CP studies in $t\bar{t}H$ at 1.4 TeV at CLIC

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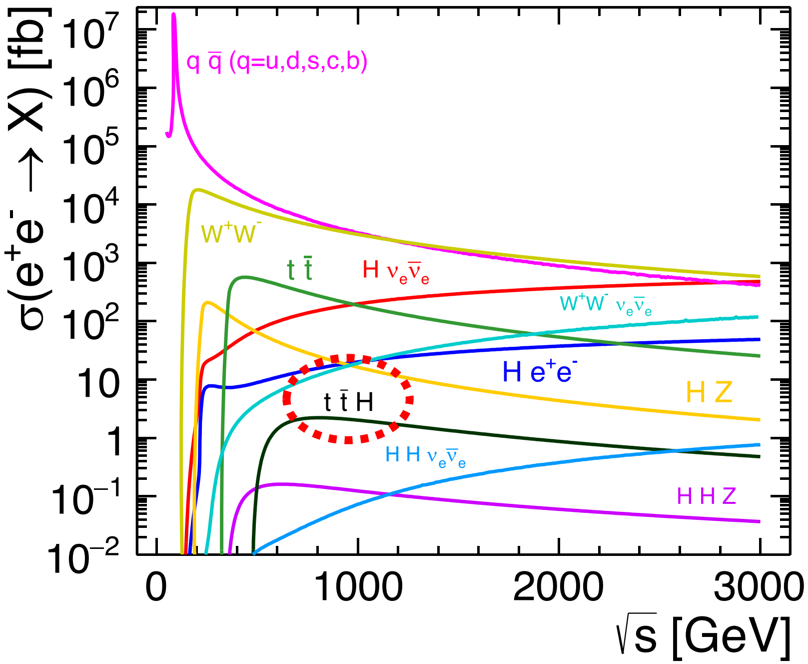
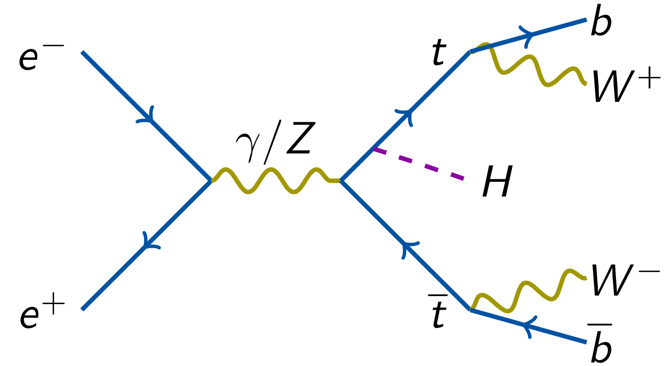
Outline

- 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

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





<u>Advantages</u>:

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 CP properties of Yukawa coupling

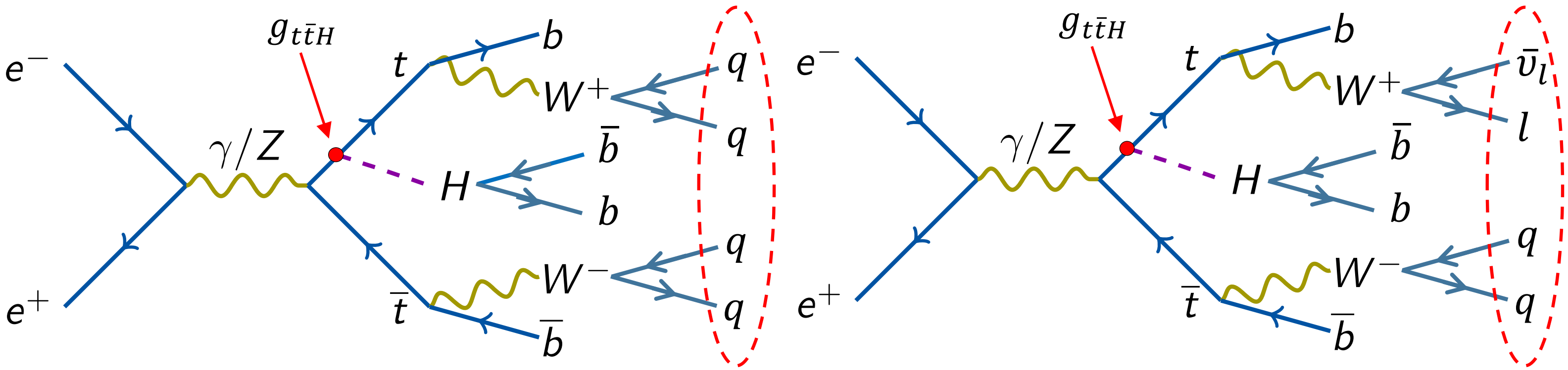
<u>Disadvantages:</u>

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



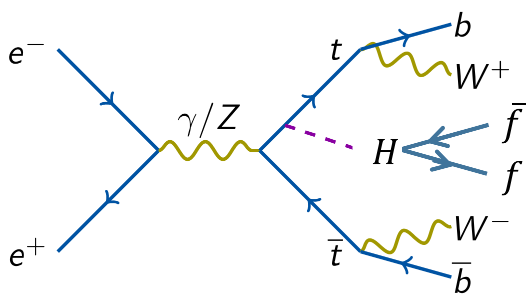
Hadronic channel: 6 jets

Semi-leptonic channel: 4 jets

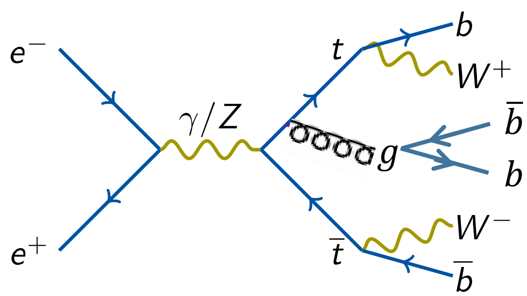
$t\bar{t}H$ decay	BR of $t\bar{t}H(b\bar{b})$	Charged leptons	Channel classification
$t\bar{t} \rightarrow 6jets + H \rightarrow b\bar{b}$	46%	0	**Hadronic**
$t\bar{t} \rightarrow 4jets + 1l + 1\bar{\upsilon}_l + H \rightarrow b\bar{b}$	45%	1	**Semi-leptonic**
$t\bar{t} \rightarrow 2jets + 2l + 2\bar{\upsilon}_l + H \rightarrow b\bar{b}$	9%	>1	Not included

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

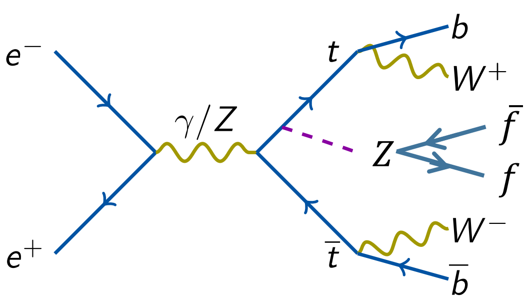
Backgrounds



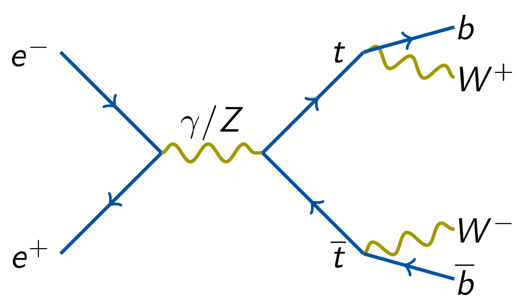
Other $t\bar{t}H$ decays



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

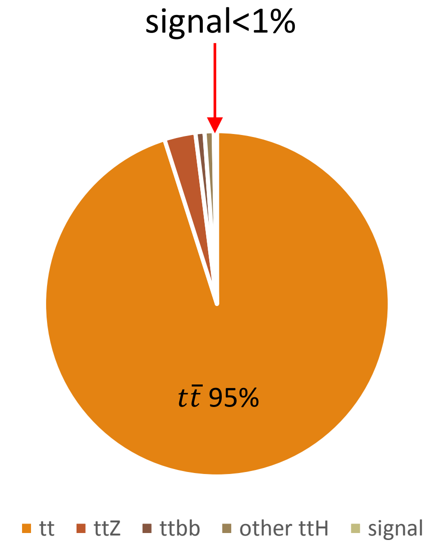


$t\bar{t}Z$



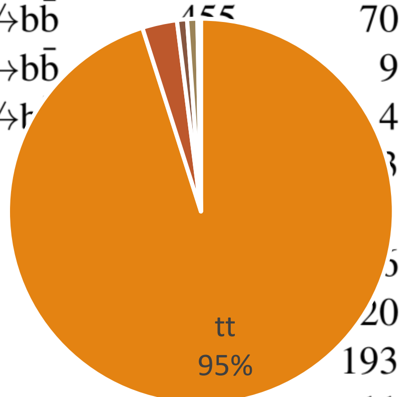
$t\bar{t}$

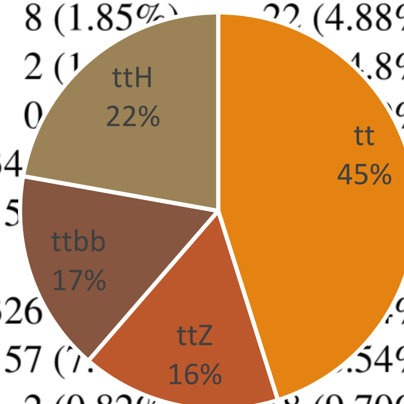
- Generator: $t\bar{t}$ (Pythia), others (Physsim)
- signal and background samples are unpolarised



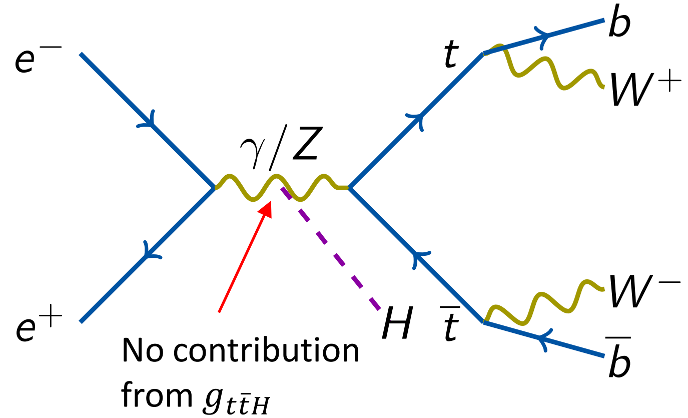
Selection efficiency after BDTG cut

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 L = 1.5ab^{-1}	LO $\Delta\sigma/\sigma$ L = 1.5ab^{-1}	NLO $\Delta\sigma/\sigma$ L = 1.5ab^{-1}	NLO $\Delta g_{ttH}/g_{ttH}$ L = 1.5ab^{-1}	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 luminosity scheme

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

Parametrisation of CP mixing in the ttH coupling:

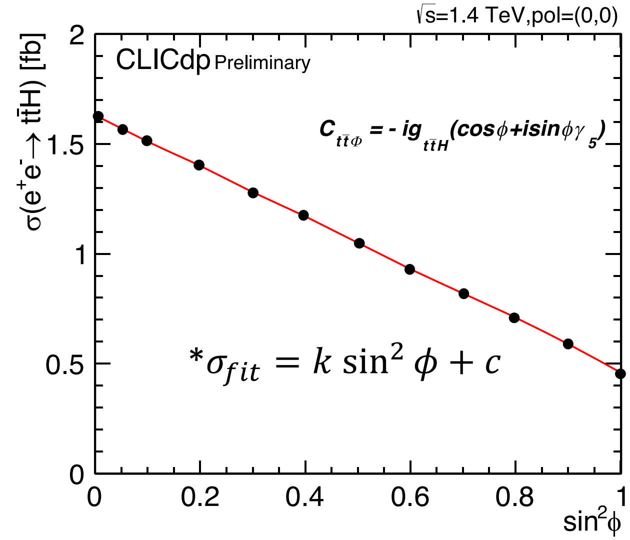
- $C_{t\bar{t}\Phi} = -ig_{t\bar{t}H}(a + ib\gamma_5)$
- SM: a = 1, b = 0 ; pure CP-odd: a = 0, b ≠ 0.

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

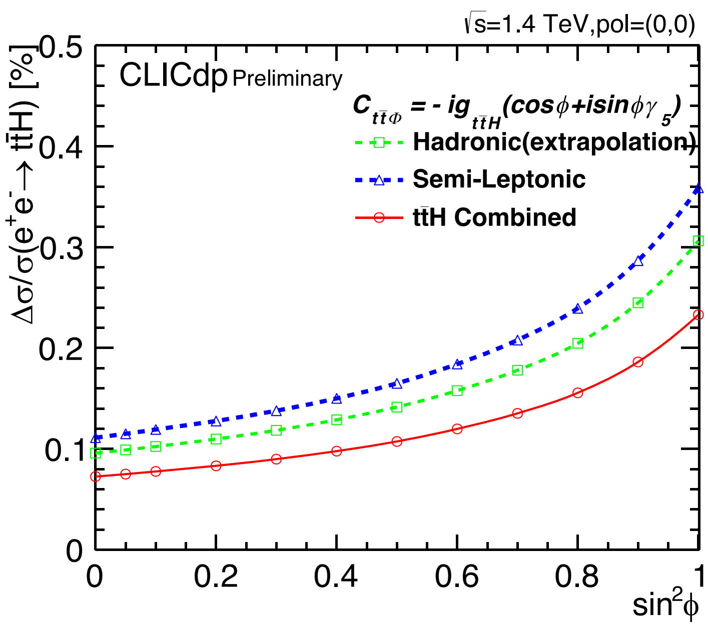
<u>$t\bar{t}H$ cross section</u> (thanks for Philipp Roloff for generating the samples):

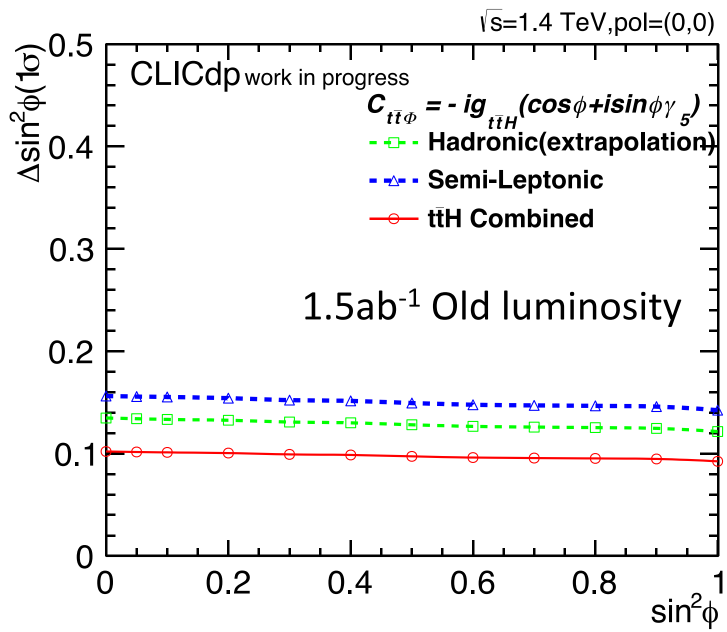
- Generator: Physsim
- $\sqrt{s}$ = 1.4 TeV
- Polarisation = (0,0)
- ISR included
- CLIC luminosity spectrum
- 12 samples produced

* Cross section decreases with more CP odd component



Cross section to CP-mixing sensitivity





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

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

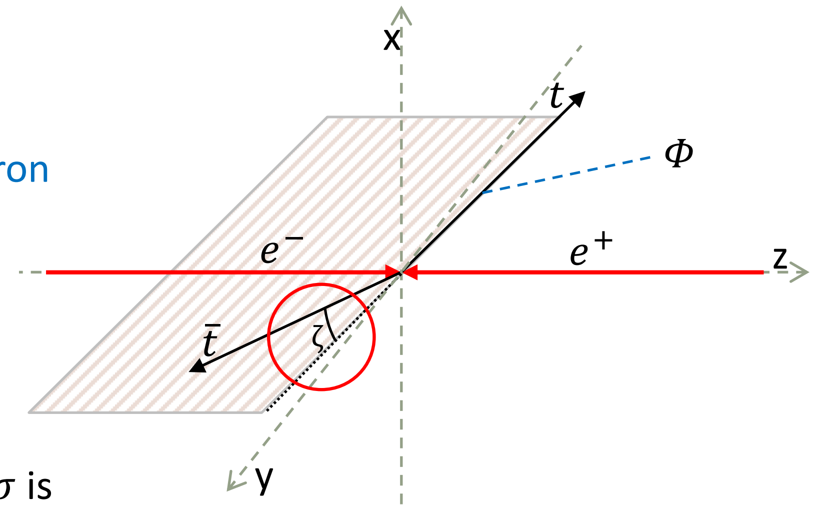
- Apply the top-Yukawa analysis procedure to all samples
- Measure $\Delta\sigma/\sigma$ for all $\sin^2(\phi)$ values in the semi-leptonic channel
- Extrapolate to result from both channels

Up-down asymmetry

Up-down asymmetry A_ϕ of antitop with respect to the top-electron plane is sensitive to CP violation.

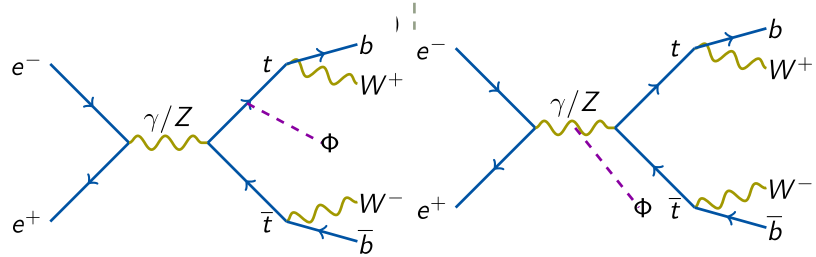
The angle ζ between the antitop and the top-electron plane is given by

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



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

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



Component of asymmetry from 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 $(bl\upsilon)$ is a top and $(bq\bar{q})$ is antitop, vice versa.

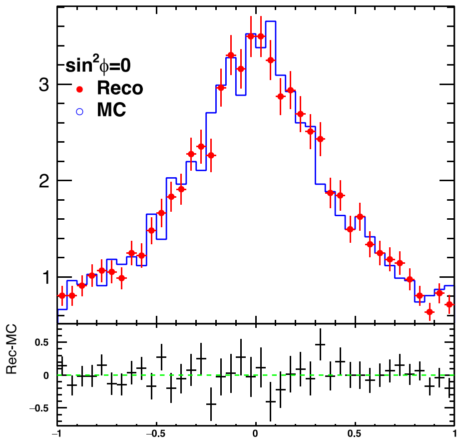
Calculation procedure:

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.

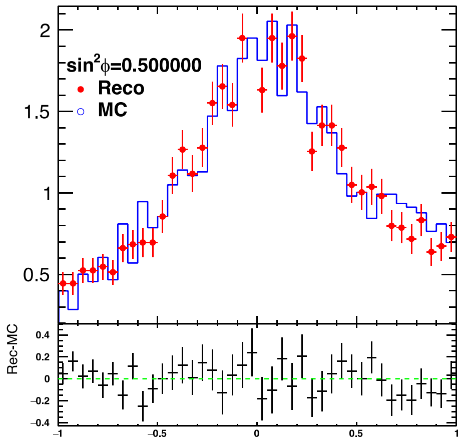
$\sin\zeta$ and A_ϕ with tight cuts

Pure CP-even



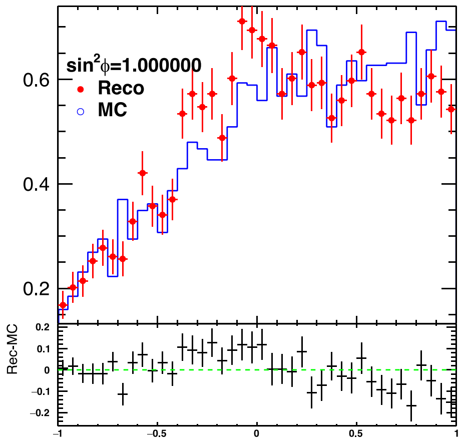
$\sin\zeta$

50% CP-even & CP-odd



$\sin\zeta$

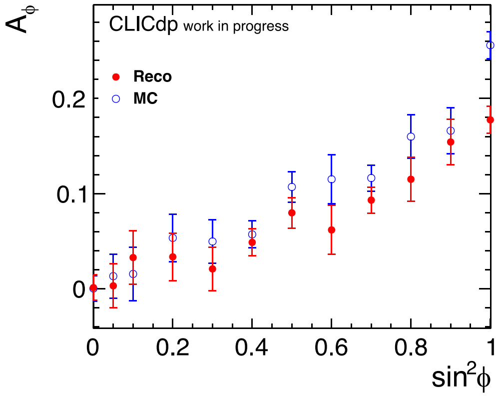
Pure CP-odd



$\sin\zeta$

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

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

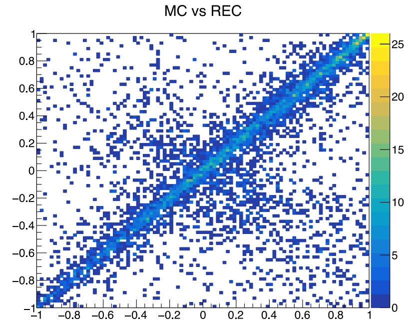


Improvement of top reconstruction

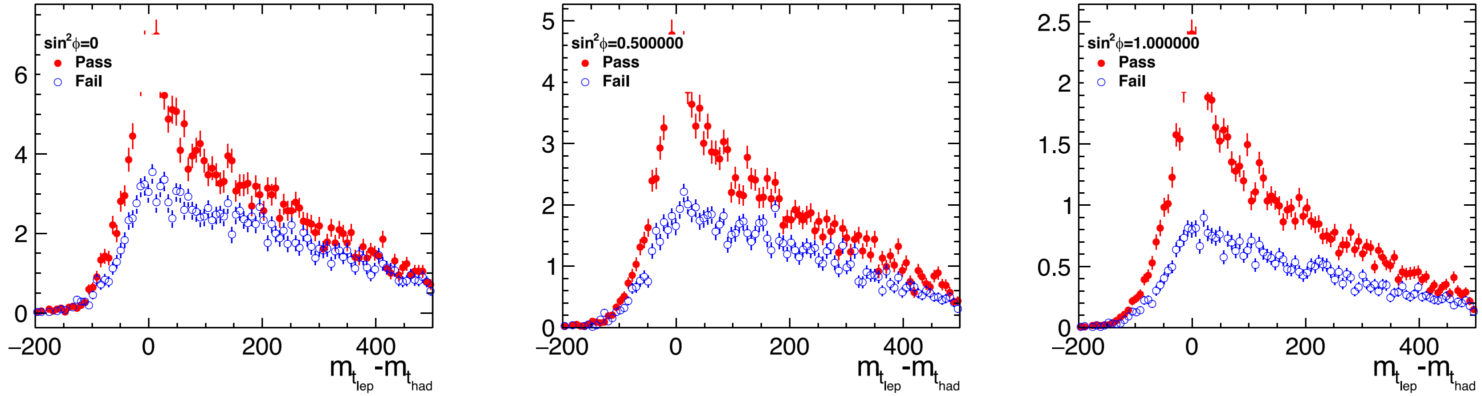
How to cut away mis-identified top?

- 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:

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

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

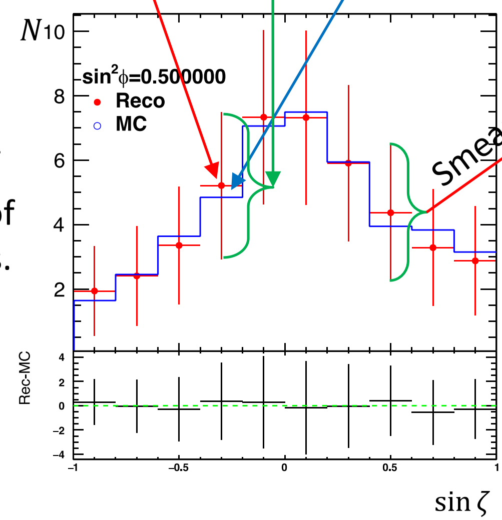
$\rightarrow$ remove hadronic taus

χ^2 template fitting

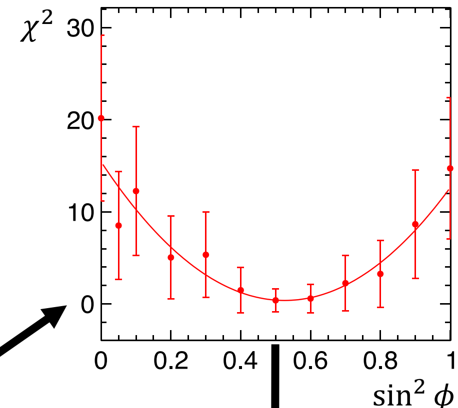
Calculate χ^2 for a specific $\sin^2\phi$ value (e.g =0.5)

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

- 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.

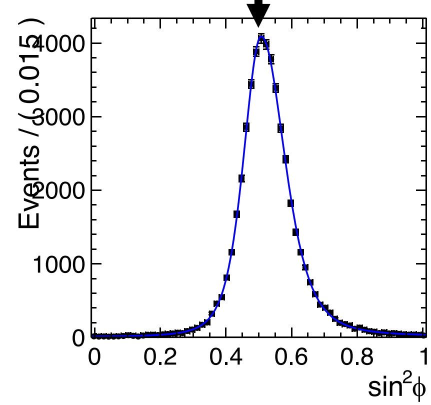


Smear as Poisson



X times

Find minimum and fill Histogram

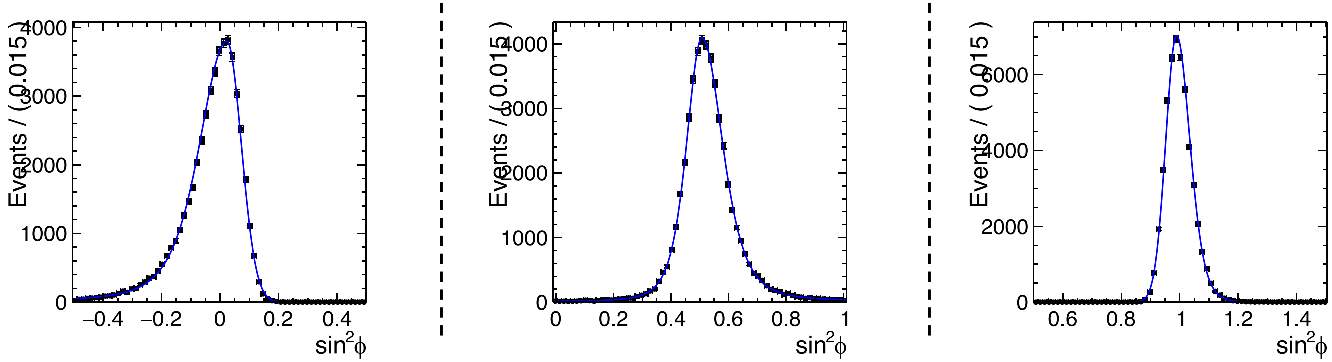


Error estimation

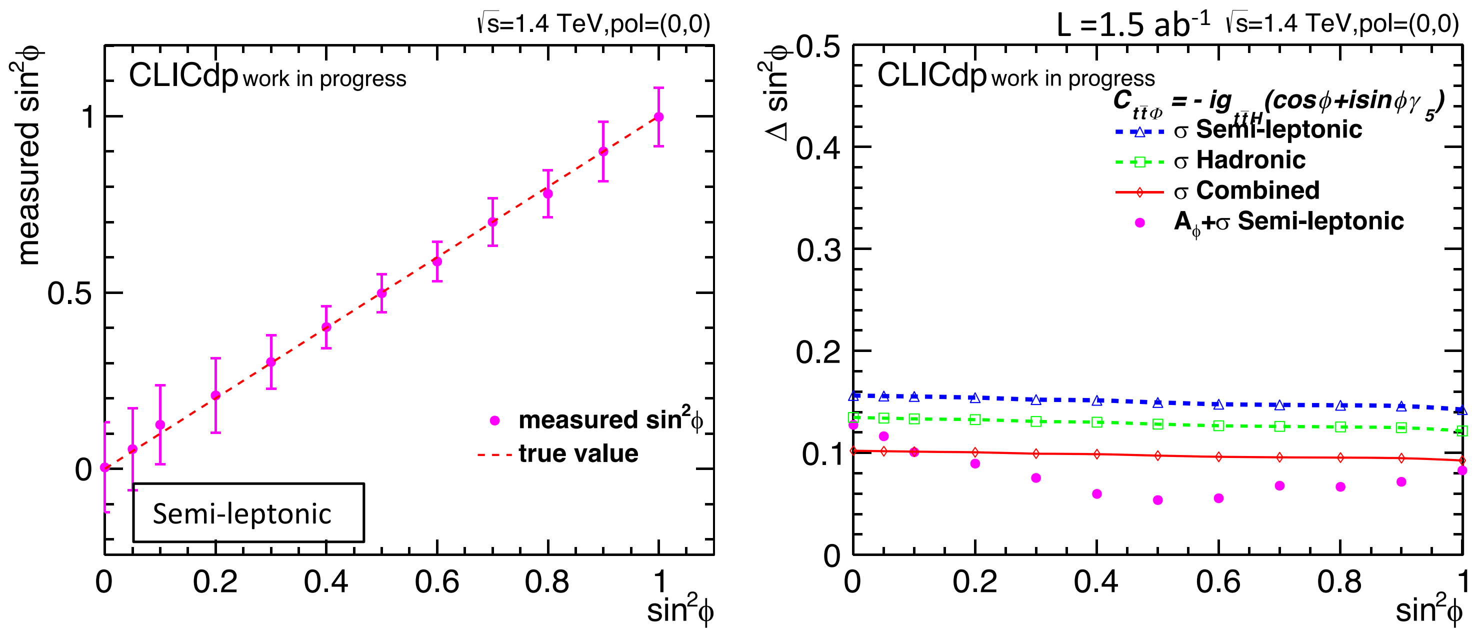
Fitting function:

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

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

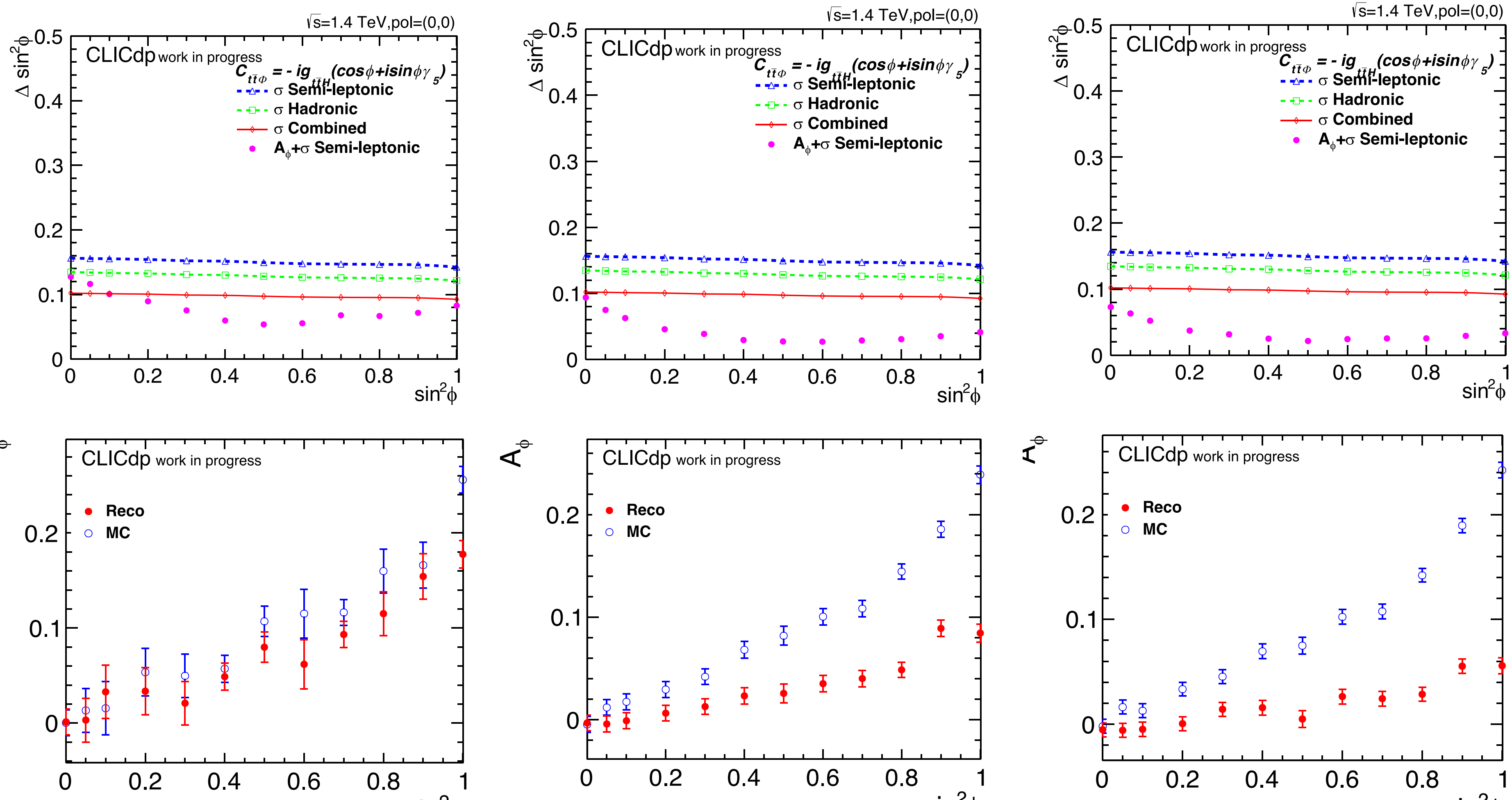


Preliminary results (tight cuts)



- 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

New method of reconstructing neutrino

<u>Old method:</u>

- Assign all the missing p_x, p_y, p_z to neutrino momentum.

<u>Issue:</u>

- ISR effect will affect the reconstructed neutrino, and hence leave a high tail in the reconstructed mass distribution of leptonic top mass.

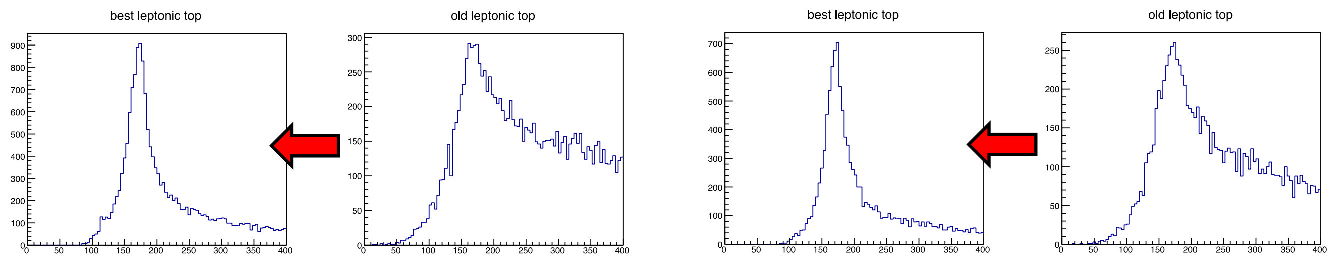
<u>Solution:</u>

(see detail in Rickard's presentation in 2017 https://indico.cern.ch/event/667391/)

- Use a new method to constrain the neutrino p_T such that the neutrino-lepton invariant mass is above the W boson mass. And then select the solution closest to the top mass after combining with other jets.

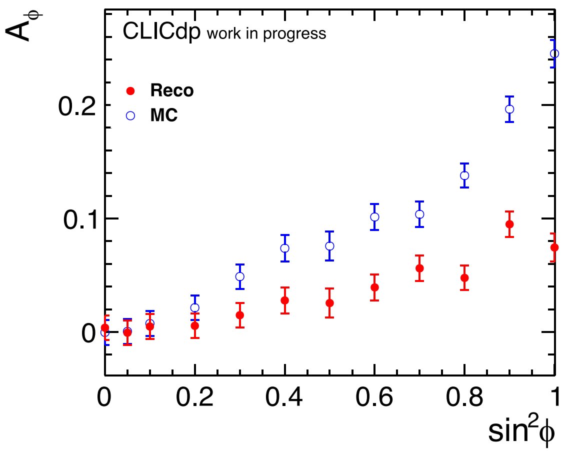
<u>Pure CP even</u> <u>Pure CP odd</u>

Top mass

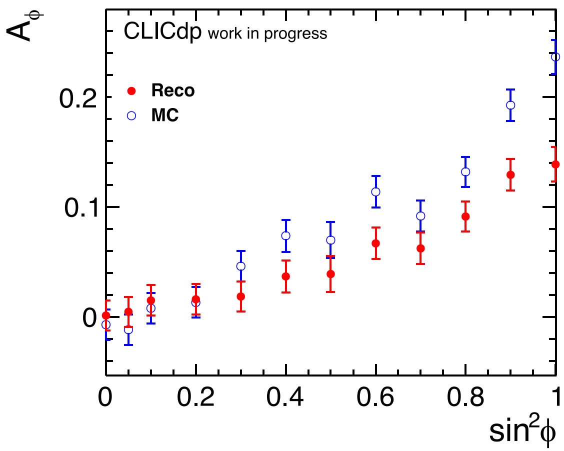


Investigation of cuts

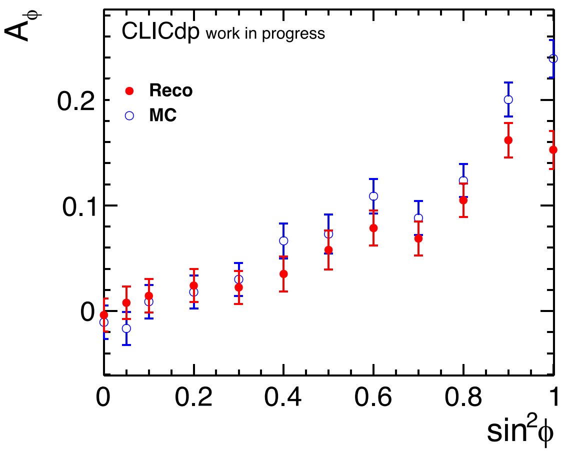
Up-down asymmetry, matching reconstructed value to MC value.
All tau leptons are removed, MVA cuts applied.



- No cuts

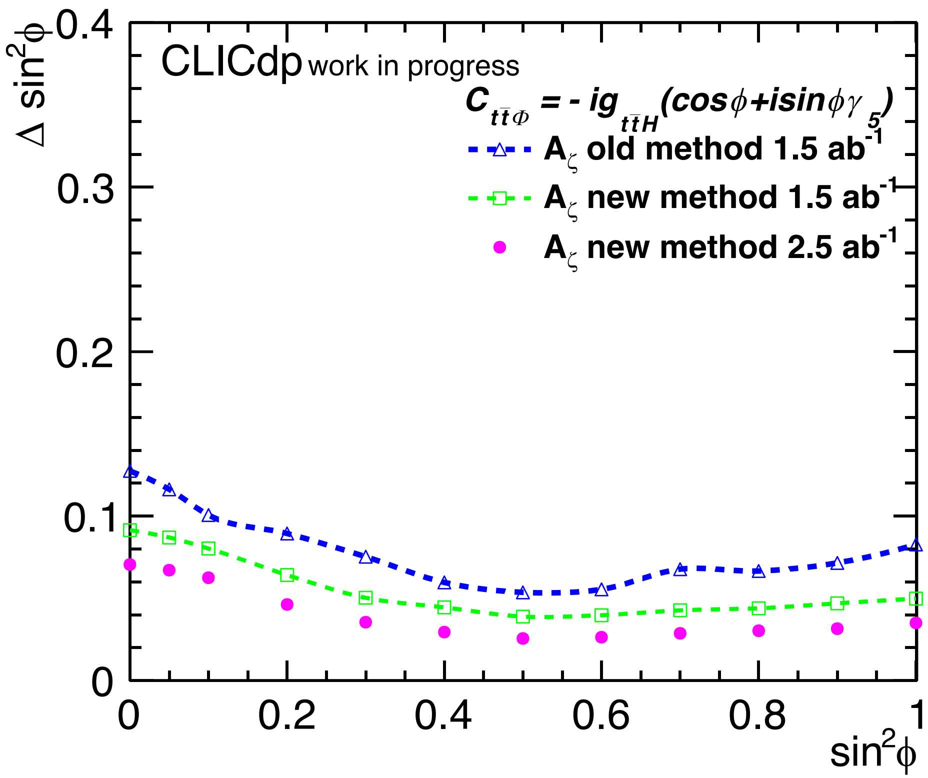


- $m_{t_{lep}} < 220$ GeV



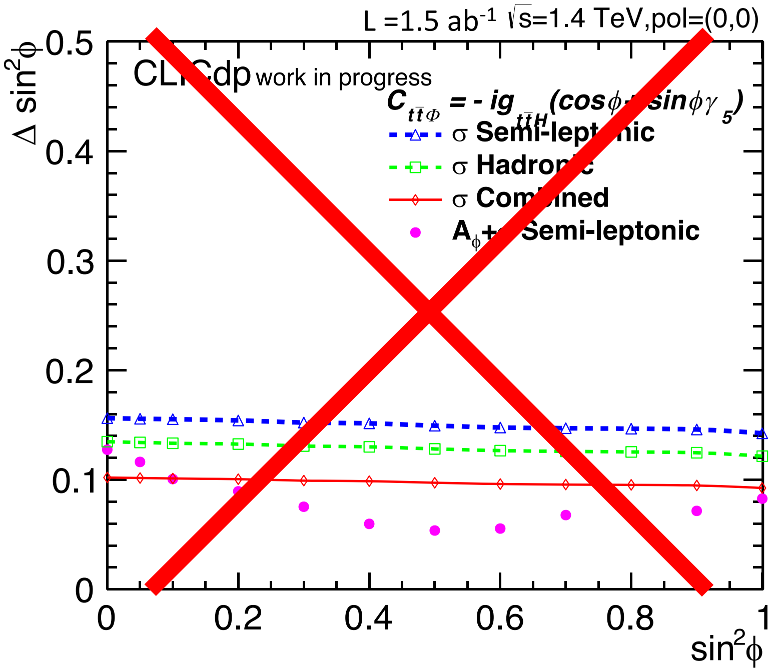
- $m_{t_{lep}} < 220$ GeV
- Jet matching $\chi^2 < 10$

Sensitivity to CP property

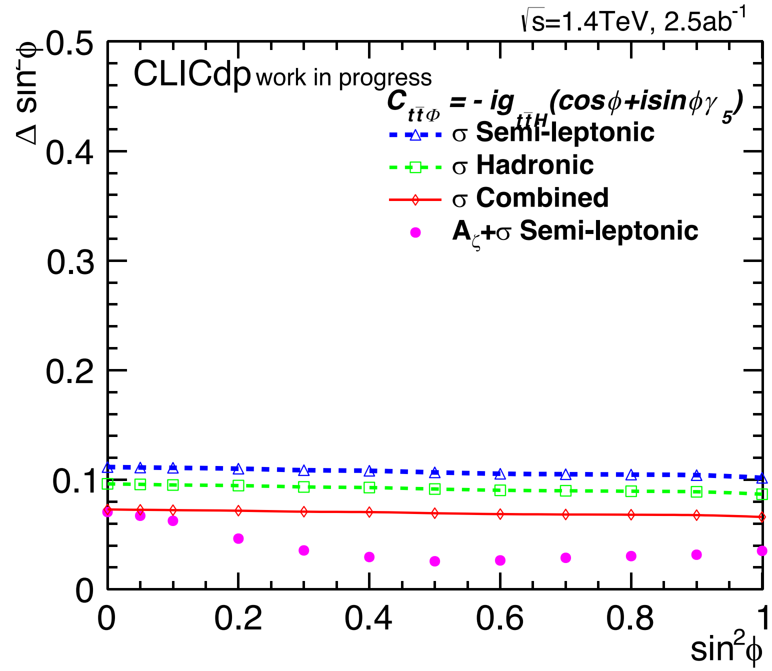


Preliminary results

Old lumi 1.5 ab^{-1}



New lumi 2.5 ab^{-1}



Summary

- This analysis has found $\frac{\Delta g_{t\bar{t}H}}{g_{t\bar{t}H}} = 2.7\%$ (polarised) with the new integrated luminosity of 2.5 ab^{-1} at $\sqrt{s}$ =1.4 TeV at CLIC,
  - Previous CLIC analysis found 4.3% with unpolarised beam and 1.5 ab^{-1}, CLICdp-Note-2014-001
  - ILC at 1 TeV found 4.5% with luminosity of 1ab^{-1} and unpolarised beam, arXiv:1409.7157
- Sensitivity to CP violation is determined $\Delta \sin^2(\phi) \simeq 0.07$ with cross section measurement with luminosity of 2.5ab^{-1} and polarised beam.
- An angular distribution using up-down asymmetry has shown an improvement to CP sensitivity $\Delta \sin^2(\phi) \approx 0.03\sim0.07$ with luminosity of 2.5ab^{-1} and polarised beam.
- Further observables such as top polarisation can be used to further increase sensitivity to CP violation sensitivity.

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

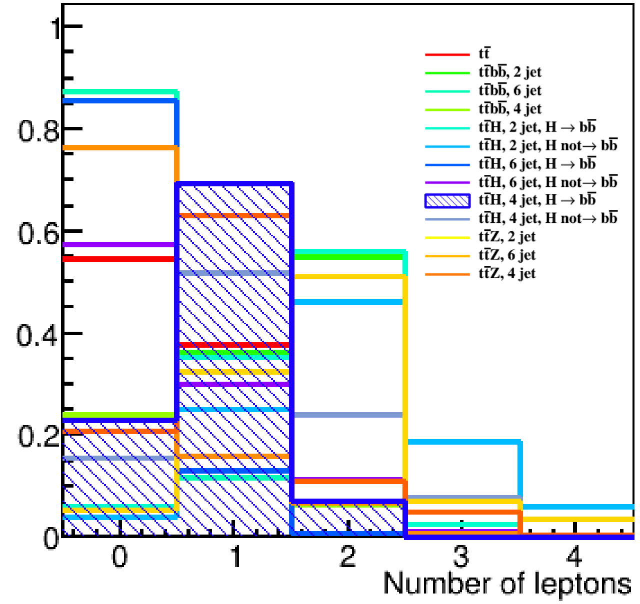
Lepton identification

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:

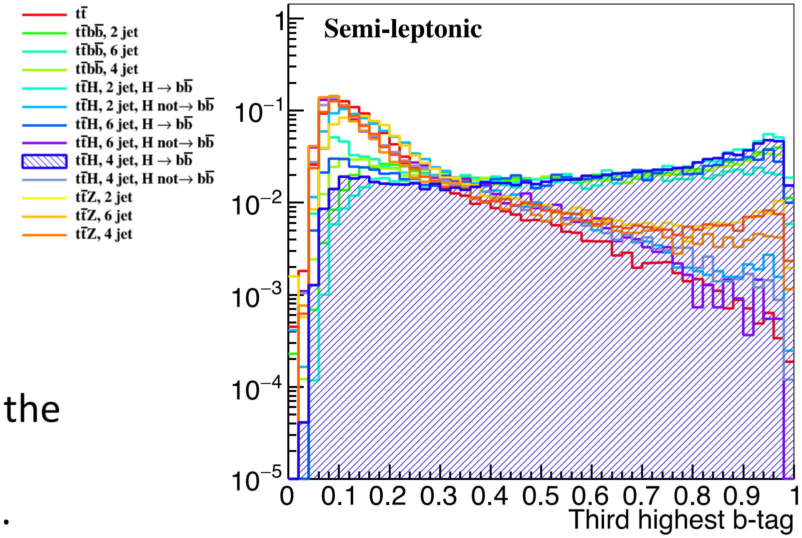
- Selects Hadronic - 86%, Semi-leptonic - 69%.

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:

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

	Mass (GeV/c^2)	$\boldsymbol{\sigma_L}$ $(\boldsymbol{GeV/c^2})$	$\boldsymbol{\sigma_R}$ $(\boldsymbol{GeV/c^2})$
$W^{\pm}$	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.

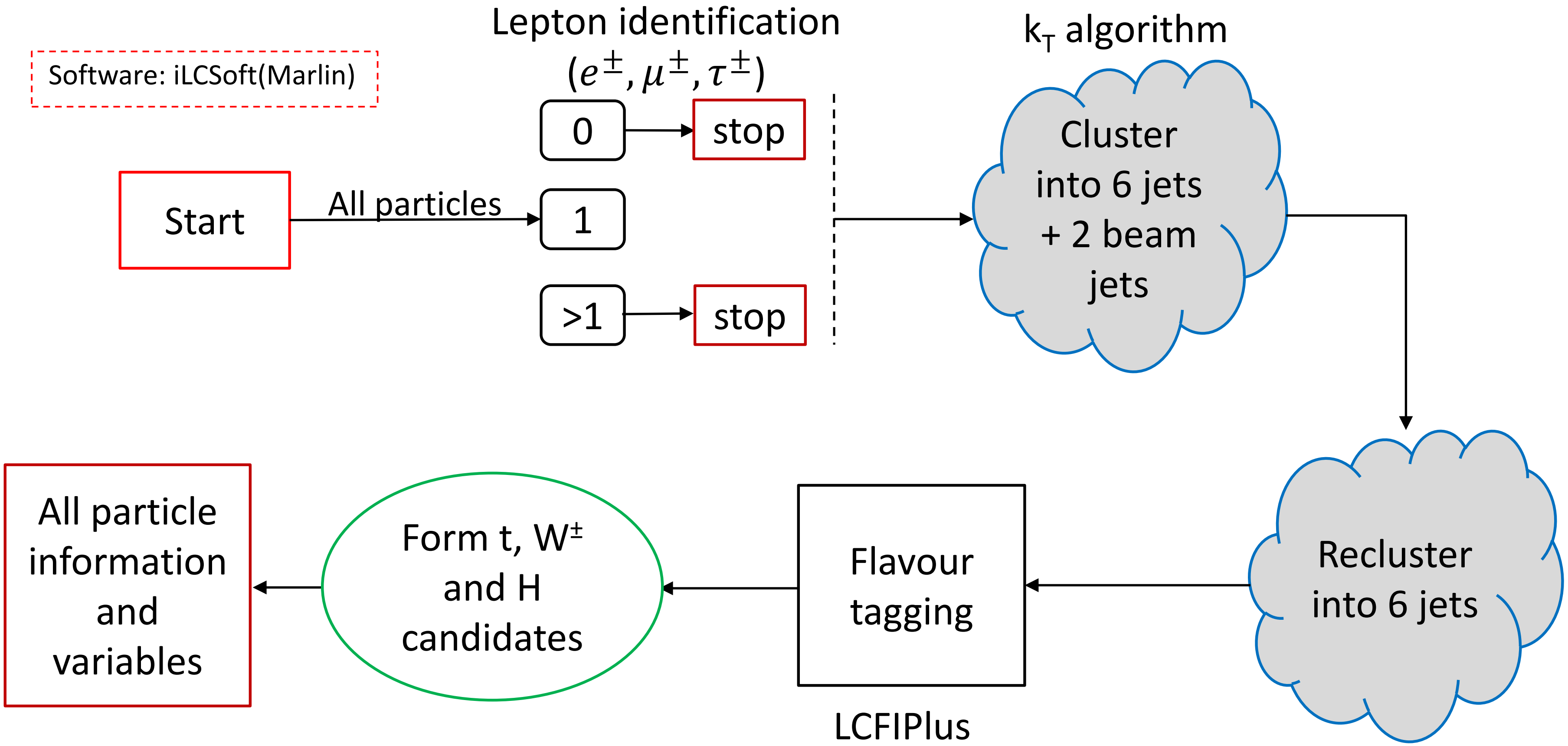
Signal and Background samples

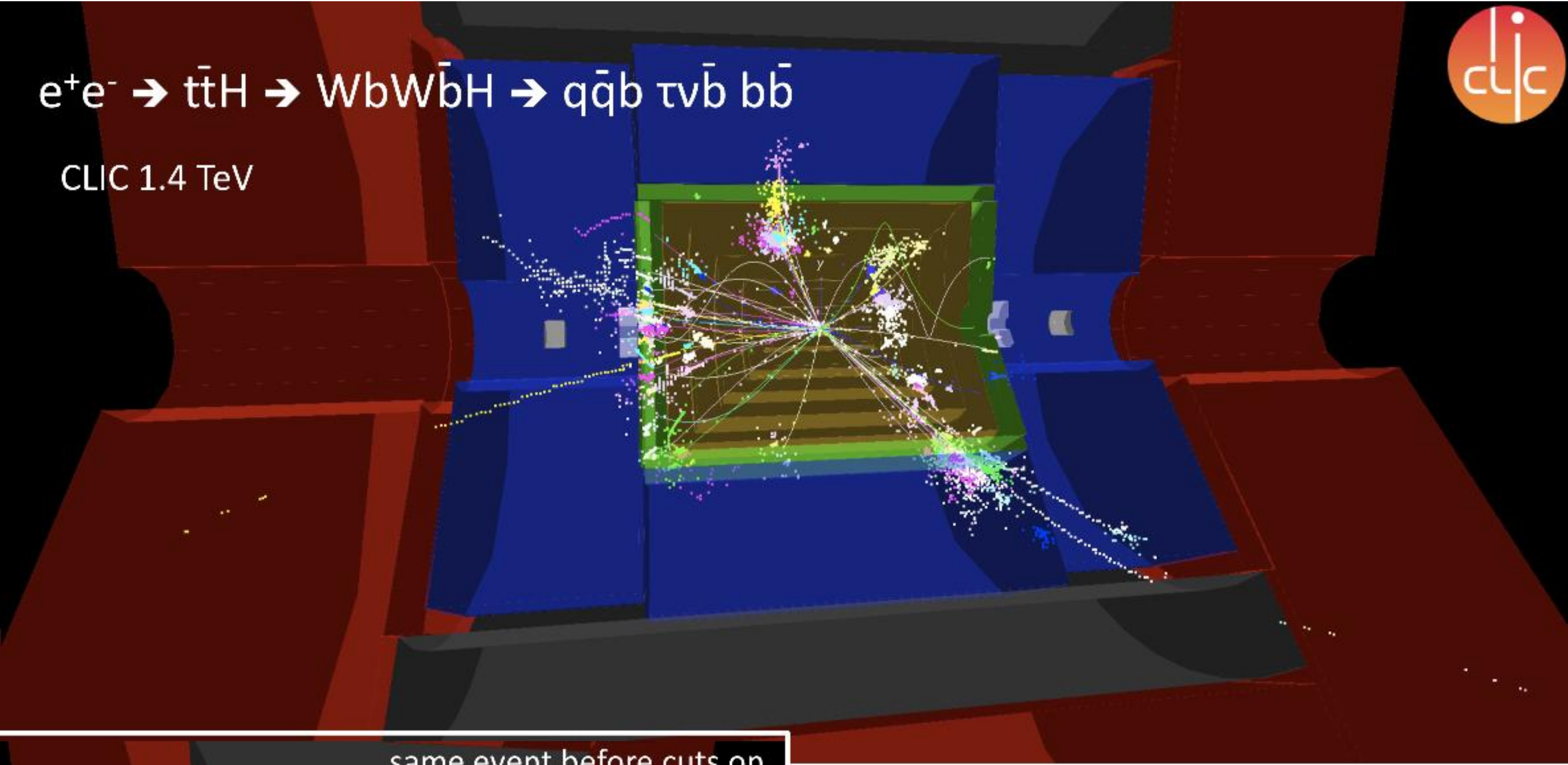
Process	Cross-section (fb)	Generator	Expected no. events
$t\bar{t}H, t\bar{t} \to 6jets, H \to bb$	0.431	Physsim	647
$t\bar{t}H, t\bar{t} \to 4jets, H \to bb$	0.415	Physsim	623
$t\bar{t}H, t\bar{t} \to 6jets, H \nrightarrow bb$	0.315	Physsim	473
$t\bar{t}H, t\bar{t} \to 4jets, H \nrightarrow bb$	0.303	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

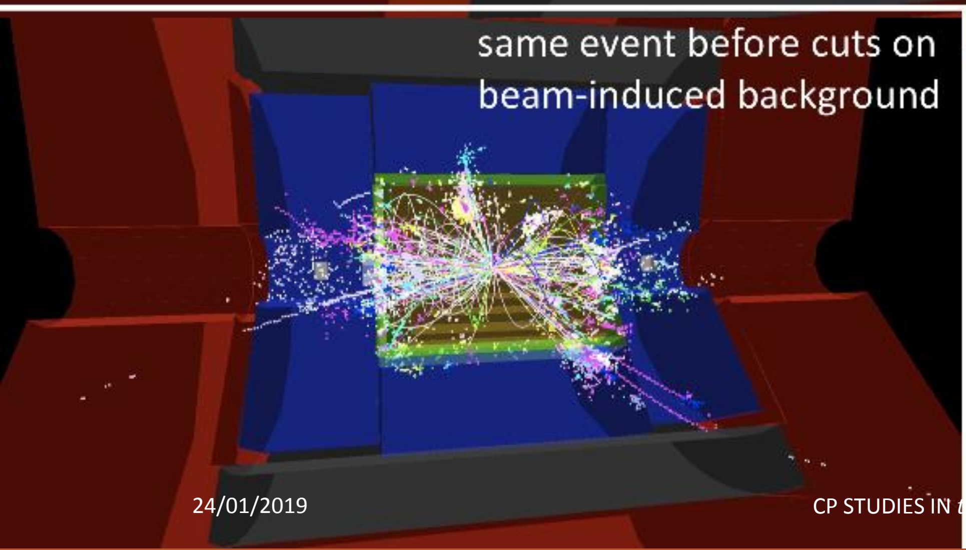
Largest bkg

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

Event reconstruction strategy

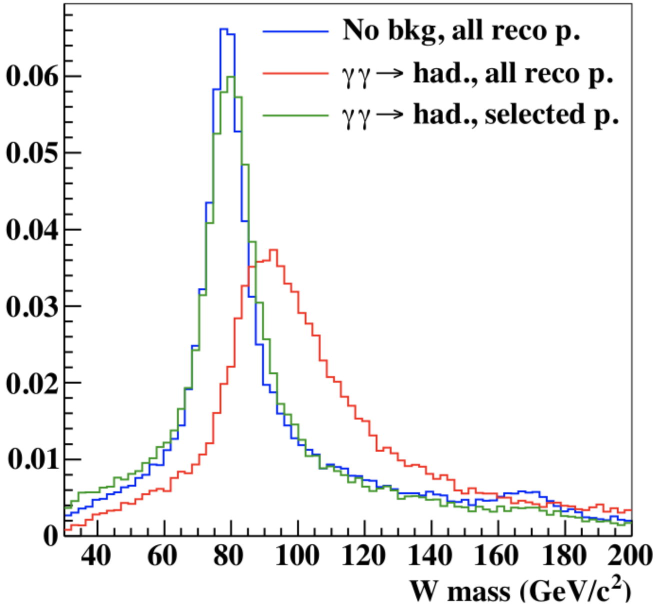






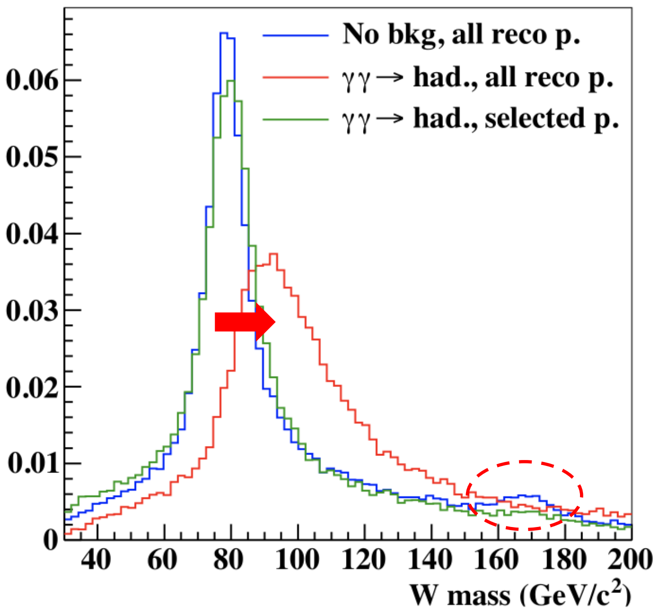
Event display of $e^+ + e^- \rightarrow t\bar{t}H$
Need to apply timing cut and momentum cut to suppress the $\gamma\gamma \rightarrow hadrons$ backgrounds.

$\gamma\gamma \to hadrons$ backgrounds



At $\sqrt{s} = 1.4$ TeV, ~ 1.3 $\gamma\gamma \to hadrons$ 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

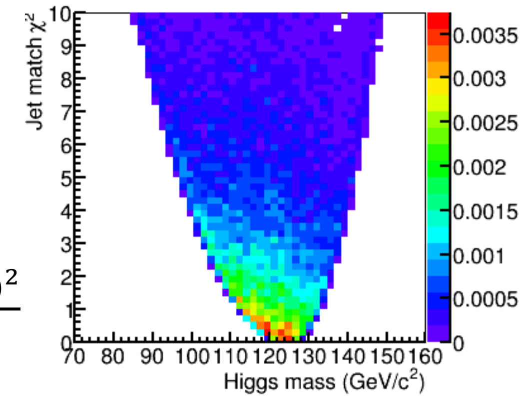
Two chi-squared variables are defined to reconstruct the $W^{\pm}$, top and Higgs candidates by combining the jets.

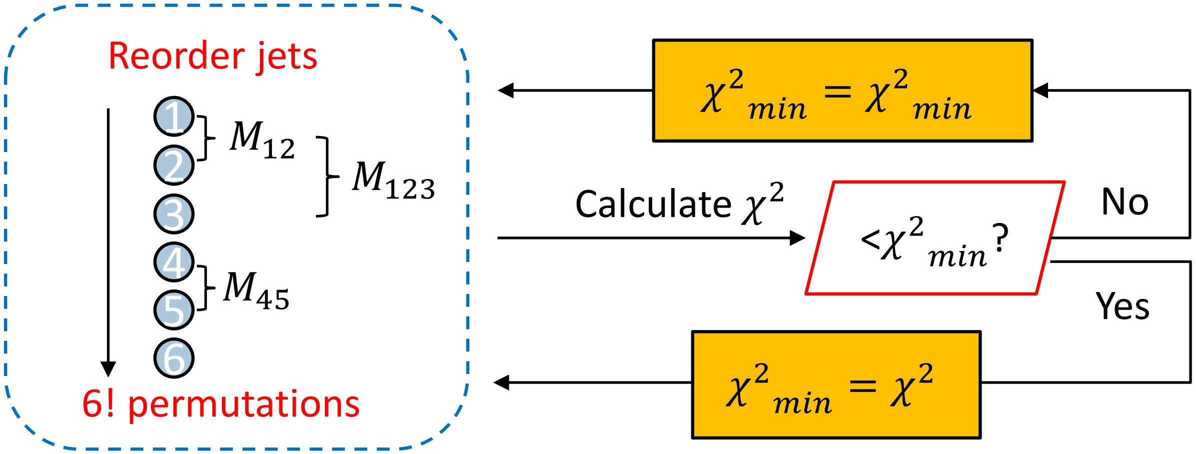
Semi-leptonic:

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

Hadronic:

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





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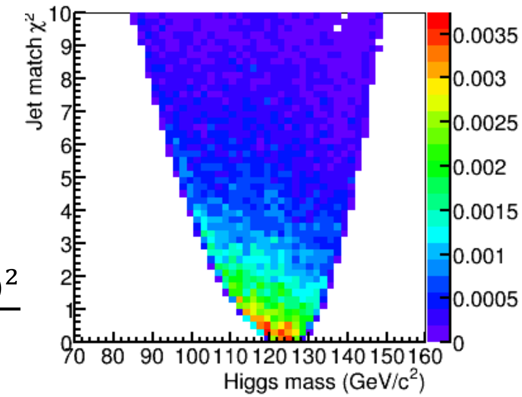
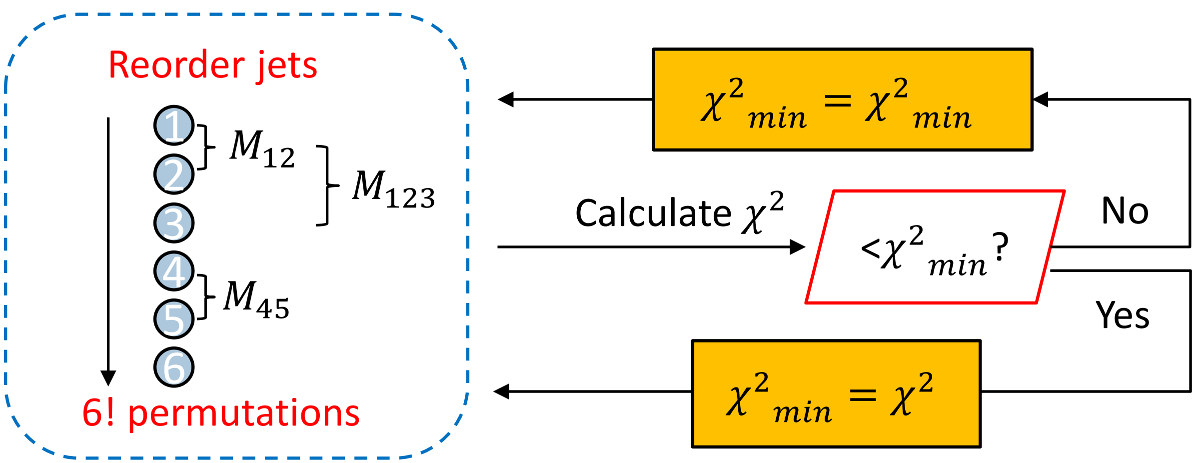
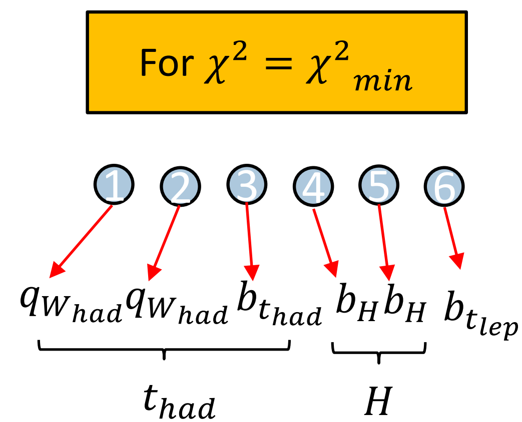
$$\chi_6^2 = \frac{(M_{12}-M_{W^{\pm}})^2}{\sigma_{W^{\pm}}^2} + \frac{(M_{123}-M_t)^2}{\sigma_t^2} + \frac{(M_{45}-M_H)^2}{\sigma_H^2}$$

Hadronic:

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

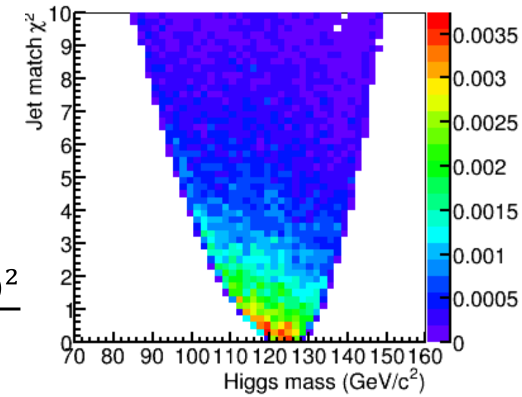






Top, $W^{\pm}$ and Higgs Reconstruction

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

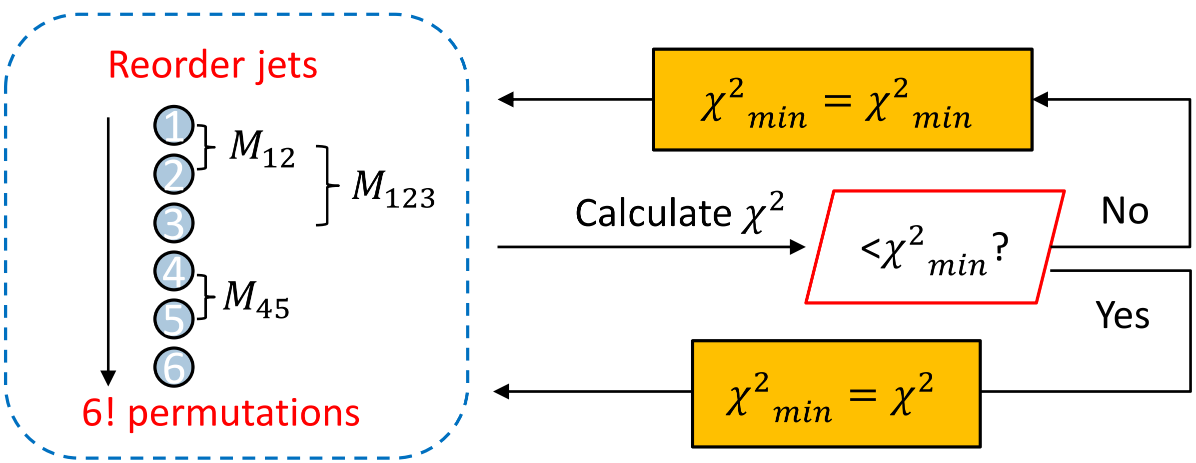


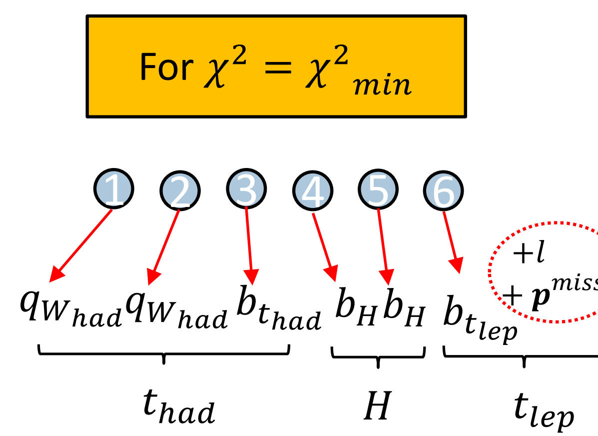
Semi-leptonic:

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

Hadronic:

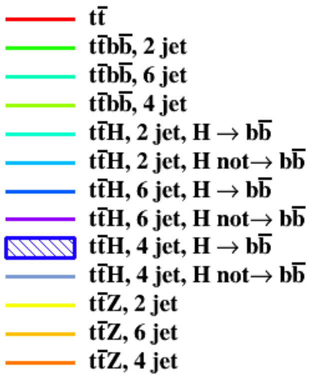
$$\chi_8^2 = \frac{(M_{12}-M_{W^\pm})^2}{\sigma_{W^\pm}^2} + \frac{(M_{123}-M_t)^2}{\sigma_t^2} + \frac{(M_{45}-M_{W^\pm})^2}{\sigma_{W^\pm}^2} + \frac{(M_{456}-M_t)^2}{\sigma_t^2} + \frac{(M_{78}-M_H)^2}{\sigma_H^2}$$

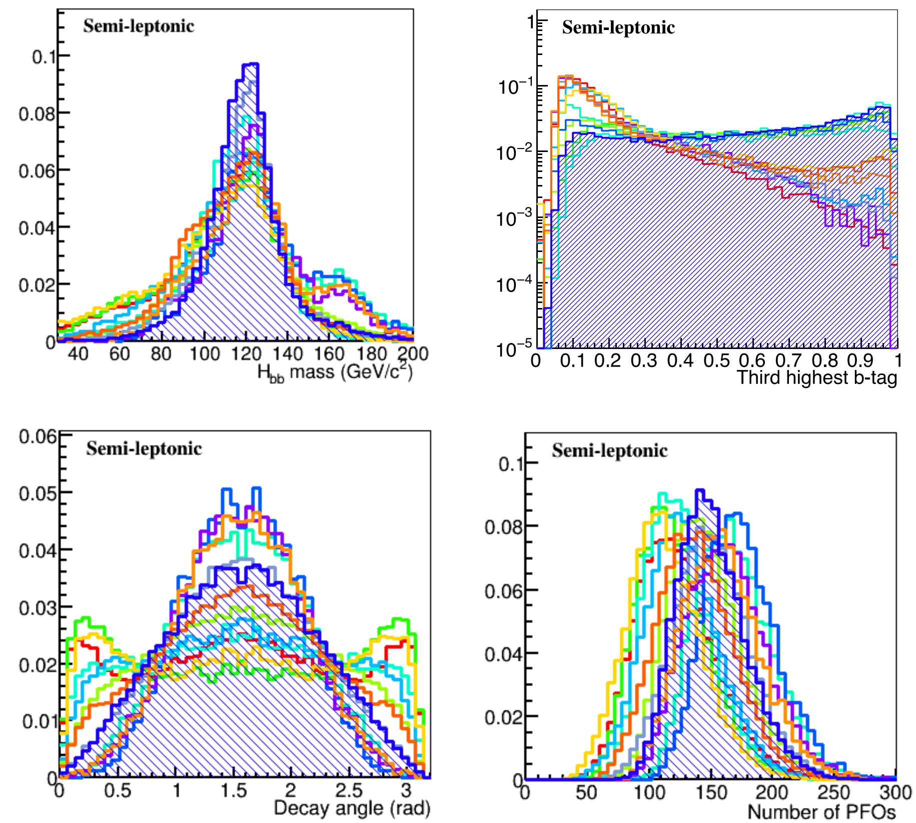




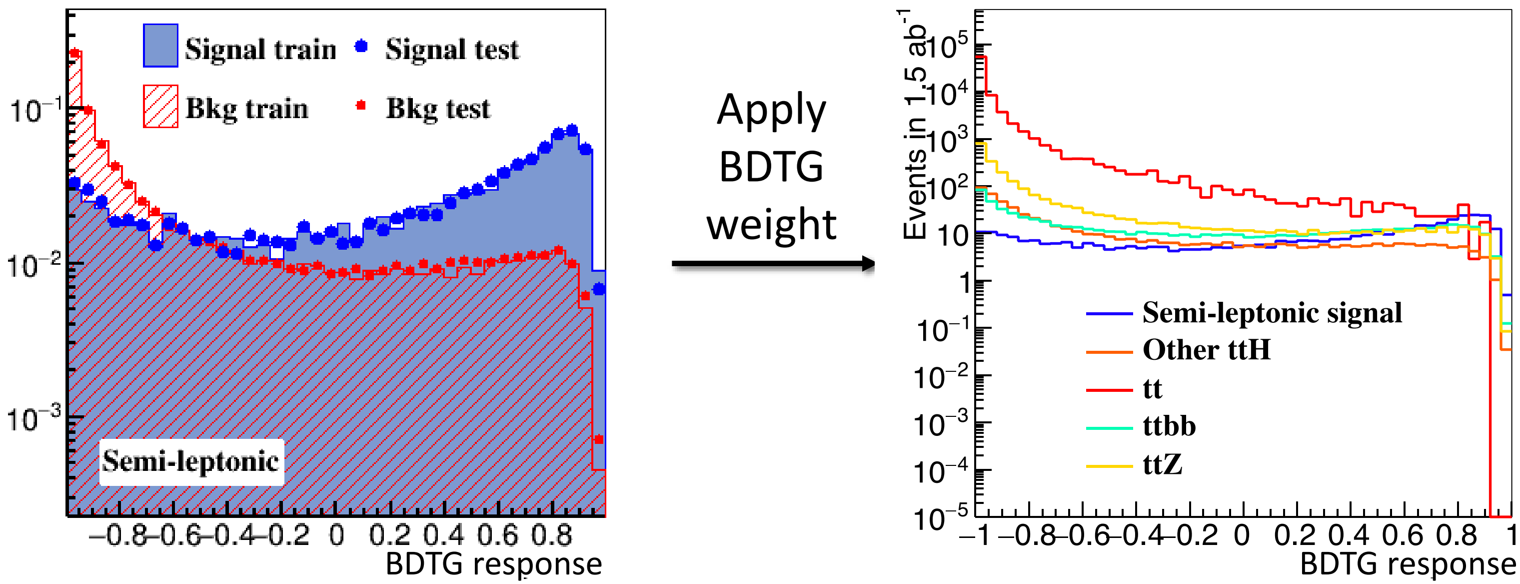
Event selection using TMVA

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

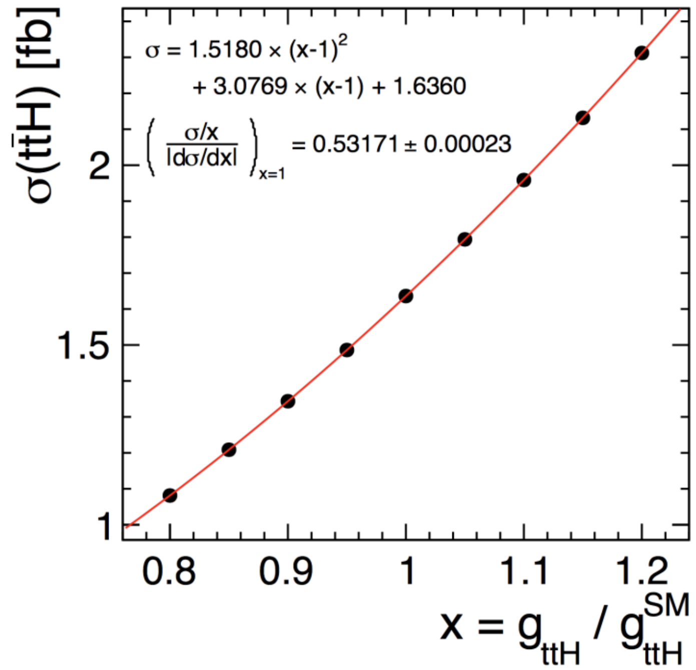


The BDTG response for signal and background samples. (Left): Normalised BDTG response.

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

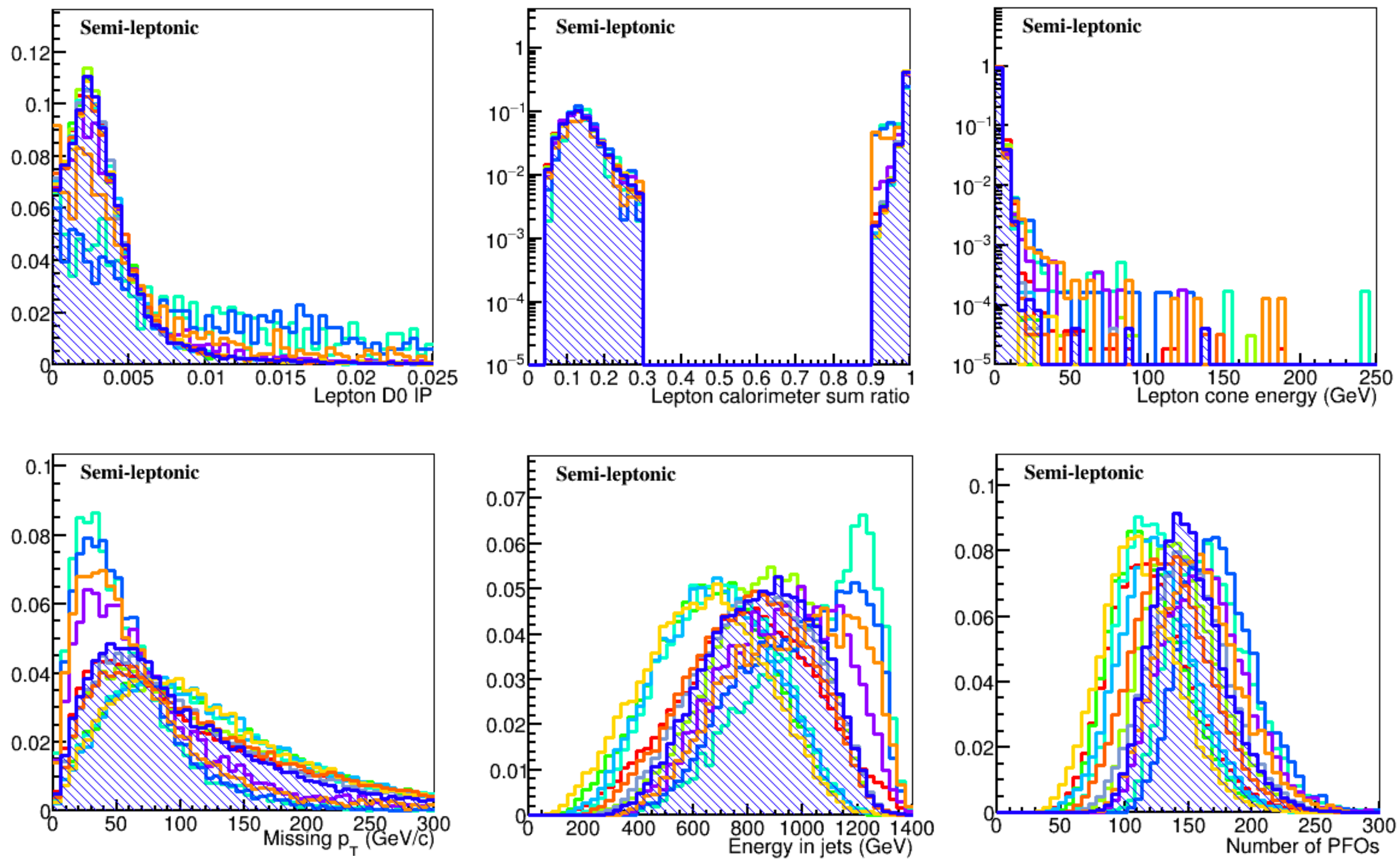
-> 23 variables

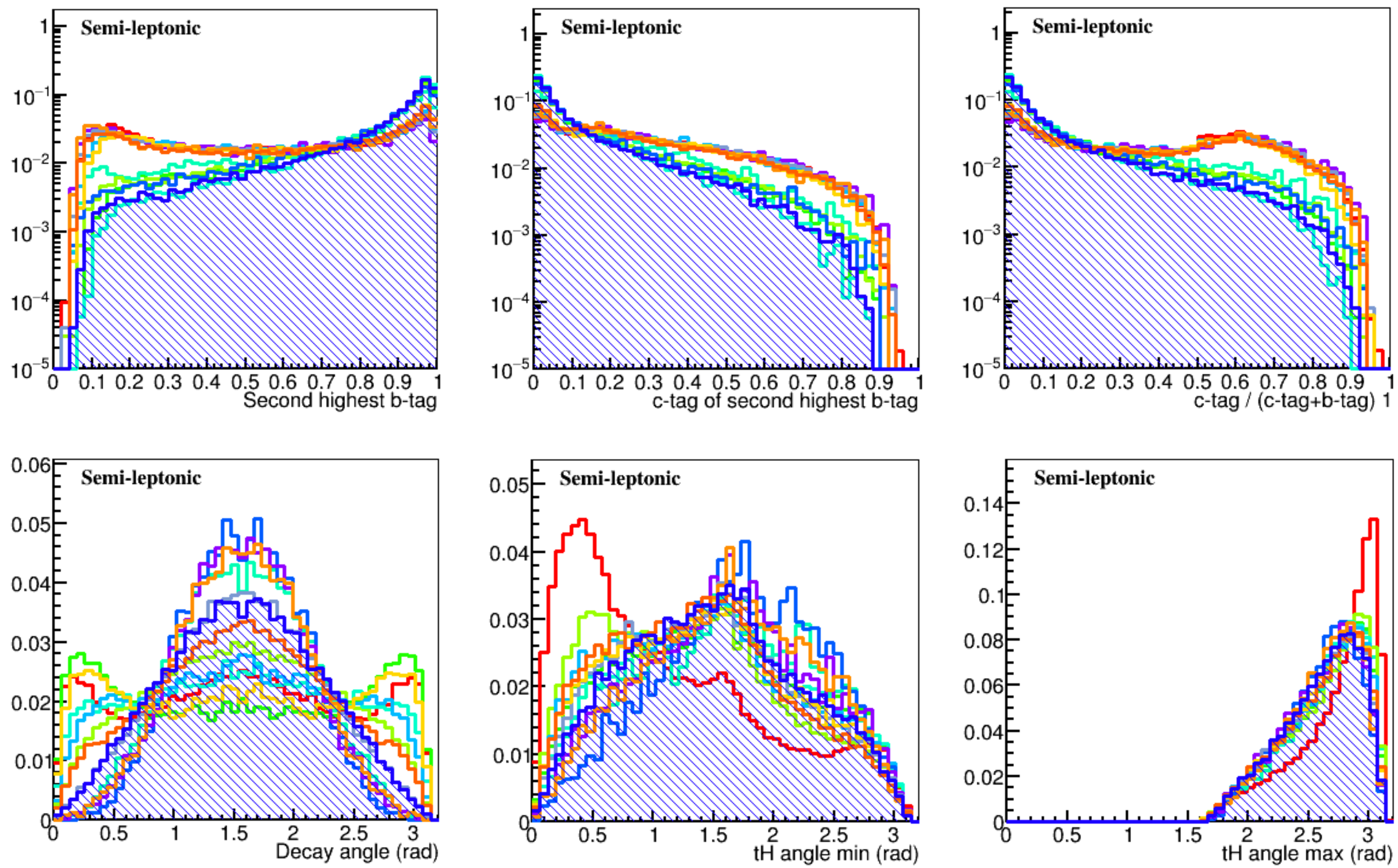
For hadronic:

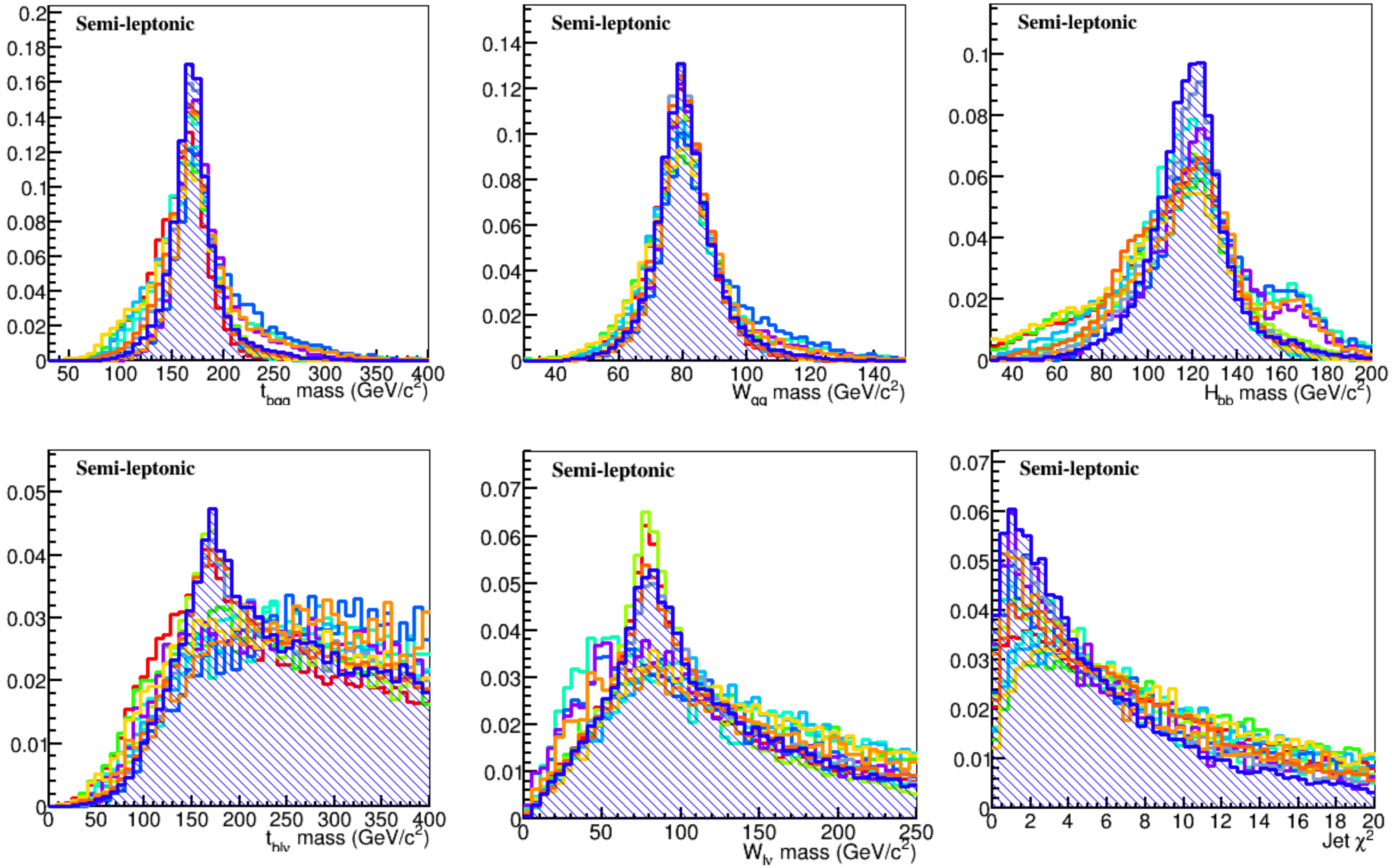
- Energy of the 4 lowest-energy jets
- Cosine of the angle of two closest jets to the beam-axis

-> 27 variables

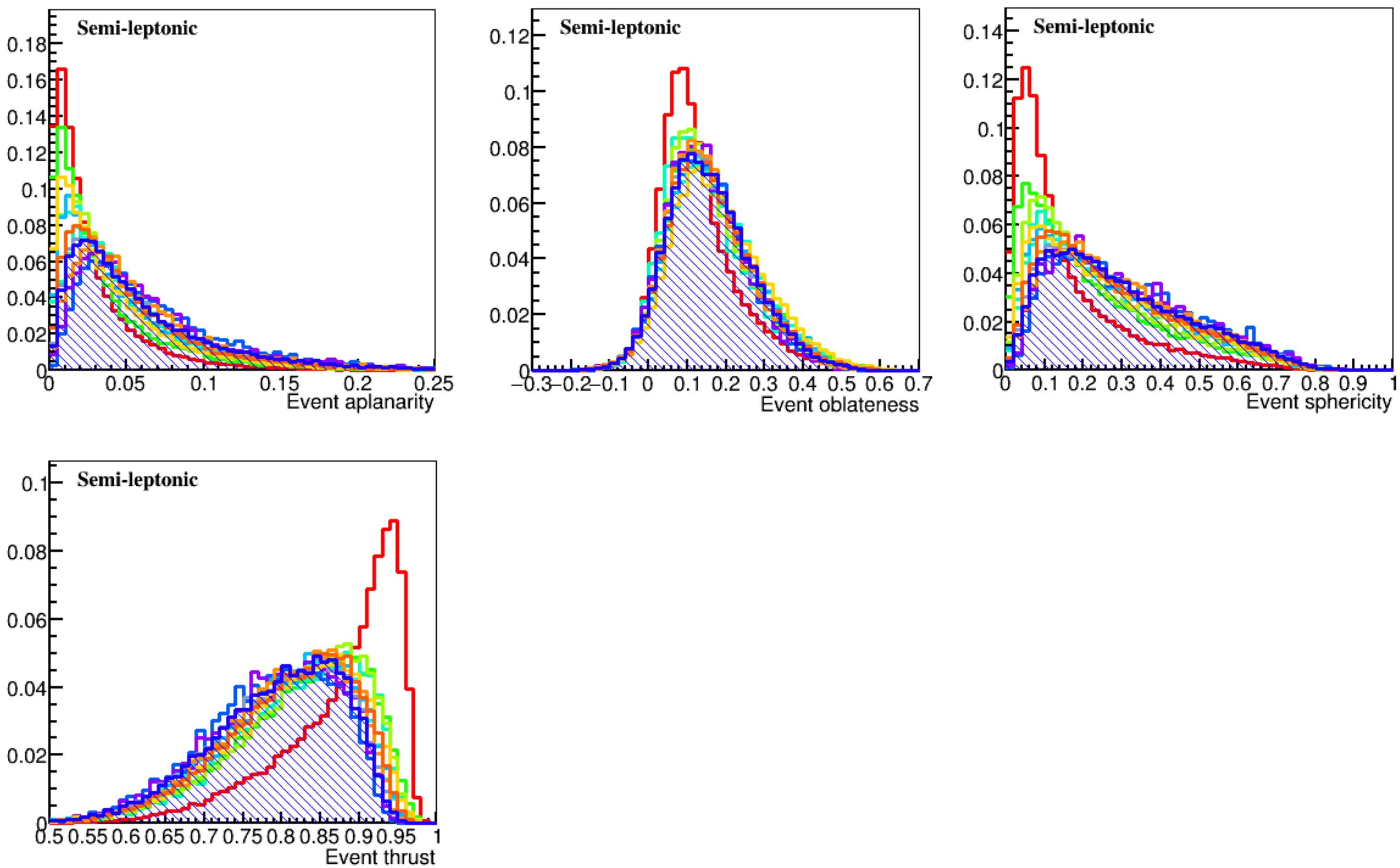
N.B The results presented here are all for the semi-leptonic signal channel.




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)

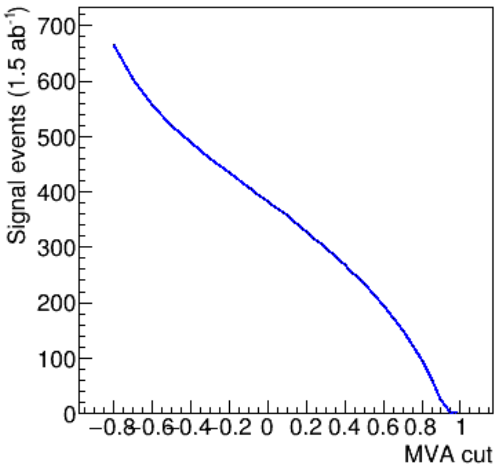


Semi-leptonic
t_{bqq} mass (GeV/c^2)
Semi-leptonic
W_{qq} mass (GeV/c^2)
Semi-leptonic
H_{bb} mass (GeV/c^2)
Semi-leptonic
$t_{bl\nu}$ mass (GeV/c^2)
Semi-leptonic
$W_{l\nu}$ mass (GeV/c^2)
Semi-leptonic
Jet χ^2

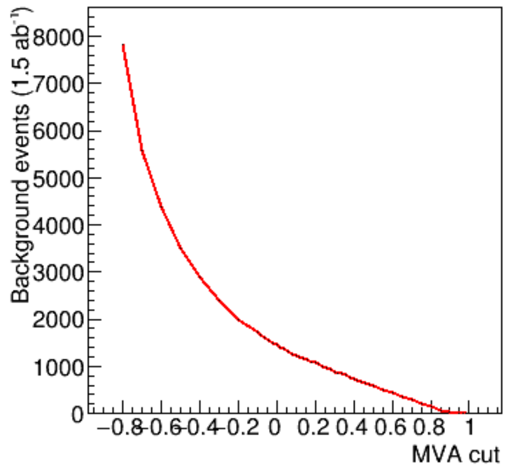


Semi-leptonic
Event aplanarity
Semi-leptonic
Event oblateness
Semi-leptonic
Event sphericity
Semi-leptonic
Event thrust

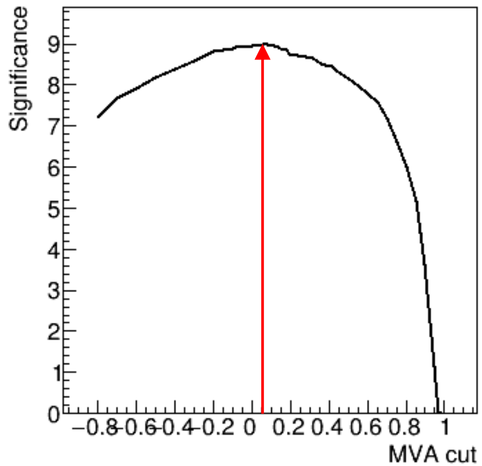
BDTG cut efficiency & optimal significance



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

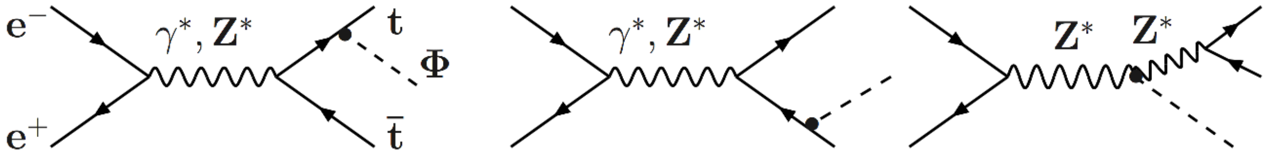
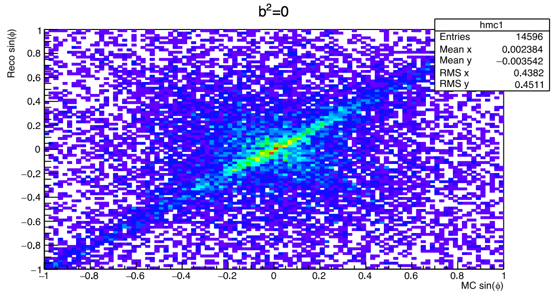


Figure: Feynman diagrams of ttH production.

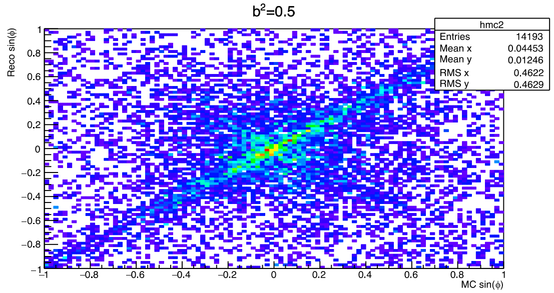
[1] Reference: R.M. Godbole, C. Hangst, M. Mu¨hlleitner, S.D. Rindani and P. Sharma, "Model-independent analysis of Higgs spin and CP properties in the process e^+e^- → ttΦ", arXiv:1103.5404v1 [hep-ph] 28 Mar 2011

MC vs Rec (investigation)

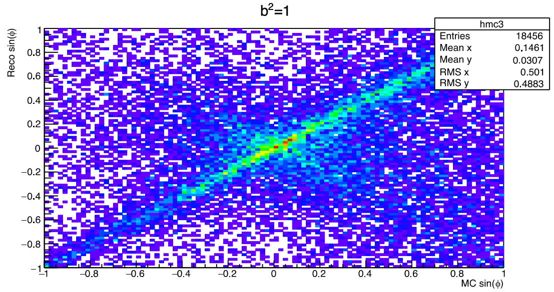
$\sin^2 \phi = 0$



$\sin^2 \phi = 0.5$



$\sin^2 \phi = 1$



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:

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

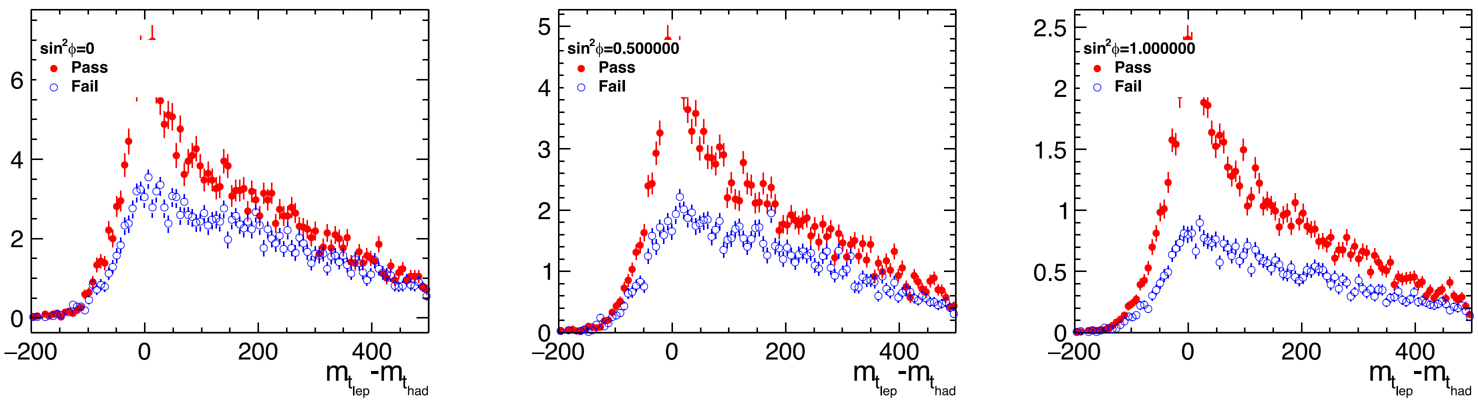
Cuts investigation

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:



→ $m_{t_l} - m_{t_q} < 100$

→ 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 $\sin\theta_\phi$.

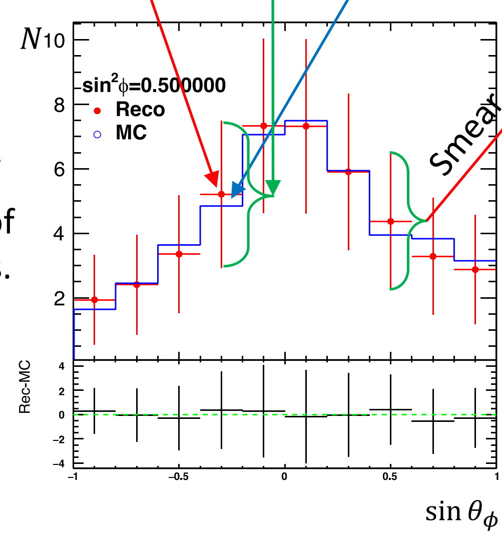
MC: Follows same calculation procedure as above, but use top, anti-top and electron 4-momentum from generator level.

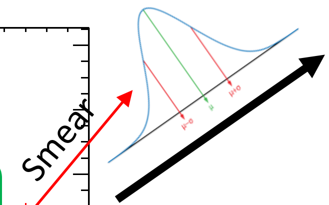
χ^2 template fitting

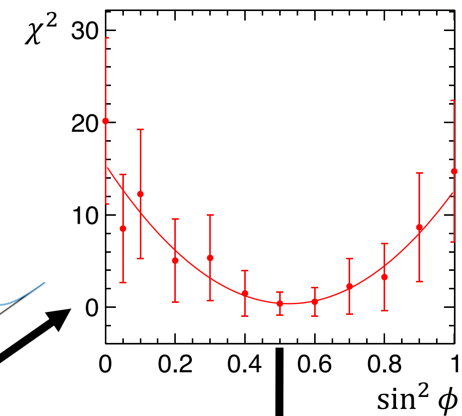
<u>Calculate χ^2 for a specific $\sin^2\phi$ value (e.g =0.5)</u>

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

- 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.

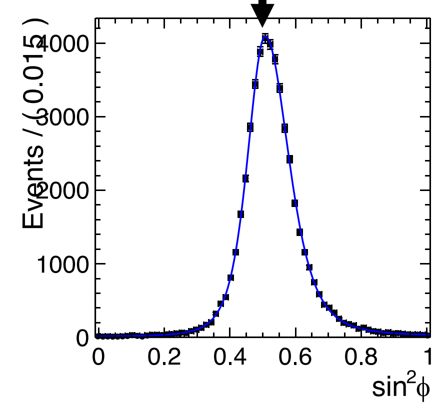






X times

Find minimum and fill Histogram

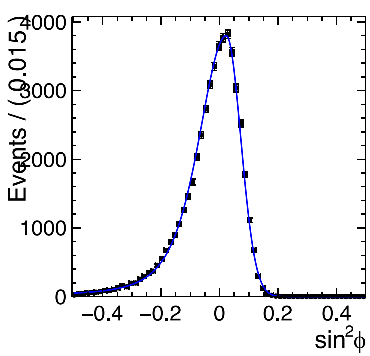


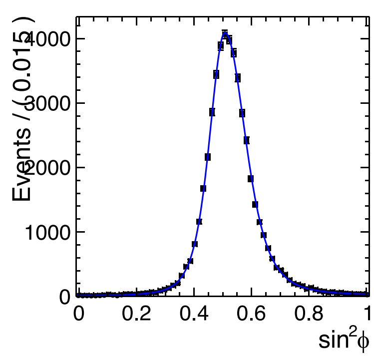
Error estimation

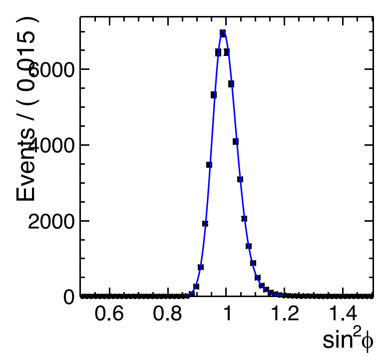
Fitting function:

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

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







The top polarisation asymmetry

The angular distribution in the decay $t \to bW \to bl\nu$ 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.

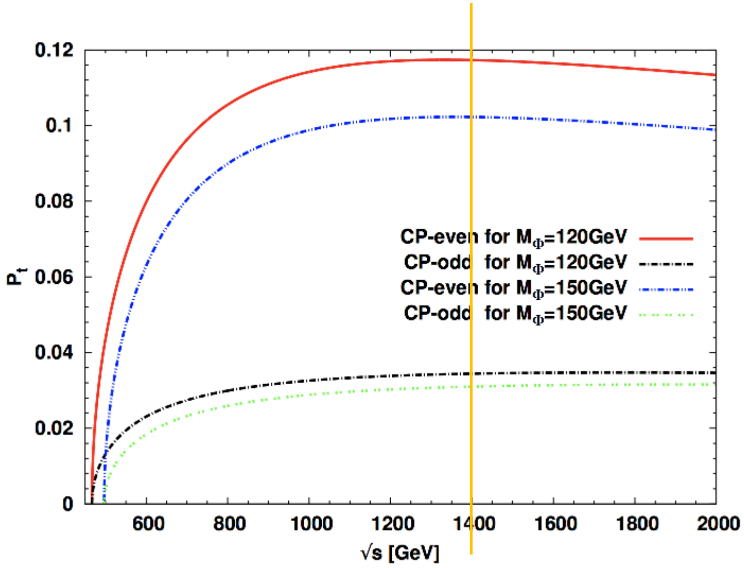


Figure : The top polarisation asymmetry for various Higgs models with unpolarised e± beams [1].