Higgs production in association with top quarks with ILD at 500 GeV and 1 TeV

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Outline

- **Top Yukawa coupling**
- **What is the required precision?**
- **How well can we measure it at ILC?**

[See also talk by Philipp Roloff]

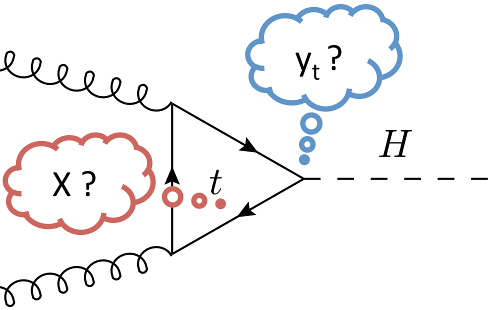
Top Yukawa Coupling

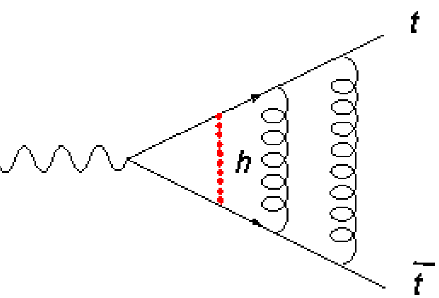
- **Higgs boson discovered!**
- Top Yukawa coupling is large
  - What role does the top quark play in EWSB?
- Need to better understand the relation between coupling and mass
  - top mass measurement at top pair threshold
  - coupling measurement in direct ttH production

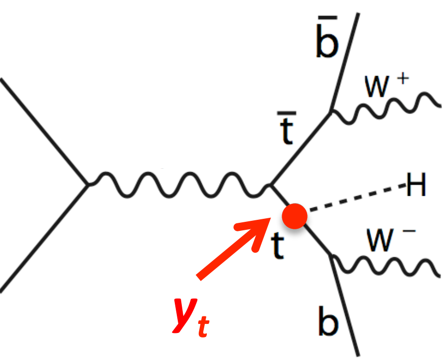
?

$$y_t = m_t \frac{\sqrt{2}}{v} \approx \frac{m_t}{174.10}$$

Indirect vs. Direct







Indirect measurement

✓ **High statistics**

→ Need higher order **loop corrections**

✓ Sensitive to new physics in the loop

→ cannot separate the tree-level coupling anomaly

Direct measurement

✓ **Model-independent**

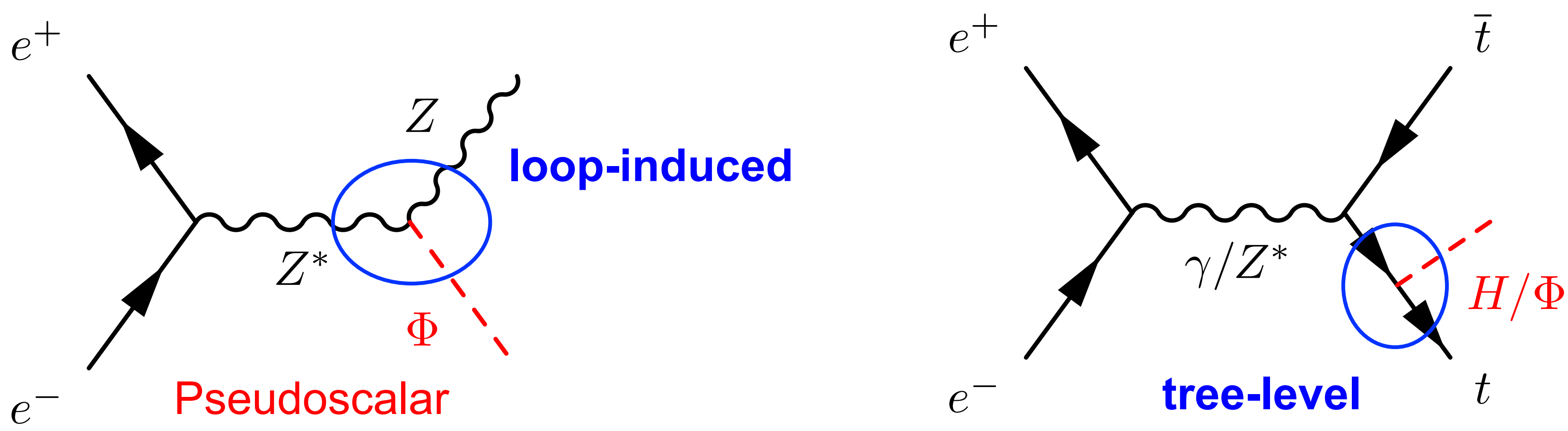
✓ Sensitive to **tree-level** anomaly

✓ Together with indirect measurement, disentangle **new physics in the loop**

→ Require energy to directly produce tth, large jet multiplicity

New Physics Effects

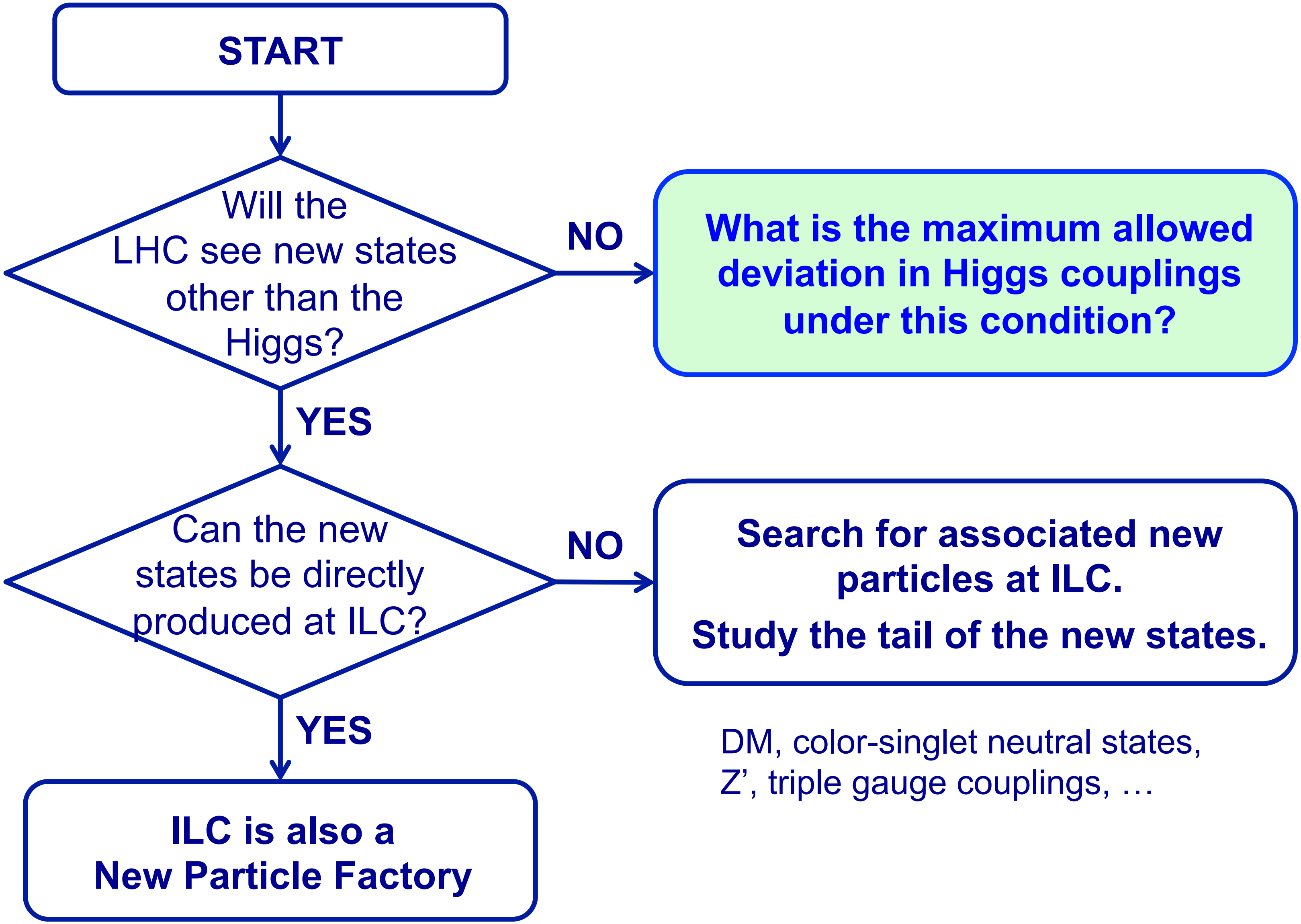
- Many NP models predict **extended Higgs sector**
  - Coupling **deviates** from the SM-prediction
    → Gives us a clue on the **required precision**
- If the Higgs boson is a CP-mixed state, ttH and ttΦ are produced via tree-level couplings
  - as opposed to loop-induced in Higgs-strahlung



→ Motivates precise measurement of top Yukawa coupling

Outline

- Top Yukawa coupling
- What is the required precision?
- How well can we measure it at ILC?



Natural SUSY, Compressed Spectra, …

If LHC doesn't see any other new particles

EW precision data
+ LHC 300 fb^{-1} (Heavy Higgs, VBF WW/HH)

Gupta, Rzehak, Wells, arXiv:1206.3560
Rzehak, Moriond EW 2013
Rzehak, ECFA LC2013

Maximum Deviation	ΔhVV	$\Delta h\bar{t}t$	$\Delta h\bar{b}b$
Mixed-in Singlet	6%	6%	6%
Composite Higgs	8%	tens of %	tens of %
Minimal Supersymmetry	$< 1\%$	3%	10%, 100%

10%: $\tan\beta > 20$ no superpartners
100%: all other cases

→ **Required precision in y_t is few % to few tens of %**

Outline

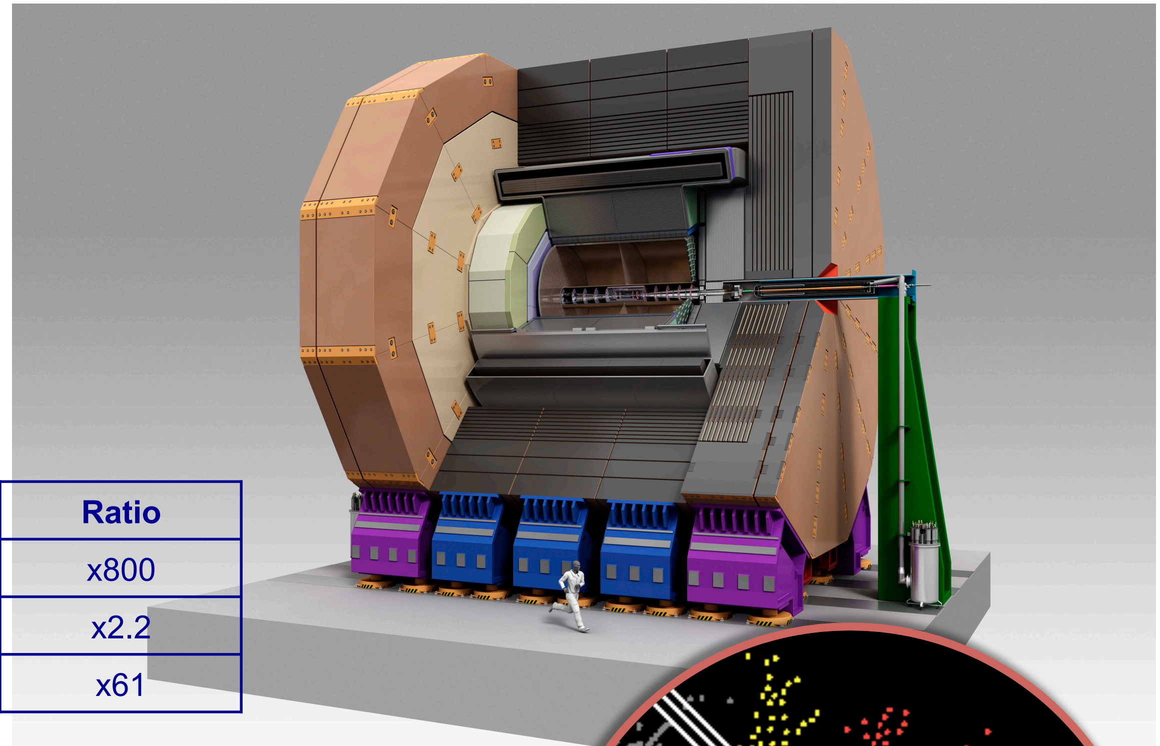
- **Top Yukawa coupling**
- **What is the required precision?**
- **How well can we measure it at ILC?**

ILD detector

Vertex Detector: pixel detectors & low material budget

Tracker: low material budget

Calorimeters: high granularity sensors



Sensor Size	ILD	ATLAS	Ratio
Vertex	5×5 mm^2	400×50 mm^2	x800
Tracker	1×6 mm^2	13 mm^2	x2.2
ECAL	5×5 mm^2 (Si)	39×39 mm^2	x61

Particle Flow Algorithm

Separate calorimeter clusters at particle level

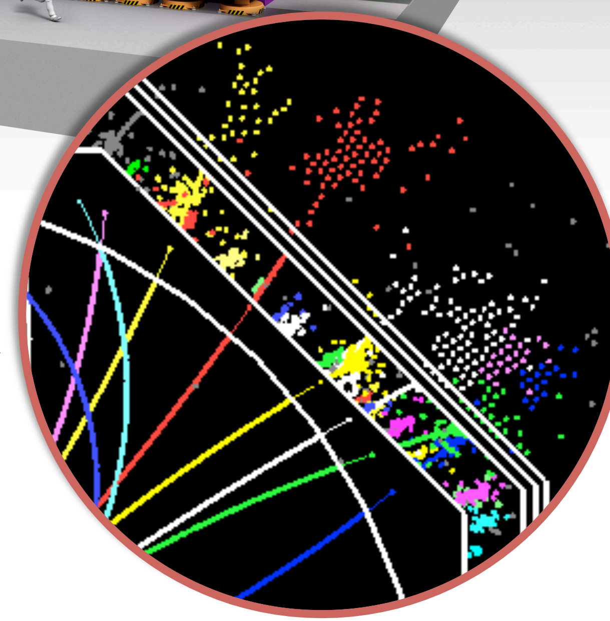
→ use *best* energy measurement for *each* particle.

→ offers unprecedented **jet energy resolution**

Charged Tracks → Tracker

Photons → ECAL

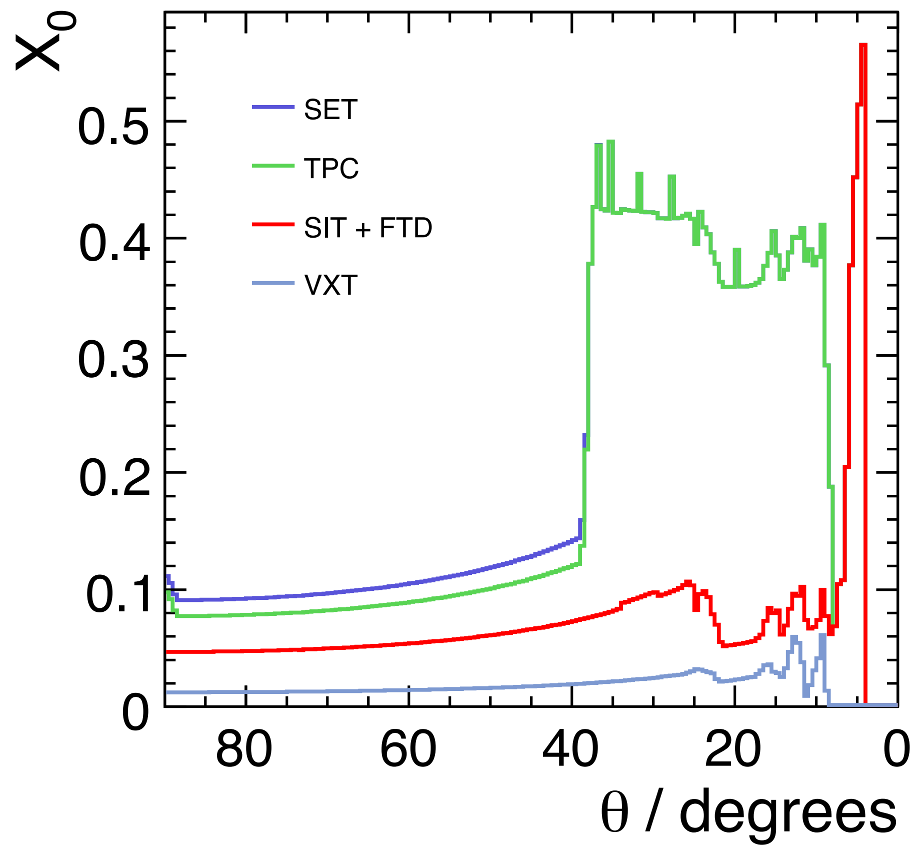
Neutral Hadrons → HCAL



Increased realism in simulation

Simulation framework has been updated in the context of the Detailed Baseline Design report, e.g.

- Beam parameters
- Beam-induced backgrounds
- Detector model
- Reconstruction algorithms
  - Tracking
  - Particle Flow
  - Flavor Tag

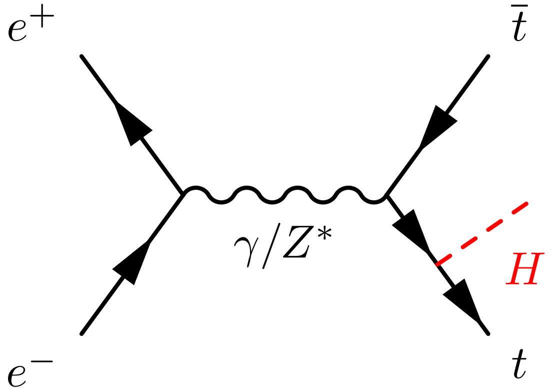


ILD Material Budget

Includes support structure, cabling, etc

→ Geant4-based full simulation

Signal



$H \to b\bar{b}$

tt $\to$

bqqbqq **(45%)**

bqqblv **(44%)**

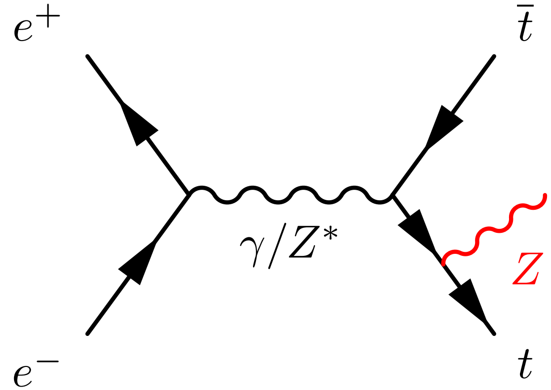
blvblv (11%)

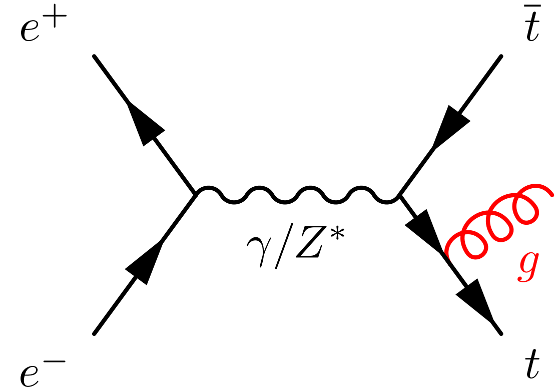
Analyze:

6 jets + lepton mode

8 jets mode

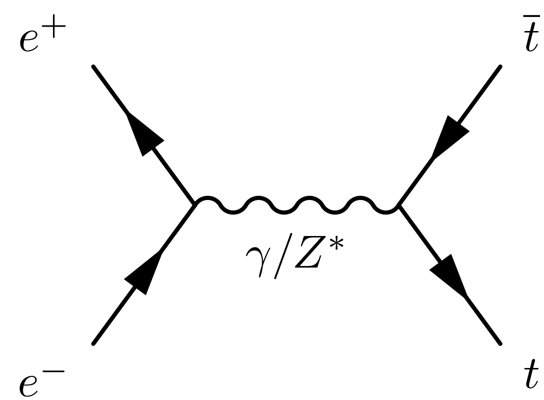
Major Backgrounds





Irreducible for $\bar{Z}$, $g^* \to bb$

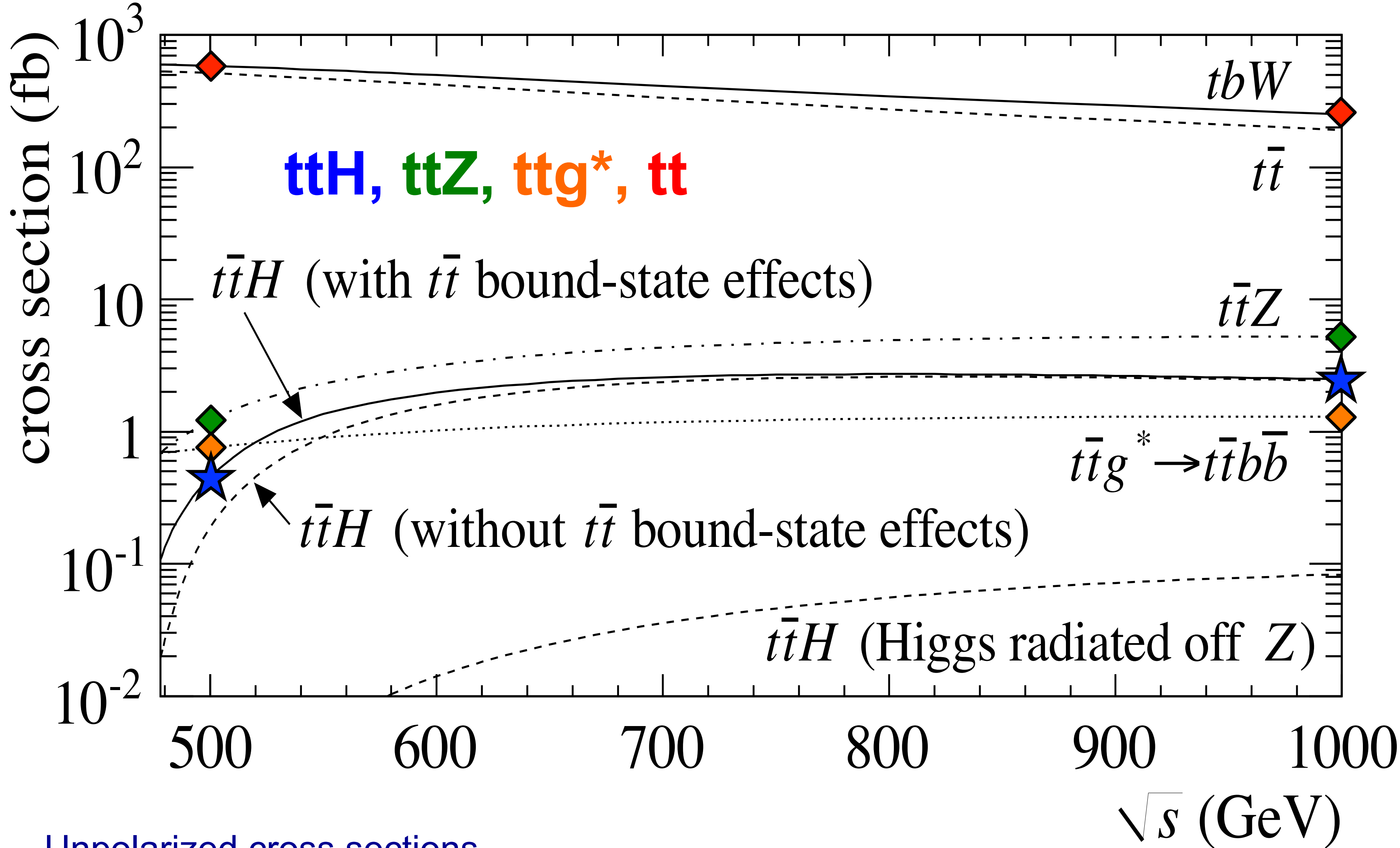
Key: mass reconstruction



Reducible but large cross section

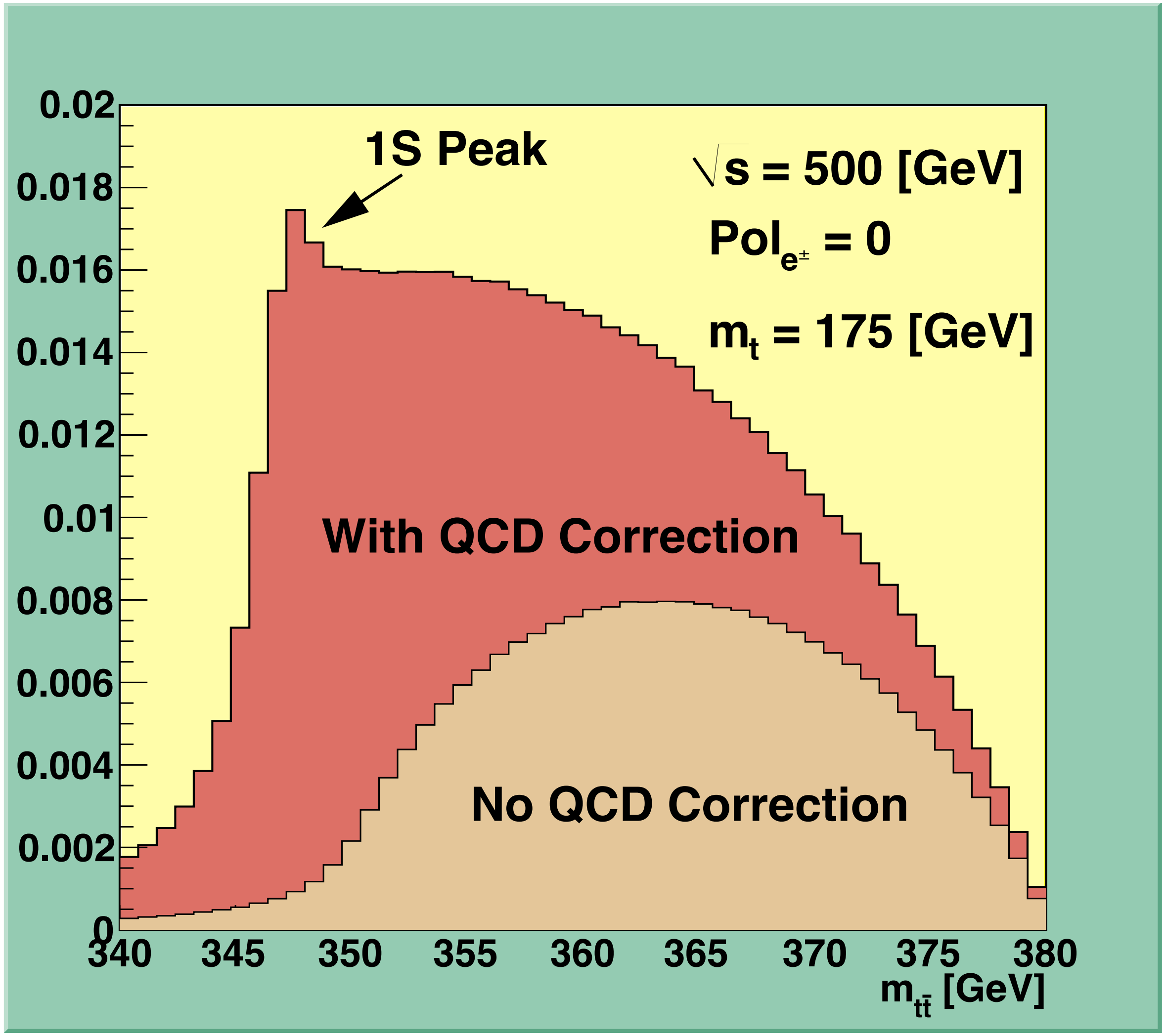
Key: b-jet tagging, event shape

Cross Sections



Unpolarized cross sections.
For ttH: m_H = 120 GeV

$t\bar{t}$ bound-state effects



$t\bar{t}$ bound-state effects **enhances (~2x)** the cross section near production threshold
Makes top Yukawa measurement at 500 GeV feasible!

Analysis Flow

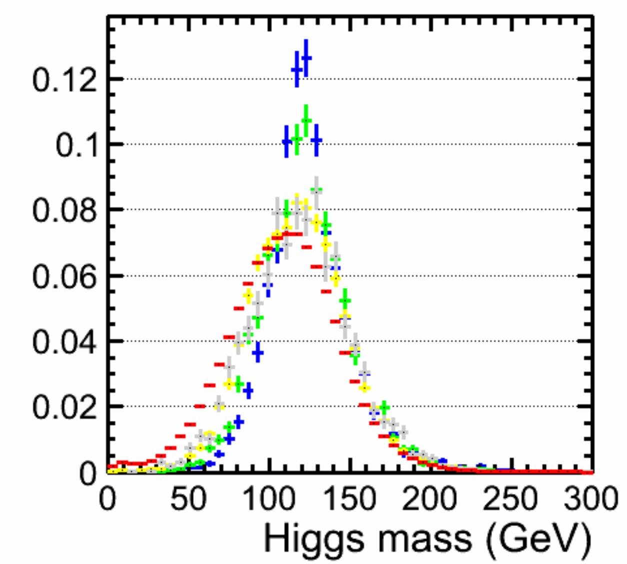
- Start with standard reconstruction samples for DBD
- Removal of γγ→hadrons pileup background
- Isolated lepton finding
  - split sample into bqqbqqbb / bqqbqqlnu
- Event selection based on
  - event shapes, b-tagging, reconstructed mass, etc
- Results cross-checked by two analyses:
  - Cut-based
  - TMVA-based with Boosted Decision Trees

Details can be found in **LC-REP-2013-004**
http://www-flc.desy.de/lcnotes/

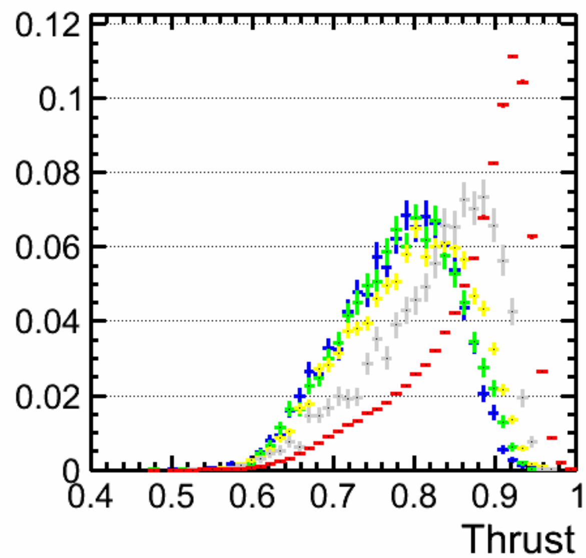
Mass reconstruction

Event shape, b tagging

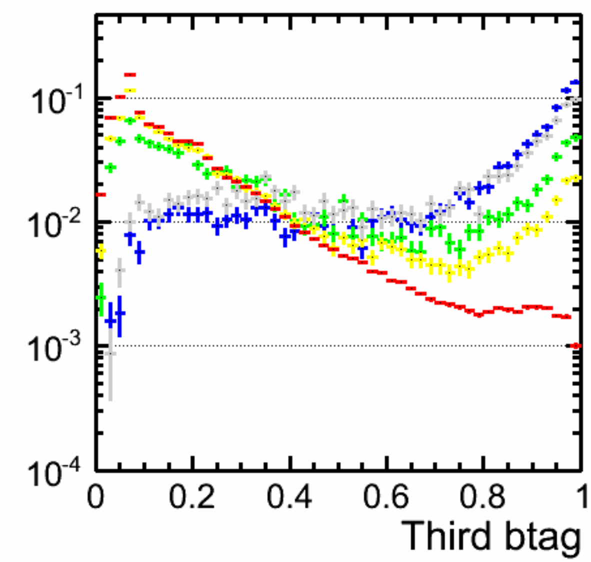
Higgs candidate mass*



Thrust



3rd b-tag



* Jet combination with most consistent candidate mass is selected.

***tt* → *bqqbqqbb* sample (with lepton veto) @ 1 TeV**

ttH 8 jet, ttH other, ttZ, ttbb, tt

Cut Analysis [$\sqrt{s}$ = 1 TeV]

	ttH 8J	ttZ	ttg*	tt
No cuts	650	5300	1400	300000
Pre-selection	650	3200	930	190000
Event Shapes	550	1900	470	**27000**
b-tagging	280	230	210	**680**
Mass	260	210	180	530

	ttH 6J+L	ttZ	ttg*	tt
No cuts	630	5300	1400	300000
Pre-selection	360	1600	440	100000
Event Shapes	150	280	86	**1800**
b-tagging	100	58	55	**130**
Mass	95	46	49	110

Need multivariate analysis to fully exploit mass information

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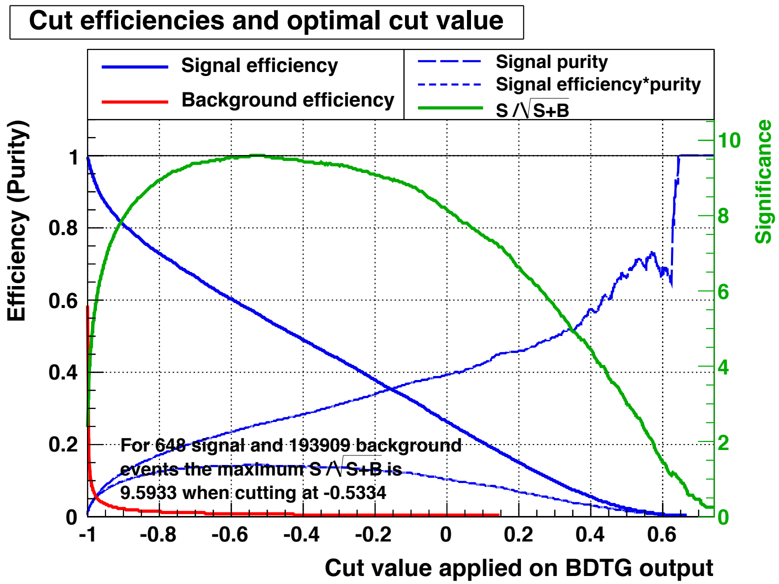
Multivariate Analysis



√s = 1 TeV	Statistical Significance	
	Cut-based	Multivariate
tth → bqqblvbb	**5.4**	**7.6**
tth → bqqbqqbb	**7.2**	**9.6**

TMVA-based analysis with BDT improves significance.

For DBD: assuming equal split between two polarizations.

- 0.5 ab^{-1} of $P(e^-, e+)=(-0.8, +0.2)$
- 0.5 ab^{-1} of $P(e^-, e+)=(+0.8, -0.2)$

Summary of Results

Detector Model	ILD		
CM Energy	**500 GeV**	**1 TeV**	
Higgs mass	125 GeV		
Beam polarization	(−0.8, +0.3)	(−0.8, +0.2)	(−0.8, +0.2), (+0.8, −0.2)
Integrated Luminosity	1 ab^{-1}	1 ab^{-1}	0.5 ab^{-1}, 0.5 ab^{-1}
$\Delta y_t/y_t$	**11%**	**3.9%**	4.3%

Scaled from m_H=120 GeV [Preliminary]

DBD benchmark configuration

~800 GeV maximum cross section for ttH (need to consider also behavior of background)

Optimization of machine running scenario is needed.

Systematic Uncertainties

So far our results give the statistical precision only.
For **O(1)%** measurements, need to address **systematic uncertainties** such as:

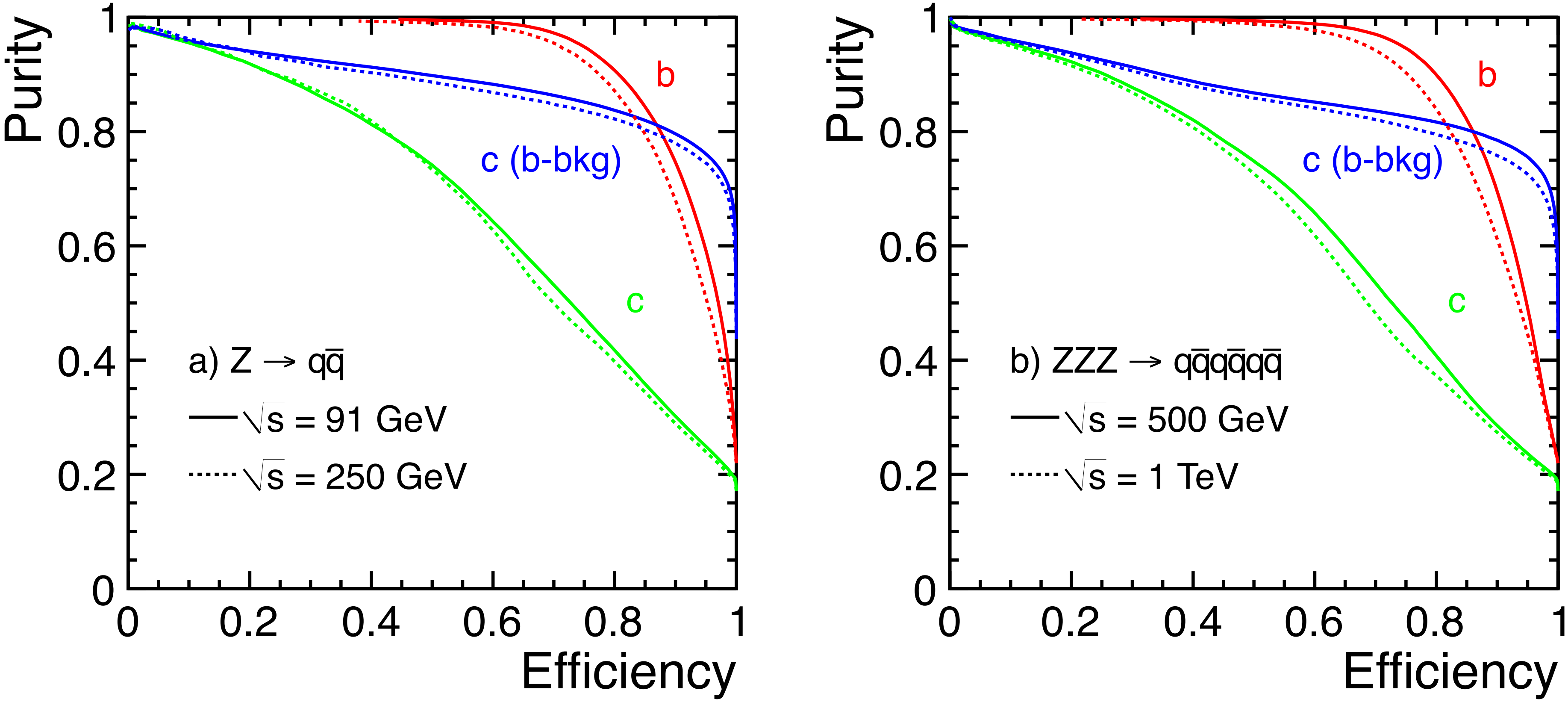
- BR(H→bb) … ~2%
- Background normalization … TBD
- Jet energy scale … TBD
- Luminosity … TBD, O(0.1)%
- Polatization … ~0.2%
- b tagging efficiency … TBD, O(1)%
- Lepton ID / isolation … TBD

→ *These are the next steps…*

Conclusions

- **Interesting physics with top Yukawa coupling**
  - relation between coupling and mass
  - new physics from direct and indirect measurements
- Maximum possible deviation of top Yukawa coupling if LHC doesn't see new particles is **a few % to few tens of %** **[Gupta, Rzehak, Wells '12]**
- Expected precision of top Yukawa coupling with the latest ILC simulations (2012-2013) have been evaluated
  - $\sqrt{s}$=500 GeV, L=1 ab^{-1}, $\Delta y_t/y_t$ **~11%** **[preliminary]**
  - $\sqrt{s}$=1 TeV, L=1 ab^{-1}, $\Delta y_t/y_t$ **~4%**

Extra Slides


Purity
Efficiency
b
c (b-bkg)
c
a) Z → qq̄
√s = 91 GeV
√s = 250 GeV
b) ZZZ → qq̄qq̄qq̄
√s = 500 GeV
√s = 1 TeV
0
0.2
0.4
0.6
0.8
1

500 GeV
(Preliminary)

1 TeV

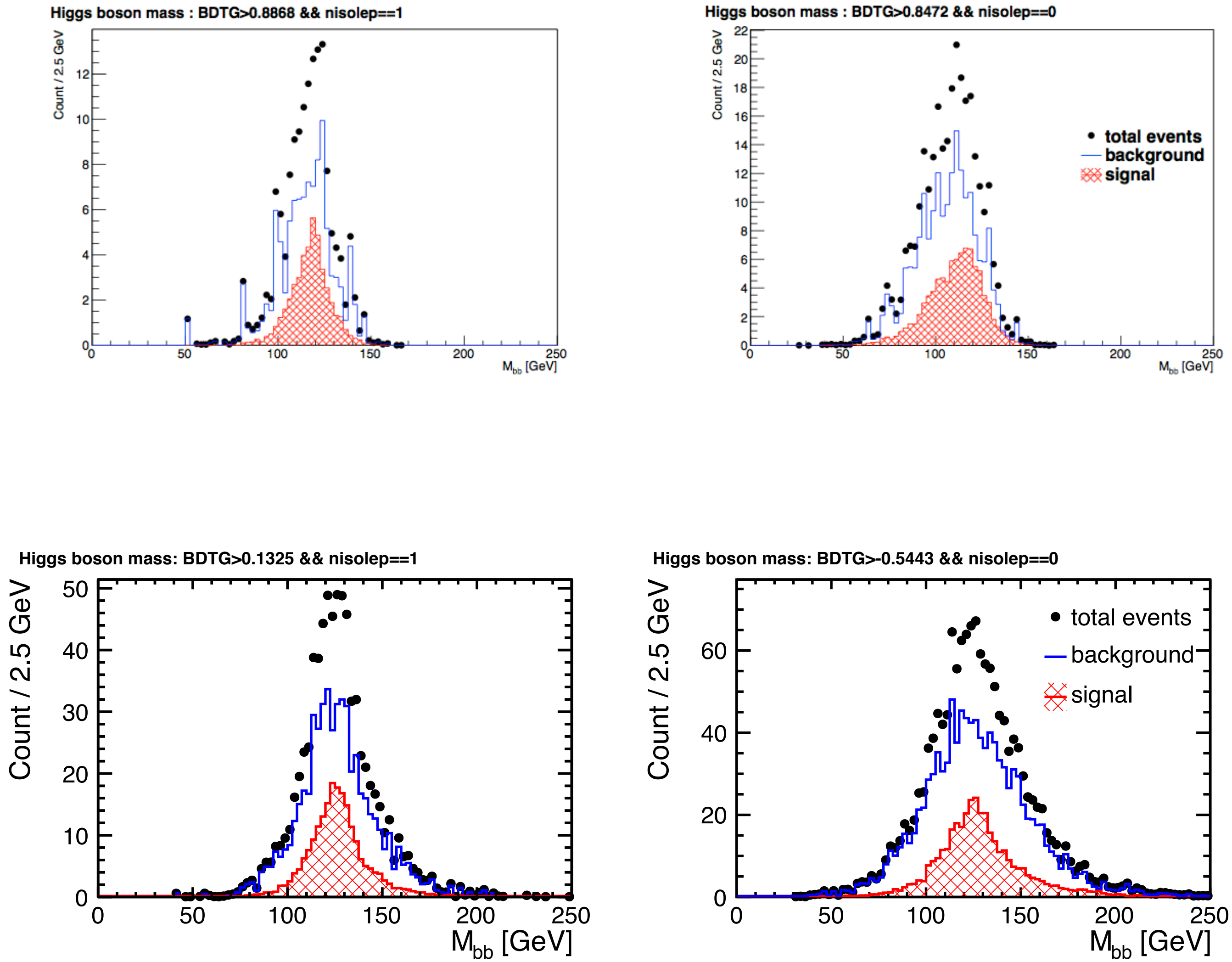
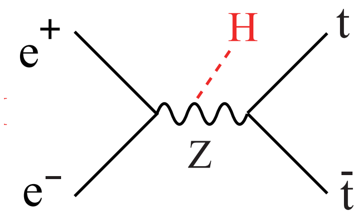


Figure 18: Reconstructed masses for the Higgs boson candidate after applying a cut on the multivariate classifier for the semileptonic (left) and hadronic (right) decay modes.

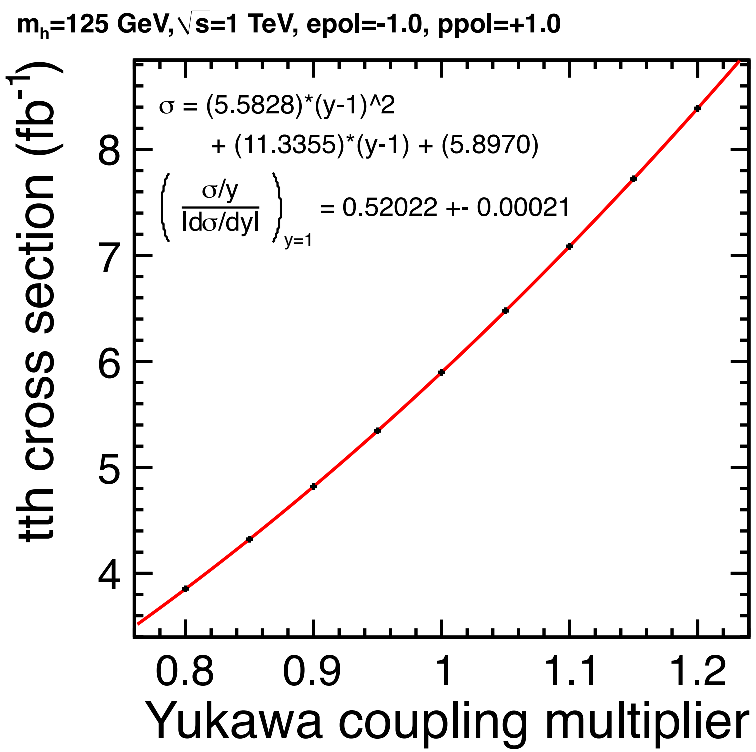
Sensitivity to top Yukawa

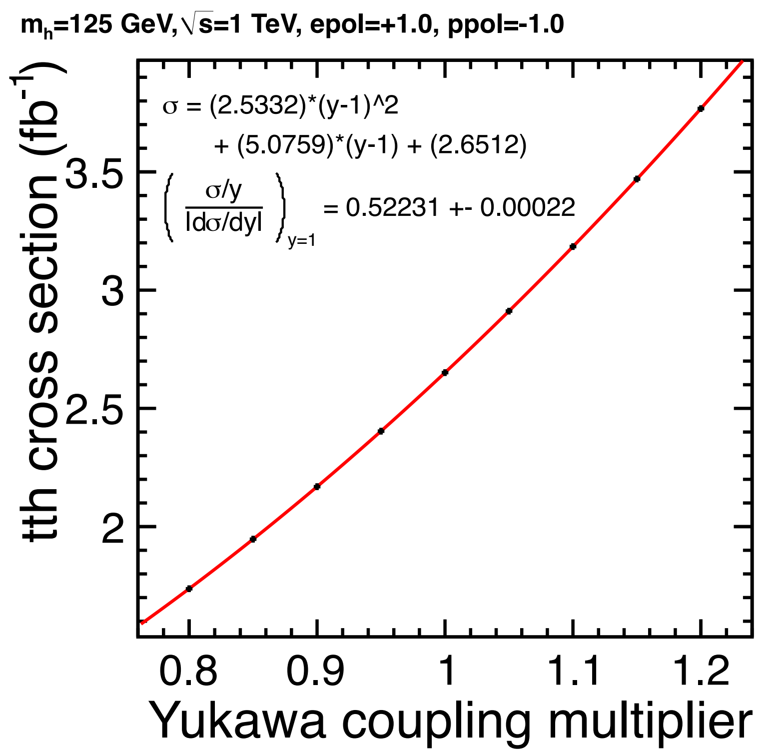


Estimate effect of non-contributing diagrams.
Dependence of cross section w.r.t. scaling of top Yukawa coupling → slope at SM value gives nominal sensitivity

$$\frac{\Delta y_t}{y_t} = (..)\,\frac{\Delta\sigma}{\sigma} \qquad \left(\frac{\sigma/y_t}{|d\sigma/dy_t|}\right)_{y_t=y_t(SM)}$$

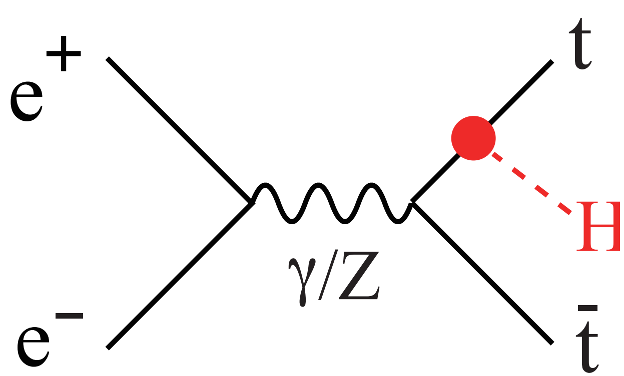
= 0.52





Signal mode

- Goal is to evaluate the precision of the top Yukawa coupling at $\sqrt{s}$ = 1 TeV
  - evaluate the precision of cross section measurement
- **Higgs boson mass set to 125 GeV in light of LHC data.**
  - BR(H→bb) = 57.8%
- There are three decay modes depending on the W decay:
  - ttH → 4 jet + 2 lepton mode: BR(tt → blνblν) = 11% -- not analyzed
  - **ttH → 6 jet + lepton mode:** BR(tt → bqqblν) = 45% for l=e,μ,τ (29% for l=e,μ)
  - **ttH → 8 jet mode:** BR(tt → bqqbqq) = 44%



Data Samples

id	process	pol	xsec	ngen	weight
106427	Pttbb-all-all	eL.pR	3.429300	21000	0.047357
106428	Pttbb-all-all	eR.pL	1.517400	10600	0.041514
106429	Pttz-all-all	eL.pR	14.020600	13829	0.294018
106430	Pttz-all-all	eR.pL	4.367100	13200	0.095944
106451	Ptth-6q-hbb	eL.pR	1.552750	17620	0.025556
106452	Ptth-6q-hbb	eR.pL	0.698000	7361	0.027499
106453	Ptth-6q-hnonbb	eL.pR	1.133670	7749	0.042427
106454	Ptth-6q-hnonbb	eR.pL	0.509620	3787	0.039026
106455	Ptth-ln4q-hbb	eL.pR	1.495560	17603	0.024639
106456	Ptth-ln4q-hbb	eR.pL	0.672430	7311	0.026673
106457	Ptth-ln4q-hnonbb	eL.pR	1.091920	6684	0.047375
106458	Ptth-ln4q-hnonbb	eR.pL	0.490940	3358	0.042398
106459	Ptth-2l2nbb-hbb	eL.pR	0.360100	800	0.130536
106460	Ptth-2l2nbb-hbb	eR.pL	0.161940	400	0.117407
106461	Ptth-2l2nbb-hnonbb	eL.pR	0.262910	600	0.127073
106462	Ptth-2l2nbb-hnonbb	eR.pL	0.118230	400	0.085717
35786	P6f_yyveev	eL.pL	0.753694	10000	0.015828
35787	P6f_yyveev	eL.pR	14.262567	14263	0.289991
35788	P6f_yyveev	eR.pL	3.191048	10000	0.092540
35789	P6f_yyveev	eR.pR	0.759213	9999	0.015945
35790	P6f_yyvelv	eL.pL	1.434391	10000	0.030122
35791	P6f_yyvelv	eL.pR	22.876428	22873	0.290043
35792	P6f_yyvelv	eR.pL	6.272190	10000	0.181894
35794	P6f_yyveyx	eL.pL	4.121621	9999	0.086563
35795	P6f_yyveyx	eL.pR	67.534318	400000	0.048962
35796	P6f_yyveyx	eR.pL	18.645337	40000	0.135179
35799	P6f_yyvlev	eL.pR	22.875149	22871	0.290053
35800	P6f_yyvlev	eR.pL	6.264408	9998	0.181704
35801	P6f_yyvlev	eR.pR	1.427611	10000	0.029980
35803	P6f_yyvllv	eL.pR	41.275472	41270	0.290038
35804	P6f_yyvllv	eR.pL	12.598244	12597	0.290029
35807	P6f_yyvlyx	eL.pR	115.979040	698099	0.048179
35808	P6f_yyvlyx	eR.pL	37.306473	60000	0.180315
35811	P6f_yyxyev	eL.pR	68.502191	400000	0.049664
35812	P6f_yyxyev	eR.pL	18.659270	40000	0.135280
35813	P6f_yyxyev	eR.pR	4.163067	10000	0.087424
35815	P6f_yyxylv	eL.pR	116.426720	699144	0.048293
35816	P6f_yyxylv	eR.pL	37.321082	60000	0.180385
35819	P6f_yyuyyu	eL.pR	84.595962	500000	0.049066
35820	P6f_yyuyyu	eR.pL	27.500471	40000	0.199378
35823	P6f_yyuyyc	eL.pR	84.581774	498800	0.049175
35824	P6f_yyuyyc	eR.pL	27.508546	40000	0.199437
35827	P6f_yycyyu	eL.pR	84.426452	500000	0.048967
35828	P6f_yycyyu	eR.pL	27.483992	40000	0.199259
35831	P6f_yycyyc	eL.pR	84.975908	500000	0.049286
35832	P6f_yycyyc	eR.pL	27.584594	40000	0.199988

Signal samples

Weights are calculated assuming data samples of:

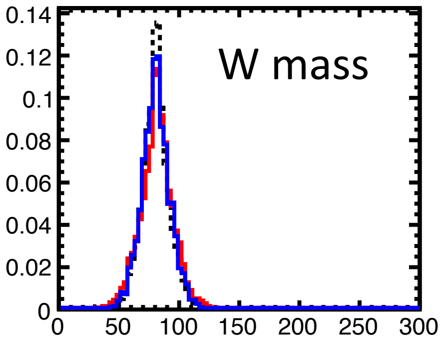
- 0.5 ab^{-1} for (−0.8, +0.2)
- 0.5 ab^{-1} for (+0.8, −0.2)

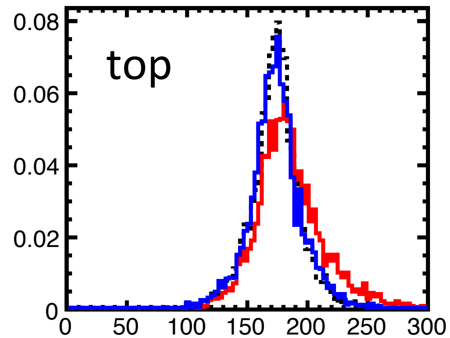
which are summed.

All weights << 1:

→ We have sufficient statistics.

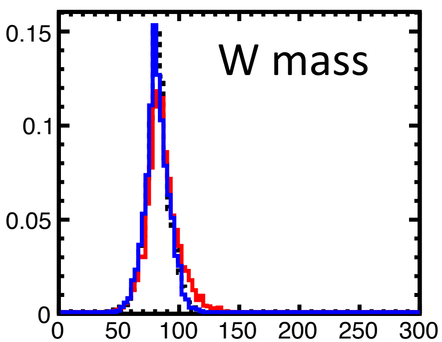
Removal of γγ→hadrons

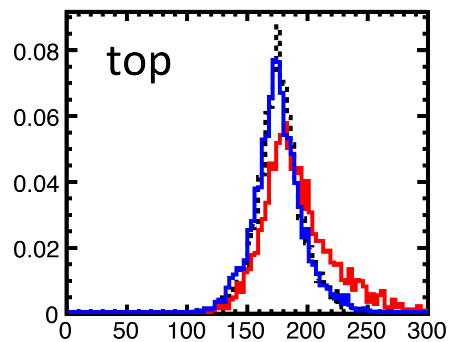




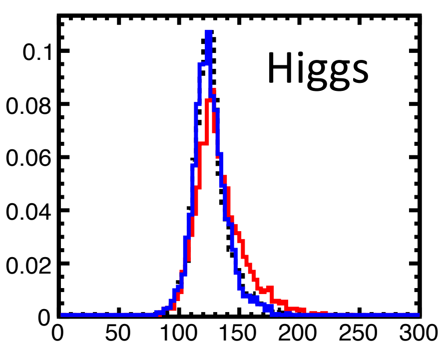
Average 4.1 events γγ→hadrons are overlaid in all simulations.

→ Degrade the mass resolution due to extra energy in the forward region.





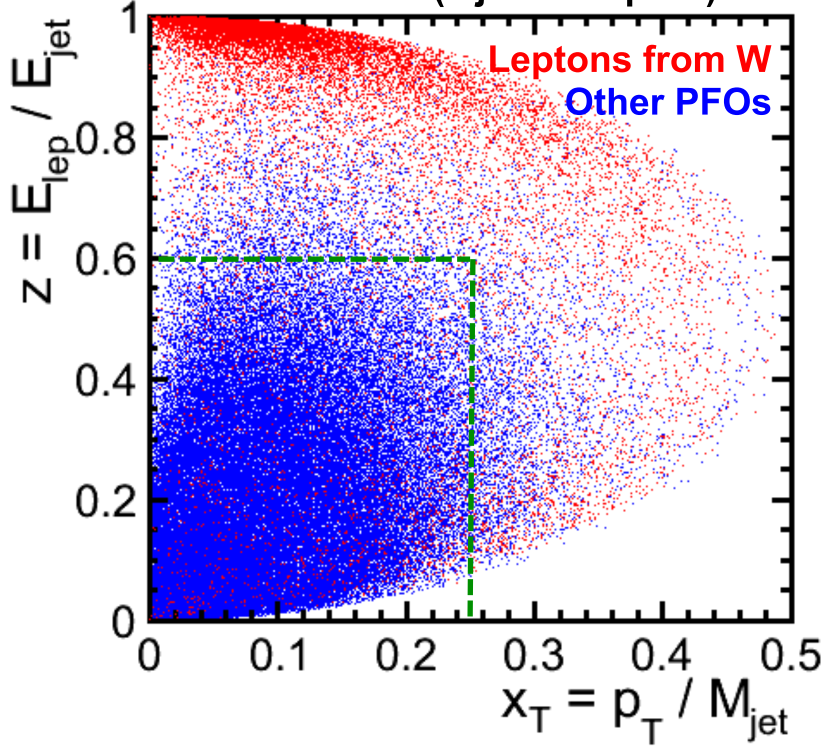
Black (dotted):
Durham (sample w/o γγ→hadrons)
Red:
Durham (sample w/ γγ→hadrons)
Blue:
Durham (sample w/ γγ→hadrons) after removing cosθ>0.94 particles



→ **Mass resolution can be recovered.**
(PFOs are mostly central for ttH process.)

kt algorithm with R=1.2 is used for final analysis

Isolated Lepton Finding



Hard isolated leptons coming from W decay

- Useful for separating 6 jet + lepton / 8 jet / background

Selection criteria based on:

- **Lepton ID with calorimeter energies** which reduces fake leptons
- **Impact parameter significance** for reducing contamination from bottom and tau decays
- **Jet-based isolation** ("LAL Lepton Finder")
  - isolated lepton in jets tends to be "leading" or have "large p_T w.r.t jet axis"

	Efficiency	Composition			
		W→e,μ	W→τ→e,μ	Other e,μ	Fake e,μ
Electrons	84.0%	94.2%	2.9%	1.6%	2.3%
Muons	90.5%	96.3%	2.4%	1.2%	0.7%

Performance of isolated lepton finder for tth 6 jets + 1 lepton sample

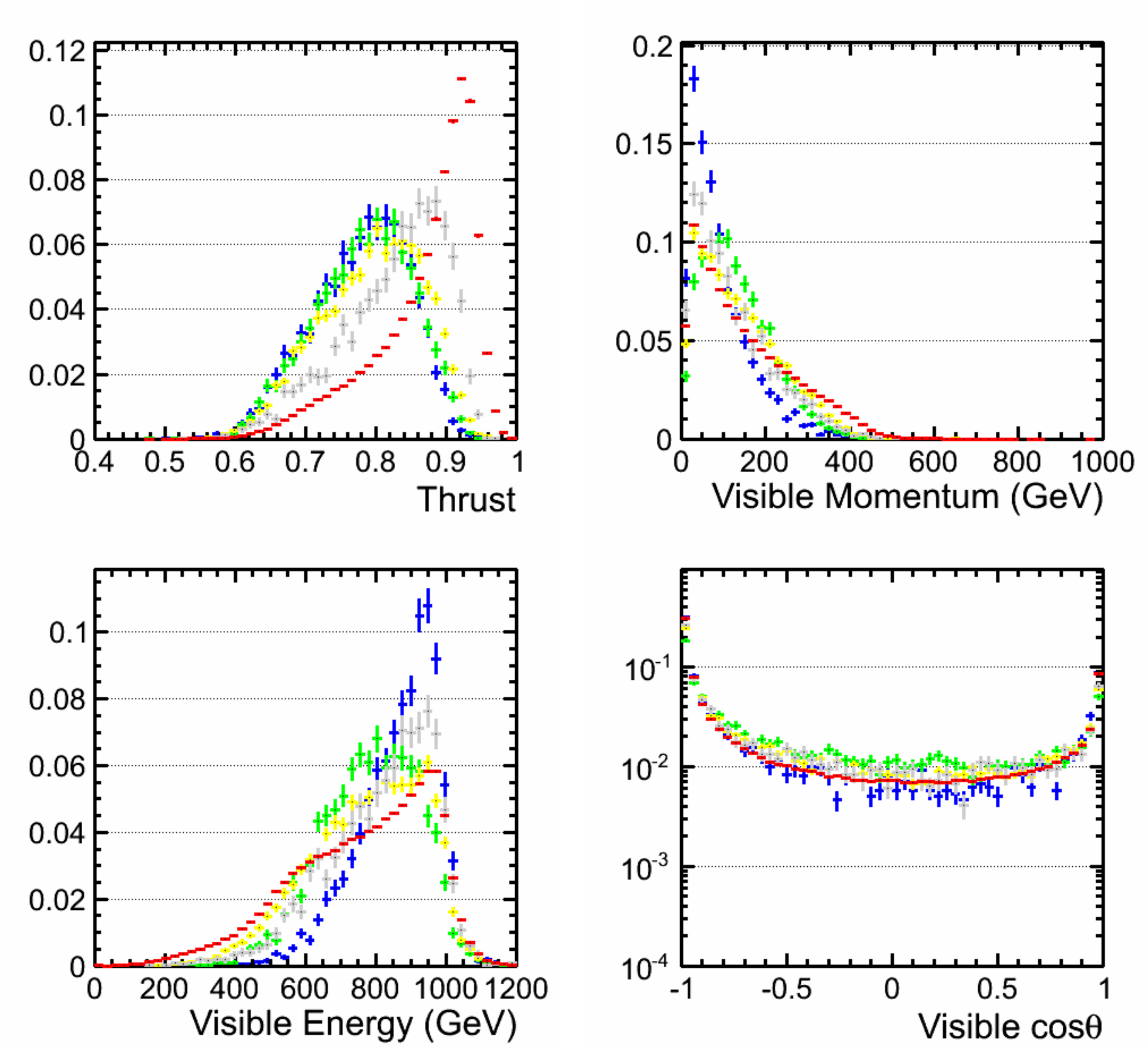
Variables (1)

ttH 8 jet
ttH other
ttZ
ttbb
tt

$$T = \max_{|\hat{n}|=1} \frac{\sum_i |\hat{n} \cdot \vec{p}_i|}{\sum_i |\vec{p}_i|}$$

Thrust definition

- dijet-like → 1
- Isotropic → 0

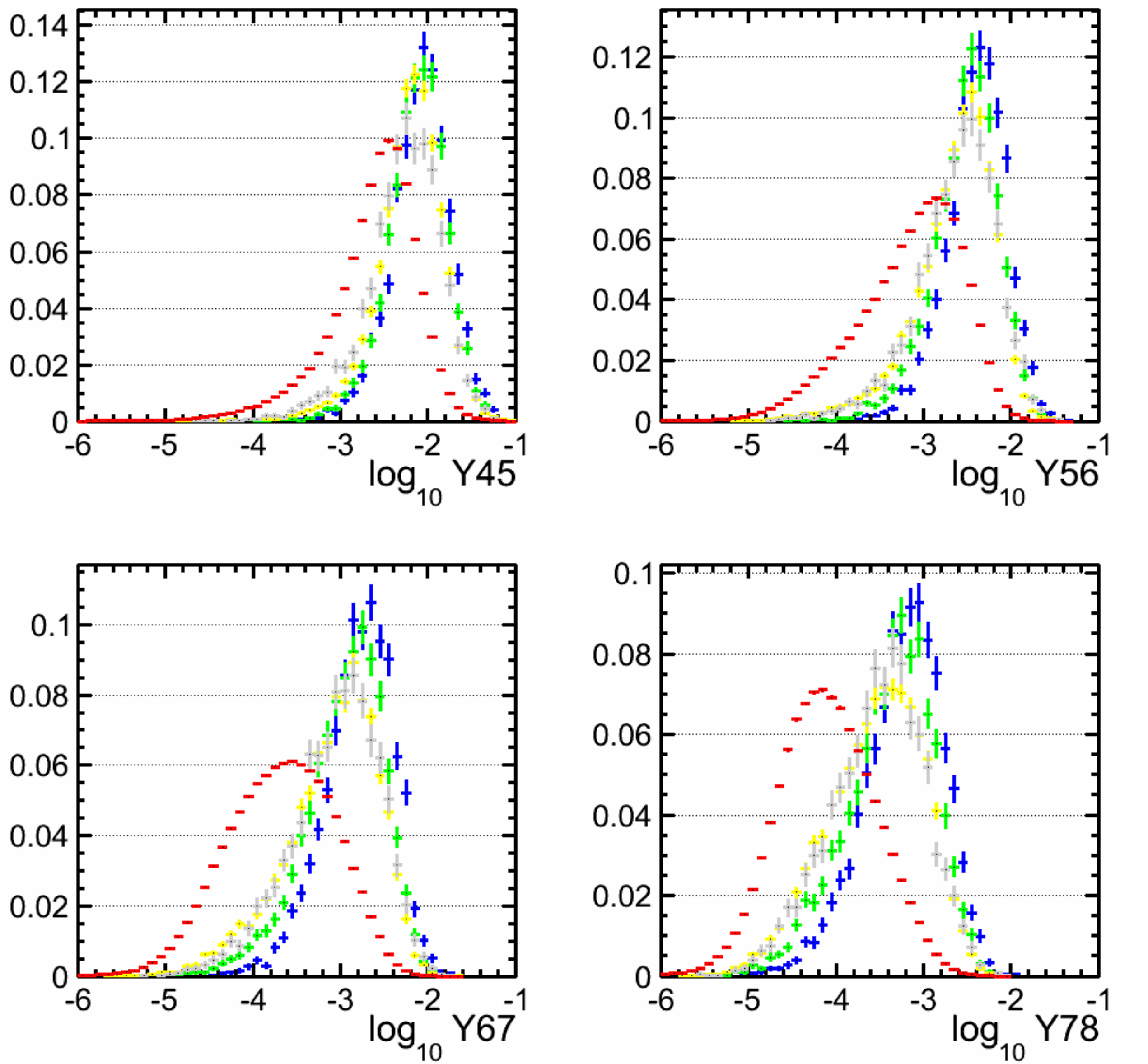


Variables (2)

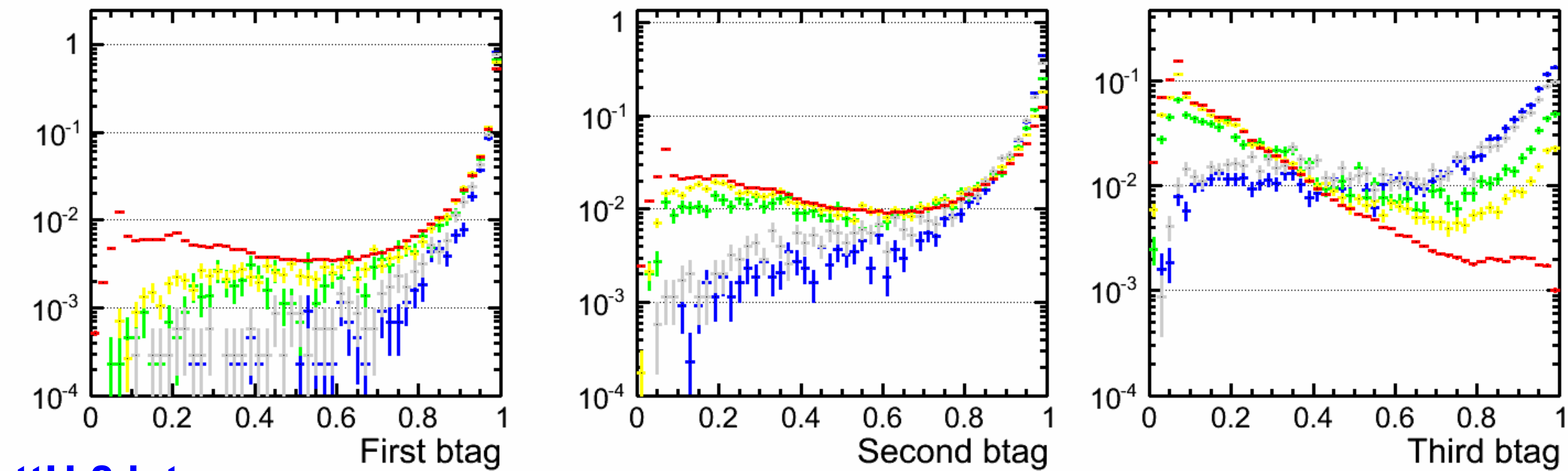
ttH 8 jet
ttH other
ttZ
ttbb
tt

Jet Finder "Y" variables

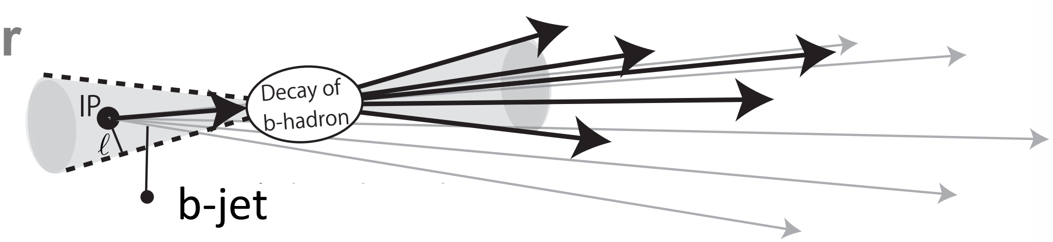
$$Y_{ij} = \frac{\max(E_i^2, E_j^2)(1 - \cos\theta_{ij})}{E_{\mathrm{CM}}^2}$$

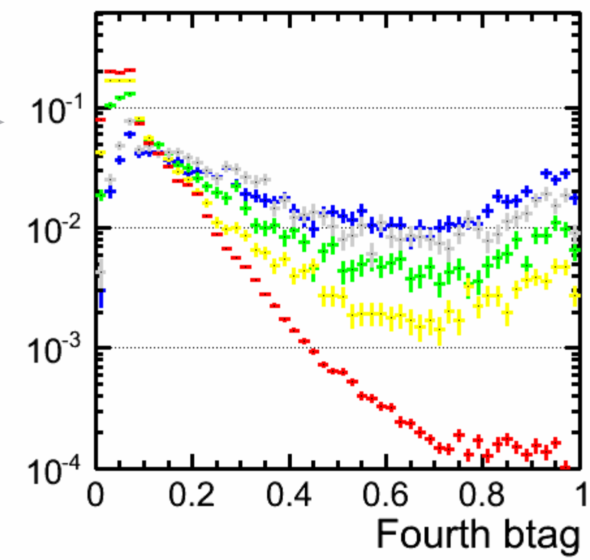


Variables (3)



ttH 8 jet
ttH other
ttZ
ttbb
tt

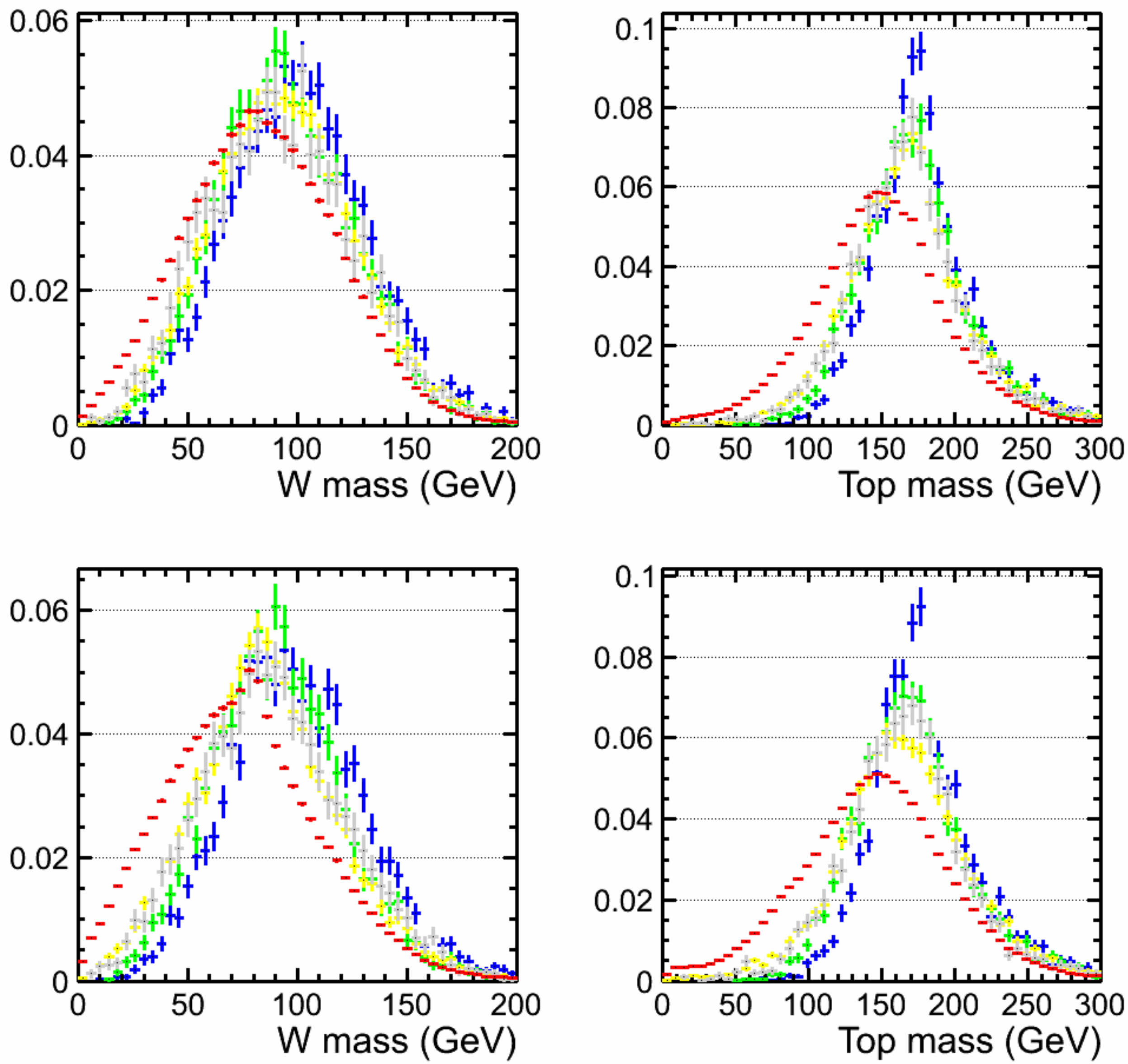




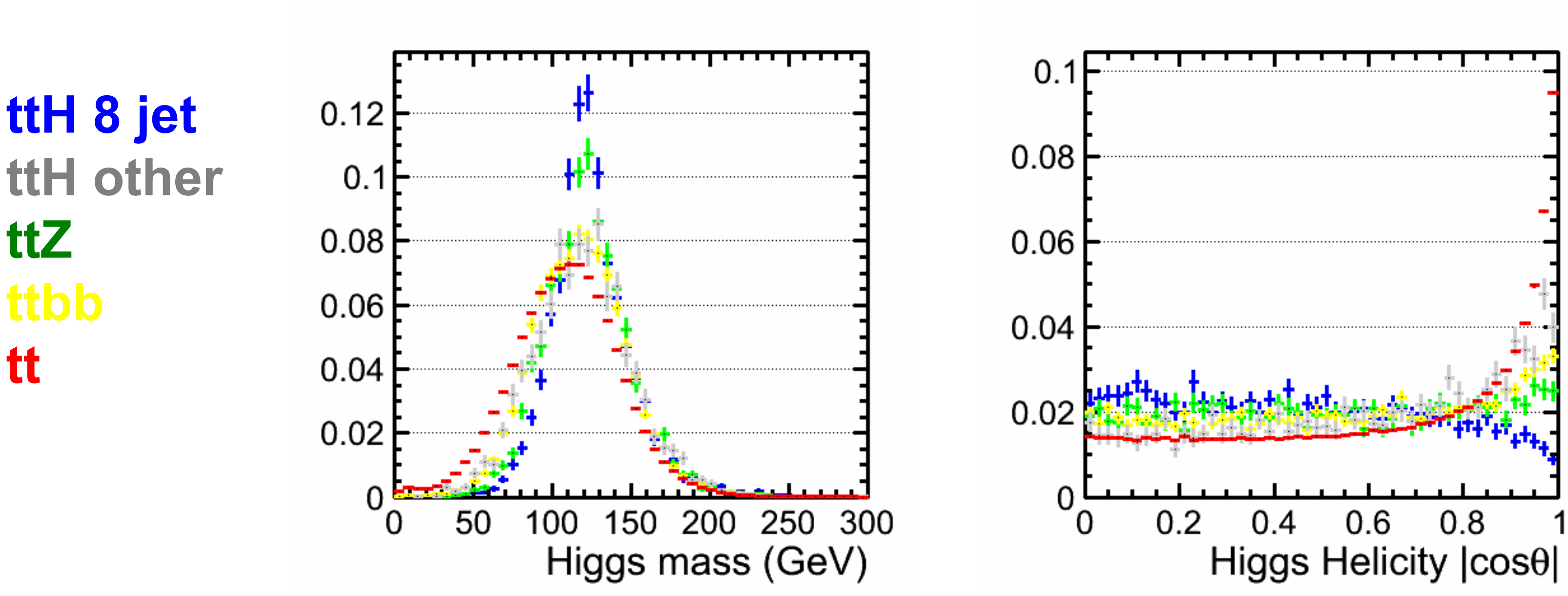
b-jet tagging: displaced tracks & secondary vertices
Multivariate analysis of variables (LCFIPlus)

Variables (4)

ttH 8 jet
ttH other
ttZ
ttbb
tt



Variables (5)



$$\chi^2 = \frac{(M_{t_1} - M_t)^2}{\sigma_{t_1}^2} + \frac{(M_{t_2} - M_t)^2}{\sigma_{t_2}^2} + \frac{(M_{b\bar{b}} - M_H)^2}{\sigma_H^2}$$

Jet combination is based on chi-squared minimization method.
Jets with 4 lowest b-tags selected for W candidates.

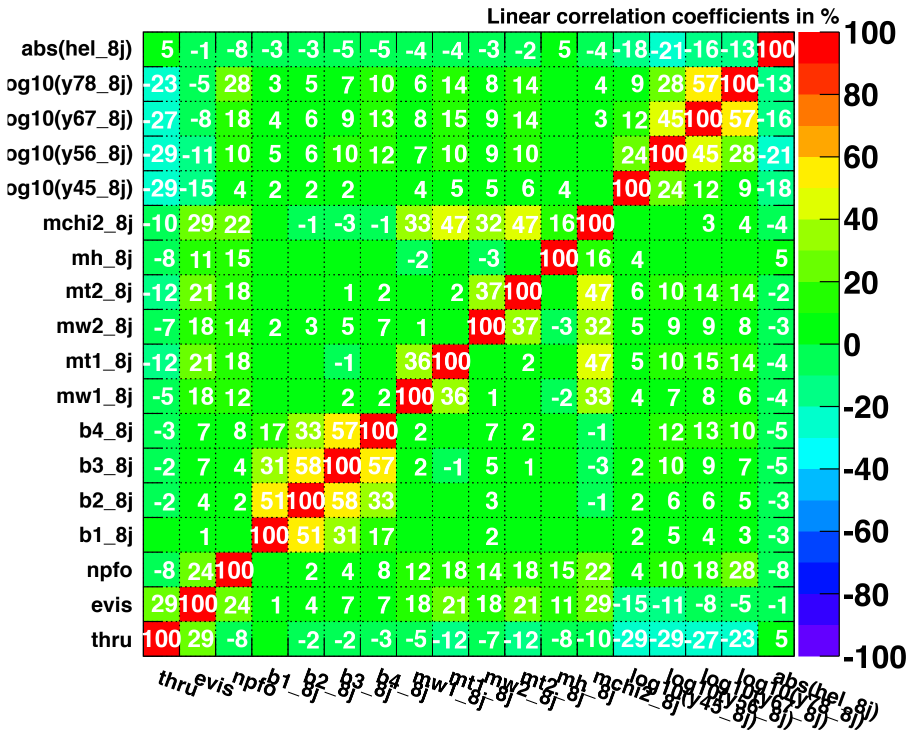
Cut-based Analysis

	$t\bar{t}h$ (4J)	$t\bar{t}h$ (6J)	$t\bar{t}h$ (8J)	$t\bar{t}h$ ($h \not\to b\bar{b}$)	$t\bar{t}Z$	$t\bar{t}b\bar{b}$	$t\bar{t}$	Sig.
No cuts	151.39	628.73	652.77	1046.10	5332.52	1434.53	306238.26	1.16
$N_{\rm iso} = 0$	20.87	261.17	647.92	556.71	3226.14	932.49	188911.38	1.47
$E_{\rm vis} > 650$ GeV	9.83	220.97	636.16	497.45	2743.54	849.34	157389.56	1.58
Thrust< 0.87	8.09	187.75	577.60	440.06	2219.68	540.88	46916.14	2.56
$Y_{78} > 0.0001$	3.65	143.55	549.52	415.51	1926.58	474.59	27472.09	3.12
$btag_4 > 0.38$	1.89	80.98	275.02	17.55	230.04	209.60	680.62	7.11
$\|\cos\theta_{\rm hel}\| < 0.9$	1.63	73.80	263.71	16.48	215.91	189.19	584.92	7.19
$m_t > 120$ GeV	1.50	68.09	255.38	15.58	207.81	178.53	530.93	7.20

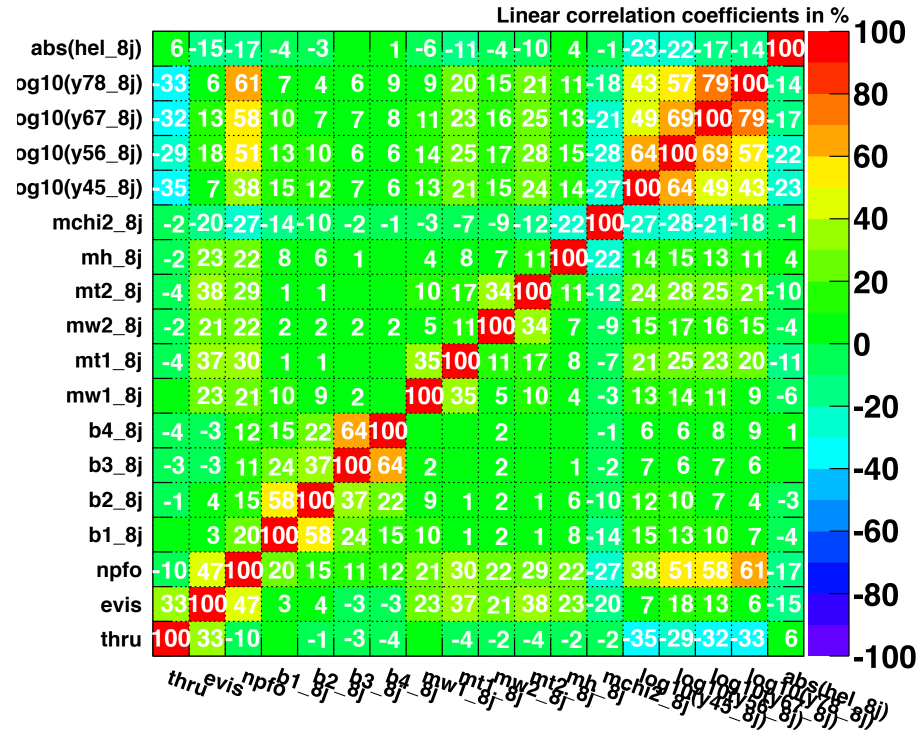
Cut-based analysis result (8 jet mode only):
Statistical significance = 7.2 sigma

Correlation Matrices

Correlation Matrix (signal)



Correlation Matrix (background)



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- Hadronic ("8 jet") analysis:
  - Cut-based analysis: 7.2 sigma
  - TMVA-based analysis: 9.6 sigma
- Semileptonic ("6 jet") analysis:
  - Cut-based analysis: 5.4 sigma
  - TMVA-based analysis: 7.6 sigma
- **Combined: 12.2 sigma, 4.3% precision in $\Delta y_t/y_t$ (TMVA)**
  - for 0.5 ab^{-1} (-0.8, +0.2) and 0.5 ab^{-1} (+0.8, -0.2)

6 jets + lepton @ 500 GeV

	tth_4j	tth_6j	tth_8j	ttbb	ttz	bb4f
No cut	58.4	235	246	1059	1905	909355
Precut	27.8	128	12.1	311	551	268090
BDT	2.4	40.6	1.3	24.8	31.1	48.9

Input Variables
thrust, evis,
y45, y78,
mh, mw1, mt1,
btag_j1, btag_j2,
btag_j3, btag_j4,
coshel1

Significance	3.63
Purity	29.7%
Efficiency (6J only)	8.2% (17.3%)

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8 jets @ 500 GeV

	tth_4j	tth_6j	tth_8j	ttbb	ttz	bb4f
No cut	58.4	235	246	1059	1905	909355
Precut	10.8	100	233	713	1191	610823
BDT	0.4	19.5	68.9	39.2	64.3	93.6

Input Variables
thrust, evis
y45, y78
mh, mw1, mt1, mw2, mt2
btag_j1, btag_j2,
btag_j3, btag_j4,
coshel1

Significance	5.25
Purity	31.6 %
Efficiency (8J only)	16.4% (28.0%)