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

PhD days - 27/04/23

Christopher Greenberg

Advisor: Nicolas Chanon

CMS Group

Outline:

Part 1: CP-violation with top quark at the LHC

1.1) Matter/Antimatter asymmetry problem

1.2) Phenomenological study of CP-violation using single top quark t-channel

1.3) Analysis status with CMS data

Part 2: Metrology measurements for the CMS tracker upgrade for the HL-LHC

2.1) The new CMS tracker

2.2) Metrology measurements

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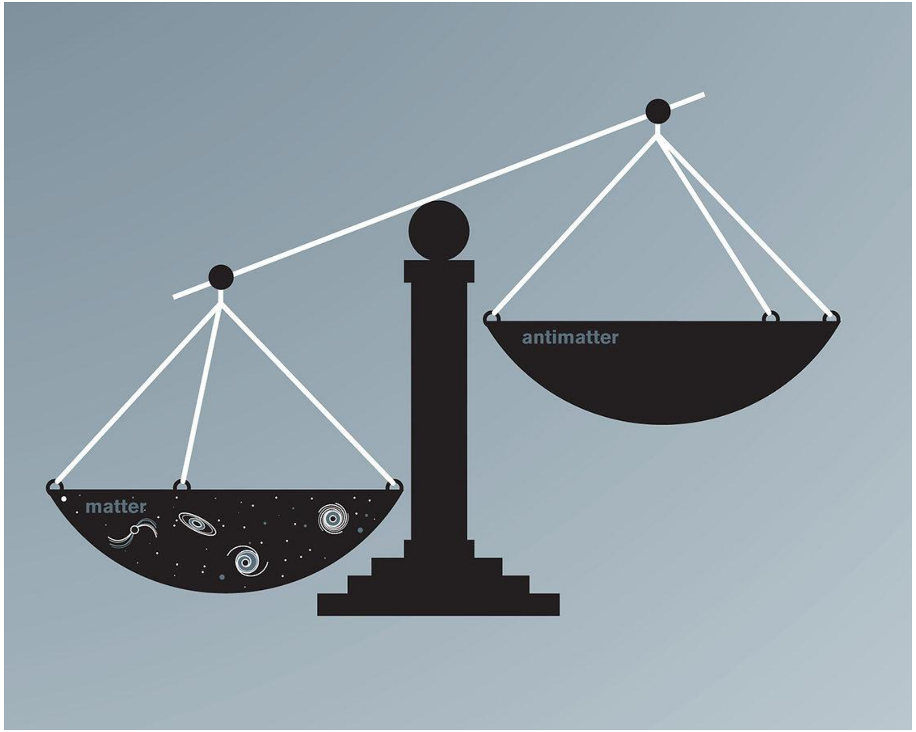
Matter and Antimatter asymmetry

The universe is baryon-number asymmetric:

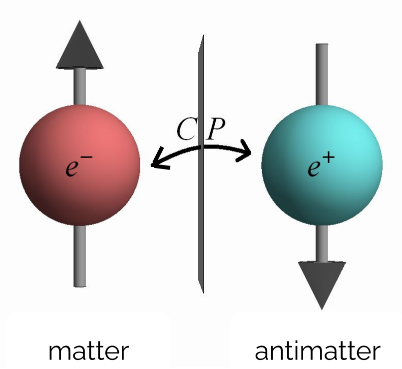


SM prediction: $$\eta_{SM} = \frac{n_B - n_{\bar{B}}}{n_\gamma} \propto 10^{-27}$$

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

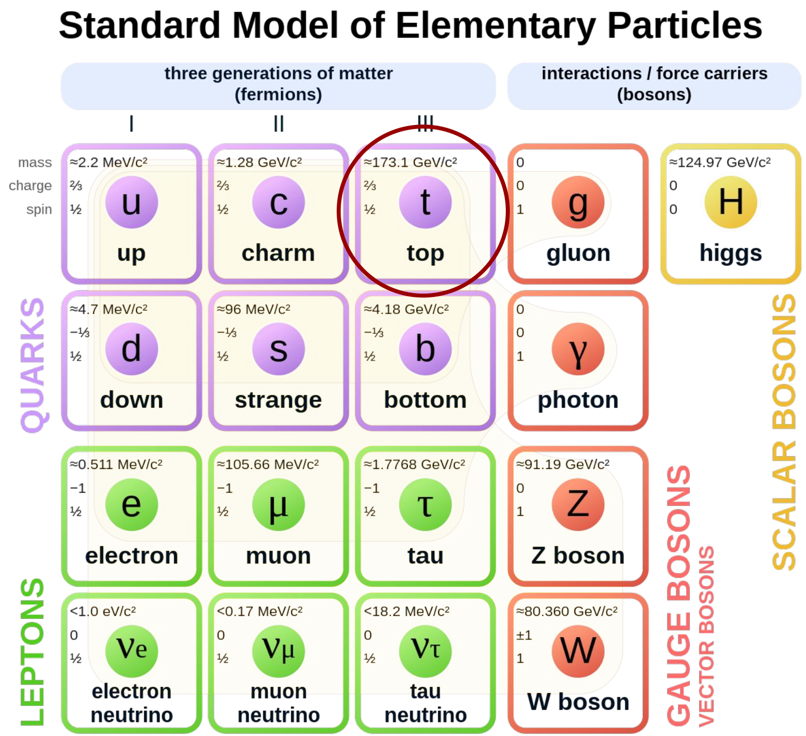
$$\Rightarrow \frac{\eta_{SM}}{\eta_{obs}} \propto 10^{-17}$$

Discrepancy between the SM prediction and observations



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

Top quark in the Standard Model (SM)

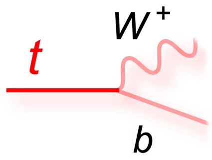


Top quark properties:

➔ **High mass**: The top quark is the heaviest known elementary particle.

➔ **Short lifetime**: The top quark decays before hadronization.

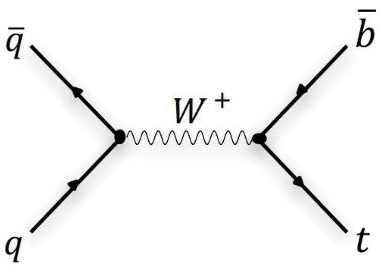
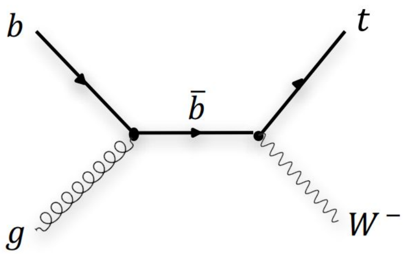
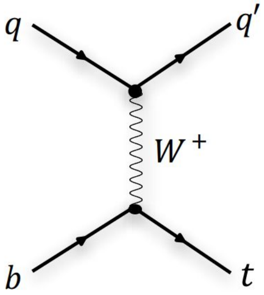
➔ **Decay mode**: The top quark decays into a bottom quark and a W boson with branching ratio ~100%.



Hence, **the top quark is an excellent candidate for measuring CP violation.**

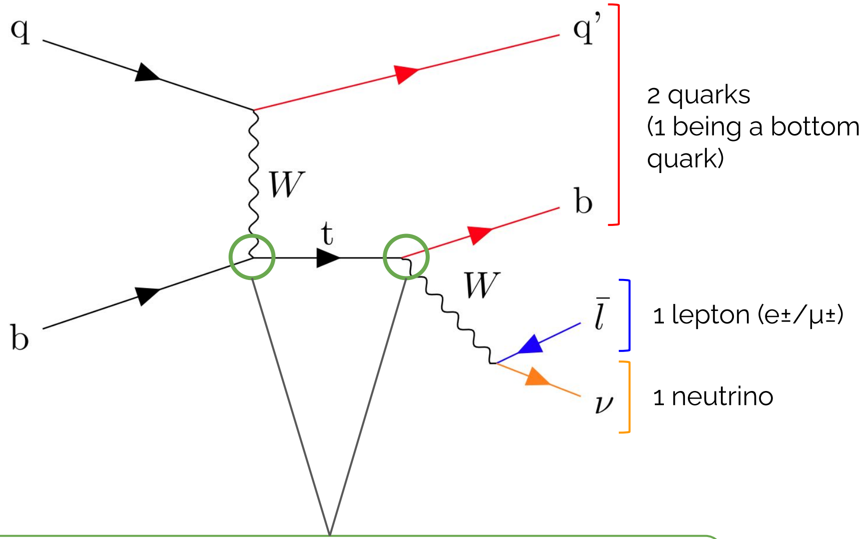
Single top quark production at the Large Hadron Collider (LHC)

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

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

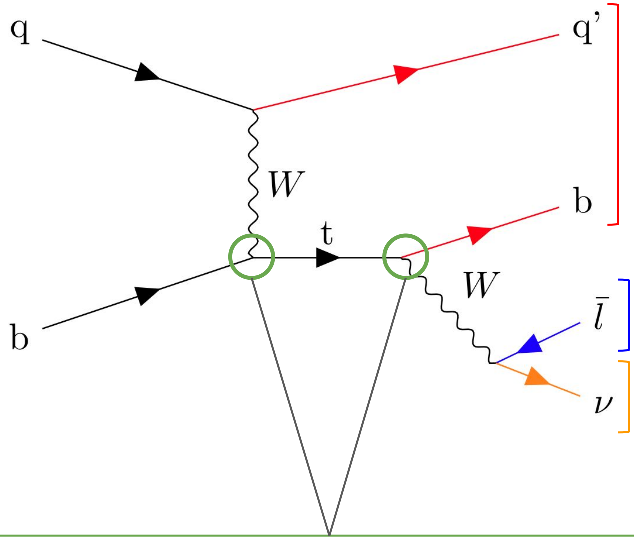
We are going to study the t-channel due to the largest cross section value.

Topology of the signal process



W_{tb} vertex at top production and decay. This vertex can be modified by CP-violation.

CP-violation with Effective Field Theory (EFT)



2 quarks
(1 being a bottom quark)

1 lepton (e±/μ±)

1 neutrino

W_{tb} vertex at top production and decay. This vertex can be modified by CP-violation.

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

$$C_{tW}\,,\, C_{tW}^I$$
$$C_{bW}\,,\, C_{bW}^I$$
$$C_{\varphi tb}\,,\, C_{\varphi tb}^I$$

6 dimension parameter space.

The SM is the origin of such space

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

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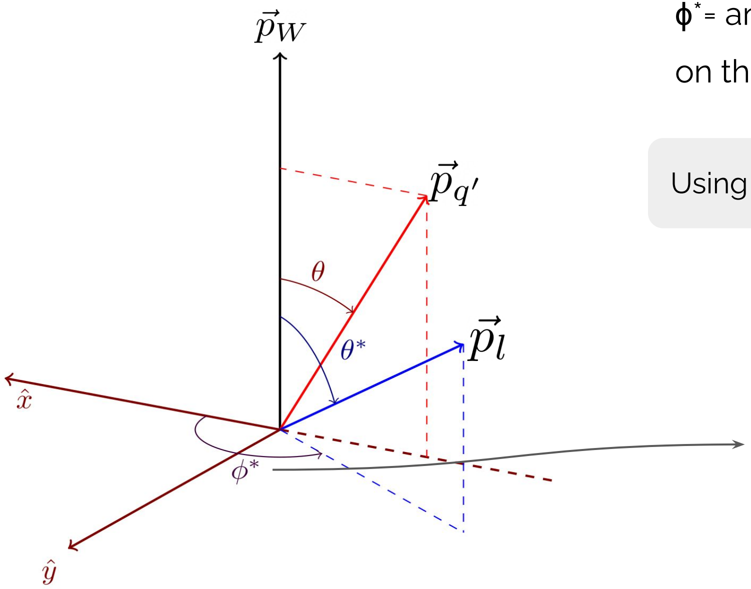
How to measure CP violation with single top t-channel

Top quark rest frame:

- **b** quark and W boson are back to back

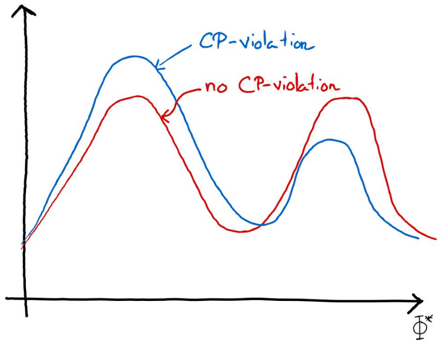


θ = angle between q' quark and W boson momenta

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

Using the distribution of these angles, the size of CP violation can be measured



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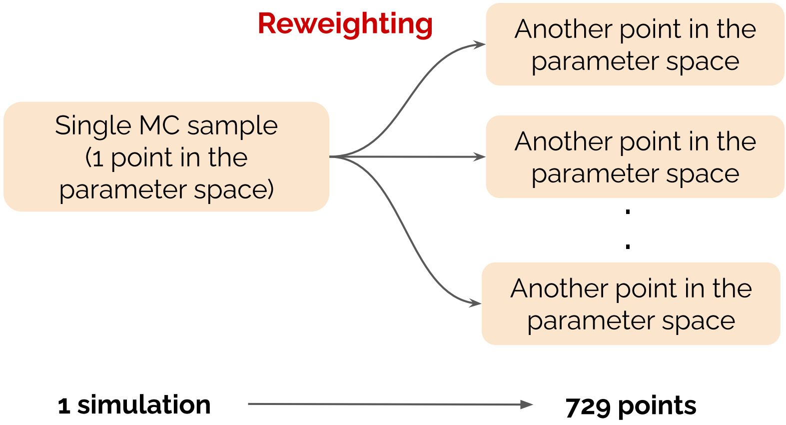
Reweighting and sample generation

- 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



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

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

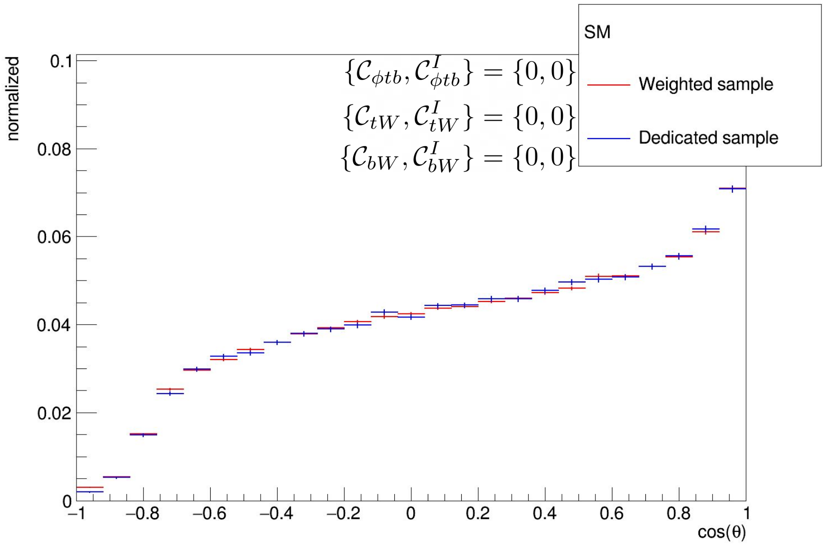
$$\{ C_{\varphi tb} , C^{I}_{\varphi tb} \} = \{-5,0,5\}$$

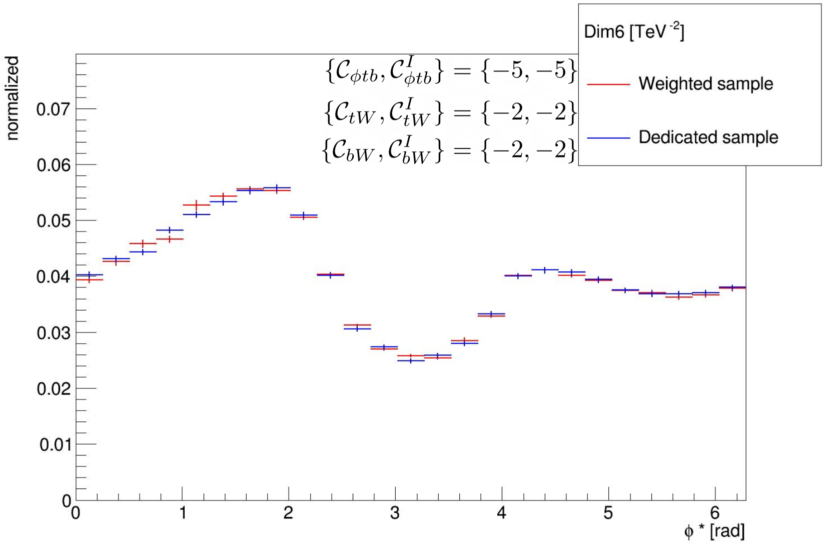
Our 6 axes of the parameter space

Different combination values

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

Validating reweighting

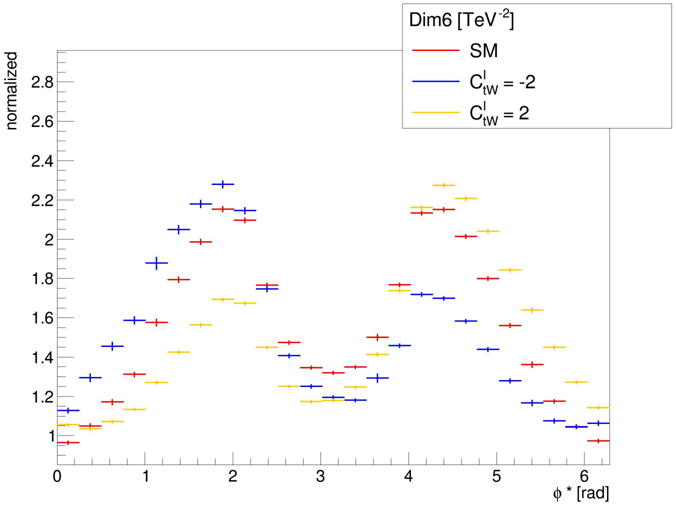


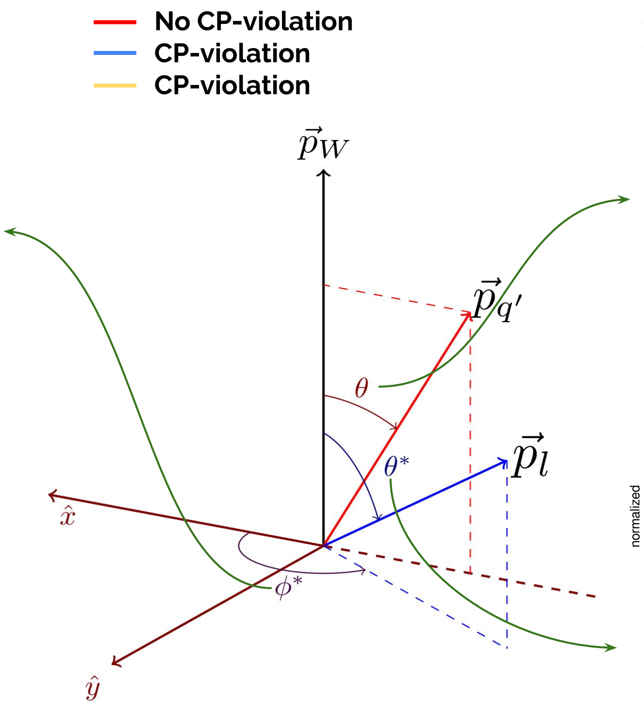


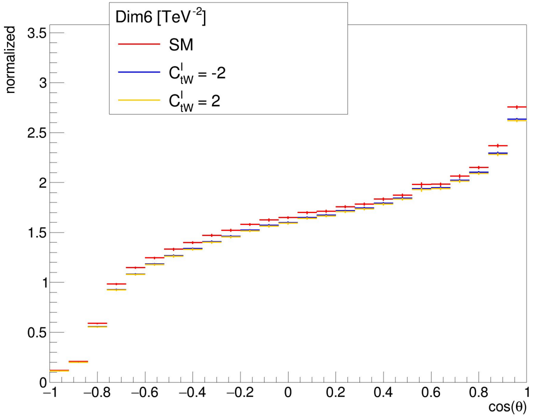
Comparing reweighted distributions of cos(θ) and ϕ^* to dedicated (non-reweighted) samples at two different distant points of the parameter space

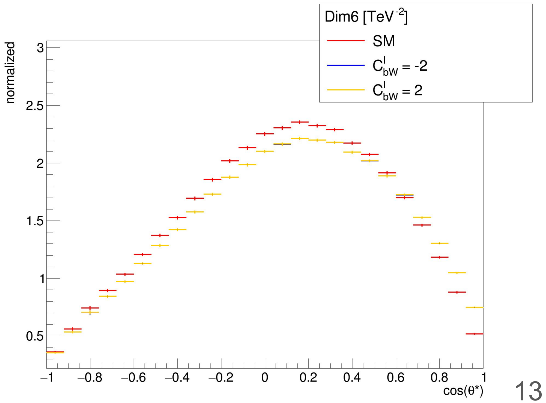
➔ **Reweighting is validated**

EFT effects on kinematic variables at parton level







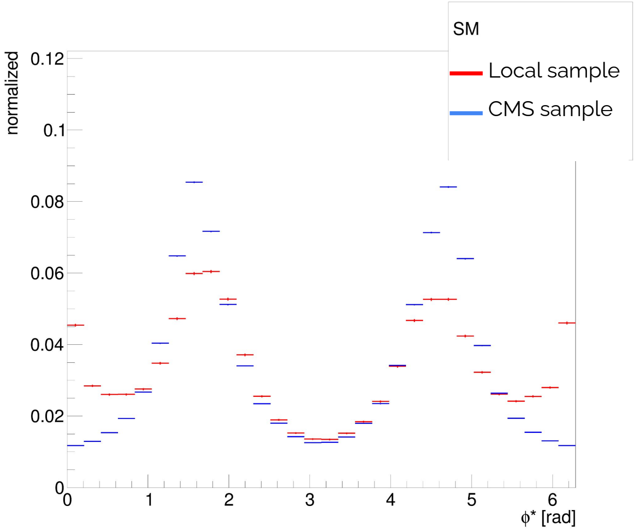


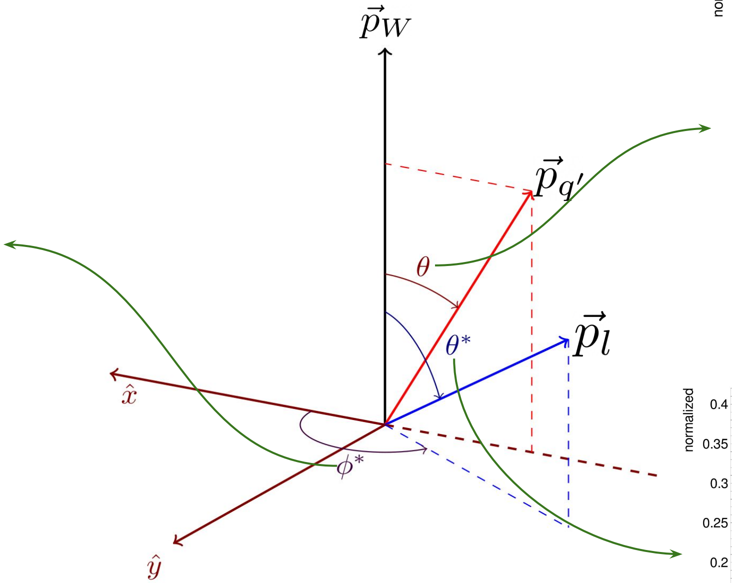
The shape of the angular distributions change as a function of the value of the EFT coefficient.

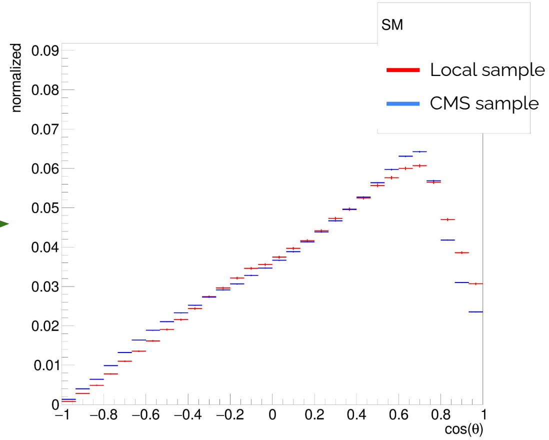
These angles are experimentally observable, we can therefore, observe CP-violation through these variables by analysing LHC collisions data.

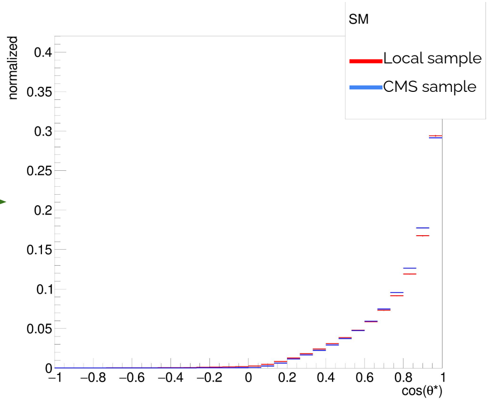
Comparing generated samples to official CMS sample at generator level

We want to verify that the physics of the generated samples are correct. For this, we compare our internal generated samples to official validated CMS samples at the SM.









Investigating discrepancy. Probably need to add an extra jet at parton level.

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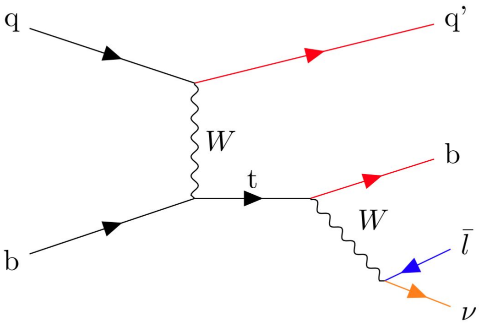
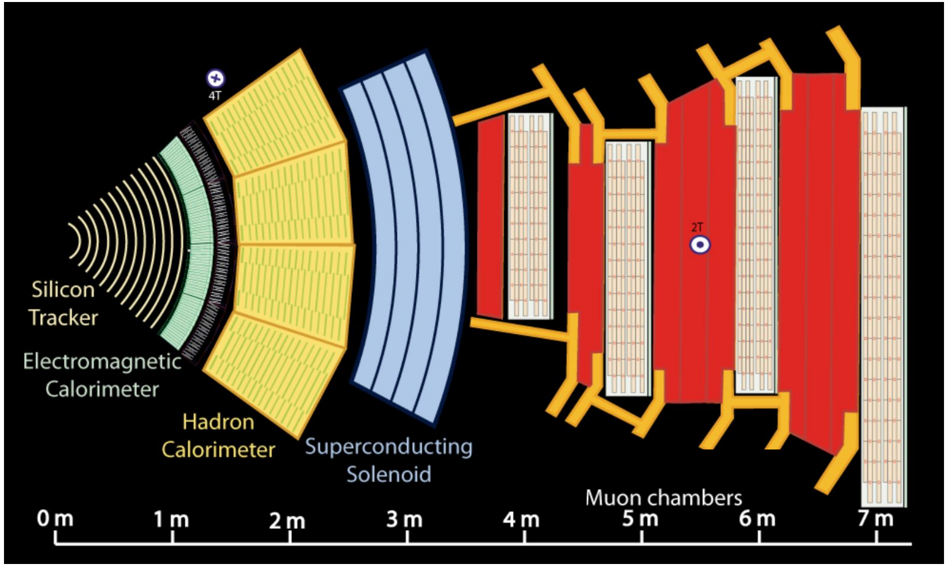
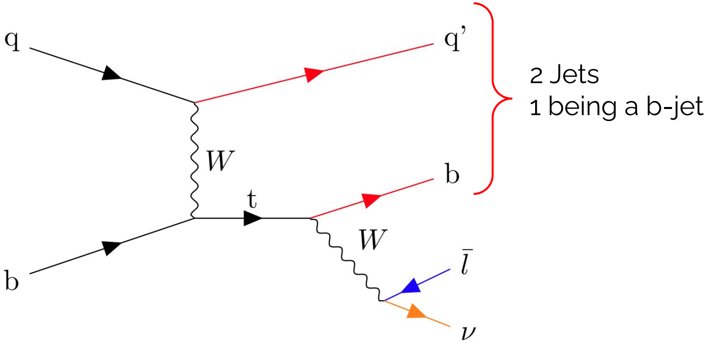
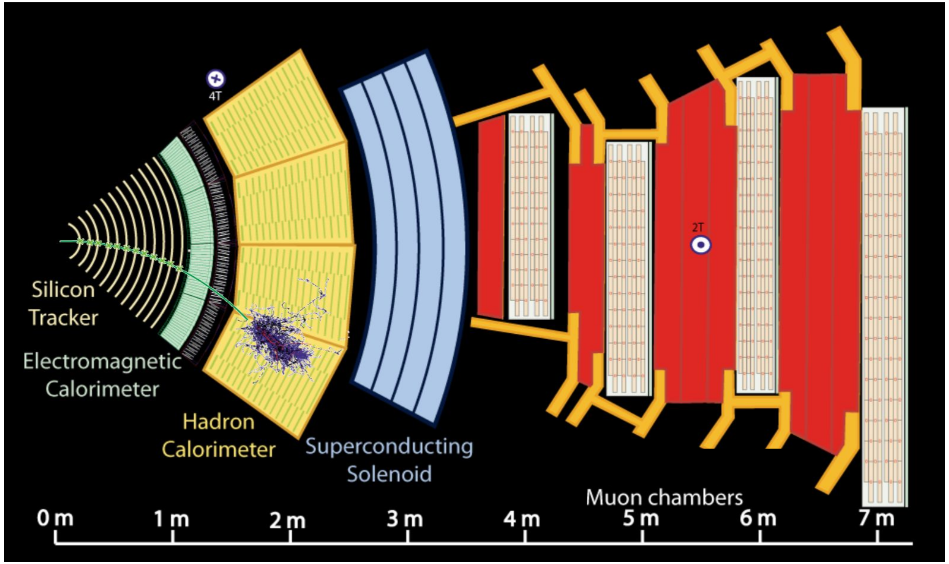
Reconstructed objects at CMS



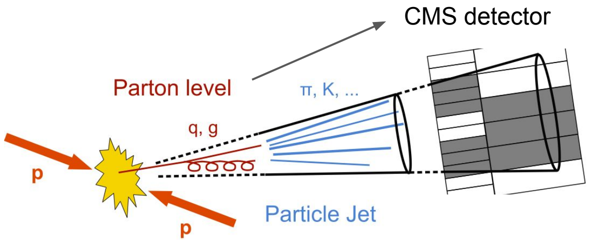


Reconstructed objects at CMS



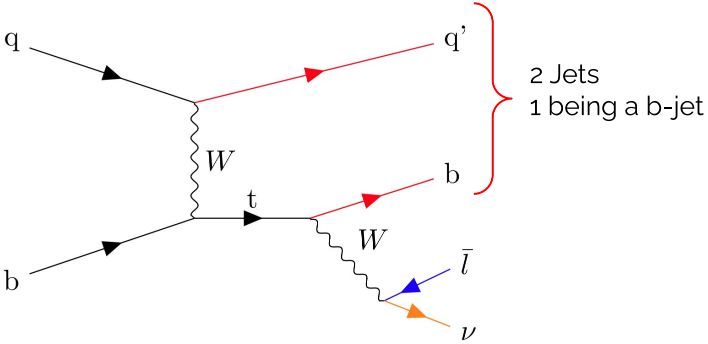


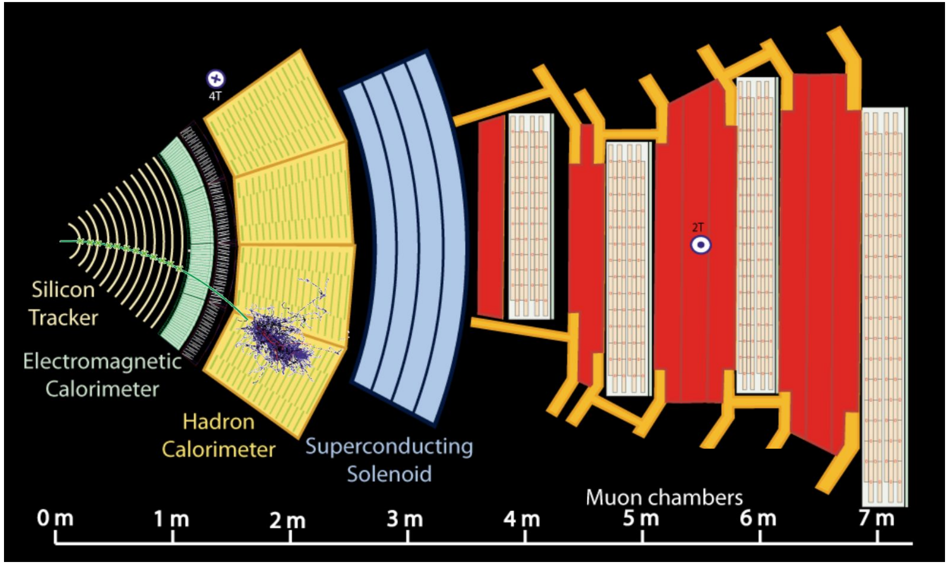
What is a jet?



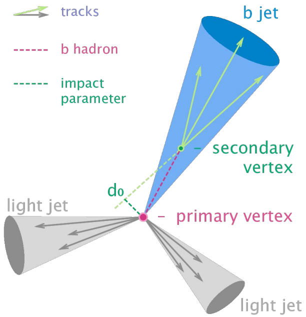
- Jets are collimated sprays of particles that are produced during p-p collisions.

Reconstructed objects at CMS



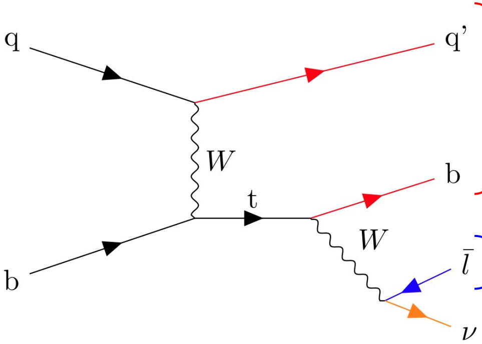


What is a b-jet?



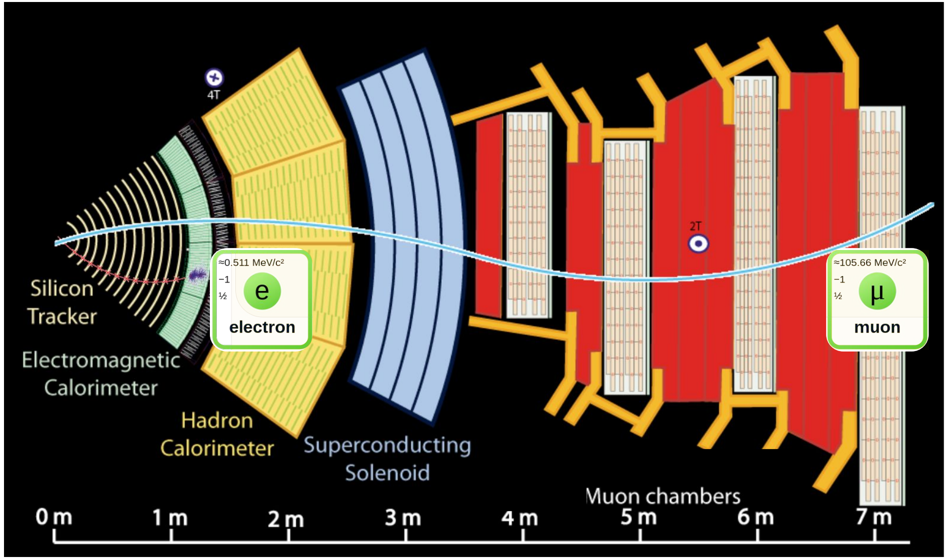
- Jets stemming from b hadrons are called b jets

Reconstructed objects at CMS

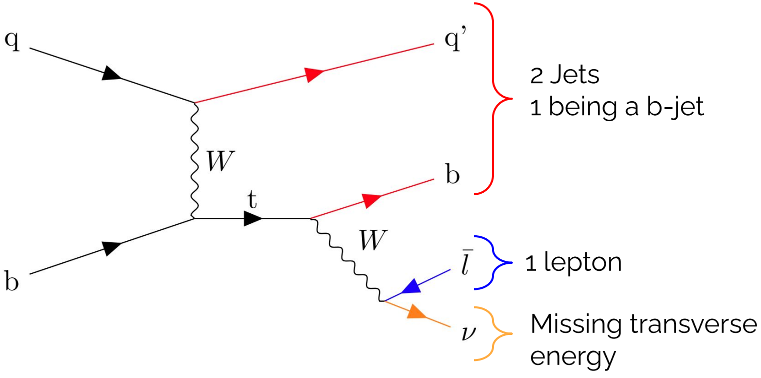


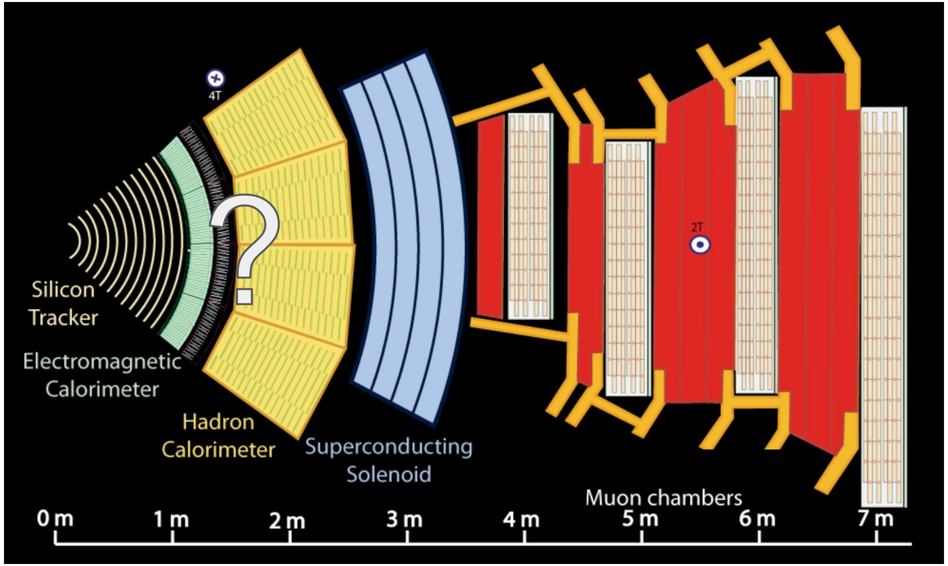
2 Jets
1 being a b-jet

1 lepton

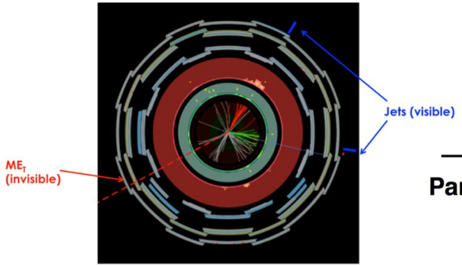


Reconstructed objects at CMS





What is Missing transverse momentum?



$p_x = p_y = 0$

$p_z = ?$

Parton 1 **Parton 2**

Control Regions

Signal region: Where we want to measure CP-violation

Signal region (2j1t):
Strictly 2 Jets with 1 being a b-jet

We are blind in the signal region to have an unbiased analysis

Control regions: Study the behavior of the background processes

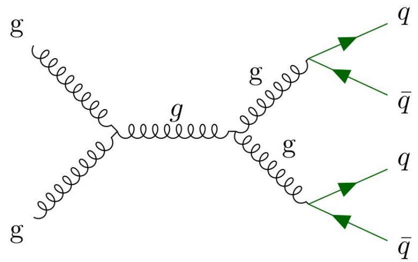
WJets region (2j0t)
Strictly 2 jets with 0 b-jets

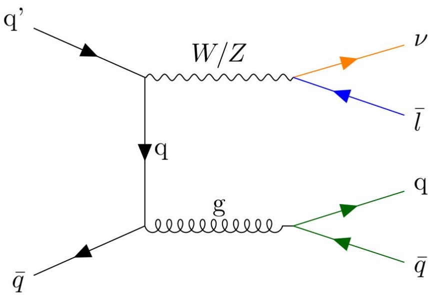
TT bar region (3j2t)
At least 3 jets with at least 2 b-jets

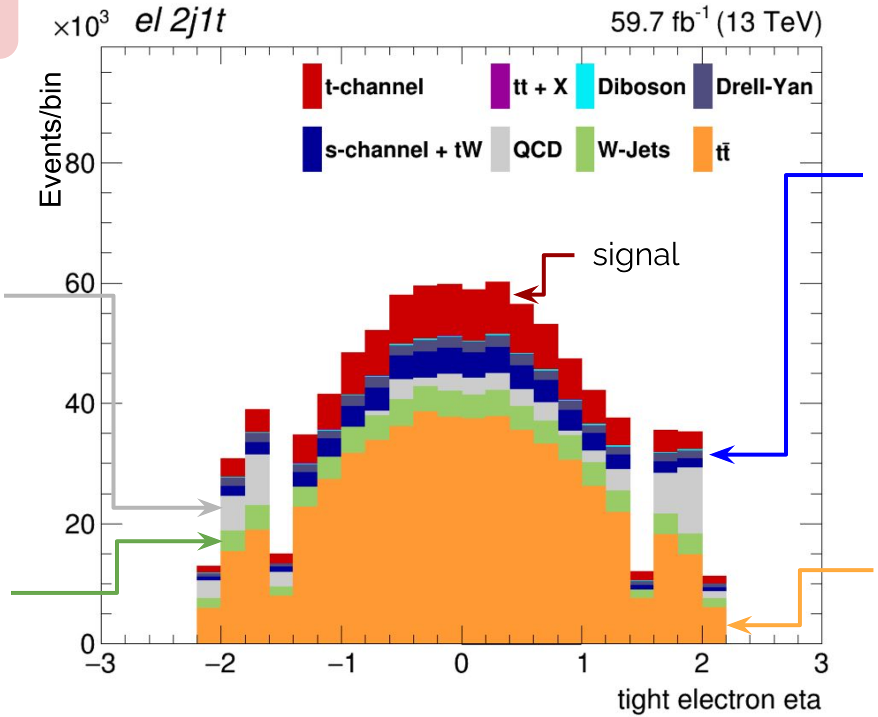
QCD enriched region
Strictly 2 jets with 0 b-jets and reverse isolation requirements on leptons

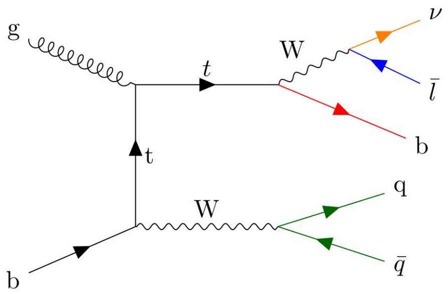
Background noise processes

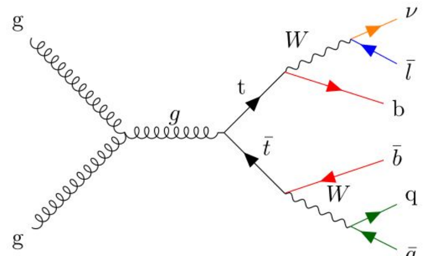
Signal region (2j1t):
Strictly 2 Jets with 1 being a b-jet











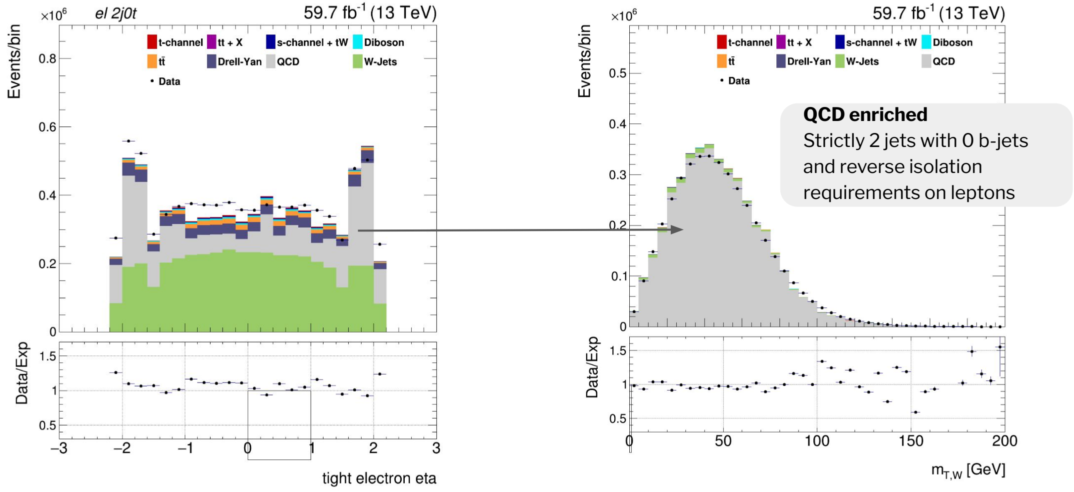
WJets and QCD control regions

WJets region (2j0t)
Strictly 2 jets with 0 b-jets

Objective: Reduce the QCD background contributions using this as control region.

Problem: The QCD background is estimated from data as there is insufficient MC available.

Solution: Create a sideband region enriched with QCD events and use the data from that sideband as a template to estimate the contribution of QCD events in the signal region

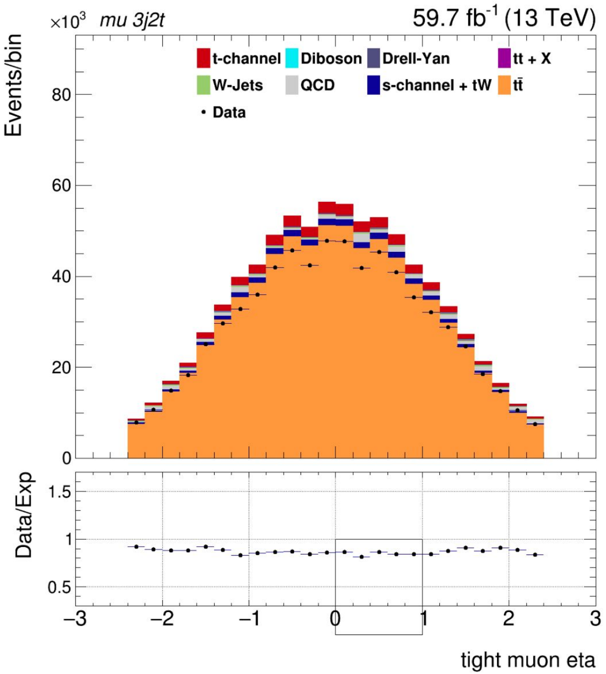


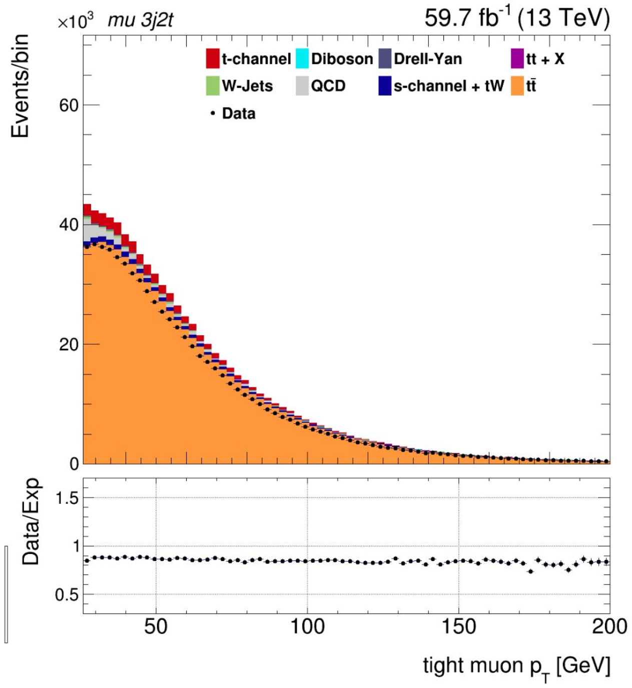
TTbar control region

We create control regions in order to reduce the background noise processes contributions

TT bar region (3j2t)
At least 3 jets with at least 2 b-jets

➔ Next step, applying lepton and b-tag scale factors will improve data/MC agreement





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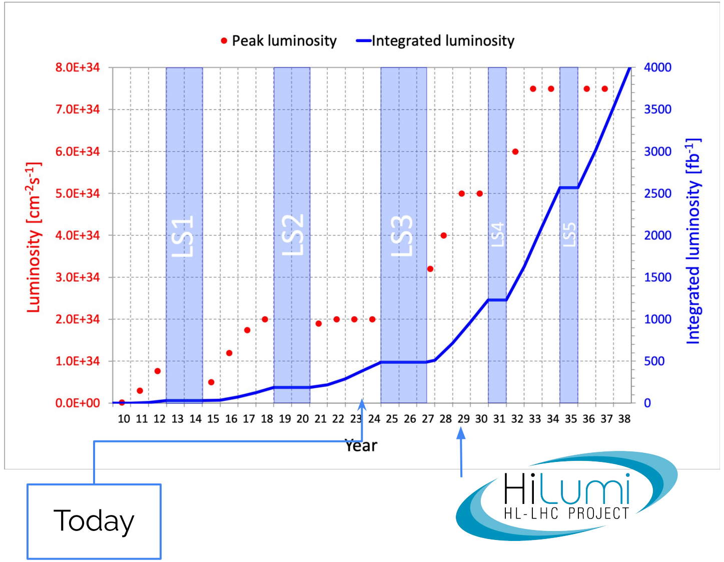
Why the CMS tracker needs an upgrade?



HL-LHC features:

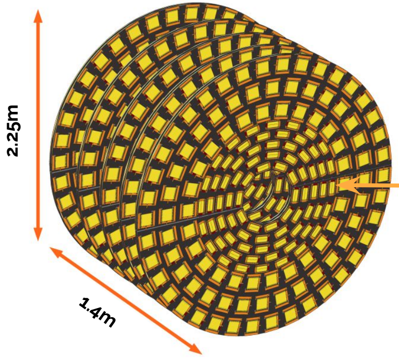
- Higher integrated luminosity (up to 4000fb^{-1})
- Higher instant luminosity peak (~x7.5 higher)
- More collisions per beam crossing. Up to between 140-200. (~38 at the end of Run2)

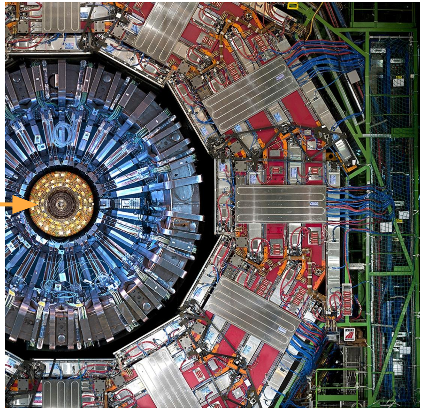
CMS tracker upgrde

- The tracker needs an upgrade to sustain the high level of radiation
- Ability to trigger data acquisition on events with high momentum tracks

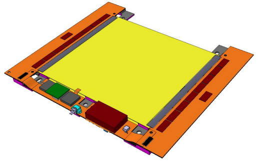
New CMS Tracker for HL-LHC

TEDD = Tracker Endcap Double-Discs

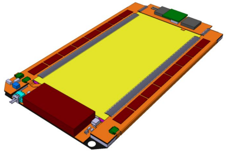


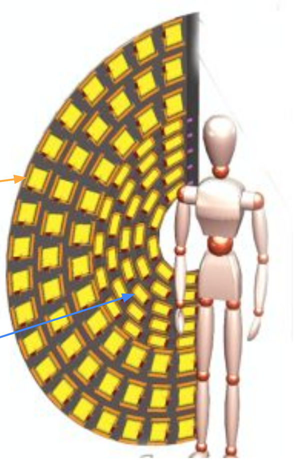


2S = strip - strip



PS = pixel - strip





Dee: Main structure of the TEDD that supports the detector modules

TEDD concept:

- Cooling at -35˚C using CO_2 at phase transition.
- Cooling pipes integrated as part of the Dee structure to minimize the weight of the structure.
  ↳ **Optimal cooling of the detection modules**

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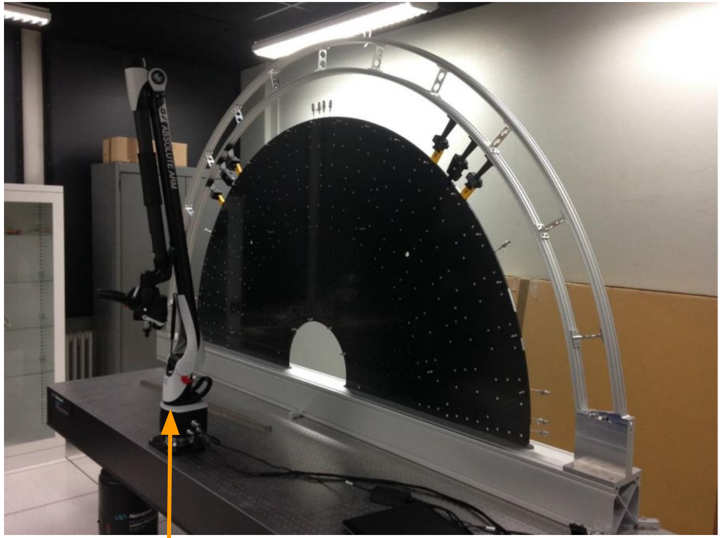
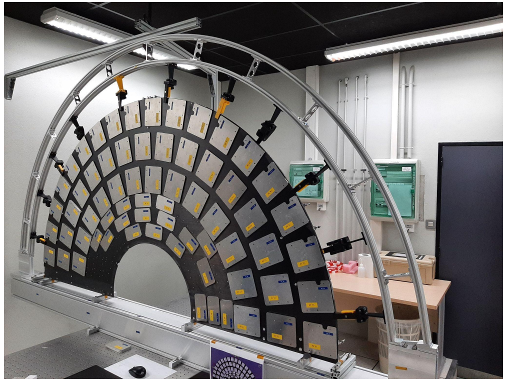
Metrology measurements



High precision metrology measurements of Dee's surface taken with the mechanical arm

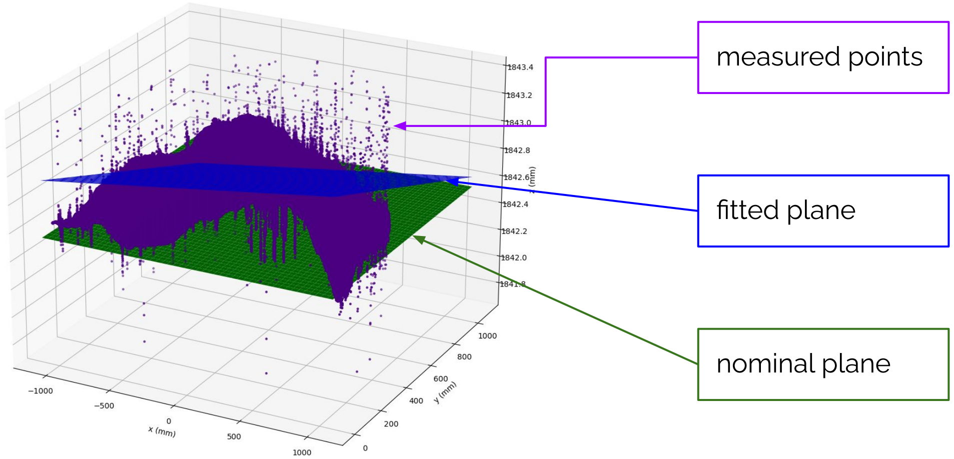
Over ~10^6 measurement points of the surface of the dee taken with the laser

LIO clean room at IP2I



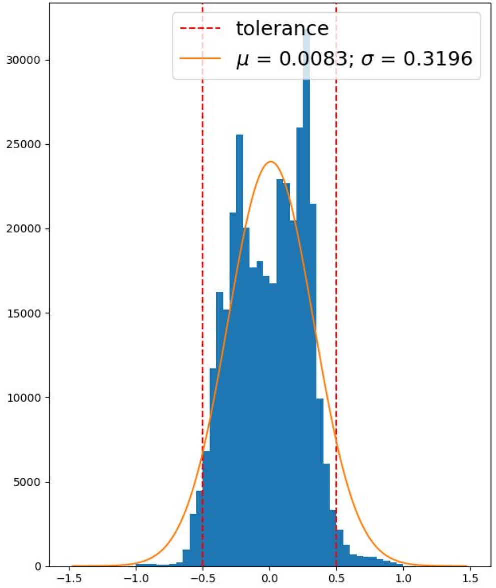
Fitting a plane to data

We want to assess the flatness of the Dee.
We can measure the distance between measured points and a nominal plane. However, the Dee surface might not be perfectly aligned with the nominal plane when performing the measurement. To avoid this bias, we fit a plane to data and measure the distance between fitted plane and measured points.

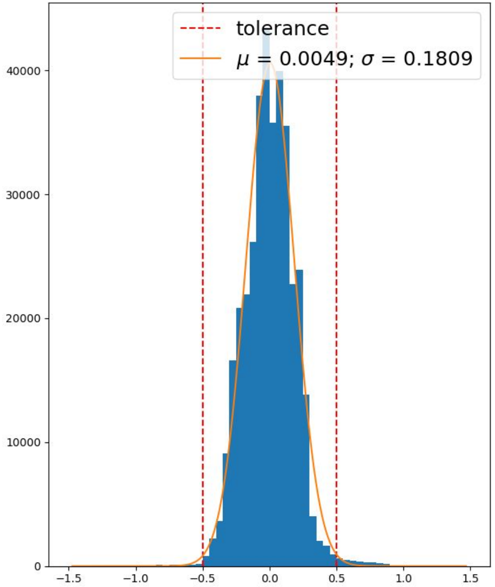


Testing Dee's flatness

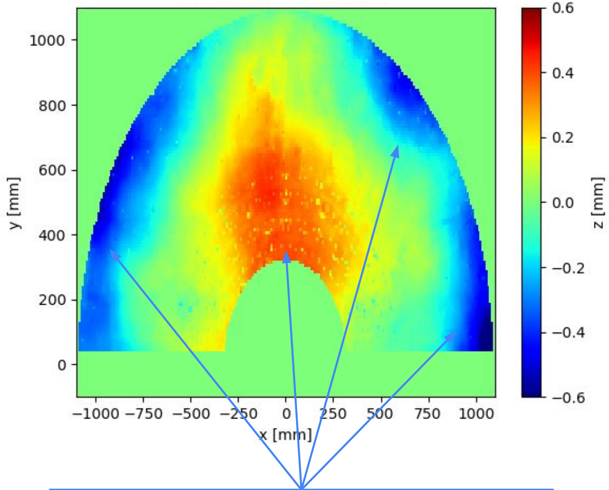
Distance between measured points and **nominal** plane



Distance between measured points and **fitted** plane



Colormap of the Dee's flatness



Distortions may be due to imperfections of gluing process in the autoclave. They are within flatness specifications (±0.5mm)

The distribution shows an improvement on the assessment of the dee's flatness for the fitted plane compared to the nominal plane.

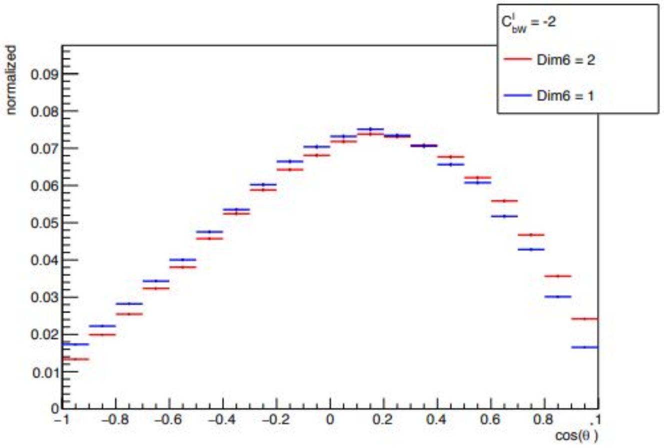
Conclusion

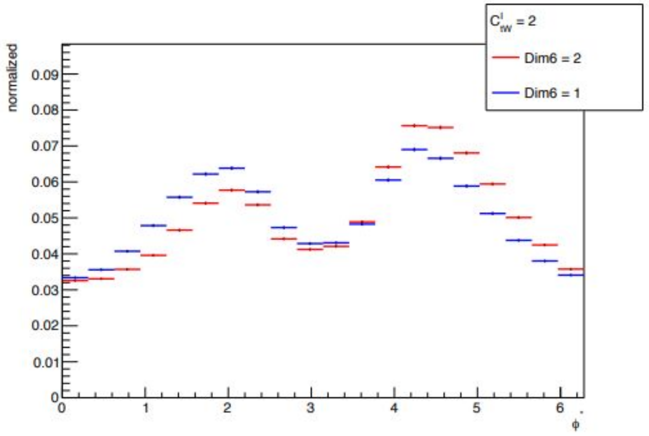
- **Phenomenology**
  - Exploring the discrepancy between CMS sample and dedicated sample.
  - Study the possibility add an extra jet to the process at parton level.
- **Analysis**
  - Next steps :
    - Finish QCD background estimate from data
    - Include remaining b jet and leptons corrections with systematic uncertainties
    - Work on signal extraction.
- **Tracker Upgrade**
  - Production of 24 Dees will start at the end of 2023.
  - The metrology analysis framework will be used to analyse all future Dees.

Thank you :)

Backup

Dim6 = 1 vs Dim6 = 2

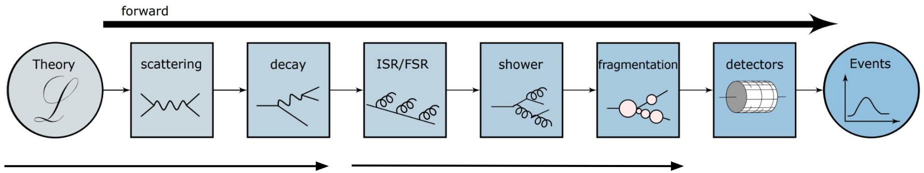




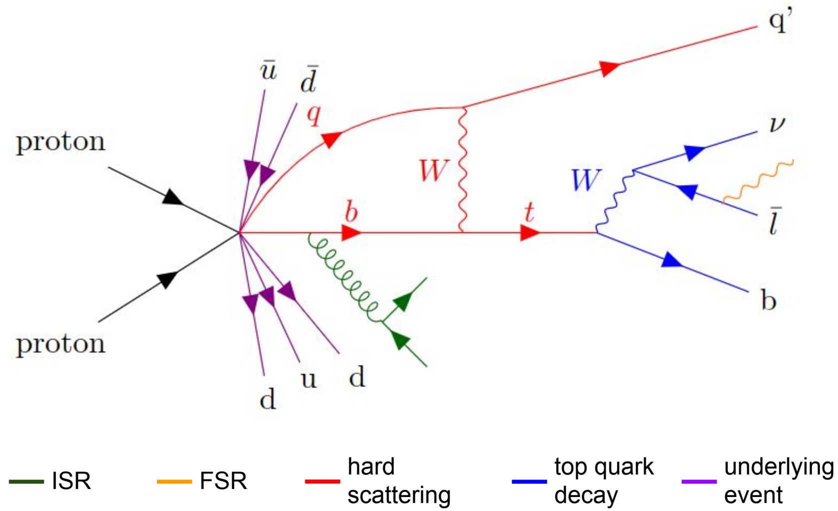
Higher precision obtained by applying EFT operators effects on top production and decay

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

Levels of information in proton-proton collisions



Event record of an exemplary t-channel single-top-quark event



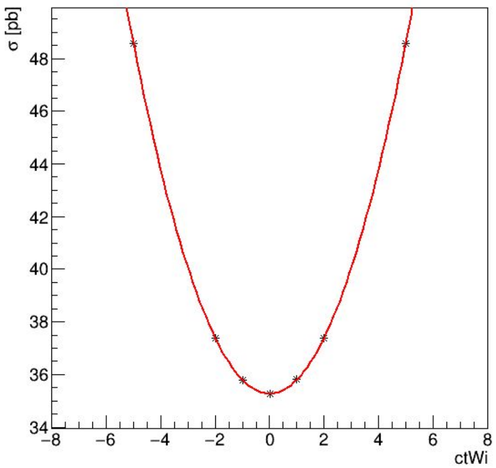
Parton level (= theory): Computation of **| *M* |²** using Feynman rules for the SMEFT model.

Generator level: Simulation of the hadronization (using parton-level information)

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

CP-violation with Effective Field Theory (EFT)

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

SMEFT Lagrangian elements:

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

- $\mathscr{L}_{eff}^{(6)}$: EFT Lagrangian
- $\mathscr{L}_{SM}$: SM Lagrangian
- $C_i^{(6)}$: EFT Coefficients
- Λ_i^2: New physics energy scale
- $O_i^{(6)}$: 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:

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

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

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

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**

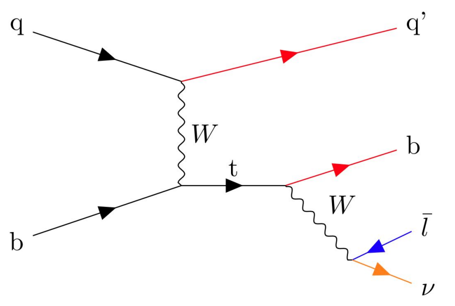
➔ **The SM is the origin of the parameter space**

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

Different channels

Object selection:

- Final state objects:
  - Only 1 lepton in the final state (electron/muon)
  - 2 jets with 1 strictly stemming from a b quark
  - MET

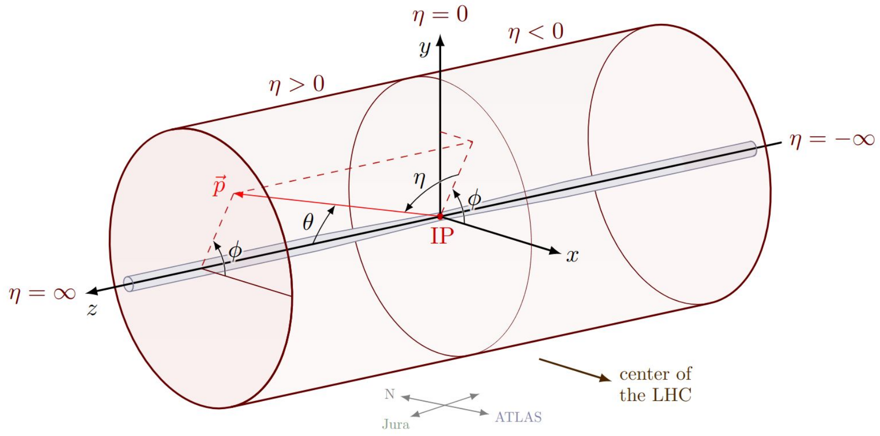


Electron channel:

- ❑ Exactly one electron
- ❑ Exactly zero muons
- ❑ pT > 32GeV
- ❑ |η| < 2.1

Muon channel:

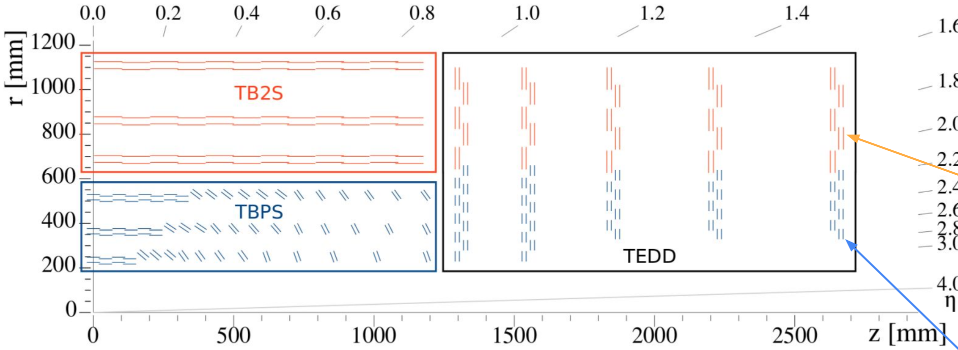
- ❑ Exactly one muon
- ❑ Exactly zero electrons
- ❑ pT > 30GeV
- ❑ |η| < 2.4



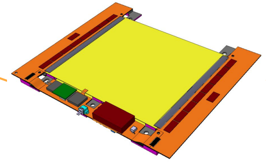
CMS coordinates system

New CMS Tracker for HL-LHC

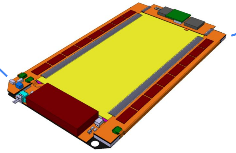
TEDD = Tracker Endcap Double-Discs

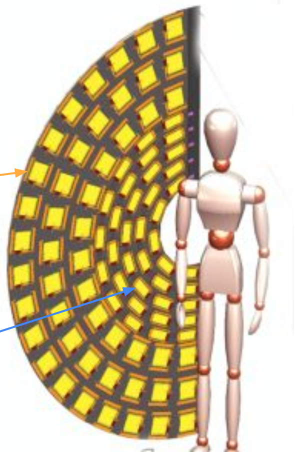


2S = strip - strip

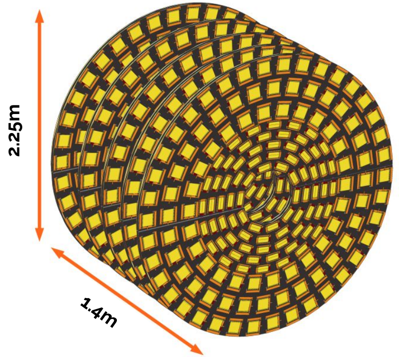


PS = pixel - strip





Dee: Main structure of the TEDD that supports the detector modules



TEDD concept:

- Cooling at -35˚C using CO_2 at phase transition.
- Cooling pipes integrated as part of the Dee structure to minimize the weight of the structure.
  ↳ **Optimal cooling of the detection modules**