Measurement of CP-violating Wtb couplings with the EFT with single top at CMS

Top LHC France 10/04/24

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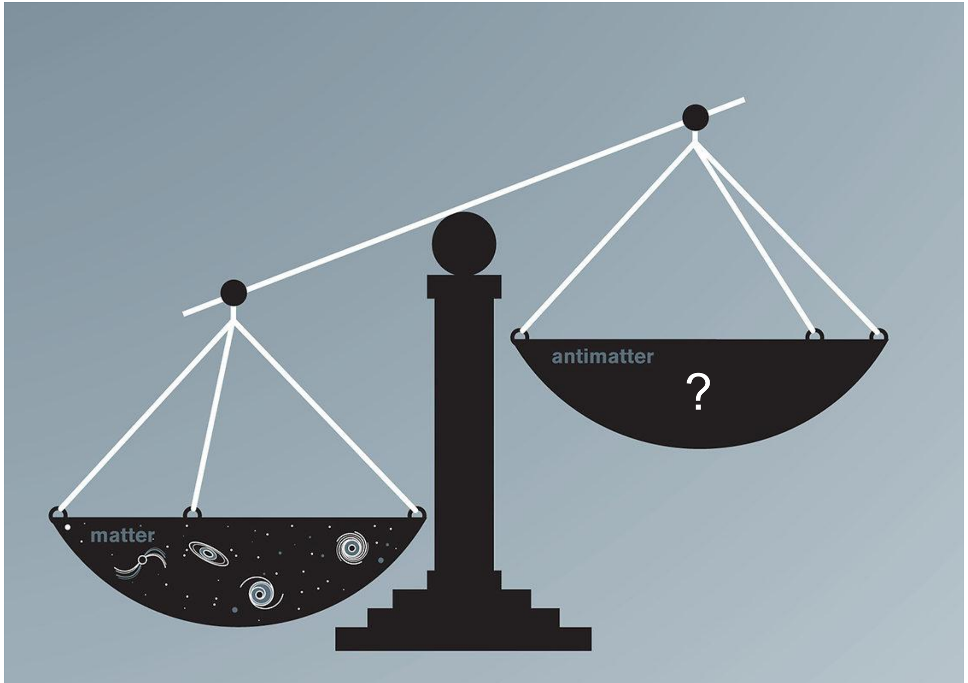
Context: Matter and Antimatter asymmetry in the Universe



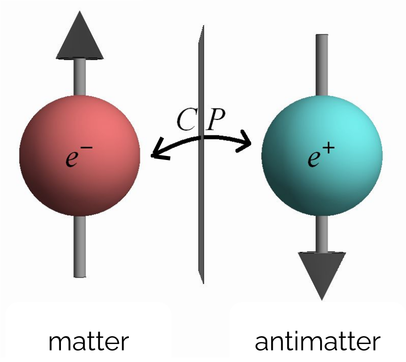
The universe is baryon-number asymmetric

SM EW baryogenesis scenario: $$\eta_{SM} = \frac{n_B - n_{\bar{B}}}{n_\gamma} \propto 10^{-27}$$

Observations: $$\eta_{obs} = \frac{n_B - n_{\bar{B}}}{n_\gamma} \propto 10^{-10}$$

$$\Rightarrow \frac{\eta_{SM}}{\eta_{obs}} \propto 10^{-17}$$

Discrepancy between the SM EW baryogenesis and observations

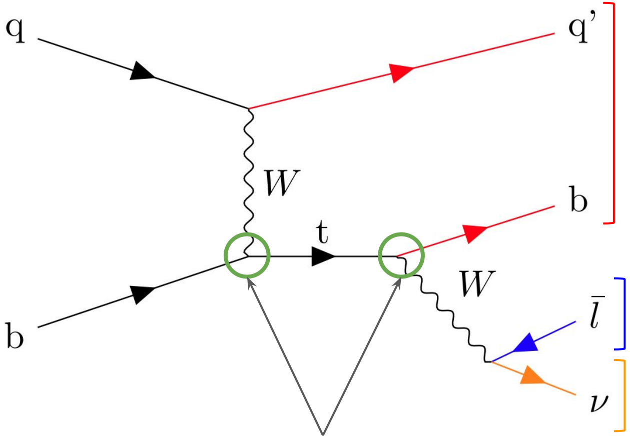


Searching for new CP violation sources involving top quarks Beyond the Standard Model (BSM).

CP-violation at Wtb vertex within the Effective Field Theory (EFT)

$$\mathscr{L}_{eff}^{(6)} = \mathscr{L}_{SM} + \sum_i \frac{C_i^{(6)}}{\Lambda_i^2} O_i^{(6)} + h.c.$$

Single top t-channel with leptonic decay (signal)



W_{tb} vertex at top production and decay.

→ This vertex can be modified by CP-violation.

We produce a sample with the following EFT variations at top **production and decay** using a **reweighting method.**

$\{ C_{tW} , C^{I}_{tW} \}$ = {-2,0,2}

$\{ C_{bW} , C^{I}_{bW} \}$ = {-2,0,2}

$\{ C_{\varphi tb} , C^{I}_{\varphi tb} \}$ = {-5,0,5}

Our 6 axes of the parameter space — Different combination values

CP violation = Non-zero value of the imaginary part of these EFTs coefficients

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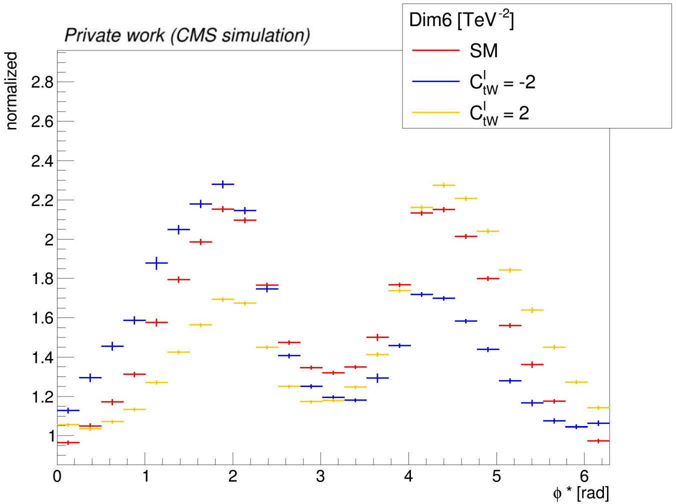
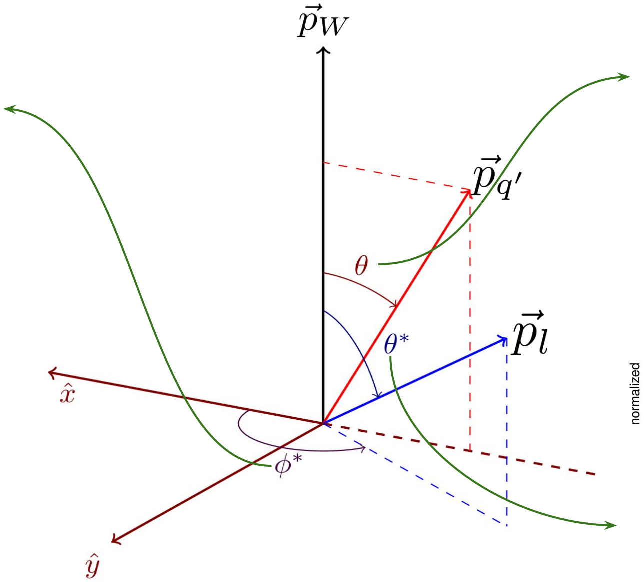
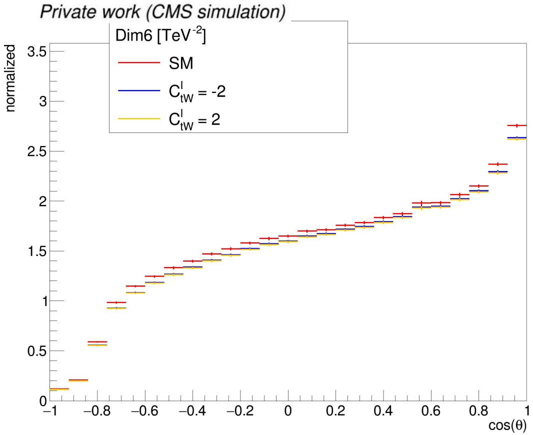
EFT impact on Kinematic Variables at parton level

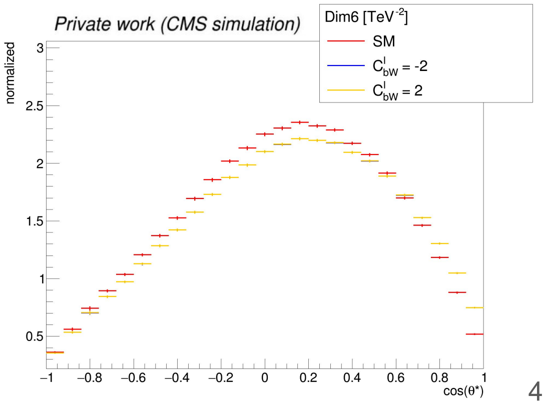


Reference frame used in ATLAS 8 TeV [JHEP12(2017)017]

$\hat{z}$ direction is defined as that of the W boson momentum







The shape of the angular distributions varies as a function of the value of the EFT coefficient.

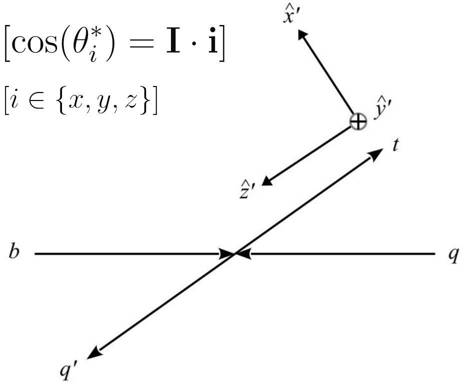
The amount of CP violation can be extracted using these angular distributions.

EFT impact on Kinematic Variables at parton level

Reference frame used in ATLAS 13 TeV [JHEP11(2022)040]

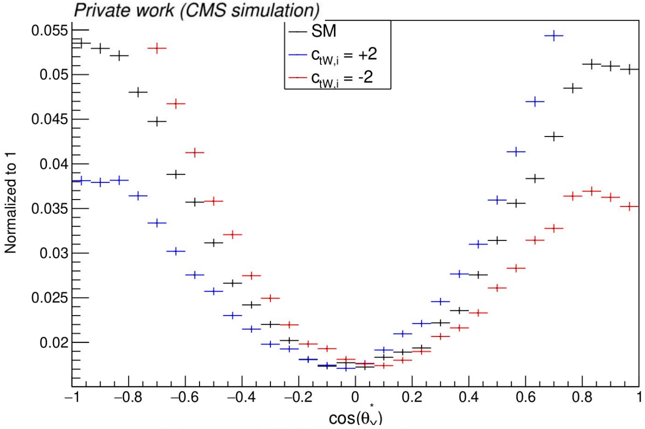
$$[\cos(\theta_i^*) = \mathbf{I} \cdot \mathbf{i}]$$

$$[i \in \{x, y, z\}]$$



$\mathbf{I}$ is a unit vector in the charged lepton direction

$\hat{z}$ direction is defined as that of the q' quark momentum



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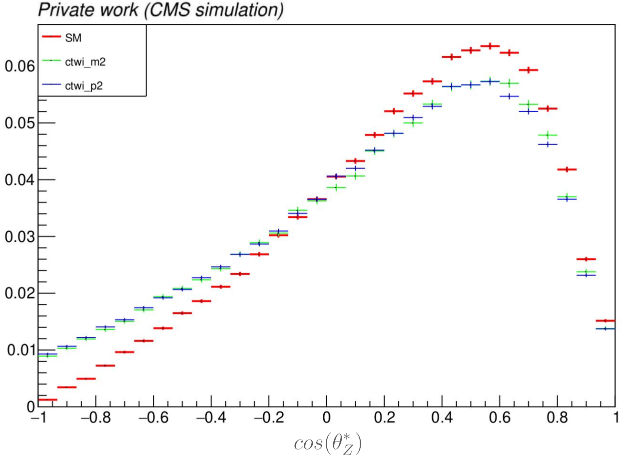

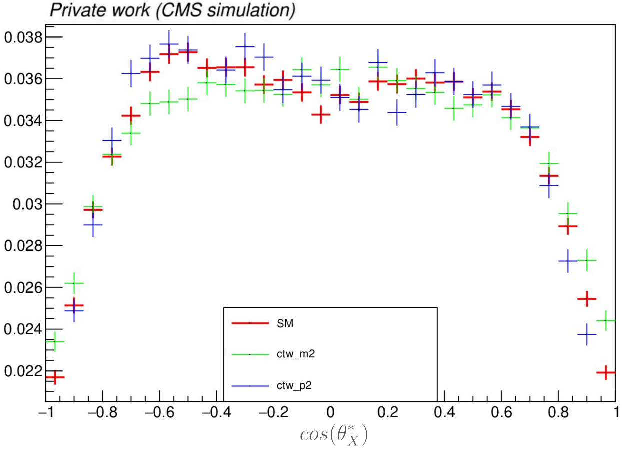

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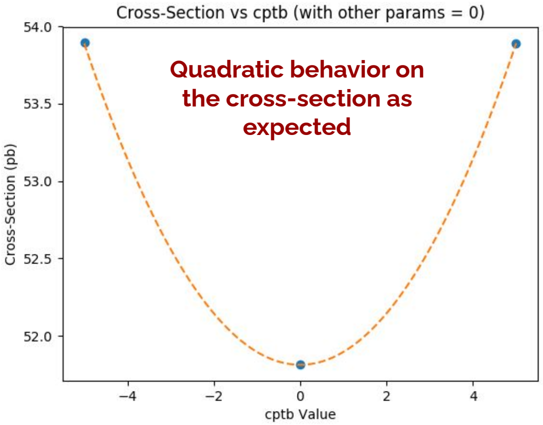
Simulating EFT with Reweighting at the Reconstruction level

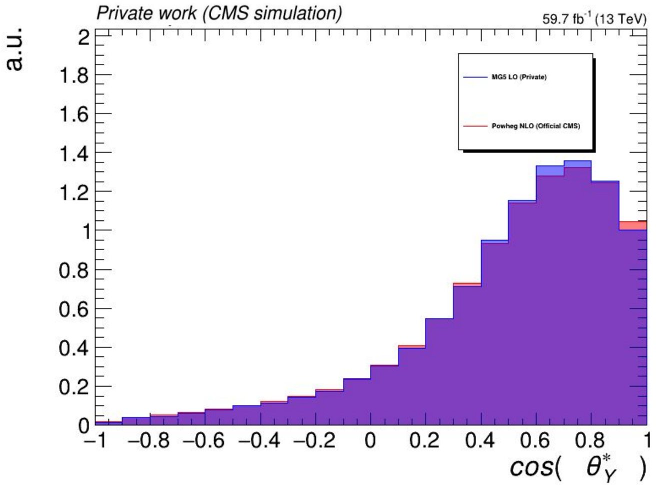
Distributions at the reconstructed level with EFT weights

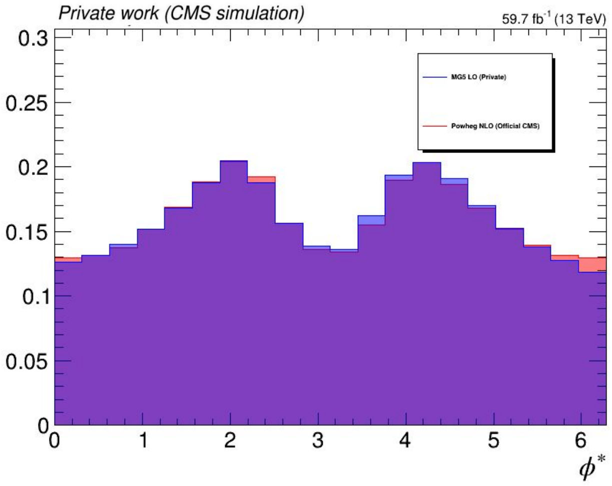
$$\mathcal{M} = \mathcal{M}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{M}_i$$

$$\sigma \propto |\mathcal{M}|^2$$

There is a reasonable agreement between LO and NLO samples at the reconstructed level.

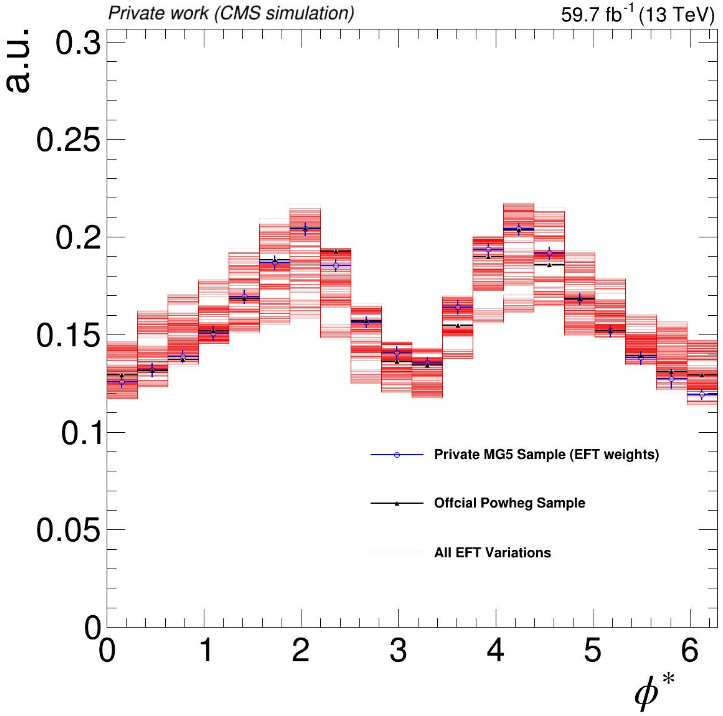


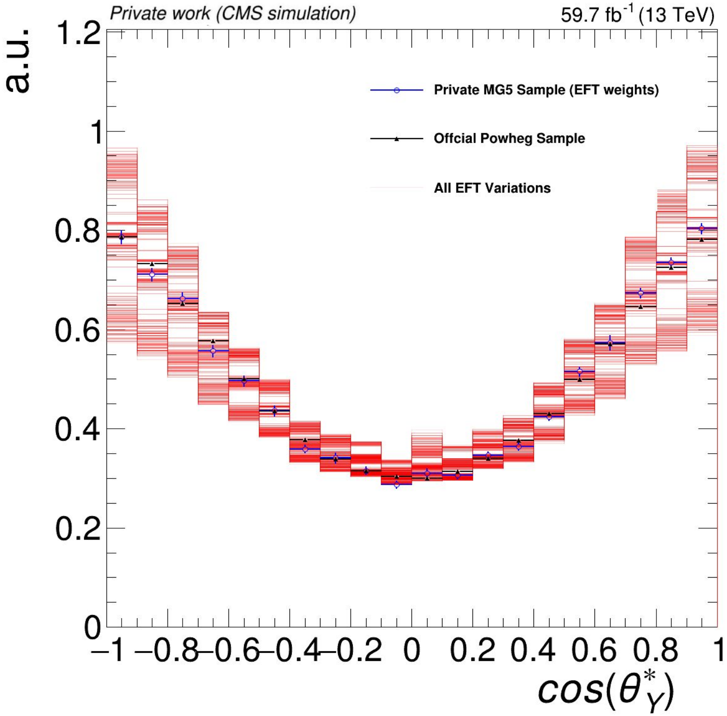




Simulating EFT with Reweighting at the Reconstruction level

Sample space with **729 Wilson Coefficient** weights (includes the SM) →All EFT variations included at the reconstructed level





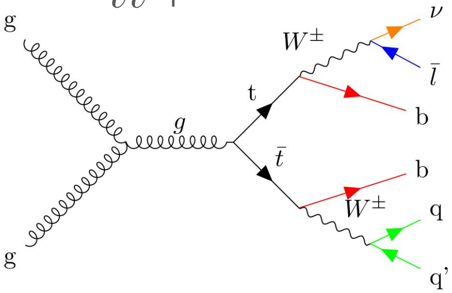
Measurement of the t-channel signal strength
(as a first step towards the EFT measurement)

SM Background Processes

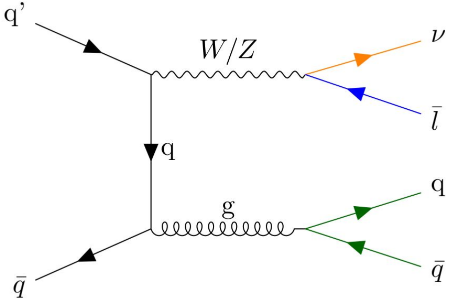
The analysis is based on the full Run2 Dataset.

Main background processes:

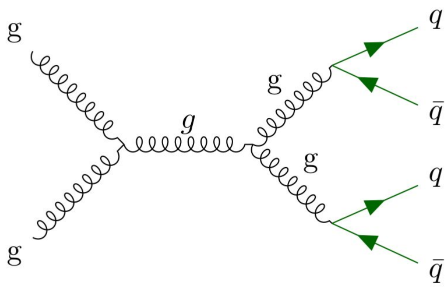
$t\bar{t}$ process



W/Z + Jets process
(includes Drell-Yan)



QCD processes



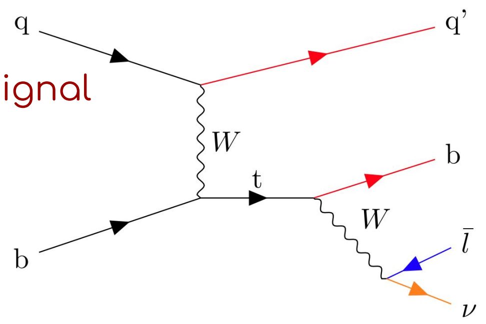
Other background processes:

- ➔ Diboson
- ➔ ttX
- ➔ Single top s-channel and tW process

- ➔ The analysis employs single muon and single electron triggers
- ➔ Isolated and non-isolated trigger paths are employed

Selection in the Muon Channel

signal



➔ All recommended CMS corrections applied (Pileup and b-tag weights, JEC, muon and electron efficiencies).

Object	pT [Gev]	$\|\eta\|$	
Muon	>26 (2018) >30 (2017 & 2016)	<2.4	Exactly one Isolated tight muon. **QCD sideband**: Exactly one reversed isolated tight muon
Good Jets	>40 ($\|\eta\|$<2.4) >60 (2.4<$\|\eta\|$<4.7)	<4.7	Tight ID and removed overlap between jets and leptons in a $\Delta R < 0.4$ cone
B-Jet	>40	<2.5	Tight and medium ID are using DeepJet tagger.

Analysis regions and Jets selection

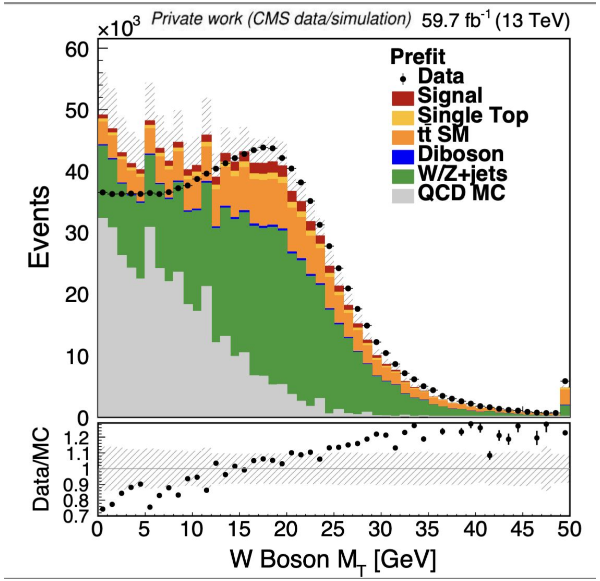
	= 0 tight and ≧ 1 medium b-jet	≧ 1 tight b-jet	≧ 2 tight b-jets
= 2 jets	W/Z-Jets Control Region.	Signal Region	Not Used
≧ 3 jets	Not Used	Not Used	TTbar Control Region

QCD background estimate:

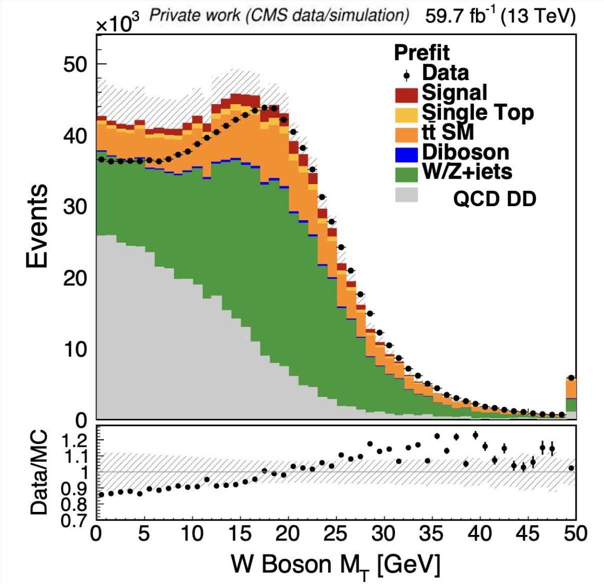
- ➔ Estimation of the QCD background from data in a **QCD sideband region.**
- ➔ Sideband region: **reversing lepton isolation** requirements.
- ➔ Creation of a region dominated by QCD.
- ➔ Utilization of non-isolated trigger paths in this region.

W/Z-Jets control region

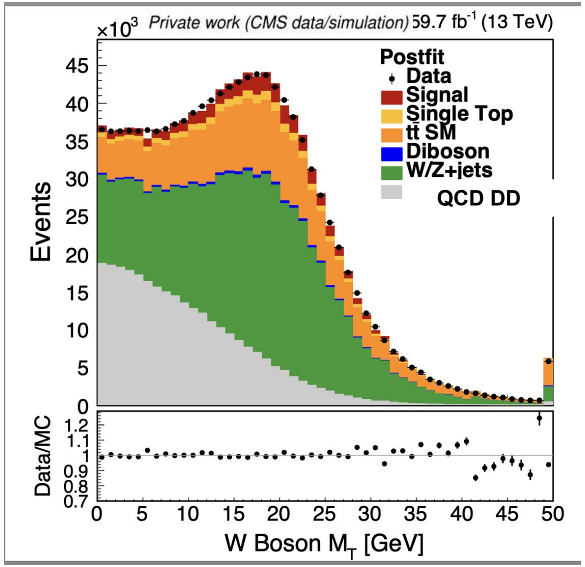
QCD MC



QCD Data Driven, pre-fit



QCD Data Driven, post-fit



Non-optimal MC QCD modeling and not enough statistics → QCD Data Driven is normalized to the amount of QCD Monte Carlo in the W/Z-Jets region before the fit → Fitted QCD Data Driven to data

Good agreement between Data and MC

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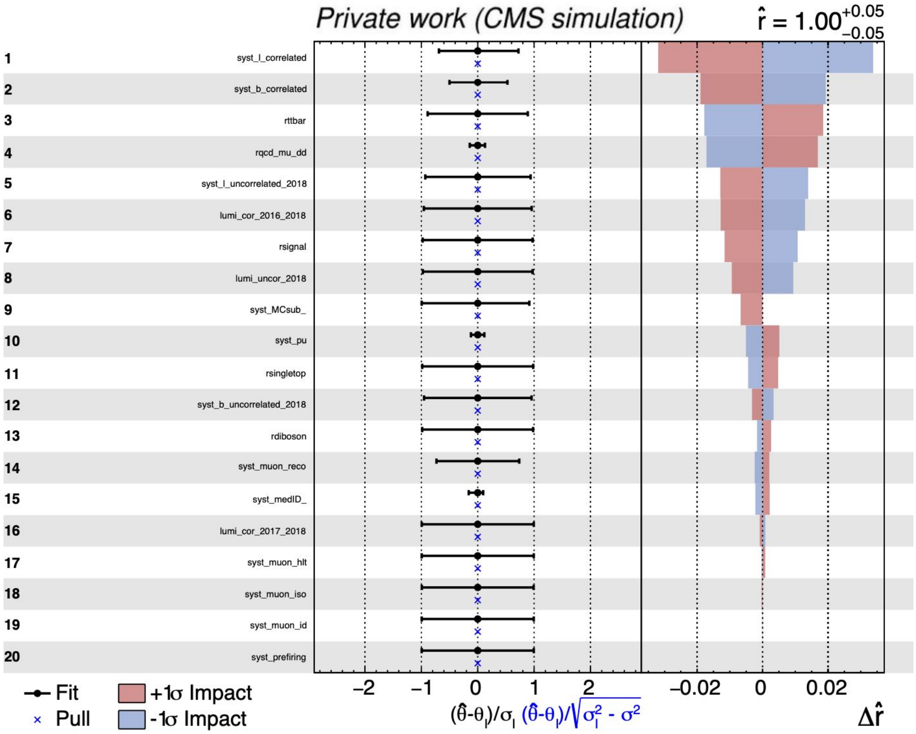
W/Z-Jets control region

First checks of the impacts of systematics:

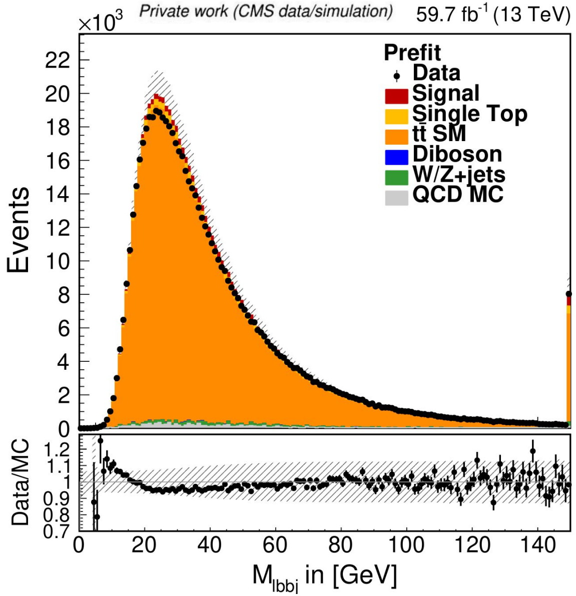
- Some constraints need to be scrutinized
- QCD Data Driven method to be improved using more systematics
- Updating rate uncertainties for each process
- Verifying nuisance correlations

Nuisance Impacts on the W/Z+Jets rate measurement in its control region



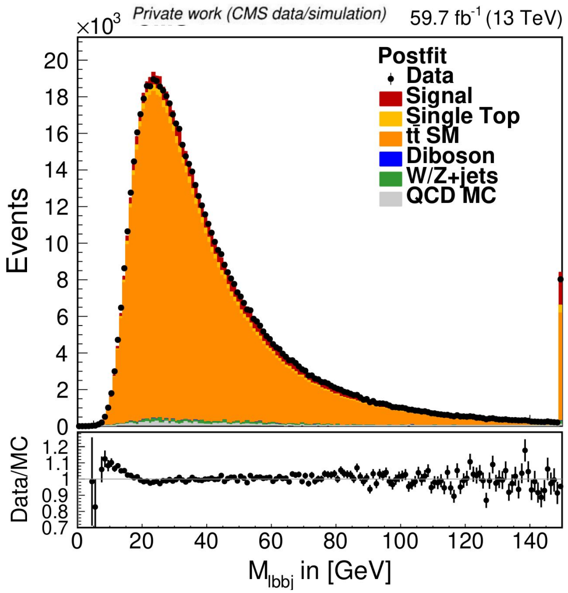
TTBar control region

QCD Data Driven, pre-fit



QCD Data Driven is normalized to the amount of QCD Monte Carlo in the W/Z-Jets region before the fit →

QCD Data Driven, post-fit

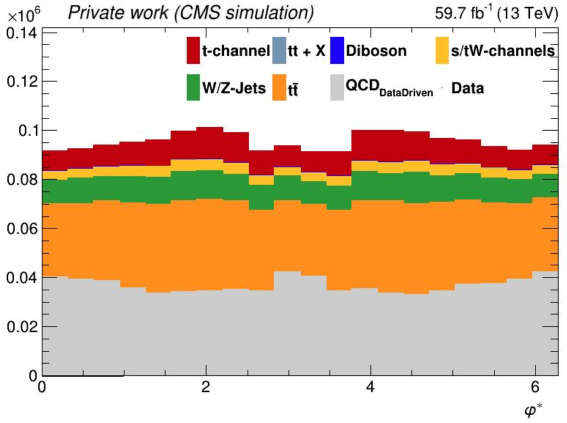


Fitted QCD Data Driven to data

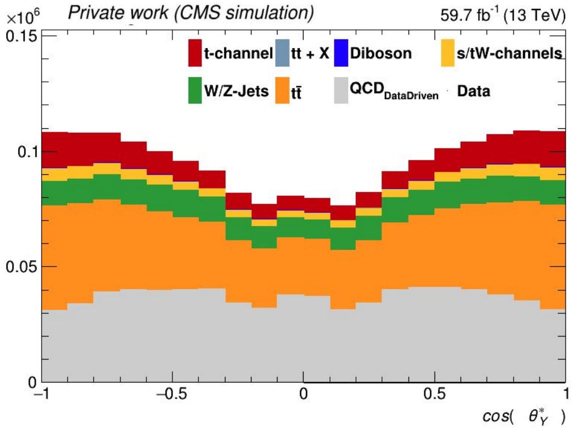
Good agreement between Data and MC

Signal region

Reference frame used in ATLAS 8 TeV [JHEP12(2017)017]



Reference frame used in ATLAS 13 TeV [JHEP11(2022)040]



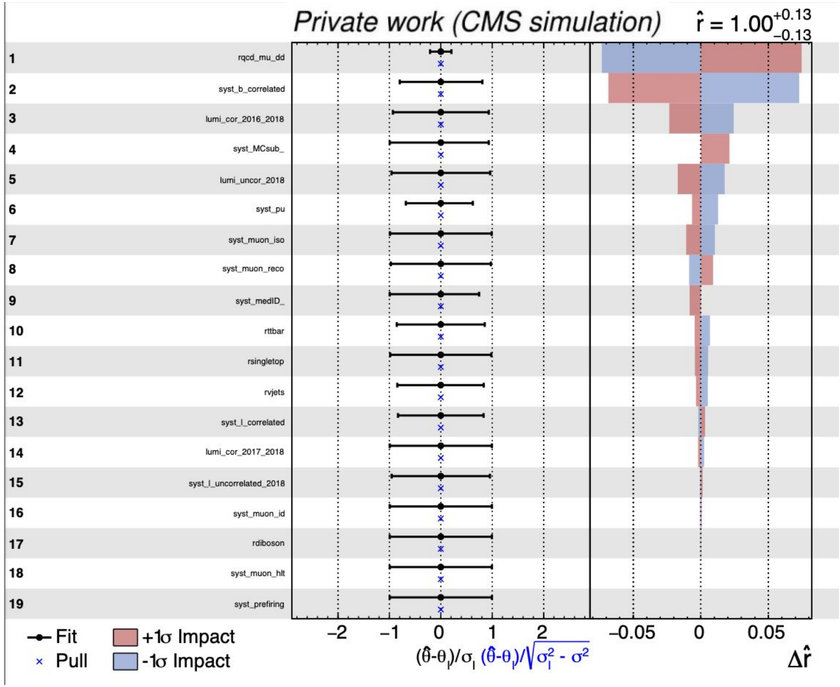
- Angular distributions in top quark rest frame will be used for measuring CP-violating EFT
- Shown are observables expected to provide good significance. Will be checked.
- Will also study improvement in sensitivity using ML

Signal region

First checks of the impacts of systematics:

- QCD Data Driven method to be improved using more systematics
- Verifying nuisance correlations

Nuisance Impacts on the t-channel signal strength measurement, using the signal region only



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Conclusion

- Employing EFT samples with reweighting procedure.
- Checked nuisance impact in the control regions using data driven QCD templates.
- ML to discriminate between signal and background being developed

Analysis TODO list:

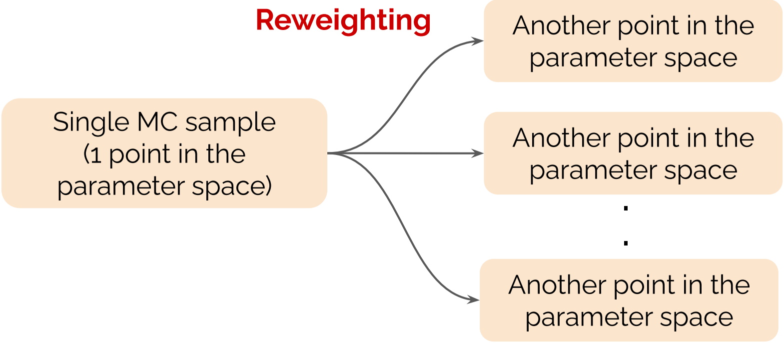
- To be implemented: electron channel
- To be finished: same analysis with 2016, 2017
- List of systematic uncertainties included to be finalized
- **Extract CP-violating EFT extraction**

Thank you for your attention

Backup

Sample generation and Reweighting

- We produce a simulation sample for single top production including EFT coefficients **at top production and decay**
- <u>Reweighting method:</u> different regions of the parameter space to be probed with a single Monte Carlo (MC) sample



$\{ C_{tW} , C^{I}_{tW} \} = \{-2,0,2\}$

$\{ C_{bW} , C^{I}_{bW} \} = \{-2,0,2\}$

$\{ C_{\varphi tb} , C^{I}_{\varphi tb} \} = \{-5,0,5\}$

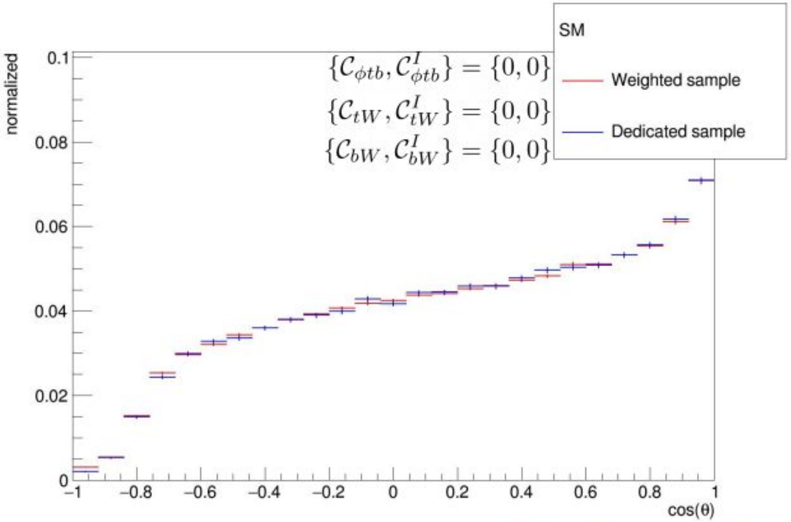
Our 6 axes of the parameter space — Different combination values

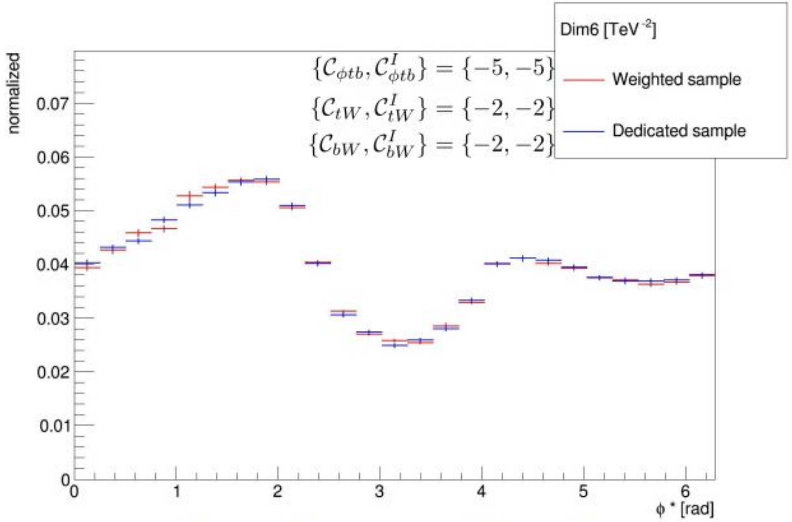
1 simulation production → **729 points parameter space**

Reweighting method is validated

Sample generation and Reweighting

Samples generated with MadGraph5_aMC@NLO, at LO using dim6top model, including EFT in production and decay [Following method in arXiv:1807.03576]

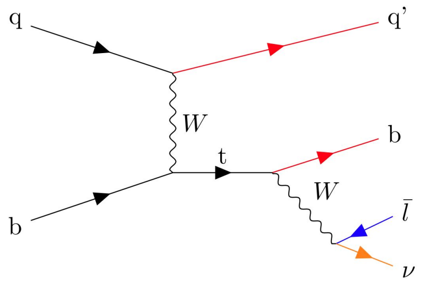


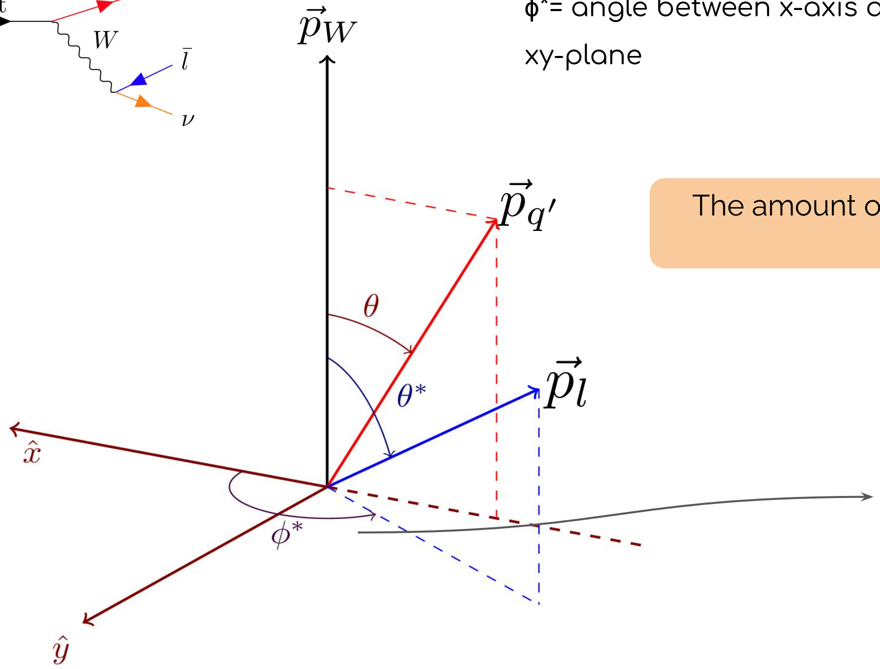


Comparing reweighted distributions of cos(θ) and ϕ^* to dedicated (non-reweighted) samples at two different distant points of the parameter space

➔ **Reweighting is validated**

Measuring CP Violation in top quark rest frame



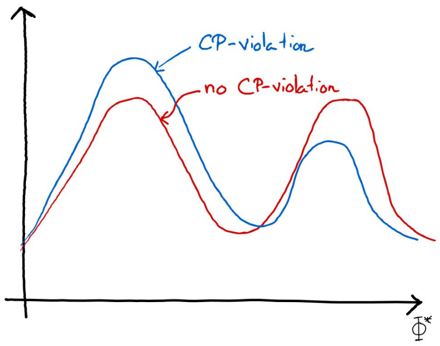


θ = angle between q' quark and W boson momenta

θ* = angle between lepton l and W boson momenta

ϕ*= angle between x-axis and the projection of the momenta of the lepton l on the xy-plane

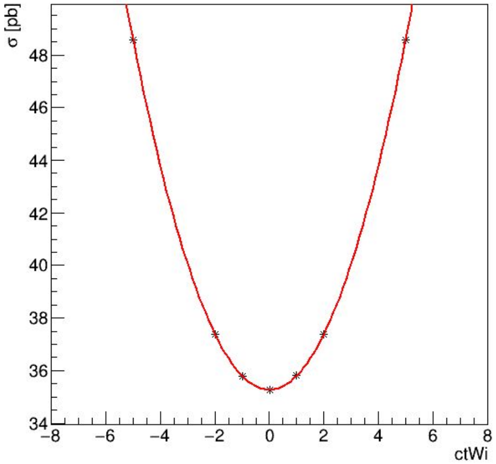
The amount of CP violation can be extracted using the distribution of these angles



Simulating EFT with Reweighting

BSM Matrix Element

$$\mathcal{M} = \mathcal{M}_{SM} + \sum_i \frac{c_i}{\Lambda^2} \overbrace{\mathcal{M}_i} \qquad \sigma \propto |\mathcal{M}|^2$$



Quadratic behavior on the cross section as expected [2]

How many WCs points to generate?

$\{C_{tW}, C^I_{tW}\} = \{-2,0,2\}$

$\{C_{bW}, C^I_{bW}\} = \{-2,0,2\}$

$\{C_{\varphi tb}, C^I_{\varphi tb}\} = \{-5,0,5\}$

6 EFTs — 3 points per EFT

3^6 = 729

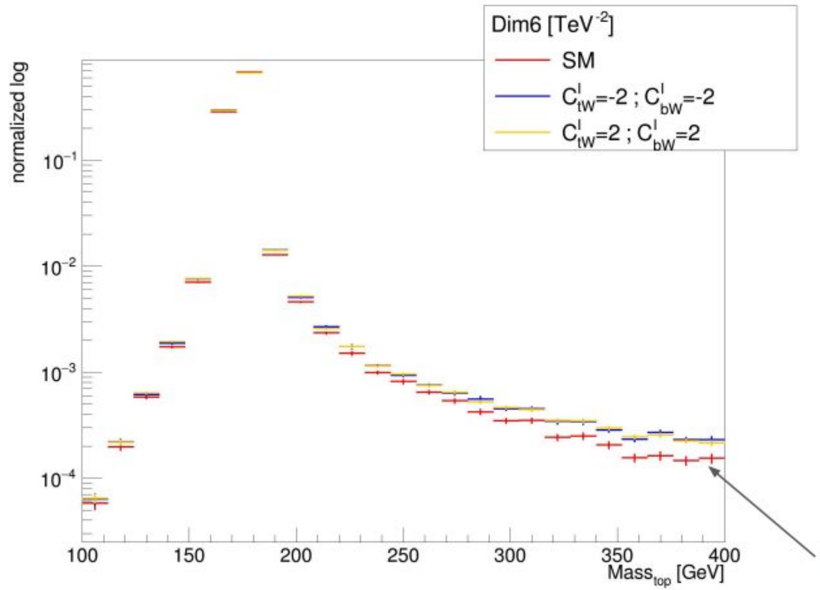
Sample space with **729 WC** points (includes the SM)

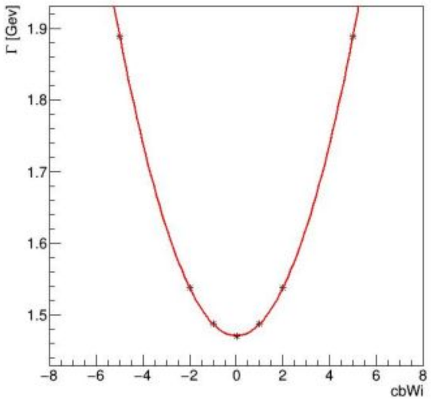
Reweighting method: Assign event weight corresponding to the WC values. We have only one sample with all combinations of WCs

[2] arXiv:1807.03576

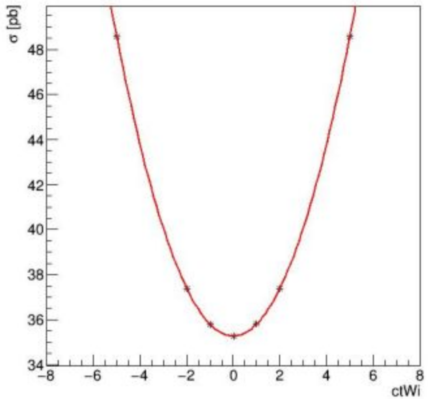
Effects on top width

Quadratic behavior as expected for the cross section and the top width



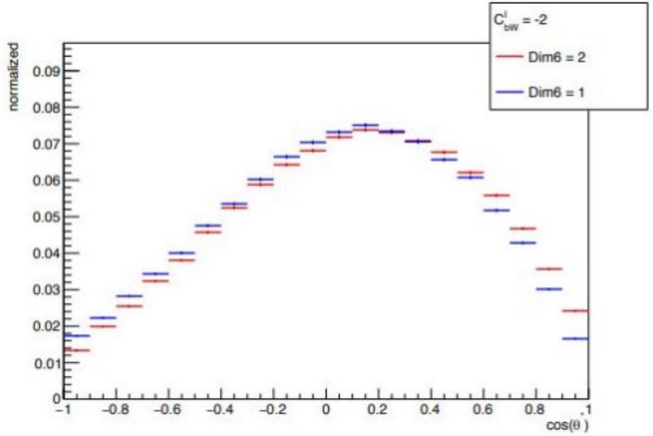


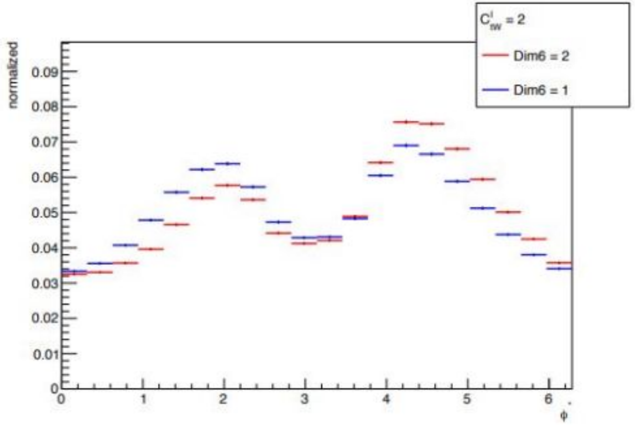
$\sigma \propto |\mathcal{M}|^2$



The impact of EFT on top width is sizeable

Effects of EFT on production only, and production + decay





Higher precision obtained by applying EFT operators effects on top production and decay

Dim6 = 1: EFT effects only on top production
Dim6 = 2: EFT effects on top production and decay

CP-violation with Effective Field Theory (EFT)

SM + **EFT** = **SMEFT**: A model independent way to include the effects of new physics

SMEFT Lagrangian elements:

$$\mathscr{L}_{eff}^{(6)} = \mathscr{L}_{SM} + \sum_i \frac{C_i^{(6)}}{\Lambda_i^2} O_i^{(6)} + h.c.$$

EFT Lagrangian

EFT Coefficients

SM Lagrangian

New physics energy scale

EFT operators

<u>CP-violation with EFT:</u> $\mathscr{L}_{eff}^{(6)} \xrightarrow{\text{CP}} \mathscr{L}_{eff}^{(6)\prime} \neq \mathscr{L}_{eff}^{(6)}$

3 Operators not symmetric under CP

CP-violation with Effective Field Theory (EFT)

3 EFT operators not symmetric under CP:

$$O_{bW}^{(6)} = (\bar{q}\sigma^{\mu\nu}\tau^I b)\tilde{\varphi}W_{\mu\nu}^I \longrightarrow C_{bW}$$

$$O_{tW}^{(6)} = (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W_{\mu\nu}^I \longrightarrow C_{tW}$$

$$O_{\varphi tb}^{(6)} = (\tilde{\varphi}^\dagger i D_\mu \varphi)(\bar{t}_i\gamma^\mu t_j) \longrightarrow C_{\varphi tb}$$

EFT operators

EFT coefficients, which are complex numbers

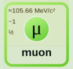
The EFT coefficients control the size of the new physics effects impacting Wtb vertex.

We are interested in both the real and imaginary parts of the three EFTs:

- ➔ **6 dimension parameter space**
- ➔ **The SM is the origin of the parameter space**

CP violation = Non zero value of the imaginary part of these EFTs coefficients

Analysis selection: Muon Channel



Muon Selection
We select strictly one Muon in the final state

	isolated muon	reversed isolated muon	loose muon	Non-iso loose muon
ρT 2017 [GeV]	>30	>30	>10	>10
ρT 2016 & 2018 [GeV]	>26	>26	>10	>10
Relative Isolation	<15%	>30%	<20% (should move to 25%)	-
|η|	<2.4	<2.4	<2.4	<2.4
Id	tight	tight	loose	loose

Signal/WJets/TTBar Regions:
- Exactly 1 isolated tight muons
- Veto events with additional loose muons
- Veto events with “veto” electrons

QCD sideband region:
- Exactly 1 tight muon with reverted isolation
- Veto events with additional loose muons
- Veto events with “veto” electrons

Analysis selections: Jets / B-Jets

Jets Selection

	good jets
|η|	<4.7
pT 2016 [GeV]	>40
pT 2017 & 2018 [GeV]	>40 (|η|<2.4) >60 (2.4<|η|<4.7)
Overlap	No overlaps within a dR=0.4 cone size

	bjets jets
all b jets must be good jets	
|η|	<2.5 (2017 & 2018) <2.4 (2016)

Meant to decrease the impact of ECAL endcap noise issue in 2017 and the failure of the power supply of HCAL modules in 2018.

As the signal signature involves a b quark, the b-tagging capability of CMS is utilized.

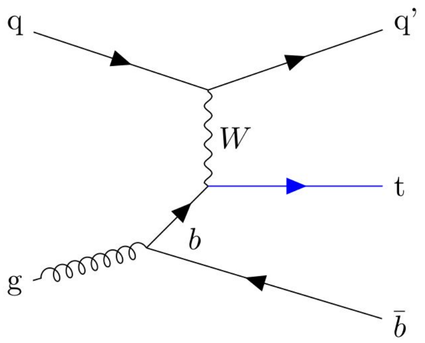
Jets produced by b quarks are identified with the **DeepJet algorithm.**

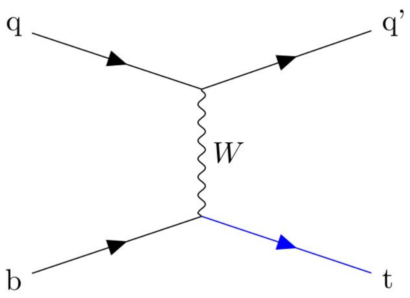
The **tight** and the **medium** working points are utilized in this analysis

Depending on the number of good jets and the number of b-tagged jets, several signal and control regions are defined.

Flavour schemes

Flavour scheme for single top t-channel





4FS
2 ⟶3 process
b quarks stem from gluon splitting

5FS
2 ⟶2 process
b quarks are massless and therefore, included in the proton PDF, they stem from the collision proton

Corrections

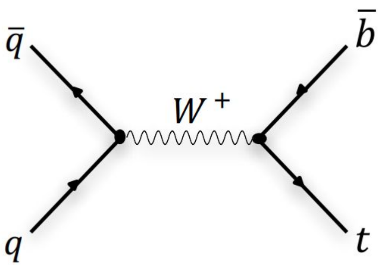
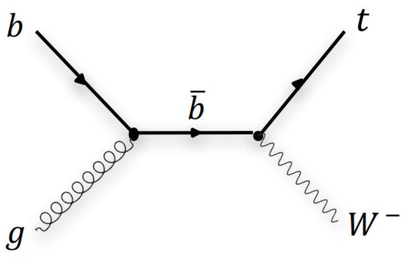
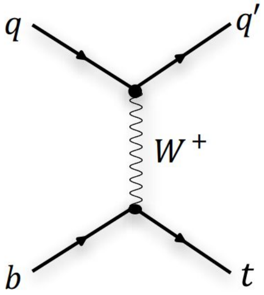
For all the corrections we are using **correctionlib** library unless specified.

- **PileUp:** MC events are reweighted in order to achieve better agreement between true number of pileup interactions and the pileup profile observed in data.
- **SFs for Muons:** Muon RECO, Id, Isolation and trigger SFs are applied.
- **Muon Rochester Correction:** We are applying Muon momentum scaling using the *Rochester* algorithm as recommended by Muon POG..
- **JEC and JER:** Energy correction of the Jets are already applied in NanoAODv9 samples. So, we are not recorrecting them. For the JEC uncertainties, we are following the JetMET recommendations. JET energy resolution correction in MC is not applied yet.
- **B-Tagging Efficiency:** Simulated events are reweighted to attain the same (Tight/Medium) B-tagging efficiency of the DeepJet algorithm as that in data.
- **ECAL Prefiring:** (Not using Correctionlib) We are applying l1prefiring weights directly using the branches saved in the NanoAODv9 samples.
- **MET phi correction:** We are applying the MET phi modulation correction both on data and MC (plot in backup).
- **HEM15/16 issue:** During 2018 C+D eras two HCal modules went off. This affected the jet energy measurement in the region $-0.87 > \varphi > -1.57$ and $-1.3 > \eta > -2.5$. We are planning to remove events where the jets which pass the analysis selection fall in this region.

Single top quark production at the LHC

The three main **single top** production modes are:

Signal

	s-channel	tW-channel	t-channel
Feynman diagrams:			
Inclusive cross-section at the LHC (13TeV/RunII):	**~ 11.7 pb**	**~ 35.9 pb**	**~ 136 pb**

We are going to study the t-channel due to its largest cross-section.

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