Phenomenology study of CP-violation with single top quark t-channel using EFT

Top LHC France - Strasbourg 16/05/2023

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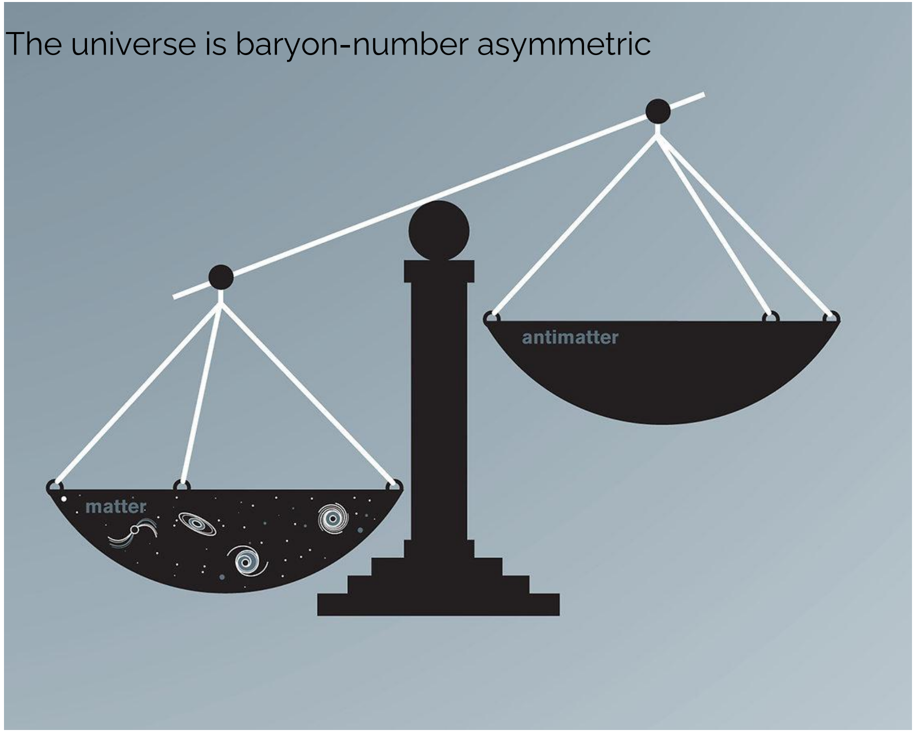
Matter and Antimatter asymmetry

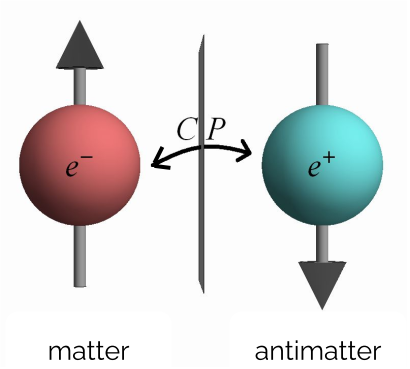


SM prediction: $\eta_{SM} = \frac{n_B - n_{\bar{B}}}{n_\gamma} \propto 10^{-27}$

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

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

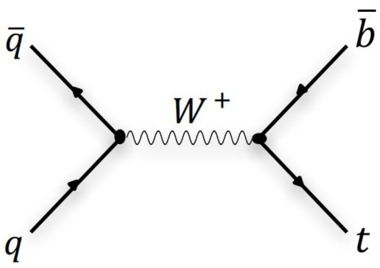
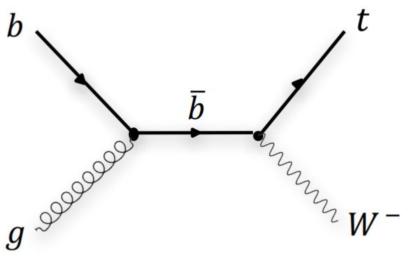
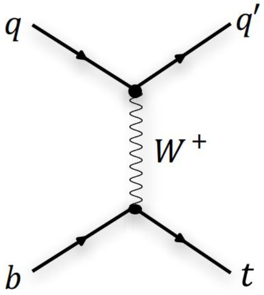
Discrepancy between the SM prediction and observations



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

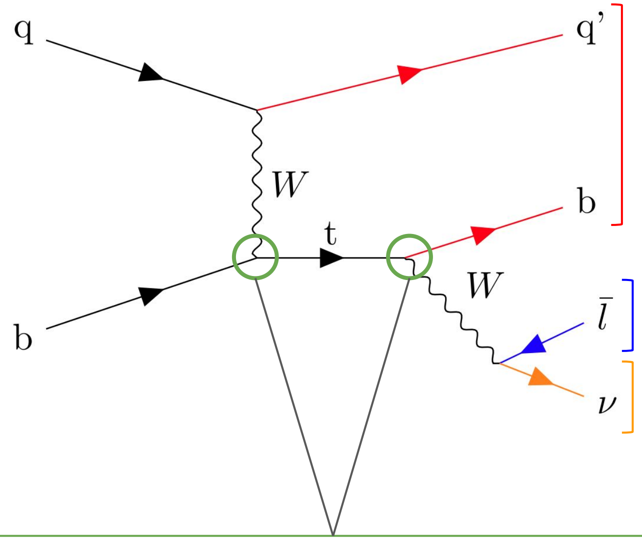
Single top quark production at the Large Hadron Collider (LHC)

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 its largest cross section.

Topology of the signal process



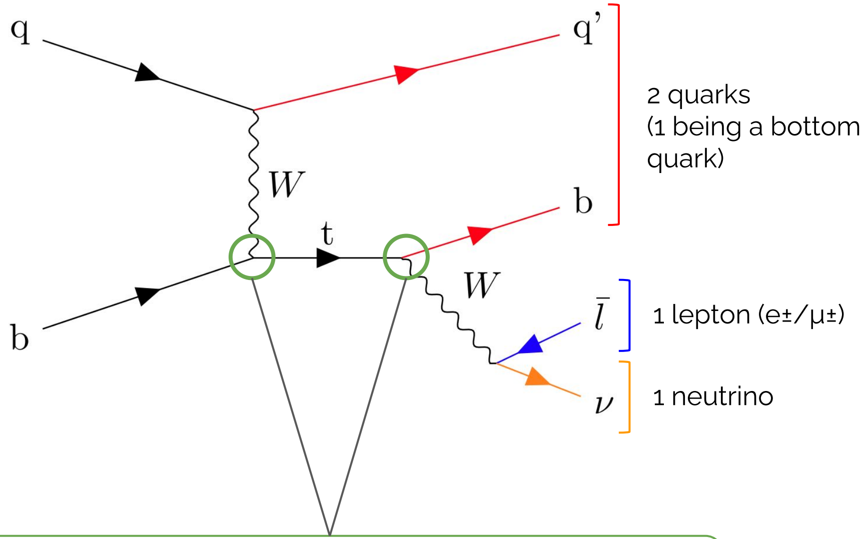
2 quarks
(1 being a bottom
quark)

1 lepton (e±/μ±)

1 neutrino

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

CP-violation with Effective Field Theory (EFT)



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

How to measure CP violation with single top t-channel

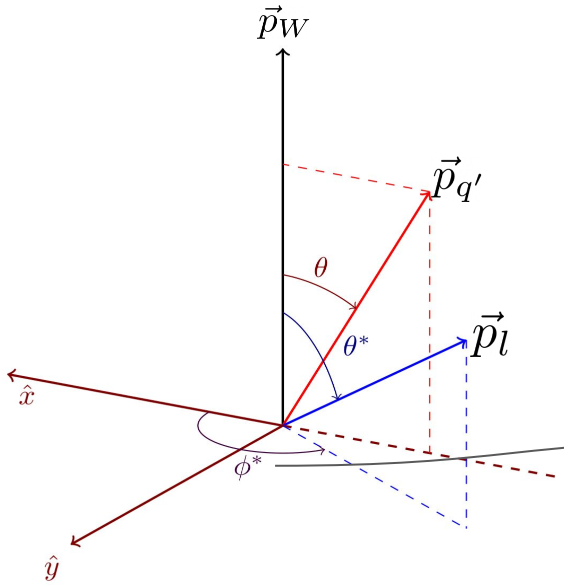
Top quark rest frame:

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

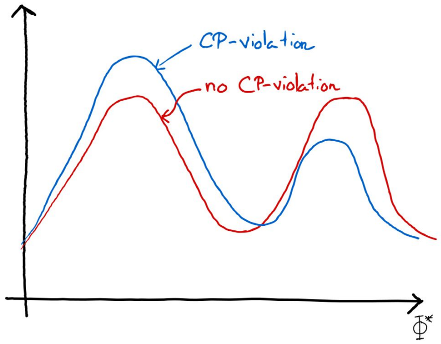
θ = angle between q' quark and W boson momenta

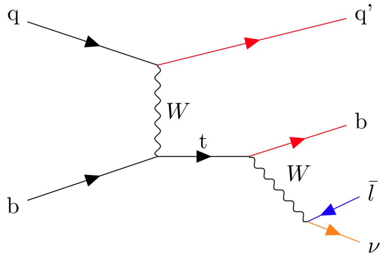
θ* = angle between lepton l and W boson momenta

ϕ*= angle between x-axis and the projection of the momenta of the lepton l on the xy-plane



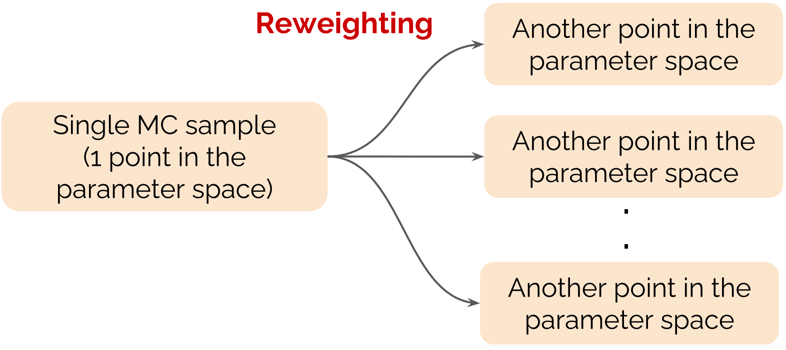
Using the distribution of these angles, the size of CP violation can be measured





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



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

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

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

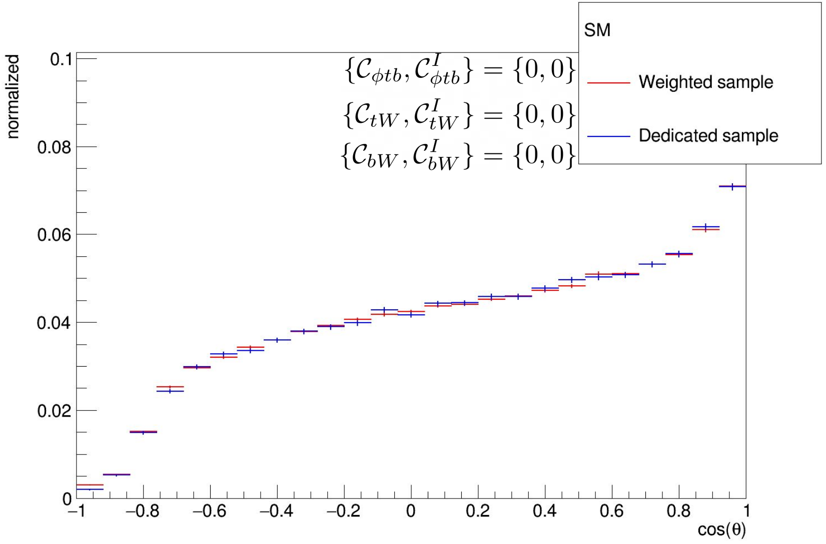
Our 6 axes of the parameter space — Different combination values

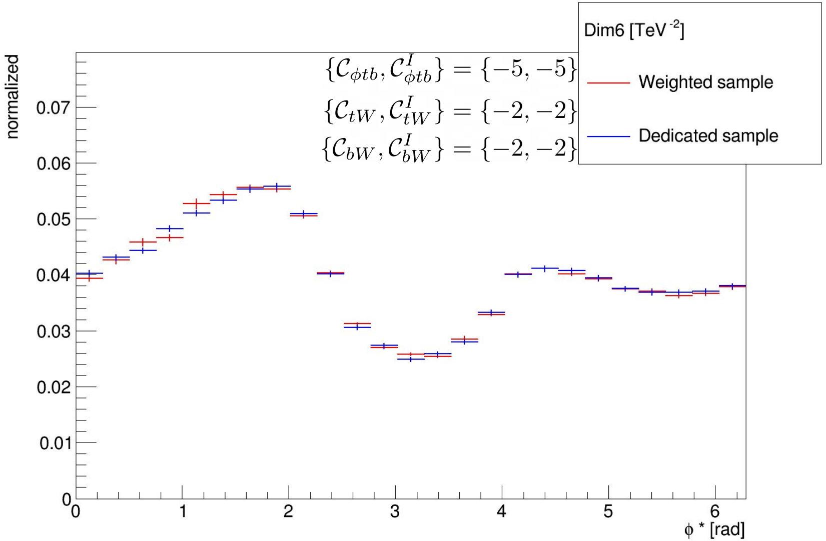
1 simulation → **729 points**

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

Validating reweighting

Samples generated with MadGraph5_aMC@NLO, at LO using dim6top model, including EFT in production and decay [Following method in arXiv:1807.03576]



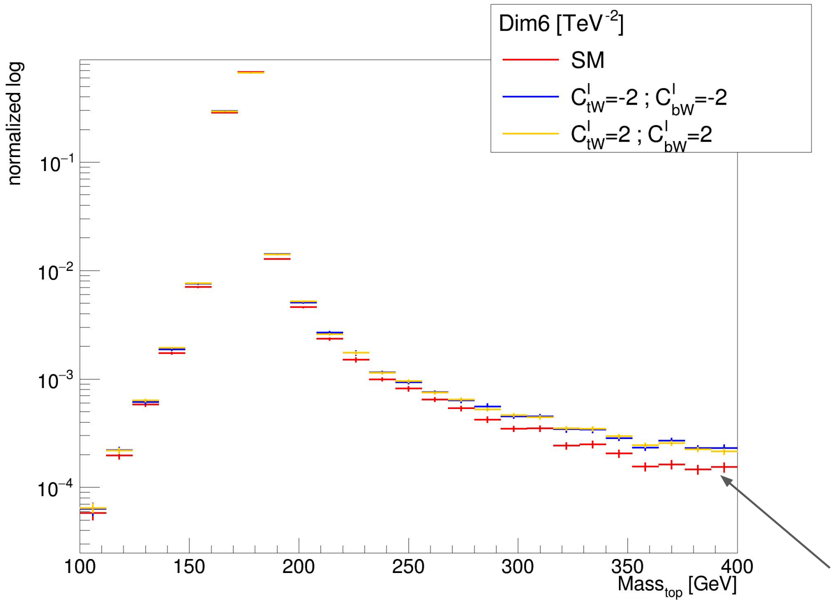


Comparing reweighted distributions of cos(θ) and ϕ^* to dedicated (non-reweighted) samples at two different distant points of the parameter space

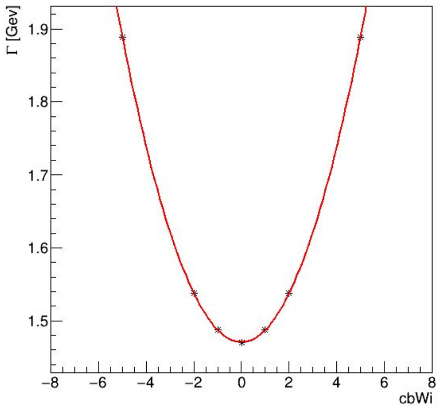
➔ **Reweighting is validated**

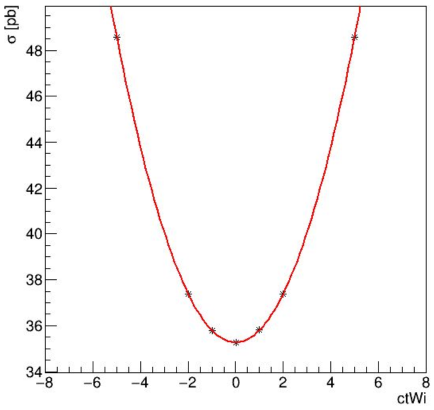
EFT impact on top width and cross section

Quadratic behavior as expected for the cross section and the top width



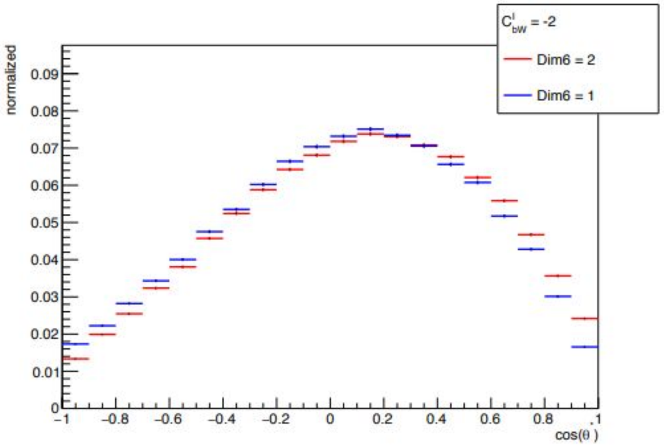
$\sigma \propto |\mathcal{M}|^2$

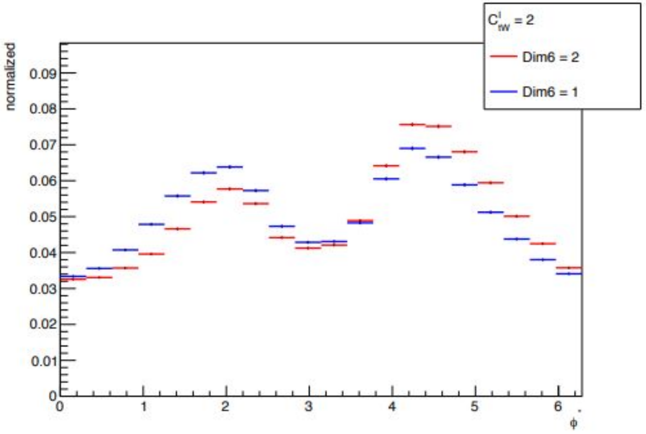




The impact of EFT on top width is sizeable

EFT effects at production and decay

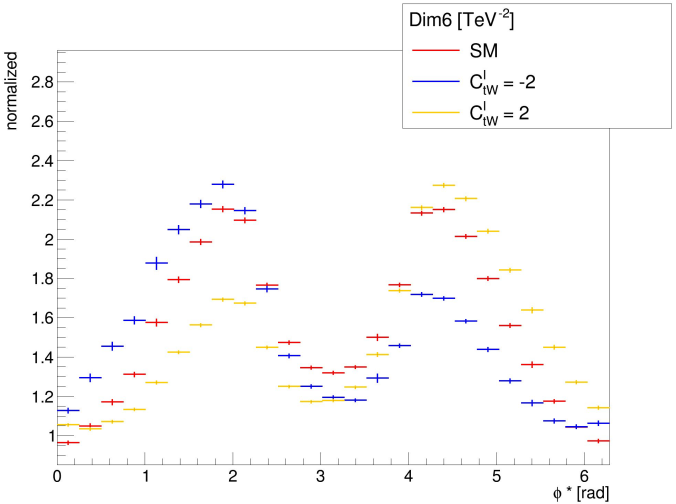




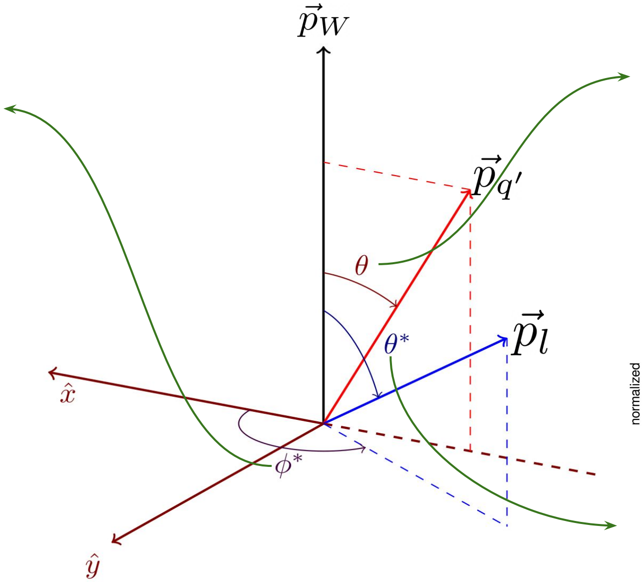
Higher precision obtained by applying EFT operators effects on top production and decay

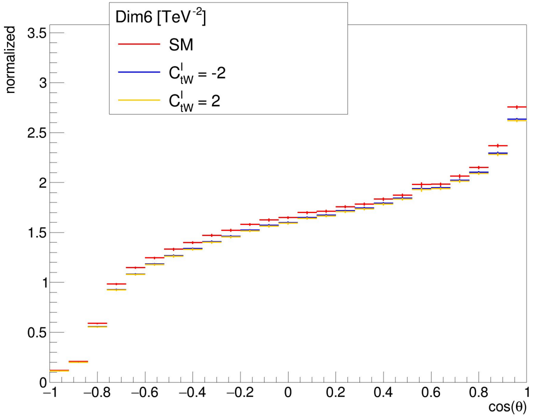
Dim6 = 1: EFT effects only on top production
Dim6 = 2: EFT effects on top production and decay

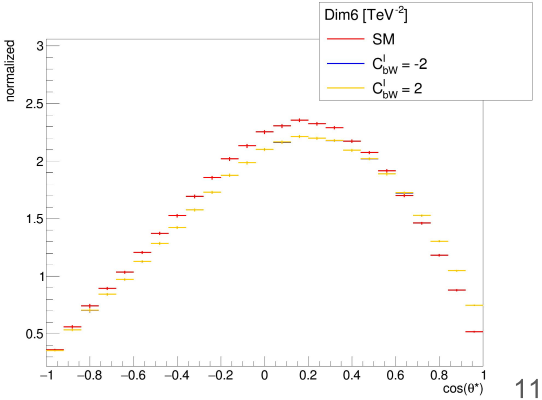
EFT effects on kinematic variables at parton level



- No CP-violation
- CP-violation
- CP-violation





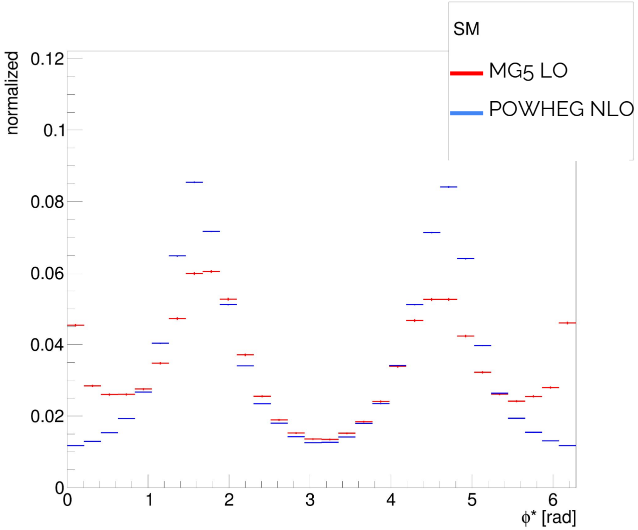


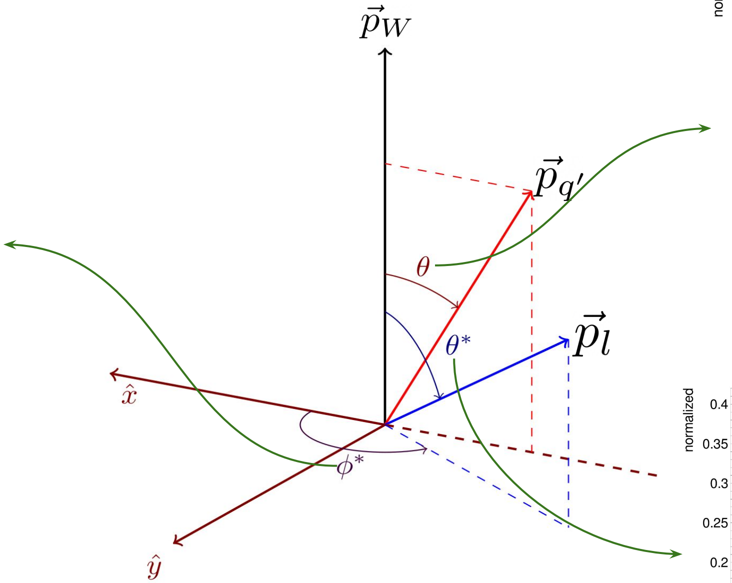
The shape of the angular distributions change as a function of the value of the EFT coefficient.

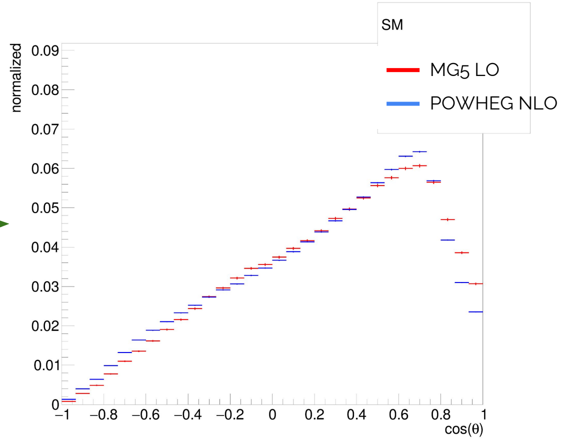
These angles are experimentally observable, we can therefore, measure CP-violation through these variables by analysing LHC collisions data.

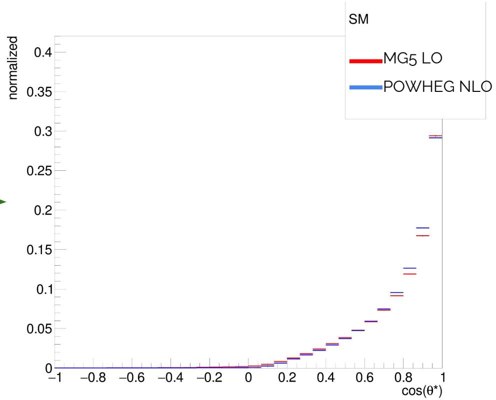
Comparing generated samples to official CMS sample at generator level

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.

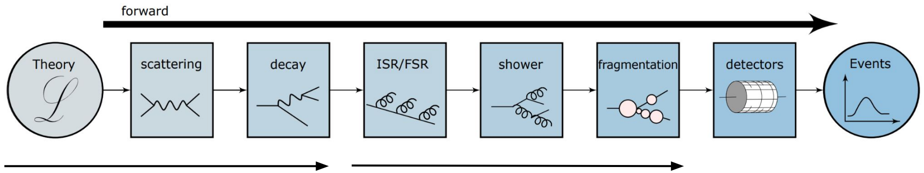
Conclusion

- Single top quark t-channel is a good candidate for searches of CP-violation
- Angular variables in the top quark rest frame are sensitive to EFT coefficients values
- A 729 points sample was produced using at reweighting at LO
- Work ongoing:
  - Exploring the discrepancy between MG5 at LO and POWHEG at NLO..
  - Study the possibility of adding an extra jet to the process at parton level.
  - Exploring a different reference frame to try new variables related to top polarization.

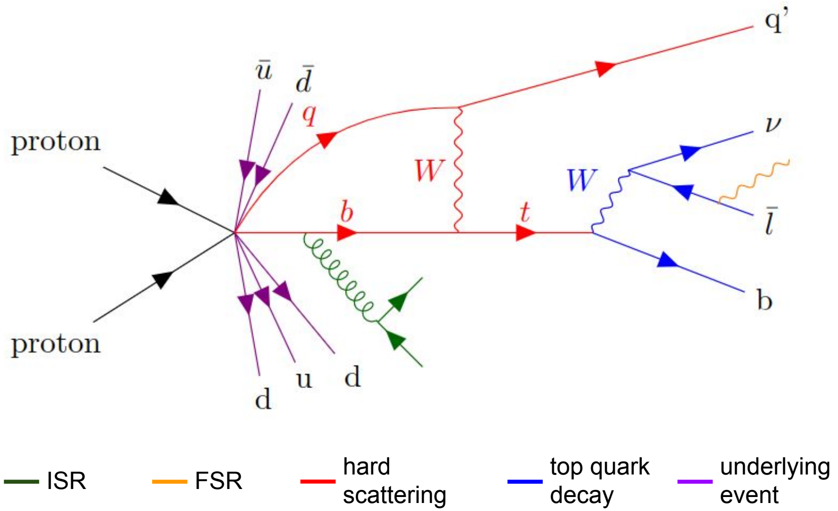
Thank you :)

Backup

Levels of information in proton-proton collisions



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



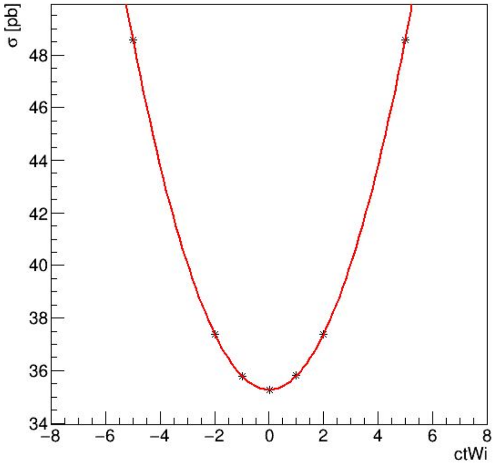
Parton level (= theory): Computation of **|** ***M*** **|²** using Feynman rules for the SMEFT model.

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

Simulating EFT with Reweighting

BSM Matrix Element

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



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:

EFT Lagrangian

EFT Coefficients

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

SM Lagrangian

New physics energy scale

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

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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.

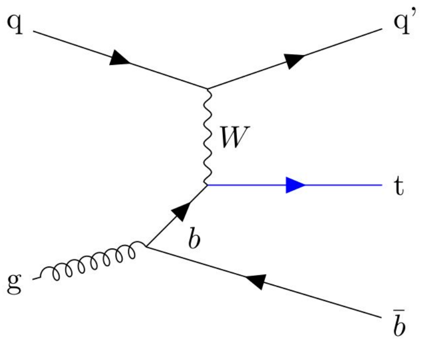
We are interested in both the real and imaginary parts of the three EFTs:

- ➔ **6 dimension parameter space**
- ➔ **The SM is the origin of the parameter space**

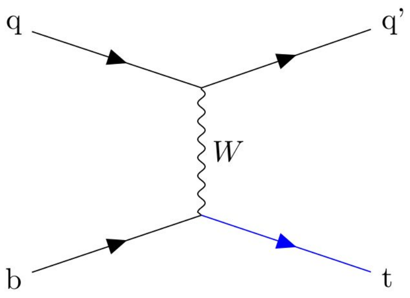
CP violation = Non zero value of the imaginary part of these EFTs coefficients

Flavour schemes

Flavour scheme for single top t-channel



4FS
2 →3 process
b quarks stem from gluon splitting

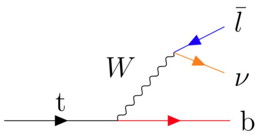


5FS
2 →2 process
b quarks are massless and therefore, included in the proton PDF, they stem from the collision proton

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 pz 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

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

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

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