First Look at Higgs to Invisible à la Tokyo/ILD

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Snowmass 2021 Letter of Interest

LOI - ILC/SiD Higgs to Invisible

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1 Introduction

The Higgs Boson, being the only true scalar particle yet discovered, is a fundamentally new entity in the world of high energy physics. As such, it imperative to explore every aspect of the Higgs properties. While, so far, experimental results are in line with the Higgs having the properties expected in the Standard Model, there is significant room for connections to new physics beyond the Standard Model. This LOI describes a study of possible decays of the Higgs into invisible particles, such as might comprise the Dark Matter.

2 The search for invisible decays of the Higgs

The ATLAS and CMS experiments at the LHC have searched for invisible decays of the Higgs in a variety of channels. The current best limit, from a single search, is from ATLAS in the vector boson fusion process [2]. The limit set is 13% at 95% c.l. This limit has, in turn, been used to set a limit as a function of mass on the dark matter-nucleon scattering cross-section, as seen in Figure 1.

Another LoI on ILC Higgs to Invisible from Brookhaven National Lab is authored by our colleague Ketevi Assamagan. We are investigating possible collaboration.

Introduction

- Assuming ILC $\sqrt{s} = 250$ GeV, $e^+e^- \to ZH$ with hadronic Z decay and invisible H decay.
- Tokyo/ILD study: documented in arXiv:2002.12048
  - Samples are full ILD simulation, signal exclusive for $Z \to q\bar{q}$.
  - Polarization scheme is 80% e^-, 30% e^+ polarized beams.
  - Luminosity sharing is 900/900 fb^{-1} (LR/RL).
- This study: preliminary (collaborators at UTA, BNL)
  - Samples are fast Delphes SiD simulation with DSiD
    - 100ab^{-1} signal generated with Whizard 2.6.4 by me, inclusive Z decays
    - 250fb^{-1} backgrounds are Whizard 1.95 by Tim Barklow for DBD
    - 10ab^{-1} backgrounds are Whizard 2.6.4 by me (not yet used here)
  - Polarization scheme is 80% e^-, 30% e^+ polarized beams.
  - Luminosity sharing is 250/250 fb^{-1} (LR/RL).
- Further notes on this study:
  - Default jets in Delphes files are Antikt jets. Jetfinding is rerun in Root using Masako Iwasaki's Durham algorithm implementation.
  - Signal selection follows Tokyo/ILD as closely as possible, but where some background can be rejected with no obvious signal loss, some pruning is done.

Tokyo/ILD Analysis: arXiv:2002.12048

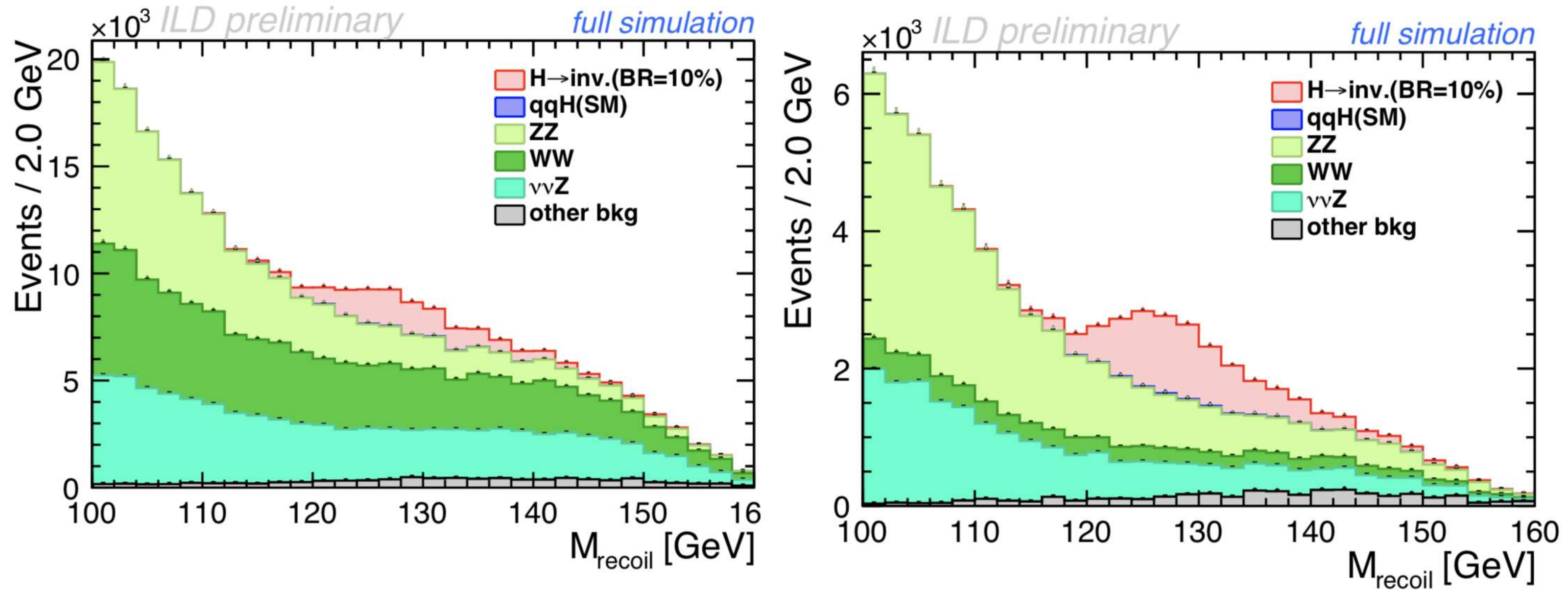


Figure 2: Recoil mass distribution after event selection at $\sqrt{s} = 250$ GeV. (left): $(P_{e^-}, P_{e^+}) = (-0.8, +0.3)$, (right): $(P_{e^-}, P_{e^+}) = (+0.8, -0.3)$.

Table 2: Selection table for $\sqrt{s} = 250$ GeV, $(P_{e^-}, P_{e^+}) = (-0.8, +0.3)$.

cut condition	signal (efficiency)	all bkg (efficiency)	significance
No Cut	18917 (1.000)	1.417×10^8 (1.000)	1.59
$N_{lep} = 0$	18880 (0.998)	9.732×10^7 (0.687)	1.91
Pre-Cut	18202 (0.962)	3.358×10^6 (0.024)	9.91
$N_{pfo} > 15 \& N_{charged} > 6$	17918 (0.947)	2.539×10^6 (0.018)	11.2
$p_{Tjj} \in (20, 80)$GeV	16983 (0.898)	1.368×10^6 (0.010)	14.4
$M_{jj} \in (80, 100)$GeV	14158 (0.748)	713194 (0.005)	16.6
$\lvert\cos\theta_{jj}\rvert < 0.9$	13601 (0.719)	539921 (0.004)	18.3
$M_{recoil} \in (100, 160)$GeV	13585 (0.718)	244051 (0.002)	26.8

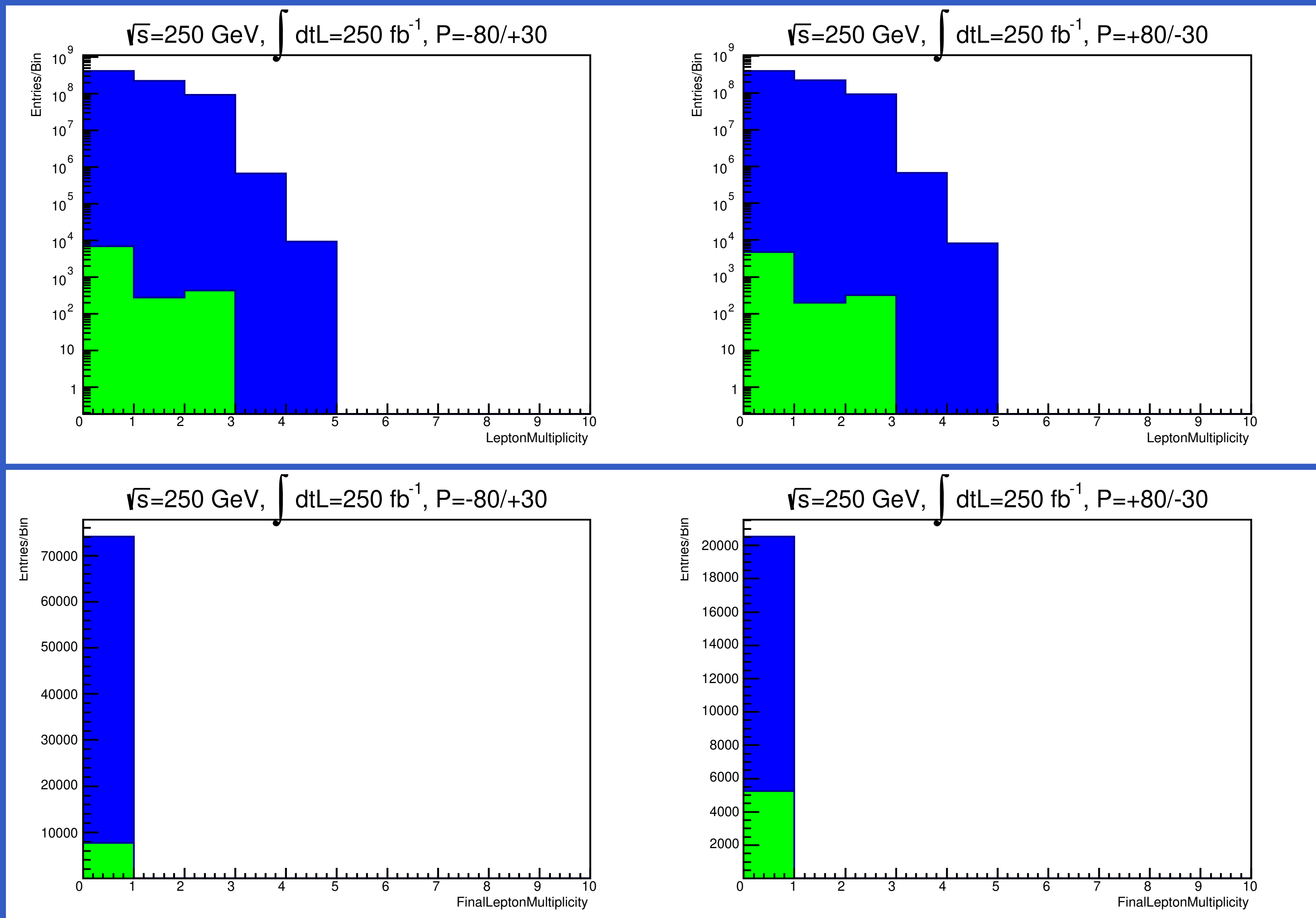
Table 3: Selection table for $\sqrt{s} = 250$ GeV, $(P_{e^-}, P_{e^+}) = (+0.8, -0.3)$.

cut condition	signal (efficiency)	all bkg (efficiency)	significance
No Cut	12776 (1.000)	7.785×10^7 (1.000)	1.45
$N_{lep} = 0$	12752 (0.998)	4.893×10^7 (0.628)	1.82
Pre-Cut	12270 (0.960)	1.329×10^6 (0.017)	10.6
$N_{pfo} > 15 \& N_{charged} > 6$	12067 (0.945)	852285 (0.011)	13.0
$p_{Tjj} \in (20, 80)$GeV	11394 (0.892)	285847 (0.004)	20.9
$M_{jj} \in (80, 100)$GeV	9481 (0.742)	165798 (0.002)	22.6
$\lvert\cos\theta_{jj}\rvert < 0.9$	9126 (0.714)	130070 (0.002)	24.5
$M_{recoil} \in (100, 160)$GeV	9115 (0.713)	62979 (0.001)	33.9

Luminosity is 900 fb^{-1} (left), 900 fb^{-1} (right). Are only four fermion backgrounds considered? The nature of “other background” is unclear. “Pre-Cut” is a loose selection on the two jet system.

Lepton Multiplicity

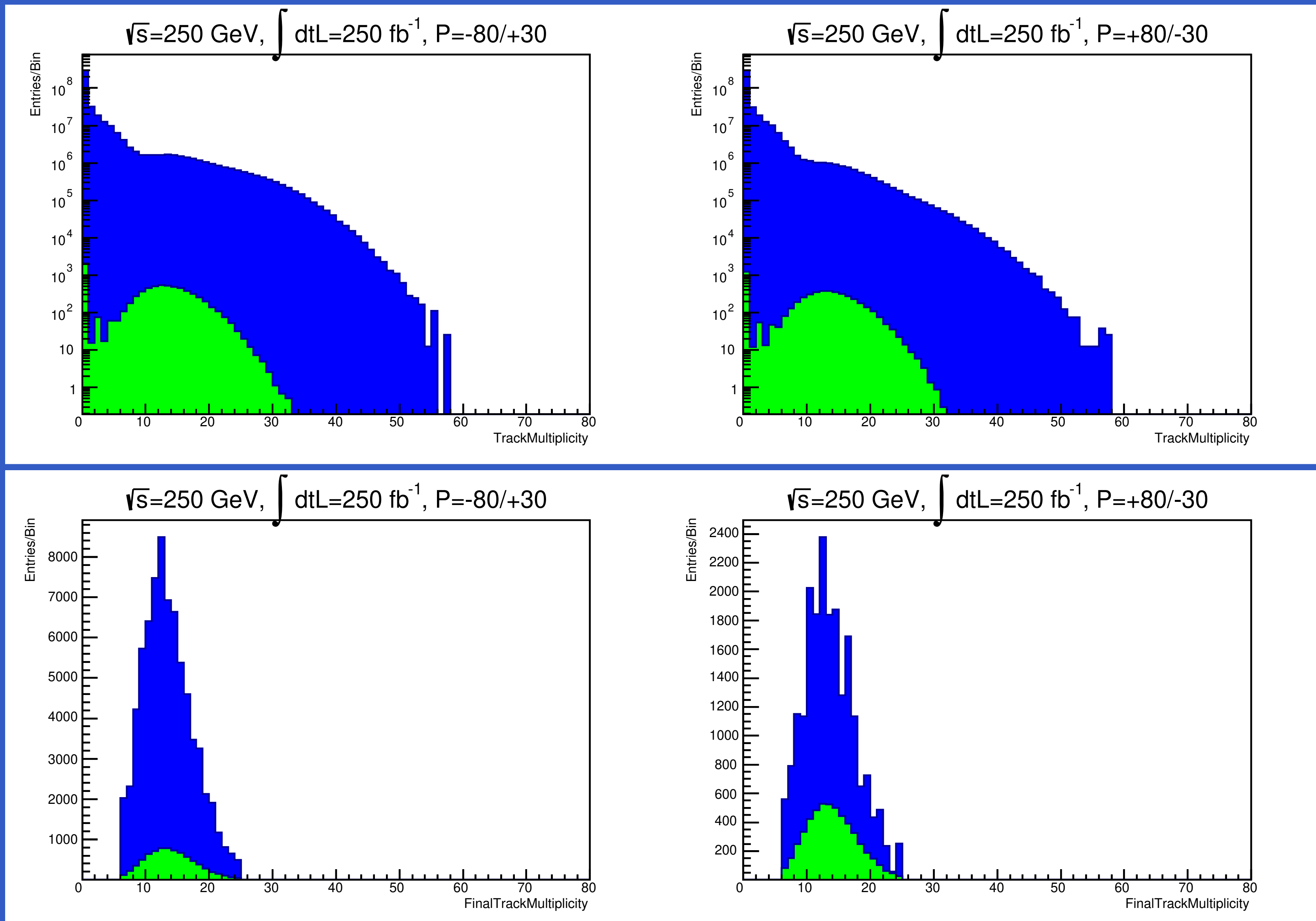
Signal is green with BR($H \to$ inv.)=0.10, all background is blue.



Require $N_e + N_\mu = 0$. Above, cumlative requirements imposed. Below, all requirements imposed.

Track Multiplicity

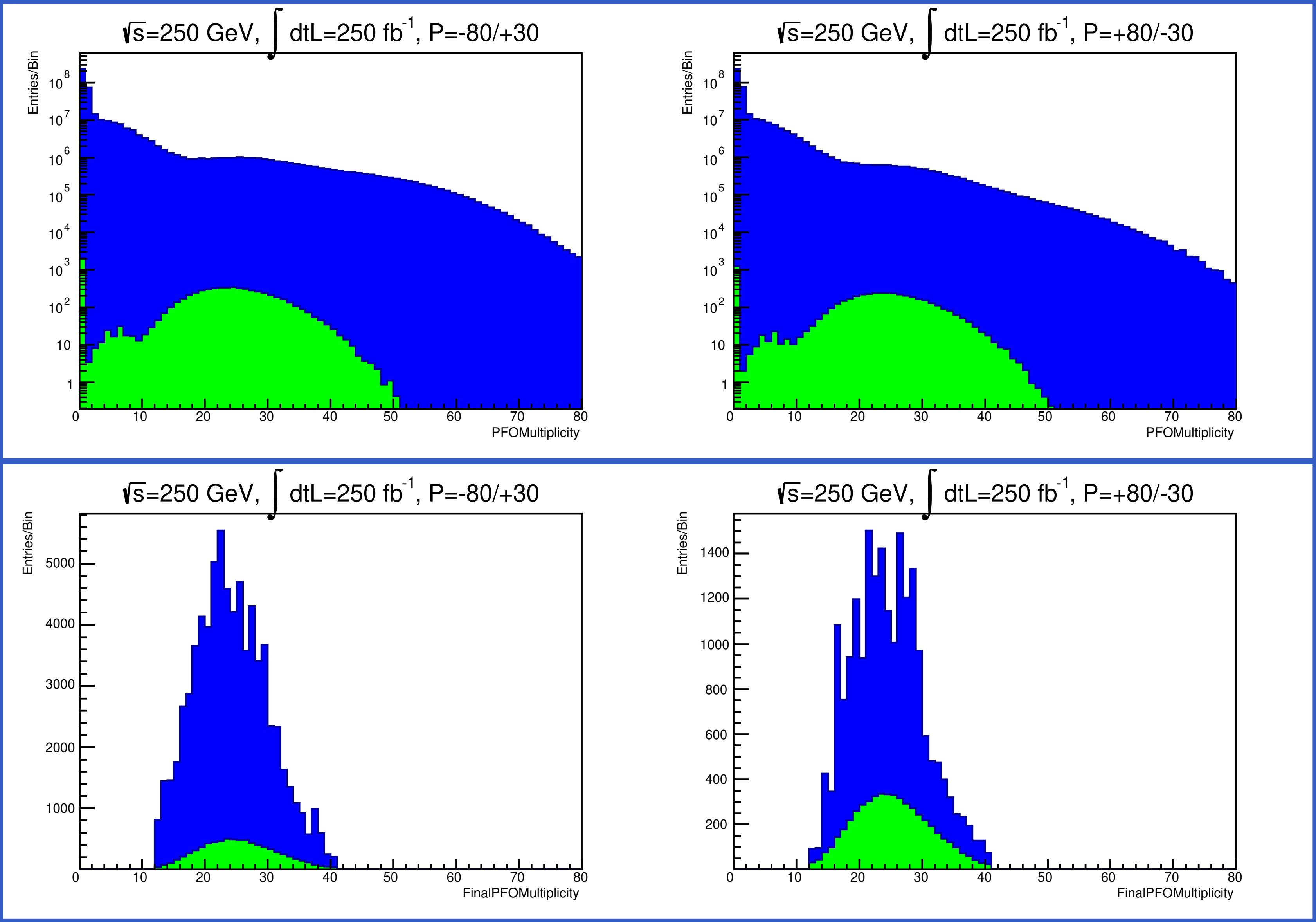
Signal is green with BR($H \to$ inv.)=0.10, all background is blue.



Require $6 \leq N_{trk} \leq 24$. Above, cumulative requirements imposed. Below, all imposed.

ECal/HCal Cluster (PFO) Multiplicity

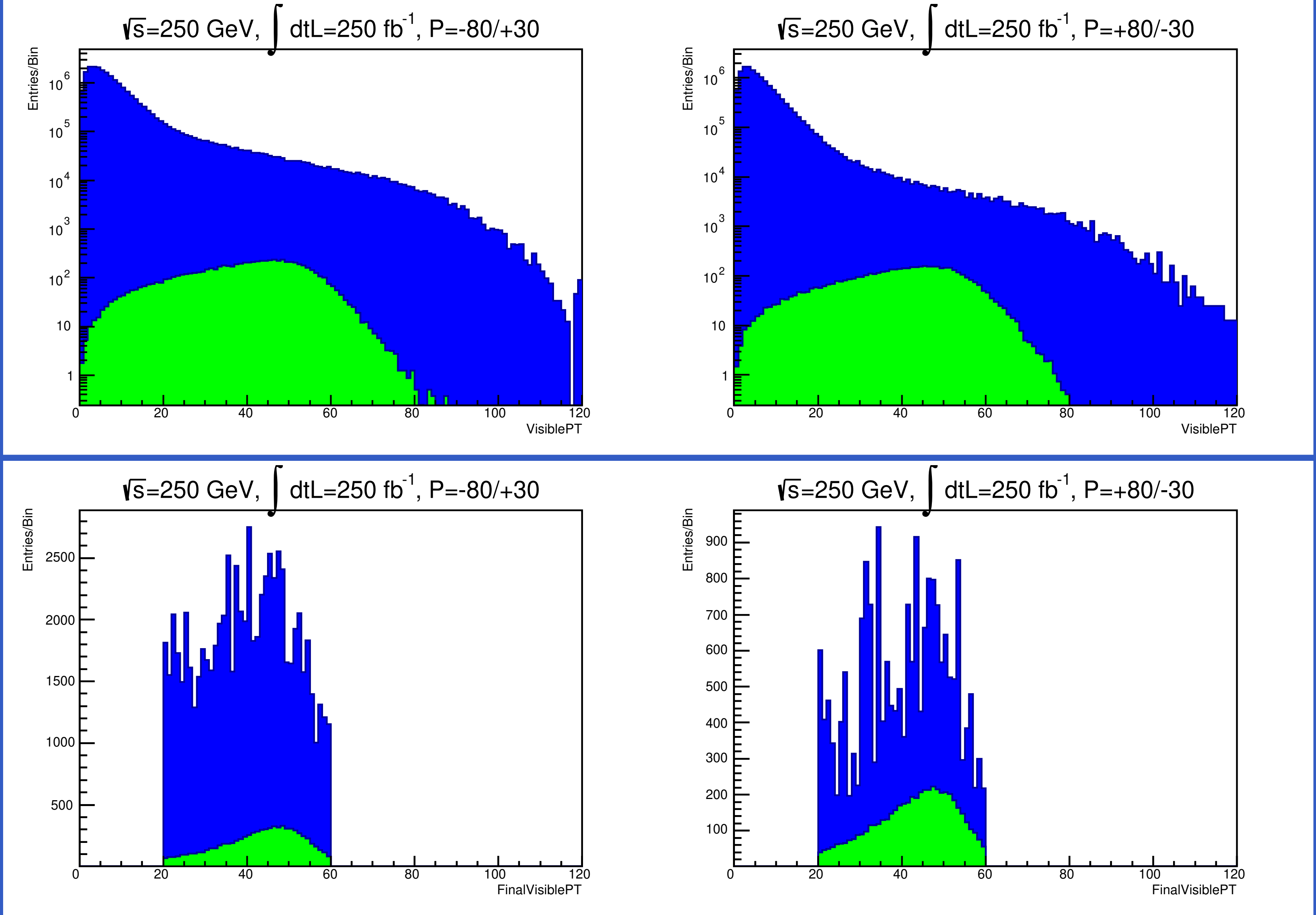
Signal is green with BR($H \to$ inv.)=0.10, all background is blue.



Require $12 \leq N_{pfo} \leq 40$. Above, cumulative requirements imposed. Below, all imposed.

Visible Transverse Momentum in ECal/HCal

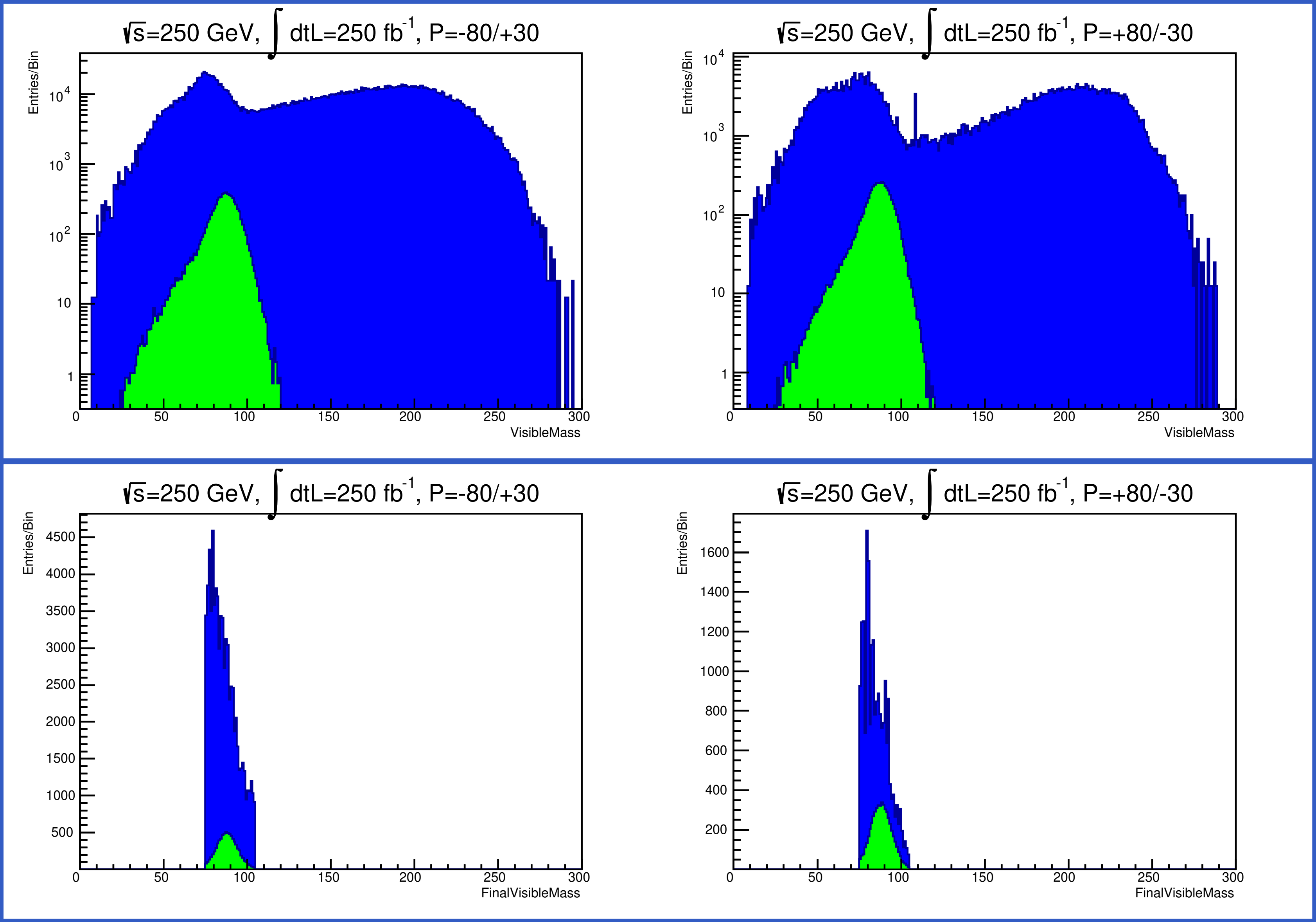
Signal is green with BR($H \to$ inv.)=0.10, all background is blue.



Require $20 \le p_T^{vis} \le 60$ GeV. Above, cumulative requirements imposed. Below, all imposed.

Visible Mass in ECal/HCal

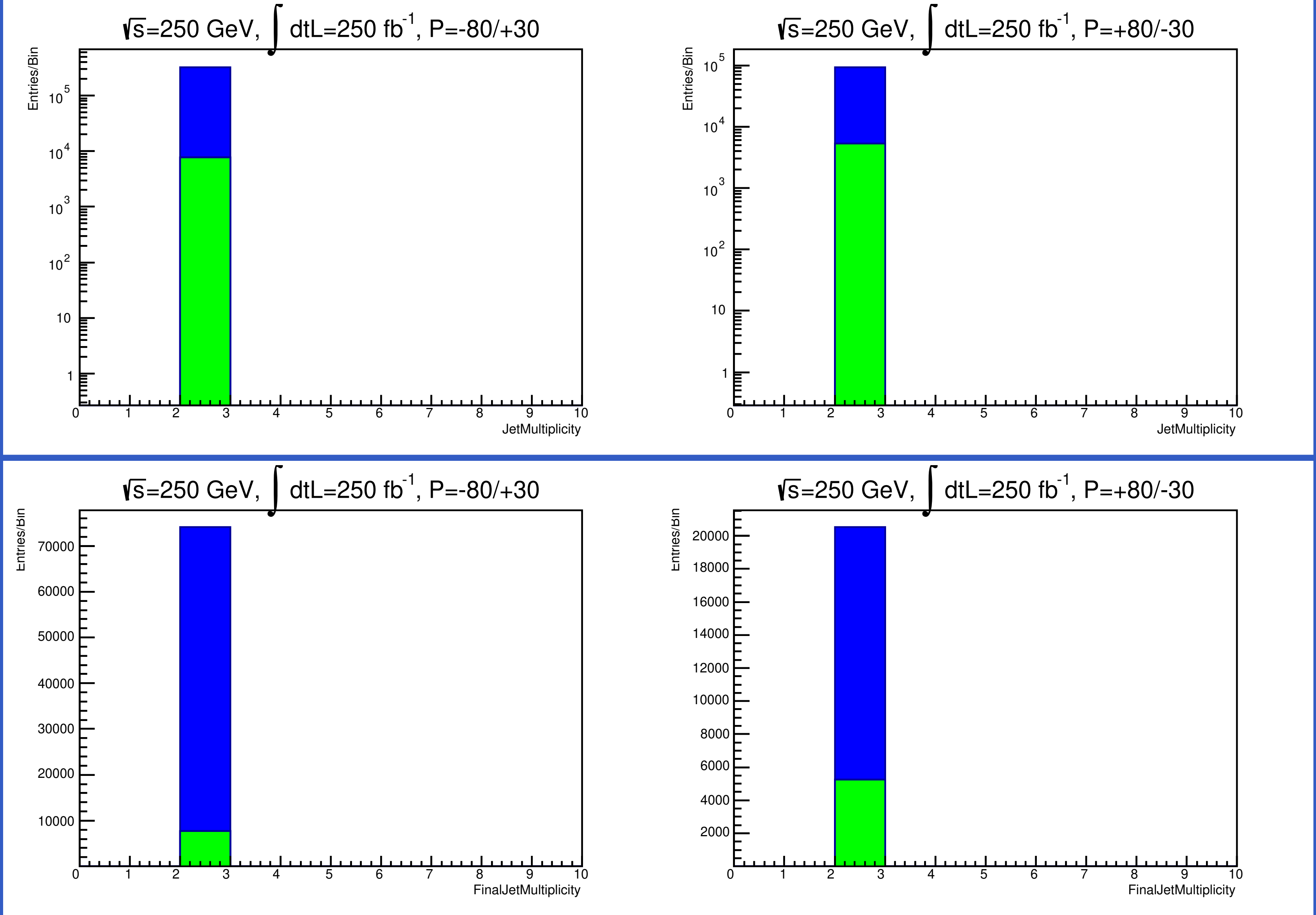
Signal is green with BR($H \to$ inv.)=0.10, all background is blue.



Require $75 \leq m_{vis} \leq 105$ GeV. Above, cumulative requirements imposed. Below, all imposed.

Jet Multiplicity

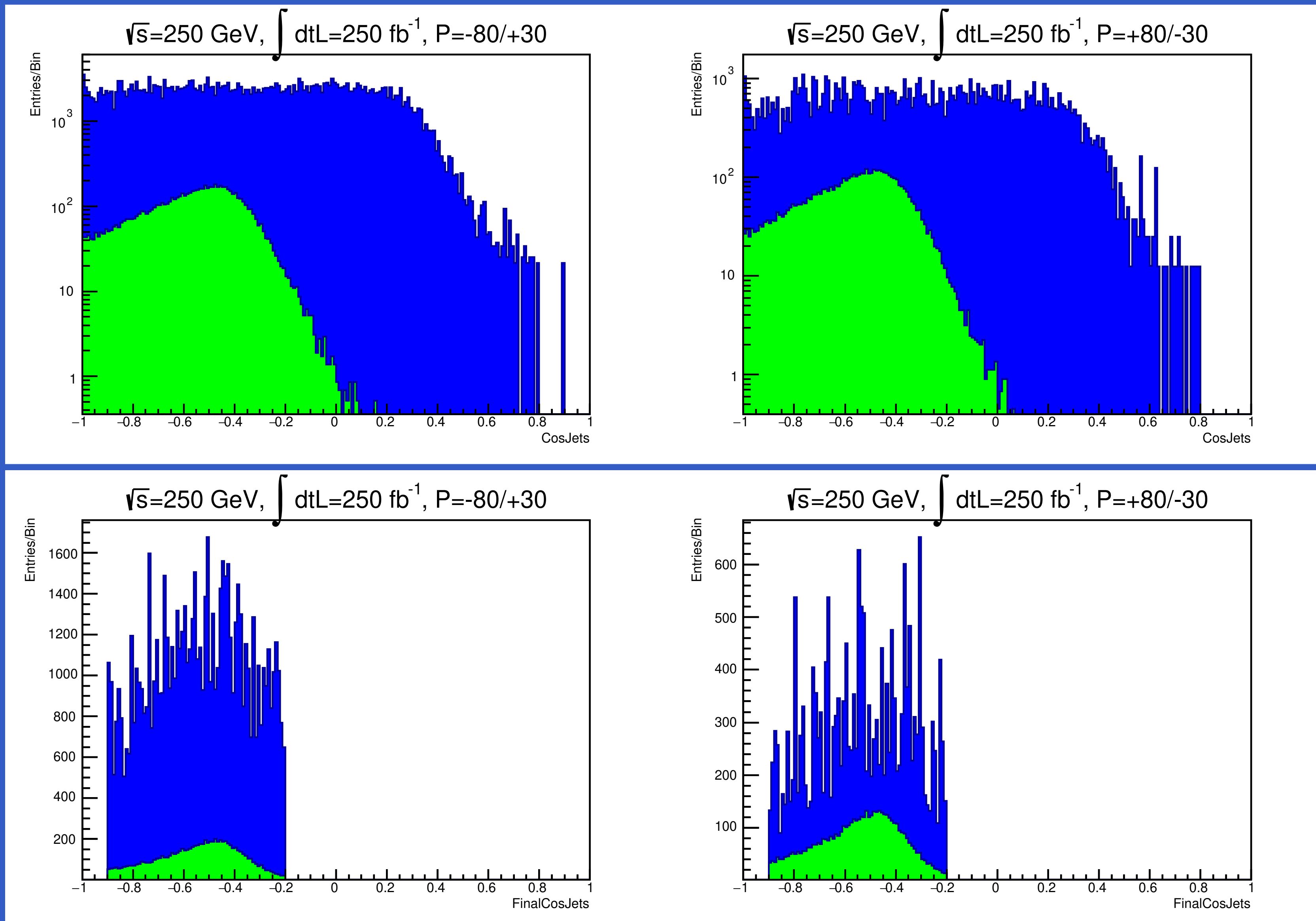
Signal is green with BR($H \to$ inv.)=0.10, all background is blue.



Require $N_{jet} = 2$. Above, cumulative requirements imposed. Below, all imposed.

Jet Angle: $\cos(j_1, j_2)$

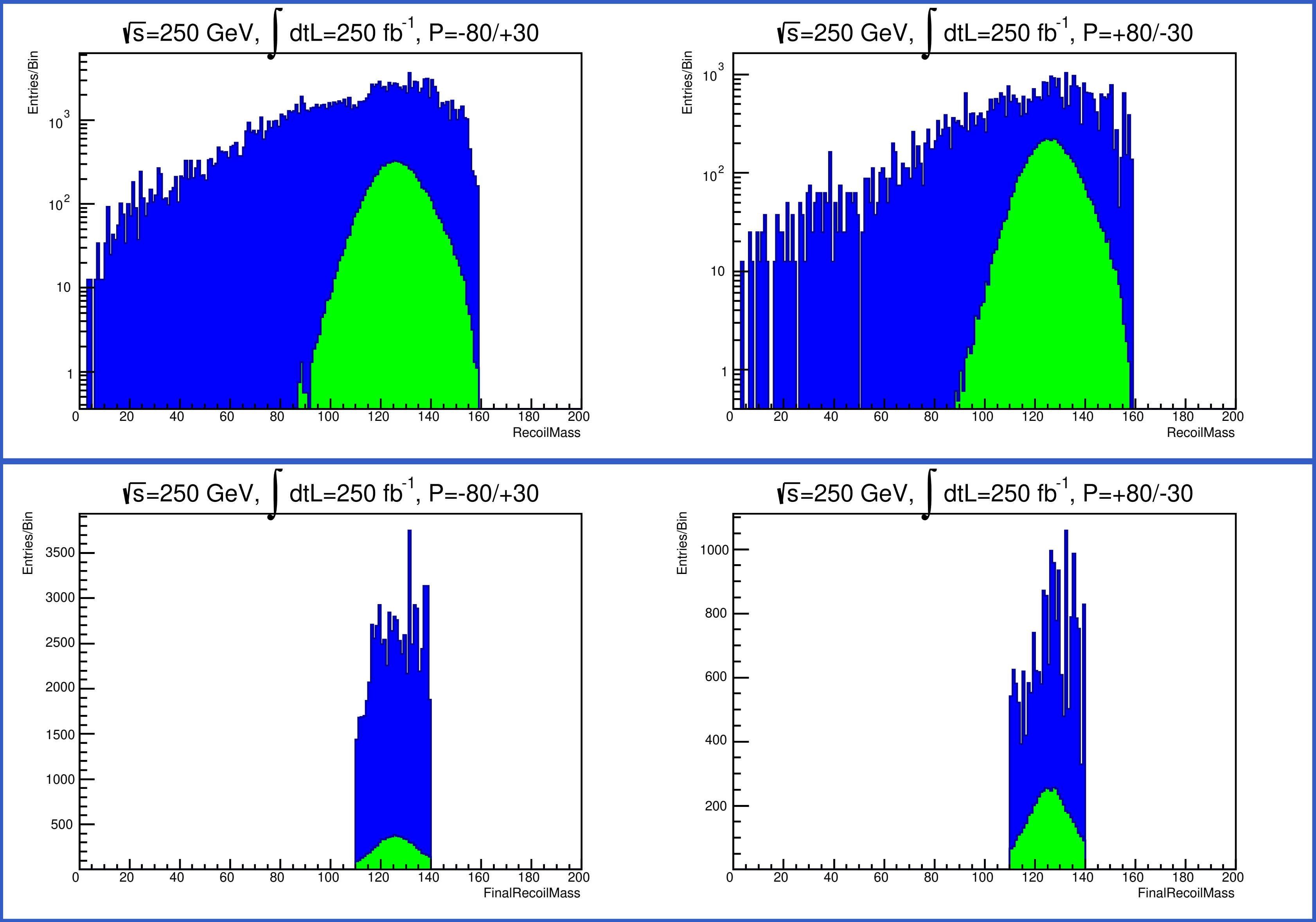
Signal is green with BR($H \to$ inv.)=0.10, all background is blue.



Require $-0.9 \leq \cos\theta_{jj} \leq -0.2$. Above, cumulative requirements imposed. Below, all imposed.

Recoil Mass

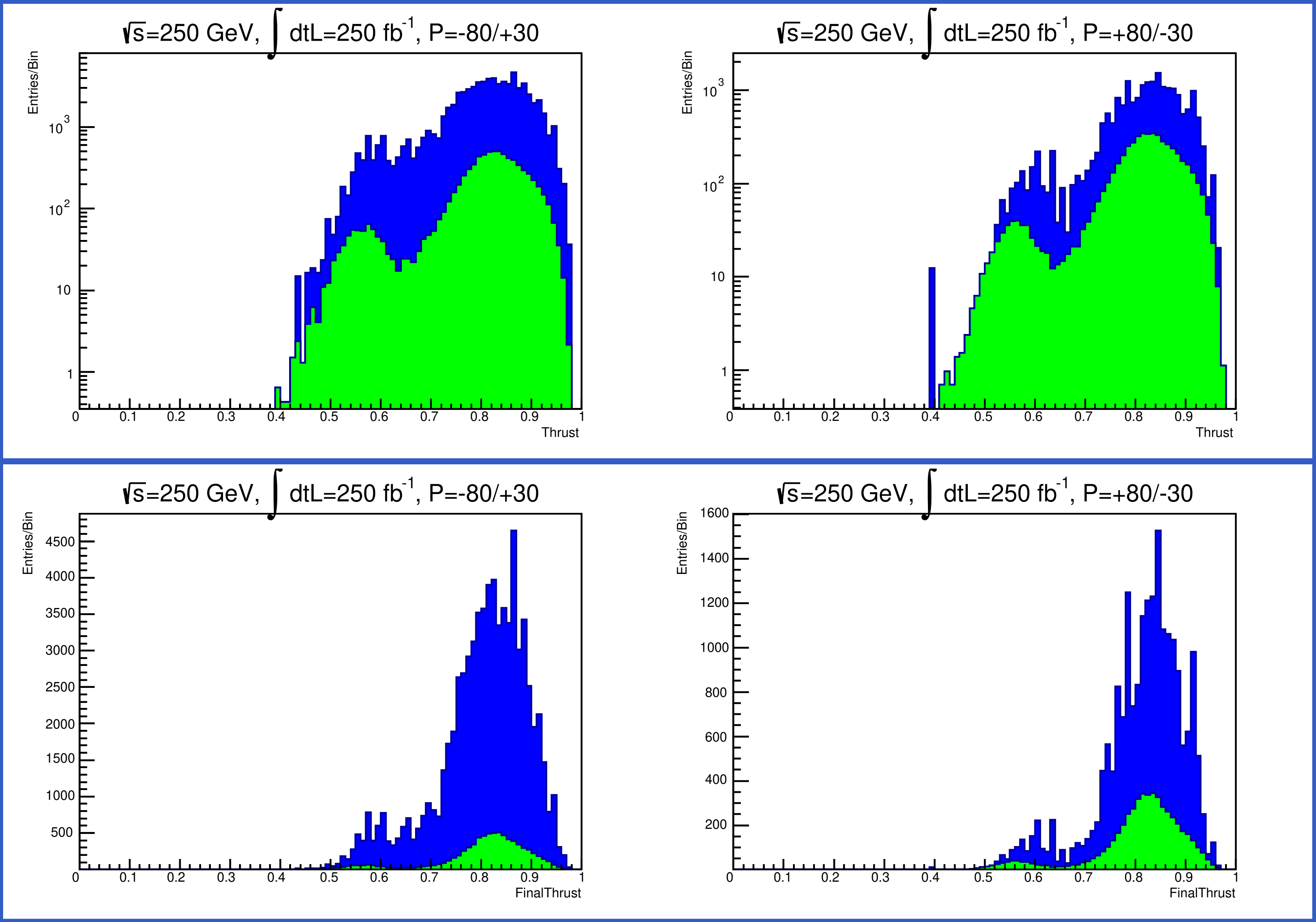
Signal is green with BR($H \to$ inv.)=0.10, all background is blue.



Require $110 \leq m_{recoil} \leq 140$ GeV. Above, cumulative requirements imposed. Below, all imposed.

Event Thrust

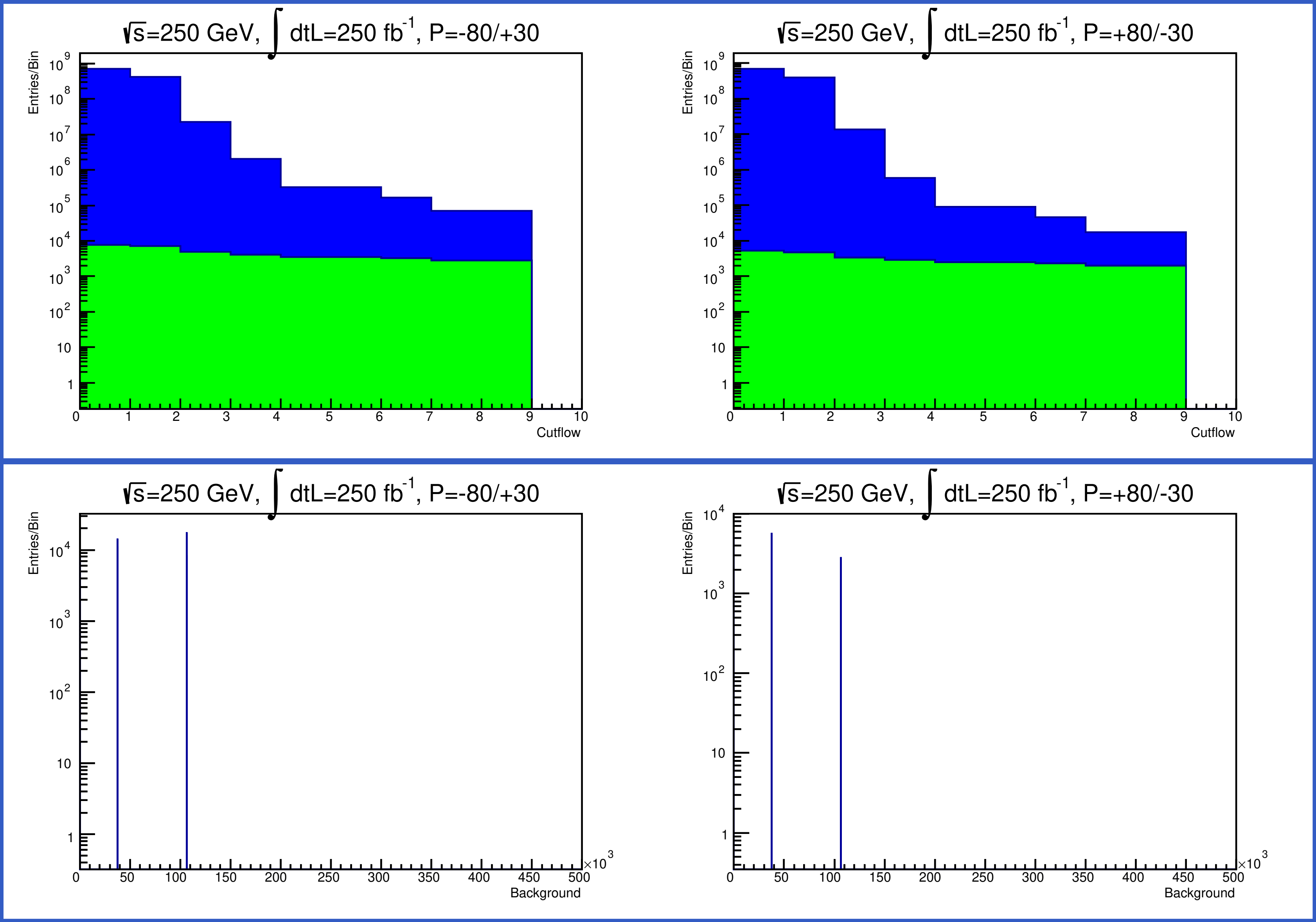
Signal is green with BR($H \to$ inv.)=0.10, all background is blue.



No cut applied. Low thrust events are likely from gluon emission $q \to gq$ (thanks Jim).

Cutflow and Background Process ID

Signal is green with BR($H \to$ inv.)=0.10, all background is blue.



Background events are identified by a process ID, common to ILD/SiD for DBD production.

Yields and Background Composition (scaled to 900fb^{-1})

Requirement	S(LR)	B(LR)	$\frac{S}{\sqrt{S+B}}$	S(RL)	B(RL)	$\frac{S}{\sqrt{S+B}}$
No Cut	2.79e+04	2.55e+09	0.552	1.89e+04	2.5e+09	0.378
$N_e + N_\mu = 0$	2.54e+04	1.48e+09	0.659	1.71e+04	1.42e+09	0.453
$\frac{6 \leq N_{trk} \leq 24}{12 \leq N_{pfo} \leq 40}$	1.74e+04	7.97e+07	1.95	1.22e+04	4.95e+07	1.74
$75 \leq m_{vis} \leq 105$ GeV	1.47e+04	7.24e+06	5.46	1.03e+04	2.11e+06	7.11
$20 \leq p_T^{vis} \leq 60$ GeV	1.26e+04	1.15e+06	11.6	8.83e+03	3.13e+05	15.6
$N_{jet} = 2$	1.26e+04	1.15e+06	11.6	8.83e+03	3.13e+05	15.6
$-0.9 \leq \cos\theta_{jj} \leq -0.2$	1.16e+04	5.91e+05	14.9	8.18e+03	1.55e+05	20.3
$110 \leq m_{rec} \leq 140$ GeV	1.01e+04	2.39e+05	20.2	7.11e+03	5.5e+04	28.5

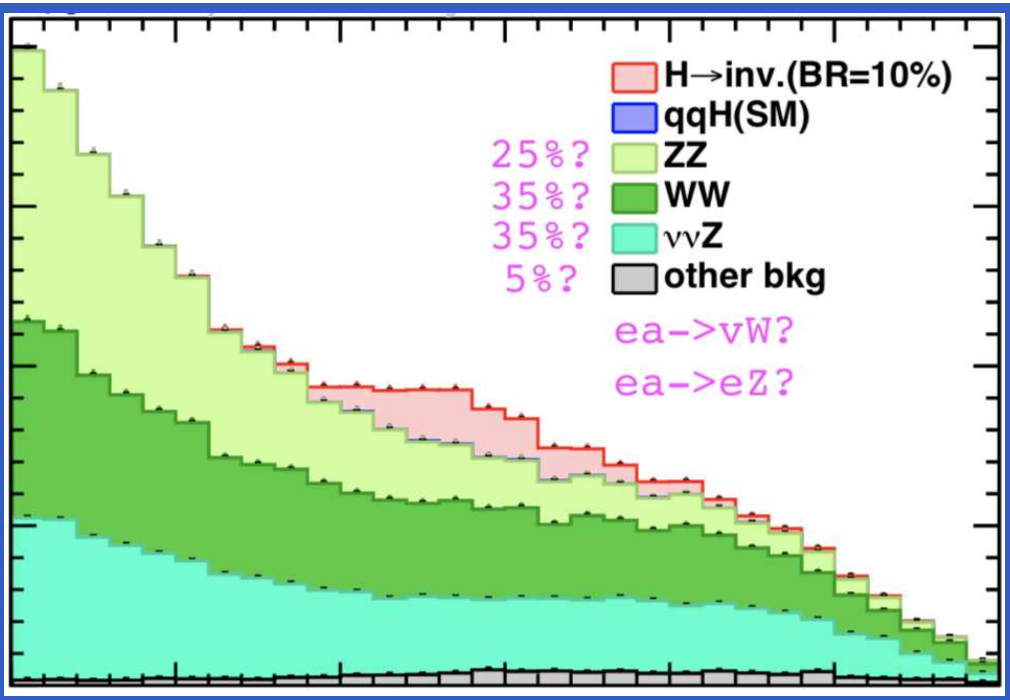
Background Composition

Process	Process ID	LR Fraction (%)	Process ID	RL Fraction (%)
3f $e^-\gamma \to e^-Z, \nu W^-$	37785	22	37785	6.5
3f $\gamma e^+ \to e^+Z, \nu W^+$	37815	17	37815	38
4f $e^+e^- \to \nu\bar{\nu}Z$	106571	13	106572	7.8
4f $e^+e^- \to ZZ$	106575	9.8	106576	19
4f $e^+e^- \to WW$	106577	26	106577	6.1
2f $e^+e^- \to q\bar{q}$	106607	7.4	106608	9.6

Tokyo/ILD Results for P=LR, 900fb^{-1}

Table 2: Selection table for $\sqrt{s} = 250$ GeV, $(P_{e^-}, P_{e^+}) = (-0.8, +0.3)$.

cut condition	signal (efficiency)	all bkg (efficiency)	significance
No Cut 30% High	18917 (1.000)	1.417×10^8 (1.000)	1.59
$N_{lep} = 0$	18880 (0.998)	9.732×10^7 (0.687)	1.91
What? Pre-Cut	18202 (0.962)	3.358×10^6 (0.024)	9.91
$N_{pfo} > 15 \& N_{charged} > 6$	17918 (0.947)	2.539×10^6 (0.018)	11.2
$p_{T\,jj} \in (20,80)$GeV	16983 (0.898)	1.368×10^6 (0.010)	14.4
$M_{jj} \in (80,100)$GeV	14158 (0.748)	713194 (0.005)	16.6
$\lvert\cos\theta_{jj}\rvert < 0.9$	13601 (0.719)	539921 (0.004)	18.3
$M_{recoil} \in (100,160)$GeV	13585 (0.718)	244051 (0.002)	26.8



Conclusions

- The Tokyo/ILD Higgs to invisible analysis (hadronic Z) with full simulation has been replicated with fast Delphes DSiD simulation.
- When the 250fb^{-1} results of this study are scaled to 900fb^{-1} and compared:
  - Signal yields are lower, 10K/7K event compared to ILD 14K/9K (LR/RL)
  - Background yields comparable, 239K/55K events compared to ILD 244K/63K
  - This yields lower signal significances, 20/29 compared to ILD 27/34
  - Background composition different, half 2f/3f and half 4f compared to ILD all 4f
- Important takeaways from using Delphes DSiD for an ILC analysis:
  - The SiD MC20 Exercise page has details on the files and their use.
  - When using the DBD background files, you must use Event.Weight to fill histograms
  - Background processes are identified with Event.ProcessID.
  - Particle Flow Objects (PFOs) should be taken from Towers (ECal/HCal Clusters)
  - Jetfinding should be rerun with the Durham e^+e^- algorithm, Antikt jets are nonideal
- Next steps:
  - Conceive a brilliant strategem to improve signal significance (p_z? NN? Z frame?).
  - Proceed to full simulation, consider possible optimization of ECal/HCal.