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

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Société Française de Physique

Part 1: Phenomenology and CP violation

Matter and Antimatter asymmetry

The universe is baryon-asymmetric:

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

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Discrepancy between theory and observation

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Sakharov conditions for baryogenesis [1]:

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

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Sakharov conditions for baryogenesis [1]:

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

→ 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.

[1] arXiv:1204.4186v2

Signal topology - Single top quark t-channel

Single top-quark is very sensitive to CP violation

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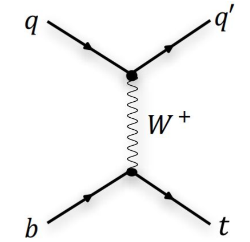

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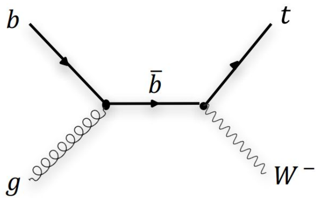

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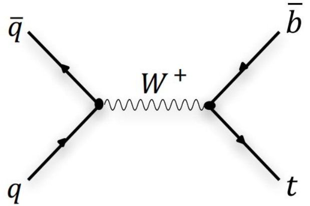

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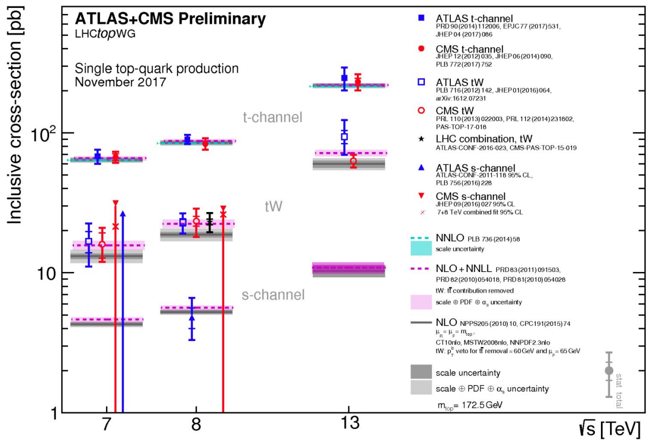

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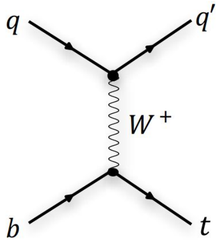

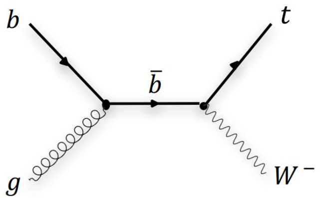

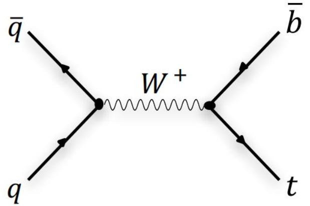

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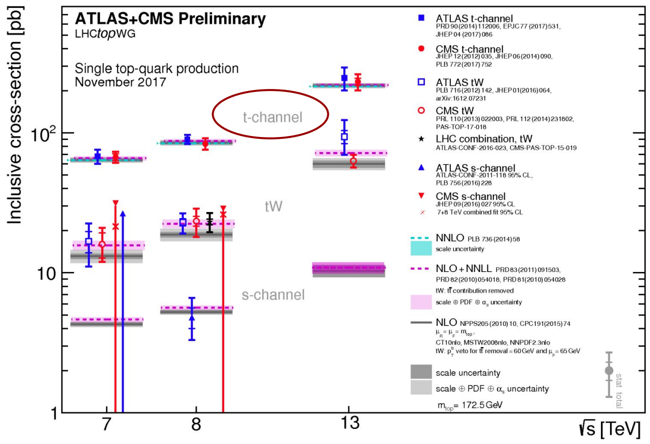

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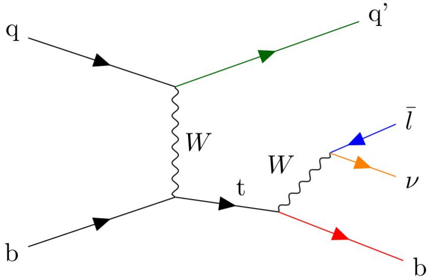

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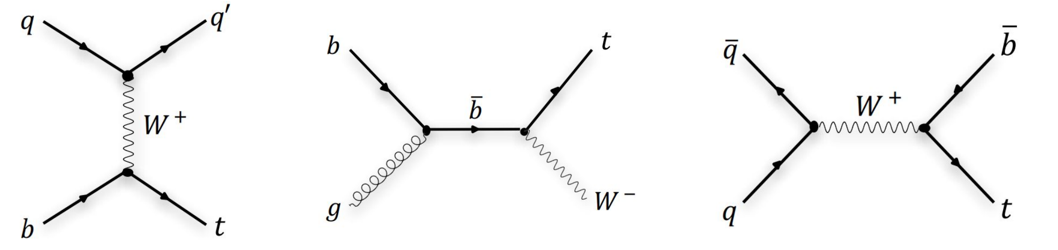

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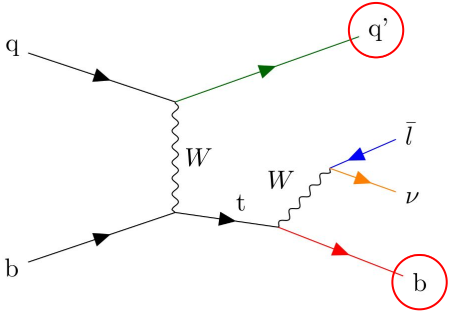

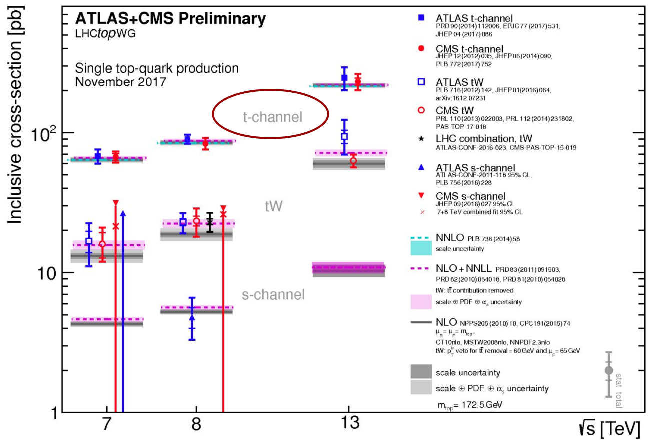

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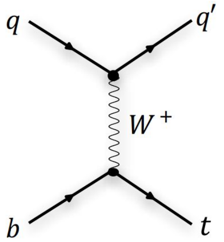

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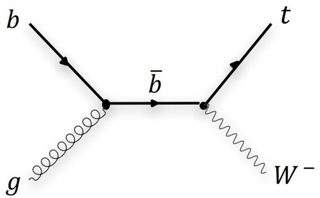

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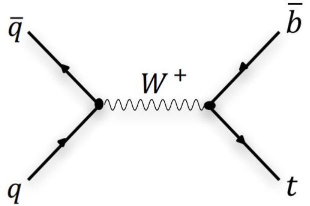

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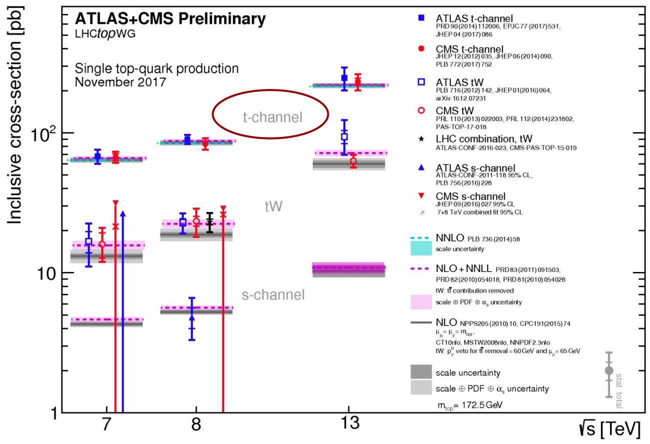

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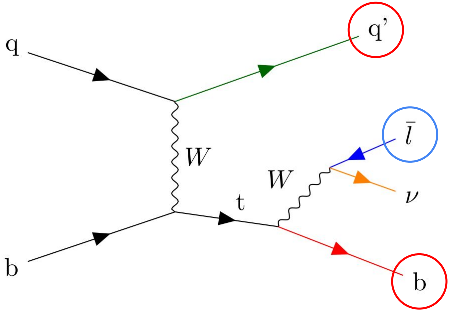

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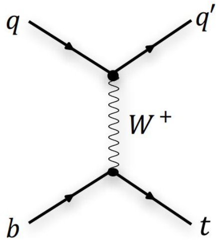

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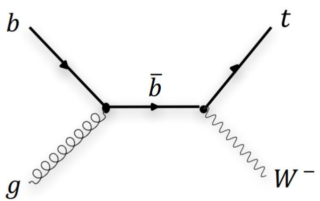

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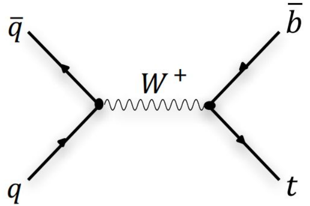

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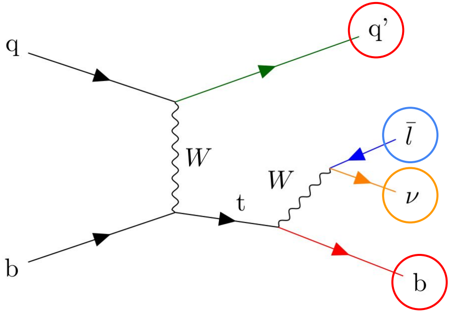

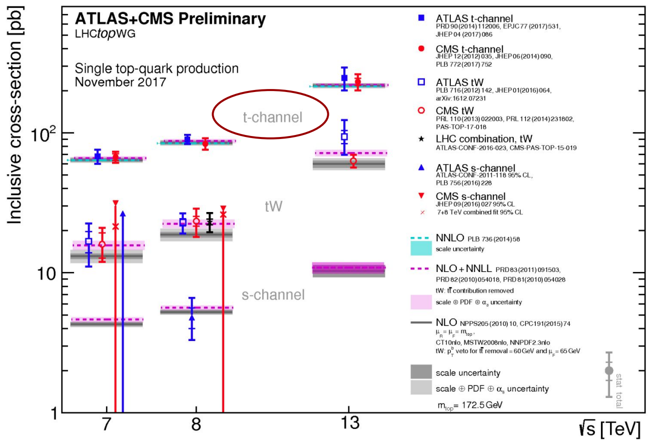

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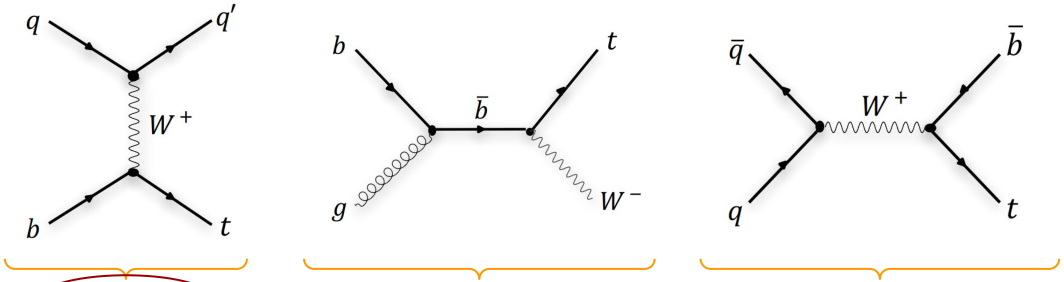

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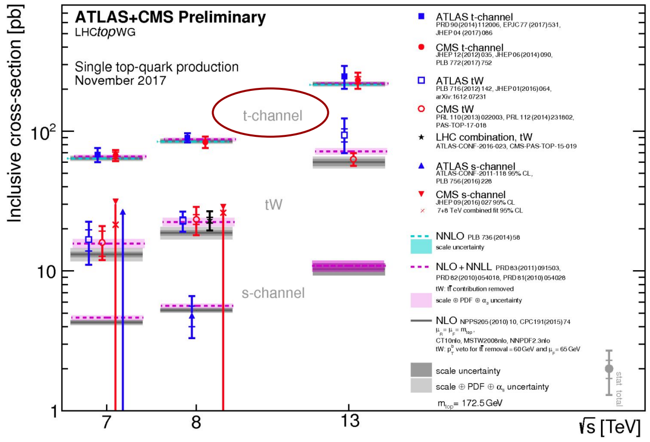

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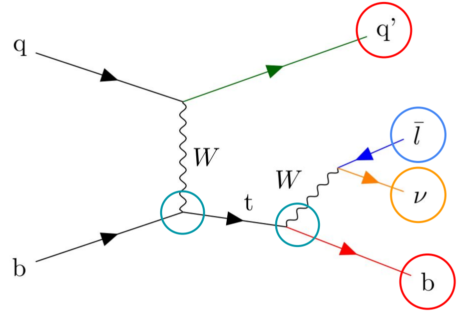

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W_{tb} vertex at top production and decay

Vertex can be modified by CP violation

Effective Field Theory (EFT)

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

SMEFT Lagrangian elements:

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

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- EFT Coefficients
- New physics energy scale
- EFT operators Energy dimension = 6

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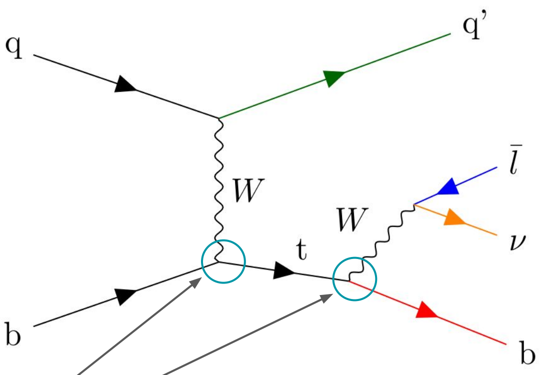

EFT operators will have an impact on the W_{tb} vertex at top production and decay

Modeling CP violation with EFT

CP symmetry violation with EFT:

$$\mathscr{L}_{eff}^{(6)} \xrightarrow{\text{CP}} \mathscr{L}_{eff}^{(6)\prime} \neq \mathscr{L}_{eff}^{(6)}$$

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EFT coefficients

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

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

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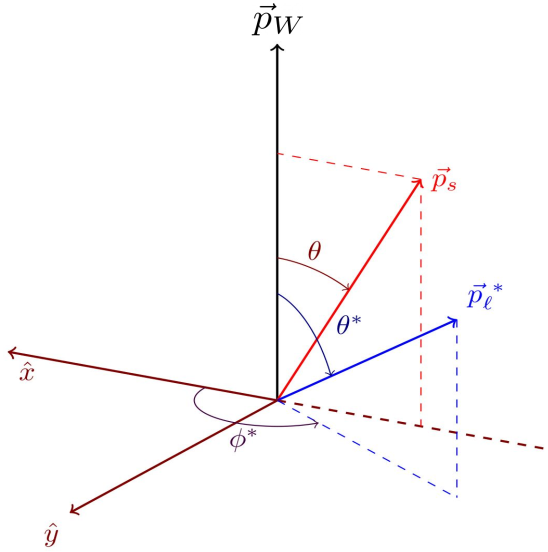
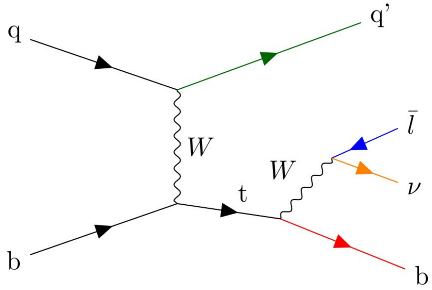
Goal of this thesis:
Measure the value of these 6 EFTs coefficients

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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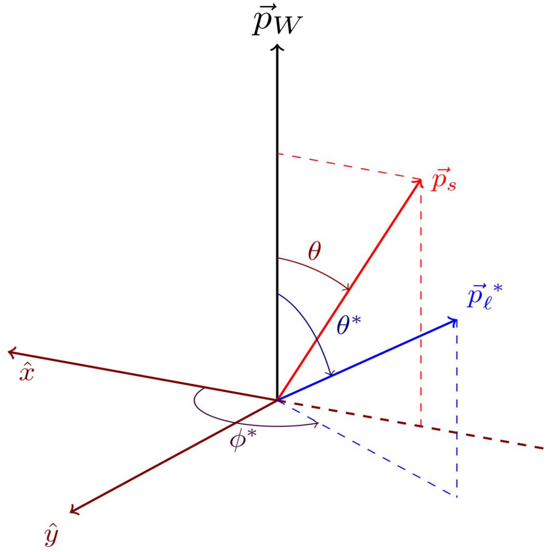

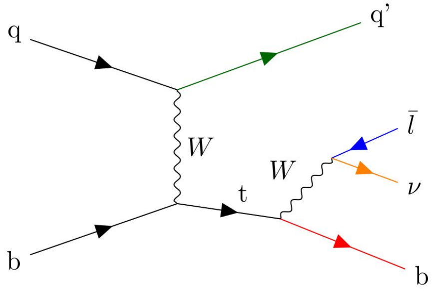

methodology

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

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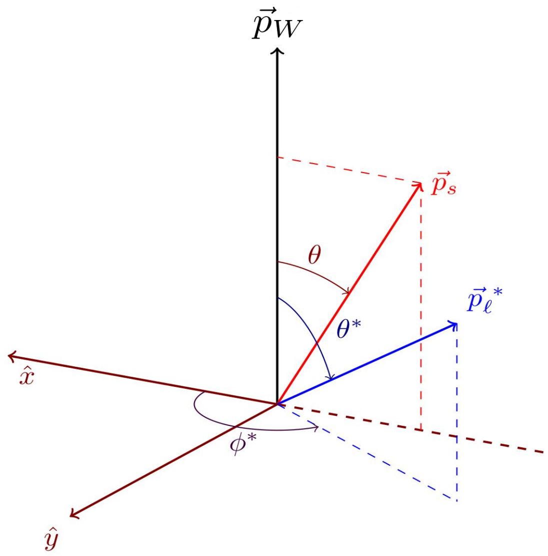

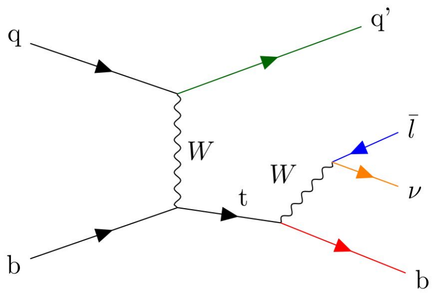

methodology:

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

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<u>Interpretation</u>: Measurement of EFT coefficients

Christopher Greenberg c.greenberg@ip2i.in2p3.fr

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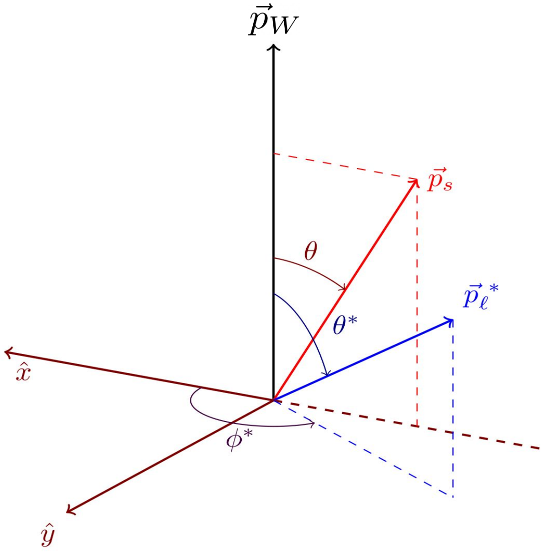

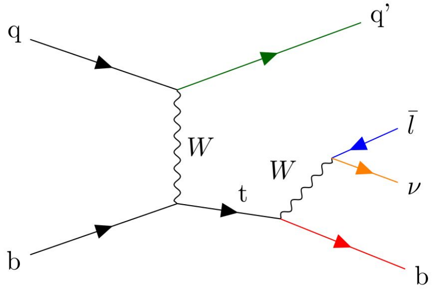

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<u>Interpretation</u>: Measurement of EFT coefficients

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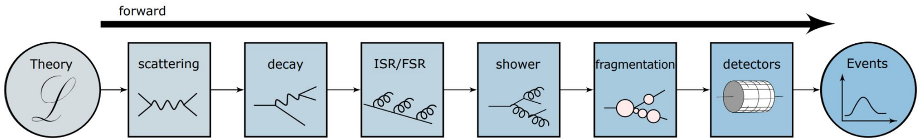
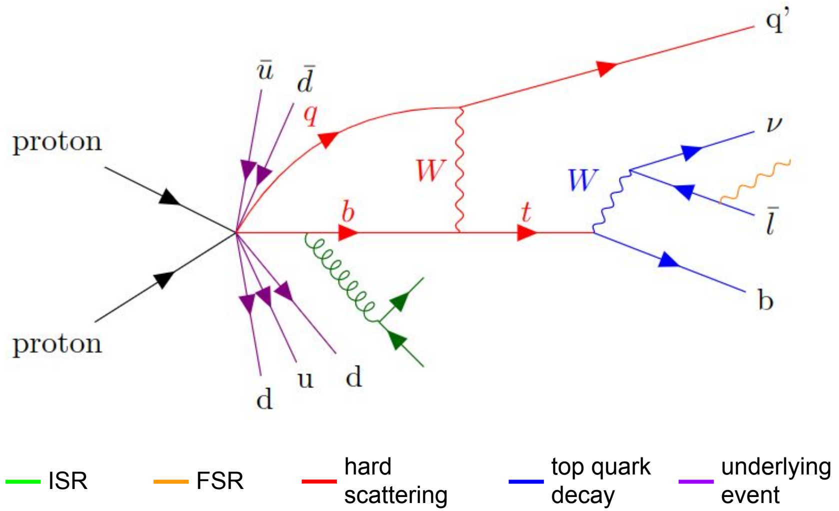
Measurement of CP violation

Levels of information in proton-proton collisions



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



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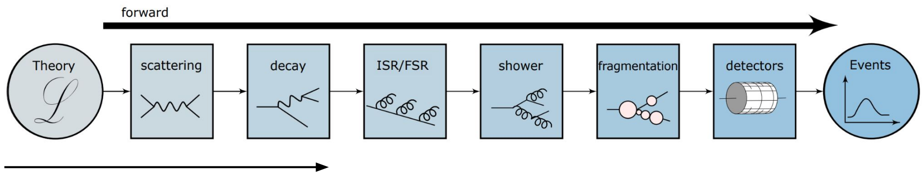

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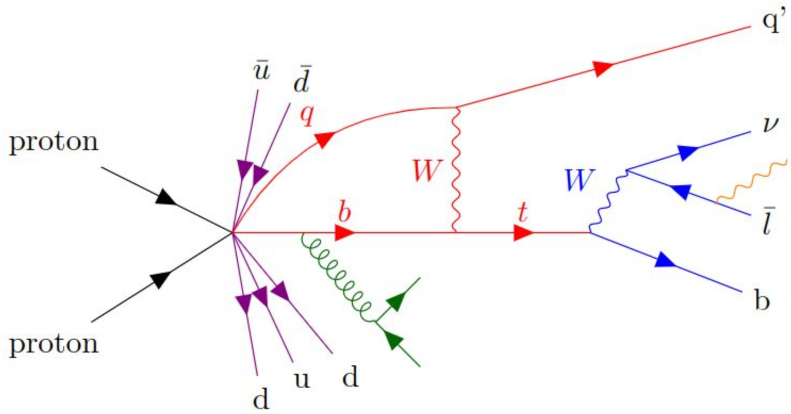

ISR — FSR — hard scattering — top quark decay — underlying event

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

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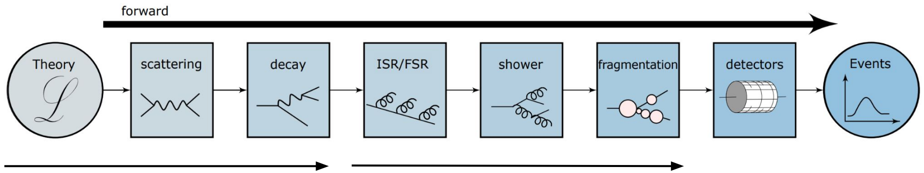

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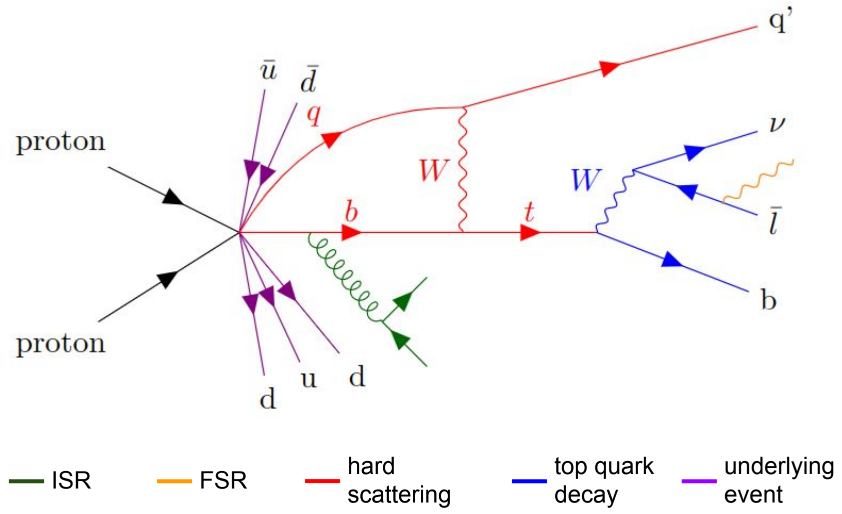

Parton level (= theory): Computation of **| *M* |²** using Feynman rules for the SMEFT model.

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

Simulating EFT with Reweighting

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

Simulating EFT with Reweighting

BSM Matrix Element

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

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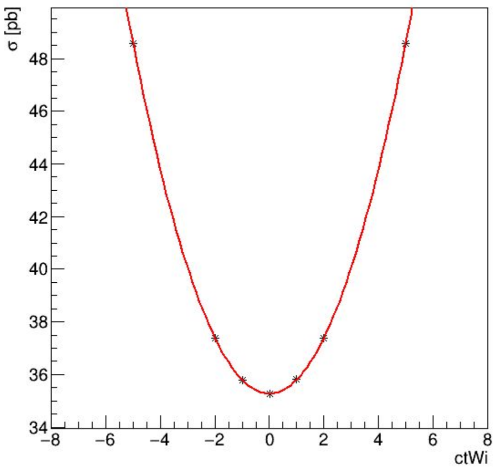

Quadratic behavior on the cross section as expected [2]

[2] arXiv:1807.03576

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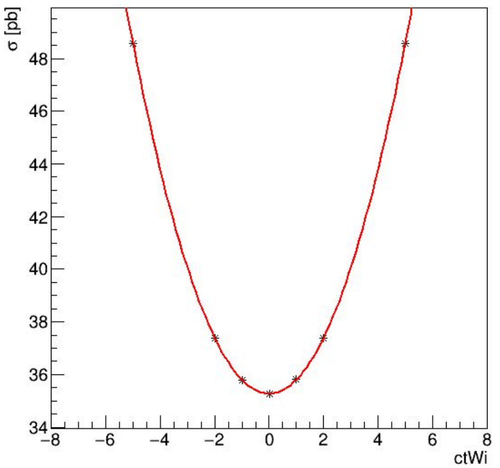

Quadratic behavior on the cross section as expected [2]

How many WCs points to generate?

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

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

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

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

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BSM Matrix Element

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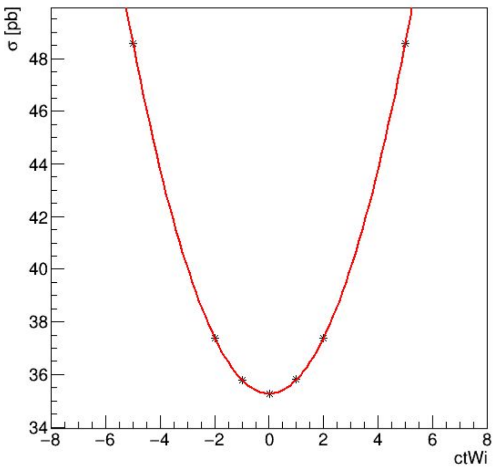


Quadratic behavior on the cross section as expected [2]

How many WCs points to generate?

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

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

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

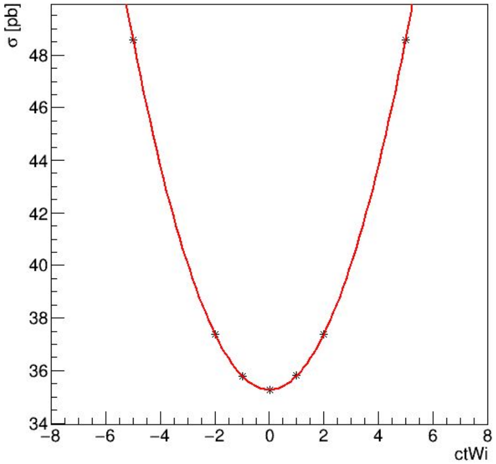
Sample space with **729 WC** points (includes the SM)

[2] arXiv:1807.03576

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?

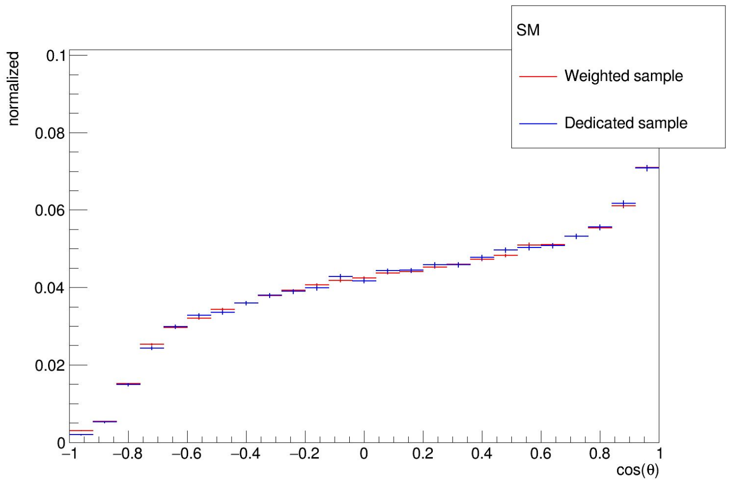
$\{C_{tW}, C^I_{tW}\} = \{-2,0,2\}$
$\{C_{bW}, C^I_{bW}\} = \{-2,0,2\}$
$\{C_{\varphi tb}, C^I_{\varphi tb}\} = \{-5,0,5\}$

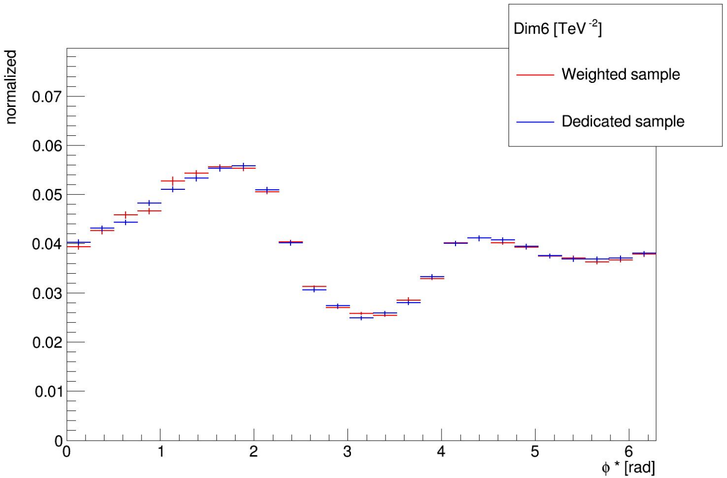
Sample space with **729 WC** points (includes the SM)

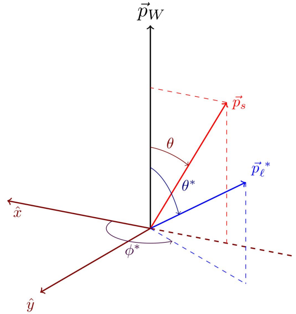
Reweighting method: Assign event weight corresponding to the WC values. We have only one sample with all combinations of WCs

[2] arXiv:1807.03576

Validating Reweighting method



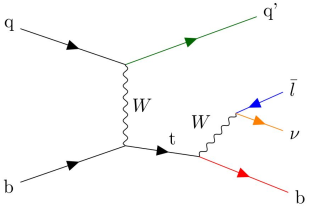




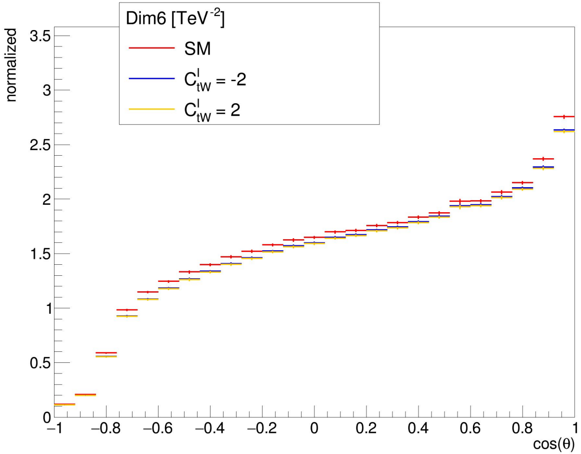
We compare reweighted distributions to dedicated distributions to ensure that they are able to be consistently reproduce as much of the relevant phase space as possible.

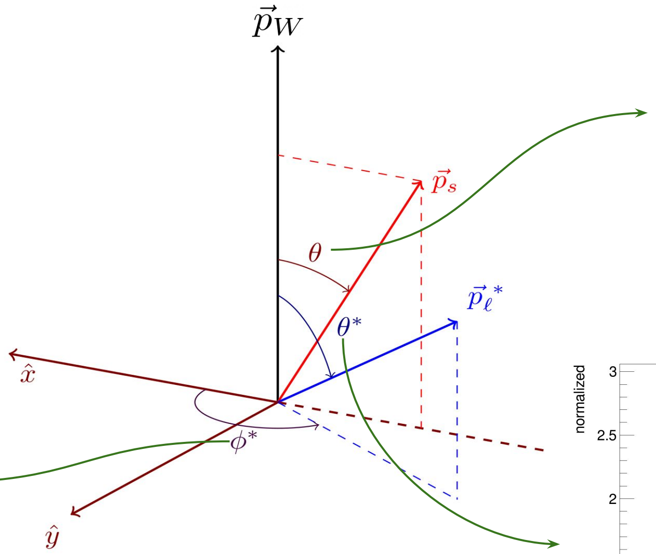
Reweighting validated for this phase space

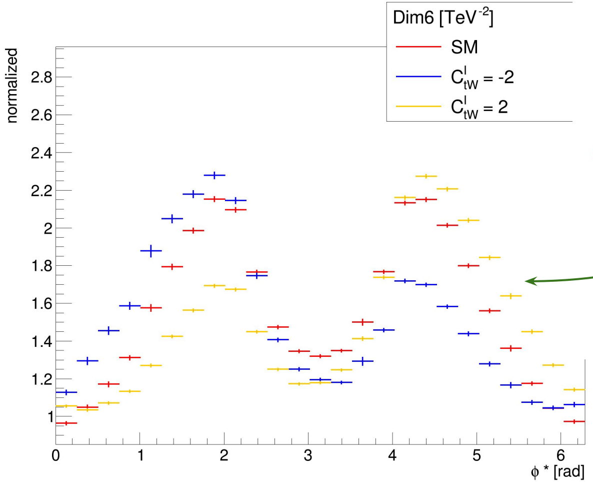
EFT effects on kinematic variables at parton level

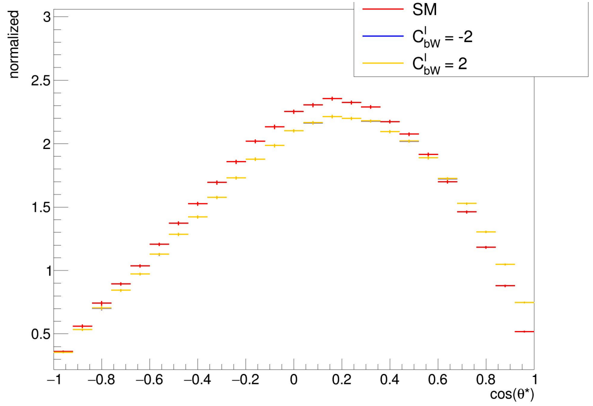


Precision: **LO**



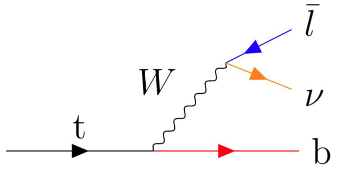






Top reconstruction at generator level

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



Energy conservation:

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

Lack pz component at detector level (ν^μ)

We have all these elements ($b^\mu + l^\mu$)

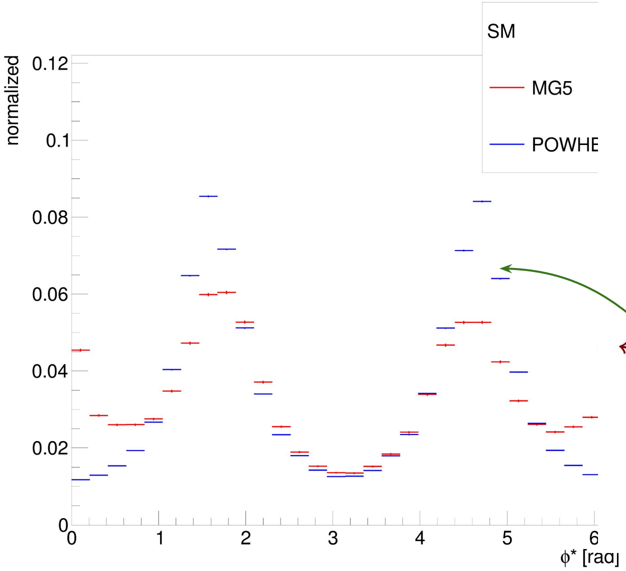
2 sets of solutions

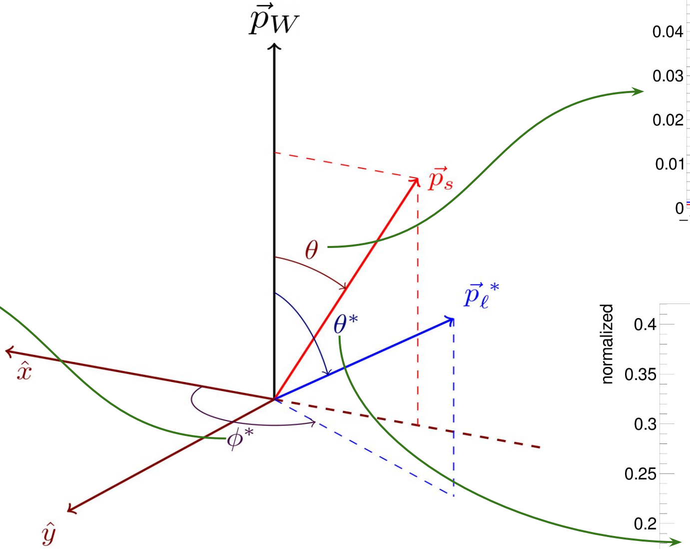
$$\begin{cases} \vec{p}_{T,\nu} = \begin{pmatrix} p_{x,\nu} \\ p_{y,\nu} \end{pmatrix} = \begin{pmatrix} E_{T,miss} \cdot cos(\phi_{miss}) \\ E_{T,miss} \cdot sin(\phi_{miss}) \end{pmatrix} \\ p^{\pm}_{z,\nu} = \frac{\Lambda p_{z,l}}{p^2_{T,l}} \pm \sqrt{\frac{p^2_{z,l}\Lambda^2}{p^4_{T,l}} - \frac{1}{p^2_{T,l}}(E_l^2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

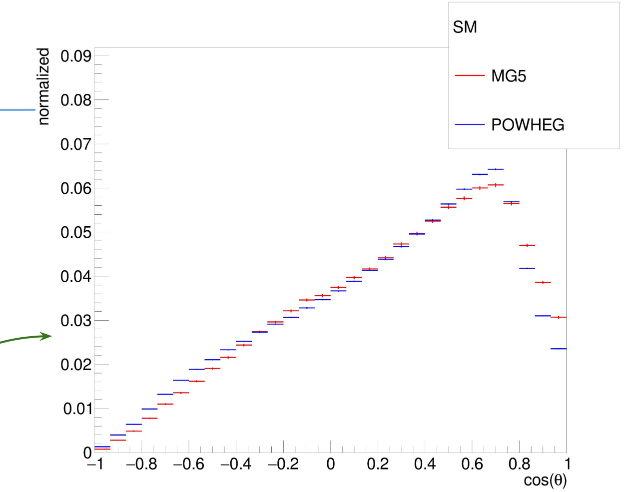
$$\begin{cases} \vec{p}_{T,\nu} = \begin{pmatrix} p_{x,\nu} \\ p_{y,\nu} \end{pmatrix} = \begin{pmatrix} p_{T,\nu} \cdot cos(\phi_{\nu}) \\ p_{T,\nu} \cdot sin(\phi_{\nu}) \end{pmatrix} \\ p_{z,\nu} = \frac{\Lambda p_{z,l}}{p^2_{T,l}} \end{cases}$$

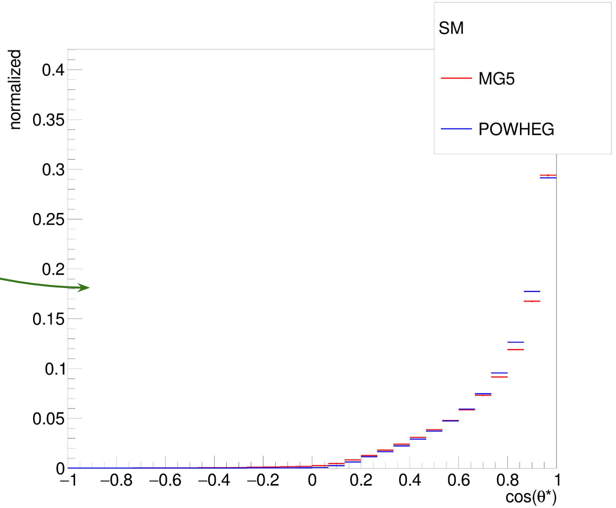
Comparing to CMS sample at the SM

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





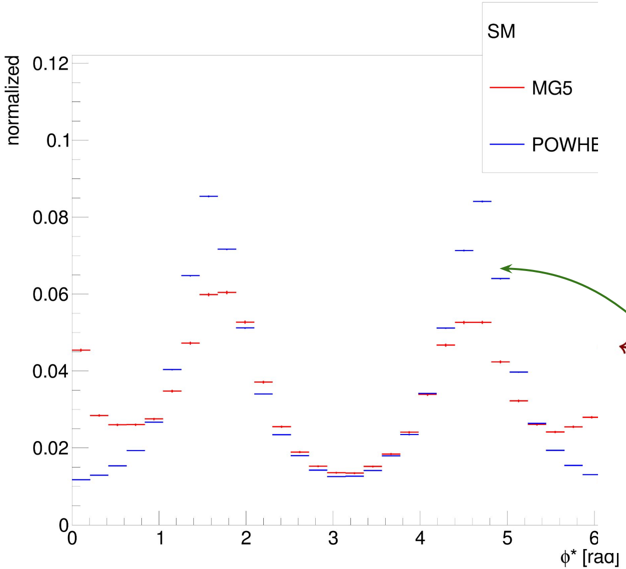


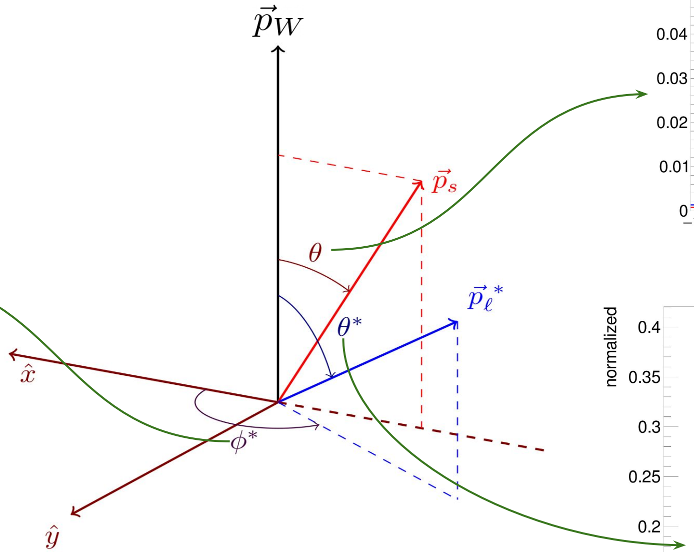


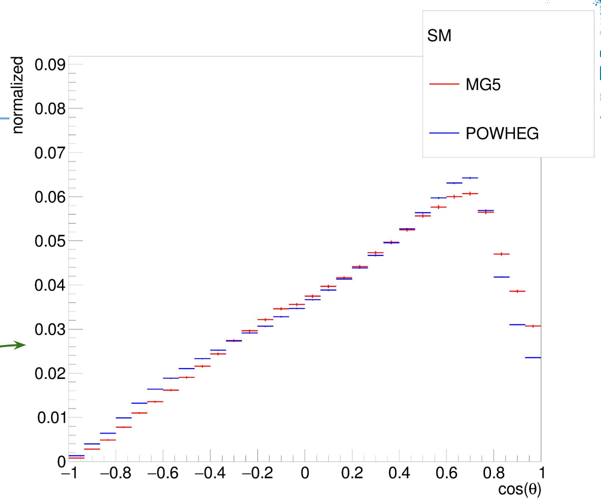
Comparing to CMS sample at the SM

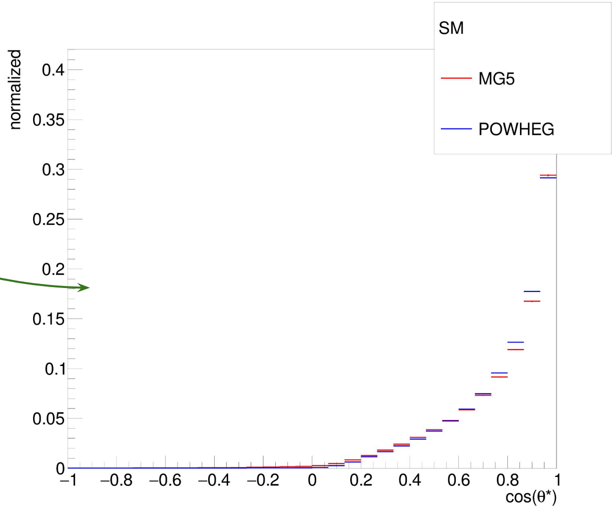
LO (Leading Order)

NLO (Next to Leading Order)





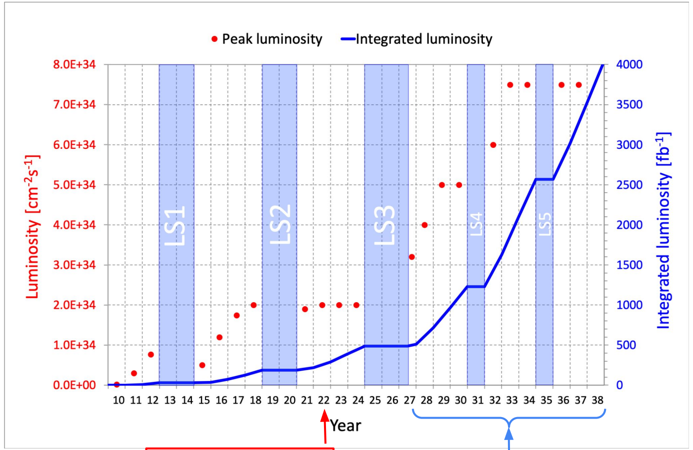




Investigating discrepancy. Probably need additional jets at ME level to reproduce the NLO

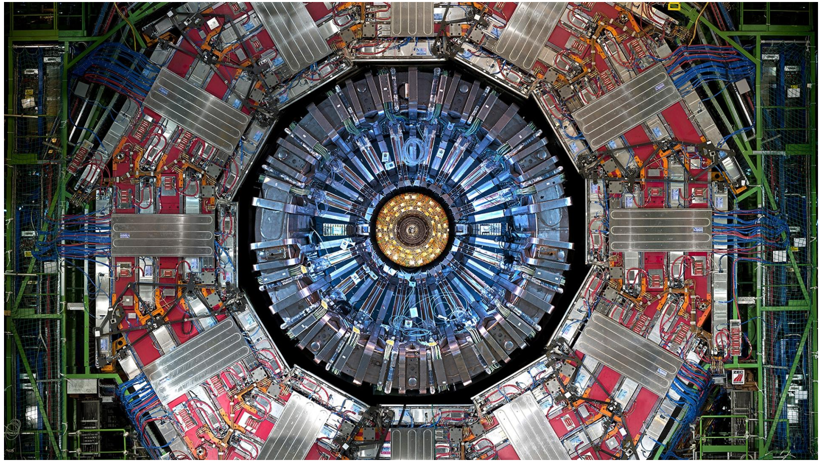
Part 2: CMS tracker upgrade

Why the CMS tracker needs an upgrade?



Today: Run3

HL-LHC PROJECT



HL-LHC features:

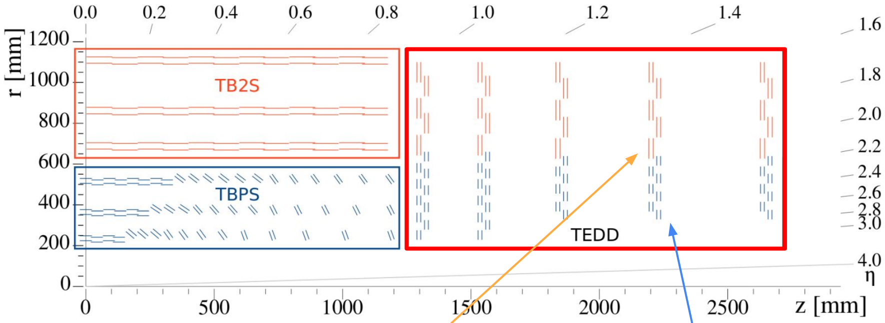
- Higher integrated luminosity (up to 4000fb^{-1})
- Higher instant luminosity peak (~x7.5 higher)
- More collisions per beam crossing. Up to between 140-200. (~38 at the end of Run2)

Why upgrade the CMS tracker?

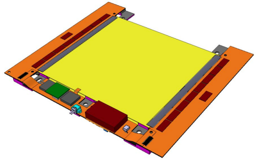
- The tracker needs an upgrade to sustain the high level of radiation
- Ability to trigger data acquisition on events with high momentum tracks

New CMS Tracker for HL-LHC

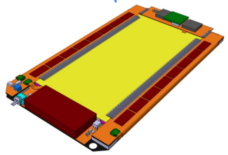
TEDD = Tracker Endcap Double-Discs



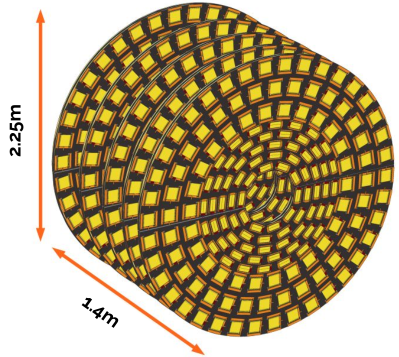
Detection Modules:

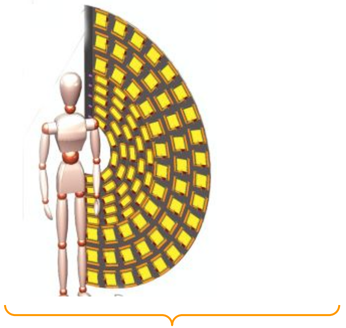


2S = strip - strip



PS = pixel - strip





Dee: Main structure of the TEDD

TEDD concept:

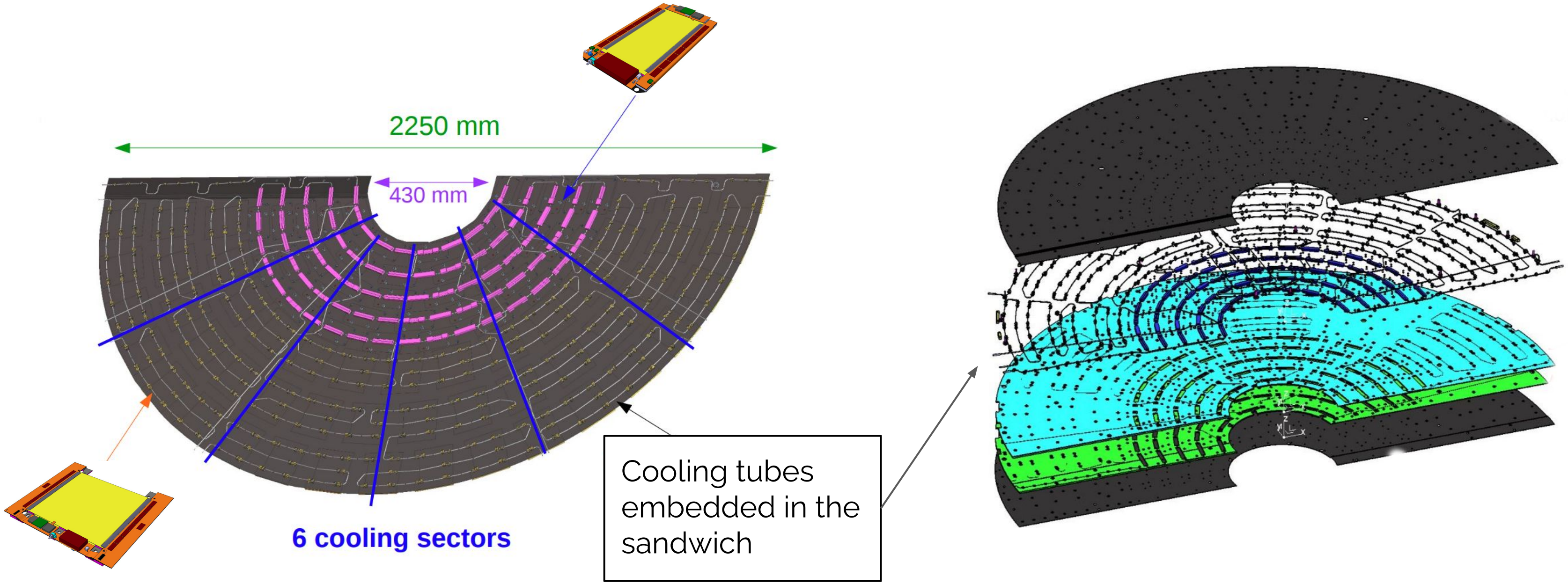
- Cooling at -35˚C using CO_2 at phase transition.
- Cooling pipes integrated as part of the Dee structure to minimize the weight of the structure.

↳ **Optimal cooling of the detection modules**

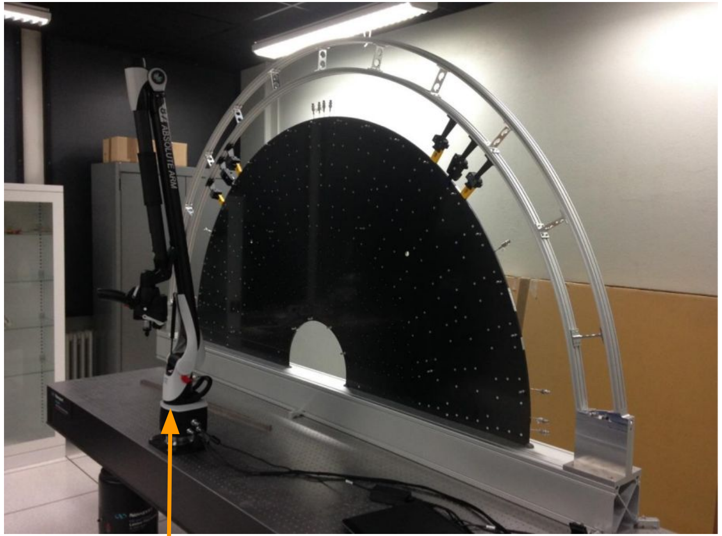
Anatomy of a Dee

The Dee is the main element of the TEDD design:

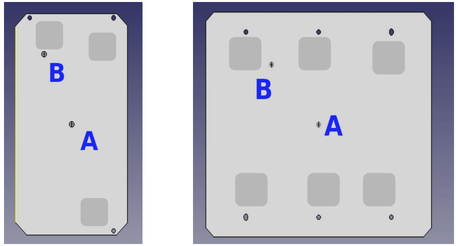
- Composite structure with carbon fiber skins and inserts on both surfaces to mount the 2S and PS modules.



Metrology measurements



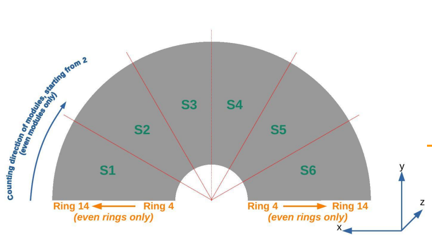
Metrology measurements of Dee's inserts taken with the mechanical arm



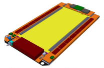
Dummy high precision fake 2S and PS
modules

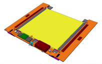
A and B are reference points for measurement
A: Center
B: Upper left corner

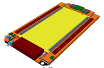
Reference points precision on XY plane

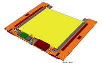


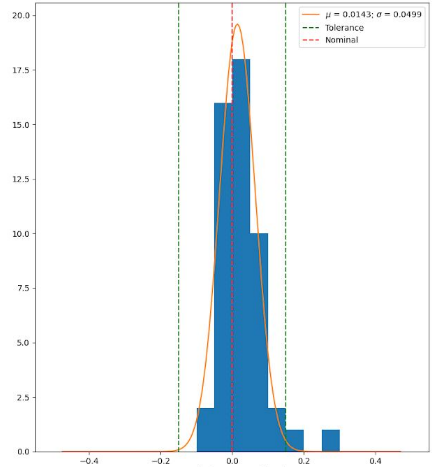
➔ Test on the ability to mount the high precision dummy modules onto the Dee

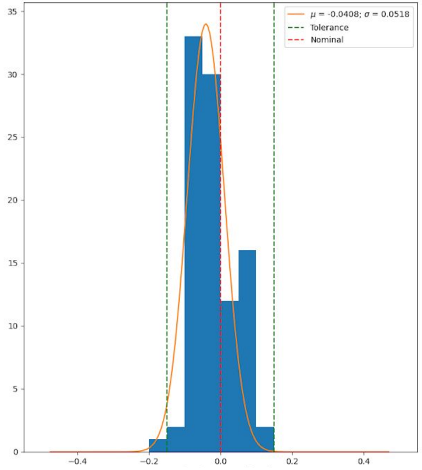

PS

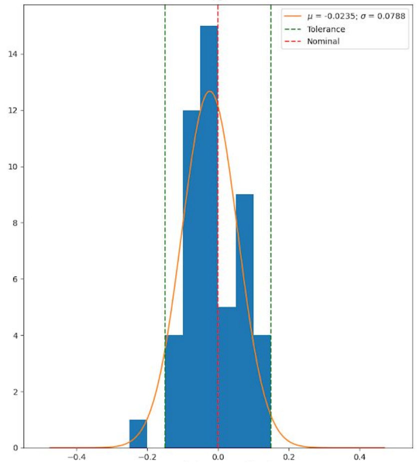

2S

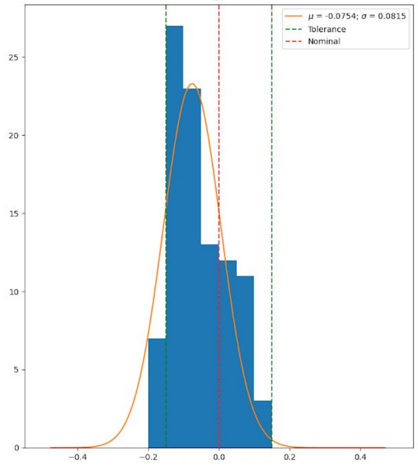

PS


2S





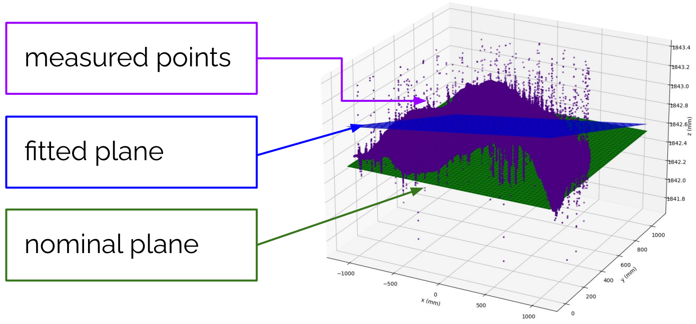


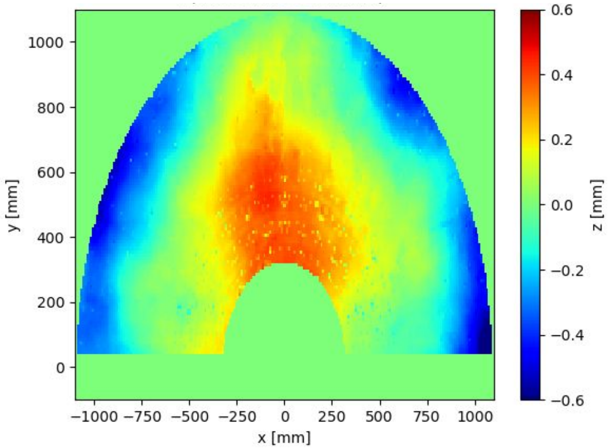


ΔX = nominal(x) - measured(x) [mm]
Tolerance = ±0.15 mm

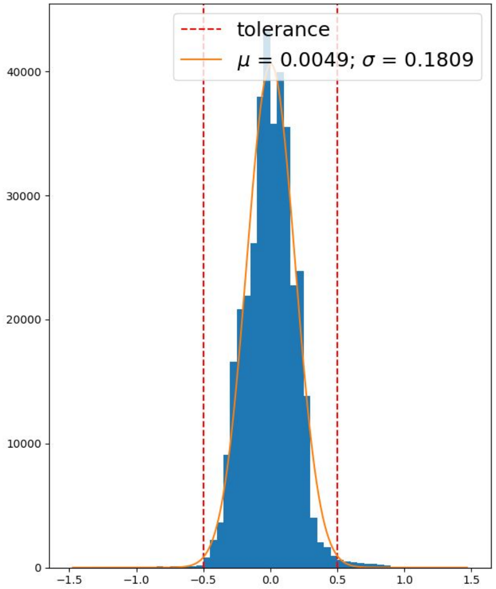
ΔY = nominal(y) - measured(y) [mm]
Tolerance = ±0.15 mm

Testing Dee's flatness

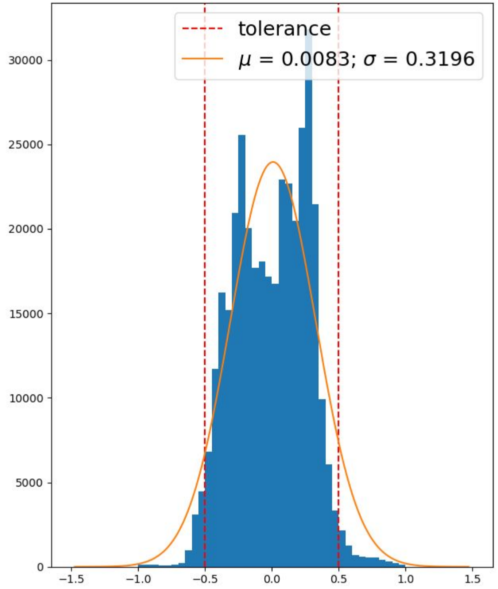




Distance between measured points and **fitted** plane



Distance between measured points and **nominal** plane



Summary and perspectives

- ➢ 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->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

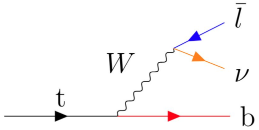
Thank you for your attention

Backups

Top reconstruction

Energy conservation:

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



$$b^\mu = (E_b, \vec{p}_b)$$
$$l^\mu = (E_l, \vec{p}_l)$$

We have this info

$$\nu^\mu = (E_\nu, \vec{p}_\nu)$$

We lack the p **Z** component at detector level

$$(W^\mu)^2 = m_W^2$$
$$= 2(E_l E_\nu - \vec{p}_{T,l} \cdot \vec{p}_{T,\nu} - p_{z,l} p_{z,\nu})$$

UR limit (LHC)

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

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

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

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

Christopher Greenberg c.greenberg@ip2i.in2p3.fr

MG5 setup

Syntax for single top t-channel process

- **5 flavour-scheme usage** (as recommended by: arXiv:1802.07237)
  - define p = p b b~
  - set b-mass to 0 in the *param_card.dat*: *5 0.000000e+00 #mb*

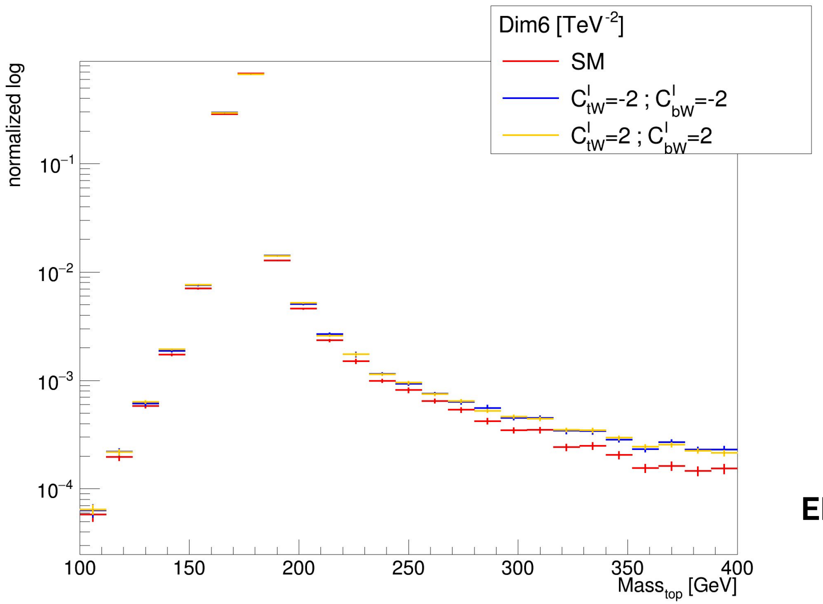
- **Full-chain process generation**:
  - EFT effects at production and at decay at LO

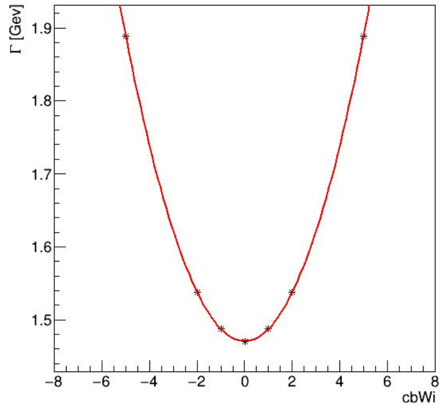
  - generate p p > w+ b j $$ w+ w- z a DIM6=2 FCNC=0 QED=3 QCD=0, w+ > l+ vl (single top)
  - add process p p > w- b~ j $$ w+ w- z a DIM6=2 FCNC=0 QED=3 QCD=0, w- > l- vl~ (single antitop)

- **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