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$H \rightarrow \mu^+\mu^-$ at ILD

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Outline

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- Motivation for the analysis
- Software and sample used
- Lepton identification strategies
- Analysis selection and optimisation
- Results and conclusion

$H \rightarrow \mu^+\mu^- \; at \sqrt{s} = 1TeV$

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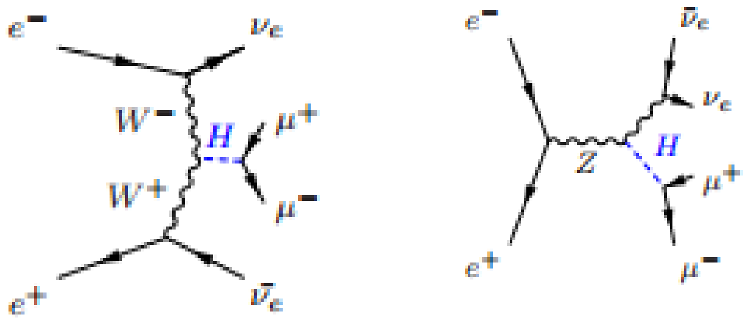
This channel can be used for two complementary purposes

- **Physics**: Higgs coupling to second generation particles
- **Detector optimisation**: benchmark for tracking system

We focussed on specific ILC parameters

- Centre of mass of 1 TeV
- Expected 500 fb^{-1} of integrated luminosity
- Beam state Polarisation (P_{e^-}, P_{e^+}) = (-0.8 , +0.2)
- WW fusion is the dominant process



The analysis builds on the $H \rightarrow \mu^+\mu^-$ 1 TeV DBD benchmark note by Costantino Calancha

Software and samples

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MC samples are those produced for the DBD

rv01-16-p03.sv01-14-01-p00.mILD_o1_v05.E1000-B1b_ws.I37582.Pvvh_mumu.eL.pR-00001-DST.slcio

The following samples for signal and backgrounds were take into account. Only a subset of the full list is used given the results of the DBD note which showed that all other backgrounds are removed with loose cuts

Process	Cross Section in fb
$\nu_e\bar{\nu}_e H \rightarrow \nu_e\bar{\nu}_e\mu^+\mu^-$ (signal)	0.089
$\nu_e\bar{\nu}_e Z \rightarrow \nu_e\bar{\nu}_e l^+l^-$	254.9
$ZZ/WW \rightarrow \nu_l\bar{\nu}_l l^+l^-$	190.9
$WW \rightarrow \nu_\mu l^+\bar{\nu}_\tau l^-$	184.7
$\gamma\gamma \rightarrow \nu_e\bar{\nu}_e l^+l^-$	132.9

Muon identification strategies

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Three methods to reconstruct muons were compared

- Method 1: DBD-like selection, simple cut based approach
- Method 2: More sophisticate list of cuts presented at the ILD high level reconstruction workshop
- Method 3: Neural network based selection using the new Isolated Lepton Tagging Processor (July version)

Method 1	Method 2
Charge != 0 At least 1 associated track At least 1 Associated Cluster Energy > 15 GeV $\frac{(E_{EM} + E_{HAD})}{P} < 0.3$	
$\frac{E_{EM}}{E_{TOT}} < 0.5$	Primary vertex Energy Yoke > 1.2

Input variables of NN

Ecal energy
Hcal energy
Yoke energy
dE/dx
shower profile
d0/δd0
z0/δz0
~~Relatively momentum with respect to closest jet~~

Disabled as there are no jets

Analysis strategy

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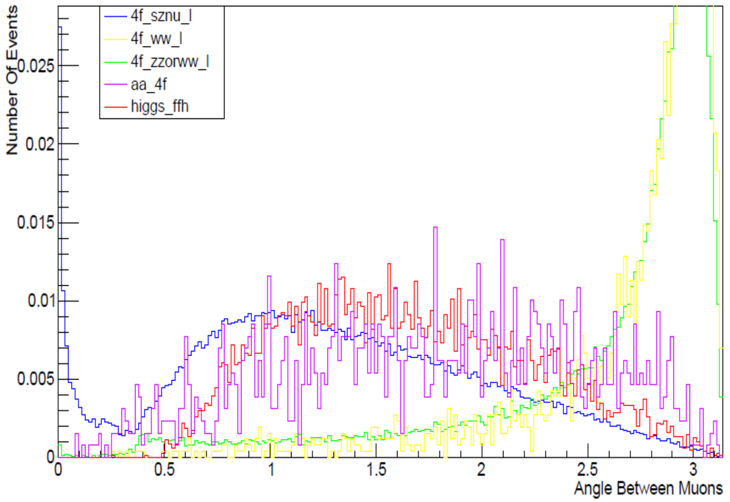
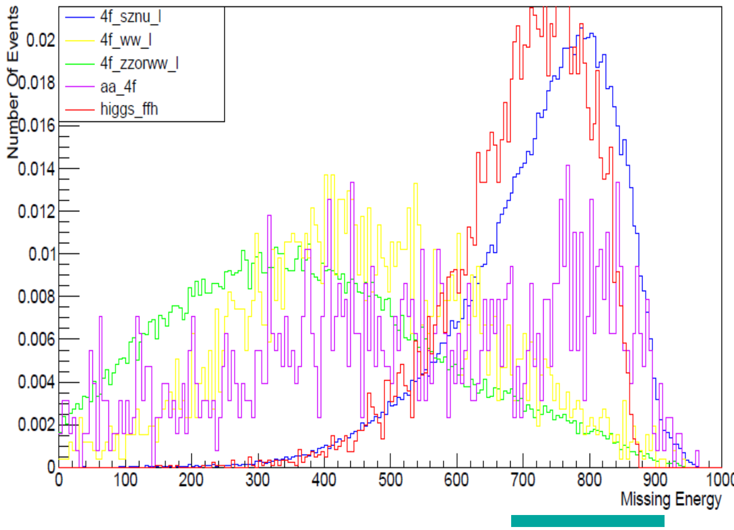
We implemented a series of loose cuts similar to those described in the DBD note

- Exactly two muons
- Invariant Higgs Mass within 30 GeV of 125 GeV
- Angle between muons > 0.5
- Missing energy > 300 GeV
- Number of charge particle < 4
- Number of charged leptons < 3





Cutflow

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Cut Name	All	Two muons	System energy	Invariant mass	Angle Between Muon	Missing Energy	NCharged PFOs	NCharged Leptons	Normalized
higgs_ffhLR	10000	8092	8092	7914	7913	7895	7872	7858	35
4f_sznu_lLR	471580	106519	106261	8528	8427	8397	8376	8355	2256
4f_ww_lLR	341898	2904	2011	182	182	171	168	168	45
4f_zzorww_lLR	352948	61952	26193	2493	2448	2163	2146	2137	577
aa_4fBB	54774	10368	10368	2623	2623	2623	2619	2619	1338

The significance after these cuts is 0.54

- Small compared with DBD result of 2.3 but we have not used strong cut on reconstructed Higgs mass (|M-125|<1GeV in DBD note)
- Having enough statistics allowed use to use MVA

Multi Variate Analysis

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We compared two methods from TMVA

- Fisher
- ANN (MLP) with 8 variables and 13 nodes in the hidden layer

Input variables

- Angle between muons
- Leading muon energy
- Sub-leading muon energy
- Missing energy
- Di-muon system energy
- Leading muon p_z/p
- Sub-leading muon p_z/p
- Di-muon system invariant mass

Input variables

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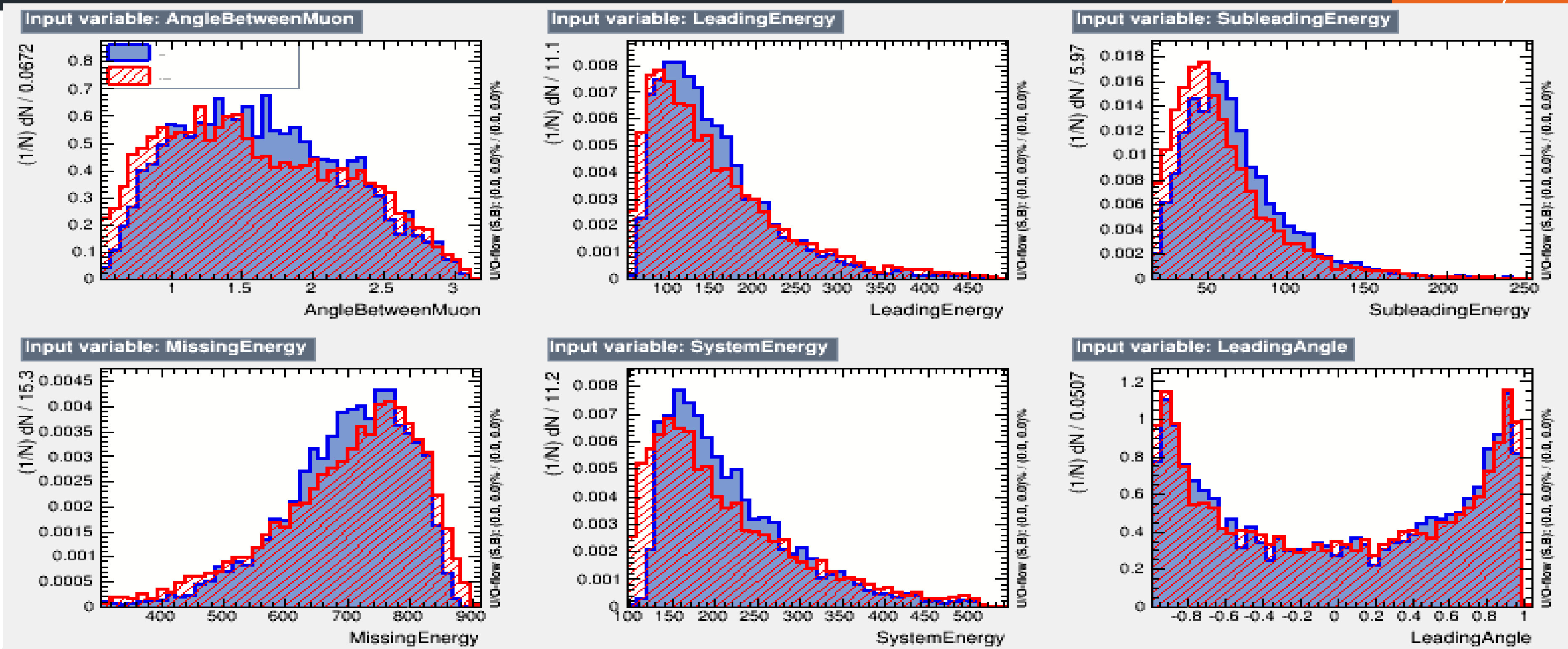

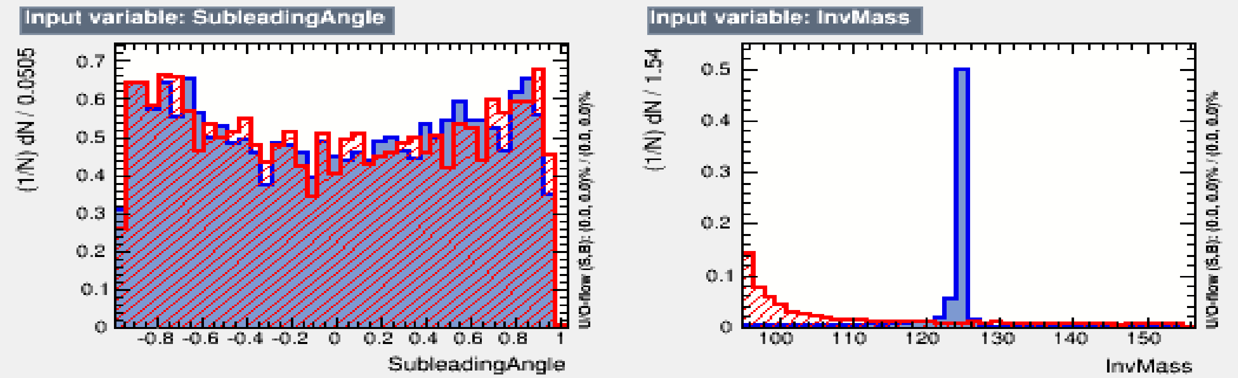

Higgs

Backgrounds

Control plots

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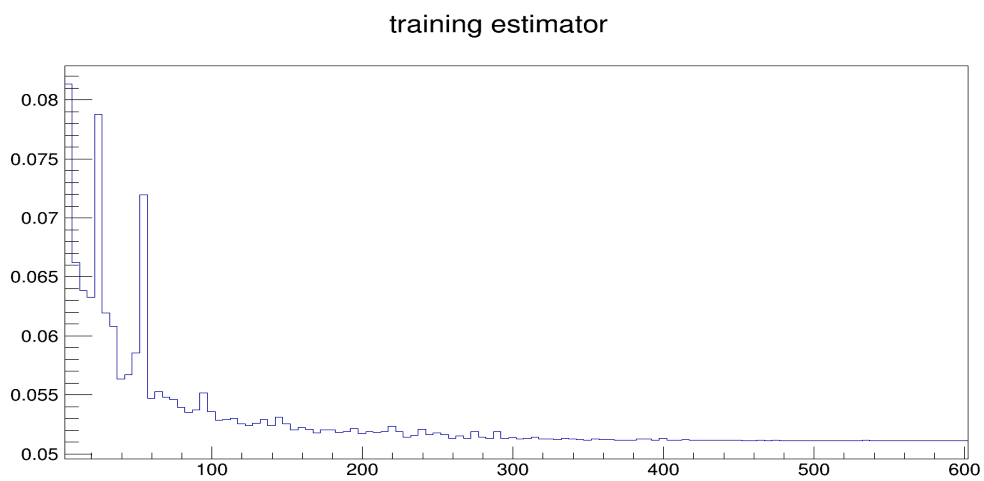
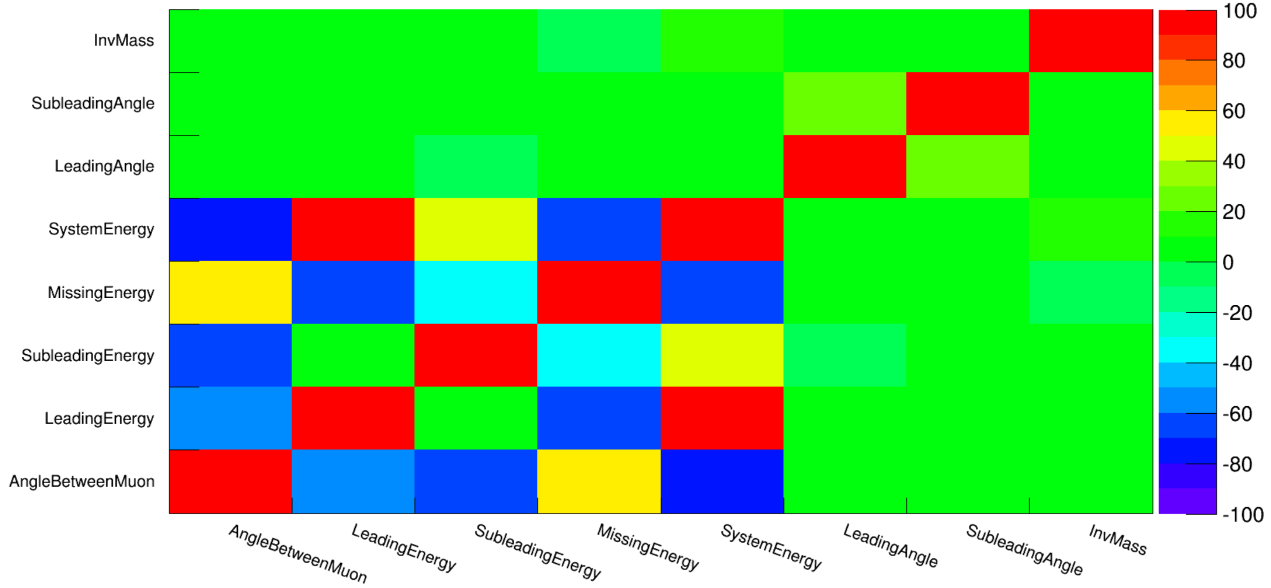


Training converged



Signal/background separation

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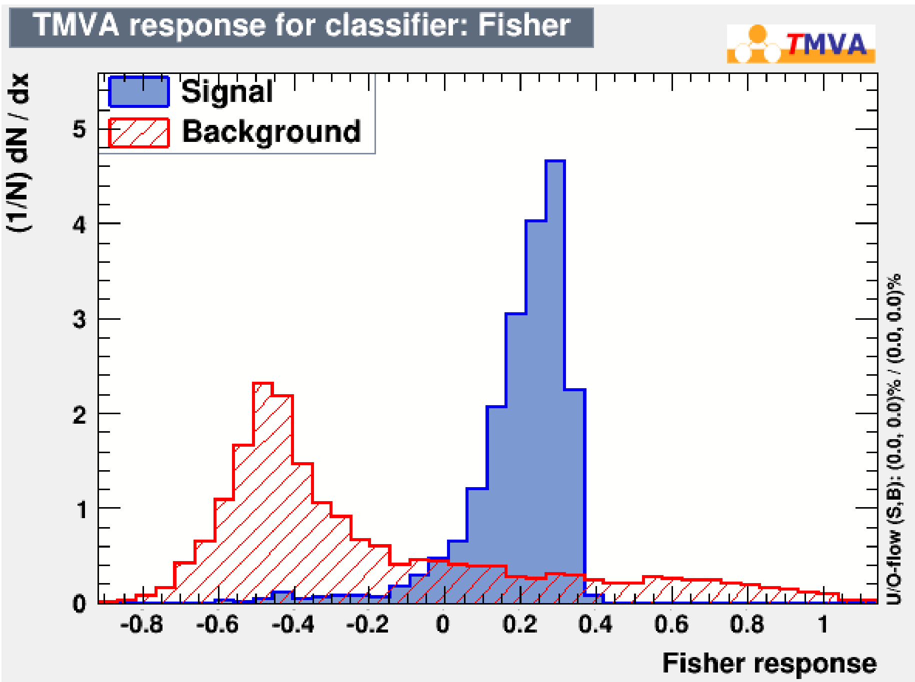

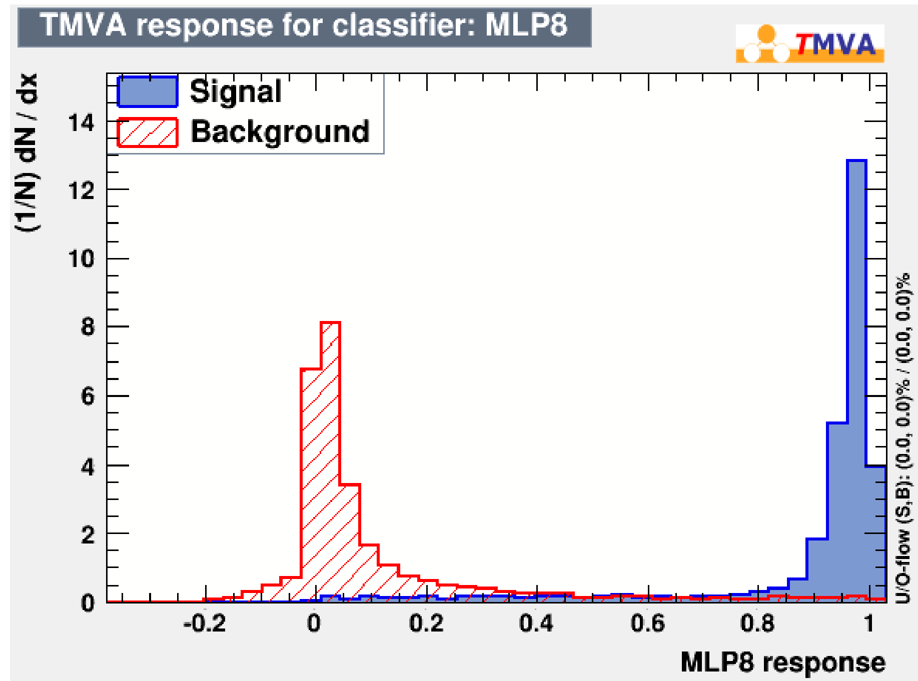

ROC curves

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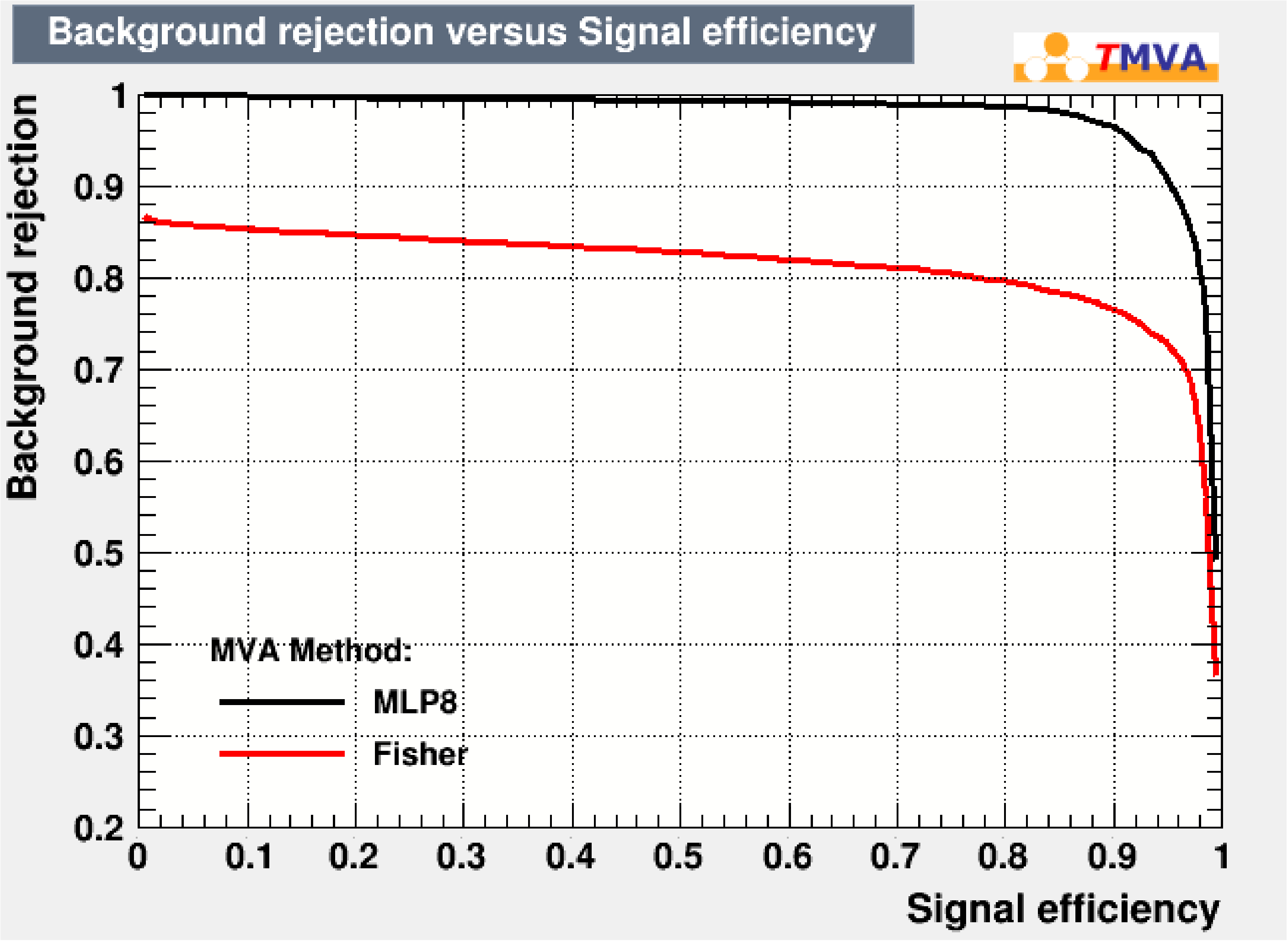

Significance

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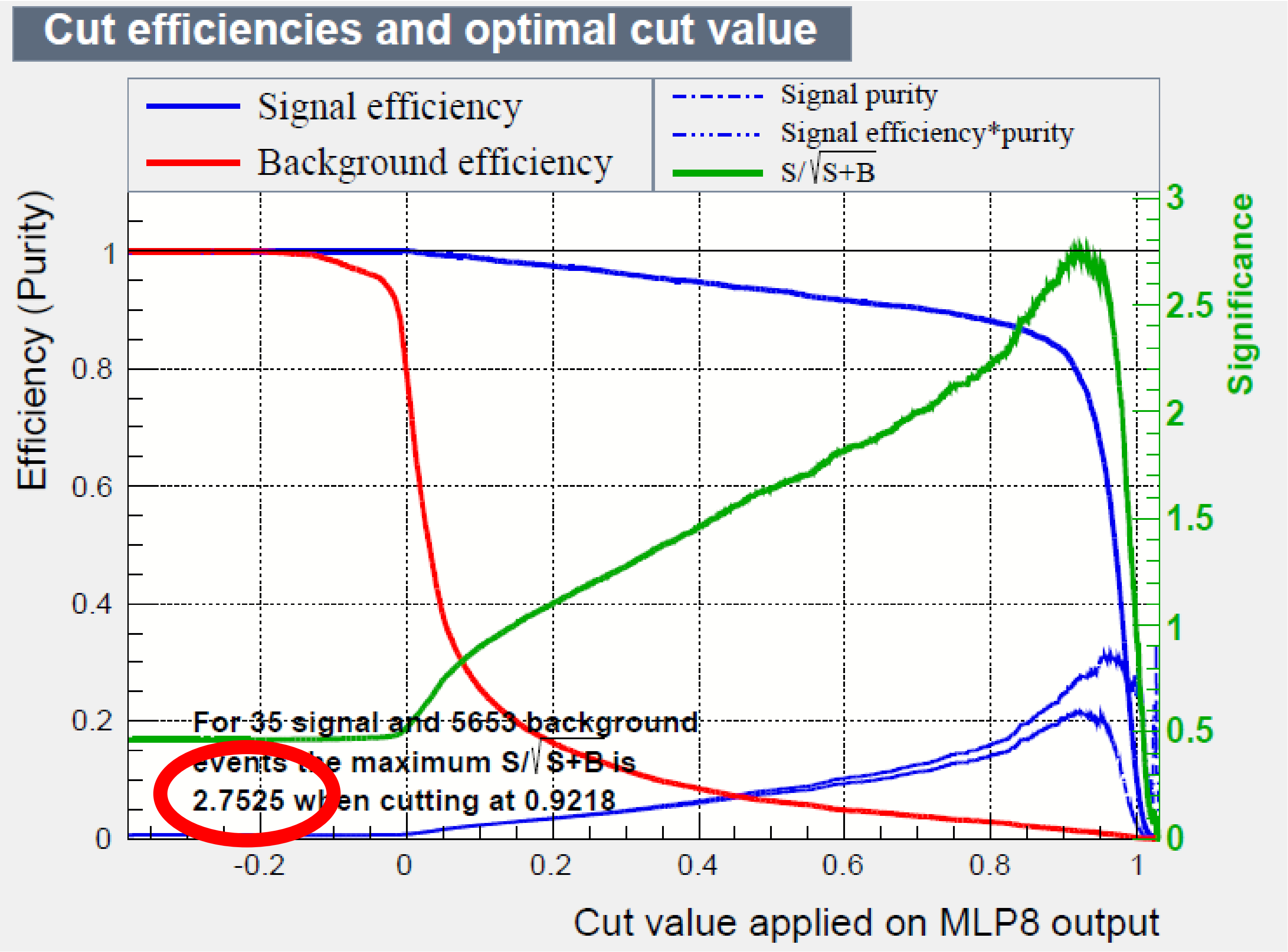

Result for the three muon selections

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Figure of merit is significance $\sigma = \frac{S}{\sqrt{S+B}}$

- DBD benchmark note $\sigma \approx 2.3$
- N_s number of signal events, N_b number of background events passing NN cut
- All values normalised to 500 fb^{-1}

Method	1	2	3
N_S	40	35	37
N_B	8012	5653	6565
σ_{Fisher}	0.70	0.86	0.83
σ_{ANN}	2.57	2.75	2.70

Different cut on Higgs mass

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We tried to modify the cut on the Higgs mass to test if we could increase the sensitivity

Method 1	|M-125|	< 30GeV	< 5GeV	< 3GeV
	N_S	40	36	34
	N_B	8012	1017	606
	σ_{Fisher}	0.7	1.31	1.54
	σ_{ANN}	2.57	2.42	2.47

Method 2	|M-125|	< 30GeV	< 5GeV	< 3GeV
	N_S	35	32	31
	N_B	5653	664	399
	σ_{Fisher}	0.86	1.26	1.61
	σ_{ANN}	2.75	2.47	2.66

Method 3	|M-125|	< 30GeV	< 5GeV	< 3GeV
	N_S	37	34	32
	N_B	6565	801	477
	σ_{Fisher}	0.83	1.22	1.53
	σ_{ANN}	2.70	2.33	2.29

Fisher improves

NN get worse

Quality variables in NN

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We tried to include parameters that are a direct benchmark for the tracking reconstruction into the NN.

We decided to use the χ^2 of the reconstructed track of two muons

Method	1	2	3
σ_{ANN8}	2.57	2.75	2.70
σ_{ANN10}	2.53	2.75	2.63

We observed no improvement which is probably due to the strong cuts already applied at track reconstruction level

Invariant Mass

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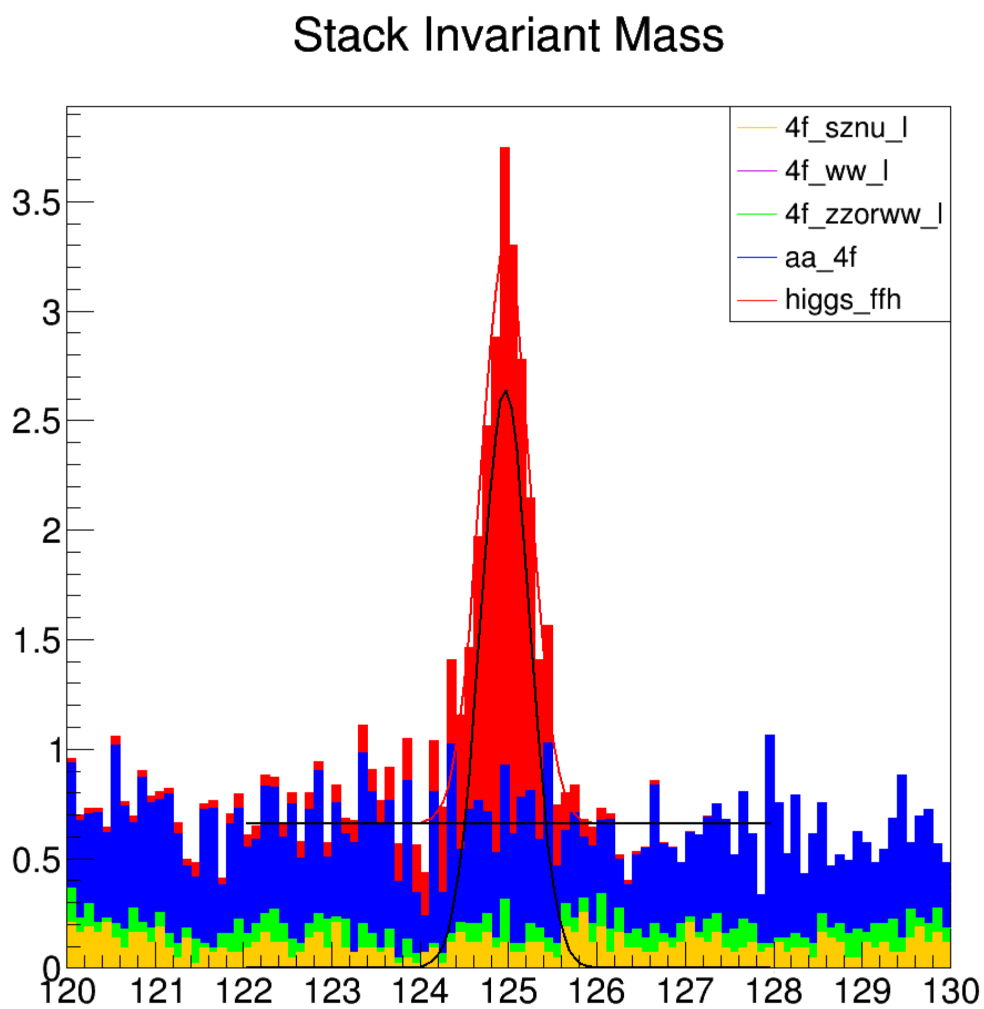

Fit of peak (gauss) and background (flat) using sidebands

Low cut	High cut	Ns	Nb	Significance
123	127	18.34	26.30	2.74
123.1	126.9	18.34	24.99	2.79
123.2	126.8	18.34	23.67	2.83
123.3	126.7	18.34	22.36	2.87
123.4	126.6	18.34	21.04	2.92
123.5	126.5	18.34	19.73	2.97
123.6	126.4	18.34	18.41	3.02
123.7	126.3	18.34	17.10	3.08
123.8	126.2	18.34	15.78	3.14
123.9	126.1	18.34	14.47	3.20
124	126	18.33	13.15	3.27
124.1	125.9	18.31	11.84	3.34
124.2	125.8	18.26	10.52	3.40
124.3	125.7	18.11	9.21	3.47
124.4	125.6	17.75	7.89	3.51
124.5	125.5	16.98	6.58	3.50
124.6	125.4	15.53	5.26	3.41
124.7	125.3	13.13	3.95	3.18
124.8	125.2	9.62	2.63	2.75

Using the values from the fit we performed an optimisation of the cut around the Higgs mass peak

The best result is achieved using 0.6 GeV cut, this is already a significant improvement from the 1 GeV cut applied before (3.27 → 3.51)

Conclusion

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We performed the full analysis of the $H \rightarrow \mu^{+}\mu^{-}$ channel using the latest available full simulation of the ILD detector

- We applied the latest recommendation for lepton reconstruction and managed to significantly improve the muon selection and the achieved significance
- By using MVA we managed to further improve the significance achievable by ILD on this channel from the DBD σ =2.3 to σ =3.5
- This only includes 1 TeV, so a higher significance should be achievable by including all centre-of-mass energies
- Note that the main background is gamma-gamma to four fermions so this is not only a ILD benchmark but also an ILC benchmark

We plan to write an ILD note after presenting this work at LCWS