# Searches for CP symmetry violation in the top quark sector with CMS at the LHC, and metrology measurements for the tracker Endcap upgrade at the High Luminosity LHC

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CMS group

Outline :

1. Analysis of CMS data : search for CP violation using single top quark production in the t-channel.

2. Upgrade of the CMS tracker for the HL-LHC : metrological analysis of mechanical structures (dees).

3. Phenomenological study: reinterpretation of LHC data for the search for CPT violation.

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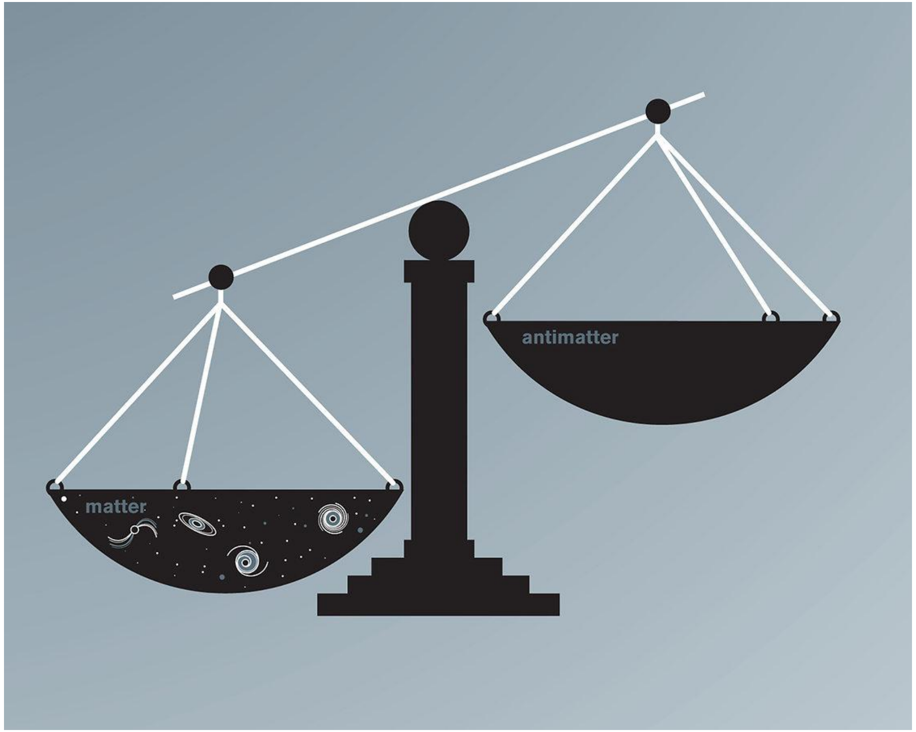
# Motivation : Matter-antimatter asymmetry

Asymmetry of the baryon-number in the Universe

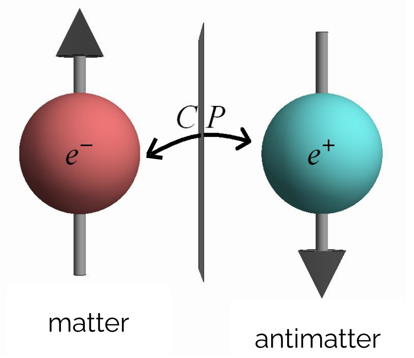



SM predictions : $\eta_{SM} = \frac{n_B - n_{\bar{B}}}{n_\gamma} \propto 10^{-20}$

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

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

**Discrepancy between the SM prediction and observations**



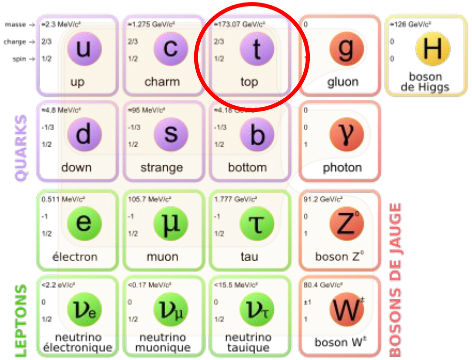

C : Charge conjugation Q ⟶ -Q

P : Parity transformation $\vec{r} \longrightarrow -\vec{r}$

**This asymmetry can be explained by the existence of sources of CP or CPT violation during baryogenesis.**

# Context : Top quark and CMS detector at the LHC

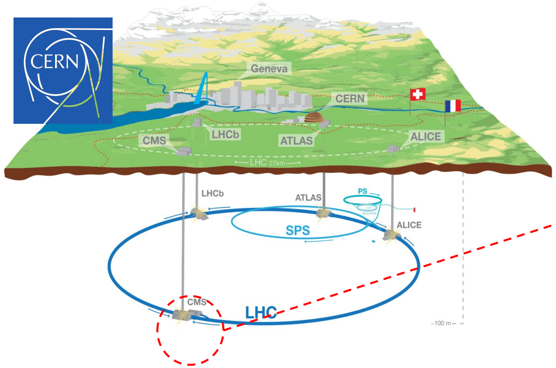
**The top quark as a probe for CP violation searches**

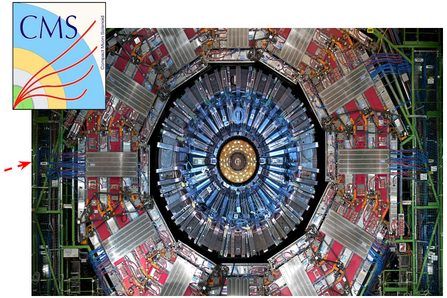



**Top quark** :

- ➔ Heaviest elementary particle
- ➔ Mass close to potential new physics energy scale
- ➔ Ideal candidate for search of Beyond the Standard Model physics (CP violation)

**Analysis carried out in the context of LHC Run 2 with the CMS detector**

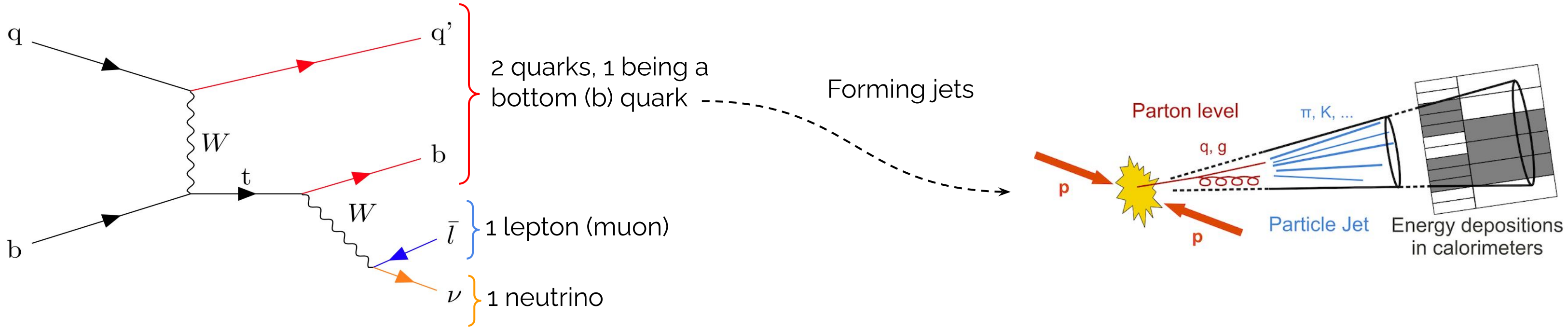



**Top quarks are produced in large numbers at the LHC :** about **100 million** generated during Run 2 (2015–2018).

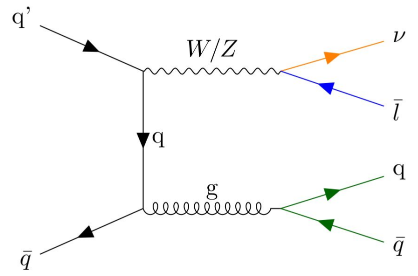
# Signal and background processes of the analysis

**Search for CP violation** through single top quark production in the t-channel and their subsequent decay into W and b.

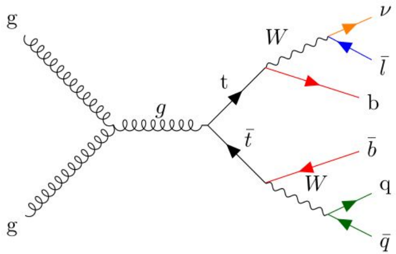



**Background processes** can mimic signal in the case where jets or leptons are misidentified or not reconstructed :

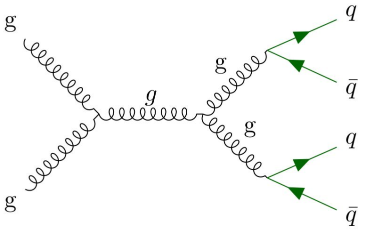
W + jets



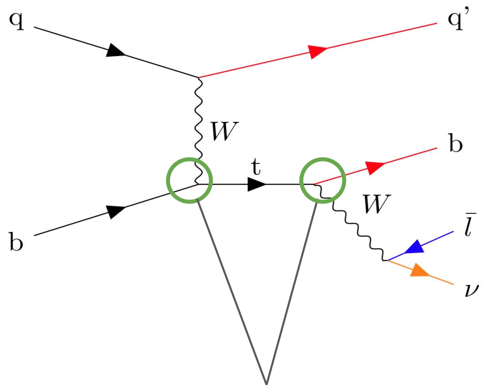

$t\bar{t}$




Quantum ChromoDynamic (QCD) processes



# Goal of the analysis on the search of CP violation




Wtb vertex

Signal process dynamic

Analysis in the framework of *Effective Field Theory (EFT)*

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

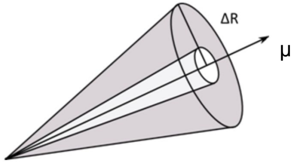
| Non-Hermitian Operators involving two quarks and a boson | Wilson Coefficients |
|---|---|
| $O_{uW}^{(6)} = (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi} W_{\mu\nu}^I$ | $c_{tW} + ic_{tW}^I$ |
| $O_{dW}^{(6)} = (\bar{q}\sigma^{\mu\nu}\tau^I b)\varphi W_{\mu\nu}^I$ | $c_{bW} + ic_{bW}^I$ |
| $O_{\varphi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

➔ EFT impacting both the production and decay of top quark

➔ This vertex can be modified by CP violation

The goal of this analysis is to measure the imaginary part of the 3 Wilson coefficients

# Analysis strategy - Regions




$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$

- We require events with **exactly 1 isolated muon** (criterion on the energy deposit in a cone with opening ΔR around the muon)

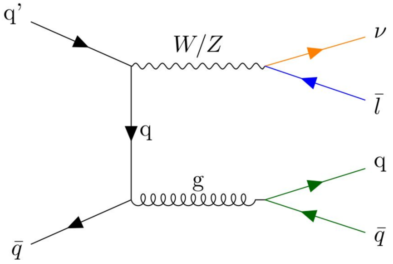
**Events are divided into three regions according to their number of jets, including b-quark jets (identified using a b-tagging algorithm) :**

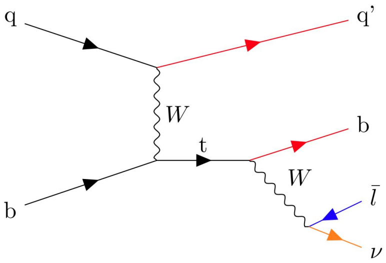
Signal region (SR) , W+jets Control region and ttbar CR

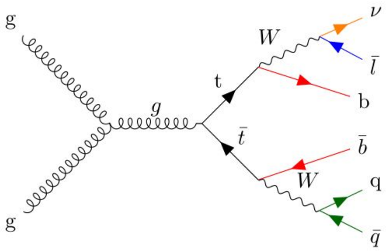
Measure CP violating coefficients ← Signal region (SR)

Constrain backgrounds ← W+jets Control region and ttbar CR

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



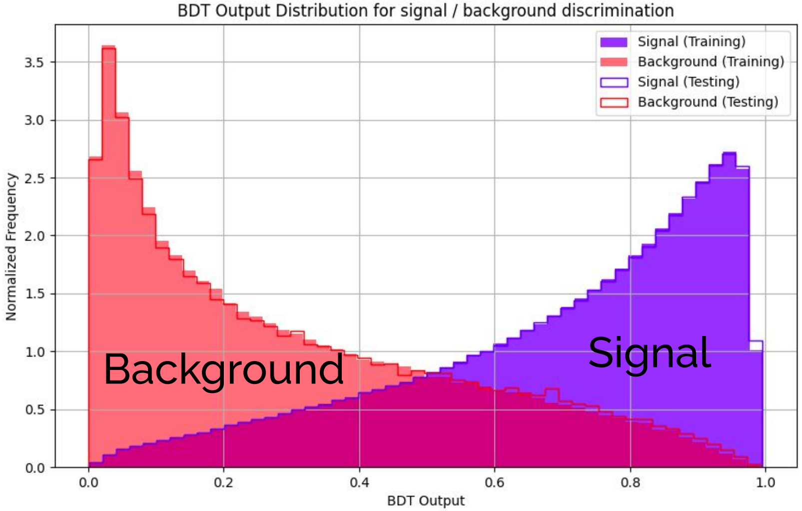



# Analysis strategy - Machine learning technique

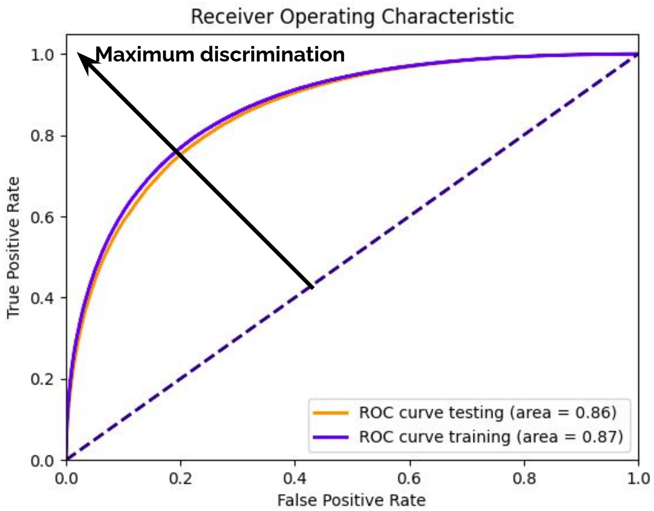
*The Signal Region has a large contribution from other background processes*

- ➔ The strategy is to optimize the signal extraction by using a **Boosted Decision Tree** (BDT) to discriminate single top t-channel (signal) from W+jets and QCD processes.
- ➔ The BDT model is trained with the simulated events in the SR using **distribution of discriminating variables**, e.g. the angular separation between the 2 jets

The output is a powerful discriminating distribution :




The performance of the model is assessed with a ROC curve :




Similar performance for the training and testing datasets indicates that the model is **not** overtrained

# Analysis strategy - QCD estimation

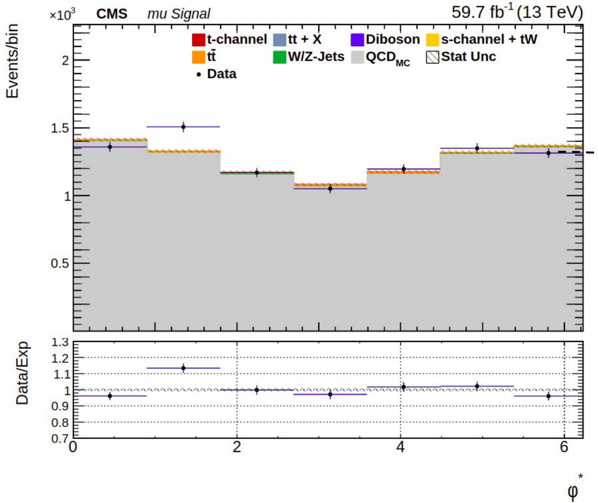
QCD processes have a large impact on this analysis but :
- ➔ insufficient simulated MC events available
- ➔ MC QCD is badly modeled

A **QCD enriched region** (sideband region) is defined for each signal and control region to estimate QCD from data by :

- Inverting the isolation criterion on the muon (a non-isolated muon, i.e. surrounded by significant hadronic activity, is typical of QCD processes)
- Removing the BDT score requirement in the sideband of the SR (to avoid depleting the QCD sideband and losing statistics)

*An example with φ* (variable discriminating SM and EFT) :*

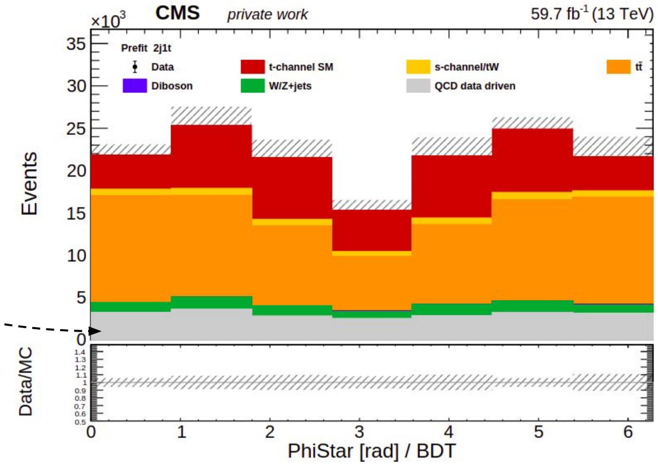
**QCD sideband of SR**




Shape of data in the QCD sideband is extracted …

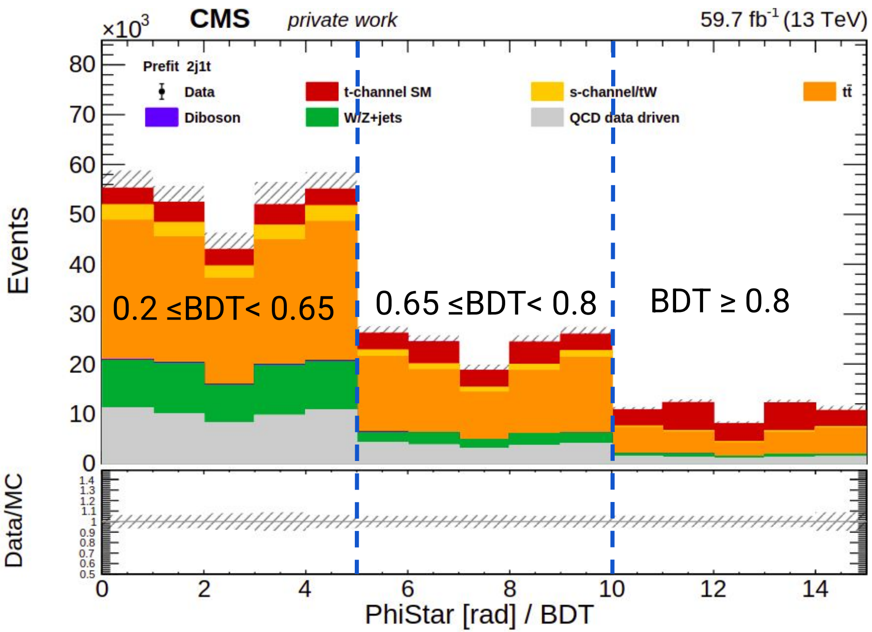
… to estimate the QCD in the SR

**SR**

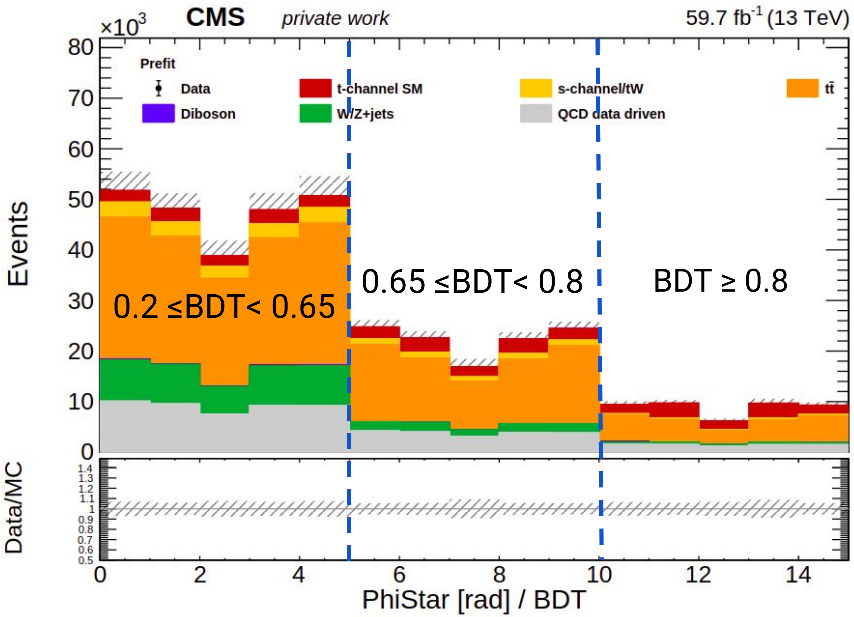


# Fit strategy - Signal region

- The SR is separated into a **Top** and **Antitop** channel, determined from the lepton charge
- The $\varphi^*$ distribution in bins of the BDT is used to measure the CP violating EFT coefficients




**Top channel**



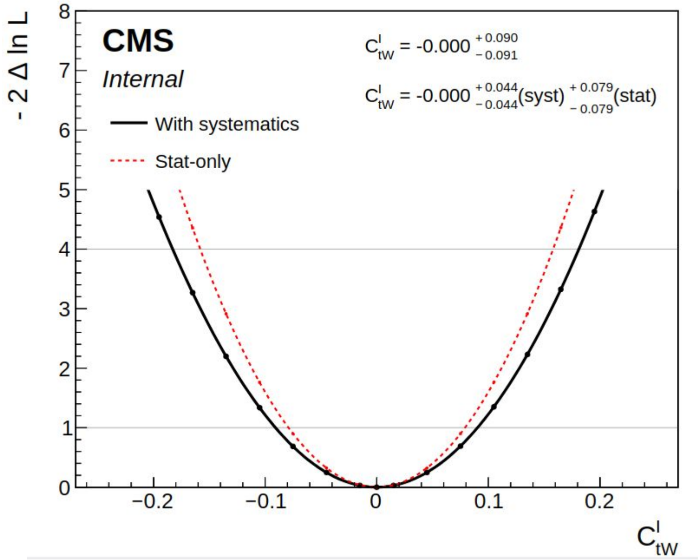

**Antitop channel**

# Expected results on the measurement of the coefficients

- Fit performed using the **likelihood ratio method** with the BDT vs $\phi^*$ distribution in the SR
- The SRs are fitted **simultaneously** with the CRs
- We obtain **expected sensitivity** of the analysis on the measurement of the coefficients

| Source | $C^I_{tW}$ | $C^I_{bW}$ |
|---|---|---|
| Best fit | $-0.00$ | $+0.00$ |
| **Total unc.** | **$+0.09$ / $-0.09$** | **$+1.08$ / $-1.13$** |
| Stat. unc. | $+0.08$ / $-0.08$ | $+0.44$ / $-0.44$ |
| MC stat. unc. | $+0.04$ / $-0.04$ | $+0.43$ / $-0.48$ |
| Other syst. unc. | $+0.01$ / $-0.02$ | $+0.88$ / $-0.92$ |

Uncertainties determined with a likelihood scan




- ➔ Sensitivity dominated by **statistics for $C^I_{tW}$** and **other systematics for $C^I_{bW}$**
- ➔ Reduce the data statistical part by improving the signal/background discrimination

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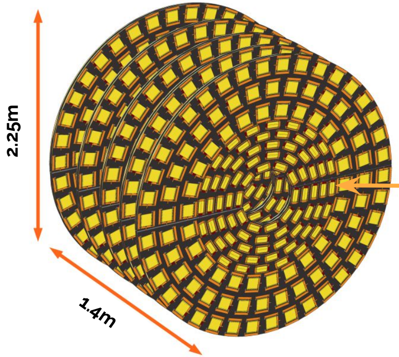
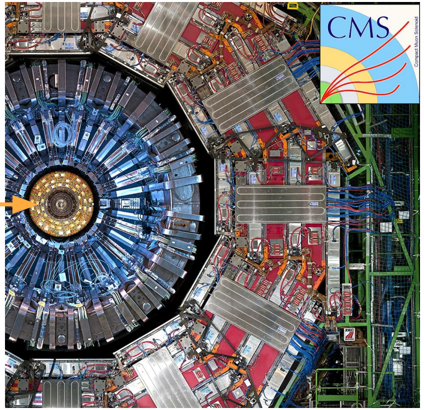
# The new CMS tracker for HL-LHC

TEDD = Tracker Endcap Double-Discs, future CMS tracker for the HL-LHC

**The CMS tracker needs an upgrade to :**

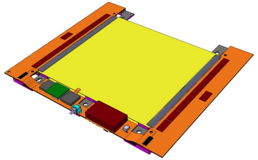
- sustain the high level of radiation
- trigger data acquisition on events with high momentum tracks



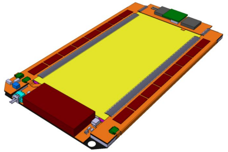




CMS detector at CERN

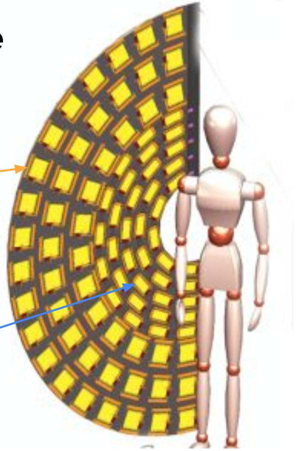
2S = strip - strip



PS = pixel - strip

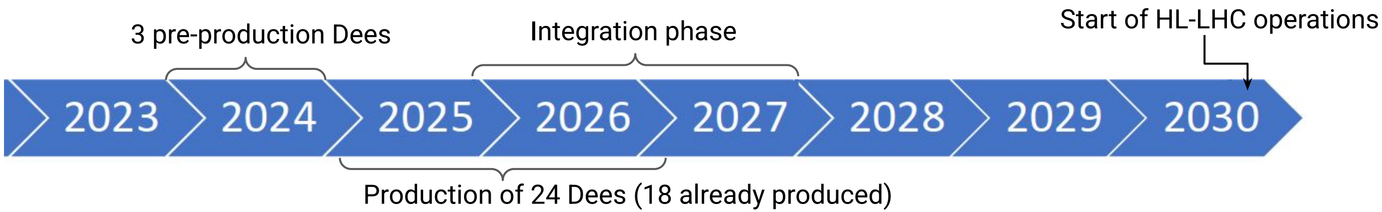


**Dee**



Main mechanical structure of the TEDD holding the detection modules

CMS group at IP2I is responsible of the **construction** and **qualification** of 24 Dees

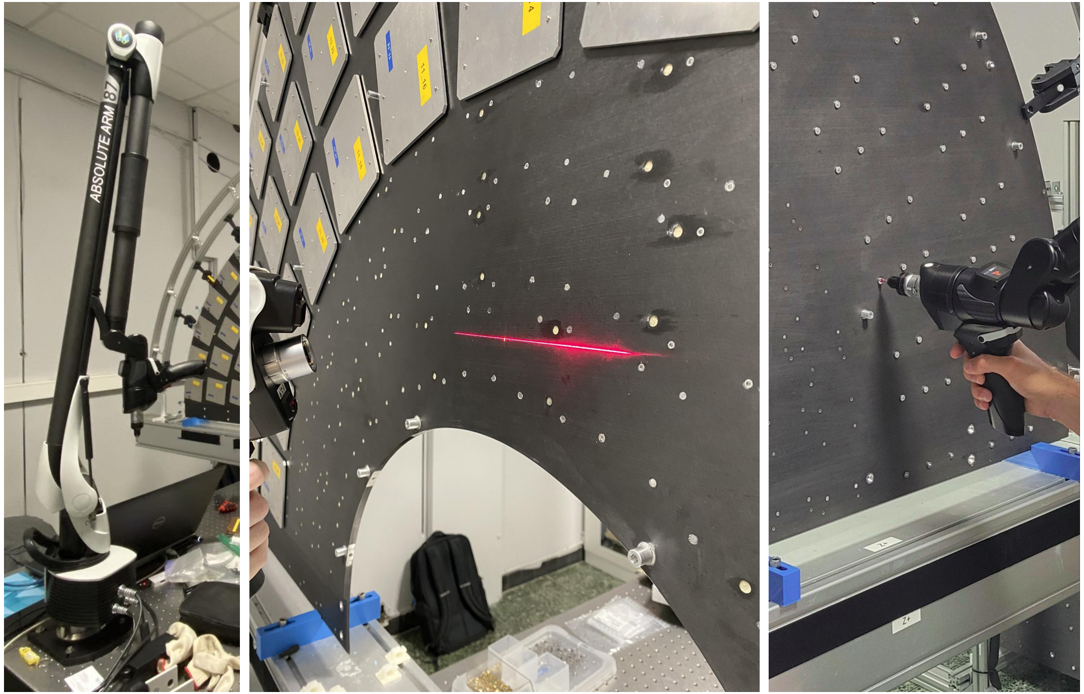


# Metrology measurements : Data taking

Metrology is a step of the qualification of the Dees : the **flatness** of the structure and the **displacement of the inserts** are verified

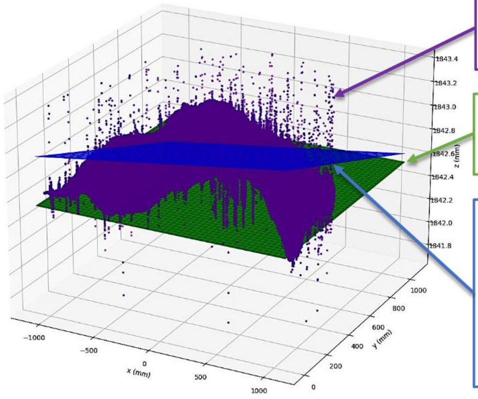
Metrology performed with a **Hexagon Arm** equipped with :

- a laser head AS1 (precision is 0.04 mm) to scan the Dee's flatness on its surface (N~$10^6$ points in 3D)
- a spherical ruby tip (ø 6 mm) for precise position measurement of the inserts (±0.03 mm)



# Dee flatness measurement

Excessive deformation of a Dee could prevent the proper assembly of a double-disk.

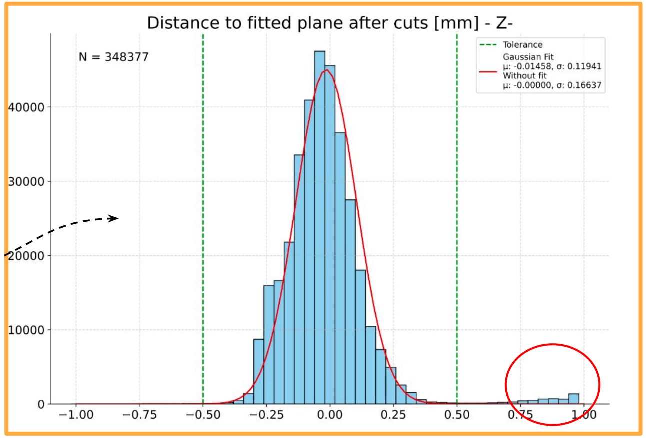


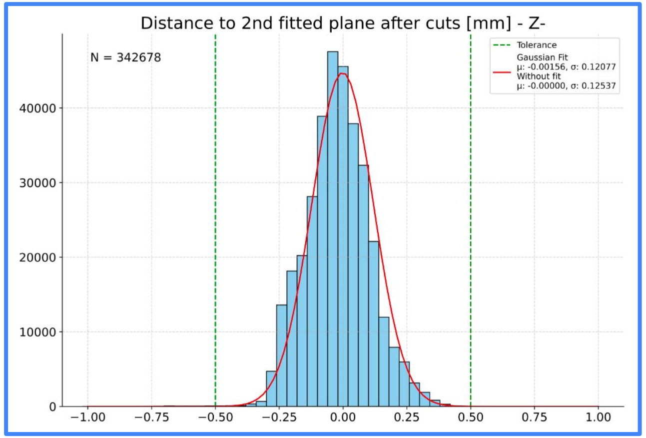

**High-density scanning**: used a laser head mounted on a hexagon arm to collect ~1 million points per scan.

**Nominal-plane method (default)**: compute each point's distance to the design plane—but misalignments can bias results.

**Fitted-plane method (New)**: fit the best-match plane through the measured data, then calculate point-to-fitted-plane distances.

**Benefit**: removes global tilt, isolating true local deviations for an unbiased flatness metric.




Tail of the distribution outside of the specifications

➔ Due to the detection of inserts on the Dee's surface but non relevant for the flatness measurement

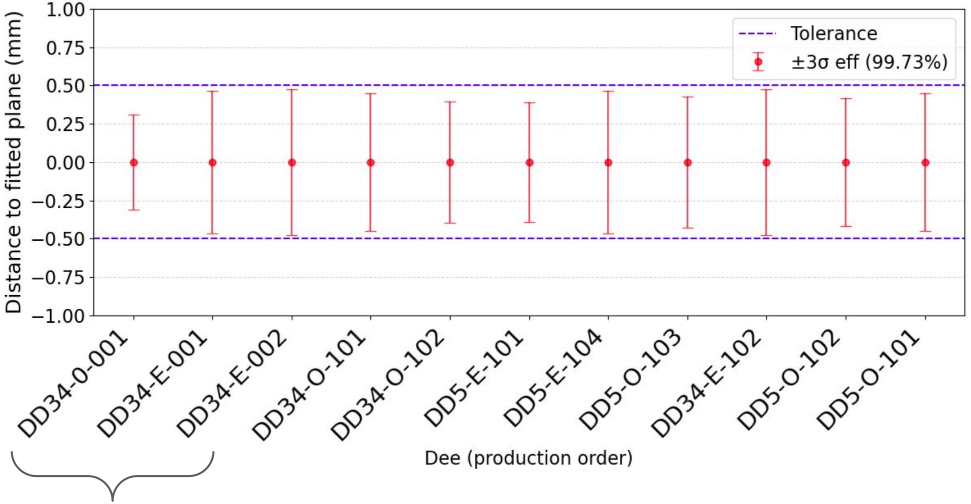
**Cleaning of the data** is performed by applying a Z-cut relative to fitted plane for outlier filtering

# Summary of the metrology measurement over production

Throughout the entire duration of the thesis : 24 Dees to analyze in total (16 observables for each of the 2 sides of a Dee).

➔ I worked on a way to present a large number of results in a compact form
➔ Automatic filling of files with Dee data during the execution of the analysis framework

*Example with the summary of Dee flatness*




pre-production Dees

Specifications : Nearest distance between measured points and fitted planes comprised between **±0.5 mm**

Effective sigma : smallest interval containing 3$\sigma$ of the population

➔ Stable flatness of the Dees throughout production

➔ All Dee's flatness are within specifications

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# Motivation and context of the phenomenological study

Use of a **CPT-violating** model within the **EFT formalism** : the **Standard Model Extension** (SME) :

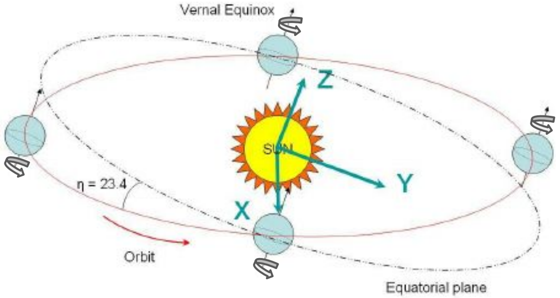
- ➔ Motivated by frameworks such as string theory or loop quantum gravity
- ➔ Inclusion of all CPT-violating operators in the Standard Model Lagrangian

Part of the SME Lagrangian governing odd CPT symmetry : $\mathcal{L}^{CPT-} \supset (1-\gamma^5)b_\mu \bar{t}\gamma^\mu t + \ldots$

CPT violating coefficient ≡ **constant vector** in an inertial reference frame

Reference frame used to present the results : Sun-centered frame (**SCF**)

Measurement frame : Laboratory frame (**CMS detector**)




- ➔ The **rotation of CMS around the Earth's axis** induces a **modulation of the top quark production cross section** as a function of **sidereal time** (T~23h 56min)

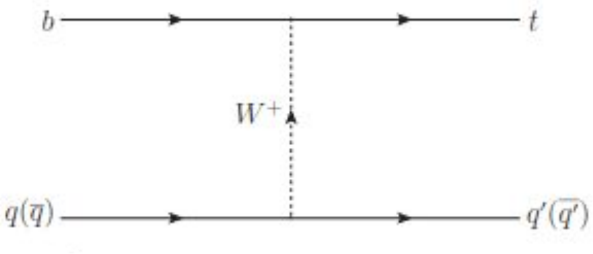
Temporal modulation function : $f_{SME}(t) = b_\mu R^\mu{}_\nu \frac{\delta P^\mu}{P}$

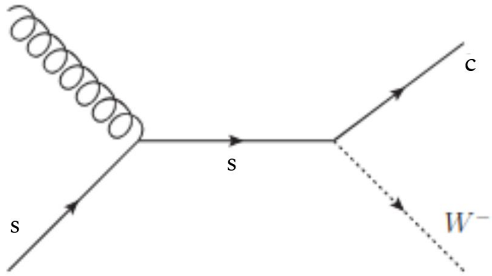
*Time-dependent rotation matrix relating the SCF and the CMS reference frame*

*Ratio of the process cross section including CPT-violating corrections to the Standard Model case*

# CPT induced temporal modulation

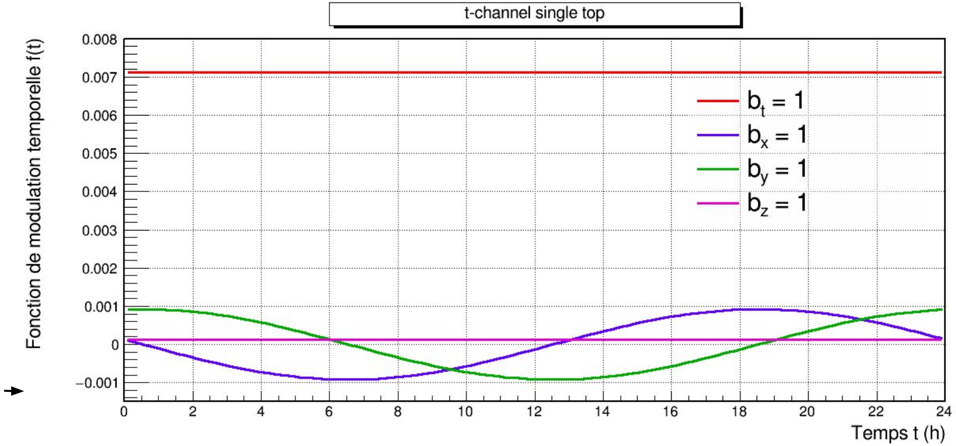
We aim to evaluate the sensitivity that could be achieved on the measurement of $b_\mu$ at the LHC using two processes : **single top in the t-channel** and **W+c**.



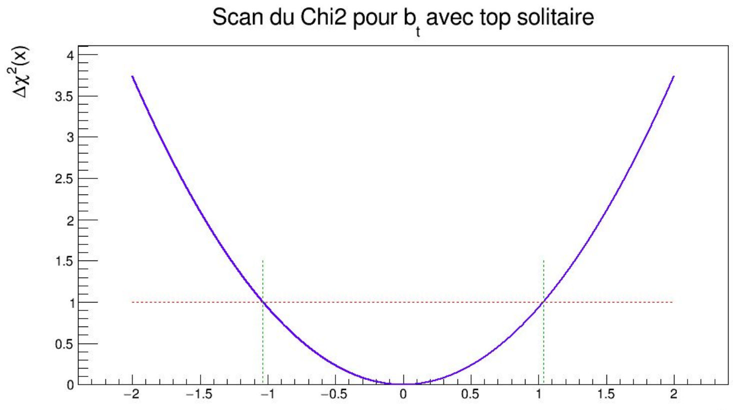




- Selections are applied at parton level on generated events for both processes
- Ratio of the process cross section is computed for each event
- Rotation matrix linking CMS and SCF is calculated
- Temporal modulation is computed

$$f_{SME}(t) = b_\mu R^\mu{}_\nu \frac{\delta P^\mu}{P}$$



# Expected sensitivity on CPT violating coefficients measurement




- Simplified estimate of the statistical and systematic uncertainty on the expected sensitivity to the CPT-violation coefficient with LHC Run 2, using the **χ² method**

Top related coefficient

| | My study employing **single top** process 95% C.L. **expected** | [arXiv:2405.12162] employing top-antitop mass difference in $t\bar{t}$ event 95% C.L. **observed** |
|---|---|---|
| $b_T$ (GeV) | [−2.72, 2.72] | [−0.13, 0.29] |
| $b_X$ (GeV) | [-22.52, 22.52] | [−0.8, 0.8] |
| $b_Y$ (GeV) | [−22.52, 22.52] | [−0.8, 0.8] |
| $b_Z$ (GeV) | [−116.72, 116.72] | [−4.6, 4.6] |

Charm related coefficient

| My study employing **W+c** process 95% C.L. expected |
|---|
| [−0.028, 0.028] |
| [−13.98, 13.98] |
| [−13.98,13.98] |
| [−31.62, 31.62] |

# Perspectives

- **CMS analysis : CP violation with single top t-channel**
  - Use a machine learning technique for lepton identification
  - Add the measurement of the third coefficient : $C^{l}_{\varphi tb}$
  - Start the pre-approval process of the analysis

- **Tracker Upgrade**
  - Dee production well ongoing, still 15 Dees to analyze

- **CPT phenomenology study**
  - Simulated how quarks and gluons hadronize (turn into detectable particles) using a MC generator for my samples of simulated events
  - Working on estimating sensitivity with event selection applied on hadronized events

# Thank you for your attention :)

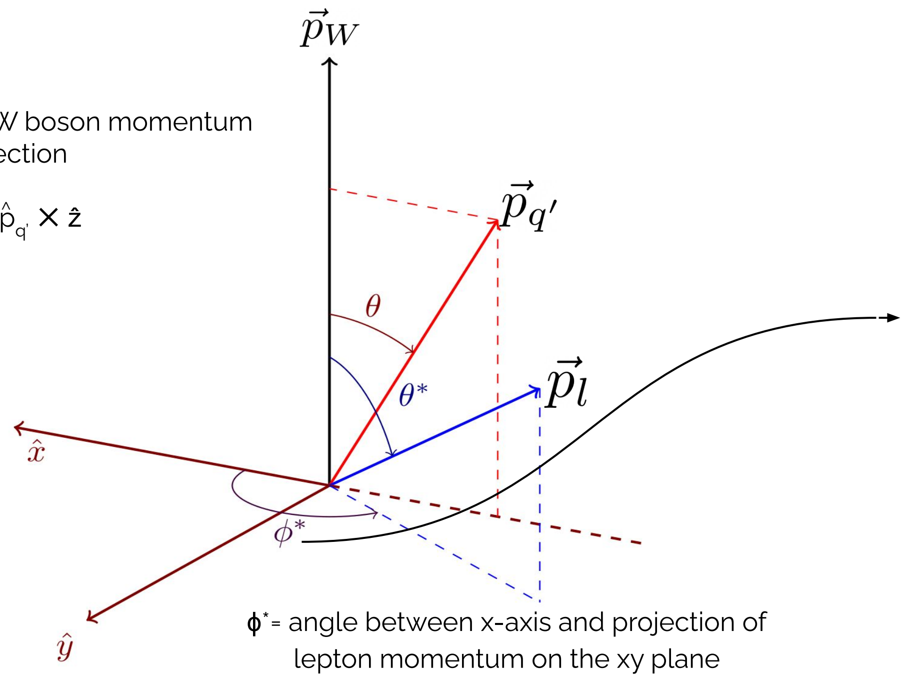
# EFT impact on angular variables

**Top quark rest frame**

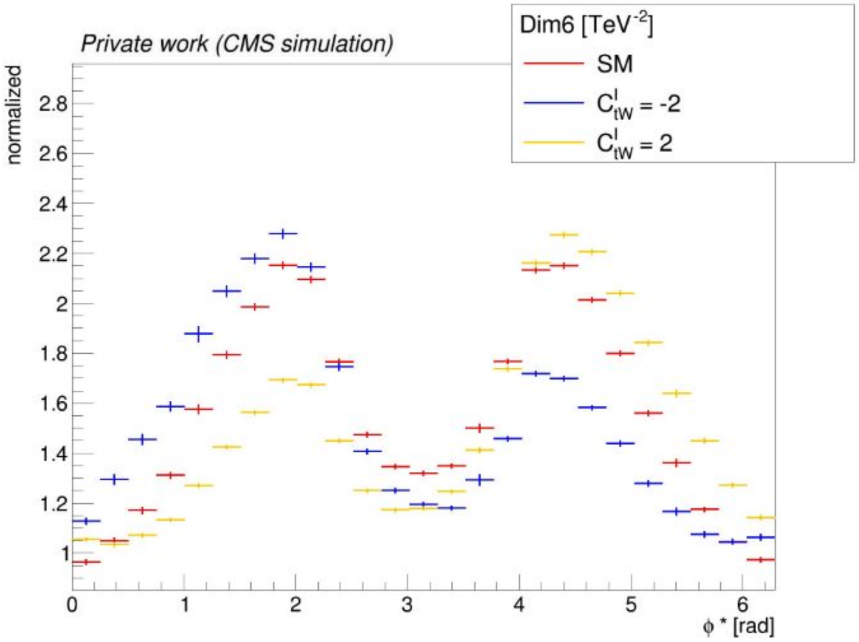
Reference frame used in ATLAS 8 TeV [arXiv:1707.05393]

**ẑ** : W boson momentum direction

$\hat{y} = \hat{p}_{q'} \times \hat{z}$




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



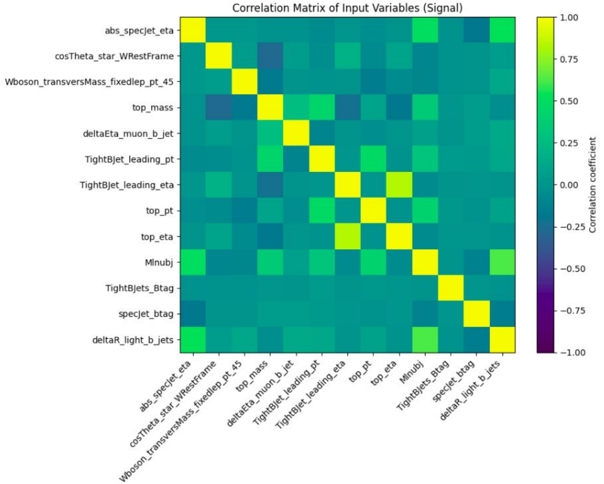

The shape of the distribution varies depending on the value of the EFT coefficient

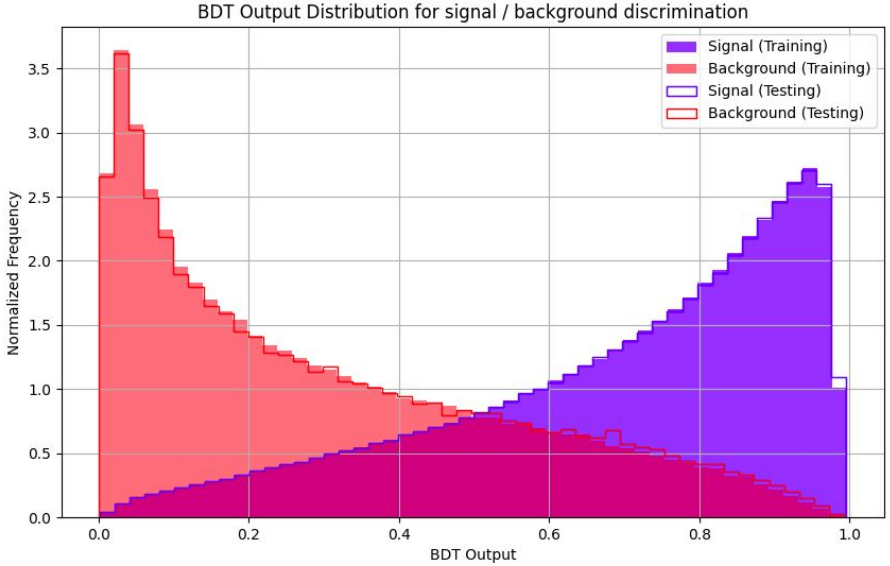
The value of EFT coefficients can be extracted using such angular distributions

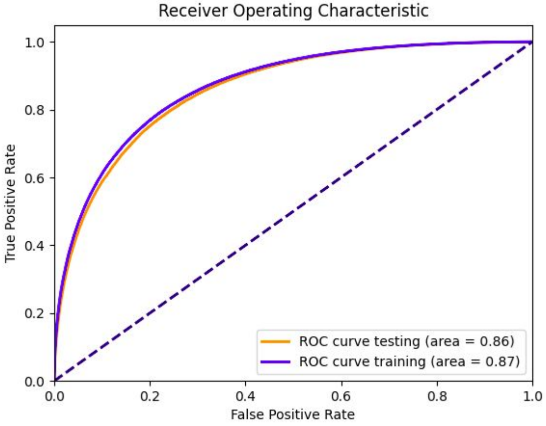
# Analysis strategy - MVA in the **Signal Region**

Trained a **new BDT** in the SR to discriminate **single top (ST) t-channel** from **W+jets and QCD processes** (previous BDT was signal vs. all backgrounds)

**Input variables for the BDT** : cos(θ*), η of the spectator jet, spec jet btagging score, $M_T W^{,fix}$, top $p_T$, top η, $M_{top}$, Δη(μ, b-jet), ΔR(spec jet, b-jet), b-jet $p_T$, b-jet η, b-jet btagging score, lepton $p_T$, $M_{l\nu bj}$

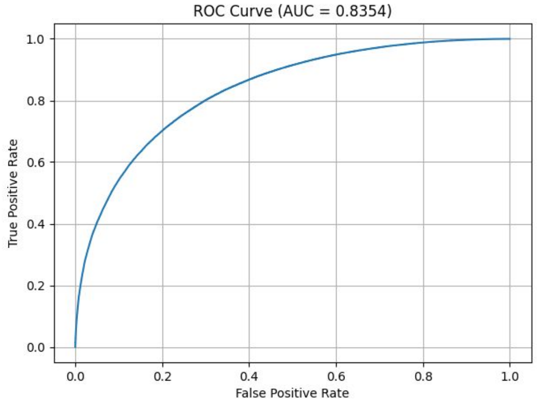


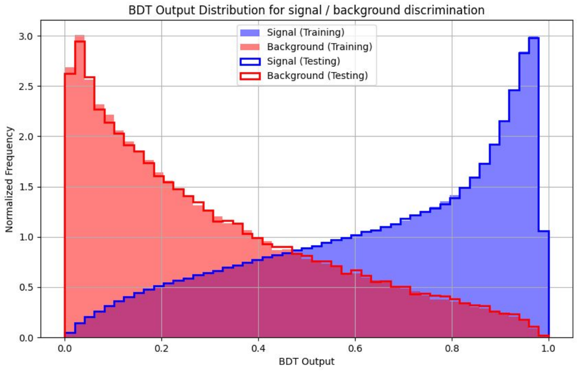



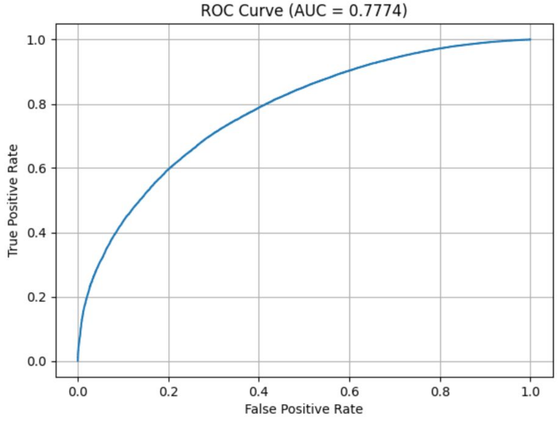
# Complements on the BDT

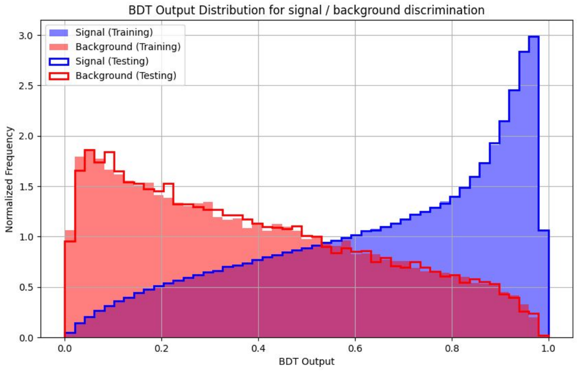
## W+jets



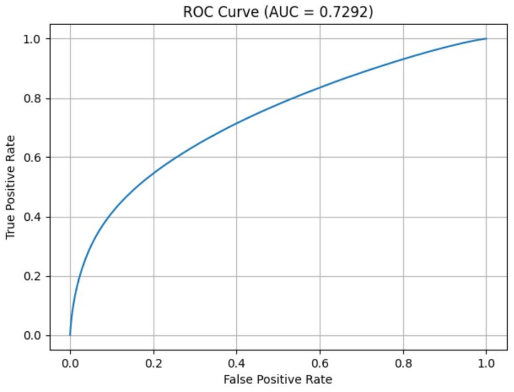



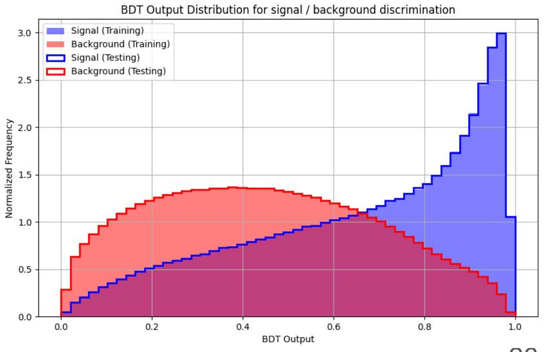

## QCD




## $t\bar{t}$

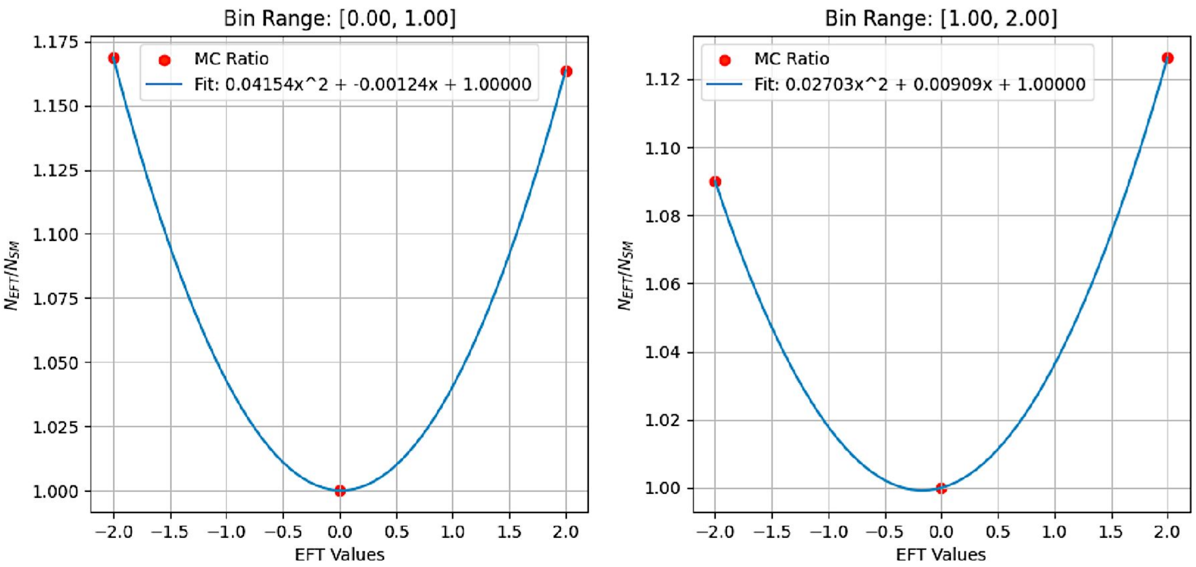


Evaluating the expected statistical sensitivity by fitting the SM+EFT model to the Asimov (SM) dataset using a profile likelihood statistical method (CMS Combine)

Using AnalyticAnomalousCoupling plugging to model the EFT template : https://github.com/amassiro/AnalyticAnomalousCoupling

This framework provides a Combine-based model for EFT fits overcoming the issues of negative templates that may arise from interference terms




- Fitting polynomial of order 2 in each bin of our observable
- Using the three parameters of the fit to produce the templates

$$\text{Sm} = |\mathcal{A}_{SM}|^2,$$

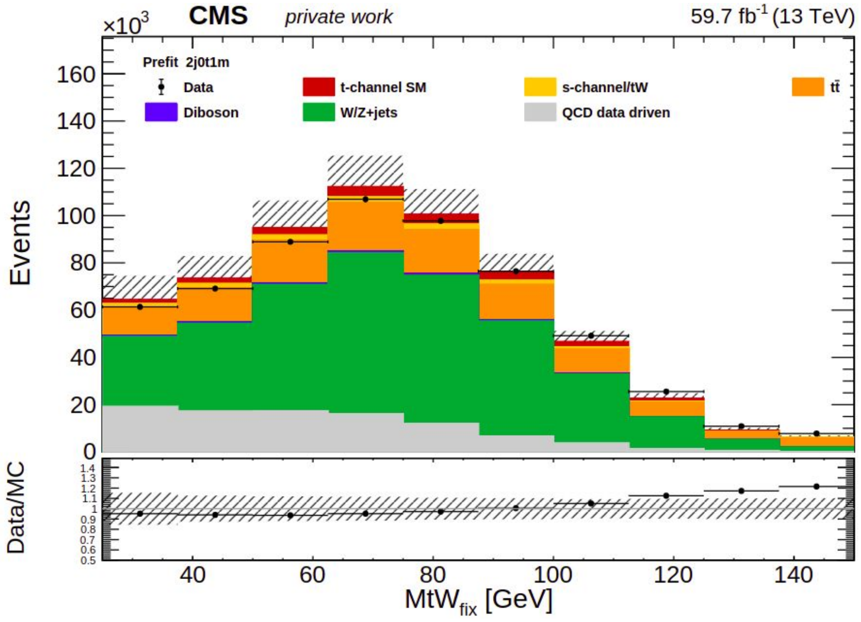
$$\text{Lin}_\alpha = 2\Re(\mathcal{A}_{SM}\mathcal{A}_{Q_\alpha}^\dagger)$$

$$\text{Quad}_\alpha = |\mathcal{A}_{Q_\alpha}|^2$$

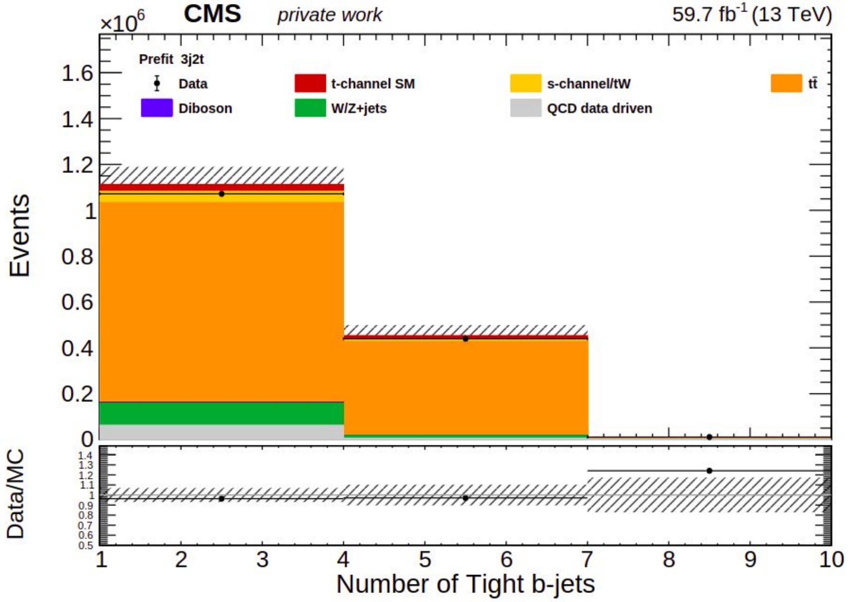
# Fit strategy - Control regions

Variables in the CRs are chosen because they **separate the main background process** in the control region **from other processes**, allowing its **contribution to be accurately estimated.**

**W+Jets CR**




**tt̄ CR**

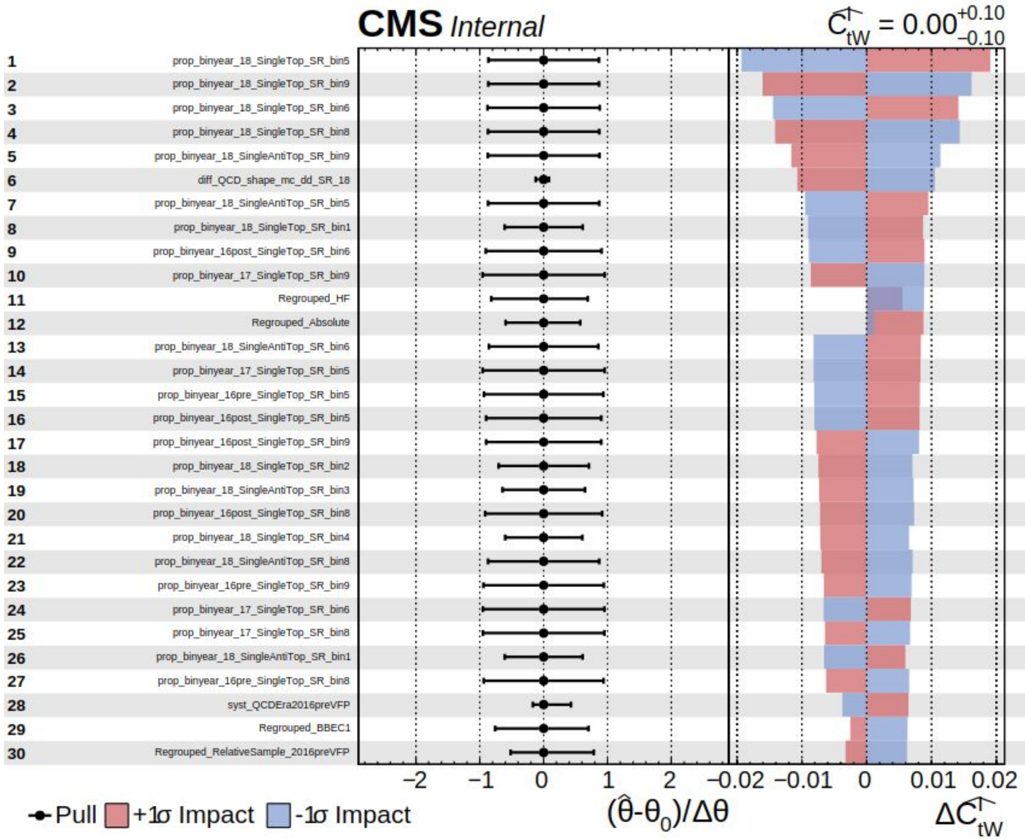



These distributions will be used in the final fit to **reduce the uncertainty on the main background normalization**

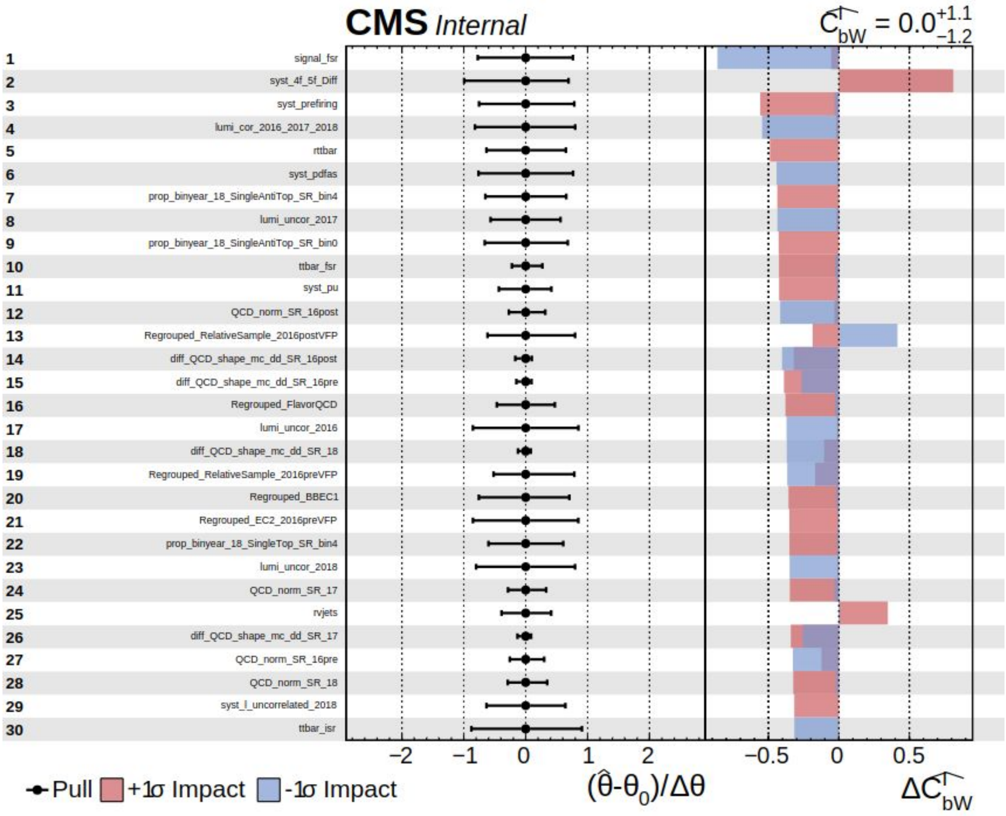
# Uncertainties impact on $C^{l}_{tW}$ **Full Run 2**

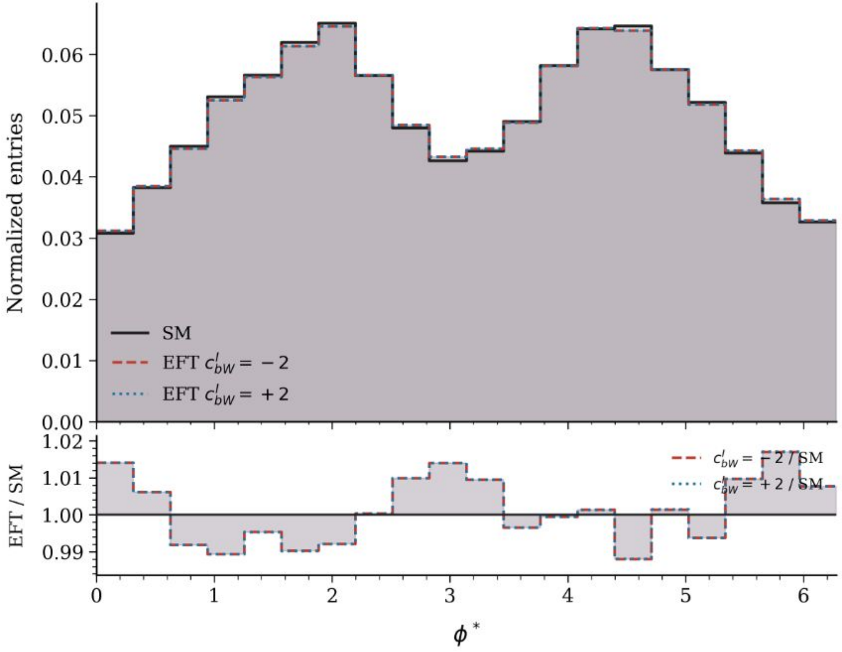
MC statistical uncertainties remain among the highest-ranked nuisance parameters, but their overall impact is significantly reduced compared to the previous strategy

Need to move to full set of JEC uncertainties (reduced one is one-sided)



# Uncertainties impact on $C^{l}_{bW}$ **Full Run 2**

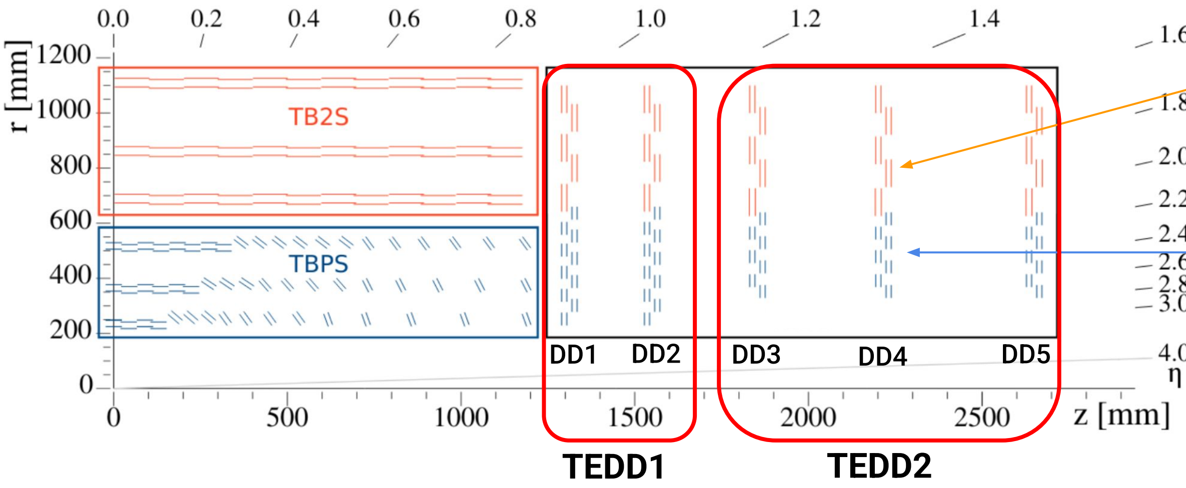


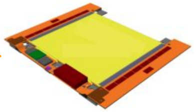

Many nuisances are one sided because $C_{bW}^{l}$ = +2 and $C_{bW}^{l}$ = -2 effect goes in the same direction.

# Tracker Endcap Double-Disks (TEDD)

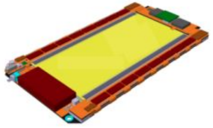
Endcap part of the future outer tracker of the CMS




<u>Detection modules</u> :

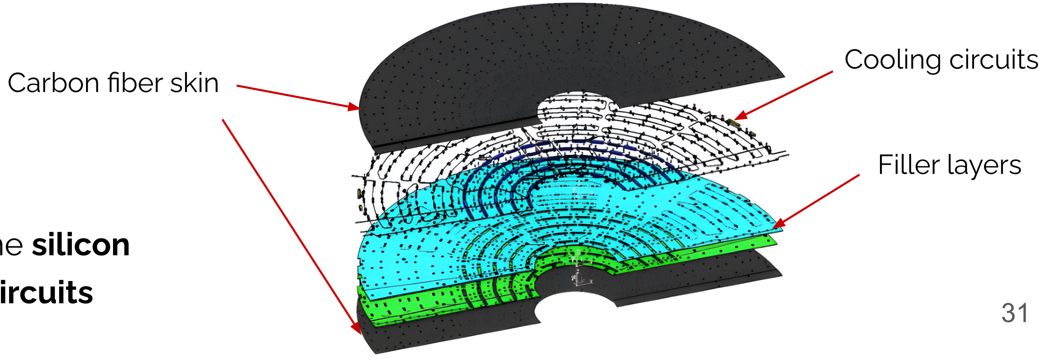


2S (strip-strip)



PS (pixel-strip)

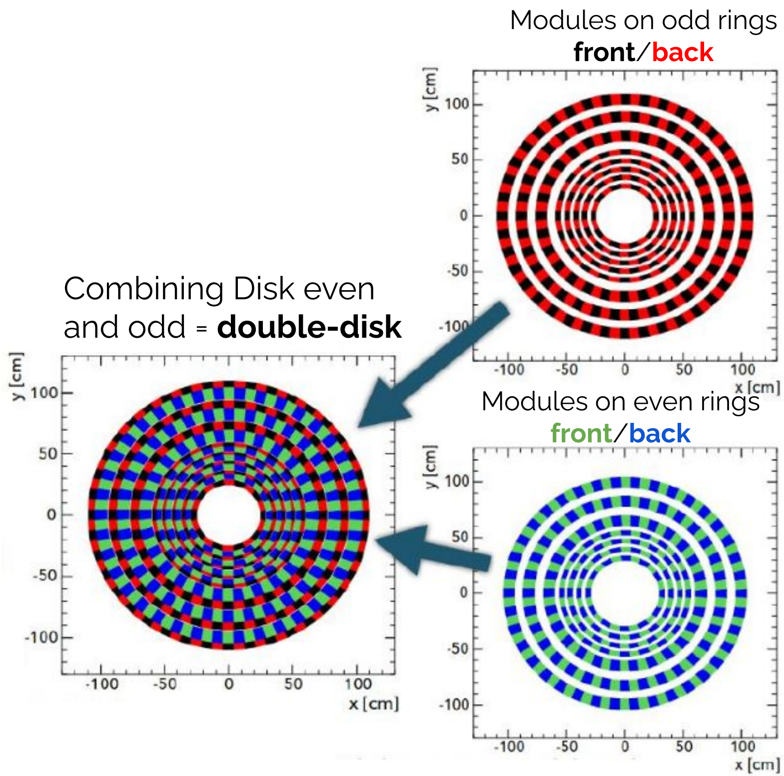
- Each TEDD is composed of 5 double-disks
  - TEDD1 : DD1 & DD2 ⇒ DESY
  - **TEDD2 : DD3, DD4 & DD5 ⇒ IP2I**
- A disk is made of 2 Dees
- **Dee** : elementary **mechanical structure** holding the **silicon detection modules** and embedding the **cooling circuits**



# TEDD geometry

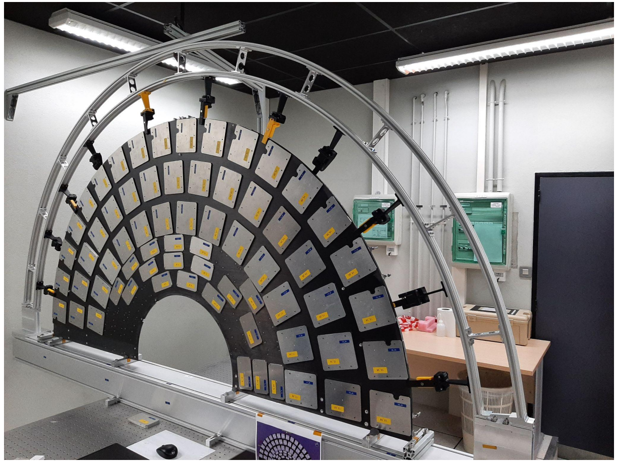
Modules will be arranged in rings on both sides of the Disks :

- each Disk provides **complete φ coverage**
- combining the odd and even Disks ensures **full radial coverage**

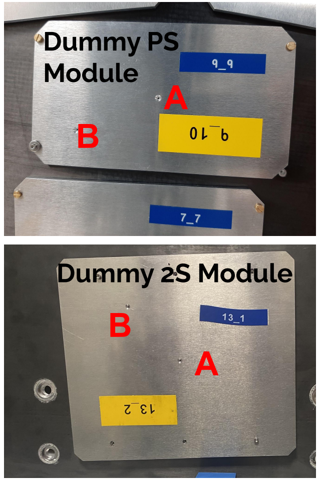


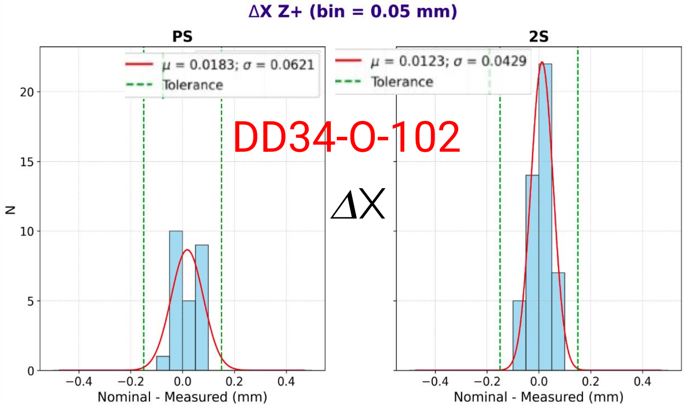
# Displacement of PS and 2S modules

The X and Y displacement of the 2S and PS modules is verified in metrology to ensure the modules can be properly integrated



Conic shaped reference points on the PS and 2S modules




**Measurements** : Dummy modules with precision holes are mounted onto the Dee. The XY coordinates of conic shaped A and B points are measured.

- ΔX = Displacement on the X axis
- ΔY = Displacement on the Y axis

} Determined using difference between nominal and measured position of A point

- Δθ = Rotation of the module } Determined using angular difference between nominal and measured AB line

# Data cleaning DD35-O-102