ICEPP
The University of Tokyo

Searching for heavy neutral leptons through exotic Higgs decays

3rd ECFA Workshop, Oct. 9, 2024 @ Paris

Simon Thor (KTH)
Masaya Ishino, Junping Tian (U. Tokyo)

Paper accepted by PRD, arXiv:2309.11254

Image source: Sterile Neutrino Contraints

Higgs as probe of BSM

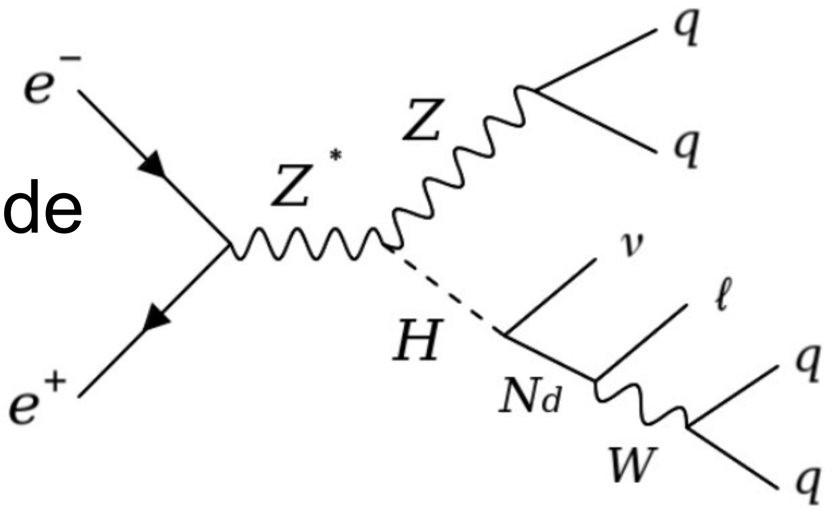
- No signs of BSM yet (except neutrino mass)
- Higgs boson one of the least understood SM particles
  - Might be connected to BSM, e.g., a dark sector
- Precision measurements of Higgs could lead to discoveries

Heavy neutral leptons

- Also known as sterile neutrinos, dark neutrinos etc.
- Various models
  - Majorana particle that gives neutrinos mass via Type-I Seesaw mechanism
  - Dark sector model with $SU(2)_D$ that result in matter-antimatter asymmetry [arXiv:1910.08068]
- In this study: $m_Z < m_{Nd} < m_H$

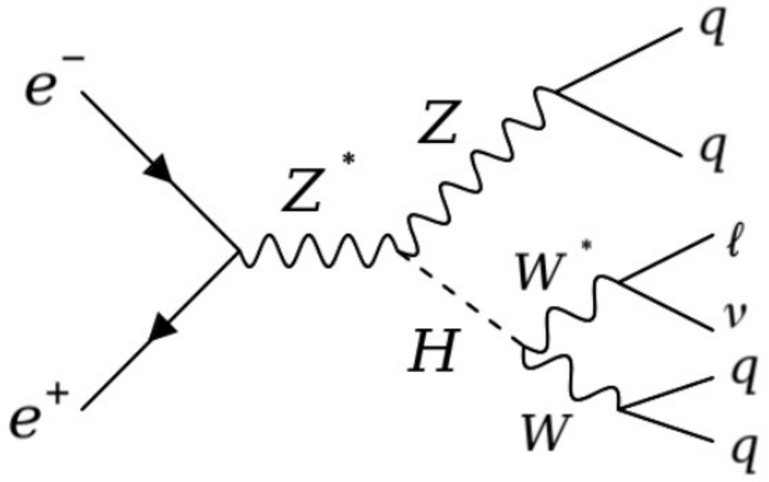
BSM signal

- Exotic Higgs decay: H→vN_d
- Only e, μ channels
- Focus on hadronic decay mode
- Signal characteristics:
  - 4 jets
  - 1 isolated lepton
  - Missing 4-momentum
- Free parameters: HNL mass, BR(H→vN_d)BR(N_d→lW)

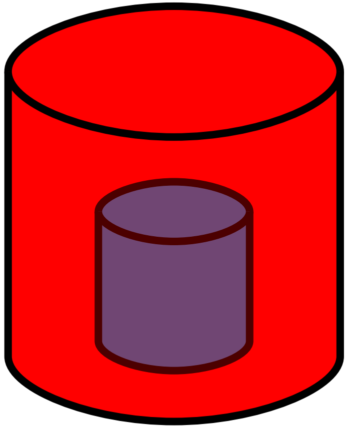


Dominant background

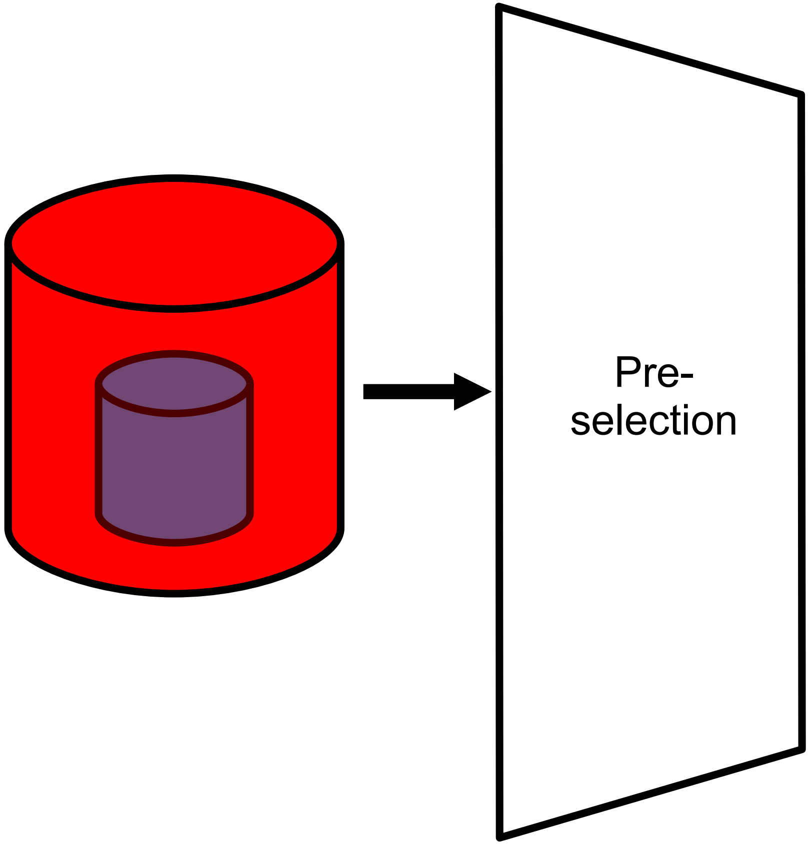
- Same final state as signal
- Also includes a W boson
  - Problem for invariant mass reconstruction
- W* can be used for filtering this background



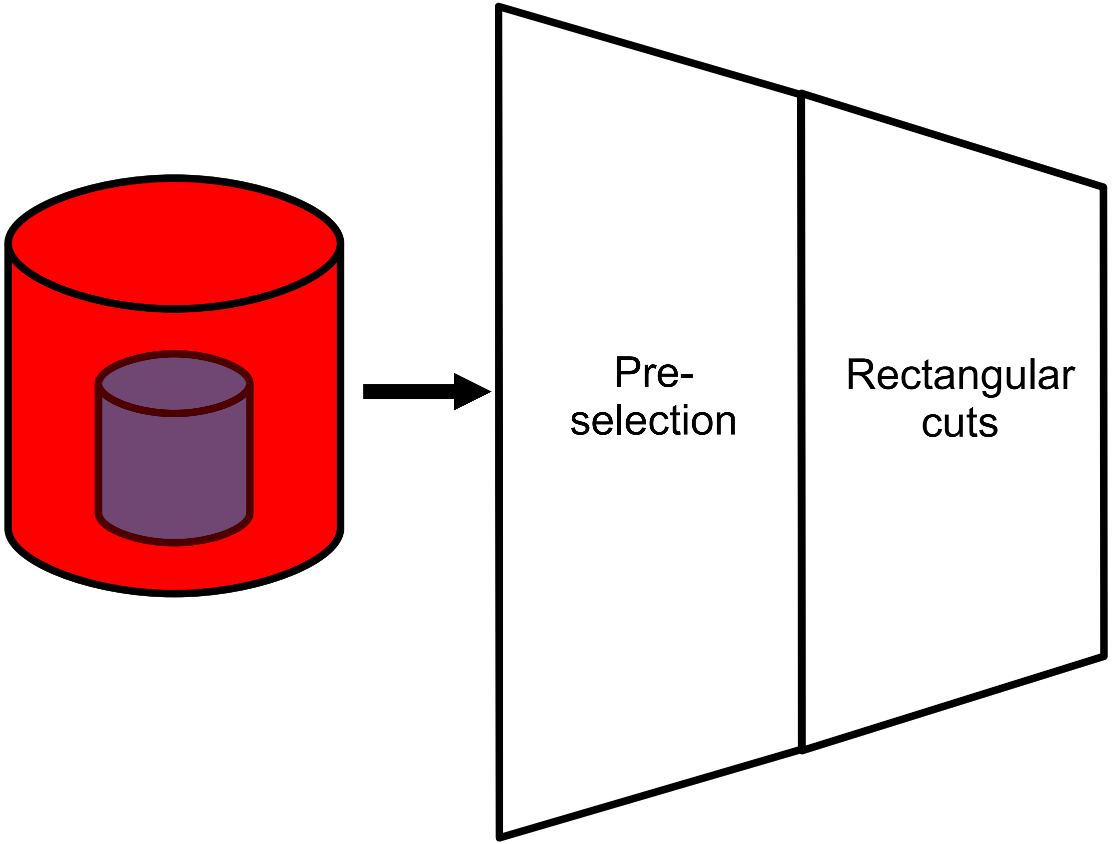
Method



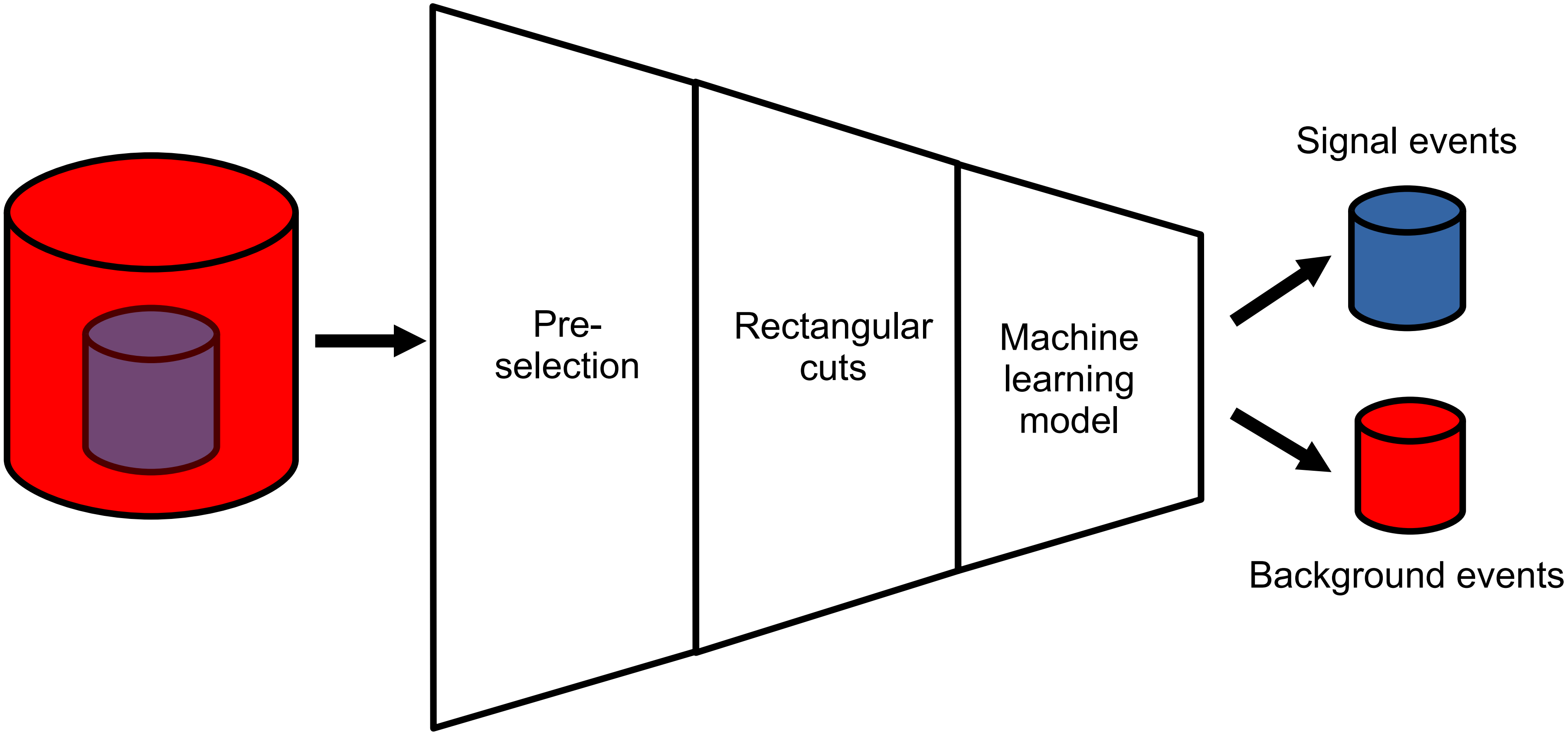
Method



Method



Method


Pre-
selection
Rectangular
cuts
Machine
learning
model
Signal events
Background events

Dataset

- Full detector (ILD) simulations
  - Whizard (event generation)→Pythia (parton shower + hadronization) →Geant4 (detector simulation)→Marlin (reconstruction)
- 1000 fb^{-1} each of beam polarization (-0.8, +0.3), (+0.8, -0.3)
- $\sqrt{s}$ = 250 GeV
- Aligns with currently proposed configuration of ILC

Signal

- m_{ND} = 95, 100, 105, 110, 115, 120 GeV
- ~200 000 events per mass per beam polarization

Pre-selection

- Require at least one isolated lepton (neural network)
  - Muon: lepton finder output > 0.5
  - Electron: lepton finder output > 0.2

- Cluster remaining particles to 4 jets with Durham clustering
- 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 from invariant mass from MC truth jets

Rectangular cuts

- Optimize cuts to maximize significance $\sigma = s/\sqrt{(s+b)}$
- Separate cuts for each beam polarization, HNL mass

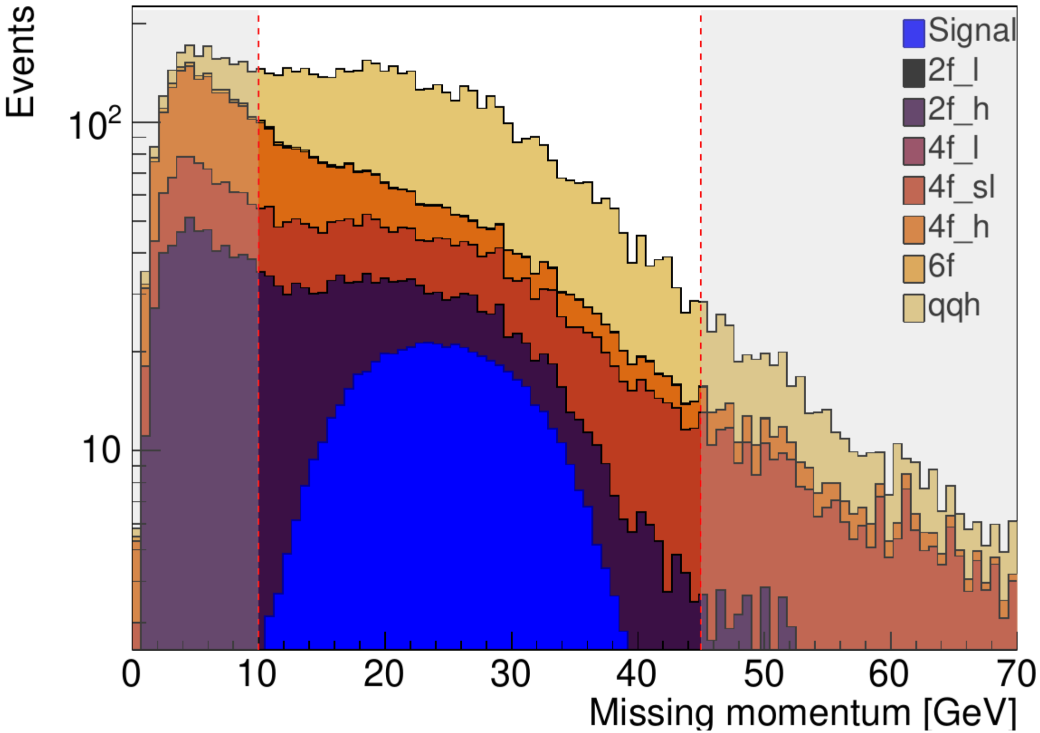
Example (m=100 GeV, (+0.8, -0.3) beam polarization)

- (Lepton energy)/50 + (missing energy)/100 < 1
- Isolated lepton finder output > 0.6
- 160 GeV < 4-jet invariant mass < 220 GeV
- Durham jet distance $y_{4\to3}$ > 0.004 (if jets are more likely from 4 or 3 quarks)
- At least 4 particles in each jet
- 10 GeV < Missing momentum < 45 GeV

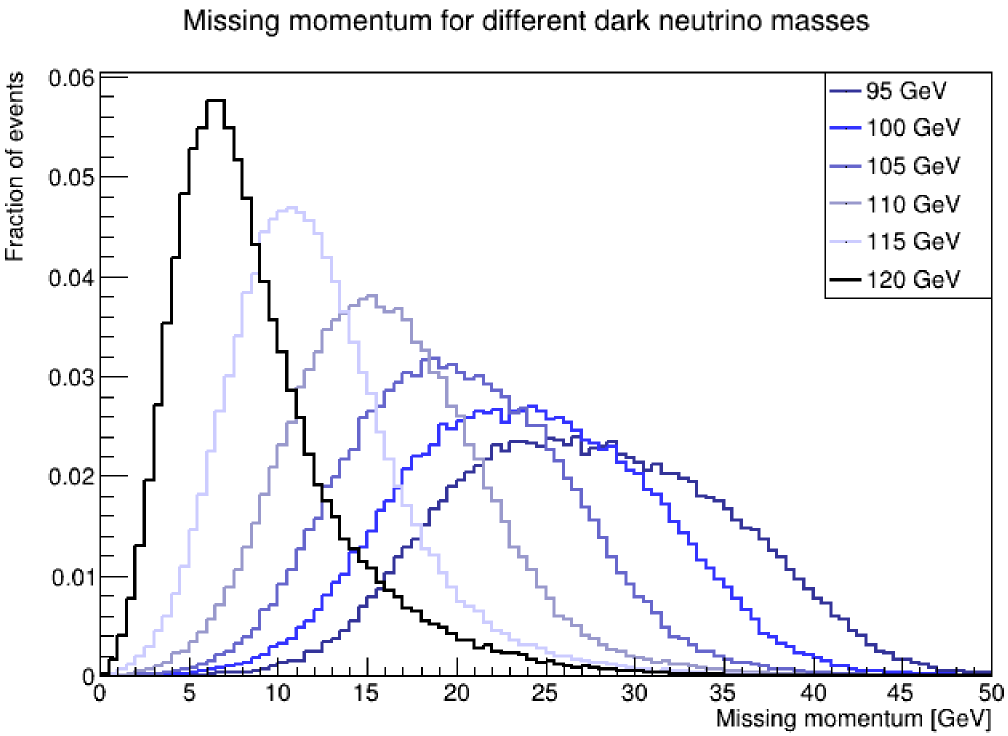
$$y_{4\to3} = \min_{i,j}\left\{\frac{2\min\{E_i,E_j\}^2(1-\cos(\theta_{ij}))}{E_{vis}^2}\right\}$$

Missing momentum cut

- Differs significantly for different dark neutrino masses

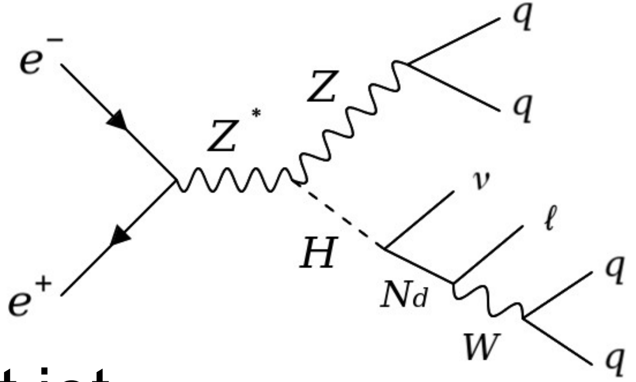


m=100 GeV, (+0.8, -0.3) beam polarization



Machine learning

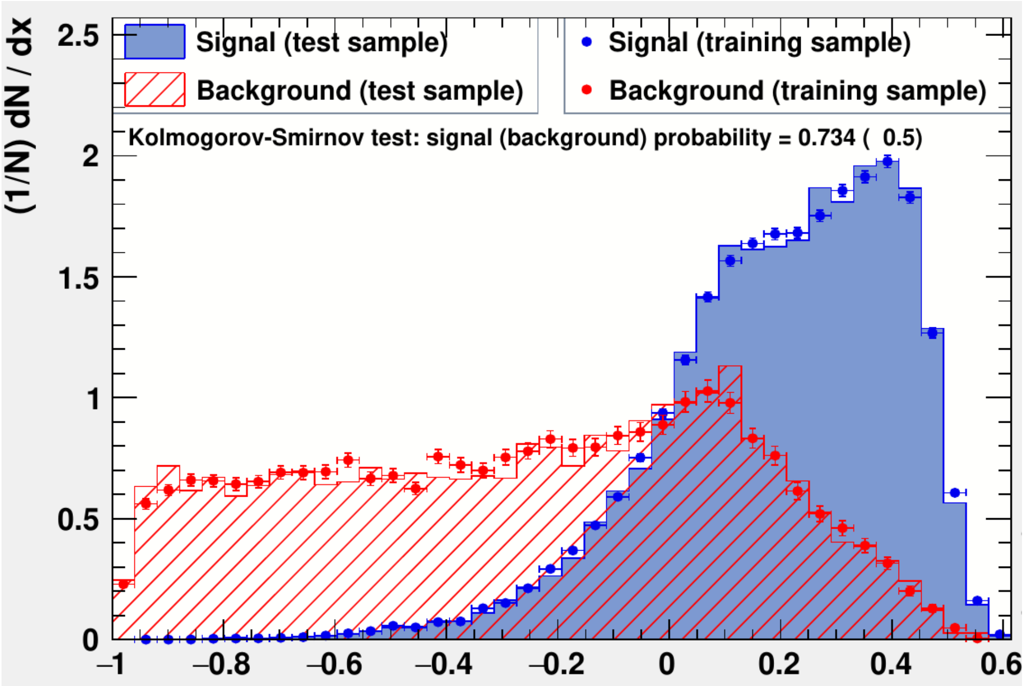
- Boosted decision tree
- Separate BDT for each mass, beam polarization

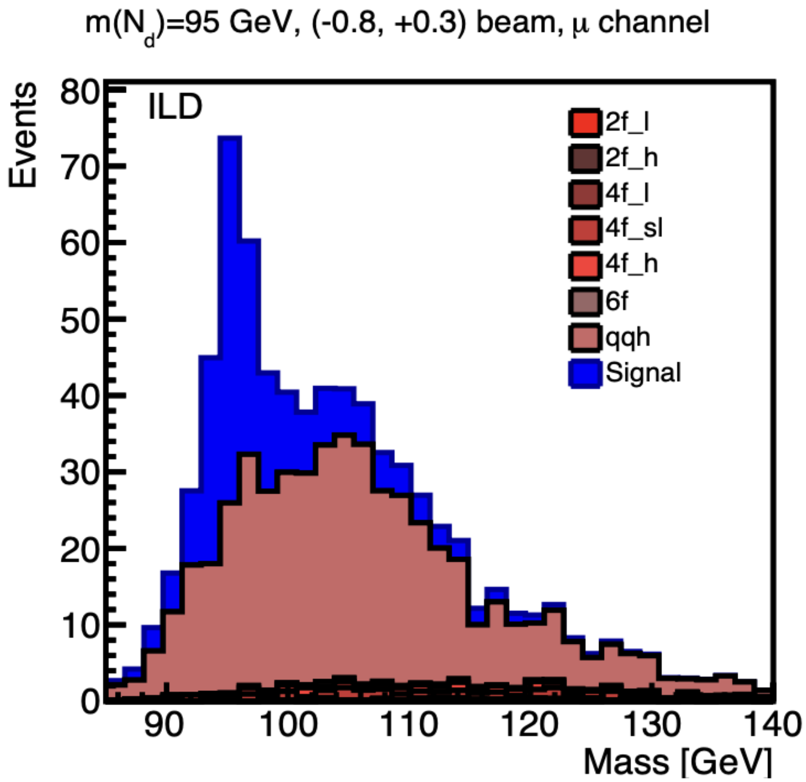


Input parameters

- Lepton energy, missing energy
- 4-jet combined momentum
- Angle between isolated lepton and closest jet
- Lepton, Missing 4-momentum, Z boson production angle
- Lepton helicity angle in dark neutrino rest frame
- Higgs, Z boson, W boson, dark neutrino invariant mass

After cuts: signal & background

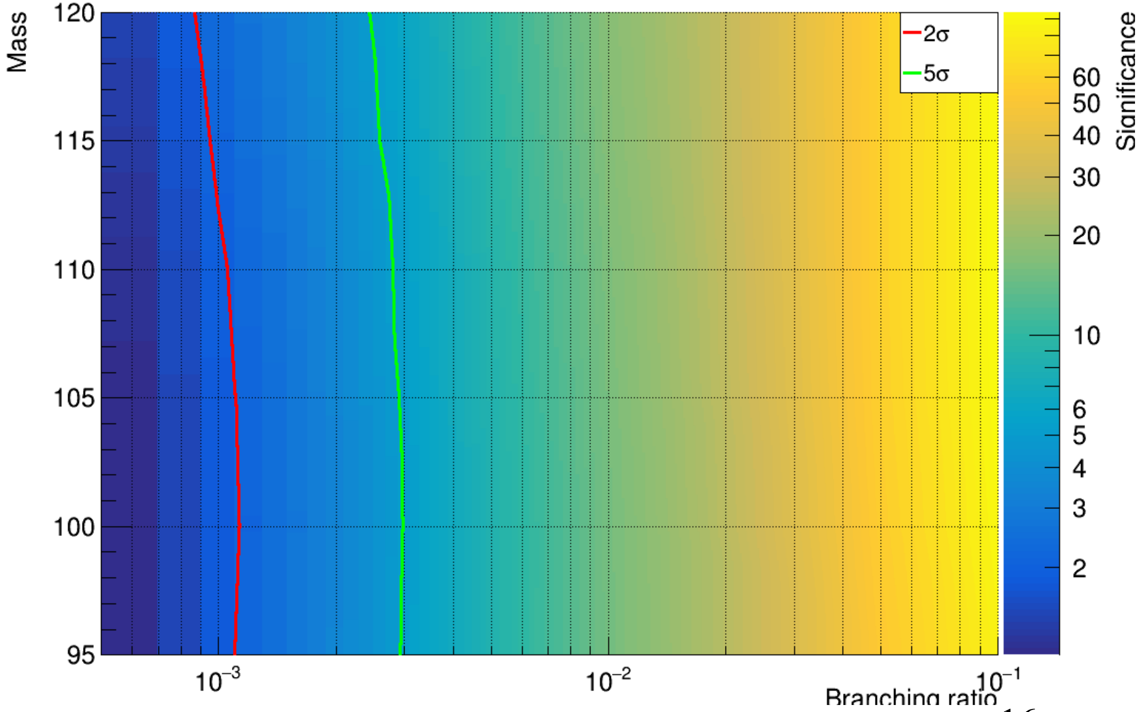




Total significance

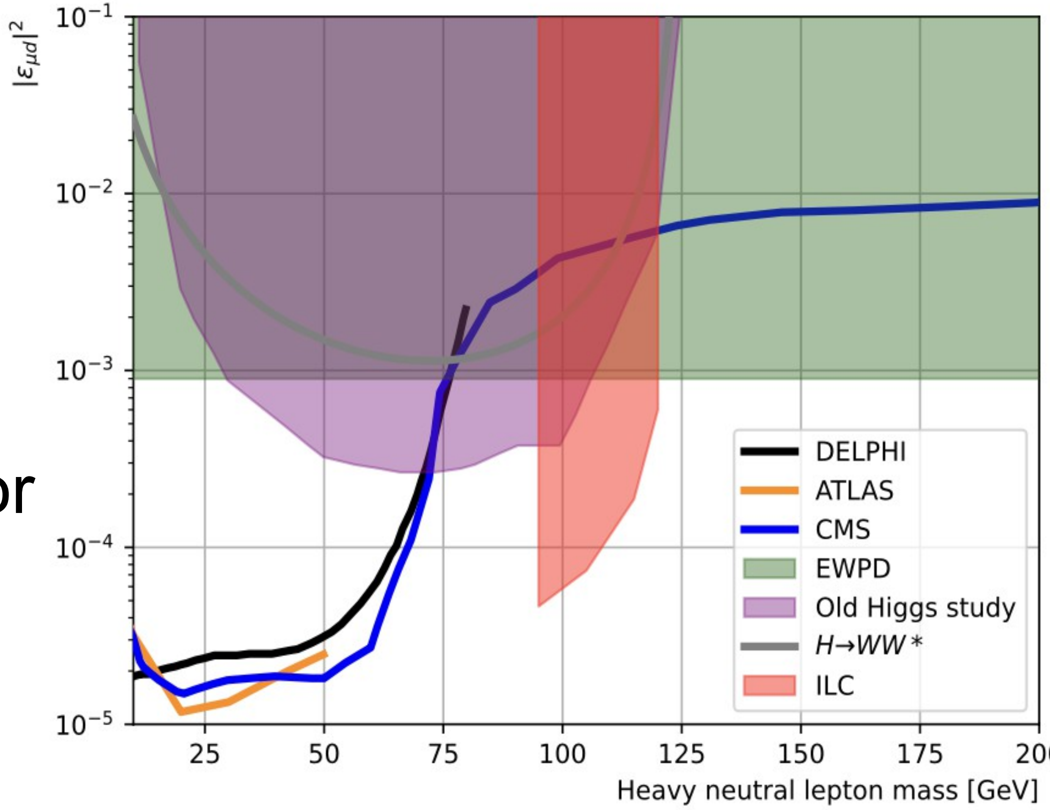
- Background reduced by factor of ~200 000
- ~20% of signal left
- H branching ratio can be probed down to **0.1%**
- By some estimates, BR measurements could be **25x** better than HL-LHC!

Exclusion plot

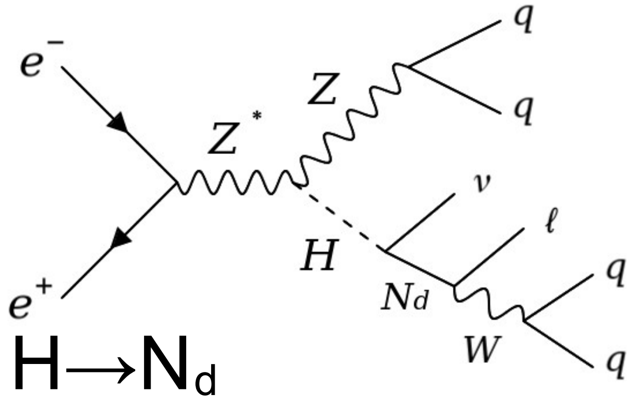


Exclusion

- Convert branching ratio to mixing angle between SM neutrino and HNL
- Exclusion improved by factor of 10 compared to current constraints (possibly more)



Summary



- Study heavy neutral lepton model
- $m_Z < m_{Nd} < m_H$
- First ever full detector simulation for $H \rightarrow N_d$
- Rectangular cuts + machine learning
- Constrain $BR(H \rightarrow vN_d)BR(N_d \rightarrow lW)$ to **0.1%** (at 2σ)
- 25x higher significance compared to HL-LHC
  - **ILC allows for high precision measurements!**
- Accepted by PRD: arXiv:2309.11254

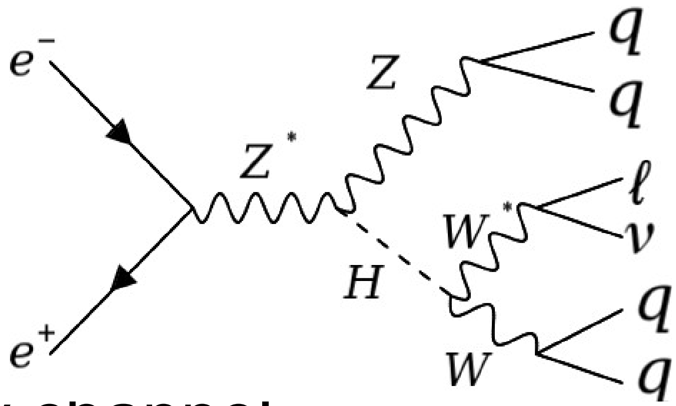
ICEPP
The University of Tokyo

Thank you for listening!

Image source: Sterile Neutrino Contraints

Side outcome: H→WW*

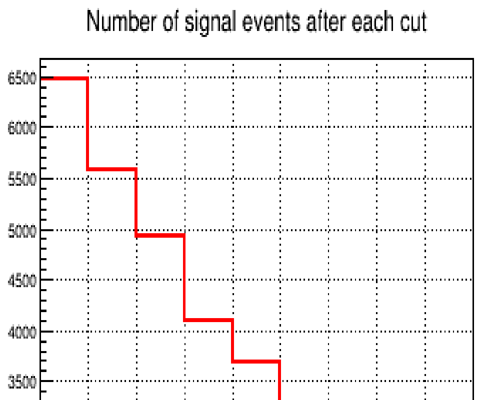
- H→WW*→qq lν dominant background
- H→WW* interesting to study on its own
  - Key to Higgs total width

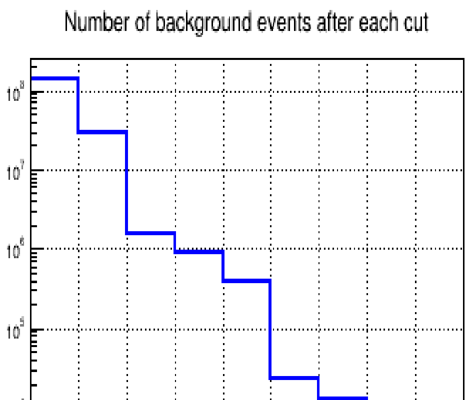


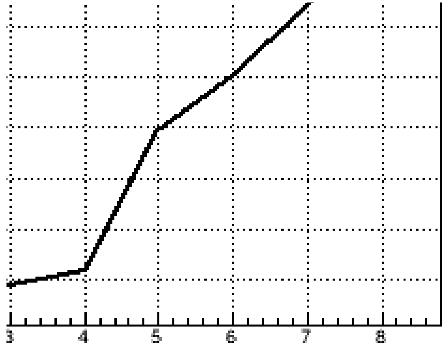
- Only investigate H→WW*→qq lν decay channel
- Same workflow as dark neutrino analysis
- Dark neutrino-related input parameters to BDT are removed
- No lepton channel separation (yet)

Cut table | (-0.8, +0.3) 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

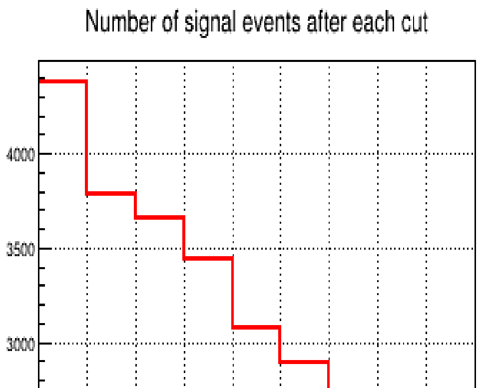


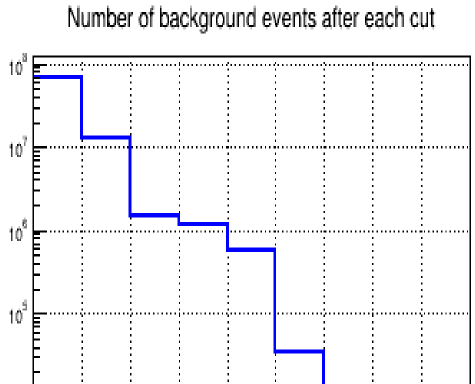


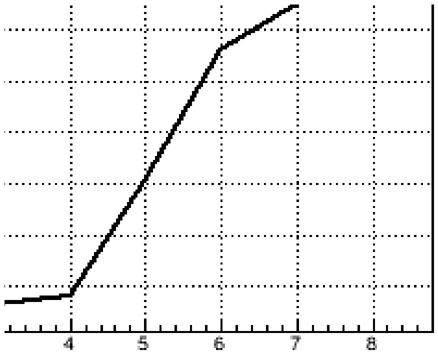


Cut table | (+0.8, -0.3) beam

	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

- Combined significance: **58σ**
- Previous study of same decay channel 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 at ILC

Particles in dark sector

- Two Higgs doublets
- Higgs potential:

$$V(\Phi) = \mu_1^2 \Phi_1^\dagger \Phi_1 + \mu_2^2 \Phi_2^\dagger \Phi_2 - \mu_3^2 (\Phi_1^\dagger \Phi_2 + c.c.) + \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \left[\frac{1}{2}\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \lambda_6 (\Phi_1^\dagger \Phi_1)(\Phi_1^\dagger \Phi_2) + \lambda_7 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_2) + c.c.\right].$$

field	$SU(2)_D$	γ_5	Q_1	Q_2	$\mathbb{Z}_2$
$\Phi_{1,2}$	**2**	0	0	0	+
L_1	**2**	−1	+1	0	+
$N_{u,d}$	**1**	+1	+1	0	+
L_2	**2**	−1	0	+1	−

- $\lambda_{5,6,7}$ are complex (CP violation)
- Left-handed L_{1u}, L_{1d} with charge Q_1
- Right-handed N_u, N_d (dark neutrinos) with charge Q_1
- L_2: massless particle with charge Q_2
  - Exists to counteract Witten's anomaly but not important

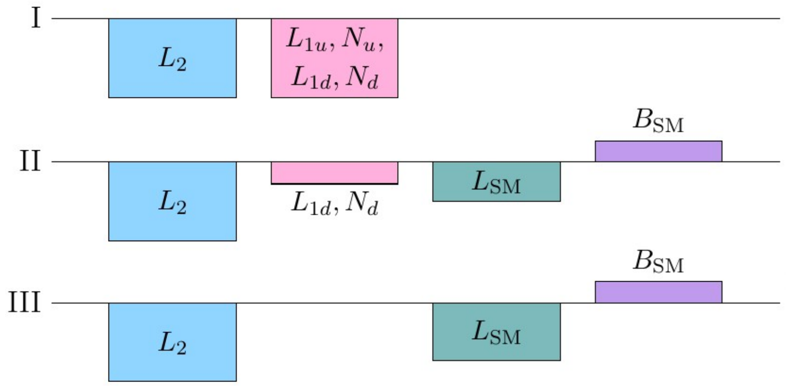
Early universe

I. Dark first-order phase transition in early universe
   - More particles than antiparticles in dark sector

II. N_u decays to SM leptons
   - Q_1 asymmetry converted to SM lepton asymmetry
   - Some leptons converted to baryons through SM sphaleron

III. After EW symmetry breaking, N_d decays to SM leptons

   →additional lepton asymmetry



Techincal details

- Use ROOT::RDataFrame in Jupyter notebook
  Simplifies:
  - Making and analyzing cuts
  - Defining new variables
  - Running the code in parallel→performance boost
  - Visualize the filtered data
  - Exploratory data analysis

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

Boosted decision tree

- Multiple binary decision trees are trained
- When evaluating an event, the trees ”vote” if the event is signal or background
- The BDT output is the weighted mean of all trees
- Events are reweighted such that signal and background is equal in size

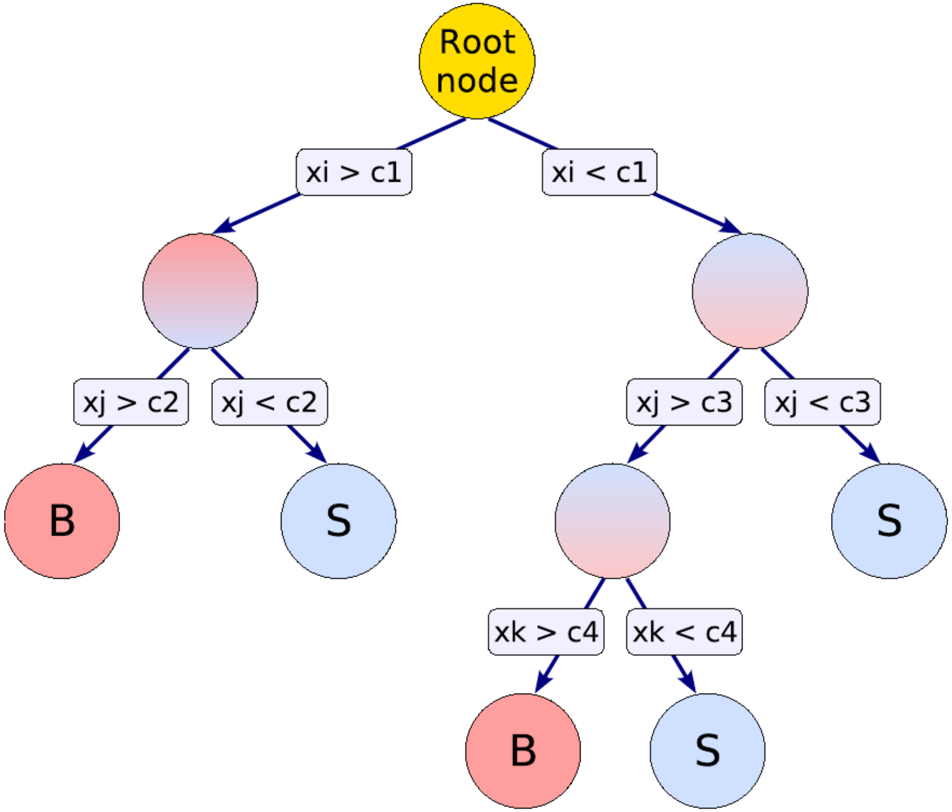
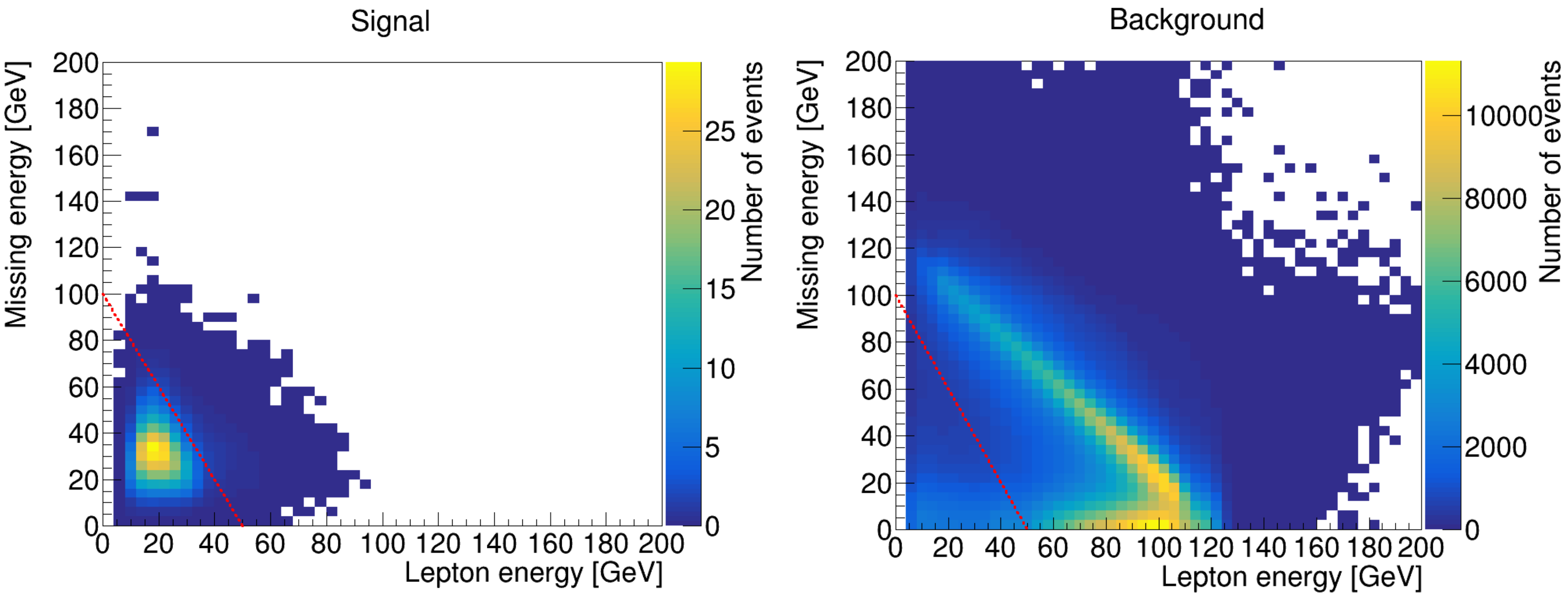


Image source: TMVA User Guide

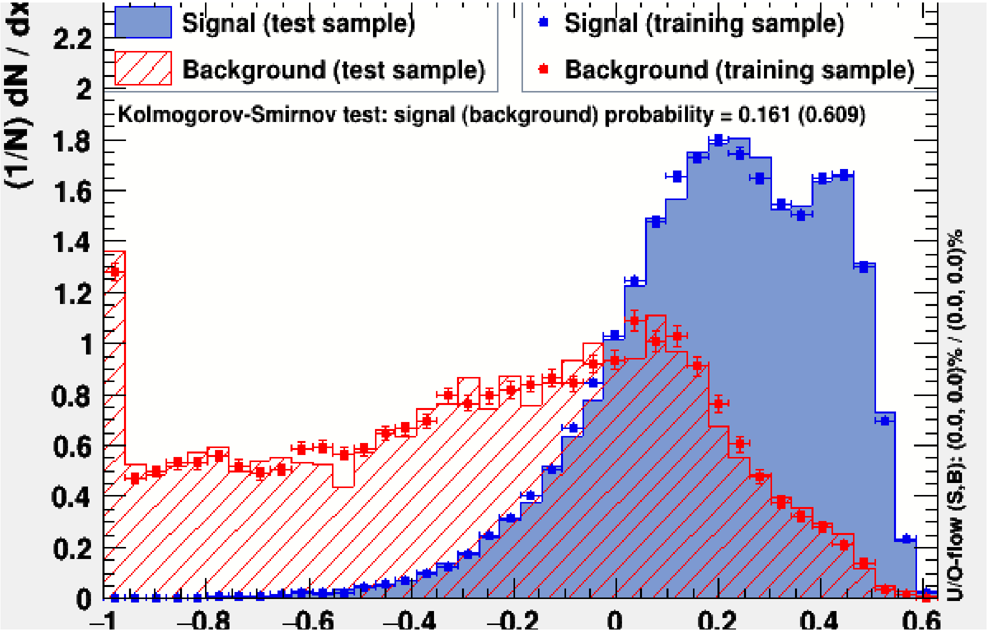
Lepton/missing energy distribution



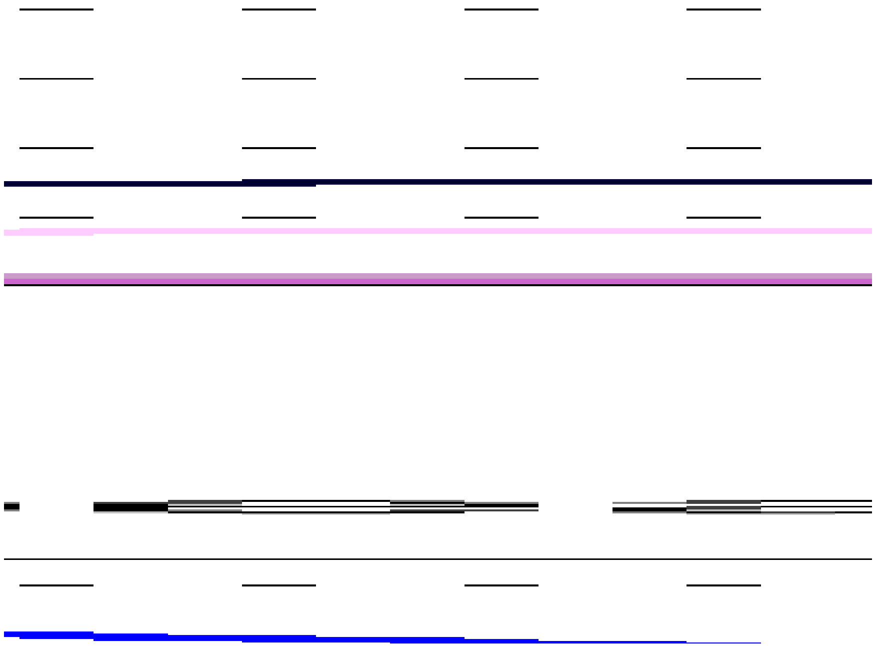
m=100 GeV, (+0.8, -0.3) beam polarization

Machine learning output

- Confirm that BDT is not overtrained
- Find optimal BDT cut value to maximize significance

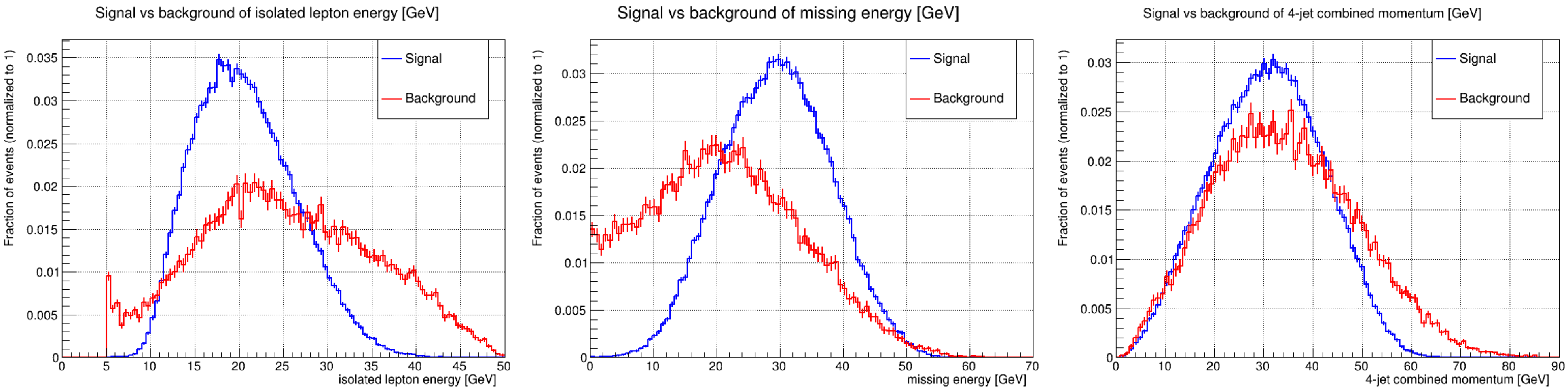


100 GeV dark neutrino mass, (-0.8, +0.3) beam polarization



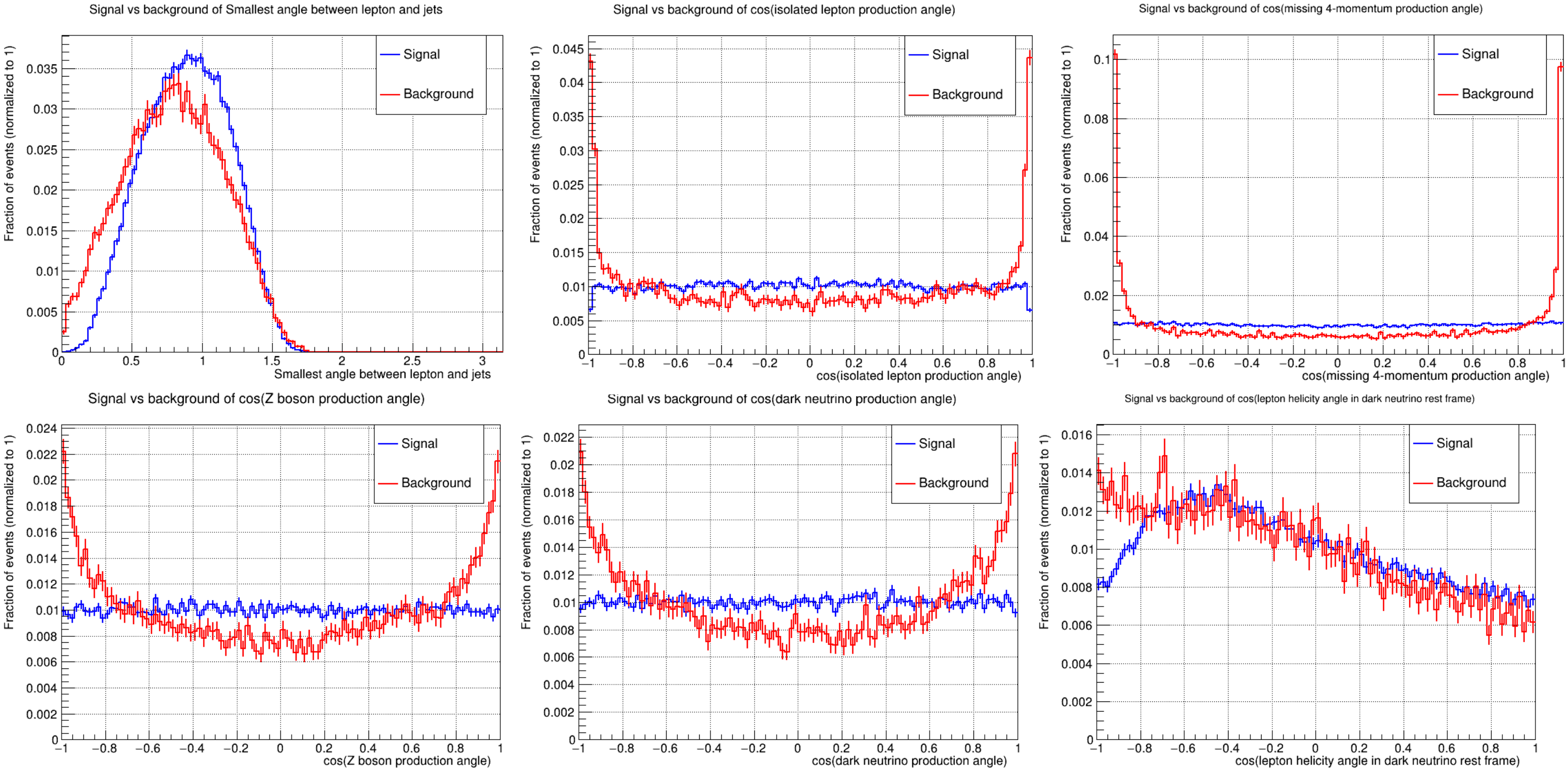
100 GeV dark neutrino mass, (-0.8, +0.3), e channel

BDT parameter distributions - energies



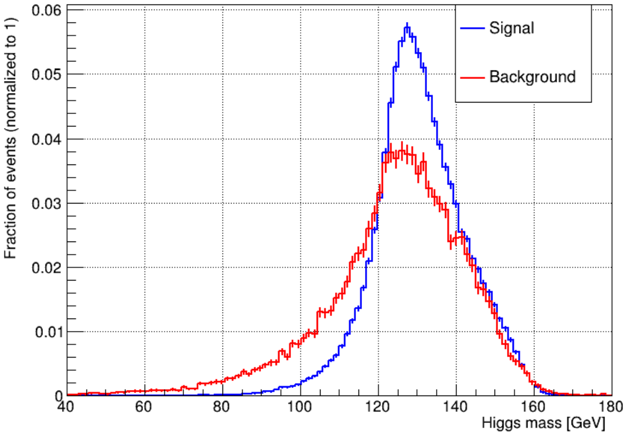
100 GeV dark neutrino mass, (-0.8, +0.3) beam polarization

BDT parameter distributions - angles

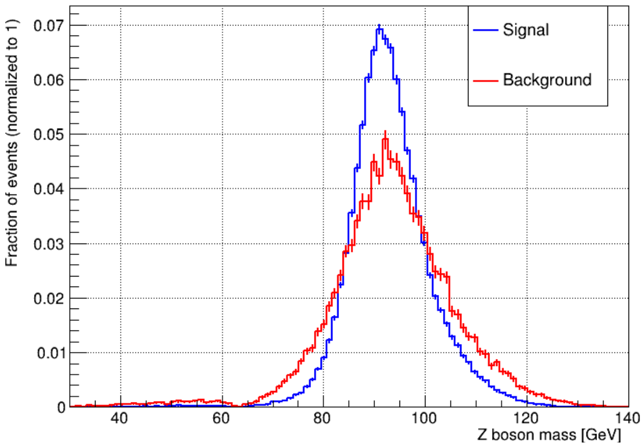


BDT parameter distributions - masses

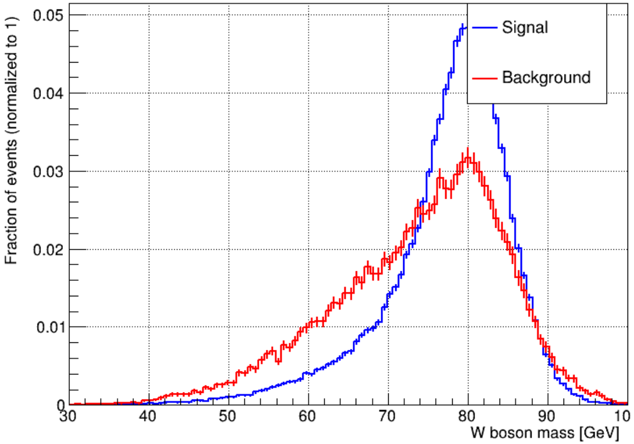
Signal vs background of Higgs mass [GeV]



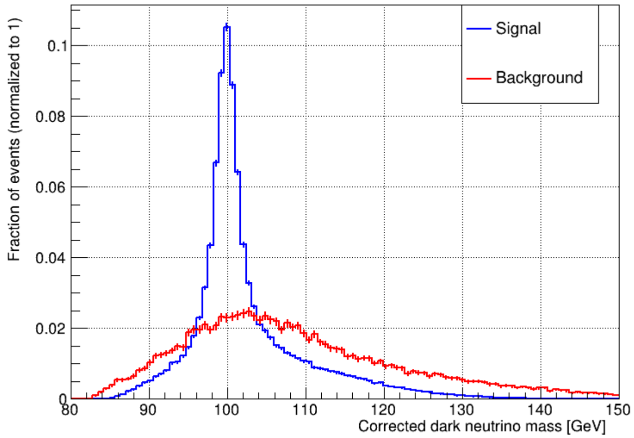
Signal vs background of Z boson mass [GeV]



Signal vs background of W boson mass [GeV]



Signal vs background of Corrected dark neutrino mass [GeV]



Example cut table for dark neutrino

1% branching ratio

100 GeV

(-0.8, +0.3)

Electron channel

	Total signal	Total background	Significance	2f_l	2f_h	4f_l	4f_sl	4f_h	6f	qqh
No cuts	1396	136859842	0.12	12982897	77324421	10379315	19163106	16800470	1278	208355
Pre-selection	1233	30132034	0.22	7366002	1606336	7651845	13260215	220833	872	25932
leptype == 11	627	14973089	0.16	1184642	1402269	4919234	7252824	198385	514	15221
elep/50. + emis/100. < 1	580	1136651	0.54	44637	248305	504438	192462	139969	415	6425
0.8 < mvalep	482	557011	0.65	28048	36926	348278	123436	16772	335	3217
(180. < mvis) && (mvis < 225.)	438	235510	0.90	13427	17309	126473	67151	8377	220	2553
0.007 < y34	376	19834	2.65	79	1762	298	9504	5855	200	2136
3 < min_n	357	10234	3.47	0	920	1	1726	5458	171	1957
(15. < mis.P()) && (mis.P() < 45.)	325	3498	5.26	0	256	0	671	1131	30	1410
MVA cut	242	825	7.41	0	56	0	59	146	13	552

1% branching ratio

120 GeV

(+0.8, -0.3)

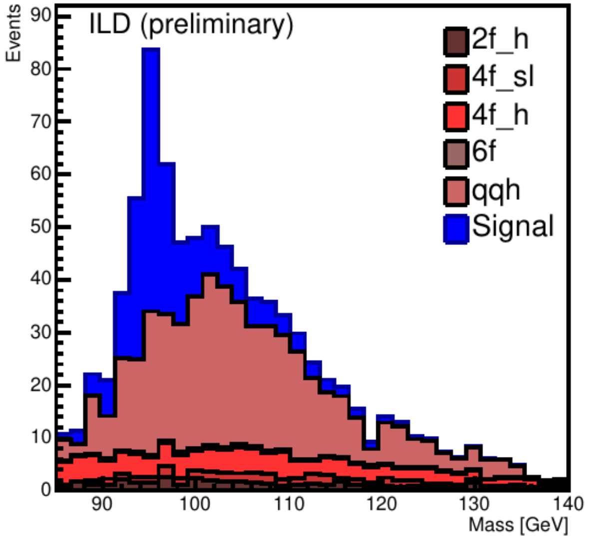
Muon channel

	Total signal	Total background	Significance	2f_l	2f_h	4f_l	4f_sl	4f_h	6f	qqh
No cuts	941	66651497	0.12	10314870	45672588	6114301	2839022	1570051	260	140405
Pre-selection	891	12565351	0.25	5696748	979693	4109167	1739683	22431	194	17434
leptype == 13	448	6449265	0.18	4803207	116849	976723	542562	2613	45	7267
elep/70. + emis/90. < 1	434	609993	0.56	79961	30687	461188	32974	1971	40	3172
0.6 < mvalep	431	561464	0.57	74804	19446	433438	29481	1301	39	2956
(160. < mvis) && (mvis < 220.)	406	290455	0.75	60239	16091	186398	24018	1049	23	2636
0.004 < y34	381	16966	2.89	432	2630	1067	9535	900	22	2380
4 < min_n	335	4074	5.04	0	747	0	742	693	16	1876
(0. < mis.P()) && (mis.P() < 20.)	316	2309	6.17	0	599	0	389	582	13	725
MVA cut	197	245	9.38	0	70	0	20	27	2	126

Mass distributions

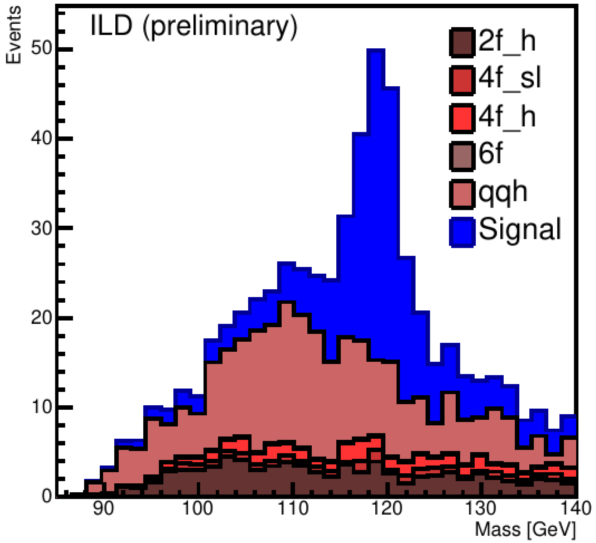
- Corrected mass: $m_{N_D} - m_W + m_{W_0}$
- W boson jet momentum error dominant for dark neutrino reconstruction→error removed in correction

95 GeV mass, (-0.8, +0.3), e channel

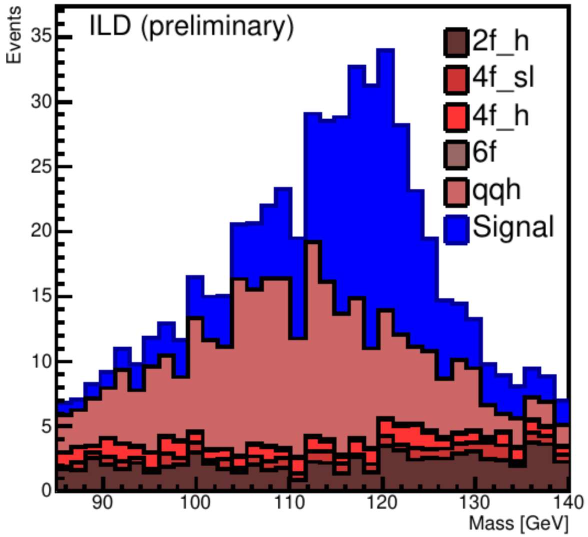


120 GeV mass, (+0.8, -0.3), μ channel

Corrected

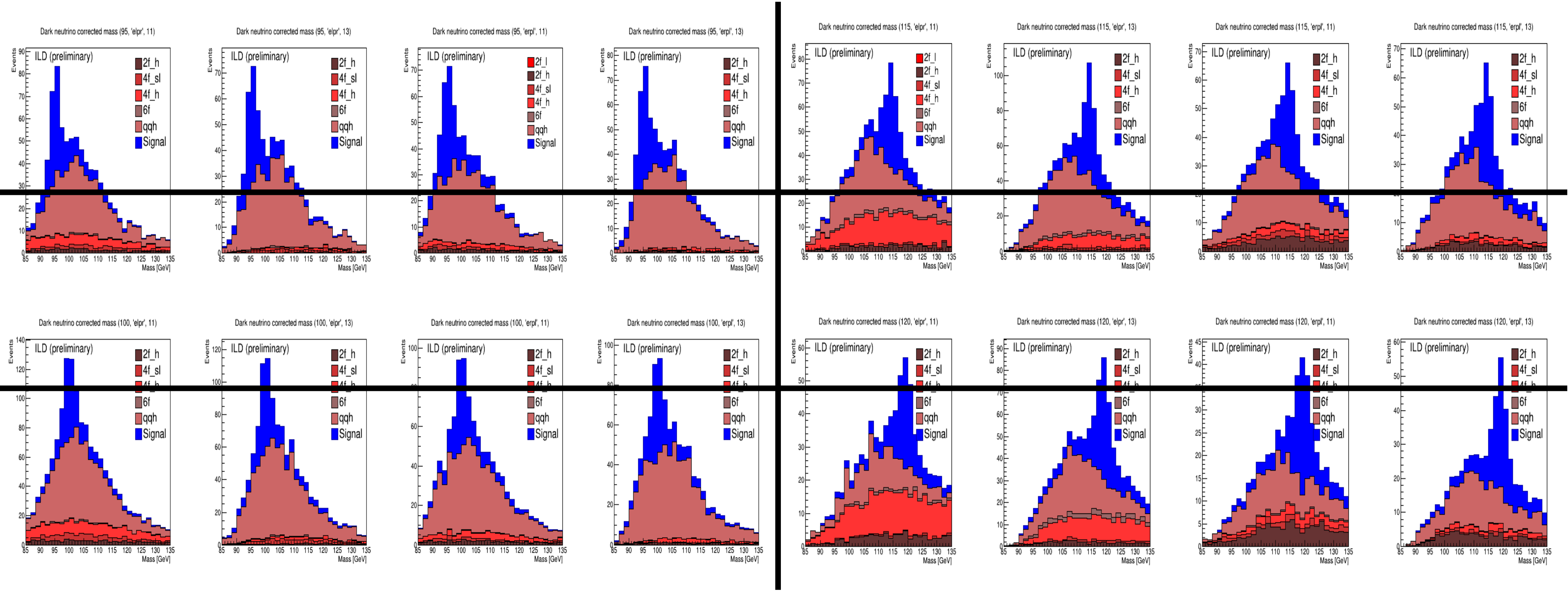


Not corrected



*Dark neutrino mass not used as input to MVA

Mass distributions



Potential improvements

- Lepton helicity angle in dark neutrino rest frame is incorrectly reconstructed

- Slight increase of negative angles
- Caused by error in jet clustering
  - W and Z jets are mixed

- **Improved jet clustering algorithms crucial for future collider experiments**