The way to new physics through the single top quark

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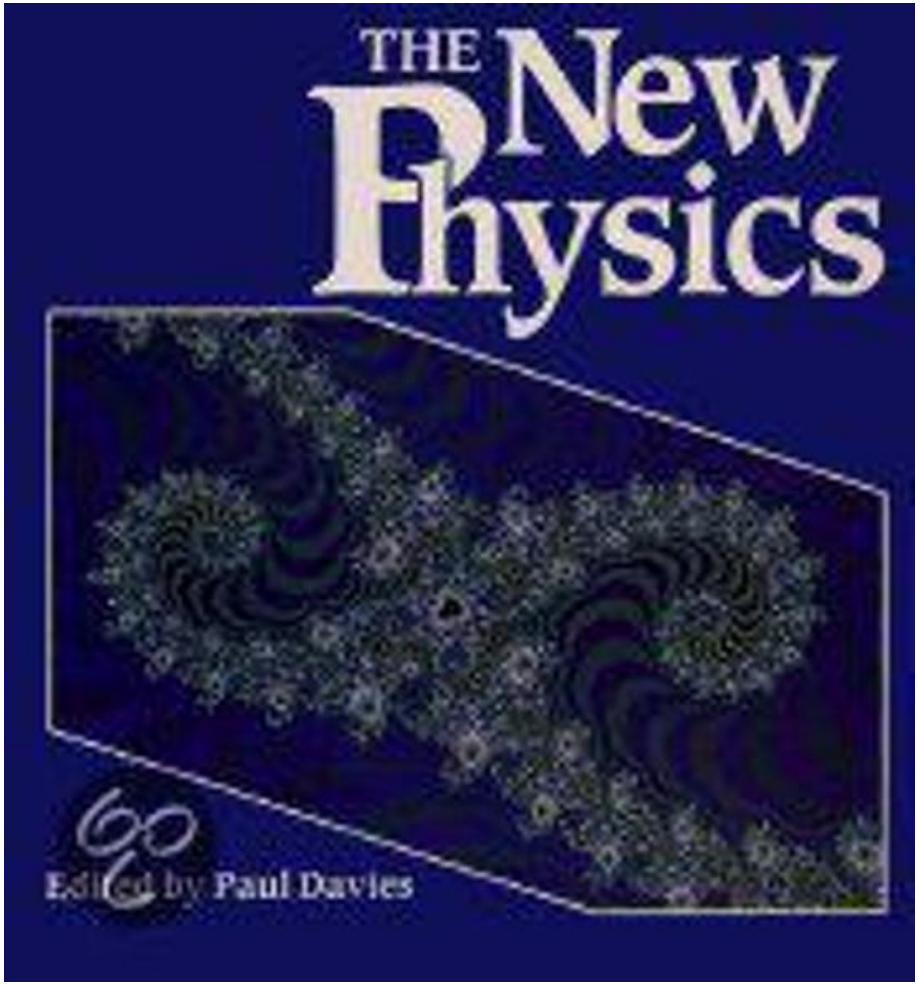
New Physics?

- 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)

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

Coupling coefficient

$$\mathcal{L}_{\mathrm{SM}} + \sum_i \frac{C_i}{\Lambda^2} O_i^{[6]} \tag{1}$$

Operator

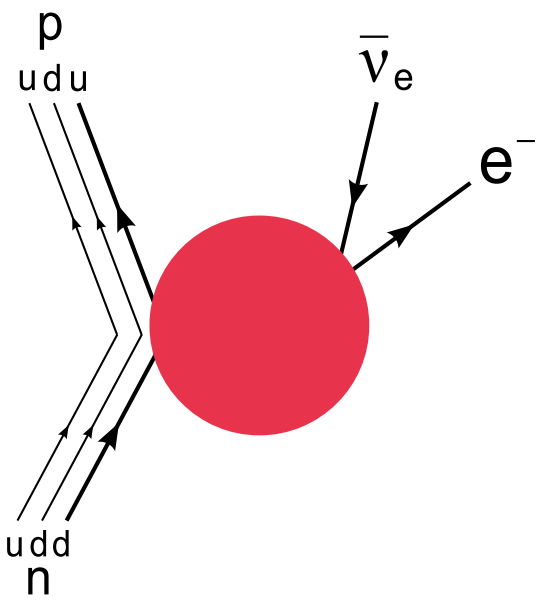
Standard Model

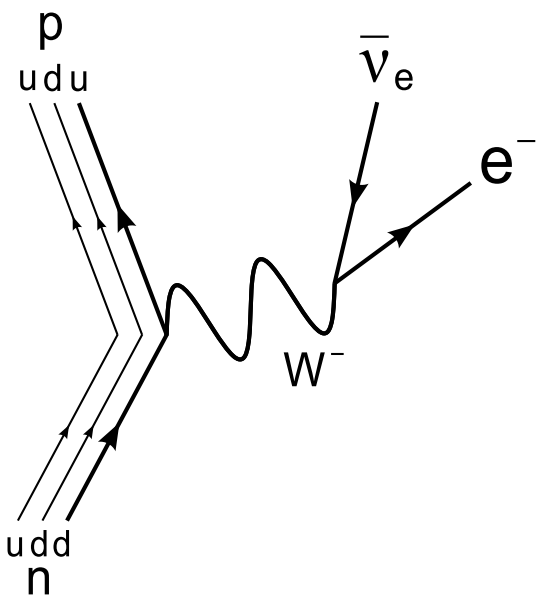
Scale of New Physics

Effective Field Theory (EFT)

How does it work

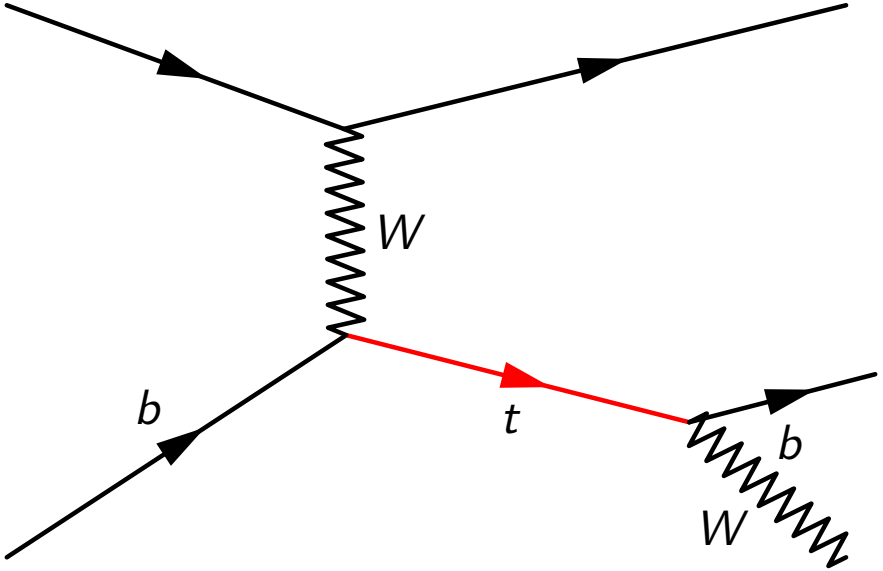
- Every operator is a vertex (a blob)
- Only with enough energy we can resolve it
- We use it all the time!
- Particle Physics example → beta-decay





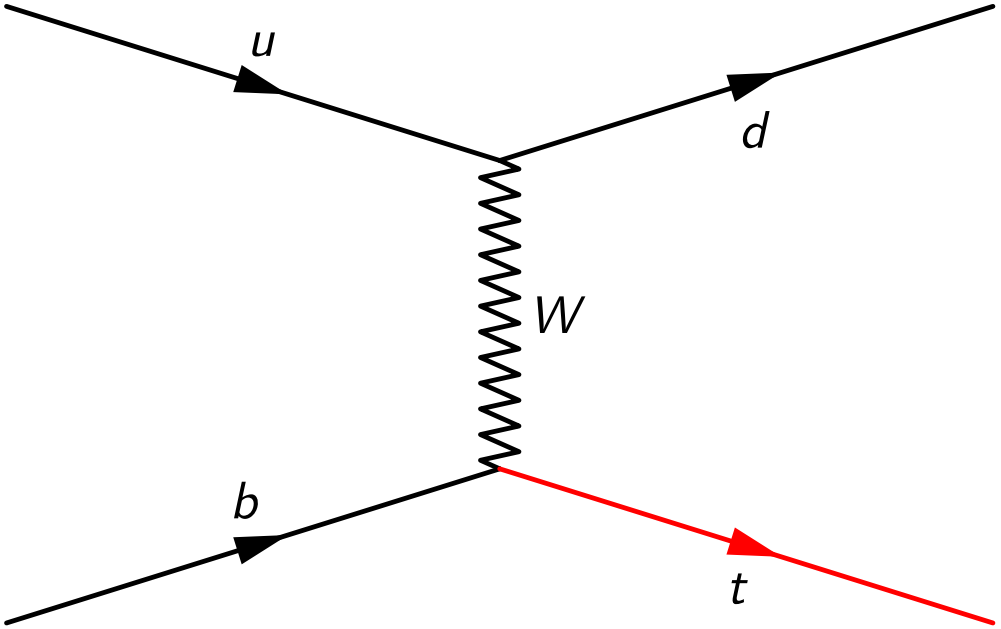
Single Top Quark

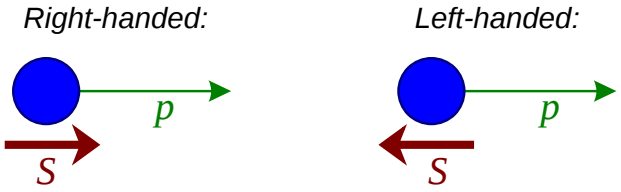
- Top is the heaviest "known" particle
- Decay length is shorter then the QCD scale
- Single tops are polarized
- Same vertex in production and decay



Polarized Top

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



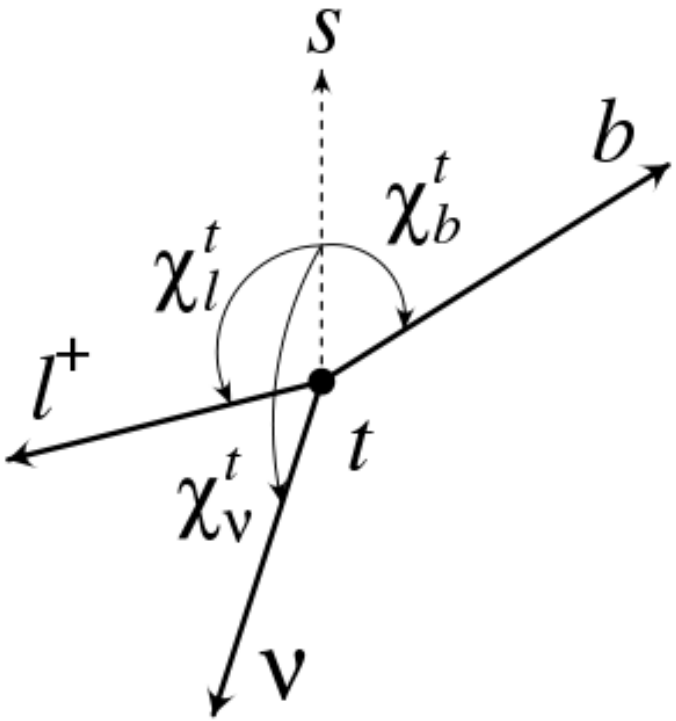


Note:

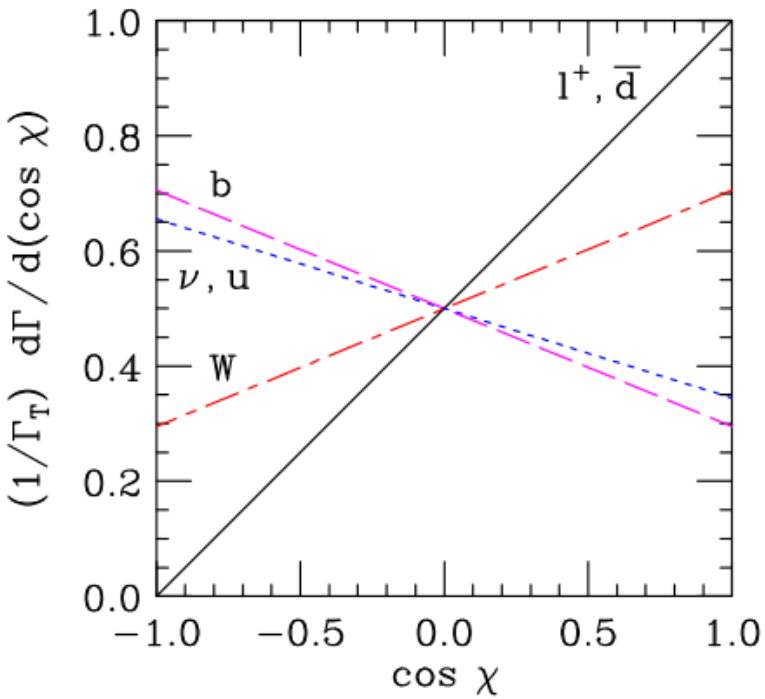
top decays to W b
W decays to e or μ

Polarization Angles

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



Angle definition in top rest frame

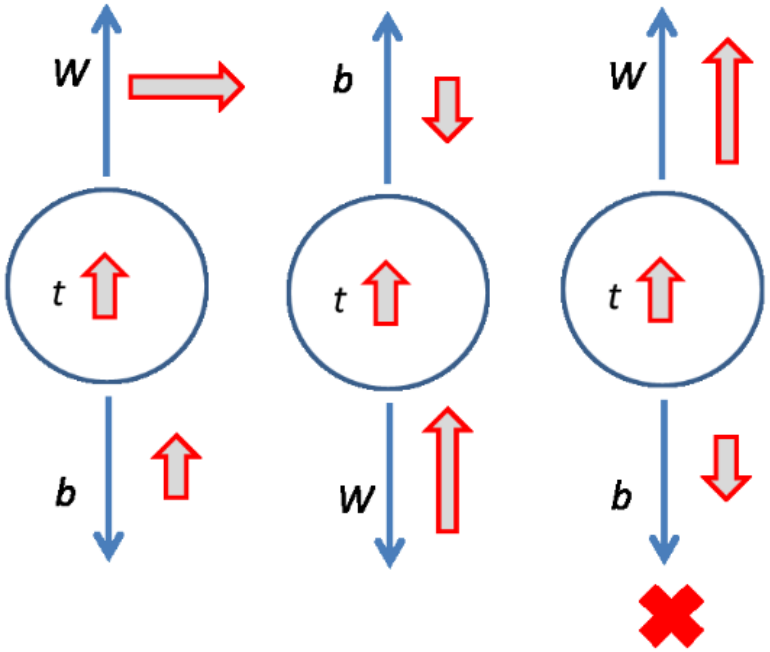


Angular correlation of top spin

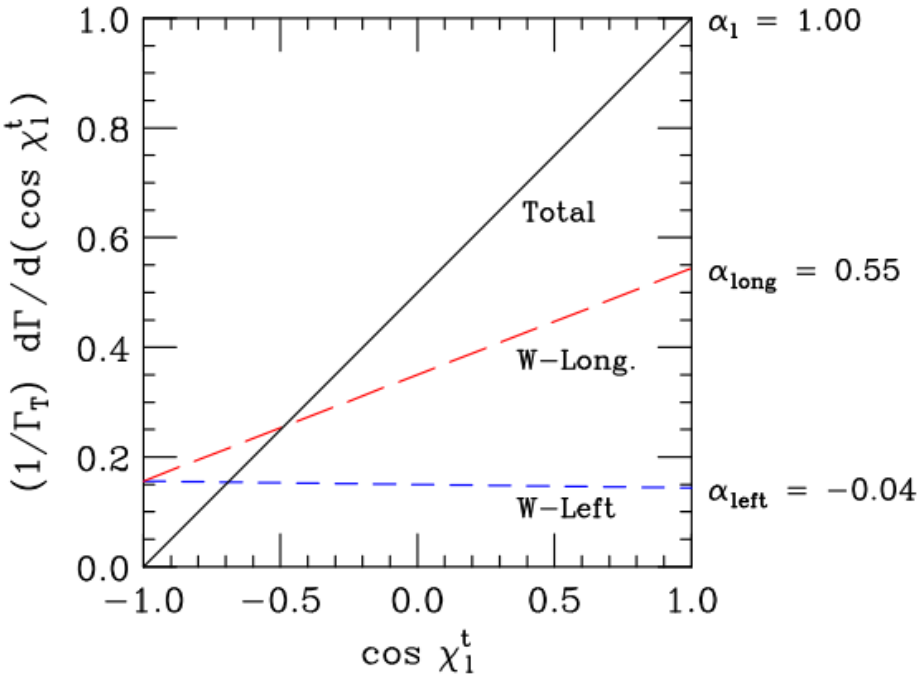
Taken from *Mahlon 2000*

Polarized Top

$$\alpha_l = 1?$$

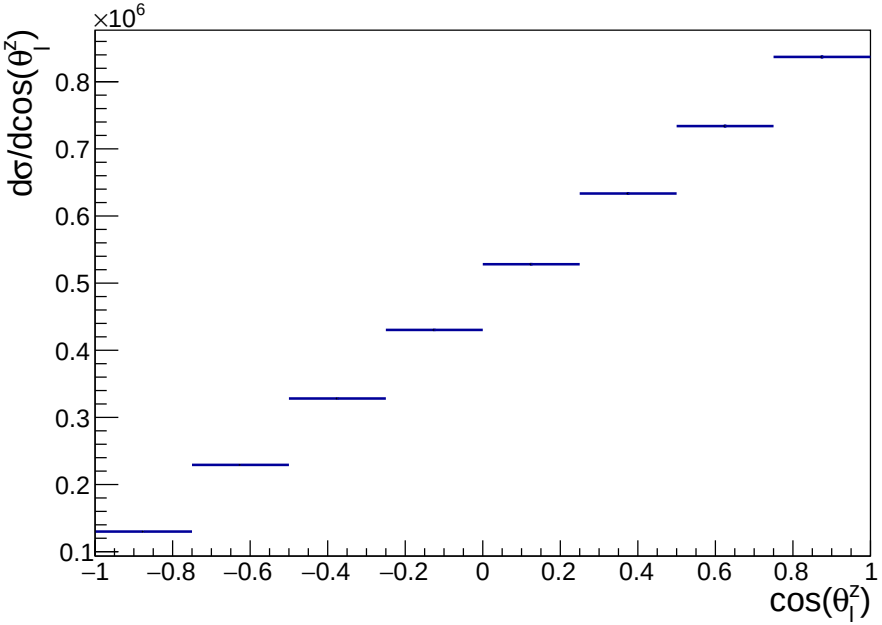


Polarized Top decay
(taken from Research Proposal)

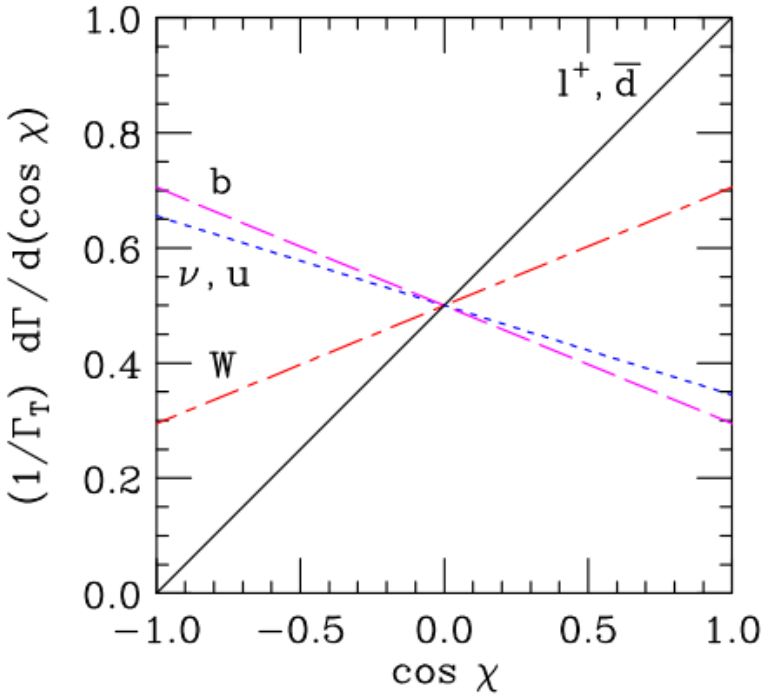


Interference between W helicity states
(taken from *Mahlon 2000*)

Polarized Top

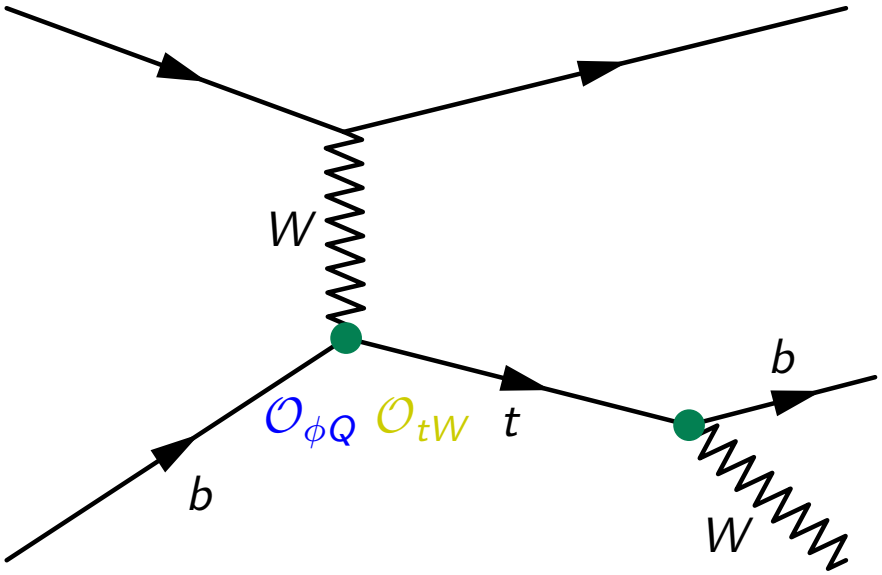


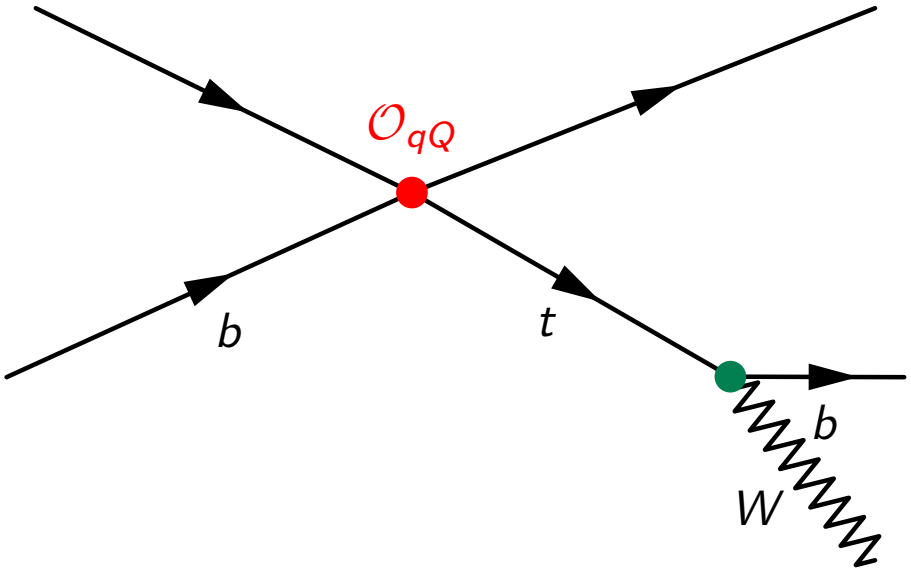
Angular correlation
of the charged lepton
from Monte Carlo pp collisions



Angular correlation of top spin

EFT in Single Top

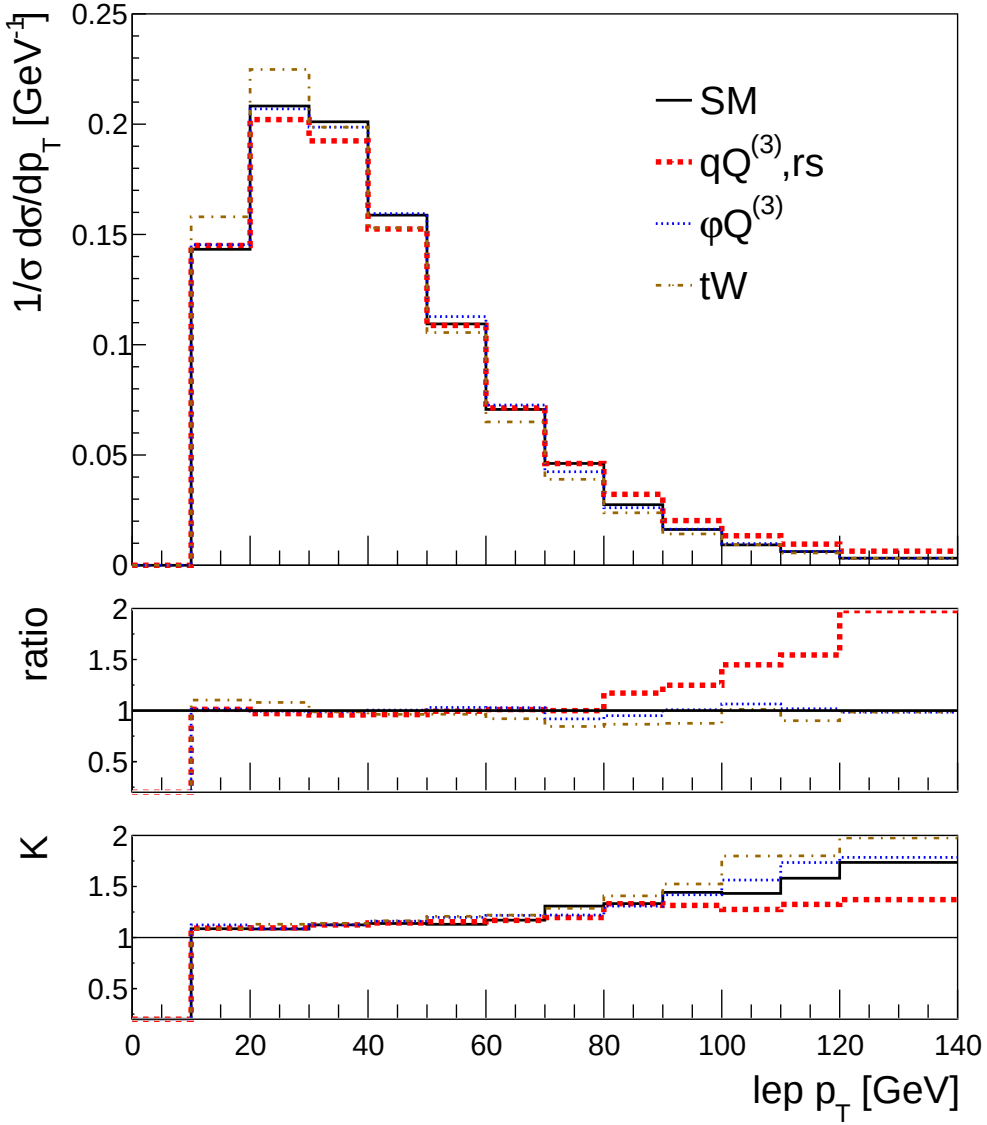




3 Operators:

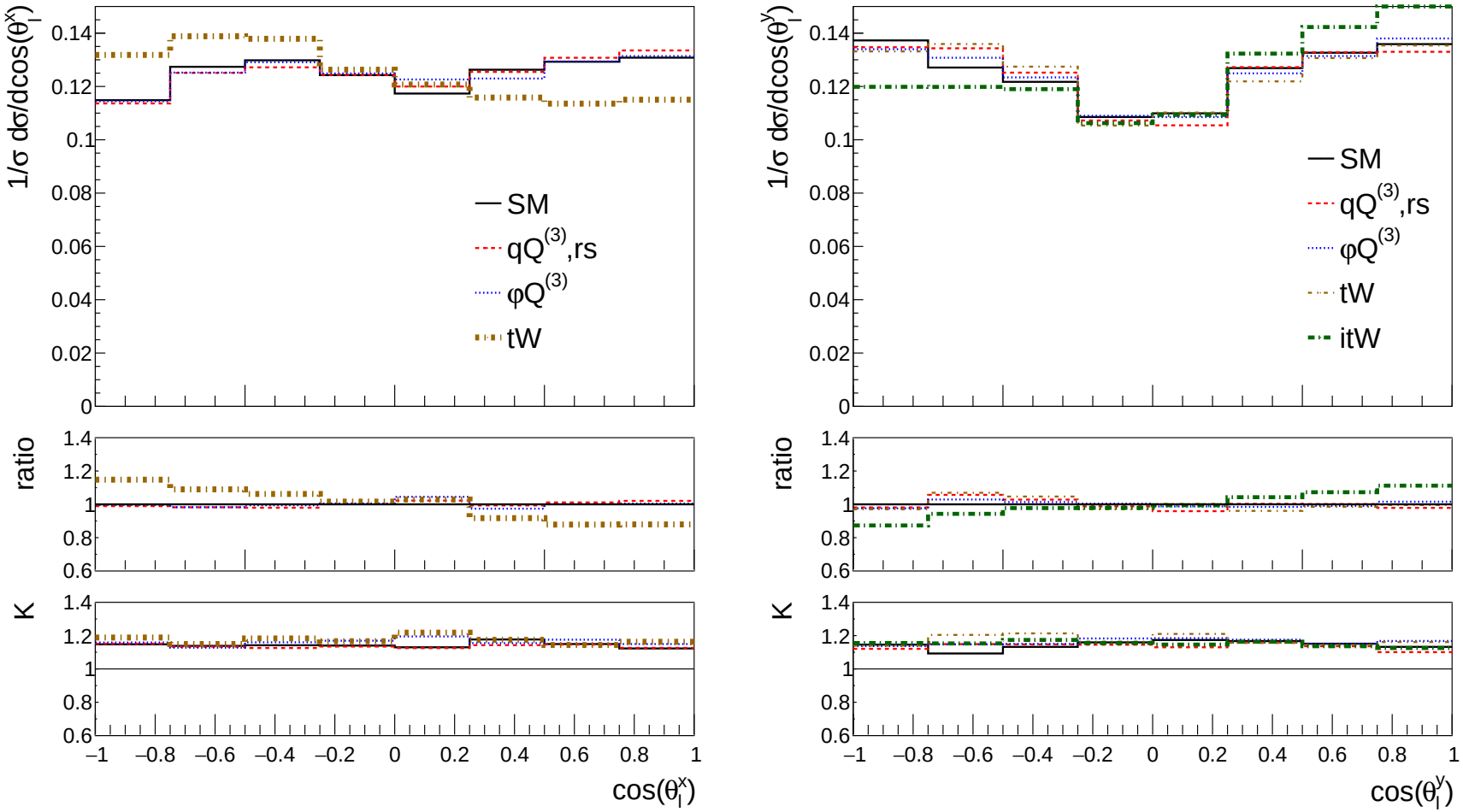
$\mathcal{O}_{qQ}$ $\mathcal{O}_{\phi Q}$ $\mathcal{O}_{tW}$

Sensitivity to NP



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

Sensitivity to NP



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

What is next?

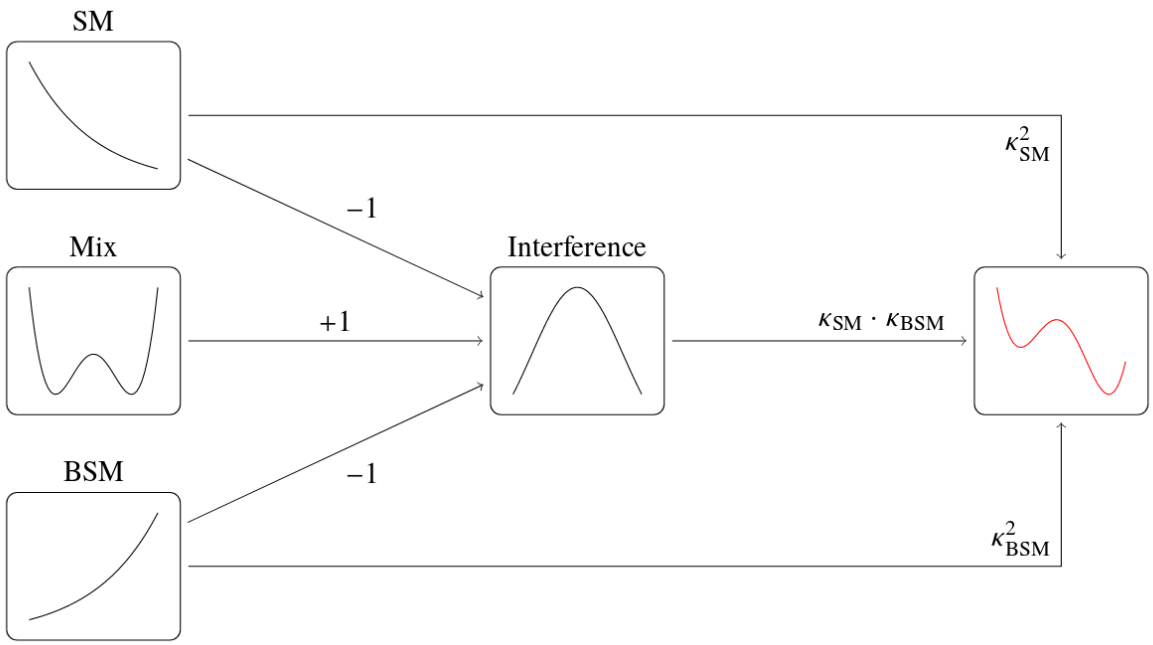
- Measurement in ATLAS
- We are good in measuring angles!
- Not possible to generate every coupling value
- Morphing!

Morphing

Modelling a continuous signal in a multidimensional space of coupling parameters

How does it work

- Generate template samples
- Obtain values for all the terms
- Reweigh each bin



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Summary

- EFT is the way to go in precision physics
  - Indirect search
  - Model independent
  - Incorporates symmetries
- Single Top is a rich process $\rightarrow$ Polarization Angles
- Sufficient sensitivity to New Physics
- Morphing technique to describe full coupling parameter space
- Measurement in ATLAS

Stay Tuned

Backup

Discussion

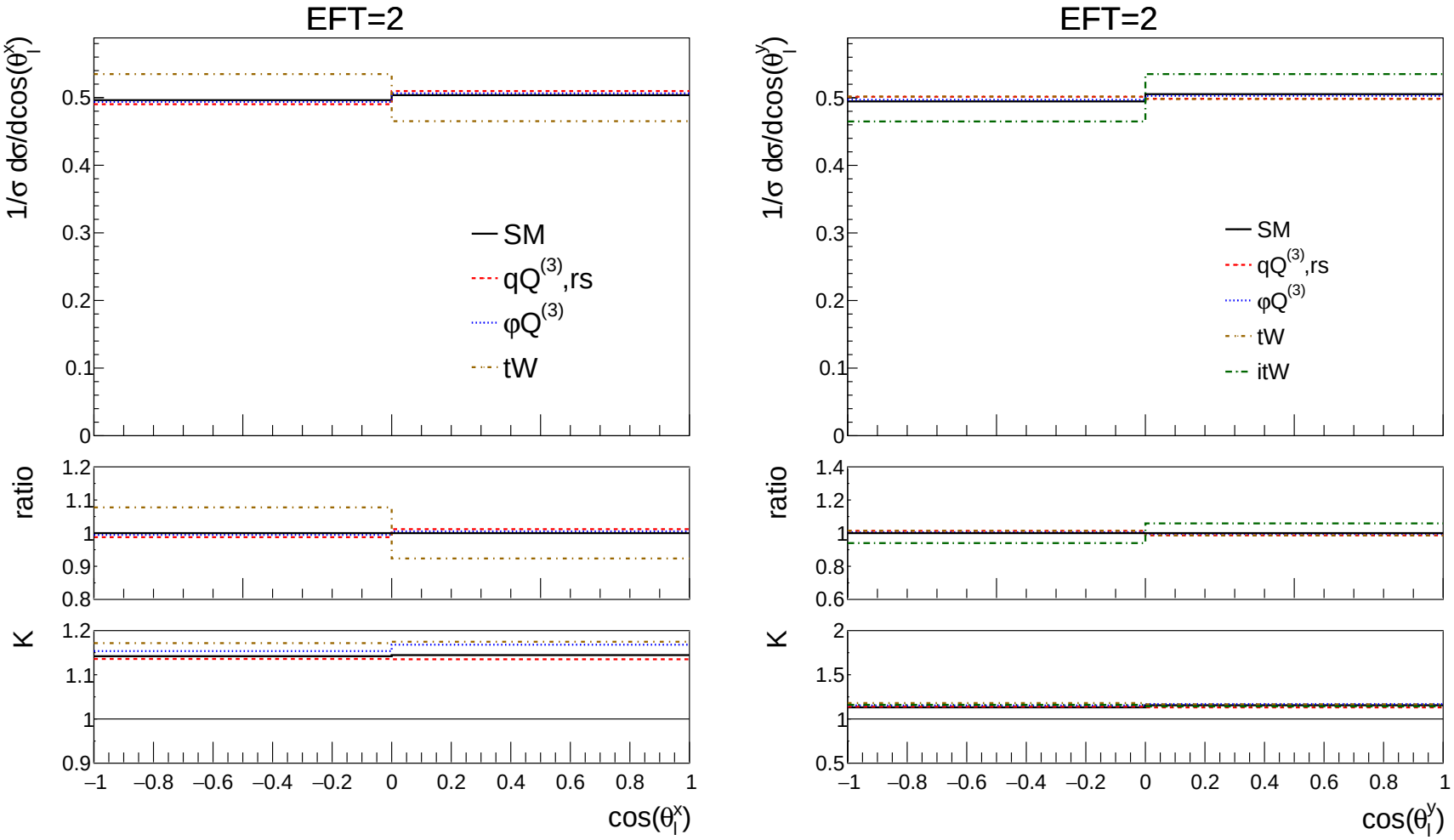
- Truth distributions
- Only scale + PDF uncertainties
- Background is SM t-channel only
- Selection cuts:
  - leptons: $p_T^l > 10$ GeV and $|\eta^l| < 2.47$
  - jets: $p_T^j > 20$ GeV and $|\eta^j| < 4.5$

Coupling values

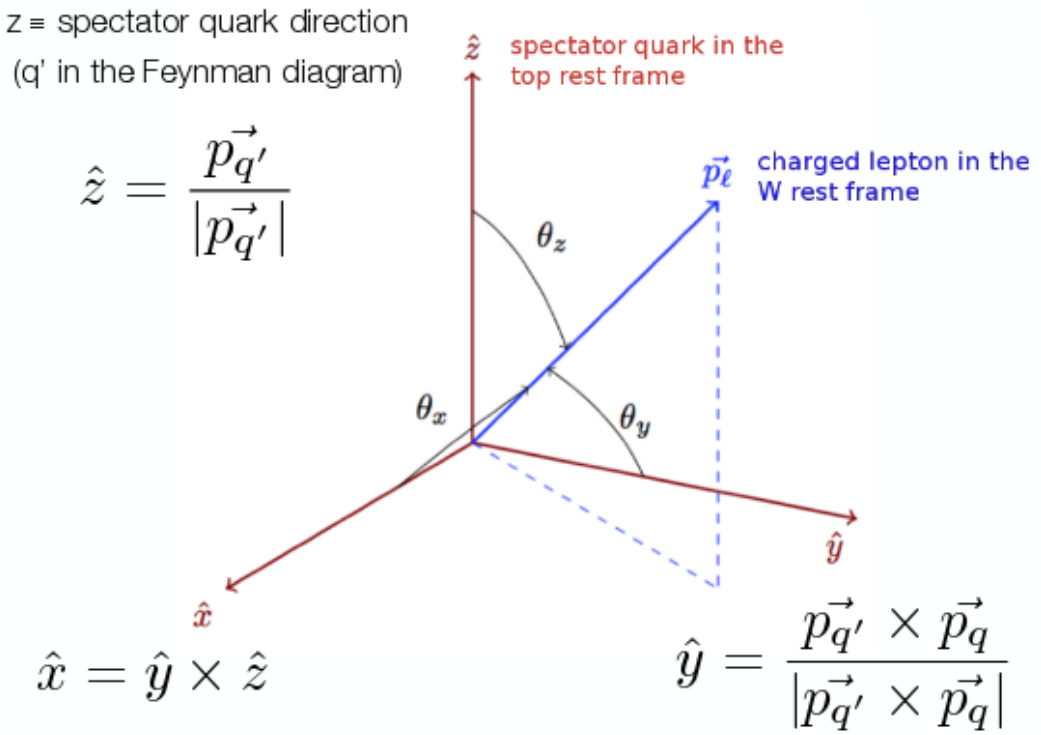
Operator	Coupling value	LO σ $\pm$scale $\pm$pdf [pb]	LO Γ_{top} [GeV]	NLO σ $\pm$scale $\pm$pdf [pb]	NLO Γ_{top} [GeV]
SM	-	$123\ \frac{+9.3\%}{-11.4\%}\ \frac{+8.9\%}{-8.9\%}$	1.49	$137\ \frac{+2.7\%}{-2.6\%}\ \frac{+1.2\%}{-1.2\%}$	1.36
$O_{\varphi Q}^{(3)}$	1	$137\ \frac{+9.3\%}{-11.4\%}\ \frac{+8.9\%}{-8.9\%}$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

The deviations lie within the uncertainty of recent single top measurements

Sensitive to NP



Polarized Top



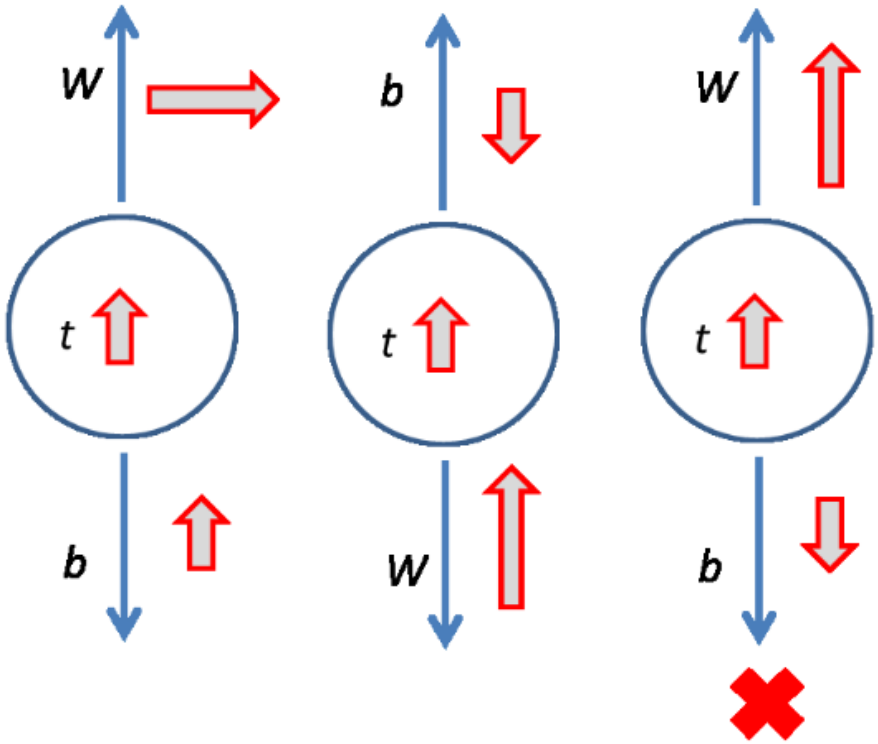
$\vec{p_q'}$ is the direction of the spectator quark and $\vec{p_q}$ is the direction of the initial quark which is taken as the beam axis

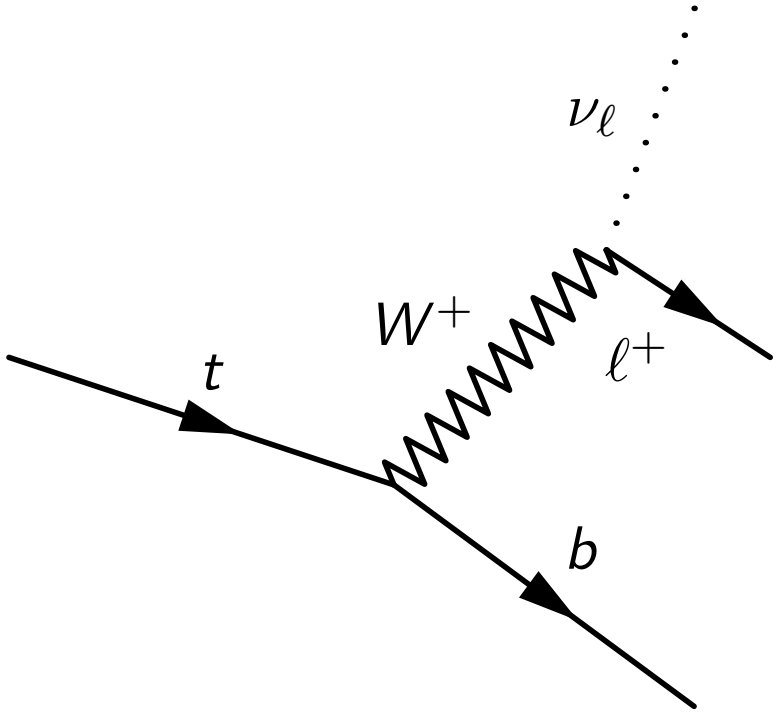
Aguilar 2014

W Helicity fractions

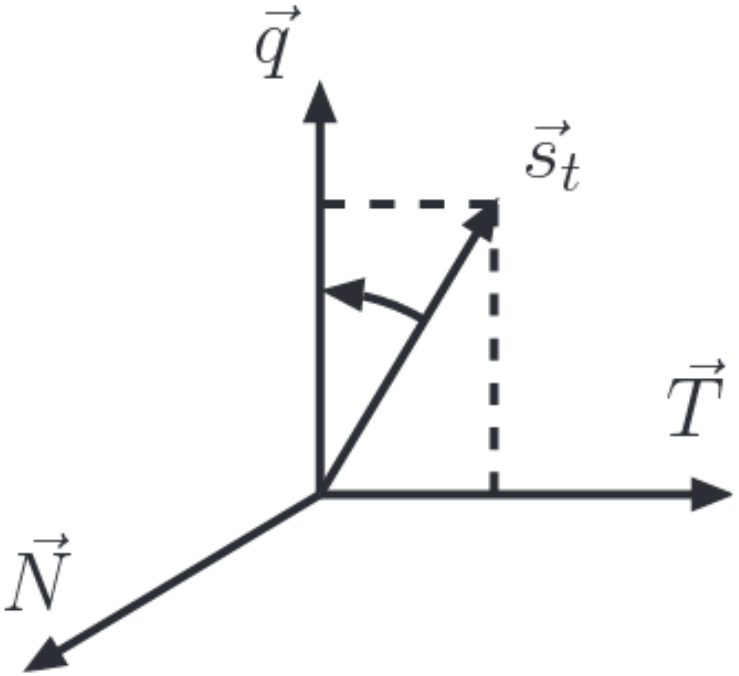
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta} = \frac{3}{8}\left(1+\cos\theta\right)^2 \cdot F_R + \frac{3}{8}\left(1-\cos\theta\right)^2 \cdot F_L + \frac{3}{4}\sin^2\theta \cdot F_0$$

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





W Helicity fractions



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

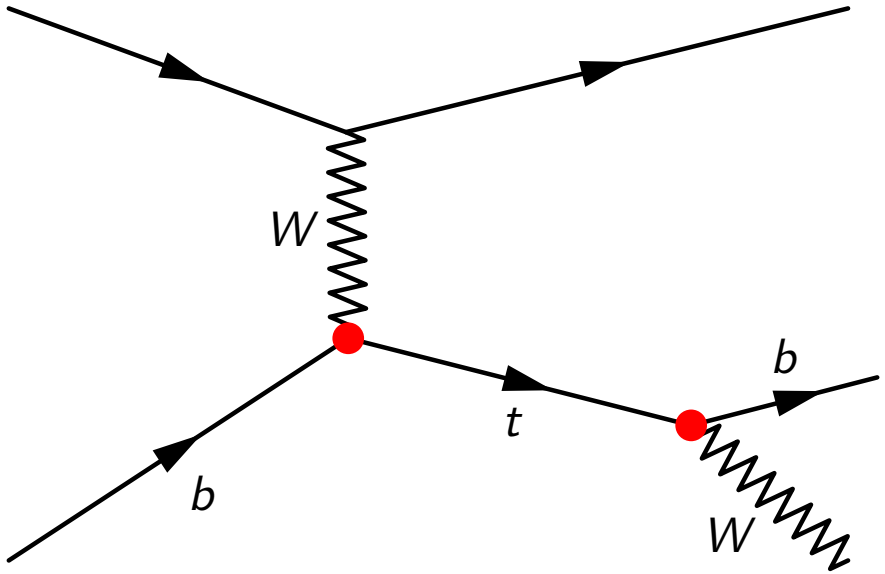
$$\hat{N} = \frac{\vec{s_t} \times \vec{q}}{|\vec{s_t} \times \vec{q}|}$$

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

$\vec{p_W}$ 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

EFT in Single Top



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

$$O_{tW} = y_t g_w(\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W^I_{\mu\nu} \quad (3)$$

$$O^{(3)}_{qQ,rs} = \left(\bar{q}_r\gamma^\mu\tau^I q_s\right)\left(\bar{Q}\gamma_\mu\tau^I Q\right) \quad (4)$$

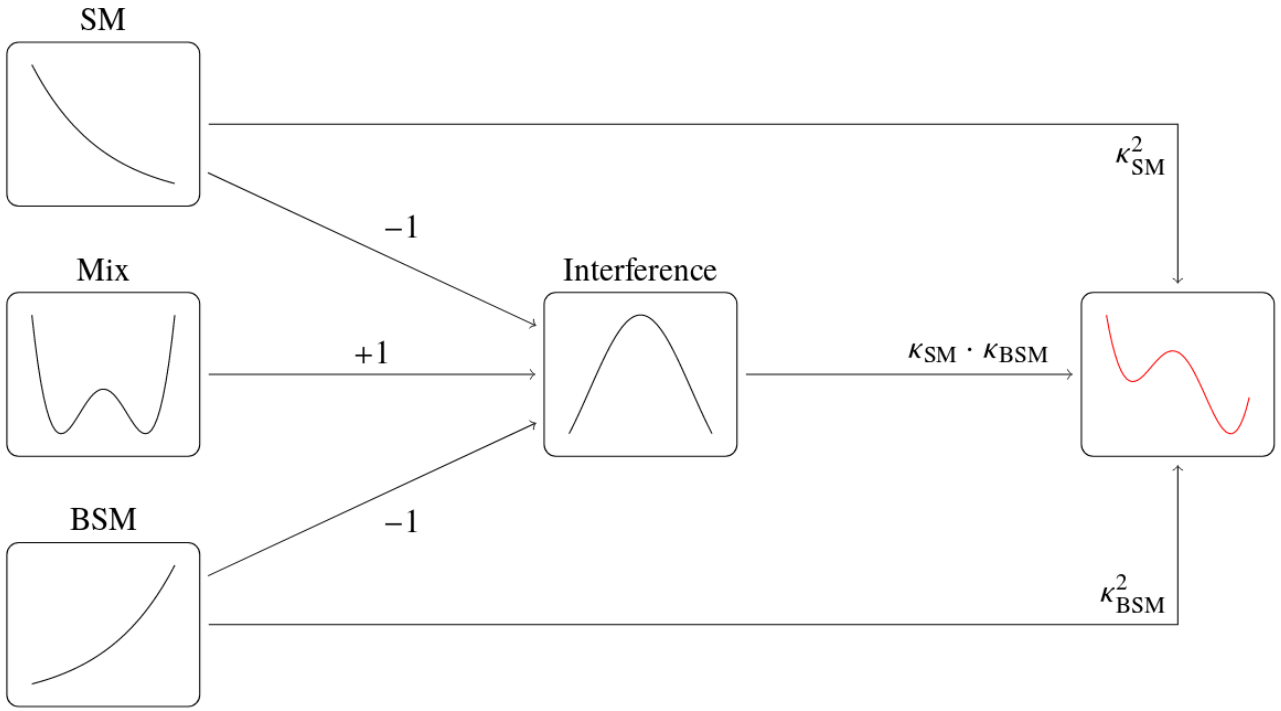
Using same notation as *Zhang 2016*

Morphing example

$$\mathcal{M}(g_{SM}, g_{BSM}) = g_{SM} \cdot O_{SM} + g_{BSM} \cdot O_{BSM}$$

$$|\mathcal{M}|^2 = SM^2 + BSM^2 + SM \cdot BSM$$

SM^2	BSM^2	$SM \cdot BSM$
1	0	0
0	1	0
1	1	1



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Morphing in Single Top

What do we have?

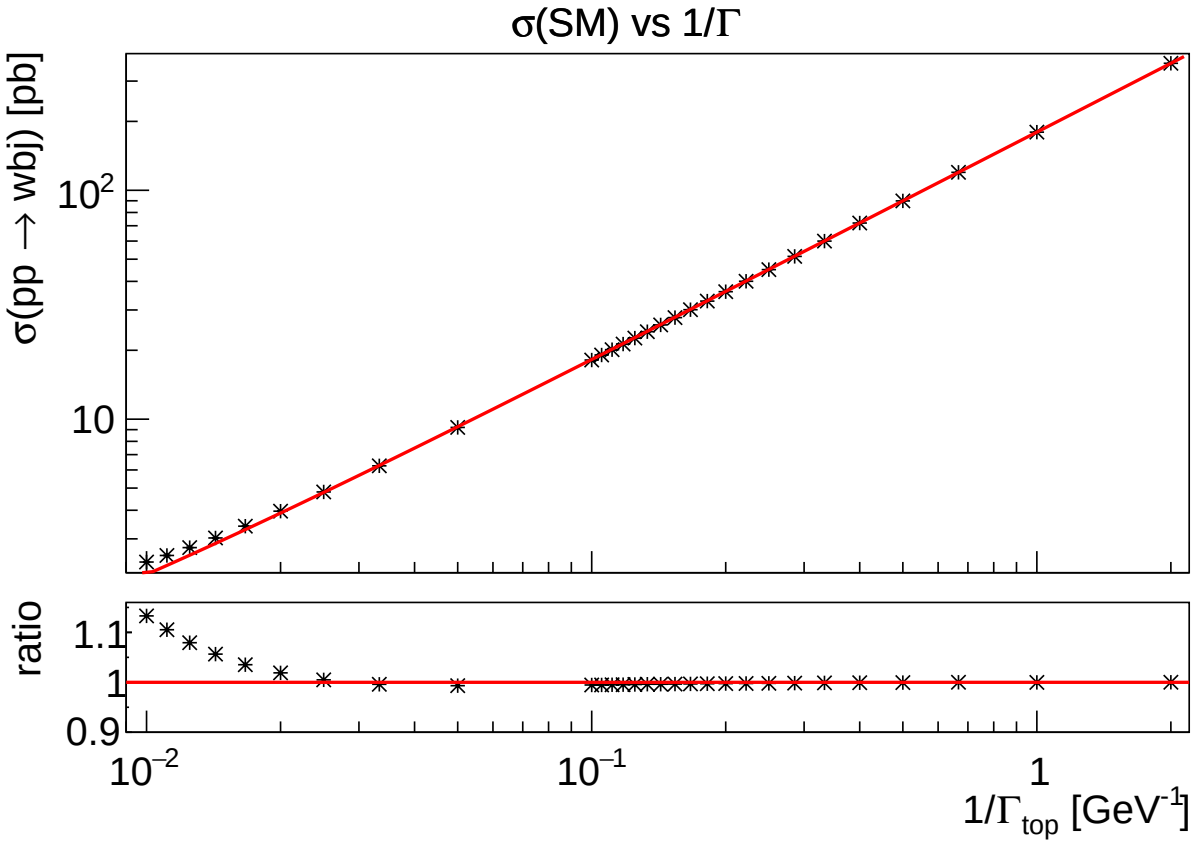
$$\mathcal{M} = \overbrace{(g_{SM}\mathcal{O}_{SM} + c_{tW}\mathcal{O}_{tW} + c_{\phi q}\mathcal{O}_{\phi q} + c_{qq}\mathcal{O}_{qq})}^{\text{production}} \cdot \overbrace{(g_{SM}\mathcal{O}_{SM} + c_{tW}\mathcal{O}_{tW} + c_{\phi q}\mathcal{O}_{\phi q})}^{\text{decay}}$$

Number of samples

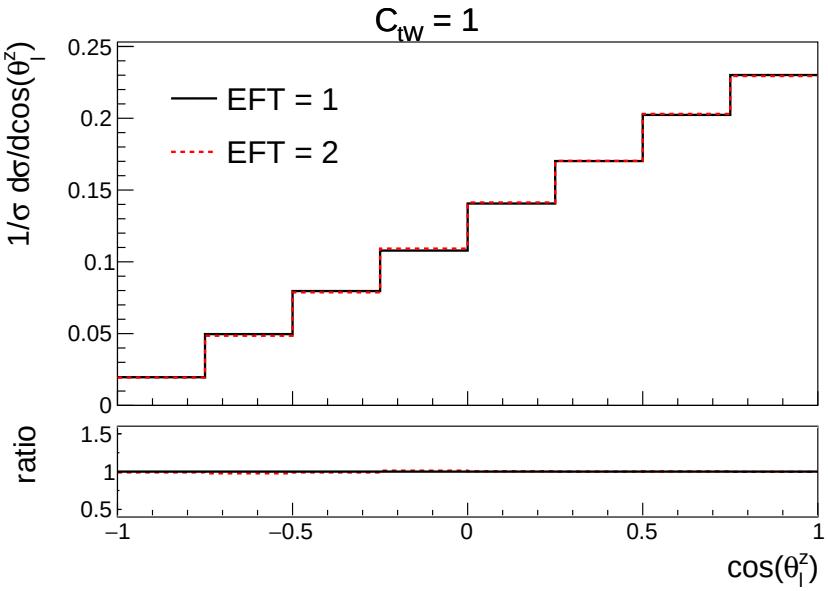
n_p	n_d	n_s	N
1	0	3	31

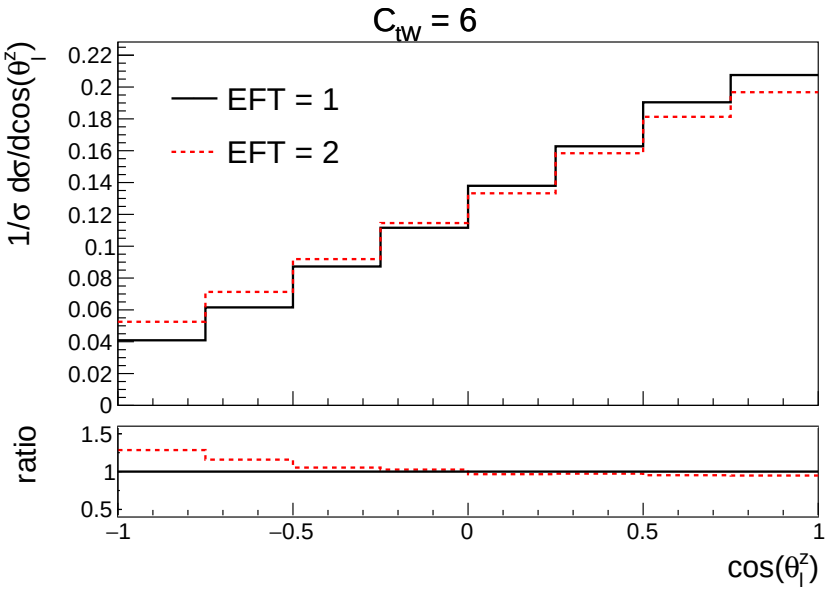
Narrow width approximation

$$\frac{1}{(p^2 - M_{\text{top}}^2)^2 + M_{\text{top}}^2 \Gamma_{\text{top}}^2} \xrightarrow{(\Gamma_{\text{top}}/M_{\text{top}} \to 0)} \frac{\pi}{M_{\text{top}} \Gamma_{\text{top}}} \delta(p^2 - M_{\text{top}}^2) \qquad (5)$$



Top width and multiple EFT insertions





Also a shape effect
Noticeable for high C

Top width and multiple EFT insertions

$$\sigma(pp \to Wbj) = \sigma(pp \to tj)\,\frac{\Gamma(t \to Wb)}{\Gamma_{\text{top}}} \tag{6}$$