Prospects for top-Yukawa coupling and Higgs boson CP at the CLIC e^+e^- collider

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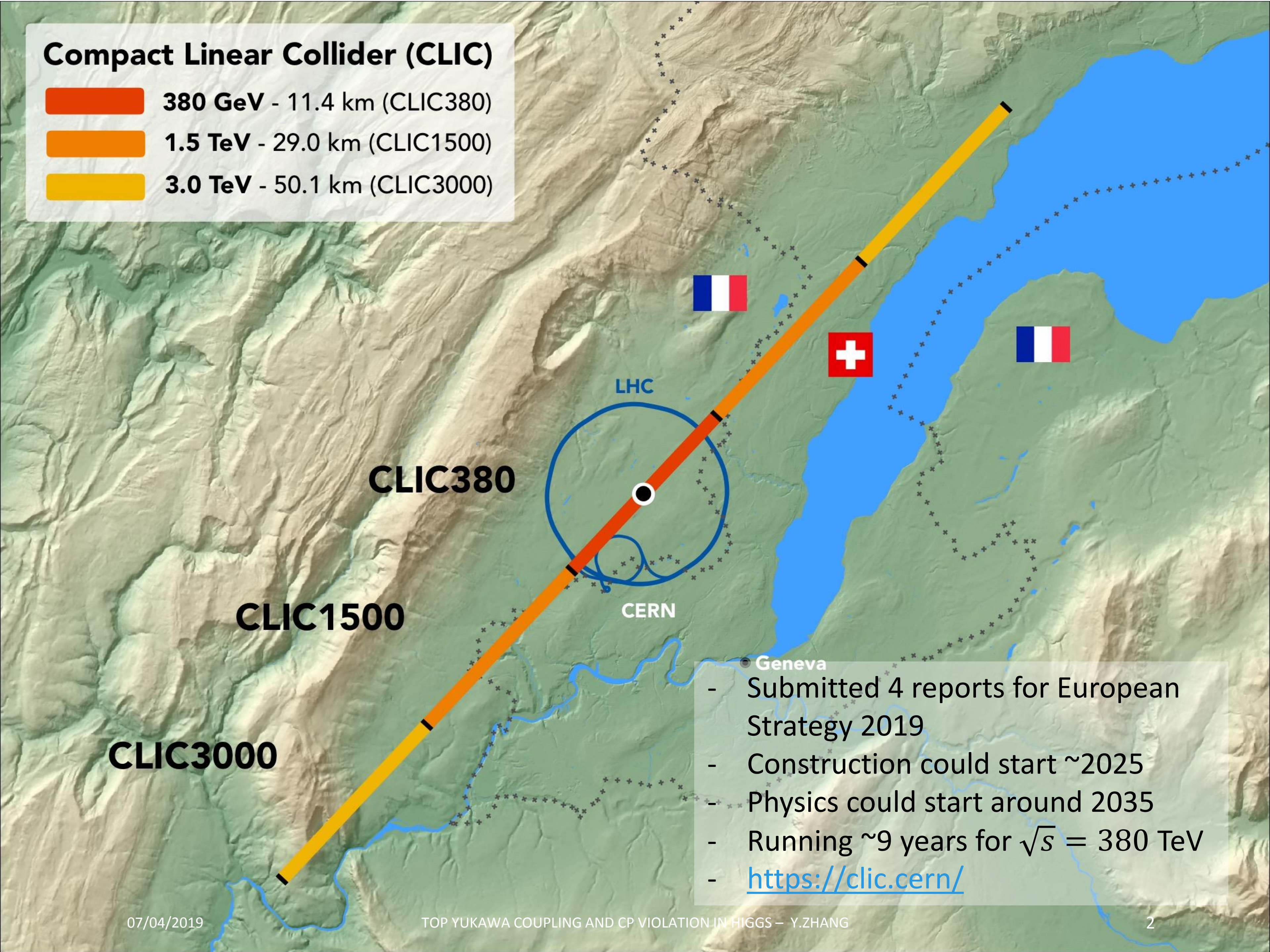
IoP Joint HEPP and APP Annual Conference 2019,
Imperial College London

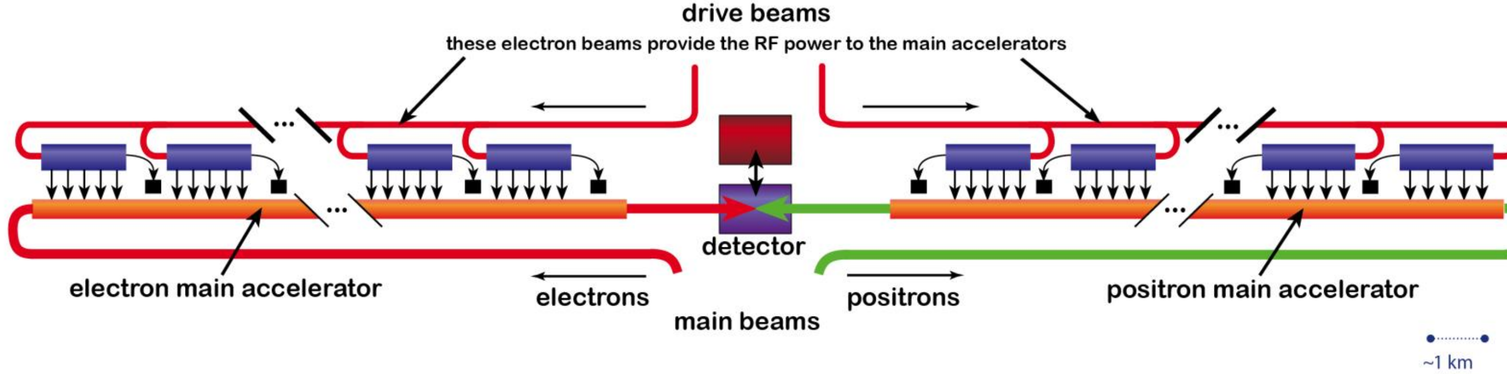
Outline

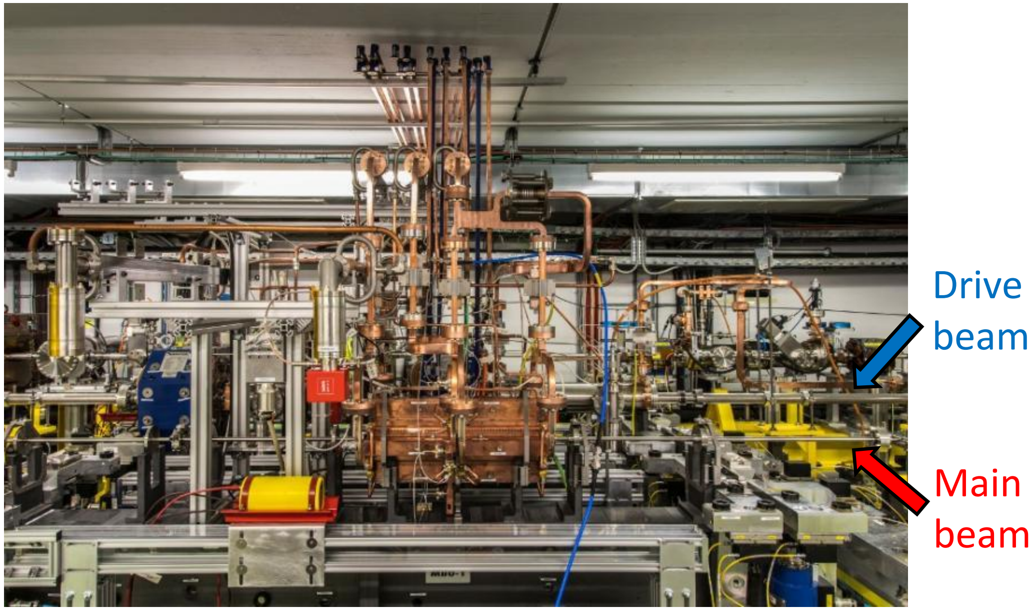
- ❑ CLIC overview
- ❑ The top Yukawa analysis at 1.4 TeV
  - Strategy and Pre-selections
  - Event Reconstruction and flavour-tagging
  - Multivariant selection (TMVA)
  - Results
- ❑ CP property of Higgs boson
  - Sample production and cross-section calculation
  - Preliminary sensitivity to CP mixing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



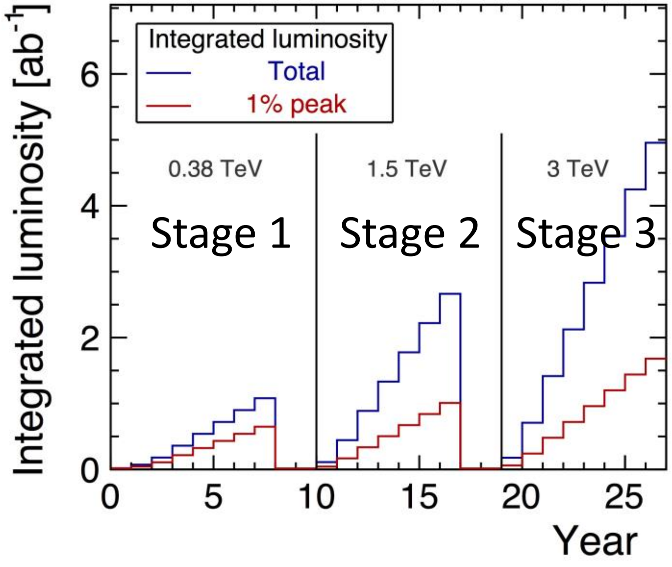
- Submitted 4 reports for European Strategy 2019
- Construction could start ~2025
- Physics could start around 2035
- Running ~9 years for $\sqrt{s} = 380$ TeV
- https://clic.cern/

Compact Linear Collider (CLIC)

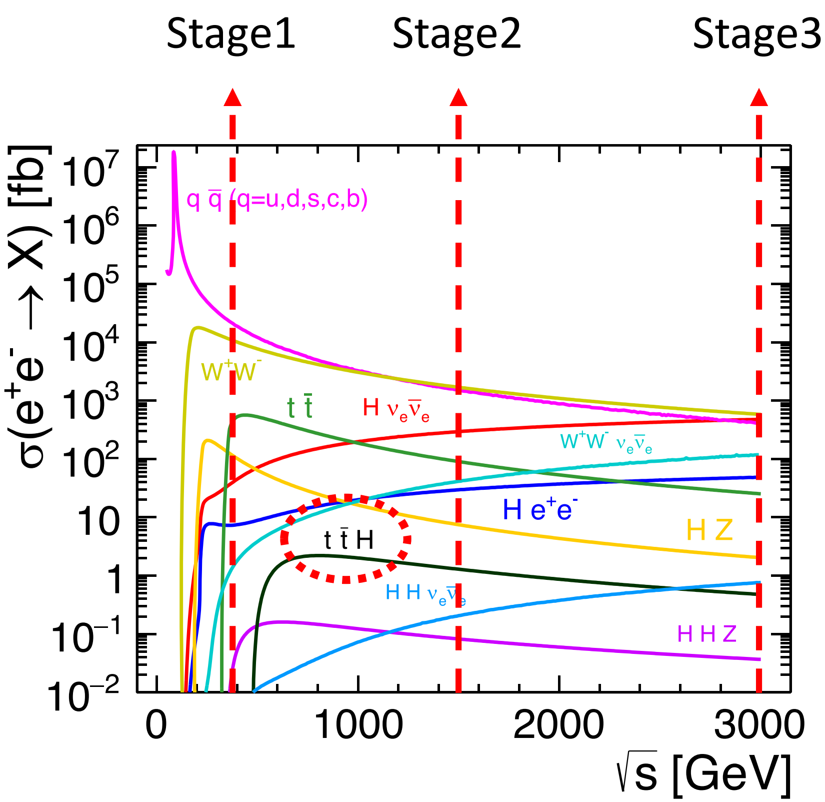


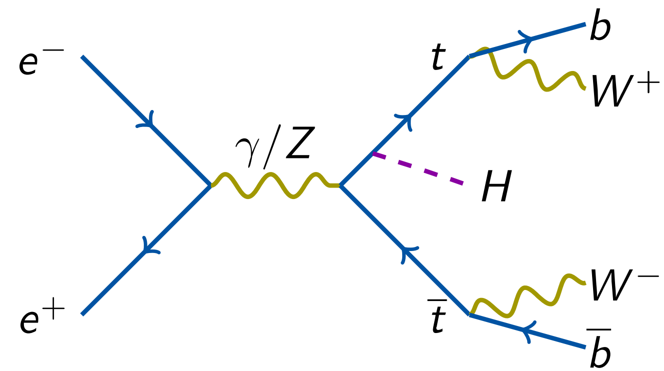


CTF3 facility



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

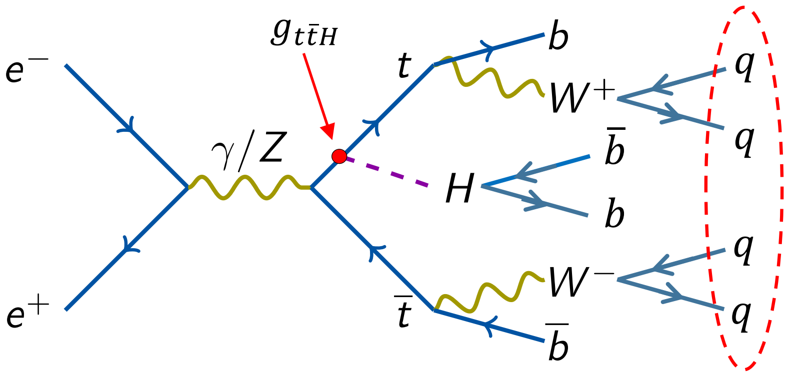
Cons:

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

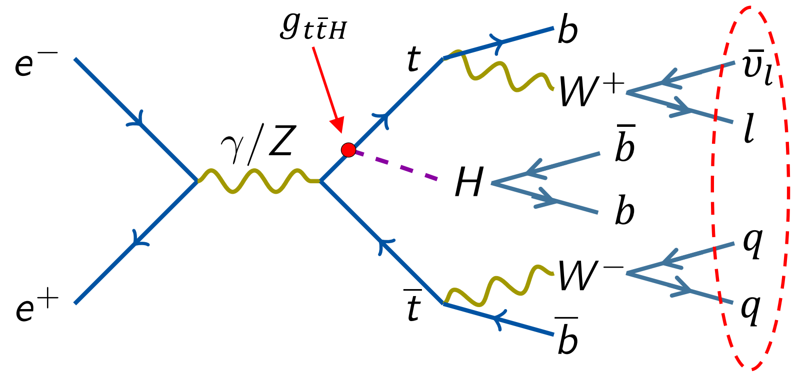
Analysis Strategy

$\sigma(e^+ + e^- \rightarrow t\bar{t}H) = 1.68$ fb at 1.4 TeV

$H \rightarrow b\bar{b}(\approx 56\%), \mathcal{L} = 2.5$ ab^{-1}



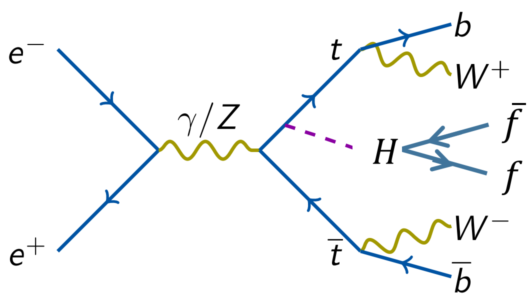
Hadronic channel: 6 jets



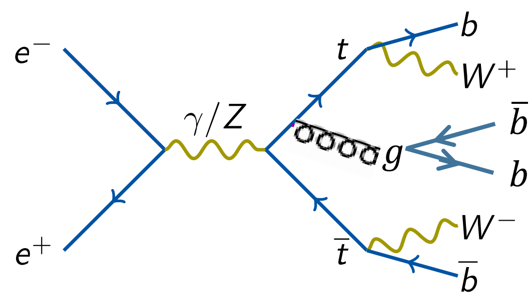
Semi-leptonic channel: 4 jets

$t\bar{t}H$ 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

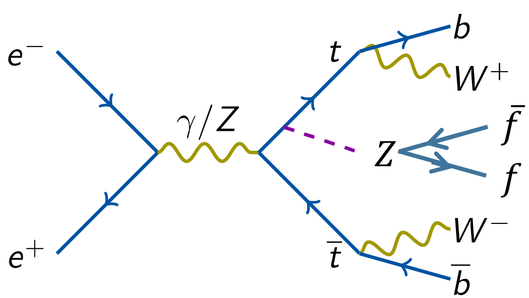
Backgrounds



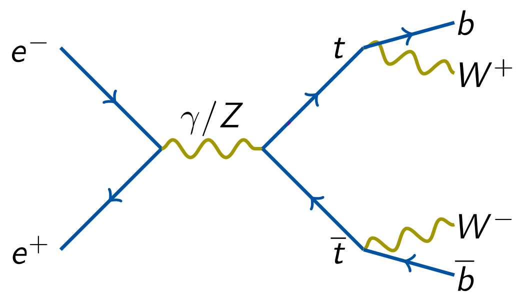
Other $t\bar{t}H$ decays



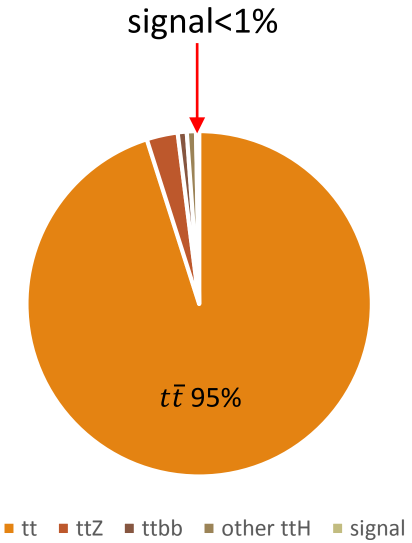
$t\bar{t}b\bar{b}$



$t\bar{t}Z$



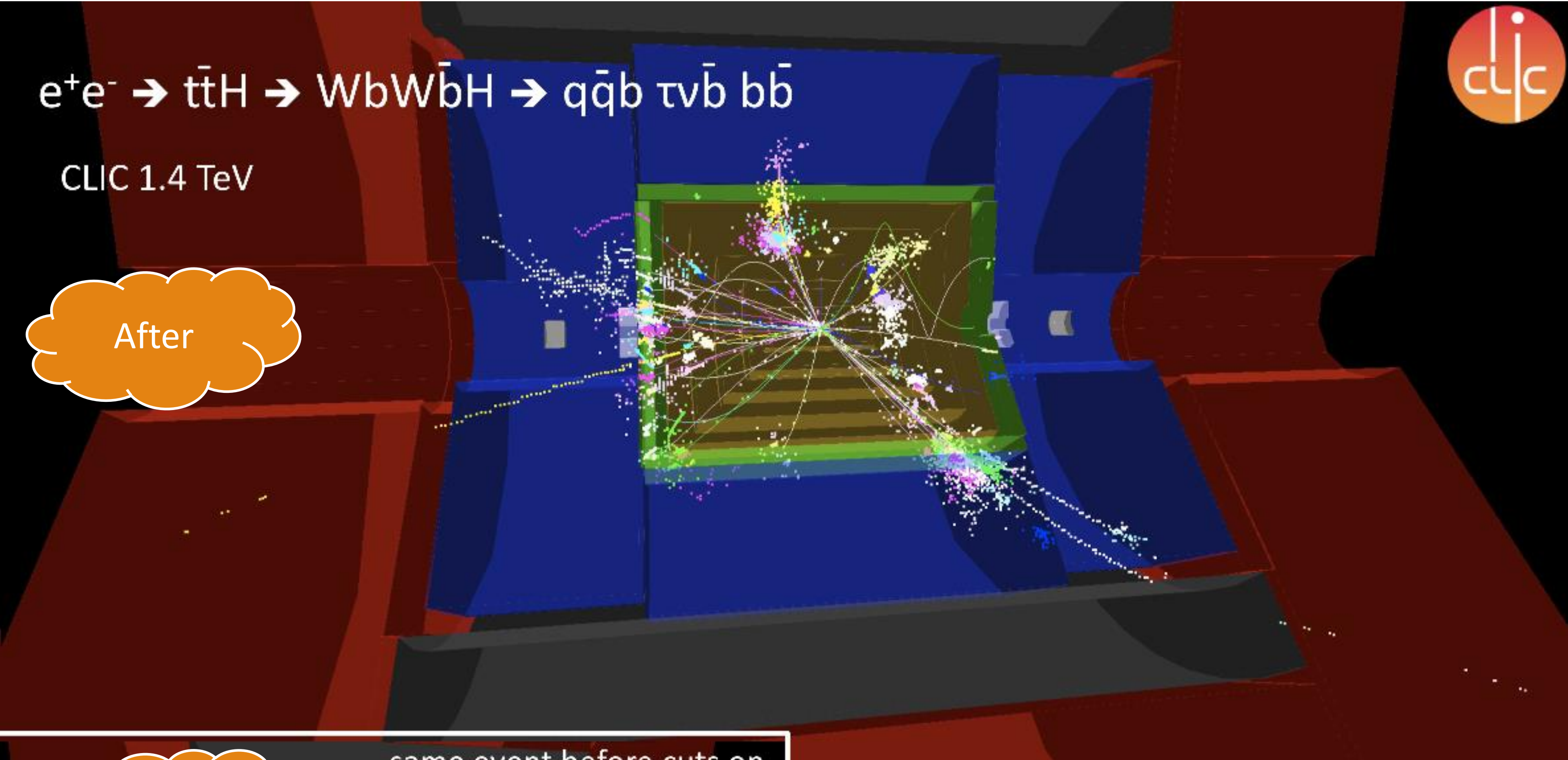
$t\bar{t}$

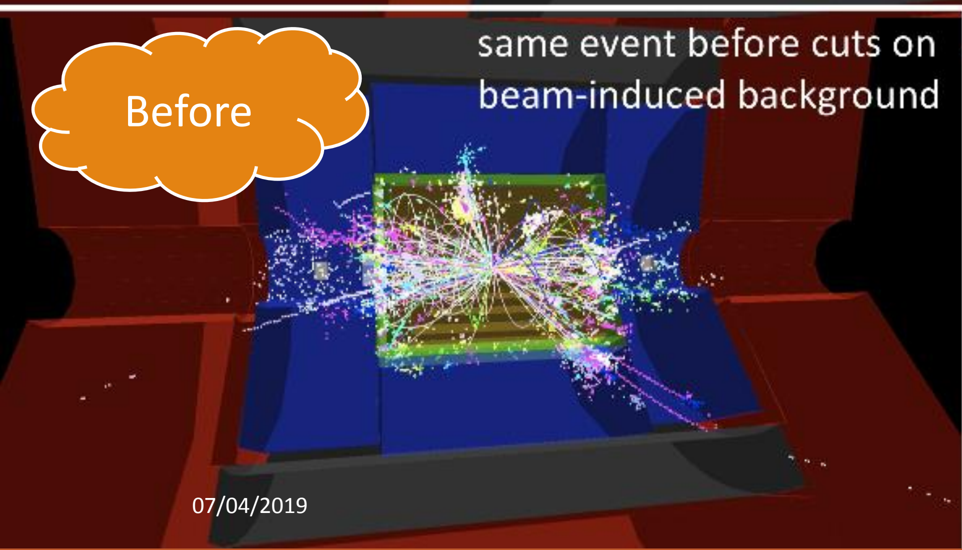


- Generator: $t\bar{t}$ (Pythia), others (Physsim)
- signal and background samples are unpolarised

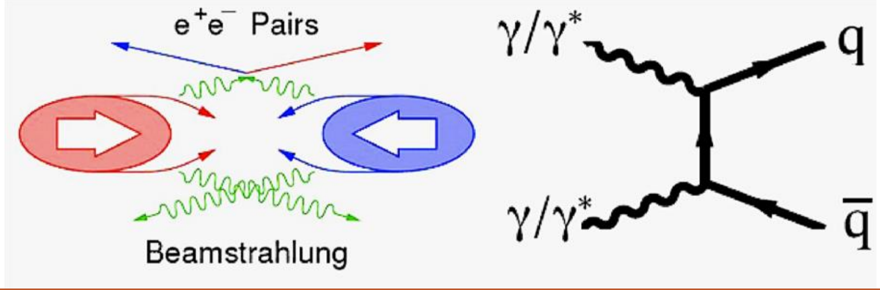
$e^+e^- \rightarrow t\bar{t}H \rightarrow WbW\bar{b}H \rightarrow q\bar{q}b\ \tau\nu\bar{b}\ b\bar{b}$

CLIC 1.4 TeV

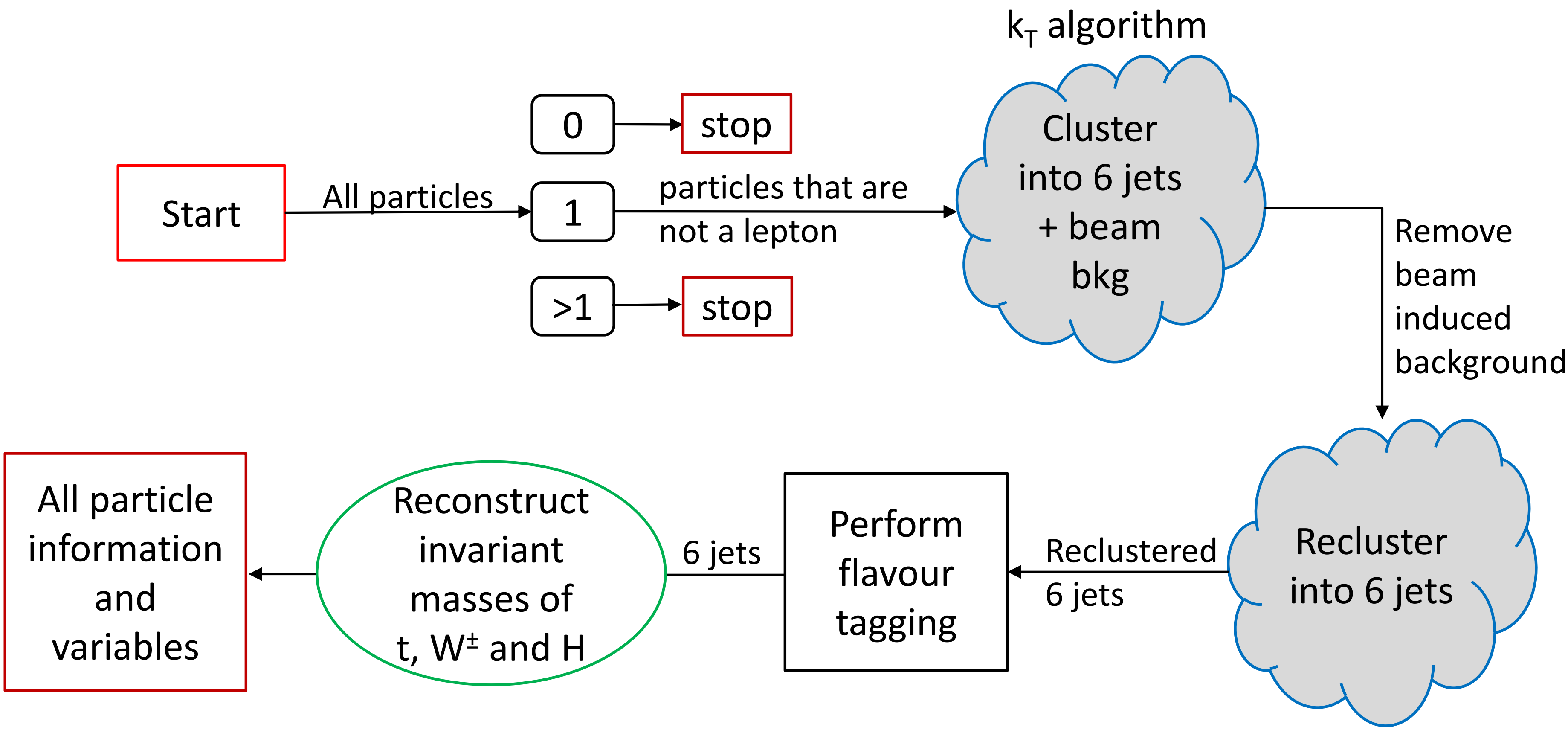




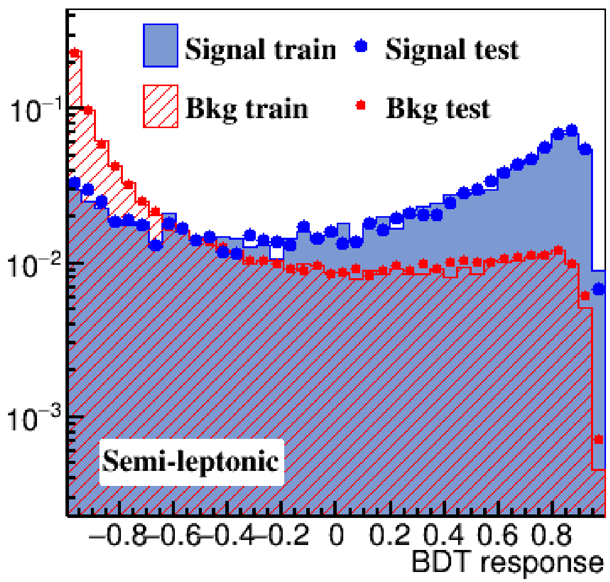
Timing cut and momentum cut applied to suppress the beam-induced backgrounds.

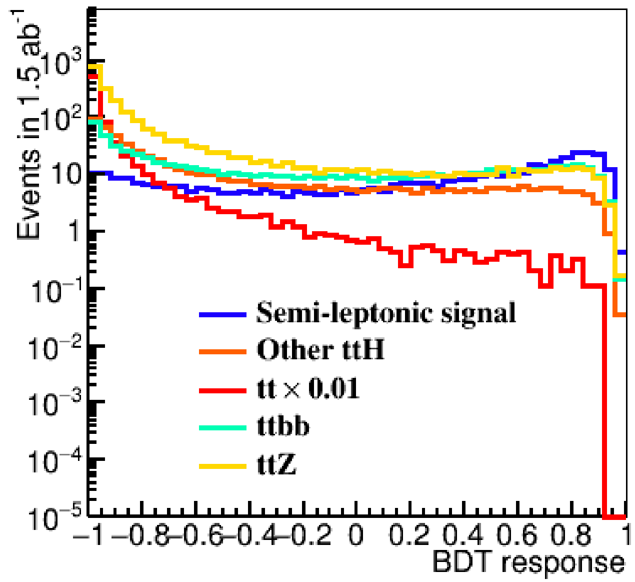


Event reconstruction strategy



BDTG response





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 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, $H\rightarrow b\bar{b}$	647	555 (85.9%)	86 (13.4%)	367 (56.8%)	38 (5.91%)
$t\bar{t}H$, 4 jets, $H\rightarrow b\bar{b}$	623	208 (33.4%)	432 (69.4%)	1 (0.14%)	270 (43.4%)
$t\bar{t}H$, 6 jets, $H\not\rightarrow b\bar{b}$	473	276 (58.4%)	143 (30.2%)	54 (11.4%)	11 (2.32%)
$t\bar{t}H$, 4 jets, $H\not\rightarrow b\bar{b}$	455	70 (15.4%)	237 (52.2%)	8 (1.85%)	22 (4.88%)
$t\bar{t}H$, 2 jets, $H\rightarrow b\bar{b}$	150	9 (6.18%)	53 (35.6%)	2 (1.65%)	22 (14.8%)
$t\bar{t}H$, 2 jets, $H\not\rightarrow b\bar{b}$	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

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, $H\to b\bar{b}$	[illegible]	208 (33.4%)	432 (69.4%)	1 (0.14%)	270 (43.4%)
$t\bar{t}H$, 6 jets, $H\not\to b\bar{b}$	[illegible]	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[illegible]	22 (4.88%)
$t\bar{t}H$, 2 jets, $H\to b\bar{b}$	[illegible]	9 (6.18%)	53 (35.6%)	2 ([illegible]	[illegible].8%)
$t\bar{t}H$, 2 jets, $H\not\to$[illegible]	[illegible]	4 (3.90%)	27 (25.0%)	0[illegible]	[illegible]%)
$t\bar{t}Z$, 6 jets	[illegible]	[illegible] (75.0%)	445 (15.7%)	34[illegible]	[illegible])
$t\bar{t}Z$, 4 jets	[illegible]	[illegible] (20.9[illegible]	[illegible]	5[illegible]	[illegible])
$t\bar{t}Z$, 2 jets	[illegible]	[illegible] (5.49%)	214 (32.5%)	[illegible]	[illegible])
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$t\bar{t}$	[illegible]	[illegible]81 (57.0%)	76732 (37.7%)	498 ([illegible]	[illegible]36%)
total $t\bar{t}H$ signal	[illegible]	[illegible]123 (45.7%)	978 (39.8%)	433 ([illegible]	[illegible].8%)
total background	211749	119846 (56.6%)	79834 (36.3%)	1287 (0.61%)	1280 (0.60%)
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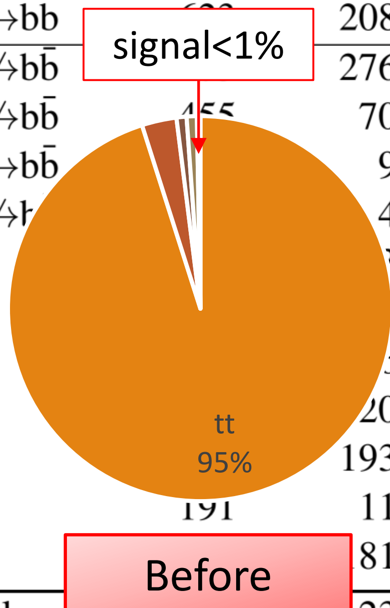
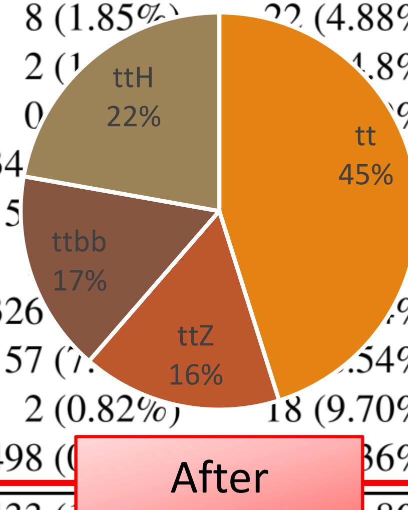
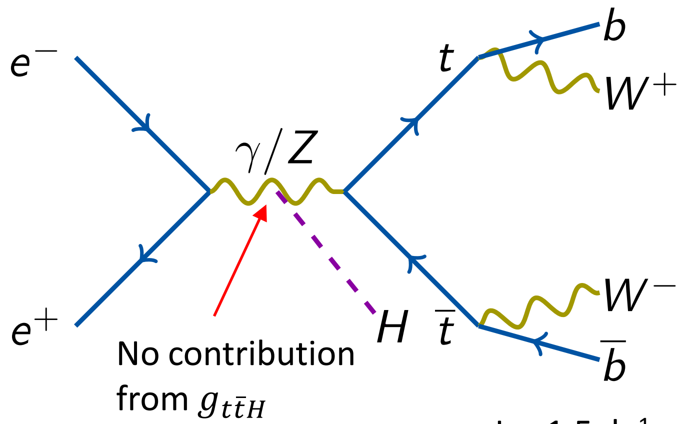




Result on top-Yukawa coupling



To translate the cross-section measurement into top-Yukawa coupling at 1.4 TeV, a linear approximation with NLO QCD prediction is used [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})	L = 2.5ab^{-1} + Polarisation
Hadronic	10.4σ	7.3%	7.5%	**2.7%**
Semi-leptonic	9.0σ			

[1] JHEP 1612 (2016) 075

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: $a = 0, b \neq 0$.

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.

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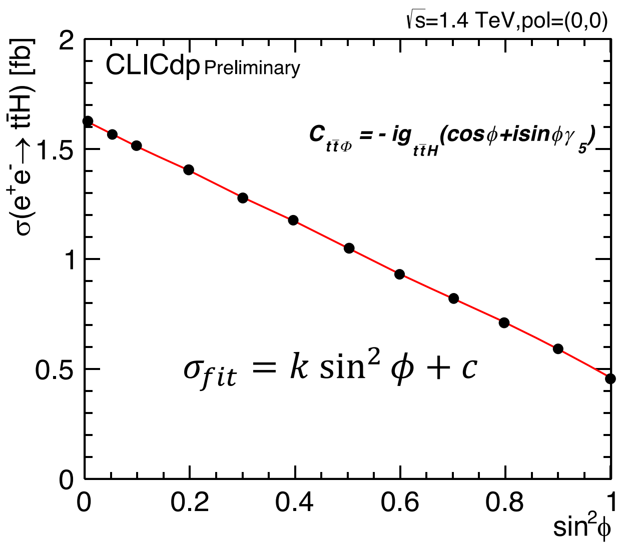
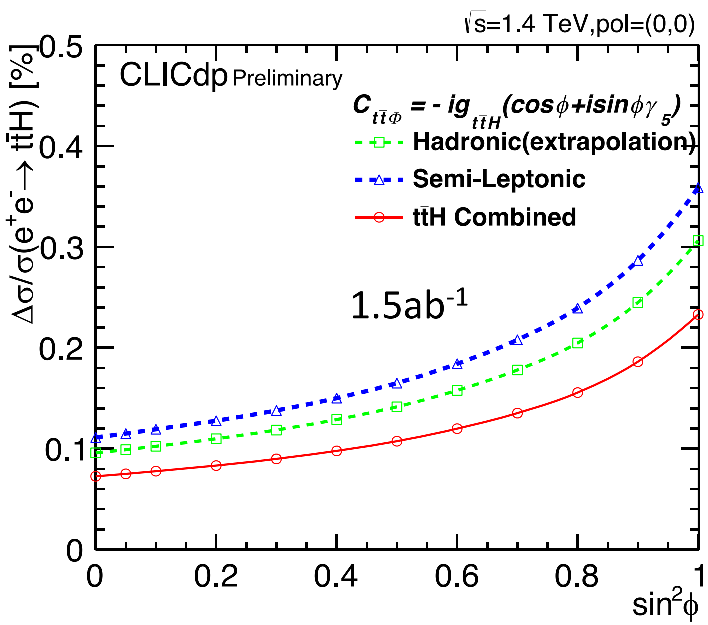
<u>$t\bar{t}\Phi$ cross section</u>

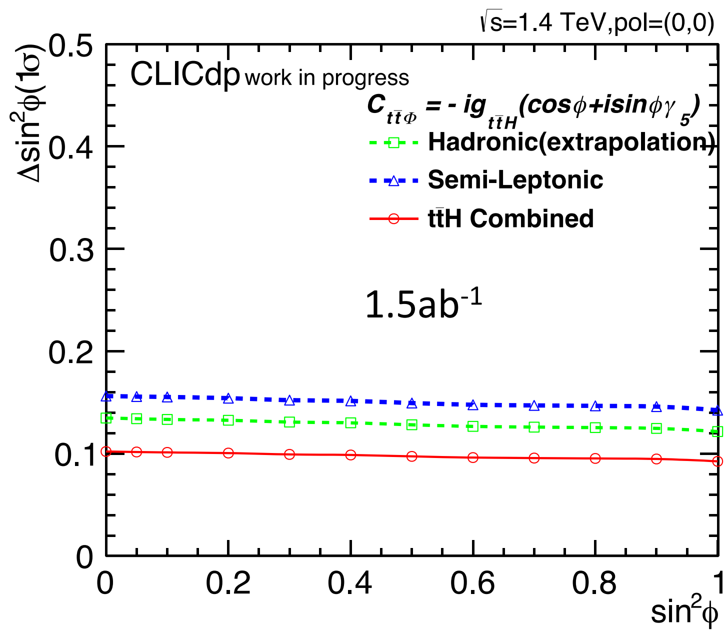
$H \to \Phi$ as Higgs boson is no longer pure CP-even

- 12 different values of $\sin(\phi)$ samples produced



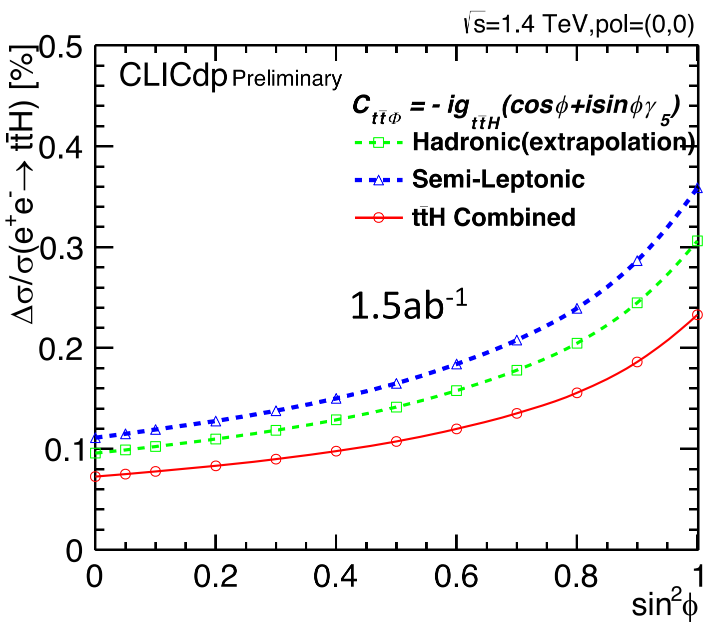
Cross section to CP-mixing sensitivity

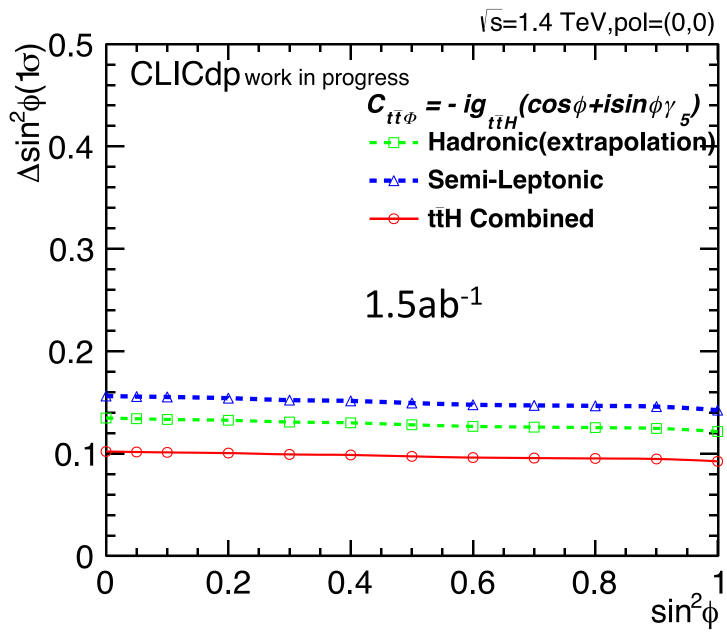




- Apply the top-Yukawa analysis procedure to all samples
- Measure $\Delta\sigma/\sigma$ for all $\sin^2(\phi)$ values in the semi-leptonic channel
- Extrapolate to result to include fully-hadronic channel

Cross section to CP-mixing sensitivity





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

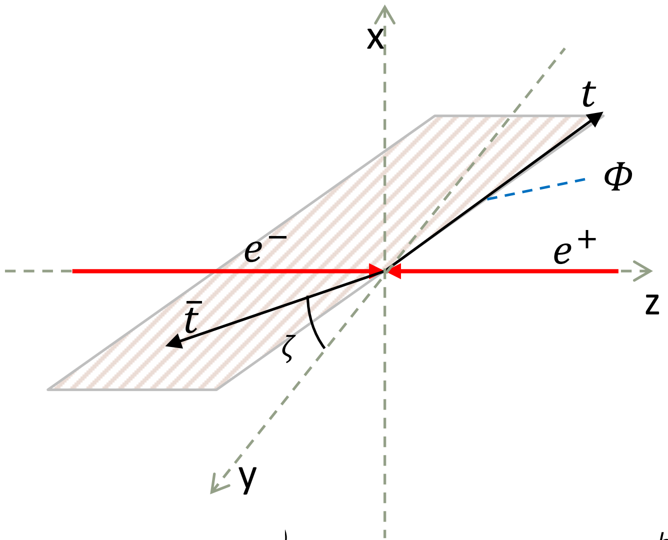
$$\Rightarrow \Delta\sin^2\phi = \frac{1}{k}\frac{\Delta\sigma}{\sigma}\sigma$$

Up-down asymmetry

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

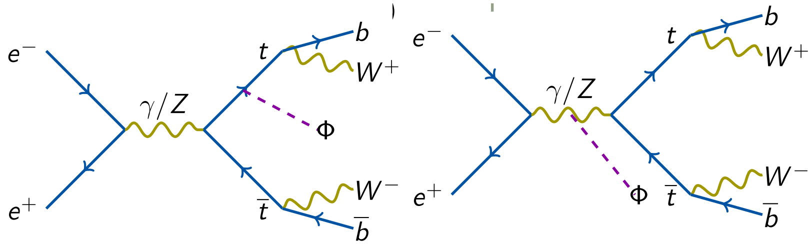
The angle ζ between the antitop and the top-electron plane is given by

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



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

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

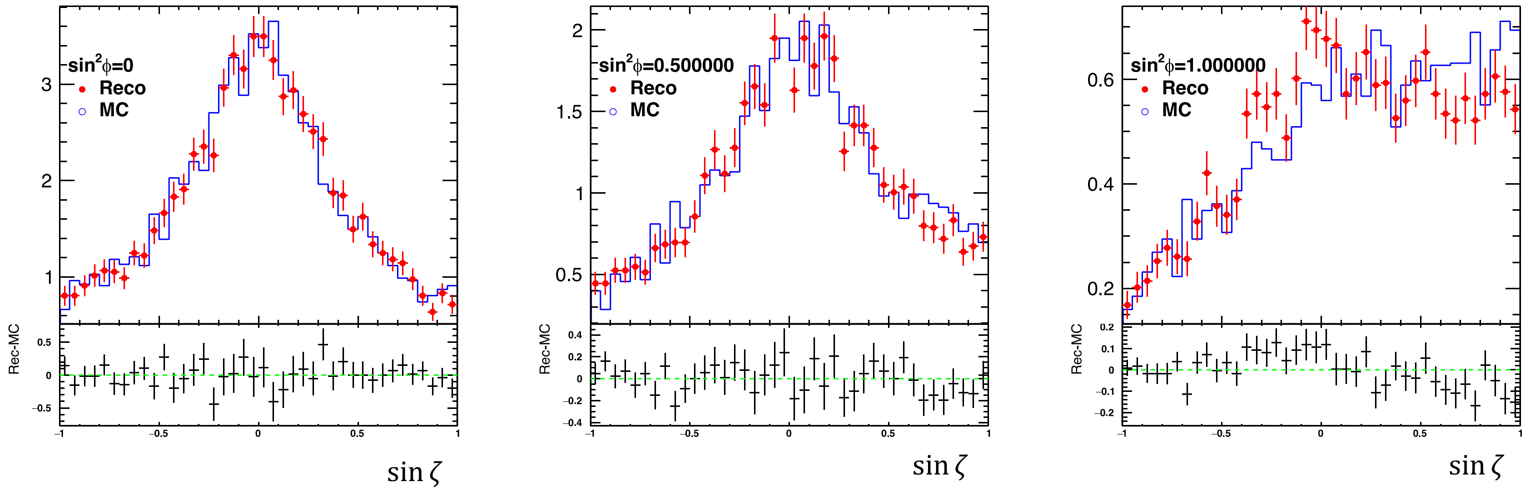


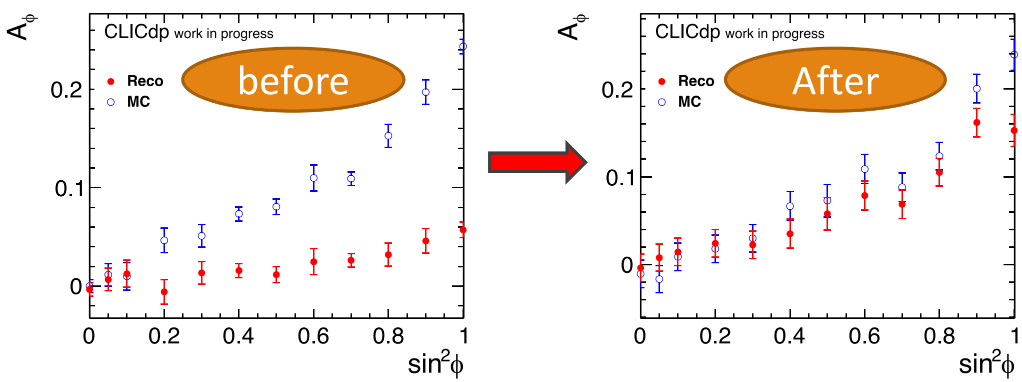
Component of asymmetry from interference between $t\bar{t}\Phi$ and $ZZ\Phi$!

[1] arXiv:1103.5404v1

$\sin\zeta$ and A_ϕ with tight cuts

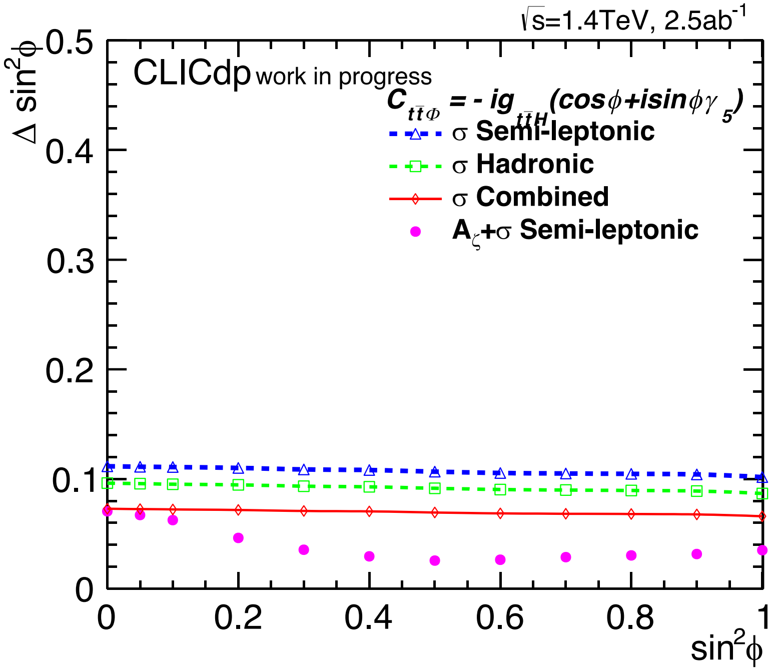
Pure CP-even | 50% CP-even & CP-odd | Pure CP-odd





<u>Quality cuts:</u>
Remove taus and mis-reconstructed tops

Preliminary results on mixing angle



With integrated luminosity 2.5 ab^{-1} at 1.4 TeV

- Combined cross section:

  $$\Delta \sin^2(\phi) \simeq 0.07$$

- Up-down asymmetry + cross section in semi-leptonic channel:

  $$\Delta \sin^2(\phi) \simeq 0.03 - 0.07$$

Summary

- CLIC is a mature option for a high energy electron positron collider to make precision measurements of the top quark, Higgs boson and potential new particles

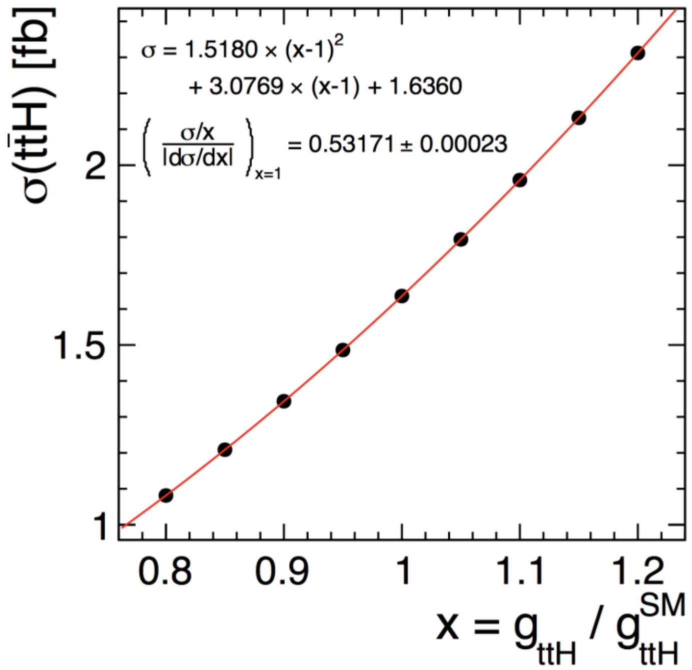
- My analysis has found $\frac{\Delta g_{t\bar{t}H}}{g_{t\bar{t}H}} = 2.7\%$ with polarised beam and an integrated luminosity of 2.5 ab^{-1} at $\sqrt{s}$ =1.4 TeV at CLIC,
  - HL-LHC projection at 3000 fb^{-1} measures ~10% precision, ATL-PHYS-PUB-2014-016
  - ILC at 1 TeV found 4.5% with luminosity of 1 ab^{-1} and unpolarised beam, arXiv:1409.7157

- Sensitivity to Higgs boson CP mixing 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 up to $\Delta\sin^2(\phi) \approx 0.03$ with luminosity of 2.5ab^{-1} and polarised beam.

Backup Slides

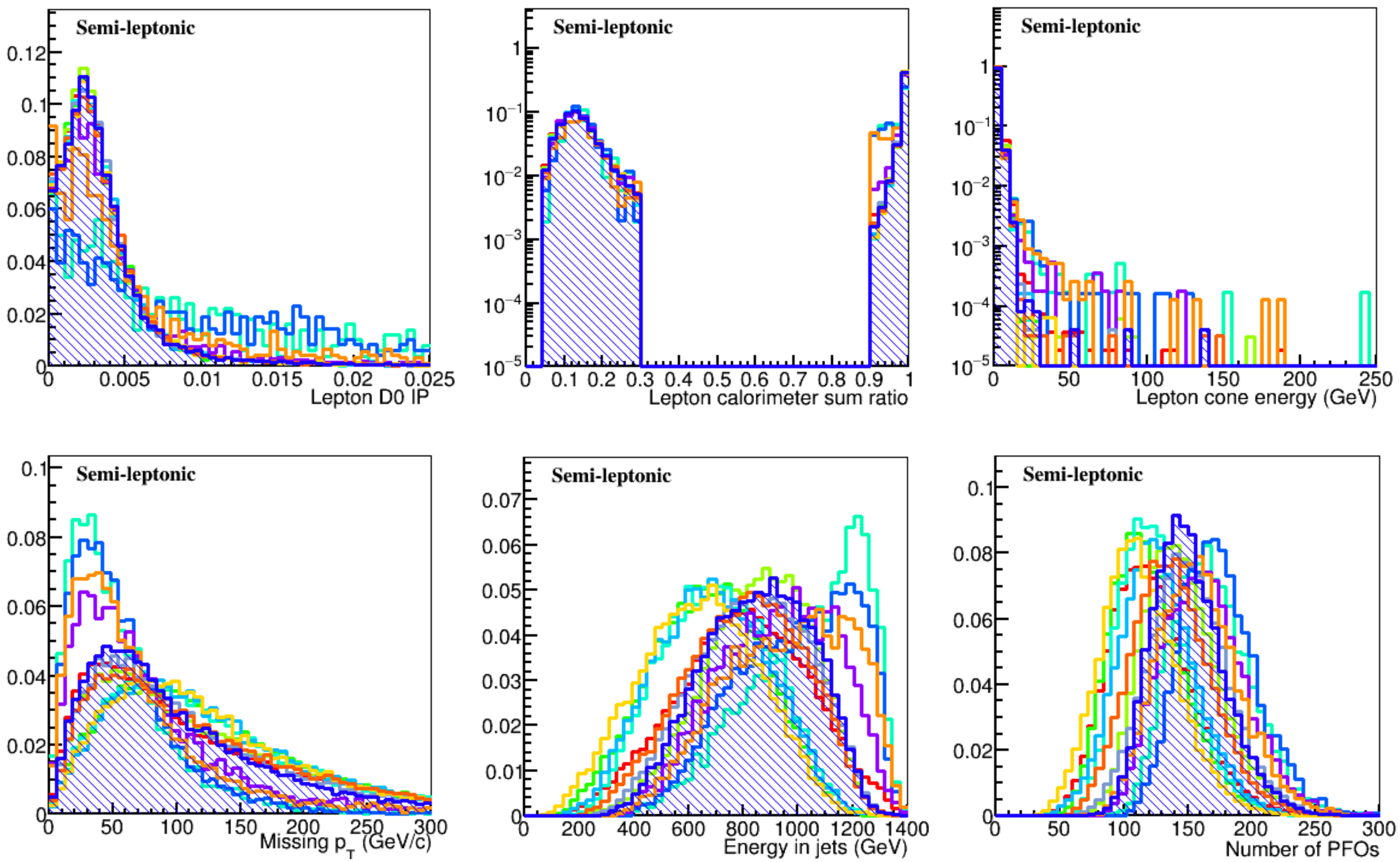
Result on top-Yukawa coupling

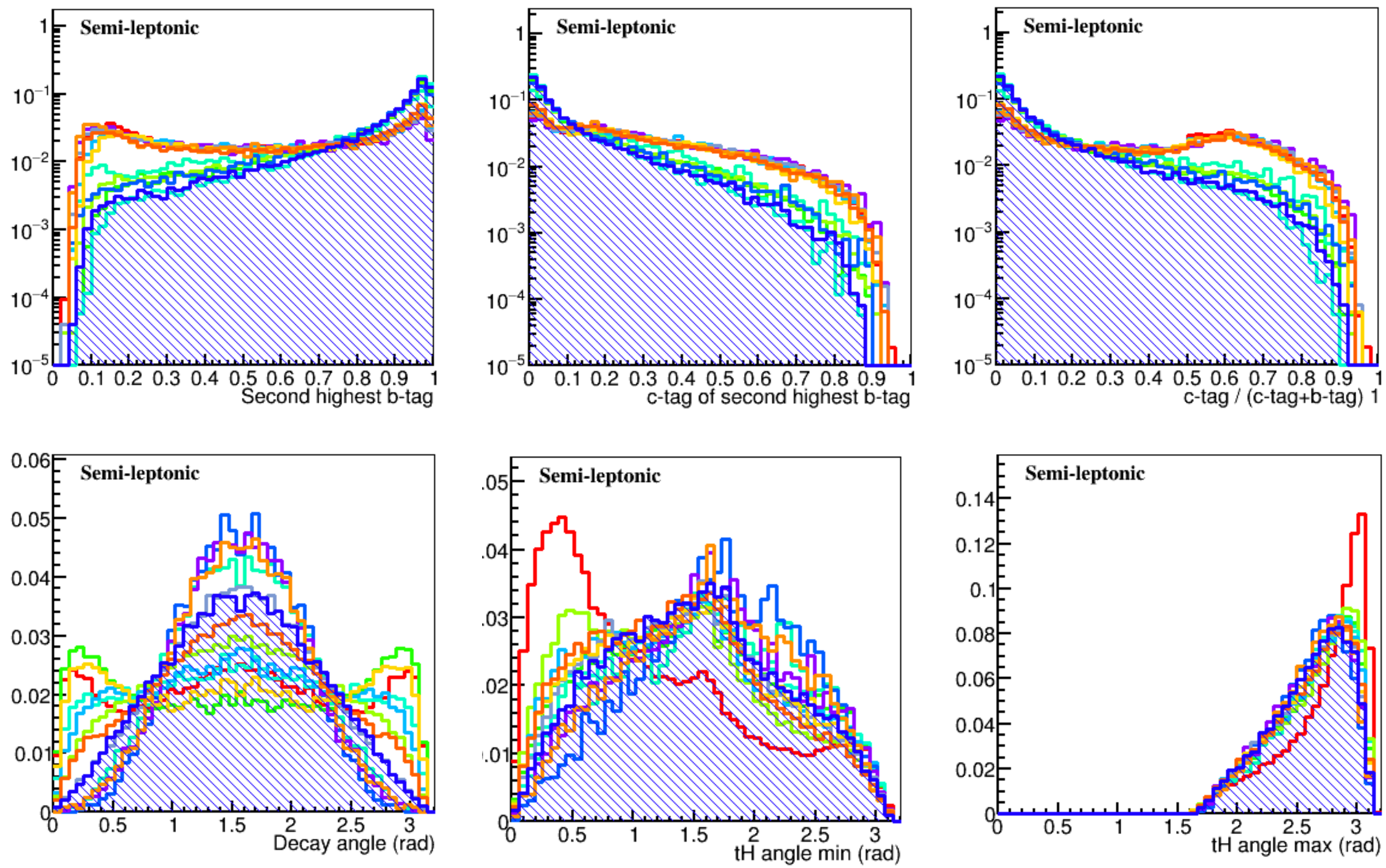


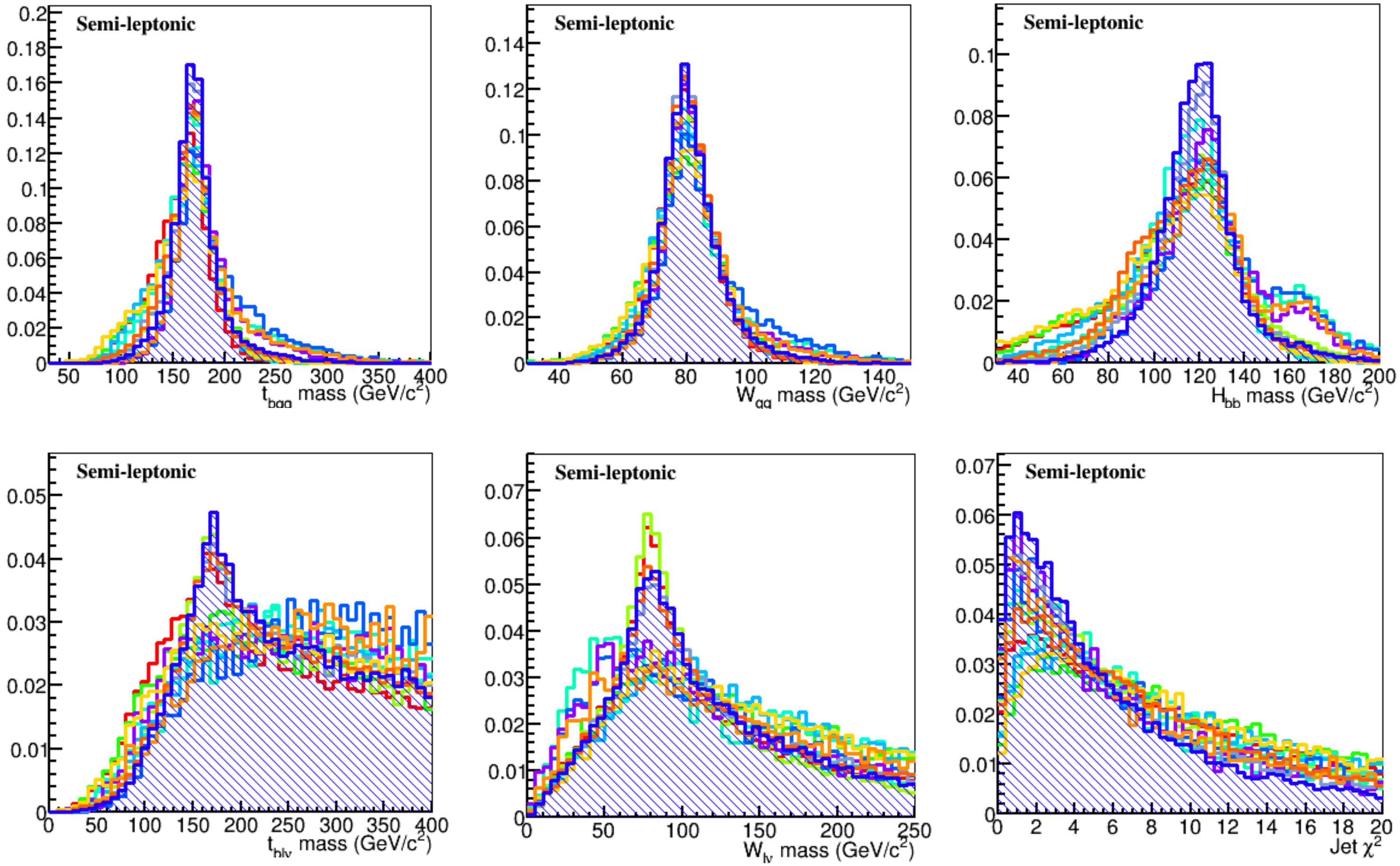
To translate the cross-section measurement into top Yukawa coupling at 1.4 TeV, a linear approximation is used (old, using quadratic fit):

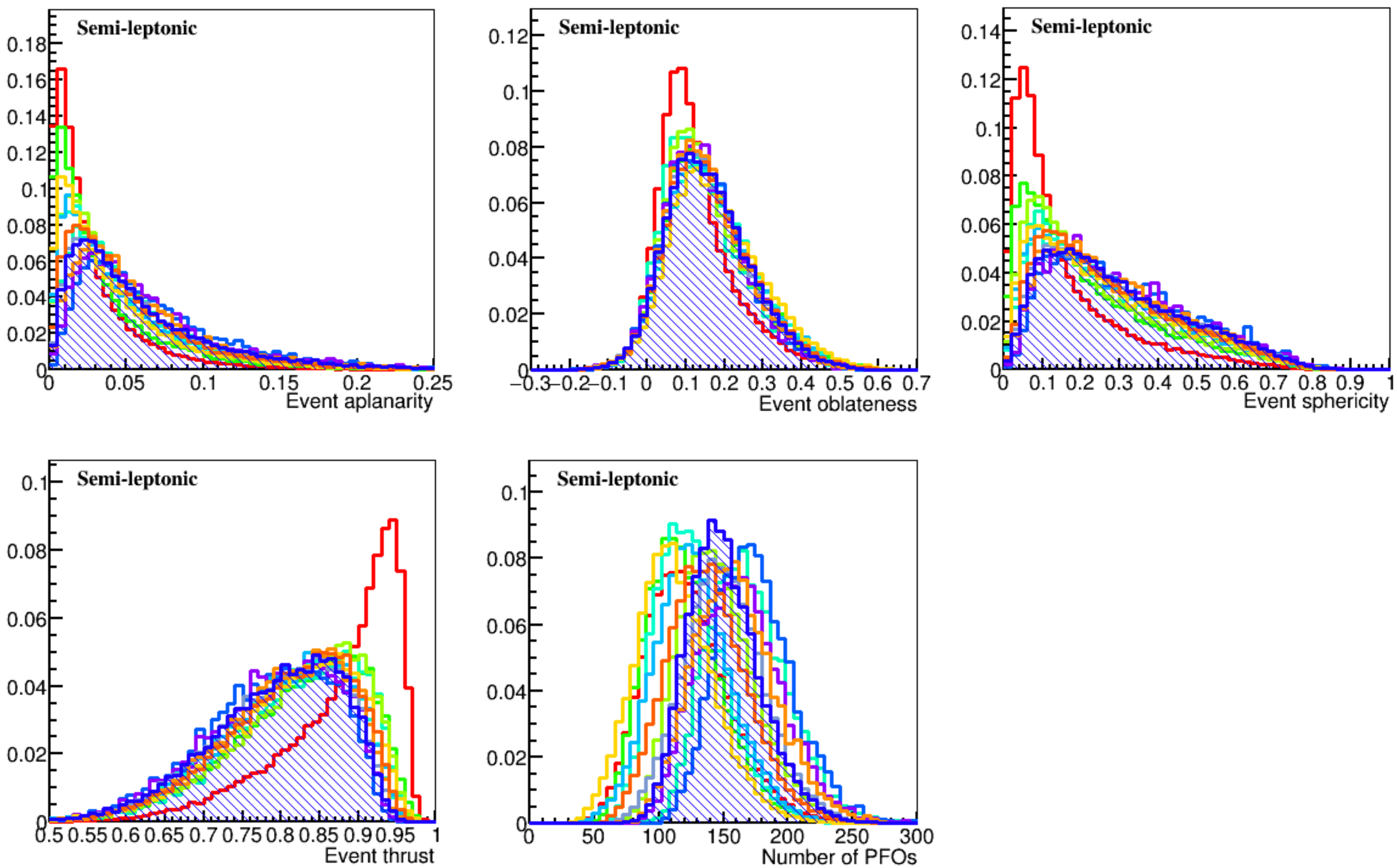
$$\frac{\Delta g_{t\bar{t}H}}{g_{t\bar{t}H}} = 0.53\,\frac{\Delta\sigma(t\bar{t}H)}{\sigma(t\bar{t}H)}$$

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
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0 0.05 0.1 0.15 0.2 0.25
Event aplanarity
Semi-leptonic
0.12
0.1
0.08
0.06
0.04
0.02
0
−0.3−0.2−0.1 0 0.1 0.2 0.3 0.4 0.5 0.6 0.7
Event oblateness
Semi-leptonic
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
Event sphericity
Semi-leptonic
0.1
0.08
0.06
0.04
0.02
0
0.5 0.55 0.6 0.65 0.7 0.75 0.8 0.85 0.9 0.95 1
Event thrust
Semi-leptonic
0.1
0.08
0.06
0.04
0.02
0
0 50 100 150 200 250 300
Number of PFOs

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

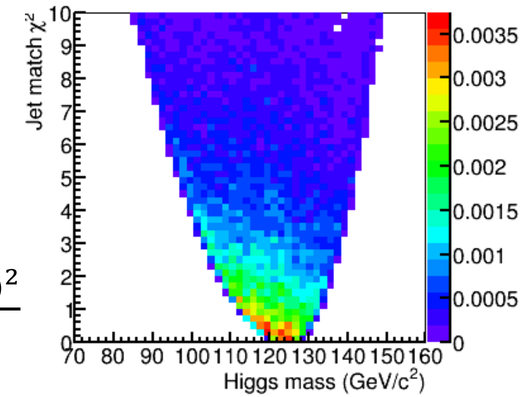
Chi-square method is used to reconstruct the $W^{\pm}$, top and Higgs candidates by combining the jets.

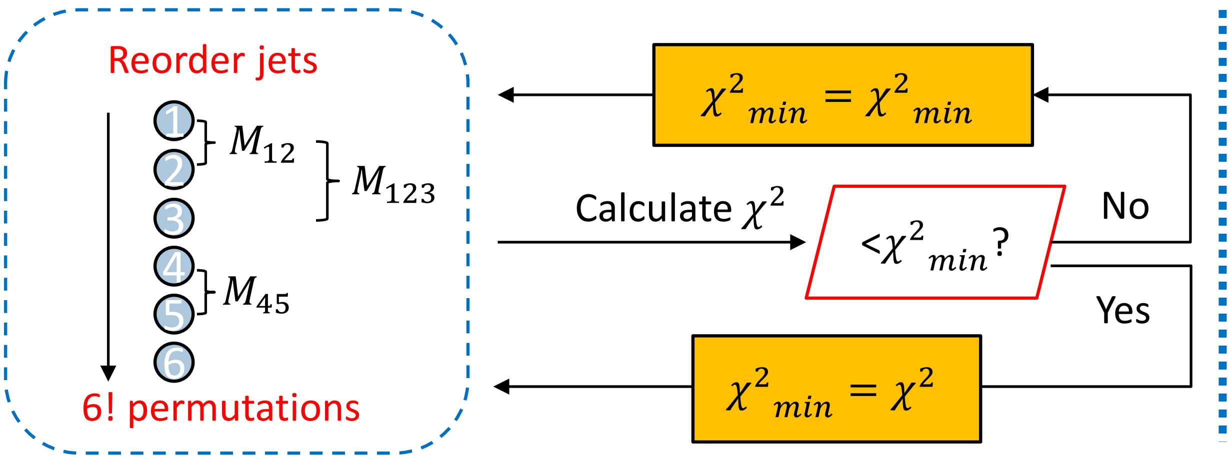
Semi-leptonic:

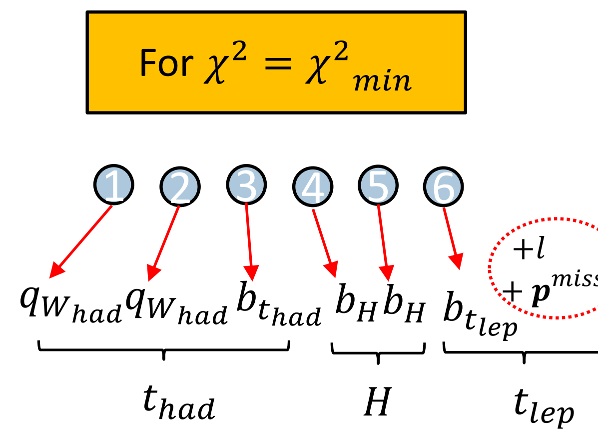
$$\chi_6^2 = \frac{(M_{12}-M_{W^\pm})^2}{\sigma_{W^\pm}^2} + \frac{(M_{123}-M_t)^2}{\sigma_t^2} + \frac{(M_{45}-M_H)^2}{\sigma_H^2}$$

Hadronic:

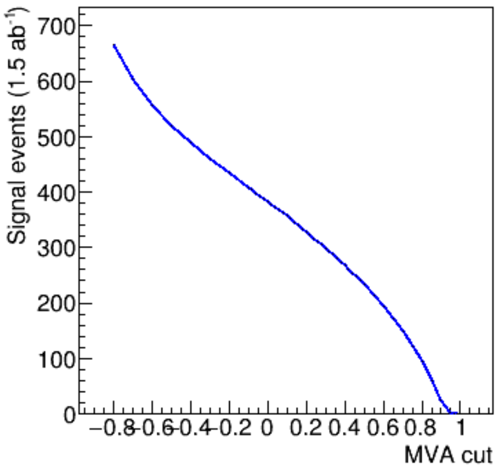
$$\chi_8^2 = \frac{(M_{12}-M_{W^\pm})^2}{\sigma_{W^\pm}^2} + \frac{(M_{123}-M_t)^2}{\sigma_t^2} + \frac{(M_{45}-M_{W^\pm})^2}{\sigma_{W^\pm}^2} + \frac{(M_{456}-M_t)^2}{\sigma_t^2} + \frac{(M_{78}-M_H)^2}{\sigma_H^2}$$



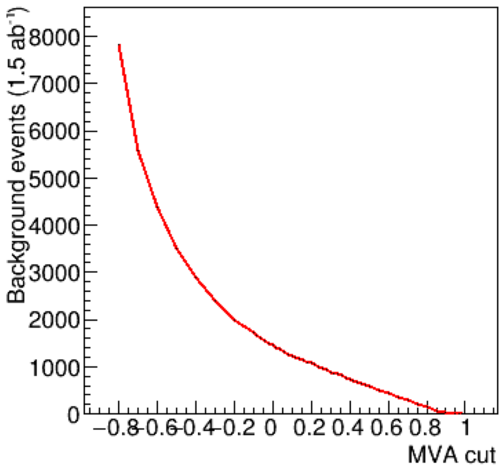




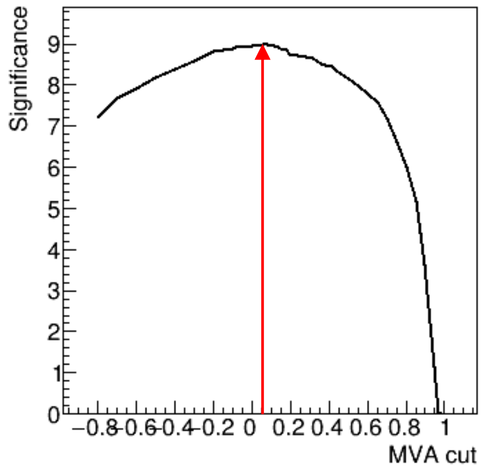
BDTG cut efficiency & optimal significance



signal



background

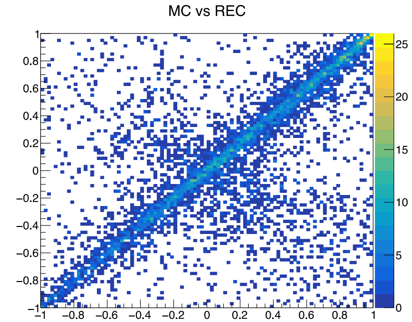


significance

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

Optimal significance obtained for the semi-leptonic channel.

Improvement of top reconstruction

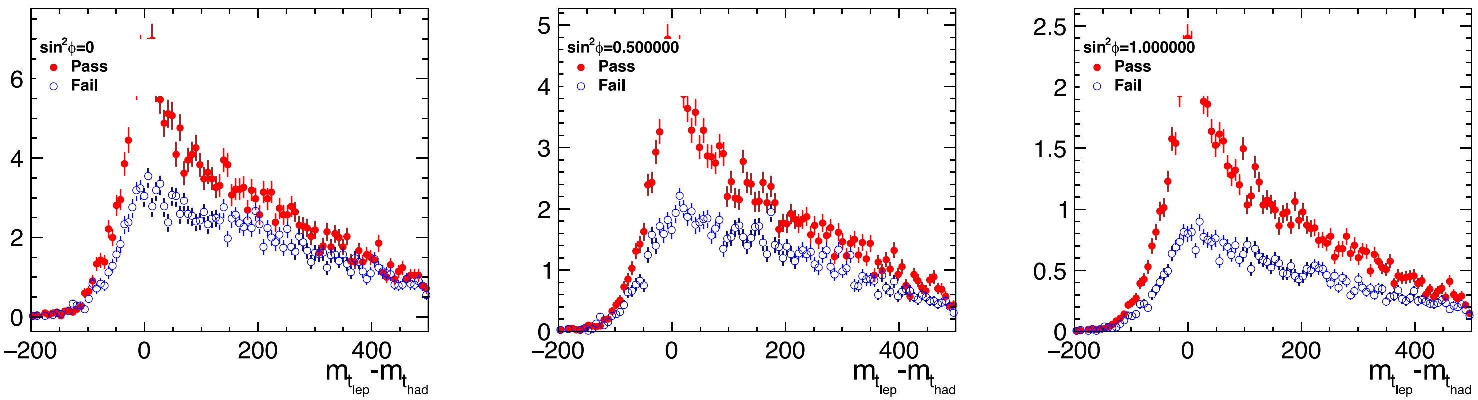


How to cut away mis-identified top?

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

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

<u>Example</u>: $m_{t_{lep}} - m_{t_{had}}$ from reconstruction:



Tight cuts:

→ $m_{t_l} - m_{t_q} < 100$

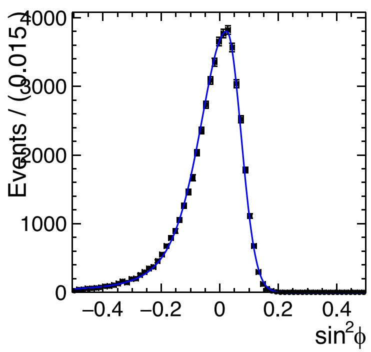
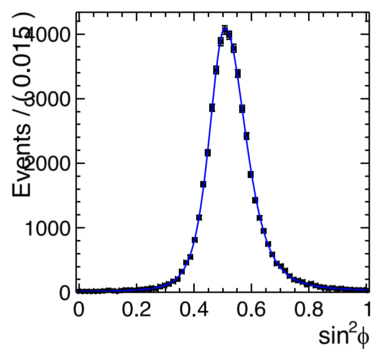
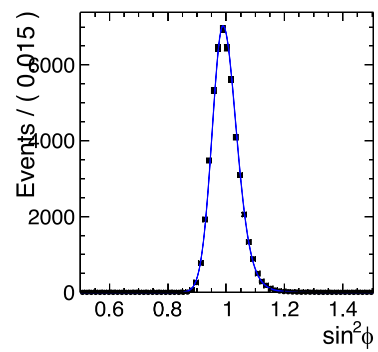
→ jetmatch $\chi^2 < 10$ (χ^2 used to match jets into *t*, *W* and *H*)

→ remove hadronic taus

Error estimation

Fitting function:

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

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

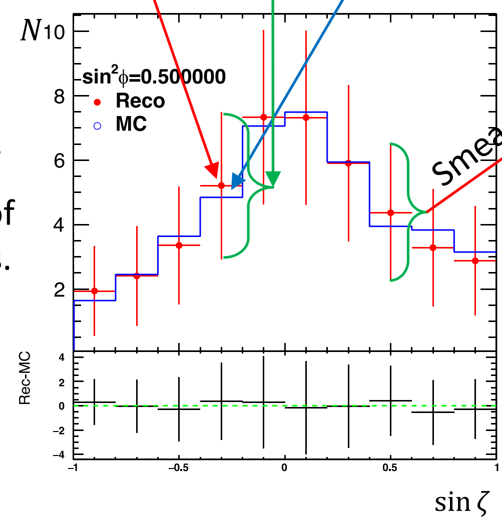
NB: Bin size=20 for all.

χ^2 template fitting

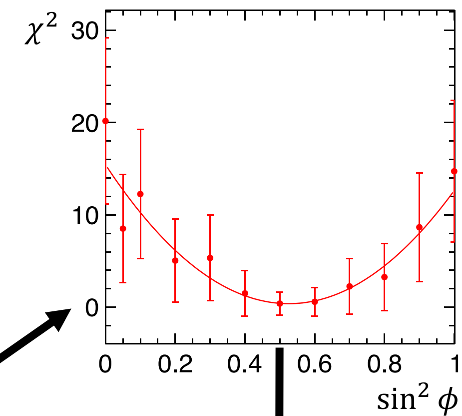
<u>Calculate χ^2 for a specific $\sin^2\phi$ value (e.g =0.5)</u>

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

- 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.

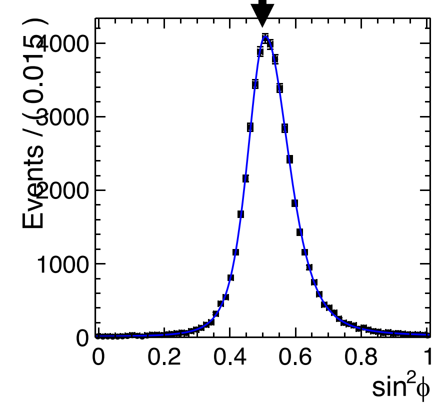


Smear as Poisson



X times

Find minimum and fill Histogram



Sensitivity to CP property