INSTITUTE FOR RESEARCH IN FUNDAMENTAL SCIENCES

LCWS2021

INTERNATIONAL WORKSHOP ON FUTURE LINEAR COLLIDERS

Constraining the Top quark EFT using Top Pair Production in Association with a Jet at Future Lepton Colliders

Talk at International Workshop on Future Linear Colliders (LCWS2021), 15-18 March 2021

P. Eslami, R. Jafari, H. Khanpour, M. Mohammadi Najafabadi

Outlines

- Motivations
- Top EFT
- Current limits
- Production of $e^{-}e^{+} \rightarrow t\bar{t} + \text{jet}$
- Event selection
- Discrimination of signal from background processes
- Results
- Summary and conclusions

Motivations

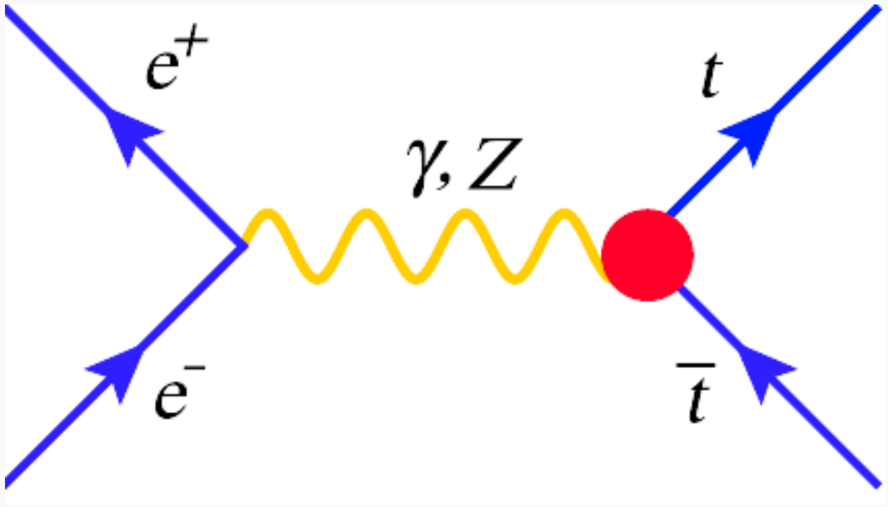
➢ At lepton collider, the $t\bar{t}$ production ($e^+e^- \rightarrow Z^*/\gamma \rightarrow t\bar{t}$) is highly sensitive to top electroweak couplings.

➢ The total rate is much smaller than the LHC, but the $e^+e^- \rightarrow Z^*/\gamma \rightarrow t\bar{t}$ process is background free.

➢ It would provide an accurate way to probe the top quark electroweak interactions.

➢ There are studies of the prospects for constraining the top electroweak interactions within the SMEFT at future linear colliders using the top quark pair production. For instance:

- Top quark electroweak couplings at future lepton colliders, Eur. Phys. J. C (2017) 77:535
- Global and optimal probes for the top-quark effective field theory at future lepton colliders, JHEP 10 (2018) 168
- Probing top-Z dipole moments at the LHC and ILC, JHEP 08 (2015) 044
- …



Top Quark EFT

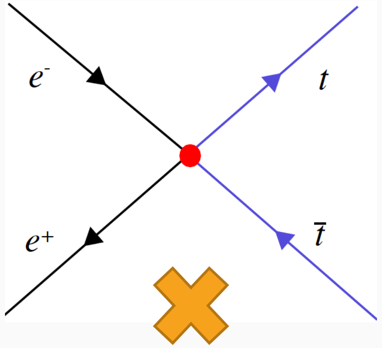
- The aim is to study the improvement in the sensitivity of the top electroweak interactions within the SMEFT by including $e^+e^- \rightarrow t\bar{t}$ **+ jet** to $e^+e^- \rightarrow t\bar{t}$ process.

- If the new physics that couples to the top quark is heavy and/or weakly coupled → a proper formulism of the impacts of new physics is to consider SM as an effective theory.

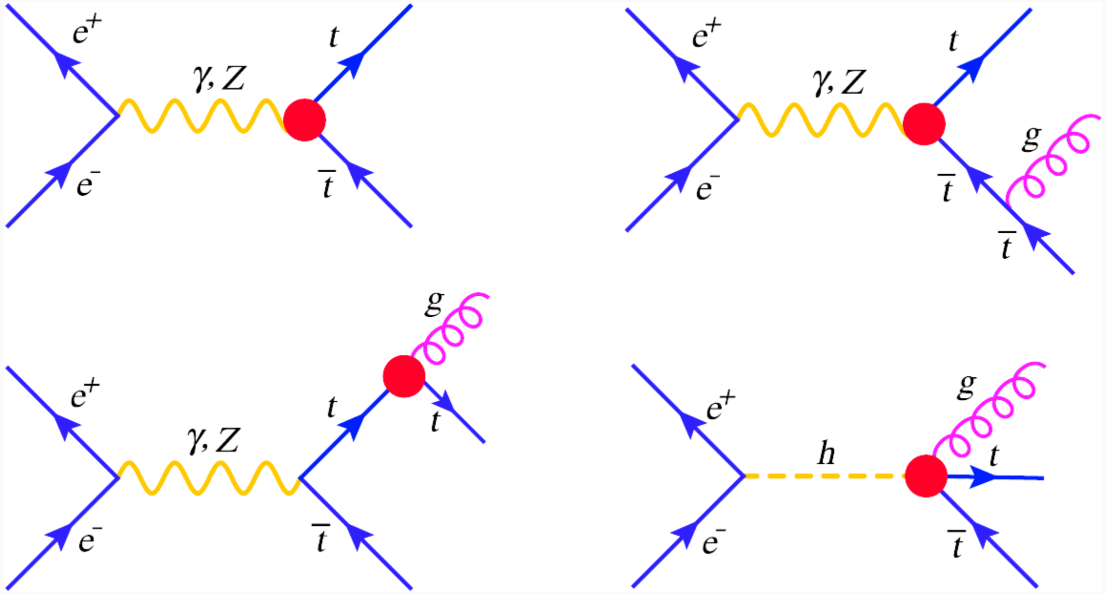
- Non-standard couplings can be parameterized by operators of dimension d > 4. The leading effects for collider observables typically enter at d = 6.

- ***Zee*** and ***γee*** vertices have been tightly bounded from the LEP and electroweak precision observables →**Not considered**.

- It is assumed that new physics only affects top EW and top strong interactions-->
  Four fermi $e^+e^-t\bar{t}$ is neglected.



$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i \mathcal{O}_i}{\Lambda^2}$$

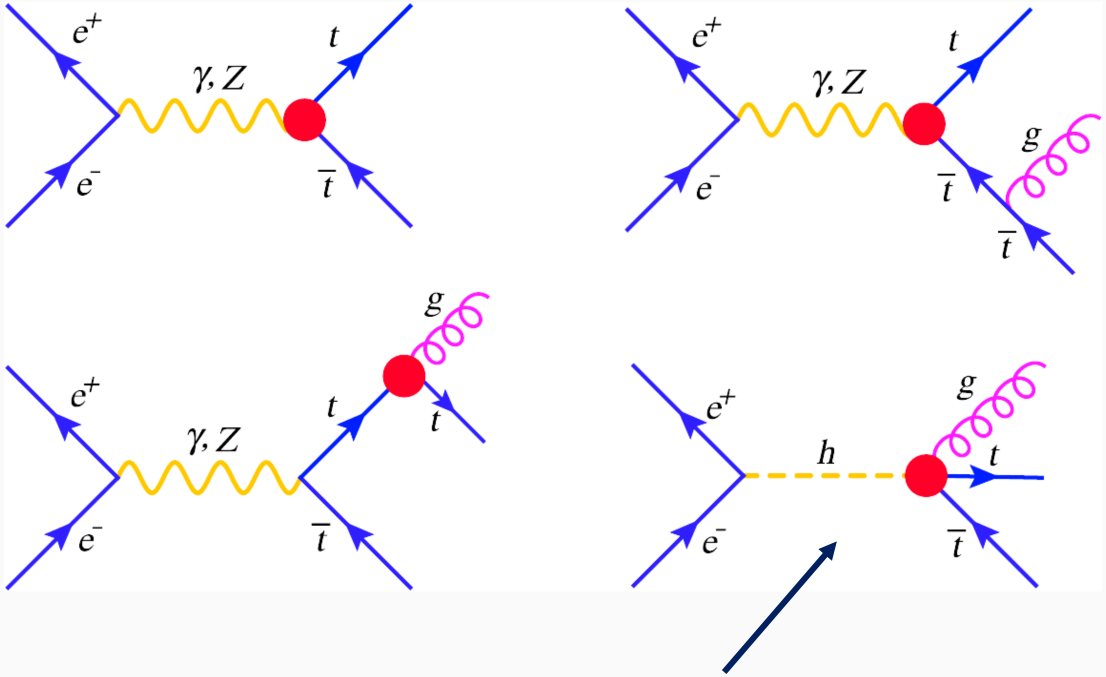


Top Quark EFT

In addition to the top EW interactions, ***$gt\bar{t}$*** interaction can be probed.

List of CP-conserving operators which affect the $t\bar{t}$+jet production in the SILH basis:

$$\mathcal{O}_{uW} = \bar{Q}_L \sigma^i H^c \sigma^{\mu\nu} u_R W^i_{\mu\nu},$$
$$\mathcal{O}_{uB} = \bar{Q}_L H^c \sigma^{\mu\nu} u_R B_{\mu\nu},$$
$$\mathcal{O}_{uG} = \bar{Q}_L H^c \sigma^{\mu\nu} \lambda^a u_R G^a_{\mu\nu},$$
$$\mathcal{O}_{HQ} = (\bar{Q}_L \gamma^\mu Q_L)(H^\dagger \overleftrightarrow{D}_\mu H)$$
$$\mathcal{O}'_{HQ} = \left(\bar{Q}_L \gamma^\mu \sigma^i Q_L\right)(H^\dagger \sigma^i \overleftrightarrow{D}_\mu H),$$
$$\mathcal{O}_{Hu} = (\bar{u}_R \gamma^\mu u_R)(H^\dagger \overleftrightarrow{D}_\mu H),$$



O_{uG} generates the new four-leg interaction of ***$hgt\bar{t}$*** → contributes to the $t\bar{t}$ + jet production

Current Limits

The derived constraints on the considered Wilson coefficients in this work from an up-to-date global fit to experimental data from the Tevatron, and from LHC Runs I and II:

$$-8.2 \times 10^{-4} \leq \bar{c}_{uG} \leq 1.8 \times 10^{-3},$$
$$-4.6 \times 10^{-2} \leq \bar{c}_{uB} \leq 7.0 \times 10^{-2}, -0.593 \leq \bar{c}_{Hu} \leq 0.496,$$
$$-8.9 \times 10^{-3} \leq \bar{c}_{uW} \leq 6.5 \times 10^{-3}, -0.369 \leq \bar{c}_{HQ} \leq 0.375,$$
$$-3.92 \times 10^{-2} \leq \bar{c}'_{HQ} \leq 2.27 \times 10^{-2}.$$

$$\mathcal{O}_{uW} = \bar{Q}_L \sigma^i H^c \sigma^{\mu\nu} u_R W^i_{\mu\nu},$$
$$\mathcal{O}_{uB} = \bar{Q}_L H^c \sigma^{\mu\nu} u_R B_{\mu\nu},$$
$$\mathcal{O}_{uG} = \bar{Q}_L H^c \sigma^{\mu\nu} \lambda^a u_R G^a_{\mu\nu},$$
$$\mathcal{O}_{HQ} = (\bar{Q}_L \gamma^\mu Q_L)(H^\dagger \overleftrightarrow{D}_\mu H)$$
$$\mathcal{O}'_{HQ} = \left(\bar{Q}_L \gamma^\mu \sigma^i Q_L\right)(H^\dagger \sigma^i \overleftrightarrow{D}_\mu H),$$
$$\mathcal{O}_{Hu} = (\bar{u}_R \gamma^\mu u_R)(H^\dagger \overleftrightarrow{D}_\mu H),$$

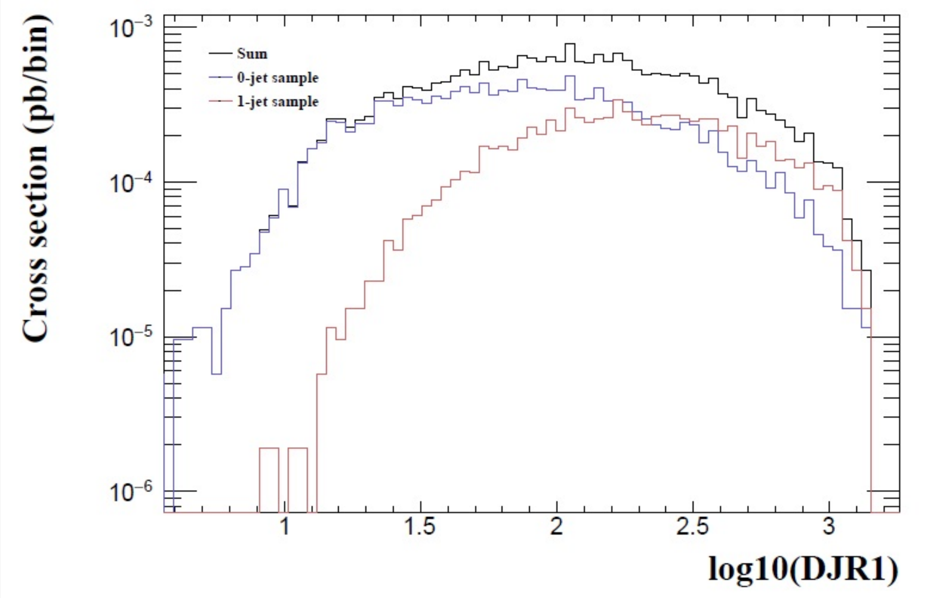
Experimental data:

- total cross-sections, - differential distributions (for both single top and pair production),
- the top quark width, - charge asymmetries, - polarization information from top decay products.

JHEP 04 (2016) 015, updated in 2018

Top quark pair+jet cross section vs c_i

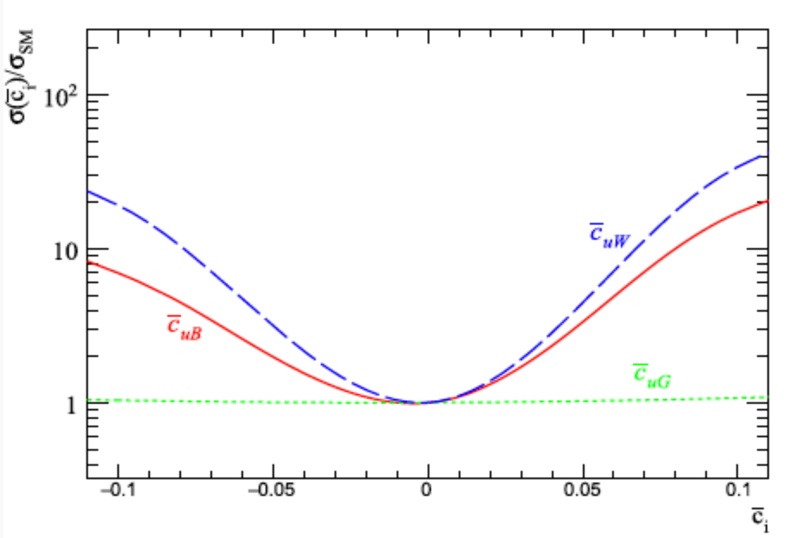
- ❖ Top quark pair +jet is produced with up to one additional parton in the final state using leading-order matrix elements.
- ❖ The 0-, 1-parton events are merged using the MLM matching scheme to avoid double counting and to separate regions described by matrix element and parton showers for collinear jets.

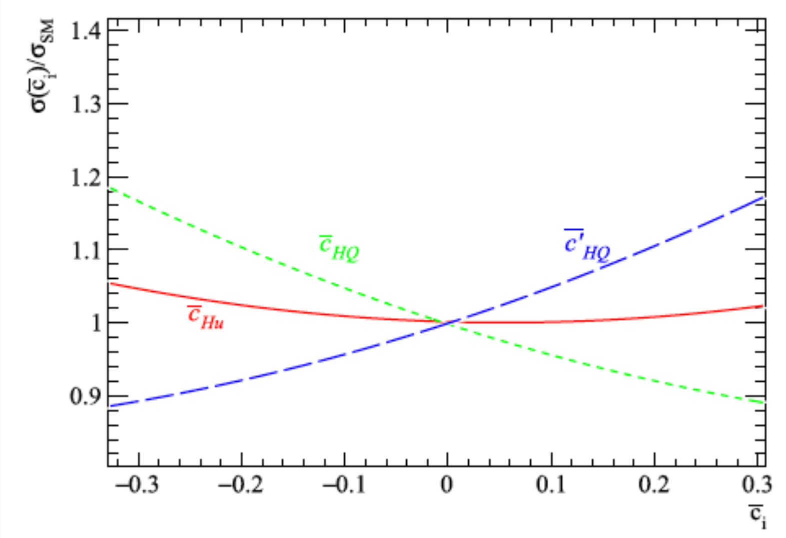


xqcut variable and qcut are set to 20 GeV and 30 GeV

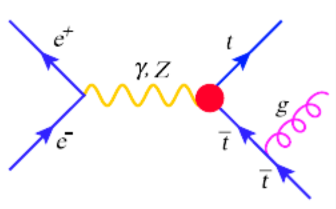
A smooth transition between events with 0 and 1 jet in the DJR distribution

The ratio of the total cross-section in the presence of the operators to the SM obtained using MadGraph5.





Cross Section vs √s



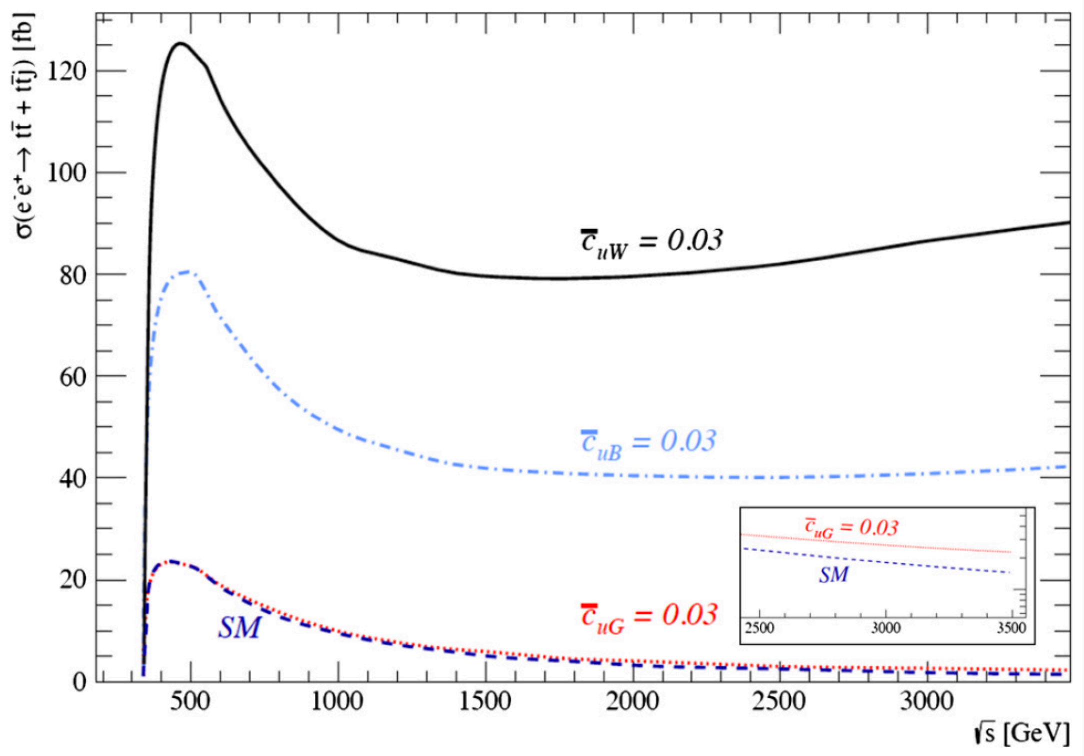
- $\sigma(e^+e^- \to t\bar{t} + \text{jet})$ as a function of the center-of-mass energy at LO for three signal scenarios as well as the SM.

- A significant enhancement occurs at top quark pair threshold.

- The O_{uW} and O_{uB} operators lead to much larger increase in the cross section of signal w.r.t O_{uG} .

- The virtual γ/Z boson momenta could grow up to the total center-of-mass energy while less momentum is running to the O_{uG} vertex.

For the SM, the production rate approximately falls down as $1/\sqrt{s}$.



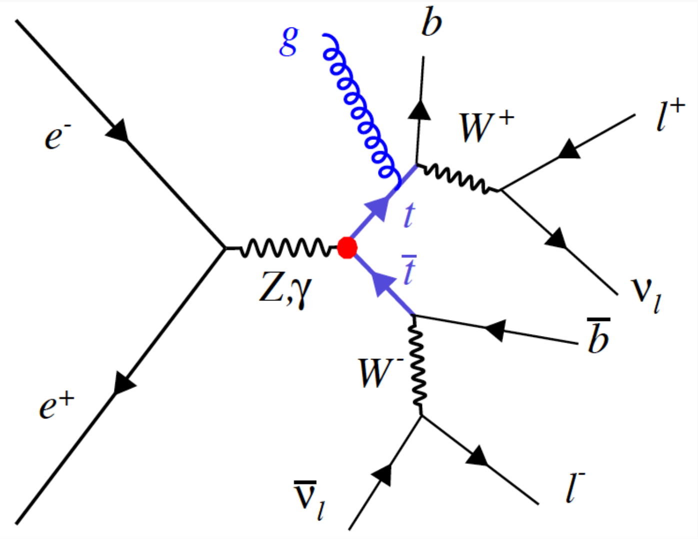
p_{Tj} > 20 GeV

The operators O_{uW} and O_{uB} are expected to be tightly constrained, due to their much stronger impact on the cross section.

Analysis setup and Simulation details

To have a clean signature → dileptonic decay channel
The final state consists of:

- at least two jets from which two are *b*-jets originating from the top quarks decay,
- two opposite sign charged leptons,
- missing momentum.



- SM production of $t\bar{t}$+*jet*
- Single top production tWj
- $e^-e^+ \to ZZV \to 2l$+jets+missing momentum, $V=\gamma,Z$
- $e^-e^+ \to W^+W^-V \to 2l$+jets +missing momentum, where $V=\gamma,Z$.
- $e^-e^+ \to VVV'V' \to 2l$+jets +missing momentum, where $V,\ V'=W^{\pm},\ Z,\ \gamma$.

- MadGraph5 package is used to generate the signal and background events at $\sqrt{s}$ = 500 GeV and 3 TeV
- The generated samples are passed through the PYTHIA 6 for parton shower, hadronization, and decay of unstable particles.
- Simulation of detector: DELPHES 3.4.1
- Detector: ILD card is used.
- Jet reconstruction: the anti-k_T algorithm based on the FastJet package with the cone size parameter R = 0.5.

Event selection

- At least 2 jets, from which exactly two must be b-tagged
- Exactly 2 opposite sign isolated leptons

- $P_T > 20$ GeV for jets
- $P_T > 10$ GeV for leptons
- $|\eta| \leq 2.5$ for all objects
- $\Delta R > 0.4$ for all jets and leptons
- ME > 20 GeV

- To suppress the contributions of the SM background processes → a multivariate technique
- Gradient Boosted Decision Trees (BDTG) is used for discriminating signal from backgrounds and to achieve the best sensitivity.

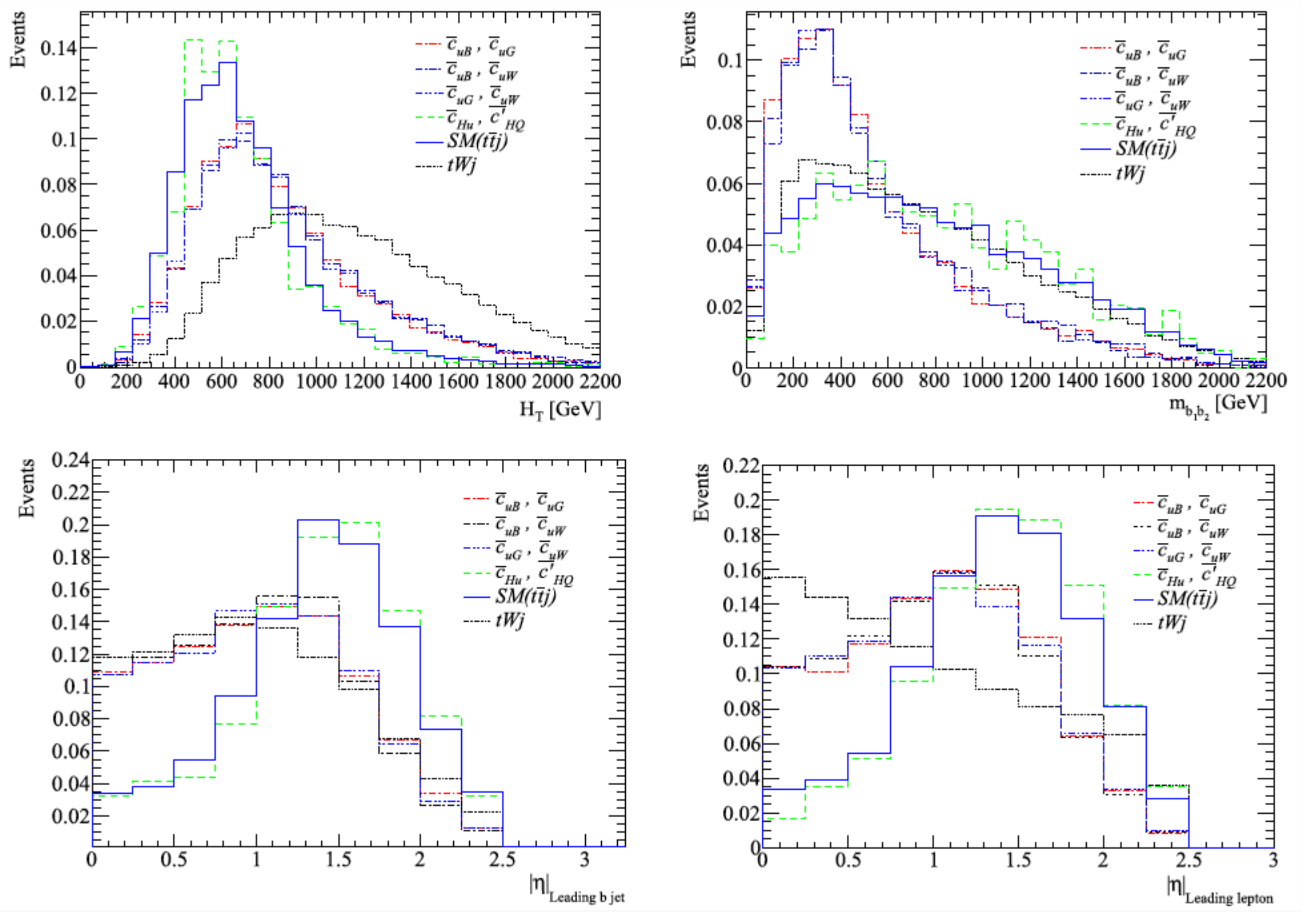
MVA input variables

Input variables:

- ❑ scalar sum of p_T of the leptons and jets (H_T);
- ❑ invariant mass of the two b-jets (m_{b1b2});
- ❑ η of the leading lepton;
- ❑ η of the leading and sub-leading b-jets;
- ❑ angular separation of two b-tagged jets **Δ**R(b1, b2).

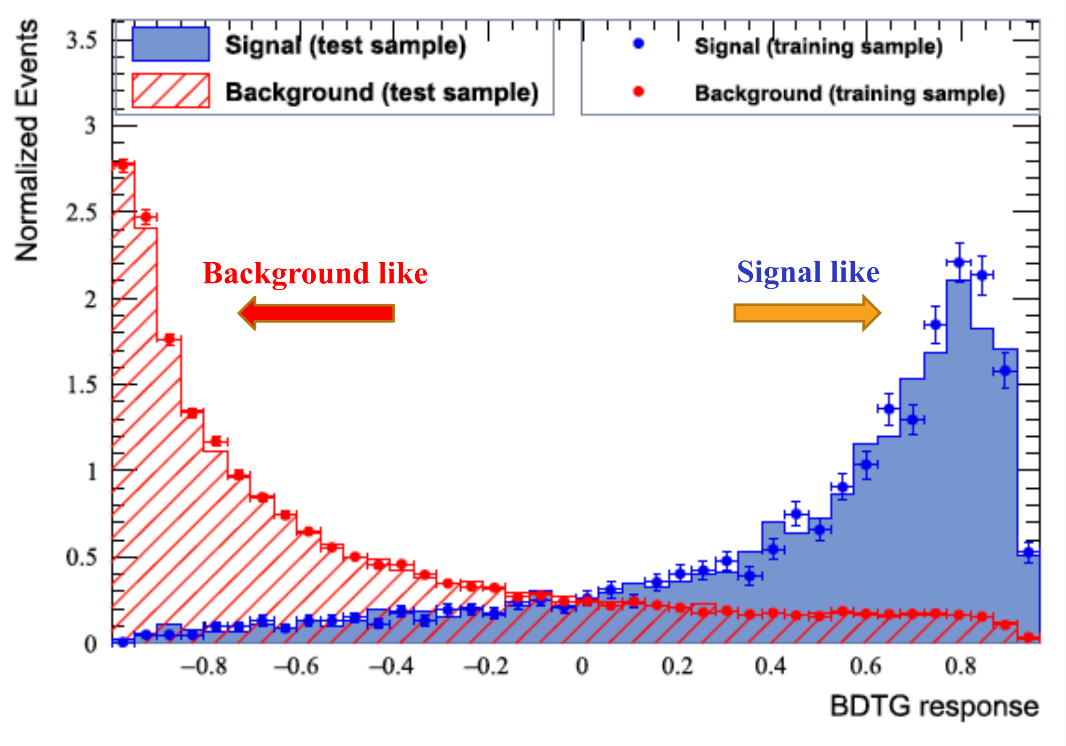
✓ Similar input variables for all signal scenarios are used (**more effective to use different inputs**)

✓ All backgrounds according to their rates are used for training.



Classifier output

BDTG output for the signal with $c_{uB} = c_{uG} = 0.1$ and for the backgrounds at 3 TeV



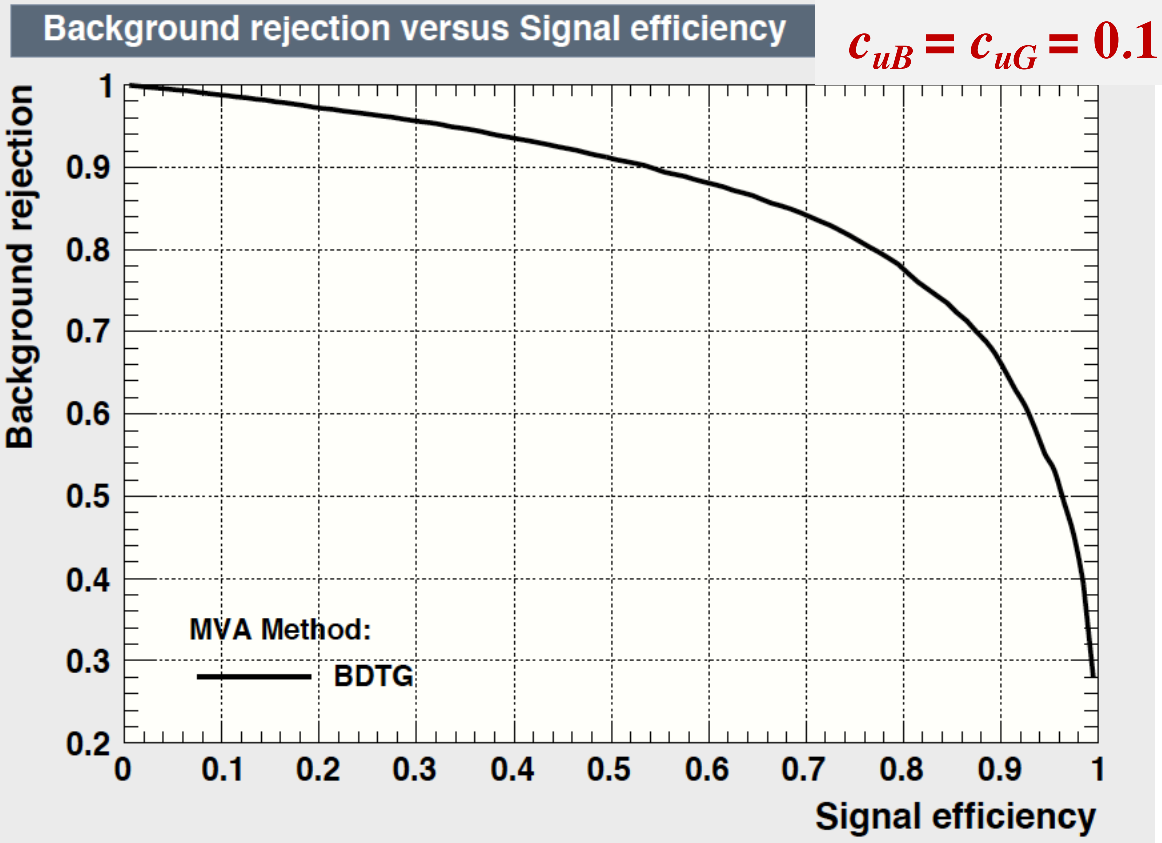
The optimum cut on the BDTG response is chosen so that the best sensitivity is achieved.

Expected cross sections of signal and background processes at √s = 500 and 3000 GeV after the multivariate analysis.

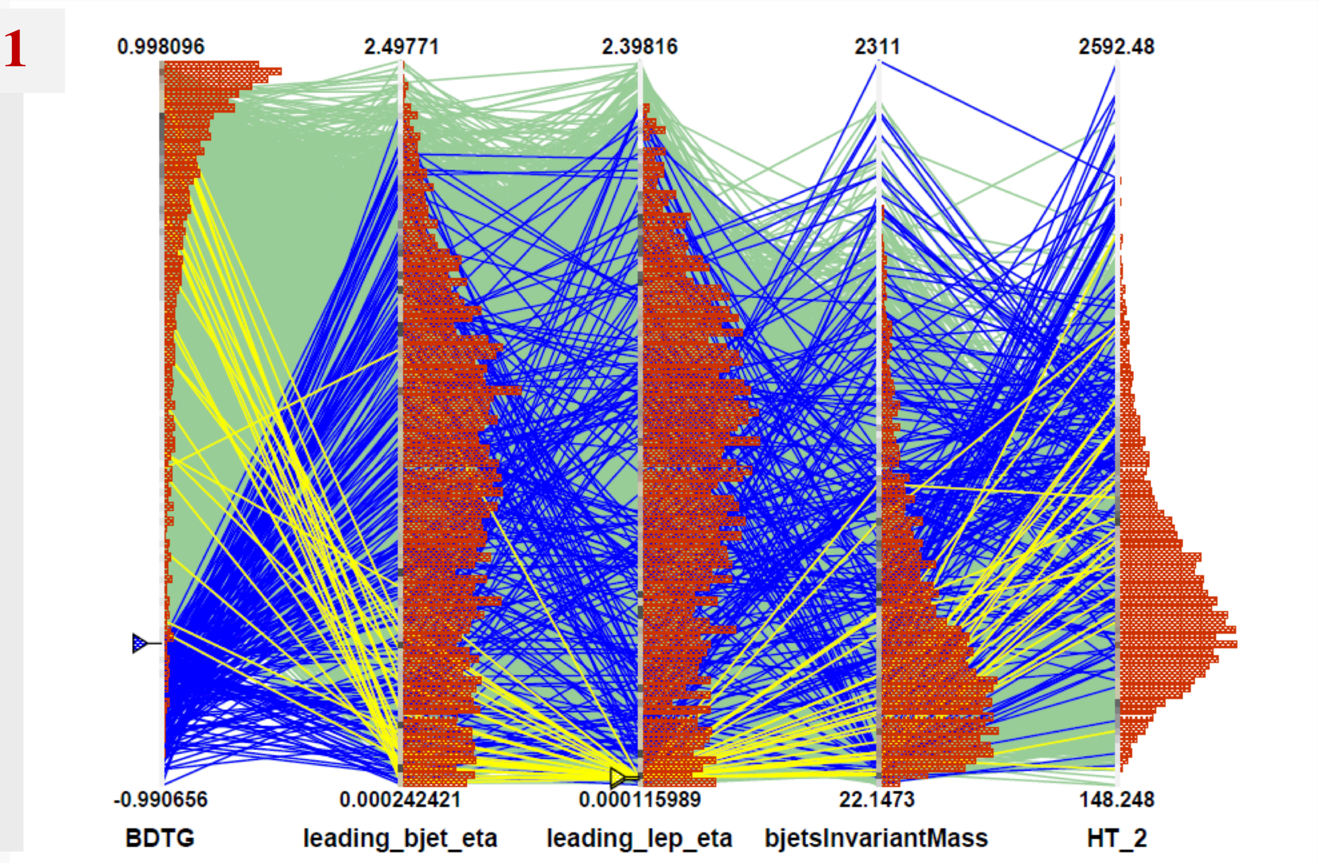
$\sqrt{s} = 3000$ GeV	Couplings	Signal	$t\bar{t}$ + jet	tWj	$WWV + ZZV$	$VVV'V'$
MVA	$(\bar{c}_{uW}, \bar{c}_{uB})$	4.42	0.0021	0.0041	0.0005	0.000043
$\sqrt{s} = 500$ GeV	Couplings	Signal	$t\bar{t}$ + jet	tWj	$WWV + ZZV$	$VVV'V'$
MVA	$(\bar{c}_{uW}, \bar{c}_{uB})$	247.5	3.6	0.17	0.03	0.000023

The BDTG output has been checked in terms of the power of discrimination from the receiver operator characteristic (ROC) of the output of BDTG output.

Classifier background rejection vs. signal efficiency and parallel coordinates



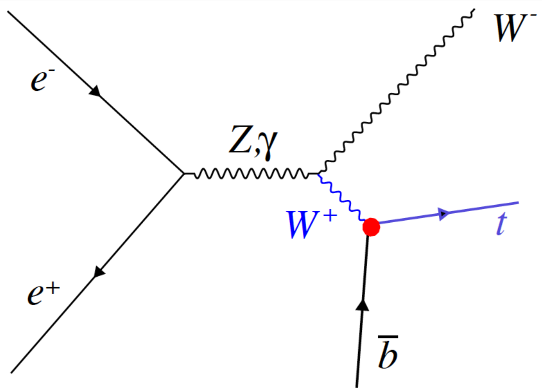
$c_{uB} = c_{uG} = 0.1$

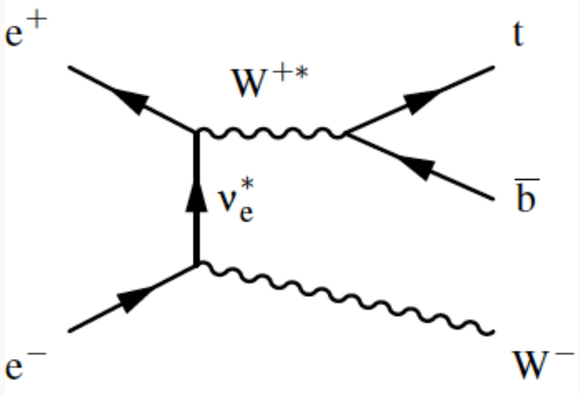


Impact of operators on the backgrounds

- Considered operators affect the background processes.

- After all cuts and multivariate analysis, backgrounds are suppressed remarkably → impacts of dimension six operators on the backgrounds are not sizeable.





- The impact of the O_{HQ} , O'_{HQ} , O_{Hu} operators on tWj is quite negligible.
- The deviations that VVV(V) processes, V = $W^{\pm}, Z, \gamma$, receive from the operators and are of the order of $10^{-4,-5}$ fb for $c_i = 0.1$.
- The impact of operators on the tWj background when limits are set on the Wilson coefficients.

For instance, the change in the cross section of the tWj background at $\sqrt{s}$ = 500 GeV in different scenarios (O_{uW} , O_{uB} , O_{uG}) are as follows:

$$\Delta\sigma_{tWj} = \sigma_{tWj}(\bar{c}_{uW} = 0.1, \bar{c}_{uG} = 0.1) - \sigma_{tWj}(0.0, 0.0) = 0.632$$

$$\Delta\sigma_{tWj} = \sigma_{tWj}(\bar{c}_{uW} = 0.1, \bar{c}_{uB} = 0.1) - \sigma_{tWj}(0.0, 0.0) = 0.637$$

$$\Delta\sigma_{tWj} = \sigma_{tWj}(\bar{c}_{uB} = 0.1, \bar{c}_{uG} = 0.1) - \sigma_{tWj}(0.0, 0.0) = 3.9 \times 10^{-3},$$

Results

The expected individual bounds at 95% CL on the coefficients from $e^- + e^+ \to t + \bar{t} + jet$

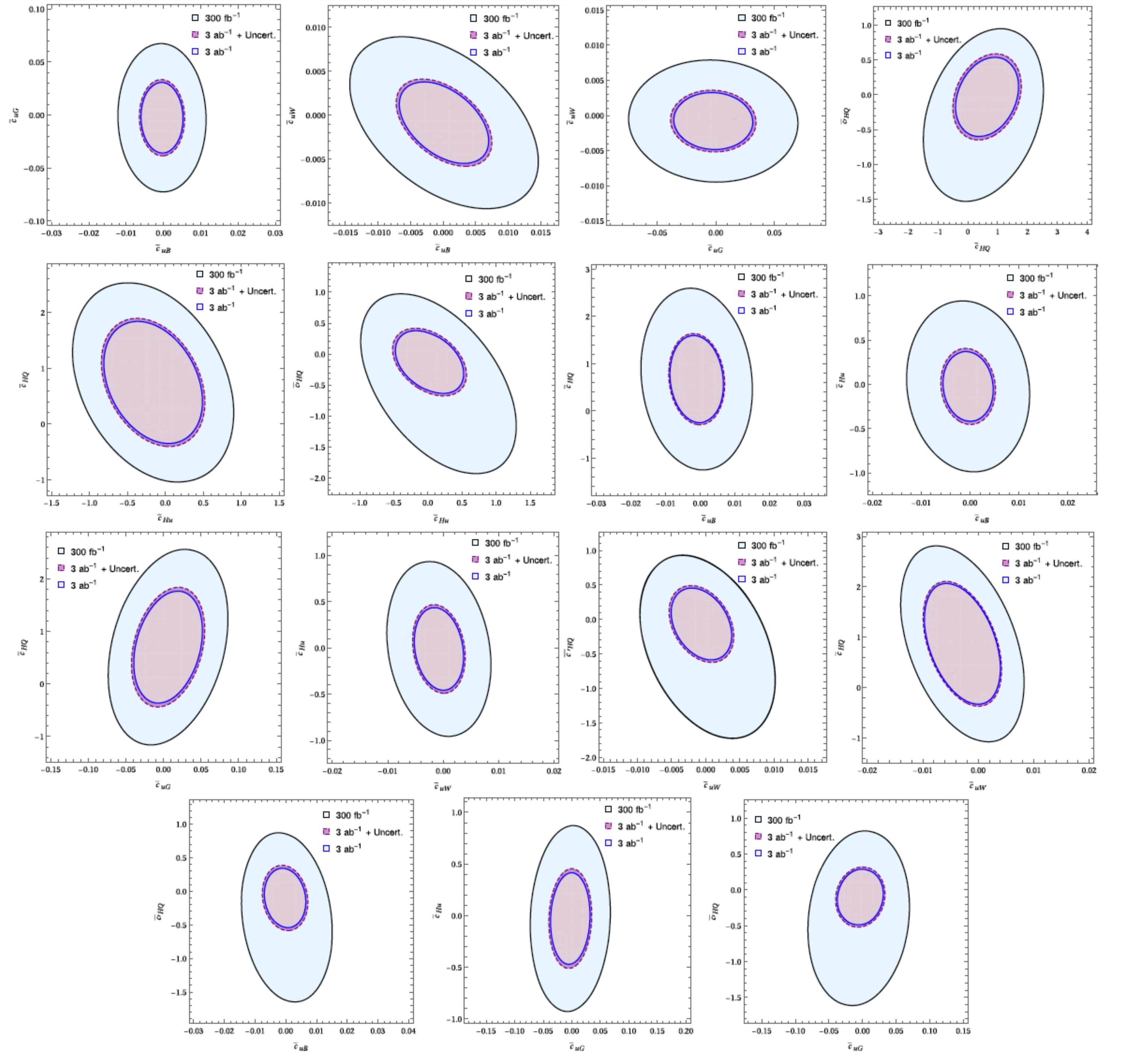
Wilson coefficient	500 GeV, 500 fb^{-1}	500 GeV, 4 ab^{-1}	3 TeV, 300 fb^{-1}	3 TeV, 3 ab^{-1}
$\bar{c}_{uB}$	$[-0.0476, 0.0009]$	$[-0.017, 0.0003]$	$[-0.013, 0.012]$	$[-0.0067, 0.0058]$
$\bar{c}_{uG}$	$[-0.11, 0.073]$	$[-0.039, 0.025]$	$[-0.073, 0.068]$	$[-0.038, 0.033]$
$\bar{c}_{uW}$	$[-0.0294, 0.0006]$	$[-0.011, 0.0002]$	$[-0.0098, 0.0082]$	$[-0.0051, 0.0035]$
$\bar{c}_{Hu}$	$[-0.35, 0.45]$	$[-0.12, 0.16]$	$[-1.00, 0.95]$	$[-0.51, 0.46]$
$\bar{c}_{HQ}$	$[-0.087, 1.17]$	$[-0.032, 0.41]$	$[-1.21, 2.53]$	$[-0.37, 1.69]$
$\bar{c}'_{HQ}$	$[-1.34, 0.093]$	$[-0.48, 0.034]$	$[-1.63, 0.86]$	$[-0.54, 0.31]$

$\bar{c}_{uB}$ and $\bar{c}_{uW}$ can be probed down to 10^{-4} at 500 GeV and to 10^{-3} at 3 TeV.

Two dimensional contours are more useful than the individual limits → 2D contours are provided.

Results

Two-dimensional contours of
the expected constraints at 95% CL



M.Mohammadi Najafabadi

Summary and Conclusions

- Future lepton colliders provide a satisfactory precision on measurement of top quark electroweak couplings.
- $e^{-} + e^{+} \rightarrow t + \bar{t} + jet$ provides better sensitivity to the top quark EW couplings w.r.t $e^{-}e^{+} \rightarrow t\bar{t}$.
- Multivariate analysis is exploited to discriminate signal from background separately for each signal scenario.
- $\bar{c}_{uB}$ and $\bar{c}_{uW}$ can be probed down to 10^{-4} at 500 GeV and to 10^{-3} at 3000 GeV using $t\bar{t}$+jet in dilepton channel.
- For improvement: Including the semi-leptonic channel of top pair, observables like forward-backward asymmetries, and employing various beam polarization settings.

More details of the results can be found in Physics Letters B 806 (2020) 135469

BACKUP

2D contours
for the center-of-mass energy of 500 GeV.