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Christopher Greenberg. Searches for CP symmetry violation in the top quark sector with CMS at the LHC, and the tracker Endcap upgrade for the High Luminosity LHC. Journées de Rencontre Jeunes Chercheurs 2022, Oct 2022, La Rivière in Saint-Jean-de-Monts, France. in2p3-04908042

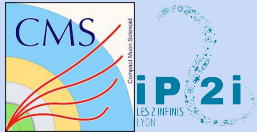
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Submitted on 23 Jan 2025

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

Christopher Greenberg

Part 1: Phenomenology and CP violation

Matter and Antimatter asymmetry

The universe is baryon-asymmetric:

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

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

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

Discrepancy between theory and observation

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Discrepancy between theory and observation

Sakharov conditions for baryogenesis [1]:

- I. Baryon number violation
- II. **CP violation**
- III. Deviation from thermal equilibrium

[1] [arXiv:1204.4186v2](https://arxiv.org/abs/1204.4186v2)

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Discrepancy between theory and observation

Sakharov conditions for baryogenesis [1]:

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The Standard Model (SM) does not provide enough sources of CP violation to explain the predominance of matter over antimatter in the observable universe

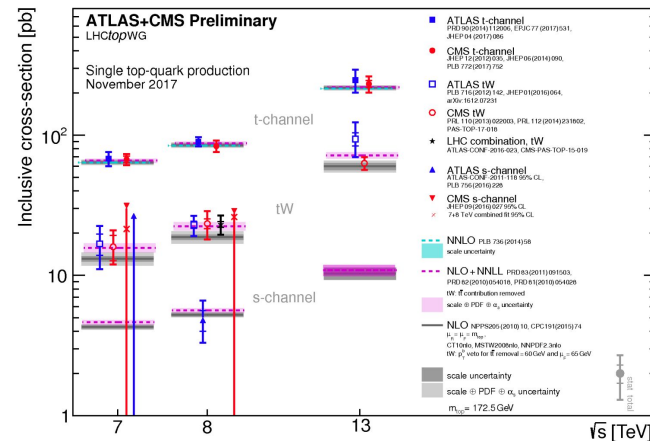
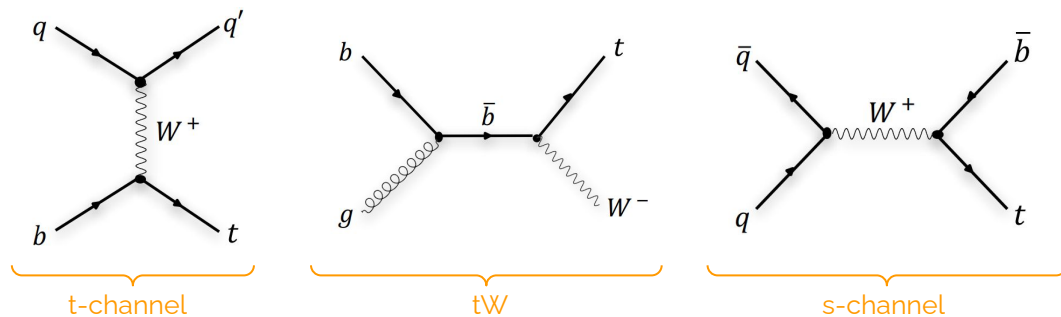
We're looking for new sources of CP violation Beyond the Standard Model (BSM) involving top quarks.

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Signal topology - Single top quark t-channel

Single top-quark is very sensitive to CP violation

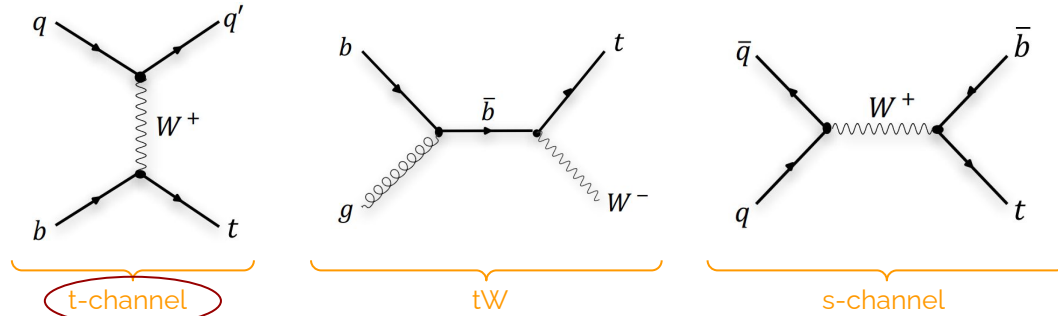
The three main production modes are:



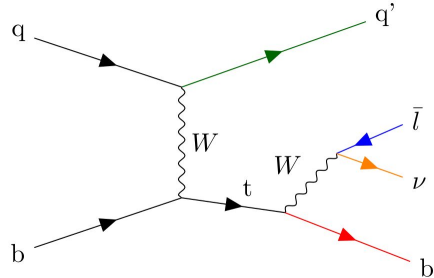
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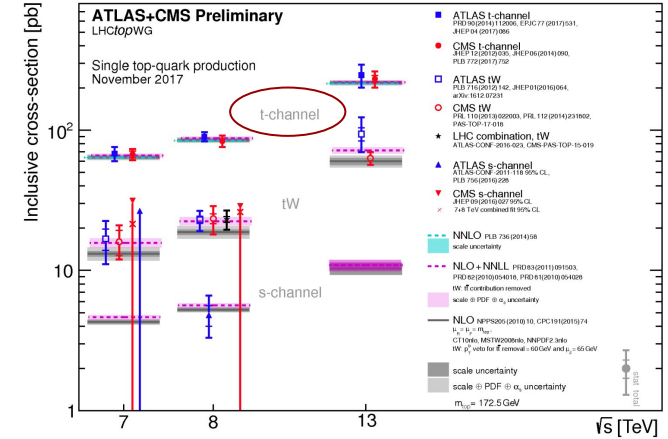
The three main production modes are:



decay mode



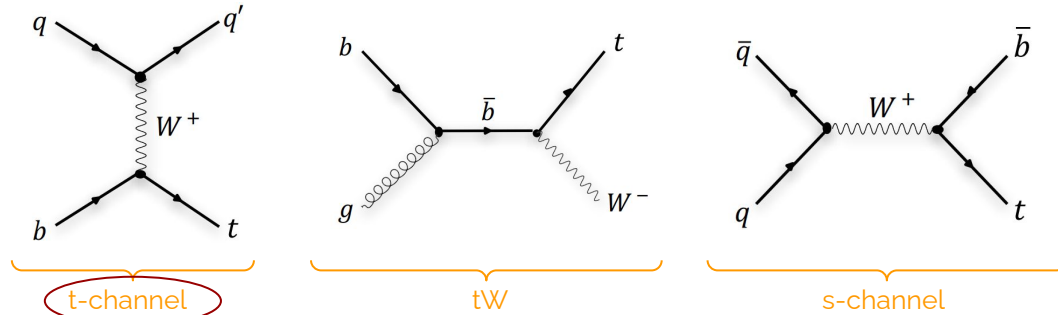
➤ The final state of the process is composed of:



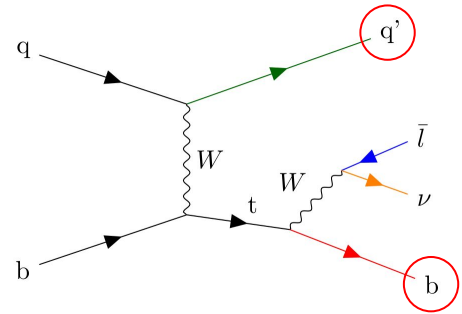
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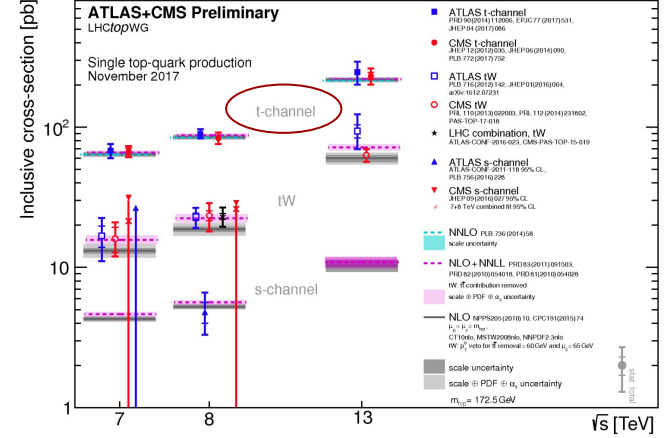
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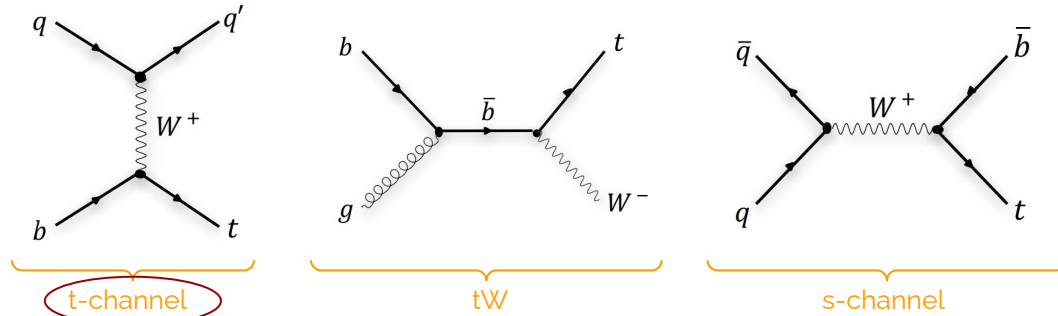
- The final state of the process is composed of:
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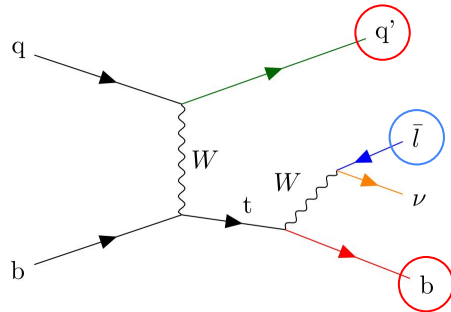
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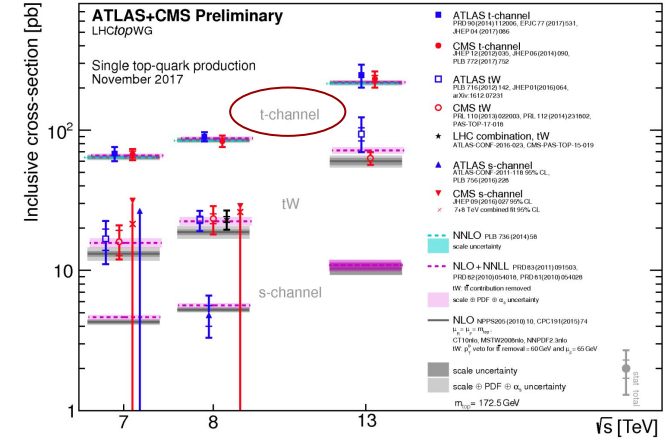
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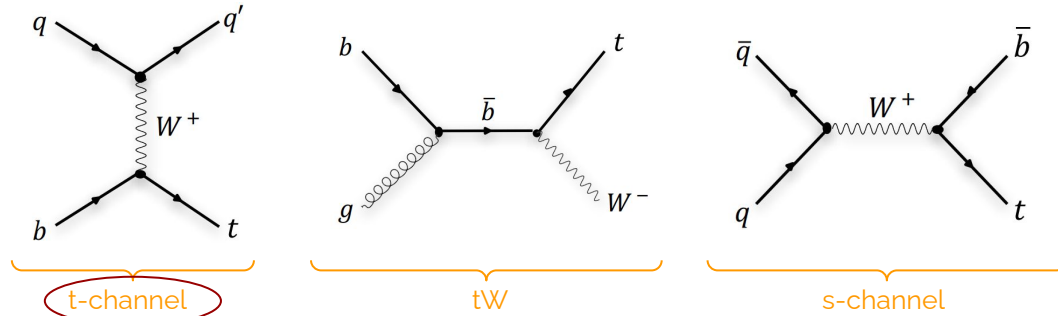
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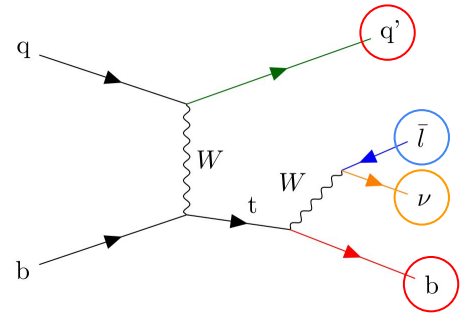
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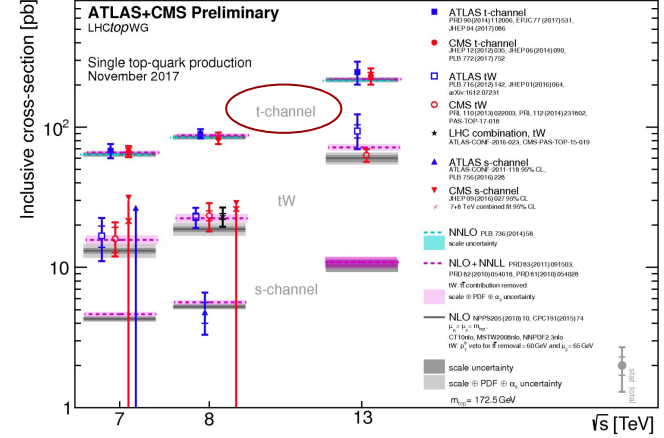
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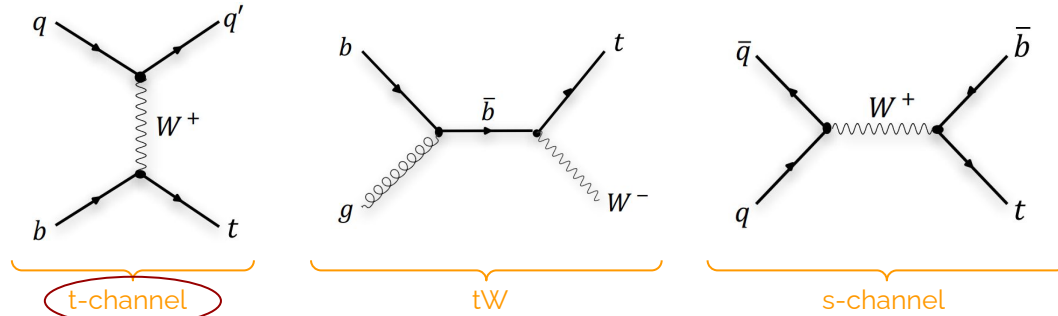
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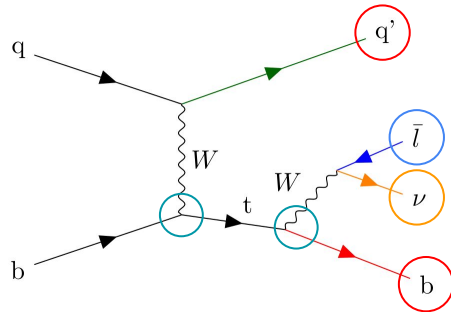
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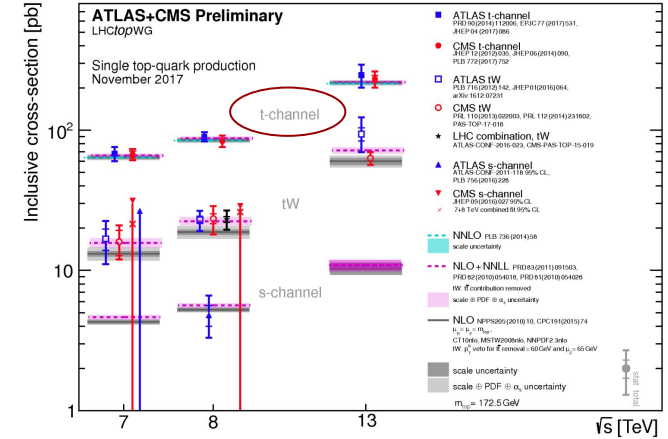


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○ W_{tb} vertex at top production and decay
 Vertex can be modified by CP violation



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

SMEFT Lagrangian elements:

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

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SM Lagrangian

New physics energy scale

EFT operators
Energy dimension = 6

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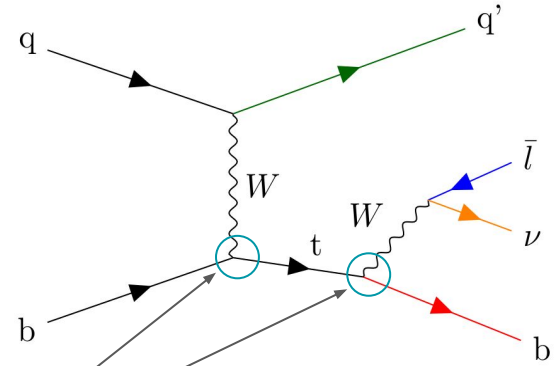
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New physics energy scale

EFT operators
Energy dimension = 6



EFT operators will have an impact on the W_{tb} vertex at top production and decay

CP symmetry violation with EFT:

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Dimension 6 operators that violate CP symmetry at Wtb vertex:

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

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EFT coefficients

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

- 6 dimensions parameter space
- The SM is the origin of the parameter space

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

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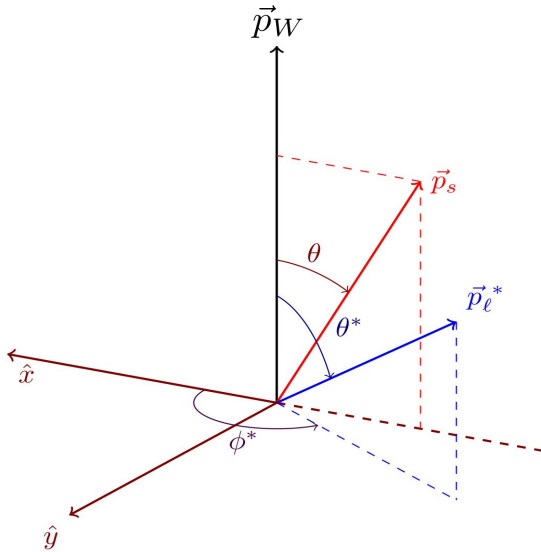
Goal of this thesis:

Measure the value of these 6 EFTs coefficients

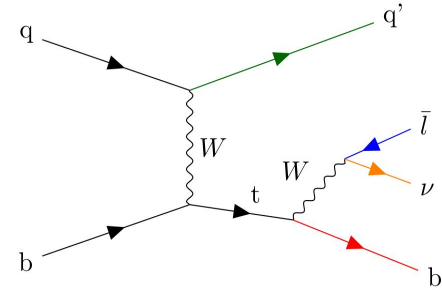
How to measure CP violation?

Top quark rest frame:

- **b** quark and W boson are back to back
- We will look at 3 angles θ , θ^* and ϕ^* in this reference frame



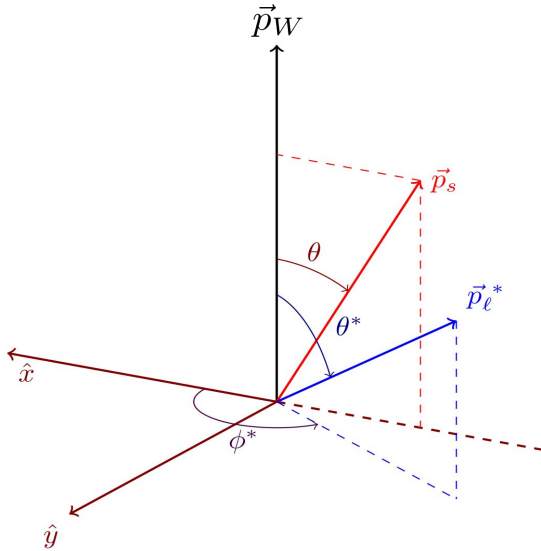
methodology



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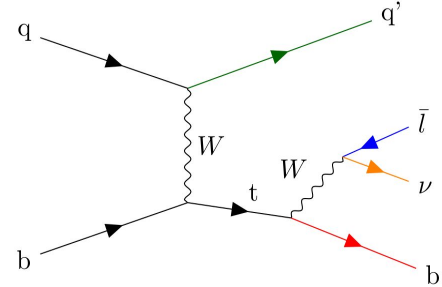
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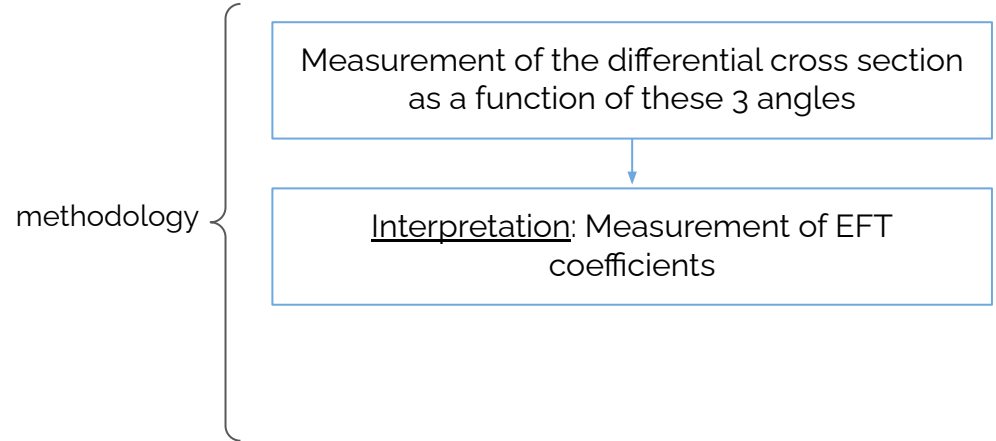
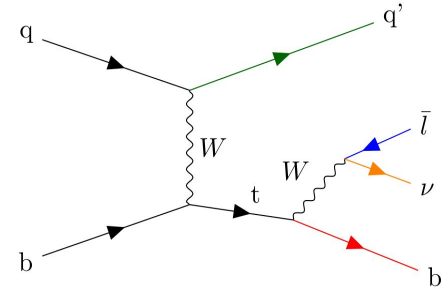
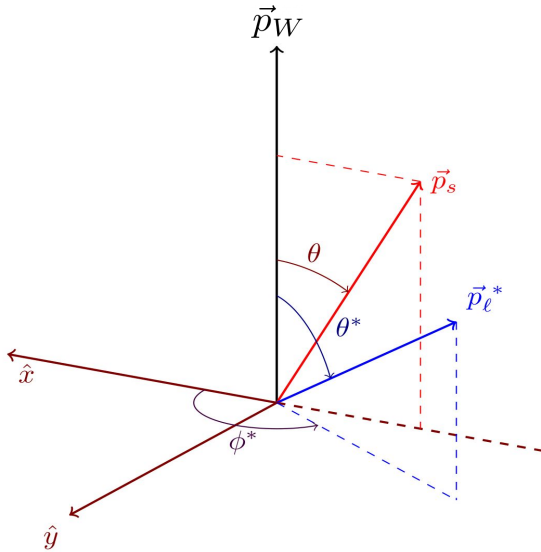
Measurement of the differential cross section as a function of these 3 angles



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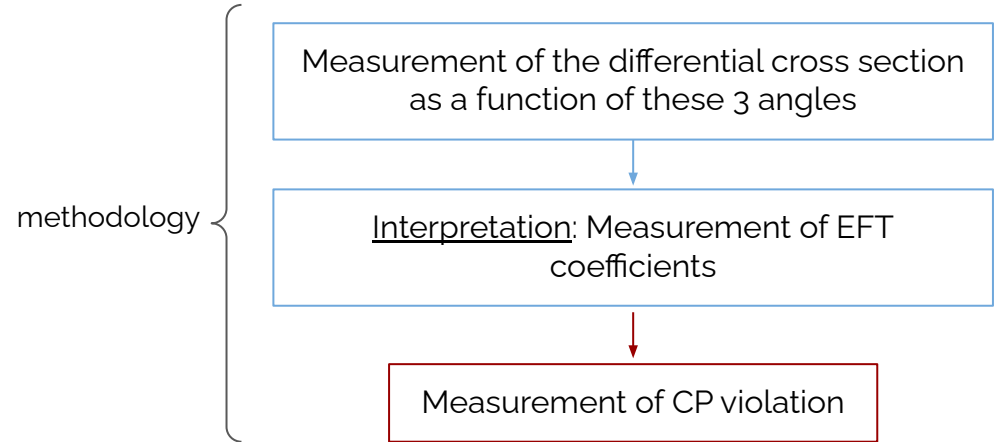
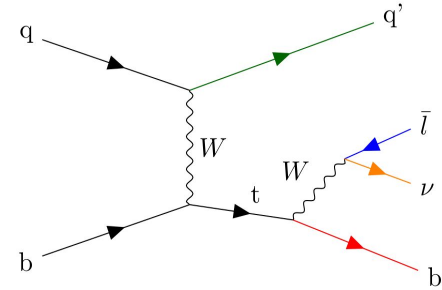
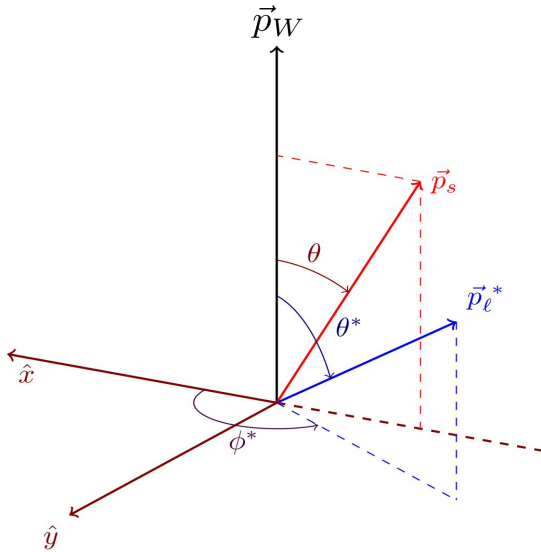
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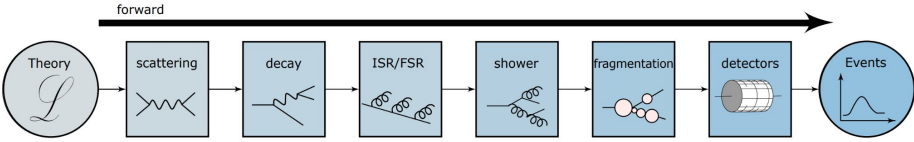
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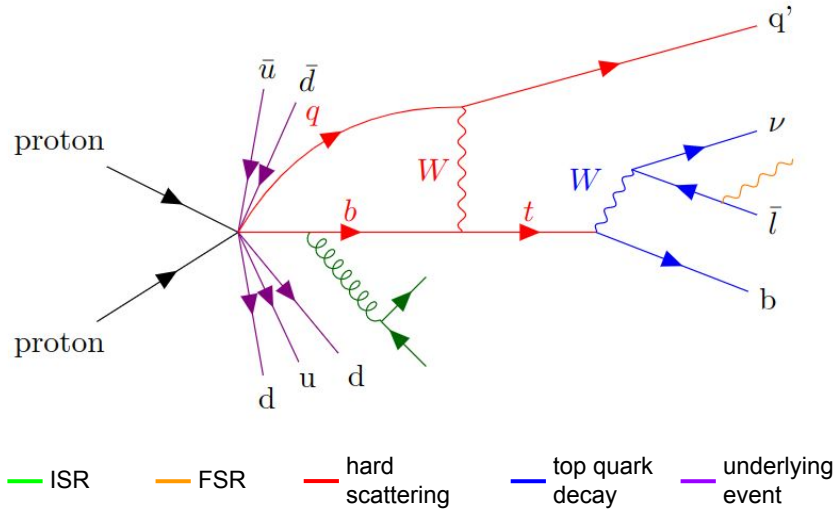
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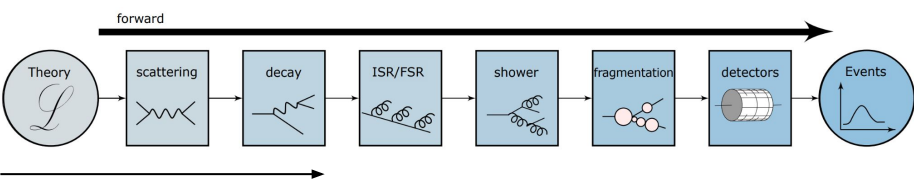
Levels of information in proton-proton collisions



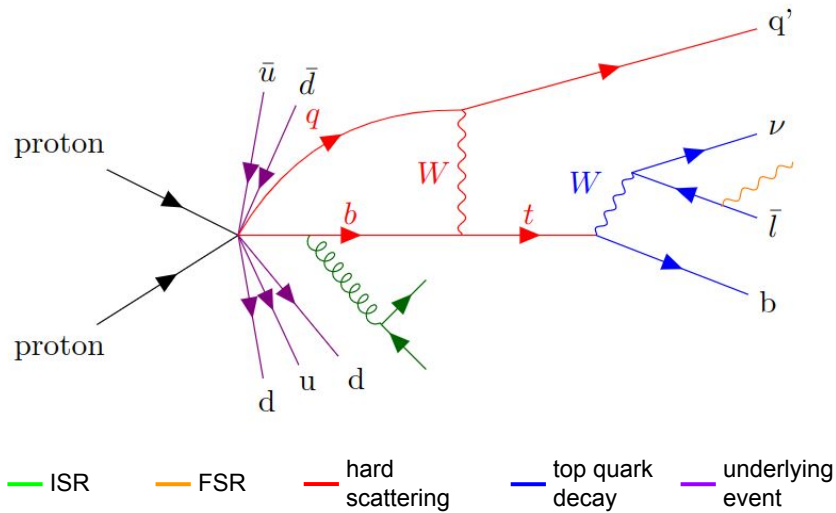
Event record of an exemplary t-channel single-top-quark event



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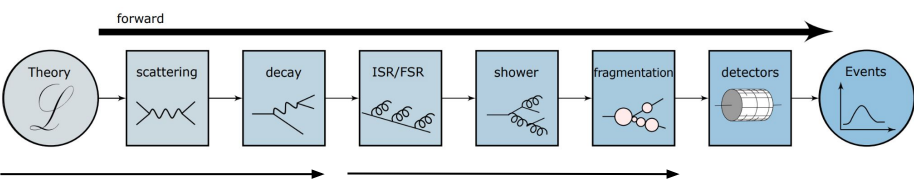


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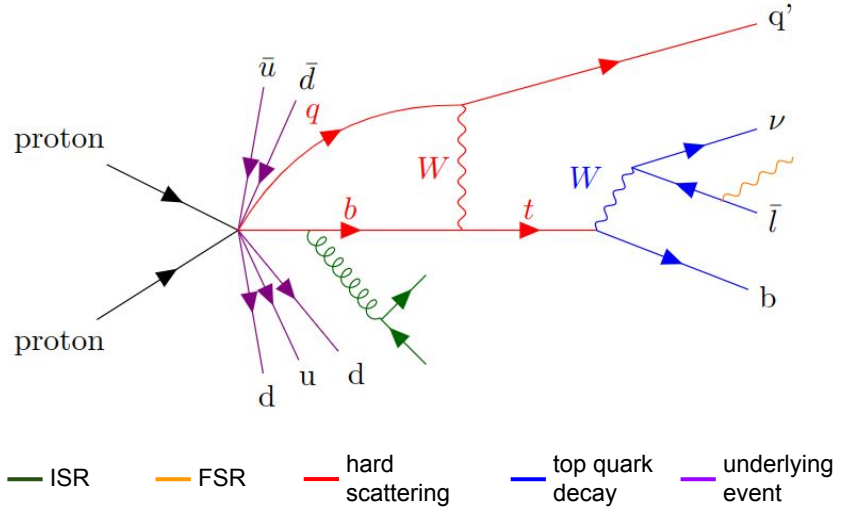


Parton level (= theory): Computation of $|M|^2$ using Feynman rules for the SMEFT model.

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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

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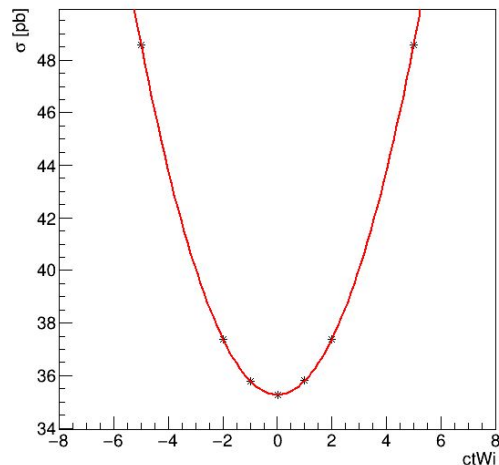
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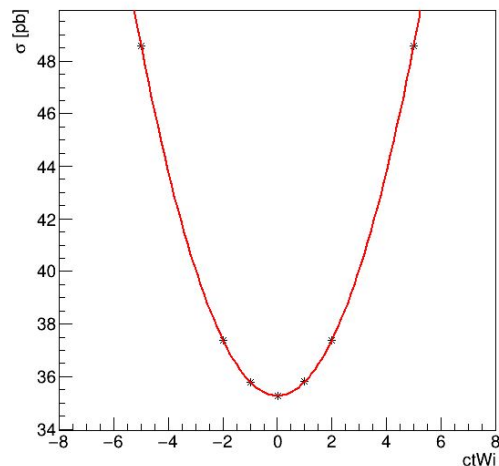


Quadratic behavior on the cross section as expected [2]

[2] [arXiv:1807.03576](https://arxiv.org/abs/1807.03576)

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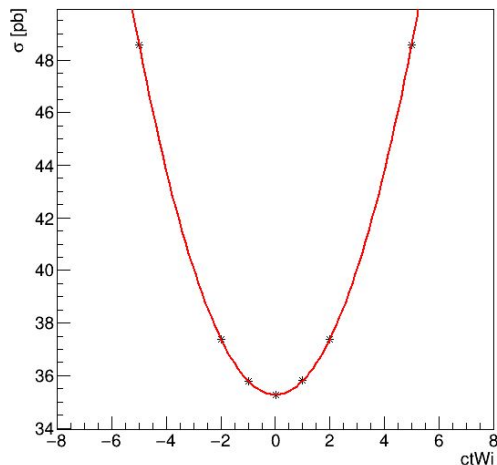
How many WC points to generate?

$$\left. \begin{aligned} \{C_{tW}, C_{tW}^I\} &= \{-2, 0, 2\} \\ \{C_{bW}, C_{bW}^I\} &= \{-2, 0, 2\} \\ \{C_{\varphi tb}, C_{\varphi tb}^I\} &= \{-5, 0, 5\} \end{aligned} \right\} \text{Sample space with } \mathbf{729} \text{ WC points (includes the SM)}$$

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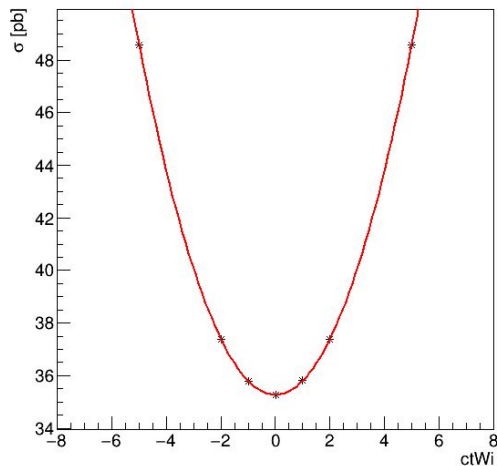
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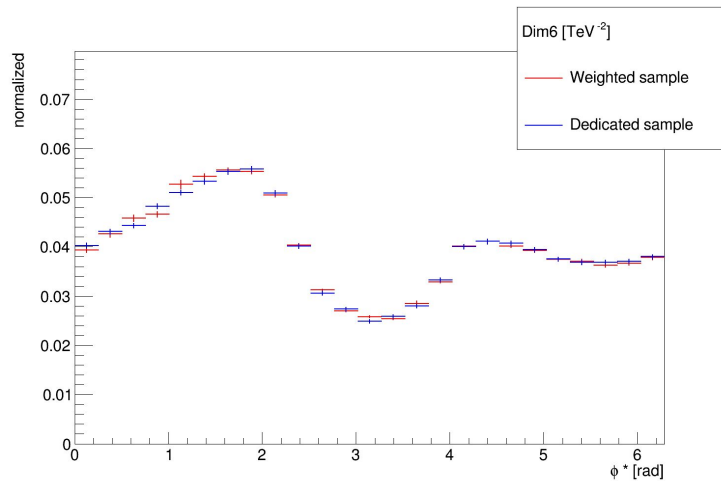
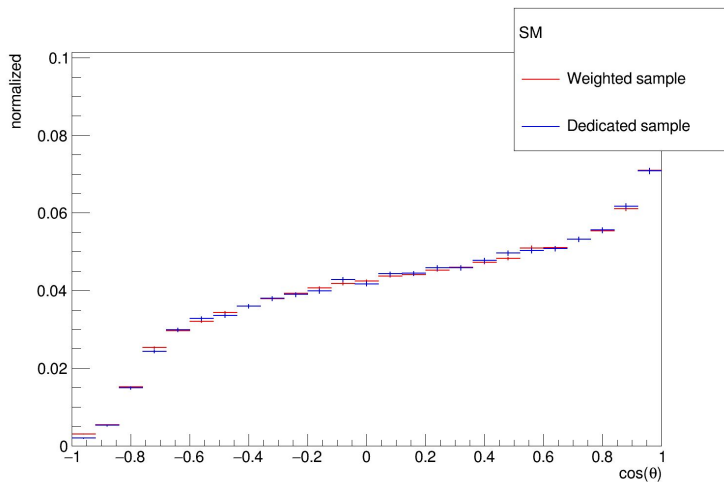
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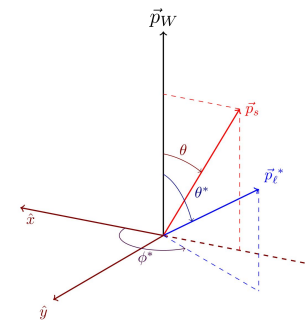
Reweighting method: Assign event weight corresponding to the WC values. We have only one sample with all combinations of WCs

Validating Reweighting method

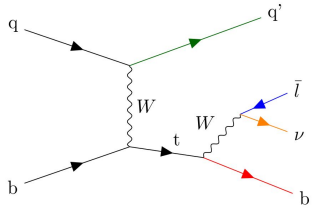


We compare reweighted distributions to dedicated distributions to ensure that they are able to be consistently reproduce as much of the relevant phase space as possible.

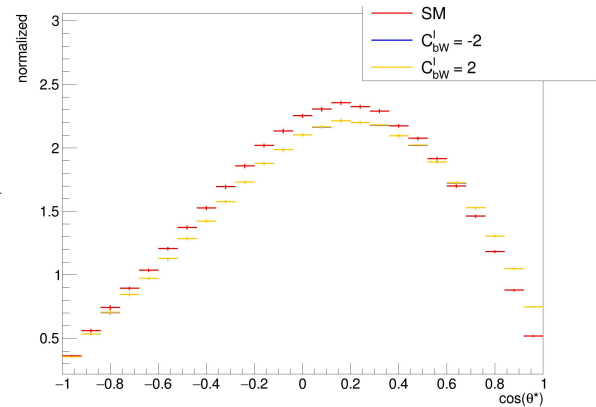
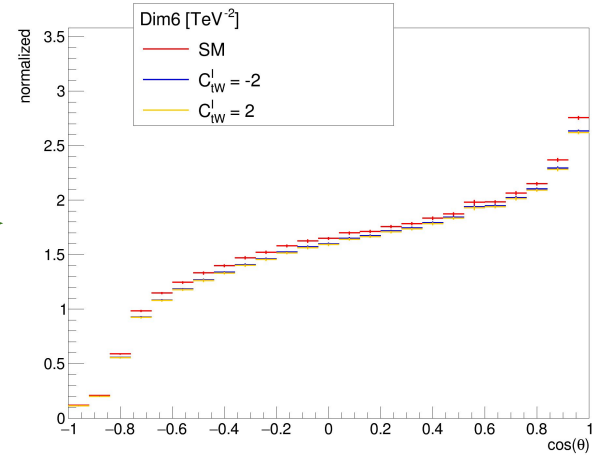
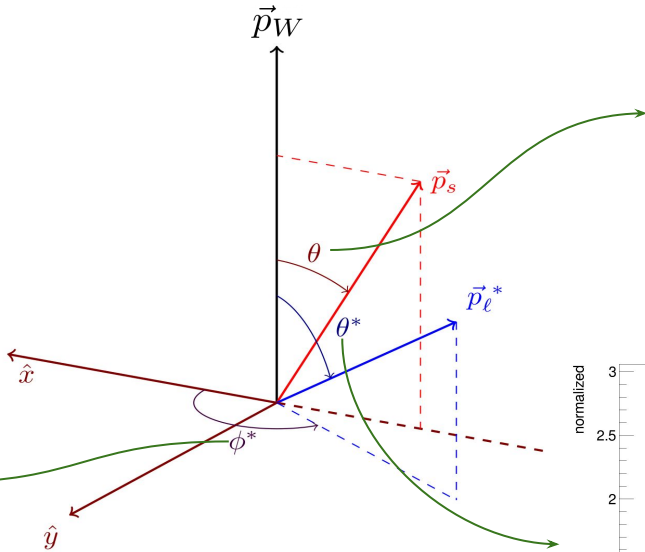
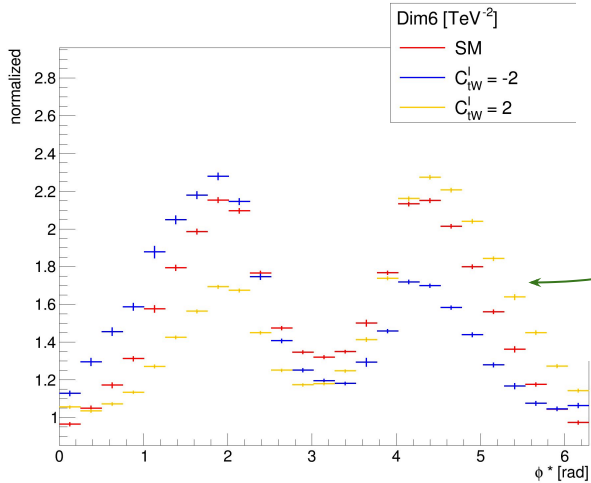
Reweighting validated for this phase space



EFT effects on kinematic variables at parton level

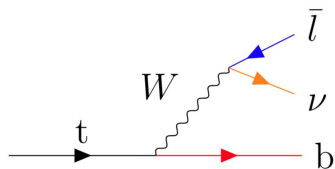


Precision: **LO**



Top reconstruction at generator level

Goal: Reconstruct angular distributions as if we were at detector level → we need to infer the p_z of the neutrino



Energy conservation:

$$t^\mu = b^\mu + W^\mu = \underbrace{b^\mu + l^\mu}_{\text{We have all these elements}} + \underbrace{\nu^\mu}_{\text{Lack } p_z \text{ component at detector level}}$$

We have all these elements

2 sets of solutions

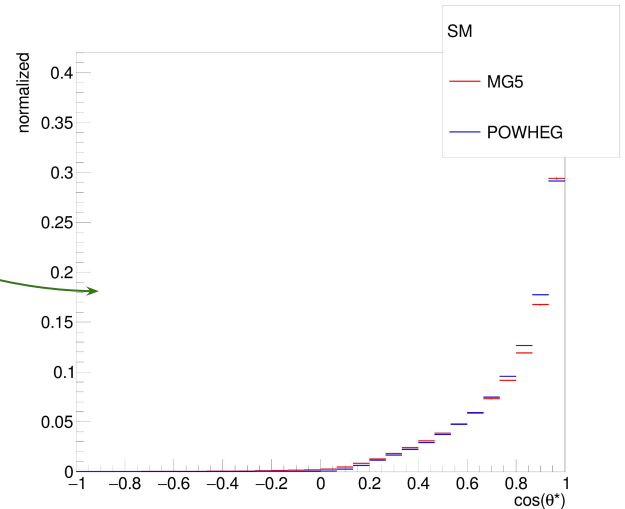
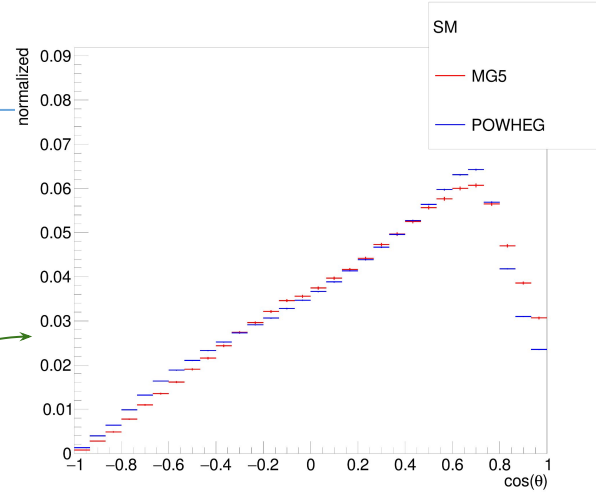
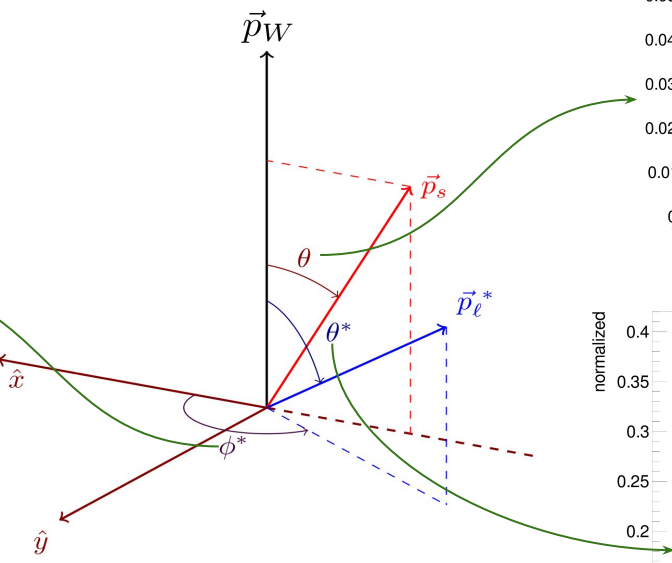
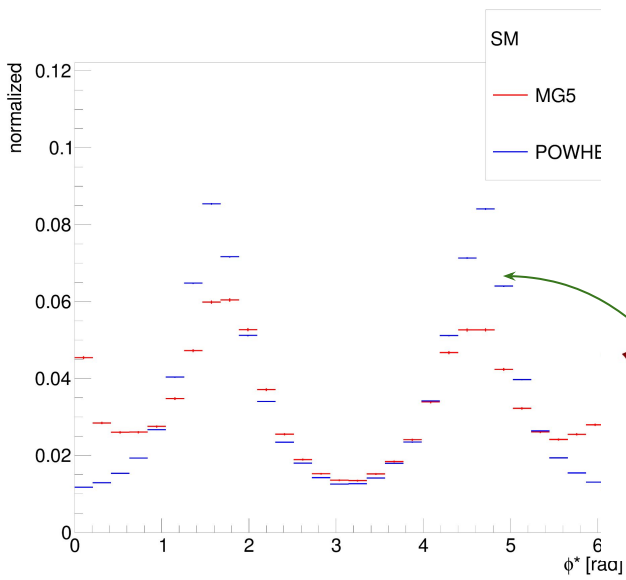
$$\begin{cases} \vec{p}_{T,\nu} = \begin{pmatrix} p_{x,\nu} \\ p_{y,\nu} \end{pmatrix} = \begin{pmatrix} E_{T,miss} \cdot \cos(\phi_{miss}) \\ E_{T,miss} \cdot \sin(\phi_{miss}) \end{pmatrix} \\ p_{z,\nu}^\pm = \frac{\Lambda p_{z,l}}{p_{T,l}^2} \pm \sqrt{\frac{p_{z,l}^2 \Lambda^2}{p_{T,l}^4} - \frac{1}{p_{T,l}^2} (E_l^2 p_{T,\nu}^2 - \Lambda^2)} \end{cases}$$

$$\begin{cases} \vec{p}_{T,\nu} = \begin{pmatrix} p_{x,\nu} \\ p_{y,\nu} \end{pmatrix} = \begin{pmatrix} p_{T,\nu} \cdot \cos(\phi_\nu) \\ p_{T,\nu} \cdot \sin(\phi_\nu) \end{pmatrix} \\ p_{z,\nu} = \frac{\Lambda p_{z,l}}{p_{T,l}^2} \end{cases}$$

Comparing to CMS sample at the SM



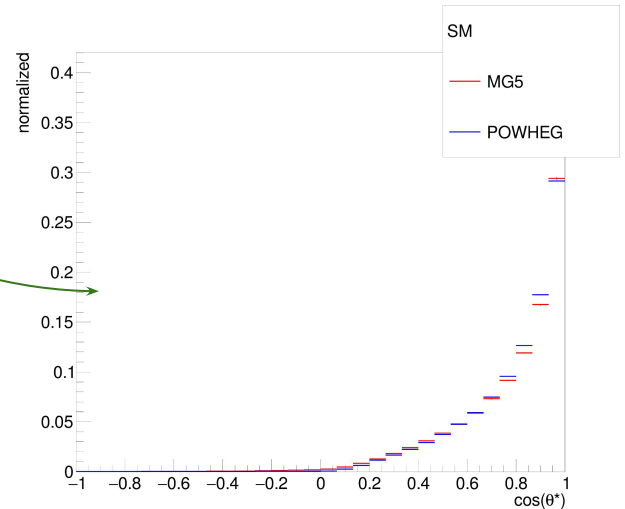
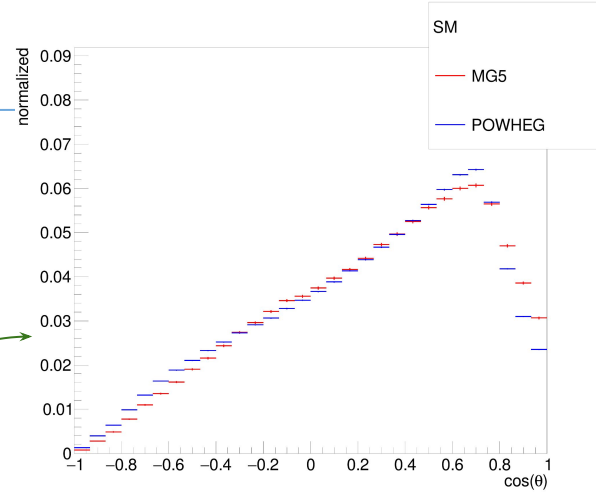
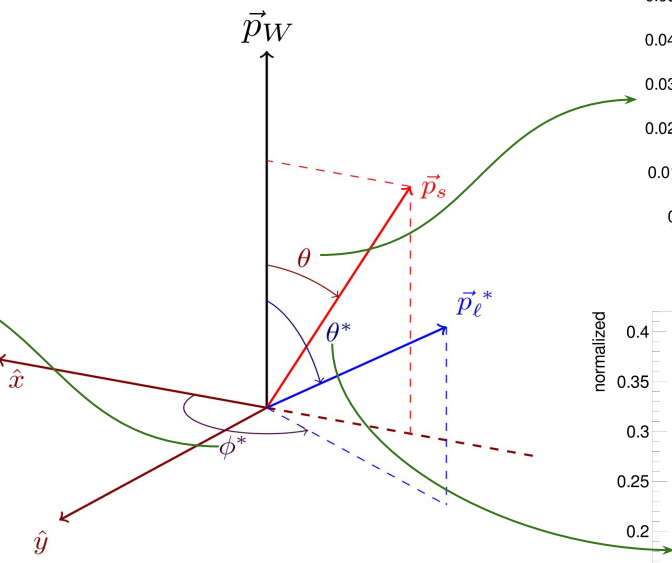
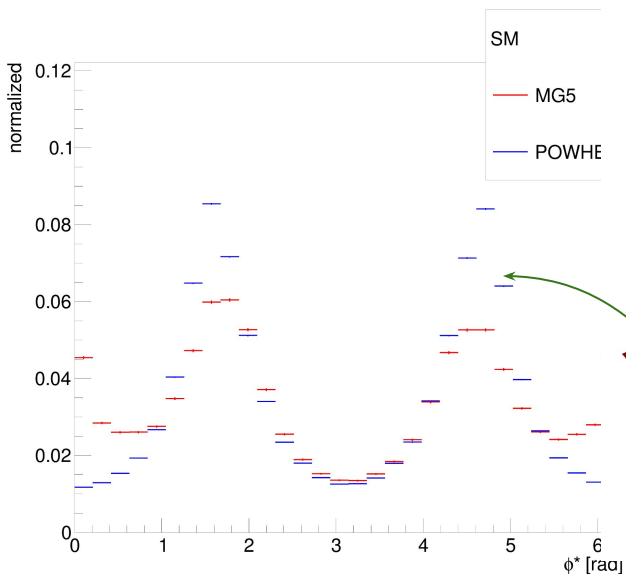
— **LO** (Leading Order)
— **NLO** (Next to Leading Order)



Comparing to CMS sample at the SM



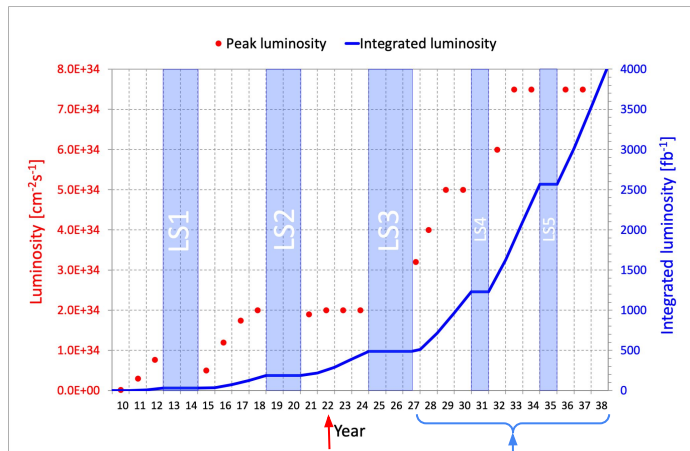
— **LO** (Leading Order)
— **NLO** (Next to Leading Order)



Investigating discrepancy. Probably need additional jets at ME level to reproduce the NLO

Part 2: CMS tracker upgrade

Why the CMS tracker needs an upgrade?

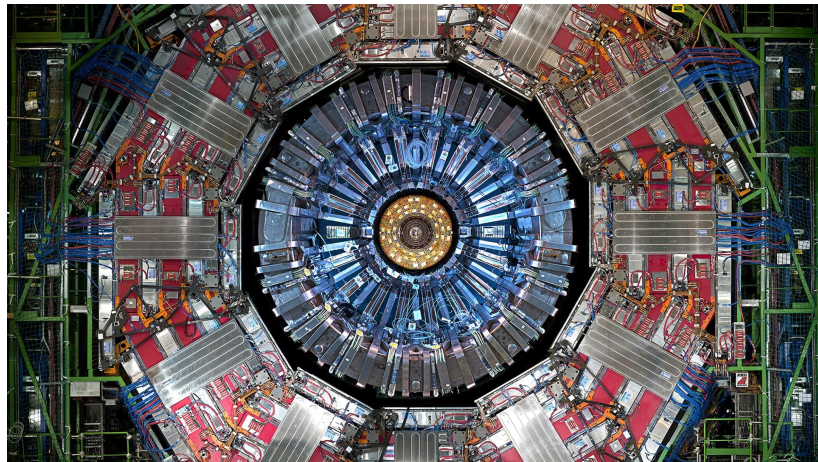


Today: Run3



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)

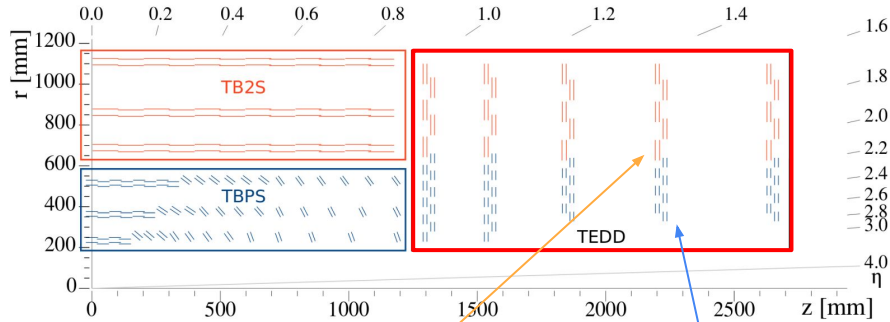


Why upgrade the CMS tracker?

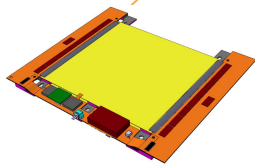
- The tracker needs an upgrade to sustain the high level of radiation
- Ability to trigger data acquisition on events with high momentum tracks

New CMS Tracker for HL-LHC

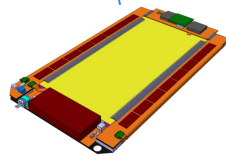
TEDD = Tracker Endcap Double-Discs



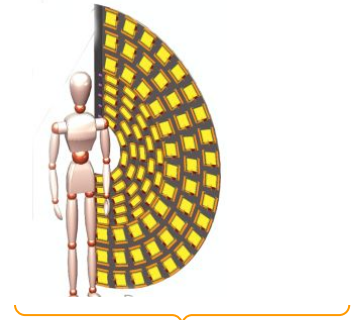
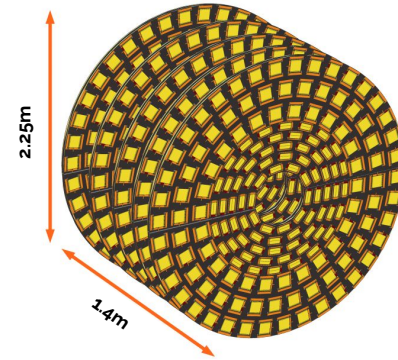
Detection Modules:



2S = strip - strip



PS = pixel - strip



Dee: Main structure of the TEDD

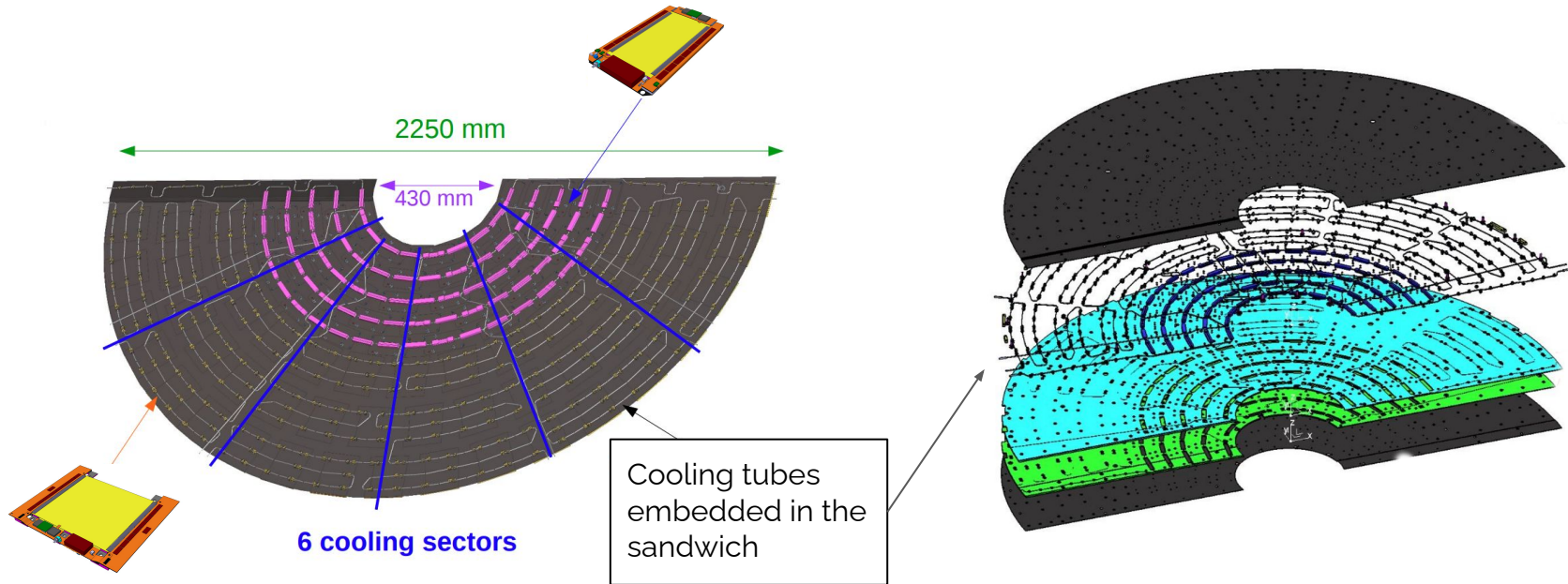
TEDD concept:

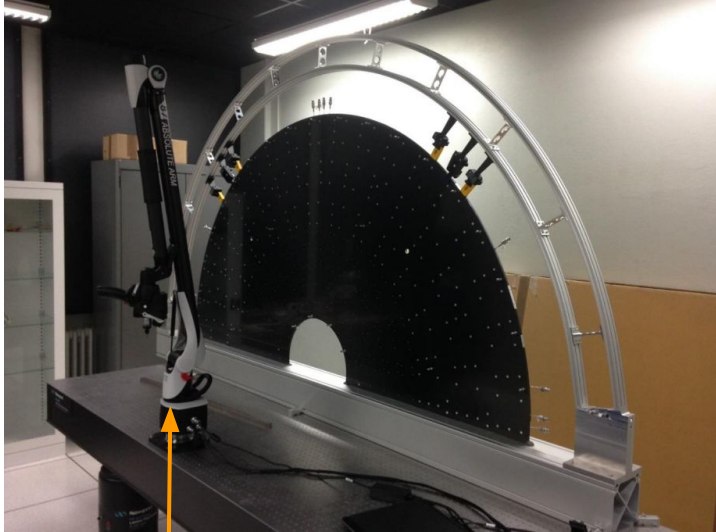
- Cooling at -35°C using CO_2 at phase transition.
 - Cooling pipes integrated as part of the Dee structure to minimize the weight of the structure.
- ↳ **Optimal cooling of the detection modules**

Anatomy of a Dee

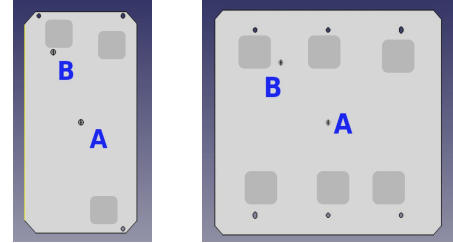
The Dee is the main element of the TEDD design:

- Composite structure with carbon fiber skins and inserts on both surfaces to mount the 2S and PS modules.





Metrology measurements of Dee's inserts taken with the mechanical arm



Dummy high precision fake 2S and PS modules

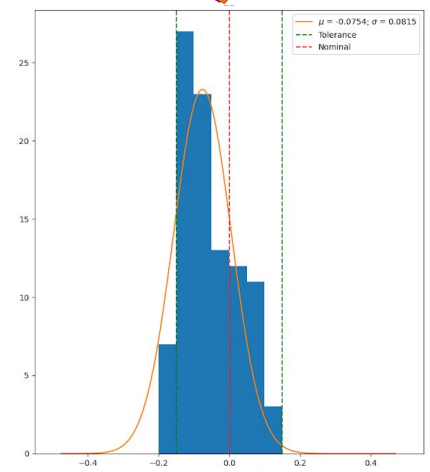
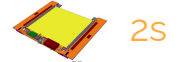
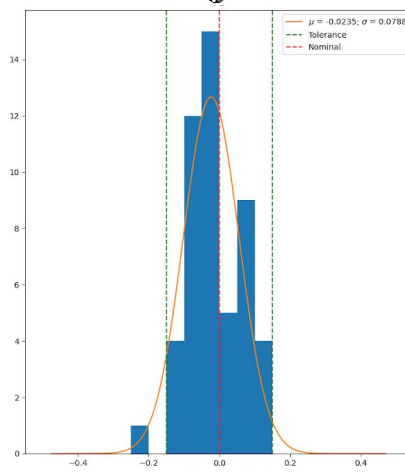
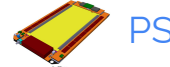
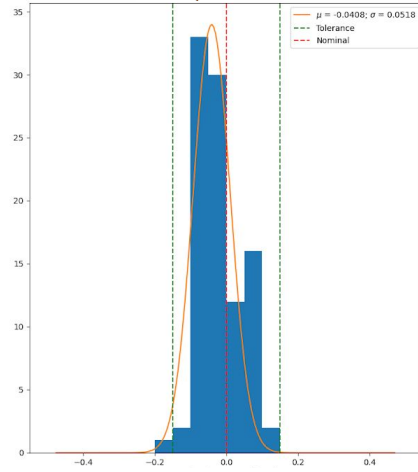
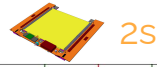
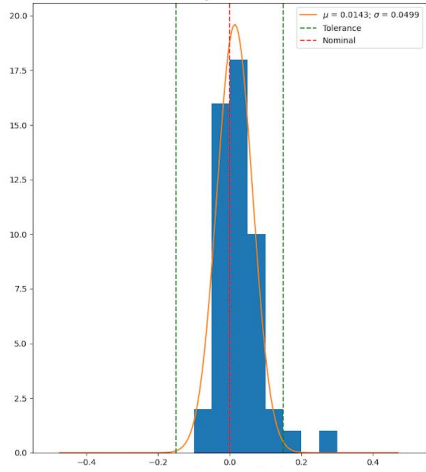
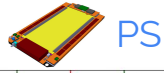
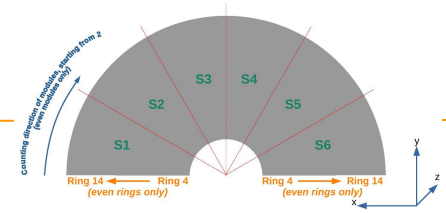
A and B are reference points for measurement

A: Center

B: Upper left corner

Reference points precision on XY plane

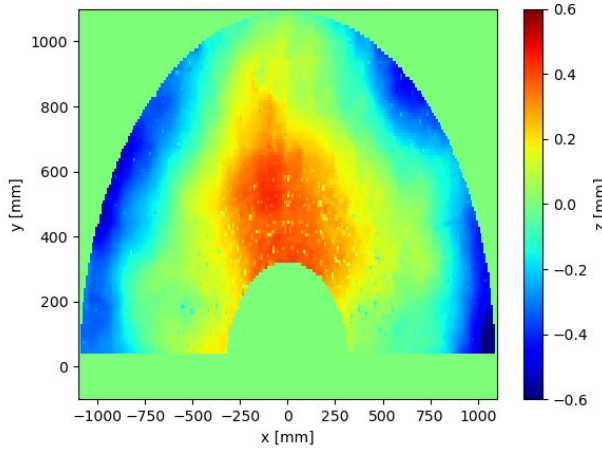
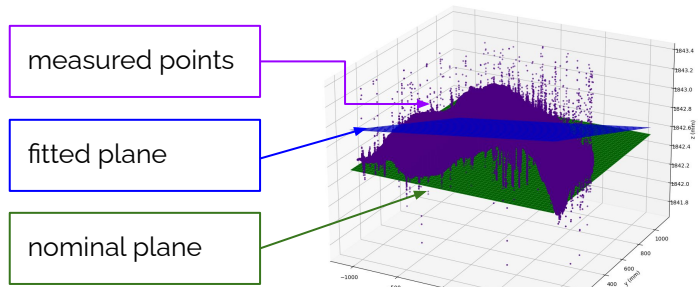
→ Test on the ability to mount the high precision dummy modules onto the Dee



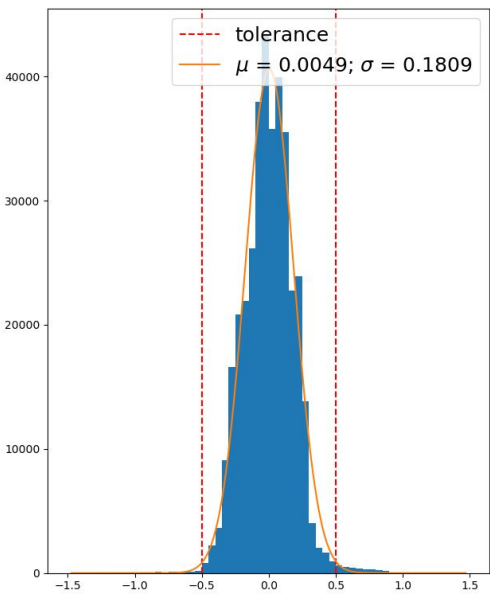
$\Delta X = \text{nominal}(x) - \text{measured}(x)$ [mm]
Tolerance = ± 0.15 mm

$\Delta Y = \text{nominal}(y) - \text{measured}(y)$ [mm]
Tolerance = ± 0.15 mm

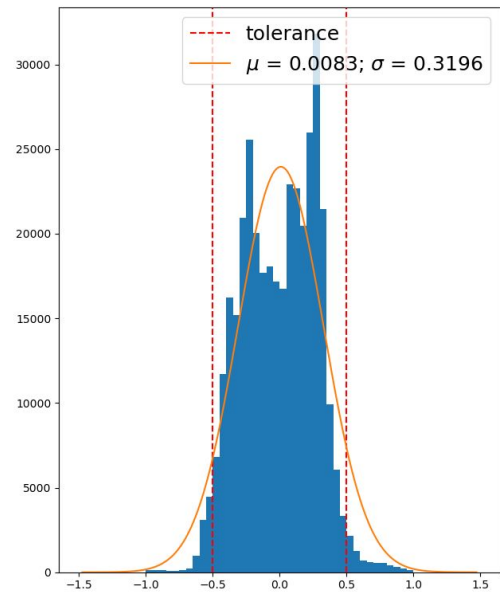
Testing Dee's flatness



Distance between measured points and **fitted** plane



Distance between measured points and **nominal** plane



- **Single top t-channel, a process to measure CP violation with Effective Field Theory**
- **Possibility to measure EFTs with LHC data**
- **Reweighting method validated**
- **Need to improve precision at generator level (LO- \rightarrow NLO)**

- **The CMS tracker will be upgraded for the HL-LHC**
- **Production of 24 Dees will start by the end of 2023**
 - **Metrology analysis prepared**

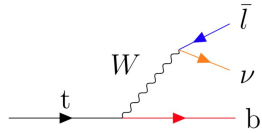
Thank you for your attention

Backups

Energy conservation:

$$t^\mu = b^\mu + W^\mu$$

$$= b^\mu + l^\mu + \nu^\mu$$



$$\left. \begin{aligned} b^\mu &= (E_b, \vec{p}_b) \\ l^\mu &= (E_l, \vec{p}_l) \\ \nu^\mu &= (E_\nu, \vec{p}_\nu) \end{aligned} \right\} \begin{array}{l} \text{We have this info} \\ \\ \text{We lack the } p_z \\ \text{component at} \\ \text{detector level} \end{array}$$

$$(W^\mu)^2 = m_W^2$$

$$= 2(E_l E_\nu - \vec{p}_{T,l} \cdot \vec{p}_{T,\nu} - p_{z,l} p_{z,\nu}) \quad \left. \vphantom{(W^\mu)^2} \right\} \begin{array}{l} \text{UR limit} \\ \text{(LHC)} \end{array}$$

↓ Squaring this equation yields:

$$p_{z,\nu}^2 p_{T,l}^2 - 2\Lambda p_{z,l} p_{z,\nu} - \Lambda^2 + E_l^2 p_{T,\nu}^2 = 0$$

Real solutions: Assuming all the MET is from the neutrino

$$\vec{p}_{T,\nu} = \begin{pmatrix} p_{x,\nu} \\ p_{y,\nu} \end{pmatrix} = \begin{pmatrix} E_{T,miss} \cdot \cos(\phi_{miss}) \\ E_{T,miss} \cdot \sin(\phi_{miss}) \end{pmatrix}$$

$$p_{z,\nu}^\pm = \frac{\Lambda p_{z,l}}{p_{T,l}^2} \pm \sqrt{\frac{p_{z,l}^2 \Lambda^2}{p_{T,l}^4} - \frac{1}{p_{T,l}^2} (E_l^2 p_{T,\nu}^2 - \Lambda^2)}$$

Complex solutions: The discriminant is set to zero and we constraint the mass of the W boson to its transverse value

$$p_{T,\nu}^\pm = \sqrt{2} |m_{T,W} \pm \frac{\vec{p}_{T,l}}{\sqrt{2}}|$$

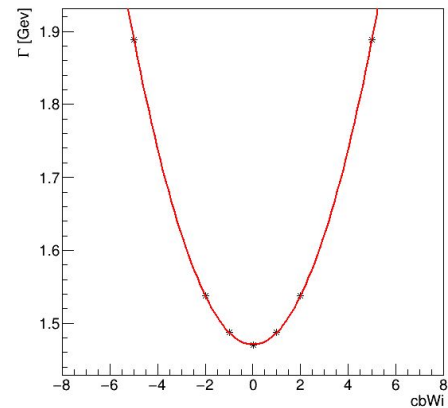
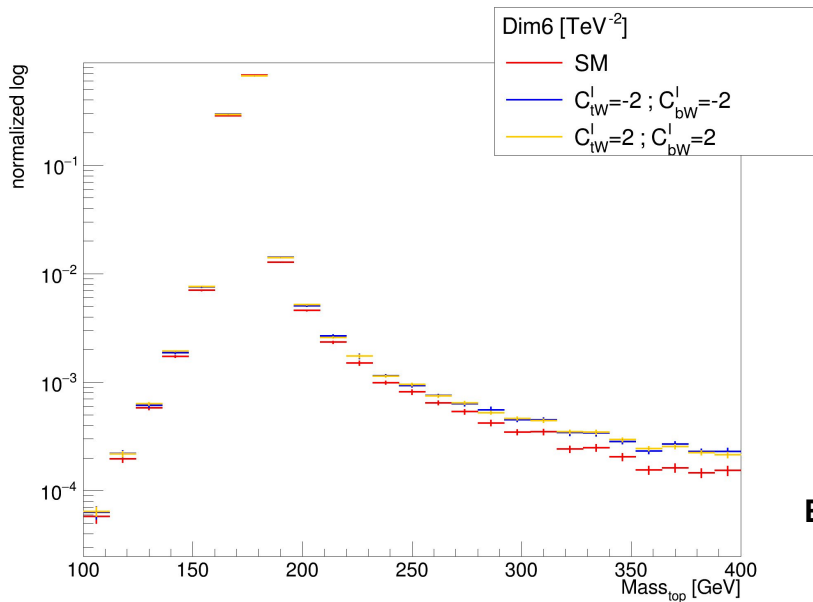
$$\vec{p}_{T,\nu} = \begin{pmatrix} p_{x,\nu} \\ p_{y,\nu} \end{pmatrix} = \begin{pmatrix} p_{T,\nu} \cdot \cos(\phi_\nu) \\ p_{T,\nu} \cdot \sin(\phi_\nu) \end{pmatrix}$$

$$p_{z,\nu} = \frac{\Lambda p_{z,l}}{p_{T,l}^2}$$

Syntax for single top t-channel process

- **5 flavour-scheme usage** (as recommended by: [arXiv:1802.07237](https://arxiv.org/abs/1802.07237))
 - define $p = p b b^{\sim}$
 - set b-mass to 0 in the *param_card.dat*: `5 0.000000e+00 #mb`
- **Full-chain process generation:**
 - EFT effects at production and at decay at LO
 - generate $p p > w^+ b j \ \$\$ w^+ w^- z a \text{ DIM6=2 FCNC=0 QED=3 QCD=0, } w^+ \rightarrow l^+ \nu_l$ (single top)
 - add process $p p > w^- b^{\sim} j \ \$\$ w^+ w^- z a \text{ DIM6=2 FCNC=0 QED=3 QCD=0, } w^- \rightarrow l^- \nu_l^{\sim}$ (single antitop)
- **Top width impact:**
 - Automatic recomputation of top width in *param_card.dat*: `DECAY 6 Auto`
- **EFT points:**
 - Modify each Wilson coefficient operator in *param_card.dat*

Effects on top width



EFT effects are sizeable

Dim6 = 1 vs Dim6 = 2

