-7
Missing Energy Cut	0.968	0.939	0.038	0.980	0.981	0.441
$N_{DVs} \geq 2$	0.102	0.715	0.014	0.0002	0.732	0.276

Background:	WW	ZZ	ZH ($Z \to \nu\nu$ $H \to bb$)	ZH ($Z \to \nu\nu$ $H \to WW$)
Missing Energy Cut	0.158	0.327	0.910	0.822
$N_{DVs} \geq 2$	0.0	0.0	0.0	0.00001

(1 event of 10,000 passed, corresponds to 0.71 events after reweighting to $7.2 \times 10^6\ pb^{-1}$)

Final Sensitivities / Event Yields

- Significantly increased event yield relative to original leptonic decay analysis (given $7.2 \times 10^6\ pb^{-1}$)

Events selected:

$m_s, sin\theta$	$n_{DVs} \geq 2$
20 GeV, 1e-5	16.73
20 GeV, 1e-6	117.33
20 GeV, 1e-7	2.35
60 GeV, 1e-5	0.01
60 GeV, 1e-6	35.52
60 GeV, 1e-7	13.43

m_s, sin θ	n_DVs $\geq$ 2
20 GeV, 1e-5	5.0 ± 0.166
20 GeV, 1e-6	37.1 ± 0.453
20 GeV, 1e-7	0.8 ± 0.067
60 GeV, 1e-5	0.0033 ± 0.0023
60 GeV, 1e-6	10.96 ± 0.167
60 GeV, 1e-7	6.49 ± 0.103

Sensitive (> 3 events)

Not sensitive (< 3 events)

Note: 20 GeV 1e-7 sample gained sensitivity only if combining with leptonic decay analysis yields

Uncertainty calculations yet to be performed for new results, must now incorporate having 0.7 expected background events

Strategy & Results for $Z \to q\bar{q}$

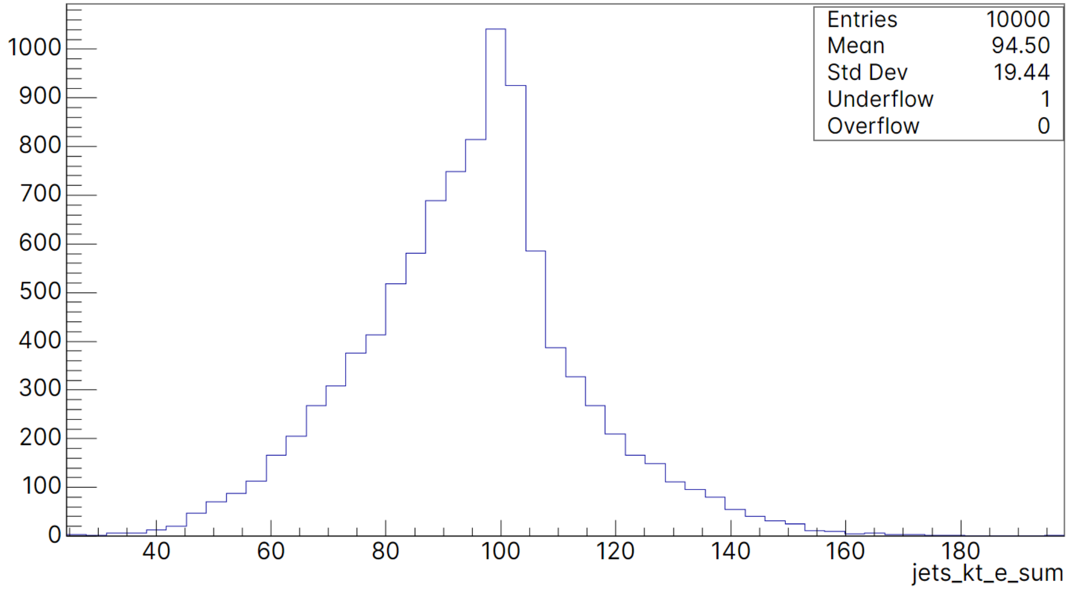
Jet Clustering Difficulties

- After initially generating samples, found that by default Winter 2023 DELPHES card used an exclusive N=2 jet clustering algorithm
  - This provided some initial confusion – but thanks to some help realized needed to recluster jets in the FCCAnalysis framework
  - Initially tried numerous inclusive jet clustering strategies, however, did not get satisfactory results where the number of reconstructed jets agreed with expected value across samples
- After a suggestion, pivoted toward a new strategy:
  - Perform displaced vertexing as normal, and then remove all particles associated with those reconstructed displaced vertices
  - With the remaining particles, perform k_t algorithm R = 0.5, E_0 scheme, N=2 exclusive jet clustering
  - Same process repeated for signal and background, allowing for consistency to perform cuts on jets that are reconstructed (ideally from Z)

Backgrounds and Jet Energy Cut

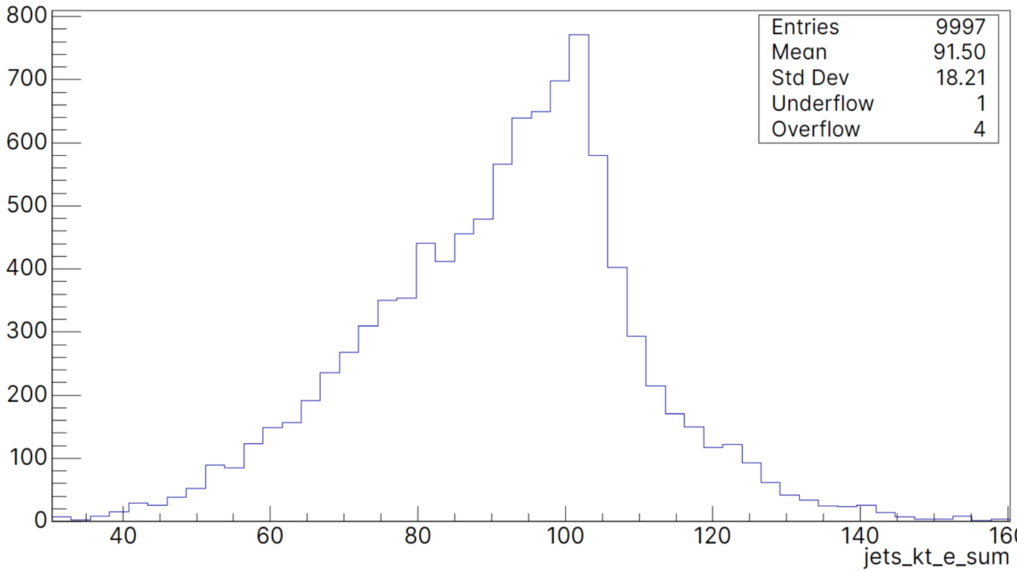
- Chose WW, ZZ, ZH ($Z \rightarrow q\bar{q}, (q = u, d, s, c, b), H \rightarrow bb, WW$) as backgrounds (total of 8 different samples as $u\bar{u}, d\bar{d}$ samples combined)
- Wanting to mimic the Z invariant mass cut done by original analysis, decided to perform cut on the total jet energy from the two reconstructed jets
  - This should provide an initial small level of background rejection while maintaining high signal sensitivity
  - Again for around for $\sim 10 - 50$ background events $\geq 2\ DVs$ reconstructed
- Due to lack of time, further cuts or further optimization of jet energy cuts were not performed, but further background rejection is required

Signal Jet Energy Distributions



Summed Jet Energy (GeV)

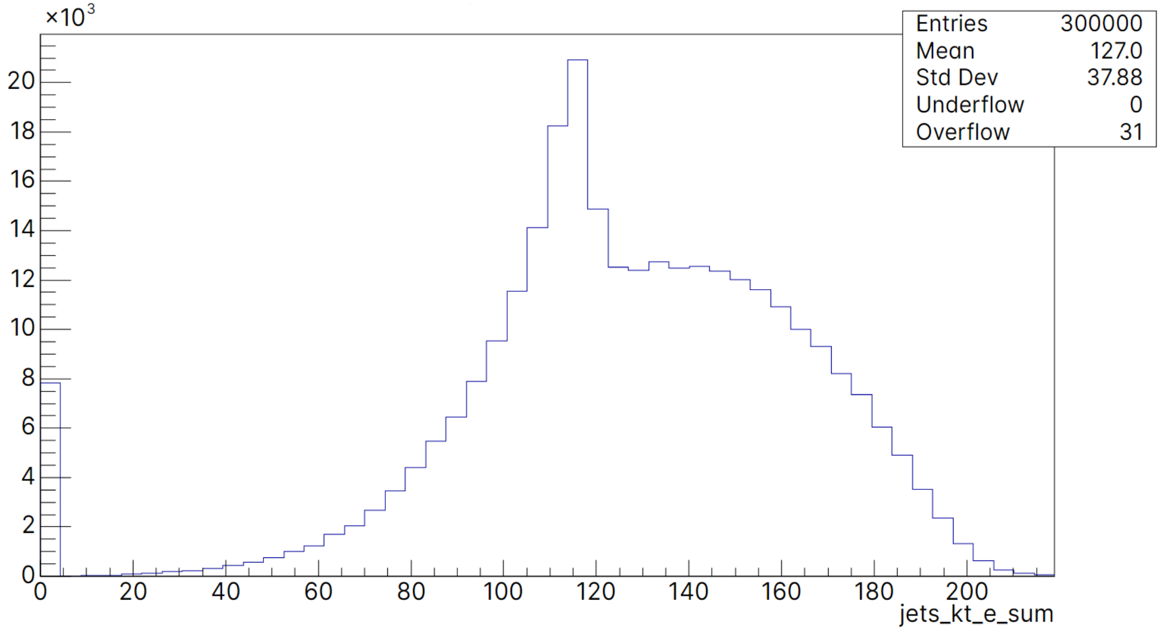
$m_s = 20 \text{ GeV}, \sin(\theta) = 10^{-6}$



Summed Jet Energy (GeV)

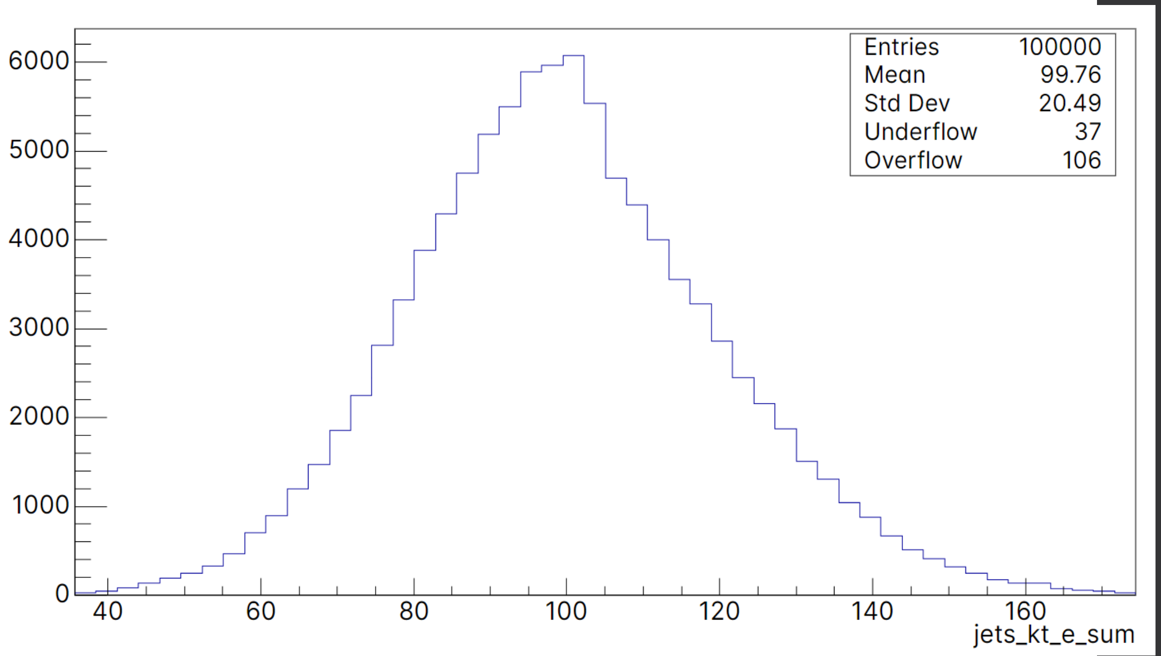
$m_s = 60 \text{ GeV}, \sin(\theta) = 10^{-6}$

Background Jet Energy Distributions



Summed Jet Energy (GeV)

$e^+e^- \rightarrow WW$



Summed Jet Energy (GeV)

$e^+e^- \rightarrow ZH\ (Z \rightarrow b\bar{b}, H \rightarrow WW)$

As expected, some differences in distribution between signal and WW, ZZ distributions, but highly similar to ZH distributions

Cut Efficiencies

- After some optimization, settled on very loose cut of $40\ GeV < \sum E_{Jet} < 140\ GeV$ to retain high signal efficiency across all signal points to at least give indication of potential increase in signal yield
- This yielded the following efficiencies / event yields (for background):

Signal:	20 GeV, 1e-5	20 GeV, 1e-6	20 GeV, 1e-7	60 GeV, 1e-5	60 GeV, 1e-6	60 GeV, 1e-7
Jet Energy Cut	0.865	0.971	0.964	0.971	0.978	0.967
$N_{DVs} \geq 2$	0.096	0.735	0.018	0.0002	0.726	0.425

Z decay mode → H decay mode →

Background:	WW	ZZ	ZH, qq, WW	ZH, qq, bb	ZH, cc, WW
Jet Energy Cut	0.587	0.683	0.954	0.816	0.958
$N_{DVs} \geq 2$	1183.6 ev.	97.8 ev.	1.65 ev.	4.5 ev.	1.1 ev.
	ZH, cc, bb	ZH, ss, WW	ZH, ss, bb	ZH, bb, WW	ZH, bb, bb
Jet Energy Cut	0.829	0.955	0.818	0.962	0.846
$N_{DVs} \geq 2$	3.9 ev.	1.4 ev.	6.3 ev.	2.3 ev.	6.3 ev.

Signal Yields

- Significantly increased event yield relative to original leptonic decay analysis (given $7.2 \times 10^6\ pb^{-1}$)

Events selected:

$m_s, sin\theta$	$n_{\mathrm{DVs}} \geq 2$
20 GeV, 1e-5	109.9
20 GeV, 1e-6	843.5
20 GeV, 1e-7	20.66
60 GeV, 1e-5	0.07
60 GeV, 1e-6	246.4
60 GeV, 1e-7	144.2

m_s, sin θ	n_DVs ≥ 2
20 GeV, 1e-5	5.0 ± 0.166
20 GeV, 1e-6	37.1 ± 0.453
20 GeV, 1e-7	0.8 ± 0.067
60 GeV, 1e-5	0.0033 ± 0.0023
60 GeV, 1e-6	10.96 ± 0.167
60 GeV, 1e-7	6.49 ± 0.103

Sensitive (> 3 events)

Not sensitive (< 3 events)

Note: due to large number of background events, unable to determine sensitivity at this stage

Summary & Future Work

- Have obtained good (but optimizable) results by adding $Z \rightarrow$ invisible decays to signal, increasing signal yield per sample by up to a factor of three
  - Gained sensitivity to $m_s = 20\ GeV, \sin(\theta) = 1e - 7$ signal point
- Have obtained very preliminary results in adding $Z \rightarrow$ hadronic decays to signal, increasing signal yield per by up to a factor of twenty
  - This factor will inevitably decrease with cuts that properly reject background
  - Some innovation will be necessary to determine how to better reject background before DV cut
- Code has been merged to LLP fork of FCCAnalyses repo.
- More backgrounds (other Higgs decays) could be incorporated for a more thorough analysis
- Plan to make an FCC note about these results & IDEA vs. CLD detector card comparison
- This work should be taken up by another student potentially starting this Fall?

Backup

Signal Sensitivities

Final Cut Efficiencies:

$N_{DVs} \geq 2$ Efficiencies	20 GeV, 1e-5	20 GeV, 1e-6	20 GeV, 1e-7	60 GeV, 1e-5	60 GeV, 1e-6	60 GeV, 1e-7
IDEA	0.091	0.672	0.014	0.0002	0.672	0.398
CLD (min. hits = 6)	0.092	0.109	0.002	0.0002	0.654	0.0502
CLD (min. hits = 5)	0.094	0.293	0.0042	0.0003	0.684	0.123
CLD (min. hits = 4)	0.096	0.441	0.0056	0.0002	0.687	0.183

Final Events Selected:

$N_{DVs} \geq 2$ Events	20 GeV, 1e-5	20 GeV, 1e-6	20 GeV, 1e-7	60 GeV, 1e-5	60 GeV, 1e-6	60 GeV, 1e-7
IDEA	5.02	37.09	0.77	0.003	10.97	6.50
CLD (min. hits = 6)	5.08	6.02	0.11	0.003	10.67	0.82
CLD (min. hits = 5)	5.19	16.17	0.23	0.005	11.16	2.01
CLD (min. hits = 4)	5.30	24.34	0.31	0.003	11.21	2.99

Sensitive (> 3 events)

Not sensitive (< 3 events)