DIS 2021

Measurements of the top quark electro-weak couplings with the ATLAS experiment at the LHC

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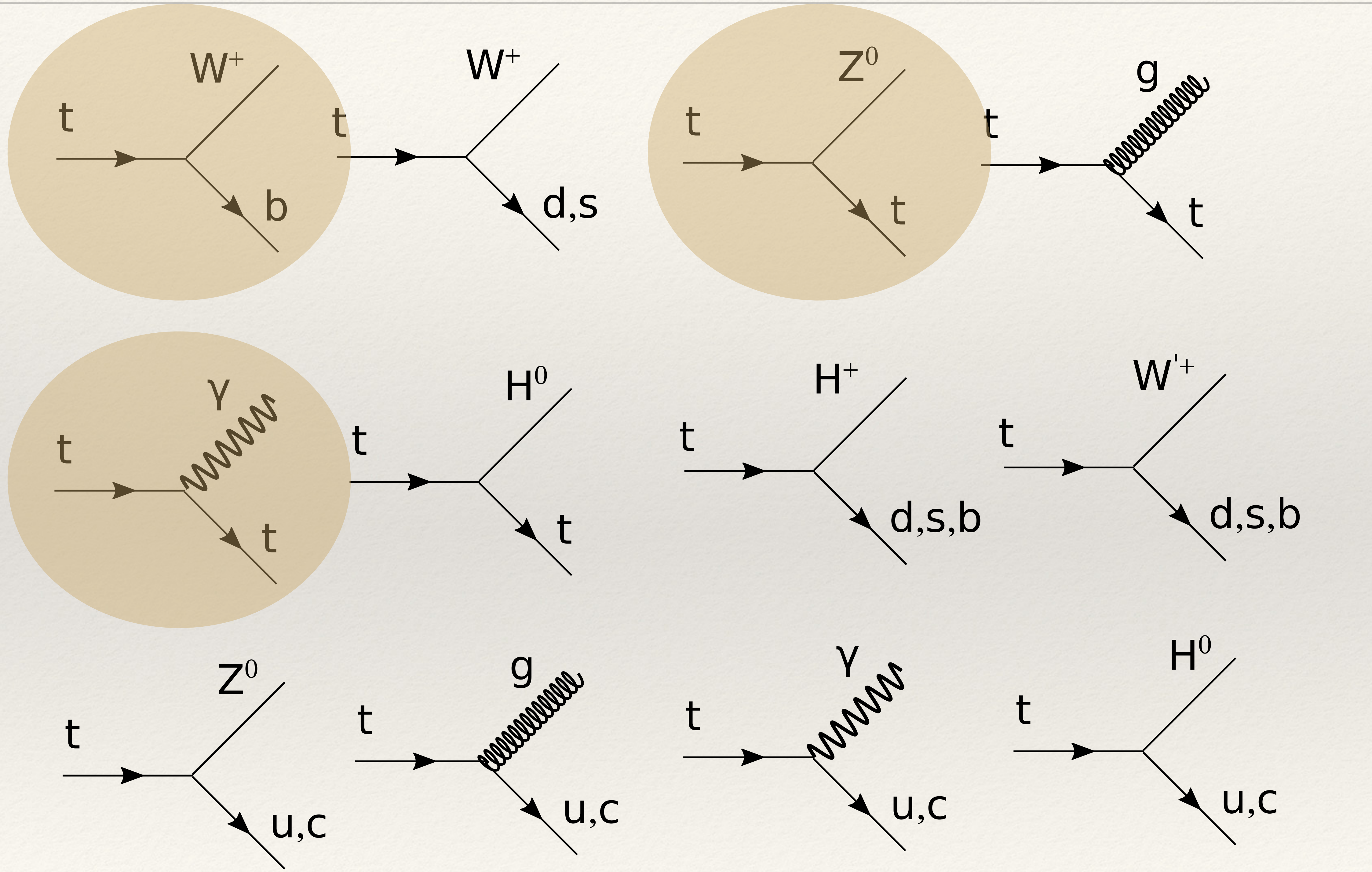
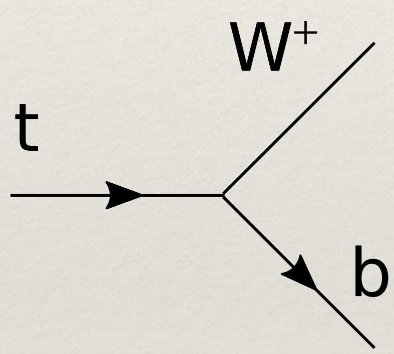
Catalogue of standard & exotic processes involving the top quark. Top physics program is concerned with all of these. This talk puts the spotlight on EW vertices.



EFT, anomalous couplings & the Wtb vertex

The effect of BSM physics at a high mass scale Λ is parameterized using higher dimensional operators

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum c_i \mathcal{O}_i + \ldots$$



$$\mathcal{O}_{\phi q}^{3(ij)} = \left(\phi^\dagger \overleftrightarrow{D}^I_\mu \phi\right)\left(\bar{q}_i \gamma^\mu \tau^I q_j\right)$$
$$\mathcal{O}_{\phi ud}^{(ij)} = \left(\tilde{\phi}^\dagger D^\mu \phi\right)\left(\bar{u}_i \gamma^\mu \tau^I d_j\right)$$
$$\mathcal{O}_{uW}^{(ij)} = \left(\bar{q}_i \sigma^{\mu\nu} \tau^I u_j\right)\tilde{\phi} W^I_{\mu\nu}$$
$$\mathcal{O}_{dW}^{(ij)} = \left(\bar{q}_i \sigma^{\mu\nu} \tau^I d_j\right)\phi W^I_{\mu\nu}$$

After EW symmetry breaking, for 3rd generation

$$\mathcal{O}_{\phi q}^{3} \to -\frac{gv^2}{\sqrt{2}}\bar{b}_L \gamma^\mu t_L W^-_\mu$$
$$\mathcal{O}_{\phi tb} = \left[\frac{gv^2}{2\sqrt{2}}\bar{b}_R \gamma^\mu t_R W^-_\mu\right]^\dagger$$
$$\mathcal{O}_{tW} = 2v\bar{b}_L i\sigma^{\mu\nu} q_\nu t_R W^-_\mu$$
$$\mathcal{O}_{bW} = \left[2v\bar{b}_R i\sigma^{\mu\nu} q_\nu t_L W^-_\mu\right]^\dagger$$

Anomalous couplings:

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

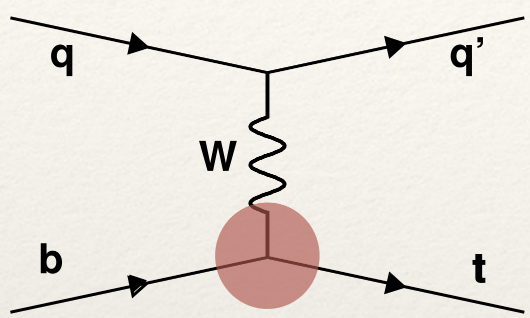
$$V_L = V_{tb} + \frac{v^2}{\Lambda^2}c_{\phi q}^{(3)} \qquad V_R = \frac{1}{2}\frac{v^2}{\Lambda^2}c^*_{\phi tb} \qquad g_L = -\sqrt{2}\frac{v^2}{\Lambda^2}c^*_{bW} \qquad g_R = -\sqrt{2}\frac{v^2}{\Lambda^2}c_{tW}$$

There are three ATLAS measurements that contribute to constraints on the couplings:

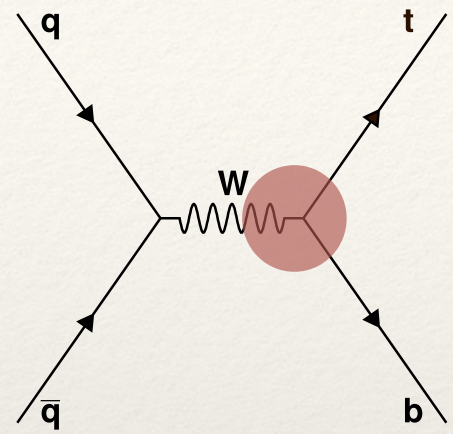
- The single-top production cross-section.
  - PRD 90 (2014) 11206 (7 TeV)
  - EPJC 77 (2017) 531 (8 TeV)
  - JHEP 04 (2017) 086 (13 TeV)
- Measurement of W-boson helicity fractions in $t\bar{t}$ events.
  - EPJC 77 2017 264 (8 TeV)
  - JHEP 08 (2020) 051 (8 TeV, ATLAS/CMS combination)
- Measurement of angular distributions in the decay of single top quarks.
  - JHEP 12 (2017) 017 (8 TeV)

Electroweak production (single top)

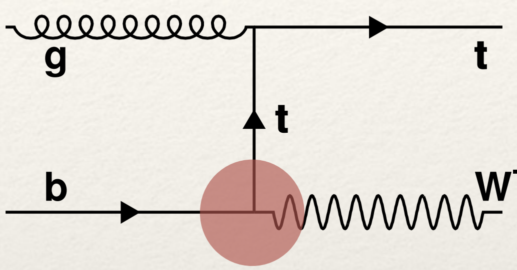
t-channel

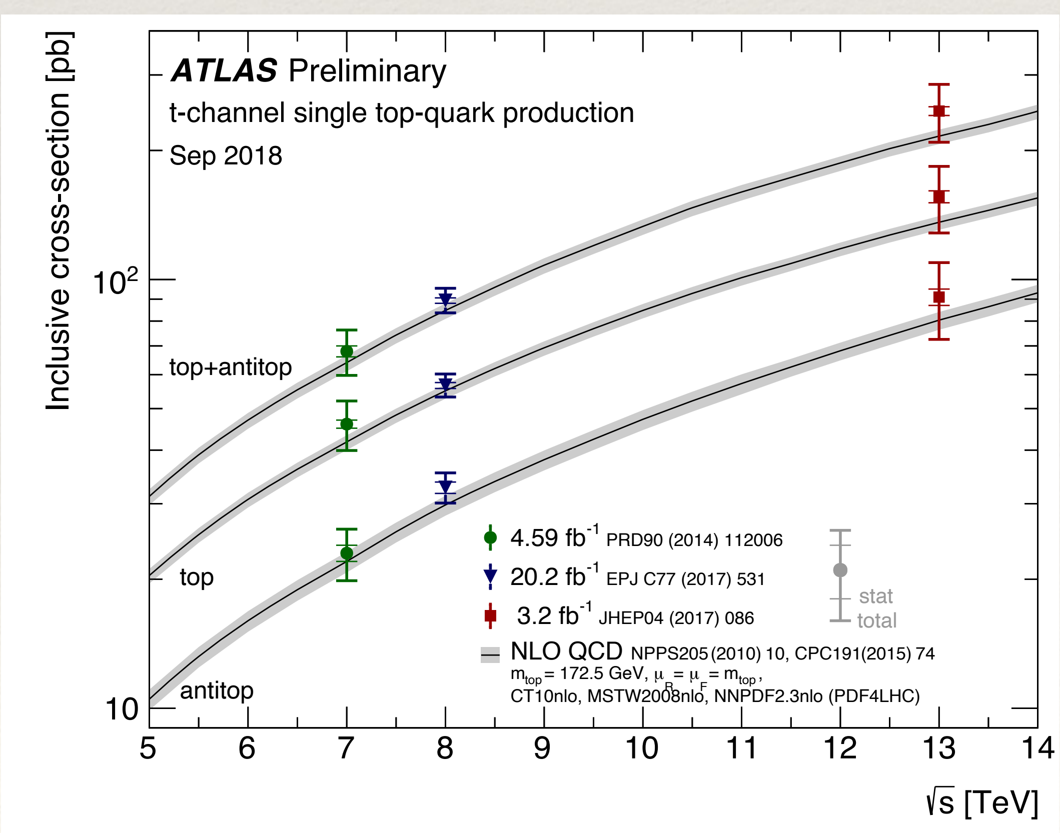


s-channel



tW-channel

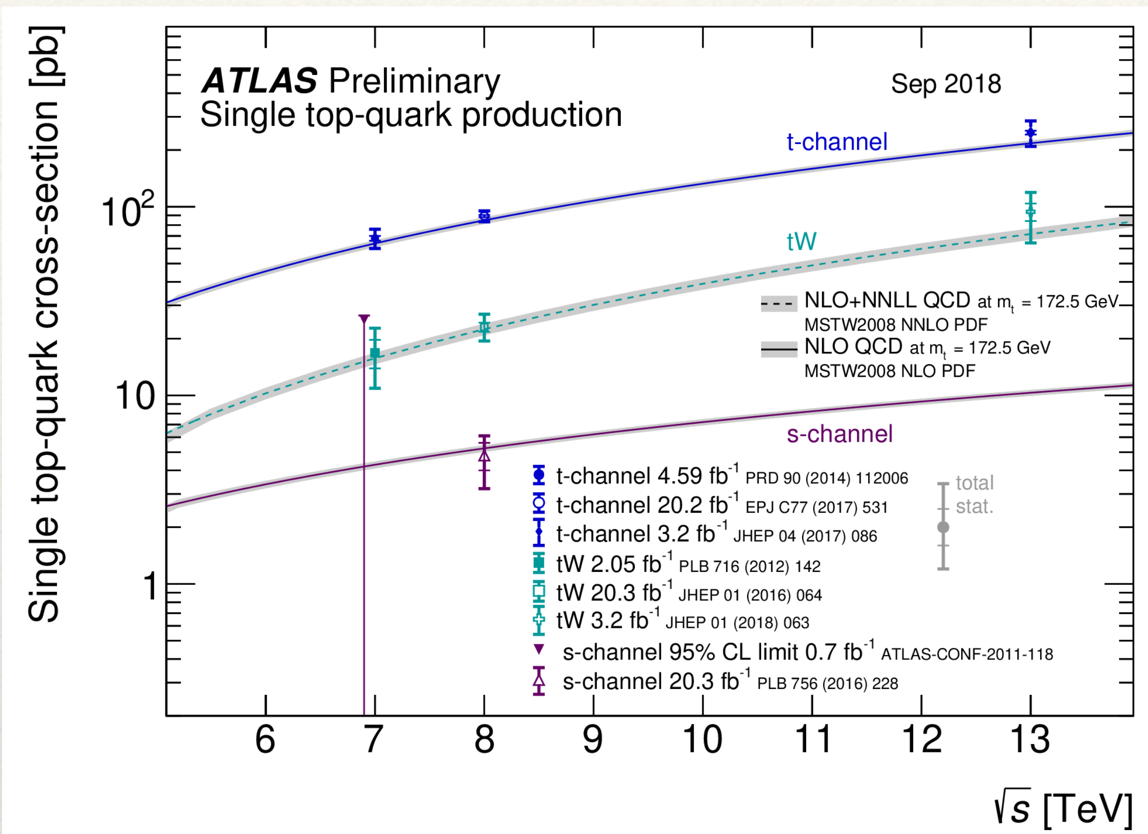




Cross-sections have a quadratic dependence on EFT coefficients.

Due to the prevalence of up-type valence quarks, the single-top cross section is larger than the single-antitop cross section.

Single top cross section measurements in ATLAS

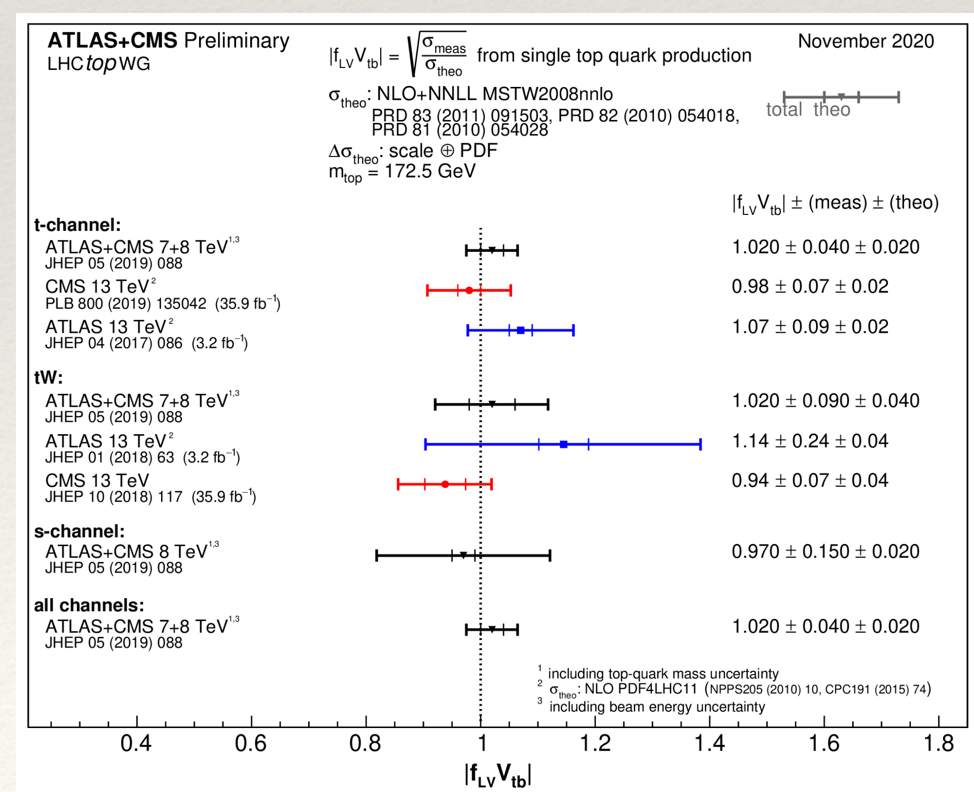


The most precise measurements are obtained at $\sqrt{s} = 8$ TeV.

More precision is required at $\sqrt{s} = 13$ TeV, where current measurements are based on only 3.2 fb^{-1} of the available 139 fb^{-1} (work in progress).

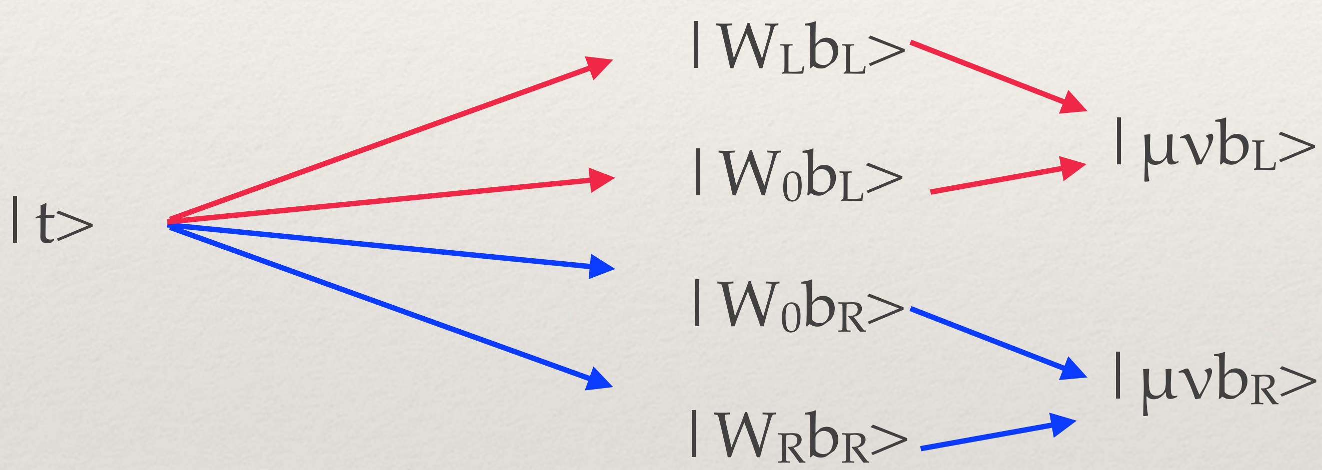
Cross section measurements are interpreted in terms of $f_{LV}V_{tb}$.

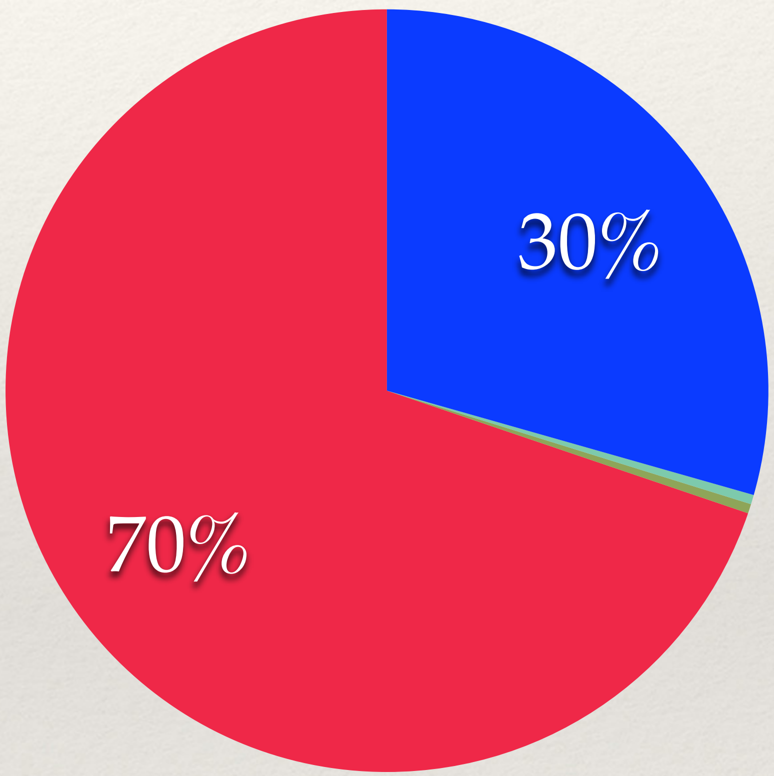
f_{LV} is an overall form factor incorporating the effects of all BSM physics.



The Wtb vertex from top quark decay

Four transition amplitudes are involved in the decay of the top quark.
Interference occurs between pairs of transitions.





In principle it is possible to measure:

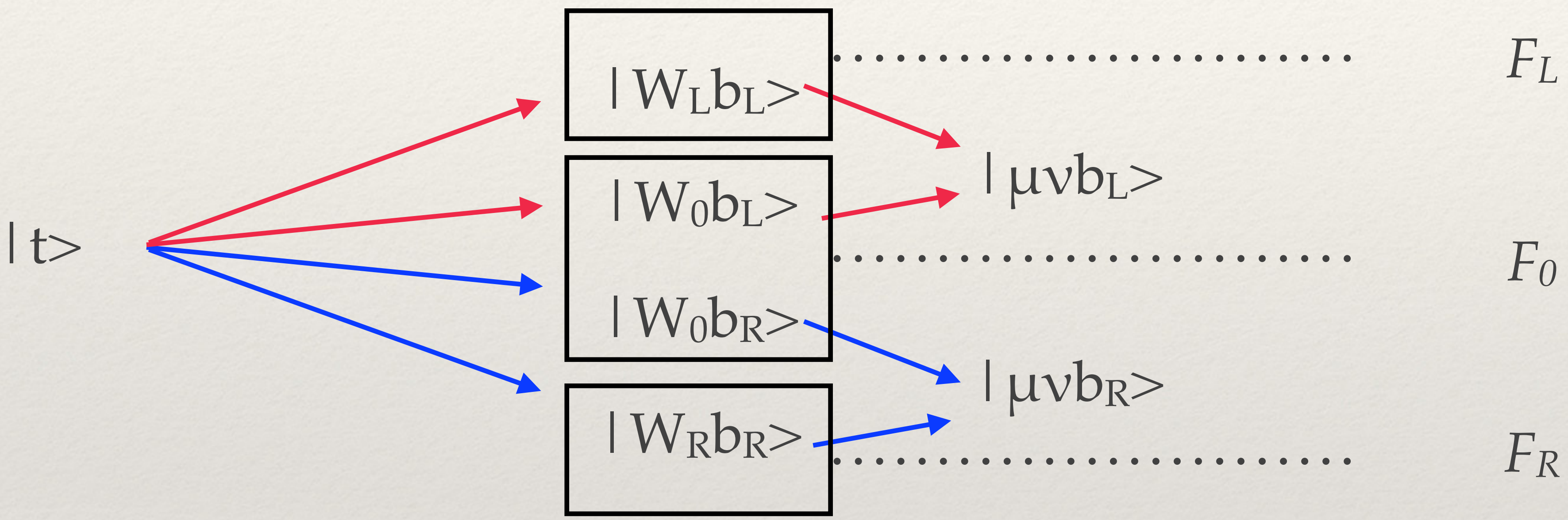
- four amplitudes
- ~~two~~ one phase~~s~~ (only one because amplitudes to right handed b's are tiny.)

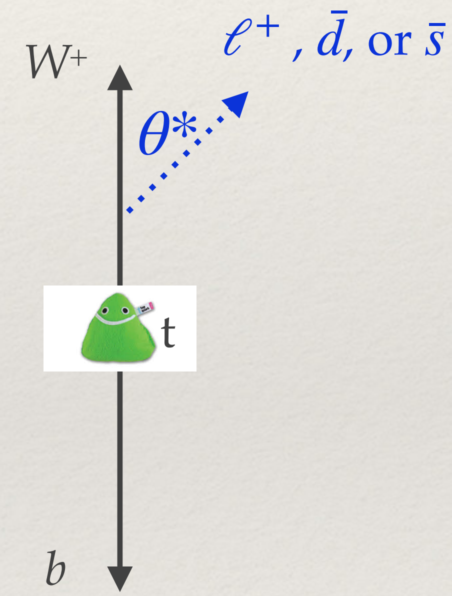
and then to relate these to the V_L, V_R, g_L, and g_R

alternately, to $c_{\phi q}^{(3)}$, $c_{\phi tb}$, c_{bW}, and c_{tW}

EPJC 77 (2017) 264: W-boson helicity fractions in top quark decay

Main innovation: use of both the leptonic and hadronic side in the lepton+jets channel.





The determination of helicity fractions in top decay uses the helicity angle θ^*: the angle between the antifermion from the W^+ in the W^+ rest frame, and the W^+ in the top rest frame.

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

Since $F_0 + F_L + F_R = 1$, there only two of three quantities are independently constrained in a fit to the helicity angle θ^*

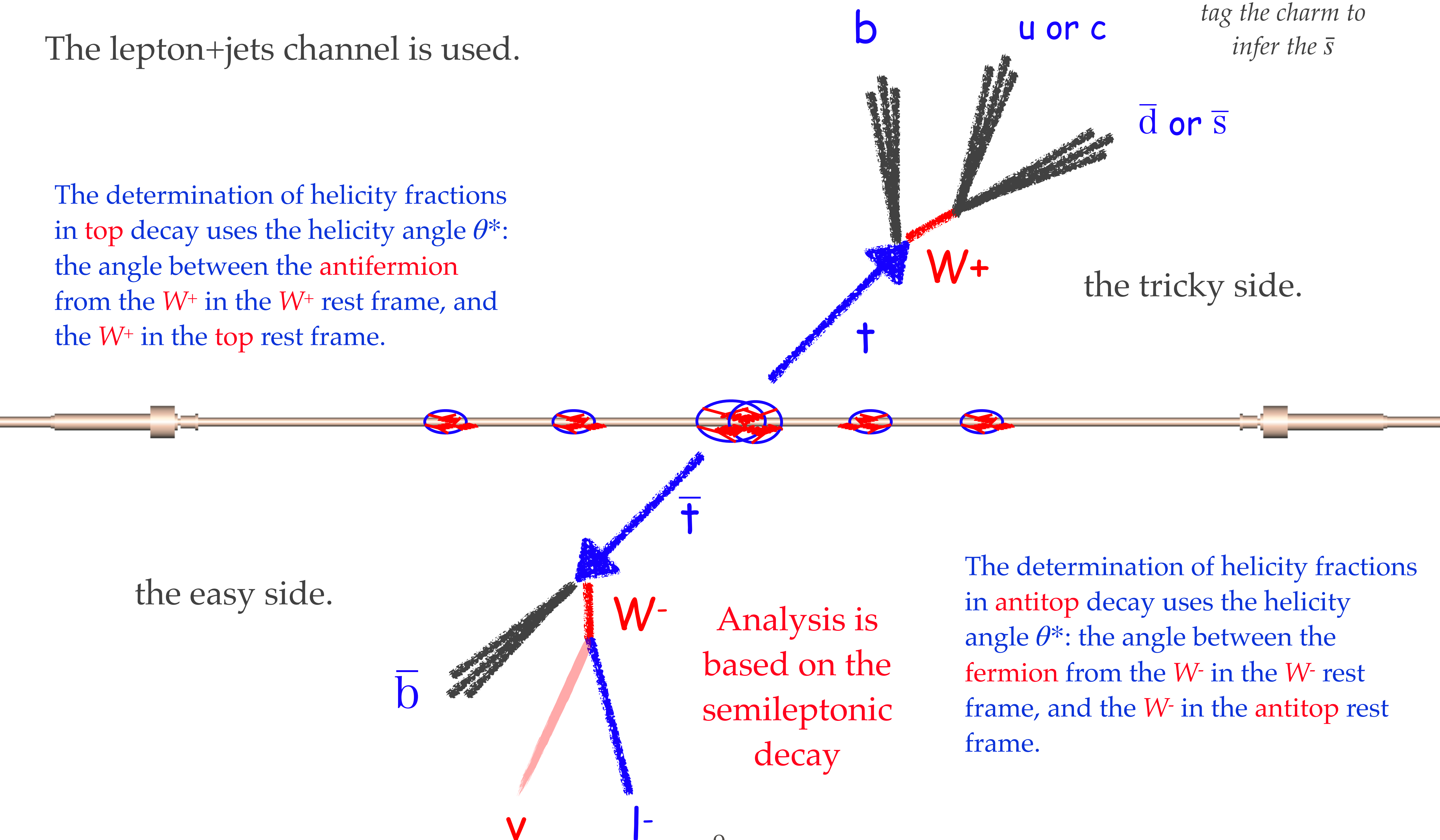
The analysis EPJC 77 (2017) 264 is carried out in $t\bar{t}$ events

The lepton+jets channel is used.

tag the charm to infer the $\bar{s}$

The determination of helicity fractions in top decay uses the helicity angle θ^*: the angle between the antifermion from the W^+ in the W^+ rest frame, and the W^+ in the top rest frame.

the tricky side.



the easy side.

Analysis is based on the semileptonic decay

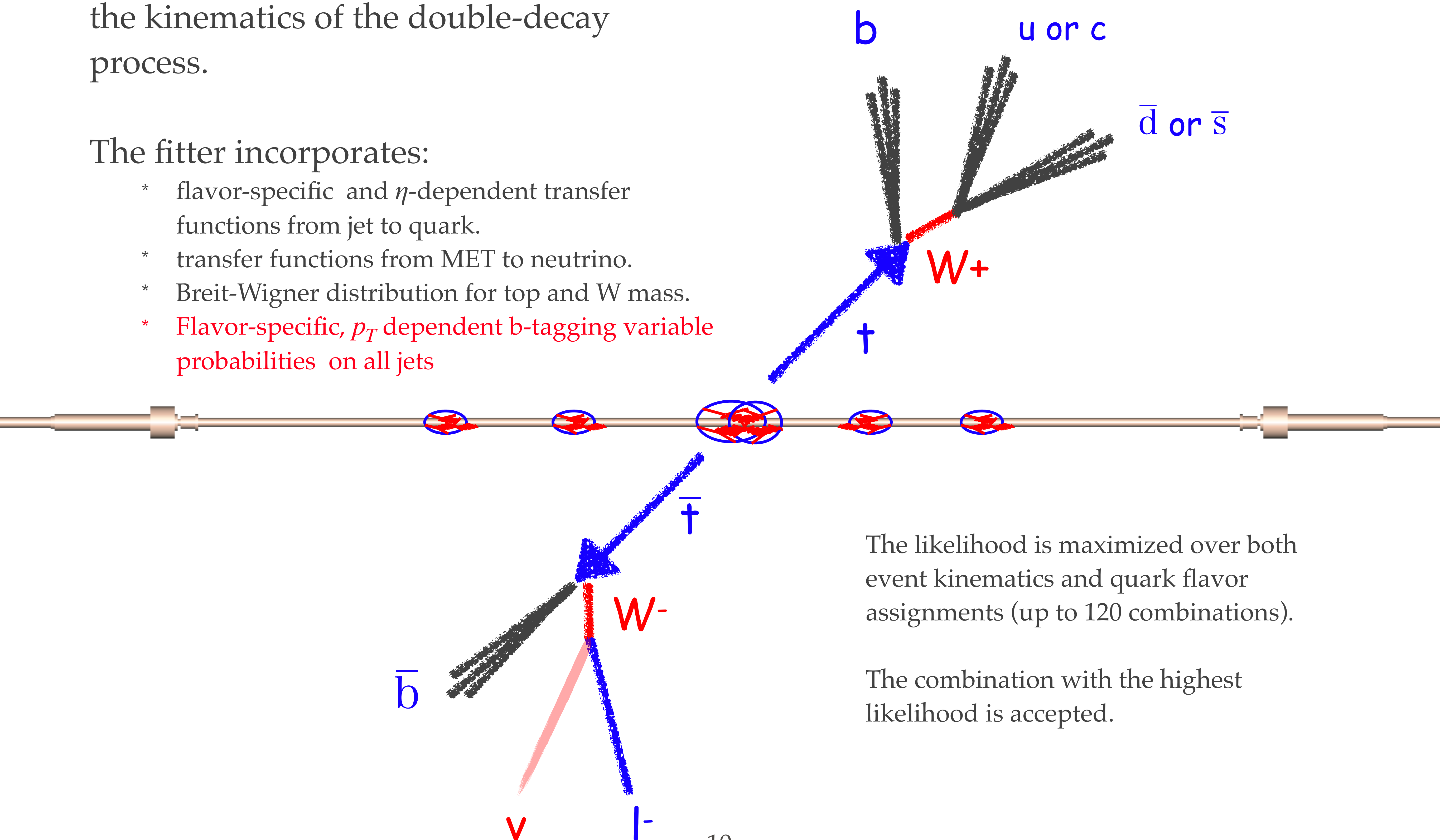
The determination of helicity fractions in antitop decay uses the helicity angle θ^*: the angle between the fermion from the W^- in the W^- rest frame, and the W^- in the antitop rest frame.

Event reconstruction, more precisely:

Kinematic fitter (KLFitter) is used to infer the kinematics of the double-decay process.

The fitter incorporates:

- * flavor-specific and η-dependent transfer functions from jet to quark.
- * transfer functions from MET to neutrino.
- * Breit-Wigner distribution for top and W mass.
- * Flavor-specific, p_T dependent b-tagging variable probabilities on all jets



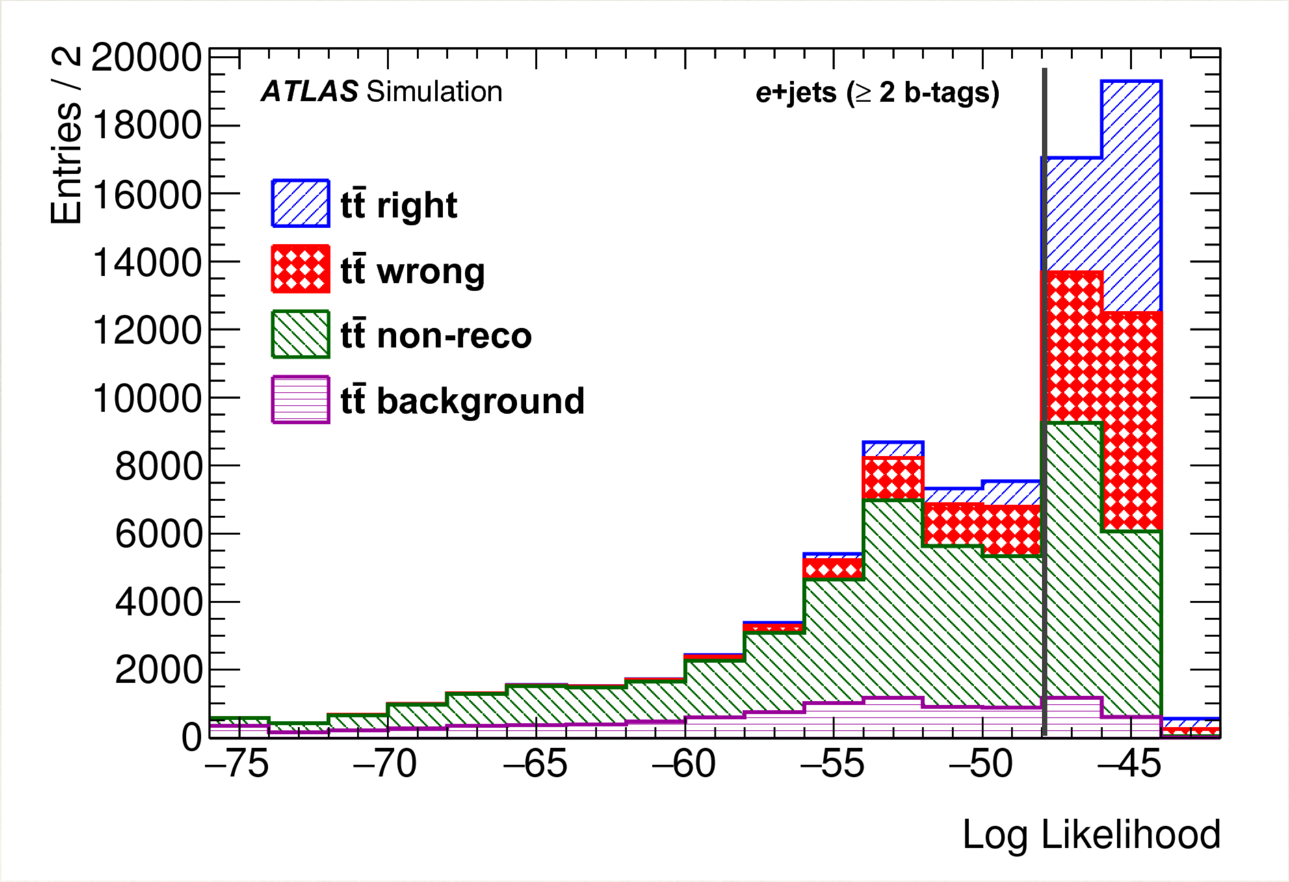
The likelihood is maximized over both event kinematics and quark flavor assignments (up to 120 combinations).

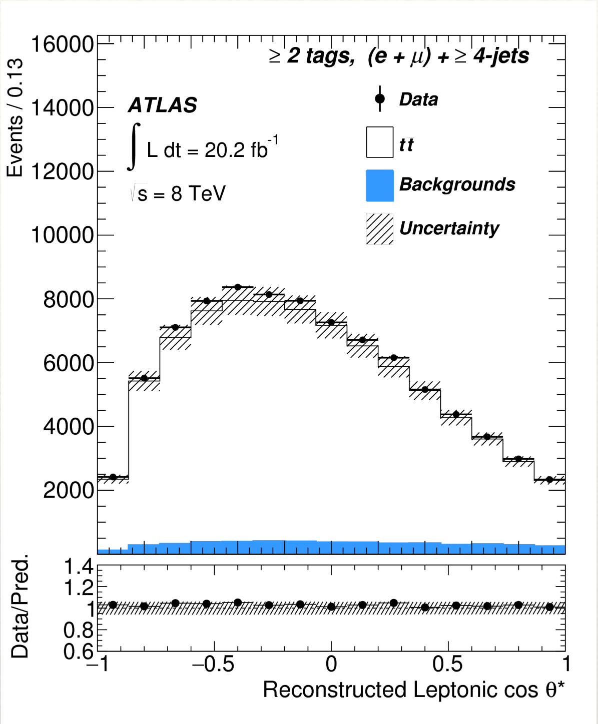
The combination with the highest likelihood is accepted.

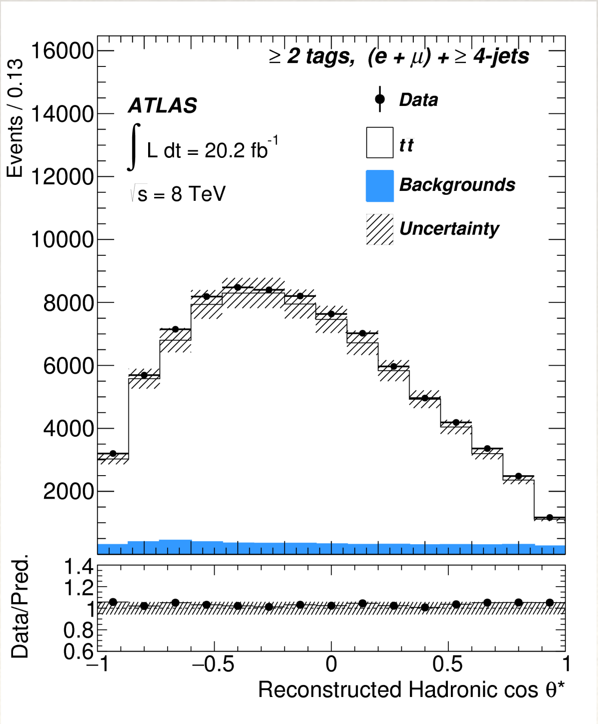
Event reconstruction

Log likelihood after minimization over kinematic parameters and jet assignment combinations.

cut



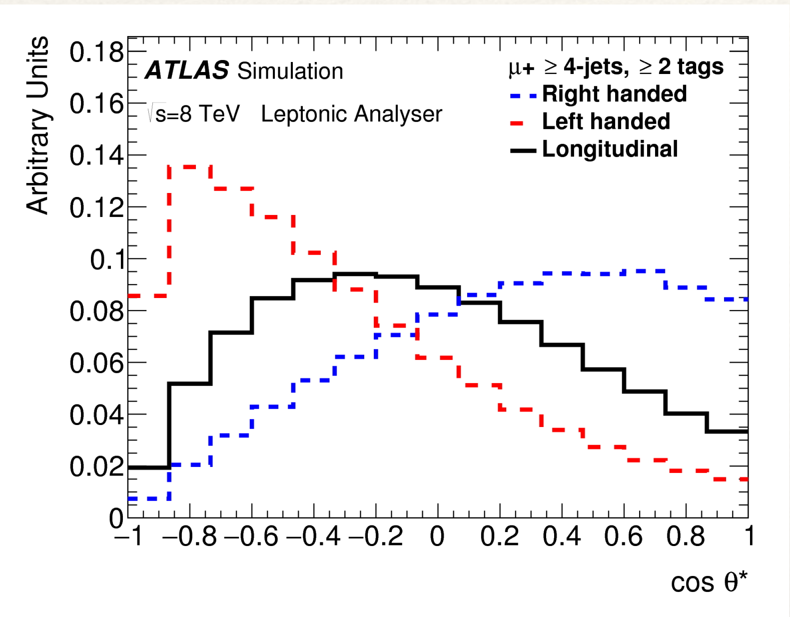




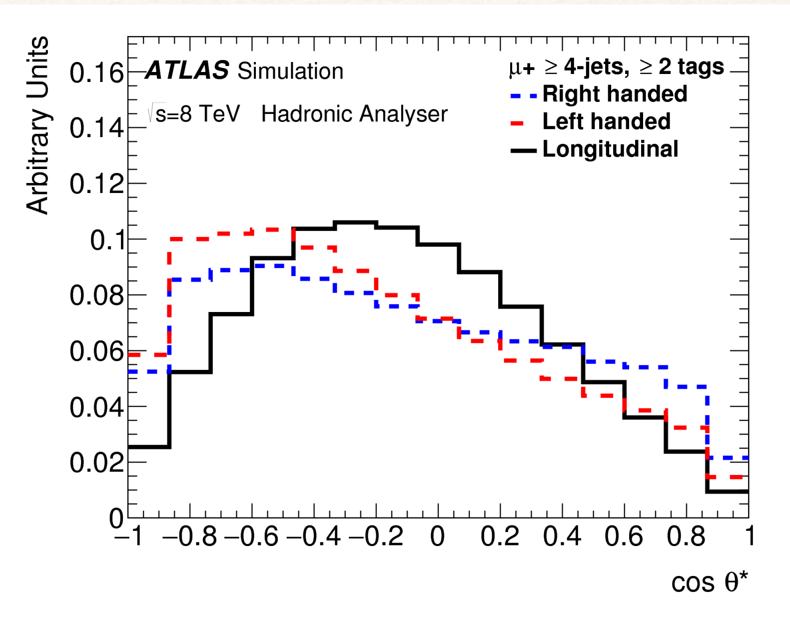
In 60% of $t\bar{t}$ lepton+jet events, the assignment of down-type quark is correct.

Template-fits are performed simultaneously in

the leptonic channel

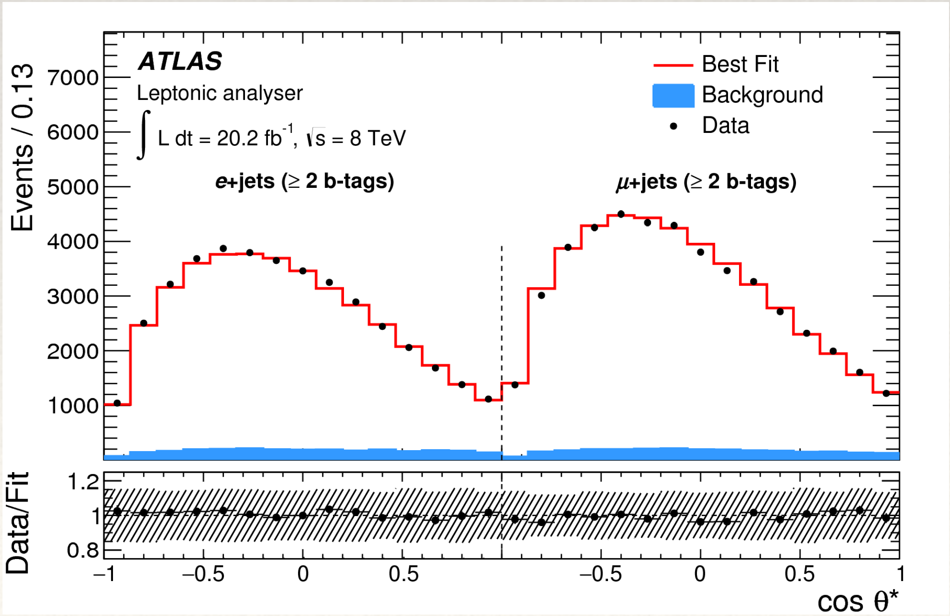


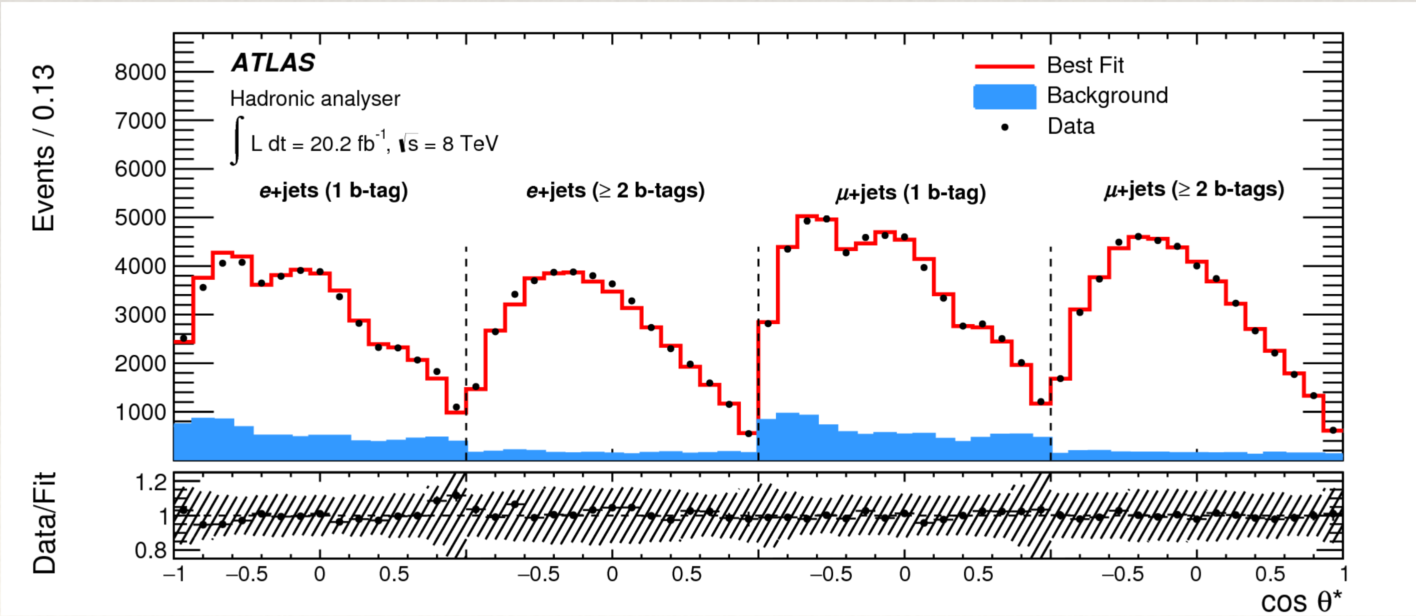
the hadronic channel



Templates for the signa are derived from NLO $t\bar{t}$ signal MC reweighted at the generator level to distributions from the relevant *W* boson polarization.

Then the data is fit to templates for the signal and all background sources.



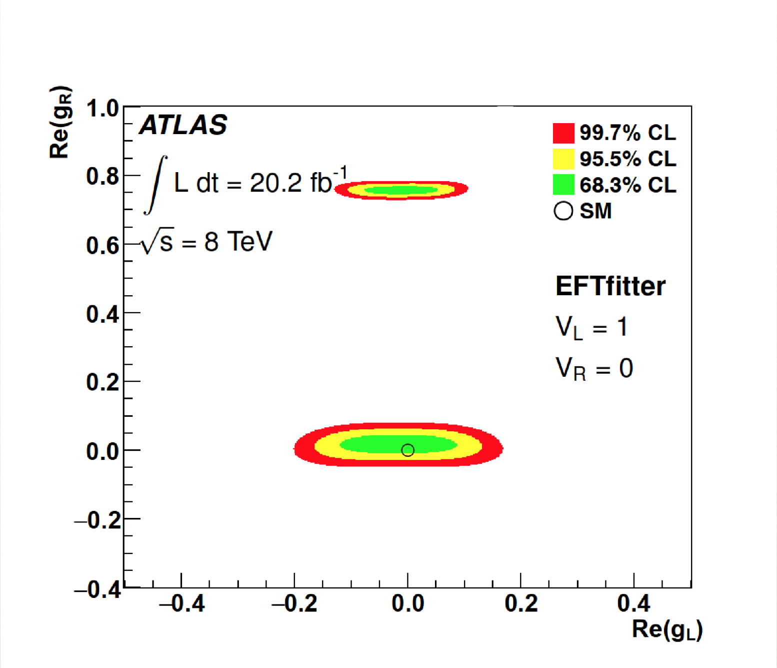


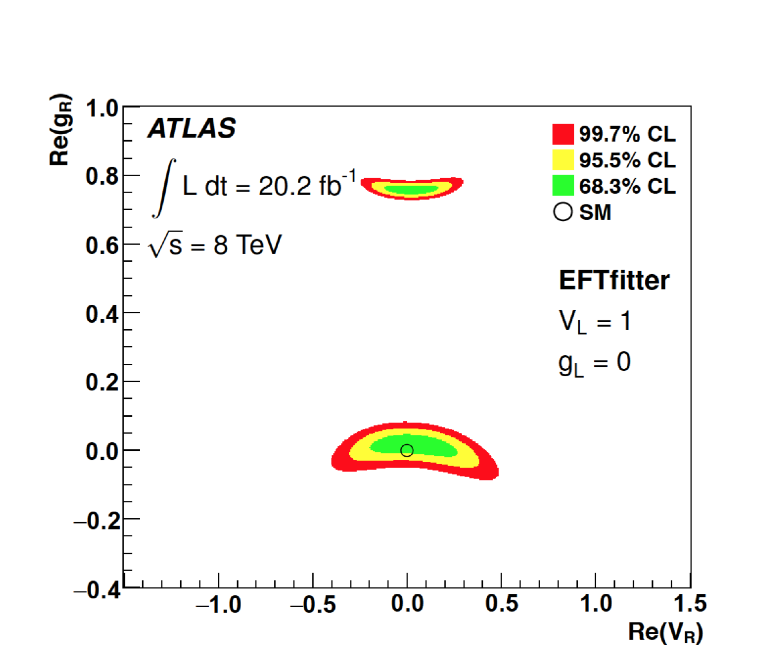
Results

$F_0 = 0.709 \pm 0.012 \text{ (stat)} \pm 0.015 \text{ (syst)}$

$F_R = -0.008 \pm 0.006 \text{ (stat)} \pm 0.012 \text{ (syst)}$

$F_L = 0.299 \pm 0.008 \text{ (stat)} \pm 0.013 \text{ (syst)}$





Assumptions:

- All anomalous couplings are real.
- Unconsidered couplings are fixed to their SM values.

The measurements are consistent with the Standard Model; however

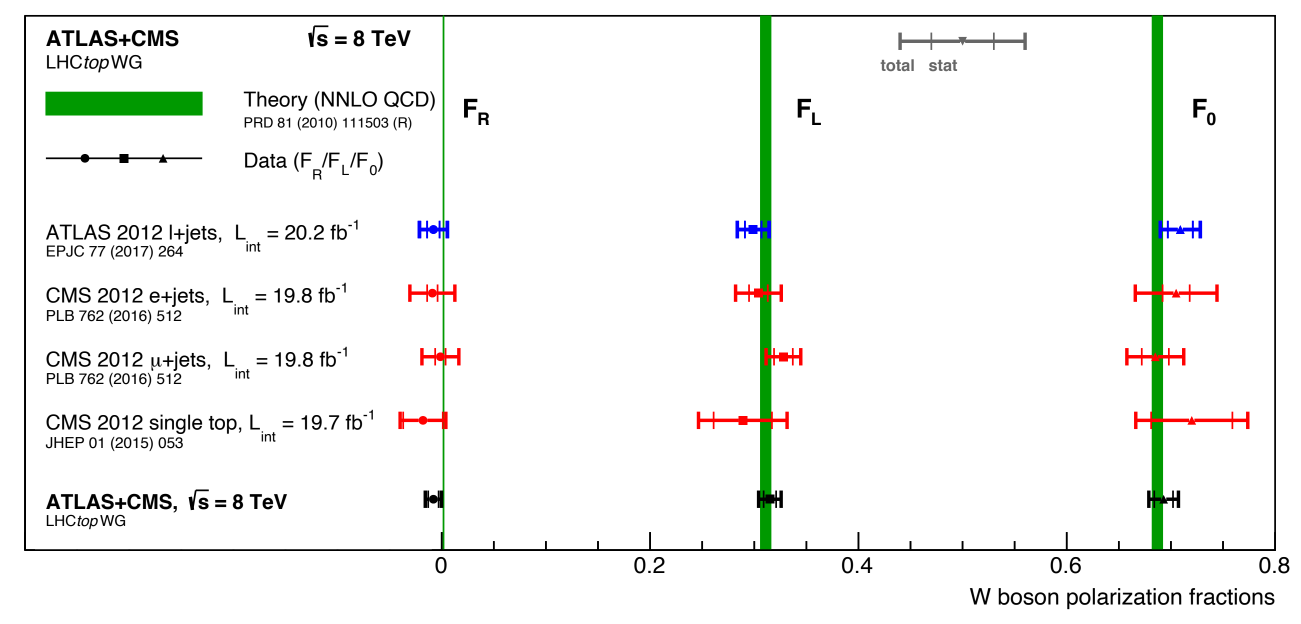
- there is an ambiguity, as shown in the plots.
- there is essentially no constraint on the couplings if the above assumptions are not imposed.

$$F_0 = \frac{|V_L - x_w g_R|^2 + |V_R - x_w g_L|^2}{|V_L - x_w g_R|^2 + |V_R - x_w g_L|^2 + 2\,|x_w V_L - g_R|^2 + 2\,|x_w V_R - g_L|^2}$$

$$F_L = \frac{2\,|x_w V_L - g_R|^2}{|V_L - x_w g_R|^2 + |V_R - x_w g_L|^2 + 2\,|x_w V_L - g_R|^2 + 2\,|x_w V_R - g_L|^2}$$

$$F_R = \frac{2\,|x_w V_R - g_L|^2}{|V_L - x_w g_R|^2 + |V_R - x_w g_L|^2 + 2\,|x_w V_L - g_R|^2 + 2\,|x_w V_R - g_L|^2}$$

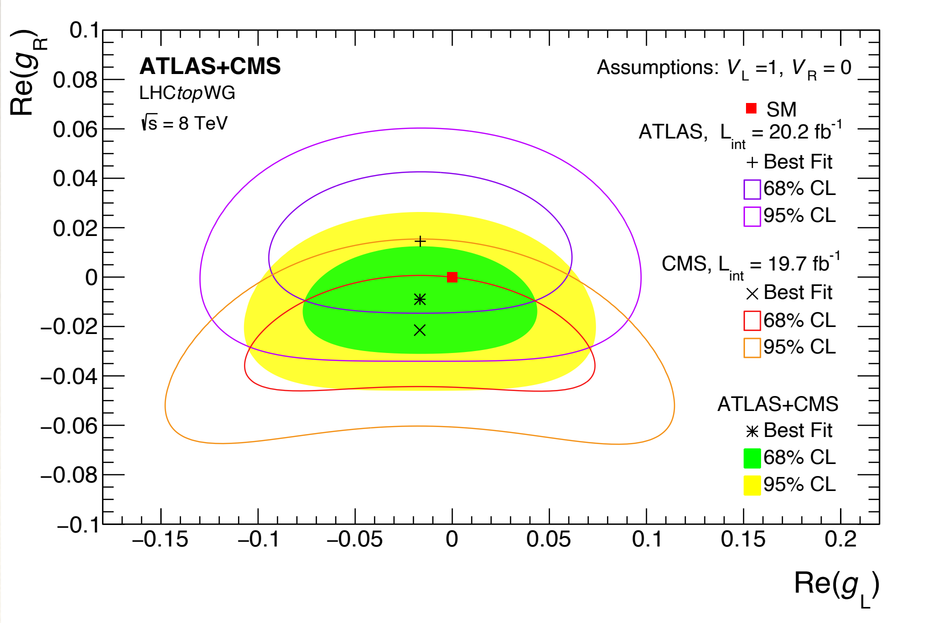
ATLAS-CMS combination

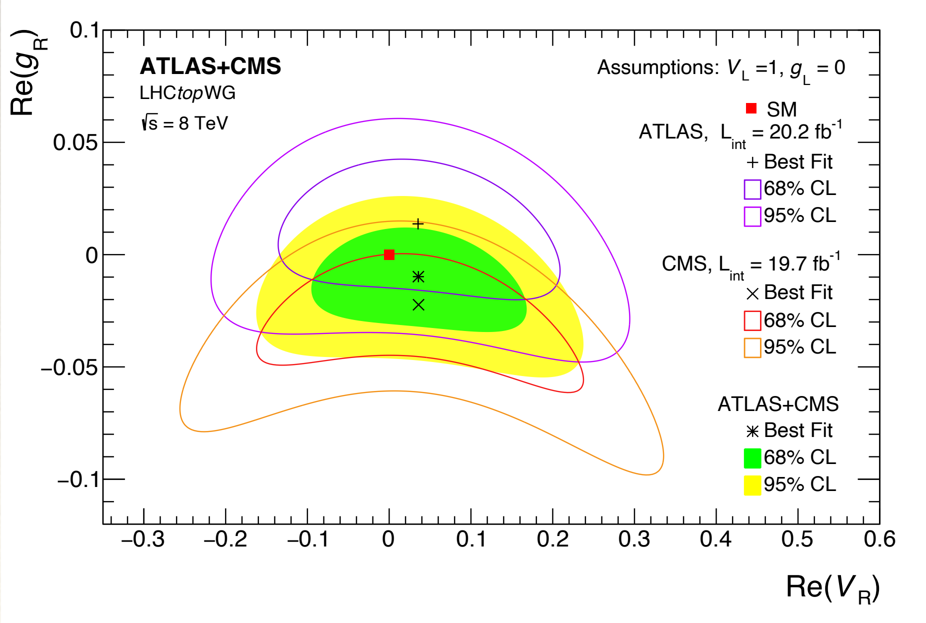


Results are very precise and agree with the standard model.

Production of right-handed W's too small to be observed.

In the ATLAS-CMS combination, the ambiguity is resolved using the cross section measurements.





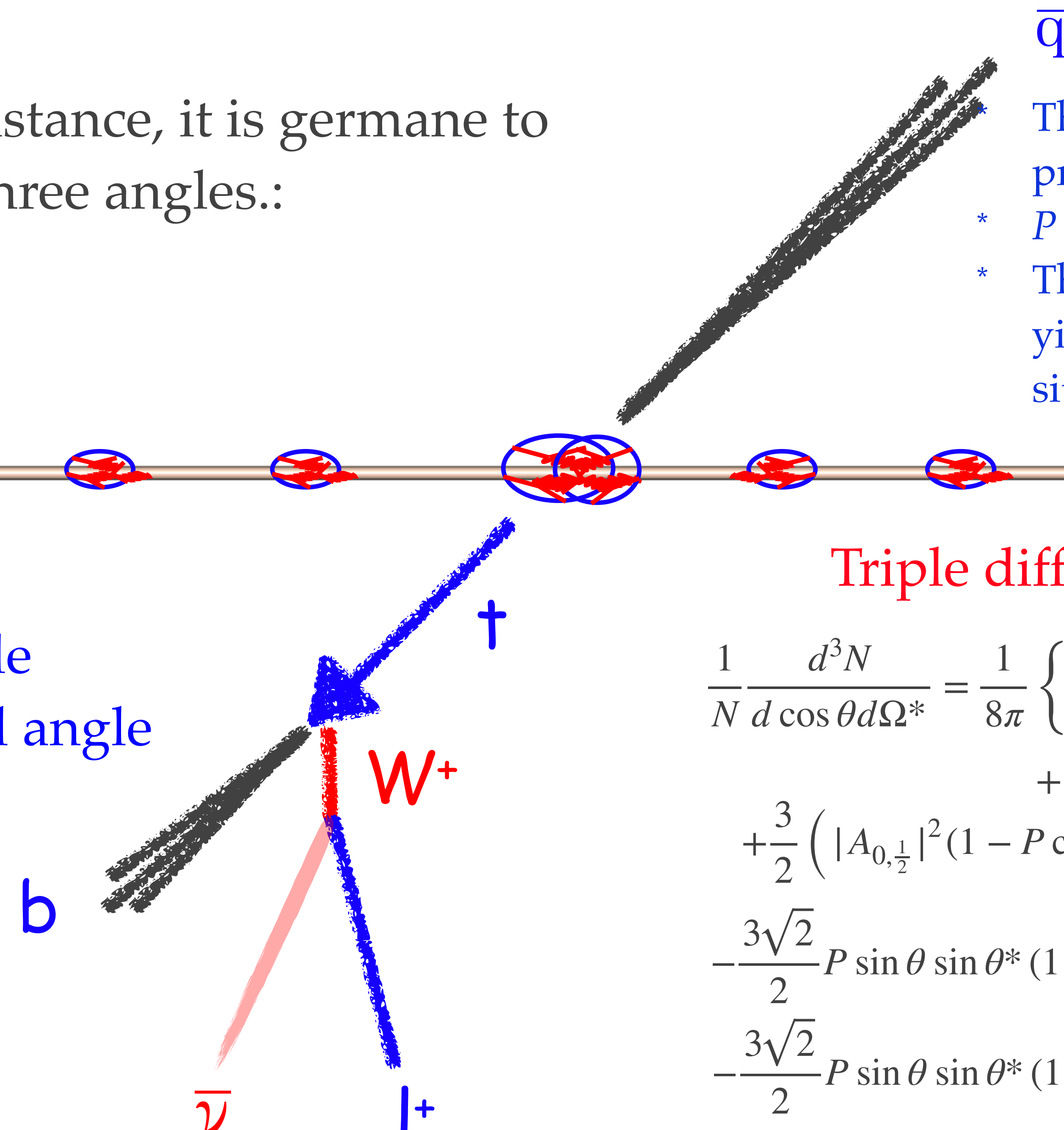
Angular analysis in single top t-channel

- JHEP 12 (2017) 017 (8 TeV)

In single top t-channel events, the top quark is almost fully polarized along the direction of the spectator quark.

Because of that circumstance, it is germane to consider not one but three angles.:

- The A's are the amplitudes we previously encountered.
- P is the polarization==>
- The triple differential cross section yields new information only in situations where $P \neq 0$



θ: t decay polar angle

θ*: W decay polar angle

ϕ*: W decay azimuthal angle

Triple differential decay rate

$$
\begin{aligned}
\frac{1}{N}\frac{d^3N}{d\cos\theta d\Omega^*} = \frac{1}{8\pi}\Bigg\{ & \frac{3}{4}|A_{1,\frac{1}{2}}|^2(1+P\cos\theta)(1+\cos\theta^*)^2 \\
& +\frac{3}{4}|A_{-1,-\frac{1}{2}}|^2(1-P\cos\theta)(1-\cos\theta^*)^2 \\
& +\frac{3}{2}\left(|A_{0,\frac{1}{2}}|^2(1-P\cos\theta)+|A_{0,-\frac{1}{2}}|^2(1+P\cos\theta)\right)\sin^2\theta^* \\
& -\frac{3\sqrt{2}}{2}P\sin\theta\sin\theta^*(1+\cos\theta^*)\,\mathrm{Re}\left[e^{i\phi^*}A_{1,\frac{1}{2}}A^*_{0,\frac{1}{2}}\right] \\
& -\frac{3\sqrt{2}}{2}P\sin\theta\sin\theta^*(1-\cos\theta^*)\,\mathrm{Re}\left[e^{-i\phi^*}A_{-1,-\frac{1}{2}}A^*_{0,-\frac{1}{2}}\right]
\end{aligned}
$$

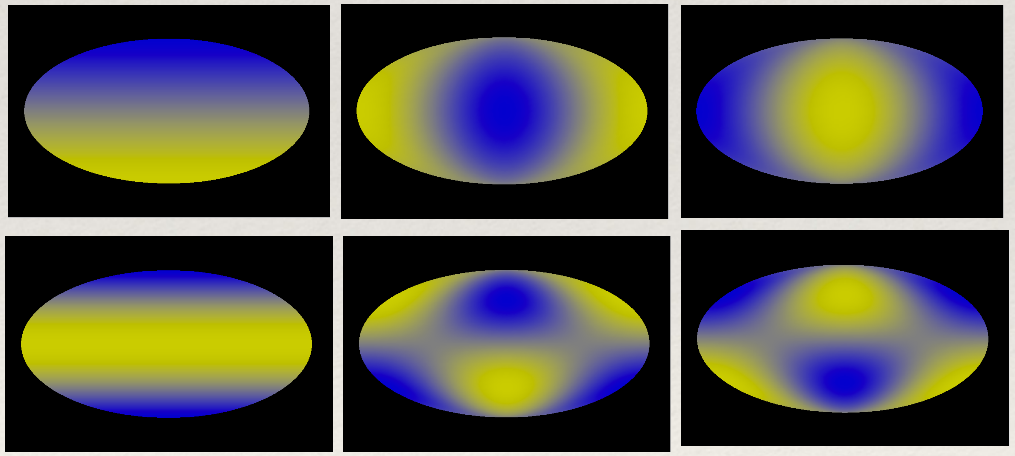
Series of analyses from ATLAS

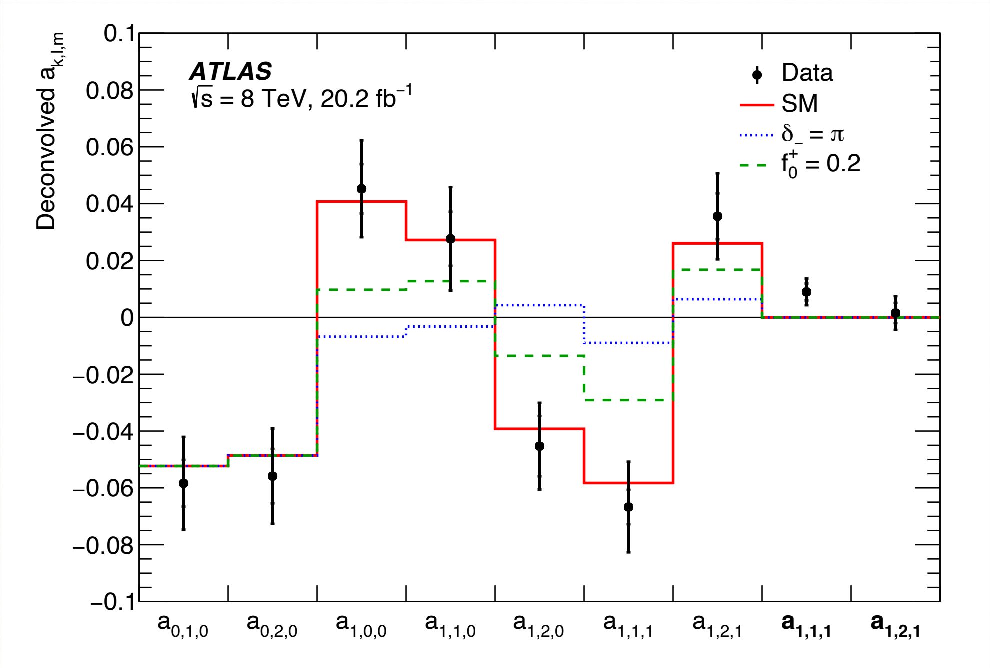
Double [JHEP 04 (2016) 023] and triple [JHEP 12 (2017) 017] differential decay rates.

Triple differential cross section:

$$\rho(\theta, \theta^*, \phi^*) \equiv \frac{1}{\Gamma}\frac{d\Gamma}{d\Omega_3}$$
$$= a^m_{k,l} M^m_{k,l}(\theta, \theta^*, \phi^*)$$

$$M^m_{k,l}(\theta_1, \theta_2, \phi) = \sqrt{2\pi} Y^m_k(\theta_1, 0) Y^m_l(\theta_2, \phi)$$
$$= \sqrt{2\pi} Y^m_k(\theta_1, \phi) Y^m_l(\theta_2, 0)$$





[JHEP 12 (2017) 017]

Decompose the differential decay rate into orthogonal functions and perform Fourier analysis.

Use Fourier techniques to deconvolve the detector.

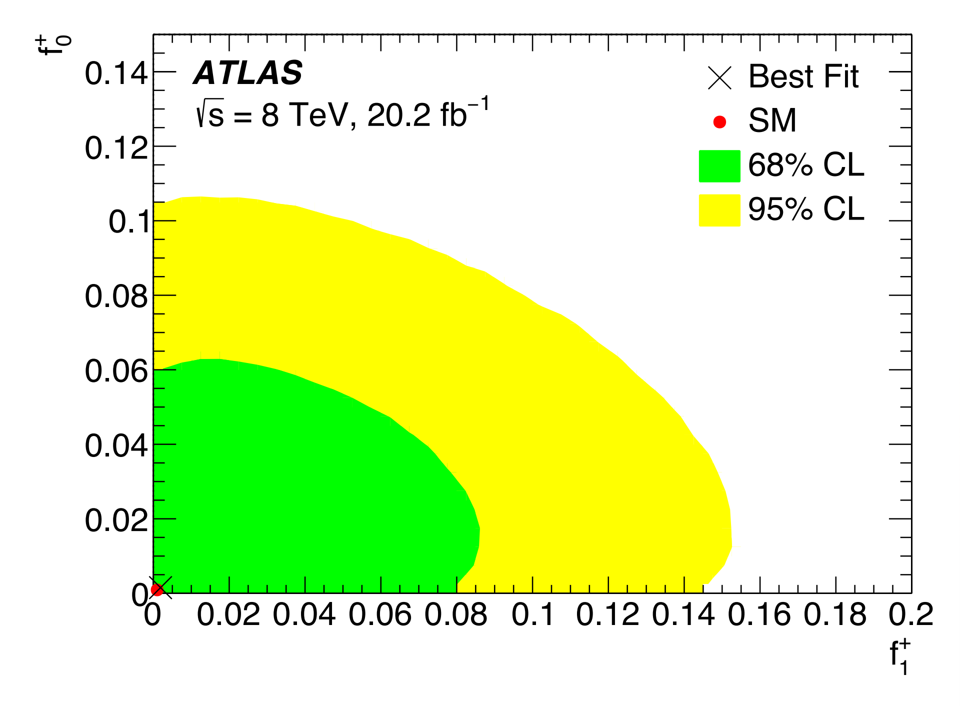
Helicity fractions & phases with *no assumptions on other parameters*

f_0^+: the fraction of b's which are right-handed in events with longitudinal W's

$f_0^+ < 0.041$ (68% CL)
$f_0^+ < 0.085$ (95% CL) *unique measurement*

f_1^+: the fraction of b's which are right-handed in events with transverse W's.

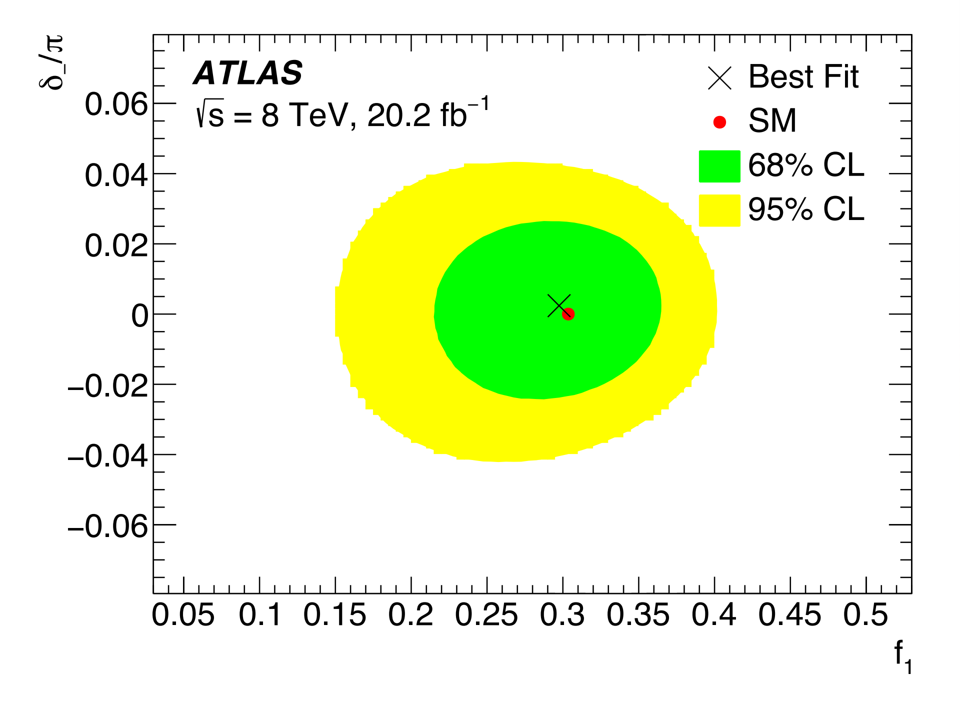
$f_1^+ < 0.053$ (68% CL)
$f_1^+ < 0.120$ (95% CL)



f_1=1-F_L: Also measured in W boson polarization analyses.

δ_-: If nonzero, could signify CP violation in top quark decay.

$$f_1 = 0.296^{+0.020}_{-0.023}\,(\text{stat.})\,^{+0.043}_{-0.046}\,(\text{syst.}) = 0.296^{+0.048}_{-0.051}\,,$$
$$\delta_- = 0.002\pi^{+0.013\pi}_{-0.014\pi}\,(\text{stat.})\,^{+0.010\pi}_{-0.011\pi}\,(\text{syst.}) = 0.002\pi^{+0.016\pi}_{-0.017\pi}\,.$$



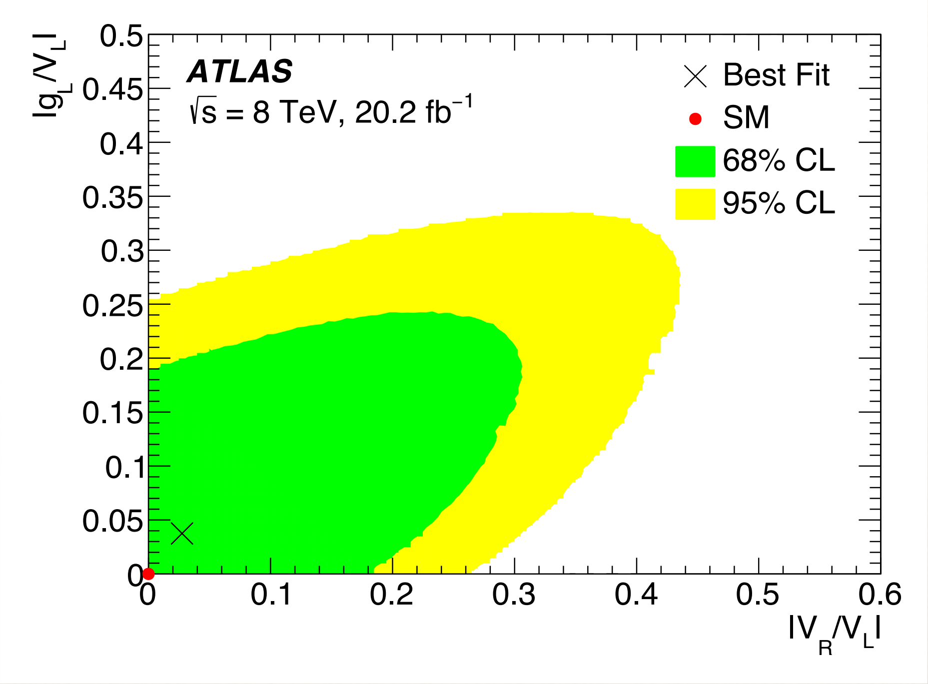
[JHEP 12 (2017) 017]

Anomalous couplings with *no assumptions on other parameters.*

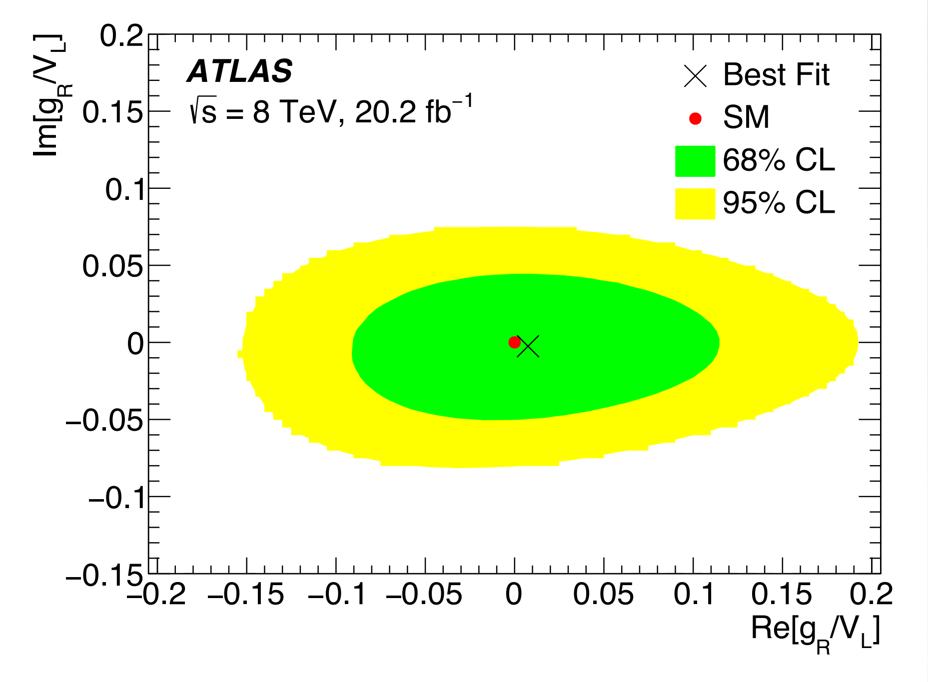
- $|V_R/V_L| < 0.23$ (68% CL)
- $|V_R/V_L| < 0.37$ (95% CL)

- $|g_L/V_L| < 0.19$ (68% CL)
- $|g_L/V_L| < 0.29$ (95% CL)

- Tighter limits exist from $b \to s\gamma$ and from W helicity fractions in $t\bar{t}$ events, but with assumptions on other parameters.

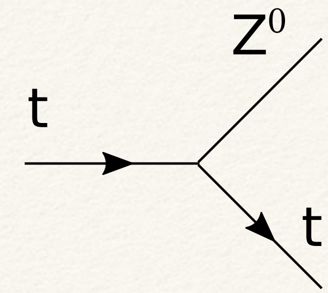


$$\mathrm{Re}\left[\frac{g_R}{V_L}\right] \in [-0.12, 0.17] \quad \text{and} \quad \mathrm{Im}\left[\frac{g_R}{V_L}\right] \in [-0.07, 0.06].$$



[JHEP 12 (2017) 017]

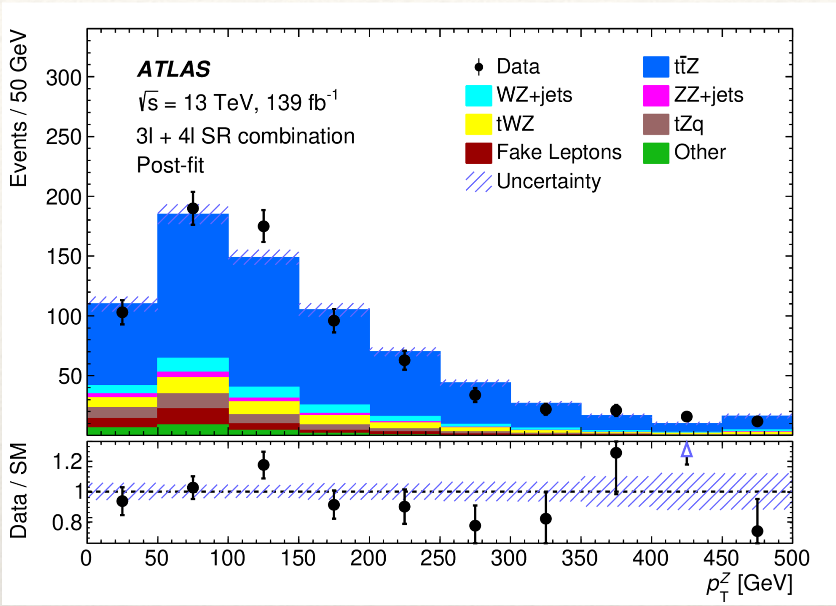
The Ztt vertex



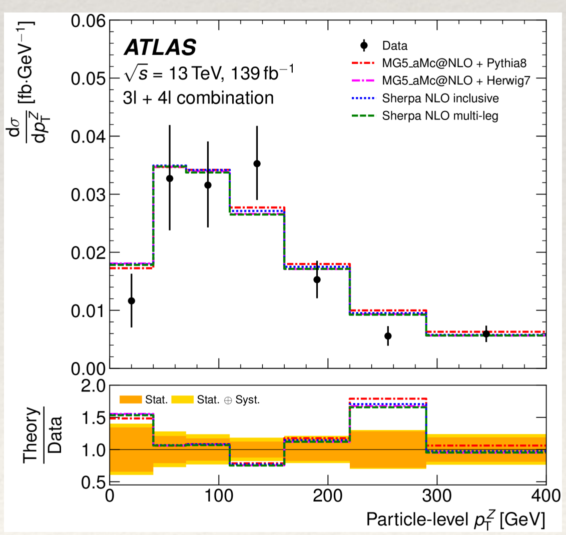
$$\mathscr{L}_{Ztt} = e\bar{t}\left[\gamma^{\mu}\left(C_{1,V} + \gamma^5 C_{1,A}\right) + \frac{i\sigma^{\mu\nu}p_{\nu}}{M_Z}\left(C_{2,V} + i\gamma^5 C_{2,A}\right)\right] t Z_{\mu}$$

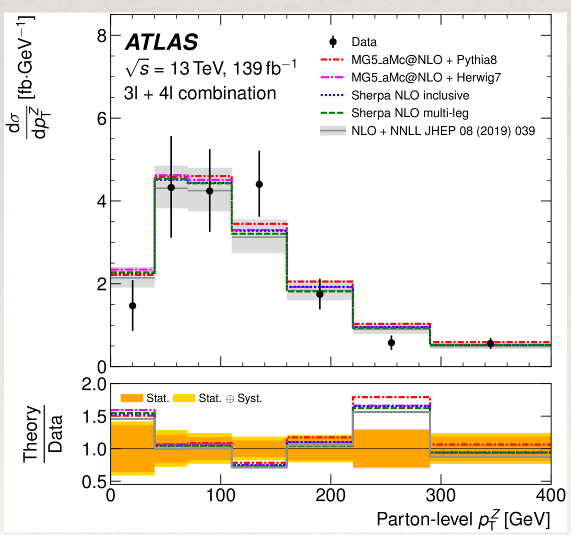
The vertex is probed in $t\bar{t}Z$ production in an updated ATLAS measurement of total and differential cross sections using full Run II data sample.

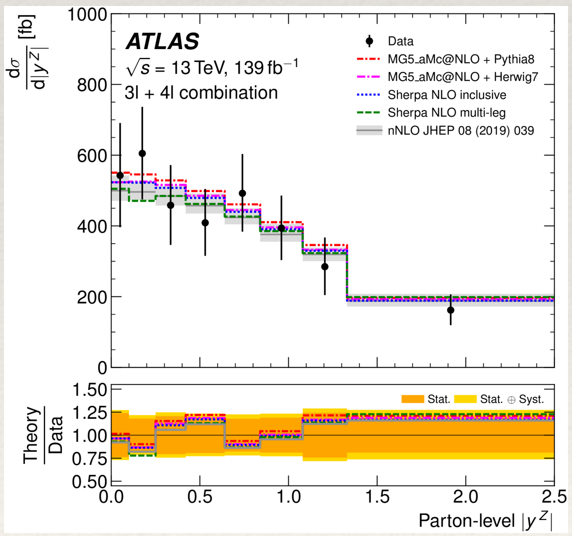
`arXiv: 2103.12603.`



3-and 4- lepton final states are considered; distributions unfolded to particle and parton level:

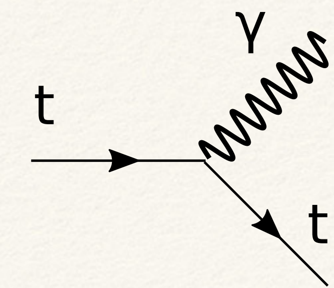




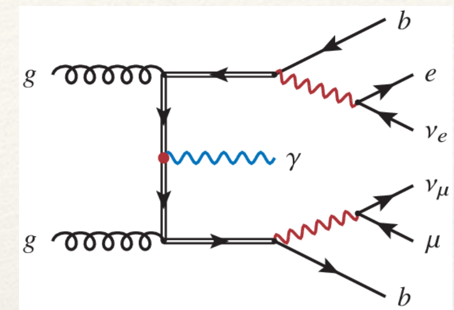


Inclusive cross section: $\sigma_{t\bar{t}Z} = 0.99 \pm 0.05\ (\text{stat.}) \pm 0.08\ (\text{syst.})\ \text{pb}$

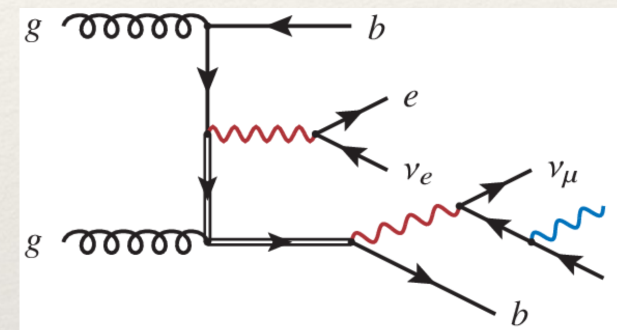
The γtt vertex



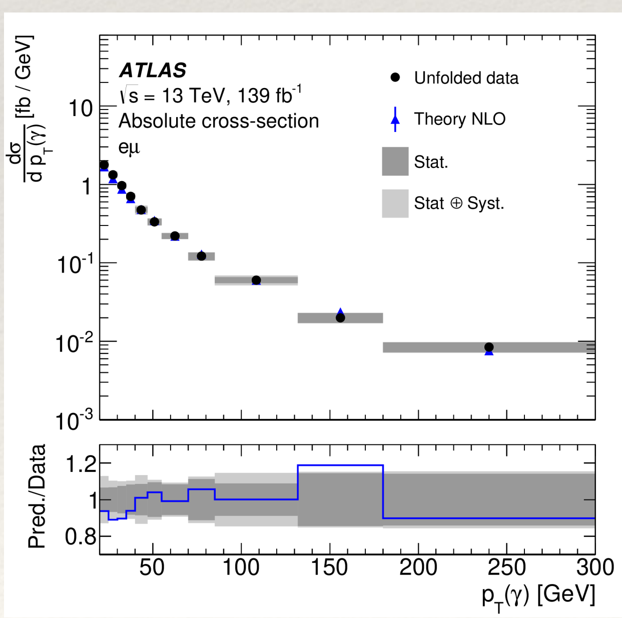
$$\boxed{\mathcal{L}_{\gamma tt} = -eQ_t\bar{t}\gamma^{\mu}tA_{\mu} - e\bar{t}\frac{i\sigma^{\mu\nu}q_{\nu}}{m_t}\,(d_V^{\gamma} + id_A^{\gamma}\gamma_5)\,tA_{\mu}}$$

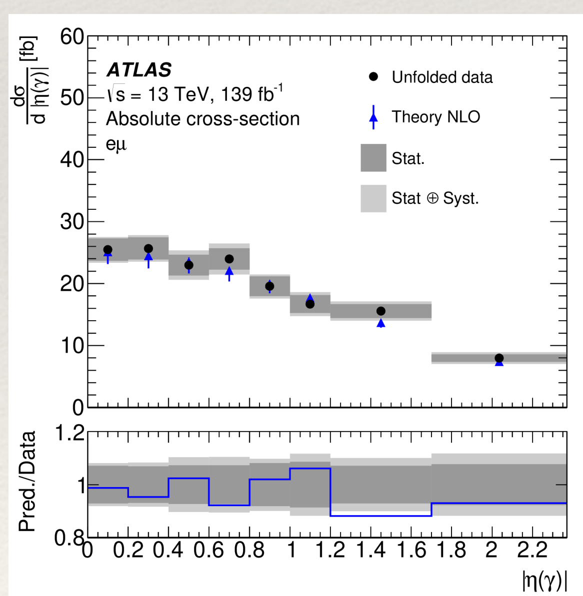


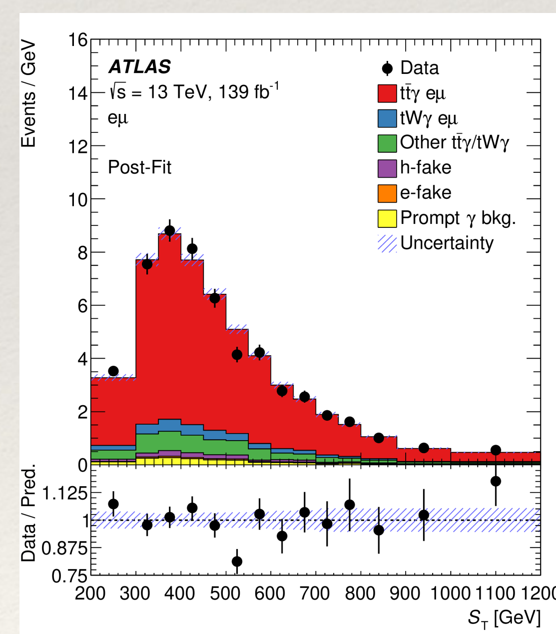
The vertex is probed in $t\bar{t}\gamma/tW\gamma$ production in an updated ATLAS measurement of total and differential cross sections using full Run II data sample. `JHEP 09 (2020) 049`



Signature: one electron, one oppositely charged muon, 2 b-jets, 1 photon.





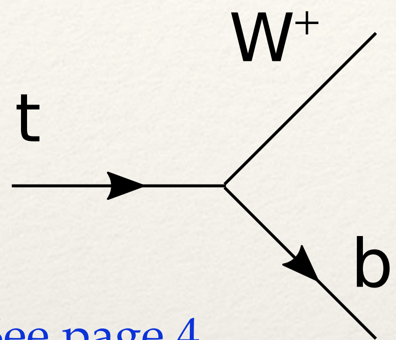


Inclusive fiducial cross section: $\sigma = 39.6 \pm 0.8\ (\text{stat})^{+2.6}_{-2.2}\ (\text{syst})\ \text{pb}$

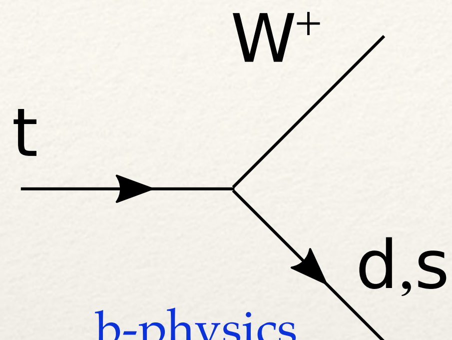
Conclusions

- We have reviewed three analysis related to the Wtb vertex: Single top cross sections, W Boson polarization in top quark decay, and angular analysis in single top t-channel events.
- $f_1 = 1 - F_L, \ f_0^+, f_1^+, \delta_-$ from single top angular distributions and $\left|f_{LV}V_{tb}\right|$ from cross section measurements represent 5 independent observables quantities.
- Helicity fraction measurements provide the best precision on two parameters, F_L and F_0 (independent of each other, but dependent on those previously mentioned).
- The Wtb vertex is described by:
    - 4 couplings strengths + 3 relative phases= 7 parameters.
- An ideal way to use all this information would be to combine it, but correlations in systematic uncertainties make this challenging.
- Future measurements are being designed with combination in mind.
- Total and differential cross sections in $t\bar{t}\gamma$ and $t\bar{t}Z$ productions measured in full Run II dataset, presaging rich opportunities to fully investigate the Ztt and γtt vertices.

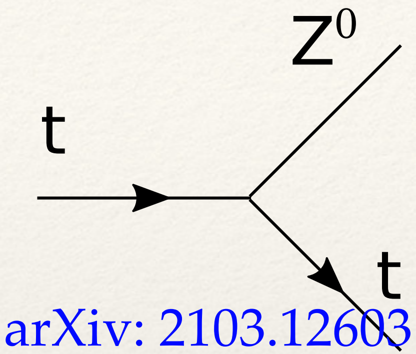
Furthermore: ATLAS results on other top couplings?



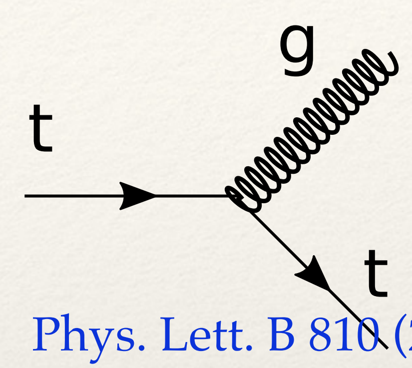
See page 4



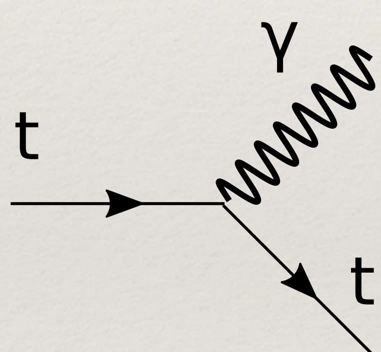
b-physics



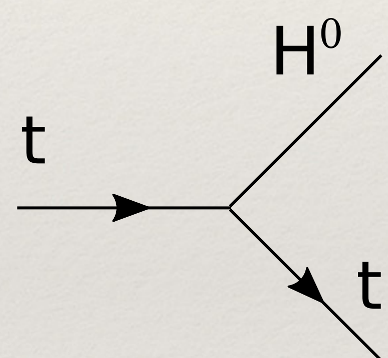
arXiv: 2103.12603.



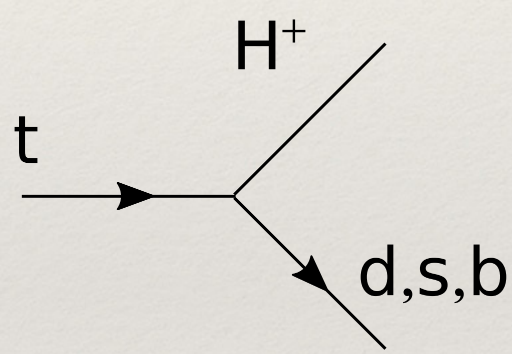
Phys. Lett. B 810 (2020) 135797



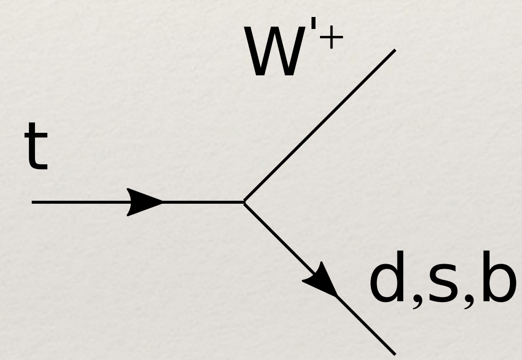
JHEP 09 (2020) 049



PLB 784 (2018) 173



exotic



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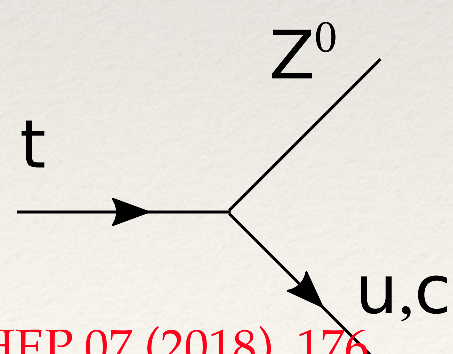
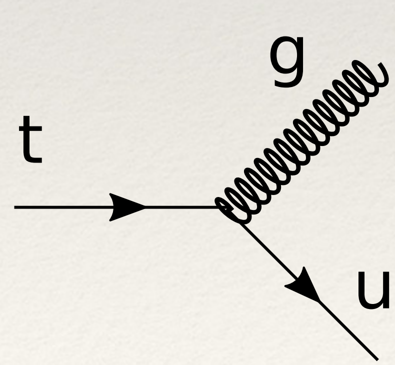
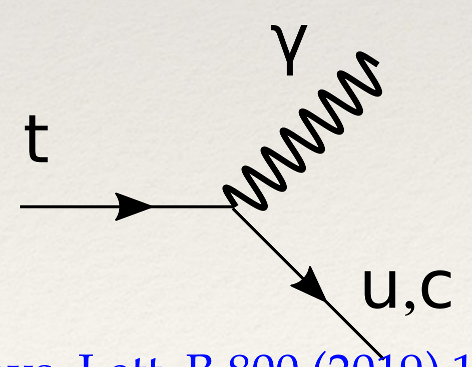


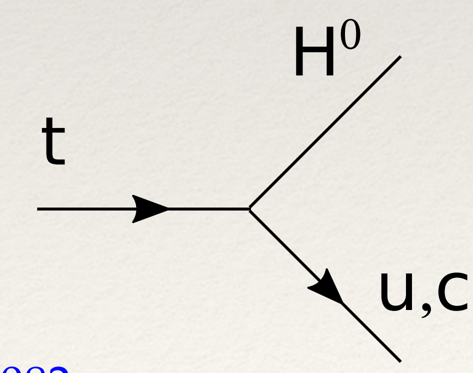
Limits. JHEP 07 (2018) 176



Eur. Phys. J. C (2016) 76:55



Phys. Lett. B 800 (2019) 135082



Limits. JHEP 05 (2019) 123