# Measurement of CP-violating Wtb couplings using EFT in single top t-channel production with CMS Run 2 data

Top LHC France

30/04/2025

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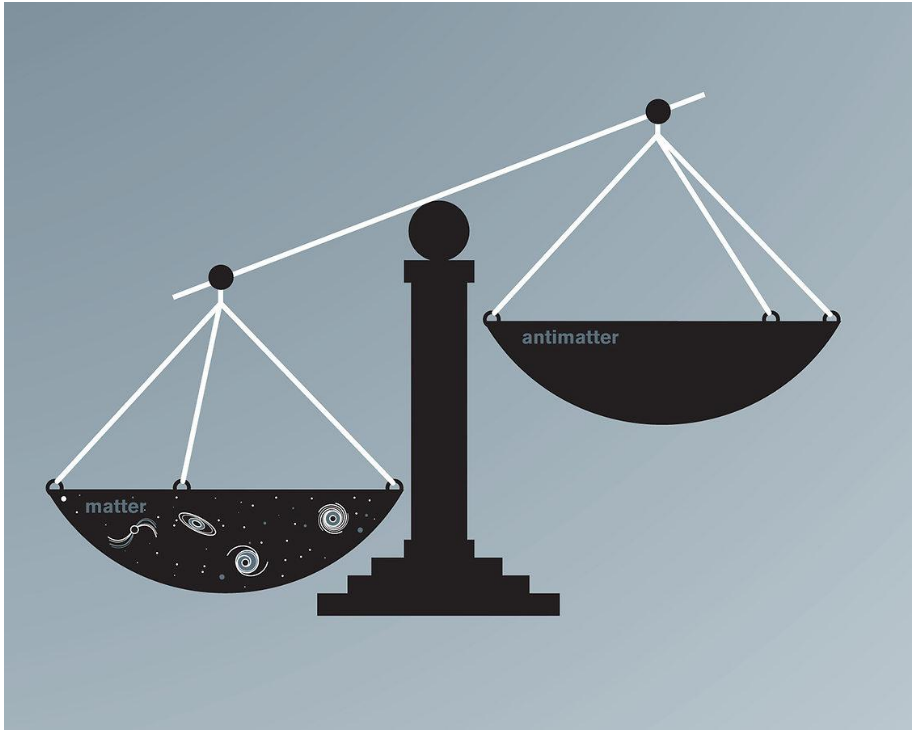
# Context : Matter and antimatter asymmetry

The universe is baryon-number asymmetric

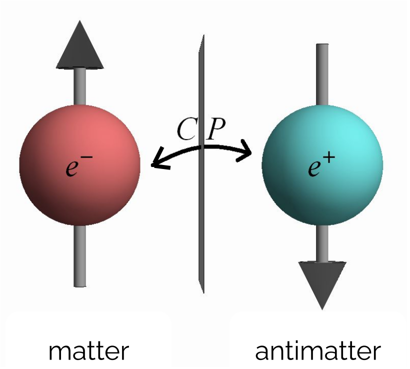



SM prediction: $\eta_{SM} = \frac{n_B - n_{\bar{B}}}{n_\gamma} \propto 10^{-27}$

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

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

**Discrepancy between the SM prediction and observations**

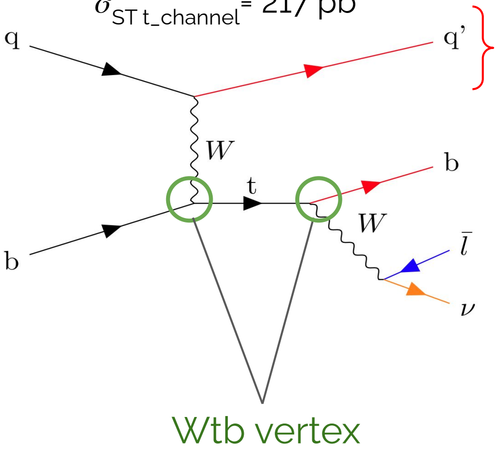



**Looking for new CP violation sources involving top quarks Beyond the Standard Model (BSM).**

# Goal of the analysis

**Measure CP violation** through the t-channel production of single-top quarks and their subsequent decay to Wb. *This process has the advantage of involving twice the Wtb vertex*

$\sigma_{\text{ST t\_channel}}$= 217 pb




Analysis performed in the context of Effective Field Theory

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

| Non-Hermitian Operators involving two quarks and a boson | Wilson Coefficients |
|---|---|
| $O_{uW}^{(6)} = (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi} W^I_{\mu\nu}$ | $c_{tW} + i c^I_{tW}$ |
| $O_{dW}^{(6)} = (\bar{q}\sigma^{\mu\nu}\tau^I b)\varphi W^I_{\mu\nu}$ | $c_{bW} + i c^I_{bW}$ |
| $O_{\varphi ud}^{(6)} = (\tilde{\varphi}^\dagger i D_\mu \varphi)(\bar{u}\gamma^\mu d)$ | $c_{\varphi tb} + i c^I_{\varphi tb}$ |

CP violation if

$c^i_{tW} \neq 0$, $c^i_{bW} \neq 0$ or $c^i_{\varphi tb} \neq 0$

- ➔ EFT impacts both the production and decay of top quark
- ➔ This vertex can be modified by CP violation
- ➔ The effect is canceled in ttbar process

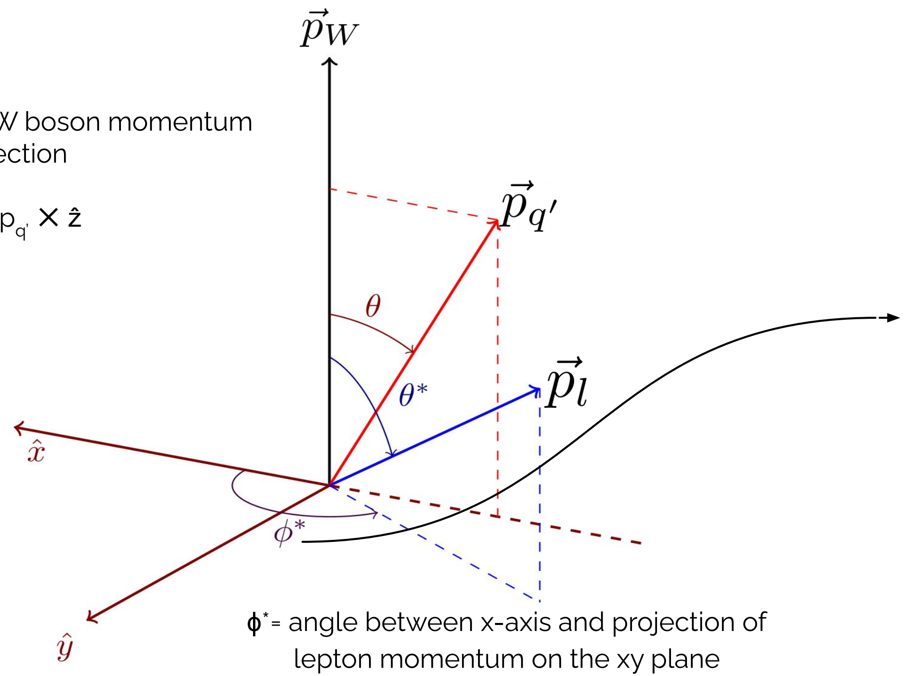
# Measuring CP violation : EFT impact on angular variables

**Top quark rest frame**

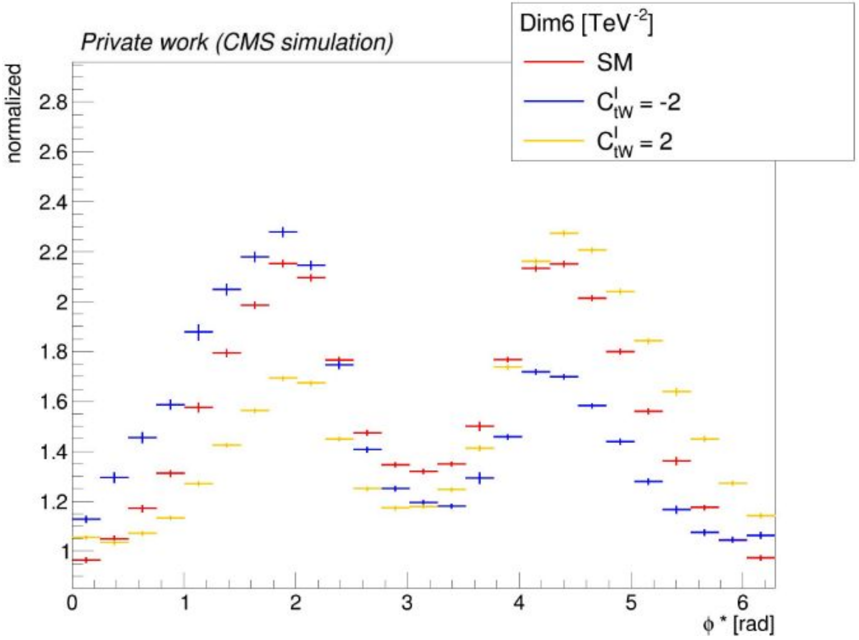
Reference frame used in ATLAS 8 TeV [arXiv:1707.05393]

**ẑ** : W boson momentum direction

$\hat{y} = p_{q'} \times \hat{z}$




$\phi^*$= angle between x-axis and projection of lepton momentum on the xy plane



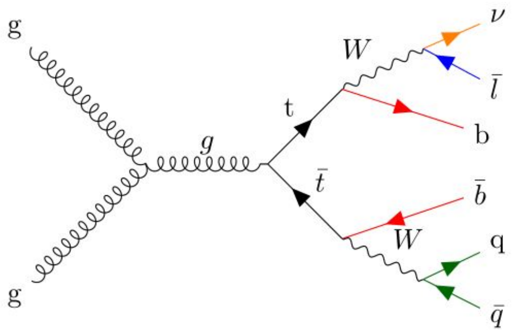

The shape of the distribution varies depending on the value of the EFT coefficient

The amount of CP violation can be extracted using such angular distributions

# SM Background processes

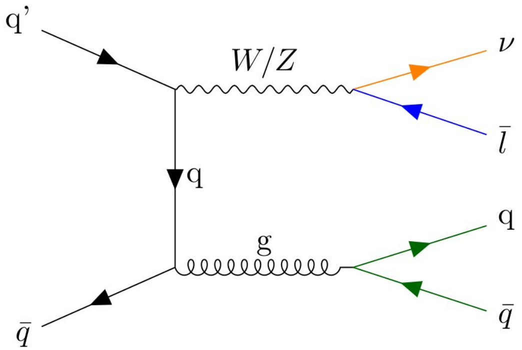
## Main background processes :

ttbar



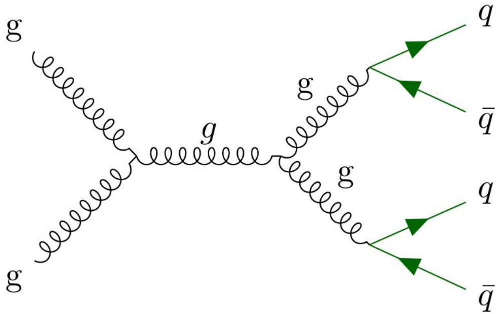

$\sigma_{ttbar}$ = 452 pb

W/Z + jets (with Drell-Yan)




$\sigma_{Wjets}$ = 84 847 pb

QCD processes




### Other backgrounds :

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

# Event samples

- **Single Top/AntiTop t-channel (SM)** : ST_t-channel_top_4f_InclusiveDecays_TuneCP5_13TeV-powheg-madspin-pythia8
- **ttbar semileptonic** : TTToSemiLeptonic_TuneCP5_13TeV-powheg-pythia8
- **W + Jets** : WJetsToLNu_TuneCP5_13TeV-madgraphMLM-pythia8
- **QCD** : pT binned (mu or EM enriched) QCD_Pt-50To80_MuEnrichedPt5_TuneCP5_13TeV-pythia8
- **tW top and anti-top** : ST_tW_top_5f_inclusiveDecays_TuneCP5_13TeV-powheg-pythia8

**EFT samples** :

➢ Generated using the dim6Top LO UFO model from Madgraph5

➢ A reweighting technique is used to get all the EFT combination

# Object definition

The **single isolated muon** trigger with $p_T$ > 24 GeV (2016, 2018) and $p_T$ > 27 GeV (2017) are used in this analysis

## Jet selection

| | Good jets |
|---|---|
| $\|\eta\|$ | < 4.7 |
| $p_T$ 2016 (GeV) | > 40 |
| $p_T$ 2017 and 2018 (GeV) | > 40 ($\|\eta\|$ < 2.4)<br>> 60 (2.4 < $\|\eta\|$ < 4.7) |
| Overlap | Removed overlap between jets and leptons in a $\Delta R$ < 0.4 cone |
| Jet Id | **Tight** (discriminate real jets from fake lepton, pile up and detector noise) |

**b-jets :**

- Must be good jets
- $|\eta|$ < 2.5 (2017 & 2018)
- $|\eta|$ <2.4 (2016)
- Tight/medium working point of DeepJet tagger used

## Muon selection

| | Isolated muon | Loose muon |
|---|---|---|
| $\|\eta\|$ | < 2.4 | < 2.4 |
| pT 2017 (GeV) | > 30 | > 10 |
| pT 2016 and 2018 (GeV) | > 26 | > 10 |
| Relative isolation | < 15% | < 25% |
| Id | tight | loose |

A reversed isolated muon is also defined by reverting the isolation : > 40%

➔ All recommended CMS corrections are applied (including pileup and b-tag weights, muon Rochester momentum correction, JEC, MET phi modulation)

# Analysis regions

Loose preselection applied to reduce fake lepton contribution :

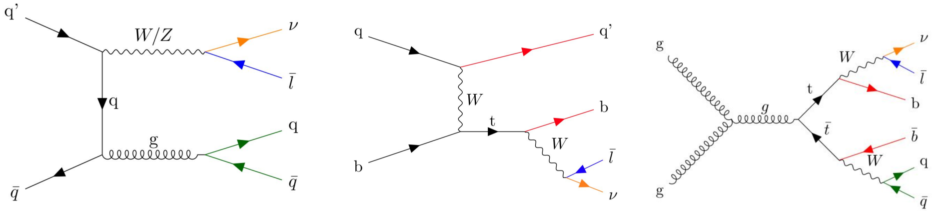
- ➢ **MET** > 20 GeV
- ➢ **Transverse mass of W boson with fixed lepton $p_T$ at 45 GeV ($M_T^{W,fix}$** ) > 25 GeV

**Lepton selection :**

- Exactly one isolated tight muon
- Veto events with additional loose muons
- Veto events with veto electrons

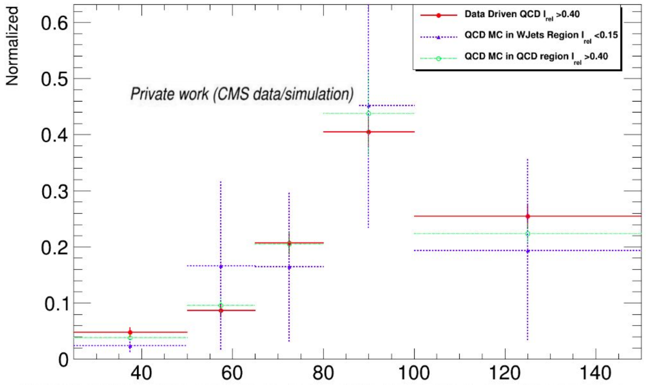
**Event categorization based on the number of Jets and b-tagged jets :** Signal region (SR) , W/Z-Jets control region (CR) and ttbar CR

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



+ **QCD measurement region** (sideband region) :

- ❖ defined for each signal and control region
- ❖ same selection but reverted muon isolation (>0.4)

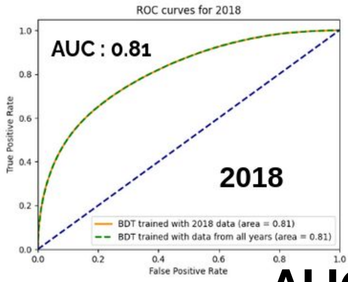


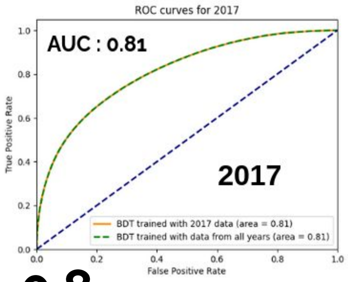

Comparison of the distribution of $M_T^{W,fix}$ for different QCD templates

# Signal Region

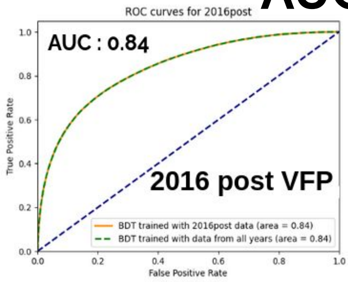
In the SR we require : **1** isolated tight muon, **2** jets and **1** tight b-jet

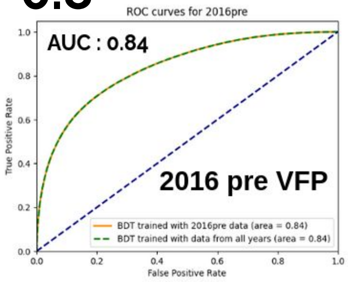
- **BDT trained in the SR using XGBoost to discriminate single top (ST) t-channel from other SM background process**
- *Input variables for the BDT* : cos($\theta^*$), $\eta$ of the spectator jet, $M_T^{W,fix}$, $M_{top}$, $\Delta\eta(\mu$, b-jet), $\Delta R$(spec jet, b-jet), b-jet $p_T$, lepton $p_T$

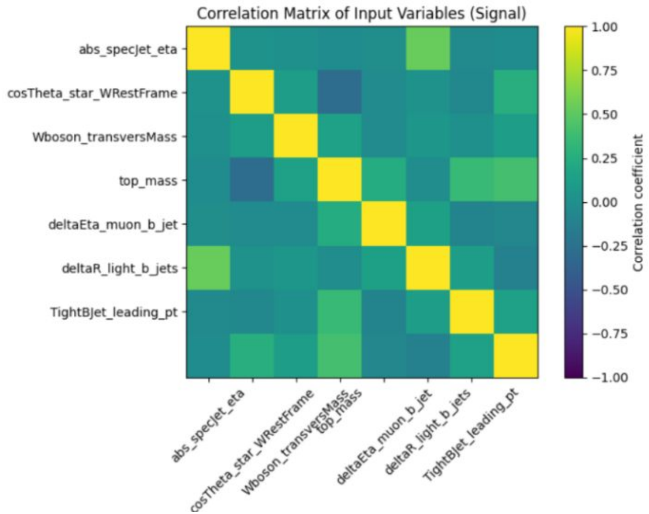


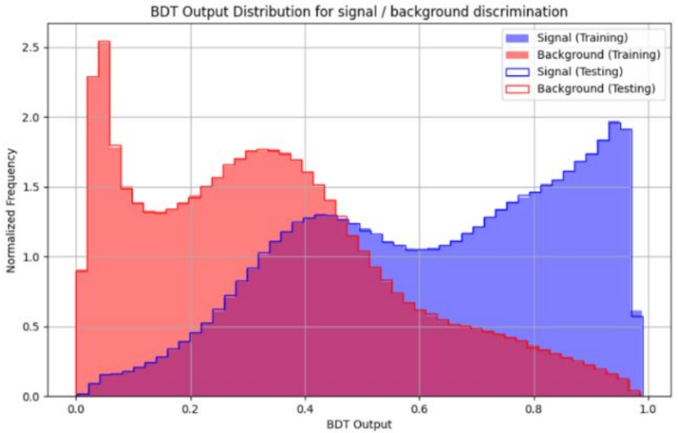




**AUC ~ 0.8**



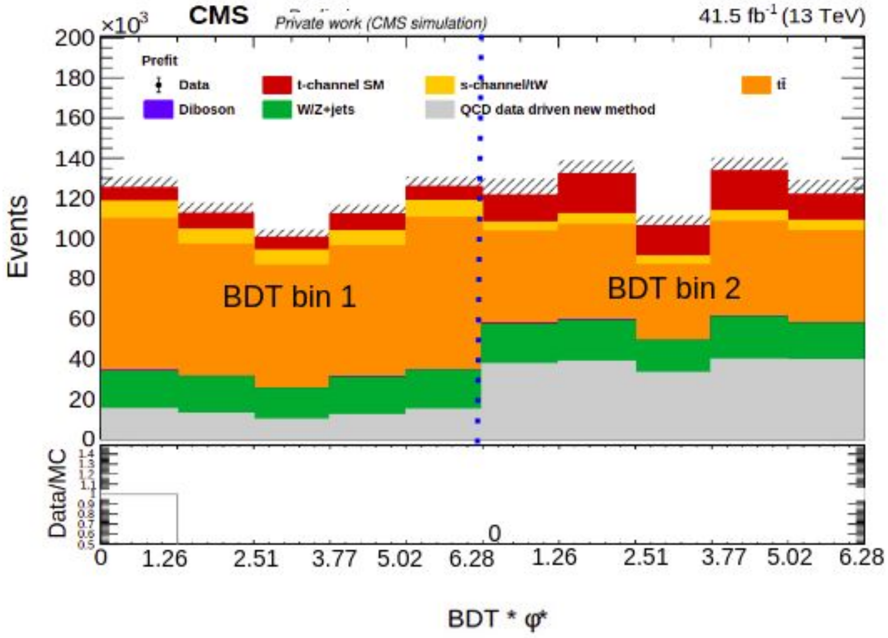



# Signal Region

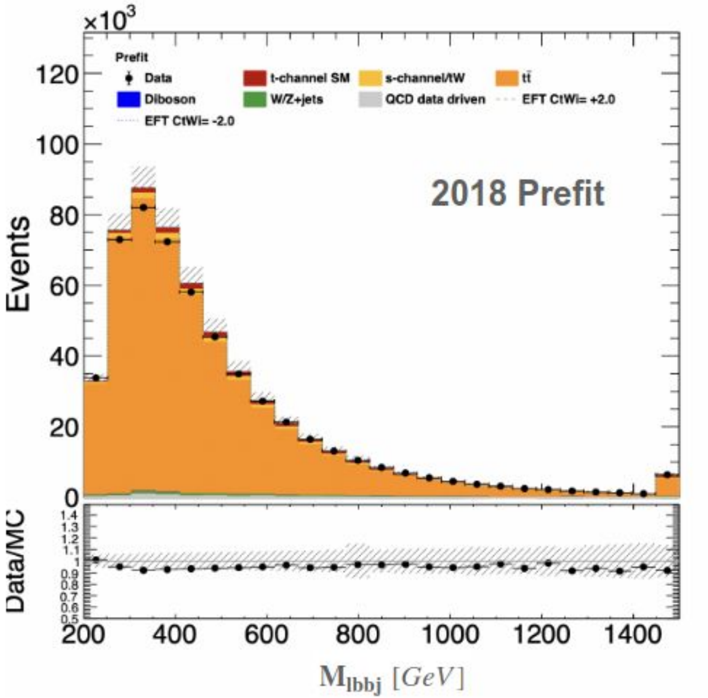
**As the measurement observable we are using the $\phi^*$ variable in bins of the BDT**

- ➔ Constructed by unrolling the 2D distribution to get a 1D distribution
- ➔ $\phi^*$ : Measure the CP violation ($c_{tW}^{i}$ Wilson Coefficient)
- ➔ BDT : Increase the sensitivity of the analysis



# TTbar Control Region

In the ttbar control region, we are using **invariant mass of the lepton and three jets** (2 tight b- tagged jets and a third jet with the highest $p_T$) system.

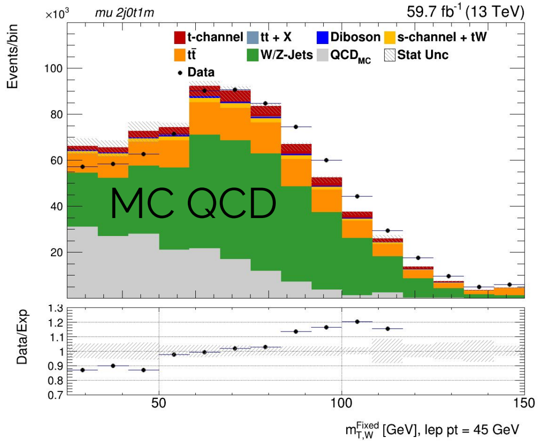



- ➔ Variable chosen for its power to discriminate between ttbar and the rest
- ➔ Good data/MC agreement observed

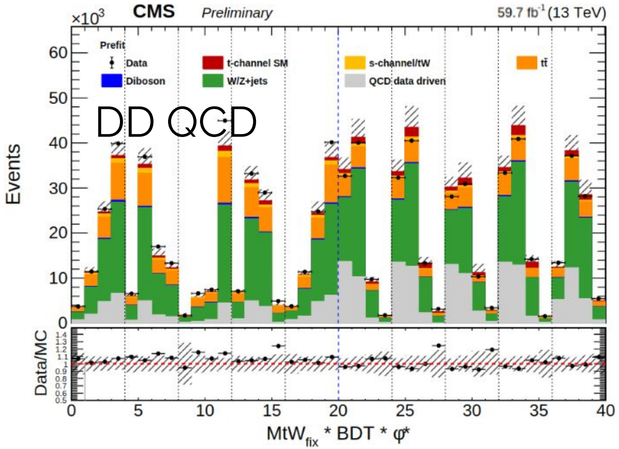
# W/Z + jets Control Region

In the W-jets CR we use the **transverse mass of the W boson with fixed lepton $p_T$ at 45 GeV ($M_{T}{}^{W}{}_{,fix}$ )** in bins of our main observable (3D distribution unrolled in 1D)

➔ Variable chosen for its power to discriminate between W+jets and the rest




Bad data/MC agreement using MC QCD




We still get unsatisfactory data/MC agreement due to bad QCD modelling : **We need a new method to estimate the QCD**

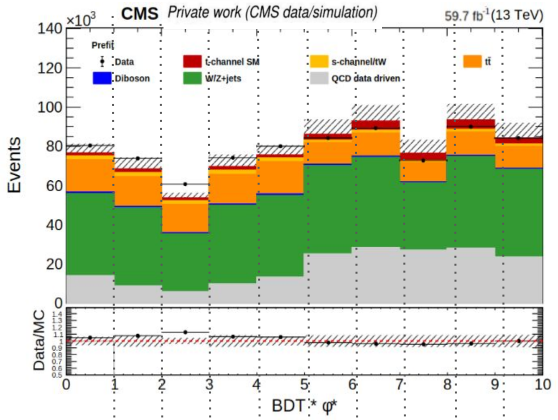
# QCD estimation strategy

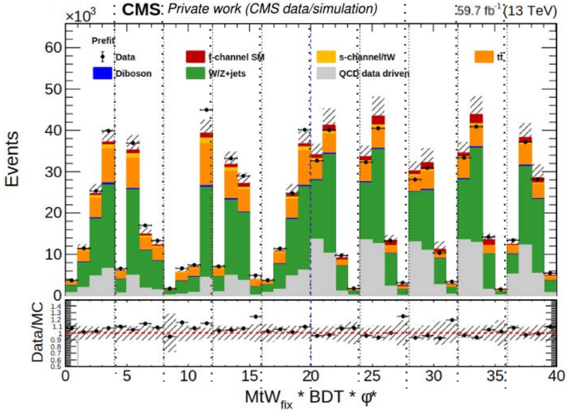
- *There is no standard method to estimate QCD (under discussion within TOP PAG)*
- *We present here our QCD estimation strategy*

**Let's take any variable**

For each bin of this variable :

1. **Build the $M_T^{W,fix}$ template** (transverse mass of the W with lepton $p_T$ fixed at 45 GeV) for every process after optimizing the binning of the variable and $M_T^{W,fix}$
2. Replace the QCD MC template by the **data driven QCD template** (obtained from the QCD sideband region) and set its normalization to that of QCD MC from SR.
3. Perform a **simultaneous fit** over all bins of the chosen variable with **n Parameters Of Interests (POIs) for the QCD normalization** (n bins of the variable)



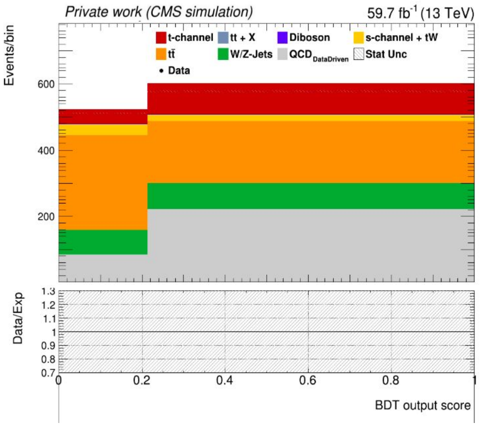

**SM t-channel rate parameter is fixed to 1**

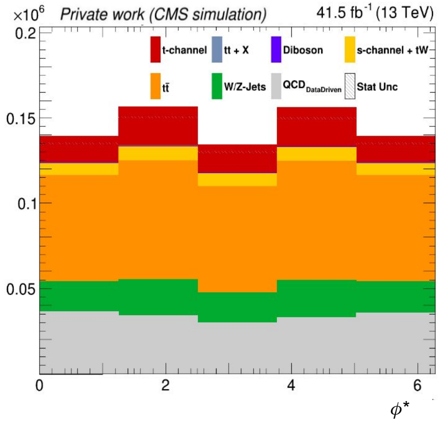
# Binning optimization

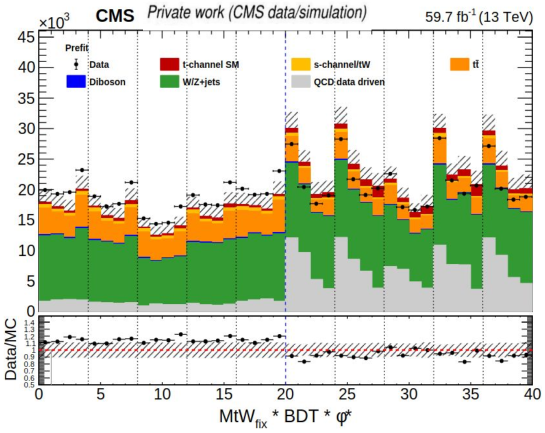
- **BDT binning** : We are using **2 bins of BDT with equal number of W+jets events** in the SR in each of them to reduce the impact of the lack of statistics for this process

- **$\phi^*$ binning** : Binning optimized in the SR by **maximizing the significance of ST t-channel with EFT over SM** (5 bins of $\phi^*$ )

- **$M_T^{W,fix}$** : Tried optimizing wrt significance of QCD over the rest but found better results using a binning with **equal number of W+jets events** in each bin. We are using 4 bins of $M_T^{W,fix}$



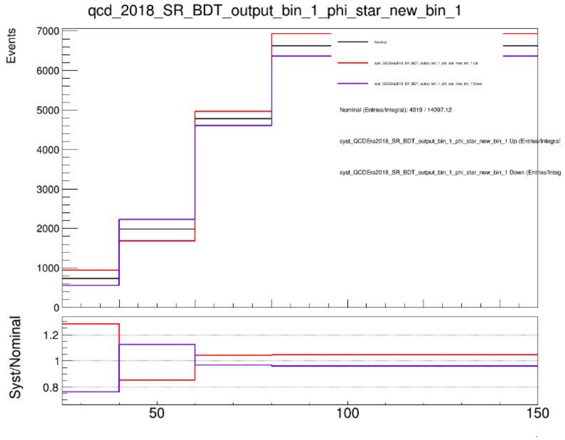
# Systematic uncertainties

| NAMES | USED | CORRELATION |
|---|---|---|
| Muon Reco | Y | All channel |
| Muon HLT | Y | All channel |
| Muon ID | Y | All channel |
| Muon Iso | Y | All channel |
| B Tagging SF | Y | All channel |
| Prefiring | Y | All channel |
| Pile Up | Y | All channel |
| Top pt | Y | Only TTbar |
| Lumi | Y | All channel |
| JES/JER | Y | As per Recom |
| ISR | Y | Not correlated |
| FSR | Y | Not correlated |
| PDF + alpha_s | Y | All channels |
| QCD Scale | Y | All channels |
| Diff btw NLO and LO | Y | Only EFT+ST |

We introduce 2 uncertainties in this analysis :

- Data Driven QCD shape/era uncertainty (constructed by choosing different data taking era)
- Difference between NLO (POWHEG samples) and LO (Madgraph samples)

All uncertainties are correlated over bins of the main observable except **QCD era uncertainty**.




Down : 2018 A, B, C era
Up : 2018 D era
Nominal

$M_T^{W,fix}$ distribution in BDT bin 1 and $\phi^*$ bin 1 with Up and Down variations of QCD era uncertainty

# QCD background fit results

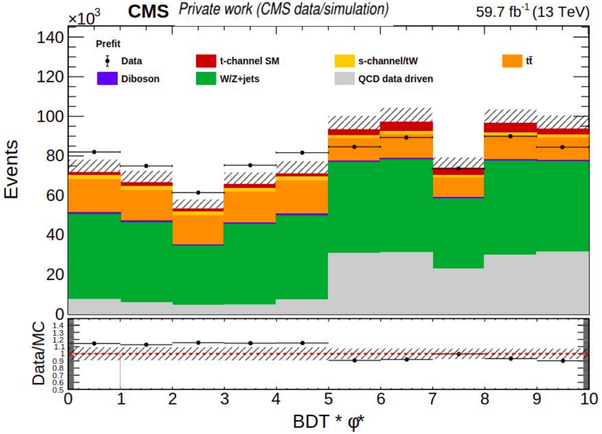
2018 results

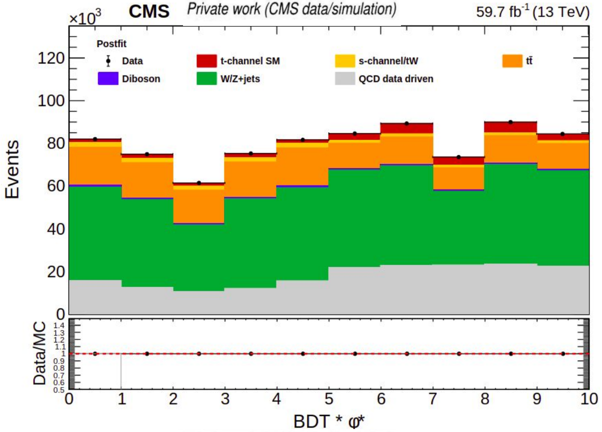
QCD Background only fit with data unblinded in the W-Jets region is performed

## Prefit

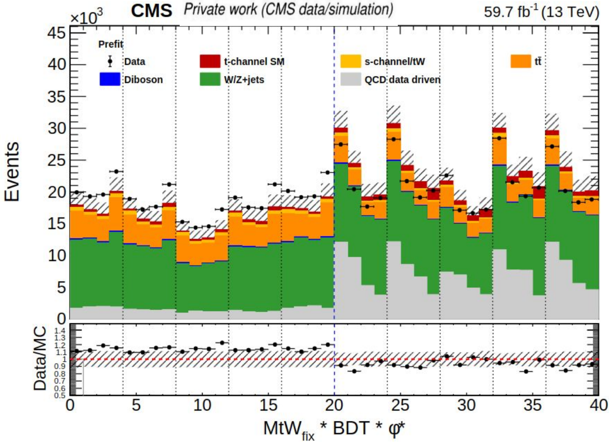
## Postfit

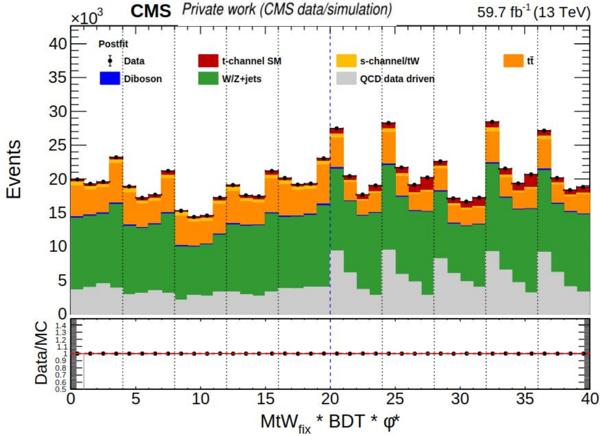
**Integrated over $M_T^{W,fix}$**




**$M_T^{W,fix}$ in bins of BDT x $\phi^*$ (used in the QCD fit)**

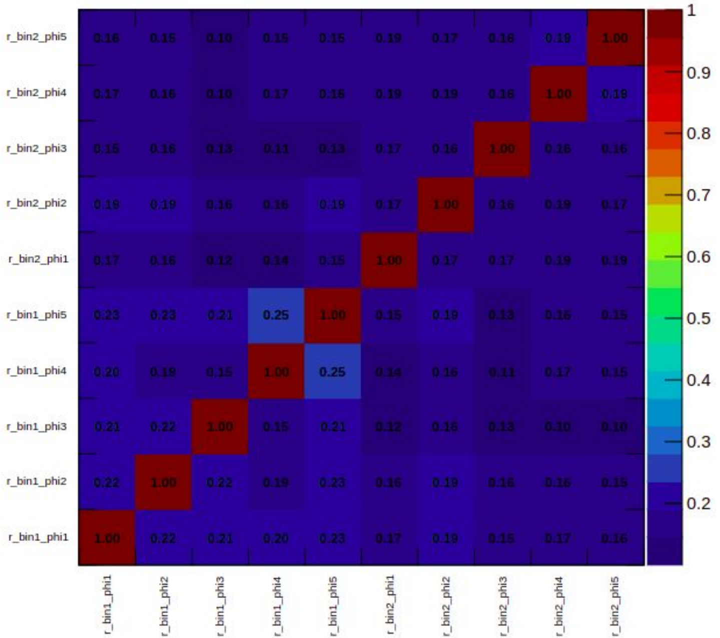


# QCD background fit results 2018 results

Uncertainties include both statistical and systematic

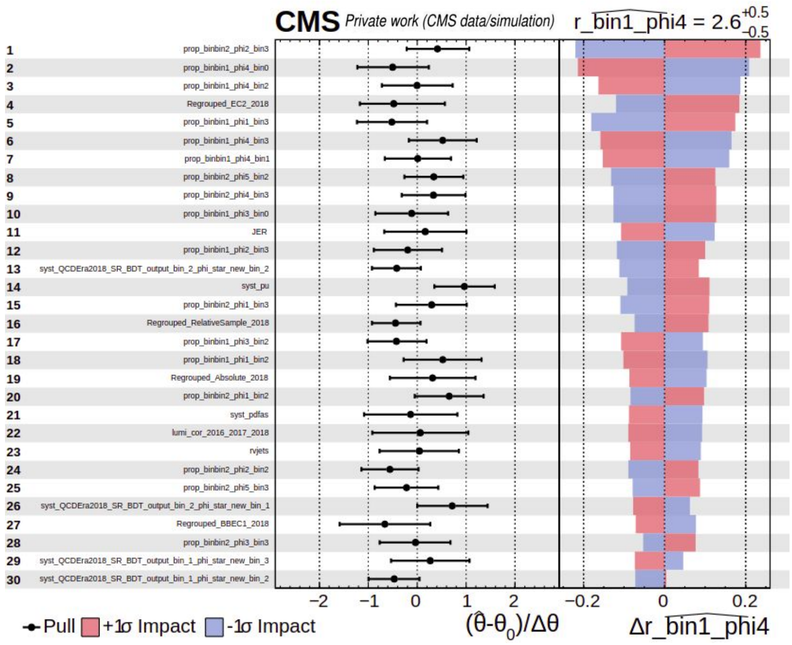
| POI Name | Best Fit Value | Uncertainty |
|---|---|---|
| r_bin1_phi1 | 2.130 | +/- 0.136 |
| r_bin1_phi2 | 2.144 | +/- 0.169 |
| r_bin1_phi3 | 2.397 | +/- 0.212 |
| r_bin1_phi4 | 2.581 | +/- 0.215 |
| r_bin1_phi5 | 2.115 | +/- 0.145 |
| r_bin2_phi1 | 0.714 | +/- 0.033 |
| r_bin2_phi2 | 0.733 | +/- 0.033 |
| r_bin2_phi3 | 1.002 | +/- 0.041 |
| r_bin2_phi4 | 0.791 | +/- 0.035 |
| r_bin2_phi5 | 0.717 | +/- 0.032 |

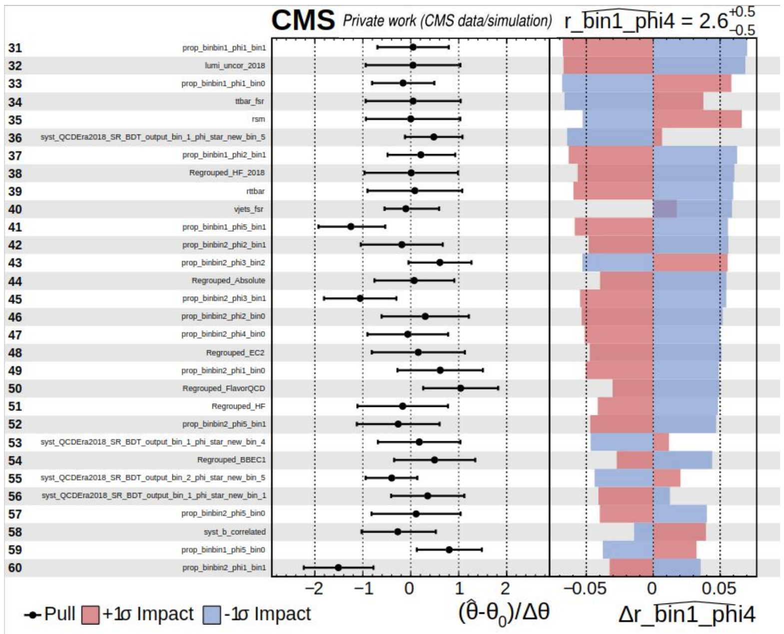



➢ Low correlations (<0.25) between the POIs

# Fit diagnostics

2018 results




➔ The impact of the nuisances on the POI of BDT bin 1 and phi star bin 4 is presented

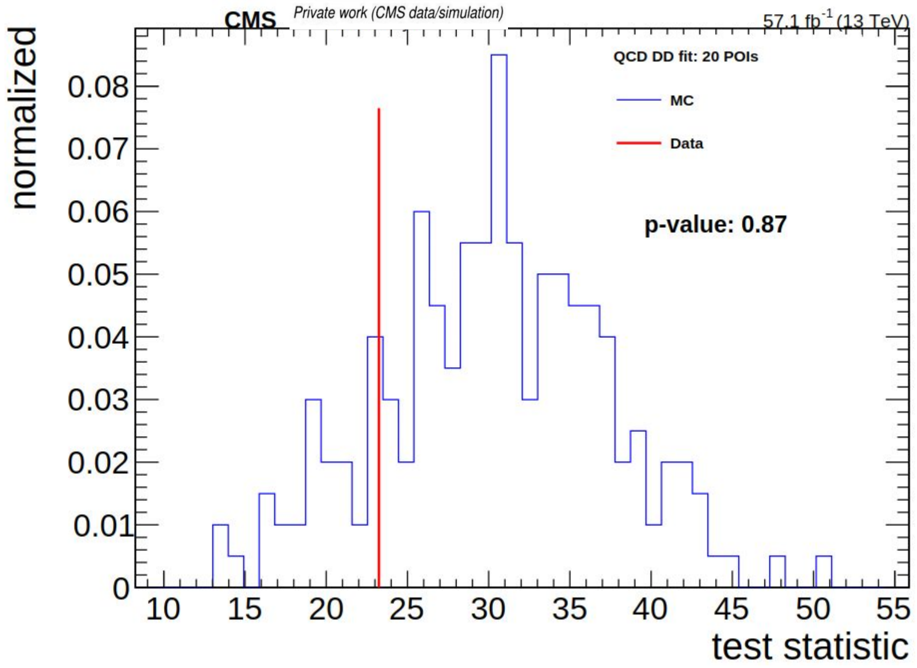
- Pulls of the nuisances are not very large
- MC statistical uncertainties have a large impact on the POIs

# Fit diagnostics

2018 results

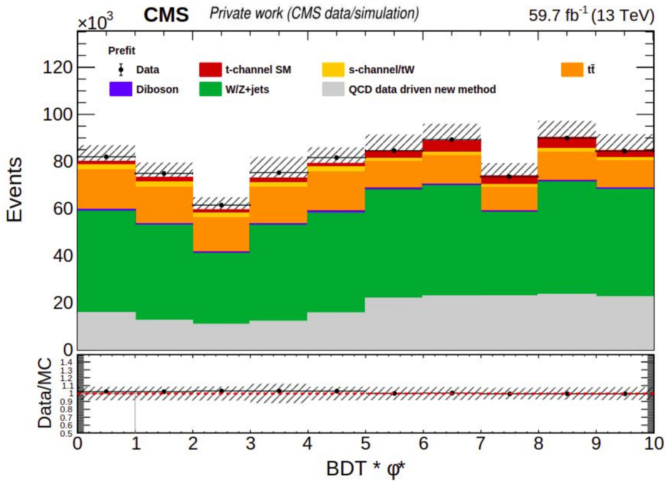
- ➢ A goodness of fit (GoF) test with the saturated model where likelihood ratio is used as test statistic, and the alternate hypothesis is considered to be the data itself, is performed.

- ➢ The observed P-value shows, the model adequately fits the data

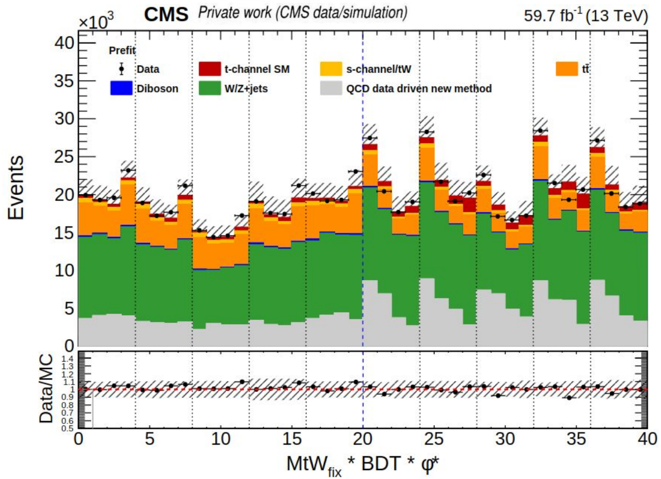


# New template for the final EFT fit

2018 results

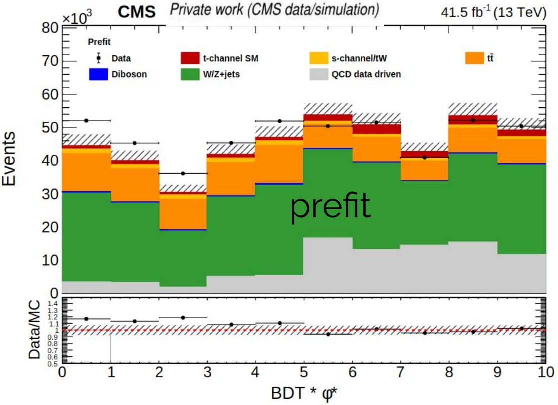


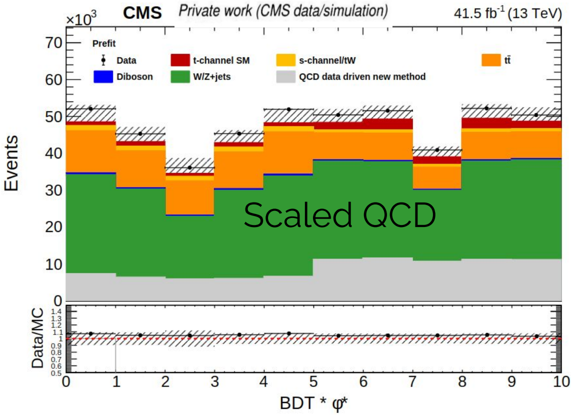

- A new QCD template ("aka" Scaled QCD) is constructed from the best fit values of the POIs
- The templates does **not** include pulled nuisances from background data fit
- Upper plot will be the input to the final EFT fit
- Clear improvement of the data/MC agreement compared to prefit (slide 12)



# QCD background fit results for other years

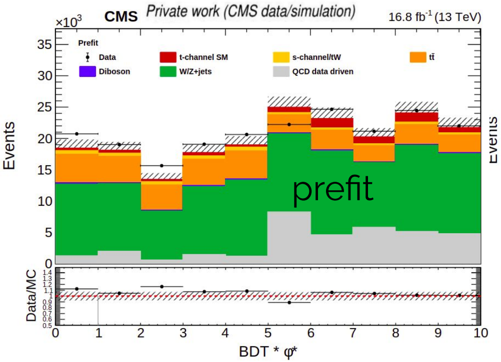
2017

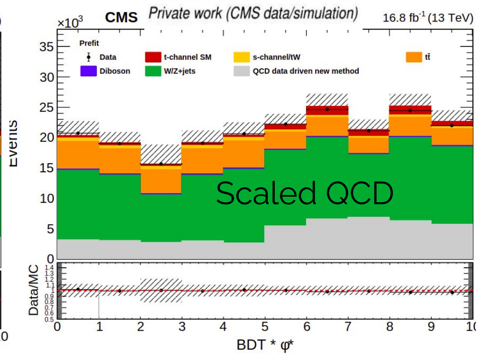


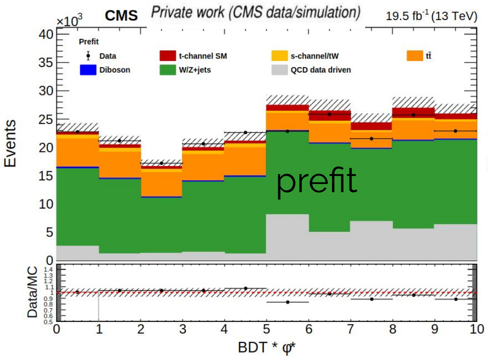

➔ Same method is used for other years showing same improvement in the data/MC agreement as in 2018.

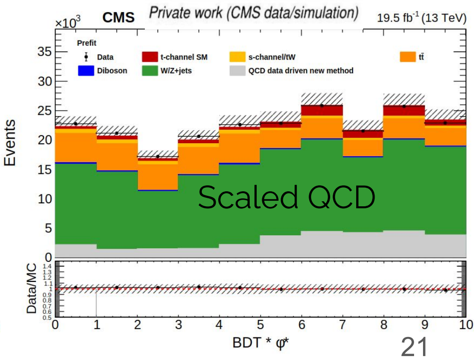
2016 postVFP




2016 preVFP



# Conclusion

**What has been done :**

- ➔ Produced private EFT samples
- ➔ Divided the analysis into signal and control regions
- ➔ Trained a BDT to improve the sensitivity of the analysis on EFT measurement
- ➔ Developed a promising QCD estimation strategy

**Plans :**

- ❏ Working on the improvement of the data/MC agreement by modifying the selection
- ❏ Perform final EFT fit with all years combined

Thank you for your attention

# Backup

# Reweighting technique

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

**Reweighting**

Single MC sample (1 point in the parameter space) → Another point in the parameter space

Single MC sample (1 point in the parameter space) → Another point in the parameter space

⋮

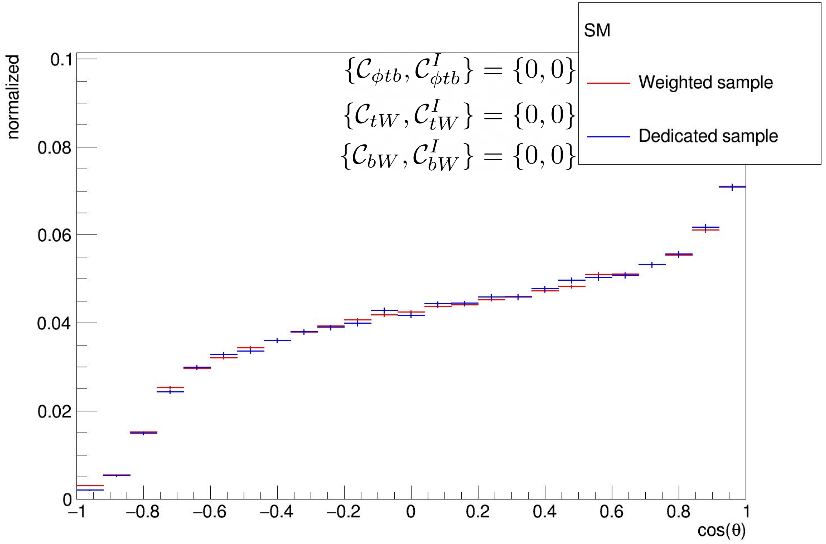
Single MC sample (1 point in the parameter space) → Another point in the parameter space

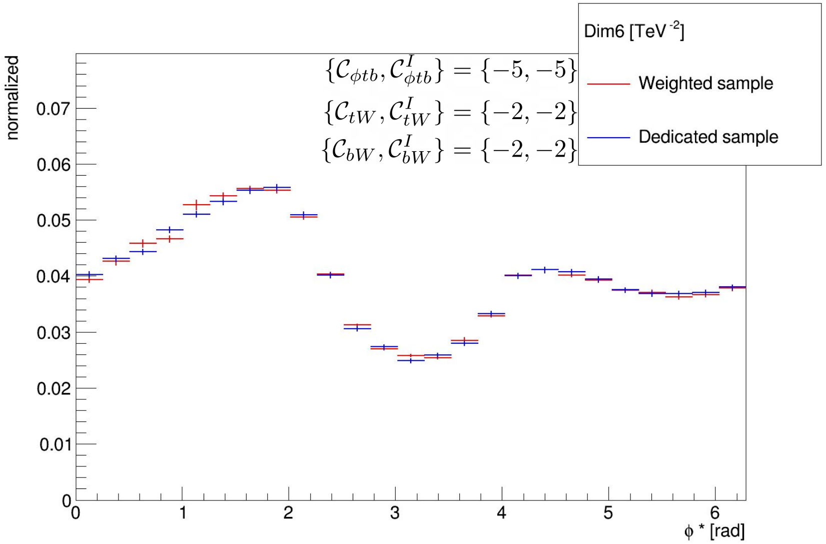
$$\underbrace{\begin{matrix} \{ C_{tW} , C^{I}_{tW} \} \\ \{ C_{bW} , C^{I}_{bW} \} \\ \{ C_{\varphi tb} , C^{I}_{\varphi tb} \} \end{matrix}}_{\text{Our 6 axes of the parameter space}} \begin{matrix} = \\ = \\ = \end{matrix} \underbrace{\begin{matrix} \{-2,0,2\} \\ \{-2,0,2\} \\ \{-5,0,5\} \end{matrix}}_{\text{Different combination values}}$$

**1 simulation** → **729 points**

The reweighting method allows to produce a single sample instead of 729

# Reweighting technique

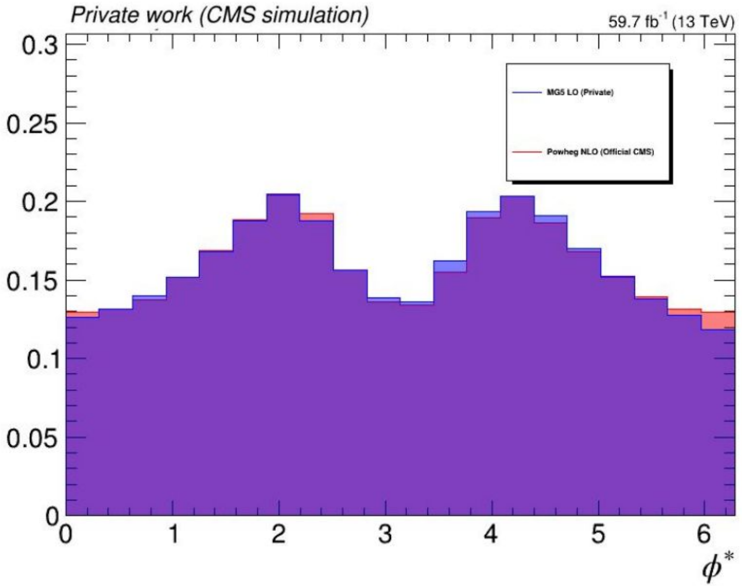


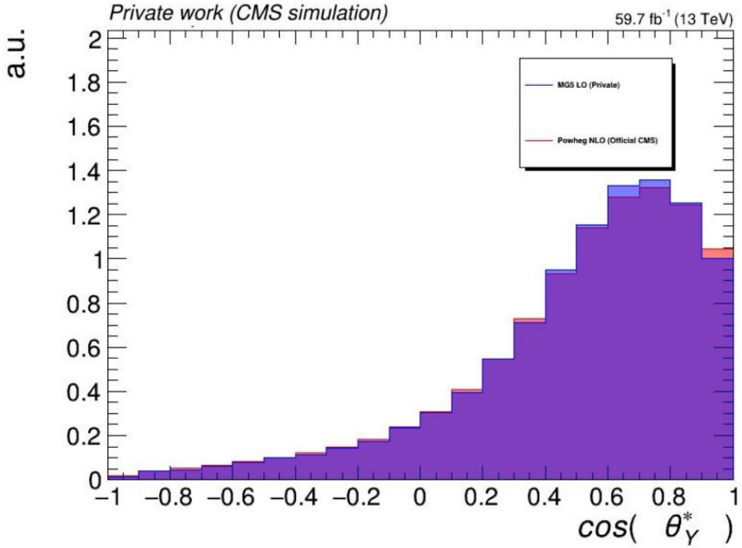




Comparing reweighted distributions of cos(θ) and $\phi^*$ to dedicated (non-reweighted) samples at two different distant points of the parameter space

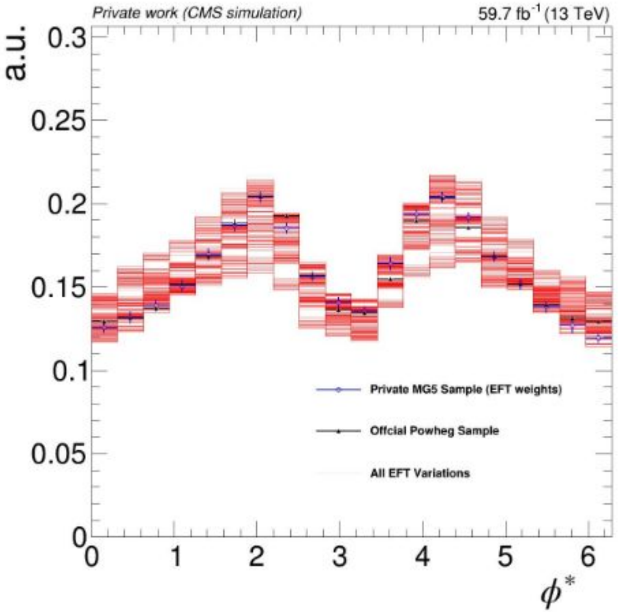
➔ **Reweighting is validated**

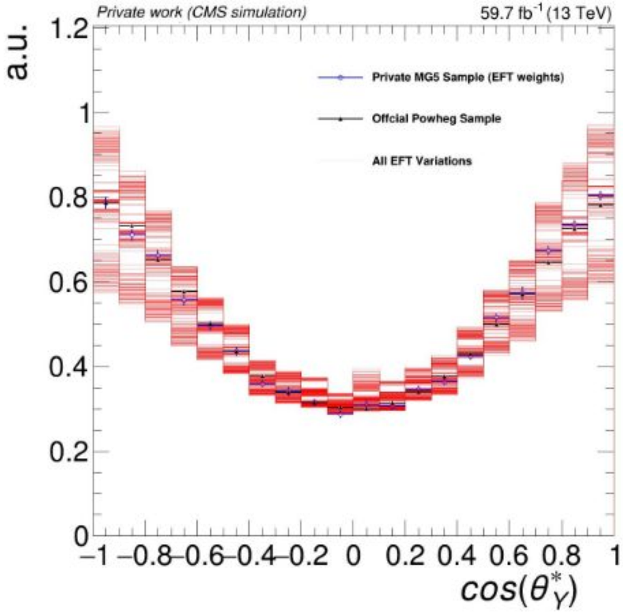
# Reweighting technique



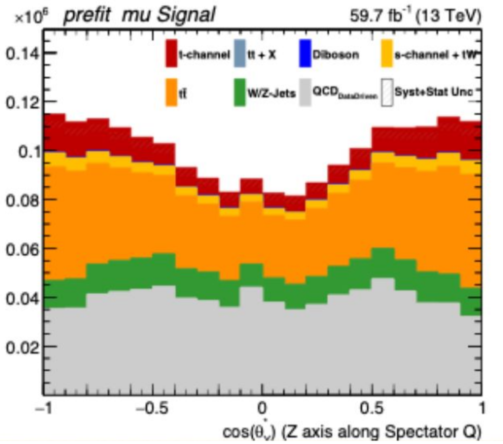



# Reweighting technique

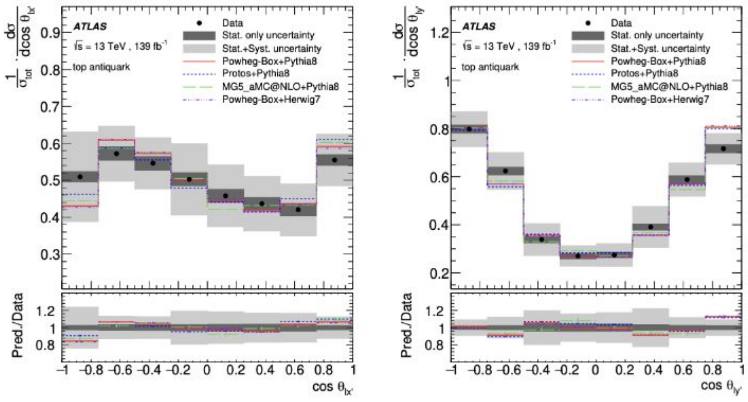


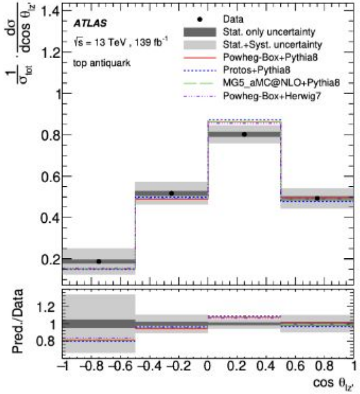
# ATLAS results




| | $C_{tW}$ | | $C_{itW}$ | |
|---|---|---|---|---|
| | 68% CL | 95% CL | 68% CL | 95% CL |
| All terms | $[-0.3, 0.8]$ | $[-0.9, 1.4]$ | $[-0.5, -0.1]$ | $[-0.8, 0.2]$ |
| Order $1/\Lambda^4$ | $[-0.3, 0.8]$ | $[-0.9, 1.4]$ | $[-0.5, -0.1]$ | $[-0.8, 0.2]$ |
| Order $1/\Lambda^2$ | $[-0.3, 0.8]$ | $[-0.8, 1.5]$ | $[-0.6, -0.1]$ | $[-0.8, 0.2]$ |




(a) (b)

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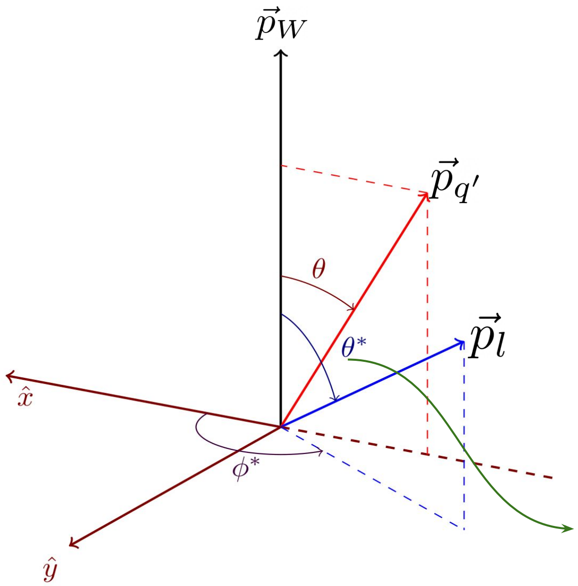
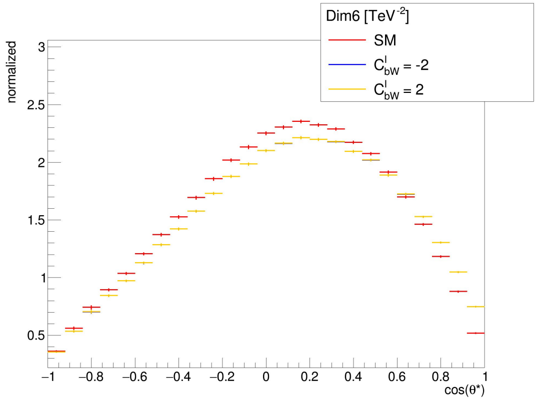
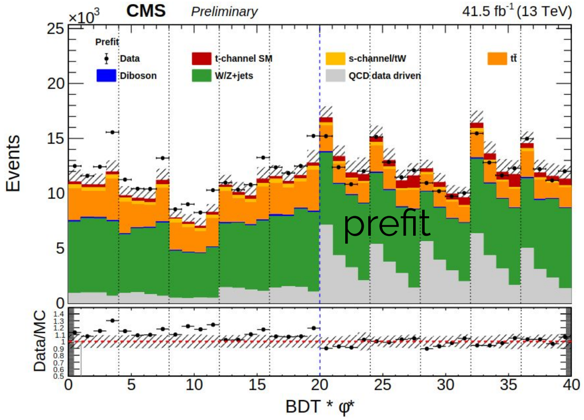
# Impact of EFT on kinematic variable

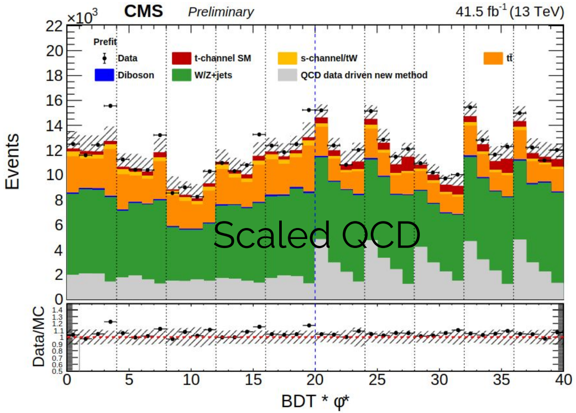


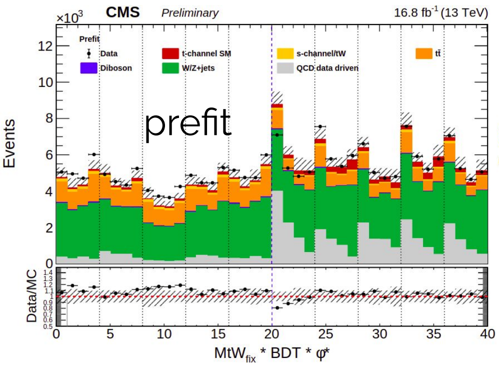
# QCD background fit results for other years

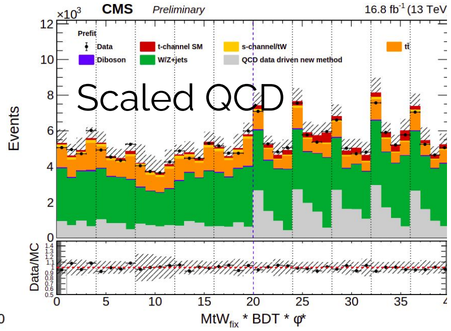
2017



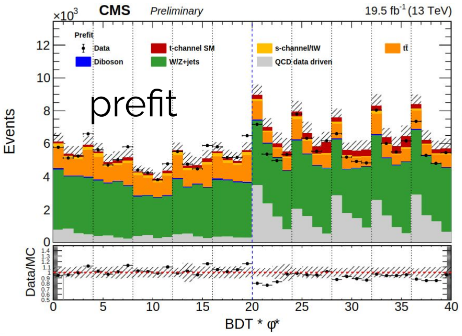



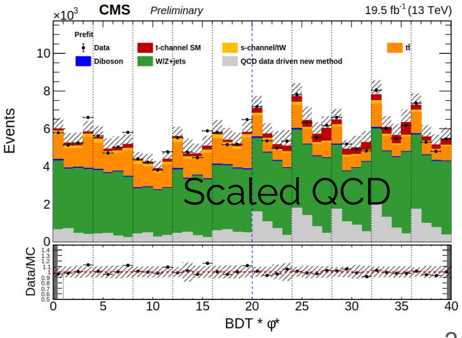

2016 postVFP



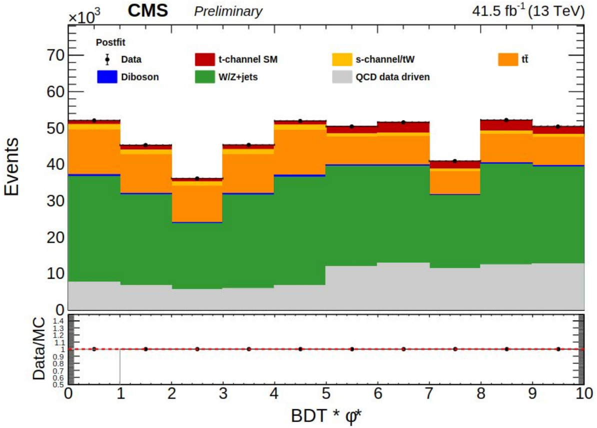

2016 preVFP

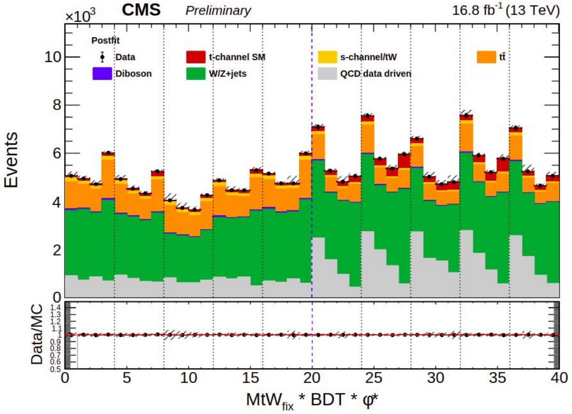


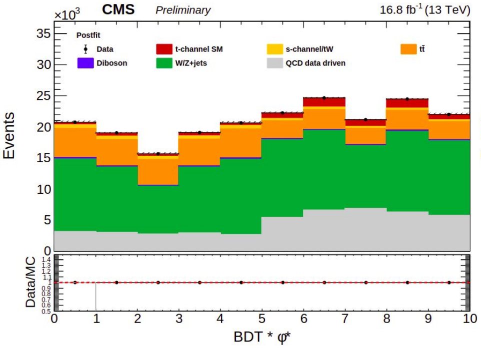
# QCD background fit results for other years *postfit*

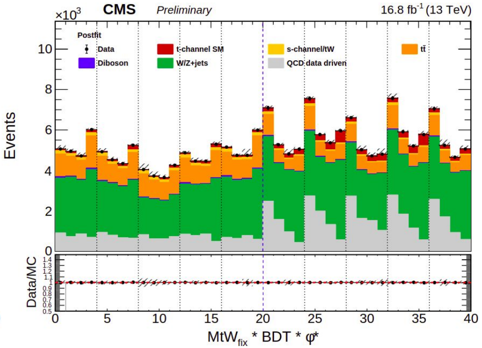
## 2017



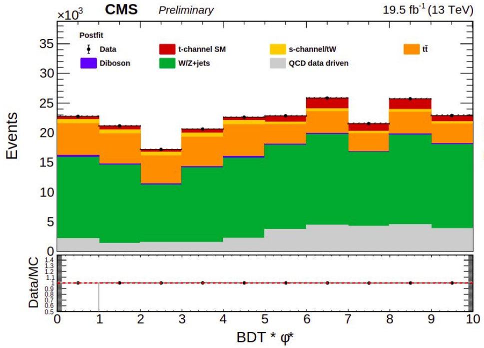



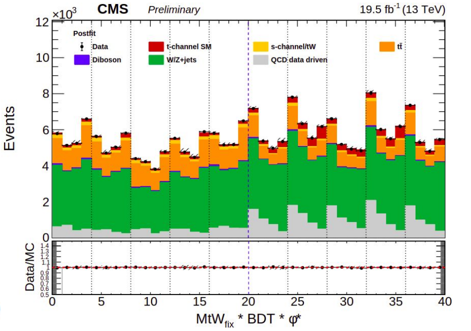

## 2016 postVFP



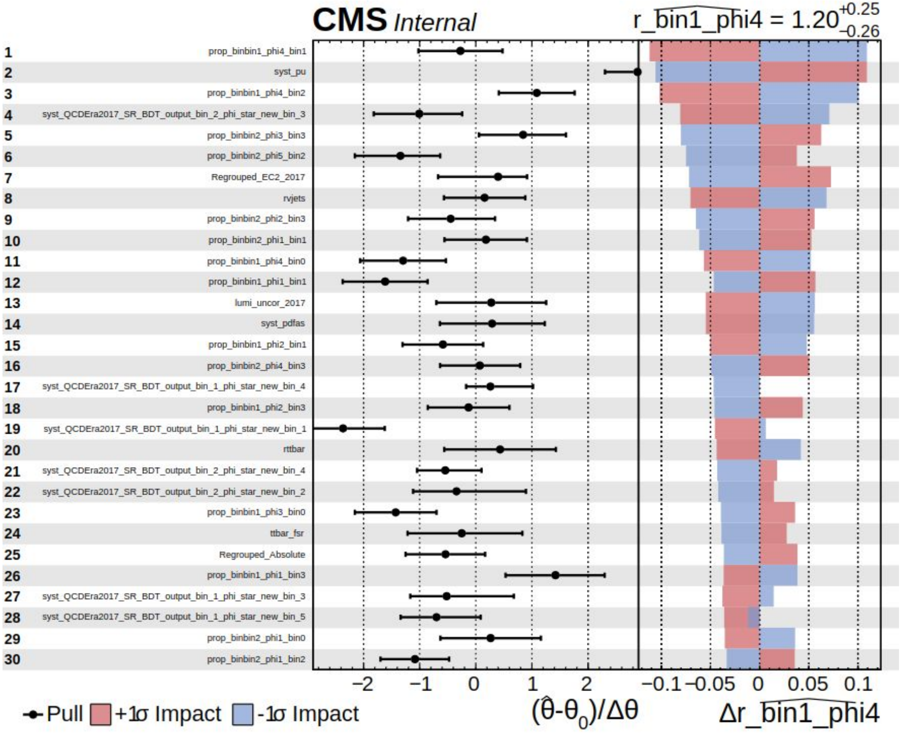

## 2016 preVFP

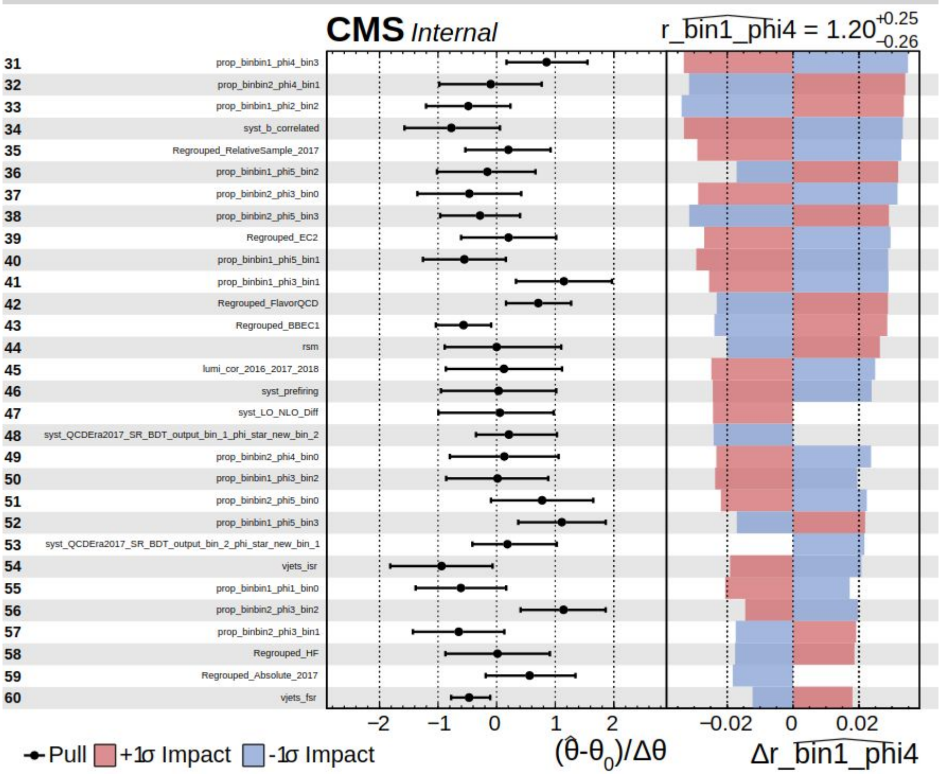


# Fit diagnostics

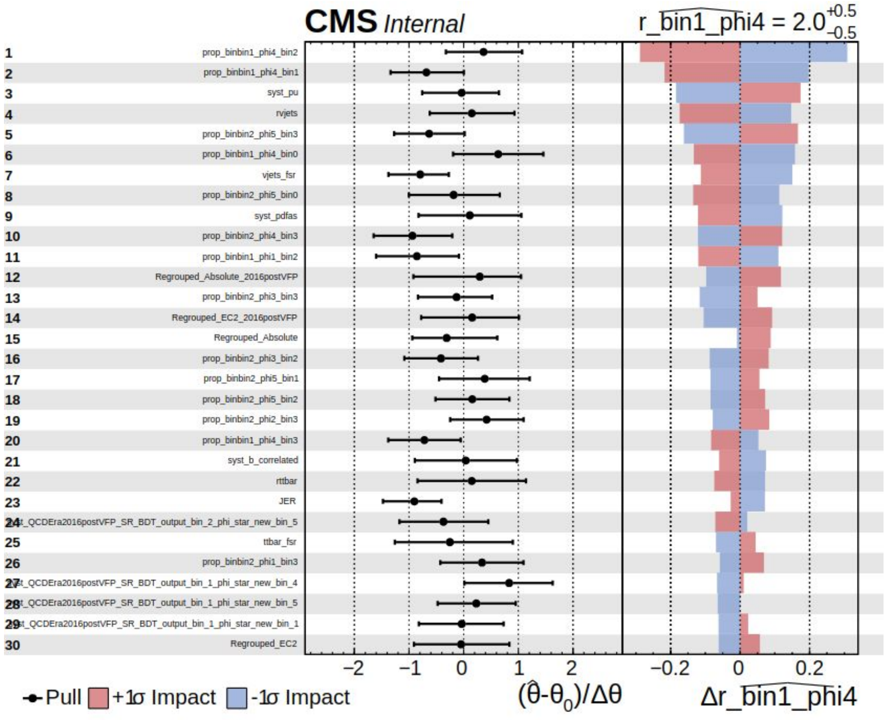
2017 results

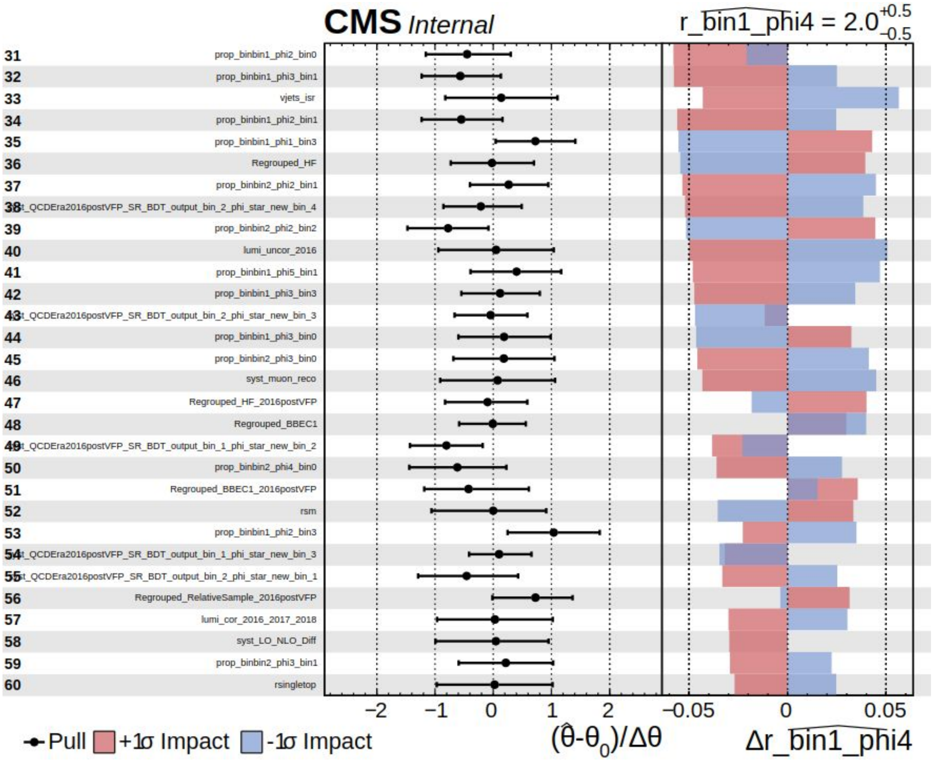


# Fit diagnostics

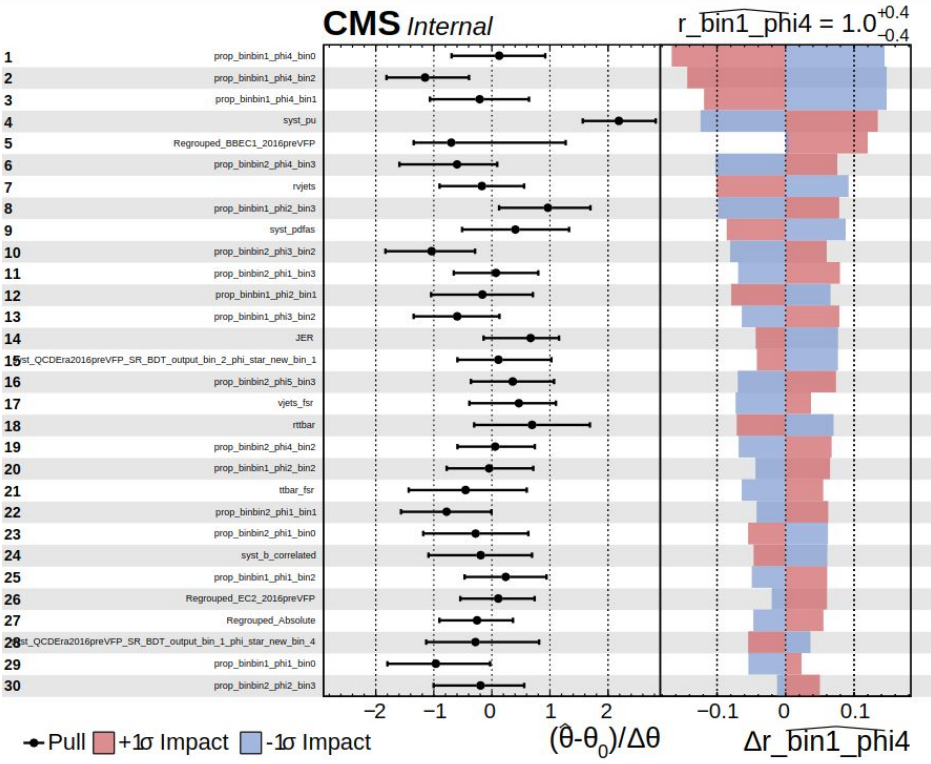
2016post results

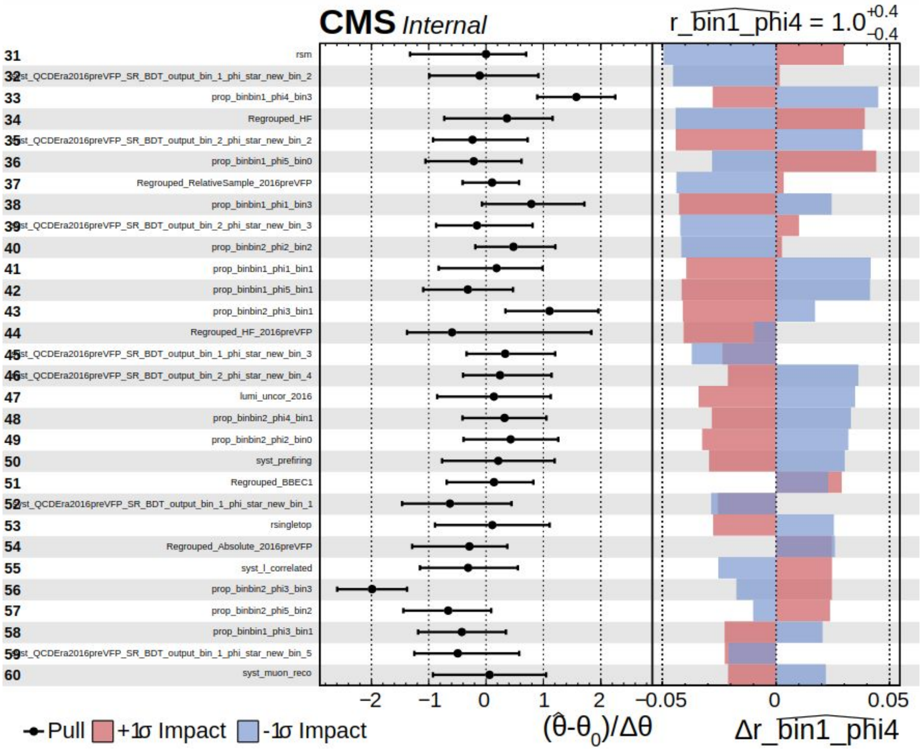


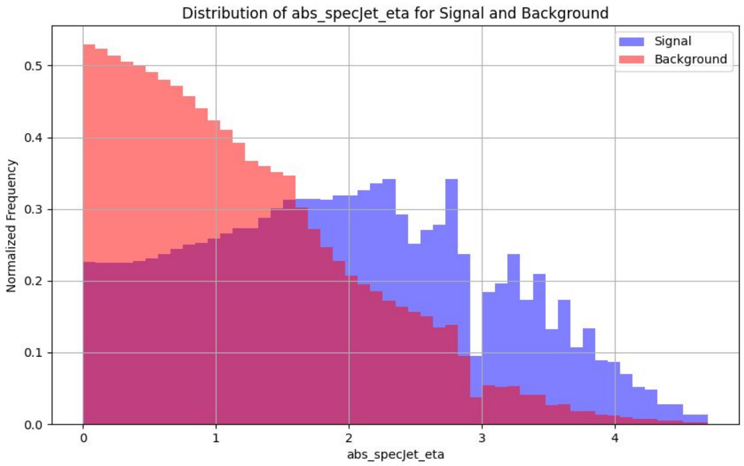
# Fit diagnostics

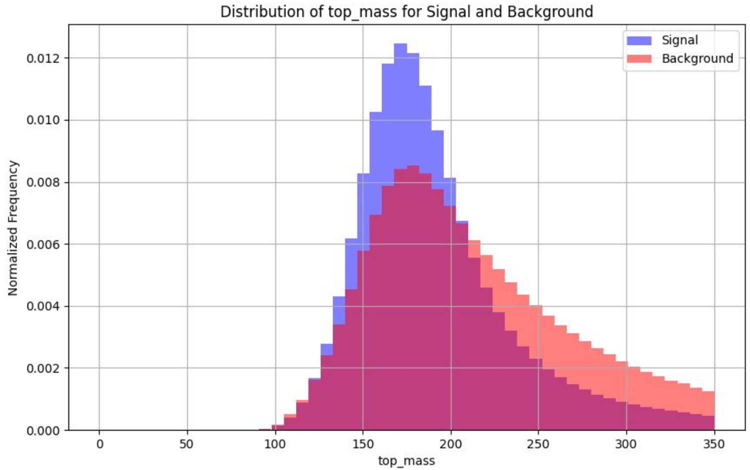
2016pre results

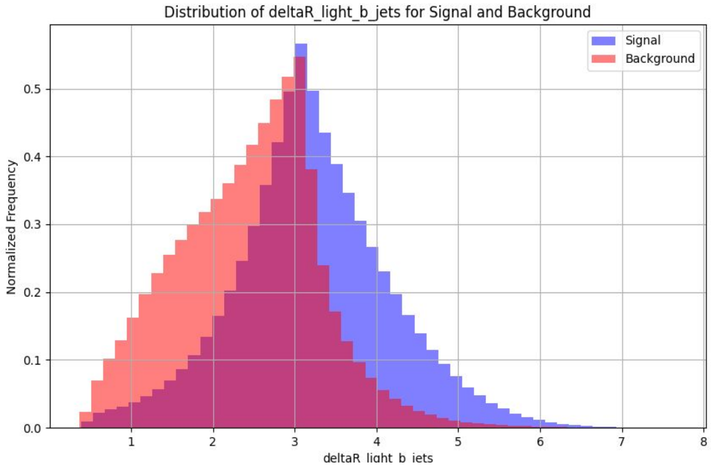


# Distribution of input variables for the SR BDT



# Binning optimization with significance

Formula used to evaluate significance (Poisson-Poisson model) taken from ATL-PHYS-PUB-2020-025 :

$$\sqrt{\sum_i \left( n_i \ln \left[ \frac{n_i(b_i + \sigma_i^2)}{b_i^2 + n_i \sigma_i^2} \right] - \frac{b_i^2}{\sigma_i^2} \ln \left[ 1 + \frac{\sigma_i^2 (n_i - b_i)}{b_i(b_i + \sigma_i^2)} \right] \right)}$$

n = QCD + non QCD

b = non QCD

$$\boldsymbol{\sigma} = \sqrt{\sum evWeight^2}$$

Optimization performed with the differential evolution algorithm from scipy.optimize (evolutionary algorithm)