Top Yukawa coupling and CP-violation in the $t\bar{t}H$ coupling at 1.4TeV

7th Linear Collider School 2018, Frauenchiemsee

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Acknowledging contributions from
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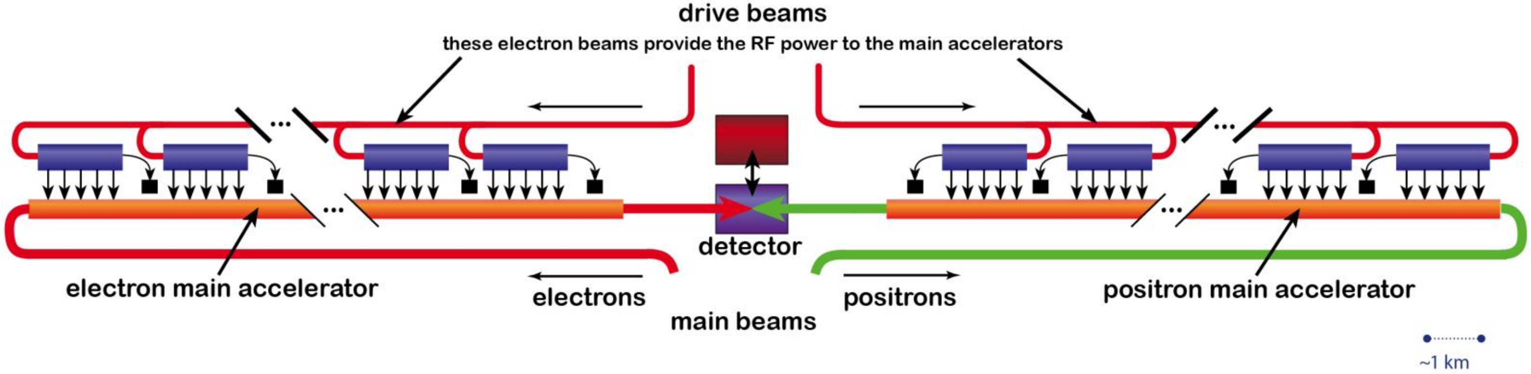
Outline

- CLIC overview
- The top Yukawa analysis at 1.4 TeV
  - Strategy and Pre-selections
  - Event Reconstruction and flavour-tagging
  - Multivariant selection (TMVA)
  - Results
- CP property of Higgs boson
  - Sample production and cross-section calculation
  - Preliminary sensitivity to CP mixing (cross-section)
  - Up-down asymmetry
  - Preliminary sensitivity to CP mixing (cross-section + up-down asymmetry)
- Summary

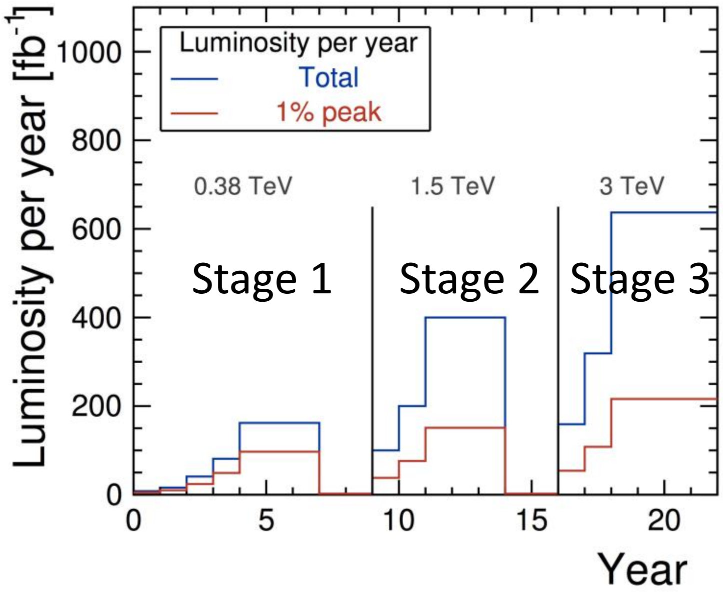
Compact Linear Collider (CLIC)



CTF3 facility

Drive beam

Main beam



2013 - 2019 Development Phase

Development of a Project Plan for a staged CLIC implementation in line with LHC results; technical developments with industry, performance studies for accelerator parts and systems, detector technology demonstrators

2020 - 2025 Preparation Phase

Finalisation of implementation parameters, preparation for industrial procurement, Drive Beam Facility and other system verifications, Technical Proposal of the experiment, site authorisation

2026 - 2034 Construction Phase

Construction of the first CLIC accelerator stage compatible with implementation of further stages; construction of the experiment; hardware commissioning

2019 - 2020 Decisions

Update of the European Strategy for Particle Physics; decision towards a next CERN project at the energy frontier (e.g. CLIC, FCC)

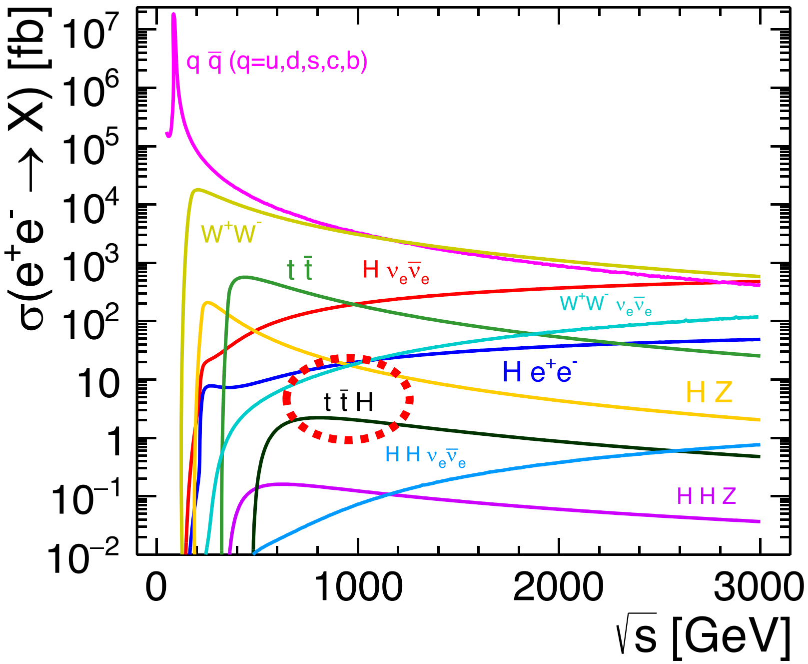
2025 Construction Start

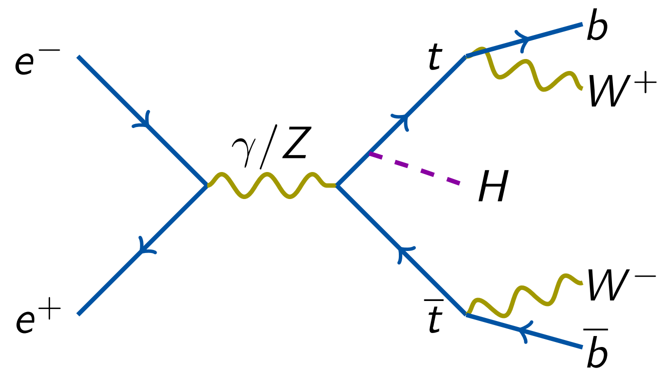
Ready for construction; start of excavations

2035 First Beams

Getting ready for data taking by the time the LHC programme reaches completion

Motivation





Pros:

1. Strongest Yukawa coupling
2. High rates of production of Higgs with top pairs
3. Direct probe of CP properties of Higgs boson

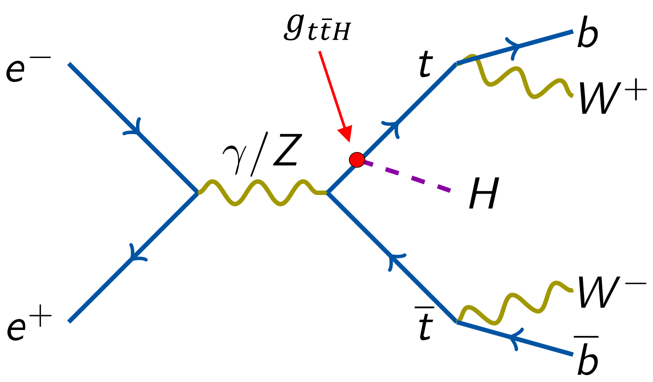
Cons:

1. Large number of final states
2. Large backgrounds, e.g. from $t\bar{t}$

Analysis Strategy

$e^+ + e^- \rightarrow t\bar{t}H\ ,\ H \rightarrow b\bar{b}$

$\sqrt{s}$ =1.4 TeV, L =1.5 ab^{-1}.



$t\bar{t}H$ decay	BR(of all possible decay of H)	No. Leptons	Channel classification
$t\bar{t} \rightarrow 6jets, H \rightarrow bb$	46%	0	**Hadronic**
$t\bar{t} \rightarrow 4jets + 1l + 1\bar{\upsilon}_l, H \rightarrow bb$	45%	1	**Semi-leptonic**
$t\bar{t} \rightarrow 2jets + 2l + 2\bar{\upsilon}_l, H \rightarrow bb$	9%	>1	Not analysed further

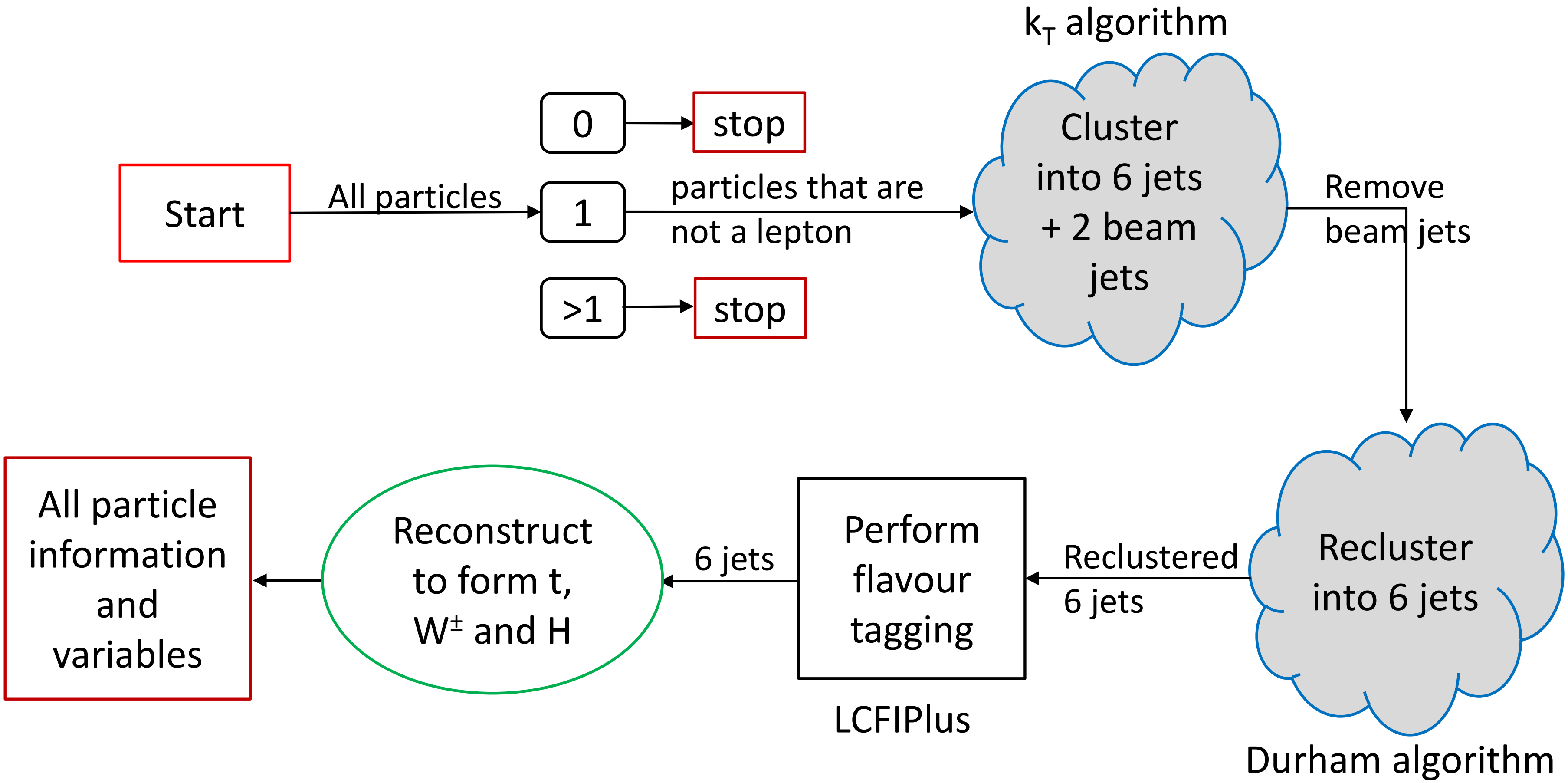
*The top-Yukawa analysis is a refinement of previous analysis CLICdp-Note-2014-001

Signal and Background samples

Process	Cross-section (fb)	Generator	Weight
$t\bar{t}H, t\bar{t} \to 6jets, H \to bb$	0.431	Physsim	0.03
$t\bar{t}H, t\bar{t} \to 4jets, H \to bb$	0.415	Physsim	0.03
$t\bar{t}H, t\bar{t} \to 6jets, H \nrightarrow bb$	0.315	Physsim	0.02
$t\bar{t}H, t\bar{t} \to 4jets, H \nrightarrow bb$	0.303	Physsim	0.02
$t\bar{t}H, t\bar{t} \to 2jets, H \to bb$	0.100	Physsim	0.006
$t\bar{t}H, t\bar{t} \to 2jets, H \nrightarrow bb$	0.073	Physsim	0.004
$t\bar{t}Z, t\bar{t} \to 6jets$	1.895	Physsim	0.1
$t\bar{t}Z, t\bar{t} \to 4jets$	1.825	Physsim	0.1
$t\bar{t}Z, t\bar{t} \to 2jets$	0.439	Physsim	0.03
$t\bar{t}bb, t\bar{t} \to 6jets$	0.549	Physsim	0.03
$t\bar{t}bb, t\bar{t} \to 4jets$	0.529	Physsim	0.03
$t\bar{t}bb, t\bar{t} \to 2jets$	0.127	Physsim	0.008
$t\bar{t}$	135.8	PYTHIA	1.5

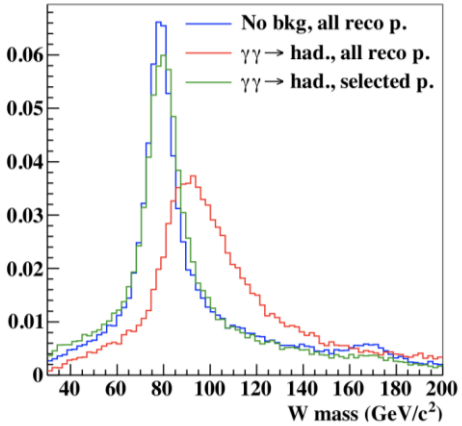
*Detector: SiD; Polarisation: (0,0)

Event reconstruction strategy



Top, $W^{\pm}$ and Higgs Reconstruction

At $\sqrt{s} = 1.4$ TeV, ~ 1.3 $\gamma\gamma \rightarrow hadrons$ per bunch-crossing. Background suppression level is changed 'Default' → 'Tight' and jet clustering radius is optimised.



Chi-square method is used to reconstruct the $W^{\pm}$, top and Higgs candidates by combining the jets.

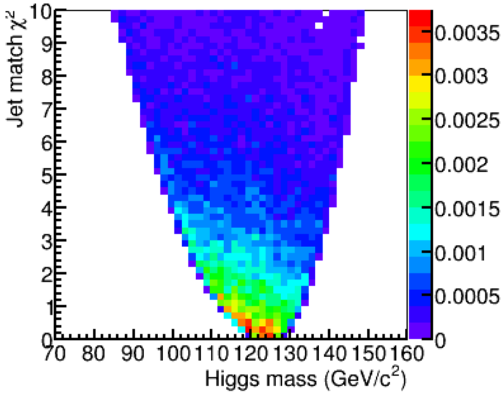
Semi-leptonic:

$$\chi_6^2 = \frac{(M_{12}-M_{W^{\pm}})^2}{\sigma_{W^{\pm}}^2} + \frac{(M_{123}-M_t)^2}{\sigma_t^2} + \frac{(M_{45}-M_H)^2}{\sigma_H^2}$$

Hadronic:

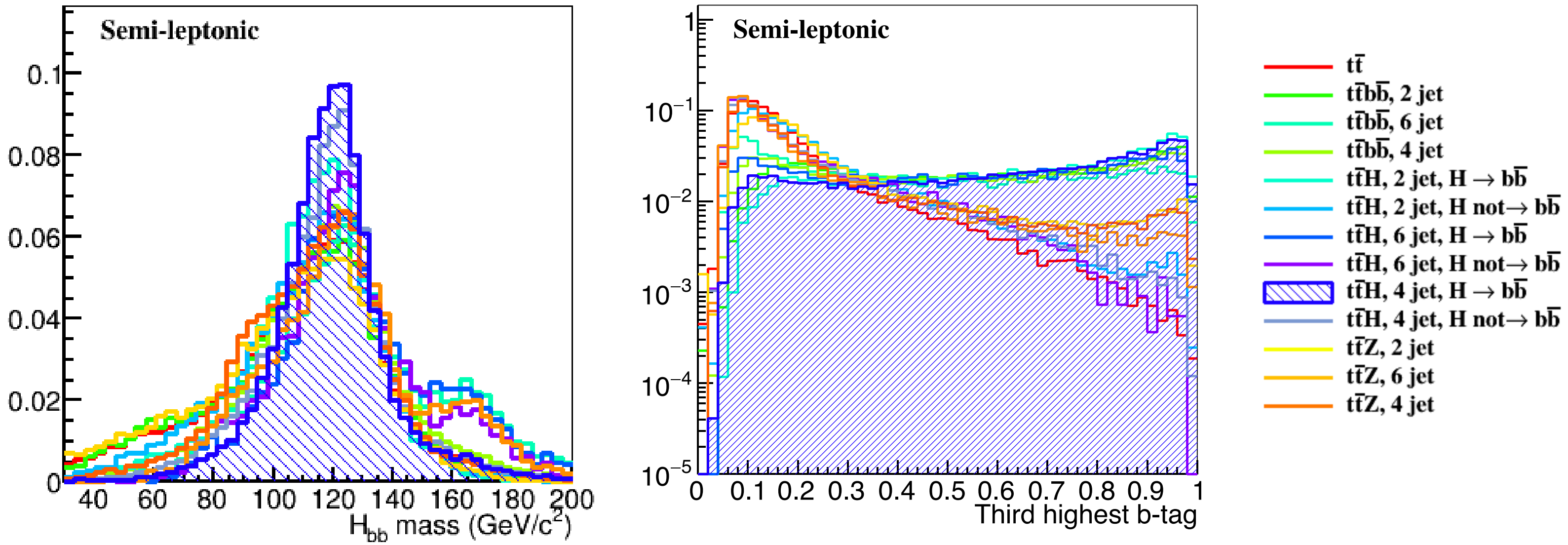
$$\chi_8^2 = \frac{(M_{12}-M_{W^{\pm}})^2}{\sigma_{W^{\pm}}^2} + \frac{(M_{123}-M_t)^2}{\sigma_t^2} + \frac{(M_{45}-M_{W^{\pm}})^2}{\sigma_{W^{\pm}}^2} + \frac{(M_{456}-M_t)^2}{\sigma_t^2} + \frac{(M_{78}-M_H)^2}{\sigma_H^2}$$

The leptonic $W^{\pm}$ and top are reconstructed using jets, an isolated lepton and a neutrino.

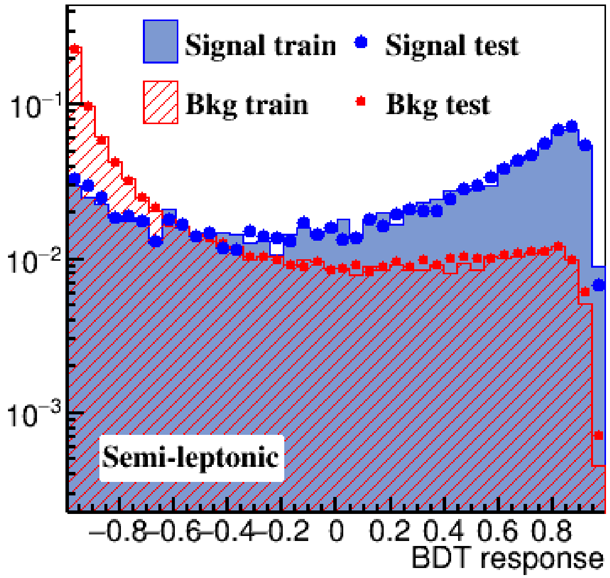


Event selection using TMVA

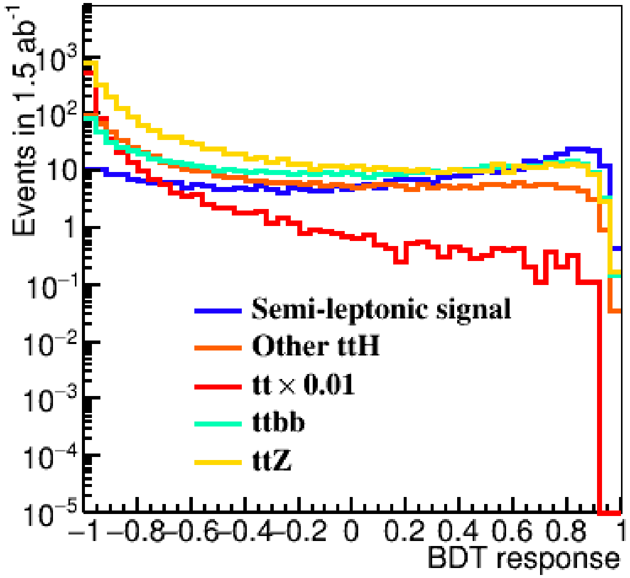
Kinematic variables and tagging information are used as input to the TMVA(BDTG) separately for the full-hadronic (27 variables) and semi-leptonic (23 variables) channels (examples plots see backup slides):



BDTG response



Apply BDTG weight



The BDTG response for signal and background samples.
(Left): Normalised BDTG response.

(Right): Scaled BDTG to number of events expected in 1.5 ab^{-1} with new set of samples by using the result from (Left).

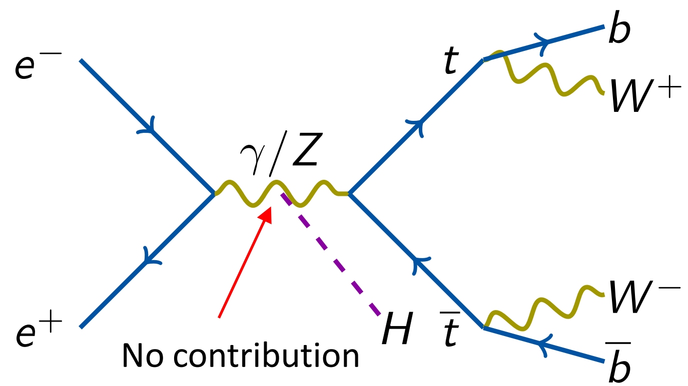
Optimise significance

$$S/\sqrt{S+B}$$

Selection efficiency after BDT

Process	Evt in 1.5 ab^{-1}	Evt with 0 Lepton	Evt with 1 Lepton	Evt pass Had BDT	Evt pass SL BDT
$t\bar{t}H$, 6 jets, $H\to b\bar{b}$	647	555 (85.9%)	86 (13.4%)	367 (56.8%)	38 (5.91%)
$t\bar{t}H$, 4 jets, $H\to b\bar{b}$	623	208 (33.4%)	432 (69.4%)	1 (0.14%)	270 (43.4%)
$t\bar{t}H$, 6 jets, $H\not\to b\bar{b}$	473	276 (58.4%)	143 (30.2%)	54 (11.4%)	11 (2.32%)
$t\bar{t}H$, 4 jets, $H\not\to b\bar{b}$	455	70 (15.4%)	237 (52.2%)	8 (1.85%)	22 (4.88%)
$t\bar{t}H$, 2 jets, $H\to b\bar{b}$	150	9 (6.18%)	53 (35.6%)	2 (1.65%)	22 (14.8%)
$t\bar{t}H$, 2 jets, $H\not\to b\bar{b}$	110	4 (3.90%)	27 (25.0%)	0 (0.11%)	1 (1.19%)
$t\bar{t}Z$, 6 jets	2843	2133 (75.0%)	445 (15.7%)	345 (12.1%)	34 (1.21%)
$t\bar{t}Z$, 4 jets	2738	571 (20.9%)	1726 (63.0%)	59 (2.14%)	217 (7.94%)
$t\bar{t}Z$, 2 jets	659	36 (5.49%)	214 (32.5%)	1 (0.22%)	16 (2.45%)
$t\bar{t}b\bar{b}$, 6 jets	824	720 (87.5%)	95 (11.6%)	326 (39.5%)	26 (3.14%)
$t\bar{t}b\bar{b}$, 4 jets	794	193 (24.3%)	552 (69.5%)	57 (7.15%)	226 (28.54%)
$t\bar{t}b\bar{b}$, 2 jets	191	11 (5.84%)	70 (36.7%)	2 (0.82%)	18 (9.70%)
$t\bar{t}$	203700	116181 (57.0%)	76732 (37.7%)	498 (0.24%)	742 (0.36%)
total $t\bar{t}H$ signal	2458	1123 (45.7%)	978 (39.8%)	433 (17.6%)	365 (14.8%)
total background	211749	119846 (56.6%)	79834 (36.3%)	1287 (0.61%)	1280 (0.60%)
Significance				10.44	9.00

Result on top-Yukawa coupling



To translate the cross-section measurement into top-Yukawa coupling at 1.4 TeV, a linear approximation with NLO QCD prediction is used (thanks to Juergen Reuter and Vincent Rothe from DESY[1]):

$$\frac{\Delta g_{t\bar{t}H}}{g_{t\bar{t}H}} = 0.503\,\frac{\Delta\sigma(t\bar{t}H)}{\sigma(t\bar{t}H)}$$

[1] JHEP 1612 (2016) 075

	Significance	$\Delta\sigma/\sigma$	$\Delta g_{ttH}/g_{ttH}$
Hadronic	10.44σ	7.3%	3.7%
Semi-leptonic	9.00σ		

CP violation in $t\bar{t}H$ production

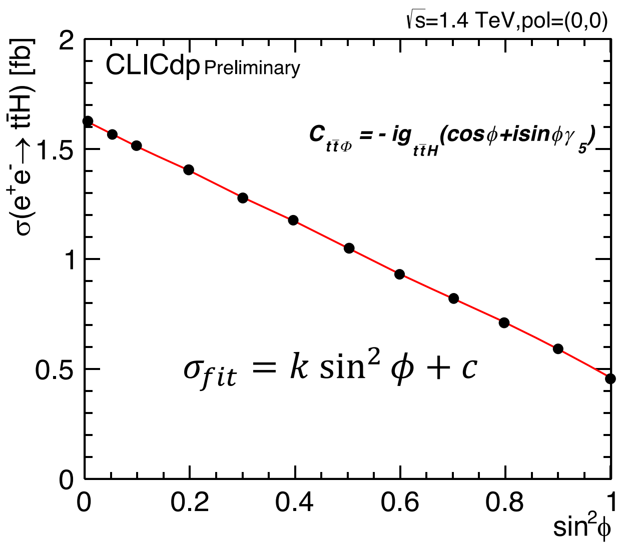
A model-independent way of parameterising the CP mixing in Higgs:

- $C_{t\bar{t}\Phi} = -ig_{t\bar{t}H}(a + ib\gamma_5)$
- SM: a = 1, b = 0 ; pure CP-odd: a = 0, b ≠ 0.

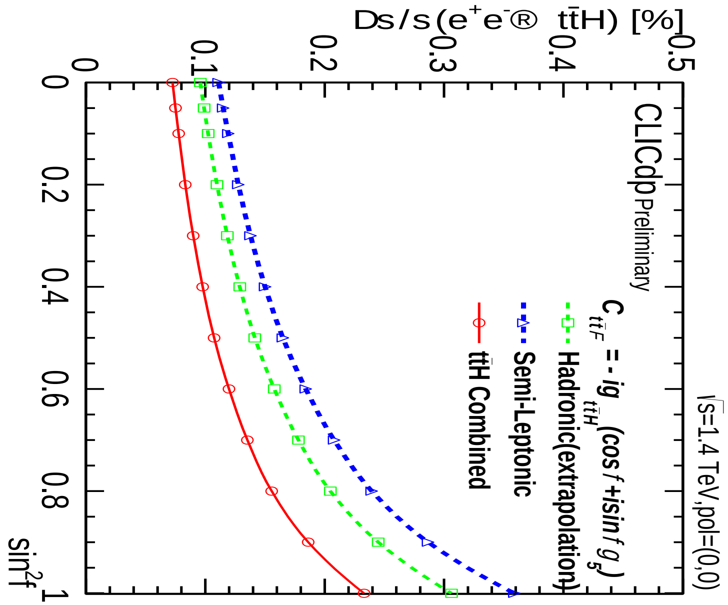
assume $a^2 + b^2 = 1$ with $a = \cos(\phi)$ and b= $\sin(\phi)$; measurement of the mixing angle ϕ indicates the CP properties of Higgs.

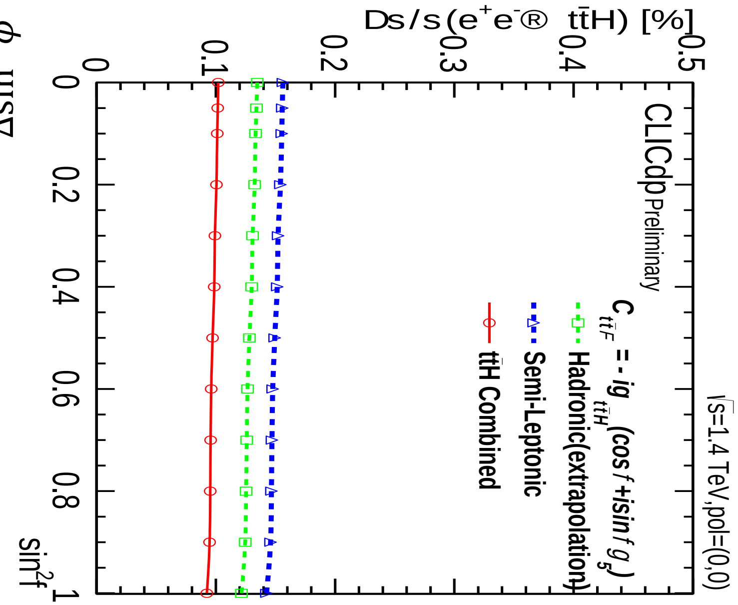
$t\bar{t}\Phi$ cross section (thanks for Philipp Roloff for generating the samples):

- Generator: Physsim
- $\sqrt{s}$ = 1.4 TeV
- Polarisation = (0,0)
- ISR included
- CLIC luminosity spectrum
- 12 samples produced



Cross section to CP-mixing sensitivity





$$\sigma_{fit} = k\sin^2\phi + C \rightarrow \Delta\sigma = k\Delta\sin^2\phi$$

$$\Rightarrow \Delta\sin^2\phi = \frac{1}{k}\frac{\Delta\sigma}{\sigma}\sigma$$

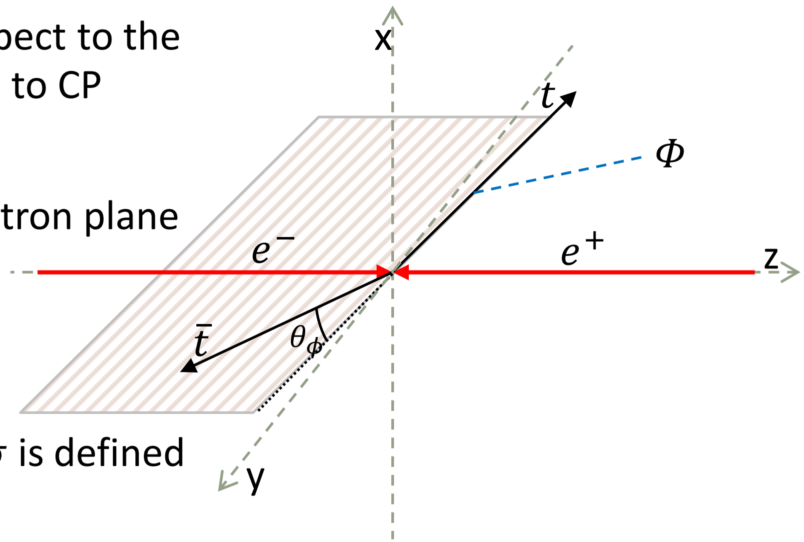
- Apply the top-Yukawa analysis procedure to all samples
- Measure $\Delta\sigma/\sigma$ for all $\sin^2(\phi)$ values in the semi-leptonic channel
- Extrapolate the hadronic result by using the cross-section ratio σ_{CP}/σ_{SM}
- Combine the result from both channels

The up-down asymmetry

The up-down asymmetry A_ϕ of an antitop with respect to the top-electron plane is an observable that is sensitive to CP violation.

The angle θ_ϕ between the antitop and the top-electron plane is given by

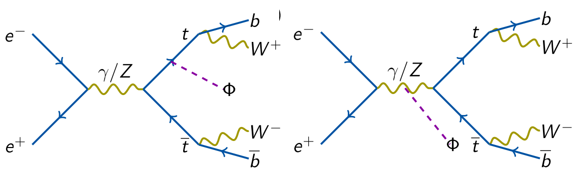
$$\sin(\theta_\phi) = \frac{\vec{p}_{\bar{t}}(\vec{q}_{e^-} \times \vec{p}_t)}{|\vec{p}_{\bar{t}}||(\vec{q}_{e^-} \times \vec{p}_t)|}$$



The up-down asymmetry of the $t\bar{t}\Phi$ cross section σ is defined as

$$A_\phi = \frac{\sigma(\sin\theta_\phi > 0) - \sigma(\sin\theta_\phi < 0)}{\sigma(\sin\theta_\phi > 0) + \sigma(\sin\theta_\phi < 0)}$$

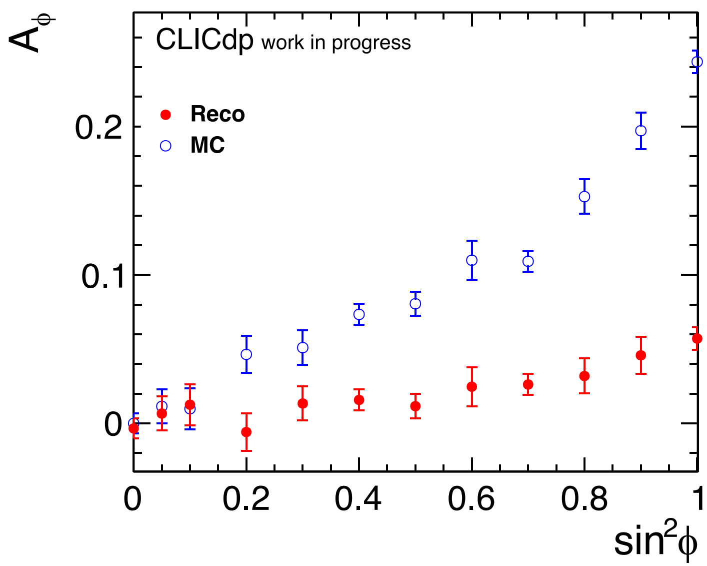
$\sigma = \sigma(up) + \sigma(down)$ where 'up' ('down') denotes the cross section integrated over $\theta_\phi \in [0, \pi)$ ($\theta_\phi \in [\pi, 2\pi)$).

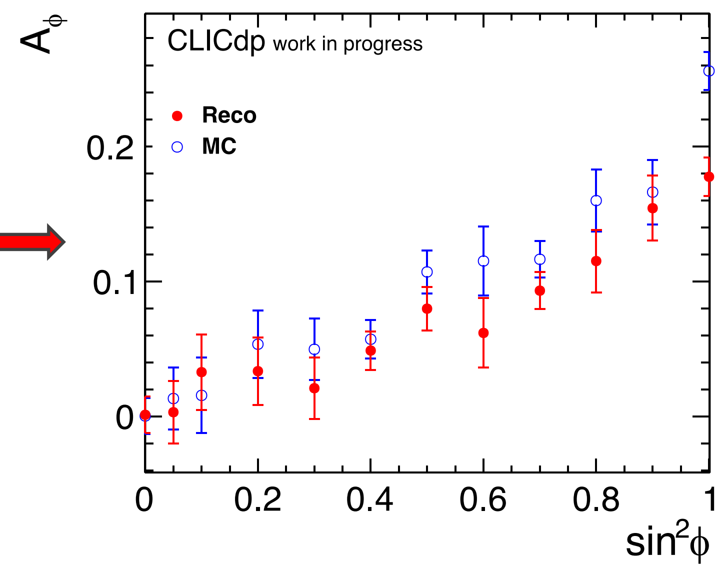


Interference between $t\bar{t}\Phi$ and $ZZ\Phi$!

[1] arXiv:1103.5404v1

A_ϕ with quality cuts



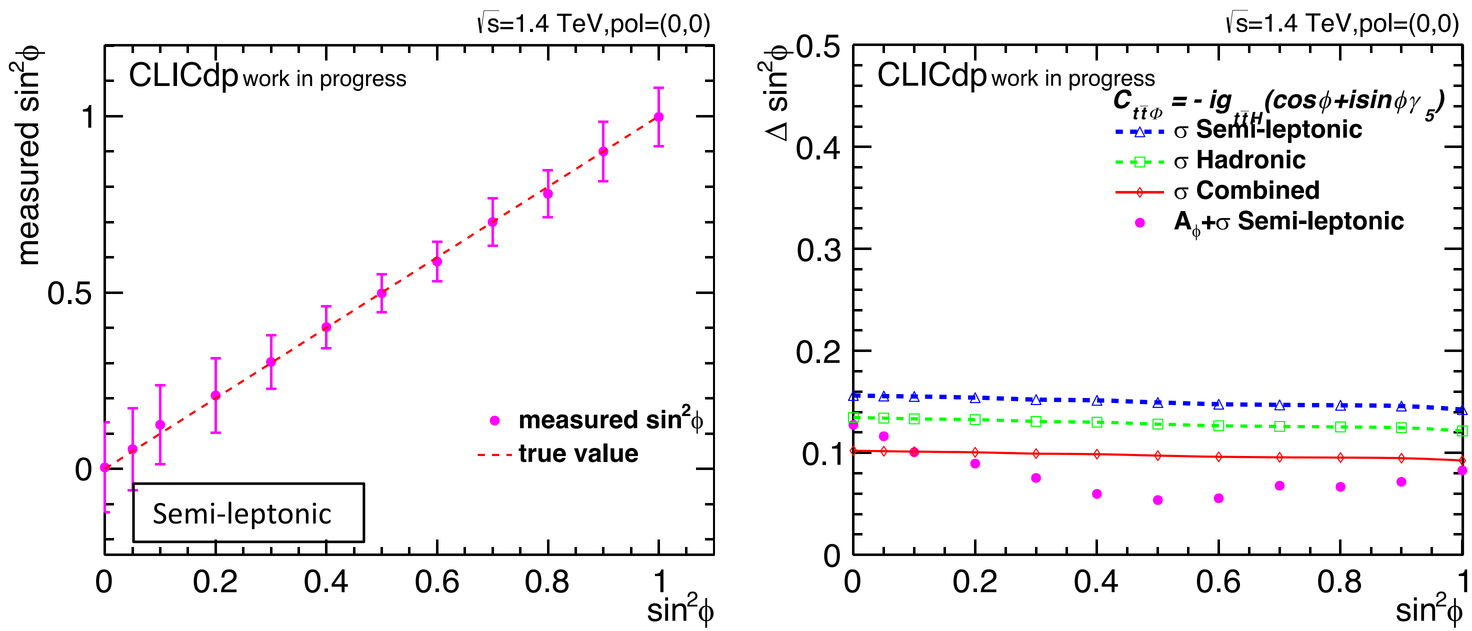


$$A_\phi = \frac{\sigma(\sin\theta_\phi > 0) - \sigma(\sin\theta_\phi < 0)}{\sigma(\sin\theta_\phi > 0) + \sigma(\sin\theta_\phi < 0)}$$

Quality cuts:

- Remove taus
- $m_{t_l} - m_{t_q} < 100$
- jetmatch $\chi^2 < 10$

Preliminary results



- The measurement of $\sin^2\phi$ by using up-down asymmetry.
- Then the errors can be extracted to measure sensitivity of CP mixing.

Summary

- This analysis has found $\frac{\Delta g_{t\bar{t}H}}{g_{t\bar{t}H}} = 3.7\%$ with integrated luminosity of 1.5 ab^{-1} at $\sqrt{s}$ =1.4 TeV at CLIC with unpolarised beam,
  - Old CLIC analysis found 4.27%,
  - ILC at 1 TeV found 4.5%.
- Improvements from increased $\gamma\gamma \rightarrow$hadrons background suppression and improved flavour-tagging performance (b-tagging specifically).

- Sensitivity to CP violation is determined $\Delta\sin^2(\phi) \simeq 0.1$ with cross section measurement.
- An angular distribution using up-down asymmetry has shown an improvement to CP sensitivity, but the method needs to be consolidated.
- Further observables to increase the CP violation sensitivity will be investigated in the future.

Thank you!

Backup Slides

Leptons

The leptons are searched in two ways:

- Isolated leptons (electron, muon): using IsolatedLeptonFinder
  - Track energy > 15 GeV
  - $d_0, Z_0, R_0 < 0.05\ mm$
  - $R_{CAL} = \frac{E_{ECAL}}{E_{ECAL}+E_{HCAL}} > 0.9,\ \text{ or }\ 0.05 < R_{CAL} < 0.3$
  - Particle energy (GeV) > 100, if cone energy >10 GeV
> 10×cone energy, if cone energy ≤10 GeV

- Tau leptons: using TauFinder
  - p_T > 2 GeV/c
  - Cone angle > 0.04 rad
  - Seed track p_T > 10 GeV/c
  - $0.01mm < R_0 < 0.5mm$
  - Reconstructed m_{tau} < 1.5 GeV/c^2
  - 0.04 < Isolation ring < 0.25 rad
  - Less than 5 particles in the isolation ring, with total energy < 5 GeV

Lepton identification

The leptons are searched in two ways:

- **Isolated leptons (electron, muon):** using IsolatedLeptonFinder

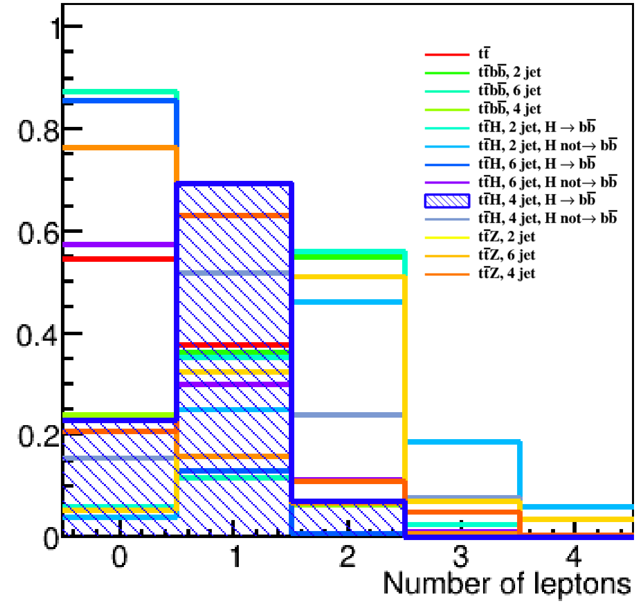
- **Tau leptons**: using TauFinder

(detailed selection criteria are in backup slide)

➢ retains 87% of truth-matched electrons and muons, 85% of taus that decay from $W^{\pm}$; 0.4% of other reconstructed particles.

Pre-selection:

➢ Selects Hadronic - 86%, Semi-leptonic - 69%.

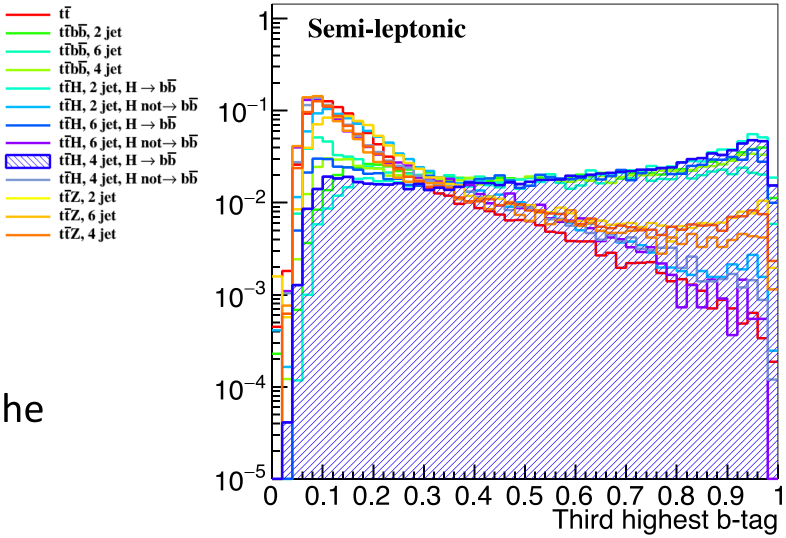


Flavour-tagging

LCFIPlus is tuned using $e^+e^- \to qqqqqq$ samples with the same flavour for all the quarks.

From the LCFIPlus, we use:

- b-tag and c-tag probability;
- y_{ij} the distance between two closest jets.



* A bug which influences the performance of the flavour-tagging has been fixed. Retuning the LCFIPlus improves the b-tagging performance.

Parameters determined

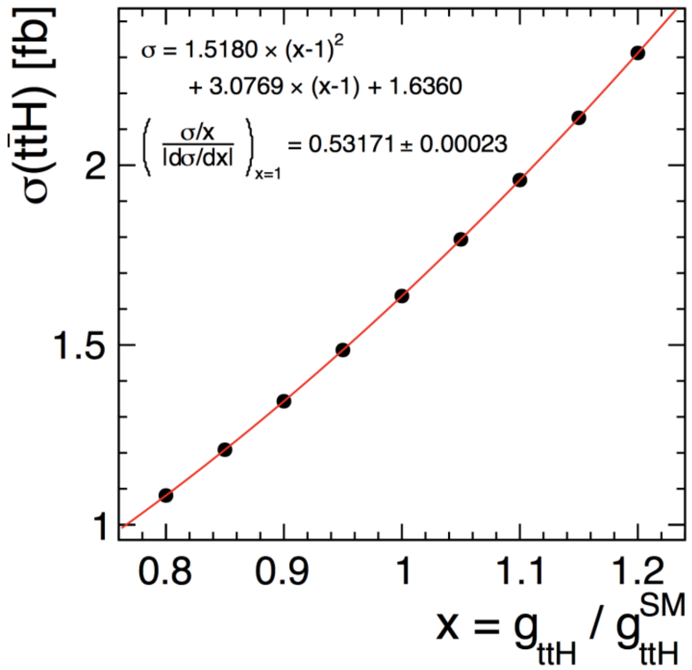
Using the modified Gaussian, the parameters in the Chi-square function can be determined:

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

	Mass (GeV/c²)	$\boldsymbol{\sigma_L}\ (\boldsymbol{GeV/c^2})$	$\boldsymbol{\sigma_R}\ (\boldsymbol{GeV/c^2})$
$W^{\pm}$	79.1	5.81	6.69
Top	169.3	12.5	12.2
Higgs	121.7	13.4	8.00

Table 2: Parameters for the invariant mass distribution of the W, top and Higgs candidates, fitted using modified Gaussian, using default background suppression and jet radius 1.0.

Result on top-Yukawa coupling



To translate the cross-section measurement into top Yukawa coupling at 1.4 TeV, a linear approximation is used (old, using quadratic fit):

$$\frac{\Delta g_{t\bar{t}H}}{g_{t\bar{t}H}} = 0.53\,\frac{\Delta\sigma(t\bar{t}H)}{\sigma(t\bar{t}H)}$$

Event selection using TMVA

These variables are used as input to the TMVA(BDTG) separately for the full-hadronic and semi-leptonic channels (examples plots see backup slides):

For both channel:

- reconstructed Higgs mass, M_{ij}
- number of reconstructed particles
- visible energy in jets
- missing p_T
- χ^2 chi-squared value of the reconstructed jets
- event shape variables thrust, sphericity and aplanarity
- 4 highest b-tag probabilities and the corresponding ctag
- cosine of decay angle of the $H \to b\bar{b}$ decay
- cosine of the angles between Higgs and top
- y_{ij}, the values y_{45}, y_{56} and y_{67}

For semi-leptonic:

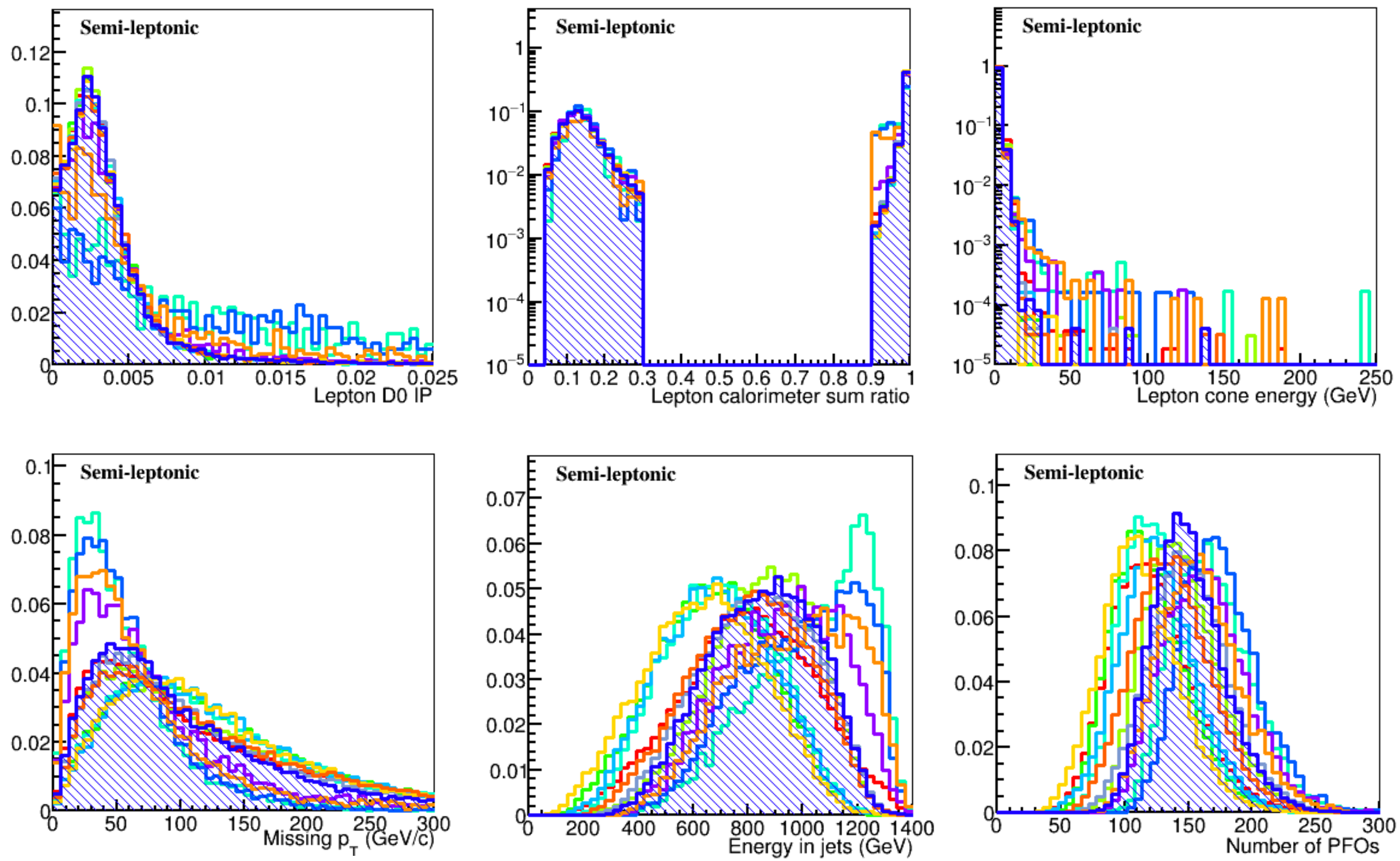
- Cone energy of the isolated lepton
- Ratio of energy deposits in the calorimeter of the isolated lepton

-> 23 variables

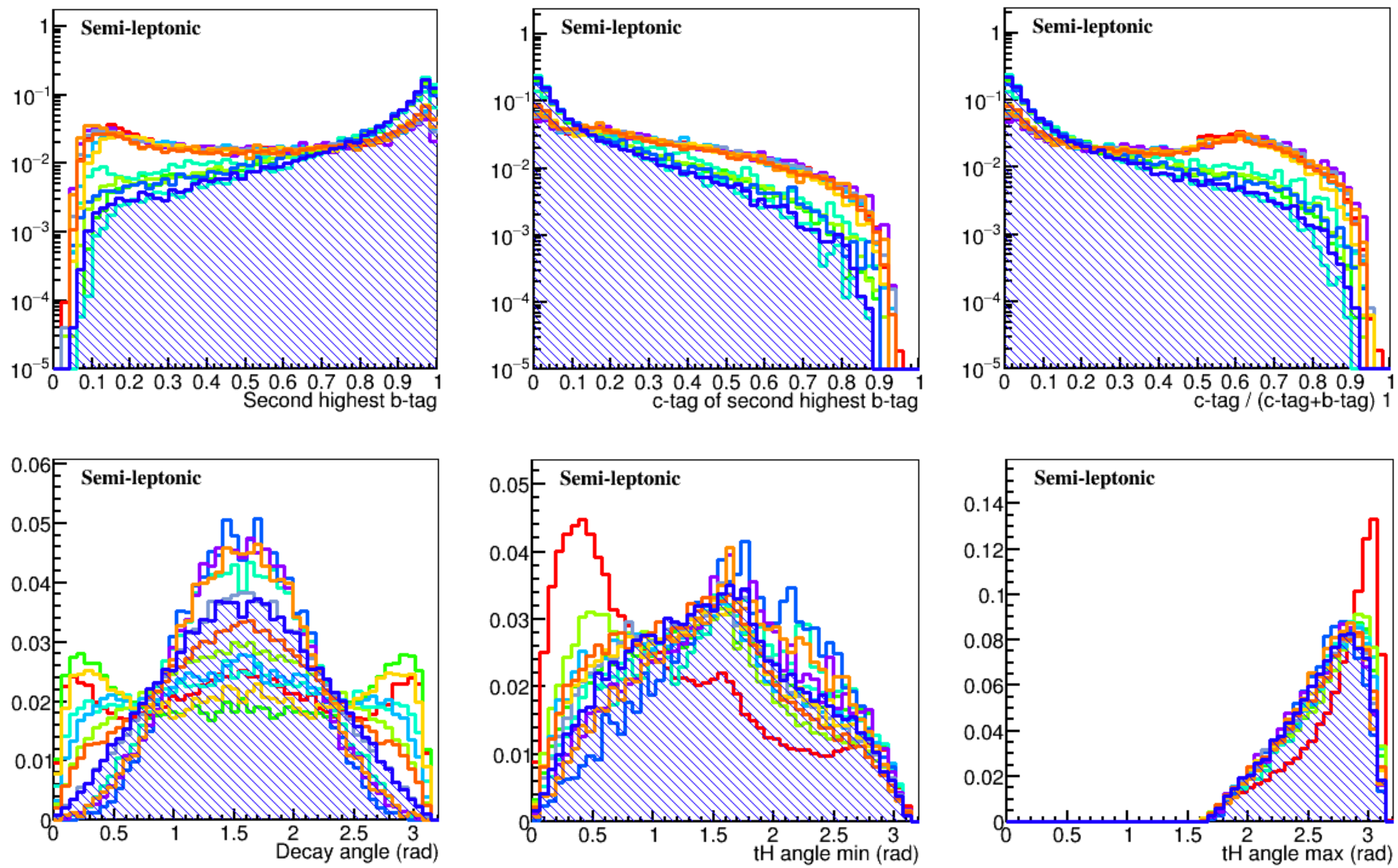
For hadronic:

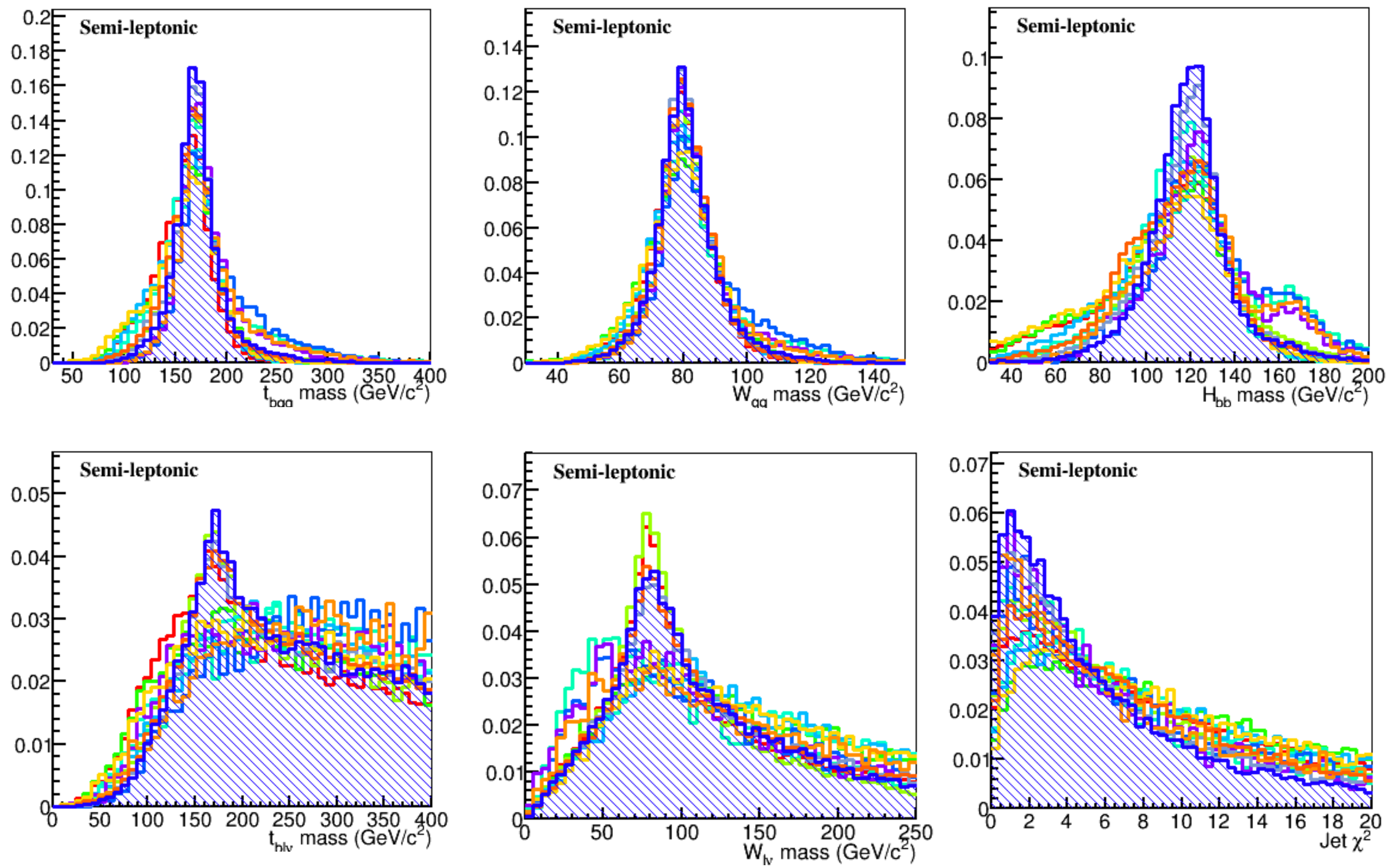
- Energy of the 4 lowest-energy jets
- Cosine of the angle of two closest jets to the beam-axis

-> 27 variables

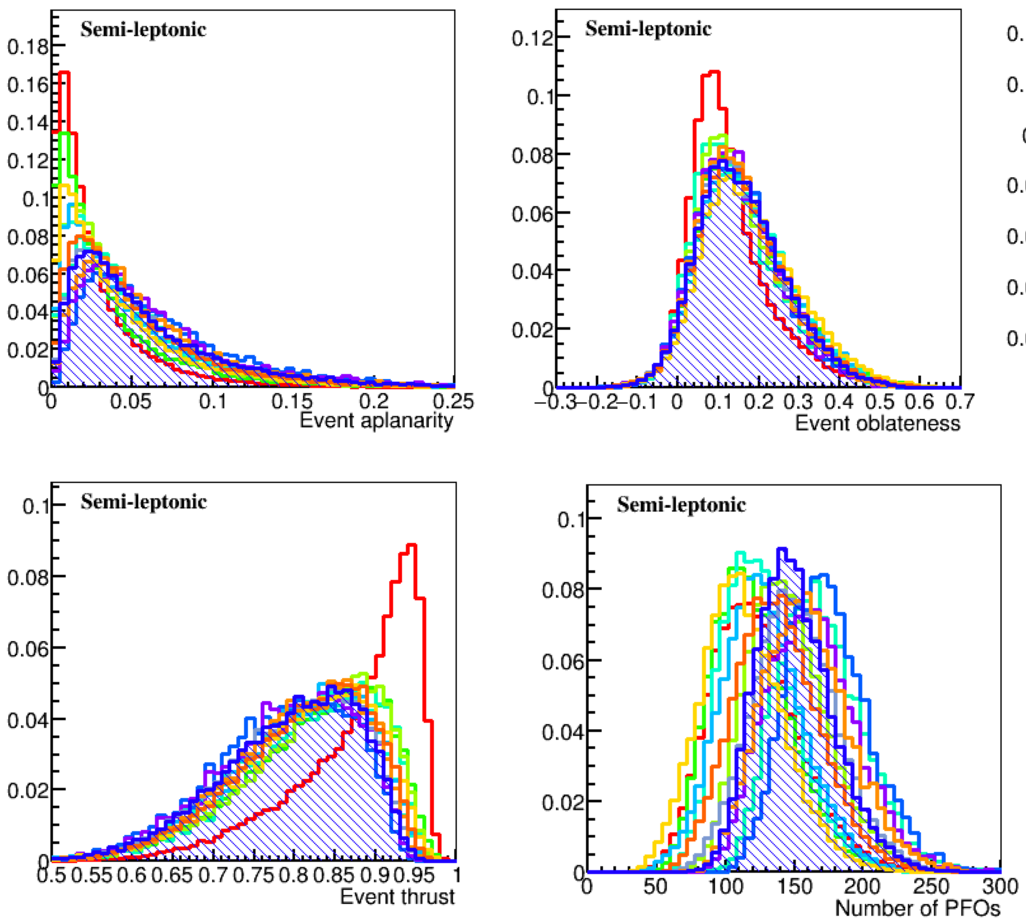


N.B The results presented here are all for the semi-leptonic signal channel.


Semi-leptonic
Second highest b-tag
Semi-leptonic
c-tag of second highest b-tag
Semi-leptonic
c-tag / (c-tag+b-tag)
Semi-leptonic
Decay angle (rad)
Semi-leptonic
tH angle min (rad)
Semi-leptonic
tH angle max (rad)

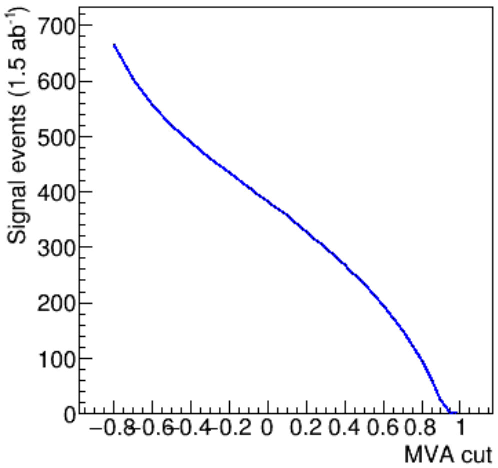


Semi-leptonic
t_{bqq} mass (GeV/c^2)
Semi-leptonic
W_{qq} mass (GeV/c^2)
Semi-leptonic
H_{bb} mass (GeV/c^2)
Semi-leptonic
$t_{bl\nu}$ mass (GeV/c^2)
Semi-leptonic
$W_{l\nu}$ mass (GeV/c^2)
Semi-leptonic
Jet χ^2

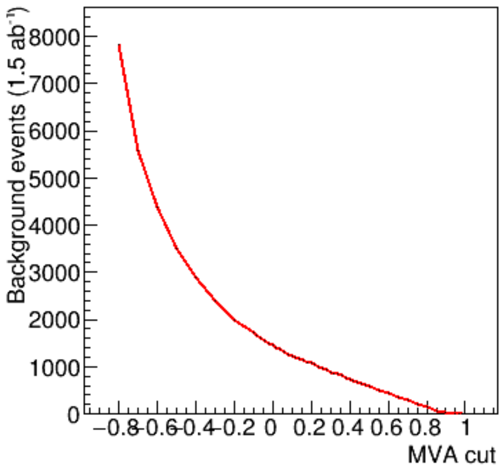


Semi-leptonic
Event aplanarity
Semi-leptonic
Event oblateness
Semi-leptonic
Event sphericity
Semi-leptonic
Event thrust
Semi-leptonic
Number of PFOs

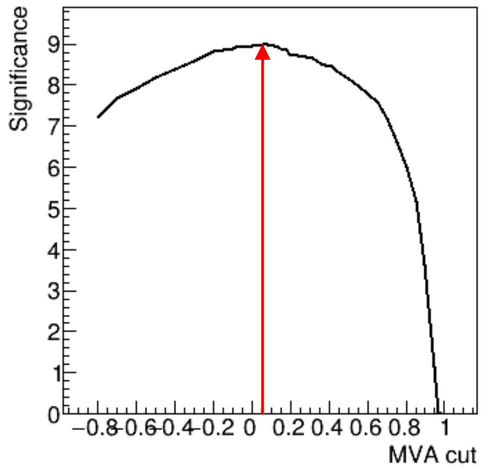
BDTG cut efficiency & optimal significance



signal



background



significance

$= S/\sqrt{S+B}$

Optimal significance obtained for the semi-leptonic channel.

CP observables

An observable sensitive to CP violation must be odd under CP transformation. There are couple of variables that we can measure to investigate the CP violation [1]:

- Up-down asymmetry
  - → directly test CP violation
- The polarisation asymmetry of the top quark
  - → distinguish between CP even and CP odd Higgs

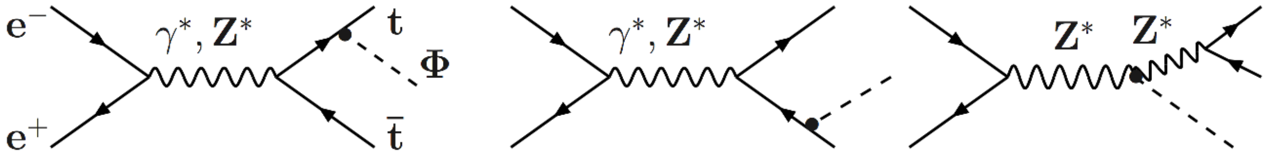
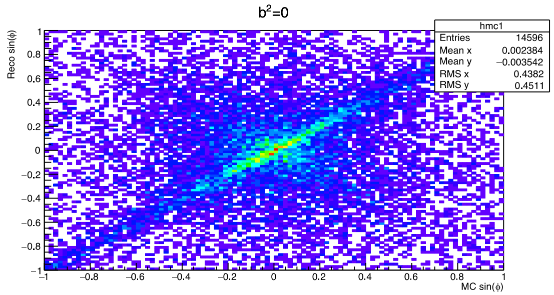


Figure: Feynman diagrams of ttH production.

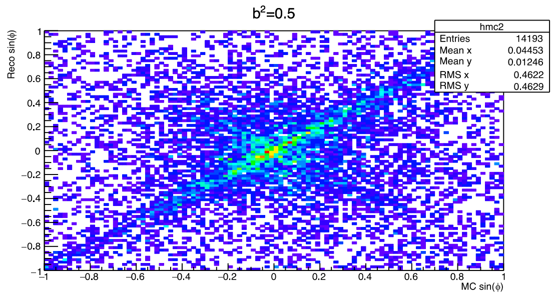
[1] Reference: R.M. Godbole, C. Hangst, M. Mu¨hlleitner, S.D. Rindani and P. Sharma, "Model-independent analysis of Higgs spin and CP properties in the process e^+e^- → ttΦ", arXiv:1103.5404v1 [hep-ph] 28 Mar 2011

MC vs Rec (investigation)

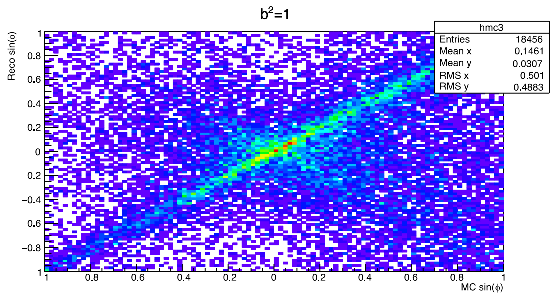
$\sin^2 \phi = 0$



$\sin^2 \phi = 0.5$



$\sin^2 \phi = 1$



Correlation of $\sin \theta_{\phi}$ between MC and Rec:

- A lot of background
- Opposite diagonal line
  - ➢ Mis-identification of top

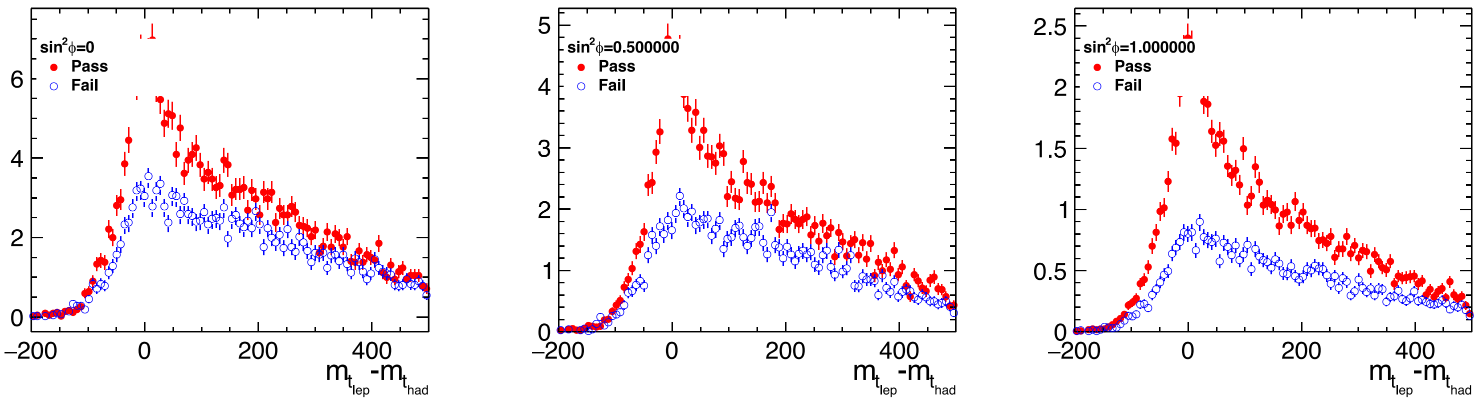
How to cut away mis-identified top?

➢ Choose suitable cuts by looking at events passing or failing:

$$\left|\sin(\theta_{\phi_{rec}}) - \sin(\theta_{\phi_{mc}})\right| < 0.05:$$

$\left|\sin(\theta_{\phi_{rec}}) - \sin(\theta_{\phi_{mc}})\right| < 0.05$

$m_{t_{lep}} - m_{t_{had}}$ from reconstruction:



→ $m_{t_l} - m_{t_q} < 100$
→ jetmatch $\chi^2 < 10$

χ^2 template fitting

1. Errors in each bin are calculated as $\sqrt{N}$
2. Calculate χ^2 for a specific $\sin^2\phi$ value (e.g =0.5),
3. Calculate χ^2 for all other $\sin^2\phi$ values with $\sin^2\phi = 0.5$ as data, and fit the χ^2 curve using $y = a + bx + cx^2$. Obtain the minimum point as the measurement for $\sin^2\phi$,
4. Smear data point by assuming Gaussian distribution and draw/fit the χ^2 curve,
5. Obtain the minimum point from fitted χ^2 curve and fill a $\sin^2\phi$ histogram. Fit the histogram to obtain mean and standard deviation.
6. Repeat procedure 1-5 for other $\sin^2\phi$ values.

$\sin(\theta_\phi)$ calculation

Top/anti-top identification (semi-leptonic):

1. Find the charge of the identified lepton ($e^\pm$, $\mu^\pm$, $\tau^\pm$),
2. If charge<0, the leptonic reconstructed $t/\bar{t}(blnu)$ is a top and $t/\bar{t}(bqq)$ is antitop, vice versa.

Calculation procedure:

1. Obtain the 4-momentum of the reconstructed top and antitop in their rest frames,
2. Assume electron 4-momentum $p_{e^-} = (0,0,7000,7000)$,
3. Boost e^-, t and $\bar{t}$ to $t\bar{t}\Phi$ rest frame,
4. Calculate the vector of electron-top plane,
5. Calculate $\sin\theta_\phi$.

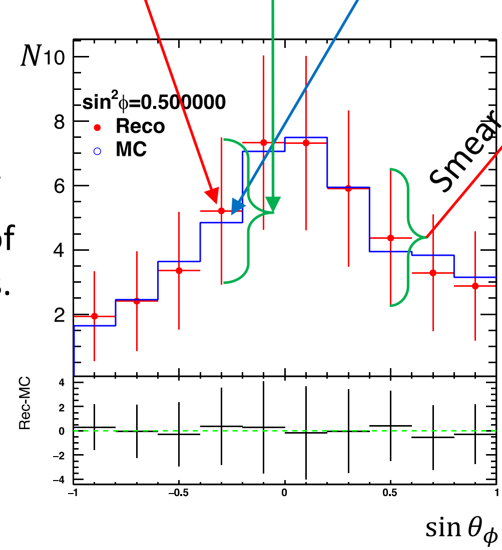
MC: Follows same calculation procedure as above, but use top, anti-top and electron 4-momentum from generator level.

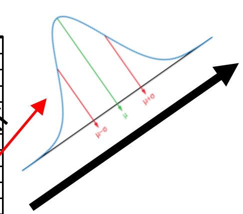
χ^2 template fitting

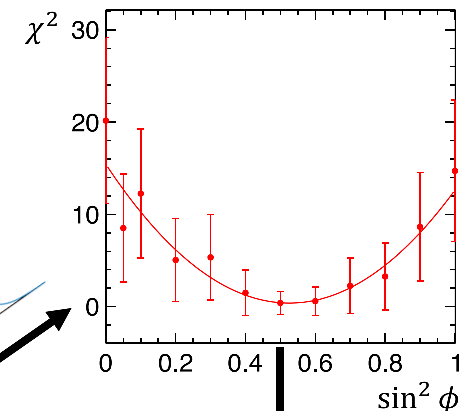
Calculate χ^2 for a specific $\sin^2\phi$ value (e.g =0.5)

$$\chi^2_n(\sin^2\phi = 0.5) = \sum_{i=1}^{nbins}\left(\frac{O_{data(\sin^2\phi=0.5)} - O_{MC(n)}}{\sigma_{data}}\right)^2$$

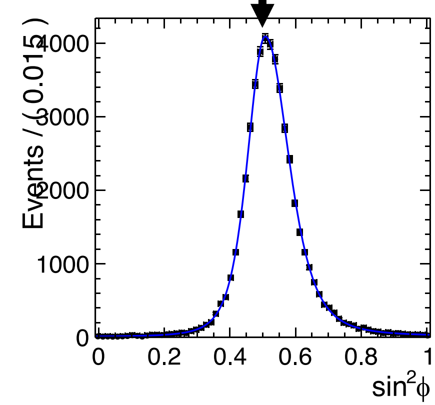
- n is the different $\sin^2\phi$ samples.
- $O_{MC(n)}$ is the number of events in the same bin of different $\sin^2\phi$ samples.







Find minimum and fill Histogram

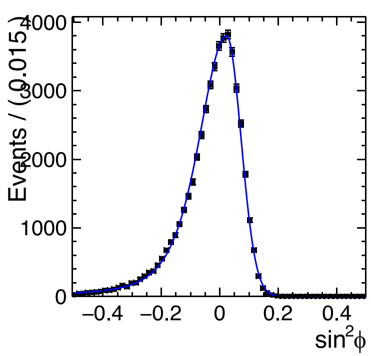


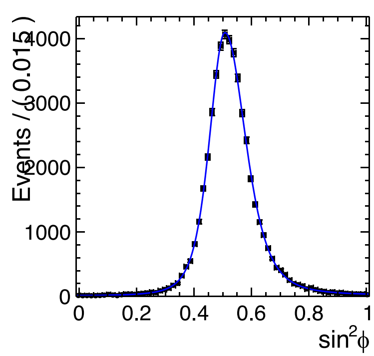
Error estimation

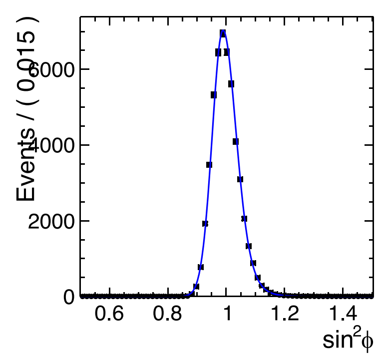
Fitting function:

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

$\sin^2\phi: 0-0.1$	$\sin^2\phi: 0.2-0.8$	$\sin^2\phi: 0.9-1$
$\Delta\sin^2\phi = \sigma_R$	$\Delta\sin^2\phi = \frac{FWHM}{2\sqrt{2\ln 2}}$	$\Delta\sin^2\phi = \sigma_L$







The top polarisation asymmetry

The angular distribution in the decay $t \to bW \to blv$ is not affected by any non-standard effects in the decay vertex, so it is a another observable in probing the Higgs CP properties.

The polarisation asymmetry is given by

$$P_t = \frac{N(t_L) - N(t_R)}{N(t_L) + N(t_R)}$$

Where $t_{L,R}$ denotes a left/right-handed top.

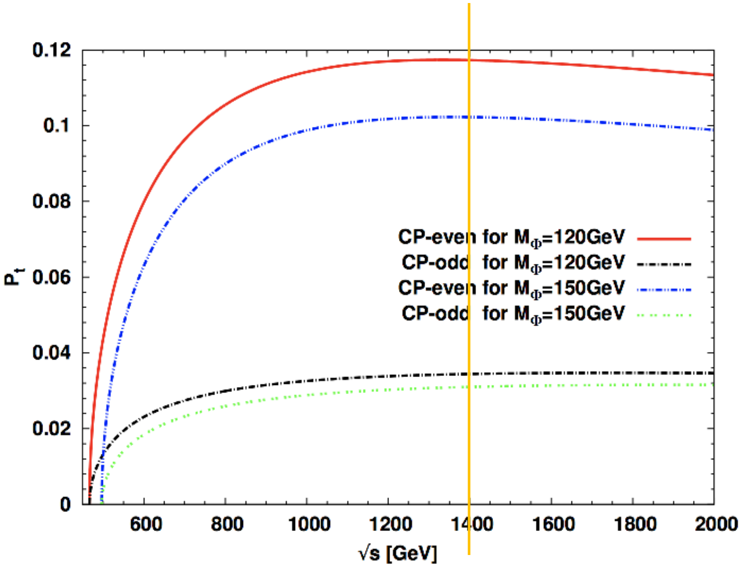


Figure : The top polarisation asymmetry for various Higgs models with unpolarised $e^{\pm}$ beams [1].