Study of Higgs Self-couplings at ILC

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motivation

SM: $\tilde{\lambda} = \lambda = \lambda_{SM} = \frac{m_H^2}{2v^2}$

Higgs Potential: $V(\eta_H) = \frac{1}{2} m_H^2 \eta_H^2 + \lambda v \eta_H^3 + \frac{1}{4} \tilde{\lambda} \eta_H^4$

physical Higgs field

mass term

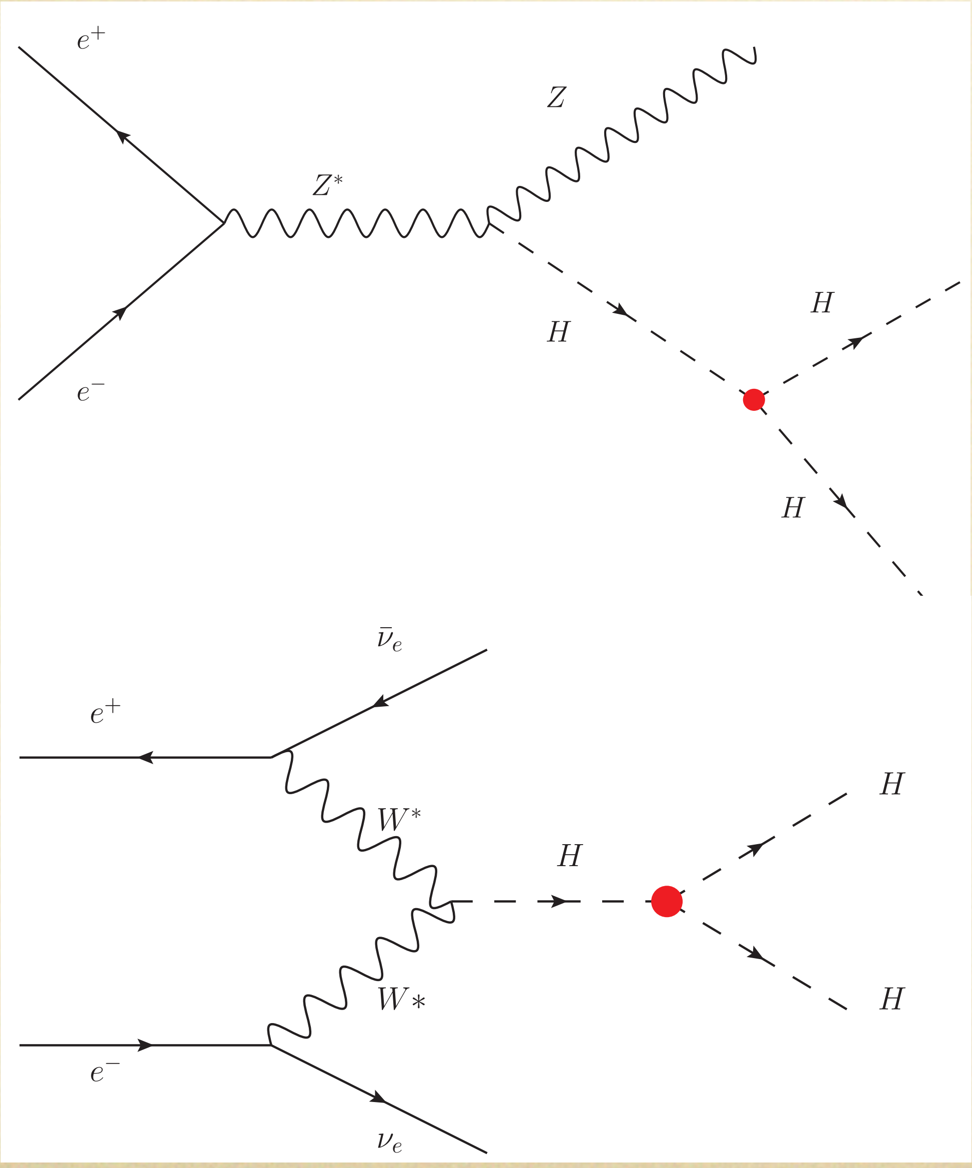
trilinear coupling

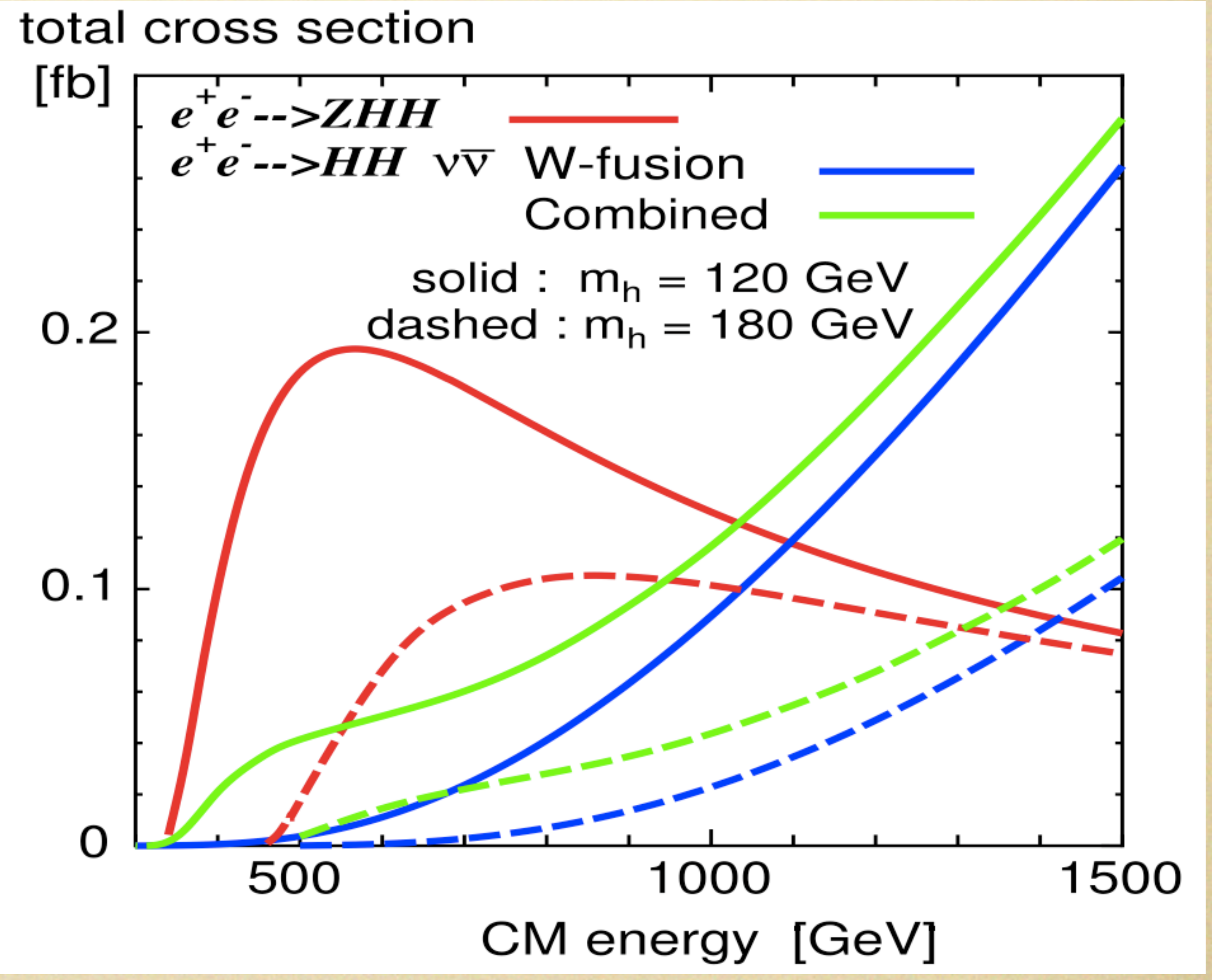
quartic Higgs coupling, which is difficult to measure at both LHC and ILC, even SLHC!

- a new interaction (non-gauge interaction).
- the non-trivial probe of the Higgs potential, offer a direct independent determination.
- accurate test of this coupling may reveal the extended nature of Higgs sector, like 2HDM and SUSY.
- difficult to measure at LHC for a light Higgs.

Measurement of the trilinear Higgs self-coupling @ ILC

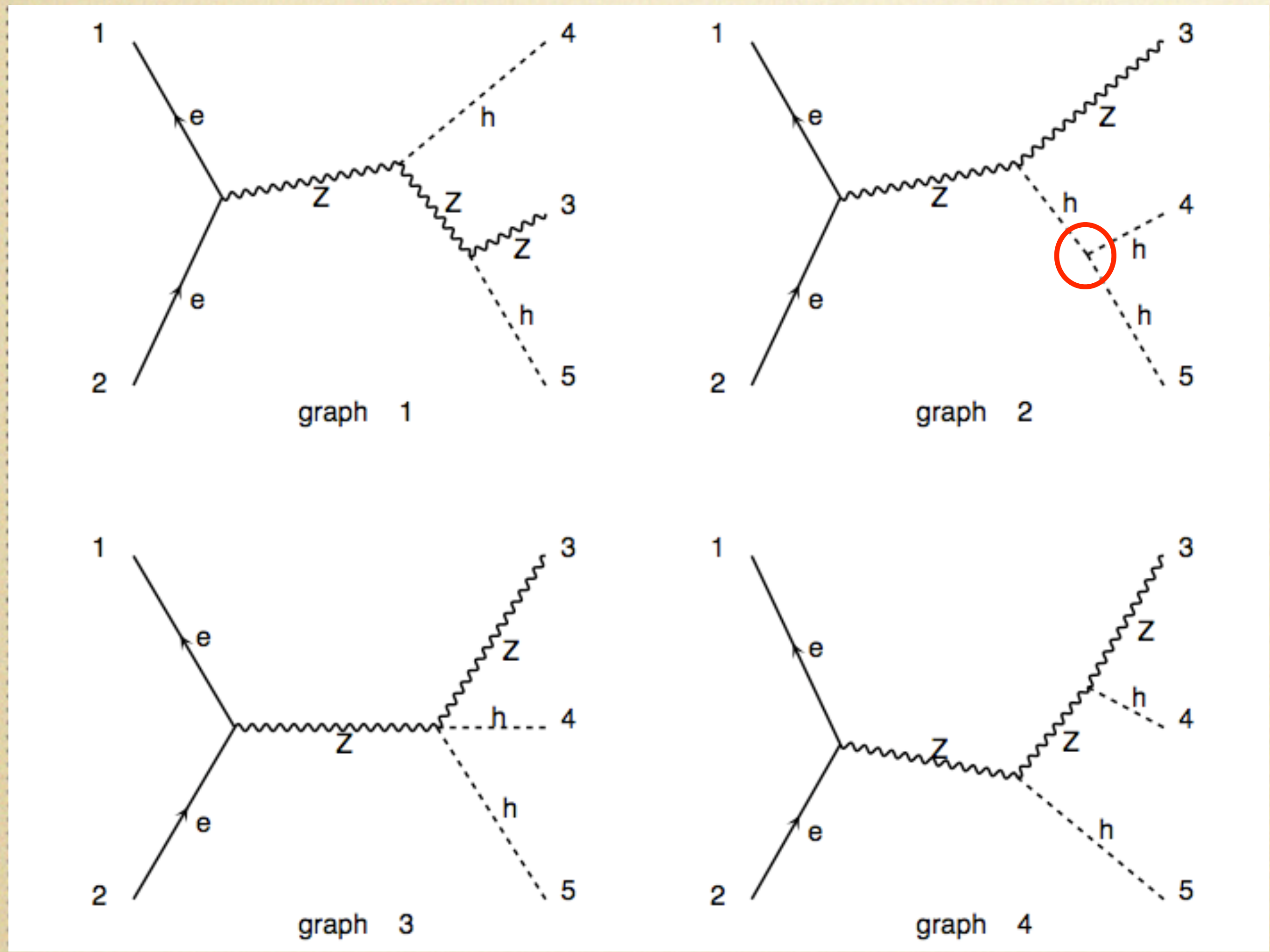
- double Higgs-strahlung (dominate at lower energy)
- WW fusion (dominate at higher energy)

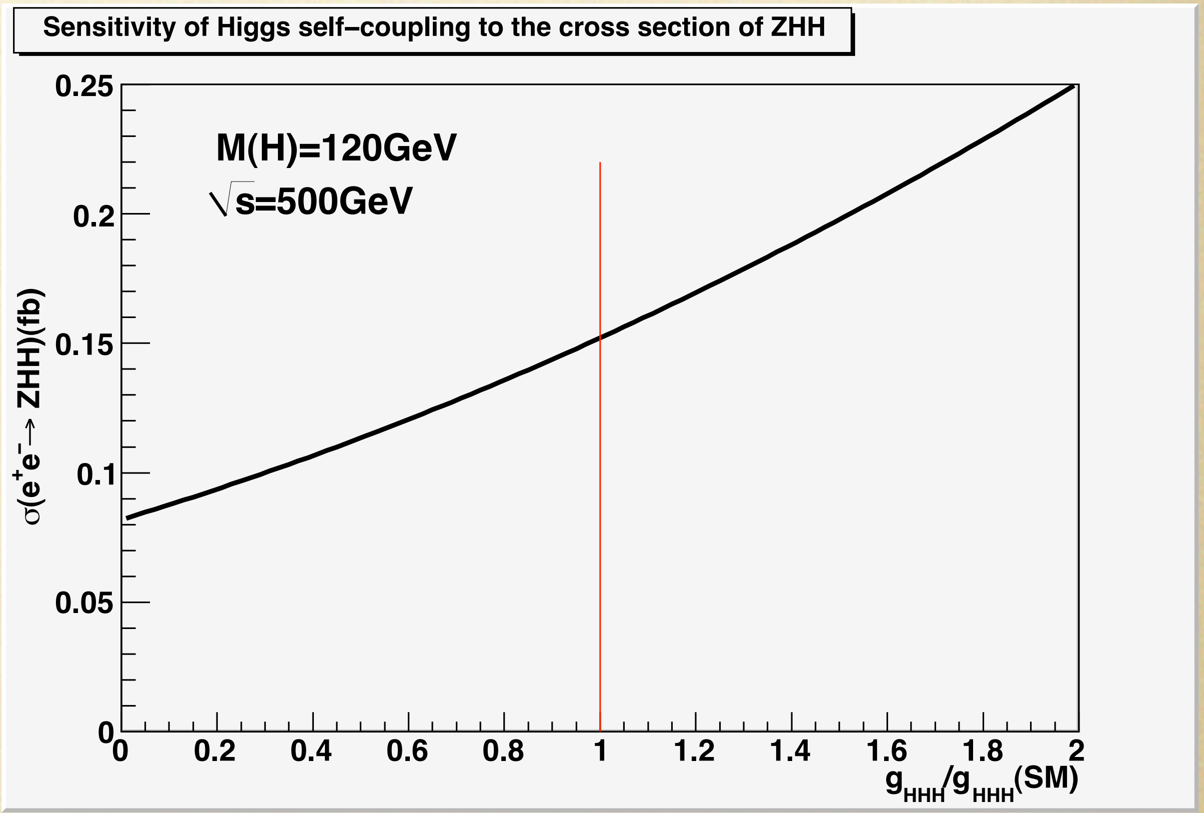




sensitivity of Higgs self-coupling to the cross section of ZHH

effection of irreducible diagram

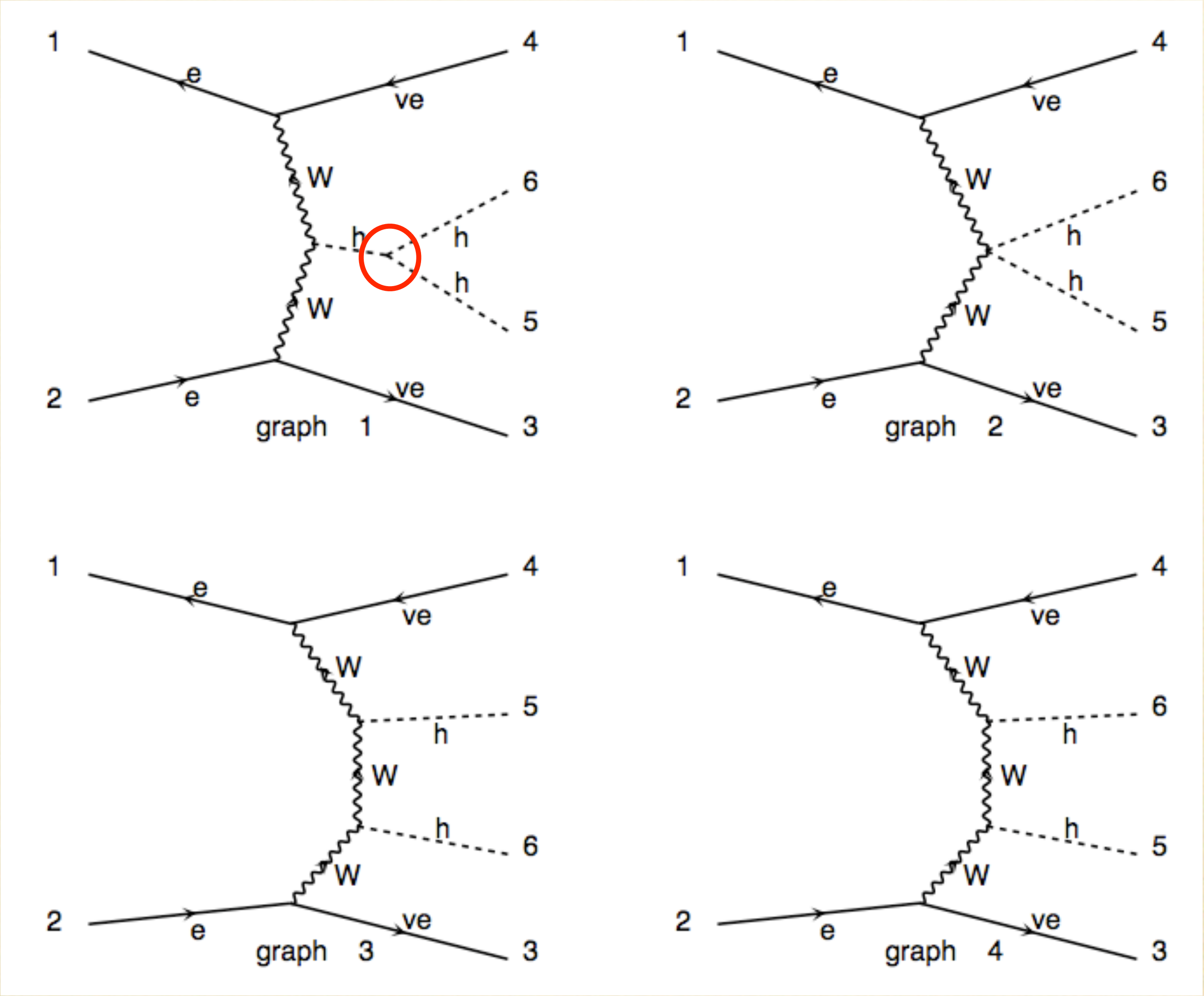


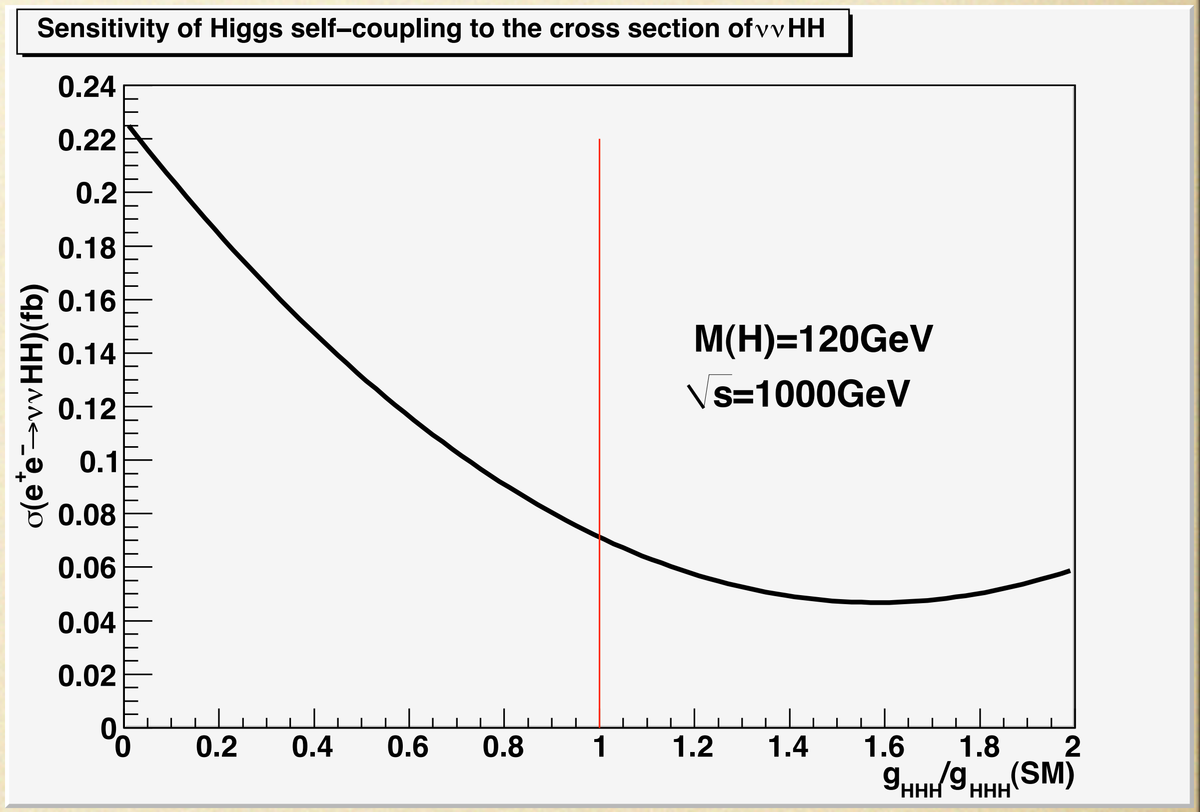


$$\frac{\Delta\lambda}{\lambda} = 1.8\frac{\Delta\sigma}{\sigma}$$

sensitivity of Higgs self-coupling to the cross section of υυHH

effection of irreducible diagram





$$\frac{\Delta\lambda}{\lambda} = 0.85\frac{\Delta\sigma}{\sigma}$$

status of the full simulation (preliminary)

Polarization: (e-,e+)=(-0.8,0.3) $e^+ + e^- \rightarrow ZHH$ $M(H) = 120\text{GeV}$ $\int Ldt = 2\text{ab}^{-1}$

Energy (GeV)	Modes	signal	background	significance	
				excess (I)	measurement (II)
500	$ZHH \rightarrow (l\bar{l})(b\bar{b})(b\bar{b})$	6.4	6.7	2.1σ	1.7σ
500	$ZHH \rightarrow (\nu\bar{\nu})(b\bar{b})(b\bar{b})$	5.2	7.0	1.7σ	1.4σ
500	$ZHH \rightarrow (q\bar{q})(b\bar{b})(b\bar{b})$	8.5	11.7	2.2σ	1.9σ
		16.6	129	1.4σ	1.3σ

I. give the confidence how significantly we can observe the ZHH events
II. give the confidence how accurately we can measure the X-section or coupling

backgrounds mainly come from ZZ(Z*), bbZ, ZZZ, ZZH, tt-bar, WWZ, WWH

setup of full simulation

- ilcsoft: v01-06 (same as LoI)
- at least 2 ab-1 statistics used to evaluate the efficiencies for most of the background and signal processes
- at least 2 ab-1 statistical independent samples used to train the neural-net.
- Polarization (e-,e+)=(-0.8,+0.3) is favored, other polarization are also checked.

$$e^+ + e^- \rightarrow ZHH \rightarrow (l\bar{l})(b\bar{b})(b\bar{b}) \rightarrow 2\ \text{leptons} + 4\ \text{bjets}$$

full simulation @ 500GeV

pre-selection:

- two isolated charged leptons (the pair nearest to Z mass is selected)
- force the other particles(PFOs) to four jets
- combine the four jets by minimizing

$$\chi^2 = \frac{(M(b,\bar{b}) - M_H)^2}{\sigma_{H_1}^2} + \frac{(M(b,\bar{b}) - M_H)^2}{\sigma_{H_2}^2} + \frac{(M(l,\bar{l}) - M_Z)^2}{\sigma_Z^2}$$

do not effect minimization

requirement implied in the pre-selection:

- |M(ll)-M(Z)| < 40 GeV
- |M(jj)-M(H)| < 80 GeV

main backgrounds:

bbcsdu, qqbb
llbb
lvbbqq
llbbbb, llbbH

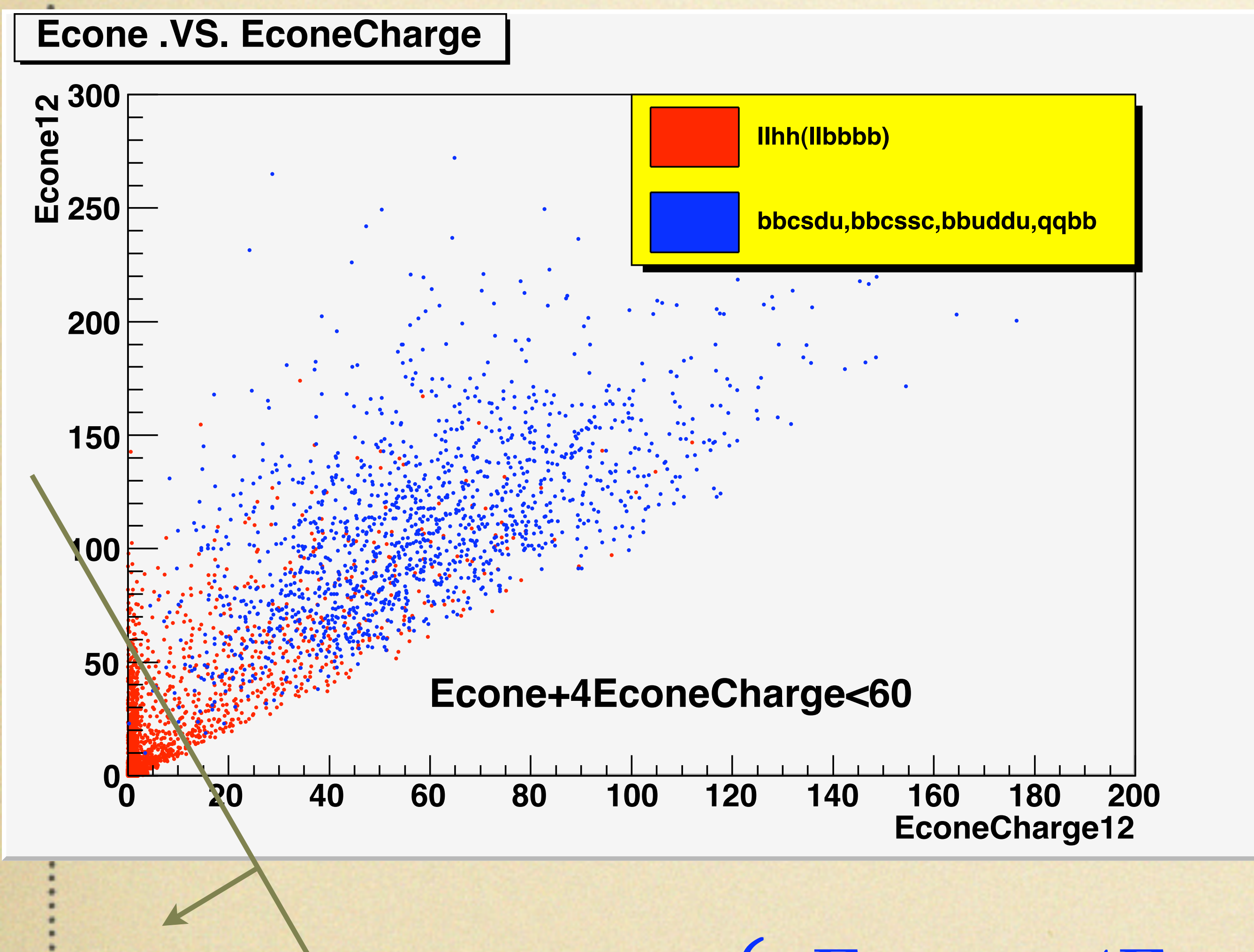
$$e^+ + e^- \to ZHH \to (l\bar{l})(b\bar{b})(b\bar{b}) \to 2\ \mathrm{leptons} + 4\ \mathrm{bjets}$$

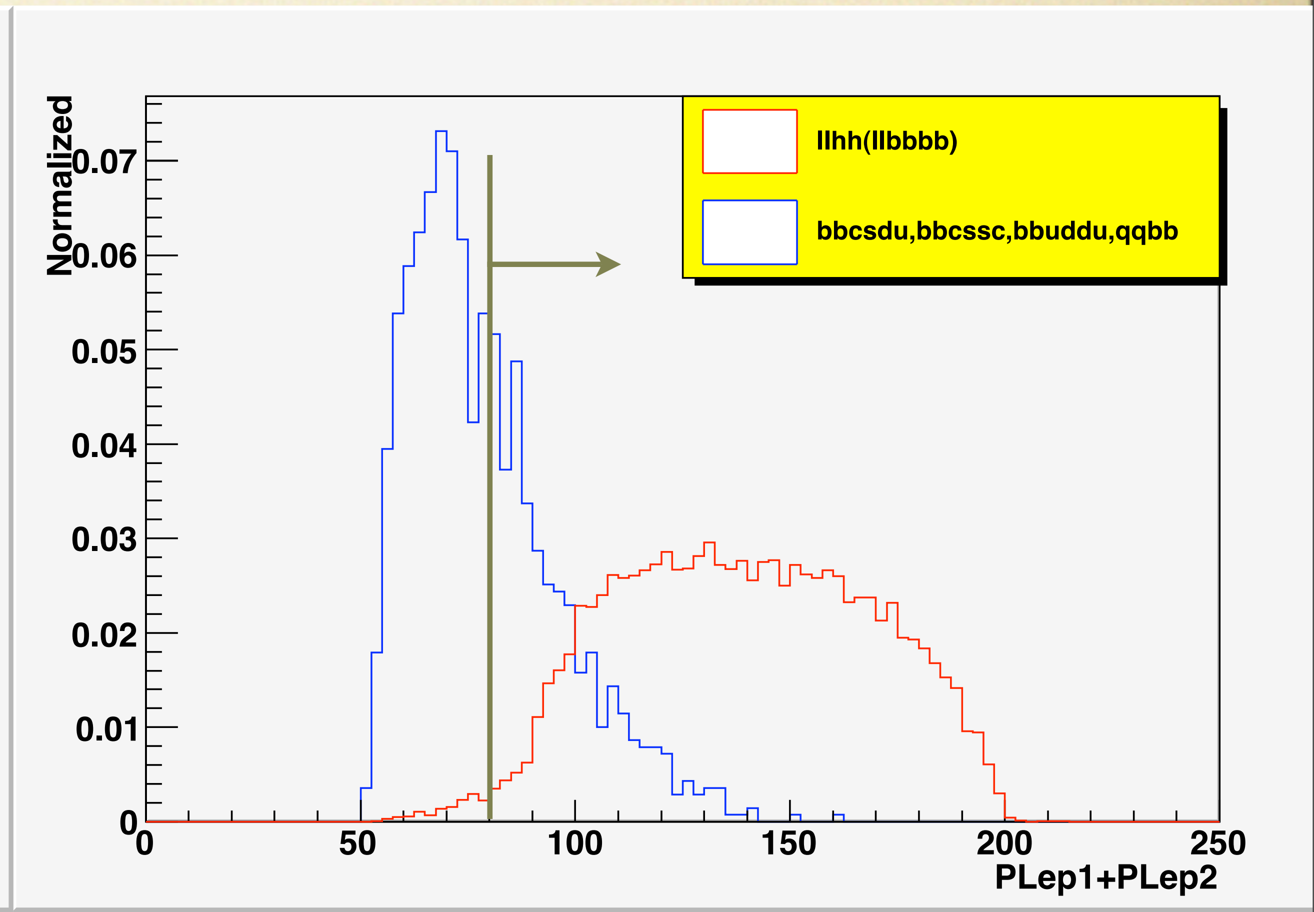
final selection:

- tighter cuts on the leptons momentum and cone energy, to further suppress the full hadronic backgrounds. left background events at least have one lepton.
- instead of training a neural-net for all the left backgrounds, which is ineffective due to the large difference of event topology, expected number and limited MC statistics, we trained several independent neural-nets to suppress the different kinds of backgrounds: jets poor (llbb), semi-leptonic (lvbbqq), two leptons four b (llbbbb, llbbH). add cut on the output of each neural-net.
- b tagging information are used separately, add cuts on the b-likeness of the four jets.
- all the cuts are optimized jointly.

llHH .vs. full hadronic backgrounds

bbcsdu, bbcssc, bbuddu, qqbb





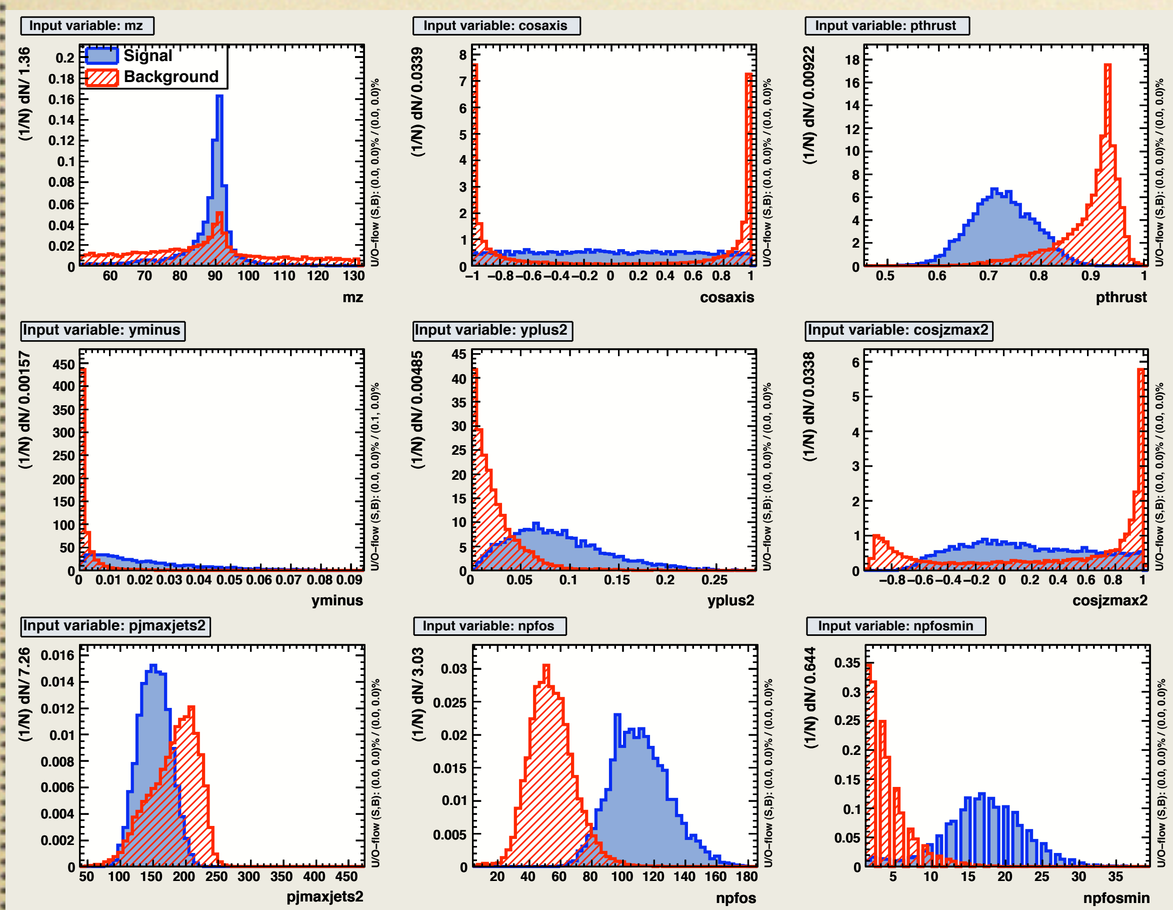
$$\begin{cases} E_{cone} + 4E_{cone}C < 60\text{GeV} \\ pLep_1 + pLep_2 > 80\text{GeV} \end{cases}$$

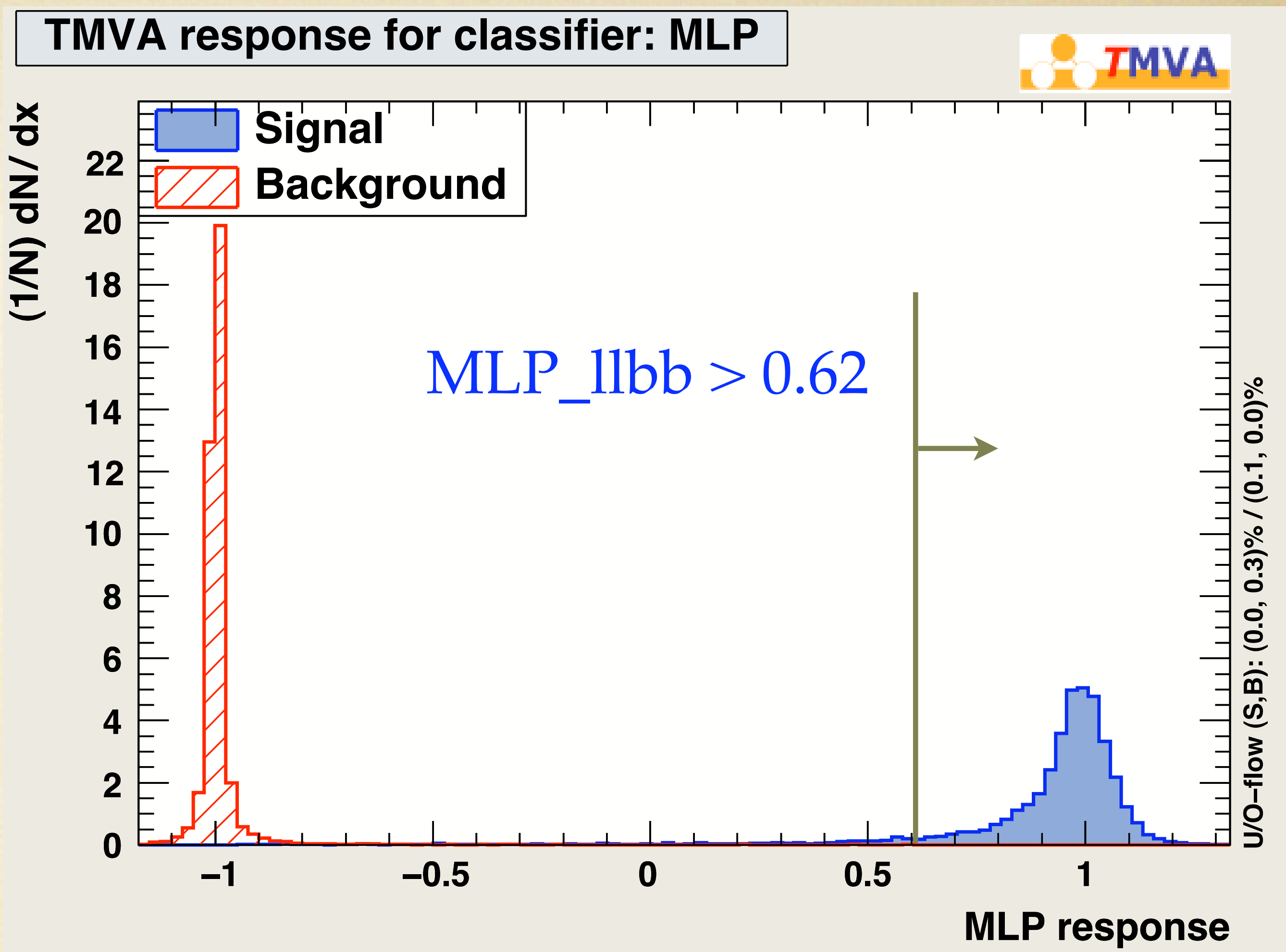
Econe: sum of cone energy of two lepton
EconeC: sum of charged cone energy
pLep: momentum of lepton

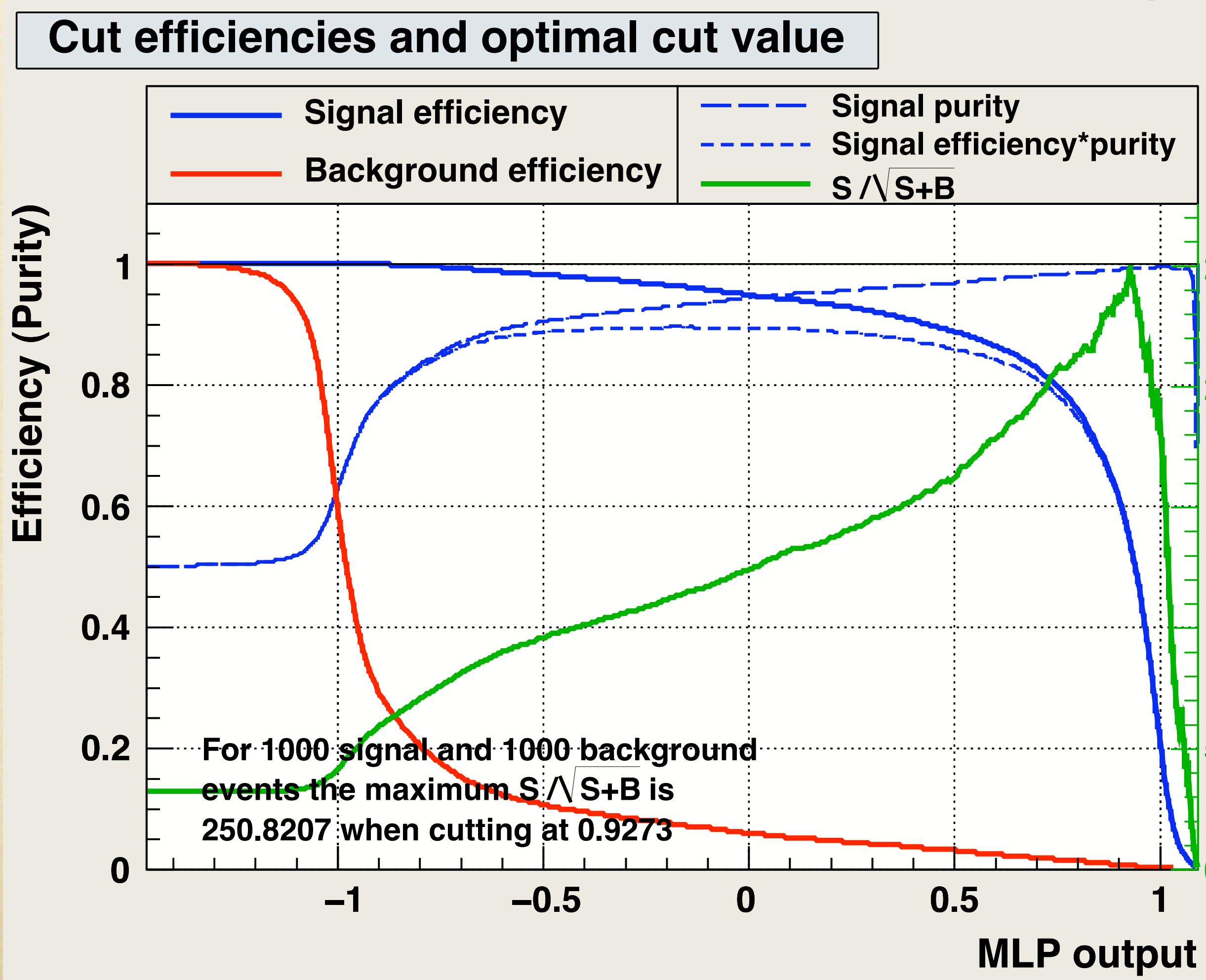
llHH .vs. llbb

inputs:

Invariant mass of two leptons
Thrust and axis of thrust
Y(4->3), Y(3->2)
Largest angle between Z and the two other jets
Largest Jet Momentum in case of two jets
Total number of PFOs
Smallest number of PFOs in a jet



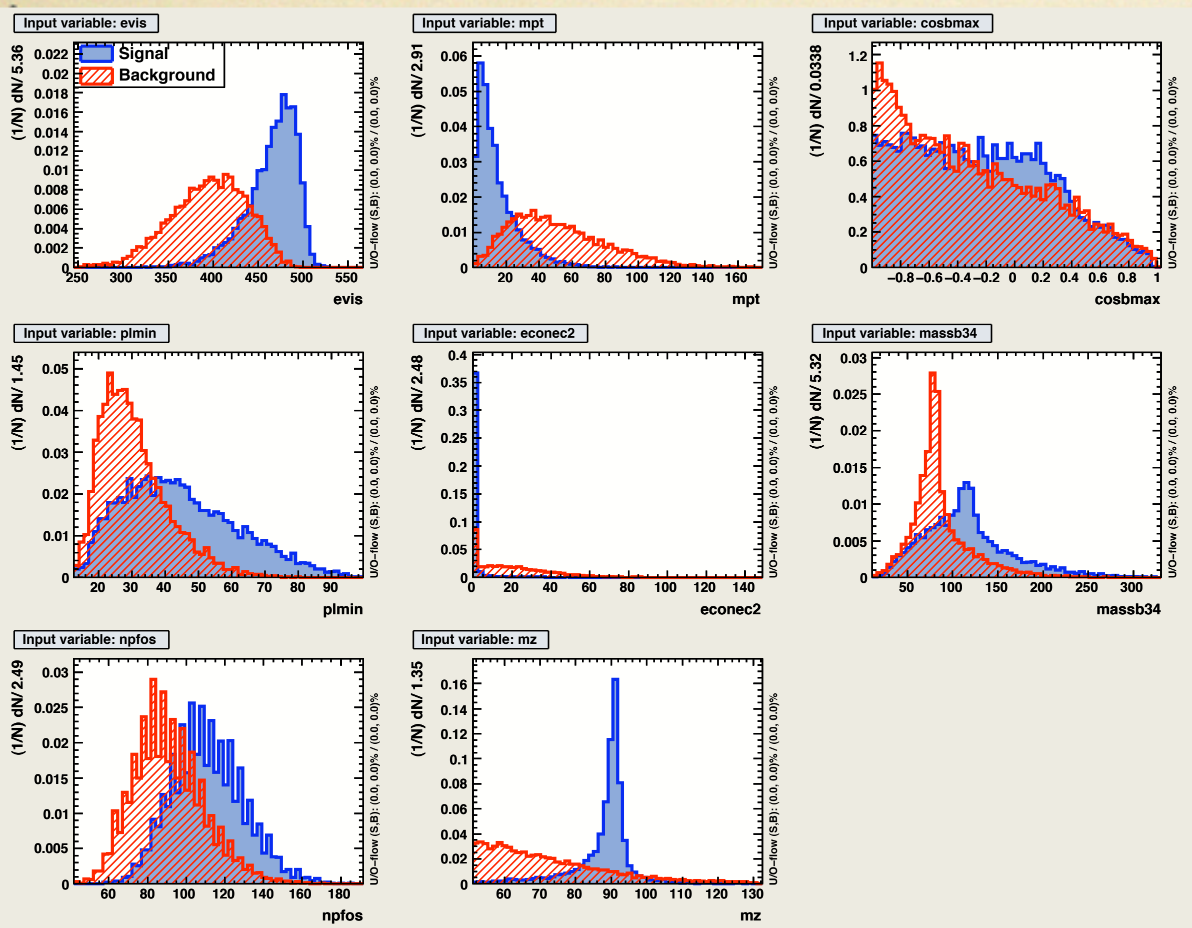


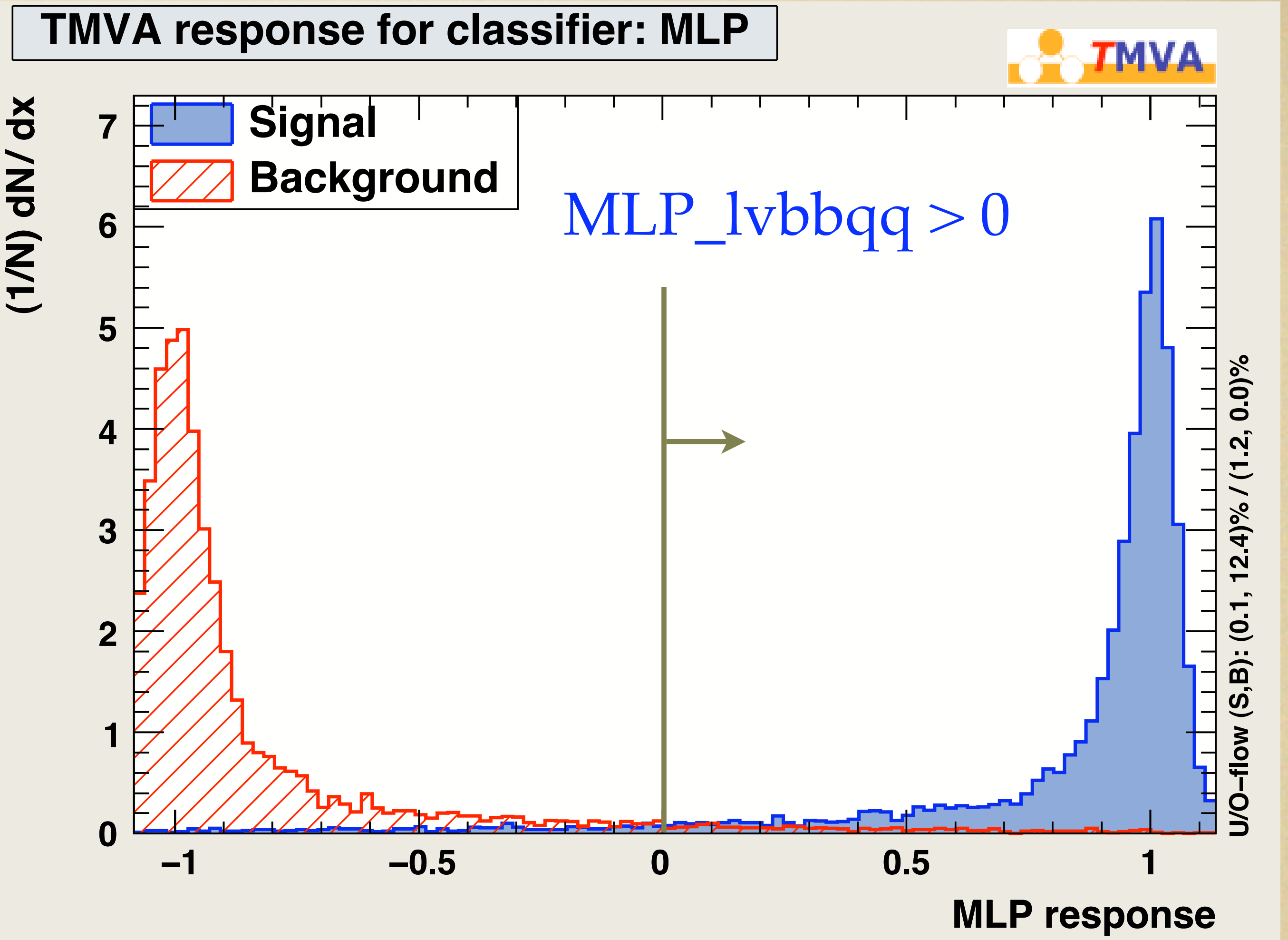


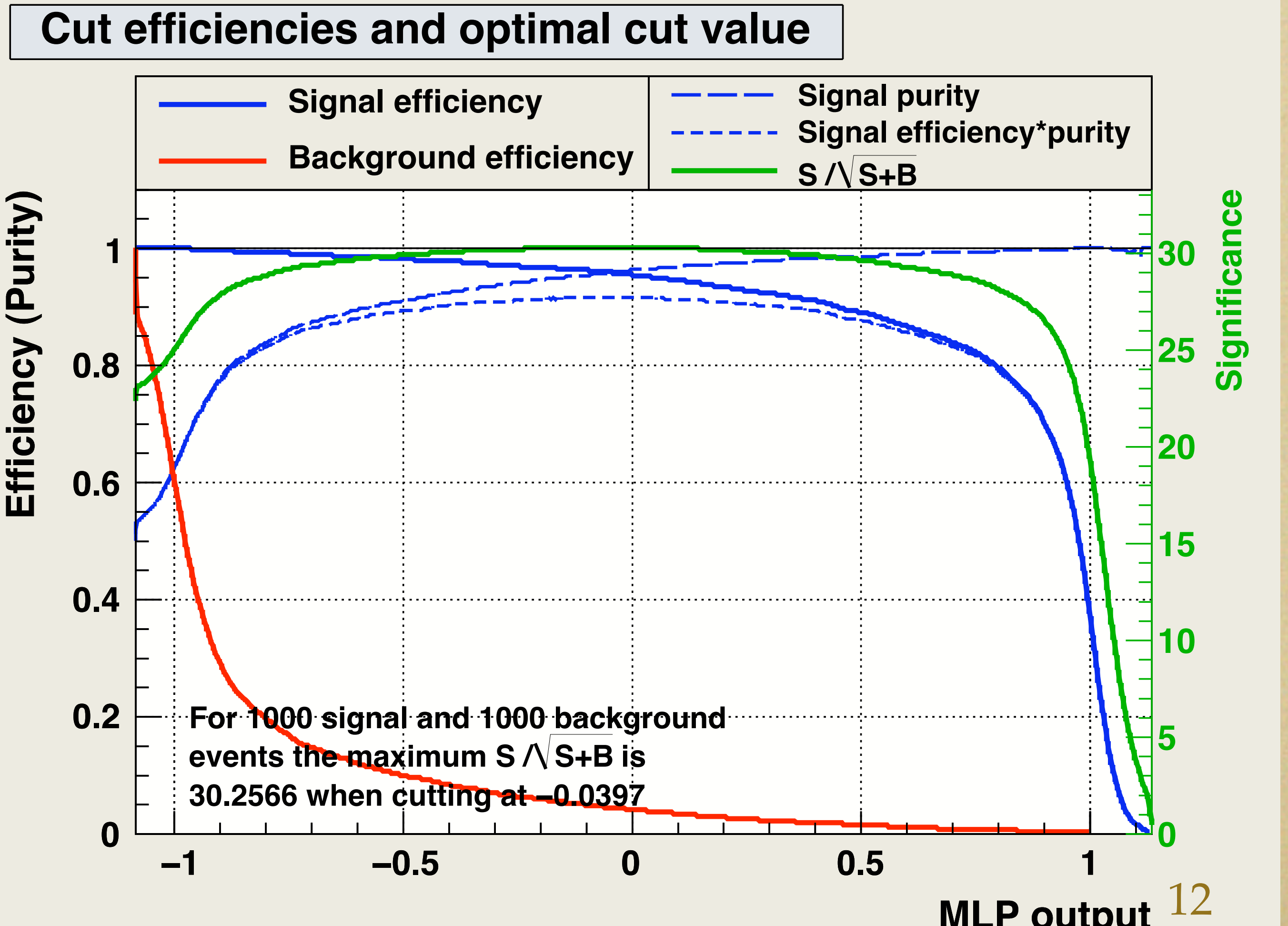
llHH .vs. lvbbqq

inputs:

Visible energy and missing Pt
Angle between two most like b jets
Momentum and cone energy of the slower leptons
Invariant mass of jets 3 and 4 (orderer by b-likeness)
Total number of PFOs
Invariant mass of two leptons



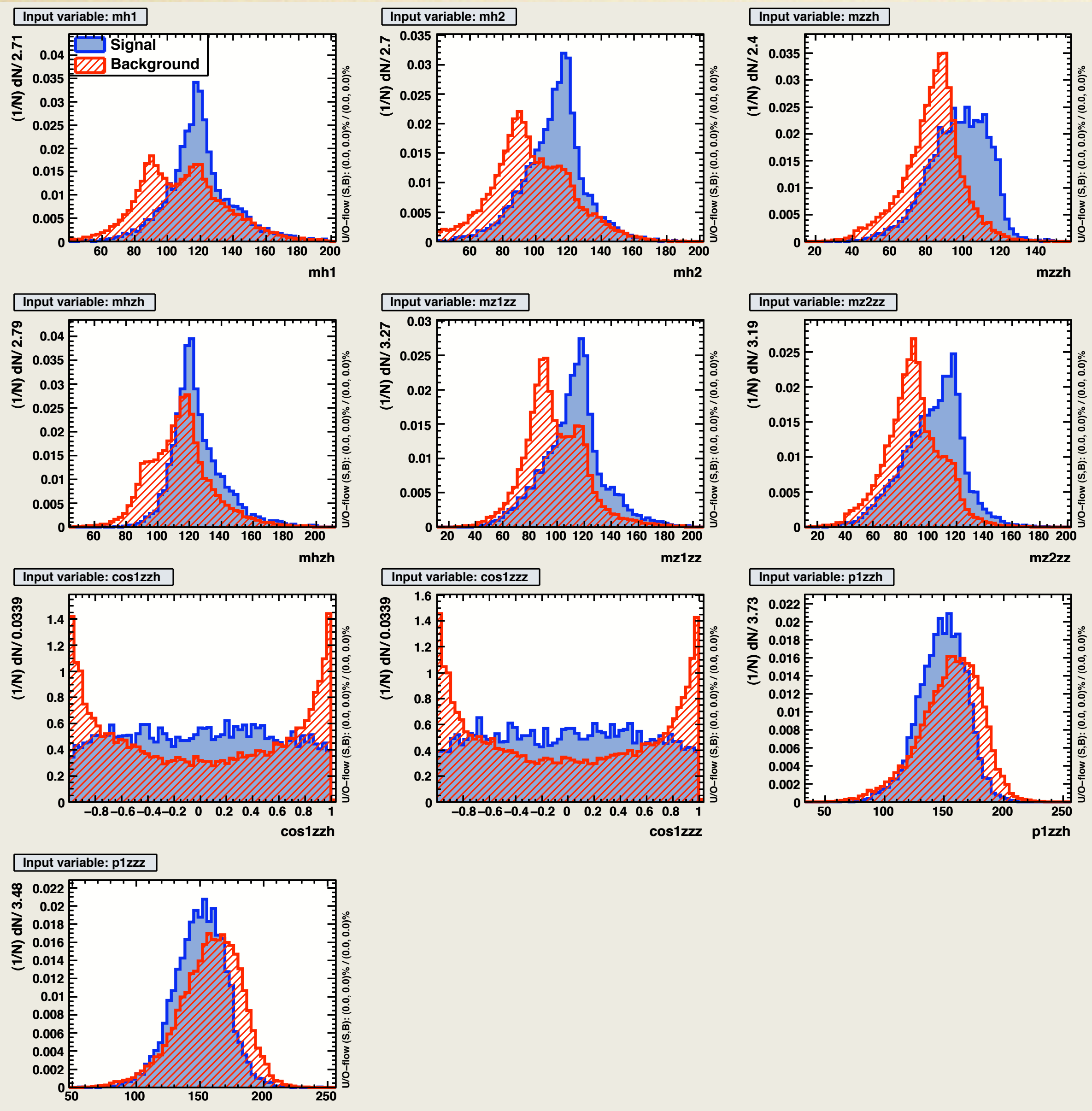


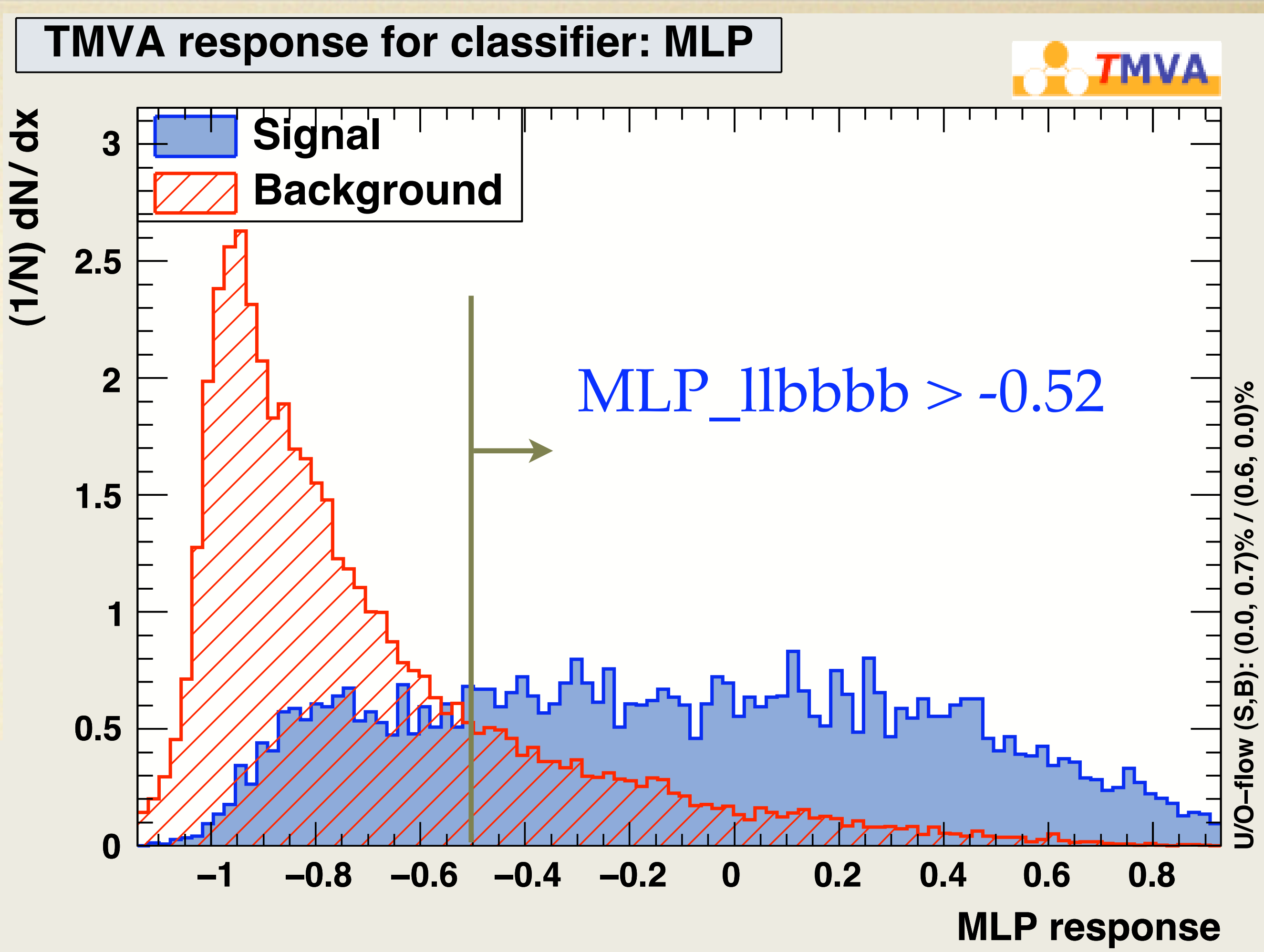


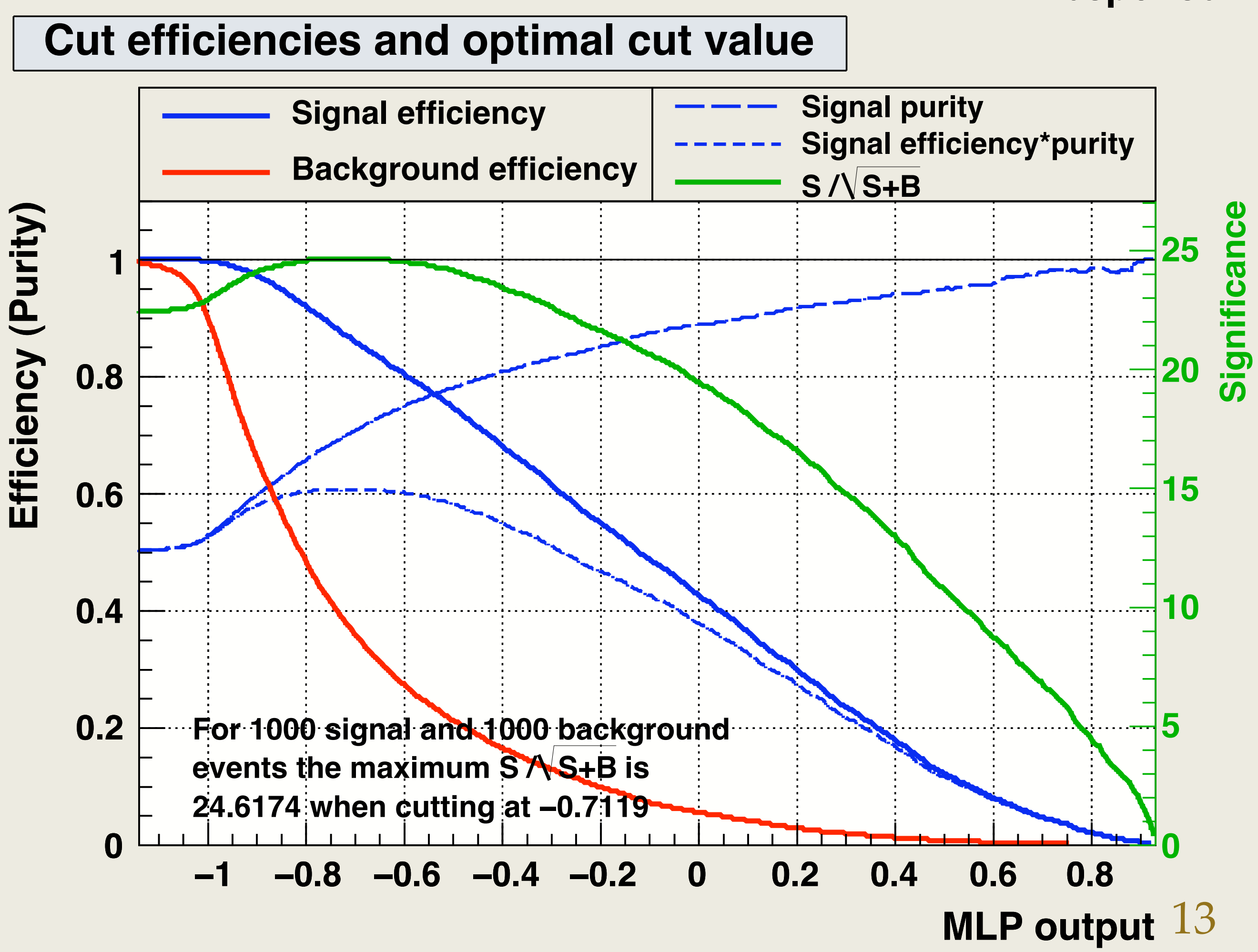
llHH .vs. llbbbb(llbbH)

inputs:

Two Higgs masses
Z and Higgs masses in case of llZH
Two Z masses in case of llZZ
Angle and momentum of the fastest boson
in case of llZH and llZZ







b tagging

4 jets are ordered by the b-likeness: bmax1 > bmax2 > bmax3 > bmax4

$$\begin{cases} \mathrm{Bmax2} > 0.62 \\ \mathrm{Bmax3} > 0.24 \end{cases}$$

reduction table (llHH)

Polarization: (e-,e+)=(0,0) $E_{\rm cm} = 500{\rm GeV}, M_H = 120{\rm GeV}$ $\int Ldt = 2{\rm ab}^{-1}$

normalized	expected	MC	pre-selection	Econe12+4Econec12<60 Plep1+Plep2>80	MLP_llbb>0.62	MLP_lvbbqq>0	Bmax2>0.62 Bmax3>0.24	MLP_llbbbb>-0.52
llhh(llbbbb)	21.2(9.50)	39827	17.4(7.81)	16.0(7.15)	11.8(6.67)	11.4(6.54)	5.40(4.96)	4.24(3.92)
BG	3160000		34037	15433	762	269	15.0	3.84
llbbbb	25.6	10924	8.75	7.57	4.56	4.54	3.35	0.63
llbbh	20.1	24000	17.0	15.9	12.0	11.7	7.14	2.04
llqqh	72.7	12000	61.2	57.4	38.5	37.8	2.02	0.65
bbbbbb	6.9	19998	0.034	0	0	0	0	0
bbcsdu	230600	405727	328.5	0	0	0	0	0
bbcssc	115600	230701	166.9	0	0	0	0	0
bbuddu	116200	231600	158.0	0	0	0	0	0
bbbb	23900	103401	99.4	0.23	0	0	0	0
qqbb	183768	353715	236	0	0	0	0	0
qqcc	103400	20672	40.02	0	0	0	0	0
lvbbqq	477600	397602	8614	975	554	70.1	1.00	0
llbb	316000	2520954	12961	7423	38.7	36.8	1.51	0.52
llcc	1434800	1611287	12511	7012	105	104	0	0

reduction table (llHH)

Polarization: (e-,e+)=(-0.8,0.3) $E_{\rm cm} = 500{\rm GeV}, M_H = 120{\rm GeV}$ $\int Ldt = 2{\rm ab}^{-1}$

normalized	expected	MC	pre-selection	Econe12+4Econec12<60 Plep1+Plep2>80	MLP_llbb>0.62	MLP_lvbbqq>0	Bmax2>0.62 Bmax3>0.24	MLP_llbbbb>-0.52
llhh(llbbbb)	31.5(14.1)	39827	25.8(11.6)	23.7(10.6)	17.6(9.93)	16.9(9.74)	8.05(7.42)	6.39(5.81)
BG			45136	19863	1240	396	26.2	6.74
llbbbb	39.7	10924	16.1	14.0	8.65	8.47	6.40	1.23
llbbh	31.8	24000	26.9	25.2	19.0	18.7	11.3	3.25
llqqh	115	12000	96.7	90.6	60.9	59.8	3.18	1.03
llbb	335019	2520954	17472	10964	82.3	78.1	3.54	1.22
lvbbqq	821199	397602	14811	1676	953	120	1.72	0
llcc	1491003	1611287	16510	10062	173	169	0	0

reduction table (llHH)

Polarization: (e-,e+)=(+0.8,-0.3) $E_{\rm cm} = 500\text{GeV}, M_H = 120\text{GeV}$ $\int Ldt = 2\text{ab}^{-1}$

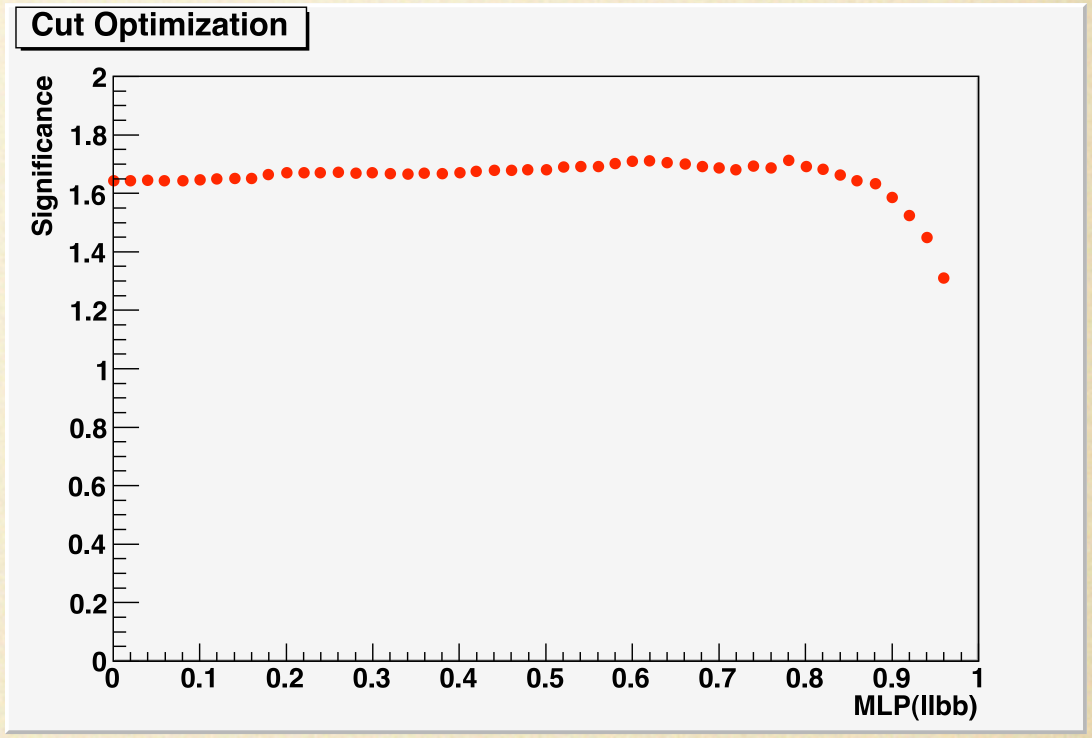
normalized	expected	MC	pre-selection	Econe12+4Econec12<60 Plep1+Plep2>80	MLP_llbb>0.62	MLP_lvbbqq>0	Bmax2>0.62 Bmax3>0.24	MLP_llbbbb>-0.52
llhh(llbbbb)	21.2(9.50)	39827	17.4(7.76)	16.0(7.10)	11.8(6.62)	11.3(6.49)	5.34(4.89)	4.14(3.81)
BG			30463	14242	608	232	11.8	3.00
llbbbb	39.7	10924	5.64	4.82	2.67	2.58	1.92	0.31
llbbh	31.8	24000	15.3	14.3	10.8	10.5	6.41	1.80
llqqh	115	12000	55.1	51.6	34.7	34.0	1.81	0.59
llbb	335019	2520954	11453	6745	24.2	23.2	0.89	0.30

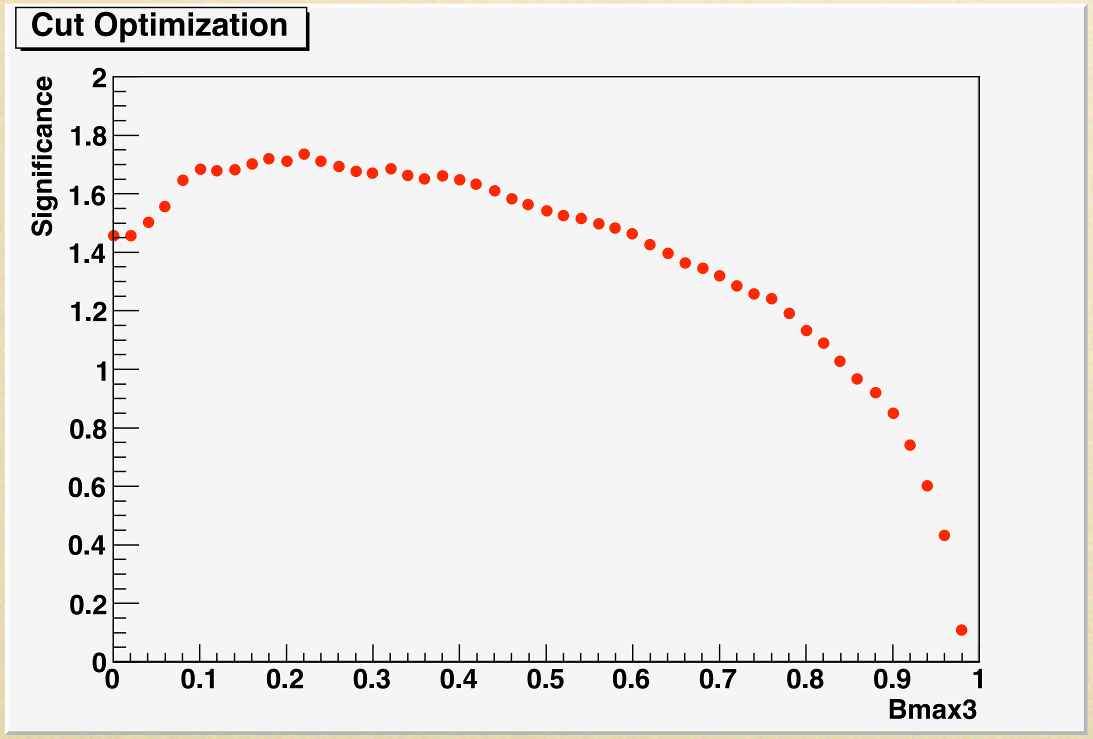
cut optimization (llHH)

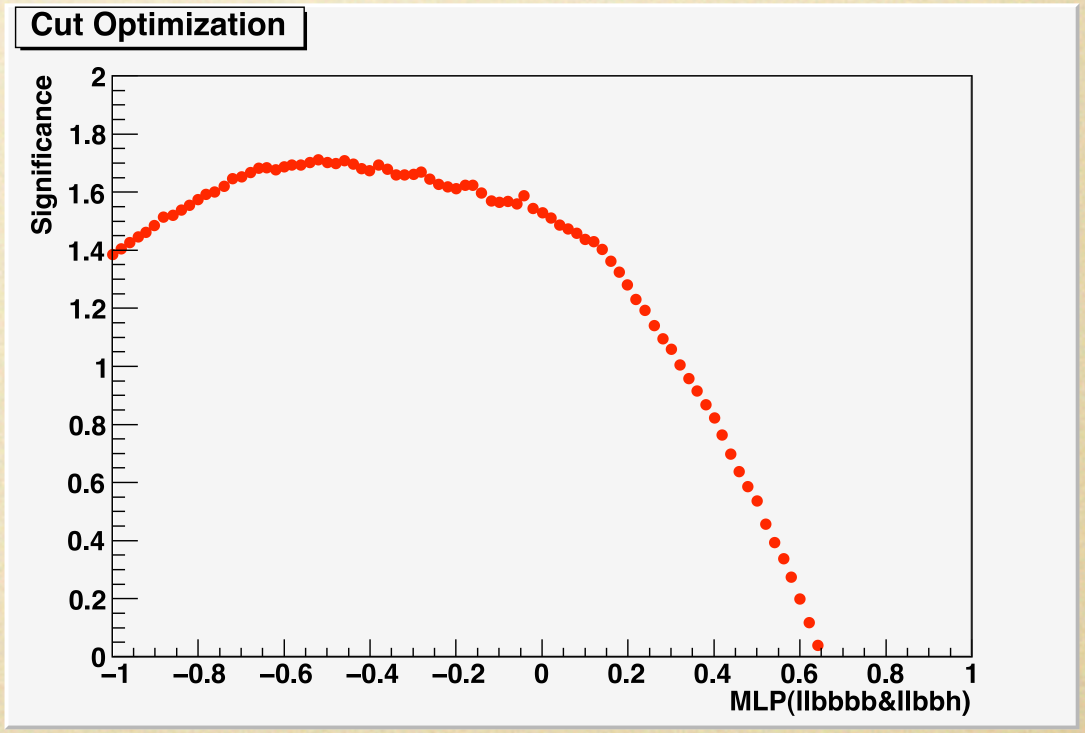
full simulation @ 500GeV

Polarization: (e-,e+)=(-0.8,0.3) $\int Ldt = 2\text{ab}^{-1}$

llhh	6.39±0.10
BG	6.74±0.35
llbbbb	1.23±0.10
llbbh	3.25±0.09
llqqh	1.07±0.04
llbb	1.22±0.32







$$e^+ + e^- \to ZHH \to (\nu\bar{\nu})(b\bar{b})(b\bar{b}) \to \nu\bar{\nu} + 4 \text{ bjets}$$

full simulation @ 500GeV

pre-selection:

- no isolated charged leptons
- force the particles(PFOs) to four jets
- combine the four jets by minimizing

$$\chi^2 = \frac{(M(b,\bar{b}) - M_H)^2}{\sigma^2_{H_1}} + \frac{(M(b,\bar{b}) - M_H)^2}{\sigma^2_{H_2}}$$

requirement implied in the pre-selection:

- | M(jj)-M(H) | < 80 GeV

final selection:

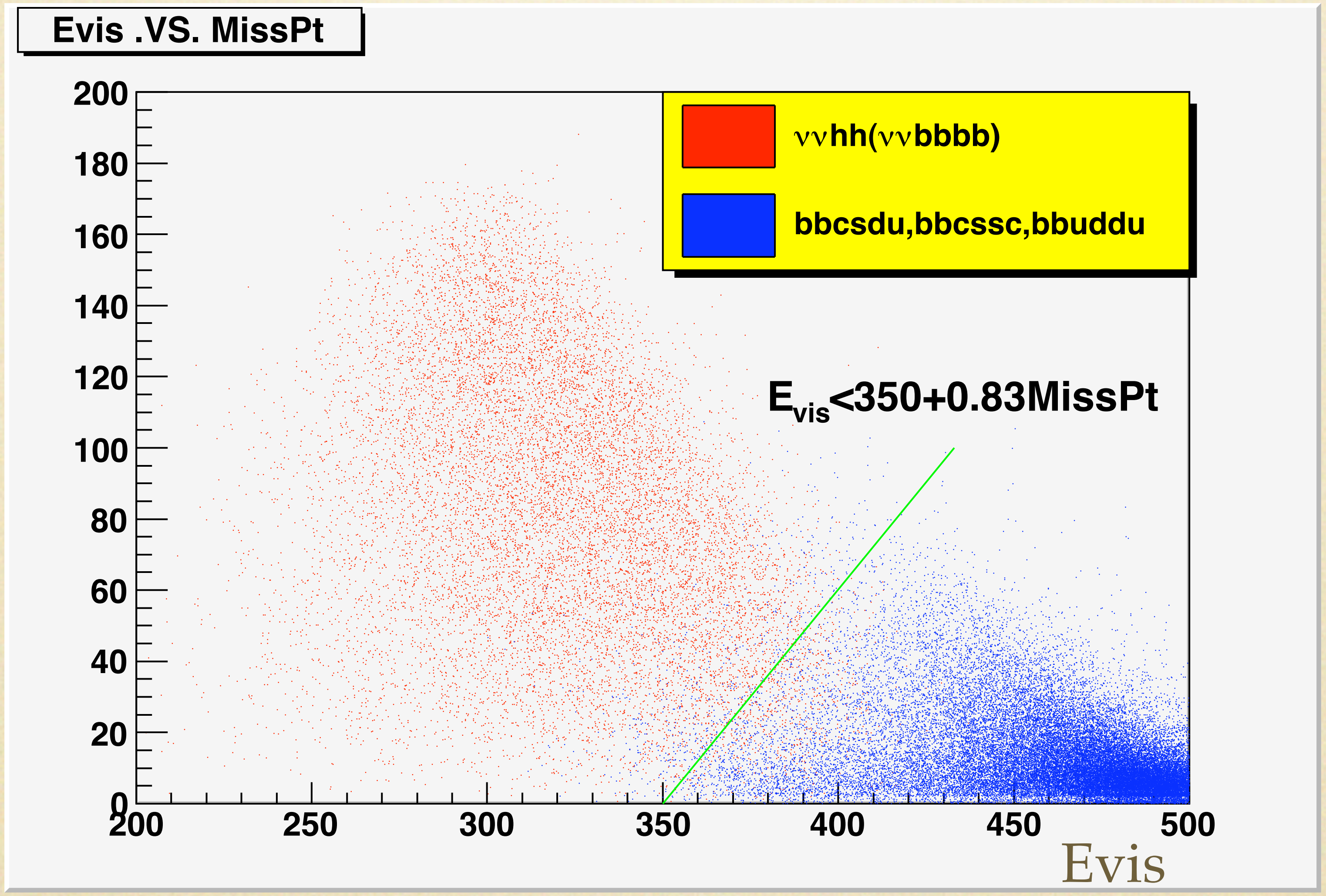
- similar strategy with llHH

main backgrounds:

bbcsdu, qqbb
vvbb
bbbb
lvbbqq
vvbbbb, vvbbH

vvHH .vs. full hadronic backgrounds

bbcsdu, bbcssc, bbuddu



$$E_{vis} < 350 + 0.83\mathrm{MissPt}$$

$$\text{Missing Mass} > 0$$

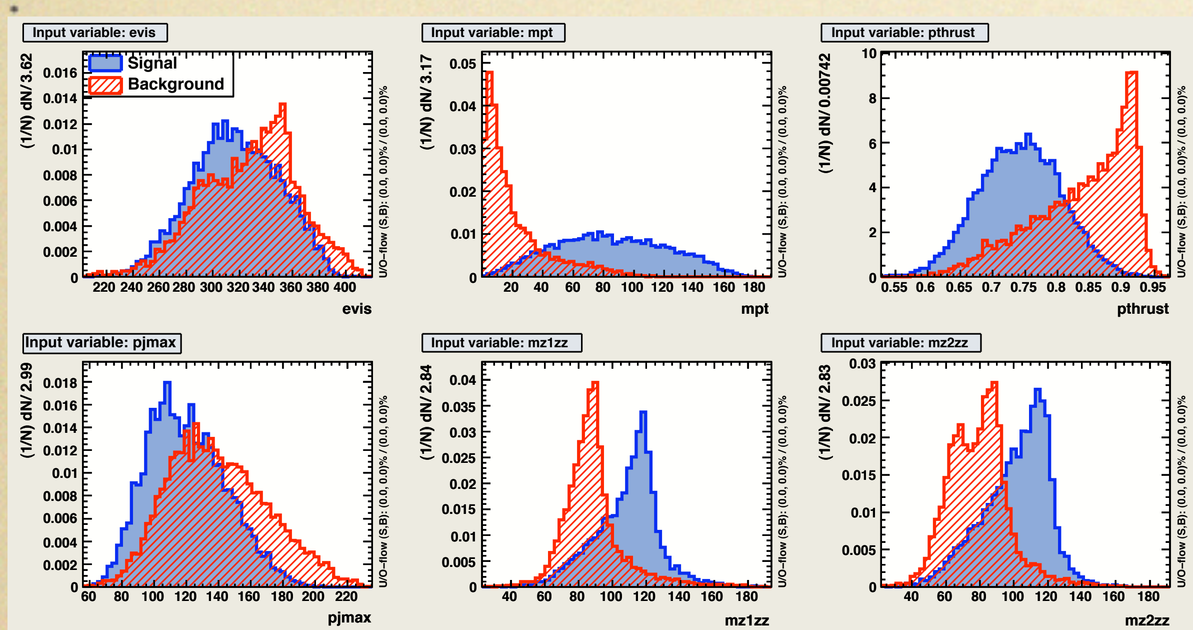
vvHH .vs. vvbb (vvh)

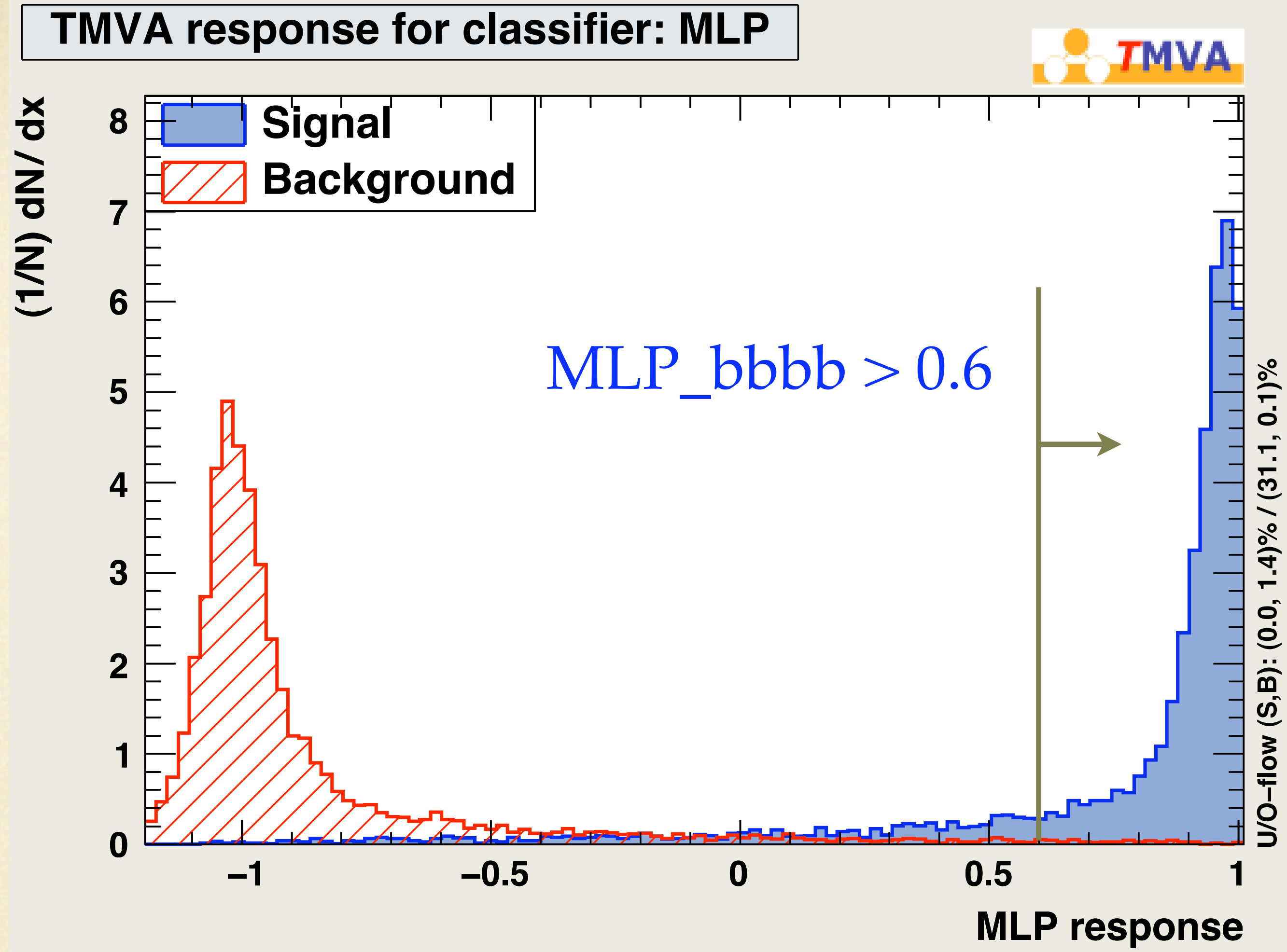
- at least 8 PFOs in a jet
- Ycut > 0.002
- invariant mass of all PFOs > 200 GeV

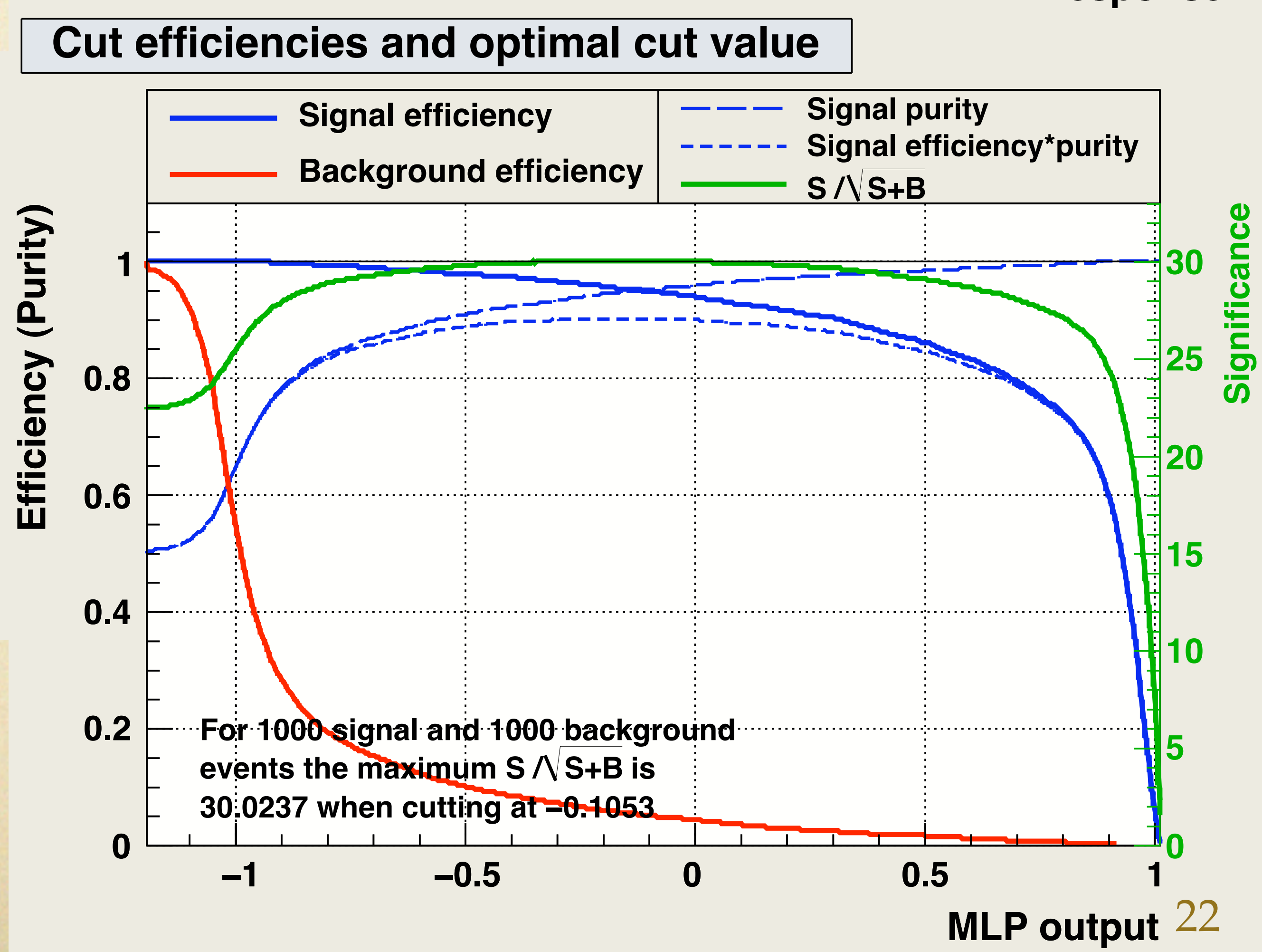
vvHH .vs. bbbb

inputs:

Visible energy and missing Pt
Thrust
Largest Jet Momentum in case of two jets
Two Z masses in case of ZZ reconstruction





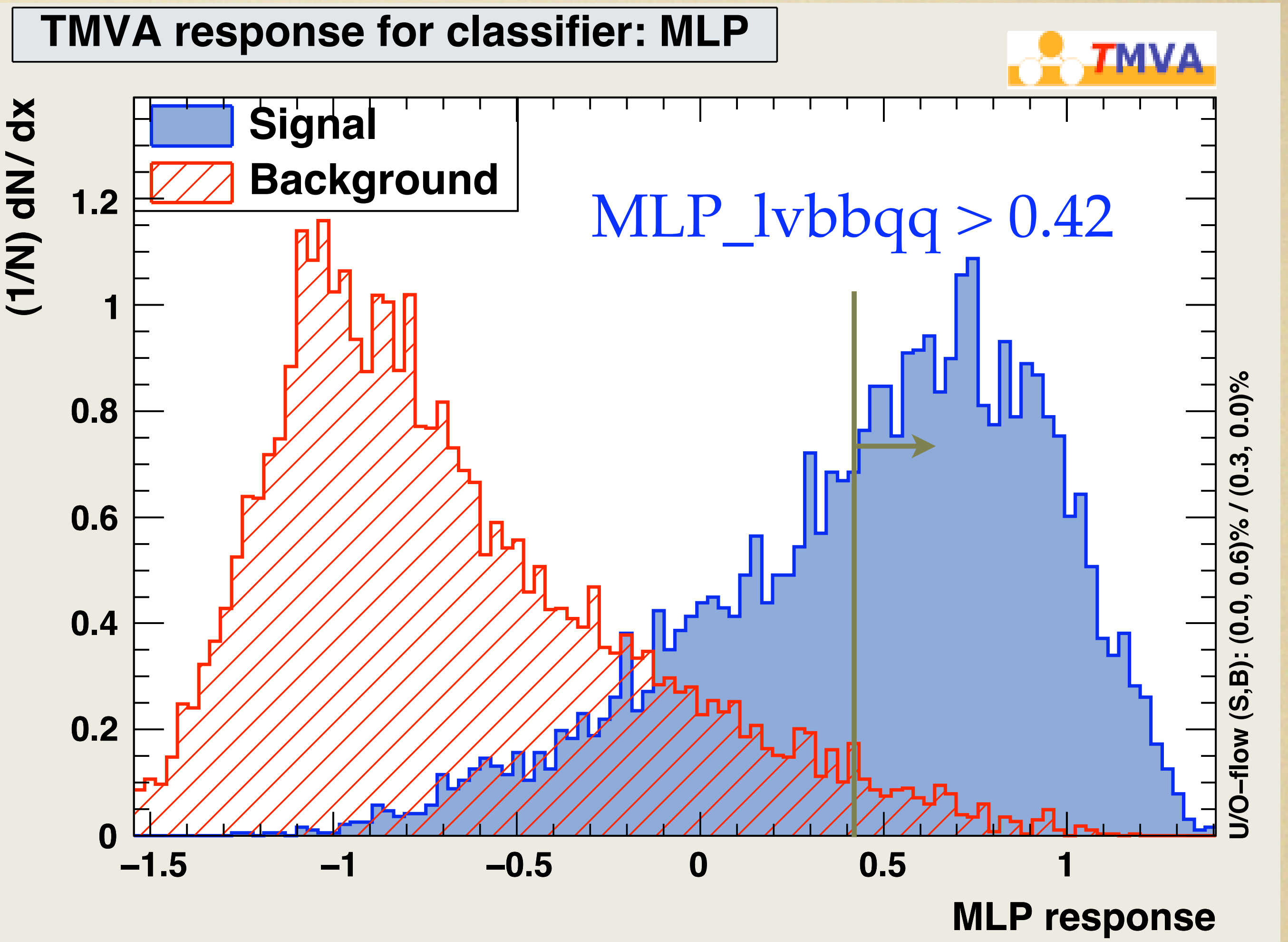


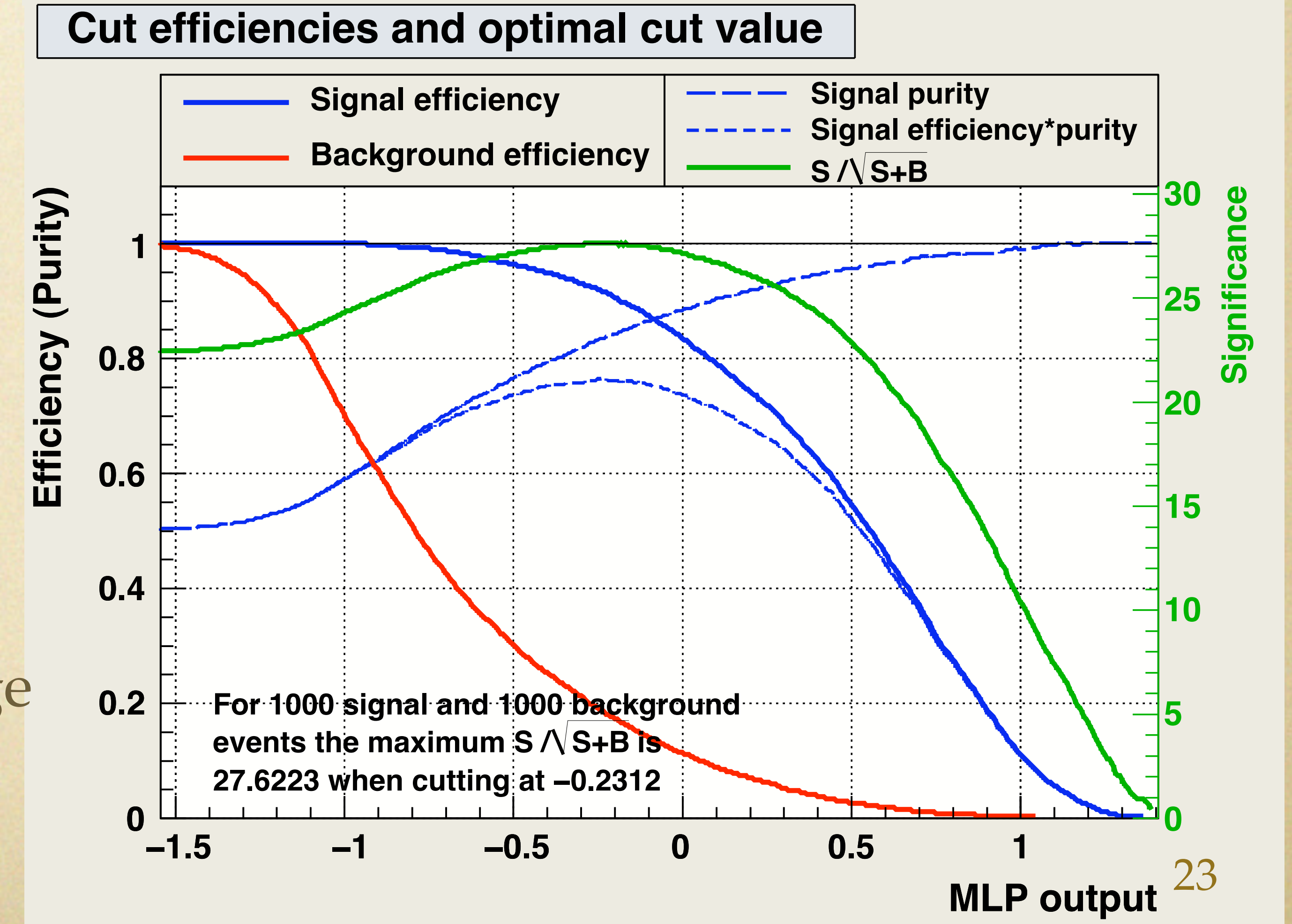
vvHH .vs. lvbbqq

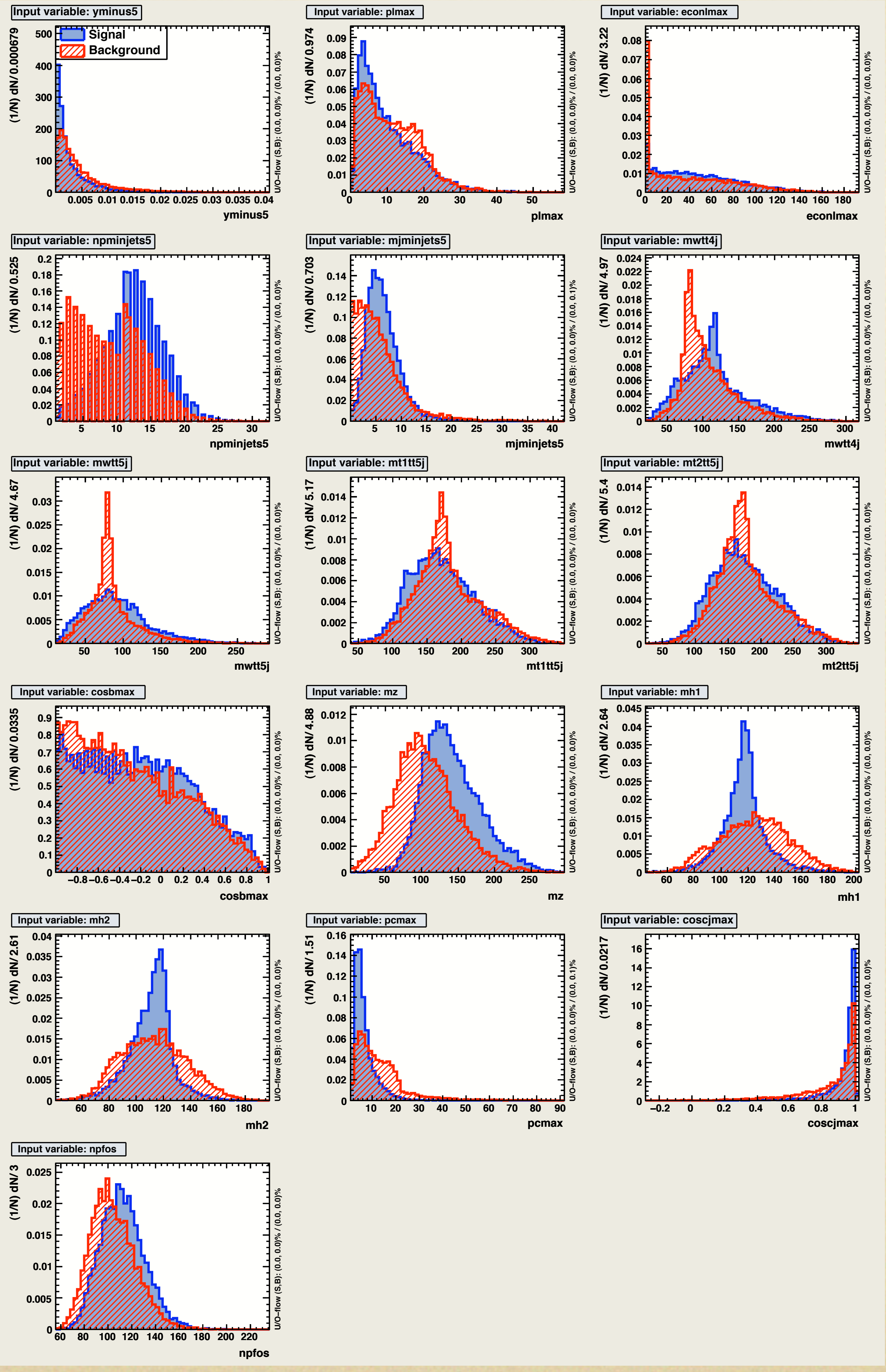
inputs:

Y(5->4)
Largest lepton momentum and its cone energy
Smallest number of PFOs in a jet in case of 5 jets and invariant mass of that jet
W mass in case of 4 jets and 5 jets
Top mass in case of 5 jets
Angle between two most like b jets
Miss mass
Two Higgs masses
Largest momentum of charged PFOs and it's angle to the nearest jet
Total number of PFOs

distribution of these inputs in next page



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Signal
Background
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Input variable: cosbmax
cosbmax
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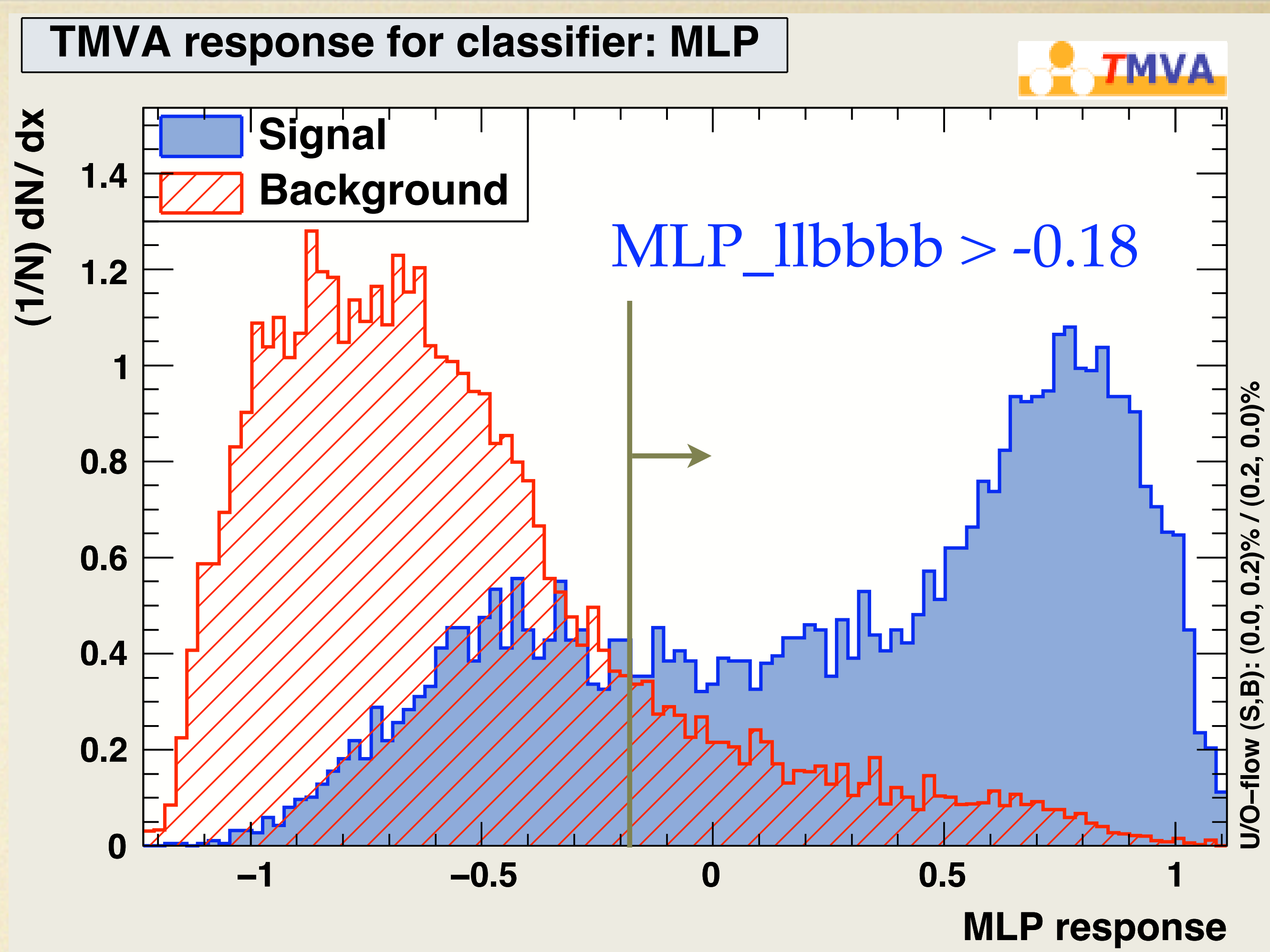
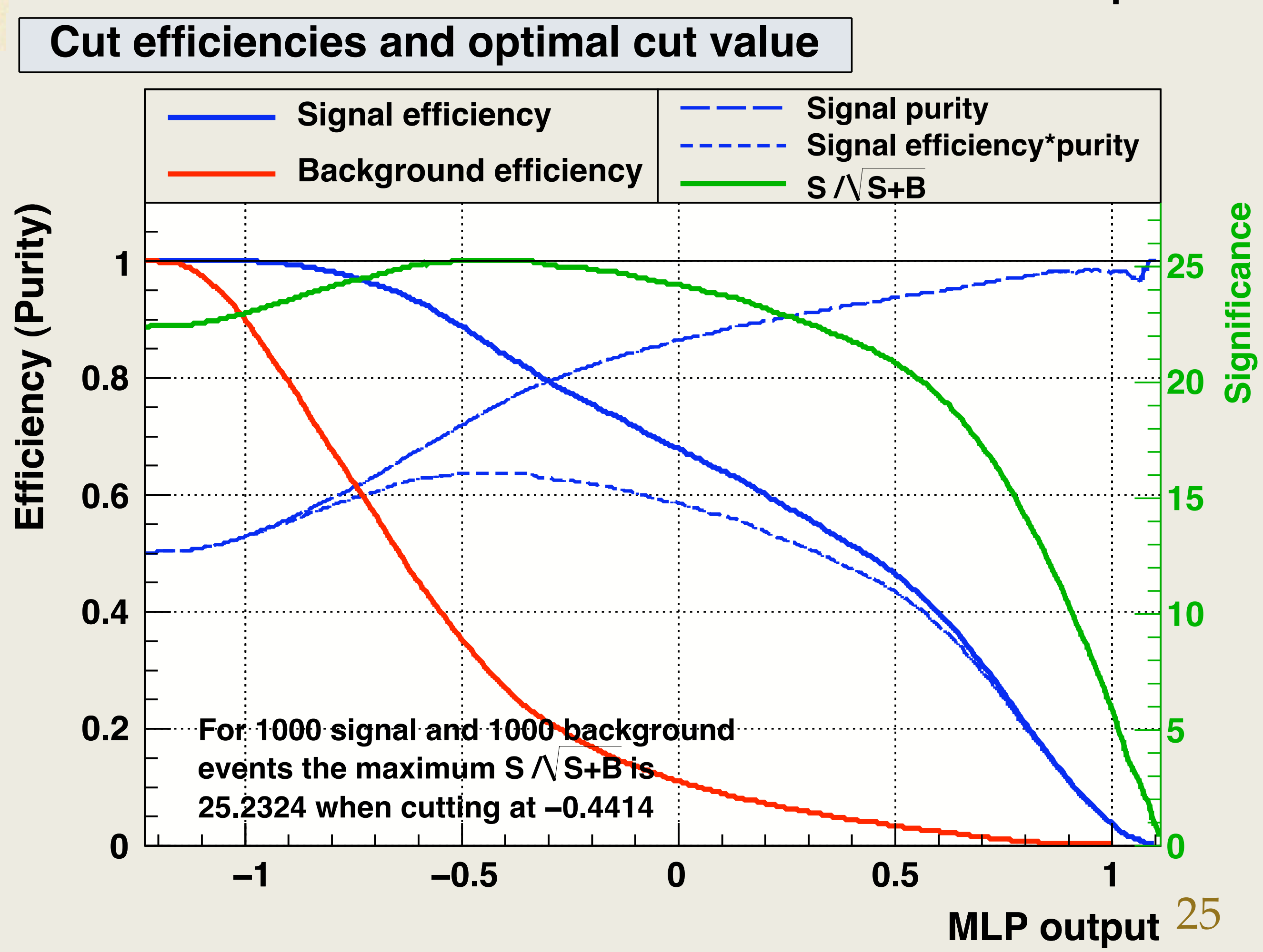
Input variable: mh1
mh1
Input variable: mh2
mh2
Input variable: pcmax
pcmax
Input variable: coscjmax
coscjmax
Input variable: npfos
npfos

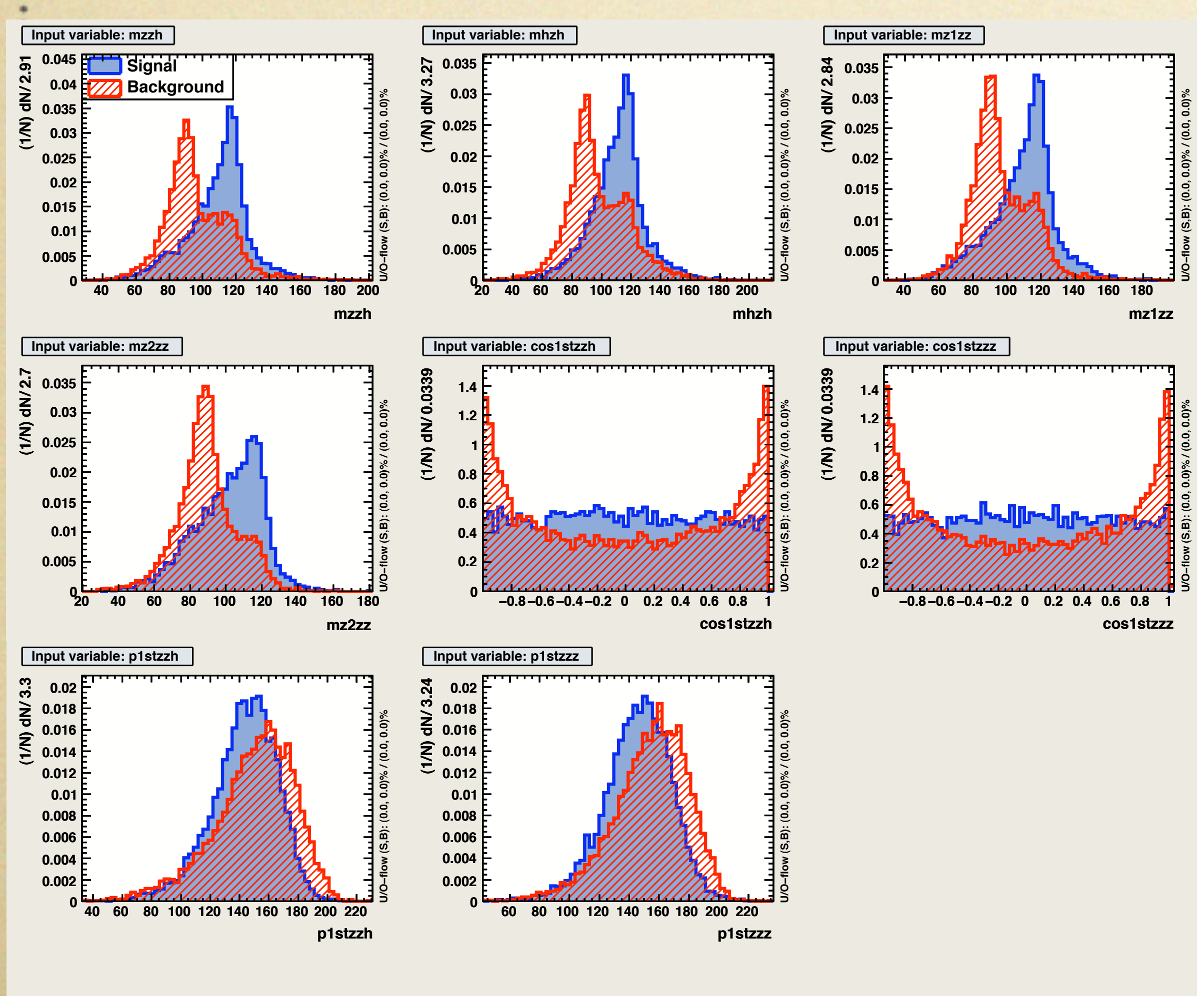
vvHH .vs. vvbbbb(vvbbH)

inputs:

Z and Higgs masses in case of vvZH
Two Z masses in case of vvZZ
Angle and momentum of the fastest boson
in case of vvZH and vvZZ







b tagging

4 jets are ordered by the b-likeness: bmax1 > bmax2 > bmax3 > bmax4

$$\mathrm{Bmax3} + \mathrm{Bmax4} > 1.15$$

very tight b tagging cut!

reduction table (vvHH) (new)

Polarization: (e-,e+)=(0,0) $E_{\rm cm} = 500{\rm GeV}, M_H = 120{\rm GeV}$ $\int Ldt = 2{\rm ab}^{-1}$

normalized	expected	MC	pre-selection	Evis<350+0.83M issPt MissMass > 0	NpfosMin>=8 Ycut>0.002 mhh>200	MLP_bbbb>0.6	MLP_lvbbqq>0.42	MLP_vvbbbb>-0.18	Bmax3+Bmax4 >1.15
νvhh(νvbbbb)	67.7(30.2)	45000	22.9(21.7)	21.8(20.7)	19.5(18.8)	16.7(16.1)	9.88(9.66)	8.09(7.92)	3.31(3.30)
BG			71837	18337	9747	5131	248	184	3.51
νvbbbb	50.5	30000	33.2	32.5	22.3	13.0	3.91	1.04	0.29
νvbbH	60.0	23670	29.4	28.5	24.9	19.0	6.63	2.54	0.97
bbcsdu	230600	405727	10775	120	119	21.6	5.12	5.12	0
bbuddu	116200	231600	1526	19.1	18.1	2.51	0	0	0
bbcssc	115600	230721	10028	139	136	23.0	4.00	4.00	0
qqbb	183700	29637	12546	1827	968	33.8	13.5	13.5	0
bbbb	23900	414165	13857	1369	1045	12.7	3.80	2.66	0.86
llbb	316000	610502	3109	145	7.69	0.53	0	0	0
νvbb	150000	30001	4015	3920	30.0	20.0	0	0	0
evbbqq	159200	242851	1301	829	678	488	11.0	7.00	0
μvbbqq	159200	241777	1289	967	841	606	19.0	15.0	0
τvbbqq	159200	1815503	13327	8942	5865	3892	181	133	1.39

reduction table (vvHH) (new)

Polarization: (e-,e+)=(-0.8,+0.3) $E_{\mathrm{cm}} = 500\mathrm{GeV}, M_H = 120\mathrm{GeV}$ $\int Ldt = 2\mathrm{ab}^{-1}$

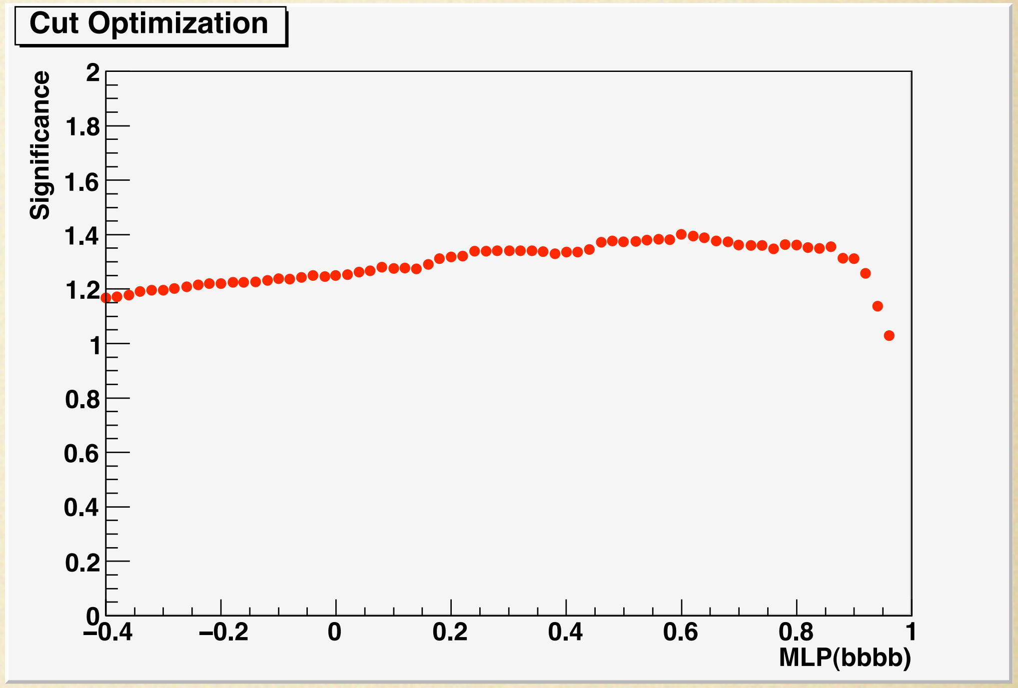
normalized	expected	MC	pre-selection	Evis-0.83MissPt <350 MissMass > 0	NpfosMin>=8 Ycut>0.002 mhh>200	MLP_bbbb>0.6	MLP_lvbbqq>0.42	MLP_vvbbbb>-0.18	Bmax3+Bmax4 >1.15
νvhh(vvbbbb)	109.9(49.0)	45000	36.7(34.7)	35.1(33.1)	31.0(29.9)	26.2(25.3)	15.6(15.3)	12.8(12.5)	5.21(5.20)
BG			122246	32598	16814	8886	444	323	7.00
vvbbbb	105	30000	69.7	68.2	46.6	27.1	8.50	2.25	0.63
vvbbH	92.7	23670	45.4	44.1	38.5	29.4	10.2	3.92	1.50
bbcsdu	394548	405727	18436	205	203	37.0	8.75	8.75	0
bbuddu	199165	231600	2616	32.7	31.0	4.30	0	0	0
bbcssc	197790	230721	17158	237	233	39.4	6.86	6.86	0
qqbb	312453	29637	21340	3108	1646	57.6	23.0	23.0	0
bbbb	40824	414165	23785	2332	1801	24.7	7.73	5.07	1.62
llbb	335019	610502	3290	183	10.2	0.14	0	0	0
vvbb	311451	30001	8336	8139	62.3	41.5	0	0	0
evbbqq	273733	242851	2237	1425	1166	839	18.9	12.0	0
μvbbqq	273733	241777	2217	1662	1446	1041	32.6	25.7	0
τvbbqq	273733	1815503	22717	15160	10140	6745	327	235	3.25

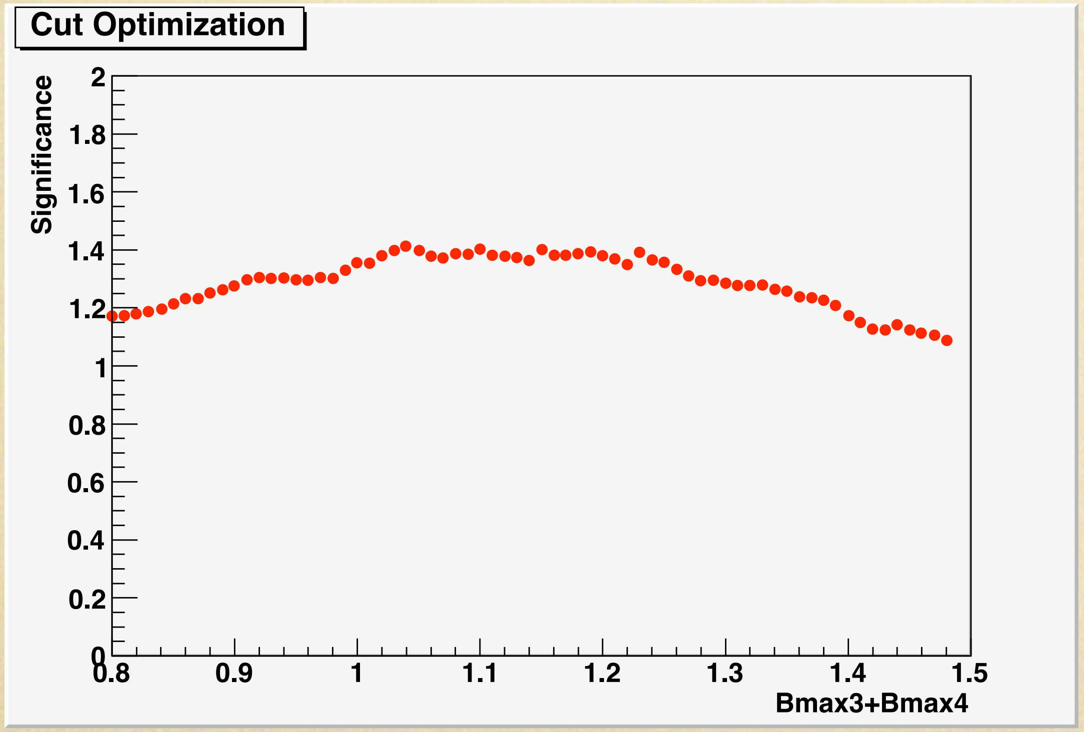
cut optimization (vvHH)

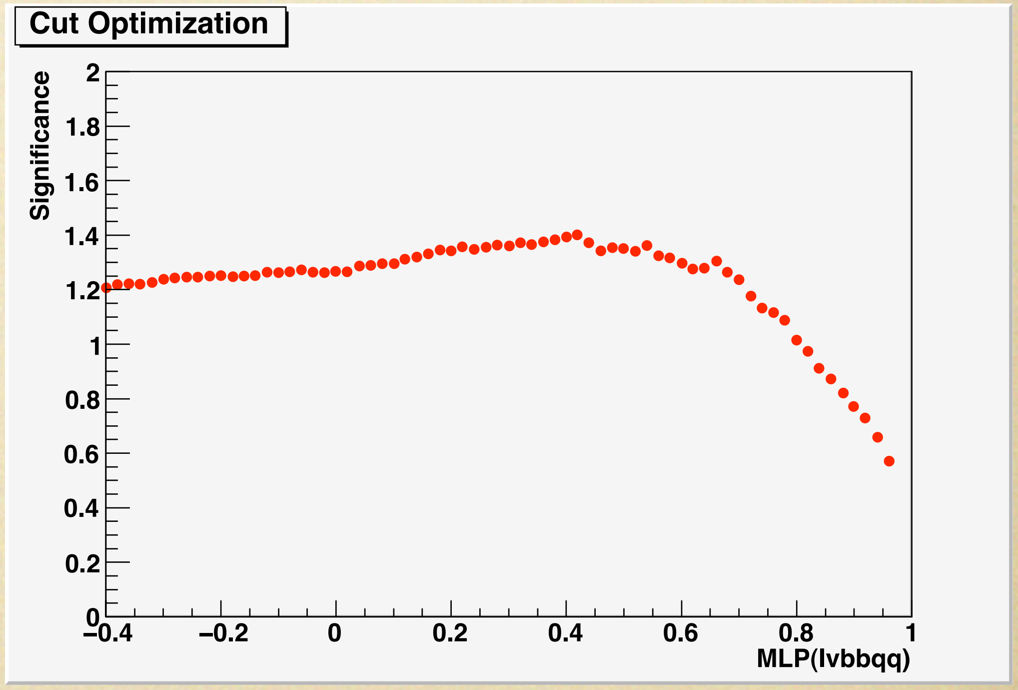
full simulation @ 500GeV

Polarization: (e-,e+)=(-0.8,0.3) $\int Ldt = 2\text{ab}^{-1}$

vvhh	5.21±0.15
BG	7.00±0.73
vvbbbb	0.63±0.10
vvbbh	1.50±0.08
bbbb	1.62±0.41
tauvbbqq	3.25±0.59







$$e^+ + e^- \to ZHH \to (q\bar{q})(b\bar{b})(b\bar{b}) \to q\bar{q} + 4 \text{ bjets}$$

full simulation @ 500GeV

pre-selection:

- not require no isolated charged leptons, but information kept
- force the particles(PFOs) to six jets
- combine the four jets by minimizing, and require the b tagging

$$\chi^2 = \frac{(M(b,\bar{b}) - M_H)^2}{\sigma^2_{H_1}} + \frac{(M(b,\bar{b}) - M_H)^2}{\sigma^2_{H_2}} + \frac{(M(q,\bar{q}) - M_Z)^2}{\sigma^2_{Z_2}}$$

requirement implied in the pre-selection:

- b likeness of the four jets from two Higgs > 0.3

final selection:

- similar strategy with llHH
- treat bbHH and qqHH differently

main backgrounds:

bbbb
lvbbqq
bbcsdu,bbcssc,bbuddu
qqbbbb, qqbbH

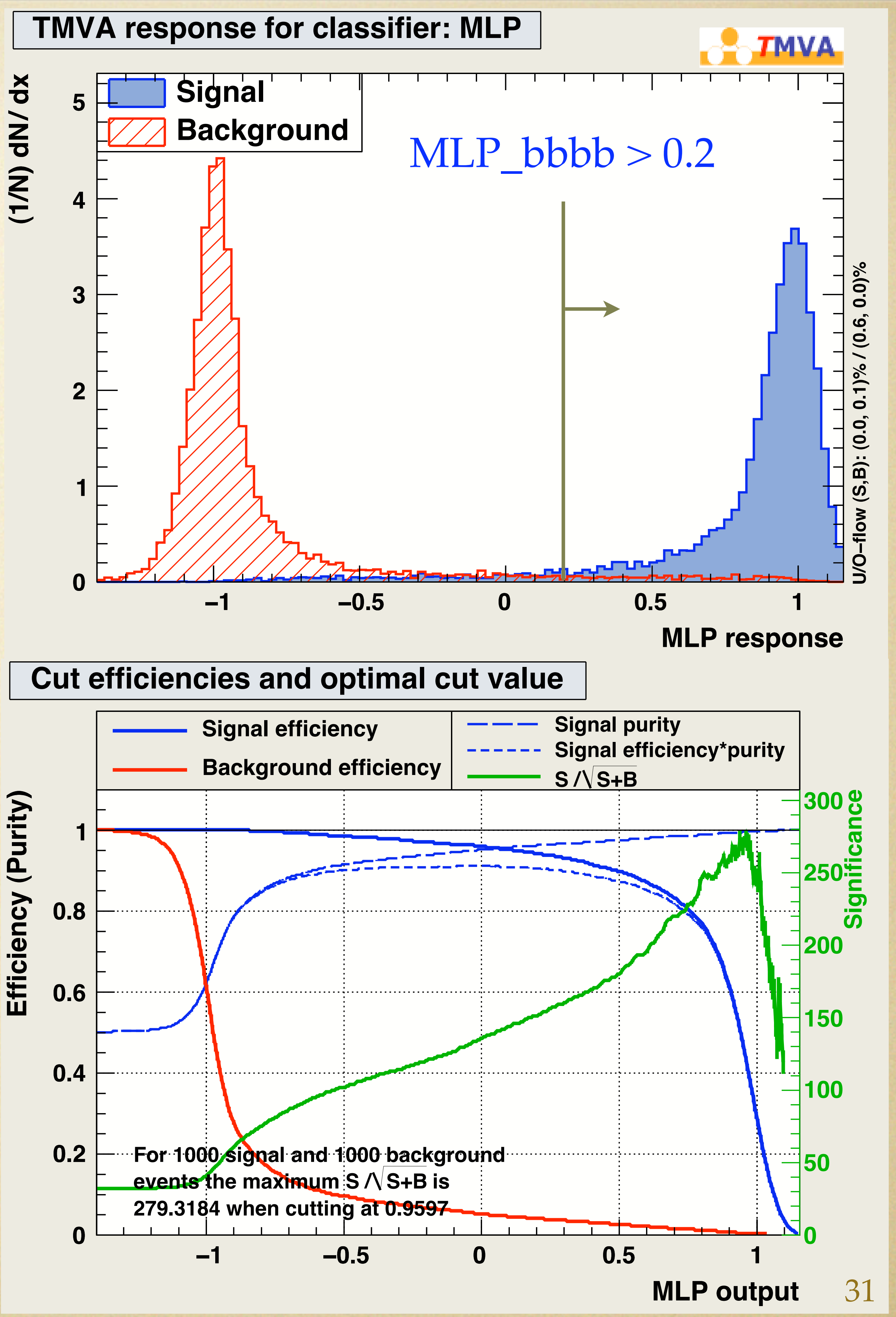
qqHH .vs. bbbb

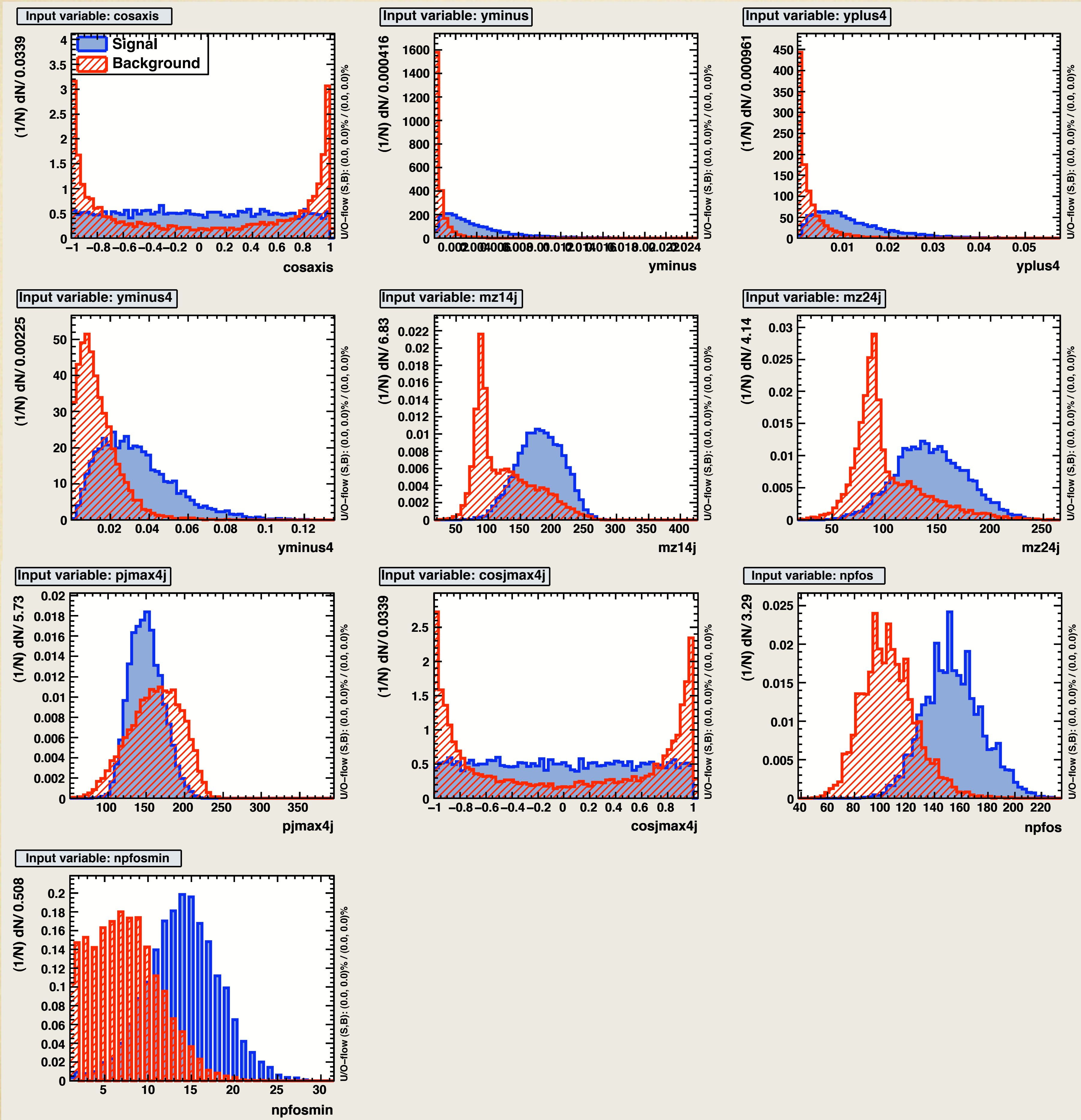
input:

Axis of thrust
Y(6->5), Y(5->4), Y(4->3)
Two Z masses in case of 4 jets
Largest jet momentum and
its polar angle (4 jets)
Total number of PFOs
Smallest number of PFOs in a jet

pre-cut: thrust < 0.9

distribution of these inputs in next page



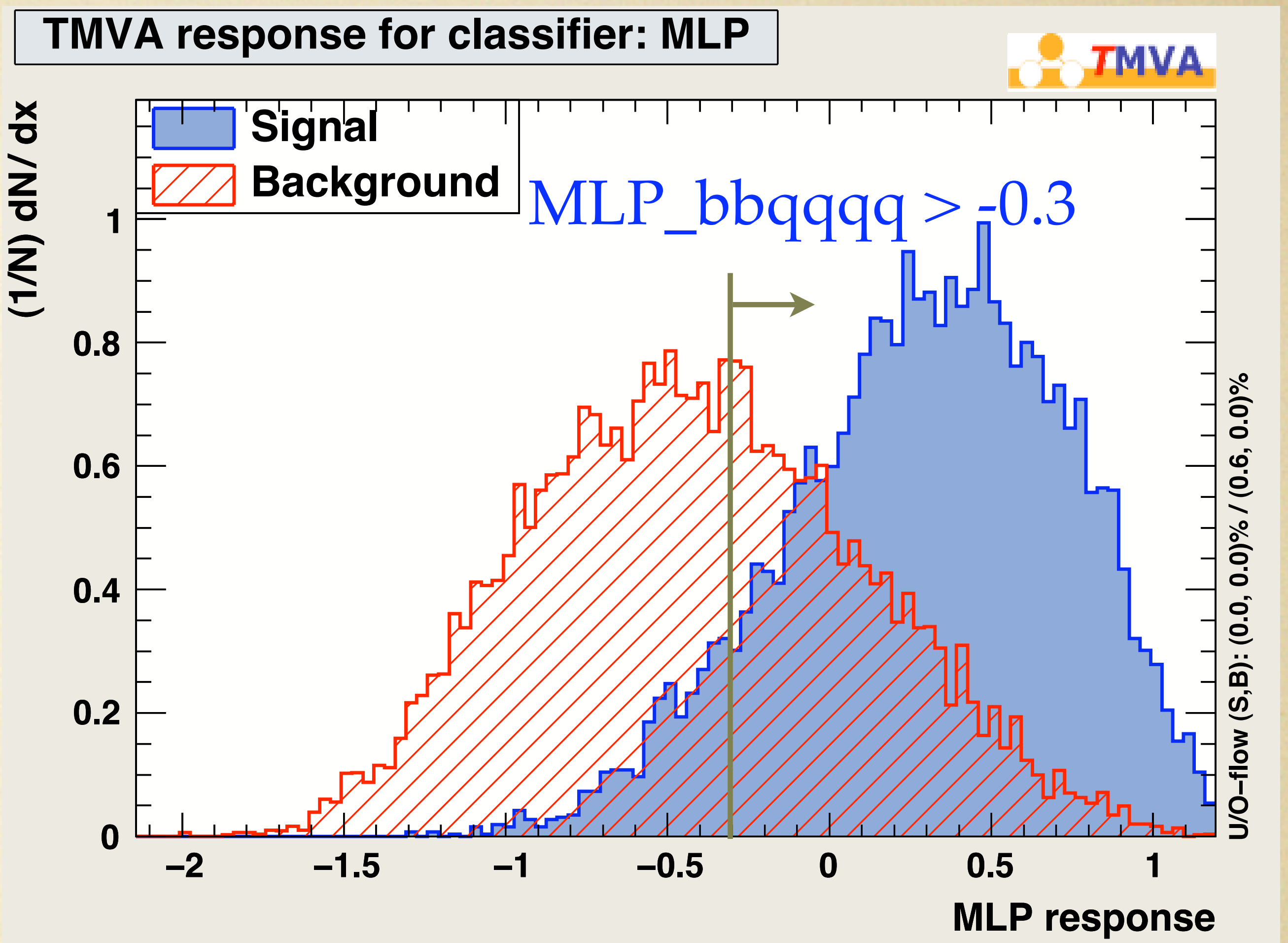


Input variable: cosaxis
Signal
Background
(1/N) dN/ 0.0339
cosaxis
Input variable: yminus
(1/N) dN/ 0.000416
yminus
Input variable: yplus4
(1/N) dN/ 0.000961
yplus4
Input variable: yminus4
(1/N) dN/ 0.00225
yminus4
Input variable: mz14j
(1/N) dN/ 6.83
mz14j
Input variable: mz24j
(1/N) dN/ 4.14
mz24j
Input variable: pjmax4j
(1/N) dN/ 5.73
pjmax4j
Input variable: cosjmax4j
(1/N) dN/ 0.0339
cosjmax4j
Input variable: npfos
(1/N) dN/ 3.29
npfos
Input variable: npfosmin
(1/N) dN/ 0.508
npfosmin
U/O-flow (S,B): (0.0, 0.0)% / (0.0, 0.0)%

qqHH .vs. bbcsdu

bbcssc

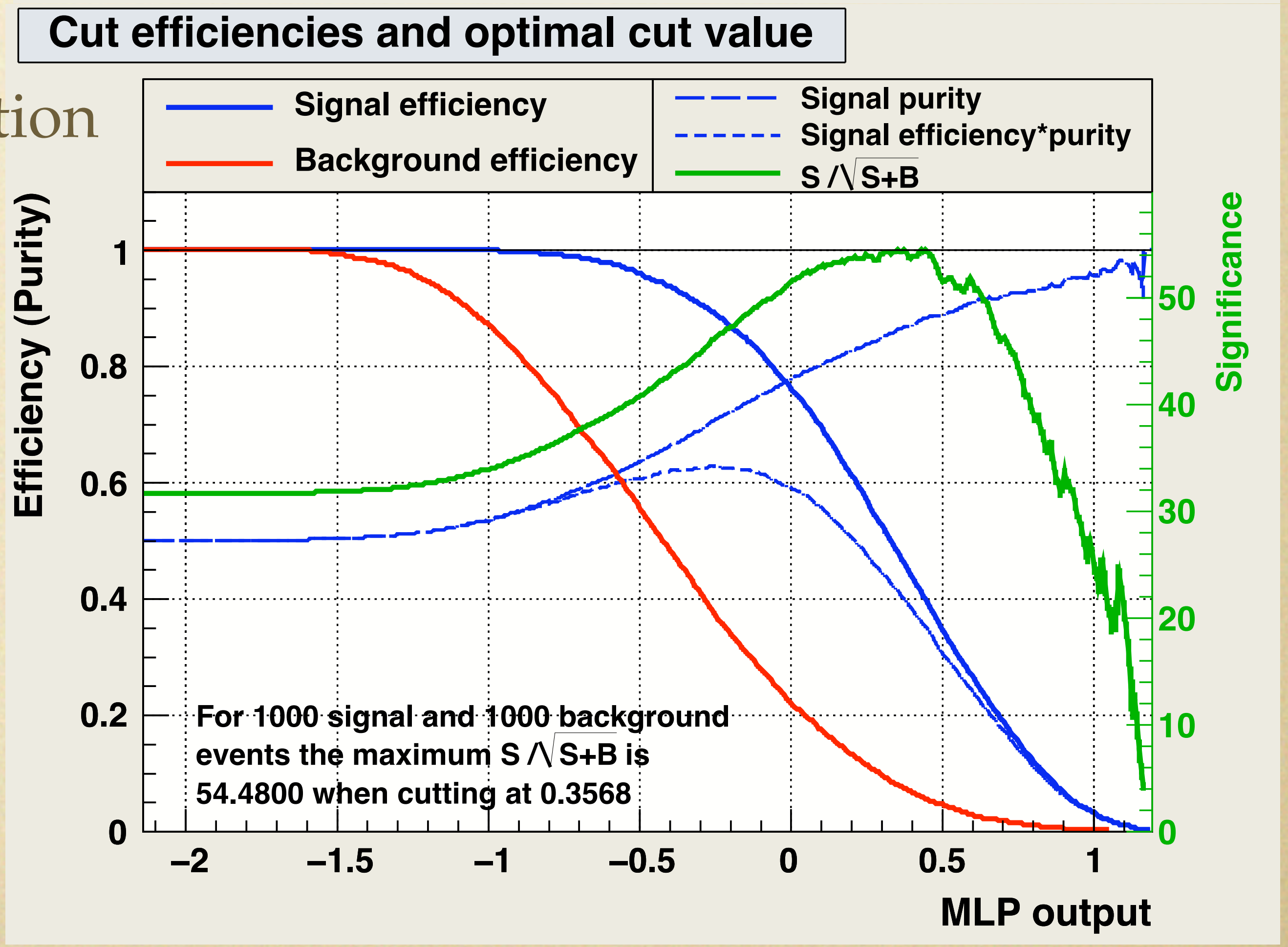
bbuddu

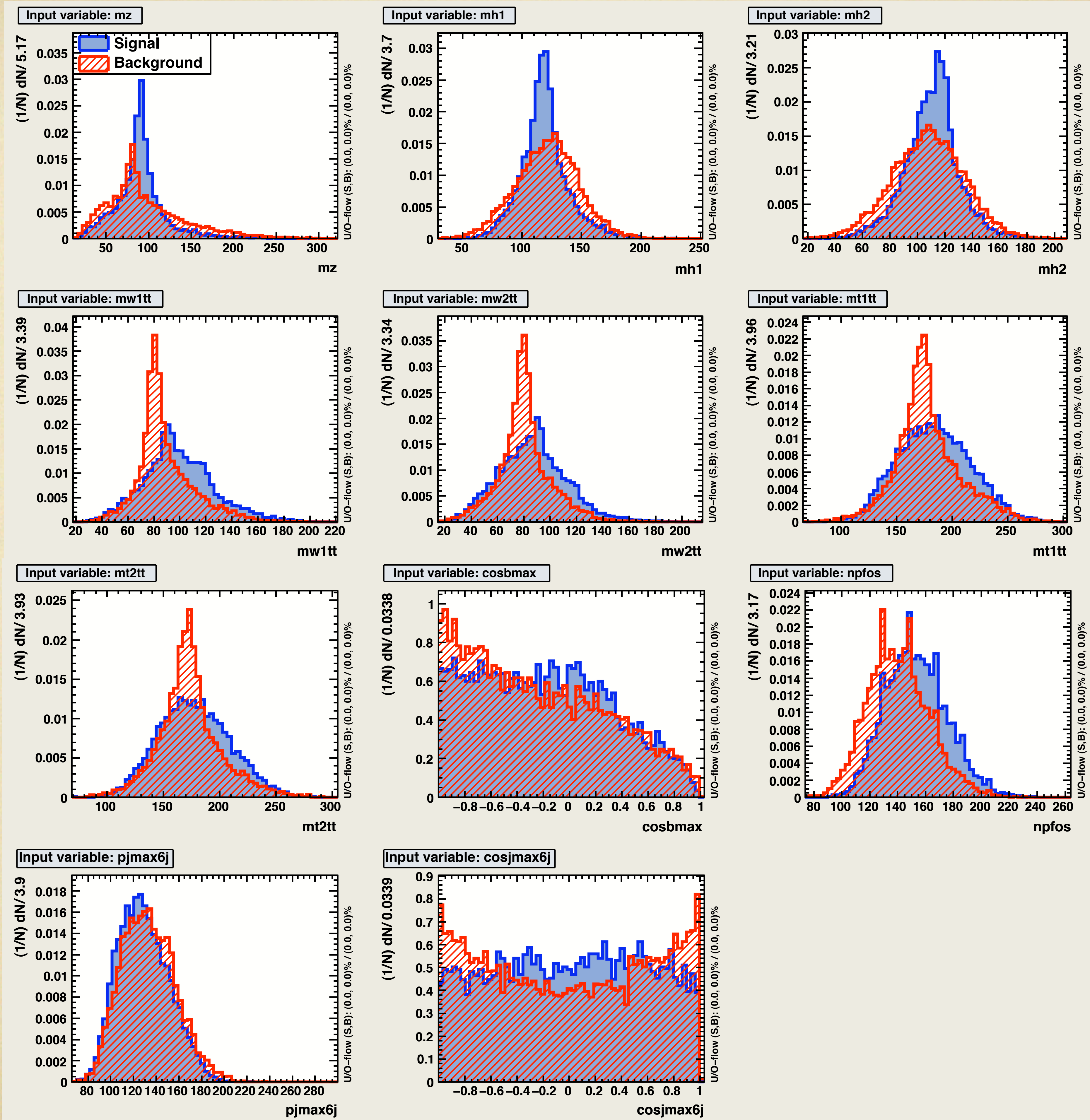


input:

Z mass
Two Higgs masses
W, Top masses in case of tt-bar reconstruction
Angle between two most like b jets
Total number of PFOs
Largest jet momentum and its polar angle

distribution of these inputs in next page



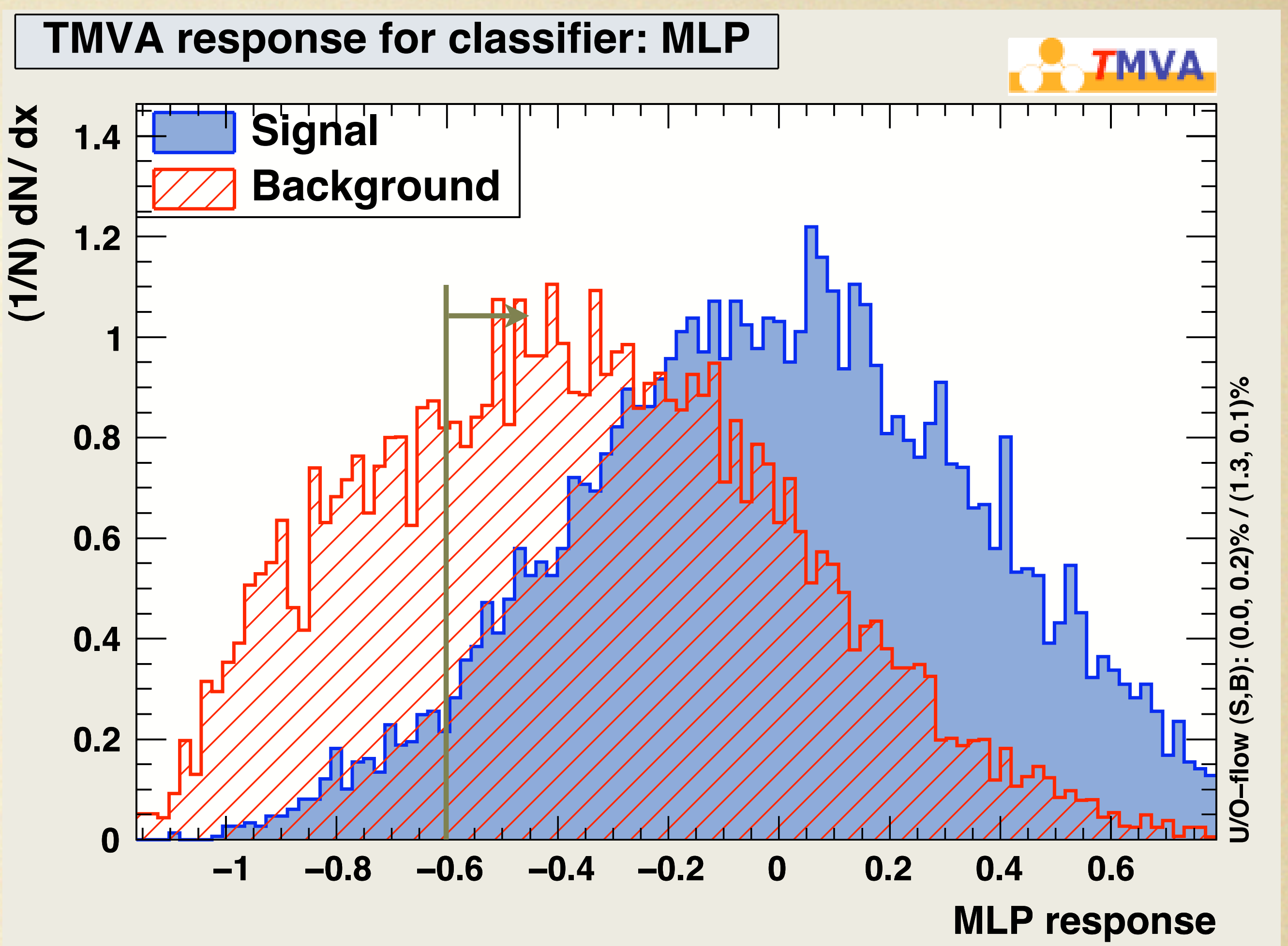

Input variable: mz
Signal
Background
(1/N) dN/ 5.17
mz
Input variable: mh1
(1/N) dN/ 3.7
mh1
Input variable: mh2
(1/N) dN/ 3.21
mh2
Input variable: mw1tt
(1/N) dN/ 3.39
mw1tt
Input variable: mw2tt
(1/N) dN/ 3.34
mw2tt
Input variable: mt1tt
(1/N) dN/ 3.96
mt1tt
Input variable: mt2tt
(1/N) dN/ 3.93
mt2tt
Input variable: cosbmax
(1/N) dN/ 0.0338
cosbmax
Input variable: npfos
(1/N) dN/ 3.17
npfos
Input variable: pjmax6j
(1/N) dN/ 3.9
pjmax6j
Input variable: cosjmax6j
(1/N) dN/ 0.0339
cosjmax6j
U/O-flow (S,B): (0.0, 0.0)% / (0.0, 0.0)%

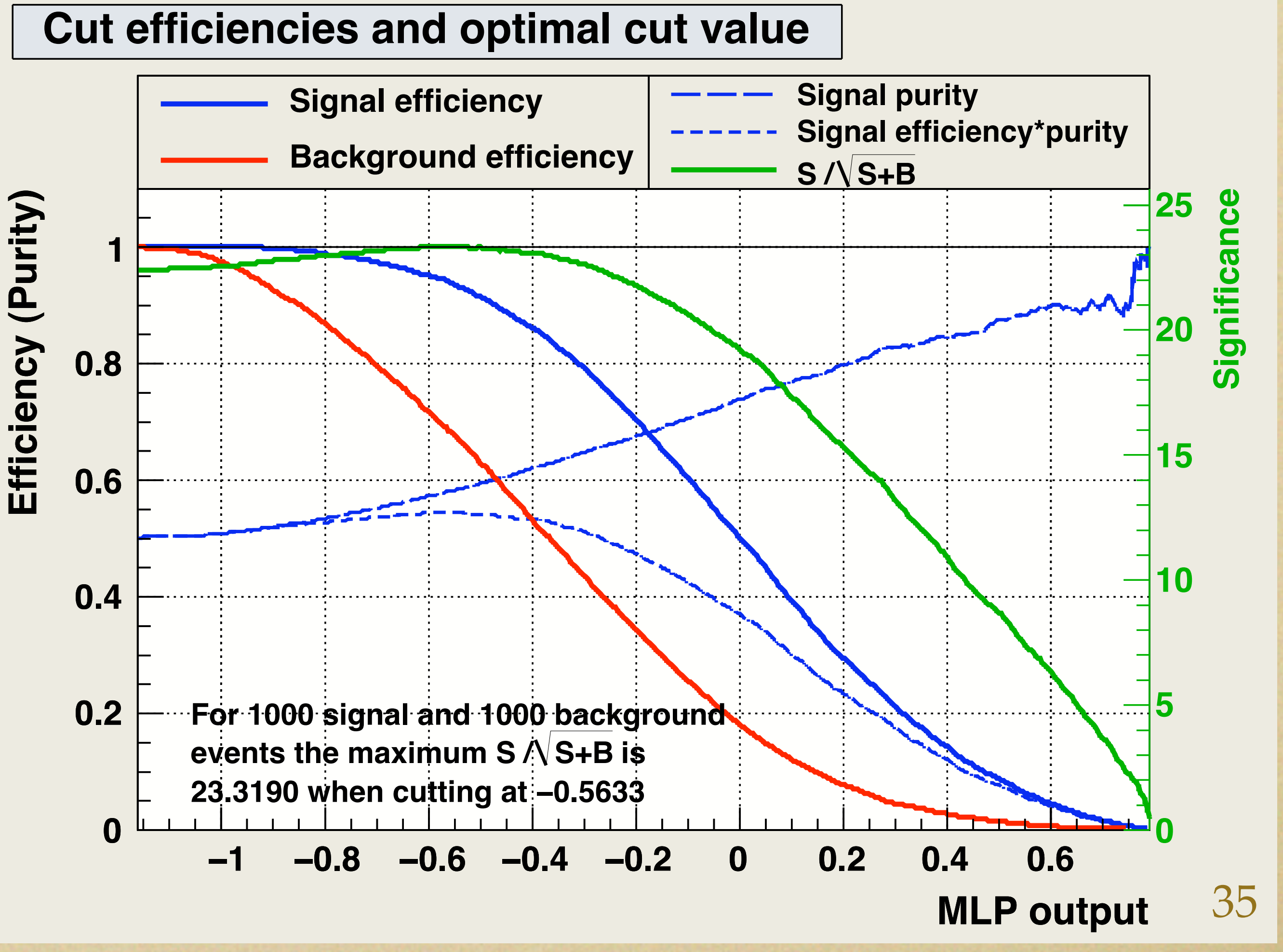
qqHH .vs. qqbbbb(qqbbH)

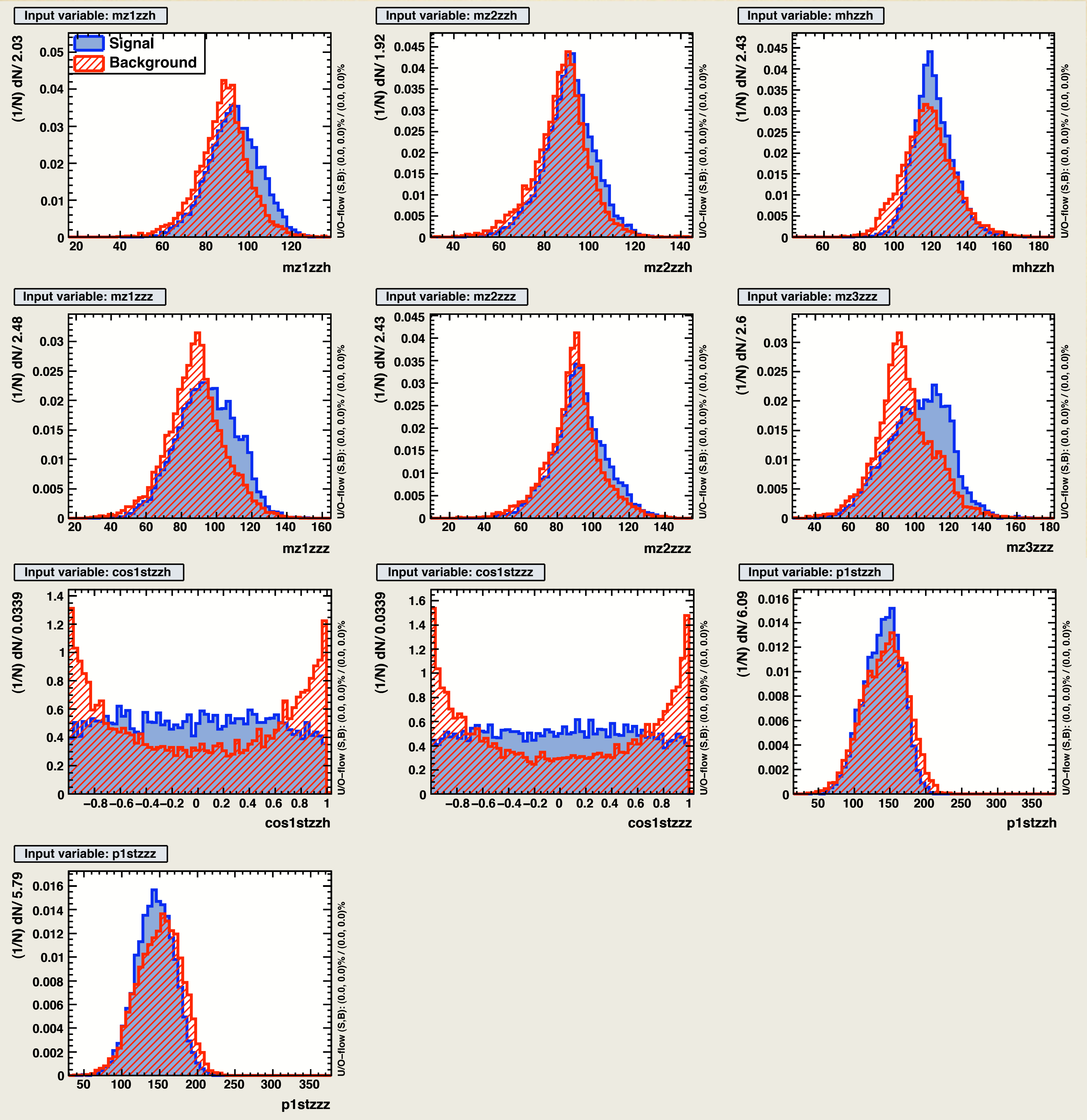
input:

Z, H masses in case of qqZH
Two Z masses in case of qqZZ
Largest momentum and its angle of three bosons in case of qqZH and qqZZ

distribution of these inputs in next page







Input variable: mz1zzh
Signal
Background
(1/N) dN/ 2.03
mz1zzh
Input variable: mz2zzh
(1/N) dN/ 1.92
mz2zzh
Input variable: mhzzh
(1/N) dN/ 2.43
mhzzh
Input variable: mz1zzz
(1/N) dN/ 2.48
mz1zzz
Input variable: mz2zzz
(1/N) dN/ 2.43
mz2zzz
Input variable: mz3zzz
(1/N) dN/ 2.6
mz3zzz
Input variable: cos1stzzh
(1/N) dN/ 0.0339
cos1stzzh
Input variable: cos1stzzz
(1/N) dN/ 0.0339
cos1stzzz
Input variable: p1stzzh
(1/N) dN/ 6.09
p1stzzh
Input variable: p1stzzz
(1/N) dN/ 5.79
p1stzzz
U/O-flow (S,B): (0.0, 0.0)% / (0.0, 0.0)%

reduction table

$(\mathrm{probZ1}+\mathrm{probZ2} > 0.9)$

P(e-,e+)=(-0.8,+0.3)

$E_{\mathrm{cm}} = 500\mathrm{GeV}, M_H = 120\mathrm{GeV}$

$\int Ldt = 2\mathrm{ab}^{-1}$

normalized	expected	MC	pre-selection	probZ1+probZ2>0.9	Evis>400 MissPt<60 ! (Plmax>20&&Econe>10)	MLP_bbbb>0.2	MLP_bbqqqq>-0.3	MLP_qqbbbb>-0.6	Bmax3>0.76 Bmax4>0.33
qqhh(qqbbbb)	313(138)	117173	82.0(65.1)	15.5(13.8)	13.9(13.0)	13.1(12.3)	12.7(11.9)	12.1(11.4)	8.50(8.15)
qqbbbb	192	59994	50.9	3.17	2.97	2.01	1.75	1.28	0.55
qqqqH(ZZH)	381	49702	45.8	6.58	5.72	5.11	4.80	4.14	2.70
bbcsdu	394548	710285	3016	29.7	29.1	22.3	14.9	13.5	1.38
bbuddu	199165	109200	374	10.5	7.92	5.37	5.37	5.37	0.28
bbcssc	197790	359084	4904	58.4	53.8	47.9	39.2	36.5	2.01
ttqq	2169	9999	170	10.0	5.08	4.83	4.70	4.49	1.85
bbbb	40824	198431	4722	598	494	2.83	2.20	1.80	1.27
lvbbqq	821199	797027	12216	230	33.2	6.18	6.18	4.39	0.07
BG			25509	951	636	100	82.2	73.7	11.7

reduction table

$(\mathrm{probZ1}+\mathrm{probZ2} > 0.9)$

Polarization: (e-,e+)=(0,0) $E_{\mathrm{cm}} = 500\mathrm{GeV}, M_H = 120\mathrm{GeV}$ $\int Ldt = 2\mathrm{ab}^{-1}$

normalized	expected	MC	pre-selection	probZ1+probZ2>0.9	Evis>400 MissPt<60 ! (Plmax>20&&Econe>10)	MLP_bbbb>0.2	MLP_bbqqqq>-0.3	MLP_qqbbbb>-0.6	Bmax3>0.76 Bmax4>0.33
qqhh(qqbbbb)	222(97.6)	117173	55.1(43.9)	10.4(9.33)	9.34(8.74)	8.84(8.31)	8.56(8.06)	8.20(7.73)	5.76(5.53)
qqbbbb	87.6	59994	27.4	1.70	1.60	1.05	0.90	0.65	0.28
qqqqH(ZZH)	241	49702	19.6	2.81	2.44	2.19	2.05	1.77	1.15
bbcsdu	230600	710285	1258	12.3	12.0	9.21	6.14	5.58	0.56
bbuddu	116200	109200	212	6.36	5.27	4.19	4.19	2.01	2.01
bbcssc	115600	359084	2874	31.7	29.2	25.6	19.9	18.2	1.38
ttqq	1203	9999	89.1	5.31	2.66	2.54	2.47	2.38	0.99
bbbb	23900	198431	4420	558	460	2.11	1.52	1.26	0.71
lvbbqq	477600	797027	7086	134	20.3	3.58	3.58	2.82	0.50
BG			16002	757	537	53.5	43.4	38.9	9.03

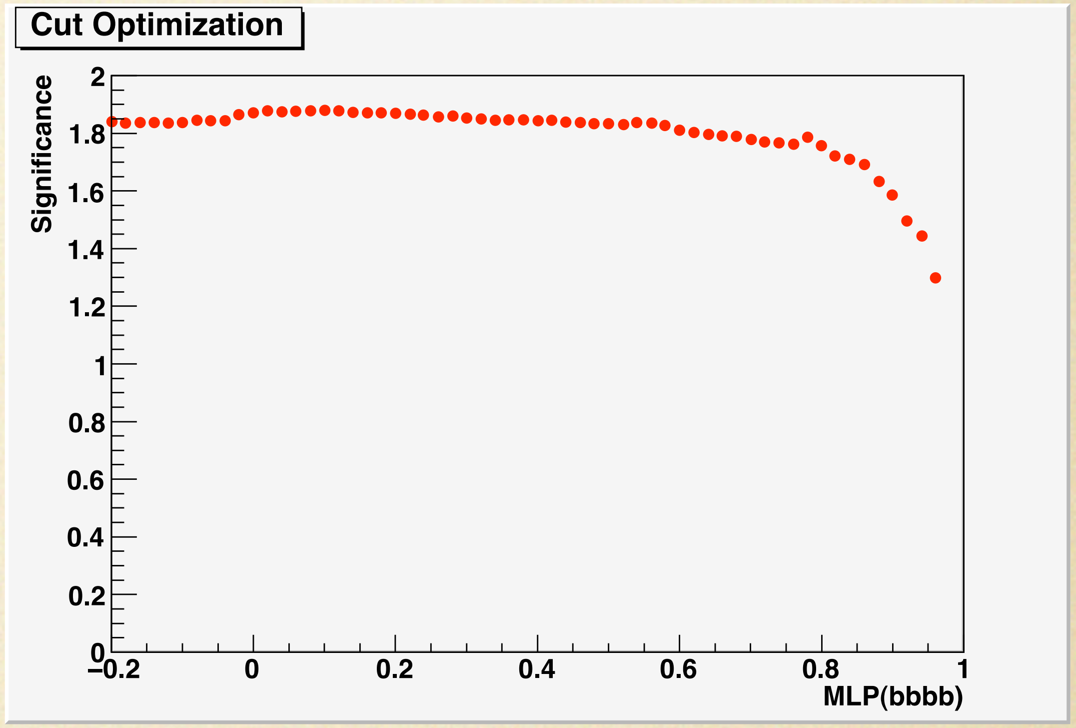
cut optimization (qqHH)

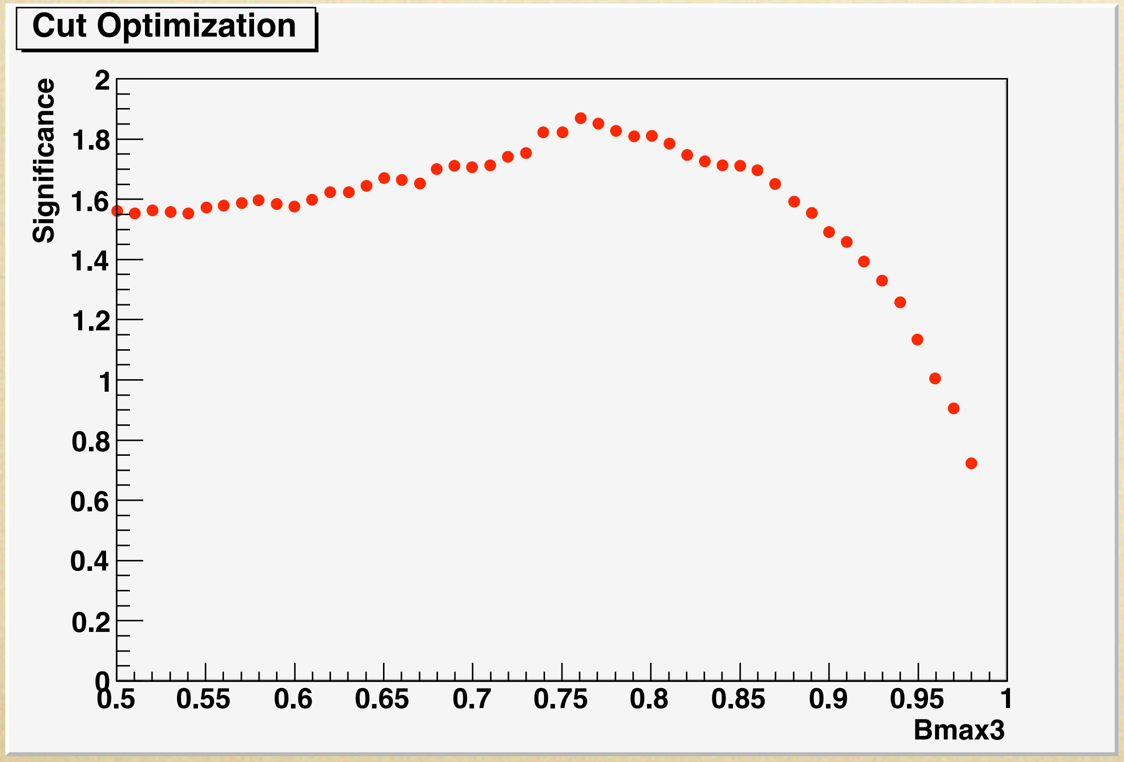
ProbZ1+ProbZ2>0.9

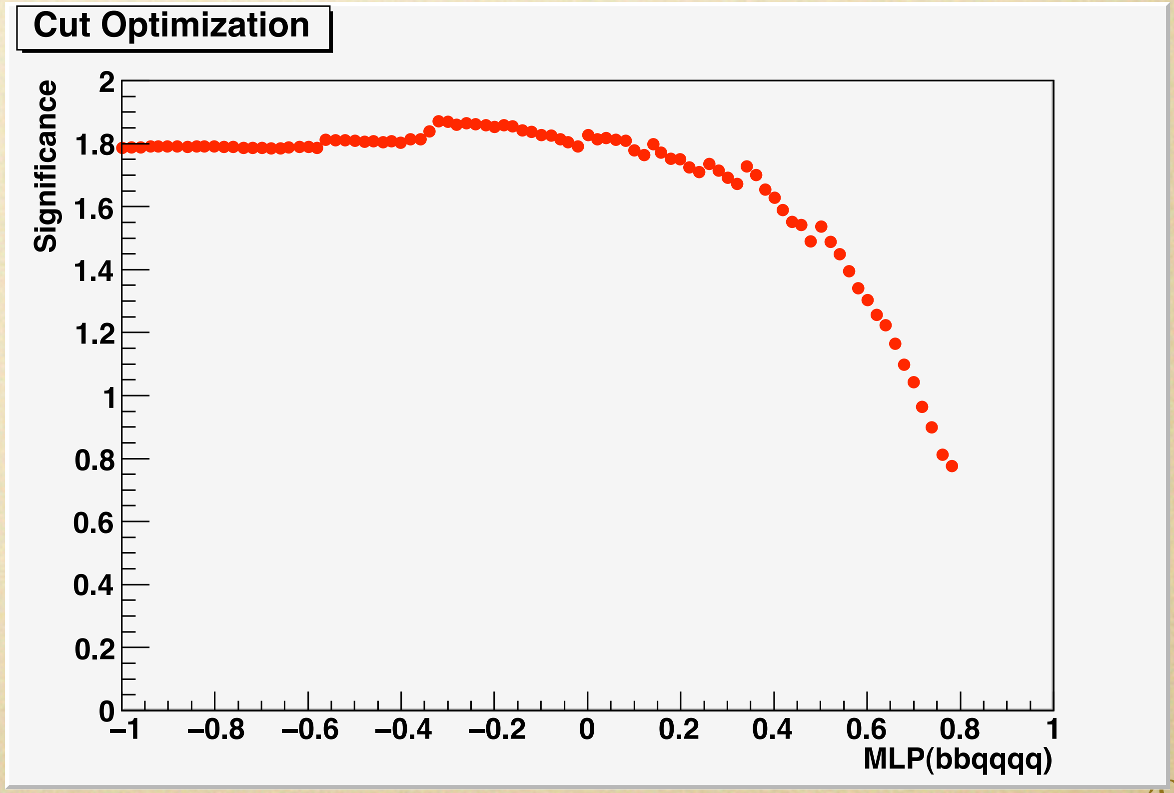
full simulation @ 500GeV

Polarization: (e-,e+)=(-0.8,0.3) $\int L dt = 2\text{ab}^{-1}$

qqhh	8.5±0.2
BG	11.7±1.5
bbbb	1.27±0.35
ttqq	1.85±0.27
bbcsdu	1.38±0.92
bbcssc	2.01±1.12
qqbbbb	2.09±0.08
qqqqh	2.70±0.14







reduction table

(probZ1+probZ2 < 0.9)

P(e-,e+)=(-0.8,+0.3)

$E_{\rm cm} = 500{\rm GeV}, M_H = 120{\rm GeV}$

$\int Ldt = 2{\rm ab}^{-1}$

normalized	expected	pre-selection	probZ1+probZ2<0.9	Plmax<20 || Econe>10	Evis>400 MissPt<60	MLP_bbbb>-0.2	MLP_bbqqqq>0.16	Bmax3>0.8 Bmax4>0.52
qqhh(qqbbbb)	313(138)	82.0(65.1)	66.4(51.3)	63.0(50.9)	57.6(48.7)	54.9(47.1)	33.1(29.1)	16.6(15.1)
qqbbbb	192	50.9	47.7	47.4	44.9	36.2	11.7	6.00
qqqqH(ZZH)	381	45.8	39.2	38.2	35.0	32.3	15.5	7.65
bbcsdu	394548	3016	2986	2973	2869	2581	469	42.2
bbuddu	199165	374	364	364	356	324	67.3	5.37
bbcssc	197790	4904	4845	4825	4616	4131	623	39.6
ttqq	2169	170	159	107	79.4	78.4	42.8	13.7
bbbb	40824	4722	4124	4106	3368	70.1	18.2	9.12
lvbbqq	821199	12216	11986	8041	1641	297	49.4	4.34
BG		25509	24557	20509	13015	7555	1298	129

reduction table

(probZ1+probZ2 < 0.9)

Polarization: (e-,e+)=(0,0) $E_{\mathrm{cm}} = 500\mathrm{GeV}, M_H = 120\mathrm{GeV}$ $\int Ldt = 2\mathrm{ab}^{-1}$

normalized	expected	pre-selection	probZ1+probZ2<0.9	Plmax<20 || Econe>10	Evis>400 MissPt<60	MLP_bbbb>-0.2	MLP_bbqqqq>0.16	Bmax3>0.8 Bmax4>0.52
qqhh(qqbbbb)	313(138)	55.1(43.9)	44.7(34.5)	42.4(34.3)	38.8(32.8)	37.0(31.7)	22.2(19.4)	11.3(10.2)
qqbbbb	192	27.4	25.7	25.6	24.2	19.2	6.06	3.08
qqqqH(ZZH)	381	19.6	16.8	16.3	14.9	13.8	6.61	3.28
bbcsdu	394548	1258	1246	1241	1197	1077	195	17.3
bbuddu	199165	212	206	206	198	175	36.3	4.19
bbcssc	197790	2874	2842	2830	2715	2430	361	22.6
ttqq	2169	89.1	83.8	56.0	41.0	40.5	22.4	7.46
bbbb	40824	4420	3862	3846	3134	44.9	11.1	5.79
lνbbqq	821199	7086	6952	4606	955	177	27.4	2.48
BG		16002	15245	12837	8290	3987	670	68.2

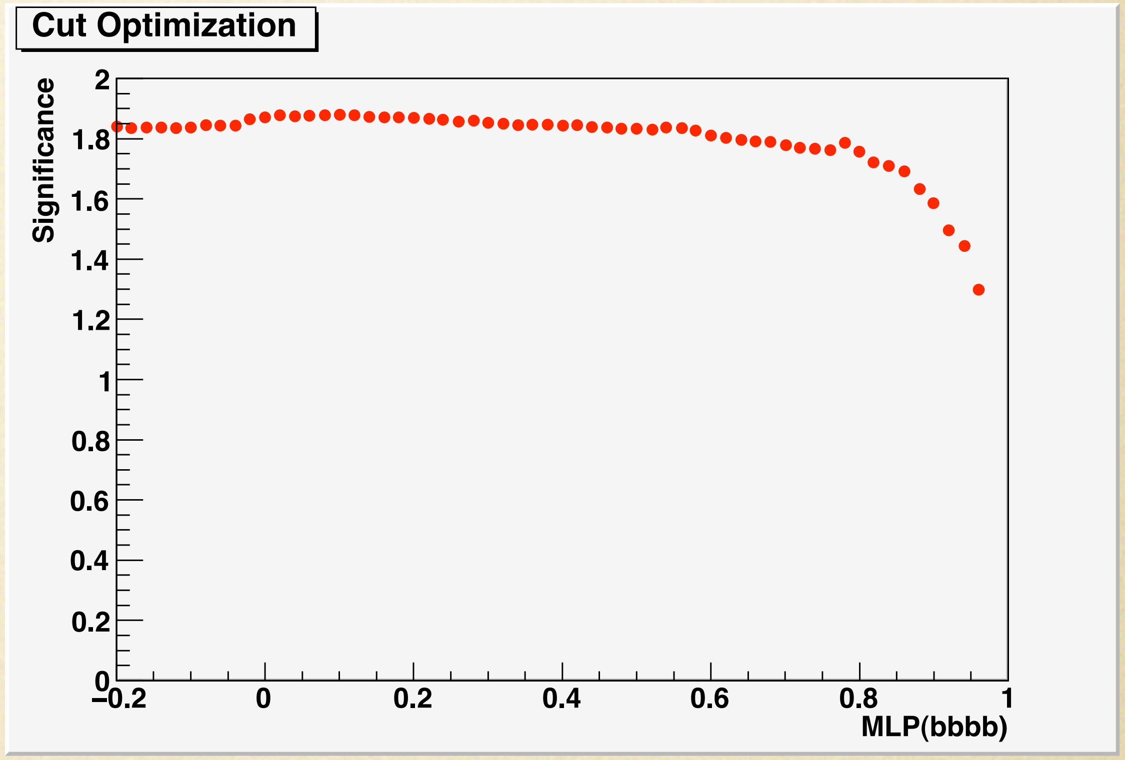
cut optimization (qqHH)

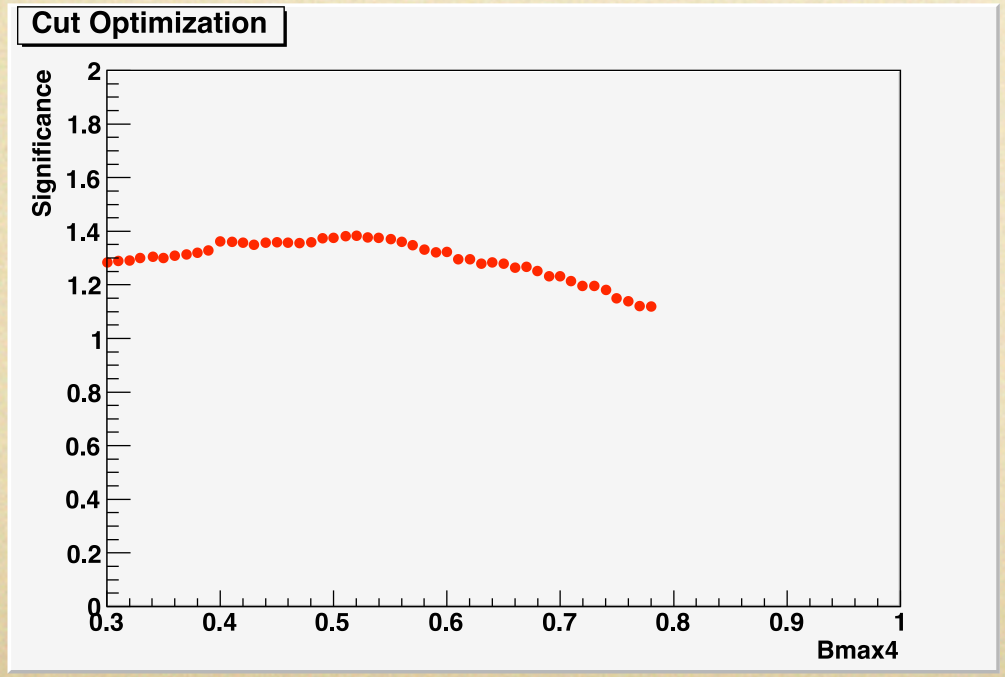
ProbZ1+ProbZ2<0.9

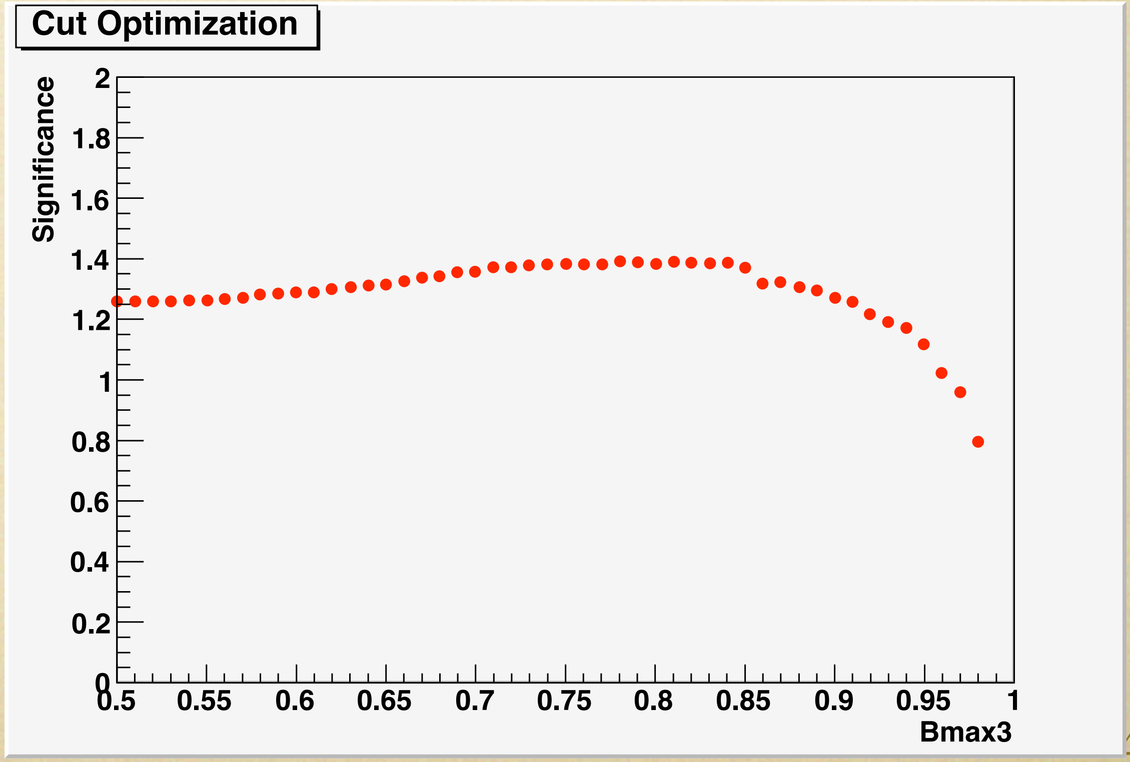
full simulation @ 500GeV

Polarization: (e-,e+)=(-0.8,0.3) $\int Ldt = 2\mathrm{ab}^{-1}$

qqhh	16.6±0.3
BG	129±8
lvbbqq	4.3±1.2
bbbb	9.1±0.6
ttqq	13.7±0.7
bbuddu	5.4±3.6
bbcsdu	42.2±5.1
bbcssc	39.6±5.0
qqbbbb	6.7±0.4
qqqqh	7.6±0.2







statistic dependence of three modes

- due to different visible energy requirements, events passed on vvHH analysis are rejected by other two analyses. ---> vvHH independent with llHH and qqHH
- due to the very energetic isolated lepton requirement, all six jets and four jets events are rejected by llHH analysis. ---> llHH independent with qqHH
- all the three analyses are statistical independent!

status of the full simulation (preliminary)

Polarization: (e-,e+)=(-0.8,0.3) $e^+ + e^- \rightarrow ZHH$ $M(H) = 120\mathrm{GeV}$ $\int Ldt = 2\mathrm{ab}^{-1}$

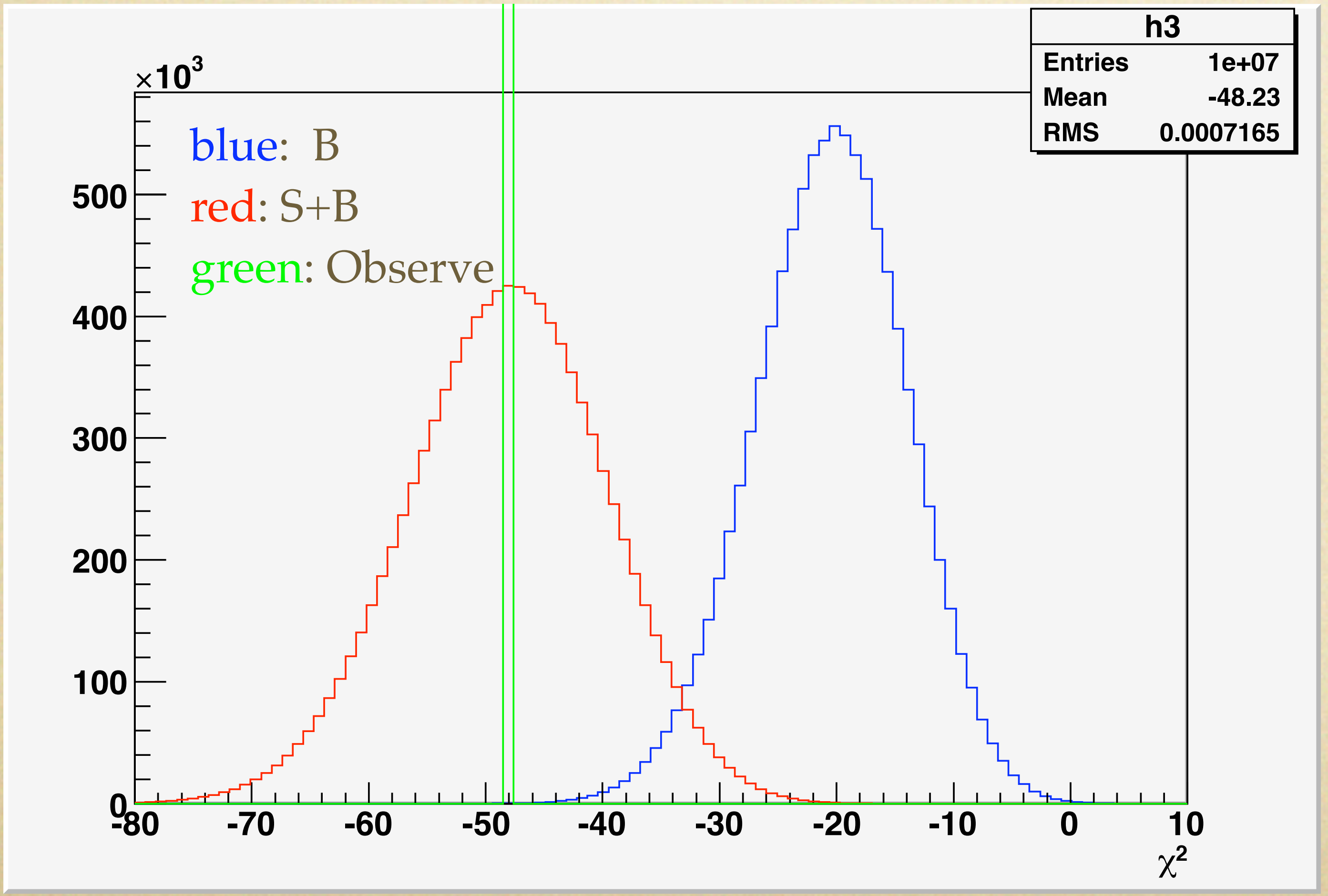
Energy (GeV)	Modes	signal	background	significance	
				excess (I)	measurement (II)
500	$ZHH \rightarrow (l\bar{l})(b\bar{b})(b\bar{b})$	6.4	6.7	2.1σ	1.7σ
500	$ZHH \rightarrow (\nu\bar{\nu})(b\bar{b})(b\bar{b})$	5.2	7.0	1.7σ	1.4σ
500	$ZHH \rightarrow (q\bar{q})(b\bar{b})(b\bar{b})$	8.5	11.7	2.2σ	1.9σ
		16.6	129	1.4σ	1.3σ

Hypothesis Test (Combined)

H0: background only H1: ZHH events exist

test: $$\chi^2 = -2\ln\frac{L_{s+b}}{L_b}$$

$$L_{s+b} = \Pi_i \frac{e^{-(s_i+b_i)}(s_i+b_i)^{n_i}}{n_i!} \qquad L_b = \Pi_i \frac{e^{-b_i} b_i^{n_i}}{n_i!}$$



$$p = \int_{-\infty}^{\chi^2_{obv}} f(\chi^2)\, d\chi^2$$

$$= 4.6 \times 10^{-5}$$

significance: 3.9σ

precision of cross section ~ 25%

precision of coupling ~ 45%

extract cross section

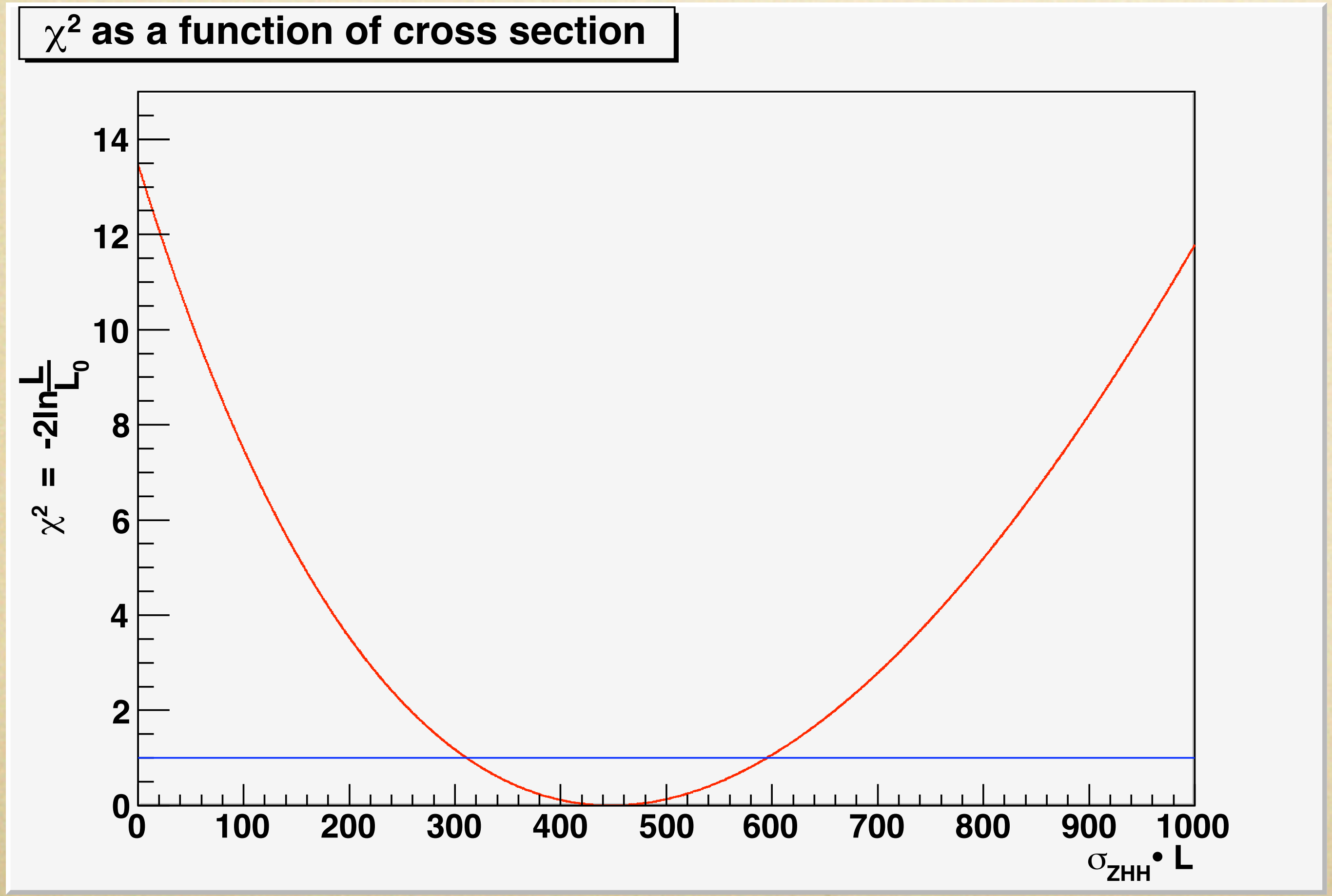
$$L_{s+b} = \Pi_i \frac{e^{-(s_i+b_i)}(s_i+b_i)^{n_i}}{n_i!}$$

bi: expected background number (known from MC)
ni: number of observed events (known from Experiment)
si: parameter related with the cross section

$$s_i = (\sigma_{ZHH} + \sigma_i) \cdot L \cdot Br_i \cdot Eff_i$$

σi: fusion contribution (known)

$$\chi^2 = -2ln\frac{L}{L_{max}}$$



$$\sigma_{ZHH} \cdot L = 448^{+145}_{-137}$$

precision of cross section: 31.5%

precision of coupling: 56.7%

summary and next to do

- three modes of ZHH are full simulated to test the possibility of Higgs self-coupling measurement.
- left polarization is favored, benefiting from the higher cross section.
- 3.9σ ZHH excess significance, 31% cross section precision, 57% coupling precision.
- statistics of some backgrounds mainly bbcsdu, bbcssc, bbuddu, tauvbbqq, evbbqq, mvbbqq need to increase
- part of the samples generated by grid have slight overestimated b tagging suppression. (0.5M tauvbbcs, 1.0M llbb) to be corrected soon.

backup

P value

$$\frac{S}{\sqrt{B}}$$

excess: assuming there is no signal, the probability of no less than observed events are backgrounds.

$$p = \int_{S+B}^{+\infty} f(x, B, \sqrt{B})\mathrm{dx} \qquad \frac{S}{\sqrt{S+B}}$$

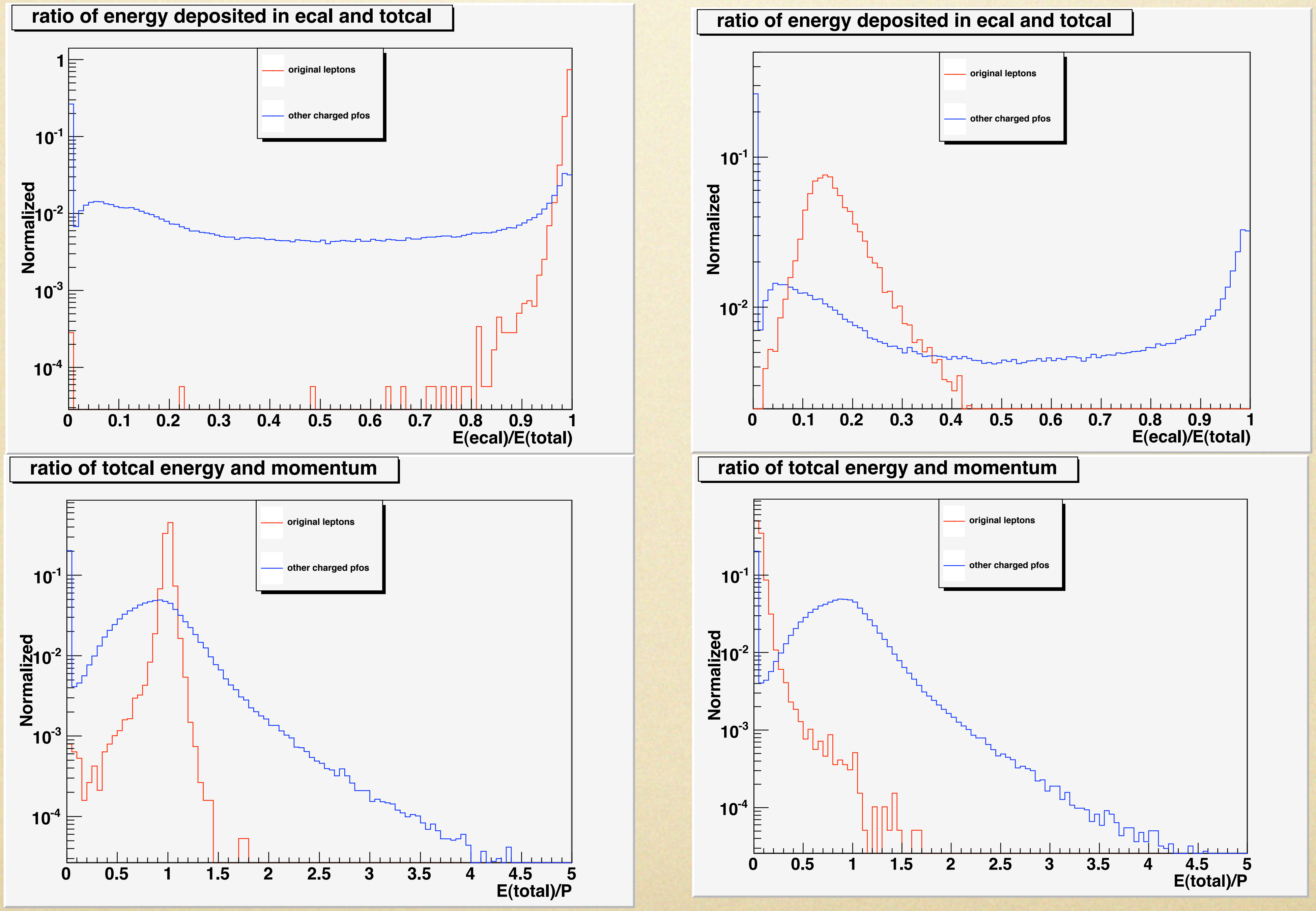
measure: assuming signal signal exists, the probability of no greater than background events are observed.

$$p = \int_{-\infty}^{B} f(x, S+B, \sqrt{S+B})\mathrm{dx}$$

identification criteria

$$e : \begin{cases} \frac{E_{ecal}}{E_{total}} > 0.9 \\ 0.8 < \frac{E_{total}}{P} < 1.2 \end{cases}$$

$$\mu : \begin{cases} \frac{E_{ecal}}{E_{total}} < 0.5 \\ \frac{E_{total}}{P} < 0.3 \end{cases}$$

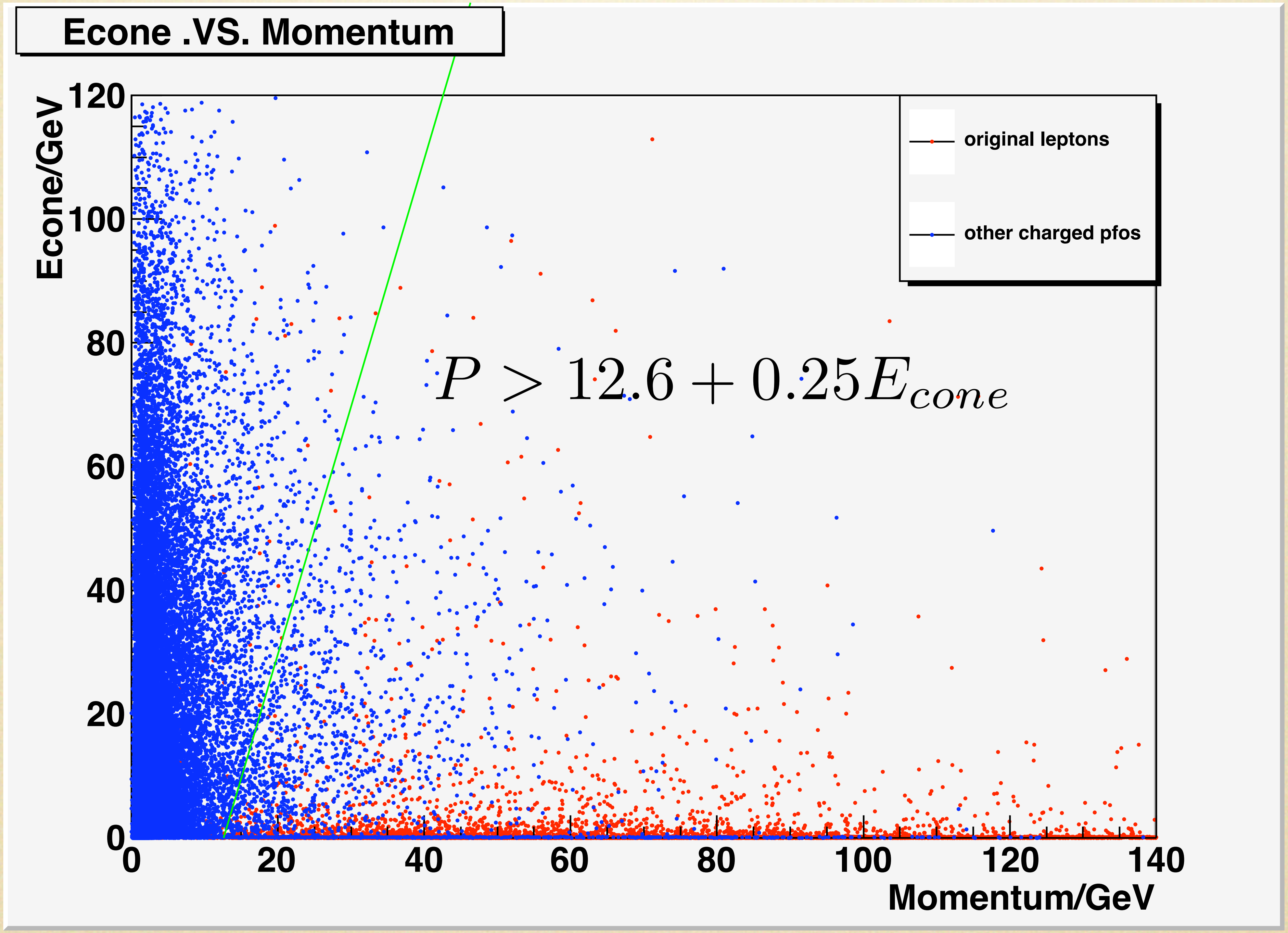


red:
original leptons

blue:
other charged pfos

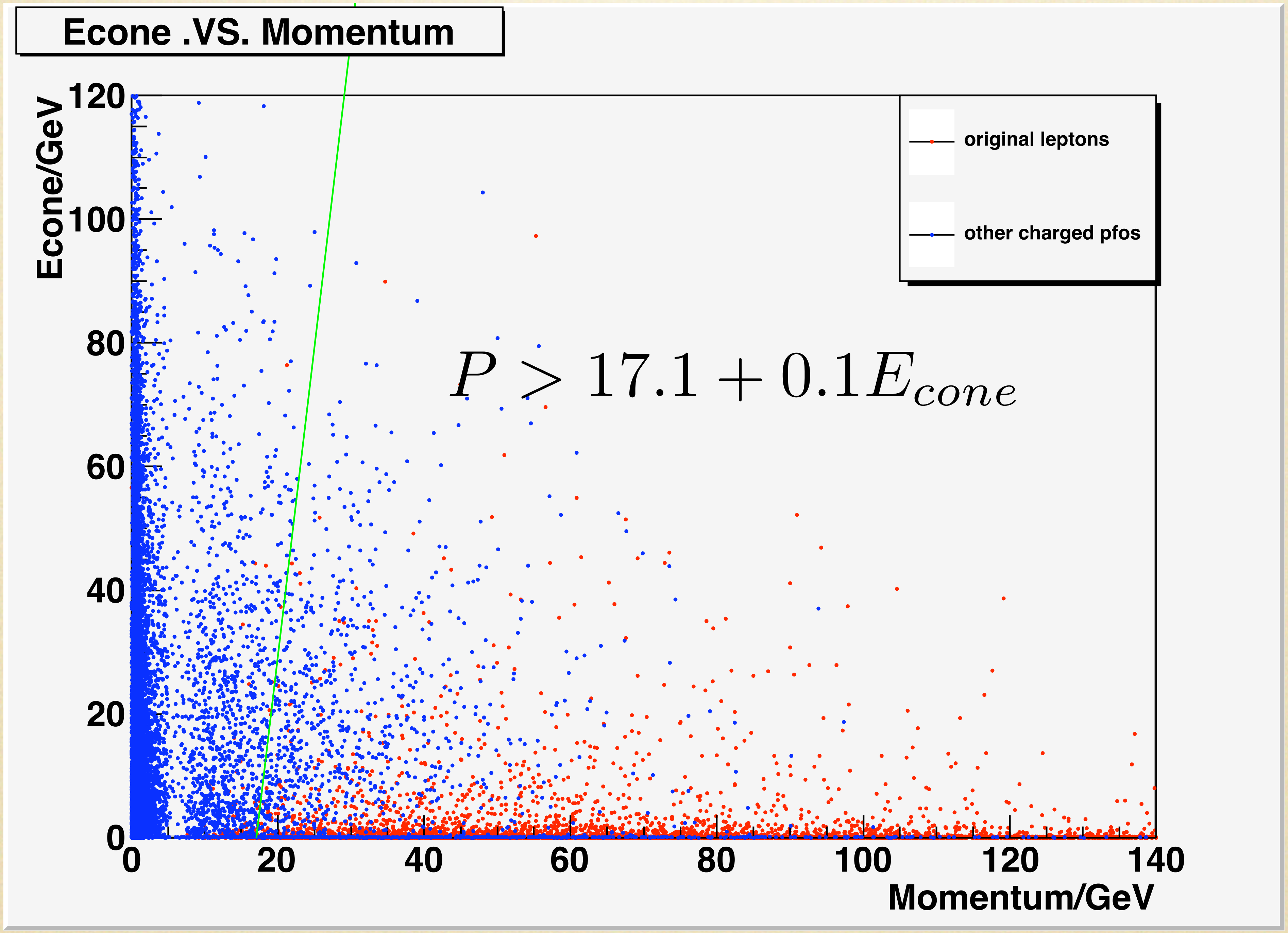
isolation (electron)

after identification



Econe is only charged. coefficients are obtained by Fisher Method in TMVA.

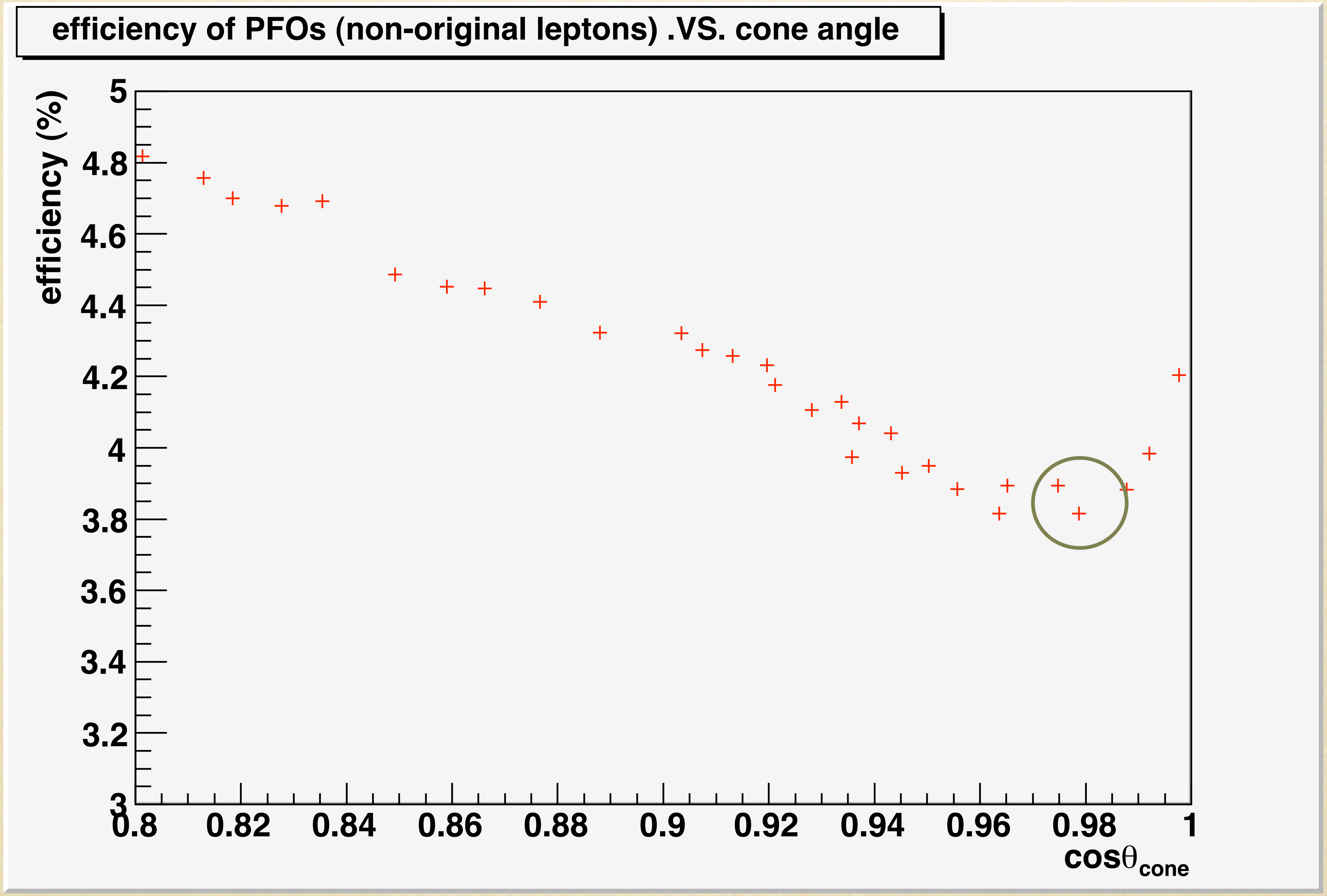
isolation (muon)



Econe is only charged. coefficients are obtained by Fisher Method in TMVA.

optimization of cone angle

keep the efficiency of original lepton to be 97.96%



$$\cos\theta = 0.98$$

electron mode

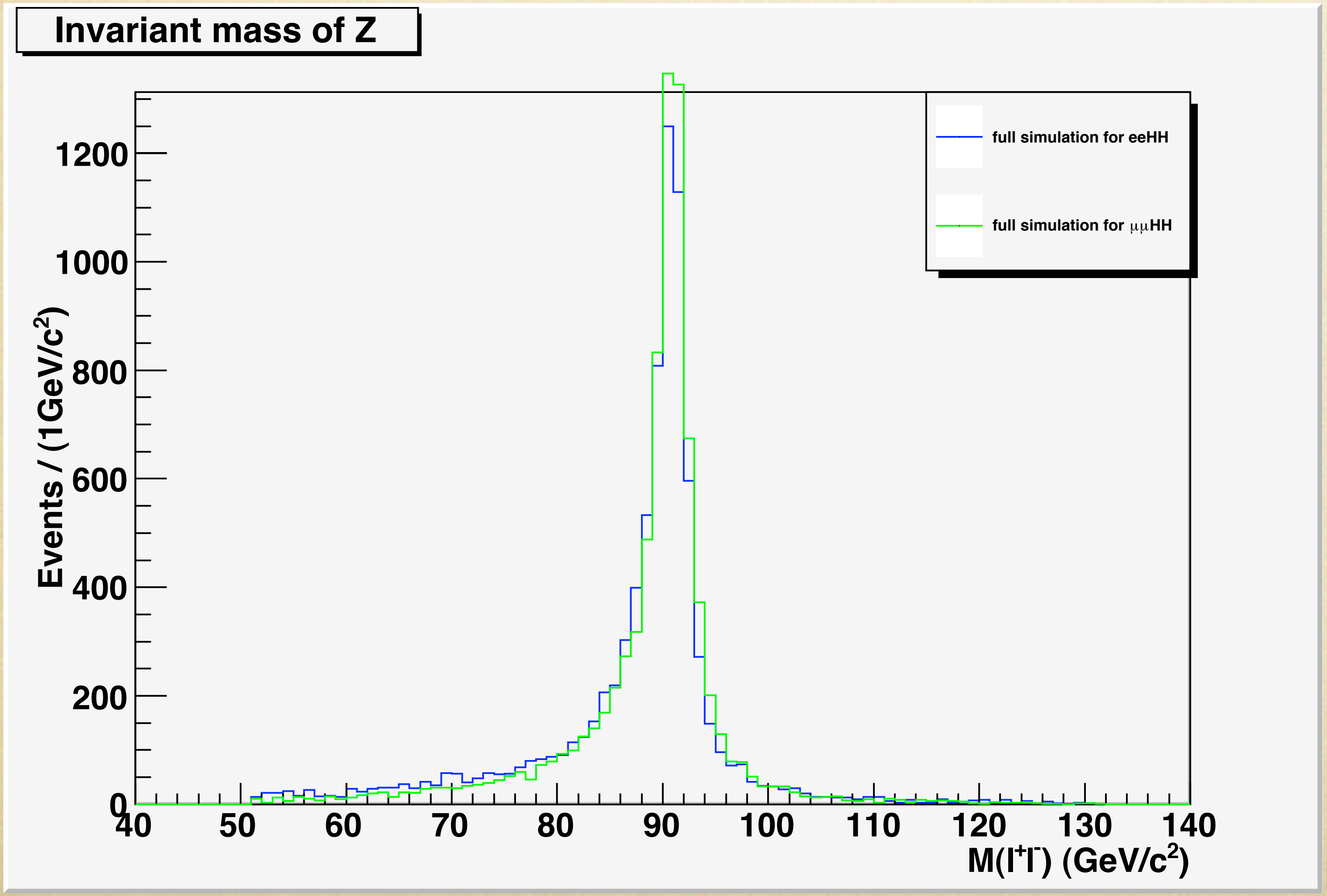
		eeHH		other PFOs	
MC events		9796		1009967	
l- found	l+ found	9447	9399	218429(-)	215659(+)
$\frac{E_{ecal}}{E_{total}} > 0.9$		9418(99.69%)	9370(99.69%)	79577(36.43%)	78509(36.40%)
$0.8 < \frac{E_{total}}{P} < 1.2$		9220(97.90%)	9155(97.70%)	25785(32.40%)	25701(32.74%)
$P > 12.6 + 0.25E_{cone}$		9035(97.99%)	8989(98.19%)	1118(4.34%)	1044(4.06%)

muon mode

		μμHH		other PFOs	
MC events		9904		1019896	
l- found	l+ found	9744	9754	220745(-)	217669(+)
$\frac{E_{ecal}}{E_{total}} < 0.5$		9480(97.29%)	9495(97.34%)	105885(47.97%)	106320(48.84%)
$\frac{E_{total}}{P} < 0.3$		9334(98.46%)	9381(98.80%)	46270(43.70%)	44581(41.93%)
$P > 17.1 + 0.1E_{cone}$		9145(97.97%)	9214(98.22%)	840(1.82%)	833(1.87%)

lepton selection

	eeHH	μμHH
MC	9796	9902
two isolated leptons	8096(82.6%)	8466(85.5%)
purity	7822(96.6%)	8275(97.7%)



blue: eeHH
green: μμHH

resolution is much smaller than the width of Z

isolated lepton selection (vvHH)

similar with the method used in $e^+ + e^- \to ZHH \to (l\bar{l})(b\bar{b})(b\bar{b})$

isolation is optimized for suppressing lvbbqq

$$e: \begin{cases} \dfrac{E_{ecal}}{E_{total}} > 0.9 \\ 0.8 < \dfrac{E_{total}}{P} < 1.2 \\ P > 19.8 + 0.55 E_{cone} \end{cases} \qquad \mu: \begin{cases} \dfrac{E_{ecal}}{E_{t}} < 0.5 \\ \dfrac{E_{t}}{P} < 0.3 \\ P > 22.3 + 0.24 E_{cone} \end{cases}$$

Eecal: energy deposited in the ECal
Etotal: energy deposited in ECal and HCal
P: momentum
Econe: charged cone energy with Cosθcone = 0.98