Top Yukawa Coupling at 1 TeV ILC
hadronic “8 jet” channel

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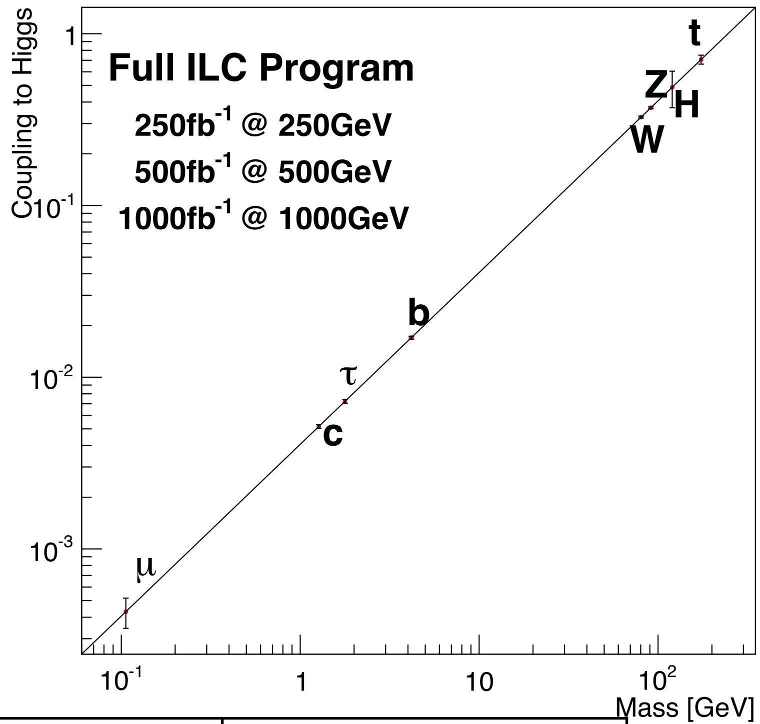
Introduction

- Top quark couples strongly to the Higgs boson (top Yukawa y_t~1)
- Important probe for verification of electroweak symmetry breaking
- Many BSM models predict **large deviations in y_t** e.g. composite Higgs models

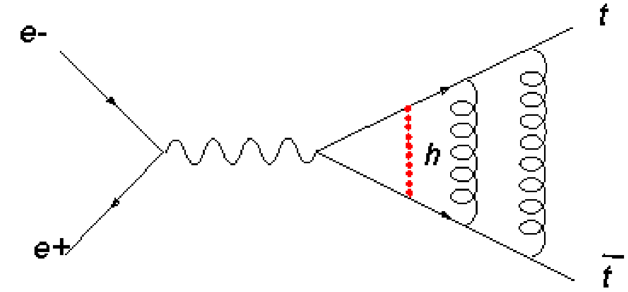


Top Yukawa coupling precision studies at LC

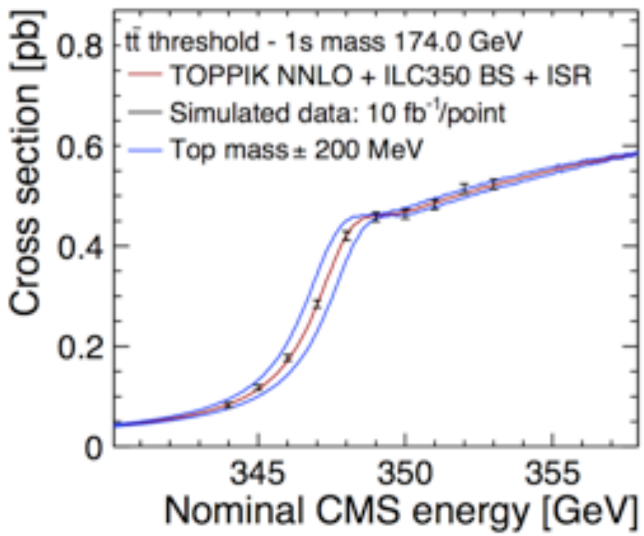
CM Energy	Simulation	Luminosity	$\Delta y_t/y_t$
500 GeV **[Phys. Rev. D 84, 014033 (2011)]**	Fast Sim	1 ab^{-1}	10%
500 GeV **[R. Yonamine, Ph.D. thesis]**	**Full Sim**	1 ab^{-1}	10%
700-800 GeV **[A. Gay, Eur.Phys.J.C49, 489 (2007)]**	Fast Sim	(various Higgs masses)	
1 TeV **[ILC TDR, 2012]**	**Full Sim**	0.5 ab^{-1} each for 2 polarizations	< 5%

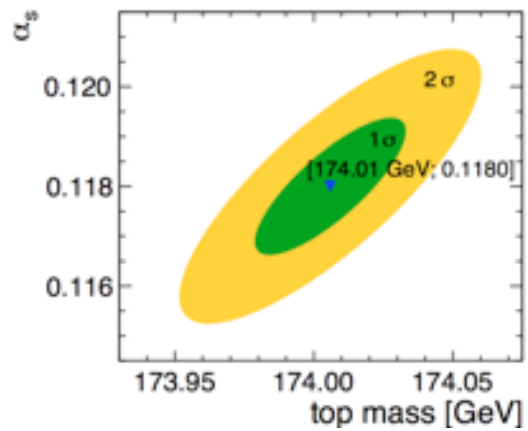
Indirect vs. direct

- **Indirect measurement** at the ttbar threshold
  - depends on theory calculation → improving
  - can be also inferred from LHC Higgs production

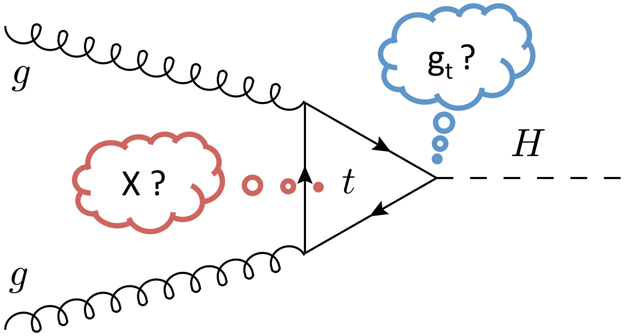


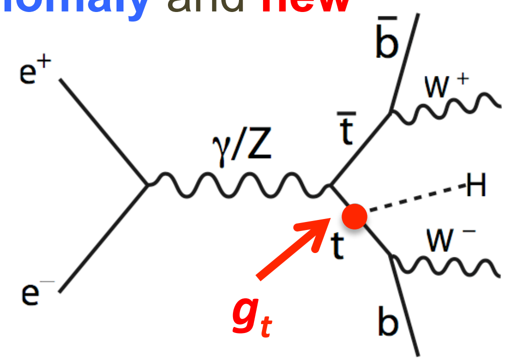
F.Simon Top Phys WS 2012





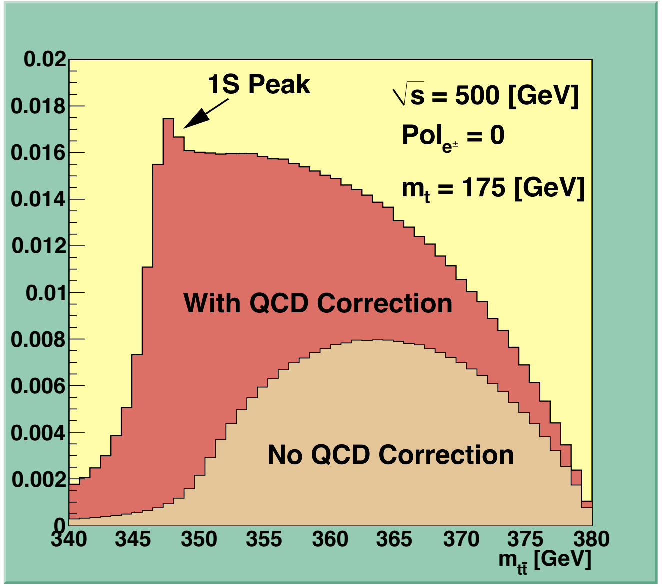
- **Direct measurement** can distinguish between **coupling anomaly** and **new particle in the loop**

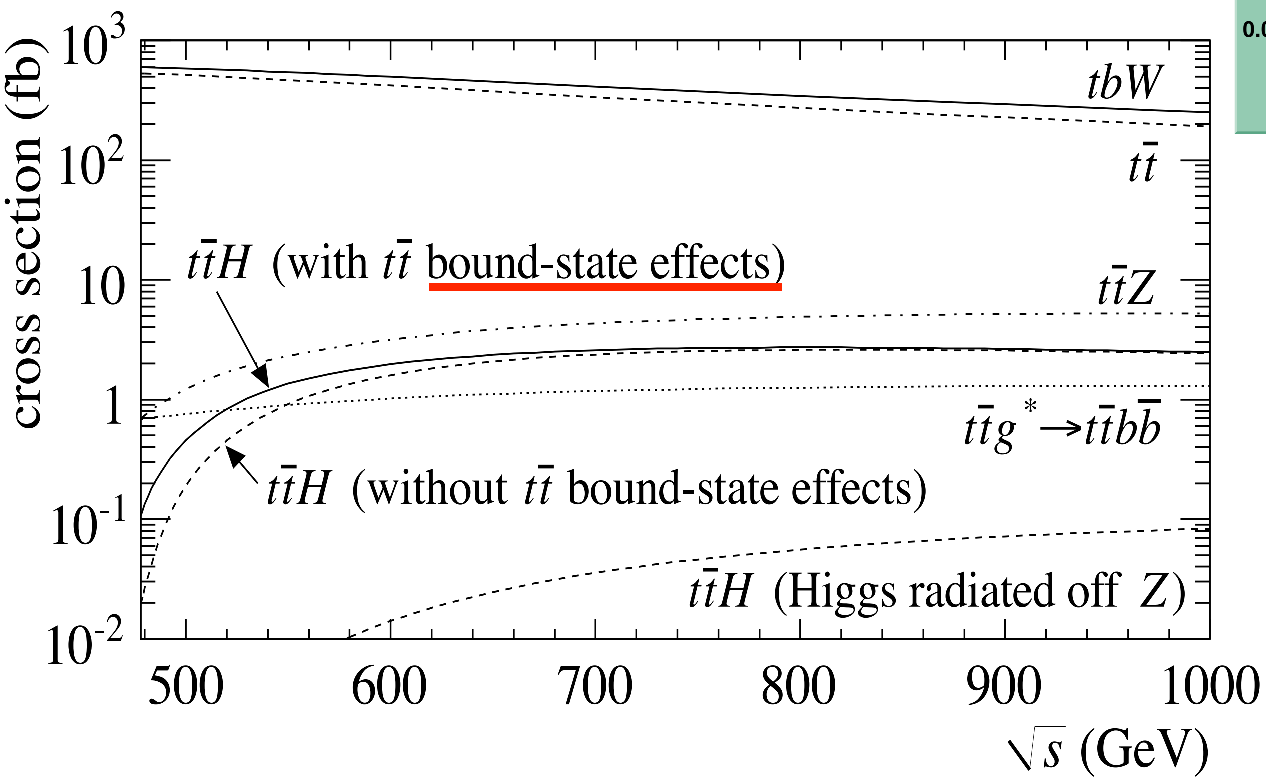


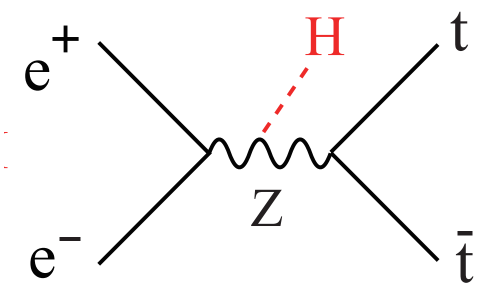


Signal and Background

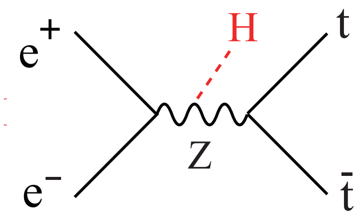
- **Signal: tth → bWbWbb**
- Irreducible backgrounds:
  - **ttZ** → bWbWbb
  - **ttg*** → bWbWbb
- Reducible background: bWbW, e.g. **tt**





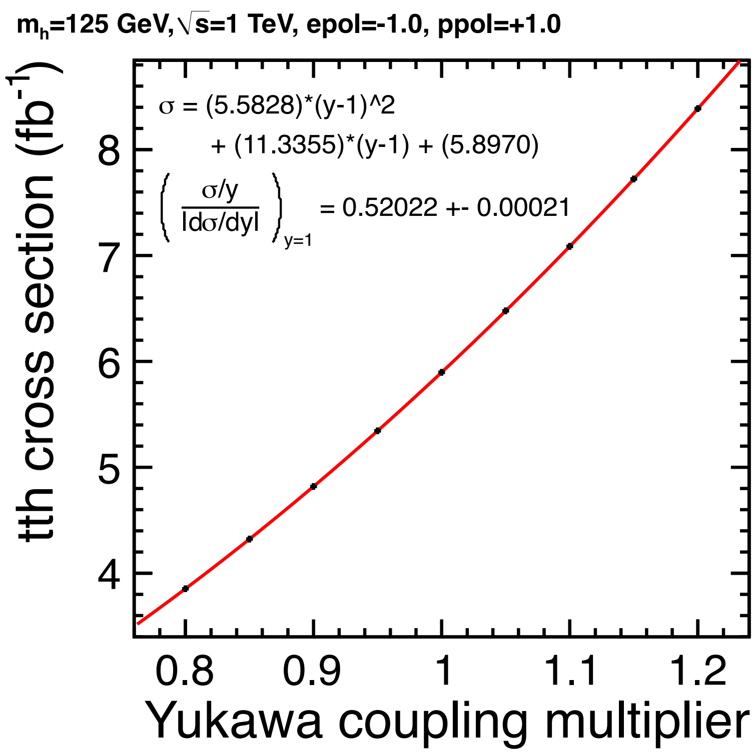


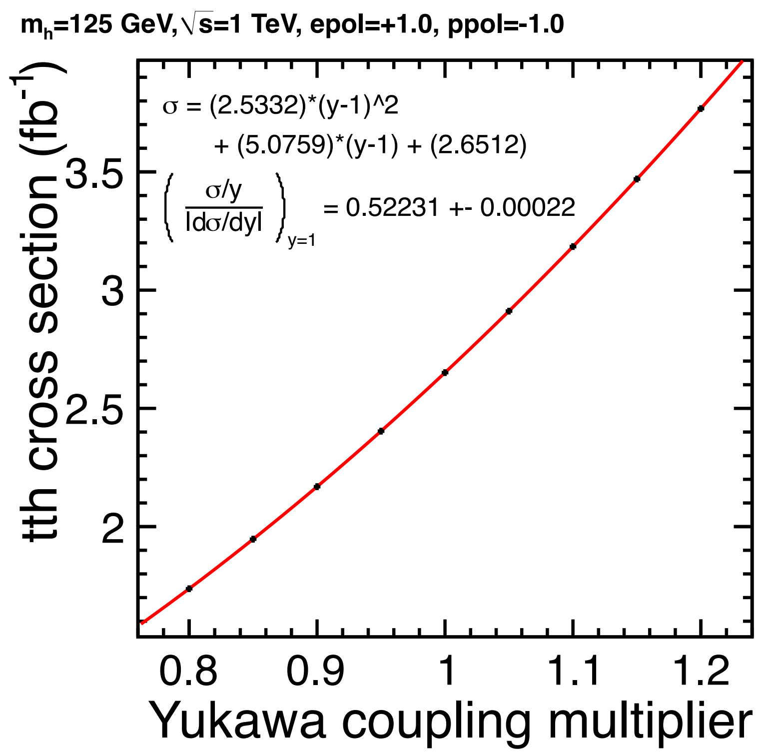
Sensitivity to top Yukawa



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

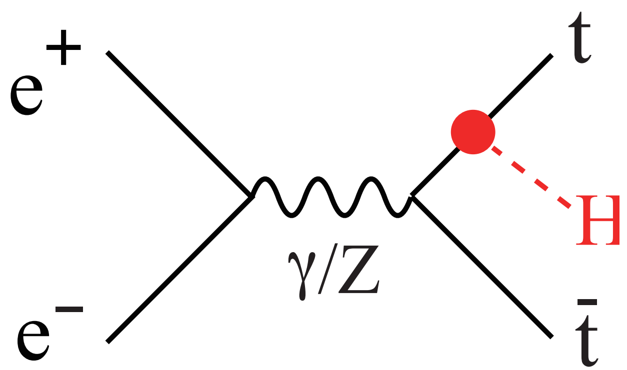
$$\frac{\Delta y_t}{y_t} = (..)\frac{\Delta\sigma}{\sigma} \qquad \left(\frac{\sigma/y_t}{|d\sigma/dy_t|}\right)_{y_t=y_t(SM)} = 0.52$$





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)

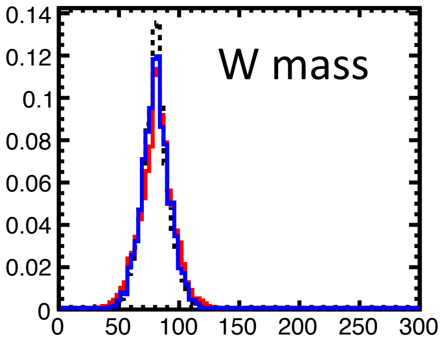
which are summed.

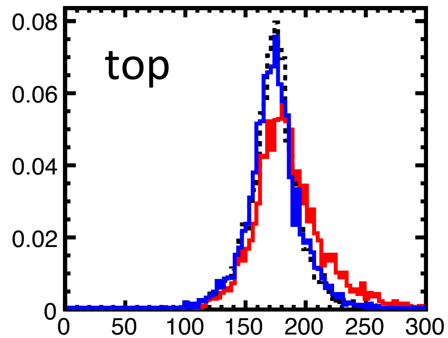
All weights << 1:
→ We have sufficient statistics.

Analysis Flow

- Start with standard reconstruction samples for DBD
- Removal of $\gamma\gamma \rightarrow$hadrons pileup background
- Isolated lepton selection
- Event selection based on
  - b-tagging, jet combination mass, etc
- Comparison of two analyses:
  - Cut-based
  - TMVA-based with Boosted Decision Trees

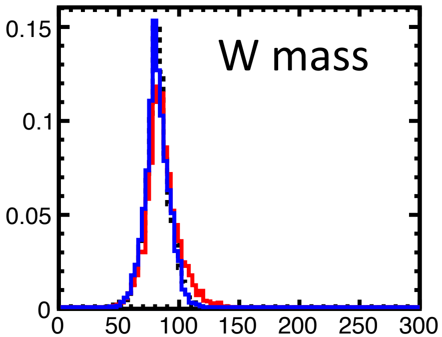
Removal of γγ→hadrons

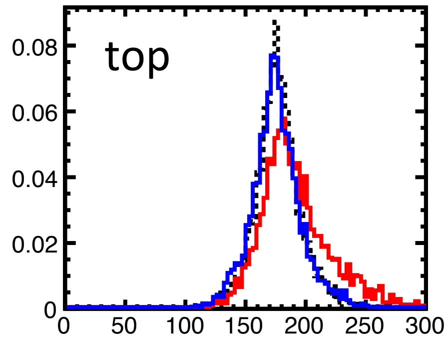




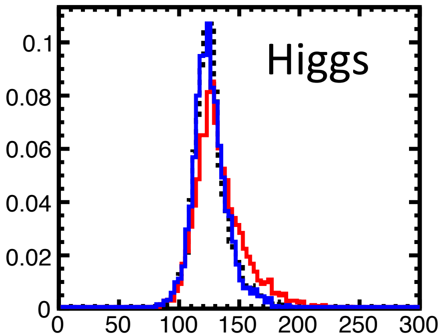
Average 4.1 events γγ→hadrons are overlaid in all simulations.

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





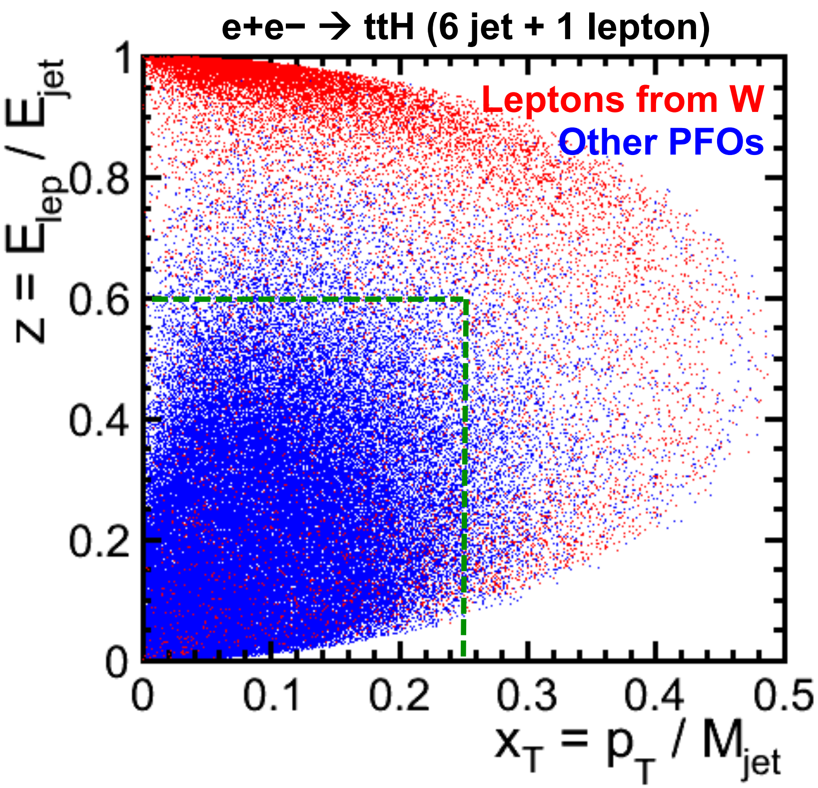
Black (dotted):
Durham (sample w/o γγ→hadrons)
Red:
Durham (sample w/ γγ→hadrons)
Blue:
Durham (sample w/ γγ→hadrons) after removing cosθ>0.94 particles



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

kt algorithm with R=1.2 is actually used for consistency with 6 jet + lepton analysis (studied by Tony Price)

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

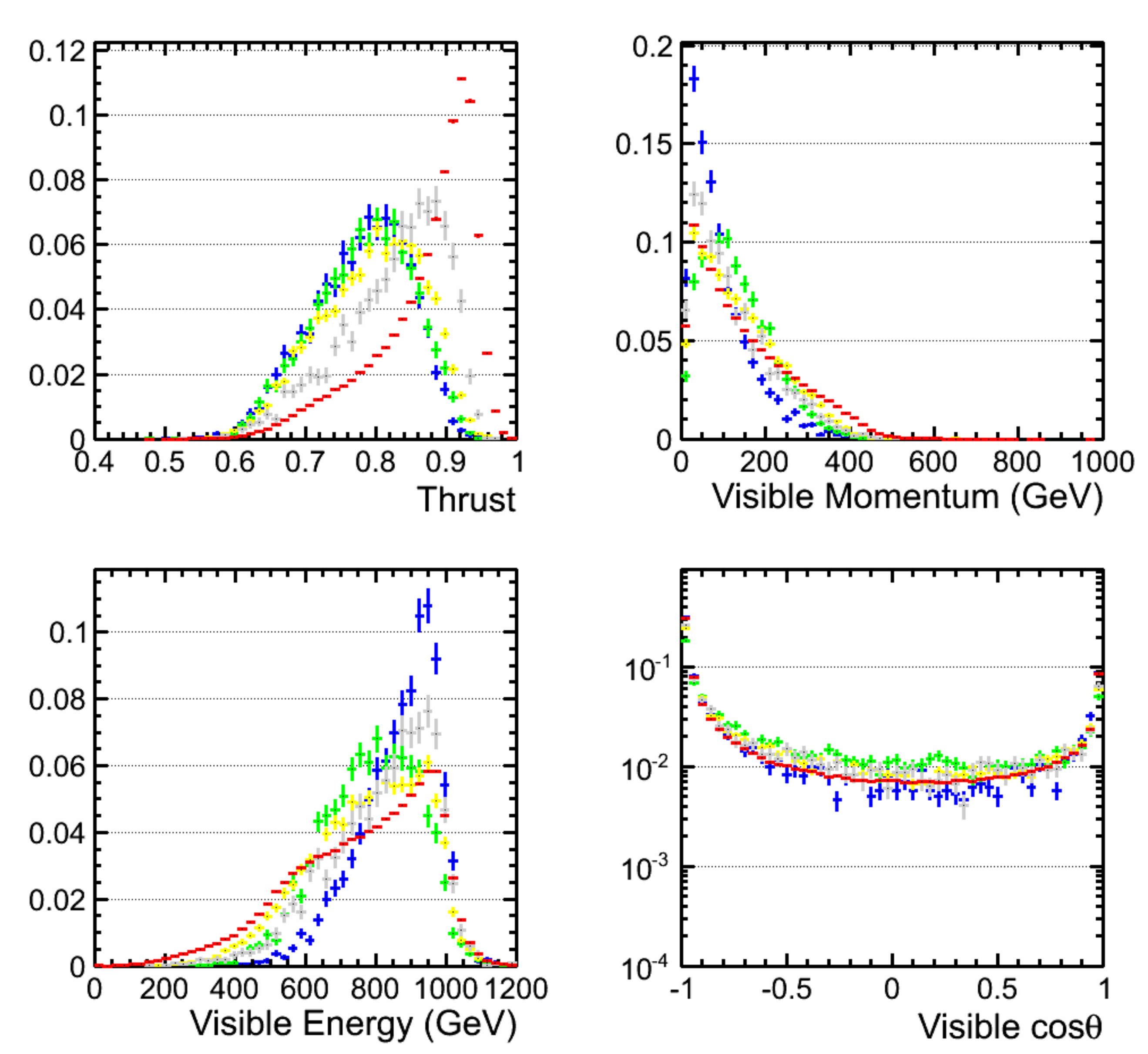
Variables (1)

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

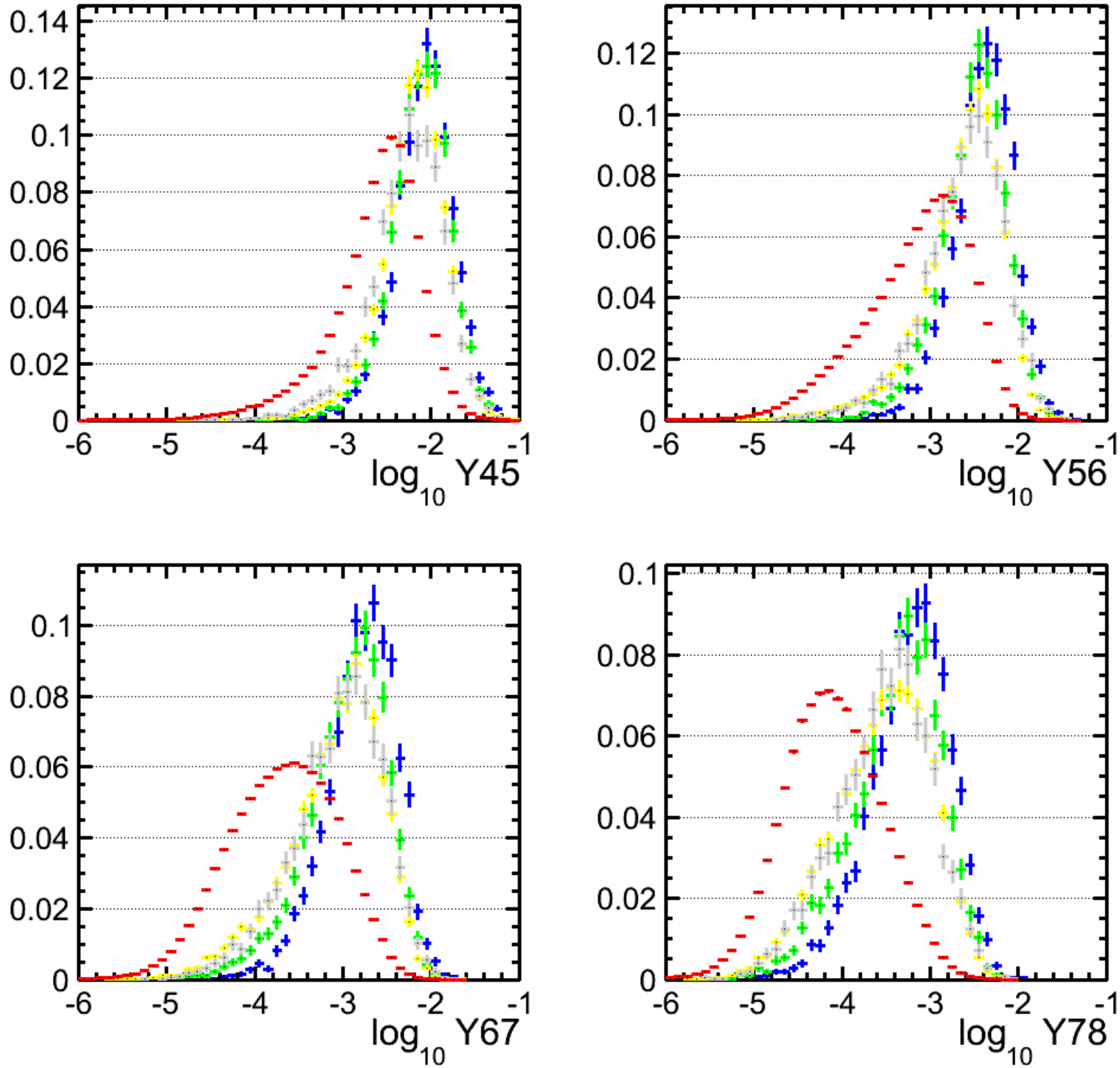


Variables (2)

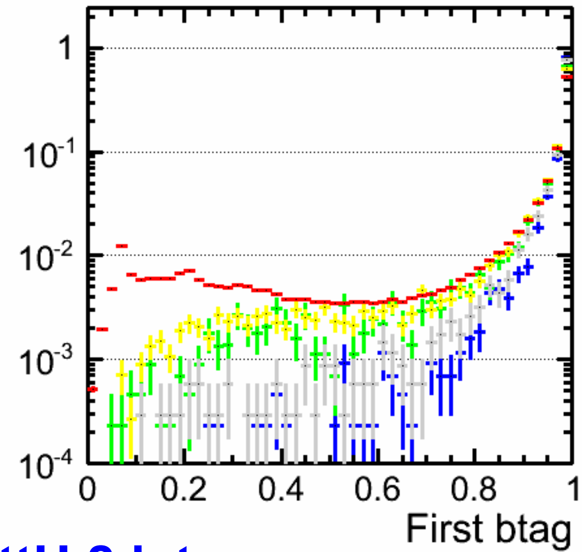
ttH 8 jet
ttH other
ttZ
ttbb
tt

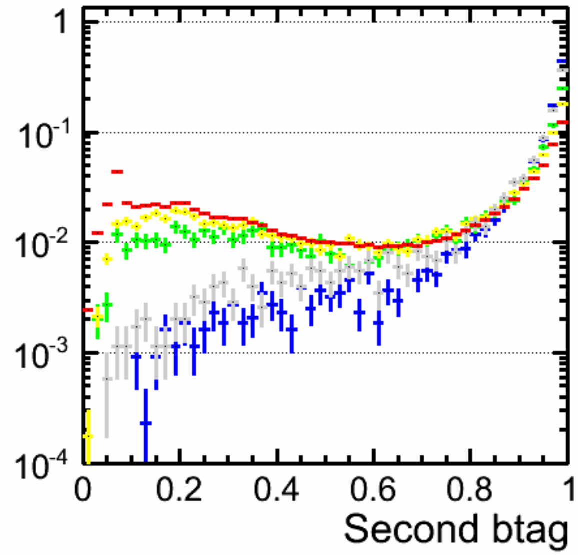
Jet Finder "Y" variables

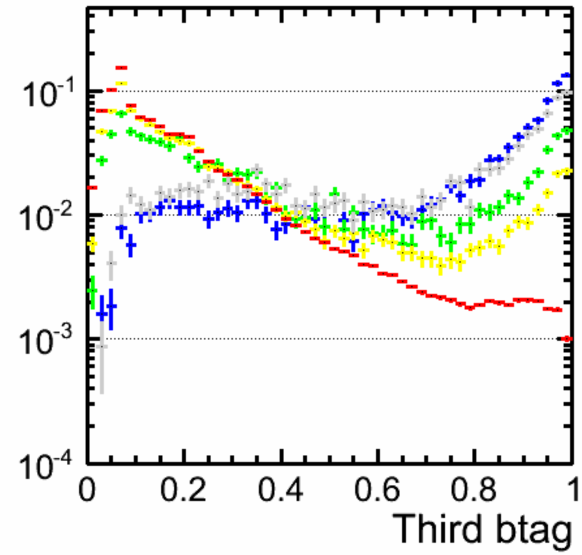
$$Y_{ij} = \frac{\max(E_i^2, E_j^2)(1 - \cos\theta_{ij})}{E_{\mathrm{CM}}^2}$$



Variables (3)







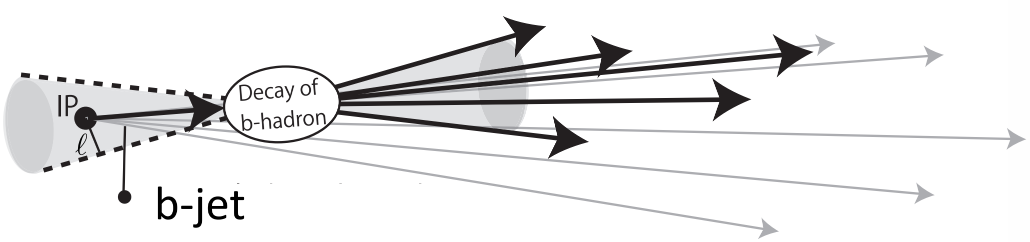
ttH 8 jet

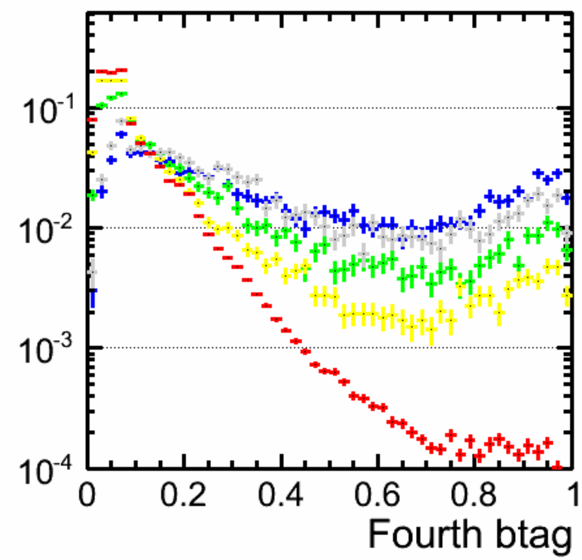
ttH other

ttZ

ttbb

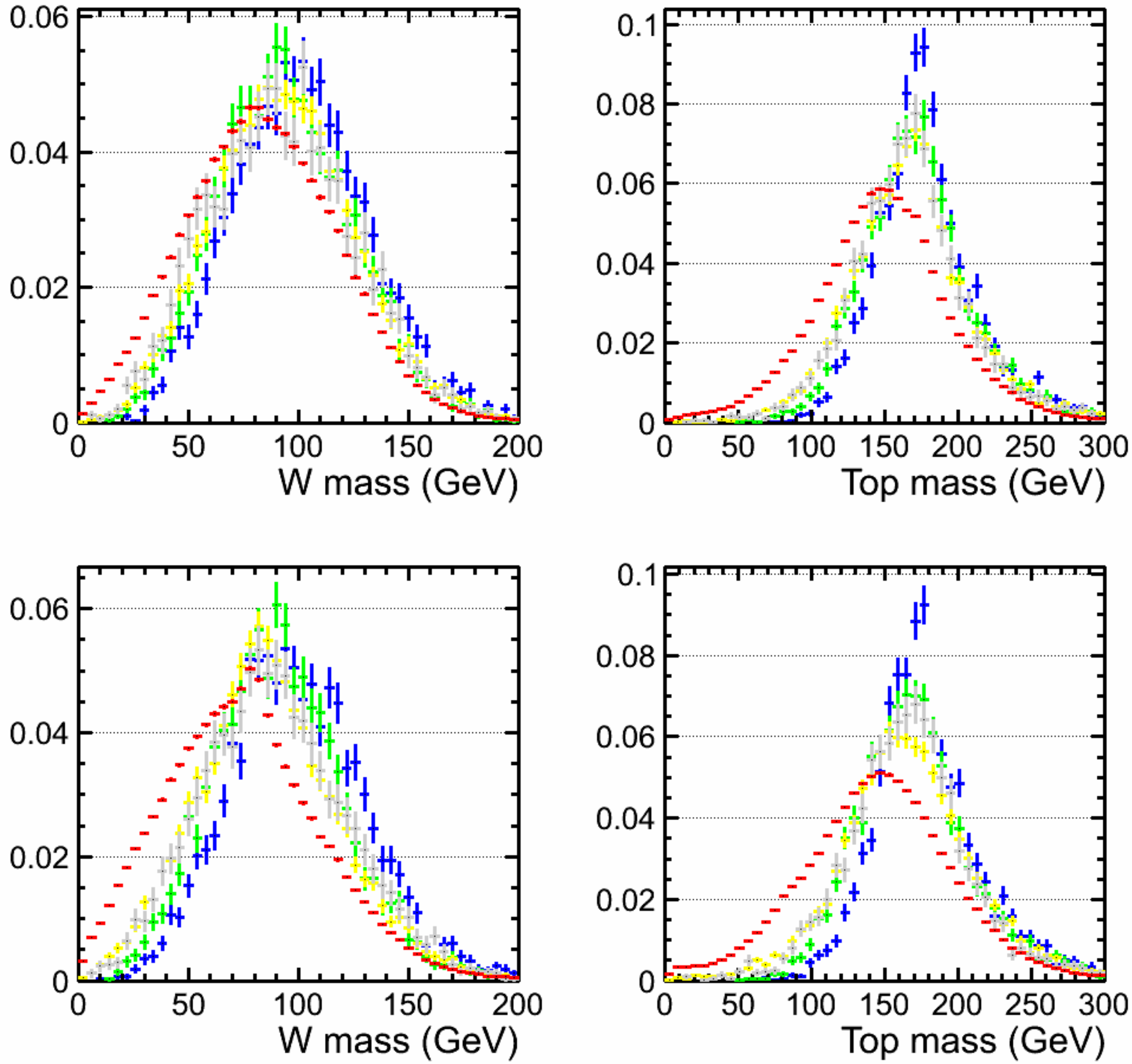
tt





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

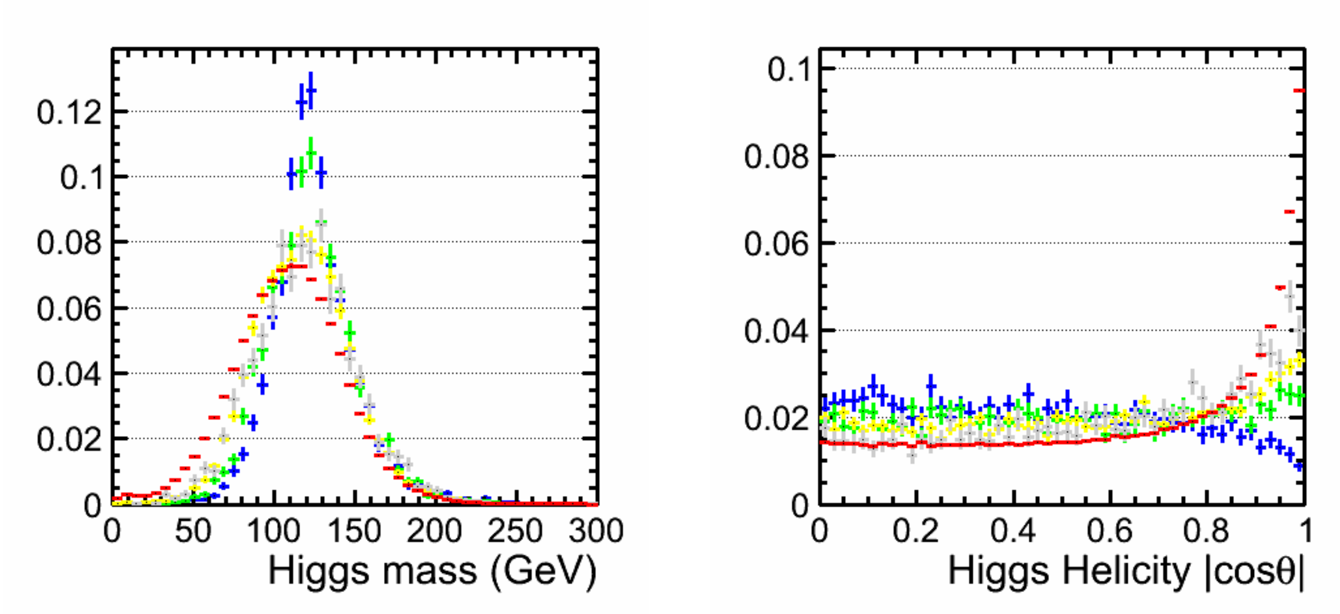
Variables (4)



ttH 8 jet
ttH other
ttZ
ttbb
tt

Variables (5)

ttH 8 jet
ttH other
ttZ
ttbb
tt



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

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

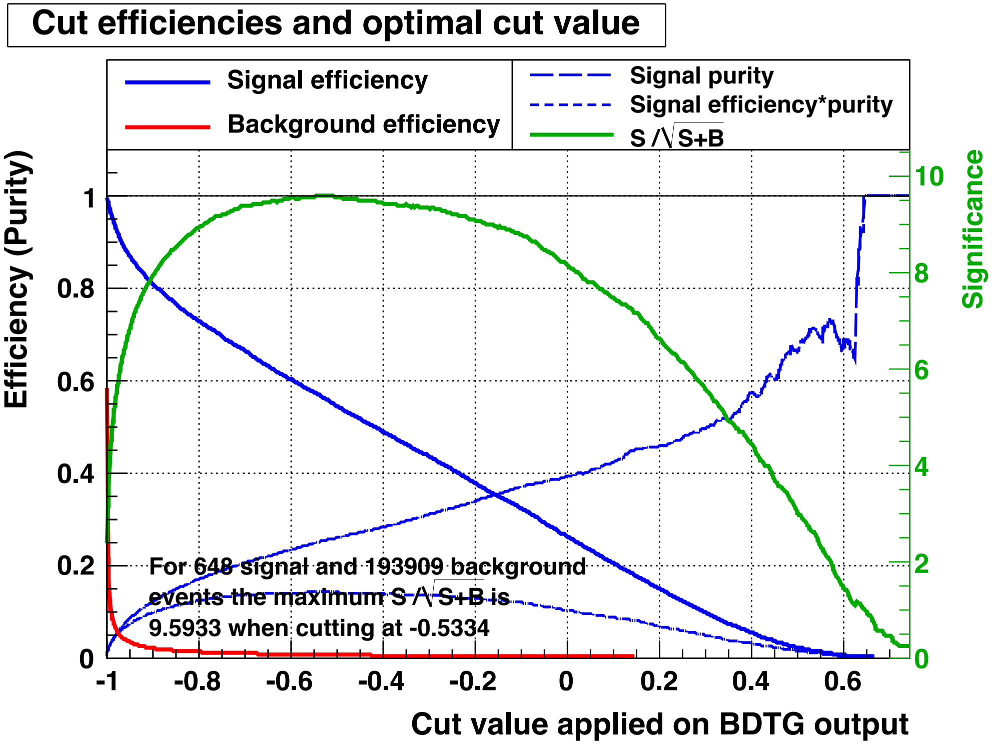
Cut-based Analysis

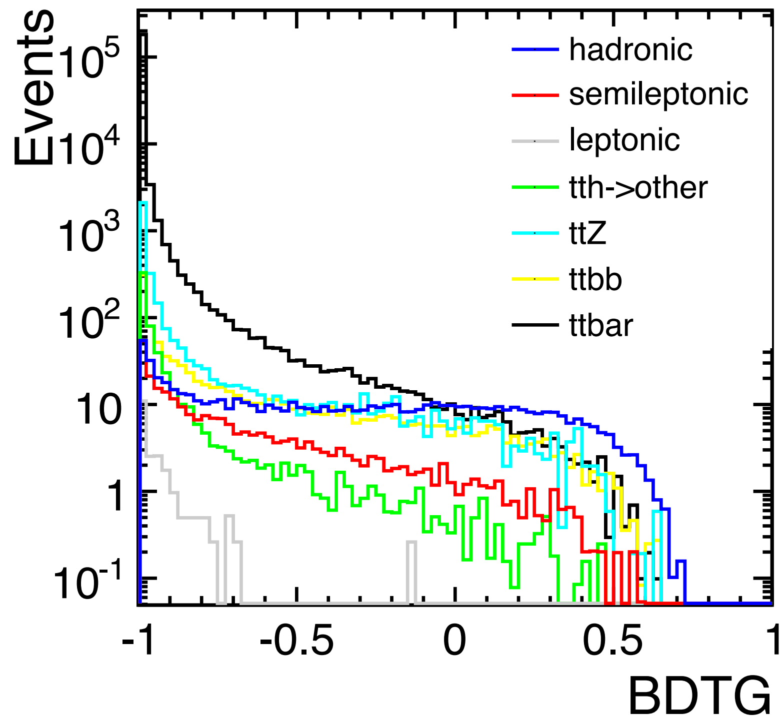
	$t\bar{t}h$ (4J)	$t\bar{t}h$ (6J)	$t\bar{t}h$ (8J)	$t\bar{t}h$ ($h \not\to b\bar{b}$)	$t\bar{t}Z$	$t\bar{t}b\bar{b}$	$t\bar{t}$	Sig.
No cuts	151.39	628.73	652.77	1046.10	5332.52	1434.53	306238.26	1.16
$N_{\mathrm{iso}} = 0$	20.87	261.17	647.92	556.71	3226.14	932.49	188911.38	1.47
$E_{\mathrm{vis}} > 650$ 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
$\lvert\cos\theta_{\mathrm{hel}}\rvert < 0.9$	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

Multivariate Analysis

- Use TMVA Boosted Decision Trees with Gradient boost
- 18 variables (shown earlier) were used



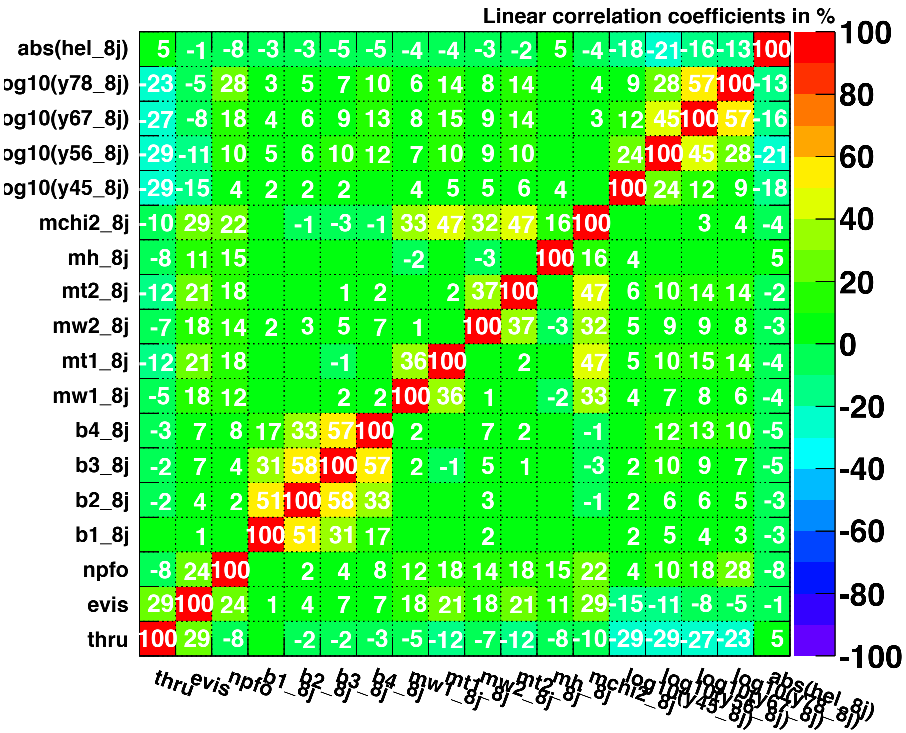


TMVA analysis result (8 jet mode only):
Statistical significance = 9.6 sigma

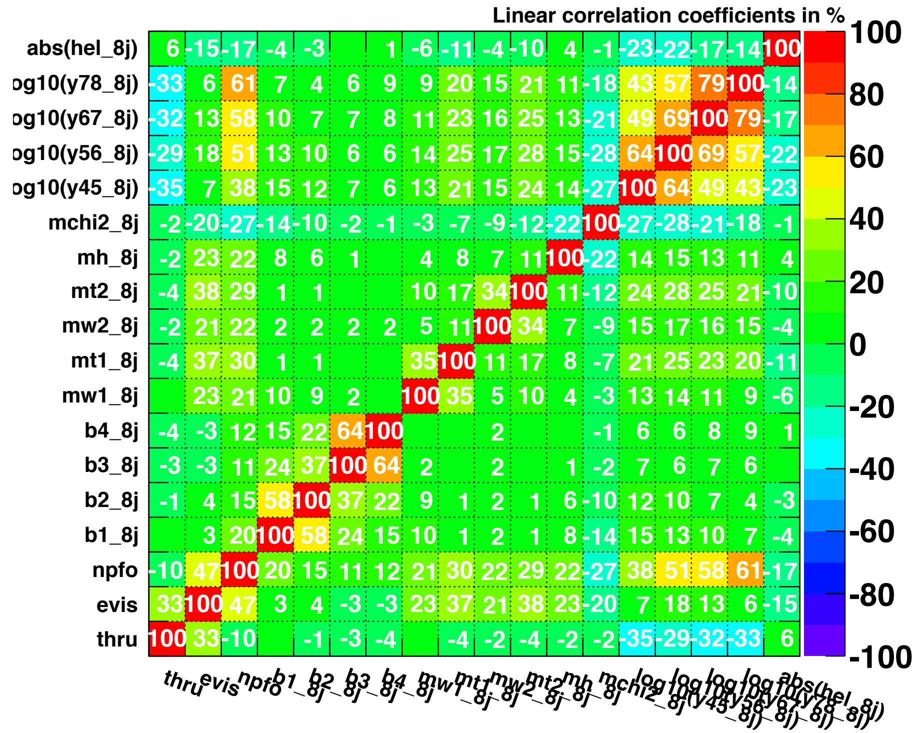
Error in normalization of the events was found and fixed.

Correlation Matrices

Correlation Matrix (signal)



Correlation Matrix (background)



Difference between cut-based and TMVA-based analysis will be studied.
The input variables are correlated.

Systematic Uncertainties

So far our results give the statistical precision only.

For **O(1)%** measurements, need to address **systematic uncertainties** such as:

- Background normalization
- Jet energy scale
- Luminosity spectrum
- B-tagging efficiency
- Lepton isolation criteria
- Lepton ID performance
- …

→ *These are the next steps…*

Conclusions

- Hadronic (“8 jet”) analysis:
  - Cut-based analysis: 7.2 sigma
  - TMVA-based analysis: 9.6 sigma
- Semileptonic (“6 jet”) analysis (**Tony Price**):
  - 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)

- To-do:
  - Include final results into DBD
  - Combine ILD + SiD works into publication
  - Consideration of systematic uncertainties