Measurement of the complete top-quark polarization vector in t-channel single-top-quark production with ATLAS detector

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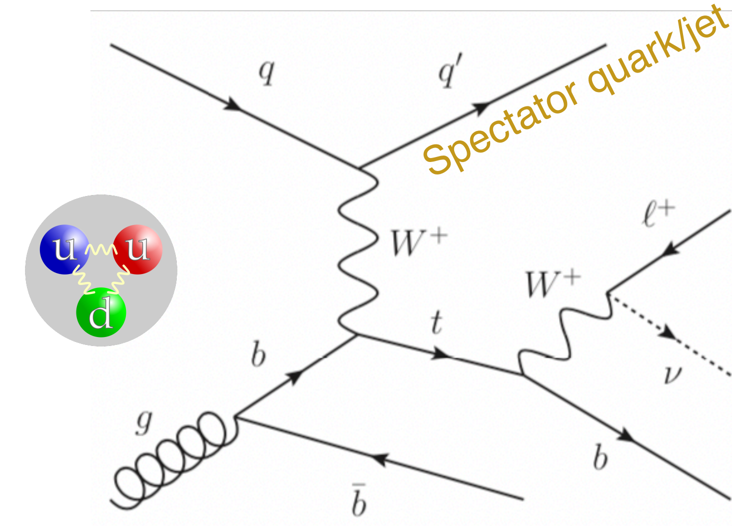
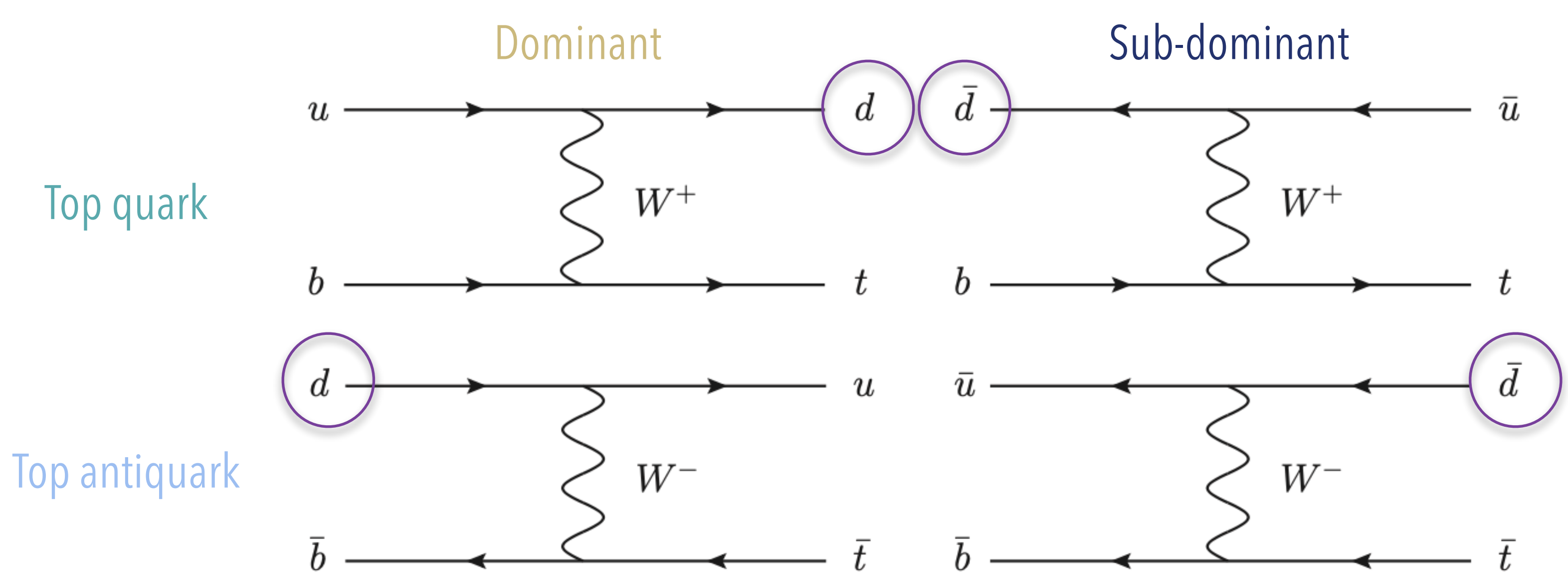
Top Quark Polarization - Introduction

At the LHC, in pp collision data...



- EW production: top quarks are highly spin-polarized due to V-A structure of EW interaction.
  - Top quark polarization can only be measured in single-top quark events.
  - t-channel is the dominant process.
- Detectable: top quark decays to an on-shell W boson before hadronization.
  - Decay products therefore preserves spin information of the top.
  - Accessible through the angular distributions.
- Spin polarization: depends upon the specific top-quark/antiquark sample.
  - Contributions from 4 subprocesses:



EW-produced single top quarks have their spin aligned with the direction of the down-type quarks

Top Quark Polarization - Introduction

Goal of Analysis

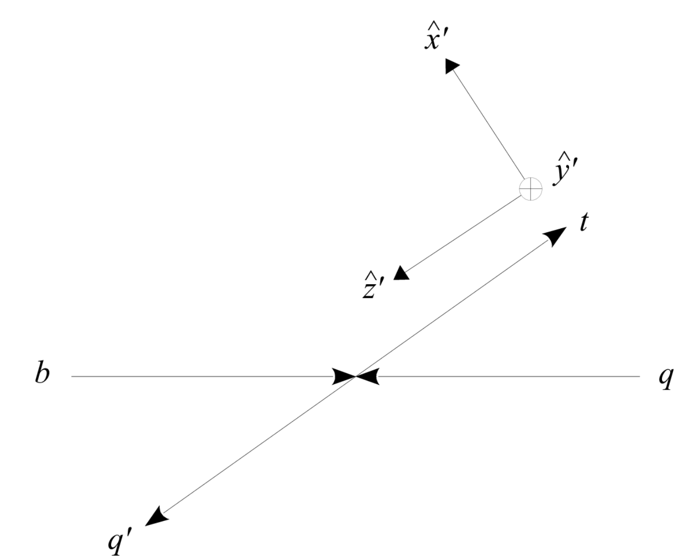
- Polarization of the top quark is determined through the angular distribution of its decay products.

$$\frac{1}{\Gamma}\frac{d\Gamma}{d(\cos\theta_l)} = \frac{1}{2}\left(1 + \alpha_l P \cos\theta_l\right)$$

- To perform a cut-based fiducial* measurement of the single top-quark polarization in *t*-channel with the full ATLAS Run II dataset at 13 TeV ($139 fb^{-1}$).
- A template fit method is devised to simultaneously measure the complete polarization vector (P_x, P_y, P_z).
- The polarization vectors of the top quark and antiquark are measured separately.
- The result is then compared to SM NLO predictions from Powheg-Box+Pythia8 generator.

Definitions

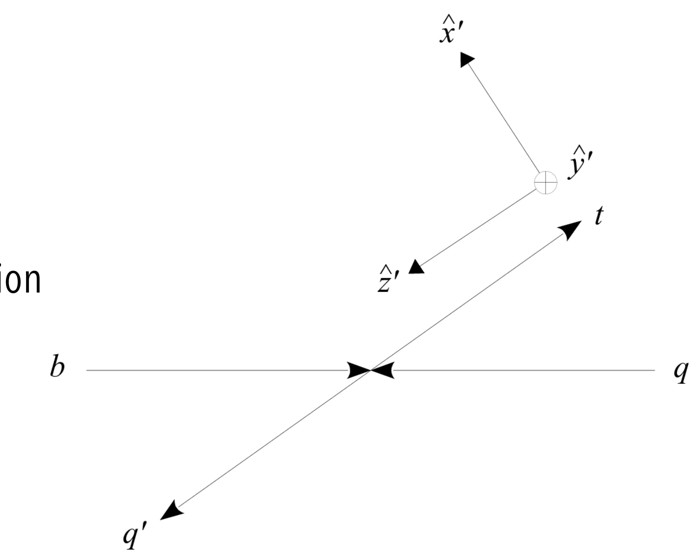
- The top spin axis is chosen to be the "spectator quark" momentum in the top rest frame.
- W boson and top quark are fully reconstructed.
- The lepton is chosen to be the primary analyzer ($\alpha_l \approx 1$). [Phys. Lett. B 539 (2002) 235]



* A fiducial region is designed to define the measurement in a model-independent way. The measurement corresponds to a phase space that is accessible to the experiment.

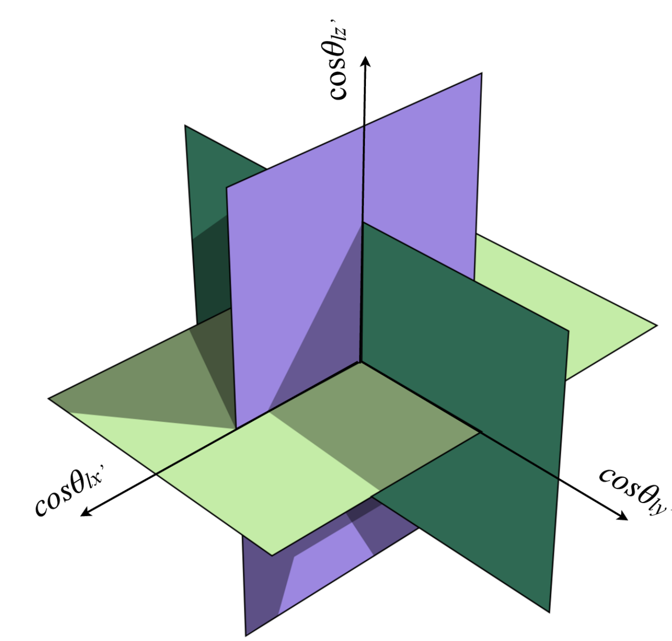
The Template Fit Strategy

- Construct 6 template t-channel samples consisting of purely polarized top quarks:
  - $P_x = \pm 1, P_y = \pm 1, P_z = \pm 1$.
  - Constructed using the *Polmanip* package:
    - Takes LHE file from Protos generator and re-decay the top quark into the final states according to the specified polarization



- Obtain sample of arbitrary polarization as a linear combination of the 6 templates.

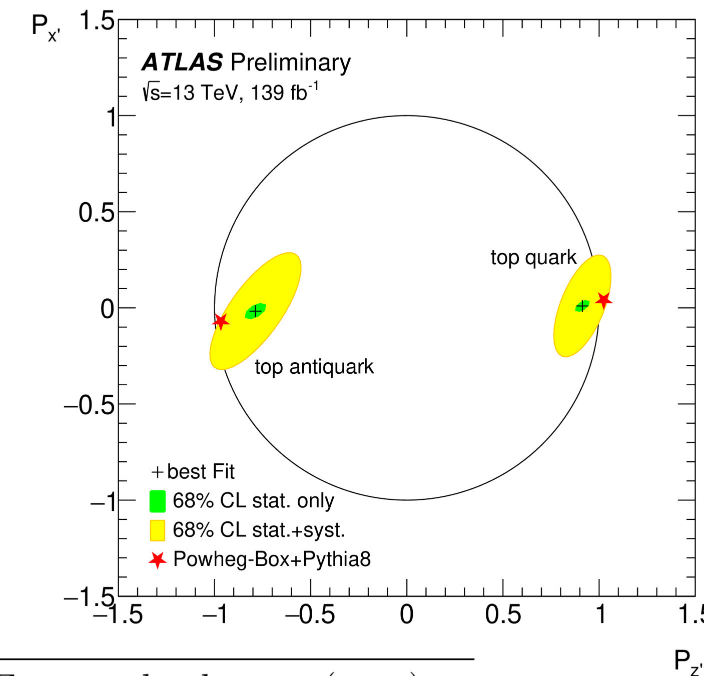
- Fit the angular distribution of lepton momentum to obtain the polarization in a given dataset
  - Octant variable $Q = 4\Theta(cos\theta_{lz} > 0) + 2\Theta(cos\theta_{lx} > 0) + \Theta(cos\theta_{ly} > 0)$
  - $\Theta(x)$ is the step function which is 1 for $x > 0$, 0 for $x \leq 0$.

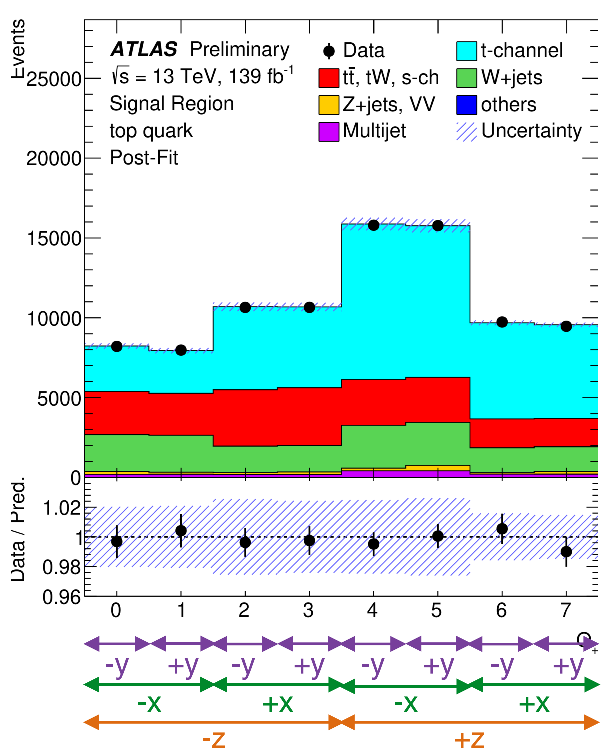


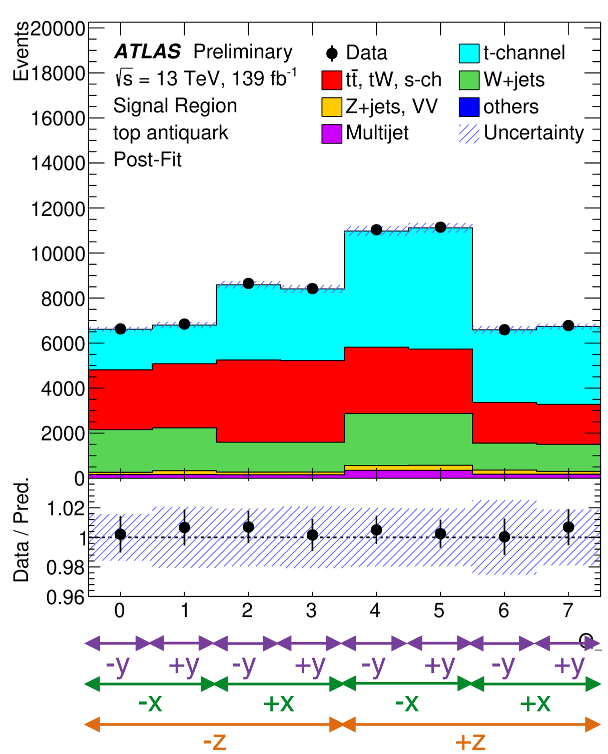
Top Quark Polarization - Results

The Template Fit Results [ATLAS-CONF-2021-027]

- Simultaneous fit of the top quark polarization $P(t)$ and top antiquark polarization $P(\bar{t})$ in cartesian coordinates:
  - 4 regions: 2 Signal Regions $(t, \bar{t})$, 2 Control Regions (W+jets, $t\bar{t}$) [See backup]
  - 6 polarization parameters + 3 normalizations
    - $P(t) = \{P_{x'}^{t}, P_{x'}^{t}, P_{x'}^{t}\}, P(\bar{t}) = \{P_{x'}^{\bar{t}}, P_{x'}^{\bar{t}}, P_{x'}^{\bar{t}}\}, N_{t-ch}, N_{t\bar{t}}$ and N_{W+jets}
  - Octant distribution Q to fit in SRs
    - Total yield from CRs split by sign of lepton charge also goes into the fit
  - Profile likelihood fit assuming no CP violation in background processes
    - average over P_y bins to avoid statistical problem





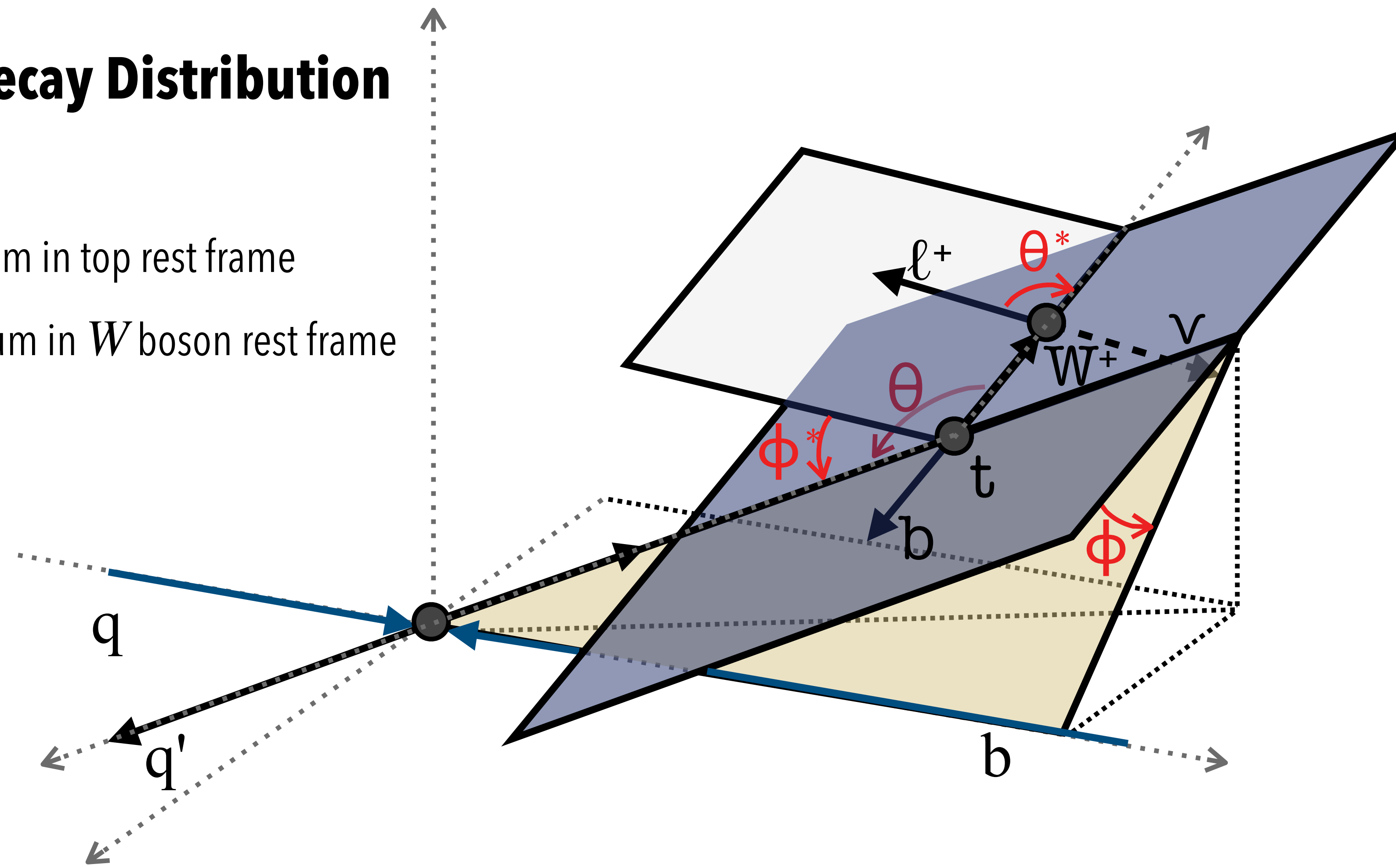


Parameter	Extracted value	(stat.)
t-channel norm.	$+1.045 \pm 0.022$	(± 0.006)
W+jets norm.	$+1.148 \pm 0.027$	(± 0.005)
$t\bar{t}$ norm.	$+1.005 \pm 0.016$	(± 0.004)
$P_{x'}^{t}$	$+0.01 \pm 0.18$	(± 0.02)
$P_{x'}^{\bar{t}}$	-0.02 ± 0.20	(± 0.03)
$P_{y'}^{t}$	-0.029 ± 0.027	(± 0.011)
$P_{y'}^{\bar{t}}$	-0.007 ± 0.051	(± 0.017)
$P_{z'}^{t}$	$+0.91 \pm 0.10$	(± 0.02)
$P_{z'}^{\bar{t}}$	-0.79 ± 0.16	(± 0.03)

Four Angle Analysis - Introduction

The Quadruple Differential Single-top Decay Distribution

- 4 angles:
  - polar/azimuthal angles (θ, ϕ) of W boson momentum in top rest frame
  - polar/azimuthal angles (θ^*, ϕ^*) of lepton momentum in W boson rest frame



- Fourier Transformation:
  - The 4-dimensional distribution ρ can be transformed into a set of coefficients $c^{j_1 j_2}_{m'm}$ [Eur. Phys. J. C (2017) 77:200]:

$$c^{j_1 j_2}_{m'm} = \int d\Omega d\Omega^* \rho(\phi, \theta, \phi^*, \theta^*) M^{j_1 j_2}_{m'm}(\phi, \theta, \phi^*, \theta^*)^*$$

  - where $M^{j_1 j_2}_{m'm}$ are orthonormal functions defined as:

$$M^{j_1 j_2}_{m'm}(\phi, \theta, \phi^*, \theta^*) = \frac{1}{4\pi}(2j_1 + 1)^{1/2}(2j_2 + 1)^{1/2} D^{j_1}_{m'm}(\phi, \theta, 0) D^{j_2}_{m0}(\phi^*, \theta^*, 0)$$

Four Angle Analysis - Introduction

Parameters of Interest (POIs)

- 4 untangled helicity fractions (3 independent params)
  - F_+ or $F_R = |a_{1,\frac{1}{2}}|^2/\mathcal{N}$
  - F_- or $F_L = |a_{-1,-\frac{1}{2}}|^2/\mathcal{N}$
  - $F_0^\pm = |a_{0,\pm\frac{1}{2}}|^2/\mathcal{N}$, $F_0 = F_0^+ + F_0^-$
- 2x2 phases of interference terms (top quark/antiquark separately):
  - $\delta_+ = \arg\, a_{1,\frac{1}{2}} a^*_{0,\frac{1}{2}}$, $\delta_- = \arg\, a_{-1,-\frac{1}{2}} a^*_{0,-\frac{1}{2}}$
- 3x2 polarization components (top quark/antiquark separately)
  - (P_x^t, P_y^t, P_z^t), $(P_x^{\bar{t}}, P_y^{\bar{t}}, P_z^{\bar{t}})$
- 13 real independent parameters in total
  - 24 measured M-function coefficients $c_{m'm}^{j_1 j_2}$ (see backup) –> well constrained measurement

$|t\rangle \to$

$\lvert W_L b_L\rangle$	$a_{-1,-1/2}$	F_-
$\lvert W_0 b_L\rangle$	$a_{0-1/2}$	F_0^-
$\lvert W_0 b_R\rangle$	$a_{0,+1/2}$	F_0^+
$\lvert W_R b_R\rangle$	$a_{+1,+1/2}$	F_+

$$F_+ + F_- + F_0^+ + F_0^- = 1$$

Previous Result (See backup)

- ATLAS measurement on LHC Run 1 7 TeV data [JHEP04(2016)023]
- ATLAS measurement on LHC Run 1 8 TeV data [JHEP12(2017)017]

Four Angle Analysis - Method

Effective Field Theory (EFT) Interpretation

- MadGraph (dim6top_UFO) LO single-top t-channel and $t\bar{t}$ EFT samples generated.
  - a grid of 582 points in the parameter space of 6 real EFT parameters: $c_{tW}, c_{icW}, c_{bW}, c_{ibW}, c_{\phi tb}, c_{qQ}$.
  - reweighing in MadGraph to reduce number of samples generated:
    - $w_{new} = \frac{|M_h^{new}|^2}{|M_h^{old}|^2} w_{old}$
- Scale the M-function coefficients at each reweighing point to NNLO:
  - $c^{j_1j_2}_{m'm}(\text{Rescaled}) = c^{j_1j_2}_{m'm}(\text{MG LO BSM}) \frac{c^{j_1j_2}_{m'm}(\text{Powheg NNLO})}{c^{j_1j_2}_{m'm}(\text{MG LO SM})}$
- Perform morphing on the 24 c's to fit the 6 EFT parameters at the reconstruction level.

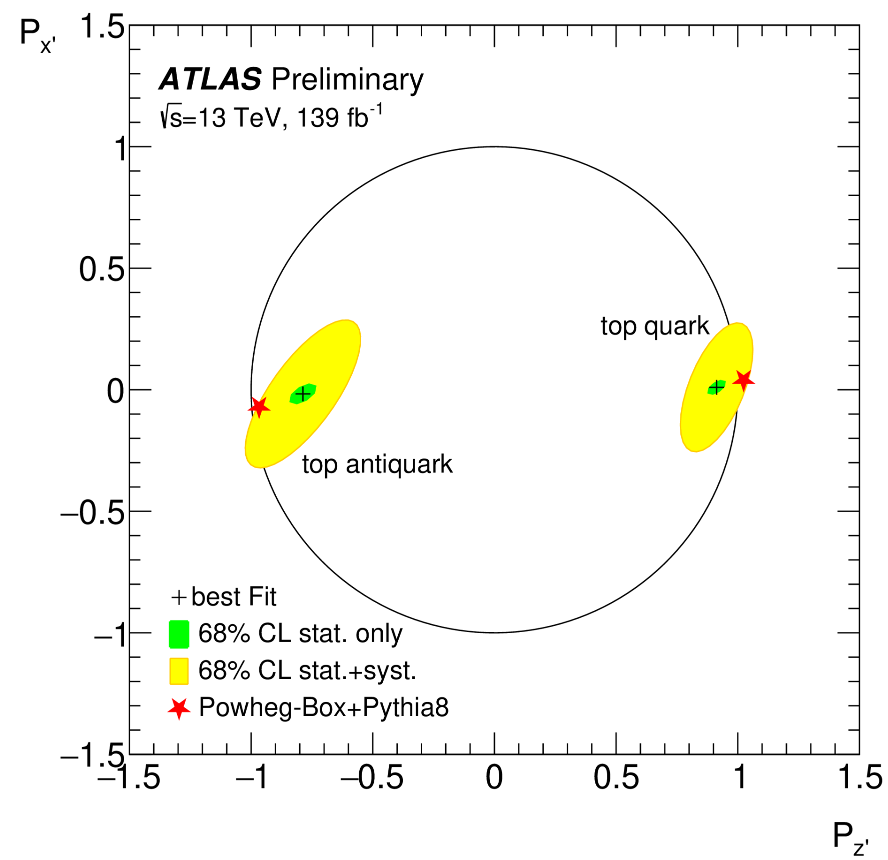
Kinematic Likelihood Fitter (KLFitter)

- A maximum likelihood fit for the neutrino, lepton and jet kinematics.
  - W & top mass, jet transfer functions, pT balance.
- Expected to perform much better than the previous algorithm.
  - Only takes W boson mass to solve a quadratic equation for the unknown longitudinal momentum of neutrino.

Conclusion

- The measurement of polarization vectors of top quark and antiquark in t-channel single-top events is presented.
  - The first measurement of separated complete top quark and antiquark polarization vectors.
  - Results measured with the ATLAS detector using the full LHC Run 2 dataset (139.0 fb^{-1}).
  - The measured polarization vectors are compatible with SM MC predictions within 68% C.L.

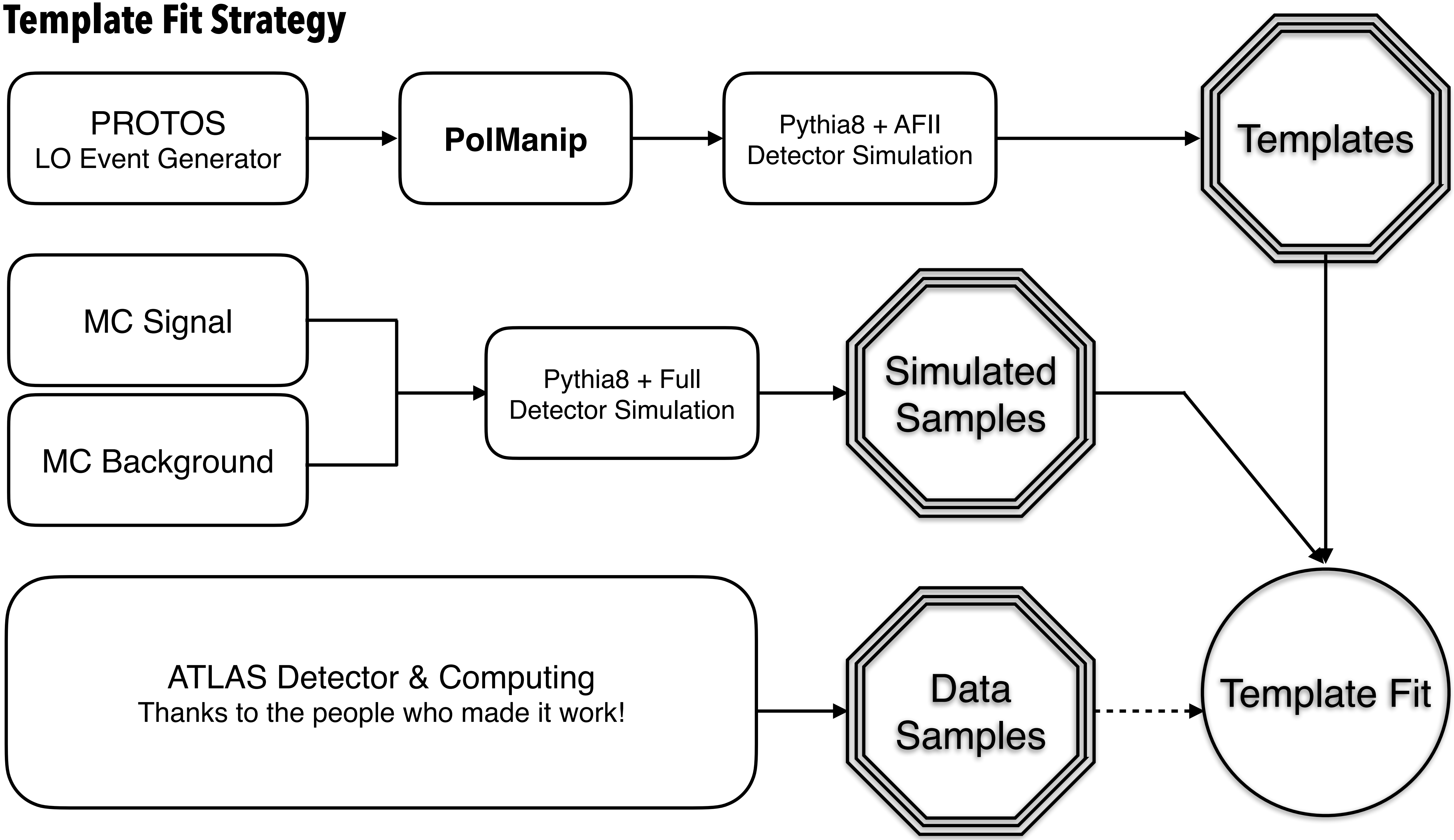
- The strategy of the quadruple differential decay rate of t-channel single-top events is presented.
  - The decay distribution is transformed into the M-function coefficients to extract physics parameters.
  - 13 POIs with 24 measured coefficients → well constrained measurement.
  - 6 real EFT parameters will be constrained using the morphing technique.
  - KLFitter will be implemented to better reconstruct the final state objects.



Backup

Top Quark Polarization - Introduction

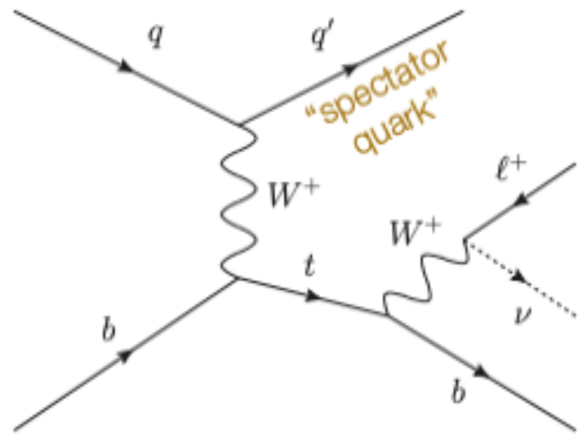
The Template Fit Strategy



Top Quark Polarization - Introduction

Event Selection Criteria - 4 Regions

- Preselection Region (PR)
- Selection Region (SR)
- W+jets Control Region = PR - SR
- Ttbar Control Region = PR with 2 b-jets and no light-jets

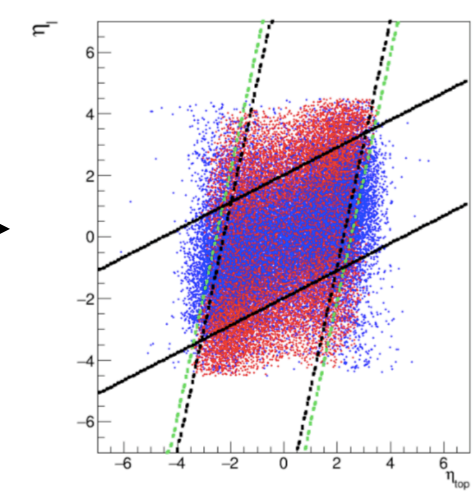


Multijet Estimation

- Mixed data-MC driven jet-electron model
  - Dijet sample
  - Convert a low EM fraction jet into a fake electron
- Data-driven anti-muon model

- PR Cuts
  - **Exactly 1 tight charged lepton (l)**
    - pT > 30 GeV, $|\eta| < 2.5$
    - Secondary loose charged lepton veto @ pT > 10 GeV
  - **Exactly 1 b-tagged jet (b)**
    - pT > 30 GeV, $|\eta| < 2.5$
  - **Exactly 1 non-b-tagged jet (j)**
    - pT > 30 GeV, $|\eta| < 4.5$
    - pT > 35 GeV for transition region $2.75 <= |\eta| < 3.5$
  - **MET > 35 GeV**
  - **m_T(l,MET) or MTW > 60 GeV**
  - **Additional Multijet Rejection**
    - "triangular cut"

- SR Cuts
  - **PR**
  - **$m_{l,b}$ < 153 GeV**
  - **$m_t \in$ [120.6, 234.6] GeV**
  - **Trapezoidal cut for η_{top} vs. η_j** →
  - **m(j,top) > 280 GeV**
  - **H_T > 170 GeV**
    - pT(l) + pT(j) + pT(b) + MET



Signal
Background

Four Angle Analysis - Introduction

24 Non-zero M-function coefficients from LO calculations [Eur. Phys. J. C (2017) 77:200]**:**

$$c^{00}_{00} = \frac{1}{4\pi},$$

$$c^{10}_{00} = \frac{1}{4\sqrt{3}\pi} P_z \left[|a_{1\frac{1}{2}}|^2 - |a_{0\frac{1}{2}}|^2 + |a_{0-\frac{1}{2}}|^2 - |a_{-1-\frac{1}{2}}|^2 \right] / \mathcal{N},$$

$$c^{10}_{10} = -(c^{10}_{-10})^* = -\frac{1}{4\sqrt{6}\pi}(P_x + iP_y) \times \left[|a_{1\frac{1}{2}}|^2 - |a_{0\frac{1}{2}}|^2 + |a_{0-\frac{1}{2}}|^2 - |a_{-1-\frac{1}{2}}|^2 \right] / \mathcal{N},$$

$$c^{01}_{00} = \lambda \frac{\sqrt{3}}{8\pi} \left[|a_{1\frac{1}{2}}|^2 - |a_{-1-\frac{1}{2}}|^2 \right] / \mathcal{N},$$

$$c^{11}_{00} = \lambda \frac{1}{8\pi} P_z \left[|a_{1\frac{1}{2}}|^2 + |a_{-1-\frac{1}{2}}|^2 \right] / \mathcal{N},$$

$$c^{11}_{10} = -(c^{11}_{-10})^* = -\lambda \frac{1}{8\sqrt{2}\pi}(P_x + iP_y) \left[|a_{1\frac{1}{2}}|^2 + |a_{-1-\frac{1}{2}}|^2 \right] / \mathcal{N},$$

$$c^{11}_{01} = (c^{11}_{0-1})^* = \lambda \frac{1}{4\sqrt{2}\pi} P_z \left[a_{0\frac{1}{2}} a^*_{1\frac{1}{2}} + a_{-1-\frac{1}{2}} a^*_{0-\frac{1}{2}} \right] / \mathcal{N},$$

$$c^{11}_{11} = -(c^{11}_{-1-1})^* = -\lambda \frac{1}{8\pi}(P_x + iP_y) \left[a_{0\frac{1}{2}} a^*_{1\frac{1}{2}} + a_{-1-\frac{1}{2}} a^*_{0-\frac{1}{2}} \right] / \mathcal{N},$$

$$c^{11}_{1-1} = -(c^{11}_{-11})^* = -\lambda \frac{1}{8\pi}(P_x + iP_y) \left[a_{1\frac{1}{2}} a^*_{0\frac{1}{2}} + a_{0-\frac{1}{2}} a^*_{-1-\frac{1}{2}} \right] / \mathcal{N},$$

$$c^{02}_{00} = \frac{1}{8\sqrt{5}\pi} \times \left[|a_{1\frac{1}{2}}|^2 - 2|a_{0\frac{1}{2}}|^2 - 2|a_{0-\frac{1}{2}}|^2 + |a_{-1-\frac{1}{2}}|^2 \right] / \mathcal{N},$$

$$c^{12}_{00} = \frac{1}{8\sqrt{15}\pi} P_z \times \left[|a_{1\frac{1}{2}}|^2 + 2|a_{0\frac{1}{2}}|^2 - 2|a_{0-\frac{1}{2}}|^2 - |a_{-1-\frac{1}{2}}|^2 \right] / \mathcal{N},$$

$$c^{12}_{10} = -(c^{12}_{-10})^* = -\frac{1}{8\sqrt{30}\pi}(P_x + iP_y) \times \left[|a_{1\frac{1}{2}}|^2 + 2|a_{0\frac{1}{2}}|^2 - 2|a_{0-\frac{1}{2}}|^2 - |a_{-1-\frac{1}{2}}|^2 \right] / \mathcal{N},$$

$$c^{12}_{01} = (c^{12}_{0-1})^* = \frac{1}{4\sqrt{10}\pi} P_z \left[a_{0\frac{1}{2}} a^*_{1\frac{1}{2}} - a_{-1-\frac{1}{2}} a^*_{0-\frac{1}{2}} \right] / \mathcal{N},$$

$$c^{12}_{11} = -(c^{12}_{-1-1})^* = -\frac{1}{8\sqrt{5}\pi}(P_x + iP_y) \left[a_{0\frac{1}{2}} a^*_{1\frac{1}{2}} - a_{-1-\frac{1}{2}} a^*_{0-\frac{1}{2}} \right] / \mathcal{N},$$

$$c^{12}_{1-1} = -(c^{12}_{-11})^* = -\frac{1}{8\sqrt{5}\pi}(P_x + iP_y) \left[a_{1\frac{1}{2}} a^*_{0\frac{1}{2}} - a_{0-\frac{1}{2}} a^*_{-1-\frac{1}{2}} \right] / \mathcal{N}.$$

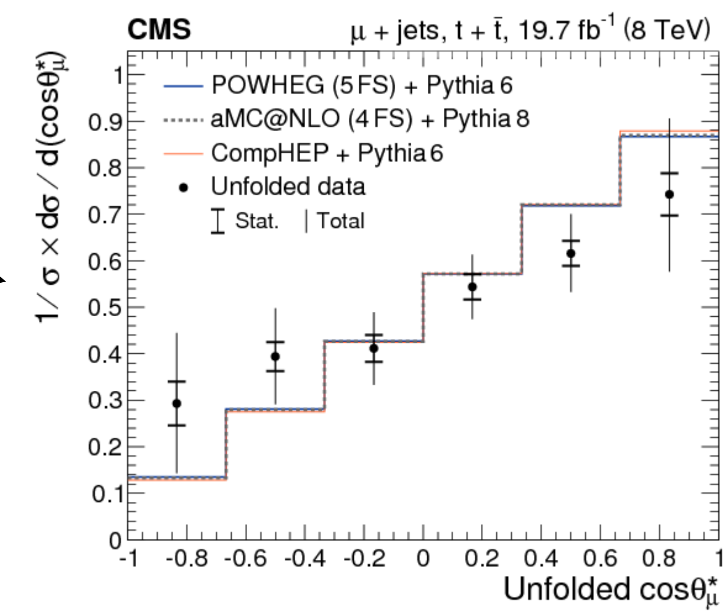
ttbar measurements

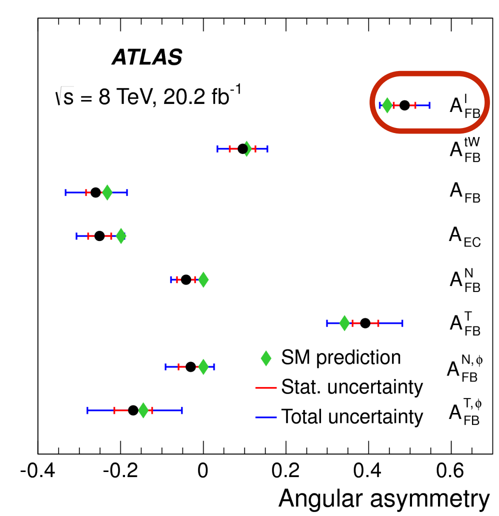
3-angle analysis

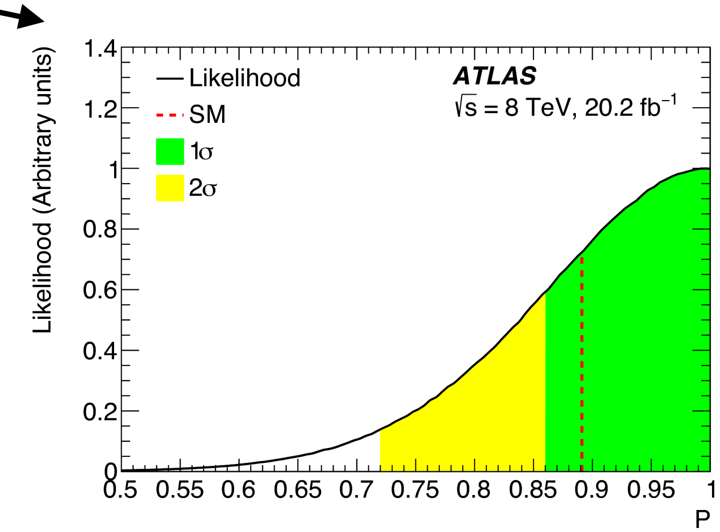
4-angle analysis

Previous analyses

- In 2016, CMS published the first measurement of the top polarization in t-channel at 8 TeV [JHEP04(2016)073].
  - represented by a differential distribution of the top cross section as a function of cosθ_l.
  - θ_l is the angle of lepton momentum in the top quark rest frame.
  - reported a smaller than expected polarization
    - $A_\mu = 0.26 \pm 0.03(stat.) \pm 0.10(syst.) \rightarrow P_z = 0.52 \pm 0.21$.
    - compared to SM predicted $A_\mu = 0.44$ or $P_z = 0.88$. (p-value = 4.6%)
- In 2017, ATLAS published two polarization measurements at 8 TeV.
  - both are consistent with the expected high polarization:
    - $P_z > 0.72$ @ 95% C.L., $P_z > 0.86$ @ 68% C.L. [JHEP12(2017)017]
    - $P_z = 0.98 \pm 0.12$. [JHEP04(2017)124]
- For all the previous analyses:
  - Only the P_z component was measured.
  - Top quark/antiquark data were not separated.
  - unfolded to parton level
    - Both detected/undetected top quarks were taken into account







Four-Angle Analysis - Previous Results

ATLAS measurement in 2017 [JHEP12(2017)017]

- Triple differential angular decay rate → 8 coefficients measured
- Helicity fractions, interference phase $\delta\_$ and polarization P_z measured → 5 POIs
    - Top quark and antiquark combined
- EFT fit on 3 independent anomalous couplings
    - One-to-one correspondence to the Wilson coefficients in the new analysis

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}\left(V_L P_L + V_R P_R\right) t W_\mu^- - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}}{M_W} q_\nu \left(g_L P_L + g_R P_R\right) t W_\mu^- + \text{h.c.}$$

$$V_L = V_{tb} + C_{\phi q}^{(3,3+3)*}\frac{v^2}{\Lambda^2} \qquad V_R = \frac{1}{2}C_{\phi\phi}^{33*}\frac{v^2}{\Lambda^2} \qquad g_L = \sqrt{2}C_{dW}^{33*}\frac{v^2}{\Lambda^2} \qquad g_R = \sqrt{2}C_{uW}^{33}\frac{v^2}{\Lambda^2}$$