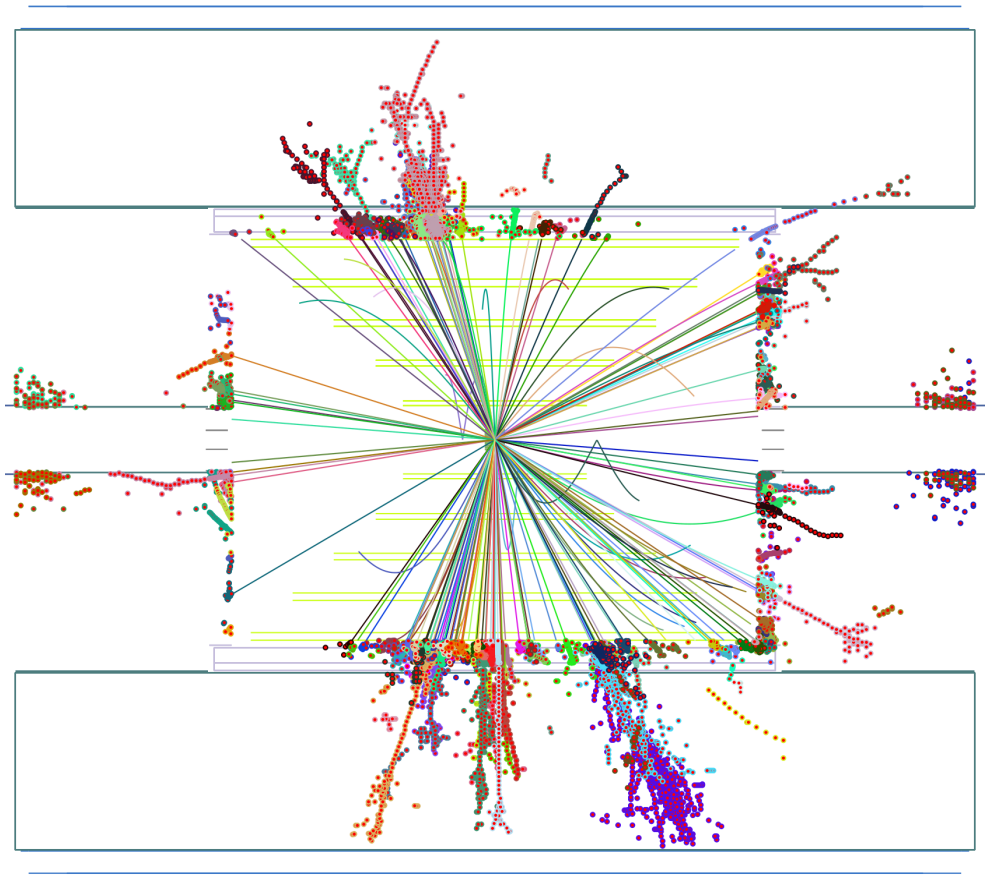
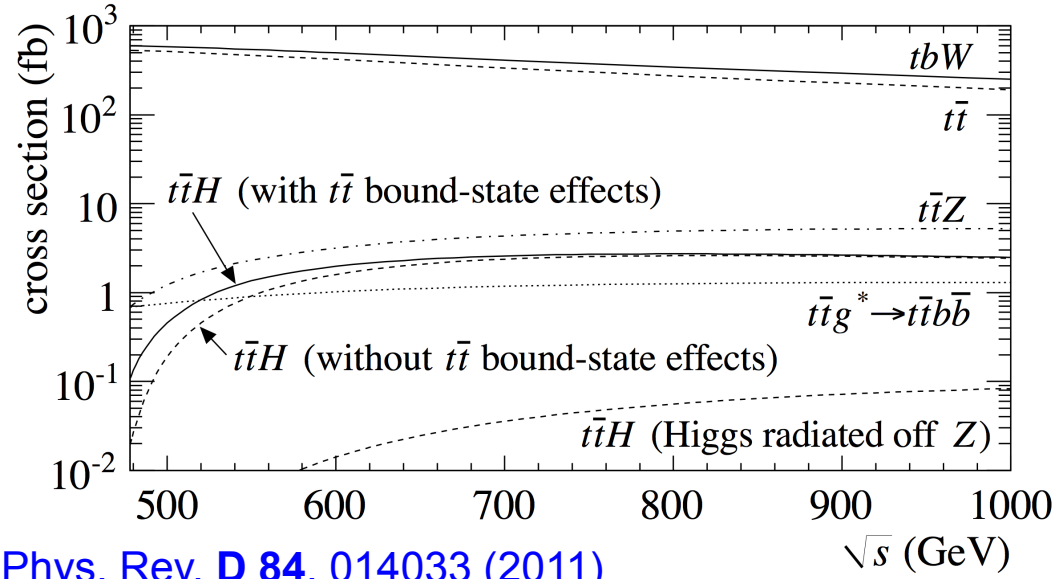
$t\bar{t}H$ at the Linear Collider

Philipp Roloff (CERN)

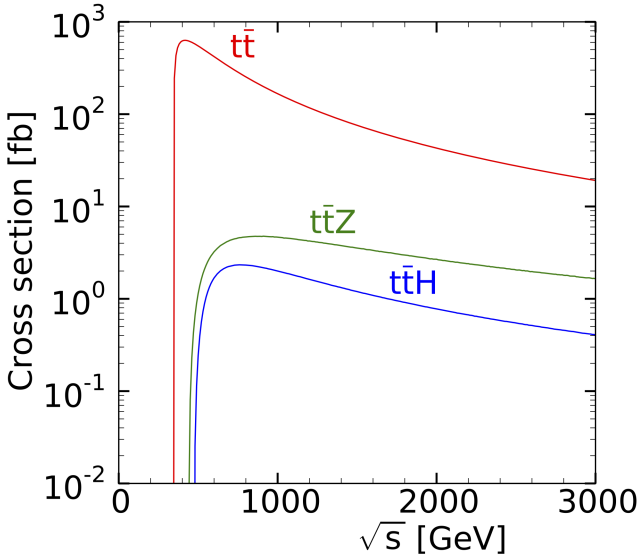


Workshop on top physics at lepton colliders
IFIC Valencia, 02/07/2015

$t\bar{t}H$ production cross section



Phys. Rev. **D 84**, 014033 (2011)

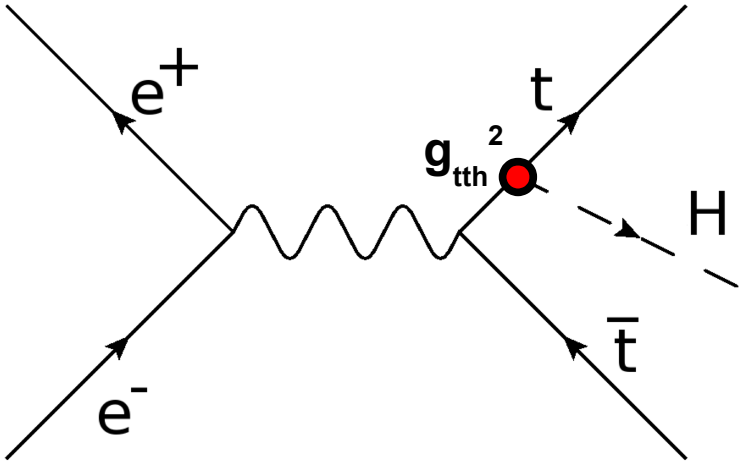


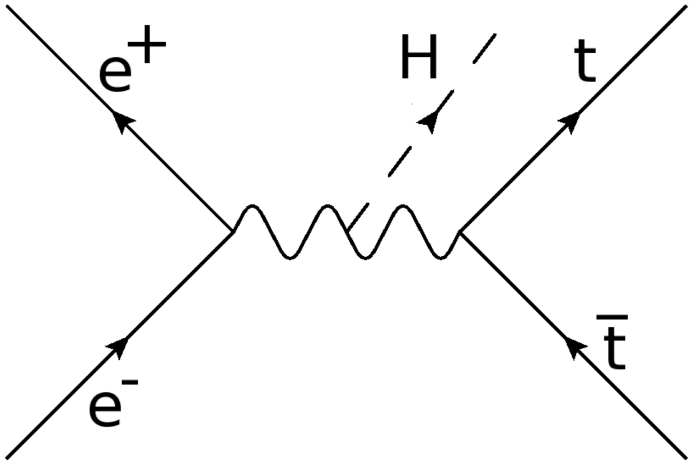
- Large impact of $t\bar{t}$ bound-state effects up to 600 GeV
- Broad maximum around 800 GeV
- The $t\bar{t}$ cross section decreases steeper with increasing $\sqrt{s}$ than the $t\bar{t}H$ signal

Recent / ongoing benchmark studies based on full detector simulations:

500 GeV, ILC (ILD):
Yuji Sudo
1 TeV, ILC (ILD & SiD):
Tony Price, Ph.R.,
Jan Strube, Tomohiko Tanabe
1.4 TeV, CLIC (CLIC_SiD):
Sophie Redford, Ph.R., Marcelo Vogel

top Yukawa coupling



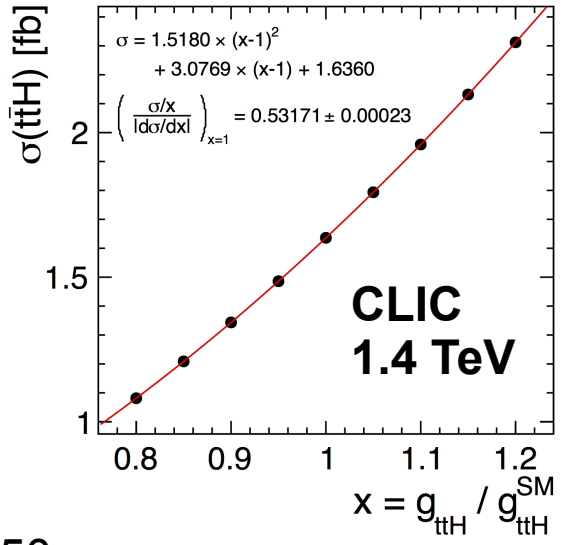


→ The $t\bar{t}H$ cross section is directly sensitive to the top Yukawa coupling g_{ttH}

Small contribution from Higgsstrahlung events:

$$\frac{\Delta g_{ttH}}{g_{ttH}} = c \cdot \frac{\Delta \sigma}{\sigma}$$

No Higgsstrahlung: c = 0.50
ILC 1 TeV: c = 0.52
CLIC 1.4 TeV: c = 0.53



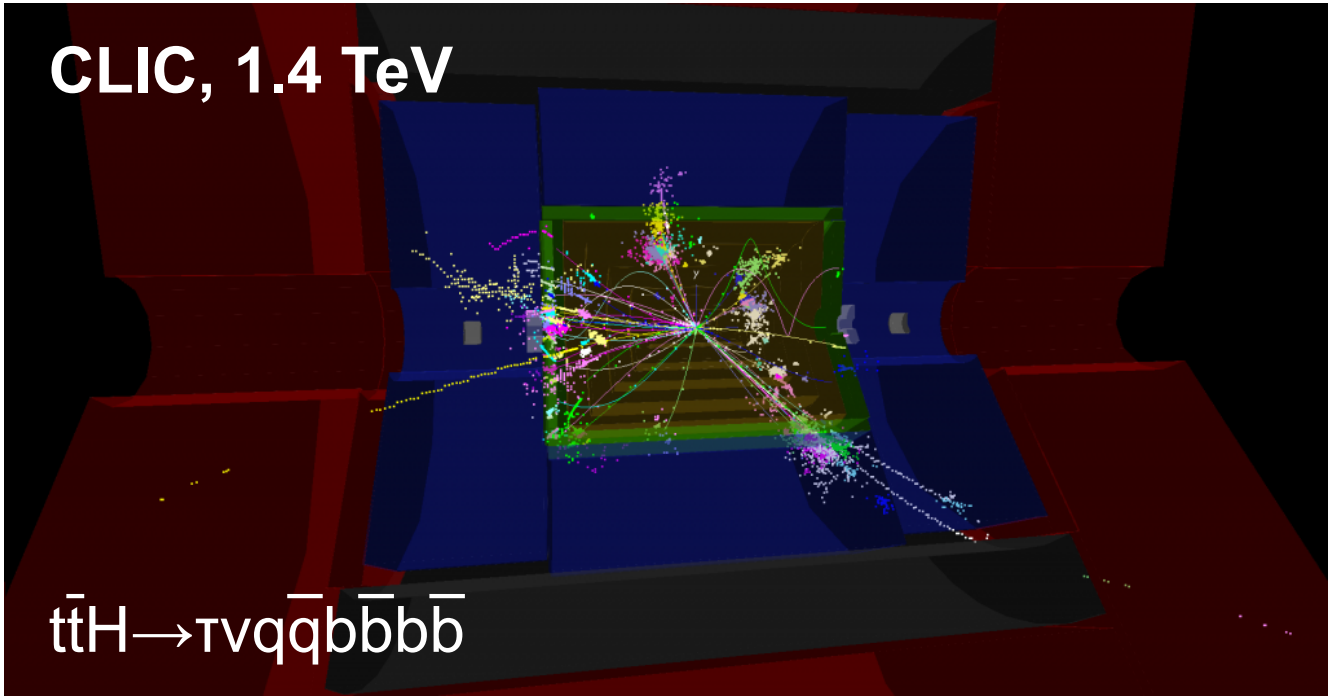
Most relevant backgrounds

Type	Final state	$P(e^-)$	$P(e^+)$	Cross section [× BR] (fb)
Signal	$t\bar{t}H$ (8 jets)	−80%	+20%	0.87
Signal	$t\bar{t}H$ (8 jets)	+80%	−20%	0.44
Signal	$t\bar{t}H$ (6 jets)	−80%	+20%	0.84
Signal	$t\bar{t}H$ (6 jets)	+80%	−20%	0.42
Background	other $t\bar{t}H$	−80%	+20%	1.59
Background	other $t\bar{t}H$	+80%	−20%	0.80
Background	$t\bar{t}Z$	−80%	+20%	6.92
Background	$t\bar{t}Z$	+80%	−20%	2.61
Background	$t\bar{t}g^* \to t\bar{t}b\bar{b}$	−80%	+20%	1.72
Background	$t\bar{t}g^* \to t\bar{t}b\bar{b}$	+80%	−20%	0.86
Background	$t\bar{t}$	−80%	+20%	449
Background	$t\bar{t}$	+80%	−20%	170

Example from 1 TeV ILC analyses,
the same background processes are dominant in the other studies

Reconstruction issues

Investigated final states:
"*8 jets*": $t(\rightarrow q\bar{q}b)\bar{t}(\rightarrow q\bar{q}b)H(\rightarrow b\bar{b})$
"*6 jets*": $t(\rightarrow qqb)\bar{t}(\rightarrow l\nu\bar{b})H(\rightarrow b\bar{b})$
["4 *jets*": $t(\rightarrow l\nu b)\bar{t}(\rightarrow l\nu\bar{b})H(\rightarrow b\bar{b})$]



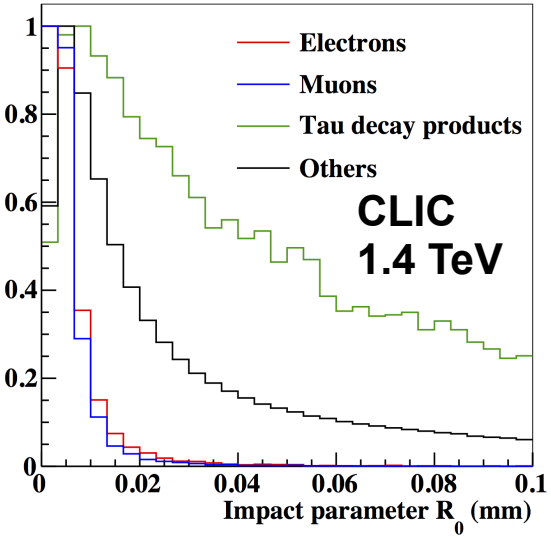
Crucial tests of various detector Performance and reconstruction aspects:

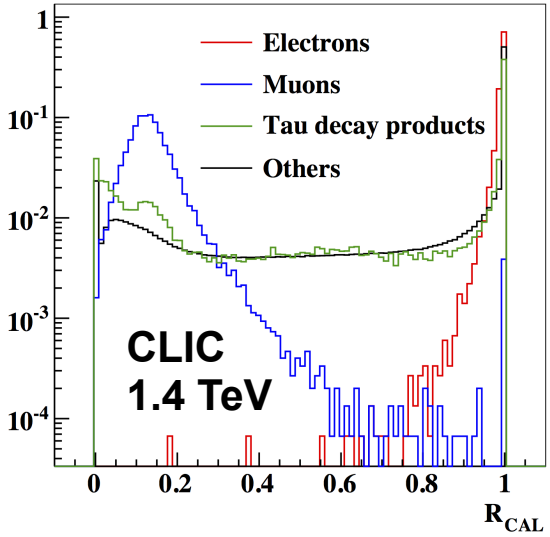
- Jet reconstruction in complex final states
- Flavour tagging
- Charged lepton identification
- Missing energy reconstruction

Lepton identification

Events classified by number of isolated lepton candidates:
0 leptons → “8 jets”, 1 lepton → “6 jets” (2 leptons → “4 jets”)

1.) Electron and muon selection:
particle energy fractions, impact parameters and isolation



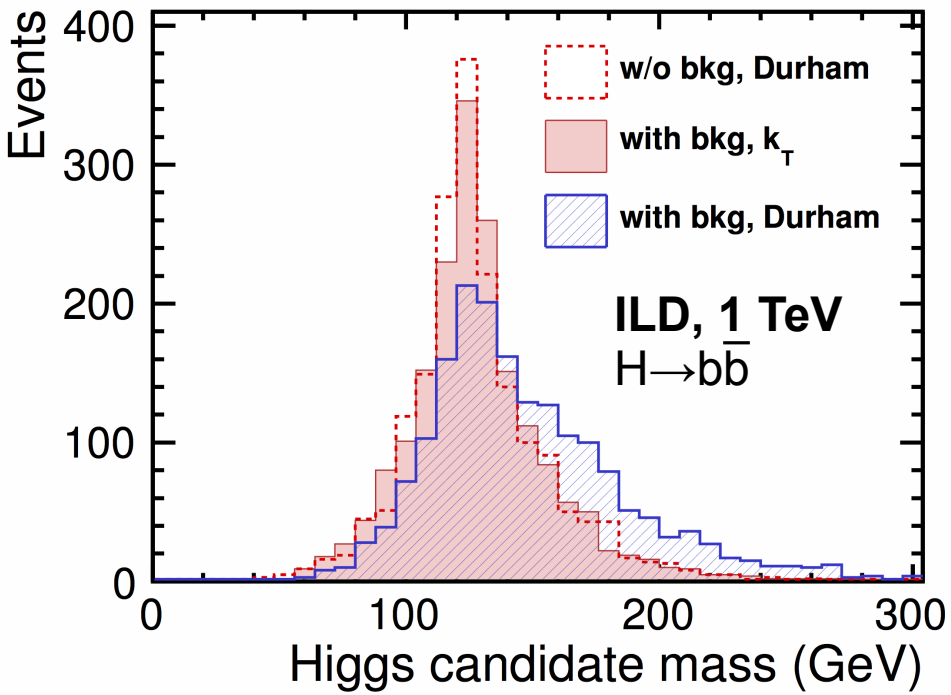


$$R_{CAL} = \frac{E_{ECAL}}{E_{ECAL} + E_{HCAL}}$$

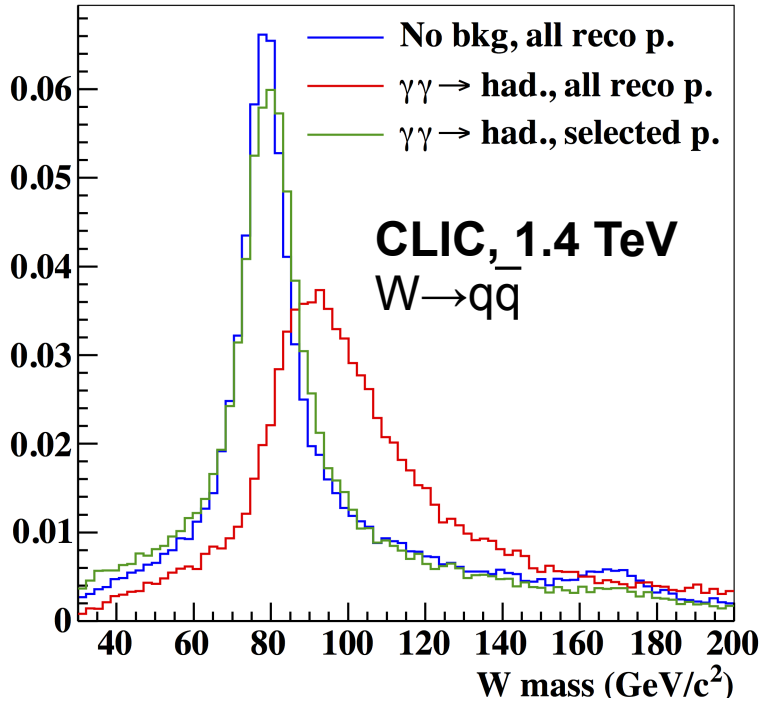
2.) Dedicated tau finders using the remaining particles
(except for ILD & SiD analyses at 1 TeV)

Jet reconstruction

- Most particles from beam-induced backgrounds (γγ→hadrons) are close to the beam pipe
- Usage of hadron-collider type jet algorithms like the longitudinally-invariant k_t algorithm important to suppress these backgrounds



1 bunch crossing of beam-induced background overlaid



Out-of-time pile-up suppressed using timing information

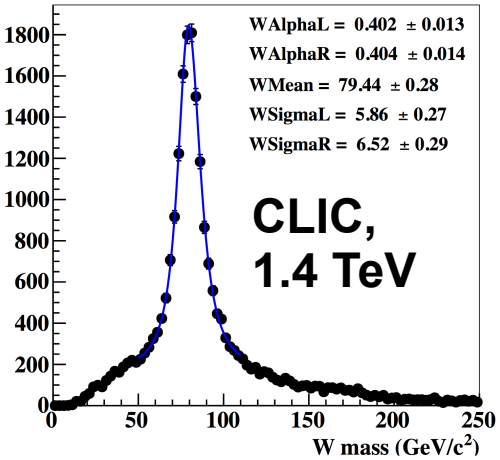
Jet pairing

Grouping the jets into W, top and Higgs candidates by minimising:

$$\chi^2_6 = \frac{(M_{12}-M_{W^\pm})^2}{\sigma^2_{W^\pm}} + \frac{(M_{123}-M_t)^2}{\sigma^2_t} + \frac{(M_{45}-M_H)^2}{\sigma^2_H},$$

$$\chi^2_8 = \frac{(M_{12}-M_{W^\pm})^2}{\sigma^2_{W^\pm}} + \frac{(M_{123}-M_t)^2}{\sigma^2_t} + \frac{(M_{45}-M_{W^\pm})^2}{\sigma^2_{W^\pm}} + \frac{(M_{456}-M_t)^2}{\sigma^2_t} + \frac{(M_{78}-M_H)^2}{\sigma^2_H}$$

At 500 GeV (near threshold) the momentum of the Higgs is small
→ angle between two jets instead of invariant mass effective

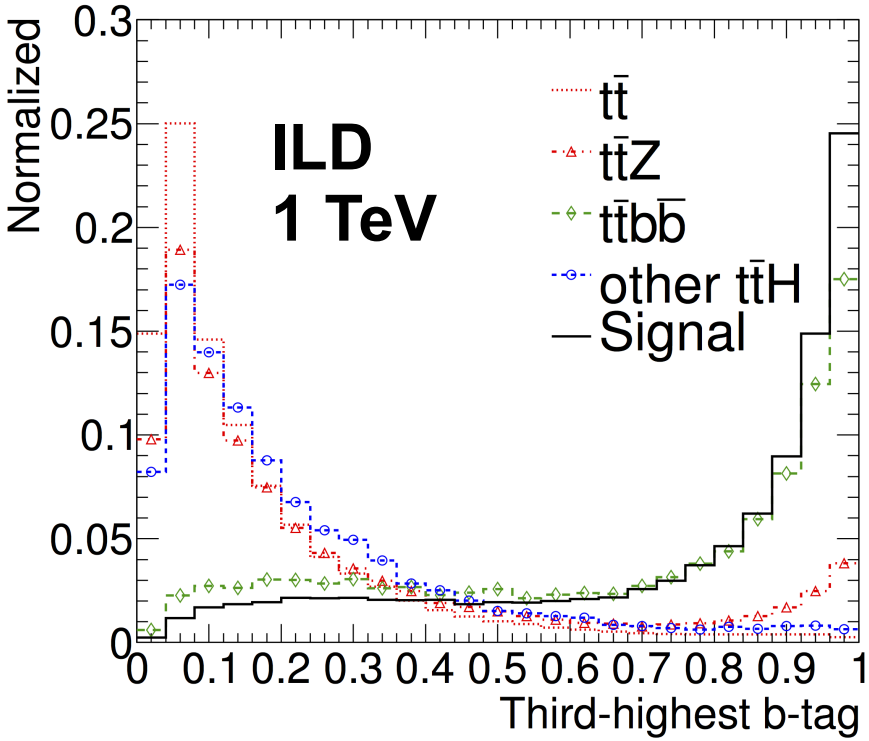


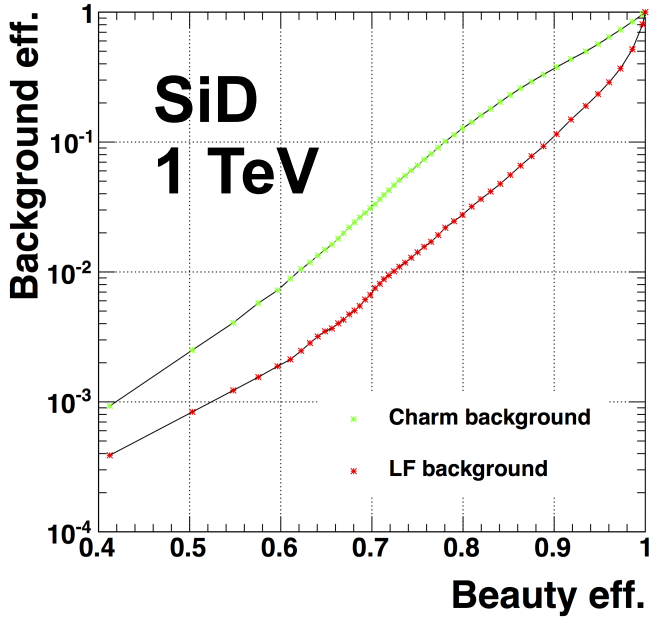
Invariant mass distributions for truth-matched candidates are asymmetric
→ using modified Gaussian with two width parameters:

$$f = \exp\left(\frac{-(x-\mu)^2}{g}\right) \begin{cases} g = 2\sigma_L^2 + \alpha_L(x-\mu)^2 \\ g = 2\sigma_R^2 + \alpha_R(x-\mu)^2 \end{cases}$$

Flavour tagging

- LCFIPlus used by all analyses
- Signal events contain four b-jets
- Third and fourth highest b-tag values especially powerful
(e.g. against $t\bar{t}$ and $t\bar{t}Z$ backgrounds)





1 bunch crossing of
$\gamma\gamma \rightarrow$ hadrons and e^+e^- pairs

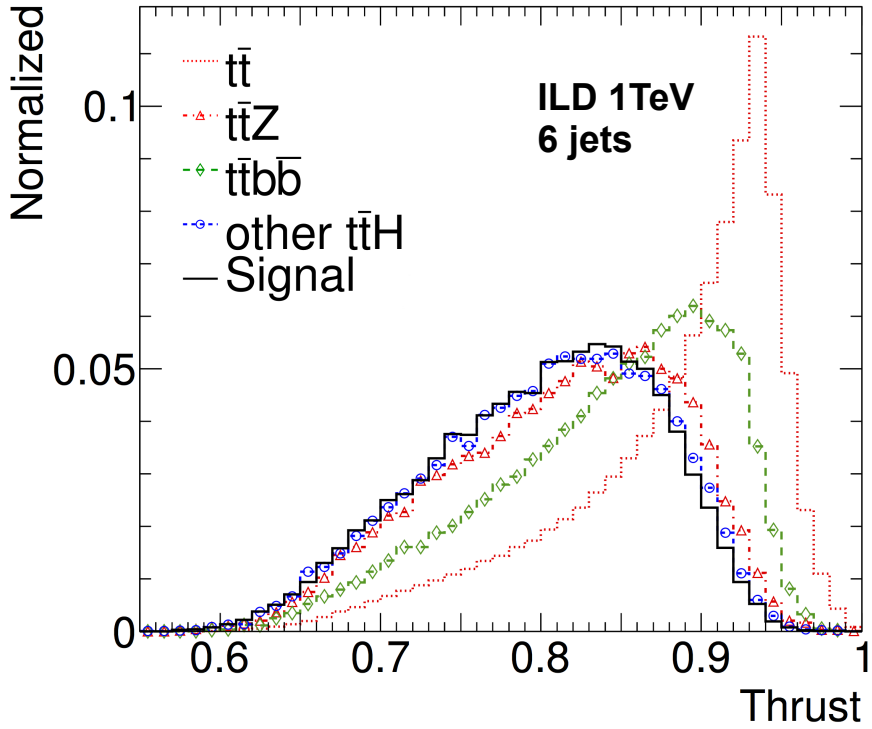
Event selection (1)

Events are selected using e.g.:

- Masses of the W, H, top candidates
- Four hightest b-tag values
- Event shape variables
- Jet clustering information
- Angular variables
- ...

Example distributions:

- Event thrust



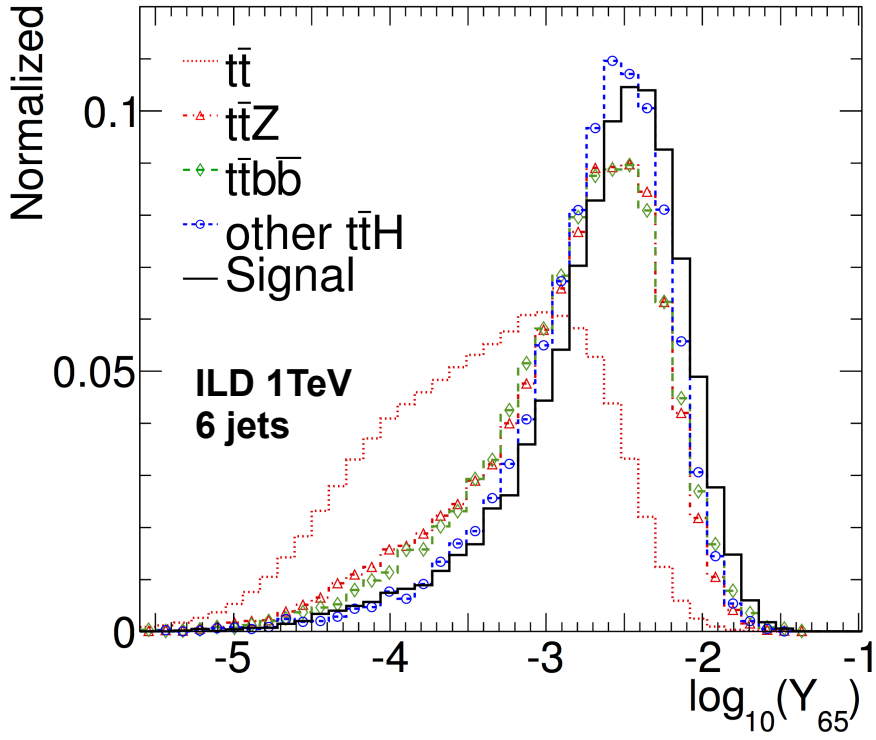
Event selection (2)

Events are selected using e.g.:

- Masses of the W, H, top candidates
- Four hightest b-tag values
- Event shape variables
- Jet clustering information
- Angular variables
- ...

Example distributions:

- Event thrust
- Jet resolution parameter Y_{65}



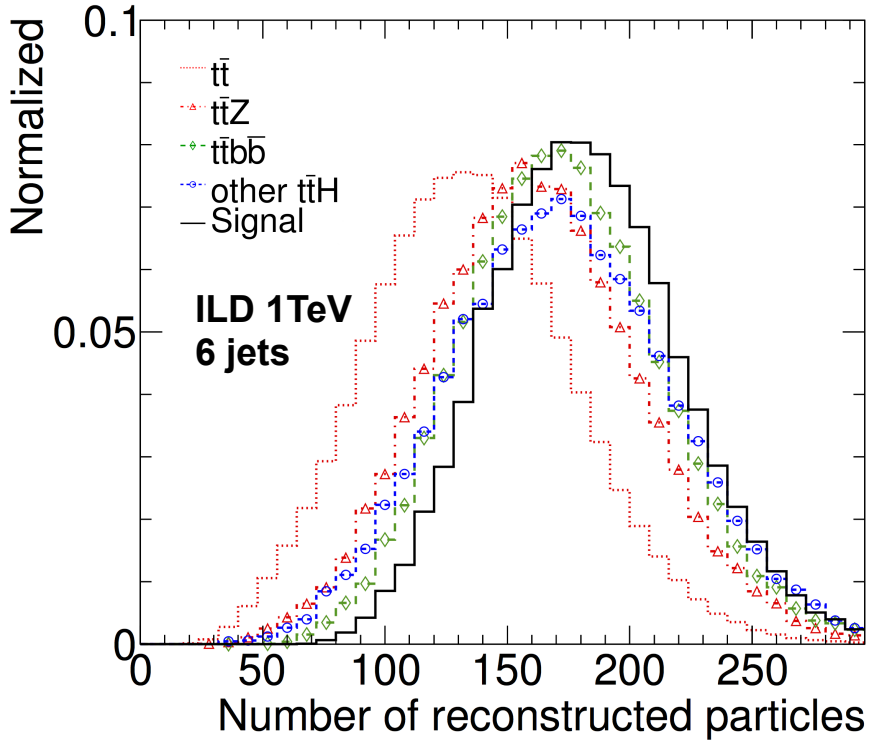
Event selection (3)

Events are selected using e.g.:

- Masses of the W, H, top candidates
- Four hightest b-tag values
- Event shape variables
- Jet clustering information
- Angular variables
- ...

Example distributions:

- Event thrust
- Jet resolution parameter Y_{65}
- Number of particles



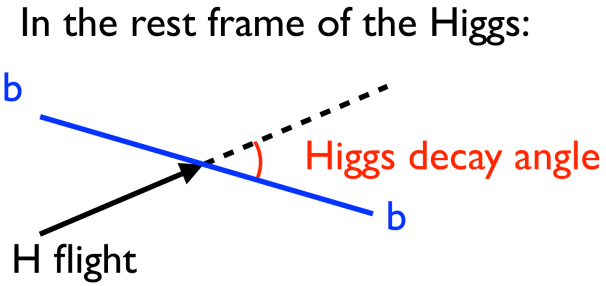
Event selection (4)

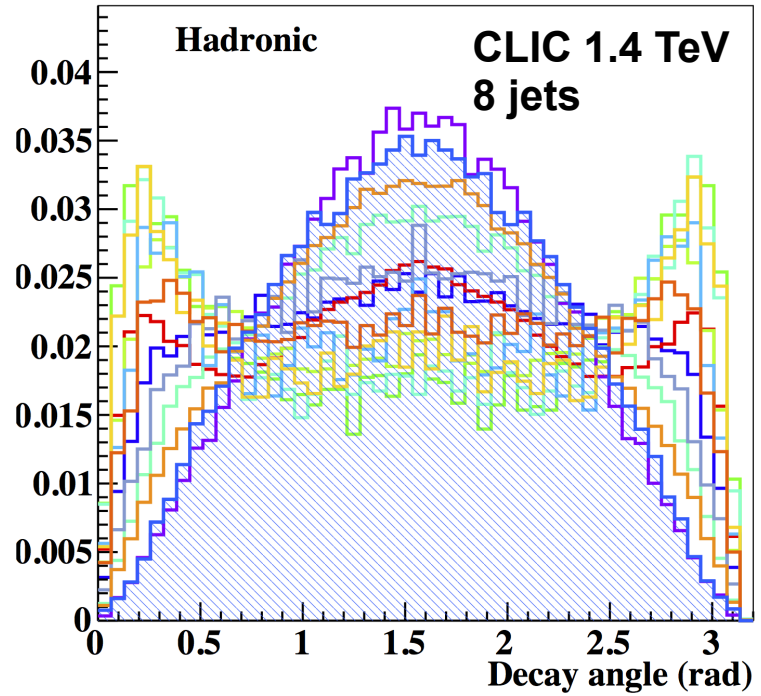
Events are selected using e.g.:

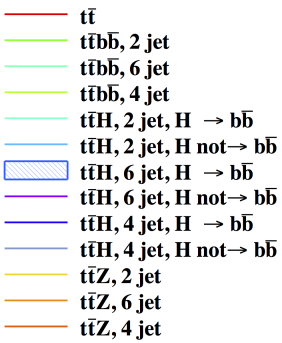
- Masses of the W, H, top candidates
- Four hightest b-tag values
- Event shape variables
- Jet clustering information
- Angular variables
- ...

Example distributions:

- Event thrust
- Jet resolution parameter Y_{65}
- Number of particles
- Higgs decay angle







Study for ILC at 500 GeV

Significance

- $\sqrt{s}$ = 500 GeV, L=500 fb^{-1}, (Pe$^-$,Pe$^+$)=(-0.8,+0.3)

	ttH→8jet		ttH→lv6jet		ttH→2l2v4jet	
Process	previous	current	previous	current	previous	current
ttH (not Signal)	0.42	0.426	0.25	0.208	0.06	0.0529
ttZ	7.17	8.45	5.19	5.12	1.41	1.29
ttbb	2.59	3.15	2.04	2.01	0.54	0.489
6f	19.24	19.4	8.39	8.80	1.88	1.72
bkgd total	**29.43**	**31.43**	**15.88**	**16.15**	**3.91**	**3.55**
Signal	**14.37**	**12.86**	**10.26**	**8.55609**	**2.62**	**2.09**
MH rang (GeV)	**(95,160)**	**(90,150)**	**(95,160)**	**(95,155)**	**(100,155)**	**(105,155)**

(Pe,Pe$^+$)	previous	current
Lumi. (fb^{-1})	500	500
8 jets	2.17	1.93
lv + 6 jets	2.00	1.72
2l2v + 4 jets	1.02	0.879

From Yuji Sudo (update of results shown at ALWS15)

Cut based analysis, currently investigating usage of multivariate classifiers

Results for ILC at 1 TeV

Events are selected using Boosted Decision Trees as implemented in TMVA:

Detector		ILD		SiD	
Sample	Before cuts	After Cuts			
		6 jets	8 jets	6 jets	8 jets
$t\bar{t}H$ 6 jets	628.7	208.0	65.5	191.6	57.4
$t\bar{t}H$ 8 jets	652.7	2.1	365.6	1.6	299.4
$t\bar{t}H \rightarrow$ other	1197.5	28.8	25.3	33.0	16.6
$t\bar{t}Z$	5332.4	126.1	260.5	105.6	187.1
$t\bar{t}b\bar{b}$	1434.5	125.4	222.6	100.1	180.7
$t\bar{t}$	308800.9	261.2	513.6	232.0	381.6
y_t statistical uncertainty		6.9%	5.4%	7.0%	5.8%
combined		4.3%		4.5%	

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

→ Very similar results for both detectors

arXiv:1409.7157
accepted by EPJ C

≈ 4% precision for 1 ab^{-1} with P(e$^-$) = -0.8, P(e$^+$) = +0.2

Results for CLIC at 1.4 TeV

Process	Evt in 1.5 ab^{-1}	Evt with 0 leptons	Evt pass Had BDT		Evt with 1 lepton	Evt pass SL BDT	
$t\bar{t}H$, 6 jet, $H \to b\bar{b}$	647	593	357	(60.2%)	49	9	(18.8%)
$t\bar{t}H$, 4 jet, $H \to b\bar{b}$	623	178	62	(35.1%)	420	233	(55.3%)
$t\bar{t}H$, 2 jet, $H \to b\bar{b}$	150	13	1	(10.7%)	61	20	(32.5%)
$t\bar{t}H$, 6 jet, $H \not\to b\bar{b}$	473	306	38	(12.3%)	127	8	(6.52%)
$t\bar{t}H$, 4 jet, $H \not\to b\bar{b}$	455	89	5	(5.81%)	246	19	(7.82%)
$t\bar{t}H$, 2 jet, $H \not\to b\bar{b}$	110	6	0	(1.52%)	33	1	(3.66%)
$t\bar{t}b\bar{b}$, 6 jet	824	737	287	(38.9%)	80	8	(9.75%)
$t\bar{t}b\bar{b}$, 4 jet	794	222	44	(19.6%)	533	175	(32.9%)
$t\bar{t}b\bar{b}$, 2 jet	191	16	1	(8.71%)	78	14	(18.1%)
$t\bar{t}Z$, 6 jet	2,843	2,335	316	(13.5%)	322	12	(3.68%)
$t\bar{t}Z$, 4 jet	2,738	711	49	(6.86%)	1,678	170	(10.2%)
$t\bar{t}Z$, 2 jet	659	54	1	(2.03%)	248	13	(5.23%)
$t\bar{t}$	203,700	111,020	1,399	(1.26%)	77,110	523	(0.68%)

1.5 ab^{-1} with unpolarised beams

Combined: $\Delta(\sigma(t\bar{t}H)) = 8.4\% \rightarrow \Delta(g_{ttH}) = 4.4\%$

≈ 4% precision for 1.5 ab^{-1} with $P(e^-) = -0.8$

CLICdp-Note-2015-001
CLICdp-Note-2014-001

→ Very similar performance as ILC at 1 TeV

What's next?

So far focussed on the total $t\bar{t}H$ production cross section, could exploit differential distributions as well

Example: CP properties of the Higgs boson, observables proposed in Eur. Phys. J. **C 71** 1681 (2011):
- Total cross section and its energy dependence
- Top polarisation asymmetry
- Up-down asymmetry of the anti-top with respect to the top-electron plane

Input welcome:
- What else could be done?
- Which other observables should be study?

Summary and outlook

• The reconstruction of $t\bar{t}H$ events is an excellent benchmark for linear collider detectors

• About 4% precision on the top Yukawa coupling achievable with 1 ab^{-1} at 1 TeV at the ILC or 1.5 ab^{-1} at 1.4 TeV at CLIC

Collider	LHC		ILC	ILC	CLIC
CM Energy [TeV]	14	14	0.5	1.0	1.4
Luminosity [fb^{-1}]	300	3000	1000	1000	1500
Top Yukawa coupling κ_t	$(14-15)\%$	$(7-10)\%$	10%	4%	4%

from arXiv:1311.2028

• Moderate improvements possible, e.g. including H→WW* decays (generation of background samples would be difficult)

• Investigation of other observables in $t\bar{t}H$ events possible