Update on the $t\bar{t}H$ studies at 1.4 TeV at CLIC

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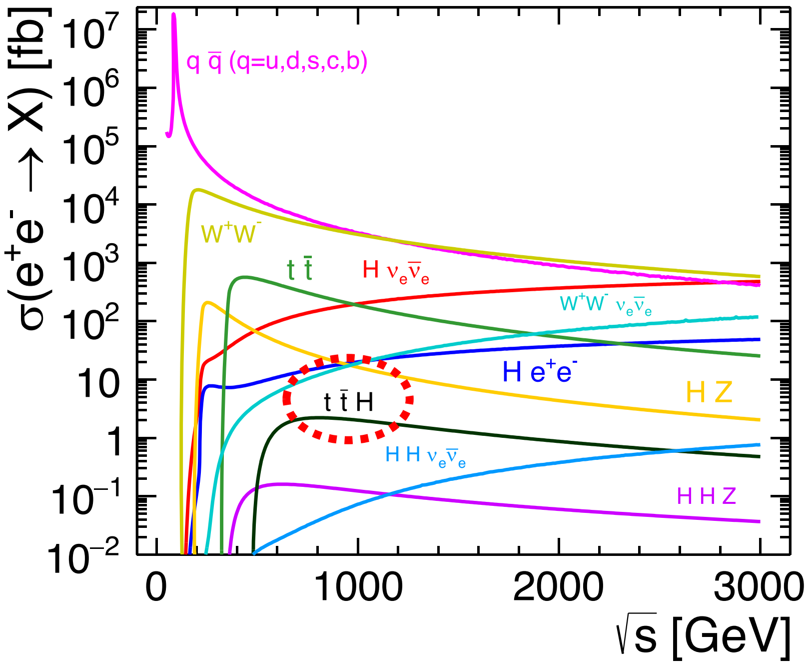
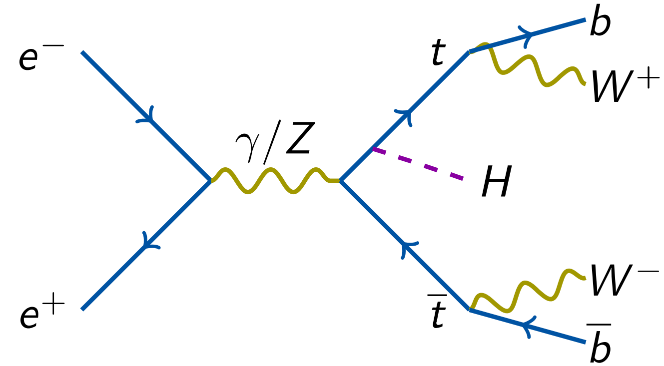
Outline

- The top-Yukawa analysis at 1.4 TeV
  - Backgrounds reduction
  - Results with polarised beam and new luminosity scheme
- CP properties 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

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





Advantages:

1. Top quark (heaviest fermion) ⇒ strongest Yukawa coupling
2. The ttH process is accessible in electron-positron collisions with at least 500 GeV centre-of-mass energy.
3. Probe of the CP properties in the ttH process

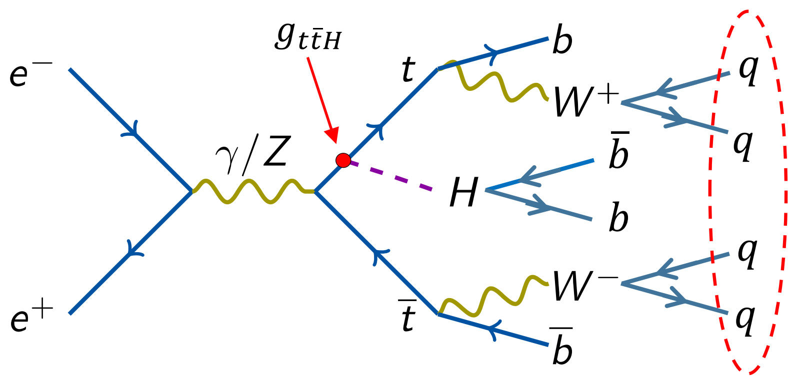
Disadvantages:

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

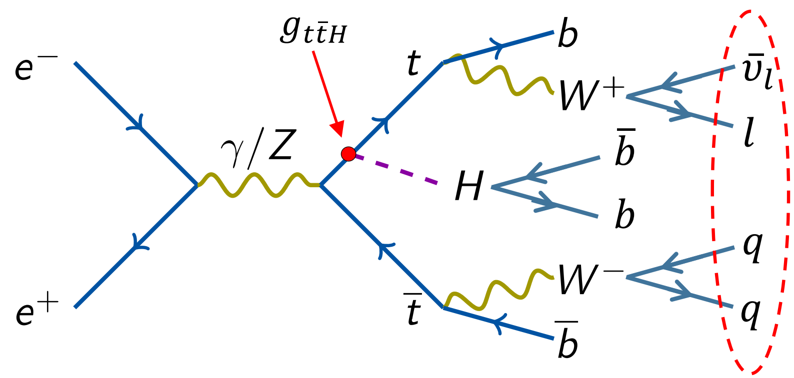
Analysis Strategy

$e^+ + e^- \rightarrow t\bar{t}H$, $H \rightarrow b\bar{b}$($\approx$ 56%) at 1.4 TeV

Detector model: CLIC_SiD



Hadronic channel: 6 jets

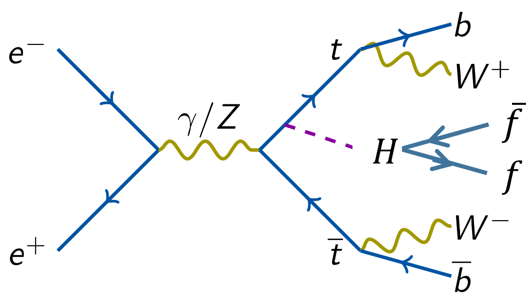


Semi-leptonic channel: 4 jets

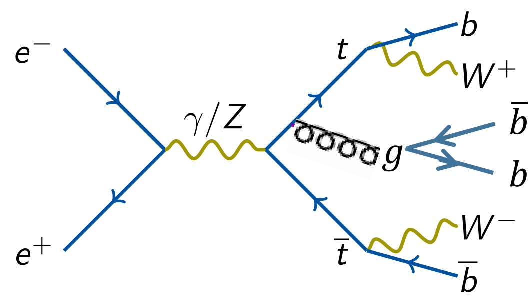
$t\bar{t}H$ decay	BR of $t\bar{t}H(b\bar{b})$	No. Leptons	Channel classification
$t\bar{t} \rightarrow 6jets + H \rightarrow b\bar{b}$	46%	0	**Hadronic**
$t\bar{t} \rightarrow 4jets + 1l + 1\bar{v}_l + H \rightarrow b\bar{b}$	45%	1	**Semi-leptonic**
$t\bar{t} \rightarrow 2jets + 2l + 2\bar{v}_l + H \rightarrow b\bar{b}$	9%	>1	Not included

*Previous analysis described in CLICdp-Note-2014-001

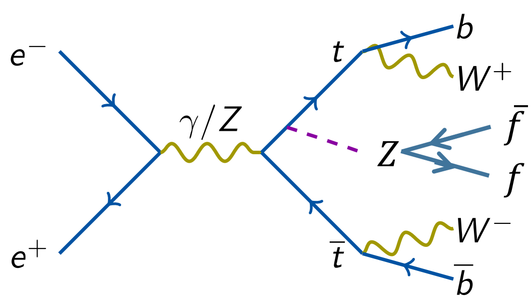
Backgrounds



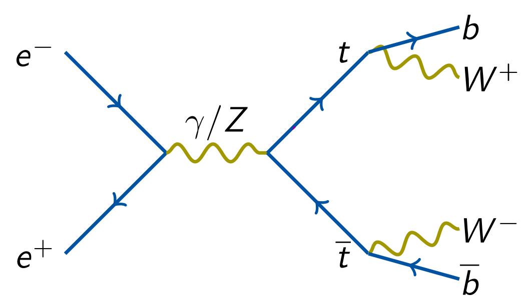
Other $t\bar{t}H$ decays



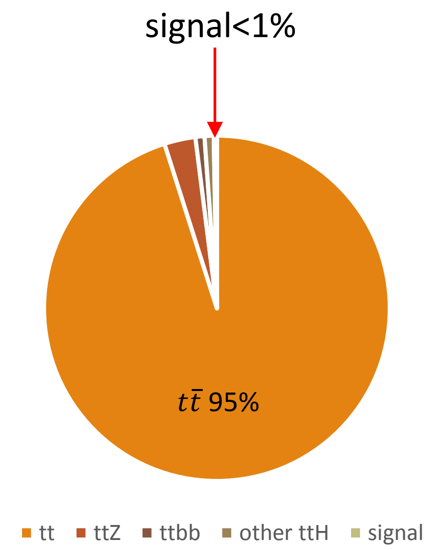
$t\bar{t}b\bar{b}$



$t\bar{t}Z$



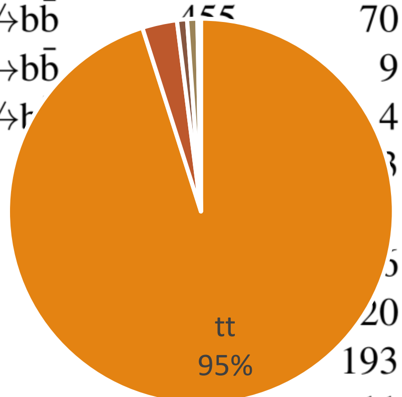
$t\bar{t}$

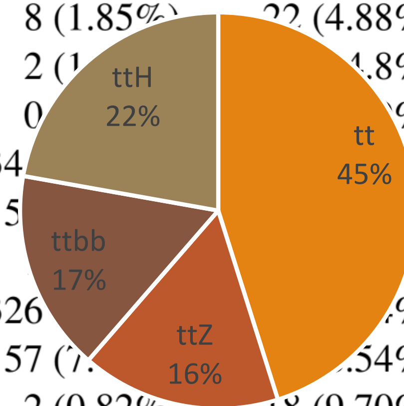


Generator: $t\bar{t}$ (Pythia), others (Physsim) all unpolarised

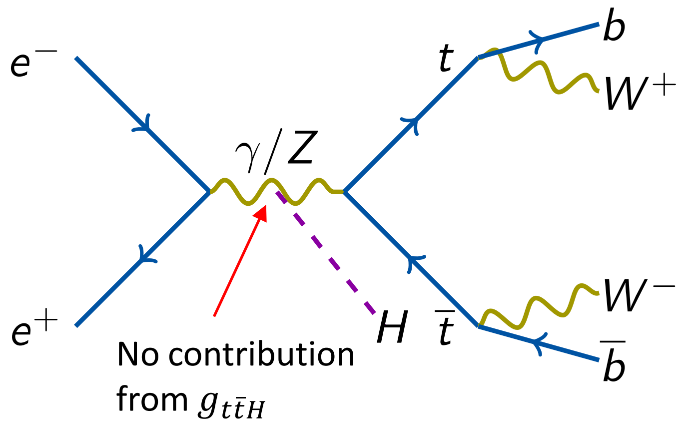
Selection efficiency after BDTG cut

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, $H\not\to b\bar{b}$	[illegible]	70 (15.4%)	237 (52.2%)	8 (1.85%)	22 (4.88%)
$t\bar{t}H$, 2 jets, $H\to b\bar{b}$	[illegible]	9 (6.18%)	53 (35.6%)	[illegible]	[illegible]
$t\bar{t}H$, 2 jets, $H\not\to b\bar{b}$	[illegible]	4 (3.90%)	27 (25.0%)	[illegible]	[illegible]
$t\bar{t}Z$, 6 jets	[illegible]	[illegible] (75.0%)	445 (15.7%)	[illegible]	[illegible]
$t\bar{t}Z$, 4 jets	[illegible]	[illegible] (20.9%)	[illegible]	[illegible]	[illegible]
$t\bar{t}Z$, 2 jets	[illegible]	[illegible] (5.49%)	214 (32.5%)	[illegible]	[illegible]
$t\bar{t}b\bar{b}$, 6 jets	[illegible]	[illegible] (87.5%)	95 (11.6%)	[illegible]	[illegible]
$t\bar{t}b\bar{b}$, 4 jets	[illegible]	193 (24.3%)	552 (69.5%)	[illegible]	[illegible]
$t\bar{t}b\bar{b}$, 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]):

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

	Significance	LO $\Delta\sigma/\sigma$	NLO $\Delta\sigma/\sigma$	NLO $\Delta g_{ttH}/g_{ttH}$	Polarised beam (-80,0)	*L = 2.5ab^{-1} + Polarisation
Hadronic	10.44σ	7.3%	7.5%	**3.8%**	3.3%	2.7%
Semi-leptonic	9.00σ					

[1] JHEP 1612 (2016) 075

* New scheme

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

Parametrisation of CP mixing in the ttH coupling:

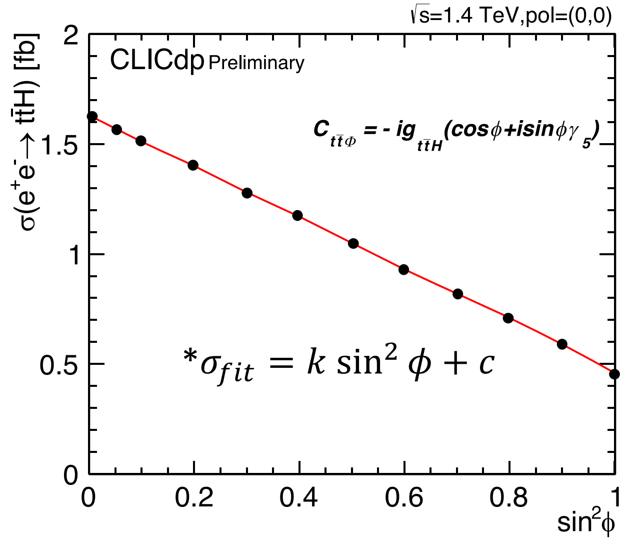
- $C_{t\bar{t}\Phi} = -ig_{t\bar{t}H}(a + ib\gamma_5)$
- SM: a = 1, b = 0 ; pure CP-odd: a = 0, b ≠ 0.

assume $a^2 + b^2 = 1$ with $a = \cos(\phi)$ and b= $\sin(\phi)$ where $\boldsymbol{\phi}$ is the mixing angle.

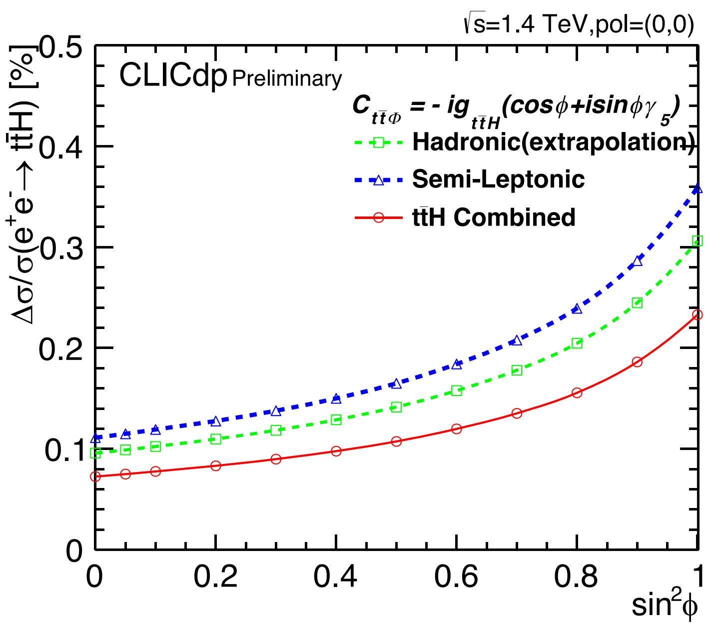
$t\bar{t}H$ cross section (thanks for Philipp Roloff for generating the samples):

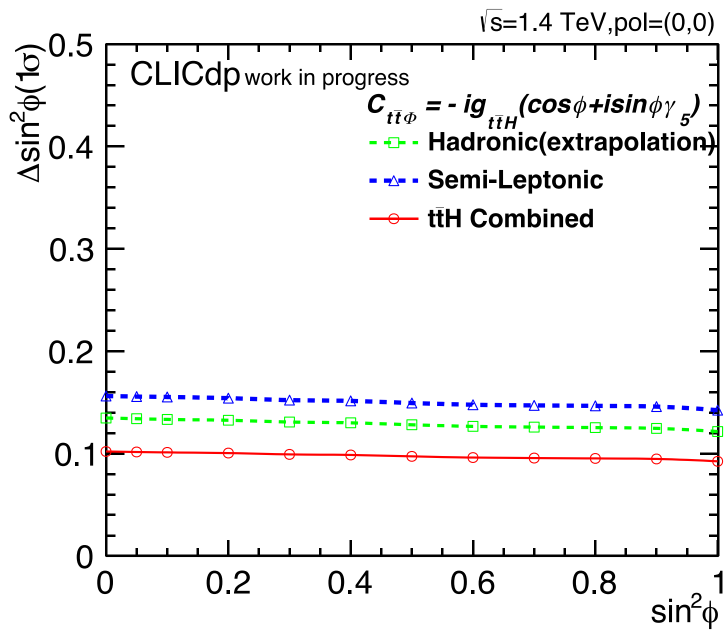
- Generator: Physsim
- $\sqrt{s}$ = 1.4 TeV
- Polarisation = (0,0)
- ISR included
- CLIC luminosity spectrum
- 12 samples produced

* Cross section generally decreases as more CP odd Higgs boson presented (with linear fit).



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 to result from both channels

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.

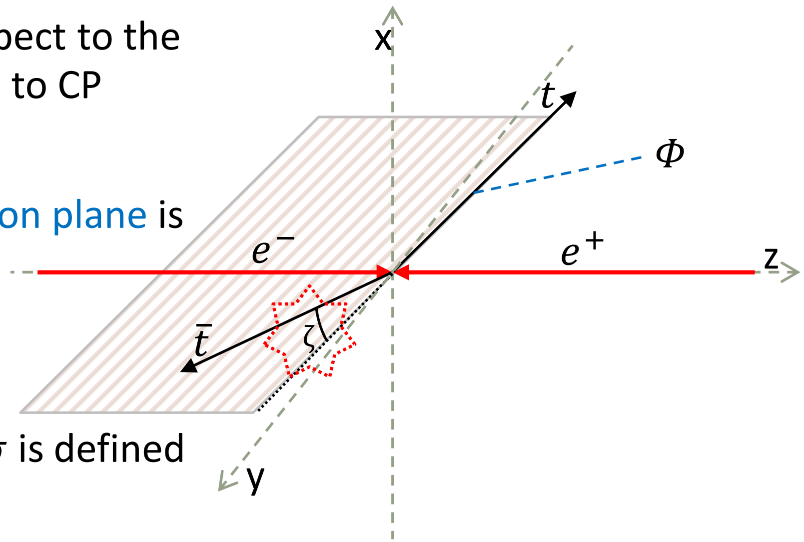
The angle ζ between the antitop and the top-electron plane is given by

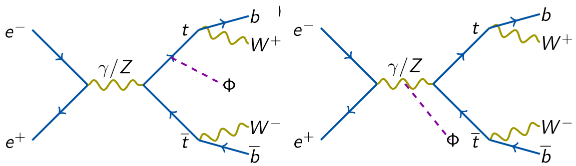
$$\sin(\zeta) = \frac{\vec{p}_{\bar{t}}(\vec{q}_{e^-} \times \vec{p}_t)}{|\vec{p}_{\bar{t}}||(\vec{q}_{e^-} \times \vec{p}_t)|}$$

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

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

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





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

[1] arXiv:1103.5404v1

$\sin(\zeta)$ 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 $(bl\nu)$ is a top and $(bq\bar{q})$ 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 $\sin\zeta$.

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

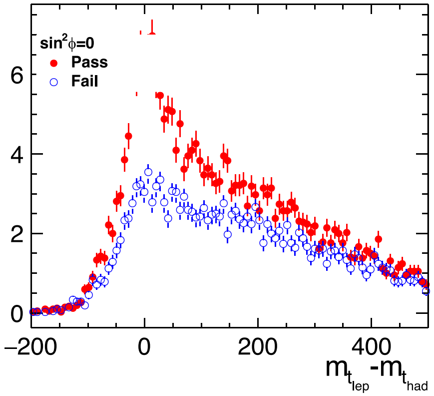
Cuts investigation

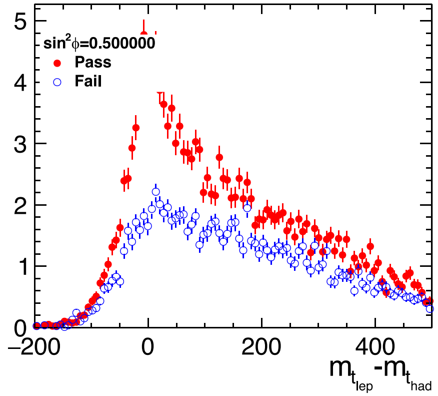
How to cut away mis-identified top?

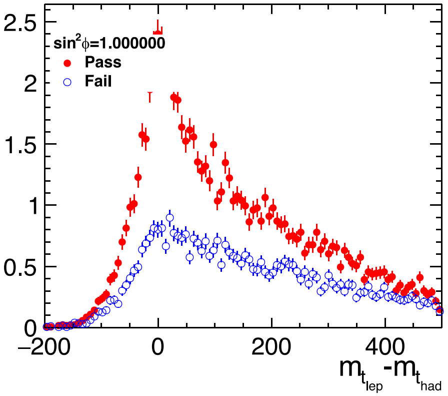
- Choose suitable cuts by looking at events passing or failing (sinζ in range -1 to 1):

$$|\sin(\zeta_{rec}) - \sin(\zeta_{mc})| < 0.05:$$

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







Tight cuts:

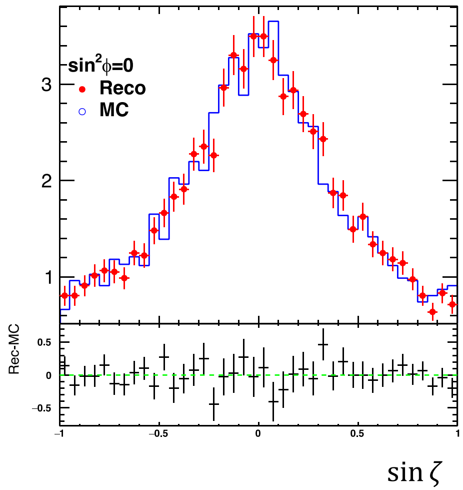
→ $m_{t_l} - m_{t_q} < 100$

→ jetmatch $\chi^2 < 10$ (χ^2 used to match jets into *t*, *W* and *H*)

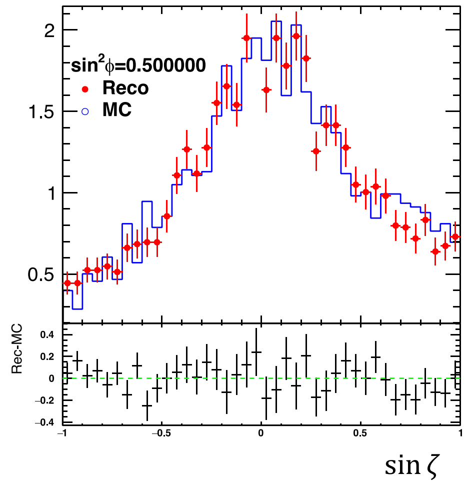
→ remove hadronic taus

$\sin\zeta$ and A_ϕ with tight cuts

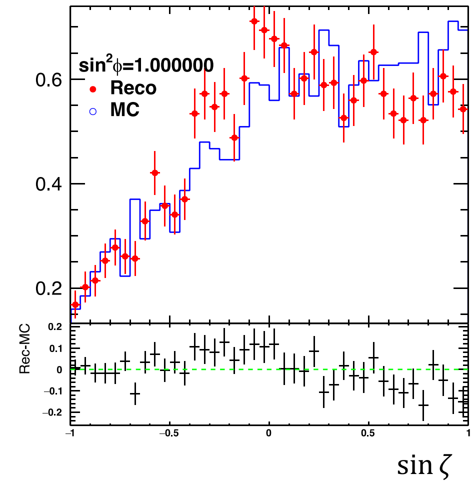
Pure CP-even



50% CP-even & CP-odd

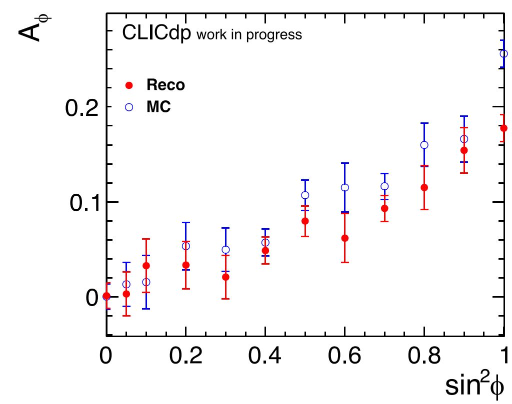


Pure CP-odd



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

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

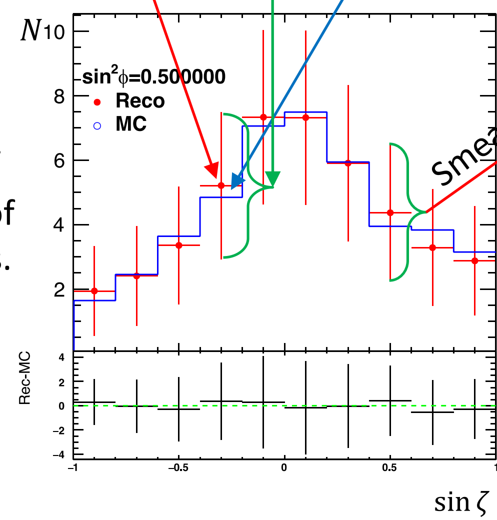


χ^2 template fitting

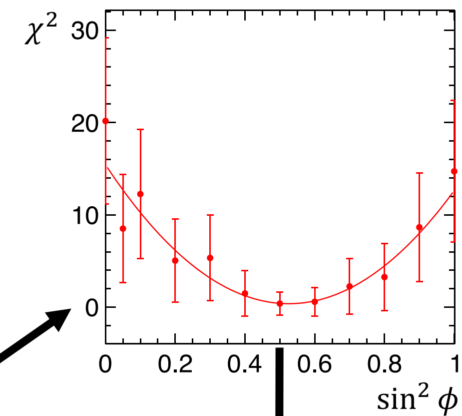
Calculate χ^2 for a specific $\sin^2\phi$ value (e.g =0.5)

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

- 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.

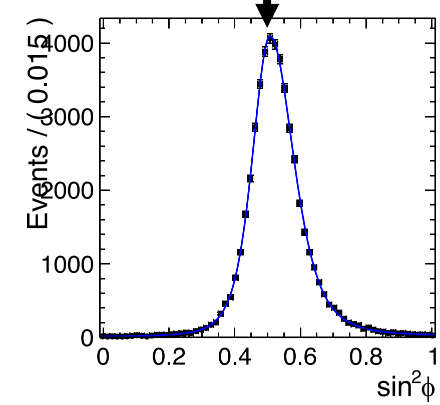


Smear as Poisson



X times

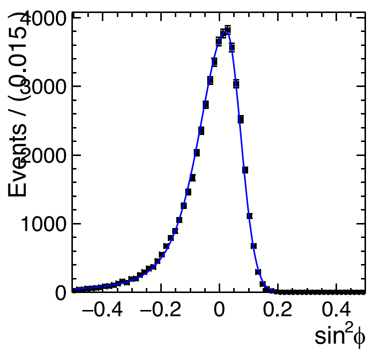
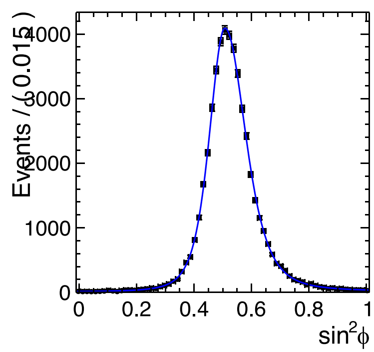
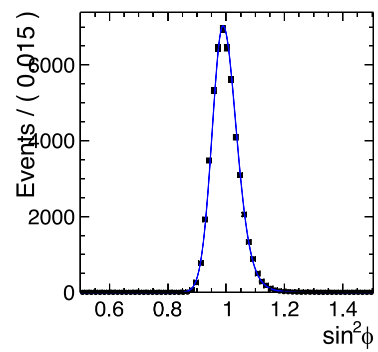
Find minimum and fill Histogram



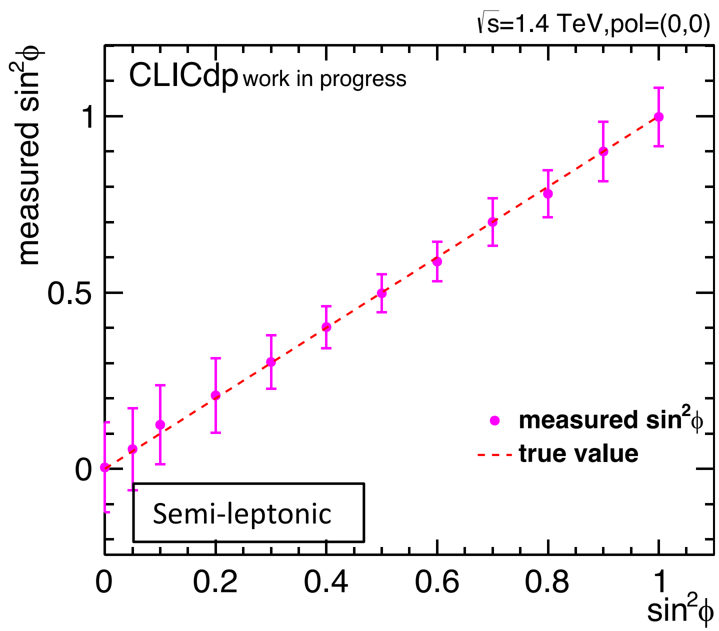
Error estimation

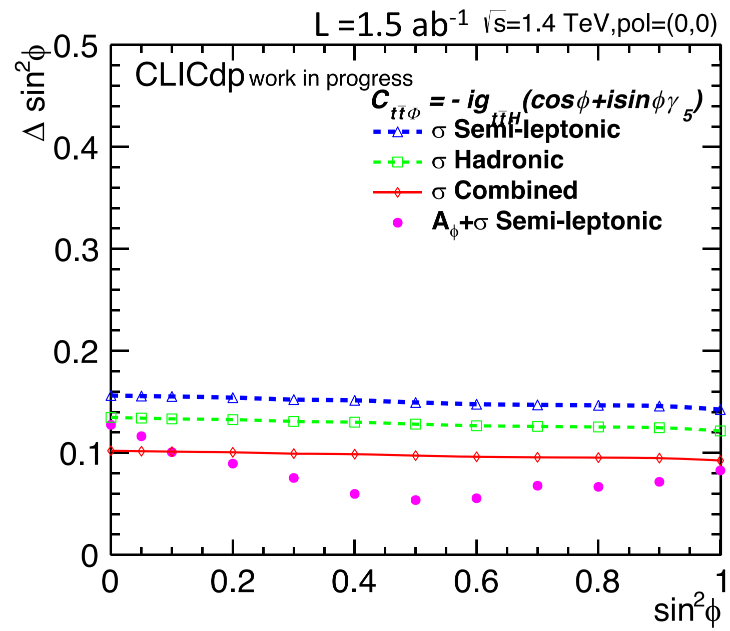
Fitting function:

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

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

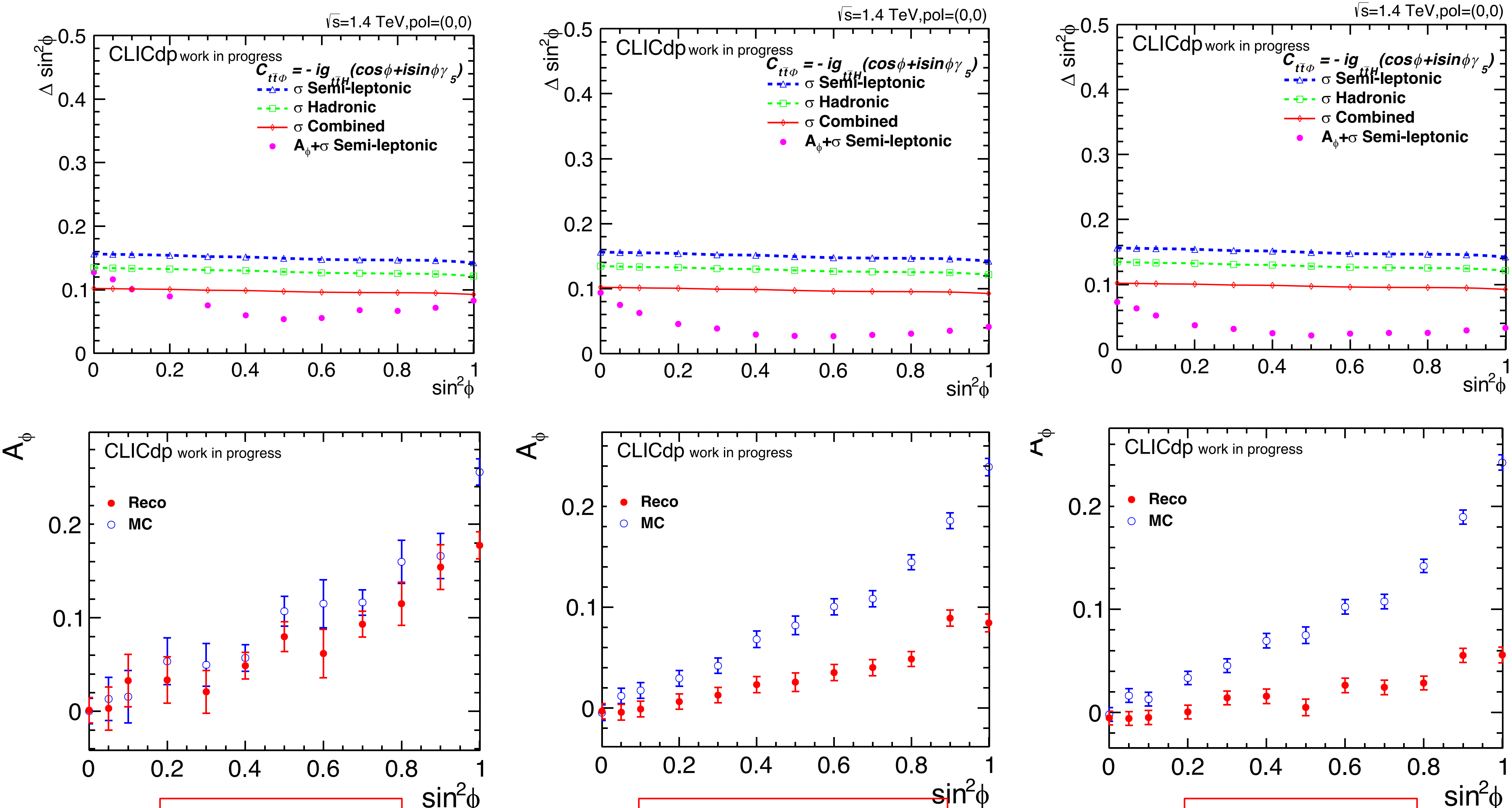
Preliminary results (tight cuts)





- Determine $\sin^2\phi$ using up-down asymmetry via χ^2 template fit.
- Then the errors can be extracted to measure sensitivity of CP mixing.
- CP mixing sensitivity improved using up-down asymmetry compared with cross-section alone (in semi-leptonic channel).

Comparison of results by loosing cuts

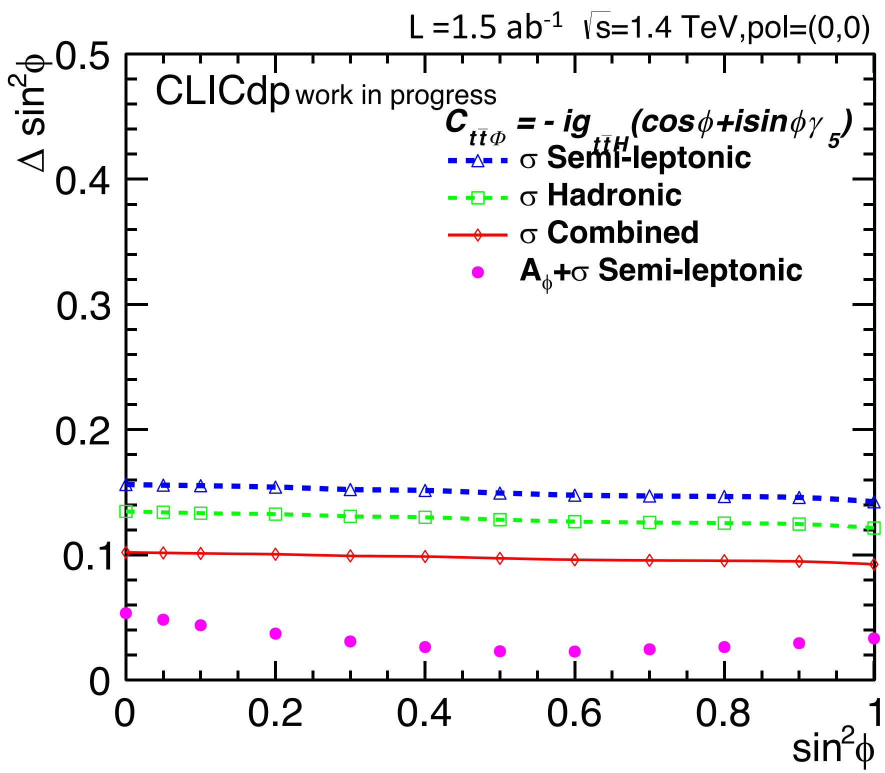


With tight cuts

MVA + remove taus

MVA cuts only

Preliminary results (MVA cuts only)



Summary

- This analysis has found $\frac{\Delta g_{t\bar{t}H}}{g_{t\bar{t}H}} = 3.8\%$ (unpolarised), 3.3% (polarised) with integrated luminosity of 1.5 ab^{-1} at $\sqrt{s}$ =1.4 TeV at CLIC,
  - Previous CLIC analysis found 4.3%, CLICdp-Note-2014-001
  - ILC at 1 TeV found 4.5%, arXiv:1409.7157
  - With luminosity of 2.5ab^{-1} and polarised beam, $\frac{\Delta g_{t\bar{t}H}}{g_{t\bar{t}H}} = 2.7\%$
- Updated NLO QCD prediction for translating from cross section to top-Yukawa coupling.
- 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 $\Delta\sin^2(\phi) \approx 0.02\sim0.05$, but the method needs to be consolidated.
- Further observables to increase the CP violation sensitivity will be investigated in the future.

Backup Slides

Leptons

The leptons are searched in two ways:

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

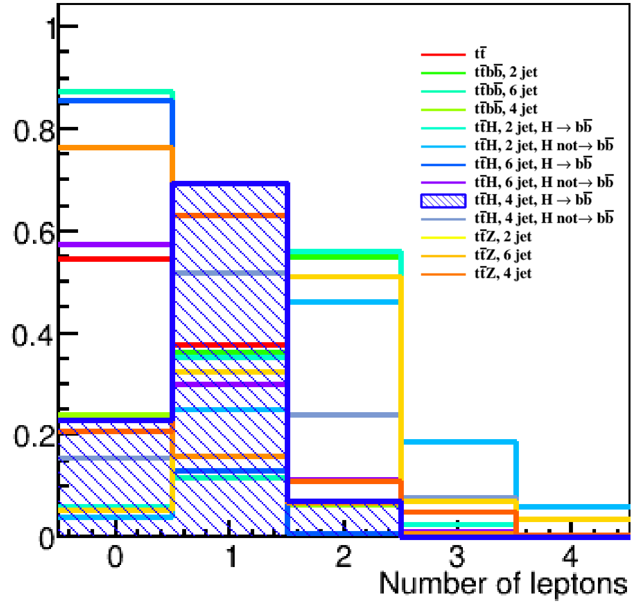
Lepton identification

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:

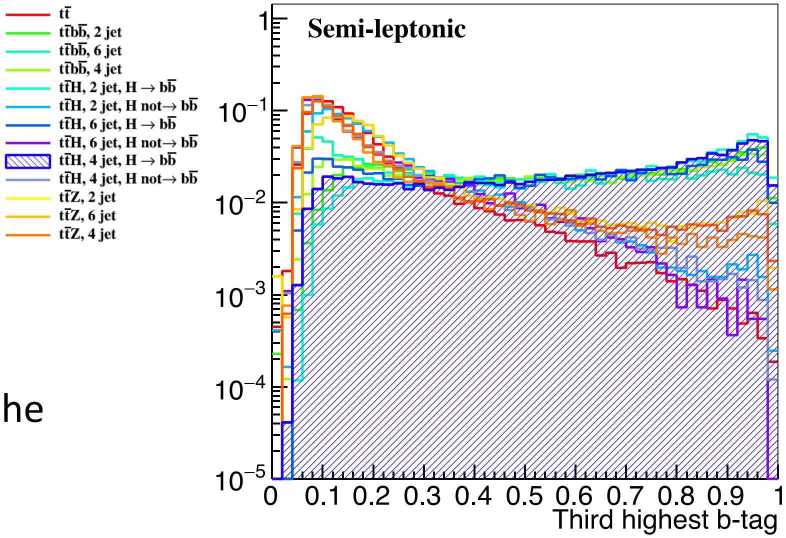
- ➢ Selects Hadronic - 86%, Semi-leptonic - 69%.

Flavour-tagging

LCFIPlus is tuned using $e^+e^- \rightarrow qqqqqq$ 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:

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

	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.

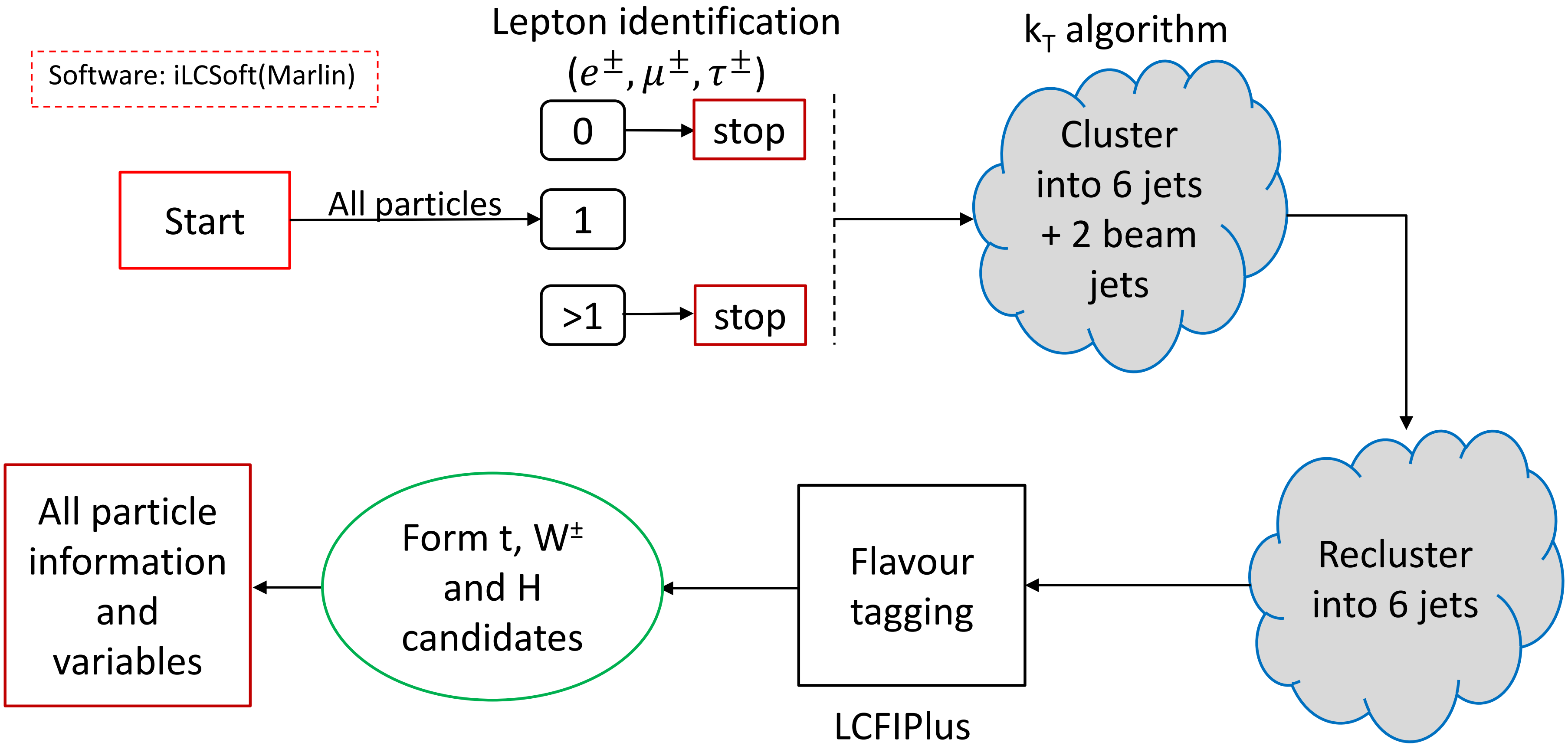
Signal and Background samples

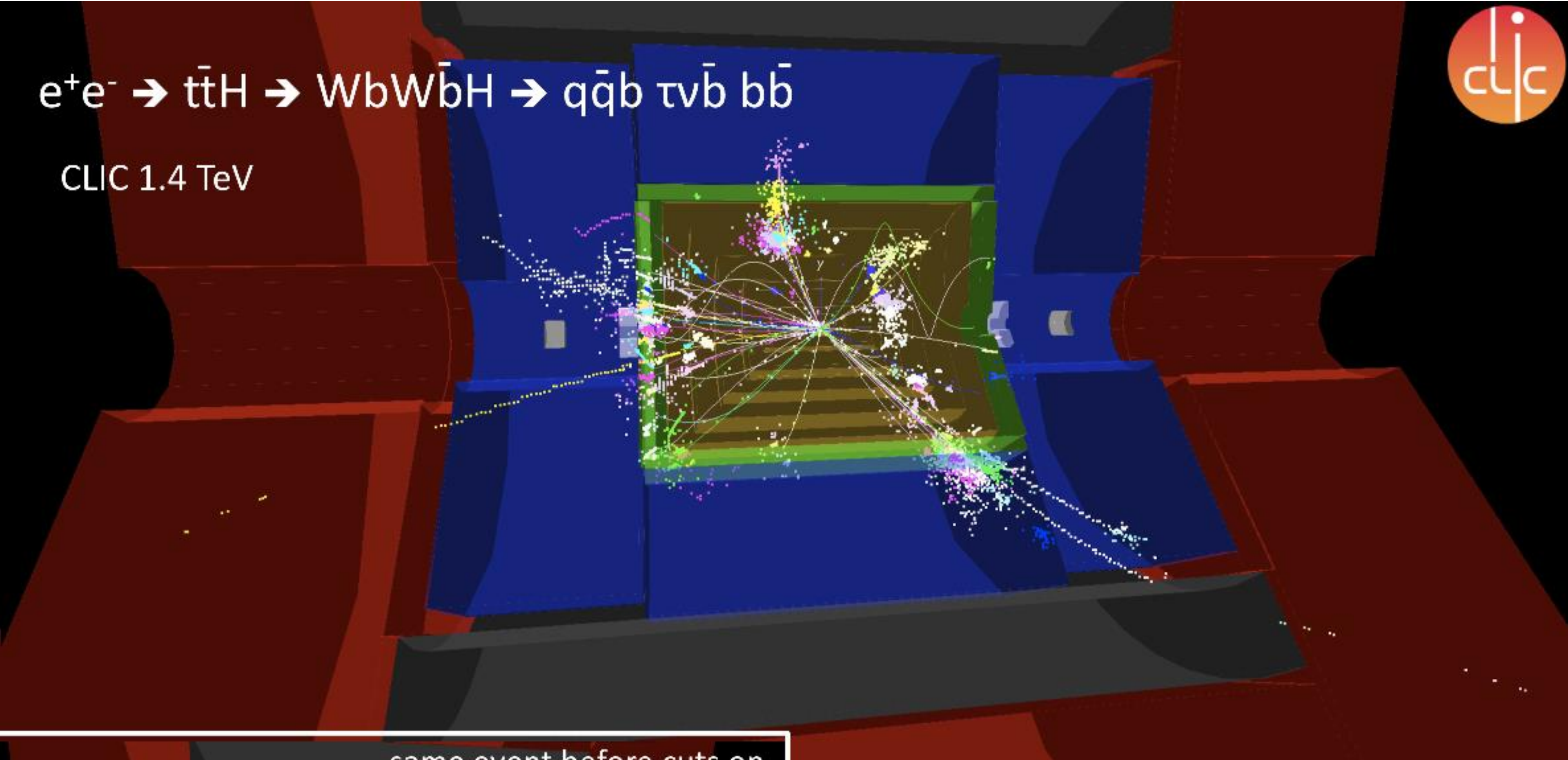
Process	Cross-section (fb)	Generator	Expected no. events
$t\bar{t}H, t\bar{t} \to 6jets, H \to bb$	0.431	Physsim	647
$t\bar{t}H, t\bar{t} \to 4jets, H \to bb$	0.415	Physsim	623
$t\bar{t}H, t\bar{t} \to 6jets, H \nrightarrow bb$	0.315	Physsim	473
$t\bar{t}H, t\bar{t} \to 4jets, H \nrightarrow bb$	0.303	Physsim	455
$t\bar{t}H, t\bar{t} \to 2jets, H \to bb$	0.100	Physsim	150
$t\bar{t}H, t\bar{t} \to 2jets, H \nrightarrow bb$	0.073	Physsim	110
$t\bar{t}Z, t\bar{t} \to 6jets$	1.895	Physsim	2843
$t\bar{t}Z, t\bar{t} \to 4jets$	1.825	Physsim	2738
$t\bar{t}Z, t\bar{t} \to 2jets$	0.439	Physsim	659
$t\bar{t}bb, t\bar{t} \to 6jets$	0.549	Physsim	824
$t\bar{t}bb, t\bar{t} \to 4jets$	0.529	Physsim	794
$t\bar{t}bb, t\bar{t} \to 2jets$	0.127	Physsim	191
$t\bar{t}$	135.8	PYTHIA	203700

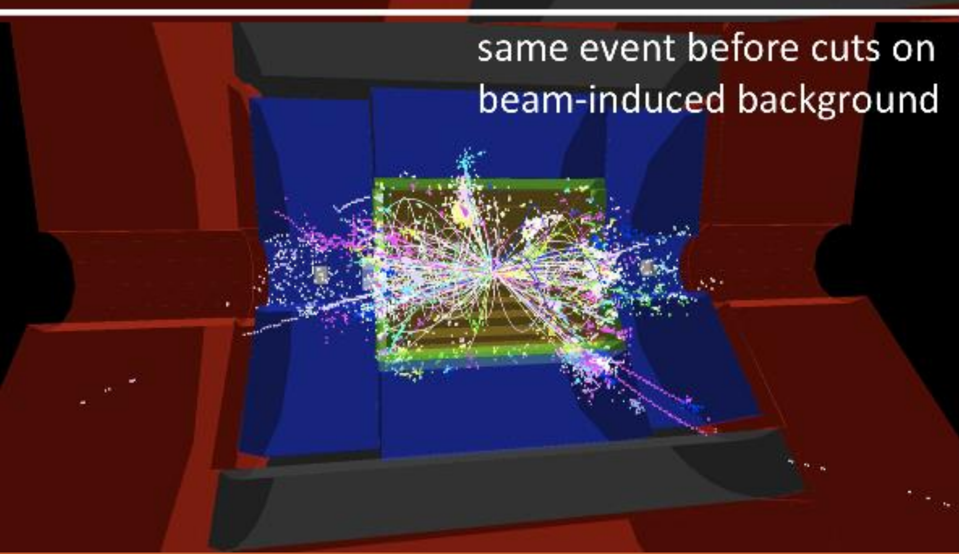
Largest bkg

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

Event reconstruction strategy

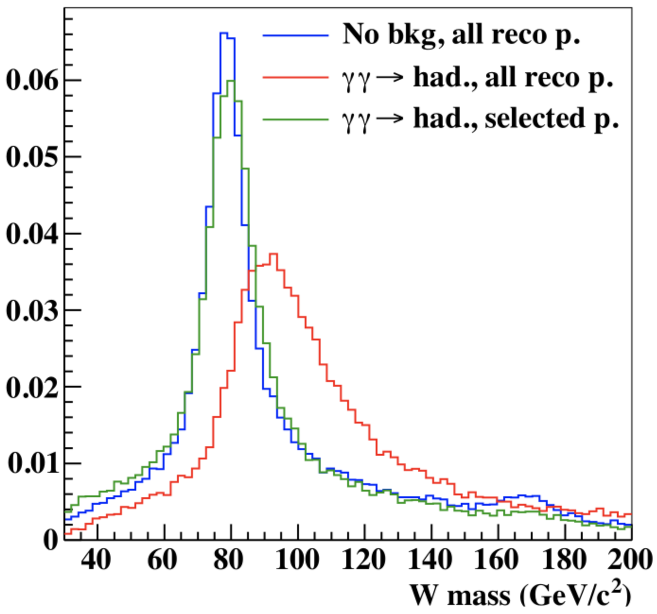






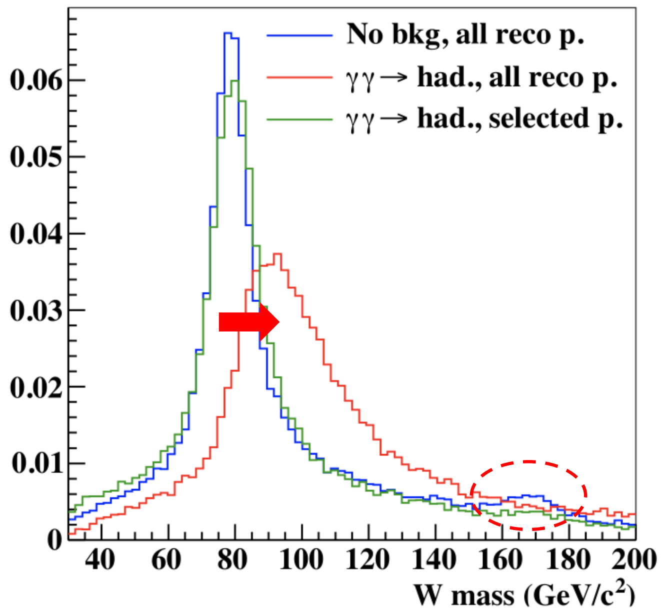
Event display of $e^+ + e^- \rightarrow t\bar{t}H$
Need to apply timing cut and momentum cut to suppress the $\gamma\gamma \rightarrow hadrons$ backgrounds.

$\gamma\gamma \rightarrow hadrons$ backgrounds



At $\sqrt{s} = 1.4$ TeV, ~ 1.3 $\gamma\gamma \rightarrow hadrons$ per bunch-crossing.

$\gamma\gamma \rightarrow hadrons$ backgrounds

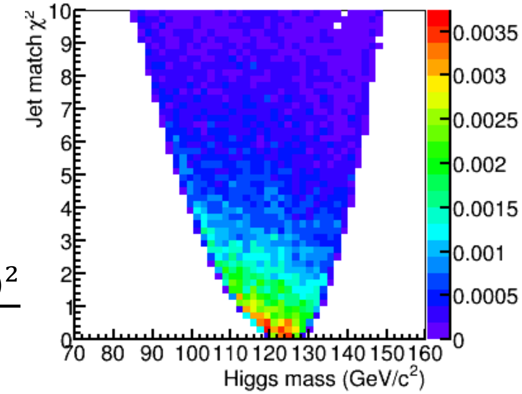


At $\sqrt{s} = 1.4$ TeV, ~ 1.3 $\gamma\gamma \rightarrow hadrons$ per bunch-crossing.

- Tighter background suppression level
- Optimised jet clustering radius

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

Two chi-squared variables are defined to reconstruct the $W^{\pm}$, top and Higgs candidates by combining the jets.

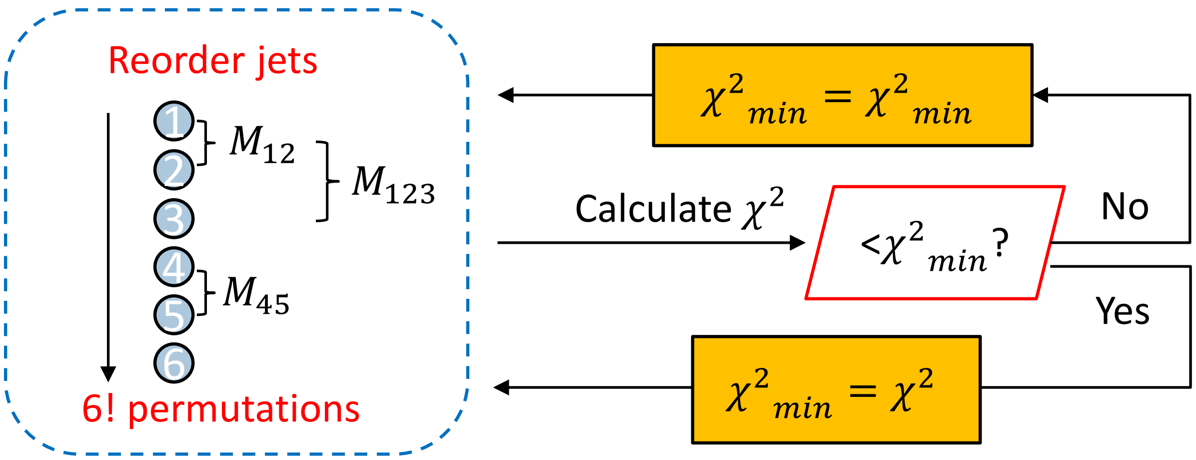


Semi-leptonic:

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

Hadronic:

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



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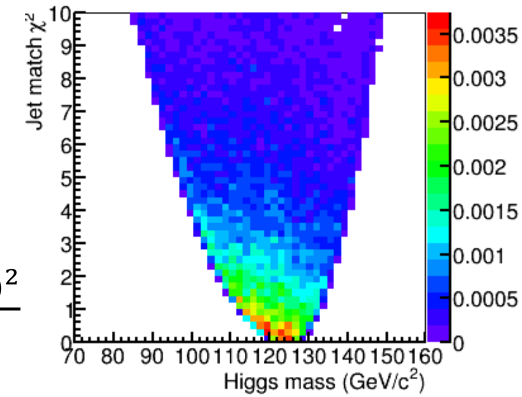

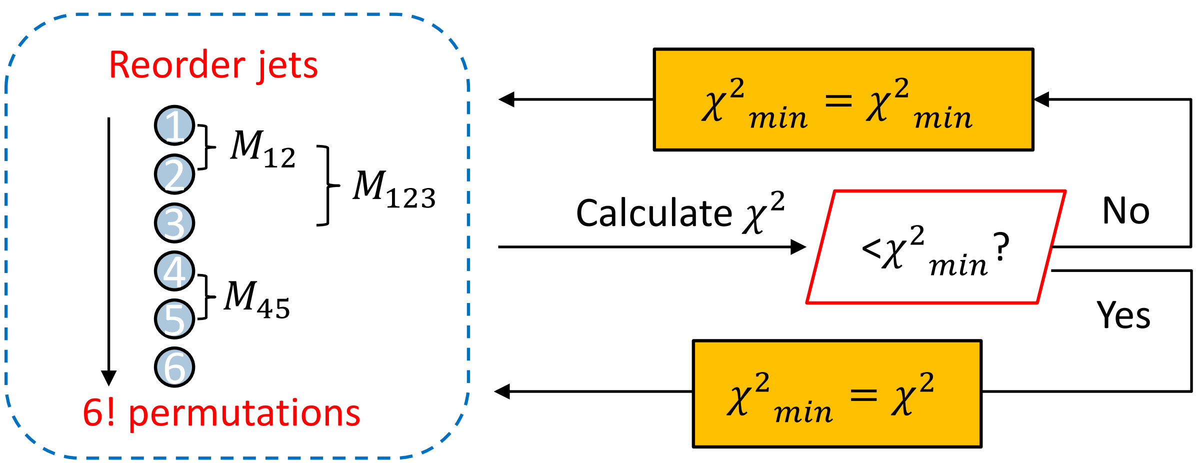

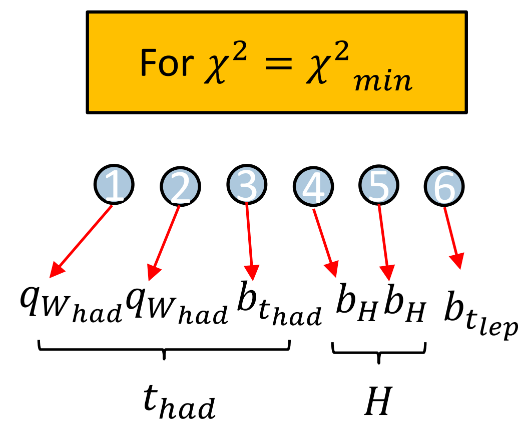

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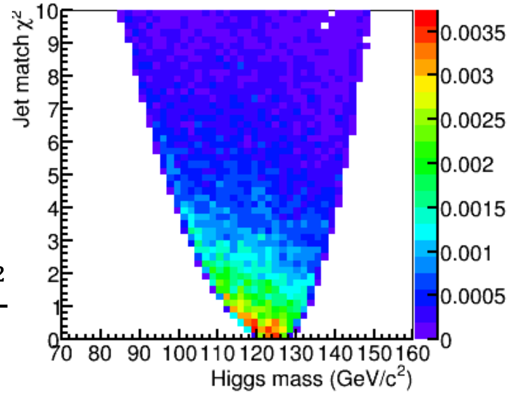
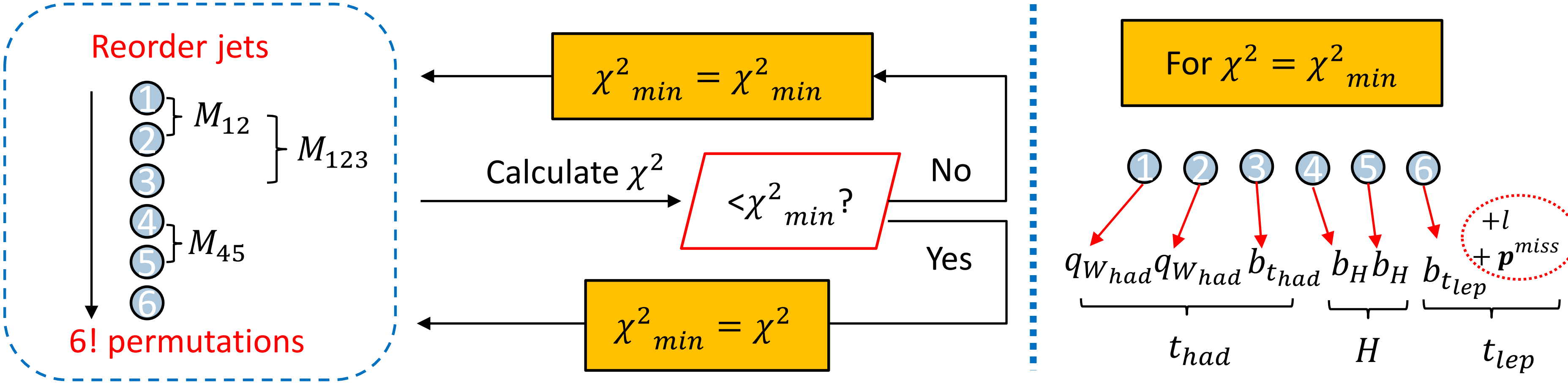
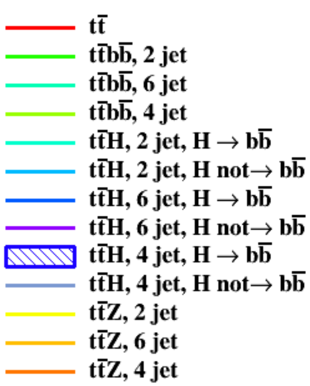
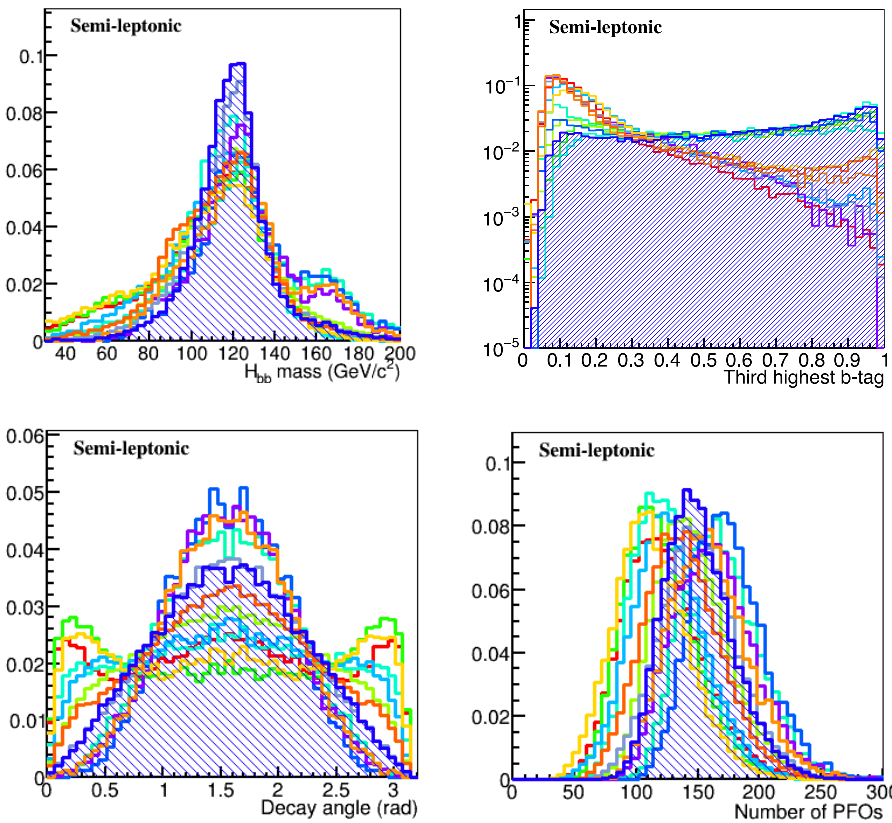




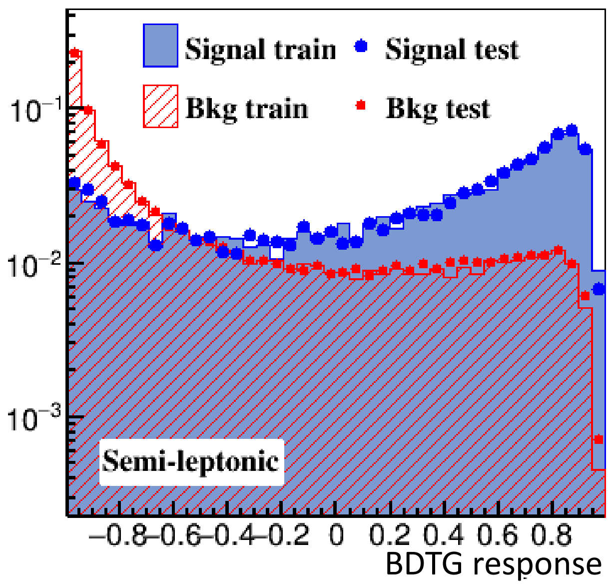
Event selection using TMVA

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

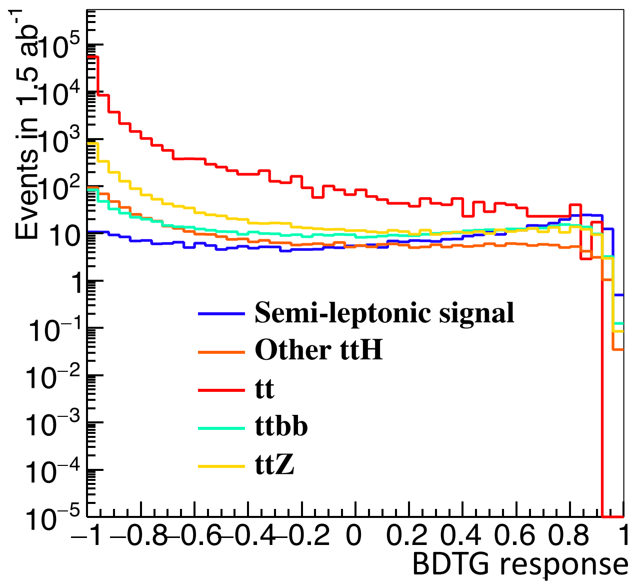




BDTG(gradient) response



Apply BDTG weight

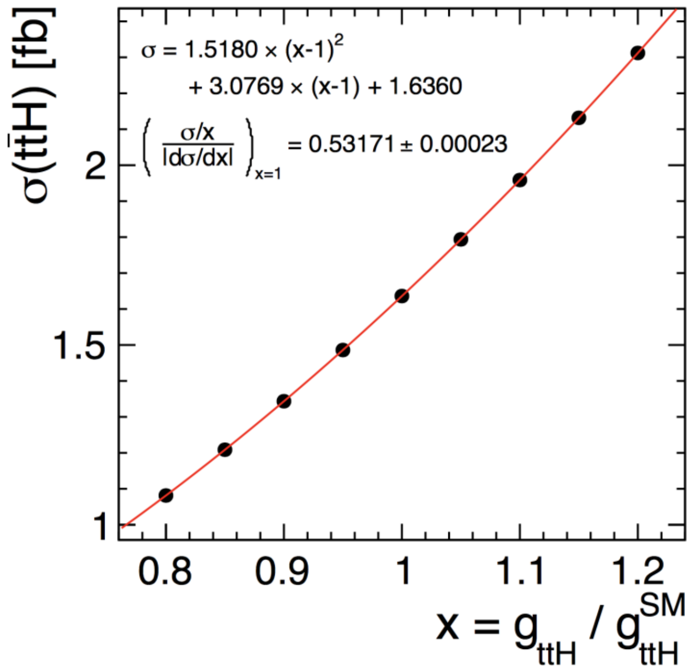


The BDTG response for signal and background samples. (Left): Normalised BDTG response.

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

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

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

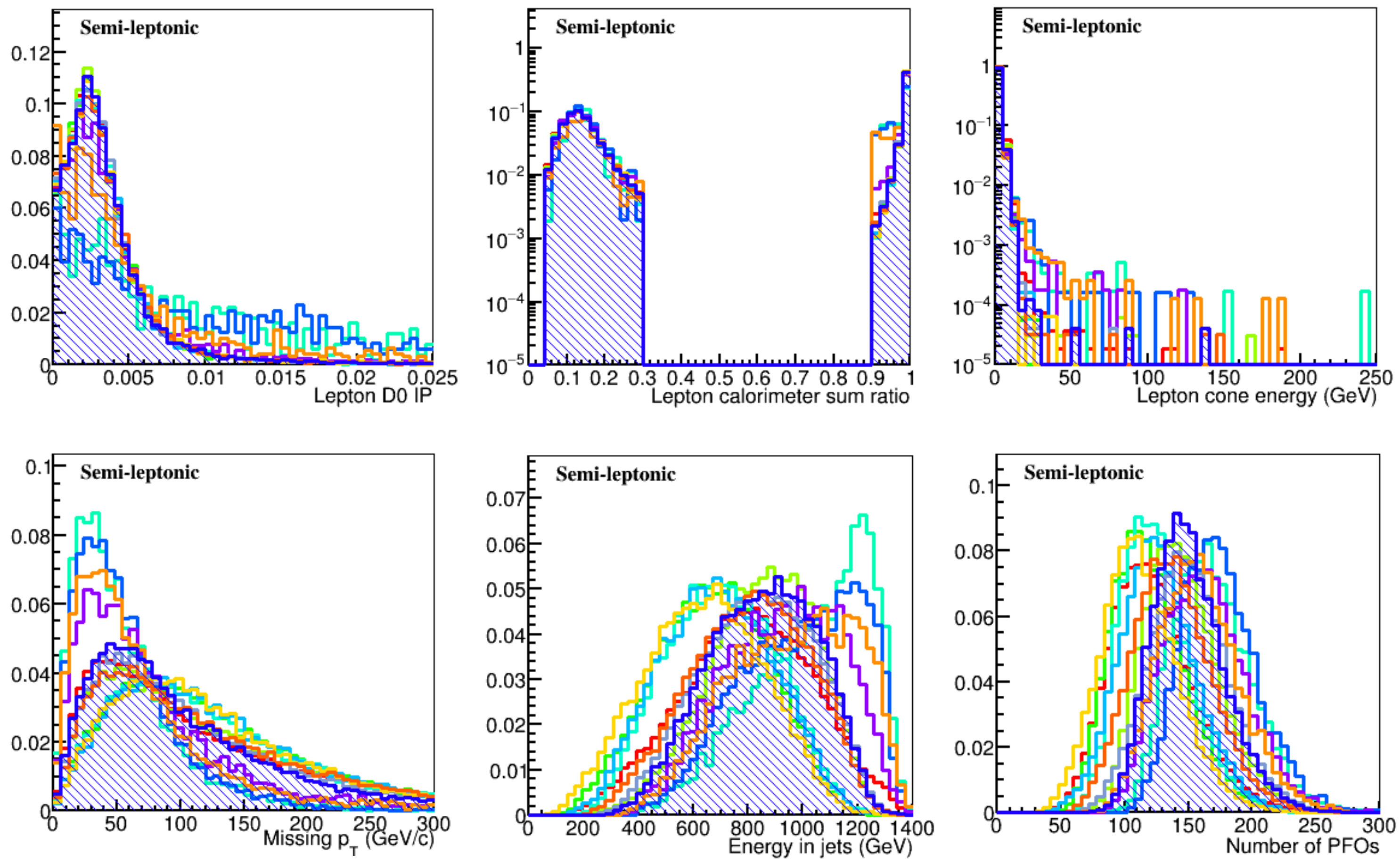
-> 23 variables

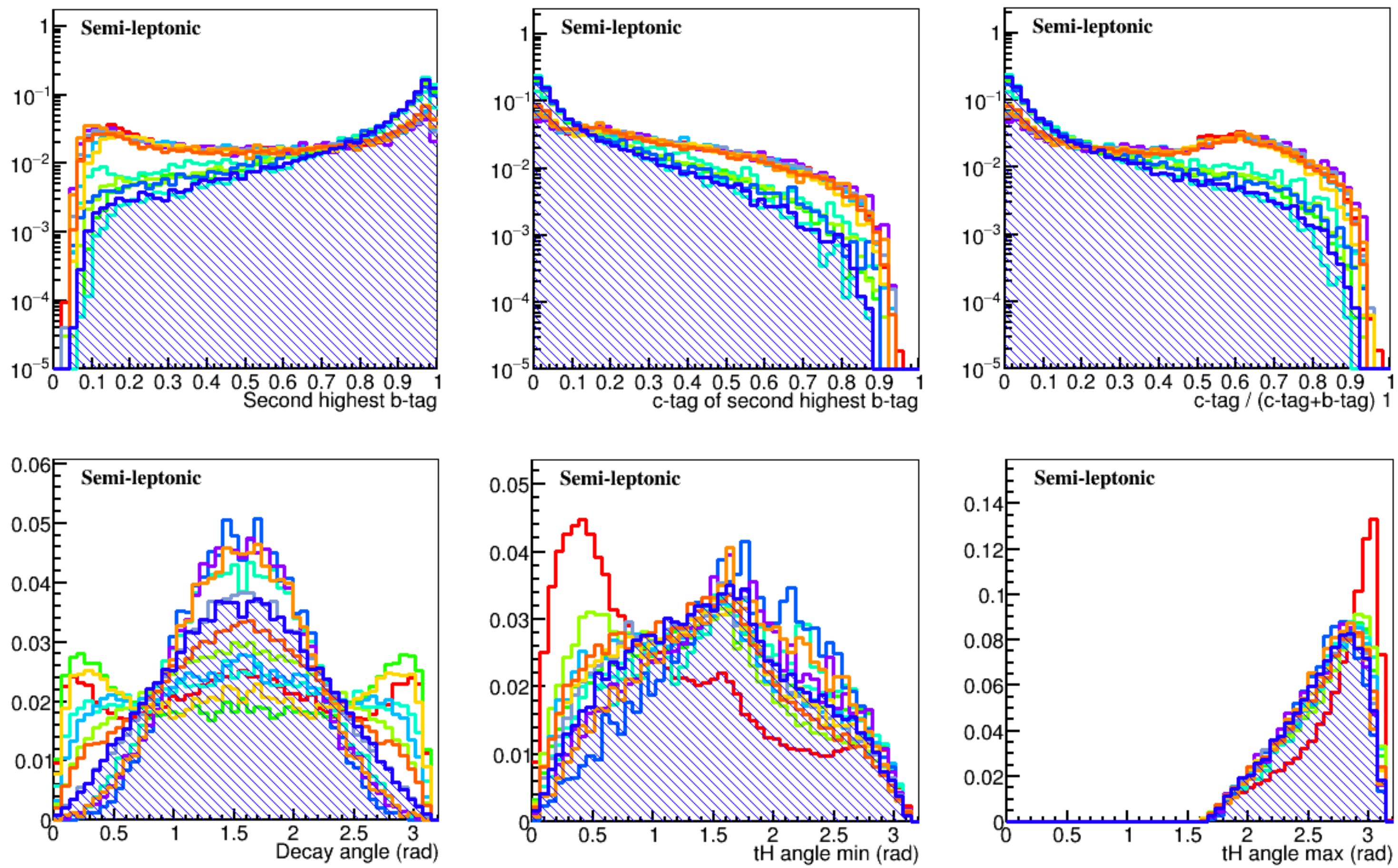
For hadronic:

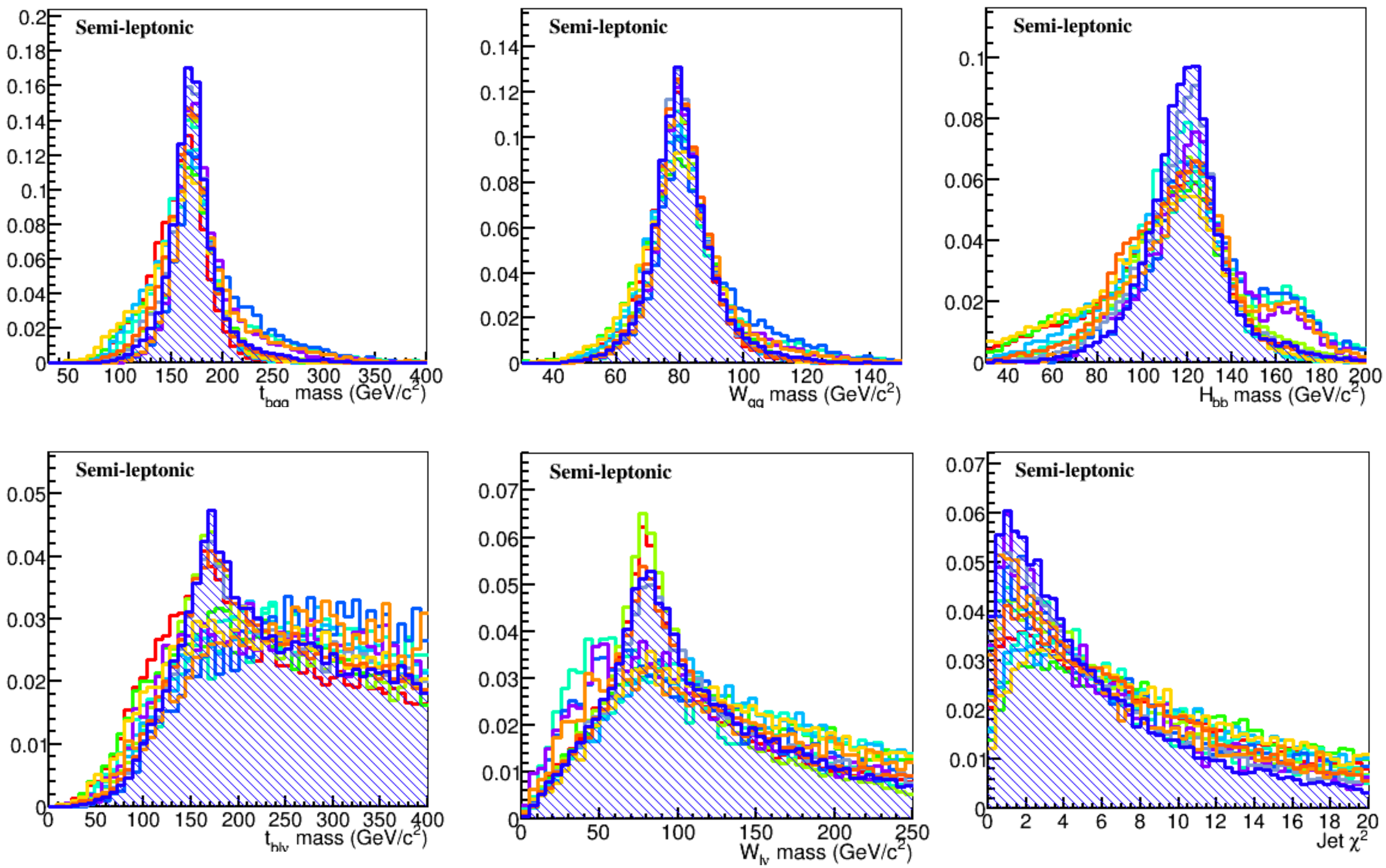
- Energy of the 4 lowest-energy jets
- Cosine of the angle of two closest jets to the beam-axis

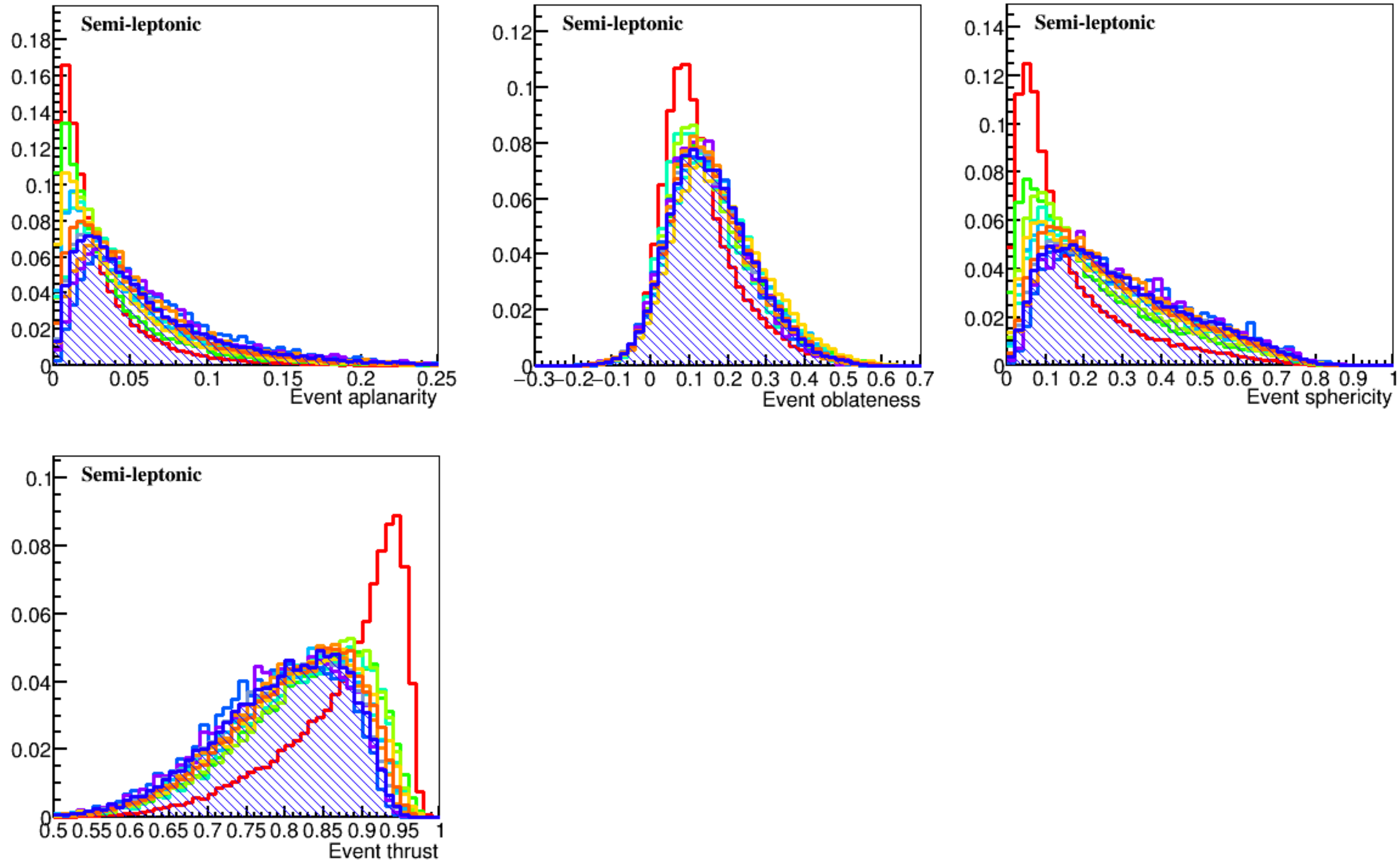
-> 27 variables

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

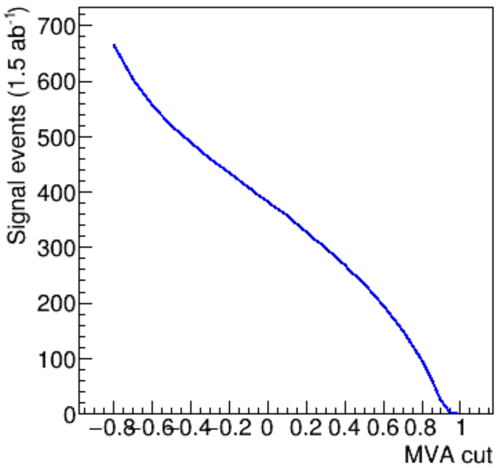



Semi-leptonic
Second highest b-tag
Semi-leptonic
c-tag of second highest b-tag
Semi-leptonic
c-tag / (c-tag+b-tag)
Semi-leptonic
Decay angle (rad)
Semi-leptonic
tH angle min (rad)
Semi-leptonic
tH angle max (rad)

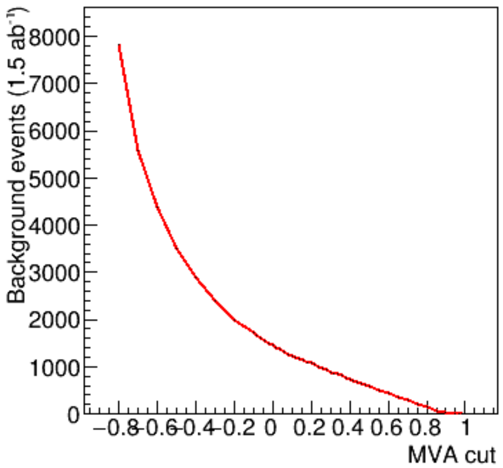

Semi-leptonic
t_bqq mass (GeV/c²)
Semi-leptonic
W_qq mass (GeV/c²)
Semi-leptonic
H_bb mass (GeV/c²)
Semi-leptonic
t_blν mass (GeV/c²)
Semi-leptonic
W_lν mass (GeV/c²)
Semi-leptonic
Jet χ²


Semi-leptonic
Event aplanarity
Semi-leptonic
Event oblateness
Semi-leptonic
Event sphericity
Semi-leptonic
Event thrust

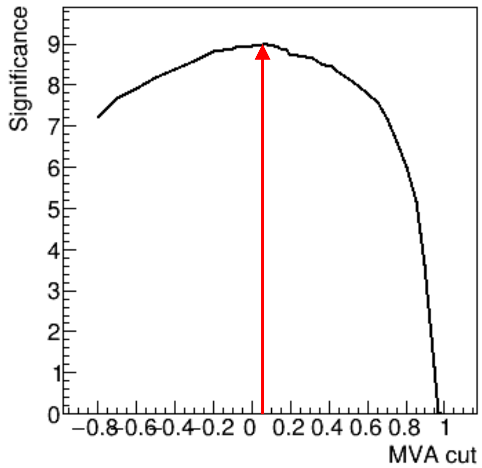
BDTG cut efficiency & optimal significance



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

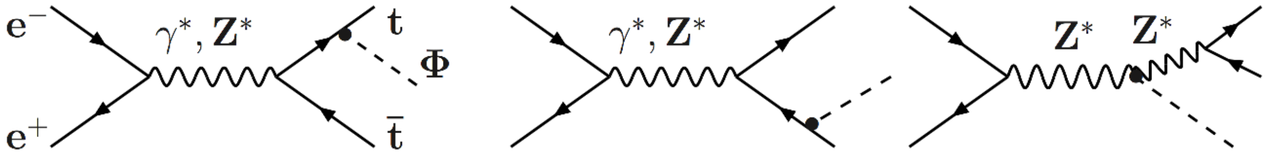
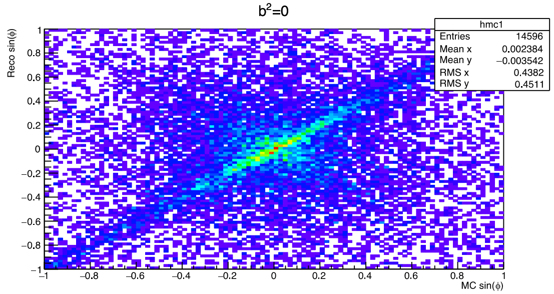


Figure: Feynman diagrams of ttH production.

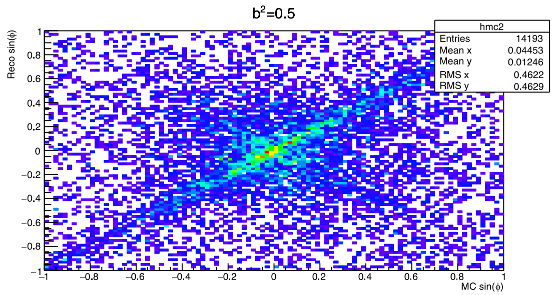
[1] Reference: R.M. Godbole, C. Hangst, M. Mu¨hlleitner, S.D. Rindani and P. Sharma, "Model-independent analysis of Higgs spin and CP properties in the process e^+e^- → ttΦ", arXiv:1103.5404v1 [hep-ph] 28 Mar 2011

MC vs Rec (investigation)

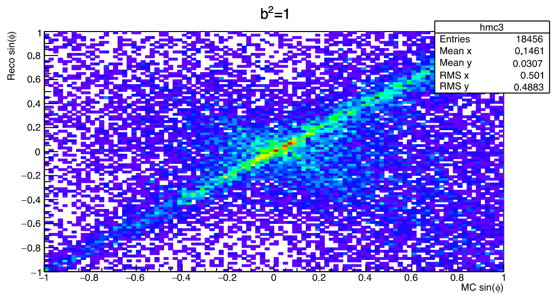
$\sin^2 \phi = 0$



$\sin^2 \phi = 0.5$



$\sin^2 \phi = 1$



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:

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

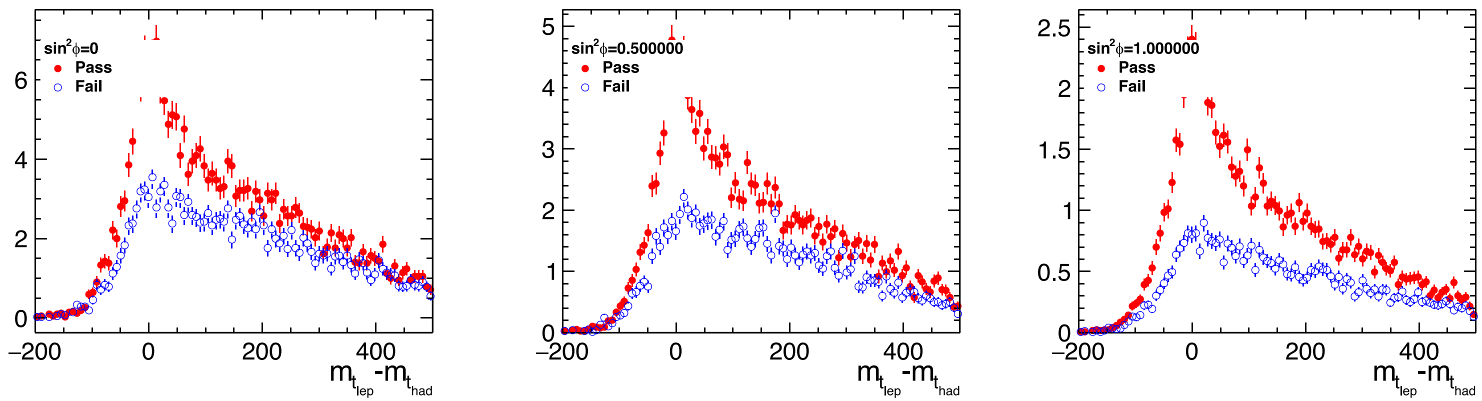
Cuts investigation

How to cut away mis-identified top?

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

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

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



$\rightarrow m_{t_l} - m_{t_q} < 100$

$\rightarrow$ 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 $\sin\theta_\phi$.

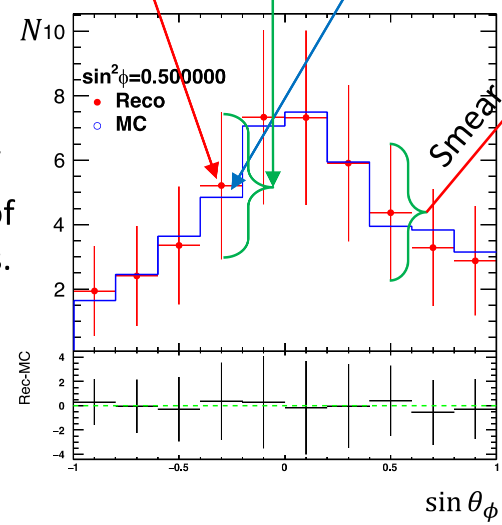
MC: Follows same calculation procedure as above, but use top, anti-top and electron 4-momentum from generator level.

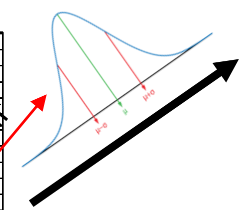
χ^2 template fitting

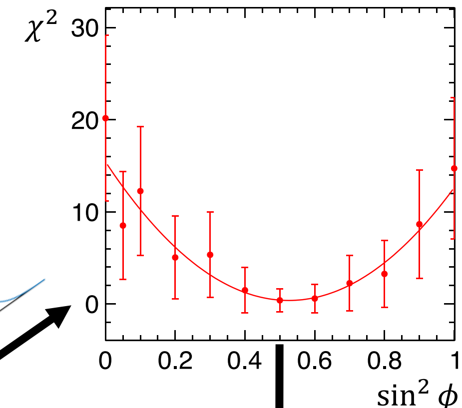
Calculate χ^2 for a specific $\sin^2\phi$ value (e.g =0.5)

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

- 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.

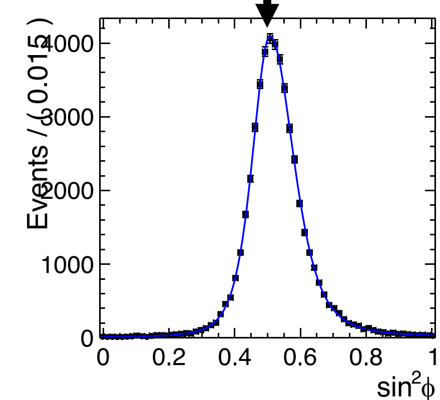






X times

Find minimum and fill Histogram

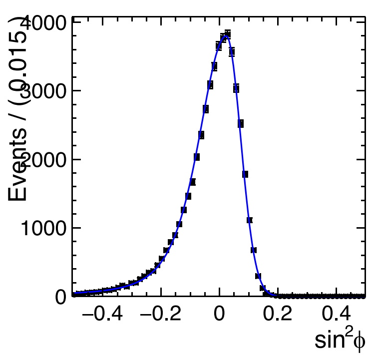


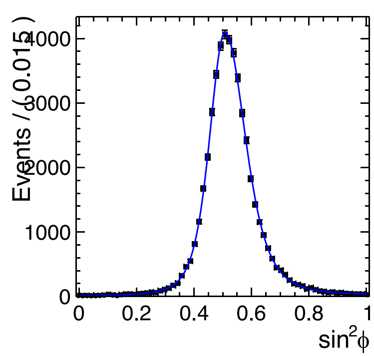
Error estimation

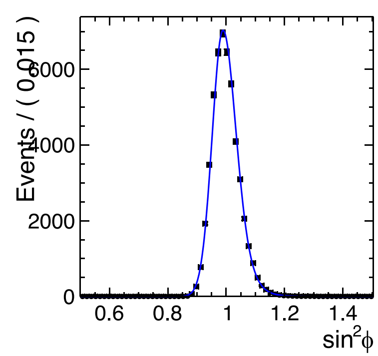
Fitting function:

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

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







The top polarisation asymmetry

The angular distribution in the decay $t \rightarrow bW \rightarrow blv$ 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.

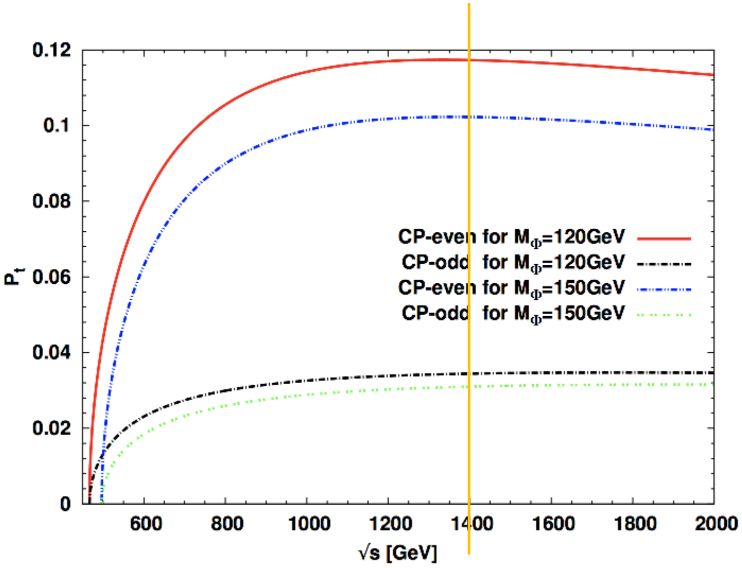


Figure : The top polarisation asymmetry for various Higgs models with unpolarised e± beams [1].