W-helicity and top-quark polarization

Contents:

- W-helicity combination ATLAS+CMS
- Top quark polarisation in single top/ EFT interpretation
- Top quark spin correlation/ search for CP-violation in ttbar

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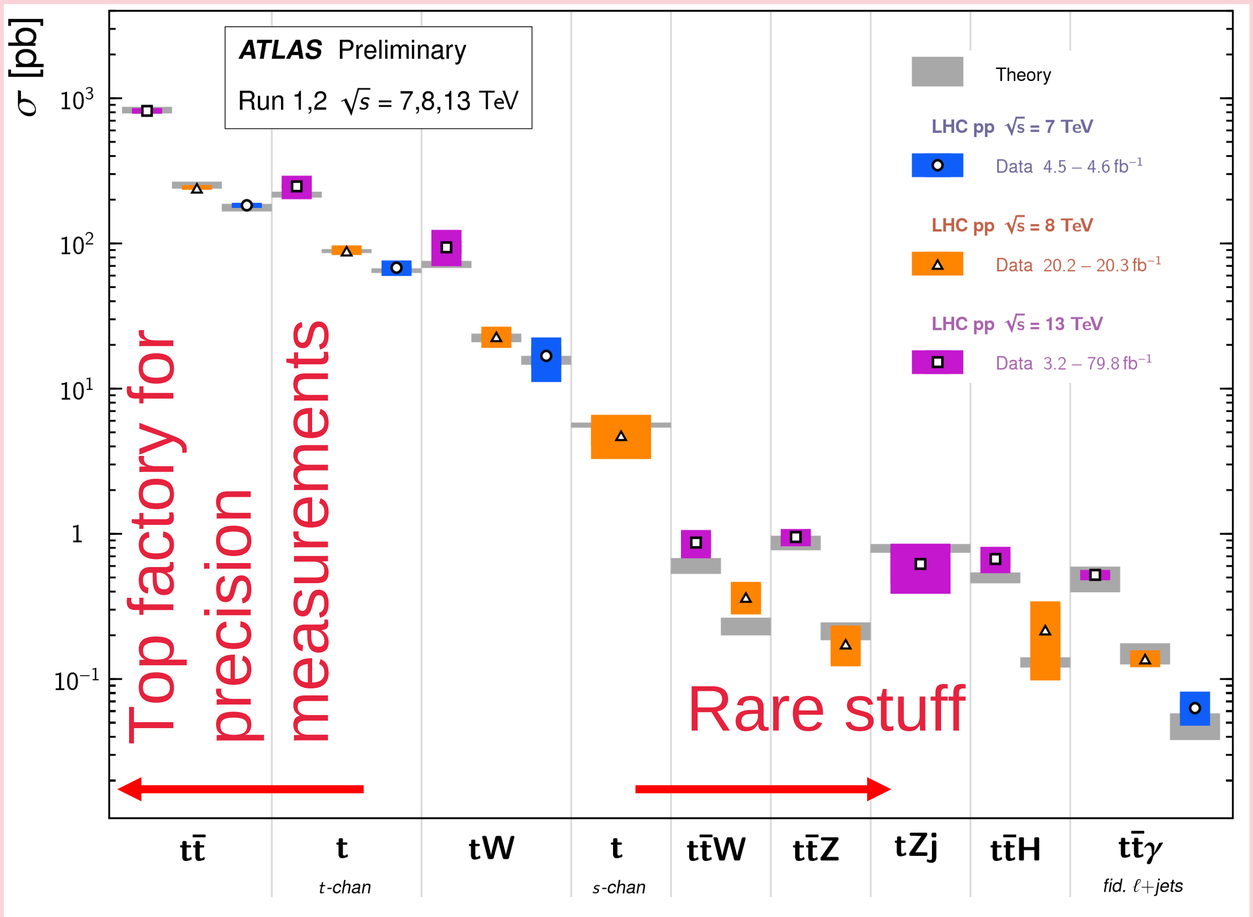
TOP QUARK PHYSICS @LHC - WHAT DO WE STUDY?

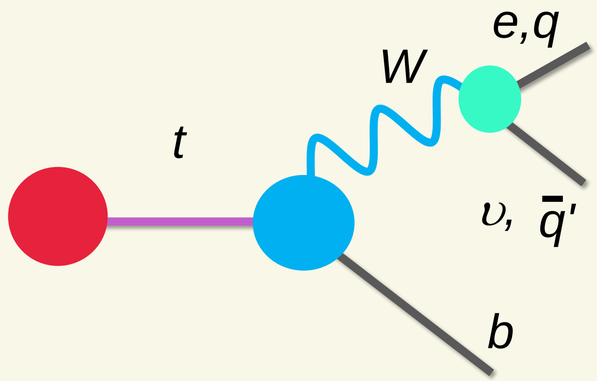


Production Cross section

- Tests of QCD (pair)
- Electroweak (single)

Top properties

- Mass
- **Spin**
- Charge, Width



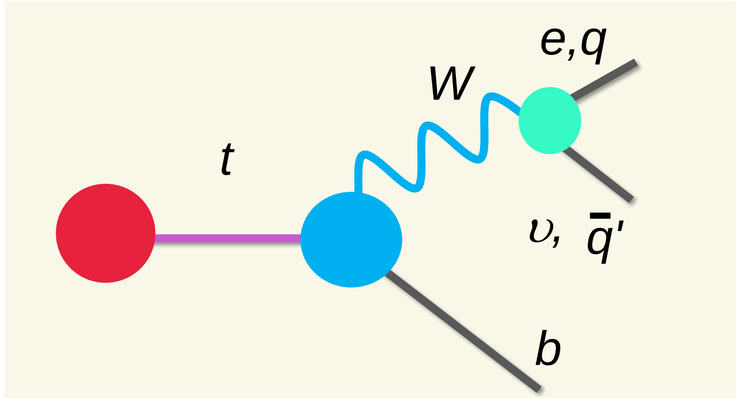
SM decay:

- $t \to Wb$ (~100%)
- W leptonic e,μ,(τ) ~22% (11%)
  → Clean but neutrino escapes (missing E_T)
- hadronic ~66%
  → Jet Energy Scale and backgrounds

Structure **W*tb* vertex**:

- *Vtb* and other couplings
- **Spin properties**
- Exotics, FCNC

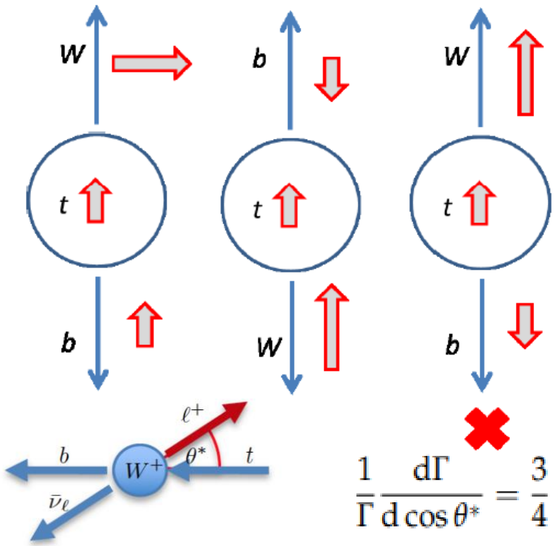
Top-quark spin; why do we care?



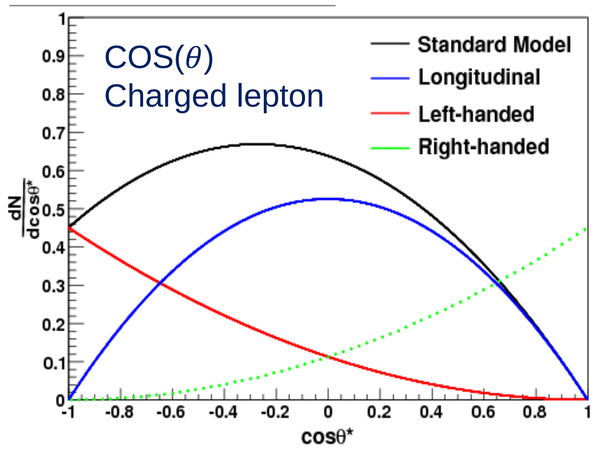
Wtb vertex: Spin structure

- Top decay products remember its Spin
- Measure Vtb and new couplings
- CP violation beyond the SM
- Cosmological context: Baryogenesis

Helicity basis

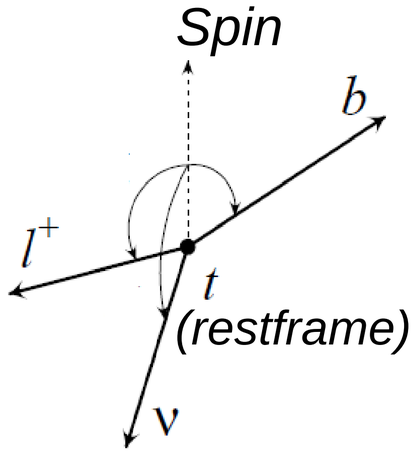


W helicity (in W rest frame)



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

Top Polarization (in top rest frame)

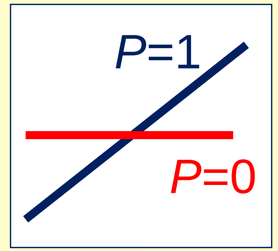


P=top polarisation

$$: \frac{1}{2}\left(1+\alpha_X P\cos\theta_X\right)$$

$$\alpha_i = \begin{cases} +1.0 & l^+ \text{ or } \bar{d}\text{-quark} \\ -0.31 & \bar{\nu} \text{ or } u\text{-quark} \\ -0.41 & b\text{-quark} \end{cases}$$

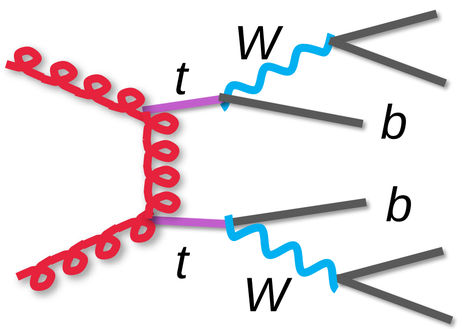
Asymmetry



W-helicity combined measurement 8 TeV

W-helicity in top quark decay

ttbar final state
‘’semi-leptonic”

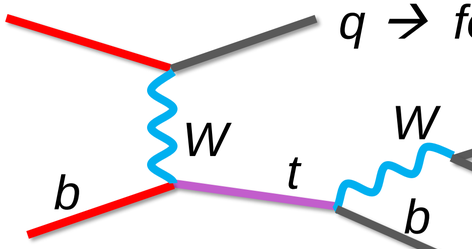


q → Jet
q’ → Jet
→ b tagged Jet
→ b tagged Jet
e,μ → isolated
υ_e, υ_μ → Missing E_T

$\sigma(13\text{TeV}) = 832^{+40}_{-46}\text{pb}$

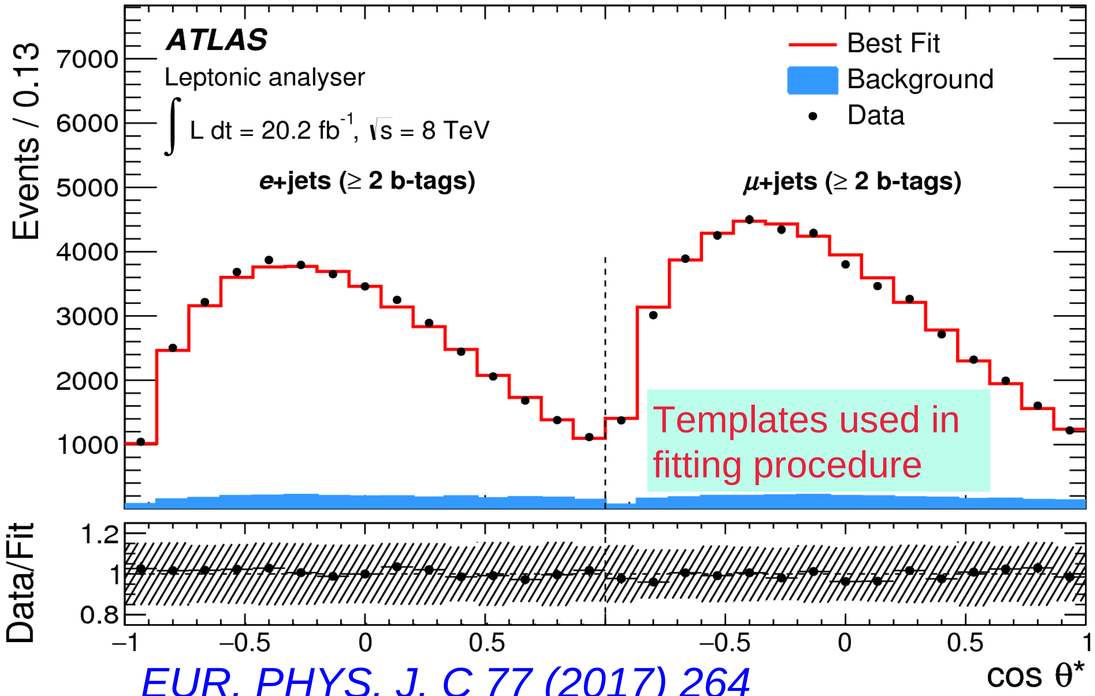
Typical cut on objects p_T>25GeV

single top
t-channel

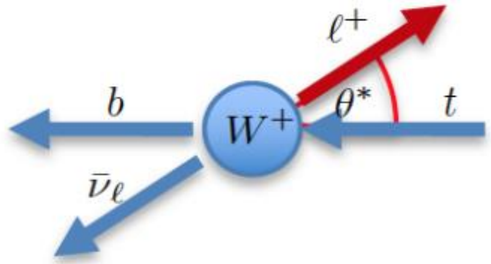


q → forward Jet
e,μ → isolated
υ_e, υ_μ → Missing E_T
→ b tagged Jet

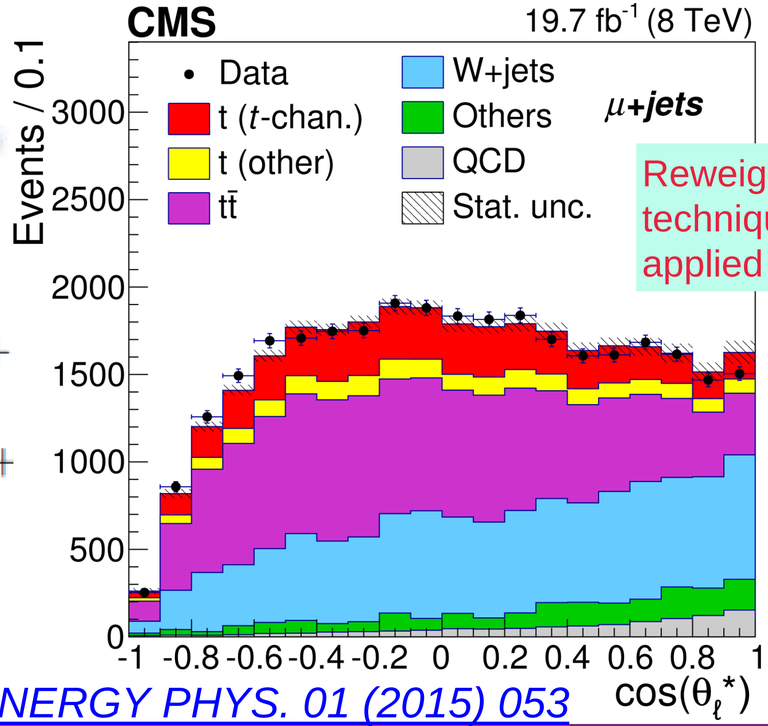
$\sigma(13\text{TeV}) = 217^{+10}_{-10}\text{pb}$



Templates used in fitting procedure



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

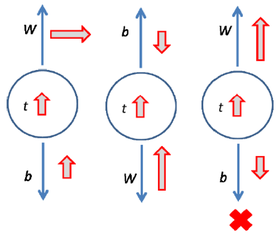


Reweighting technique applied in fit

[EUR. PHYS. J. C 77 (2017) 264]

[J. HIGH ENERGY PHYS. 01 (2015) 053]

W-helicity ATLAS+CMS combination 8 TeV



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

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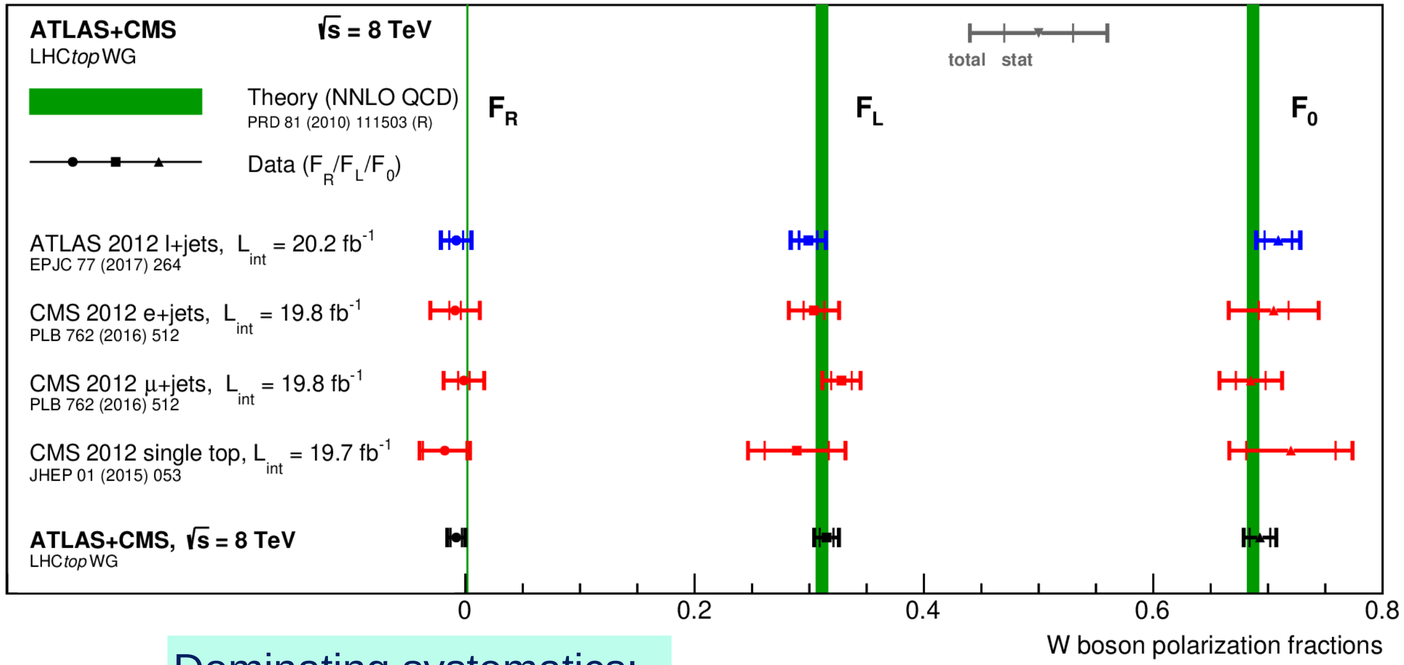
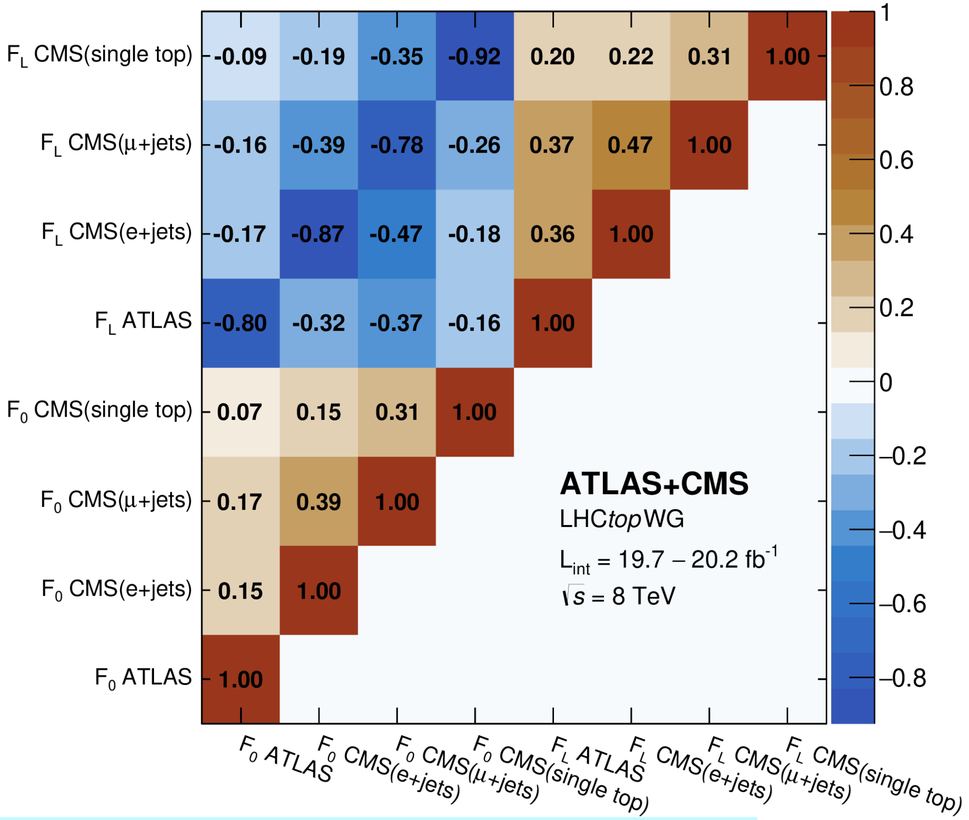
BLUE method used to combine





Dominating systematics:
-Exp: Jes, Jer
-Theo: Simulation model, radiation, scale

F0 uncertainty 2.0%, 25% more precise than inputs
FL uncertainty 3.5%, 29% more precise than inputs
FR < 0.007 at 95% CL, factor of 2 more precise than inputs

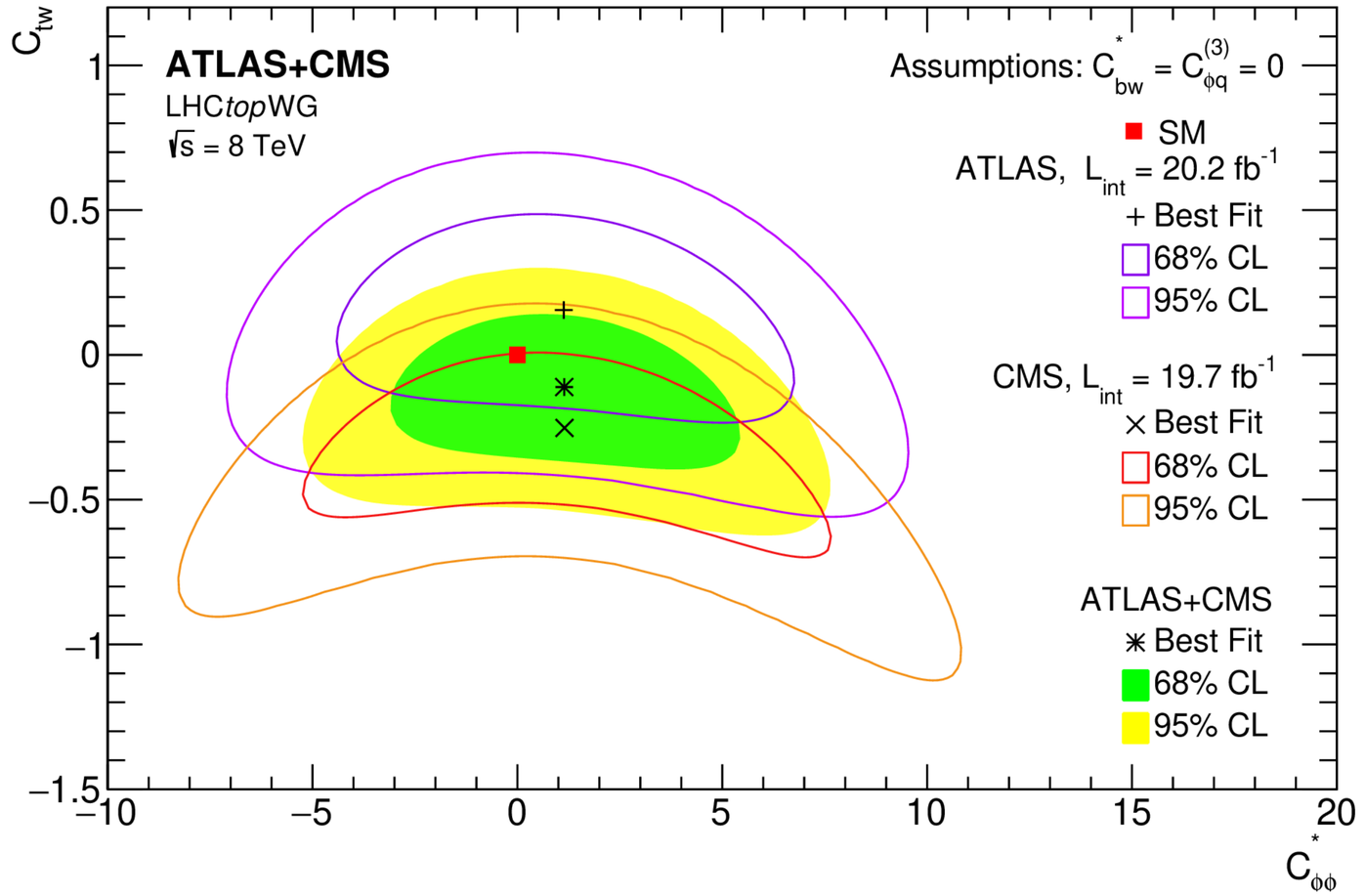
W-helicity EFT interpretation

SM Effective Field Theory (SMEFT) interpretation up to dim6

Coefficient Operator-dim6

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

Scale BSM physics. Set to 1 TeV^2



$$O_{\phi\phi} = \mathrm{i}(\tilde{\phi}^\dagger D_\mu \phi)(\bar{\mathrm{t}}_\mathrm{R}\gamma^\mu \mathrm{b}_\mathrm{R}),$$
$$O_{\mathrm{tW}} = (\bar{\mathrm{q}}_\mathrm{L}\sigma^{\mu\nu}\tau^I \mathrm{t}_\mathrm{R})\tilde{\phi}\mathrm{W}^I_{\mu\nu},$$
$$O_{\mathrm{bW}} = (\bar{\mathrm{q}}_\mathrm{L}\sigma^{\mu\nu}\tau^I \mathrm{b}_\mathrm{R})\phi\mathrm{W}^I_{\mu\nu},$$

	95%CL (INDIV.)
Coefficient	ATLAS+CMS
$C^*_{\phi\phi}$	$[-3.48, 5.16]$
C^*_{bW}	$[-0.96, 0.67]$
C_{tW}	$[-0.48, 0.29]$

Note: values kept real

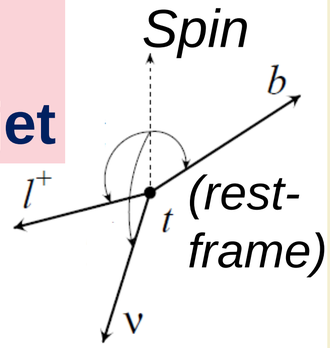
Polarized top production (single top)

Wtb vertex: Polarized production in t-channel

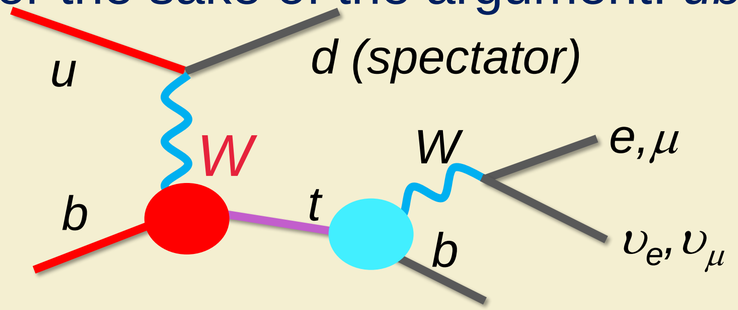
EW production:
Top spin polarized in direction of **spectator jet**

$$\frac{1}{2}(1+\alpha_l P \cos(\theta_l))$$

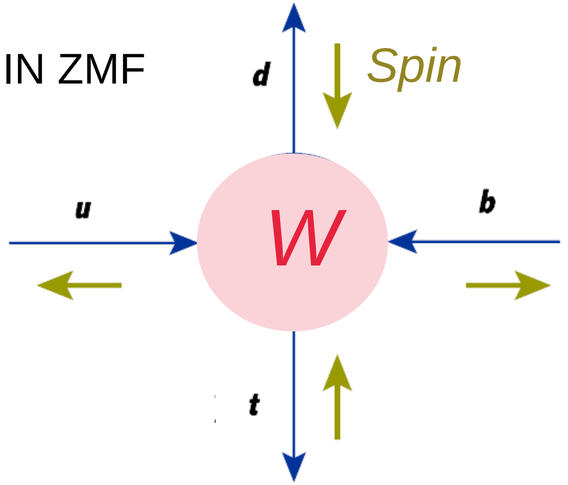
$lepton$: $\alpha_l \cong 1$ top pol.



For the sake of the argument: *ub* to *td*

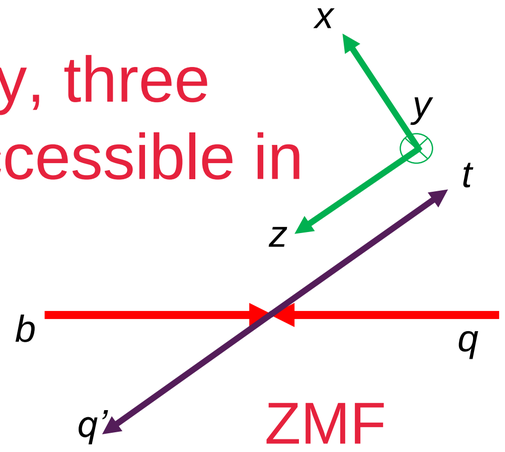


$\sigma(13\text{TeV}) = 217^{+10}_{-10}\text{pb}$



Leads to Asymmetries in angular distributions
→ secrets of the Wtb vertex

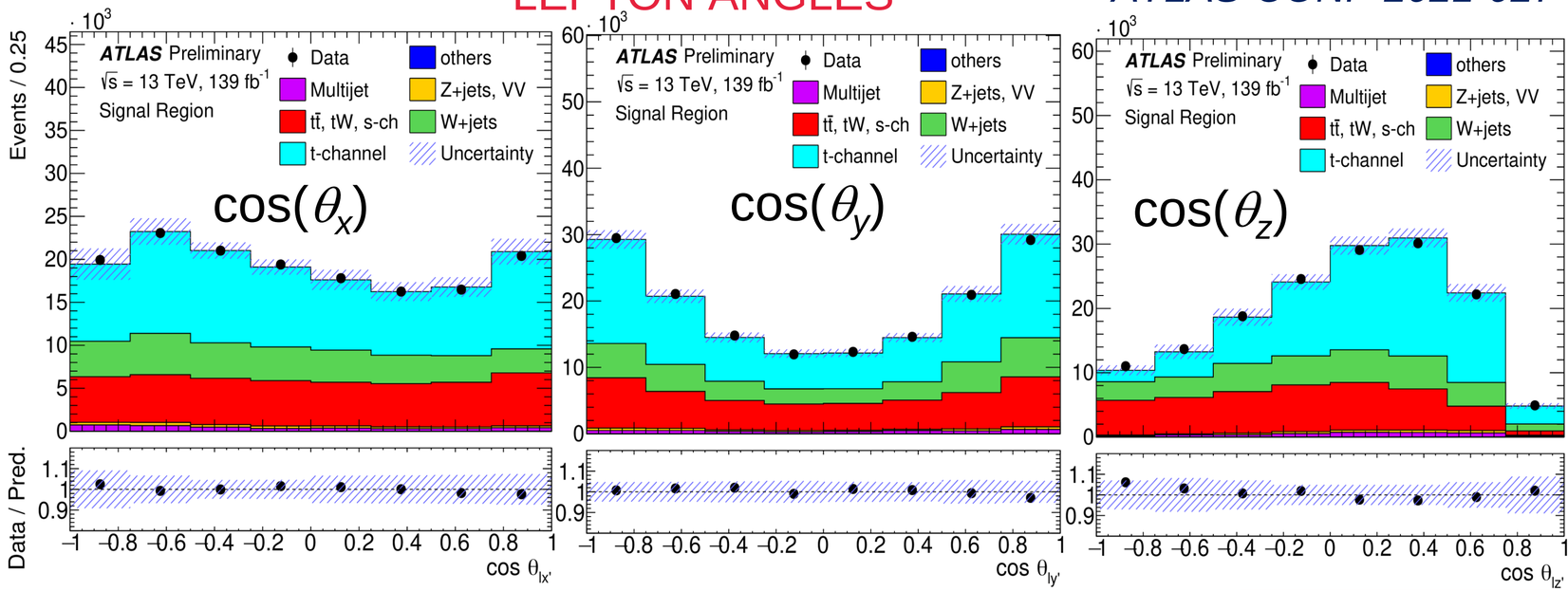
Experimentally, three projections accessible in top restframe:
P_x, P_y, P_z



ZMF

LEPTON ANGLES

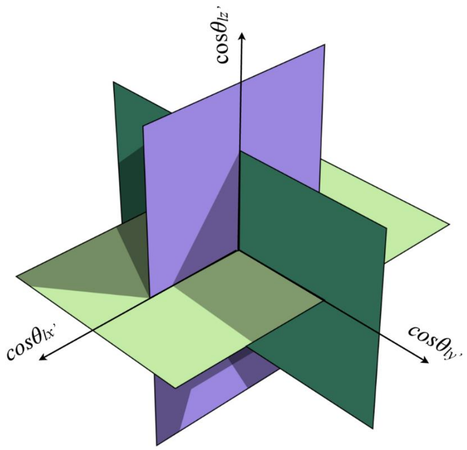
ATLAS-CONF-2021-027

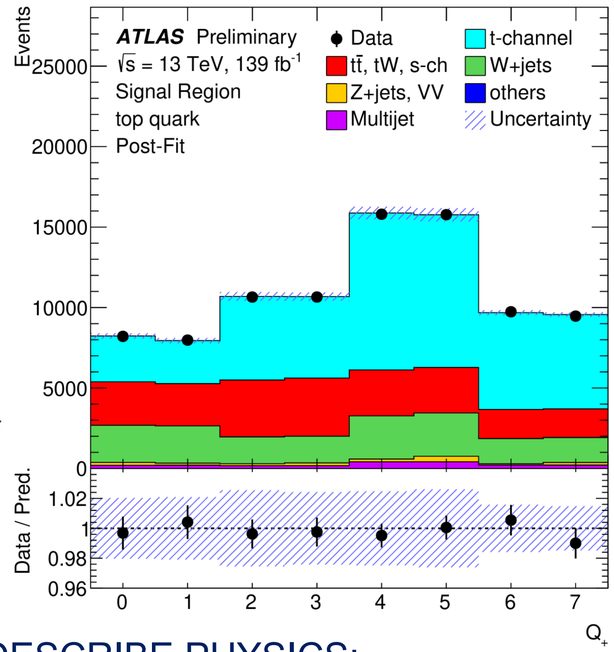


Wtb vertex: Polarized production in t-channel

The three angular cos(θ) distributions are mapped to 8 independent bins

$$Q = 4 \cdot \Theta(\cos\theta_{\ell z'}) + 2 \cdot \Theta(\cos\theta_{\ell x'}) + \Theta(\cos\theta_{\ell y'})$$

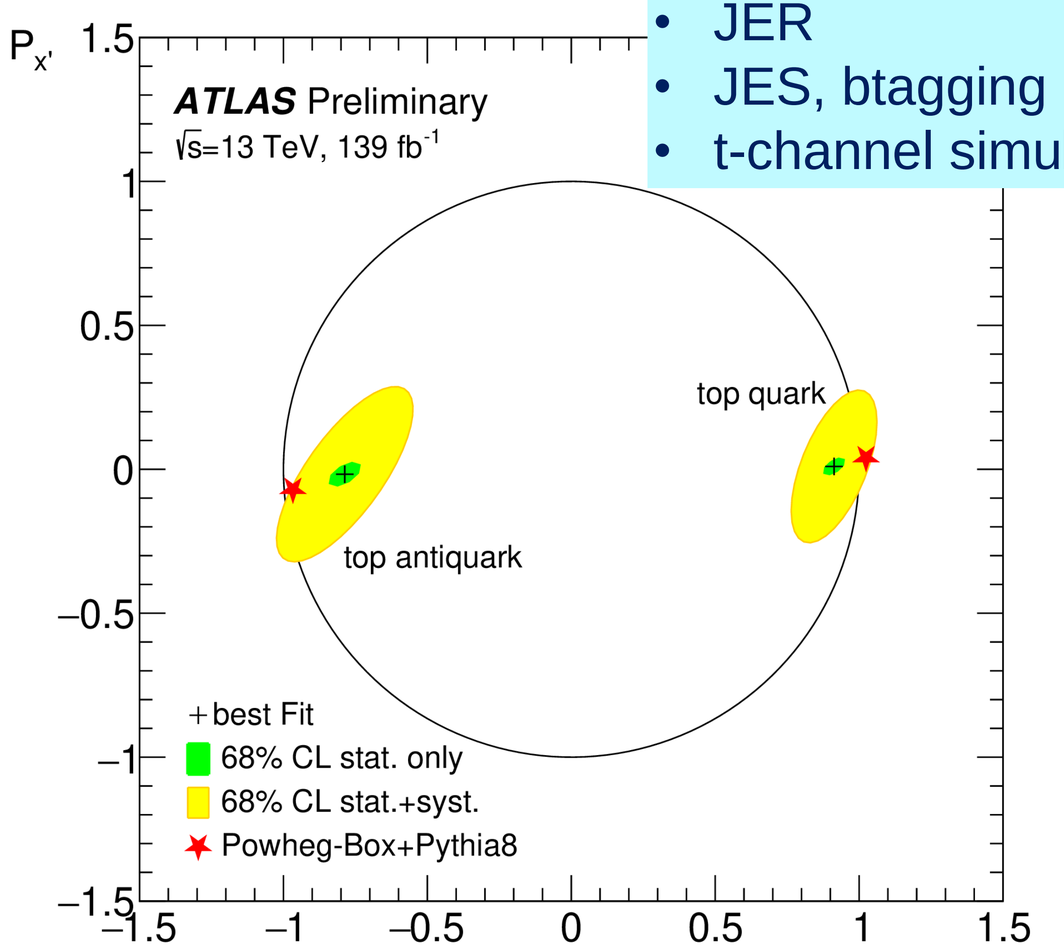




''ONLY'' 4 TEMPLATES DESCRIBE PHYSICS:

$$\frac{1+P_z}{2}\mathcal{F}_{z+} + \frac{1-P_z}{2}\mathcal{F}_{z-} + \frac{P_x}{2}\mathcal{F}_x + \frac{P_y}{2}\mathcal{F}_y$$

→ Template fit



ATLAS-CONF-2021-027

Systematics:
- JER
- JES, btagging
- t-channel simulation

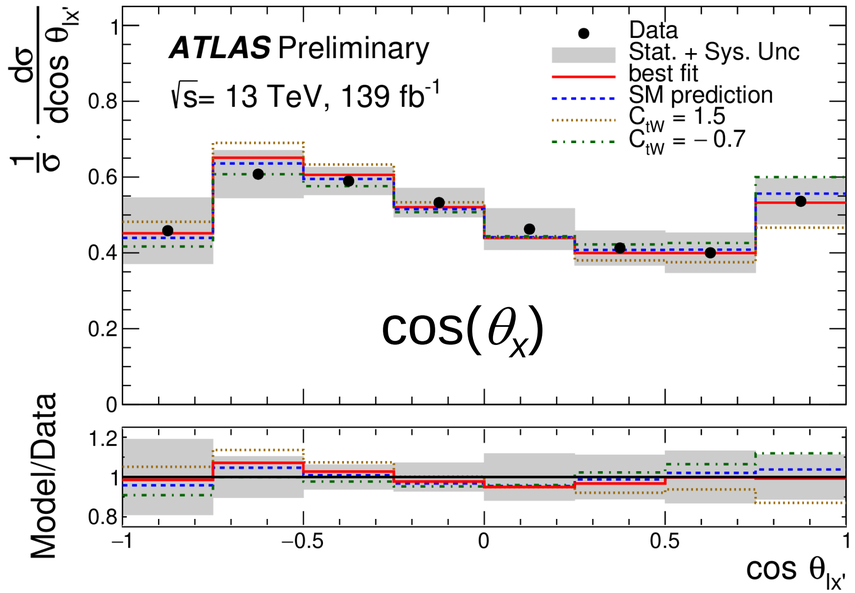
t-channel: particle level and EFT interpretation

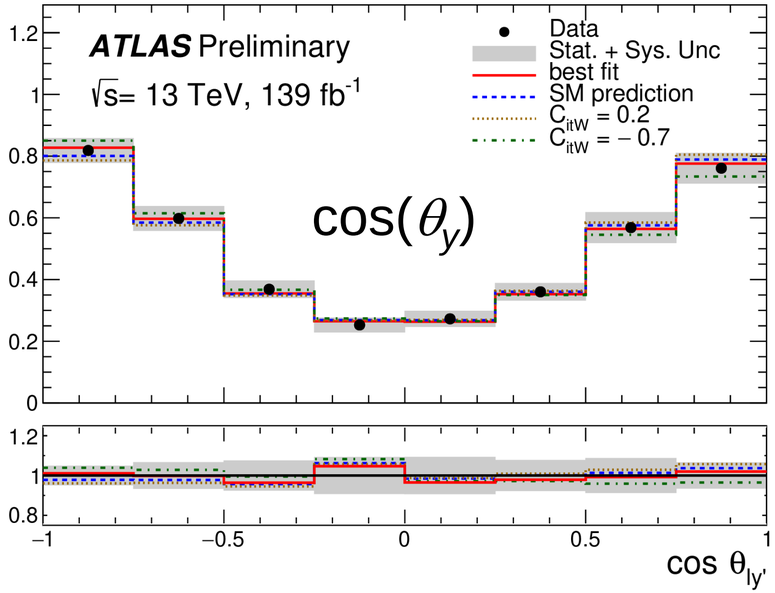
In EFT many operators can contribute, ~1000.
In t-channel only three operators that interfere with SM.

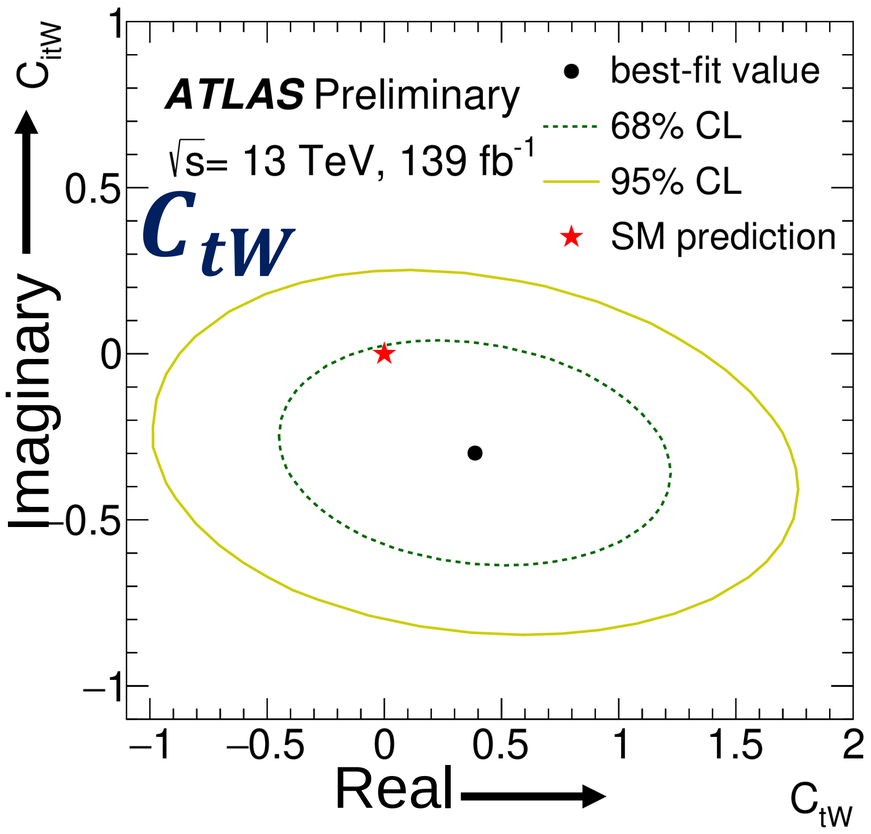
C_{tW}, C_{qQ}, $C_{\varphi Q}$

Normalized cos(θ_x) and cos(θ_y) distribution sensitive to C_{tW}

CP violation → $C_{tW} \neq C_{tW}^*$



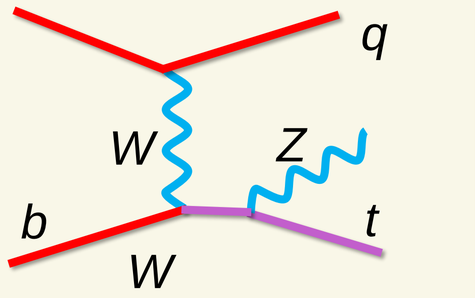




C_{tW}		C_{itW}	
68% CL	95% CL	68% CL	95% CL
[-0.2, 0.9]	[-0.7, 1.5]	[-0.5, -0.1]	[-0.7, 0.2]

Top polarization in tZq, a rare production process

CMS PAS TOP-20-010



1 EXAMPLE

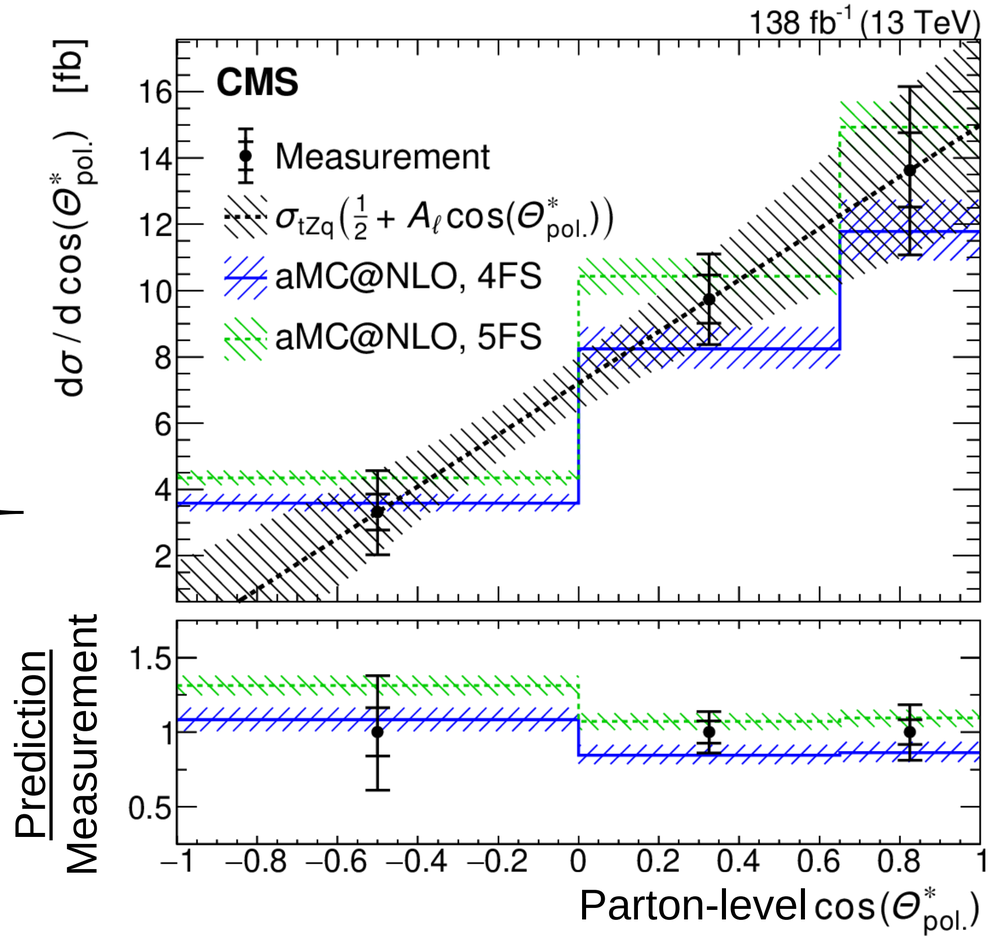
$\sigma(13\text{TeV}) = 0.8^{+0.05}_{-0.05}\text{pb}$

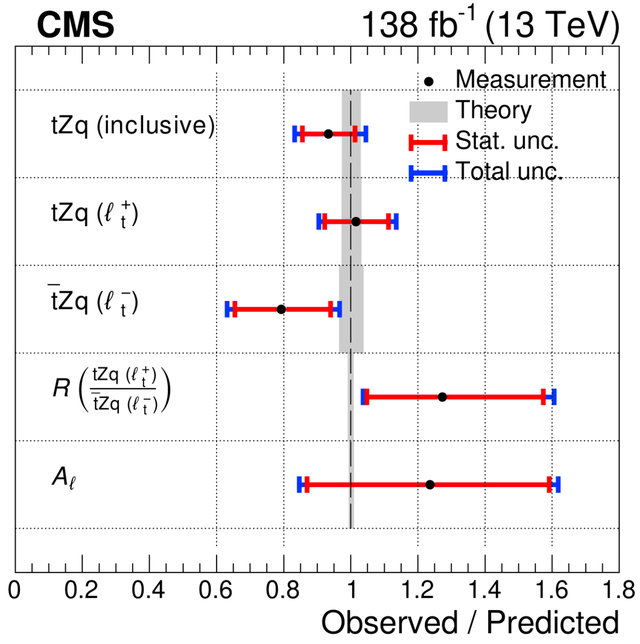
Event selection based on three leptons
1 pair consistent with *Z* decay

Polarisation angle defined in top rest frame

$$\frac{1}{2}(1+\alpha_l P \cos(\theta_l))$$

$$lepton\text{: } A_l = \frac{1}{2}\alpha_l P$$





systematics:

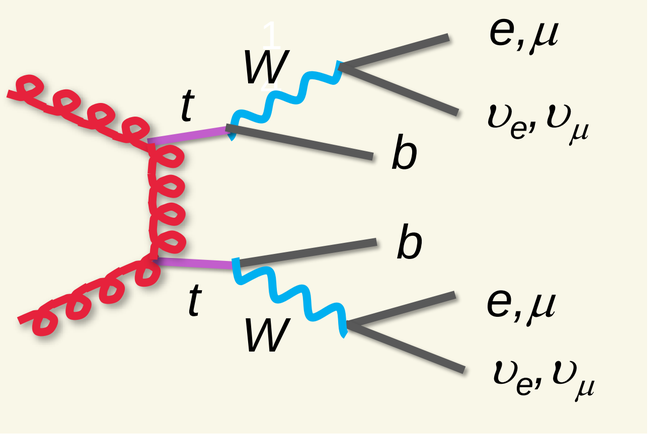
- Background modelling
- B-tagging, lepton-id
- JES
- scales and radiation

$$A_\ell = 0.54 \pm 0.16\,(\text{stat}) \pm 0.06\,(\text{syst})$$

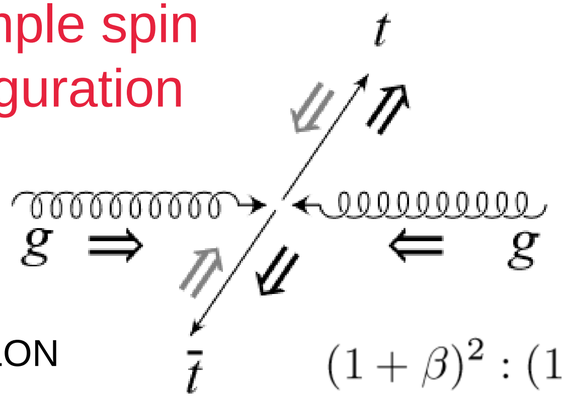
Unpolarized top production (ttbar)

Spin correlation
and
Search for CP violation

TOP QUARK PAIR PRODUCTION: SPIN CORRELATION



Example spin configuration

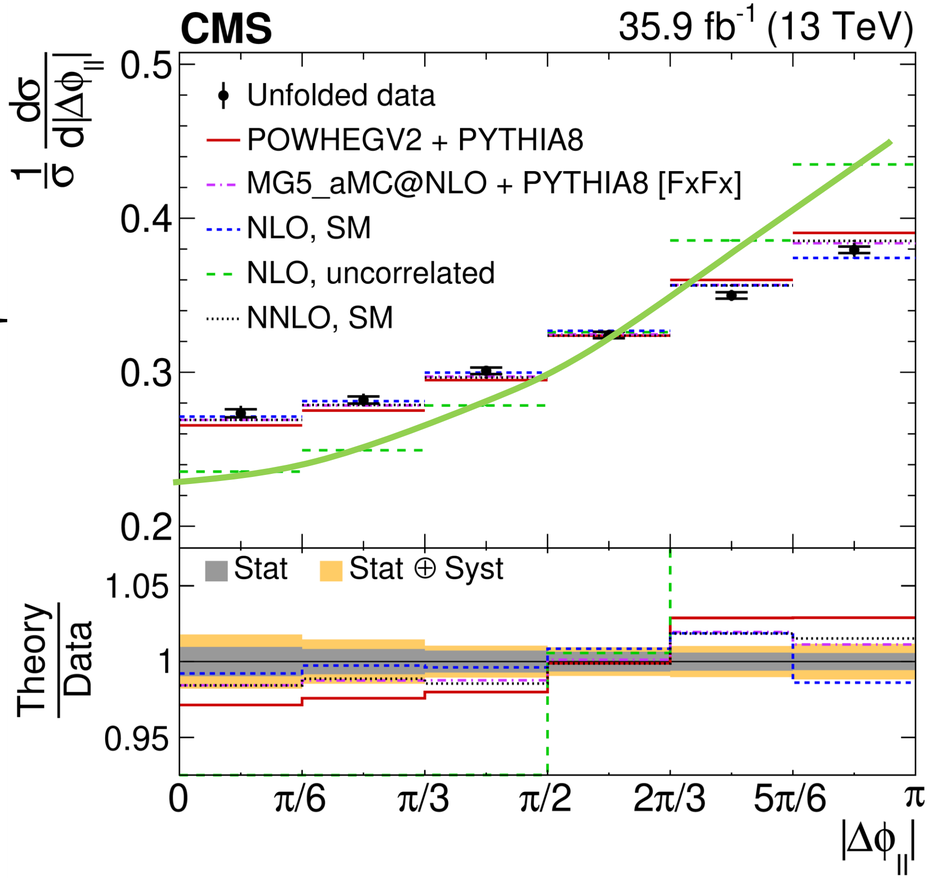


G. MAHLON

$(1+\beta)^2 : (1-\beta)^2$

Several other spin configurations possible: there is a net effect

- Many angular combinations to study (in ttbar frame)
- ''Easy'' quantity in lab frame in di-lepton events: azimuthal angle $\Delta\varphi_{ll}$



CMS: *PHYS. REV. D 100 (2019) 072002*
ATLAS: *EUR. PHYS. J. C 80 (2020) 754*

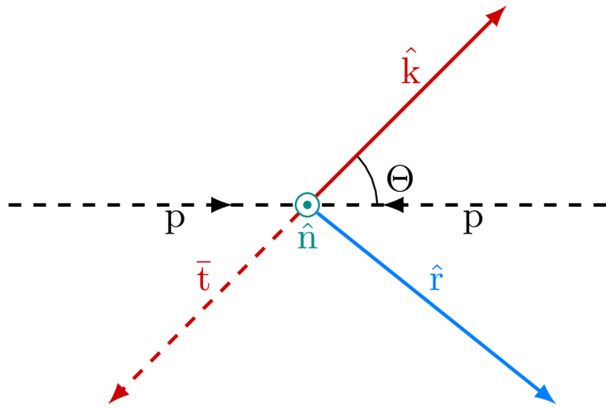
Spin correlation!

Some tension seen in data vs Powheg.

Disappears when NLO QCD- and EW- corrections are consistently included in the normalized differential cross section.

ttbar: A closer look into spin polarisation and correlation

Reminder:
top is produced unpolarised in ttbar

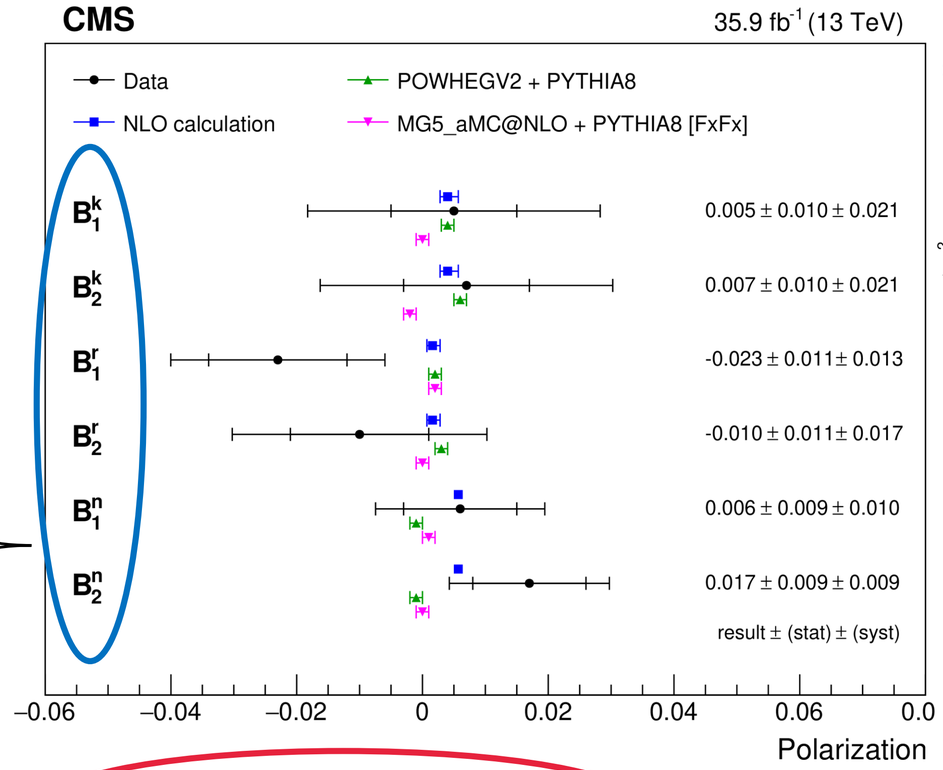


Measure 3+3 (t+tbar) angular projections of lepton in ttbar system

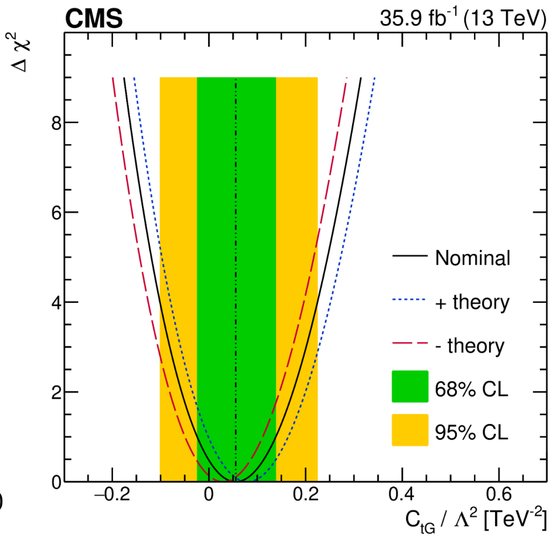
$$\frac{1}{\sigma}\frac{\mathrm{d}^4\sigma}{\mathrm{d}\Omega_1\,\mathrm{d}\Omega_2} = \frac{1}{(4\pi)^2}\left(1 + \mathbf{B_1}\cdot\hat{\ell}_1 + \mathbf{B_2}\cdot\hat{\ell}_2 - \hat{\ell}_1\cdot C\cdot\hat{\ell}_2\right)$$

Polarisation

Correlation



CMS-TOP-18-006/
PRD 100 (2019) 072002



Correlation ''matrix'' is also measured →
EFT interpretation: limits operator O_{tG}

$-0.24 < C_{\mathrm{tG}}/\Lambda^2 < 0.07\ \mathrm{TeV}^{-2}$ and $-0.33 < C^I_{\mathrm{tG}}/\Lambda^2 < 0.20\ \mathrm{TeV}^{-2}$

Chromo-magnetic-dipole-moment Chromo-electric-dipole-moment

Hunting CP violation in ttbar

Search for CP-odd new physics in semi-leptonic ttbar.

CMS PAS TOP-20-005

(di-leptonic*: CMS-PAS-TOP-18-007)*

$$\mathcal{L} = \frac{g_s}{2}\bar{t}T^a\sigma^{\mu\nu}(a_t^g + i\gamma_5 d_t^g)tG^a_{\mu\nu},$$

$$d_t^g = \frac{\sqrt{2}v}{\Lambda^2}\mathrm{Im}(d_{tG}),$$

Related to CEDM= chromo-electric-dipole-moment

(related to C'_{tG})

$$O_3 = Q_\ell \epsilon(p_b, p_{\bar{b}}, p_\ell, p_{j_1}) \propto Q_\ell \vec{p'}_b \cdot (\vec{p'}_\ell \times \vec{p'}_{j_1})$$

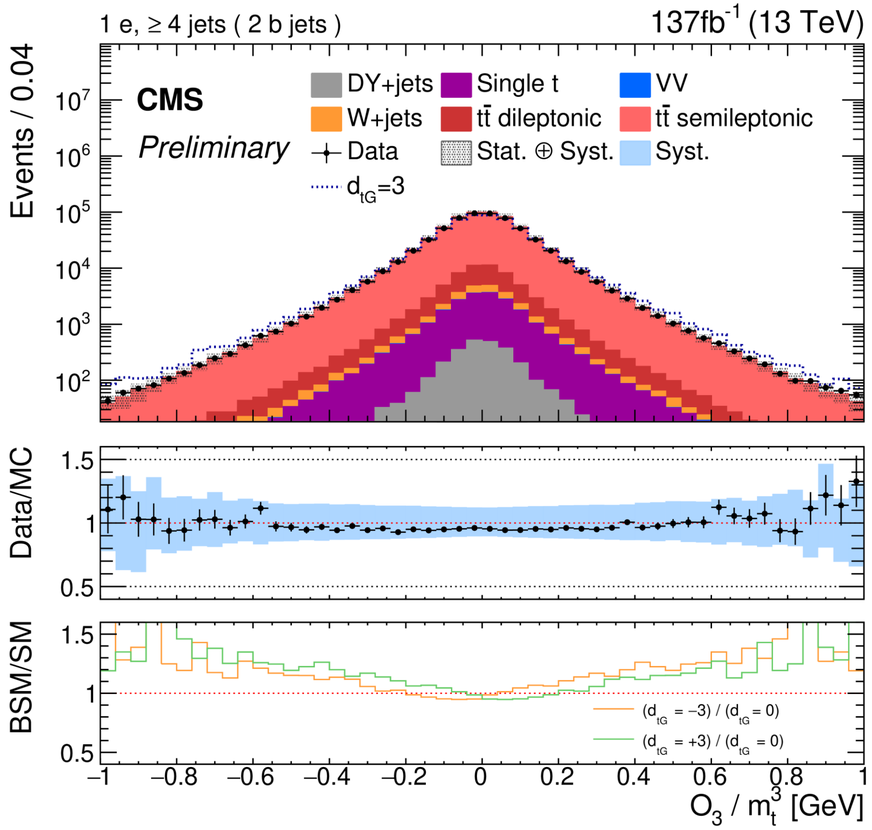
$$O_6 = Q_\ell \epsilon(P, p_b - p_{\bar{b}}, p_\ell, p_{j_1}) \propto Q_\ell (\vec{p}_b - \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j_1})$$

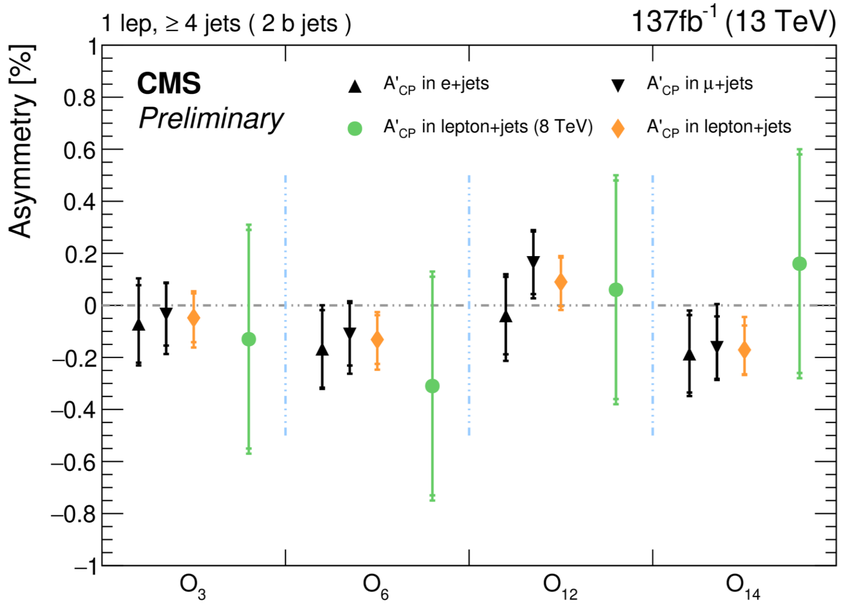
$$O_{12} = q \cdot (p_b - p_{\bar{b}}) \epsilon(P, q, p_b, p_{\bar{b}}) \propto (\vec{p}_b - \vec{p}_{\bar{b}})_z \cdot (\vec{p}_b \times \vec{p}_{\bar{b}})_z$$

$$O_{14} = \epsilon(P, p_b + p_{\bar{b}}, p_\ell, p_{j_1}) \propto (\vec{p}_b + \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j_1}).$$

$$A_{CP}(O_i) = \frac{N_{\text{events}}(O_i > 0) - N_{\text{events}}(O_i < 0)}{N_{\text{events}}(O_i > 0) + N_{\text{events}}(O_i < 0)},$$

$$i = 3, 6, 12, 14.$$





CONCLUSION

- LHC is a top factory
- Spin structure of the Wtb vertex is being pinned down

BACKUP

Wtb vertex function vs EFT

Model independent search for New Physics at the EW symmetry breaking scale

Traditional vertex function

CP violation if $g_R \neq g_R^*$

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}\left(V_{\mathrm{L}}P_{\mathrm{L}} + V_{\mathrm{R}}P_{\mathrm{R}}\right)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{m_{\mathrm{W}}}\left(g_{\mathrm{L}}P_{\mathrm{L}} + g_{\mathrm{R}}P_{\mathrm{R}}\right)tW_{\mu}^{-}$$

Newer: SM Effective Field Theory (SMEFT) interpretation up to dim6

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

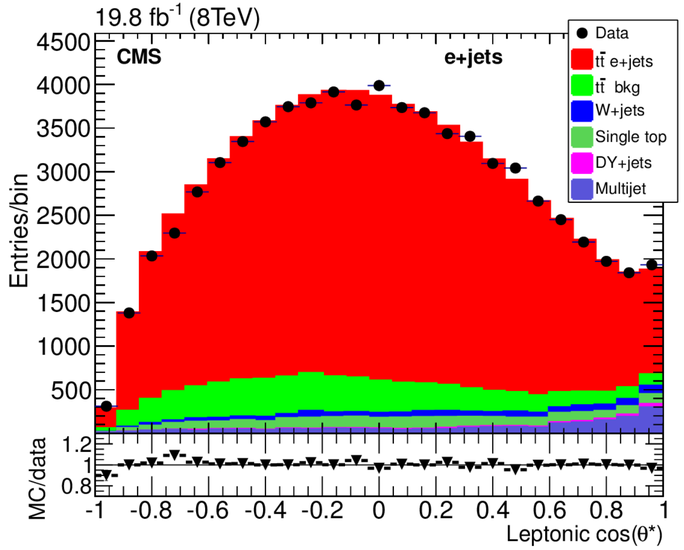
Correspond

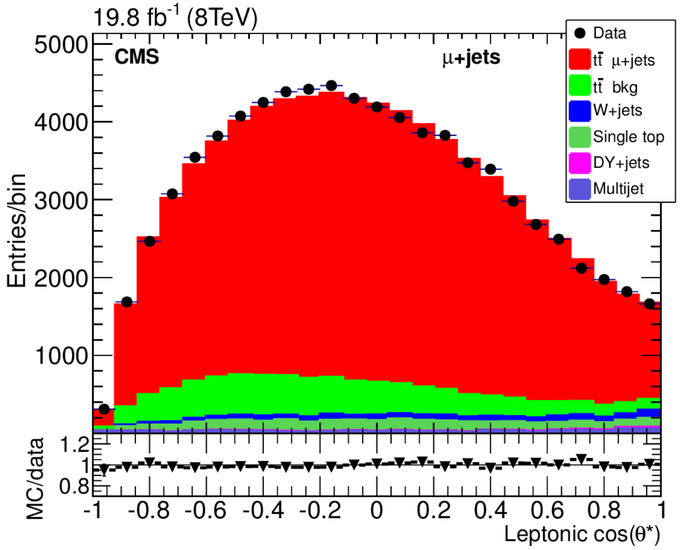
In EFT many operators can contribute, ~1000.
In t-channel only three operators that interfere with SM.

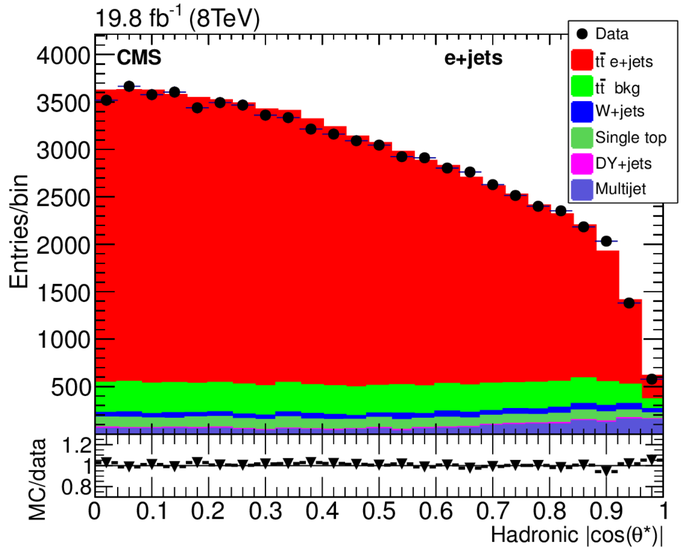
C_{tW}, C_{qQ}, $C_{\varphi Q}$

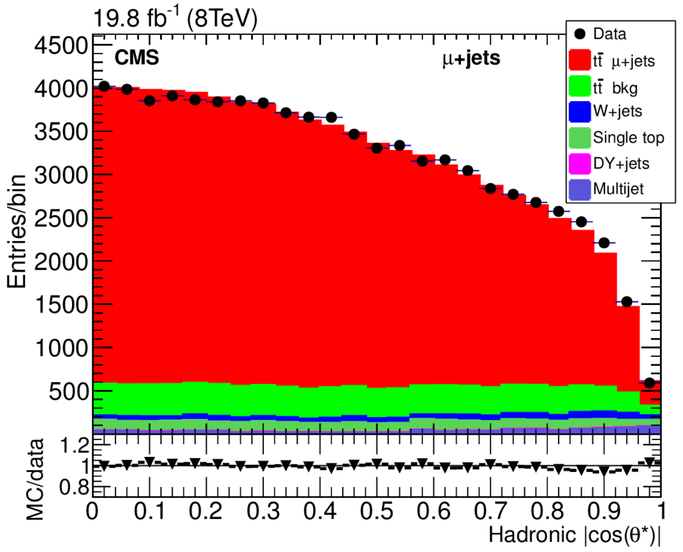
CP violation if $C_{tW} \neq C_{tW}^*$

W-HELICITY









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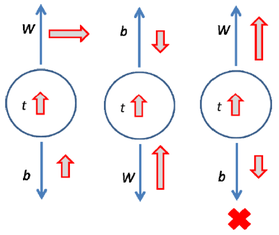
W-HELICITY ATLAS+CMS COMBINATION 8 TEV



$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta^*} = \frac{3}{4}\left(1-\cos^2\theta^*\right) F_0 + \frac{3}{8}\left(1-\cos\theta^*\right)^2 F_{\mathrm{L}} + \frac{3}{8}\left(1+\cos\theta^*\right)^2 F_{\mathrm{R}}.$$

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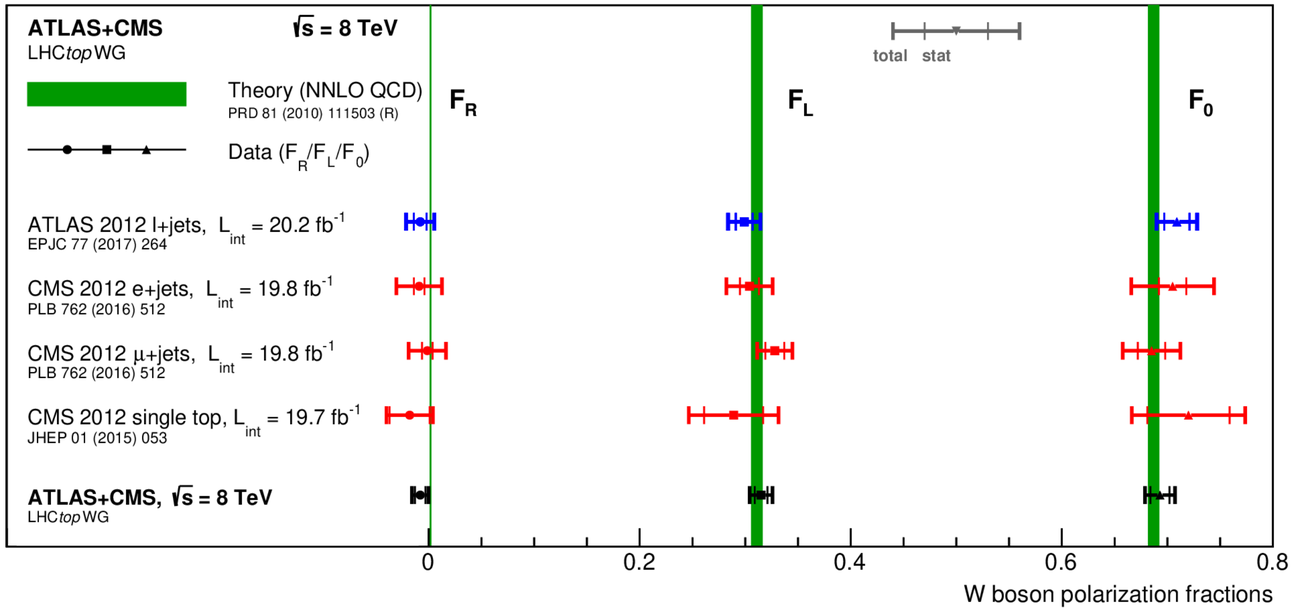
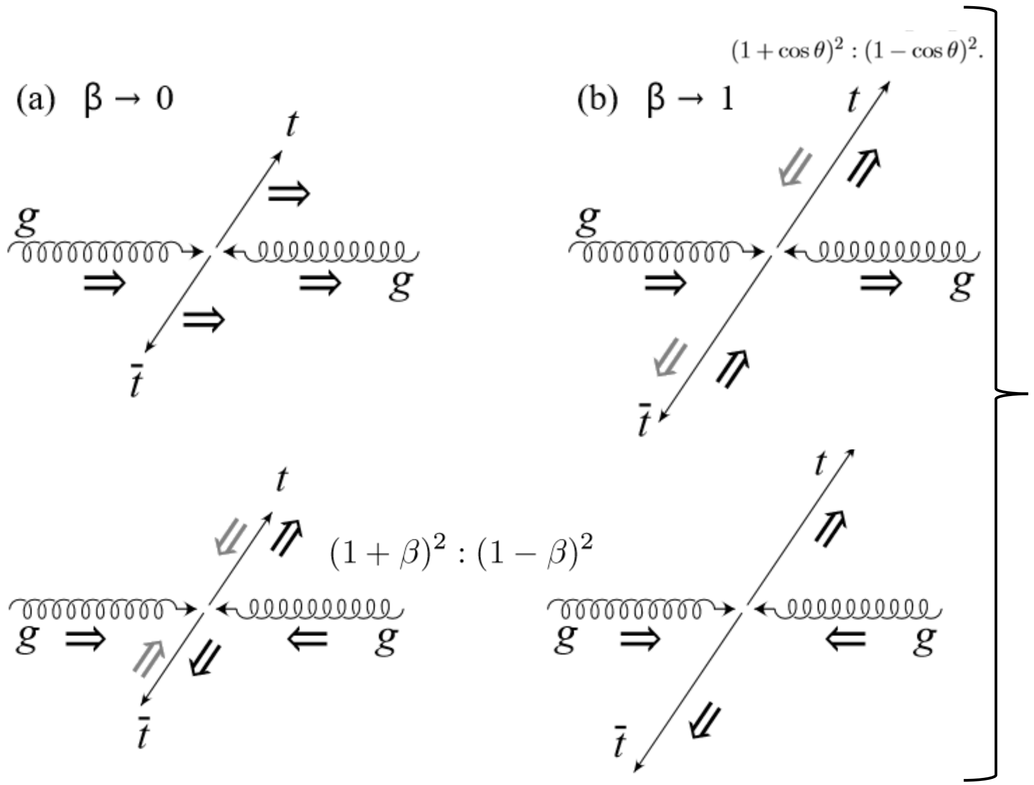


Measurement	F_0	F_{L}	F_{R}
ATLAS (ℓ+jets)	$0.709 \pm 0.012 \pm 0.015$	$0.299 \pm 0.008 \pm 0.013$	$-0.008 \pm 0.006 \pm 0.012$
CMS (e+jets)	$0.705 \pm 0.013 \pm 0.037$	$0.304 \pm 0.009 \pm 0.020$	$-0.009 \pm 0.005 \pm 0.021$
CMS (μ+jets)	$0.685 \pm 0.013 \pm 0.024$	$0.328 \pm 0.009 \pm 0.014$	$-0.013 \pm 0.005 \pm 0.017$
CMS (single top)	$0.720 \pm 0.039 \pm 0.037$	$0.298 \pm 0.028 \pm 0.032$	$-0.018 \pm 0.019 \pm 0.011$

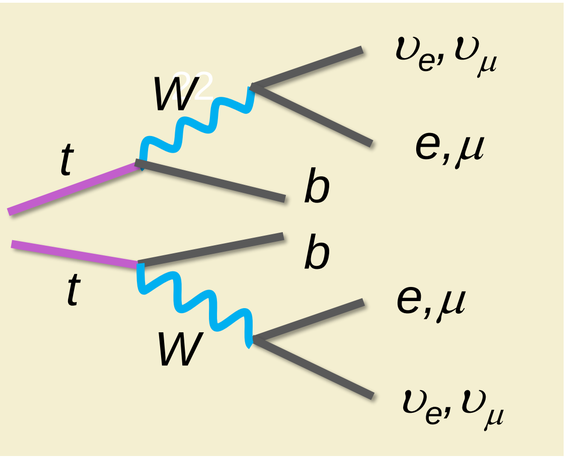
	ATLAS+CMS combination	
	F_0	F_{L}
Fractions	0.693	0.315
Uncertainty category		
Samples size and background determination		
Stat+bkg	0.009	0.006
Size of simulated samples	0.005	0.003
Detector modelling		
JES	0.004	0.002
JER	0.004	0.002
b tagging	0.001	0.001
JVF	0.001	0.001
Jet reconstruction	< 0.001	< 0.001
Lepton efficiency	0.002	0.001
Pileup	< 0.001	< 0.001
Signal modelling		
Top quark mass	0.003	0.004
Simulation model choice	0.006	0.005
Radiation and scales	0.005	0.004
Top quark p_{T}	0.001	0.002
PDF	0.001	0.001
Single top method	0.001	< 0.001
Total uncertainty	0.014	0.011

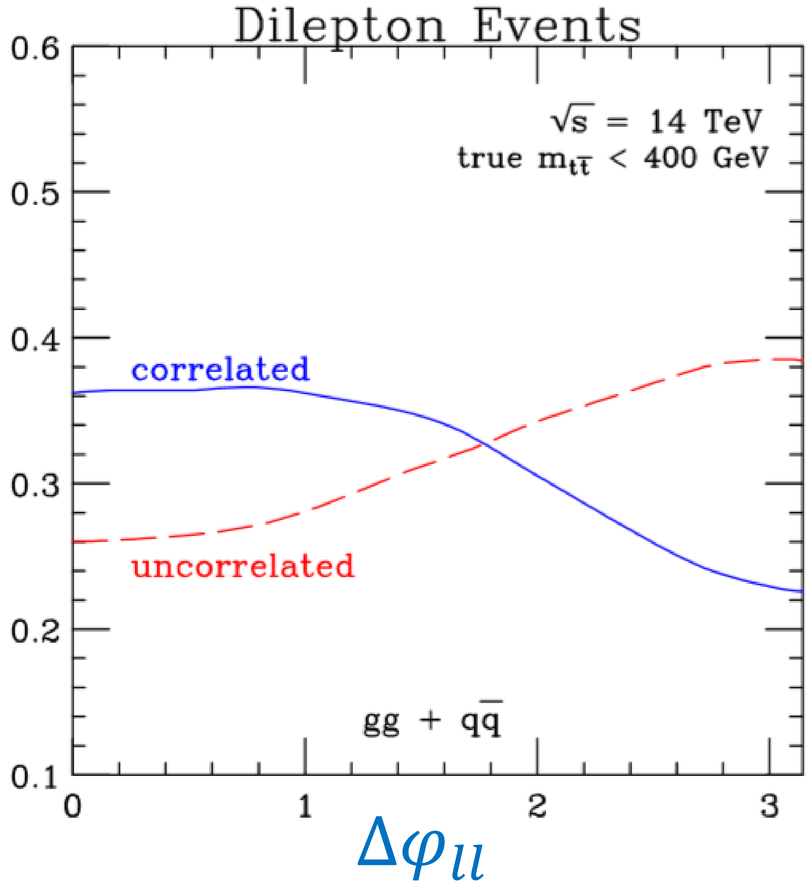
TOP QUARK PAIR PRODUCTION: SPIN CORRELATION

Top pair produced unpolarised but correlated!



- Nett effect
- Several ''optimal'' spin axis possible
- ''Easy'' quantity: in di-lepton events use azimuthal angle $\Delta\varphi_{ll}$

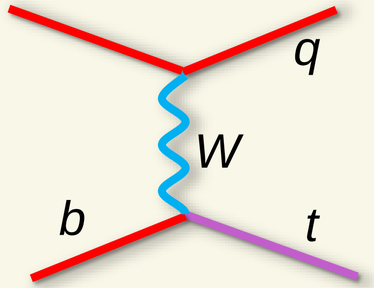




G. MAHLON

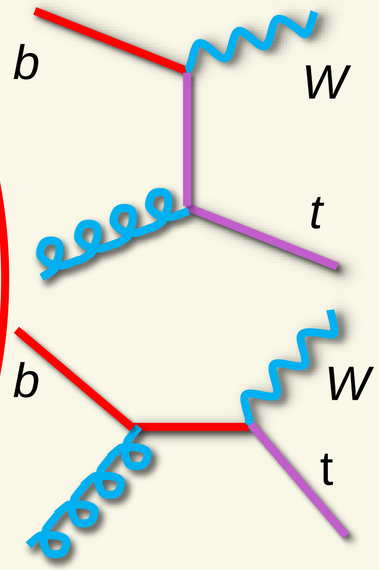
SINGLE TOP QUARK PAIR PRODUCTION

t-channel



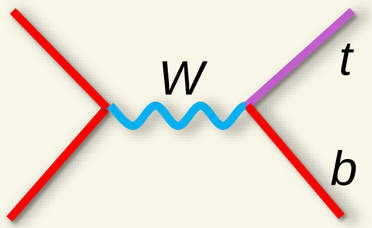
$\sigma(13\text{TeV}) = 217^{+10}_{-10}\text{pb}$

tW-channel



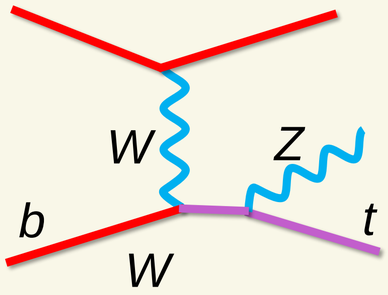
$\sigma(13\text{TeV}) = 72^{+4}_{-4}\text{pb}$

s-channel



$\sigma(13\text{TeV}) = 10.3^{+0.4}_{-0.4}\text{pb}$

tZq channel
(rare SM process)



1 EXAMPLE

$\sigma(13\text{TeV}) = 0.8^{+0.05}_{-0.05}\text{pb}$

Focus here on t-channel:
Large cross section, small background
EW Production → Spin Polarised

SM

CP violation if $g_R \neq g_R^*$

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