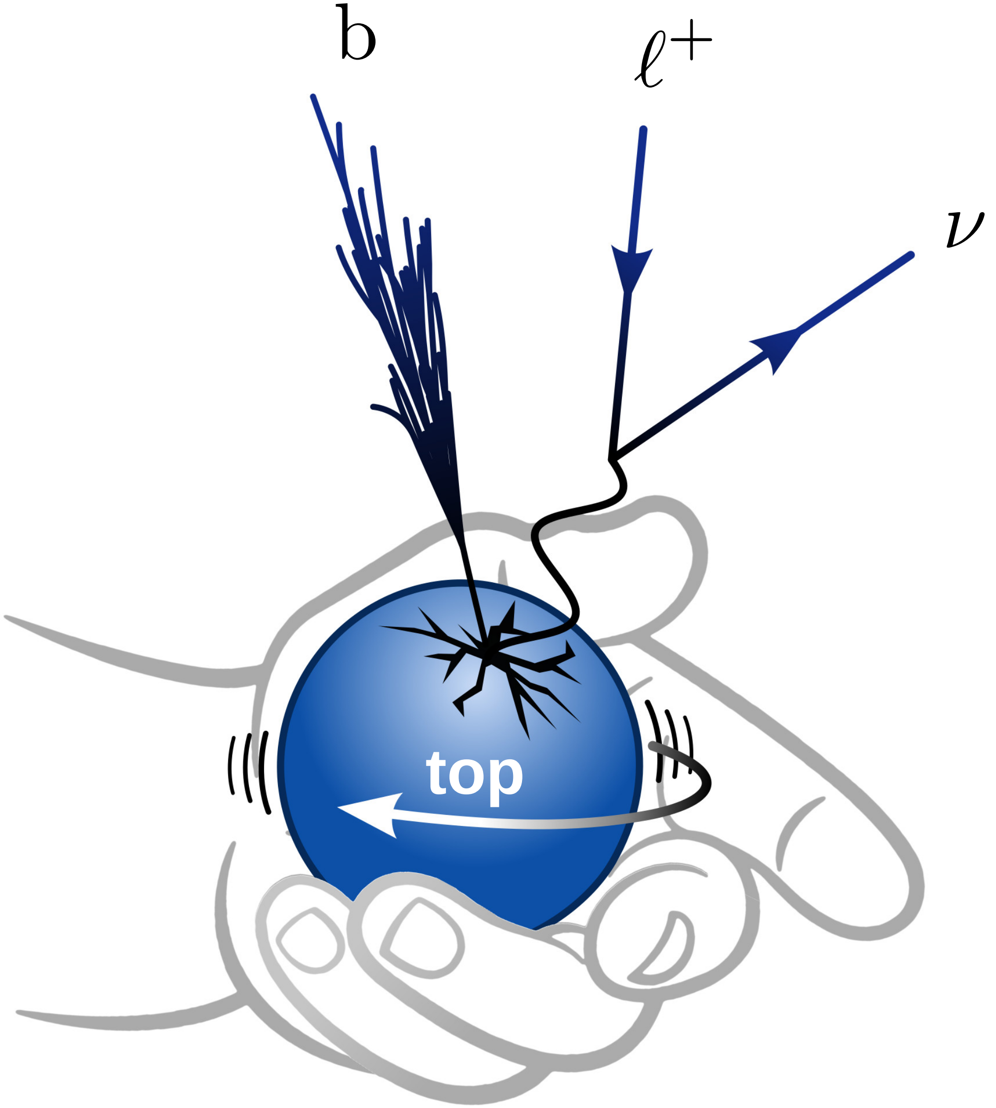

Top quark polarization measurements

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Overview

- top quark properties
  - coupling structure
  - spin analyzers
  - EFT & anomalous couplings
  - W helicity fractions

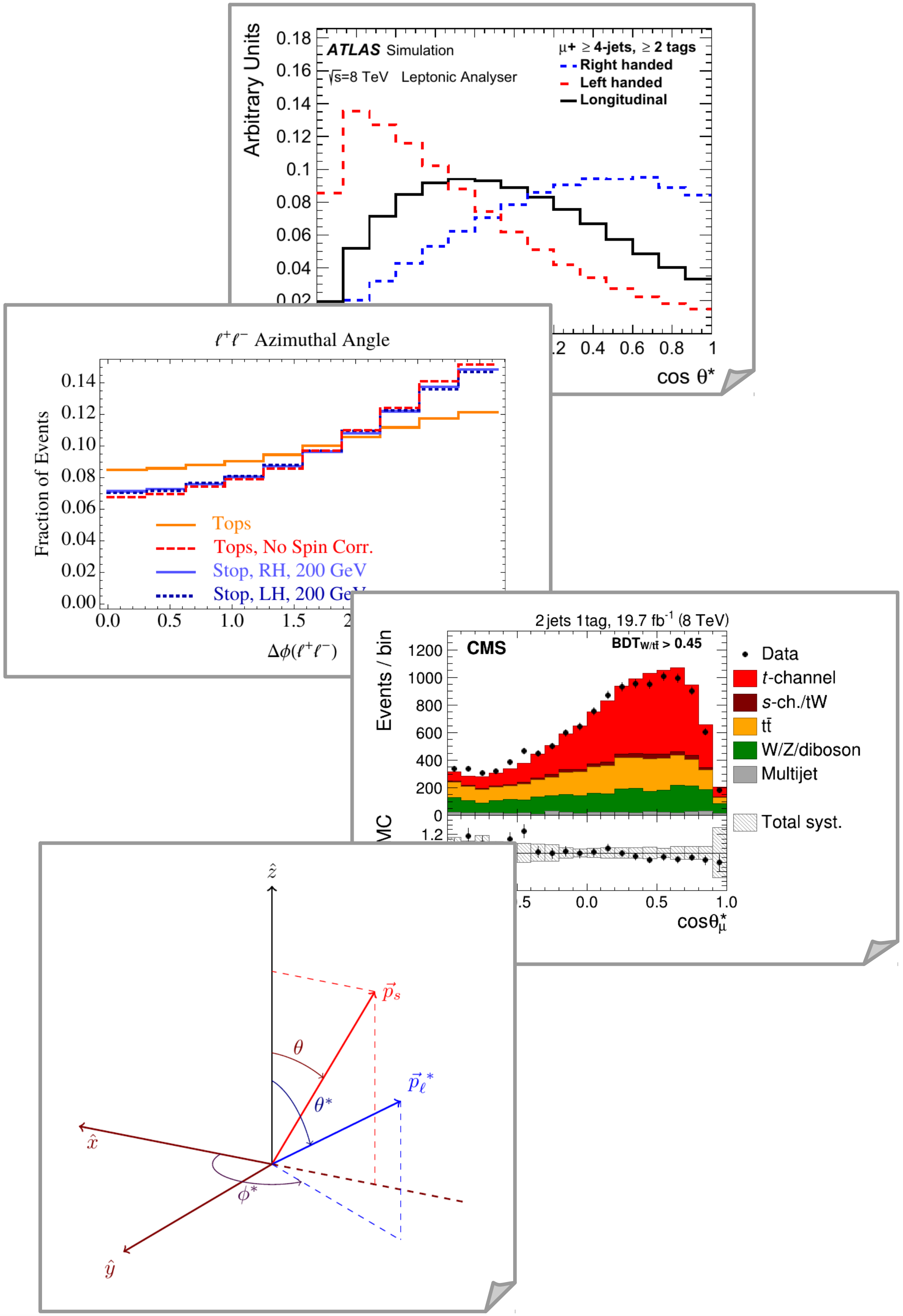
- W helicity fraction measurements by ATLAS & CMS

  Eur. Phys. J. C 77 (2017) 264
  Phys. Lett. B 762 (2016) 512

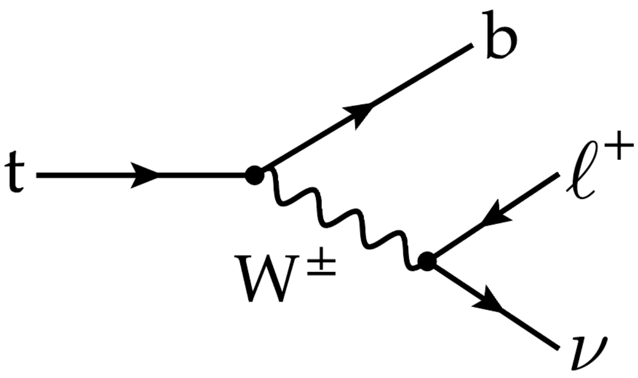
- spin correlation in $t\bar{t}$ production by ATLAS ATLAS-CONF-2018-027

- single top quark polarization in t-channel by CMS JHEP 04 (2016) 073

- Wtb vertex analysis in t-channel by ATLAS JHEP 12 (2017) 017



Top quark properties



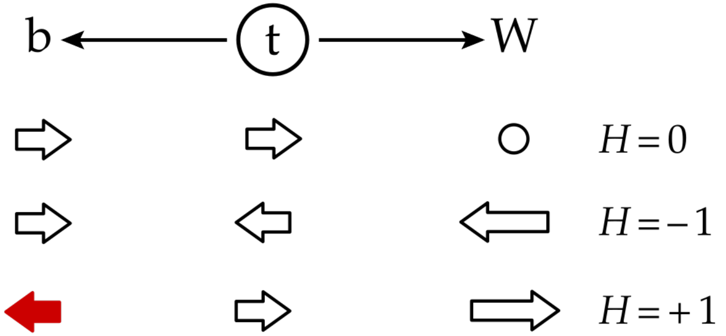
- top quark = heaviest particle of the SM: $m_{\rm top} = 172.4 \pm 0.5$ GeV $> m_{\rm H} > m_{\rm W}$ [1]
- only quark which decays via electroweak interactions to on-shell W bosons
  - → short life time: $1/\Gamma_{\rm top} = 10^{-25}\ {\rm s} < 1/\Lambda_{\rm QCD}$
  - → no hadronization, retains spin coherence
  - → can study “free quark” properties
- decays almost exclusively to bW due to CKM matrix $V_{\rm tb} \approx 1$

➢ coupling structure ⟶ influences angular distributions

$$\mathcal{L}_{Wtb}^{\rm SM} \propto \bar{b}\left(\underset{\text{V}}{\boxed{\gamma_\mu}} - \underset{\text{A}}{\boxed{\gamma_\mu\gamma_5}}\right) t W^\mu$$

- “vector” – ”axialvector” structure
- only left-handed fermions can couple to W bosons

e.g. W boson helicity



suppressed!

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[1] Phys. Rev. D 93, 072004 (2016)

Spin analyzers & EFT

- top quark "spin-analyzing power" [1]
  - dimensionless quantity $\alpha_X \in [-1;1]$
  - degree of polarization wrt. top decay product in top quark rest frame
  - for top antiquark: $\alpha_X(\mathrm{t}) = -\alpha_{\bar{X}}(\bar{\mathrm{t}})$
  - charged lepton direction ideal probe of top quark spin due to W helicity interference

Decay product X	spin-analyzing power α_X	
	LO	NLO
ℓ^+	1.00	0.998
ν	-0.32	-0.33
$\bar{\mathrm{q}}'$ (down-type)	1.00	0.93
q (up-type)	-0.32	-0.31
b	-0.41	-0.39
W^+	0.41	0.39

- characterize deviations from SM coupling structure
  - effective field theory approach

$$\mathcal{L}^{\mathrm{eff}} = \mathcal{L}^{\mathrm{SM}}_{(4)} + \frac{1}{\Lambda}\sum_i c_i^{(5)} O_i^{(5)} + \frac{1}{\Lambda^2}\sum_i c_i^{(6)} O_i^{(6)} + \mathcal{O}\left(\frac{O^{(7)}}{\Lambda^3}\right)$$

  - recast some dim.-6 effective operators into anomalous Wtb couplings

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

anomalous vector- and tensor-like couplings (in SM $\mathrm{V_L} = V_{\mathrm{tb}}, \mathrm{V_R} = \mathrm{g_L} = \mathrm{g_R} = 0$)

→ spin-analyzing powers can be parametrized as $\alpha_X(\mathrm{V_L}, \mathrm{V_R}, \mathrm{g_L}, \mathrm{g_R})$

→ note: for single top production 4-fermion operator also important (missing here)

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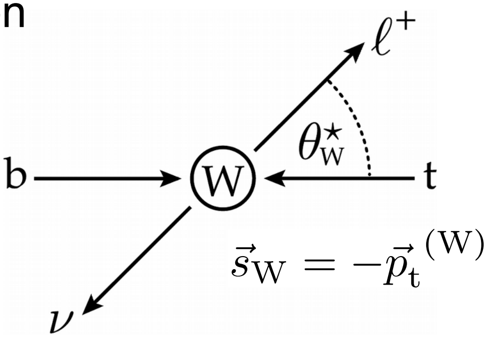
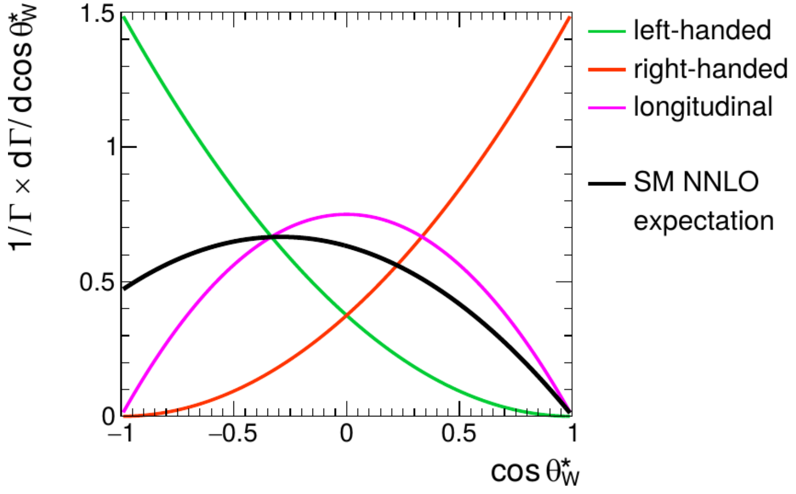
[1] Nucl.Phys. B840 349-378, 2010

W boson helicity fractions

- approximate W boson spin with reversed top quark direction in W boson rest frame

$$\cos\theta_{\mathrm{W}}^{\star} = \frac{\vec{s}_{\mathrm{W}}\cdot\vec{p}_{\ell}^{\,(\mathrm{W})}}{|\vec{s}_{\mathrm{W}}|\cdot|\vec{p}_{\ell}^{\,(\mathrm{W})}|}$$



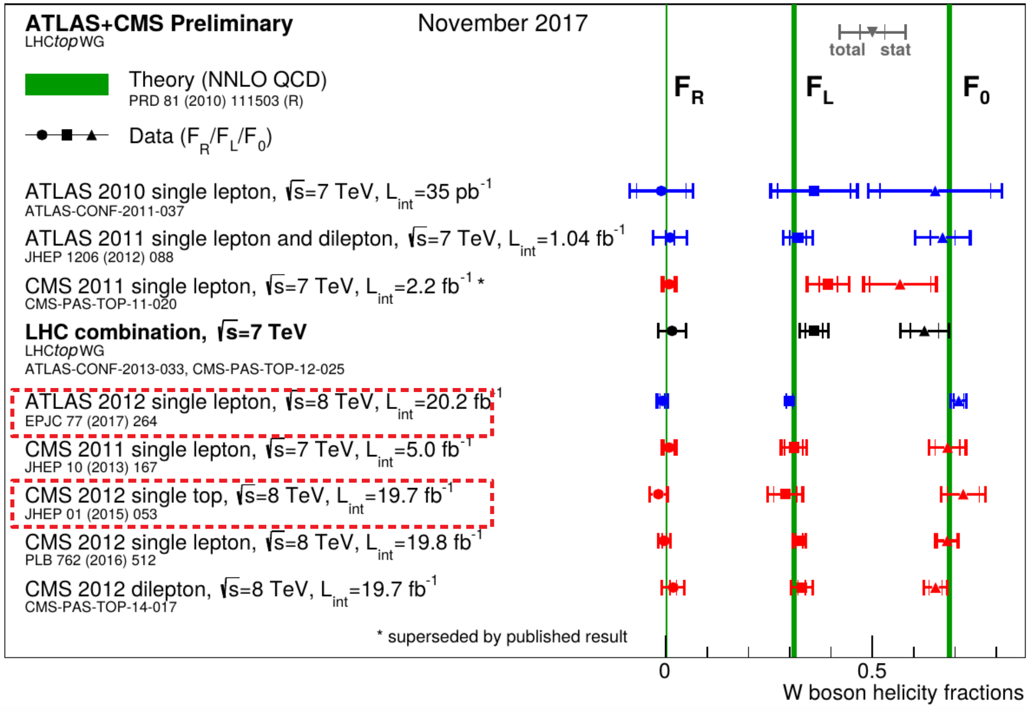


- helicity fractions

$$\frac{\mathrm{d}\Gamma}{\Gamma\cdot\mathrm{d}\cos\theta_{\mathrm{W}}^{\star}} = \tfrac{3}{8}\left(1-\cos\theta_{\mathrm{W}}^{\star}\right)^2\boxed{\mathrm{F_L}} + \tfrac{3}{8}\left(1+\cos\theta_{\mathrm{W}}^{\star}\right)^2\boxed{\mathrm{F_R}} + \tfrac{3}{4}\sin^2\theta_{\mathrm{W}}^{\star}\boxed{\mathrm{F_0}}$$

  - normalized as: $\mathrm{F_L}+\mathrm{F_R}+\mathrm{F_0}=1$
  - SM NNLO predictions [1]

    $F_L = 0.687,\ F_0 = 0.311,\ F_R = 0.002$
  - can be measured in any top quark production process!
  - $t\bar{t}$ ideal since low background & high stat.
  - single top t-channel also possible
  - overall analysis strategies very similar across process/experiment



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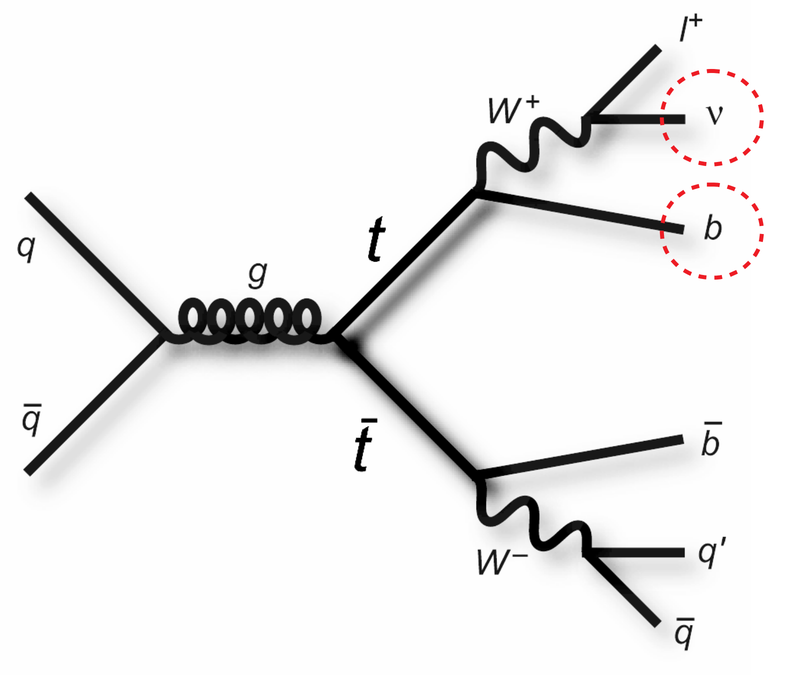
[1] Phys. Rev. D 81, 111503

Typical analysis strategy

ATLAS, Eur. Phys. J. C 77 (2017) 264
CMS, Phys. Lett. B 762 (2016) 512

- event selection targeting semileptonic $t\bar{t}$ decay
  - 1 lepton (electron or muon)
  - at least 4 jet; 2 are b-tagged
  - missing transverse energy

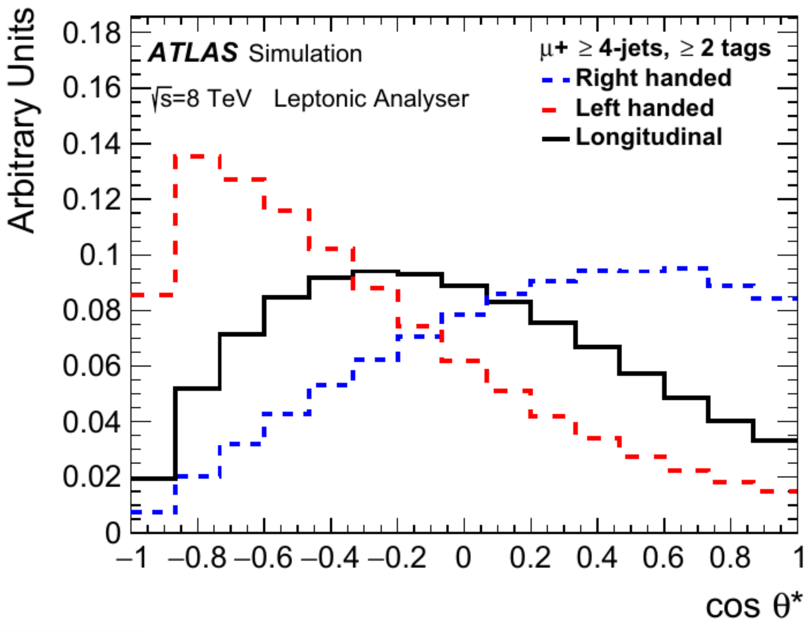


- kinematic fit
  - utilize W boson & top quark mass constraints
    - → estimate unknown p_z component of neutrino from E_T^{miss}
    - → find jet-quark assignment for calculating $\cos\theta_W^\star$

- create 3 templates from SM sample
  - event weight based on angle at generator level

$$\frac{\frac{3}{8}F_L(1-\cos\theta^*_{\text{gen}})^2+\frac{3}{4}F_0\sin^2\theta^*_{\text{gen}}+\frac{3}{8}F_R(1+\cos\theta^*_{\text{gen}})^2}{\frac{3}{8}F_L^{\text{SM}}(1-\cos\theta^*_{\text{gen}})^2+\frac{3}{4}F_0^{\text{SM}}\sin^2\theta^*_{\text{gen}}+\frac{3}{8}F_R^{\text{SM}}(1+\cos\theta^*_{\text{gen}})^2}$$

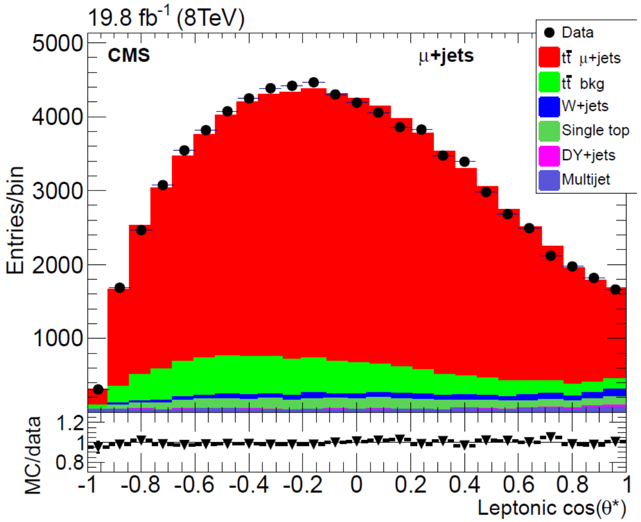
  - most backgrounds are unaffected by weights except single top quark production

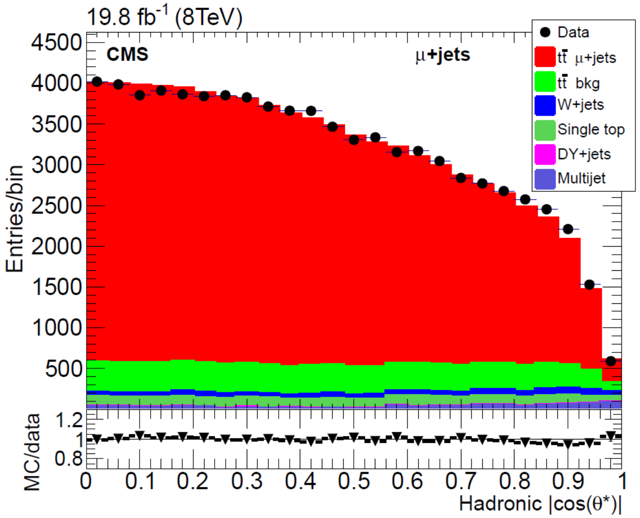


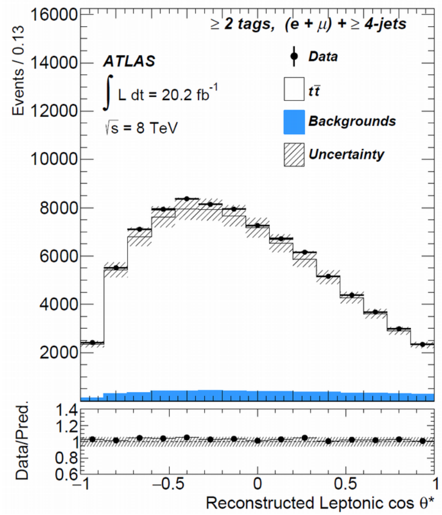
Results

ATLAS, Eur. Phys. J. C 77 (2017) 264
CMS, Phys. Lett. B 762 (2016) 512

- measure fractions through template-based ML fit to reconstructed helicity angle

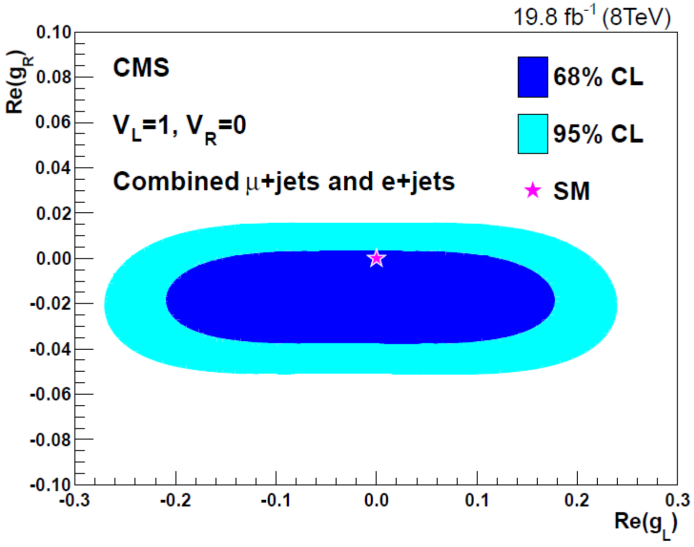


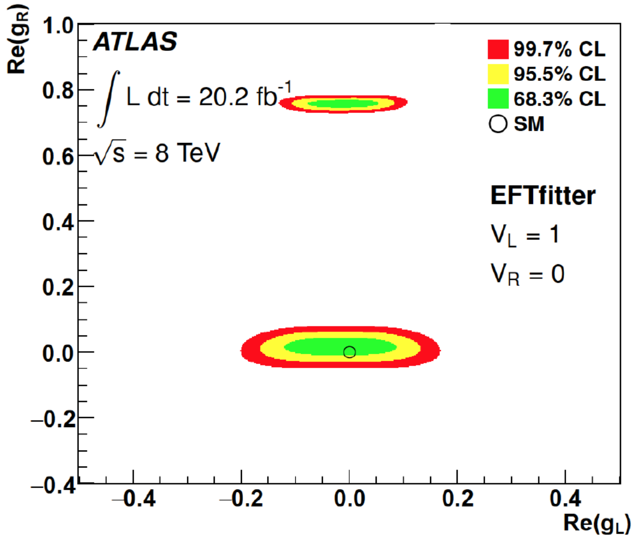




- can also reconstruct angle from $\mathrm{t} \to \mathrm{b q \bar{q}'}$; but only $|\cos\theta^\star_\mathrm{W}|$ since down-type quark cannot be distinguished from up-type quark ($\alpha_\mathrm{u} \neq \alpha_\mathrm{d}$)

- limits on anomalous tensor-like left- and right-handed couplings $(\mathrm{V_L} = 1, \mathrm{V_R} = 0)$





→ consistent with SM expectations

Spin correlation in $t\bar{t}$ production

- no net polarization of top quarks in pair production …

  … BUT, top quark spins are correlated!

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_X\, d\cos\theta_{\bar{X}'}} = \frac{1}{4}(1 + C\,\alpha_X \alpha_{\bar{X}'} \cos\theta_X \cos\theta_{\bar{X}'})$$

$$C \equiv \frac{\sigma(t_R\bar{t}_R) + \sigma(t_L\bar{t}_L) - \sigma(t_R\bar{t}_L) - \sigma(t_L\bar{t}_R)}{\sigma(t_R\bar{t}_R) + \sigma(t_L\bar{t}_L) + \sigma(t_R\bar{t}_L) + \sigma(t_L\bar{t}_R)}$$

  - difference in angles

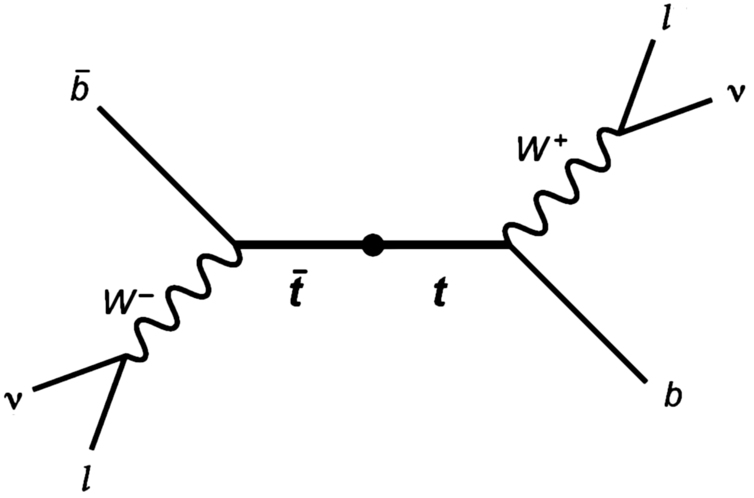
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi_{X\bar{X}'}} = \frac{1}{2}(1 + D\,\alpha_X \alpha_{\bar{X}'} \cos\varphi_{X\bar{X}'})$$

  - NLO SM prediction [1]

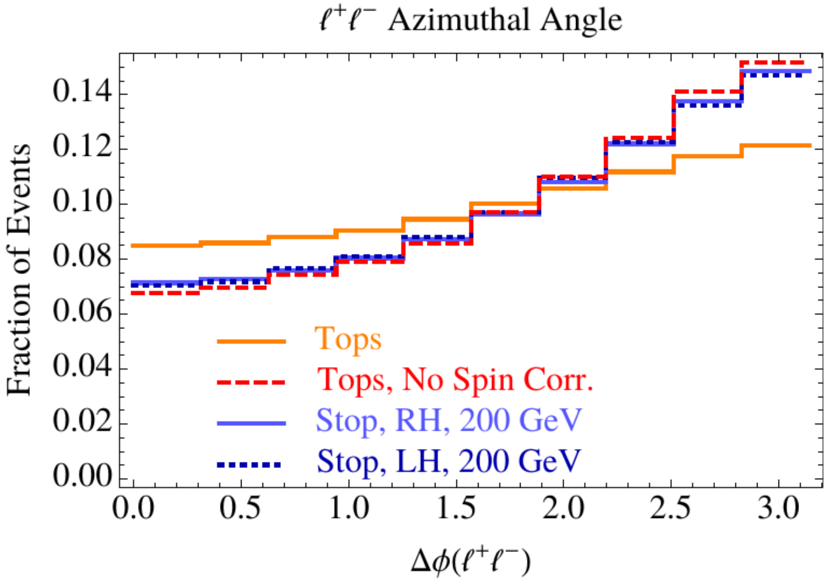
$$C = 0.326 \pm 0.012,\ D = -0.237 \pm 0.07$$

  - spin correlation depend on $m_{t\bar{t}}$

→ overall experimentally challenging since event needs to be fully reconstructed and jets/leptons correctly assigned to the corresponding top quark



- proposal: $\Delta\phi_{\ell^+\ell^-}$ in lab frame [2]
  - reconstruction of $t\bar{t}$ system not required
  - less affected by smearing/finite resolution of detector & reconstruction



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[1] Nucl.Phys. B690 81-137, 2004

[2] Phys.Rev.D81:074024,2010

Recent ATLAS measurement

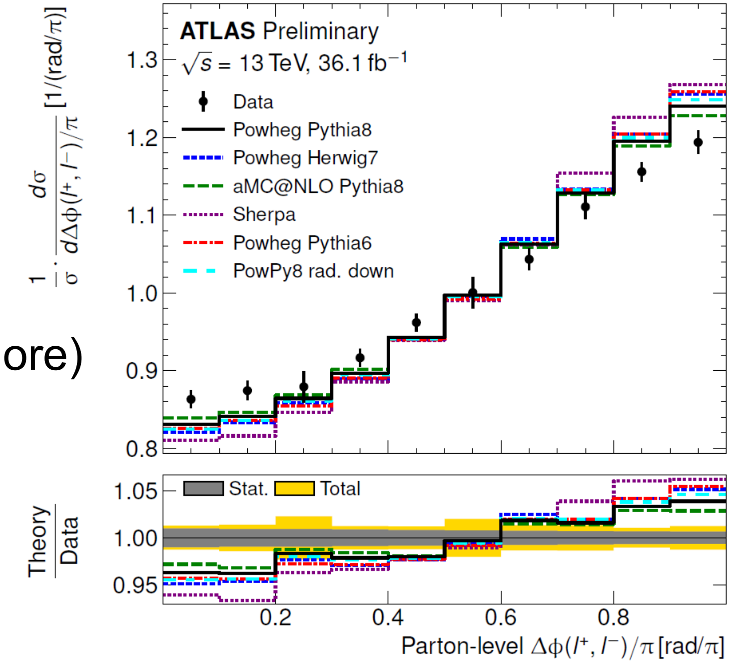
ATLAS-CONF-2018-027

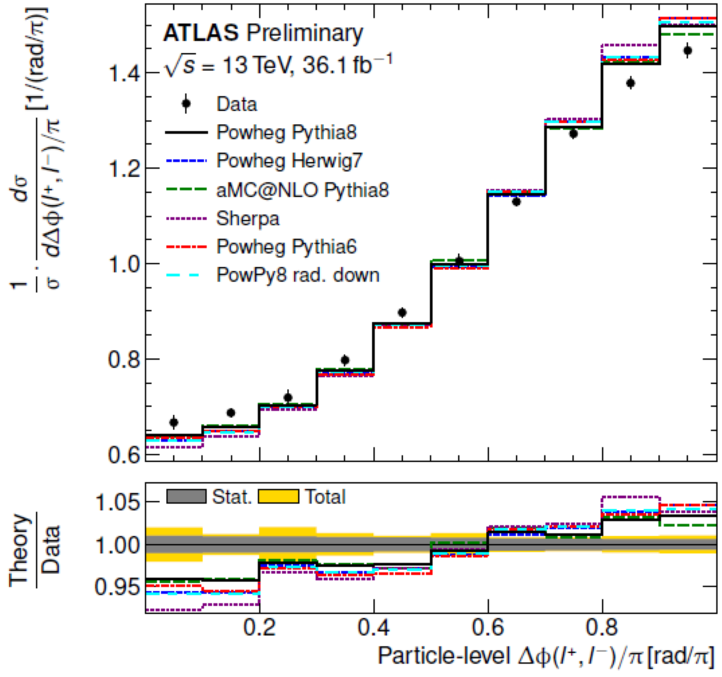
- event selection
  - 1 muon & 1 electron of opposite charge
  - 2 jets of which at least 1 is b-tagged
  - missing transverse energy
- analysis strategy
  - unfold reconstructed angle to parton/particle level (later more) using iterative ~~Bayesian~~ D'Agostini unfolding method [1]

$$\frac{d\sigma_{t\bar{t}}}{dX^i} = \frac{1}{\mathcal{L}\cdot\Delta X^i\cdot\epsilon^i_{\mathrm{eff}}}\cdot\sum_j R^{-1}_{ij}\cdot f^j_{\mathrm{acc}}\cdot\left(N^j_{\mathrm{obs}}-N^j_{\mathrm{bkg}}\right)$$

  - extracting degree of correlation through template-based fit: $n_i = f_{\mathrm{SM}}\cdot n_{\mathrm{spin}} + (1-f_{\mathrm{SM}})\cdot n_{\mathrm{nospin}}$
- results

Region	f_{SM}
$m_{t\bar{t}} < 450$ GeV	$1.11 \pm 0.04 \pm 0.13$
$450 < m_{t\bar{t}} < 550$ GeV	$1.17 \pm 0.09 \pm 0.14$
$550 < m_{t\bar{t}} < 800$ GeV	$1.60 \pm 0.24 \pm 0.35$
$m_{t\bar{t}} > 800$ GeV	$2.2 \pm 1.8 \pm 2.3$
inclusive	$1.250 \pm 0.026 \pm 0.063$ **significance: 3.2σ**





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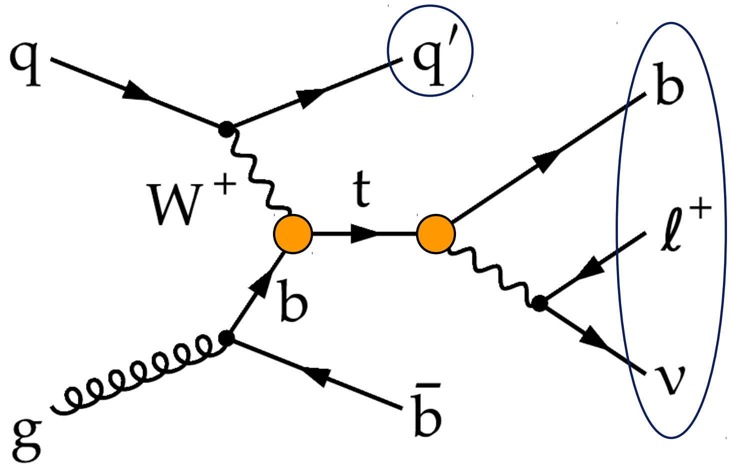
[1] Nucl.Instr.Meth. A362 (1995) 487-498

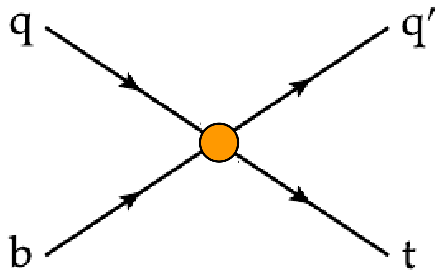
Polarization in single top production

- Wtb coupling structure in t-channel

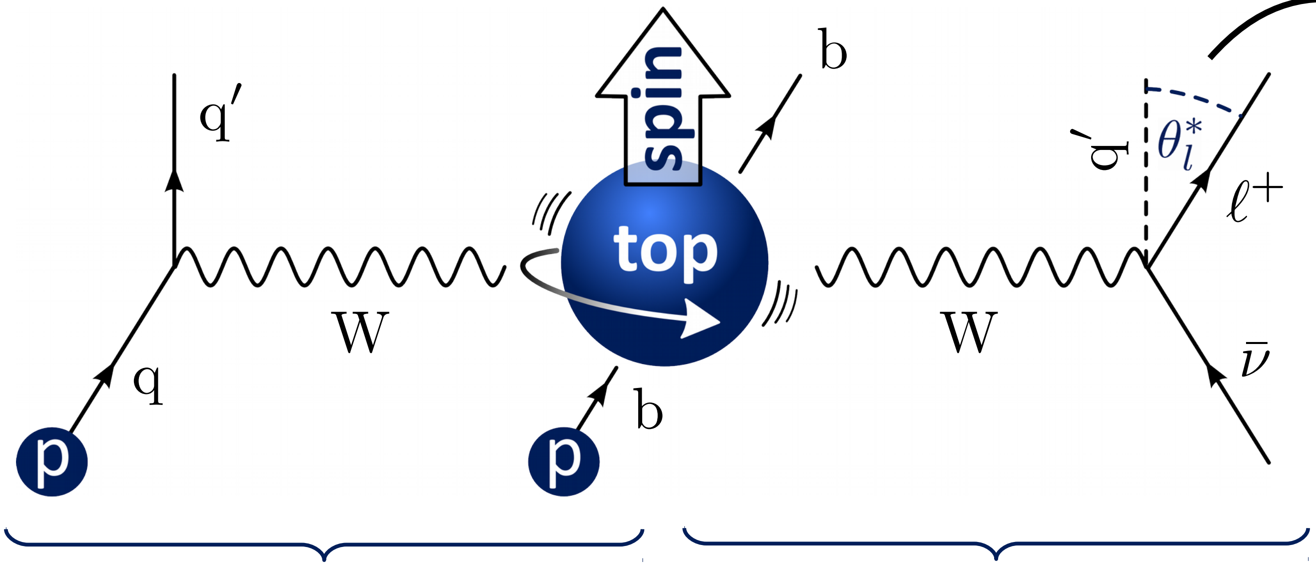


→ in SM, top quark spin aligned with spectator quark q'

→ in addition to anomalous Wtb couplings 4-fermion operator can also contribute to production side



- observable: **spin asymmetry** (sensitive to polarization)
  - in top quark rest frame



$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta_{\mathrm{l}}^\star} = \frac{1}{2}\left(1+\alpha_l P_{\mathrm{t}}\cos\theta_l^\star\right)$$

$$A_l = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} = \frac{1}{2}P_{\mathrm{t}}\cdot\alpha_l$$

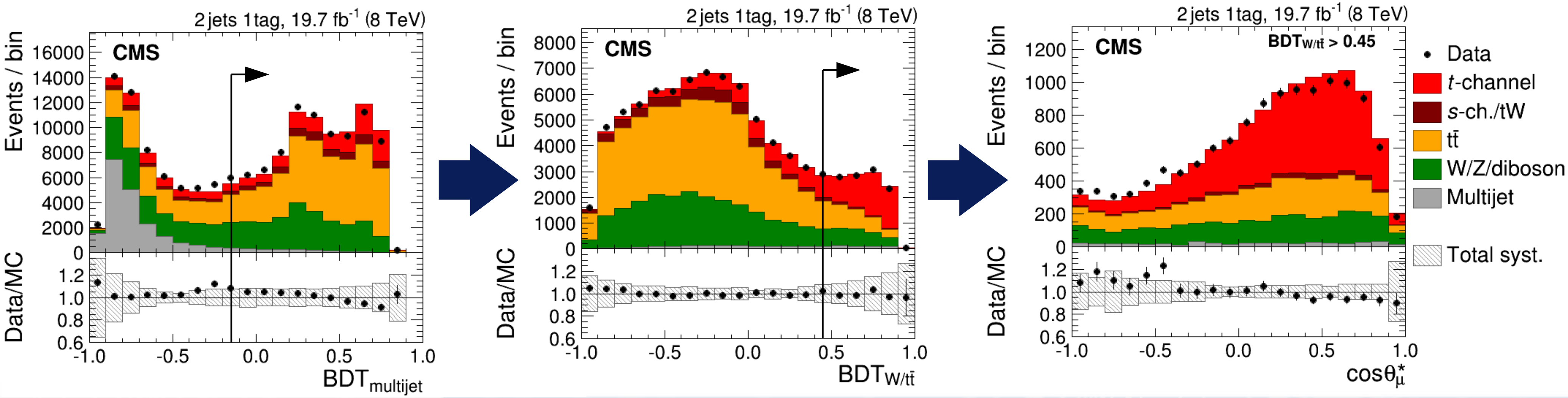
production: $\vec{s}_{\mathrm{top}}\cdot\vec{p}_{q'} \sim P_{\mathrm{top}}$

decay: $\vec{s}_{\mathrm{top}}\cdot\vec{p}_l \sim \alpha_l$

Spin asymmetry by CMS

CMS, JHEP 04 (2016) 073

- event selection
  - 1 muon, 2 jets with one b-tag, missing transverse energy
  - only ~10% of selected events from t-channel single top production
  - large background from W+jets, multijet, & $t\bar{t}$
    → use MVA to define signal-enriched phase space
- analysis strategy
  - 1st BDT for rejecting multijet events
  - 2nd BDT for rejecting remaining backgrounds from signal
  - training observables need to be carefully chosen to be uncorrelated wrt. polarization angle; otherwise result may be biased towards SM expectation
  - neutrino p_{z} reconstructed from lepton momentum & $E_{\mathrm{T}}^{\mathrm{miss}}$ using W boson mass constraint
  - perform template-based fit to discriminants for estimating background contributions
  - apply successive selection on BDT discriminants → signal-enriched phase space (S/B=~1)



Intermezzo: Unfolding

CMS, JHEP 04 (2016) 073

- general problem
  - given a reconstructed distribution (e.g. $\cos\theta^{\star}_{\ell}$), how to compare to theoretical predictions?
  - problem can be modeled as

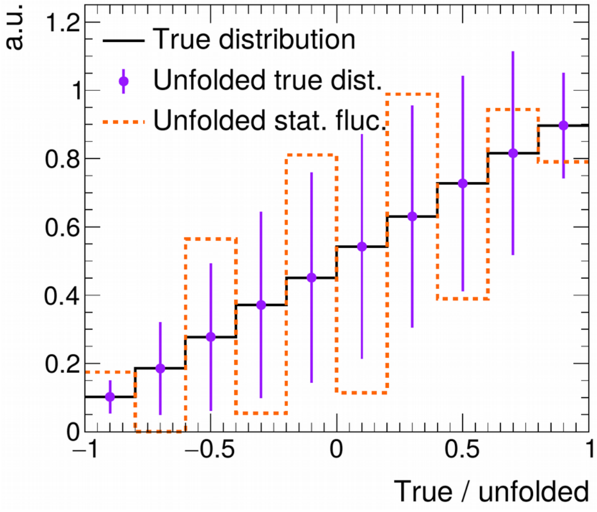
$$\underbrace{f(y)}_{\text{reco.}} = \int \underbrace{A(y)\epsilon(y)R(y,x)}_{\text{detector}} \cdot \underbrace{g(x)}_{\text{true}}\,\mathrm{d}x$$

detector acceptance, efficiency & resolution “known” from simulation

  - quantized as histogram: $\vec{y} = \tilde{\mathcal{R}}\cdot\vec{x}, \qquad \tilde{\mathcal{R}} = \mathcal{A}\cdot\mathcal{E}\cdot\mathcal{R}$
  - simple inversion of response matrix

$$\vec{x} = \left(\tilde{\mathcal{R}}\right)^{-1}\vec{y} = \left(\mathcal{U}\cdot\underbrace{\mathcal{S}}_{\text{diagonal}}\cdot\mathcal{V}\right)^{-1}\vec{y} = \mathcal{V}^{-1}\cdot\begin{pmatrix}\frac{1}{s_{11}} & & 0\\ & \ddots & \\ 0 & & \frac{1}{s_{nn}}\end{pmatrix}\cdot\mathcal{U}^{-1}\,\vec{y}$$

→ statistical fluctuations are amplified if s_{ii} are small



- regularized unfolding (aka “TUnfold” method) [1]
  - rewrite unfolding as minimization problem

$$\chi^2 = (\vec{y}-\tilde{\mathcal{R}}\,\vec{x})^T\mathcal{V}^{-1}(\vec{y}-\tilde{\mathcal{R}}\,\vec{x}) + \boxed{\mathfrak{R}_1+\mathfrak{R}_2}$$

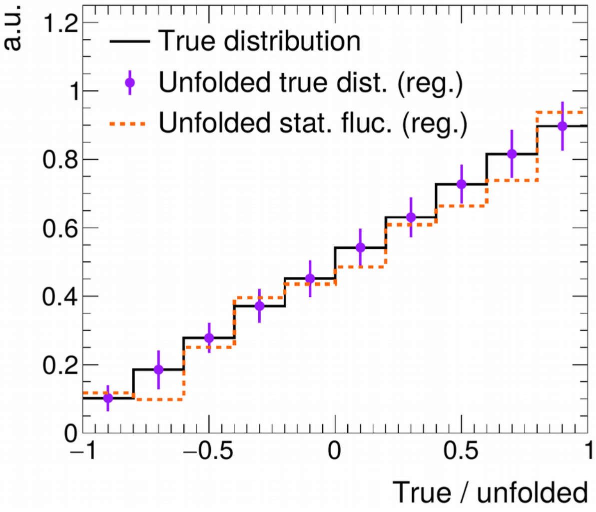
penalty terms

  - suppress oscillating solutions: $\mathfrak{R}_1 = \tau^2\vec{x}^T\boxed{\mathcal{L}^T\mathcal{L}}\vec{x}$ 2nd derivatives

→ regularization strength τ needs to be optimized

→ typically: optimize for minimal correlations between bins

  - match overall selection efficiency: $\mathfrak{R}_2 = \lambda\left(\sum y_i - \vec{\epsilon}\cdot\vec{x}\right)$



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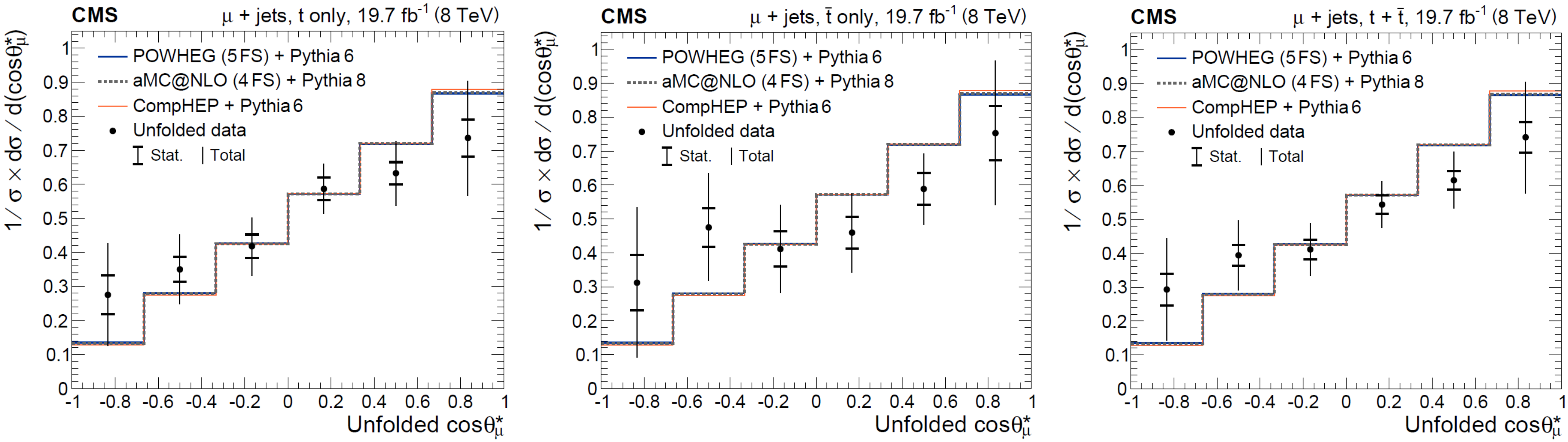
[1] JINST 7 (2012) T10003

Spin asymmetry: Results

CMS, JHEP 04 (2016) 073

- unfolded distributions of polarization angle at parton level



- measured spin asymmetries
  - separately for top quarks/antiquarks events

$$A_\mu(\mathrm{t}) = 0.29 \pm 0.03\,(\mathrm{stat}) \pm 0.10\,(\mathrm{syst}) = 0.29 \pm 0.11,$$
$$A_\mu(\bar{\mathrm{t}}) = 0.21 \pm 0.05\,(\mathrm{stat}) \pm 0.13\,(\mathrm{syst}) = 0.21 \pm 0.14,$$

} consistent within uncertainties

  - combination

$$A_\mu(\mathrm{t}+\bar{\mathrm{t}}) = 0.26 \pm 0.03\,(\mathrm{stat}) \pm 0.10\,(\mathrm{syst}) = 0.26 \pm 0.11, \longrightarrow$$

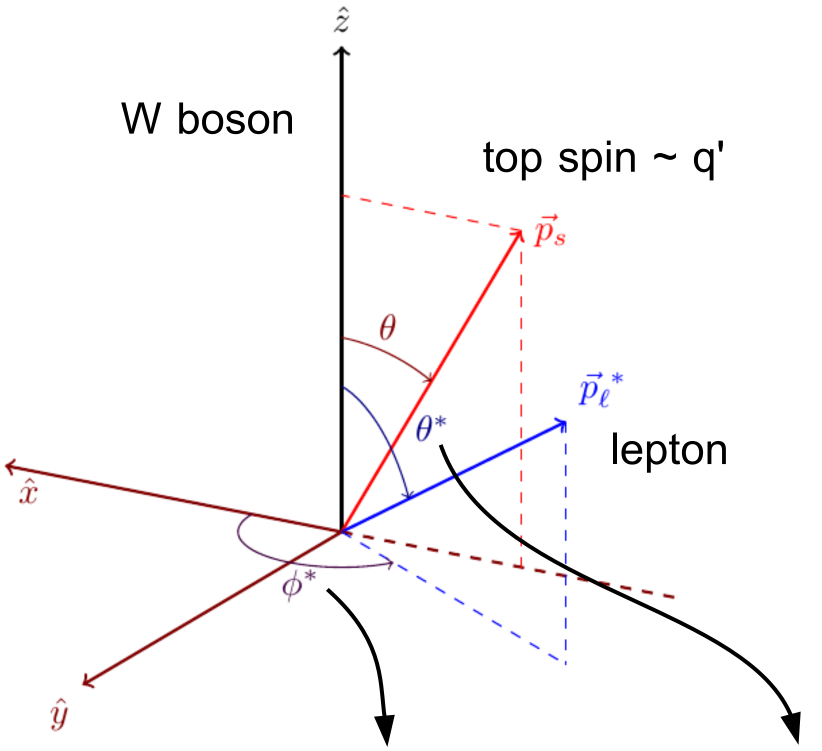
compatible with $A^{\mathrm{SM}}_{\mathrm{PowHeg}} = 0.44$ within 2.0 σ

  - 2-bin cross check w/ unregularized unfolding

$$A_\mu(\mathrm{t}+\bar{\mathrm{t}}) = 0.28 \pm 0.03\,(\mathrm{stat}) \pm 0.1\,(\mathrm{syst}) = 0.28 \pm 0.12$$

Wtb analysis in t-channel

ATLAS, JHEP 12 (2017) 017

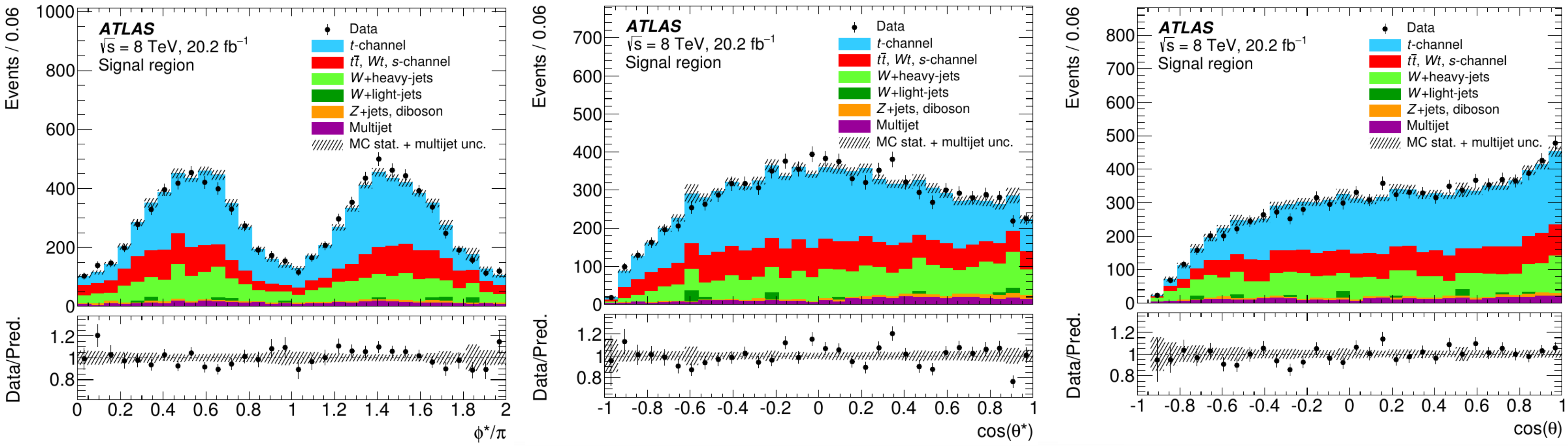


- idea
  - use triple angular distribution to set limits on anomalous Wtb couplings and polarization
  - decompose distributions into spherical harmonics

$$\varrho(\theta,\theta^*,\phi^*;P) = \frac{1}{N}\frac{\mathrm{d}^3N}{\mathrm{d}(\cos\theta)\mathrm{d}\Omega^*}$$

$$= \sum_{k=0}^{1}\sum_{l=0}^{2}\sum_{m=-k}^{k} a_{k,l,m}M_{k,l}^{m}(\theta,\theta^*,\phi^*)$$

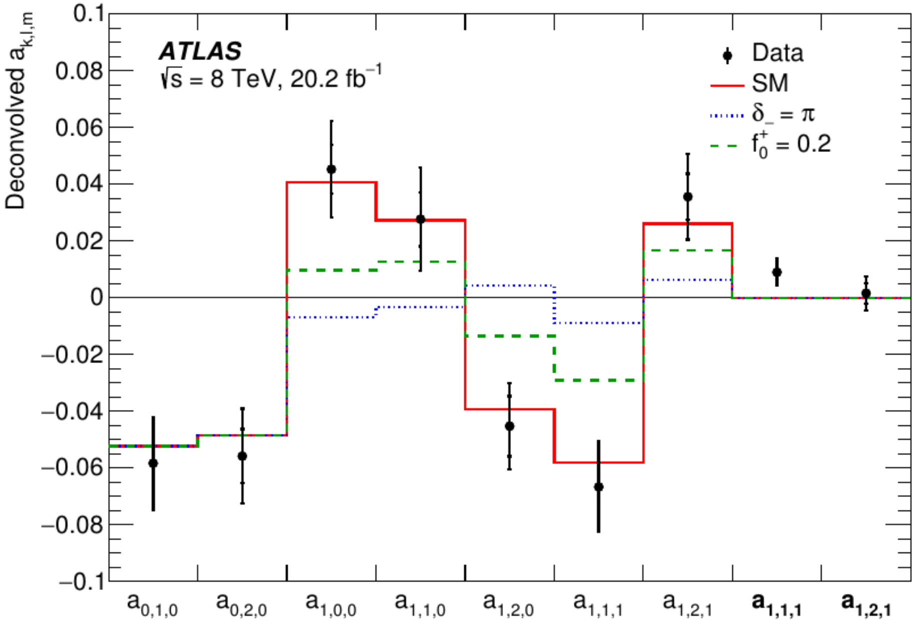
  - magnitudes $a_{k,l,m}$ depend on generalized helicity fractions $\vec{\alpha} = (f_1, f_1^+, f_0^+, \delta_+, \delta_-)$ & polarization P
  - select events with $|\eta_{j'}| > 2,\ H_\mathrm{T} > 195$ GeV & top mass window → signal-enriched phase space



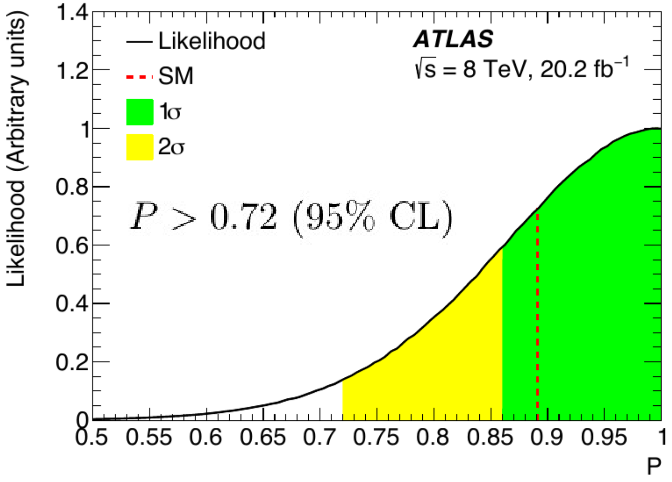
Wtb analysis: Results

ATLAS, JHEP 12 (2017) 017

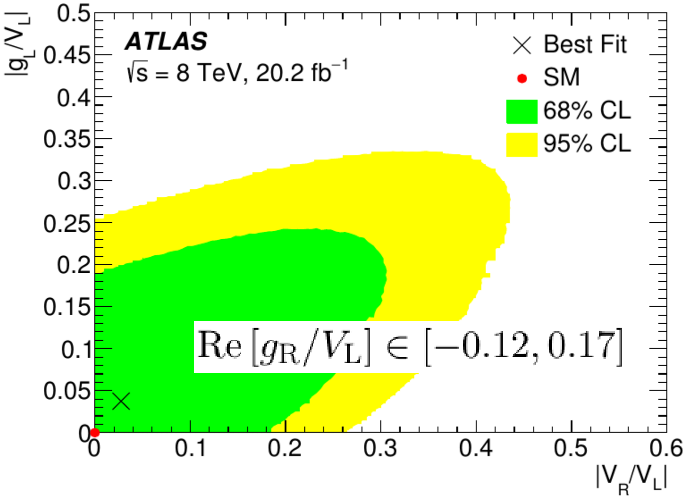
- analysis strategy
  - estimate coefficients in reconstructed distributions; subtract background contributions
  - translate coefficients to parton level through analytical unfolding
  - derive limits on anomalous couplings and top quark polarization



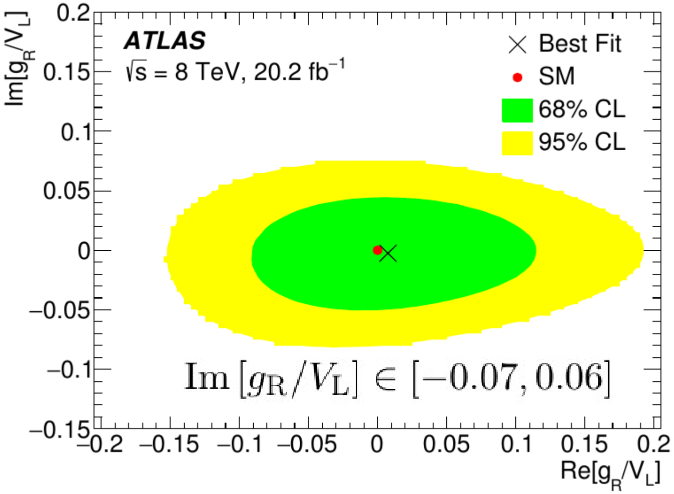
- limits on anomalous couplings



$P > 0.72$ (95% CL)



$\mathrm{Re}\,[g_\mathrm{R}/V_\mathrm{L}] \in [-0.12, 0.17]$

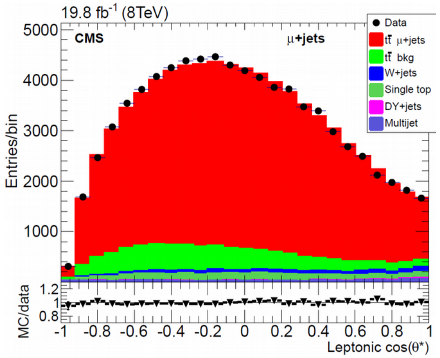


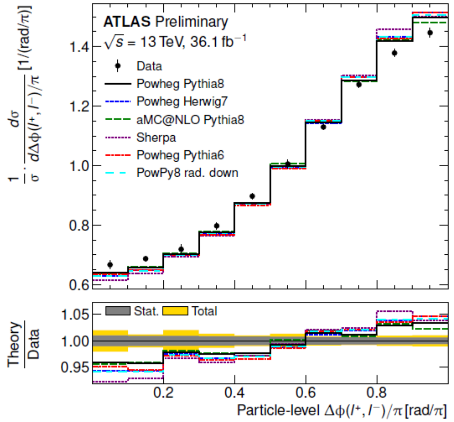
$\mathrm{Im}\,[g_\mathrm{R}/V_\mathrm{L}] \in [-0.07, 0.06]$

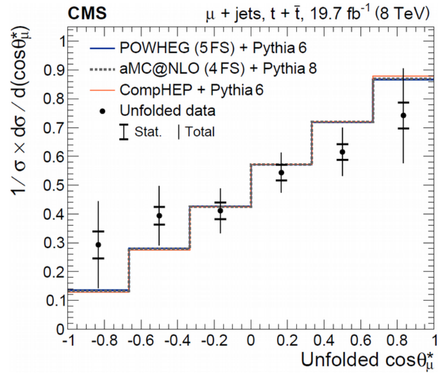
→ results in agreement with SM prediction

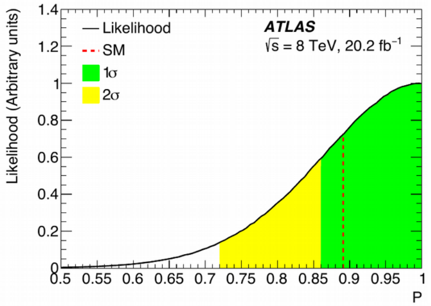
Conclusion

- top quark properties
  - V-A coupling structure dictates angular distributions
  - spin analyzing power α_X quotes alignment of top quark spin with decay product X
- W helicity fraction measurements by ATLAS & CMS
  - reweight $t\bar{t}$ SM to 3 helicity fractions F_+, F_0, F_-
  - perform template-based fit to reconstructed helicity angle
- spin correlation in $t\bar{t}$ production by ATLAS
  - observable $\Delta\phi_{\ell^+\ell^-}$ in lab frame does not require full reconstruction
  - unfold reconstructed distribution to parton/particle level
- single top quark polarization in t-channel by CMS
  - polarized top quark in production wrt. spectator quark direction
  - unfolded angle to parton level → spin asymmetry: $A = \frac{1}{2}\alpha_\ell P_\mathrm{t}$
- Wtb vertex analysis in t-channel by ATLAS
  - triple angular analysis of polarization angles in production/decay
  - estimate and unfold angular moments to parton level
  - set limits on anomalous Wtb couplings & polarization







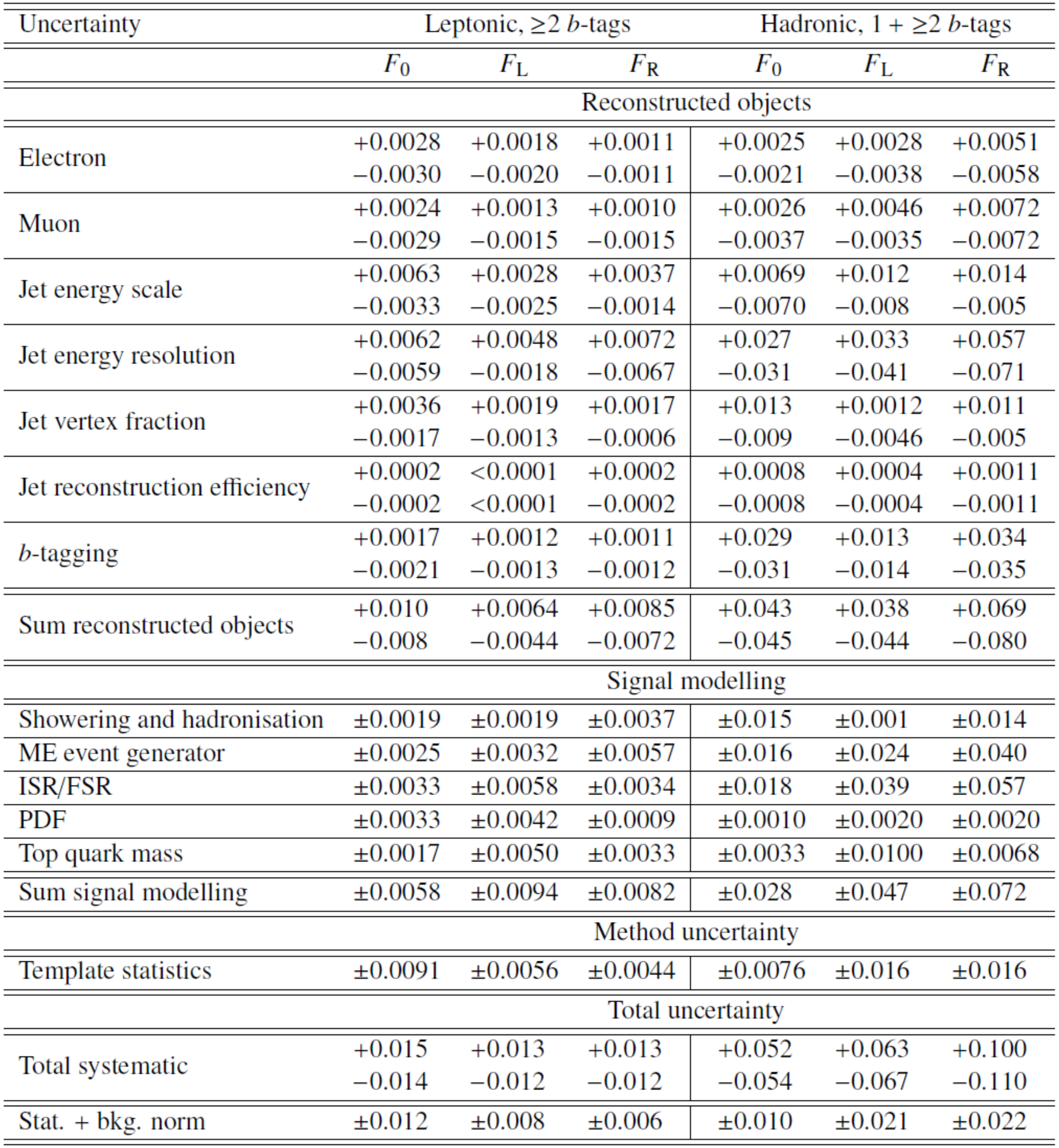


Backup

W helicity measurement

ATLAS, Eur. Phys. J. C 77 (2017) 264

- ATLAS

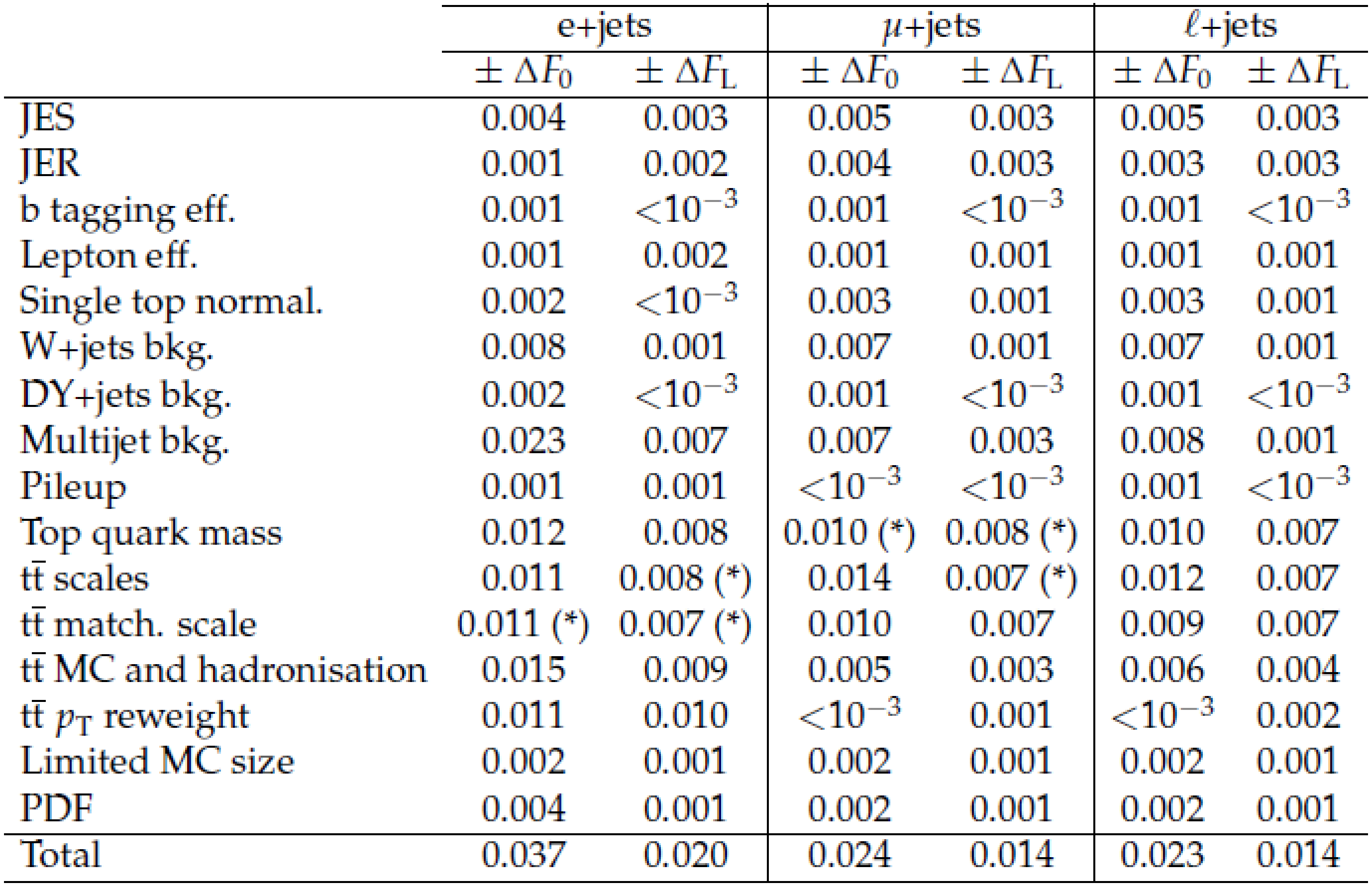


Uncertainty	Leptonic, ≥2 b-tags			Hadronic, 1 + ≥2 b-tags		
	F_0	F_L	F_R	F_0	F_L	F_R
Reconstructed objects						
Electron	+0.0028 −0.0030	+0.0018 −0.0020	+0.0011 −0.0011	+0.0025 −0.0021	+0.0028 −0.0038	+0.0051 −0.0058
Muon	+0.0024 −0.0029	+0.0013 −0.0015	+0.0010 −0.0015	+0.0026 −0.0037	+0.0046 −0.0035	+0.0072 −0.0072
Jet energy scale	+0.0063 −0.0033	+0.0028 −0.0025	+0.0037 −0.0014	+0.0069 −0.0070	+0.012 −0.008	+0.014 −0.005
Jet energy resolution	+0.0062 −0.0059	+0.0048 −0.0018	+0.0072 −0.0067	+0.027 −0.031	+0.033 −0.041	+0.057 −0.071
Jet vertex fraction	+0.0036 −0.0017	+0.0019 −0.0013	+0.0017 −0.0006	+0.013 −0.009	+0.0012 −0.0046	+0.011 −0.005
Jet reconstruction efficiency	+0.0002 −0.0002	<0.0001 <0.0001	+0.0002 −0.0002	+0.0008 −0.0008	+0.0004 −0.0004	+0.0011 −0.0011
b-tagging	+0.0017 −0.0021	+0.0012 −0.0013	+0.0011 −0.0012	+0.029 −0.031	+0.013 −0.014	+0.034 −0.035
Sum reconstructed objects	+0.010 −0.008	+0.0064 −0.0044	+0.0085 −0.0072	+0.043 −0.045	+0.038 −0.044	+0.069 −0.080
Signal modelling						
Showering and hadronisation	±0.0019	±0.0019	±0.0037	±0.015	±0.001	±0.014
ME event generator	±0.0025	±0.0032	±0.0057	±0.016	±0.024	±0.040
ISR/FSR	±0.0033	±0.0058	±0.0034	±0.018	±0.039	±0.057
PDF	±0.0033	±0.0042	±0.0009	±0.0010	±0.0020	±0.0020
Top quark mass	±0.0017	±0.0050	±0.0033	±0.0033	±0.0100	±0.0068
Sum signal modelling	±0.0058	±0.0094	±0.0082	±0.028	±0.047	±0.072
Method uncertainty						
Template statistics	±0.0091	±0.0056	±0.0044	±0.0076	±0.016	±0.016
Total uncertainty						
Total systematic	+0.015 −0.014	+0.013 −0.012	+0.013 −0.012	+0.052 −0.054	+0.063 −0.067	+0.100 −0.110
Stat. + bkg. norm	±0.012	±0.008	±0.006	±0.010	±0.021	±0.022

W helicity measurement

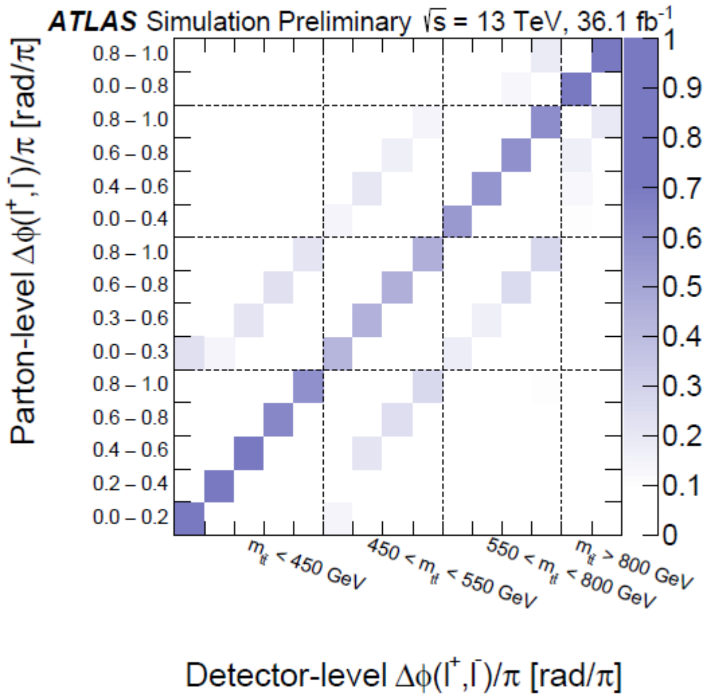
CMS, Phys. Lett. B 762 (2016) 512

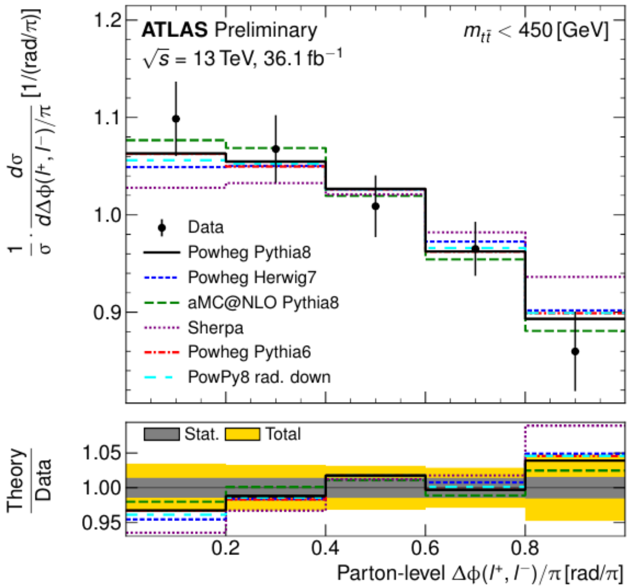
- CMS

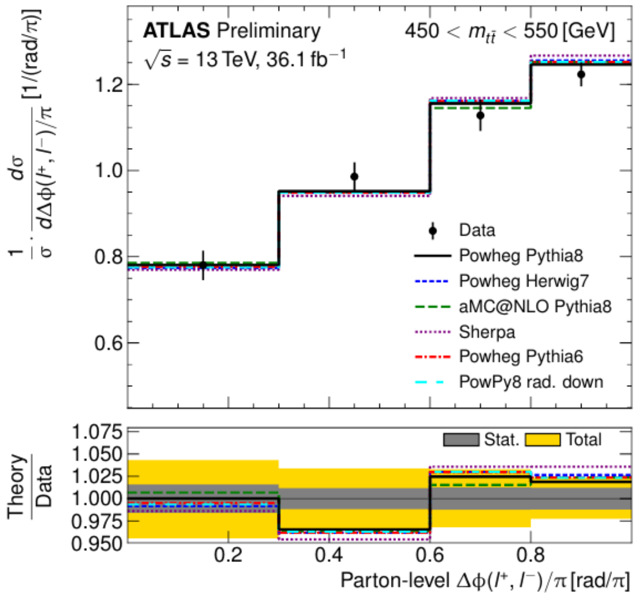


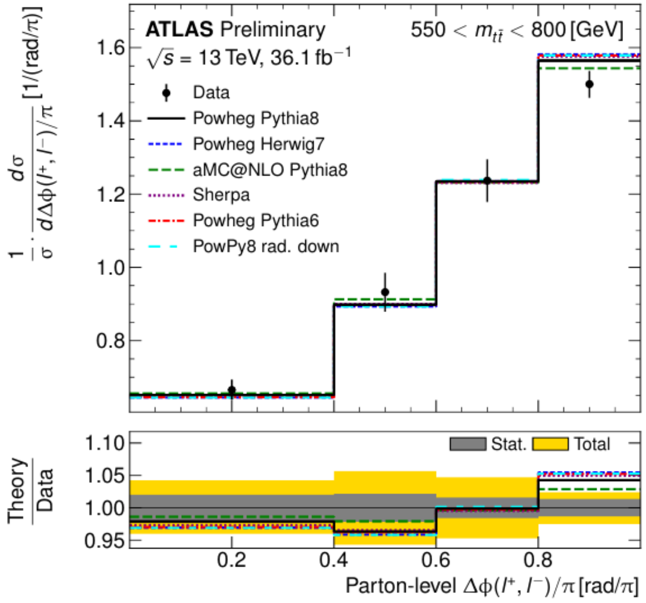
	e+jets		μ+jets		ℓ+jets	
	$\pm\,\Delta F_0$	$\pm\,\Delta F_\mathrm{L}$	$\pm\,\Delta F_0$	$\pm\,\Delta F_\mathrm{L}$	$\pm\,\Delta F_0$	$\pm\,\Delta F_\mathrm{L}$
JES	0.004	0.003	0.005	0.003	0.005	0.003
JER	0.001	0.002	0.004	0.003	0.003	0.003
b tagging eff.	0.001	$<10^{-3}$	0.001	$<10^{-3}$	0.001	$<10^{-3}$
Lepton eff.	0.001	0.002	0.001	0.001	0.001	0.001
Single top normal.	0.002	$<10^{-3}$	0.003	0.001	0.003	0.001
W+jets bkg.	0.008	0.001	0.007	0.001	0.007	0.001
DY+jets bkg.	0.002	$<10^{-3}$	0.001	$<10^{-3}$	0.001	$<10^{-3}$
Multijet bkg.	0.023	0.007	0.007	0.003	0.008	0.001
Pileup	0.001	0.001	$<10^{-3}$	$<10^{-3}$	0.001	$<10^{-3}$
Top quark mass	0.012	0.008	0.010 (*)	0.008 (*)	0.010	0.007
$\mathrm{t\bar{t}}$ scales	0.011	0.008 (*)	0.014	0.007 (*)	0.012	0.007
$\mathrm{t\bar{t}}$ match. scale	0.011 (*)	0.007 (*)	0.010	0.007	0.009	0.007
$\mathrm{t\bar{t}}$ MC and hadronisation	0.015	0.009	0.005	0.003	0.006	0.004
$\mathrm{t\bar{t}}$ p_T reweight	0.011	0.010	$<10^{-3}$	0.001	$<10^{-3}$	0.002
Limited MC size	0.002	0.001	0.002	0.001	0.002	0.001
PDF	0.004	0.001	0.002	0.001	0.002	0.001
Total	0.037	0.020	0.024	0.014	0.023	0.014

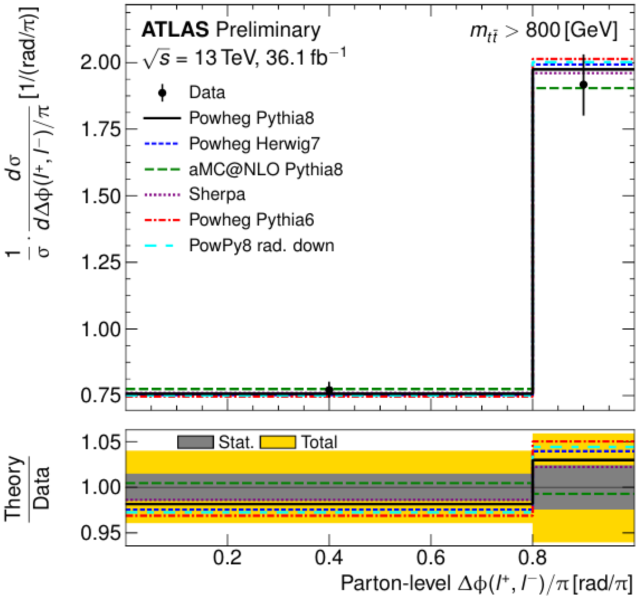
Spin correlations wrt. $m_{t\bar{t}}$





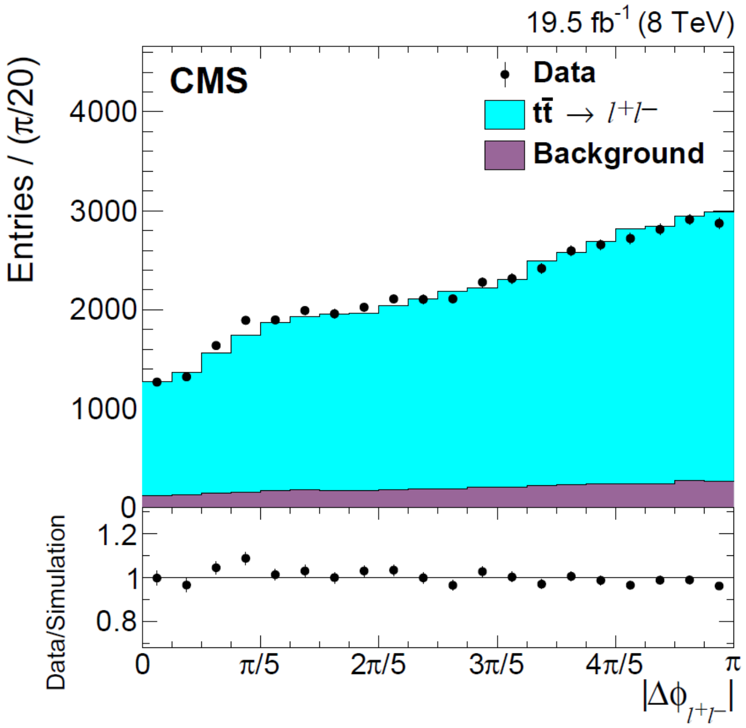


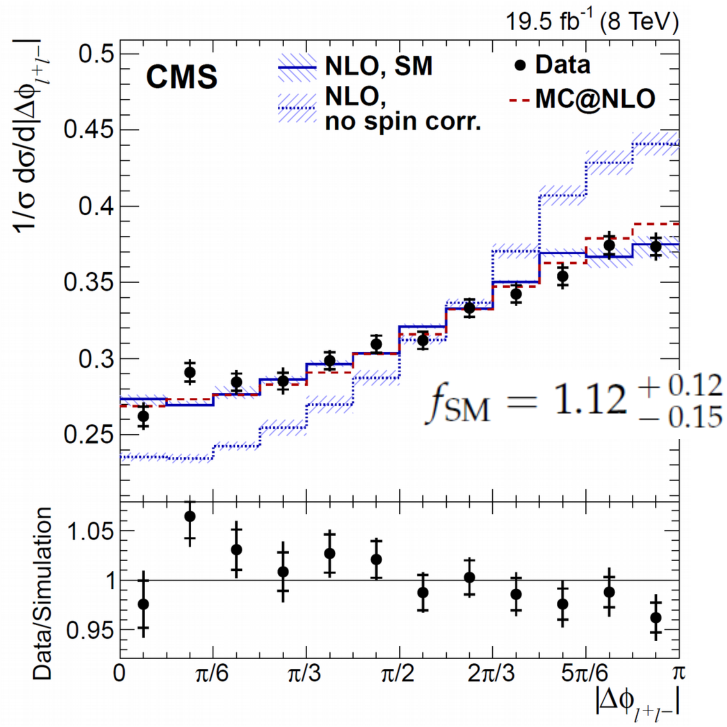




Spin correlations by CMS

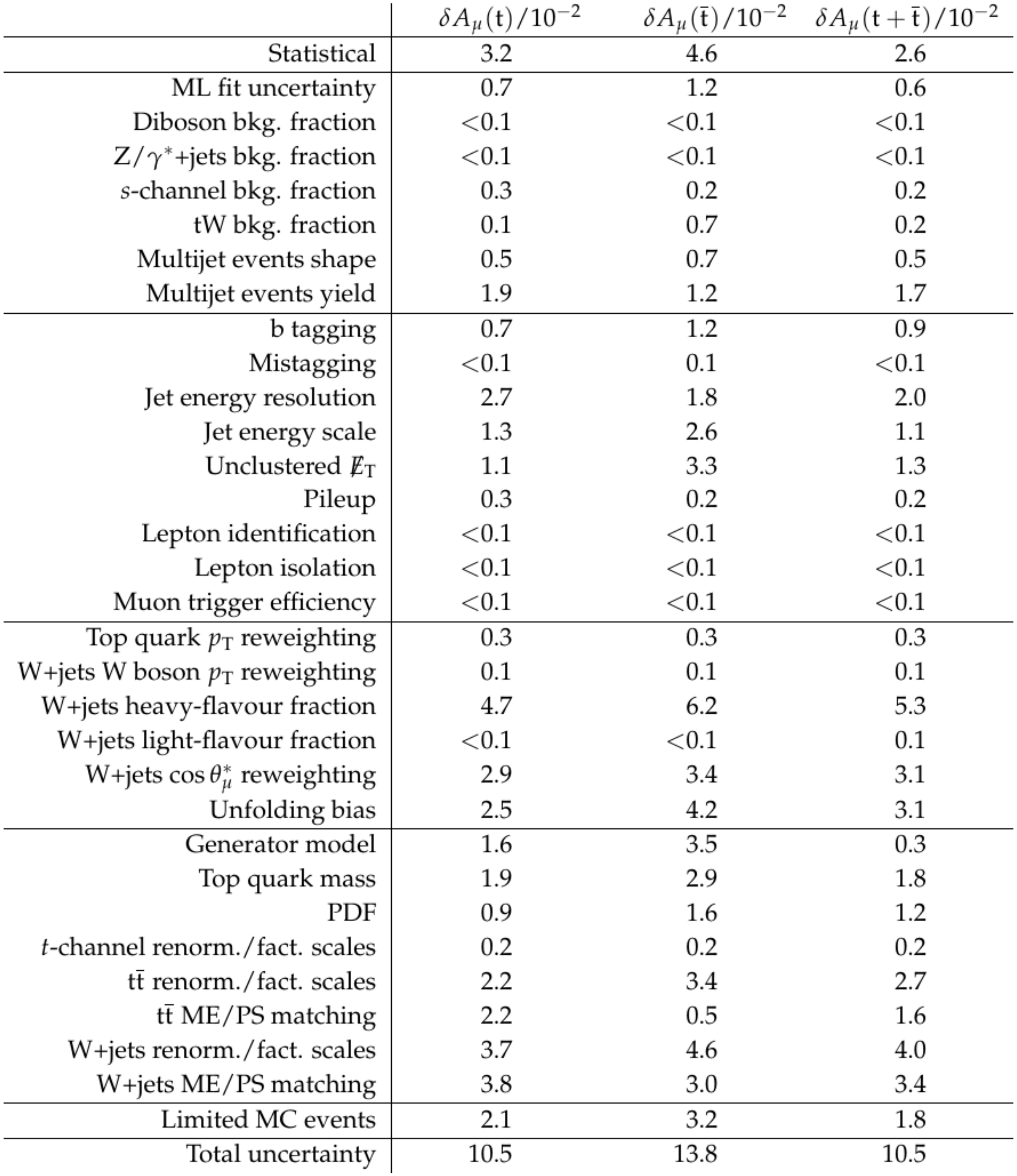
Phys. Rev. D 93 (2016) 052007





Spin asymmetry

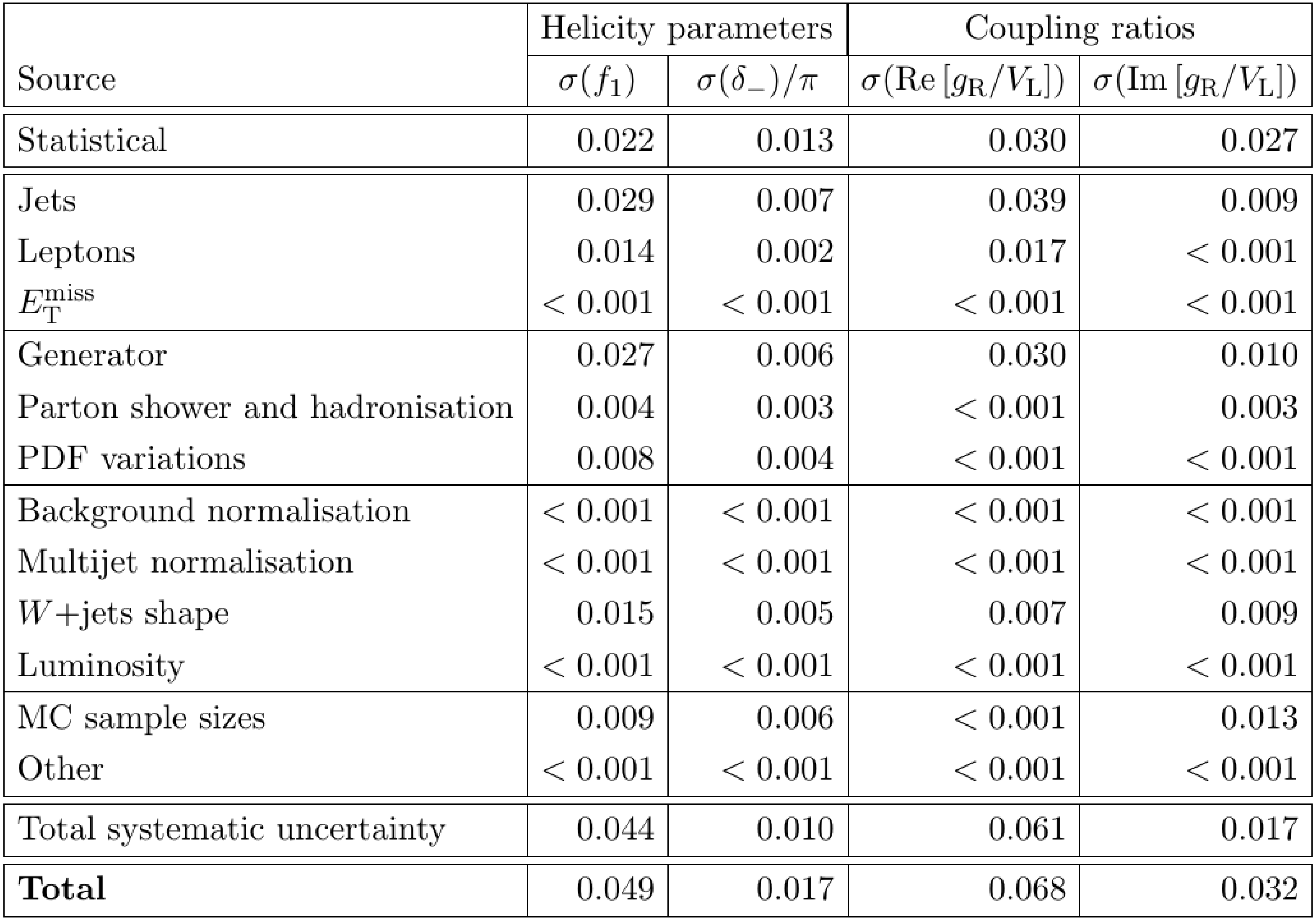
JHEP 04 (2016) 073



	$\delta A_\mu(\mathrm{t})/10^{-2}$	$\delta A_\mu(\bar{\mathrm{t}})/10^{-2}$	$\delta A_\mu(\mathrm{t}+\bar{\mathrm{t}})/10^{-2}$
Statistical	3.2	4.6	2.6
ML fit uncertainty	0.7	1.2	0.6
Diboson bkg. fraction	<0.1	<0.1	<0.1
Z/γ^*+jets bkg. fraction	<0.1	<0.1	<0.1
s-channel bkg. fraction	0.3	0.2	0.2
tW bkg. fraction	0.1	0.7	0.2
Multijet events shape	0.5	0.7	0.5
Multijet events yield	1.9	1.2	1.7
b tagging	0.7	1.2	0.9
Mistagging	<0.1	0.1	<0.1
Jet energy resolution	2.7	1.8	2.0
Jet energy scale	1.3	2.6	1.1
Unclustered $\not{E}_{\mathrm{T}}$	1.1	3.3	1.3
Pileup	0.3	0.2	0.2
Lepton identification	<0.1	<0.1	<0.1
Lepton isolation	<0.1	<0.1	<0.1
Muon trigger efficiency	<0.1	<0.1	<0.1
Top quark p_{T} reweighting	0.3	0.3	0.3
W+jets W boson p_{T} reweighting	0.1	0.1	0.1
W+jets heavy-flavour fraction	4.7	6.2	5.3
W+jets light-flavour fraction	<0.1	<0.1	0.1
W+jets $\cos\theta^*_\mu$ reweighting	2.9	3.4	3.1
Unfolding bias	2.5	4.2	3.1
Generator model	1.6	3.5	0.3
Top quark mass	1.9	2.9	1.8
PDF	0.9	1.6	1.2
t-channel renorm./fact. scales	0.2	0.2	0.2
$\mathrm{t\bar{t}}$ renorm./fact. scales	2.2	3.4	2.7
$\mathrm{t\bar{t}}$ ME/PS matching	2.2	0.5	1.6
W+jets renorm./fact. scales	3.7	4.6	4.0
W+jets ME/PS matching	3.8	3.0	3.4
Limited MC events	2.1	3.2	1.8
Total uncertainty	10.5	13.8	10.5

Wtb analysis

JHEP 12 (2017) 017



Source	Helicity parameters		Coupling ratios	
	$\sigma(f_1)$	$\sigma(\delta_-)/\pi$	$\sigma(\mathrm{Re}\,[g_\mathrm{R}/V_\mathrm{L}])$	$\sigma(\mathrm{Im}\,[g_\mathrm{R}/V_\mathrm{L}])$
Statistical	0.022	0.013	0.030	0.027
Jets	0.029	0.007	0.039	0.009
Leptons	0.014	0.002	0.017	< 0.001
$E_\mathrm{T}^\mathrm{miss}$	< 0.001	< 0.001	< 0.001	< 0.001
Generator	0.027	0.006	0.030	0.010
Parton shower and hadronisation	0.004	0.003	< 0.001	0.003
PDF variations	0.008	0.004	< 0.001	< 0.001
Background normalisation	< 0.001	< 0.001	< 0.001	< 0.001
Multijet normalisation	< 0.001	< 0.001	< 0.001	< 0.001
W+jets shape	0.015	0.005	0.007	0.009
Luminosity	< 0.001	< 0.001	< 0.001	< 0.001
MC sample sizes	0.009	0.006	< 0.001	0.013
Other	< 0.001	< 0.001	< 0.001	< 0.001
Total systematic uncertainty	0.044	0.010	0.061	0.017
Total	0.049	0.017	0.068	0.032

LO Spin analyzing power

Nucl.Phys. B840 349-378, 2010

- dependence on anomalous Wtb couplings

$$
\begin{aligned}
a_{\ell^+} = {} & \left[|V_L|^2 - |V_R|^2\right]\left(1 + x_W^2 - 2x_W^4\right) + 2\left[|g_L|^2 - |g_R|^2\right]\left(1 - \frac{x_W^2}{2} - \frac{x_W^4}{2}\right) \\
& - 12 x_W^2 x_b \,\mathrm{Re}\left[V_L V_R^* + g_L g_R^*\right] - 6 x_W \,\mathrm{Re}\left[V_L g_R^* + V_R g_L^*\right]\left(1 - x_W^2\right) \\
& + 6 x_W x_b \,\mathrm{Re}\left[V_L g_L^* - V_R g_R^*\right]\left(1 + x_W^2\right) + 12 x_W^2 \left[|V_R|^2 - |g_R|^2\right] \\
& + 6 \frac{M_W}{|\vec{q}|} x_W \log \frac{E_W + |\vec{q}|}{E_W - |\vec{q}|} \left[|g_R|^2 - x_W^2 |V_R|^2 + 2 x_W x_b \,\mathrm{Re}\, V_R g_R^*\right] \;,
\end{aligned}
$$

$$
\begin{aligned}
a_0 = {} & \left[|V_L|^2 + |V_R|^2\right]\left(1 + x_W^2 - 2x_W^4\right) + 2\left[|g_L|^2 + |g_R|^2\right]\left(1 - \frac{x_W^2}{2} - \frac{x_W^4}{2}\right) \\
& - 12 x_W^2 x_b \,\mathrm{Re}\left[V_L V_R^* + g_L g_R^*\right] - 6 x_W \mathrm{Re}\left[V_L g_R^* + V_R g_L^*\right]\left(1 - x_W^2\right) \\
& + 6 x_W x_b \,\mathrm{Re}\left[V_L g_L^* + V_R g_R^*\right] \;,
\end{aligned}
$$

LO W helicity fractions

Nucl.Phys. B840 349-378, 2010

- dependence on anomalous Wtb couplings

$$\Gamma_0 = \frac{g^2|\vec{q}|}{32\pi} A_0\,, \qquad \Gamma_\pm = \frac{g^2|\vec{q}|}{32\pi}\left(B_0 \pm 2\frac{|\vec{q}|}{m_t}B_1\right)$$

$$\begin{aligned} A_0 = {} & \frac{m_t^2}{M_W^2}\left[|V_L|^2+|V_R|^2\right]\left(1-x_W^2\right) + \left[|g_L|^2+|g_R|^2\right]\left(1-x_W^2\right) \\ & - 4x_b\,\mathrm{Re}\left[V_L V_R^* + g_L g_R^*\right] - 2\frac{m_t}{M_W}\mathrm{Re}\ \left[V_L g_R^* + V_R g_L^*\right]\left(1-x_W^2\right) \\ & + 2\frac{m_t}{M_W}x_b\,\mathrm{Re}\ \left[V_L g_L^* + V_R g_R^*\right]\left(1+x_W^2\right)\ , \end{aligned}$$

$$\begin{aligned} B_0 = {} & \left[|V_L|^2+|V_R|^2\right]\left(1-x_W^2\right) + \frac{m_t^2}{M_W^2}\left[|g_L|^2+|g_R|^2\right]\left(1-x_W^2\right) \\ & - 4x_b\,\mathrm{Re}\left[V_L V_R^* + g_L g_R^*\right] - 2\frac{m_t}{M_W}\mathrm{Re}\ \left[V_L g_R^* + V_R g_L^*\right]\left(1-x_W^2\right) \\ & + 2\frac{m_t}{M_W}x_b\,\mathrm{Re}\ \left[V_L g_L^* + V_R g_R^*\right]\left(1+x_W^2\right)\ , \end{aligned}$$

$$\begin{aligned} B_1 = {} & -\left[|V_L|^2-|V_R|^2\right] + \frac{m_t^2}{M_W^2}\left[|g_L|^2-|g_R|^2\right] + 2\frac{m_t}{M_W}\mathrm{Re}\ \left[V_L g_R^* - V_R g_L^*\right] \\ & + 2\frac{m_t}{M_W}x_b\,\mathrm{Re}\ \left[V_L g_L^* - V_R g_R^*\right]\ , \end{aligned}$$

Wtb analysis

JHEP 12 (2017) 017

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