The way to new physics through the single top quark

Nikhef

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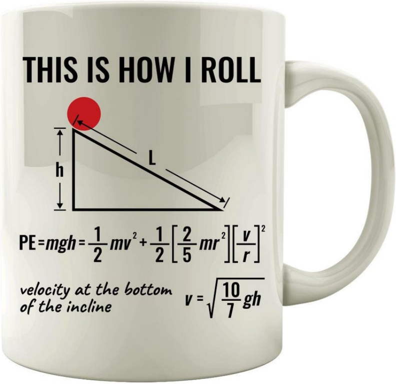
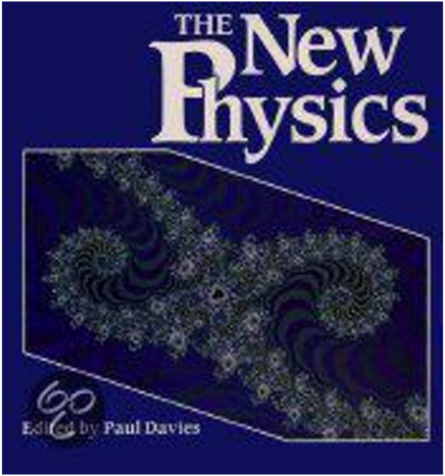
Theory Meets Experiment

26 June 2020

- Motivation
- Top Spin
- Sensitivity to effective operators
- Measurement?!



- SM is not the end
  - Gravity
  - Dark Matter
  - Matter anti-Matter
- In need of new physics
- Which theory is next?
  - SUSY
  - string theory
  - composite Higgs
  - leptoquarks
  - ...



Effective Field Theory (EFT)

Coupling coefficient

$$\mathcal{L}_{\mathrm{SM}} + \sum_i \frac{C_i}{\Lambda^2} O_i^{[6]}$$

Operator

Standard Model

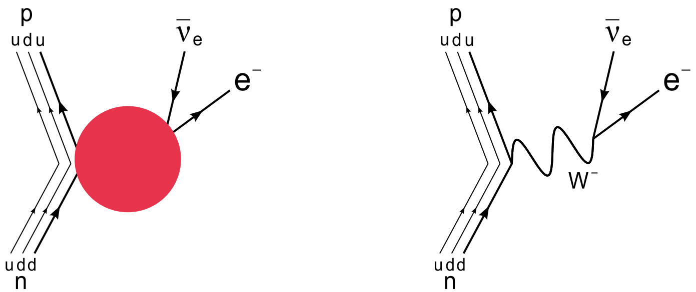
Scale of New Physics

- Precision era (lots of data)
- Indirect search
- Model independent
- Incorporates symmetries

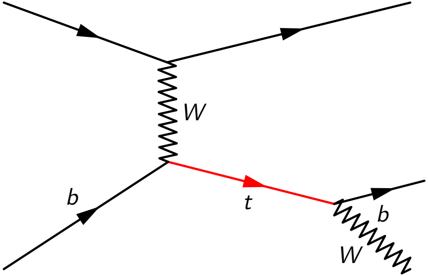
Effective Field Theory (EFT)

How does it work

- Every operator is a vertex (a blob)
- Only with enough energy we can resolve it
- We use it all the time!
- Particle Physics example → beta-decay

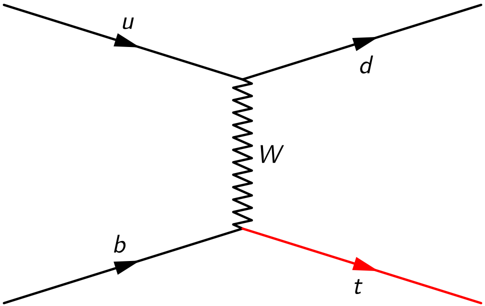


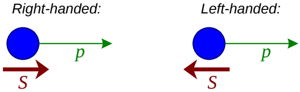
- Top is the heaviest "known" particle
- Decay length is shorter then the QCD scale
- Single tops are polarized
- Same vertex in production and decay



Polarized Top

- W only couples to left-handed particles → Top is left-handed
- Spin points along direction spectator jet
- Angular distributions are correlated to the polarization



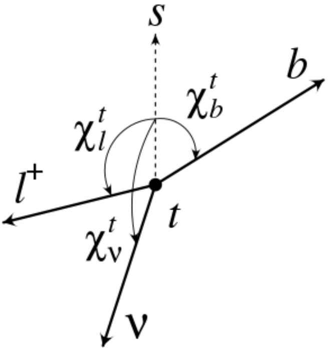


Note:

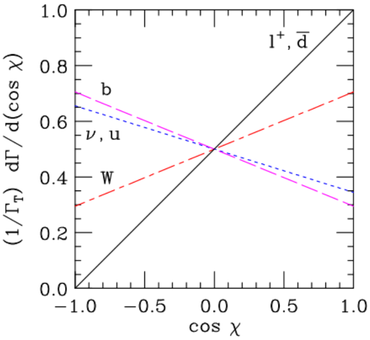
top decays to W b
W decays to e or μ

Polarization Angles

$$\frac{1}{\Gamma_T}\frac{d\Gamma}{d\left(\cos\chi_i^t\right)} = \frac{1}{2}\left(1 + P\alpha_i \cos\chi_i^t\right) \qquad \alpha = \text{spin analyzing power}$$



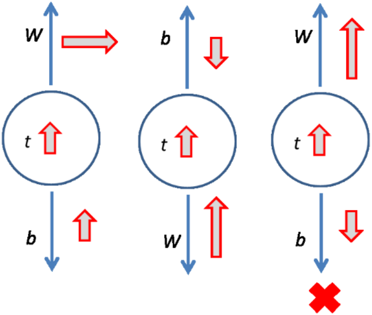
Angle definition in top rest frame



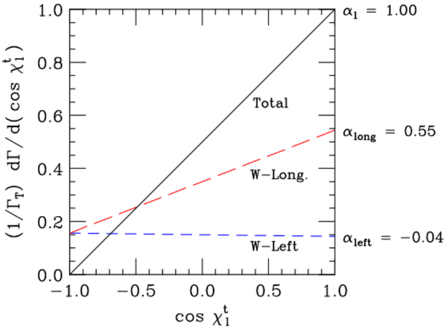
Angular correlation of top spin

Taken from *Mahlon 2000*

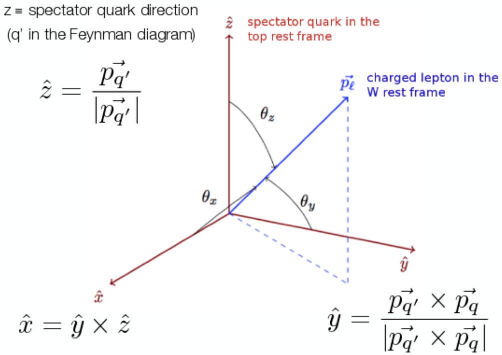
$$\alpha_l = 1?$$



Polarized Top decay
(taken from Research Proposal)

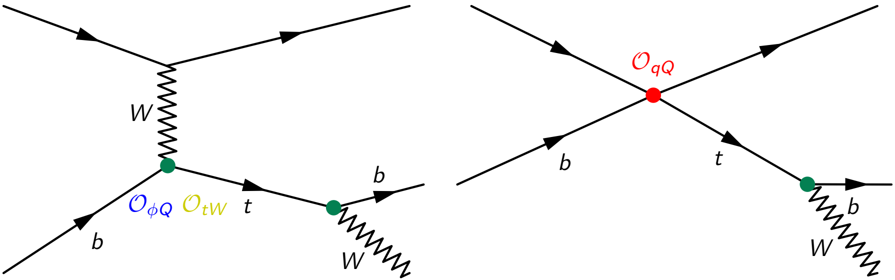


Interference between W helicity states
(taken from *Mahlon 2000*)



$\vec{p_q'}$ is the direction of the spectator quark and $\vec{p_q}$ is the direction of the initial quark which is taken as the beam axis

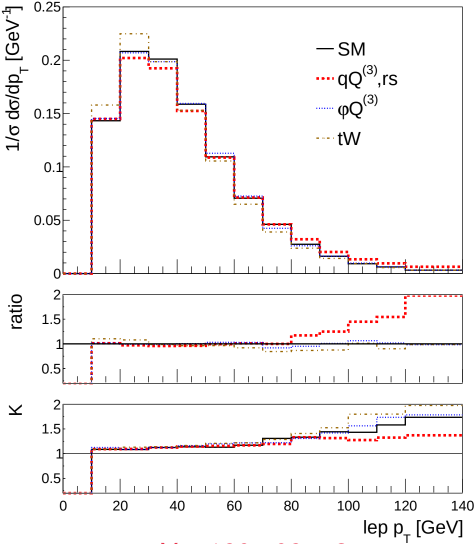
Aguilar 2014



3 Operators:

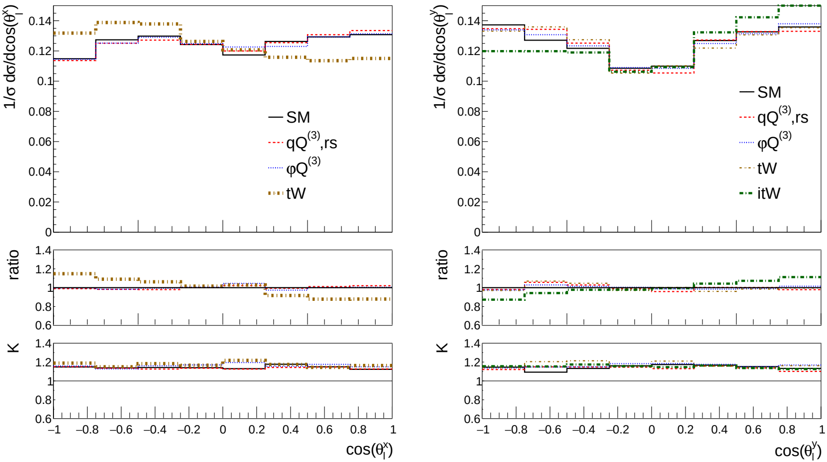
$\mathcal{O}_{\phi Q}$ $\mathcal{O}_{tW}$ $\mathcal{O}_{qQ}$

$$\frac{d\sigma_{ub\to dt}}{d\cos\theta} = \left(1 + \frac{C_{\varphi Q} y_t^2 v^2}{\Lambda^2}\right) k_1(\theta) + \frac{\mathrm{Re}\ C_{tW}}{\Lambda^2} k_2(\theta) + \frac{C_{qQ,rs}}{\Lambda^2} k_3(\theta)$$



arXiv:1807.03576

- Sensitive to the qQ operator at high lepton pT
- NLO not just a normalisation $\rightarrow$ shape effect



- Polarization angles sensitive to New Physics
- Able to distinguish between different operators
- Imaginary part of tW → CPV?

What is next?

- Measurement in ATLAS
- We are good in measuring angles!
- Not possible to generate every coupling value
- Morphing!

Modeling a continuous signal in a multidimensional space of coupling parameters

$$\sigma(c_{\mathrm{SM}}, c_{\mathrm{BSM}}) = \left| c_{\mathrm{SM}} \cdot \underline{\mathcal{O}_{\mathrm{SM}}} + c_{\mathrm{BSM}} \cdot \underline{\mathcal{O}_{\mathrm{BSM}}} \right|^2 =$$
$$c_{\mathrm{SM}}^2 \cdot \underline{\mathcal{O}_{\mathrm{SM}}^2} + c_{\mathrm{SM}} c_{\mathrm{BSM}} \cdot \underline{\mathcal{O}_{\mathrm{SM}} \mathcal{O}_{\mathrm{BSM}}} + c_{\mathrm{BSM}}^2 \cdot \underline{\mathcal{O}_{\mathrm{BSM}}^2}$$

How does it work

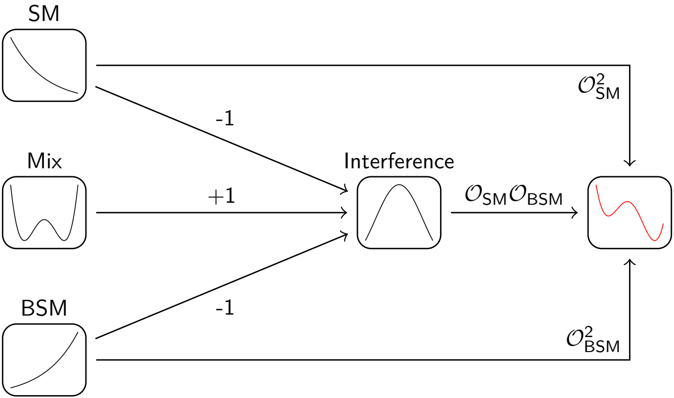
- Generate template samples
- Obtain values for all the terms
- Reweigh templates to prediction

$$\sigma(c_{\mathrm{SM}}, c_{\mathrm{BSM}}) = \sum_i w_i(c_{\mathrm{SM}}, c_{\mathrm{BSM}}) \cdot \sigma_i$$

Morphing example

$$\sigma(c_{\mathrm{SM}}, c_{\mathrm{BSM}}) =$$
$$c_{\mathrm{SM}}^2 \cdot \underline{\mathcal{O}_{\mathrm{SM}}^2} + c_{\mathrm{SM}} c_{\mathrm{BSM}} \cdot \underline{\mathcal{O}_{\mathrm{SM}} \mathcal{O}_{\mathrm{BSM}}} + c_{\mathrm{BSM}}^2 \cdot \underline{\mathcal{O}_{\mathrm{BSM}}^2}$$

	c_{SM}	c_{BSM}
SM	1	0
Mix	1	1
BSM	0	1



ATL-PHYS-PUB-2015-047

Focus on: $\mathcal{O}_{tW}$

$$\sigma(c_{\text{tW}}, c_{\text{itW}}) = \left|\underline{\mathcal{O}_{\text{SM}}} + c_{\text{tW}} \cdot \underline{\mathcal{O}_{\text{tW}}} + c_{\text{itW}} \cdot \underline{\mathcal{O}_{\text{itW}}}\right|^2_{\text{production}} \cdot \left|\underline{\mathcal{O}_{\text{SM}}} + c_{\text{tW}} \cdot \underline{\mathcal{O}_{\text{tW}}} + c_{\text{itW}} \cdot \underline{\mathcal{O}_{\text{itW}}}\right|^2_{\text{decay}}$$

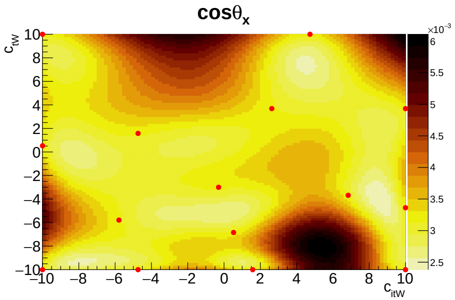
$\rightarrow$ 15 unknown terms!

$$\underline{\mathcal{O}_1} + c^1_{\text{tW}} \cdot \underline{\mathcal{O}_2} + c^2_{\text{tW}} \cdot \underline{\mathcal{O}_3} + c^3_{\text{tW}} \cdot \underline{\mathcal{O}_4} + c^4_{\text{tW}} \cdot \underline{\mathcal{O}_5} + c^1_{\text{itW}} \cdot \underline{\mathcal{O}_6} + c^2_{\text{itW}} \cdot \underline{\mathcal{O}_7} + c^3_{\text{itW}} \cdot \underline{\mathcal{O}_8} + c^4_{\text{itW}} \cdot \underline{\mathcal{O}_9}$$

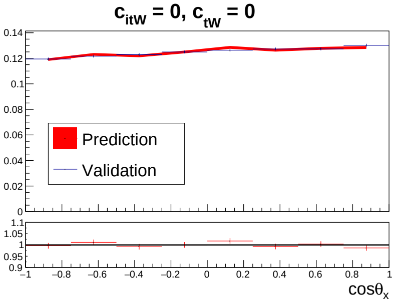
$$+ c^1_{\text{tW}} c^1_{\text{itW}} \cdot \underline{\mathcal{O}_{10}} + c^1_{\text{tW}} c^2_{\text{itW}} \cdot \underline{\mathcal{O}_{11}} + c^1_{\text{tW}} c^3_{\text{itW}} \cdot \underline{\mathcal{O}_{12}} + c^2_{\text{tW}} c^1_{\text{itW}} \cdot \underline{\mathcal{O}_{13}} + c^3_{\text{tW}} c^1_{\text{itW}} \cdot \underline{\mathcal{O}_{14}} + c^2_{\text{tW}} c^2_{\text{itW}} \cdot \underline{\mathcal{O}_{15}}$$

Morphing validation

$$\sigma = \frac{\sqrt{\sum (\text{bin error})^2}}{\sum \text{bin content}}$$



Uncertainty



Closure at SM

- left plot: red dots are inputs (rest of inputs are outside of region)
- right plot: red band is morphing prediction, blue is generated distribution (closure test)

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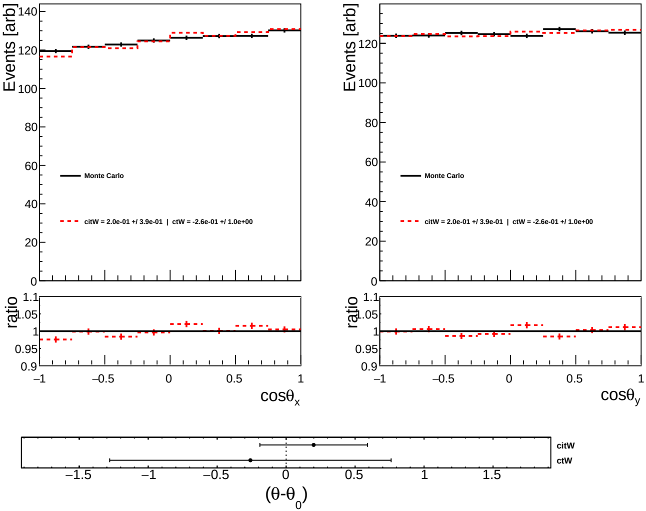
$$\sigma(c_{SM}, c_{BSM}) = \sum_i w_i(c_{SM}, c_{BSM}) \cdot \sigma_i$$

Fitresult : ictW-c0-ctW-c0



Summary

- EFT is the way to go in precision physics
- Single Top is a rich process → Polarization Angles
- Sufficient sensitivity to New Physics
- Morphing technique to describe full coupling parameter space
- Measurement in ATLAS

Stay Tuned

Backup

Discussion sensitivity plots

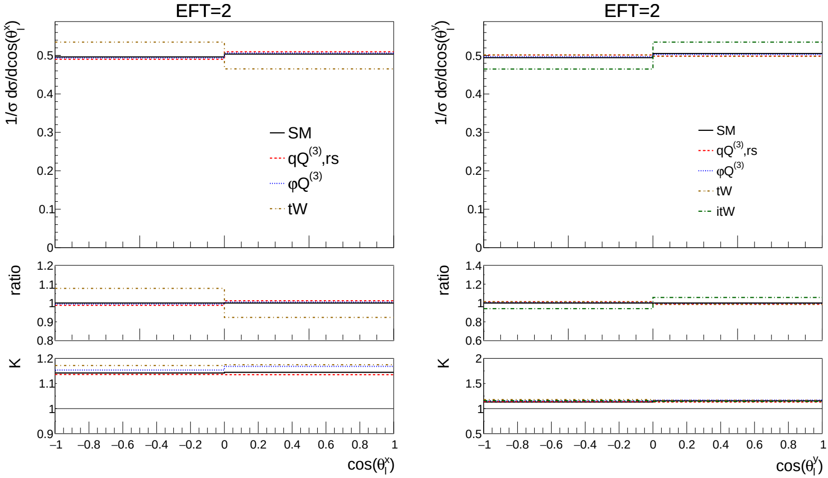
- Truth distributions
- Only scale + PDF uncertainties
- Background is SM t-channel only
- Selection cuts:
  - leptons: $p_T^l > 10$ GeV and $|\eta^l| < 2.47$
  - jets: $p_T^j > 20$ GeV and $|\eta^j| < 4.5$

Coupling values

Operator	Coupling value	LO σ ±scale ±pdf [pb]	LO Γ_{top} [GeV]	NLO σ ±scale ±pdf [pb]	NLO Γ_{top} [GeV]
SM	-	$123\ ^{+9.3\%}_{-11.4\%}\ ^{+8.9\%}_{-8.9\%}$	1.49	$137\ ^{+2.7\%}_{-2.6\%}\ ^{+1.2\%}_{-1.2\%}$	1.36
$O_{\varphi Q}^{(3)}$	1	$137\ ^{+9.3\%}_{-11.4\%}\ ^{+8.9\%}_{-8.9\%}$	1.67	$154\ ^{+2.3\%}_{-2.3\%}\ ^{+1.2\%}_{-1.2\%}$	1.52
$O_{qQ,rs}^{(3)}$	-0.4	$172\ ^{+8.7\%}_{-10.8\%}\ ^{+8.9\%}_{-8.9\%}$	1.49	$190\ ^{+2.4\%}_{-1.8\%}\ ^{+1.1\%}_{-1.1\%}$	1.35
$\mathrm{Re}\,(O_{tW})$	2	$132\ ^{+9.3\%}_{-11.4\%}\ ^{+8.8\%}_{-8.8\%}$	1.83	$148\ ^{+2.3\%}_{-2.5\%}\ ^{+1.2\%}_{-1.2\%}$	1.68
$\mathrm{Im}\,(O_{tW})$	1.75	$125\ ^{+9.2\%}_{-11.4\%}\ ^{+8.9\%}_{-8.9\%}$	1.51	$140\ ^{+2.3\%}_{-2.5\%}\ ^{+1.2\%}_{-1.2\%}$	1.38

The deviations lie within the uncertainty of recent single top measurements

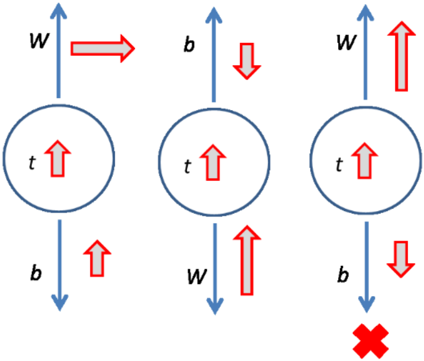
Sensitive to NP

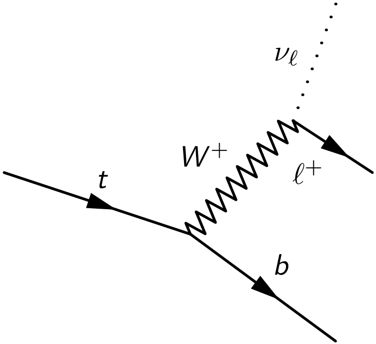


W Helicity fractions

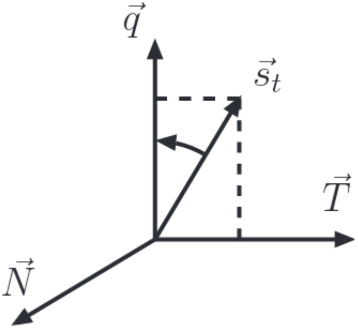
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta} = \frac{3}{8}(1+\cos\theta)^2 \cdot F_R + \frac{3}{8}(1-\cos\theta)^2 \cdot F_L + \frac{3}{4}\sin^2\theta \cdot F_0$$

θ = angle between ℓ in W rest frame and W in the t rest frame.





W Helicity fractions



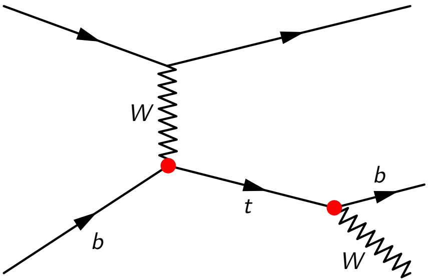
$$\hat{q} = \frac{\vec{p_W}}{|\vec{p_W}|}$$

$$\hat{N} = \frac{\vec{s_t} \times \vec{q}}{|\vec{s_t} \times \vec{q}|}$$

$$\hat{x} = \hat{q} \times \hat{N}$$

$\vec{p_W}$ is the direction of the W boson
and $\vec{s_t}$ that of the top quarks spin
both in the rest-frame of the top quark

Aguilar 2010



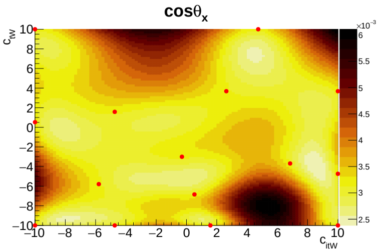
$$O_{\varphi Q}^{(3)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)\left(\bar{Q}\gamma^\mu\tau^I Q\right) \quad (1)$$

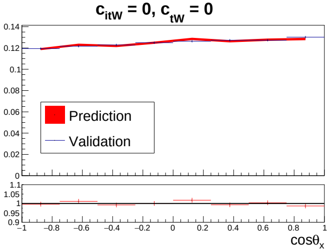
$$O_{tW} = y_t g_w(\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W^I_{\mu\nu} \quad (2)$$

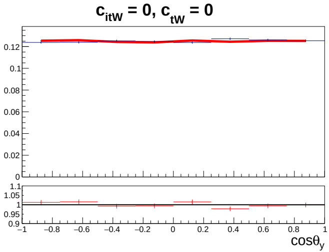
$$O_{qQ,rs}^{(3)} = \left(\bar{q}_r\gamma^\mu\tau^I q_s\right)\left(\bar{Q}\gamma_\mu\tau^I Q\right) \quad (3)$$

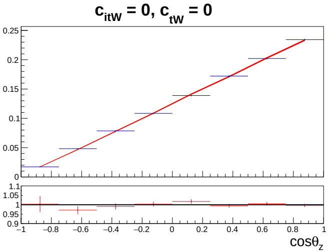
Using same notation as *Zhang 2016*

Morphing validation



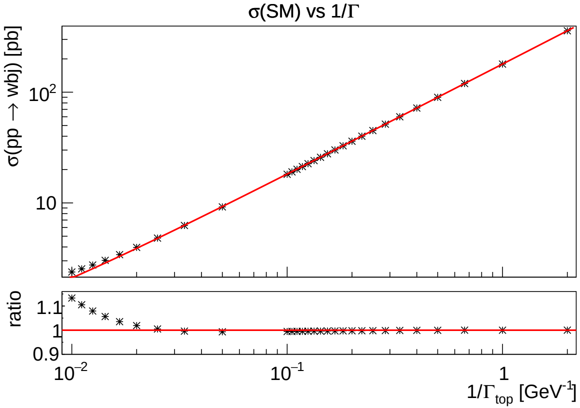




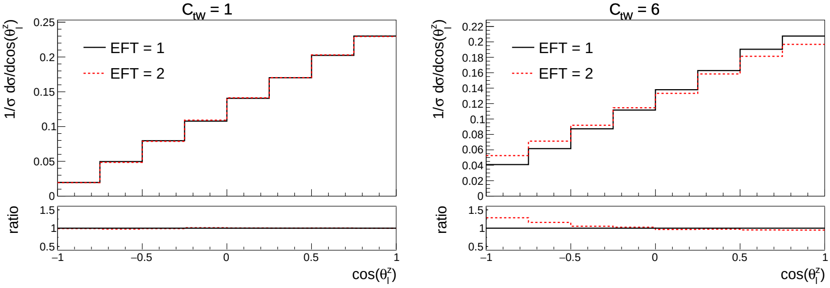


Narrow width approximation

$$\frac{1}{(p^2 - M_{\text{top}}^2)^2 + M_{\text{top}}^2\Gamma_{\text{top}}^2} \xrightarrow{(\Gamma_{\text{top}}/M_{\text{top}}\to 0)} \frac{\pi}{M_{\text{top}}\Gamma_{\text{top}}}\delta(p^2 - M_{\text{top}}^2) \qquad (4)$$



Top width and multiple EFT insertions

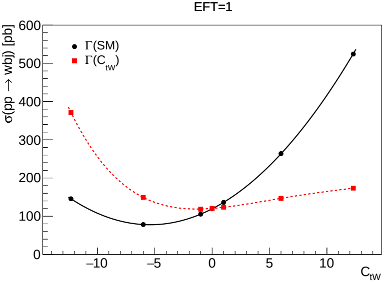


Also a shape effect
Noticeable for high C

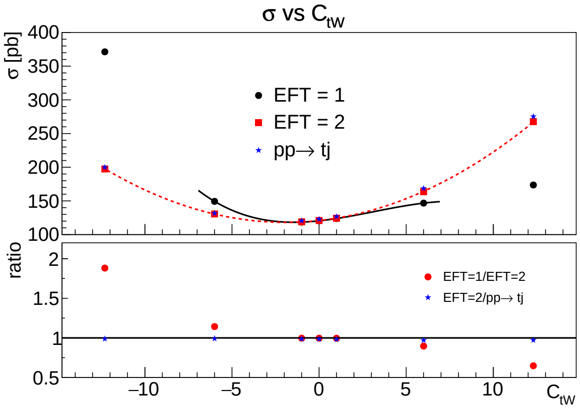
Top width and multiple EFT insertions

$$\sigma^{pp\to wbj}_{\mathrm{EFT}=2}(c_{\mathrm{tW}},\Gamma(c_{\mathrm{tW}})) = \frac{\left(\mathrm{SM}+c_{\mathrm{tW}}\cdot\mathrm{X}+c^2_{\mathrm{tW}}\cdot\mathrm{Y}\right)_{\sigma(\mathrm{prod})}\cdot\left(\mathrm{SM}+c_{\mathrm{tW}}\cdot\mathrm{X}+c^2_{\mathrm{tW}}\cdot\mathrm{Y}\right)_{\sigma(\mathrm{decay})}}{\left(\mathrm{SM}+c_{\mathrm{tW}}\cdot\mathrm{X}+c^2_{\mathrm{tW}}\cdot\mathrm{Y}\right)_{\Gamma}}$$

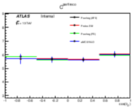
$$\sigma^{pp\to wbj}_{\mathrm{EFT}=1}(c_{\mathrm{tW}},\Gamma(c_{\mathrm{tW}})) = \frac{\left(\mathrm{SM}+c_{\mathrm{tW}}\cdot\mathrm{X}+c^2_{\mathrm{tW}}\cdot\mathrm{Y}\right)_{\sigma(\mathrm{prod})}+\left(\mathrm{SM}+c_{\mathrm{tW}}\cdot\mathrm{X}+c^2_{\mathrm{tW}}\cdot\mathrm{Y}\right)_{\sigma(\mathrm{decay})}}{\left(\mathrm{SM}+c_{\mathrm{tW}}\cdot\mathrm{X}+c^2_{\mathrm{tW}}\cdot\mathrm{Y}\right)_{\Gamma}}$$



$$\sigma(pp \to Wbj) = \sigma(pp \to tj)\,\frac{\Gamma(t \to Wb)}{\Gamma_{\text{top}}} \tag{5}$$

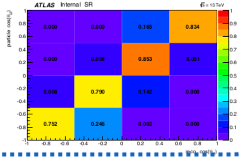


Unfolding principle

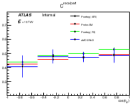


$$\frac{1}{\epsilon_k} = \frac{S_k^{\text{particle}} - S_k^{\text{particle!reco}}}{S_k^{\text{particle}}},$$

Reco. → particle migration matrix



$$N_k^{\text{particle}} = C_k^{\text{particle!reco}} \sum_j M_{jk}^{-1} C_j^{\text{reco!particle}} (N_j^{\text{data}} - B_j)$$



$$\frac{S_j^{\text{reco}} - S_j^{\text{reco!particle}}}{S_j^{\text{reco}}},$$

Region definitions

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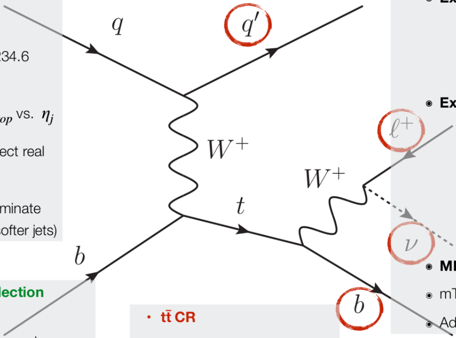
- **Selection Region (SR)**:
  - PR
  - $m_{l,b}$<153 GeV
  - 120.6 GeV < m_{top}< 234.6 GeV
  - Trapezoidal Cut on η_{top} vs. η_j
  - $m_{j,top}$> 320 GeV (select real top)
  - H_T> 190 GeV (discriminate against W+jets with softer jets)

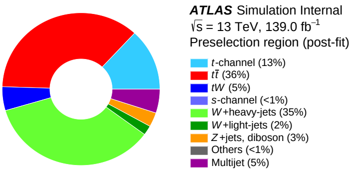


- **Preselection Region (PR)**:
  - **Exactly one tight charged lepton**
    - pT > 30 GeV, |η| < 2.5
    - Vetoing if existing a secondary high-pT (pT > 10 GeV) charged loose leptons.
  - **Exactly 2 jets, w/ exactly 1 b-tagged.**
    - pT > 30 GeV (pT>35 GeV in transition region 2.75<= |η| <3.5 to avoid mis-modeling between the central and forward calorimeters.)
    - Spectator jet (|η| < 4.5), b-jet (60 %WP (bin selection) within |η| < 2.5)
  - **MET > 35 GeV.**
  - mT(lepton-MET) [or MtW] > 60 GeV.
  - Additional multijet rejection ("triangular cut")

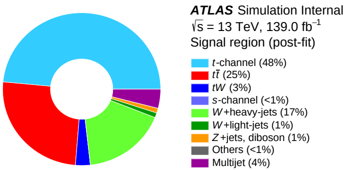
- **W+jets CR == Anti-selection Region** :
  - Enriched by selecting events passing the PR criteria, but vetoing all SR requirements.
  - PR-SR.

- **$t\bar{t}$ CR**
  - Passing all PR requirements, but requiring 2 b-tagged jets.

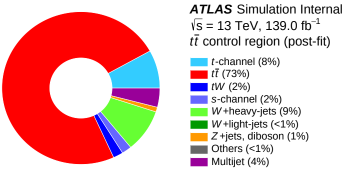
Region contributions



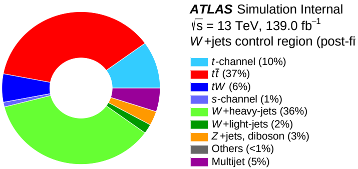
(a) Preselection region



(b) Selection region



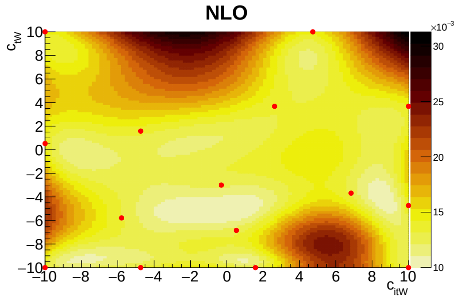
(c) ttbar control region



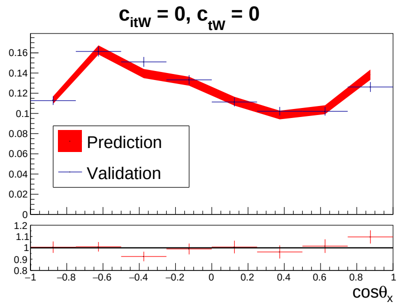
(d) W+jets control region

Morphing validation NLO SR

$$\sigma = \frac{\sqrt{\sum (\text{bin error})^2}}{\sum \text{bin content}}$$



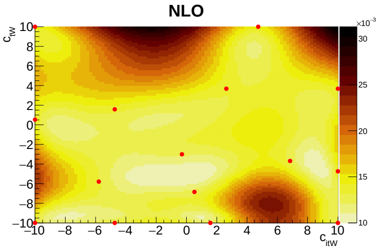
Uncertainty

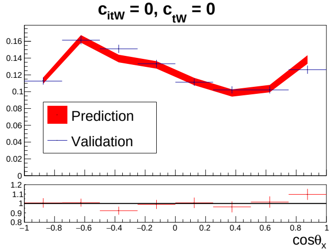


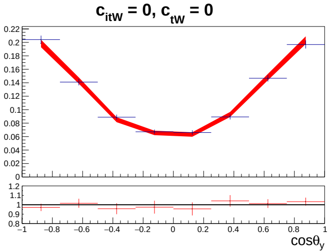
Closure at SM

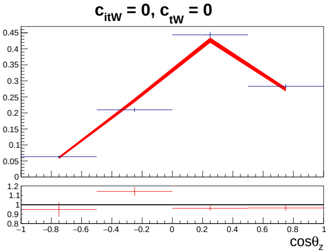
- left plot: red dots are inputs (rest of inputs are outside of region)
- right plot: red band is morphing prediction, blue is generated distribution (closure test)

Morphing validation









$$\sigma(c_{\mathrm{SM}}, c_{\mathrm{BSM}}) = \sum_i w_i(c_{\mathrm{SM}}, c_{\mathrm{BSM}}) \cdot \sigma_i$$