Direct measurements of V_{tb} and constraints on the Wtb anomalous couplings

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on behalf of the ATLAS & CMS collaborations

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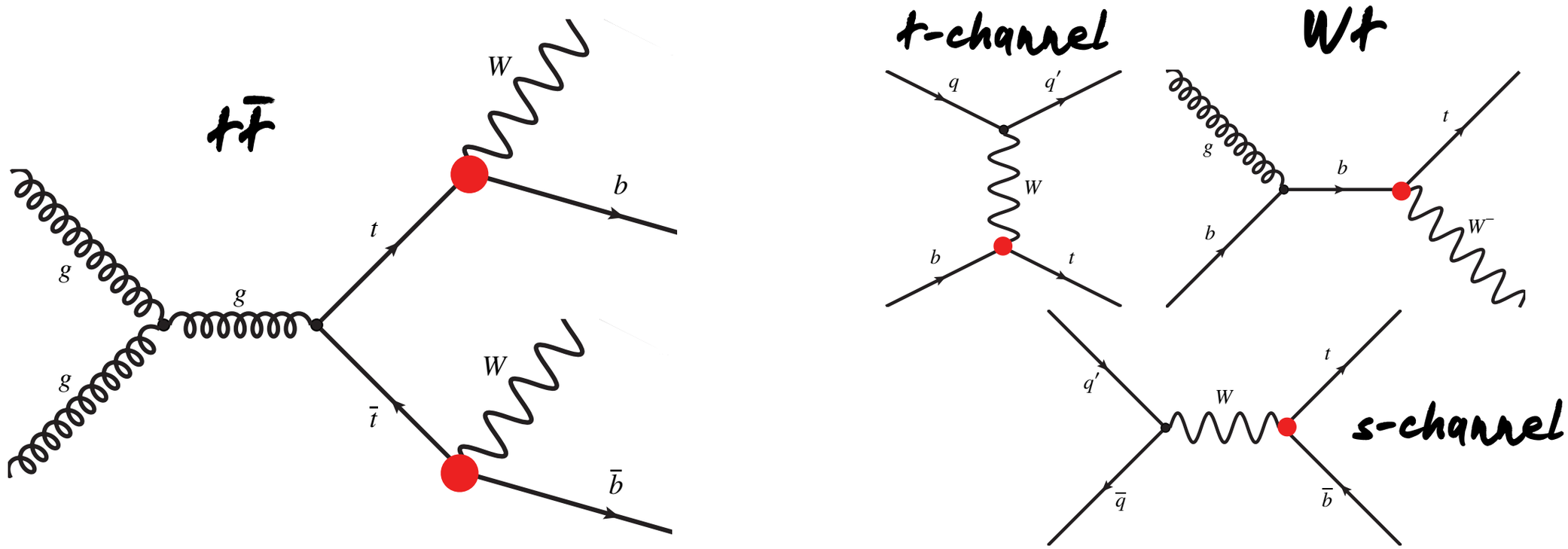
Wtb vertex

At hadron colliders, top quarks predominantly produced

- in pairs ($t\bar{t}$) via the flavour-conserving strong interaction ($gt\bar{t}$)
- singly through the electroweak (EW) interaction (Wtb)



In $t\bar{t}$ production, Wtb vertex probed through top-quark decay

- top quarks produced unpolarised and decayed through EW interaction ($t \to Wb$)

In single top-quark production, Wtb vertex studied in production and decay

- production modes also sensitive to new physics

EFT framework

New effects above EWSB scale on Wtb vertex probed in a EFT approach

- the most general Wtb lagrangian, including dim-6 operators

SM V-A term

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(V_L P_L + V_R P_R)tW^-_{\mu}$$

anom. coupl.

$$-\frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}(g_L P_L + g_R P_R)tW^-_{\mu} + \text{H.c.}$$

- in SM, at tree level, $V_L = f_{LV} V_{tb}$, $f_{LV} = 1$, $V_R = g_L = g_R = 0$
  - CKM matrix element $V_{tb} \simeq 1$
  - f_{LV} being a model-independent left-handed real form factor, encapsulating non-SM contributions
- V_R, g_L and g_R := complex anomalous couplings
  - imaginary parts related with CP violation!

How to probe Wtb?

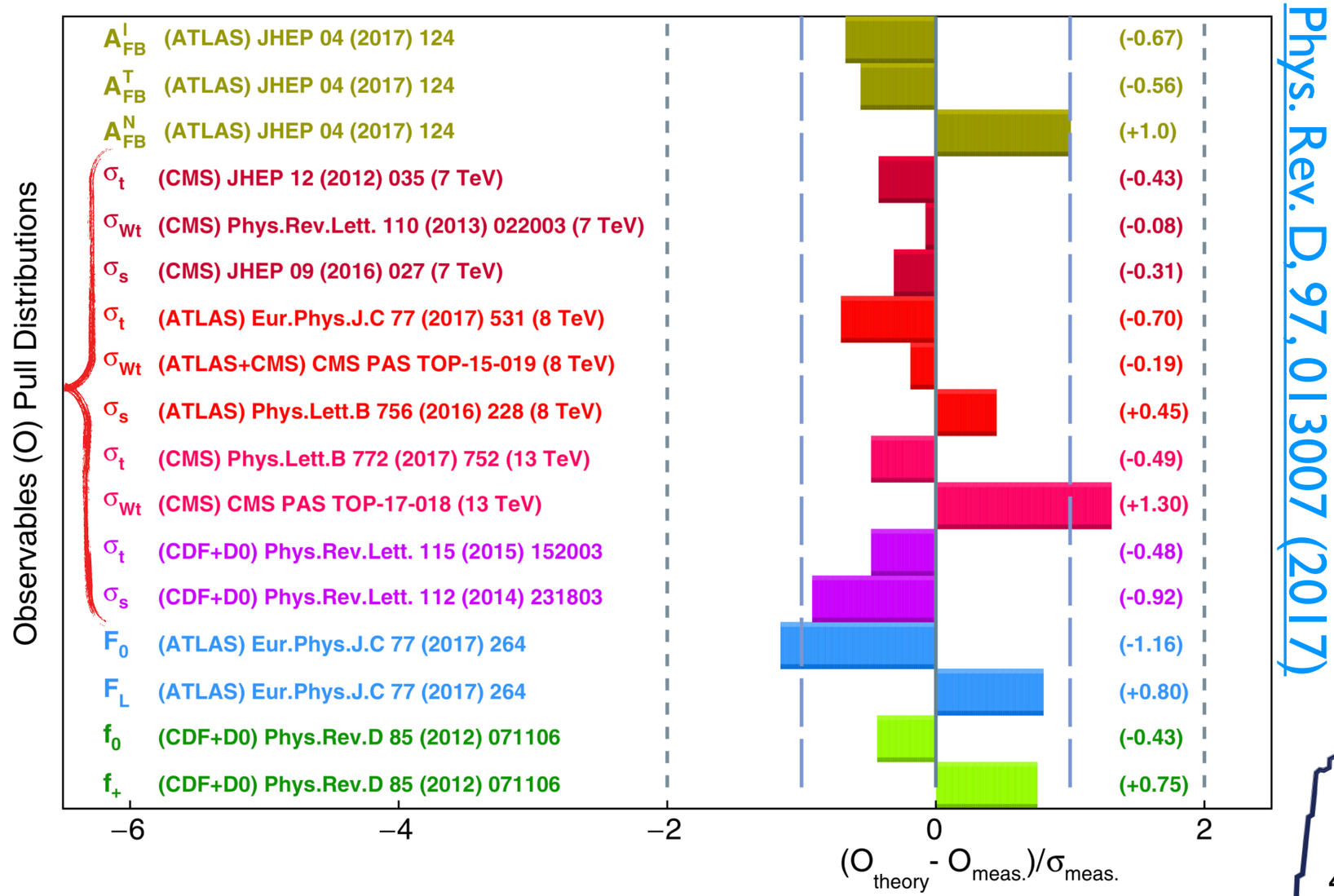
Left-handed (LH) vector coupling V_L measured from

- (directly) single top-quark production cross-section measurements
  - **assumption**: SM Wtb vertex ($V_R = g_L = g_R = 0$)
- (indirectly) BR measurements in $t\bar{t}$ production (rather model dependent)

$$|V_L| := |f_{LV} V_{tb}| = \sqrt{\sigma/\sigma_{th}}$$

Assumptions: $V_R = g_L = g_R = 0$

$|V_{td}|, |V_{ts}| \ll |V_{tb}|$

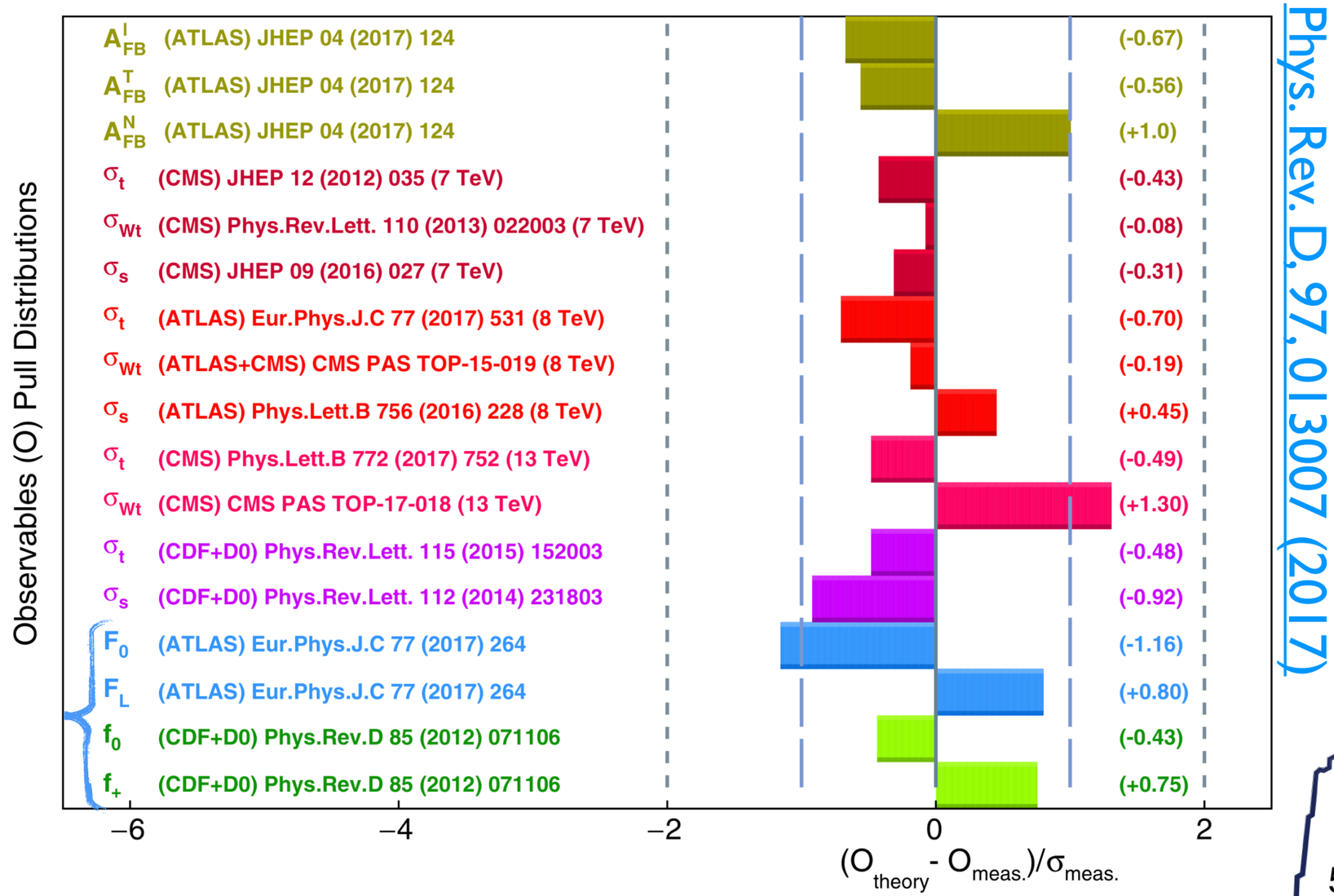


Phys. Rev. D, 97, 013007 (2017)

How to probe Wtb?

Anomalous couplings probed by means of top-quark related properties

- W boson helicity fractions (F_0, F_L, F_R) in top-quark decays
- single top-quark production and decay observables (angular distributions, etc)
  - different model assumptions according to the sensitive observable



Phys. Rev. D, 97, 013007 (2017)

$F_i = N_i/(N_0+N_L+N_R)$

i= 0, L, R (W polarizations)

Some assumptions needed:

2 ind. F, 4 (real) couplings

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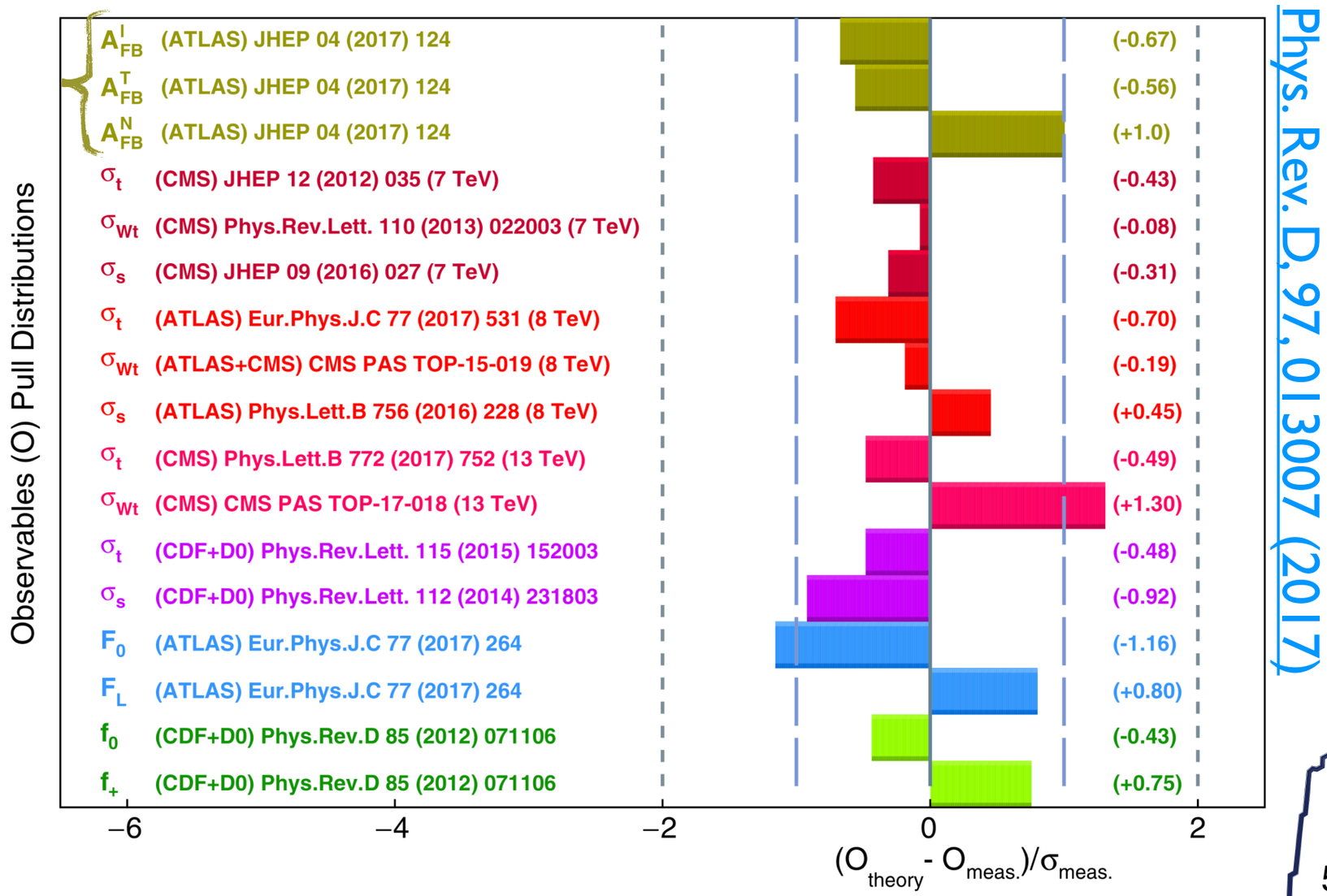
$A^i_{FB} = (N_+ - N_-)/(N_+ + N_-)$,

i=l,T,N (sensitive directions)

Assumption:

correlation neglected



Phys. Rev. D 97, 013007 (2017)

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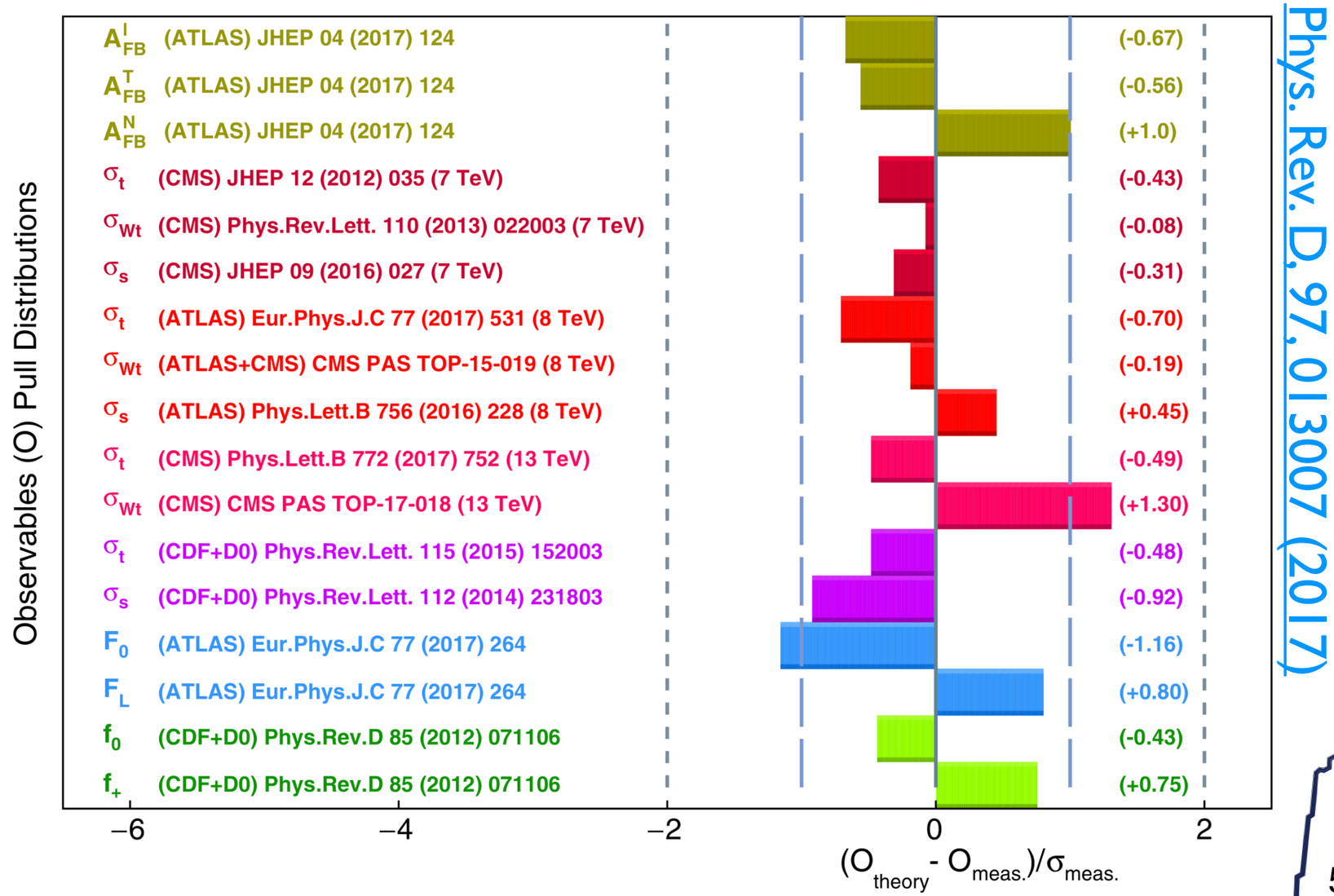
3-differential decay,

f_I, f_I^+, f_0^+, δ_+, δ_- , P

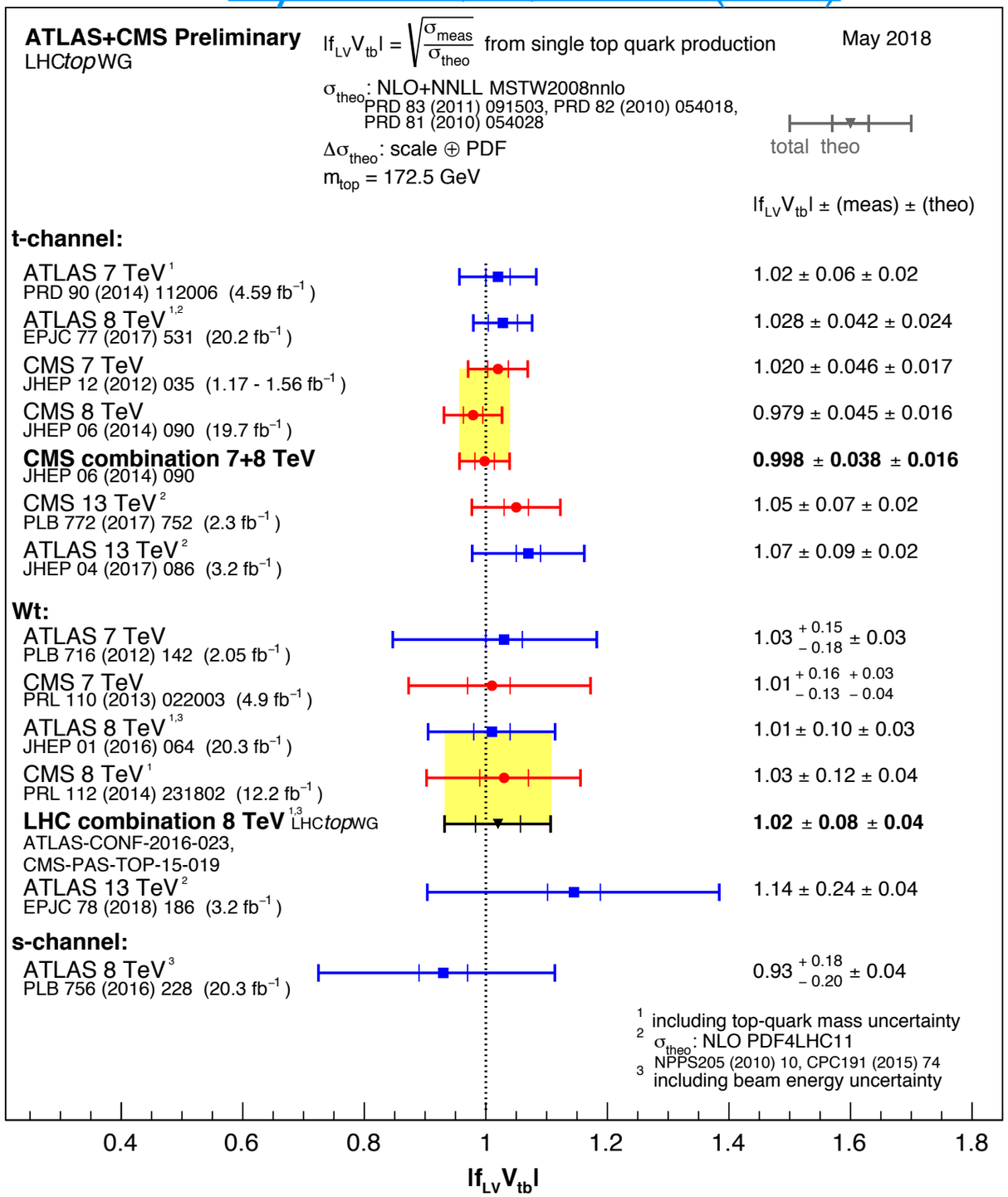
No assumption



Phys. Rev. D, 97, 013007 (2017)

Direct constraints on V_L

Phys. Rev. D, 97, 013007 (2017)



Latest results from ATLAS and CMS

- CMS t-chan analysis at 13 TeV (35.9 fb^{-1})
  - TOP-17-011
  - $|f_{LV}V_{tb}|$ = 1.00 ± 0.05 (meas) ± 0.02 (theo)
- CMS tW analysis at 13 TeV
  - CERN-EP-2018-074 (submitted to JHEP)
  - μ = 0.88 ±0.02(stat) ±0.09(syst) ±0.03(lumi)
- ATLAS tW analysis at 13 TeV
  - EPJC 78 (2018) 186
  - $|f_{LV}V_{tb}|$ = 1.14 ± 0.24 (meas) ± 0.04 (theo)

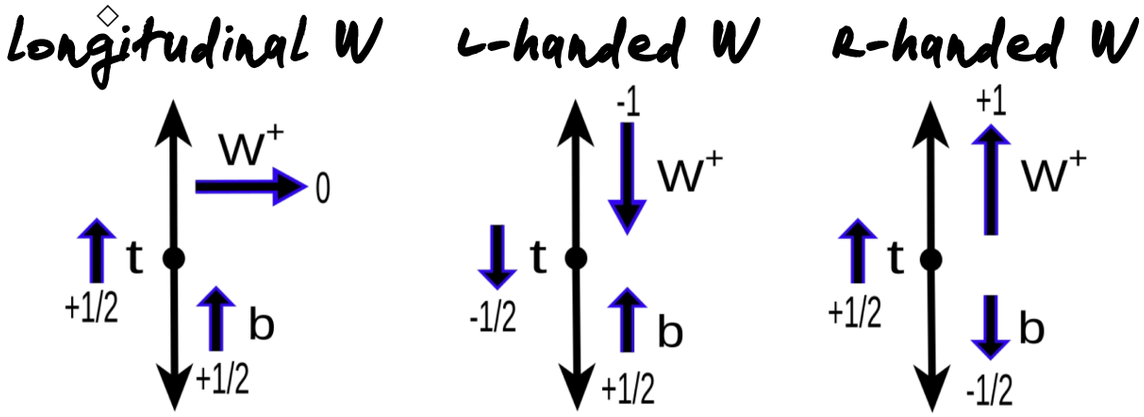
Best combination at 7+8 TeV (CMS)

- $|f_{LV}V_{tb}|$ = 0.998 ± 0.041
- ATLAS+CMS Run I combination ongoing

W helicity fractions

Wtb properties in $t\bar{t}$ events determined by structure of weak interaction

- Helicity fractions (F_R, F_L, F_0) are determined by the Wtb vertex structure
  - $F_0 + F_L + F_R = 1$
  -



→ $F_L = 0.311 \pm 0.005$

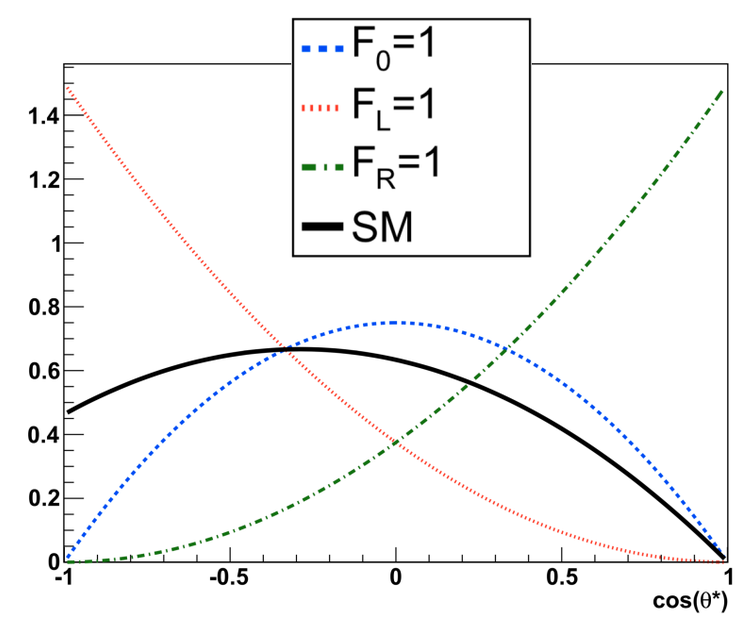
$F_0 = 0.687 \pm 0.005$

$F_R = 0.0017 \pm 0.0001$

The differential decay rate of top quarks considering the angle θ^* is given by:

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

- F_i depend on (real) anomalous couplings => deviations as hint of BSM physics

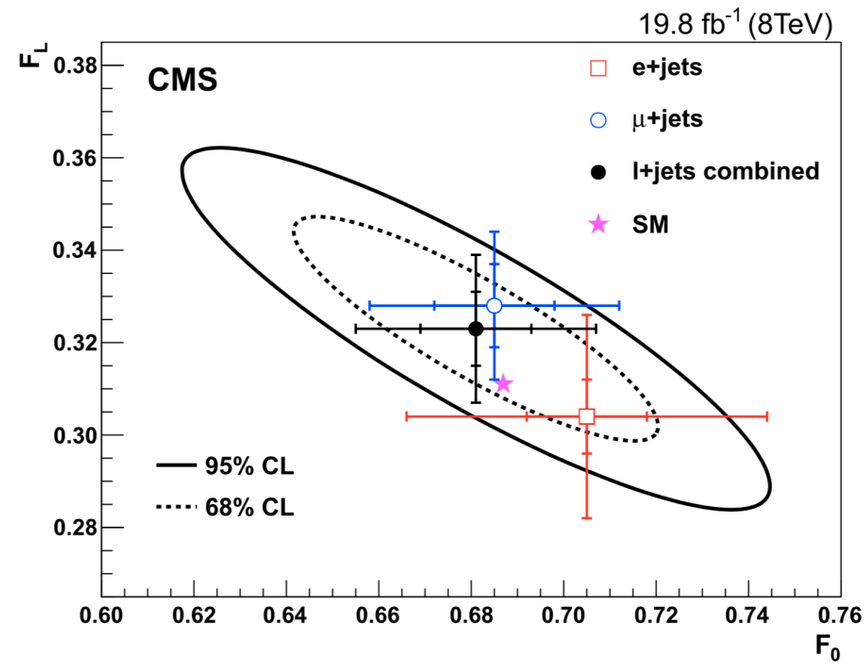


W helicity fractions

PLB 762 (2016) 512–534

Measurement in $t\bar{t}$ topology (19.8 fb^{-1}, 8 TeV)

- cut-based analysis, e and μ channels
- kinematic fitting to reconstruct $t\bar{t}$ system
  - leptonic side ONLY



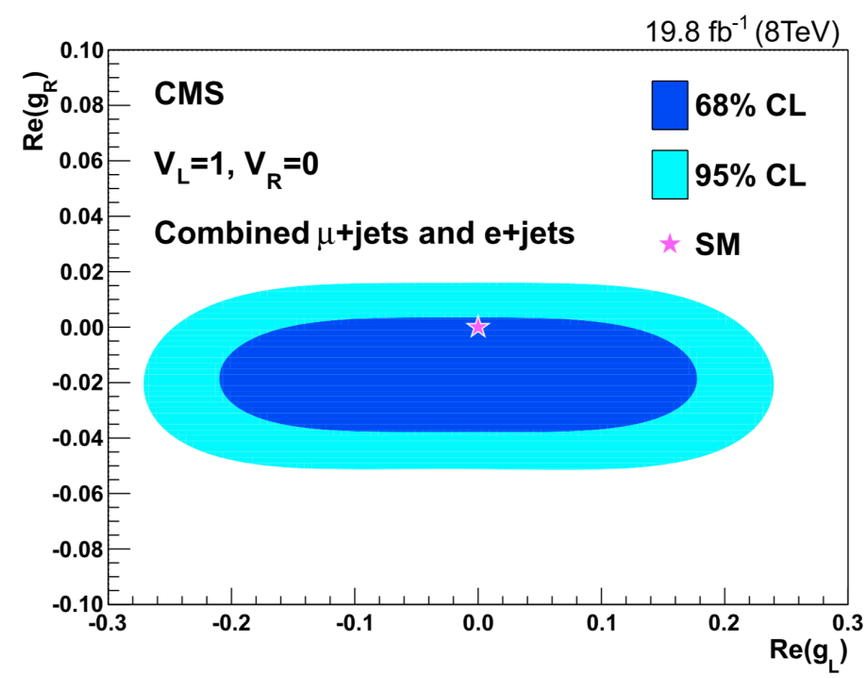
Reweighting method:

- top events $N_{t\bar{t}}$ reweighted according to decay function

$$w_{\text{lep/had/single-t}}(\cos\theta^*_{\text{gen}};\vec{F}) \equiv \left[\frac{3}{8}F_{\text{L}}(1-\cos\theta^*_{\text{gen}})^2 + \frac{3}{4}F_0\sin^2\theta^*_{\text{gen}} + \frac{3}{8}F_{\text{R}}(1+\cos\theta^*_{\text{gen}})^2\right] / \left[\frac{3}{8}F_{\text{L}}^{\text{SM}}(1-\cos\theta^*_{\text{gen}})^2 + \frac{3}{4}F_0^{\text{SM}}\sin^2\theta^*_{\text{gen}} + \frac{3}{8}F_{\text{R}}^{\text{SM}}(1+\cos\theta^*_{\text{gen}})^2\right]$$

- maximise a binned Poisson likelihood function

$$\mathcal{L}(\vec{F}) = \prod_i \frac{N_{\text{MC}}(i;\vec{F})^{N_{\text{data}}(i)}}{\left[N_{\text{data}}(i)\right]!}\exp\left[-N_{\text{MC}}(i;\vec{F})\right]$$

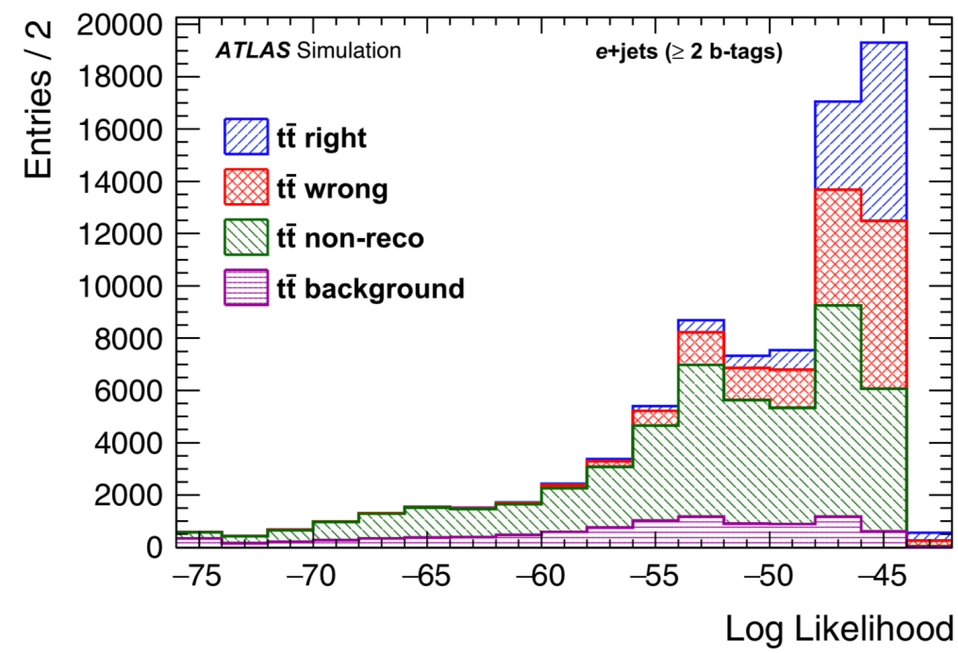


W helicity fractions

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

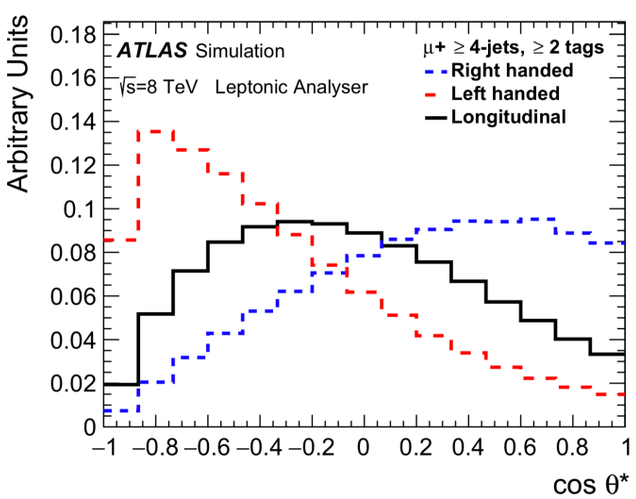
Measurement in $t\bar{t}$ topology (20.2 fb^{-1}, 8 TeV)

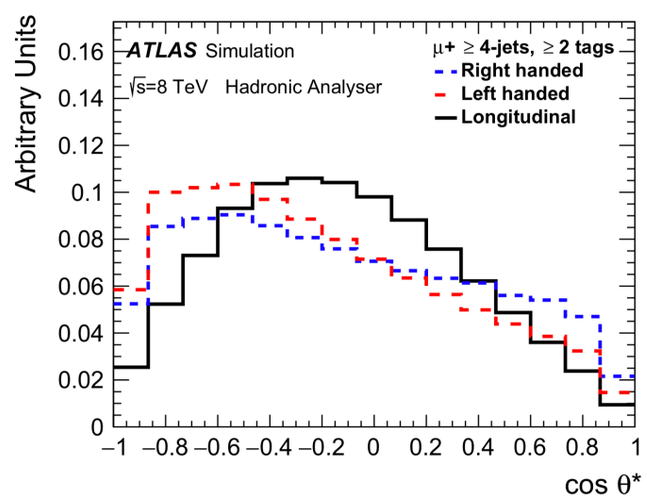
- cut-based analysis
- kinematic fitting to reconstruct $t\bar{t}$ system
  - leptonic and hadronic sides
  - hadronic analyser less sensitive



Template fit method:

- templates for F_0, F_L, F_R (per-lepton channel) by reweighting reco. distribution





Very precise measurement!

Leptonic analyser ($\geq$2 b-tags)
$F_0 = 0.709 \pm 0.012$ (stat.+bkg. norm.) $^{+0.015}_{-0.014}$ (syst.)
$F_L = 0.299 \pm 0.008$ (stat.+bkg. norm.) $^{+0.013}_{-0.012}$ (syst.)
$F_R = -0.008 \pm 0.006$ (stat.+bkg. norm.) ± 0.012 (syst.)

- combined likelihood fit (8 inputs) to extract helicity fractions

W helicity fractions

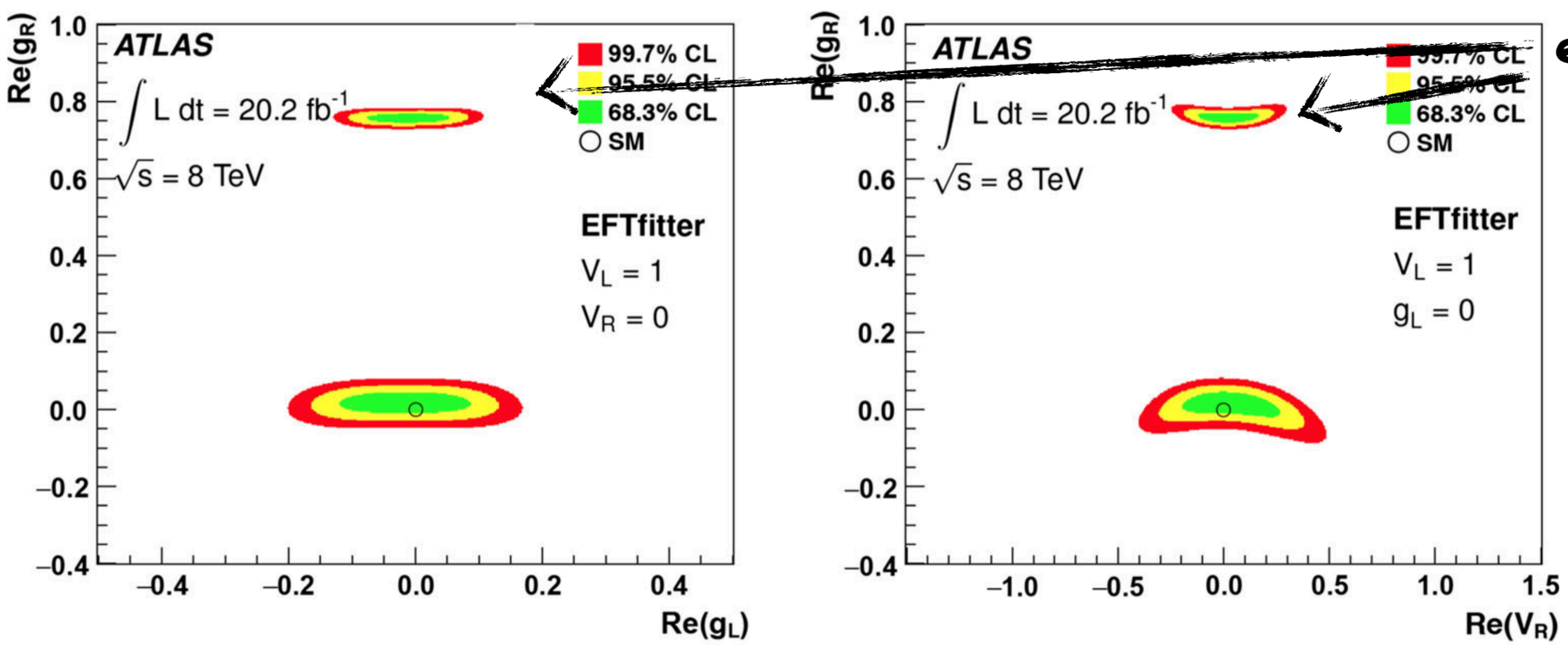
Eur. Phys. J. C 77 (2017) 264

Possibility to set limits on anomalous Wtb couplings with EFTFitter tool

- **limitation**: only place limits on combinations of (real) coupling pairs
  - other couplings set to their SM values ⇒ loss of generality

Allowed ranges:

- $\mathrm{Re}[V_R] \in [-0.24, 0.31]$ @ 95% C.L.
- $\mathrm{Re}[g_L] \in [-0.14, 0.11]$ @ 95% C.L.
- $\mathrm{Re}[g_R] \in [-0.02, 0.06]$ and $[0.74, 0.78]$ @95% C.L.



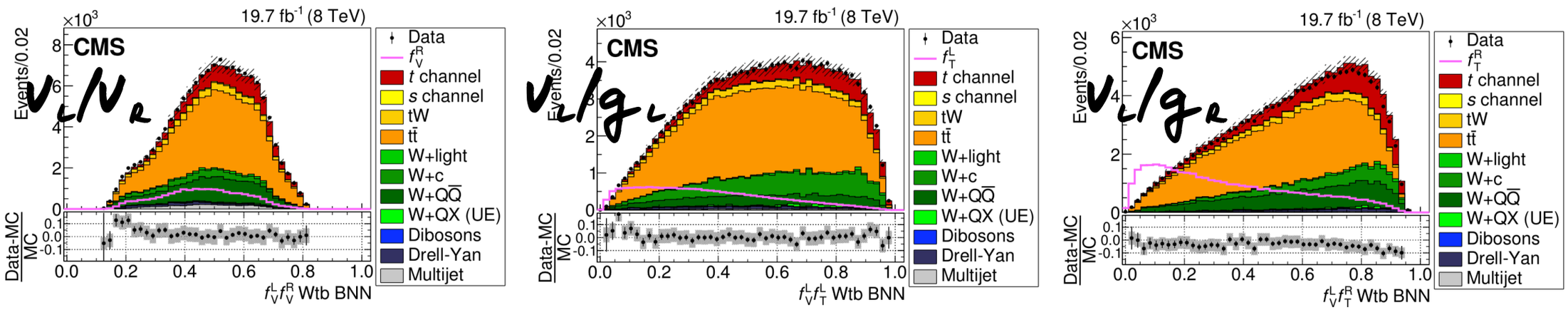
excluded by t-channel x-sec

Wtb couplings in t-chan

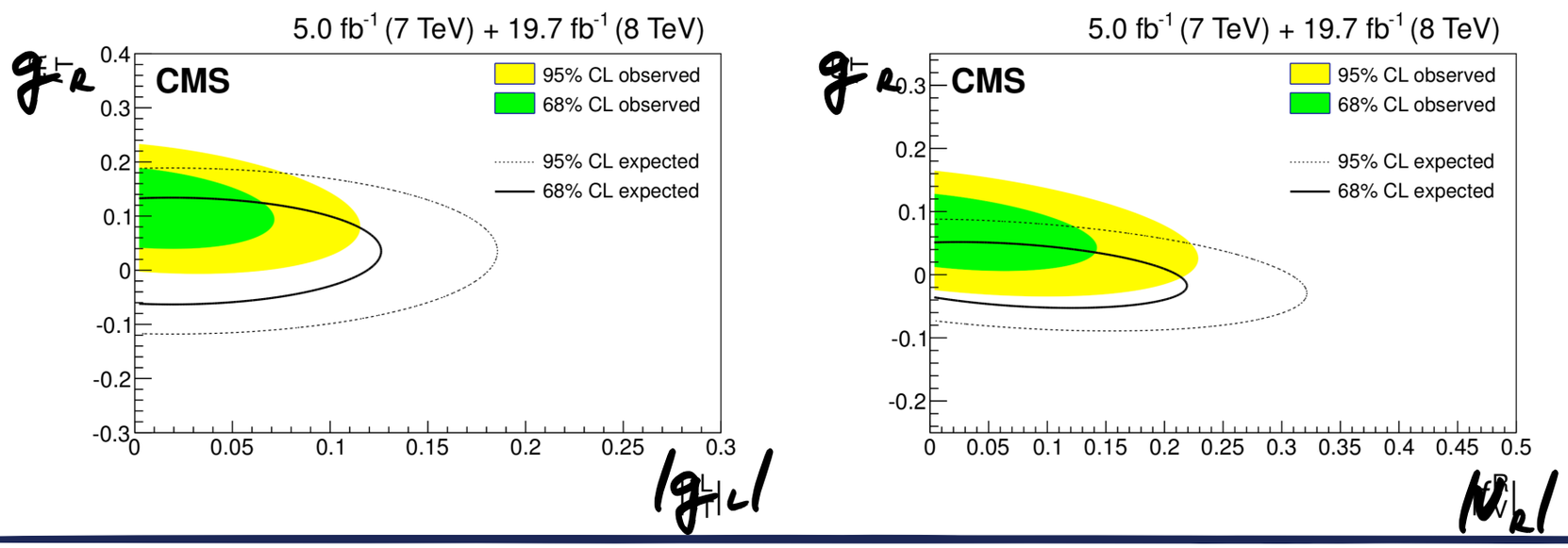
JHEP 02 (2017) 028

Search for anomalous Wtb couplings in *t*-channel single top quark production (24.7 fb^{-1}, 7-8 TeV)

- one muon and two or three jets
- Bayesian Neural Network (BNN) technique to separate V_L vs. V_R, g_R and g_L



- 1-2-3D constraints on the anomalous parameters are obtained



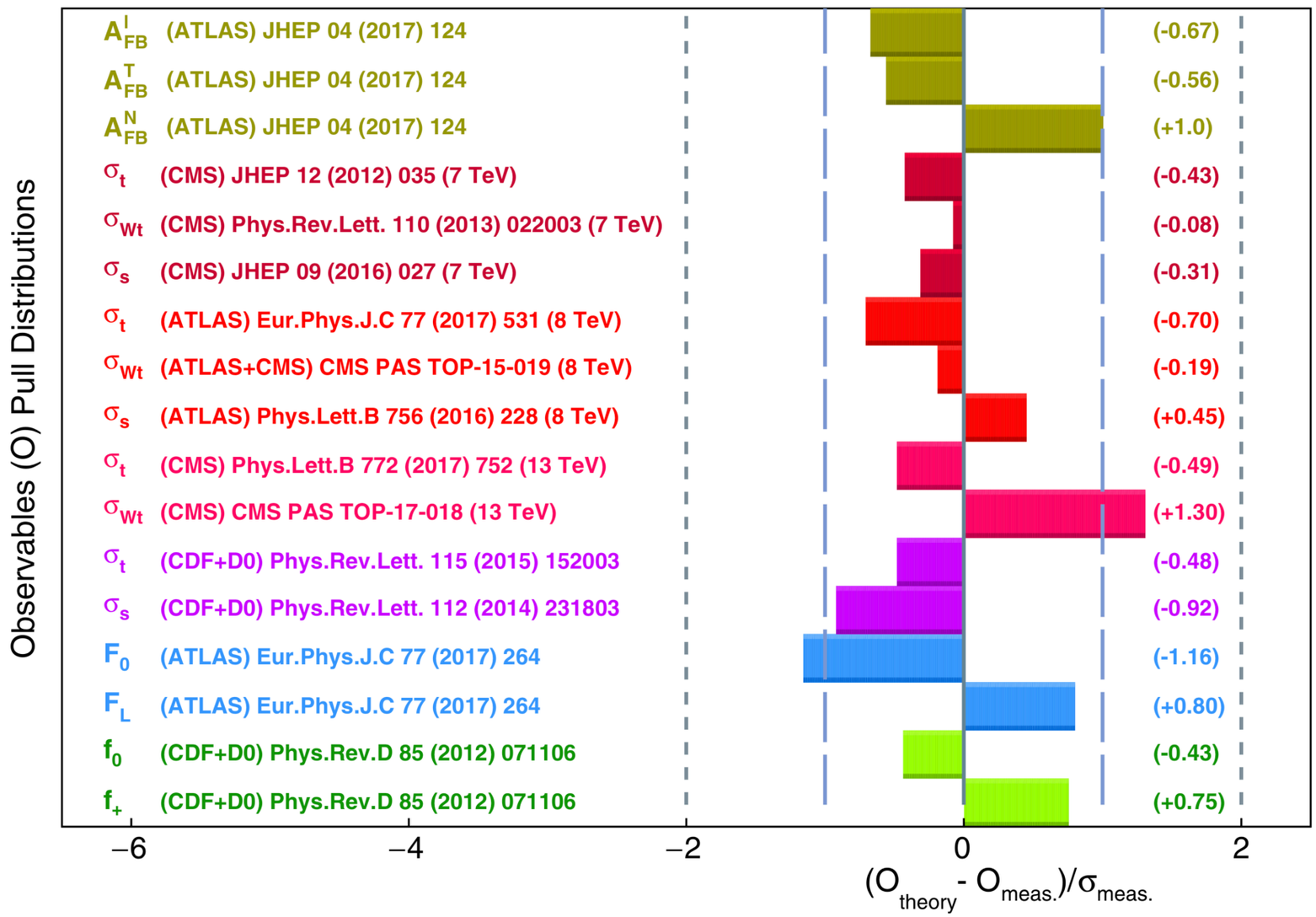
Agreement with SM predictions

Global constraints

Phys. Rev. D, 97, 013007 (2017)

Combining x-sec, W-helicity and asymmetry to increase sensitivity to BSM

- in the EFT framework
- most recent asymmetries result from ATLAS included
- very general approach: couplings (real+imaginary) allowed to vary simultaneously



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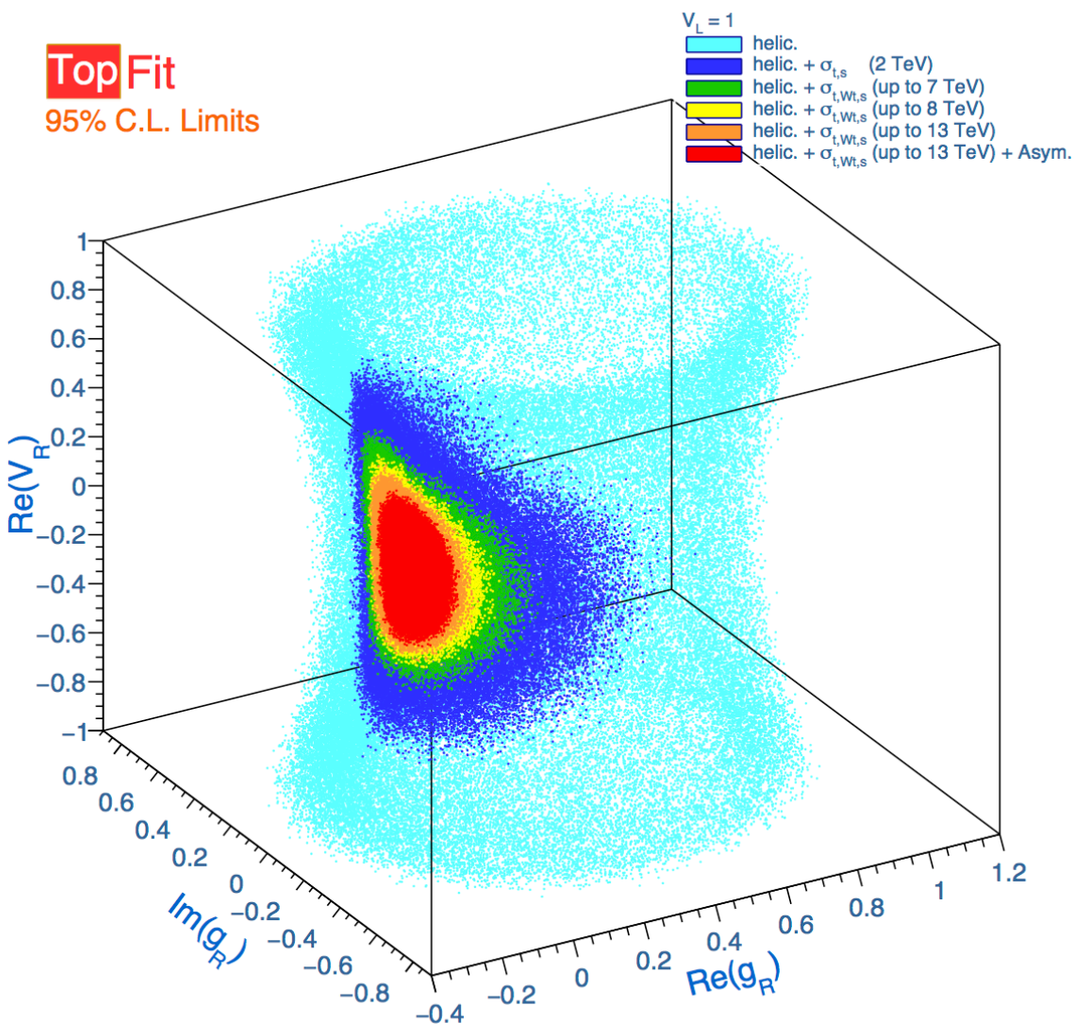

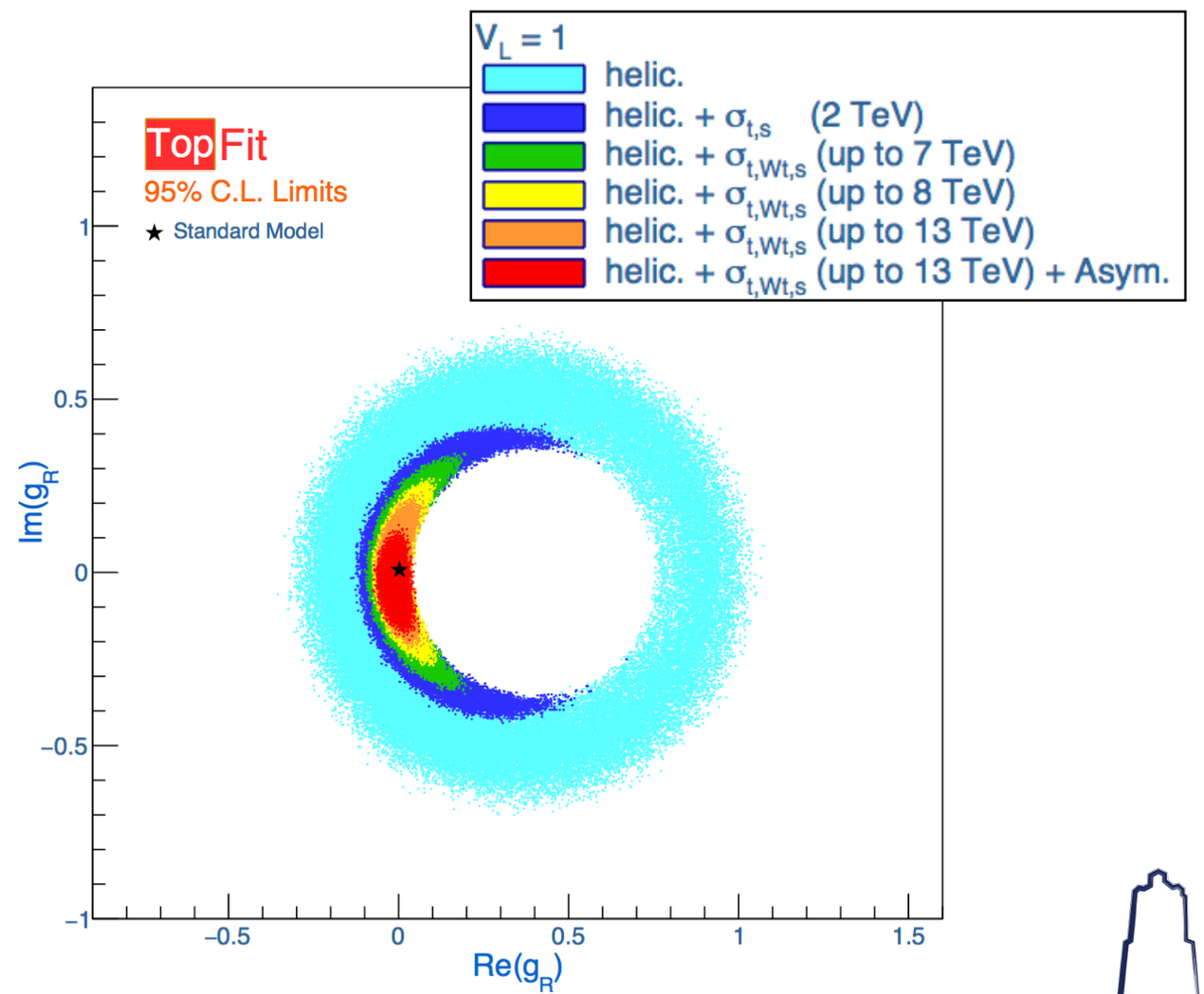

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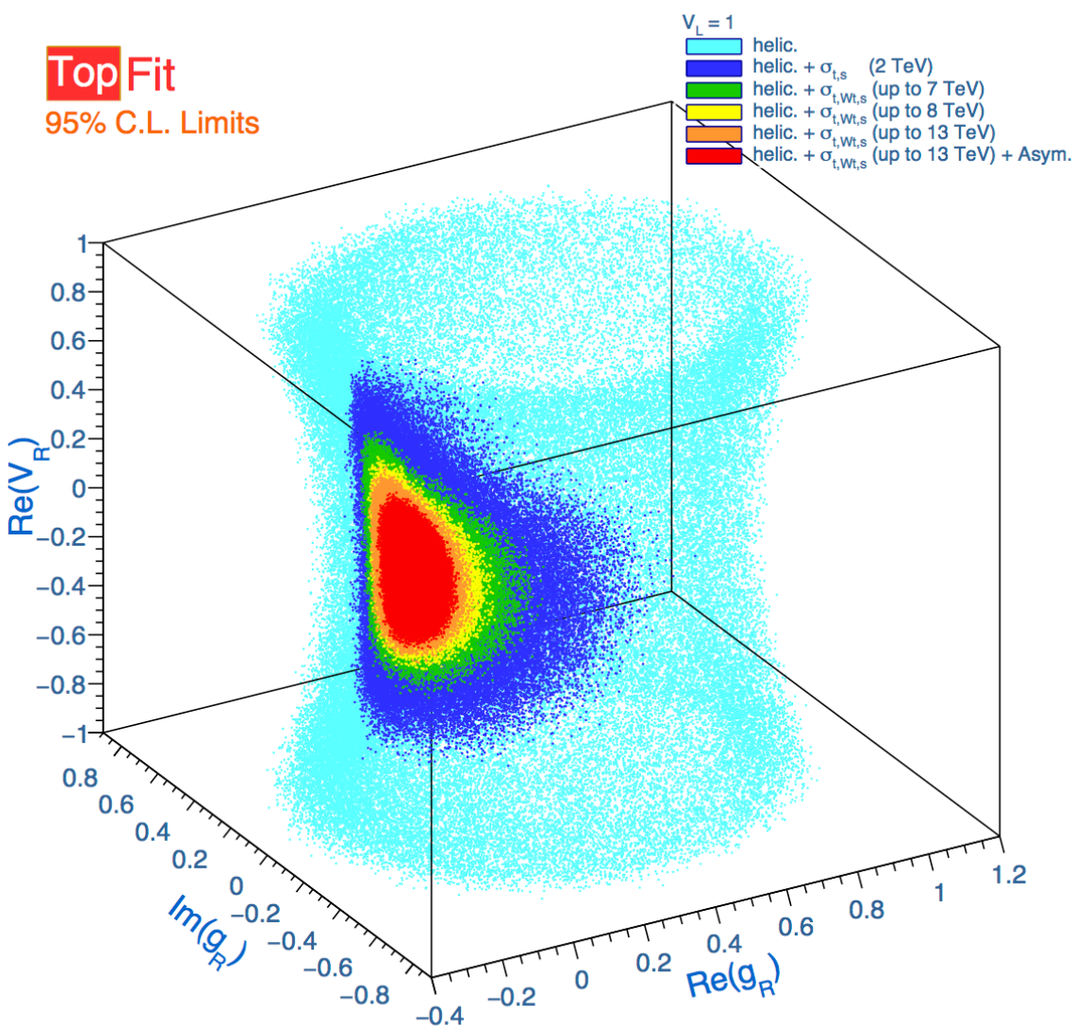


$V_L = 1$

$W_{hel} \oplus \sigma_{t,Wt,s}$	g_R	g_L	V_R
Re	[−0.07, 0.08]	[−0.18, 0.20]	[−0.33, 0.41]
Im	[−0.23, 0.23]	[−0.20, 0.19]	[−0.39, 0.36]
$\oplus A^{\ell}_{FB}, A^{T}_{FB}, A^{N}_{FB}$	g_R	g_L	V_R
Re	[−0.07, 0.06]	[−0.19, 0.19]	[−0.27, 0.33]
Im	[−0.19, 0.13]	[−0.18, 0.19]	[−0.30, 0.30]

floating V_L

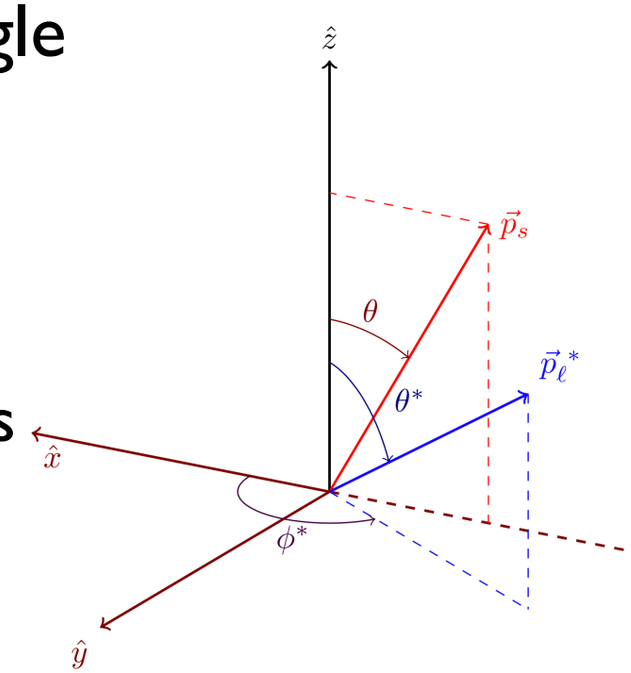
All obs.	g_R	g_L	V_R	V_L
Re	[−0.07, 0.07]	[−0.23, 0.22]	[−0.35, 0.39]	[0.85, 1.08]
Im	[−0.20, 0.15]	[−0.22, 0.23]	[−0.37, 0.39]	—

3-angle analysis

JHEP 1712 (2017) 017

Measurement of triple-differential angular decay rates of single top quarks produced in the t-channel (20.2 fb^{-1}, 8 TeV)

- 3D angular (θ, θ^*, φ^*) decay rate using the helicity formalism
- relative phases can only be measured with polarised top quarks
- polarisation (P) can only be measured in single top-quark events



$$\varrho(\theta,\theta^*,\phi^*;P) = \frac{1}{N}\frac{d^3N}{d\cos\theta d\Omega^*} = \frac{1}{8\pi}\left\{\frac{3}{4}\left|A_{1,\frac{1}{2}}\right|^2(1+P\cos\theta)(1+\cos\theta^*)^2\right.$$

W-helicity terms

$$+\frac{3}{4}\left|A_{-1,-\frac{1}{2}}\right|^2(1-P\cos\theta)(1-\cos\theta^*)^2$$

2-angle analysis

$$+\frac{3}{2}\left(\left|A_{0,\frac{1}{2}}\right|^2(1-P\cos\theta)+\left|A_{0,-\frac{1}{2}}\right|^2(1+P\cos\theta)\right)\sin^2\theta^*$$

3-angle analysis

$$-\frac{3\sqrt{2}}{2}P\sin\theta\sin\theta^*(1+\cos\theta^*)\,\mathrm{Re}\left[e^{i\phi^*}A_{1,\frac{1}{2}}A^*_{0,\frac{1}{2}}\right]$$

$$\left.-\frac{3\sqrt{2}}{2}P\sin\theta\sin\theta^*(1-\cos\theta^*)\,\mathrm{Re}\left[e^{-i\phi^*}A_{-1,-\frac{1}{2}}A^*_{0,-\frac{1}{2}}\right]\right\} =$$

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

Finite series of orthonormal M-functions

3-angle analysis

JHEP 1712 (2017) 017

Detector effects deconvolved from data by measuring differential rates using Fourier techniques (OSDE)

- The generalised helicity fractions (three independent: f_1, f_1^+, f_0^+) and phases (δ_+, δ_-) + P (nuisance) are determined **simultaneously, including all correlations**
  - possibility to separate f_0 into two components (+ and -)

$$\varrho(\theta,\theta^*,\phi^*;P) = \frac{1}{N}\frac{d^3N}{d\cos\theta d\Omega^*} = \frac{1}{8\pi}\left\{\frac{3}{4}\left|A_{1,\frac{1}{2}}\right|^2(1+P\cos\theta)(1+\cos\theta^*)^2\right.$$

W-helicity terms

$$+\frac{3}{4}\left|A_{-1,-\frac{1}{2}}\right|^2(1-P\cos\theta)(1-\cos\theta^*)^2$$

2-angle analysis

$$+\frac{3}{2}\left(\left|A_{0,\frac{1}{2}}\right|^2(1-P\cos\theta)+\left|A_{0,-\frac{1}{2}}\right|^2(1+P\cos\theta)\right)\sin^2\theta^*$$

3-angle analysis

$$-\frac{3\sqrt{2}}{2}P\sin\theta\sin\theta^*(1+\cos\theta^*)\,\mathrm{Re}\left[e^{i\phi^*}A_{1,\frac{1}{2}}A^*_{0,\frac{1}{2}}\right]$$

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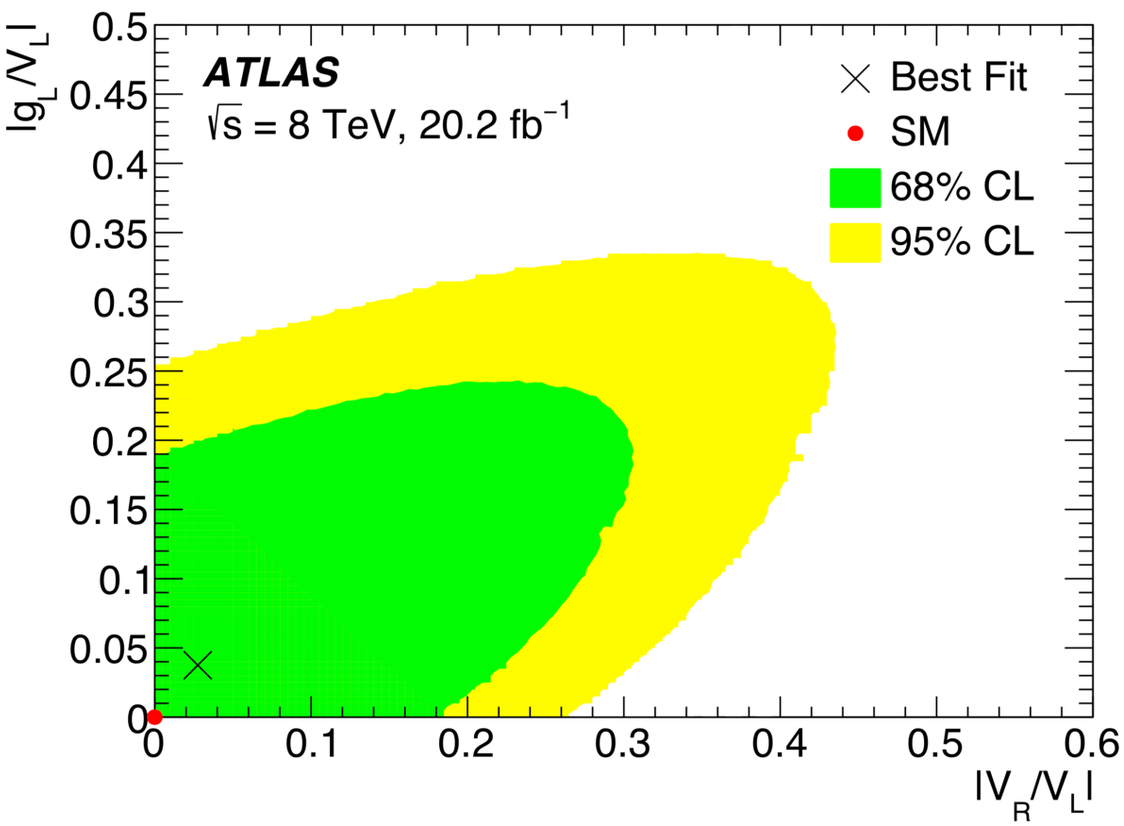
Finite series of orthonormal M-functions

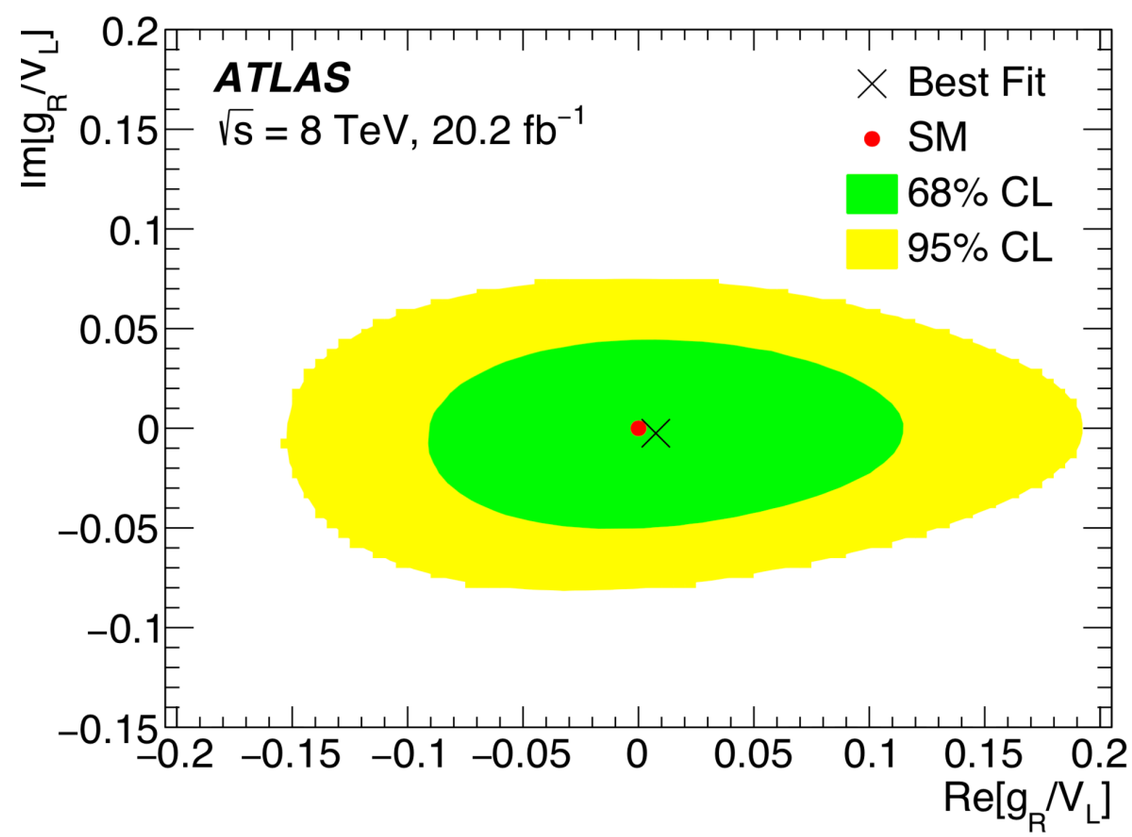
3-angle analysis

JHEP 1712 (2017) 017

Helicity fractions & phases determined w/o assumptions on other parameters

- distributions (profiles and contours) from numerical calculations of the likelihood function
- interpretation in terms of anomalous couplings V_L, V_R, g_R and g_L
- overall normalisation V_L set by cross-section measurements





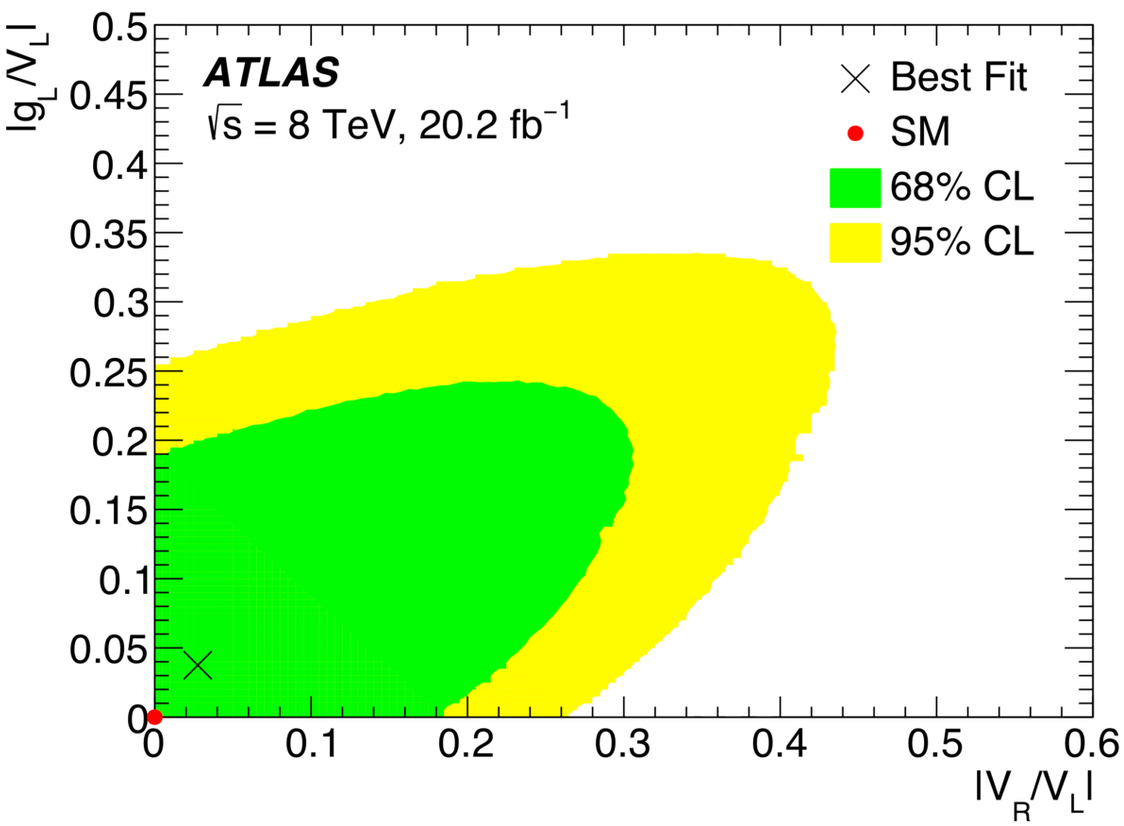
In agreement with SM predictions

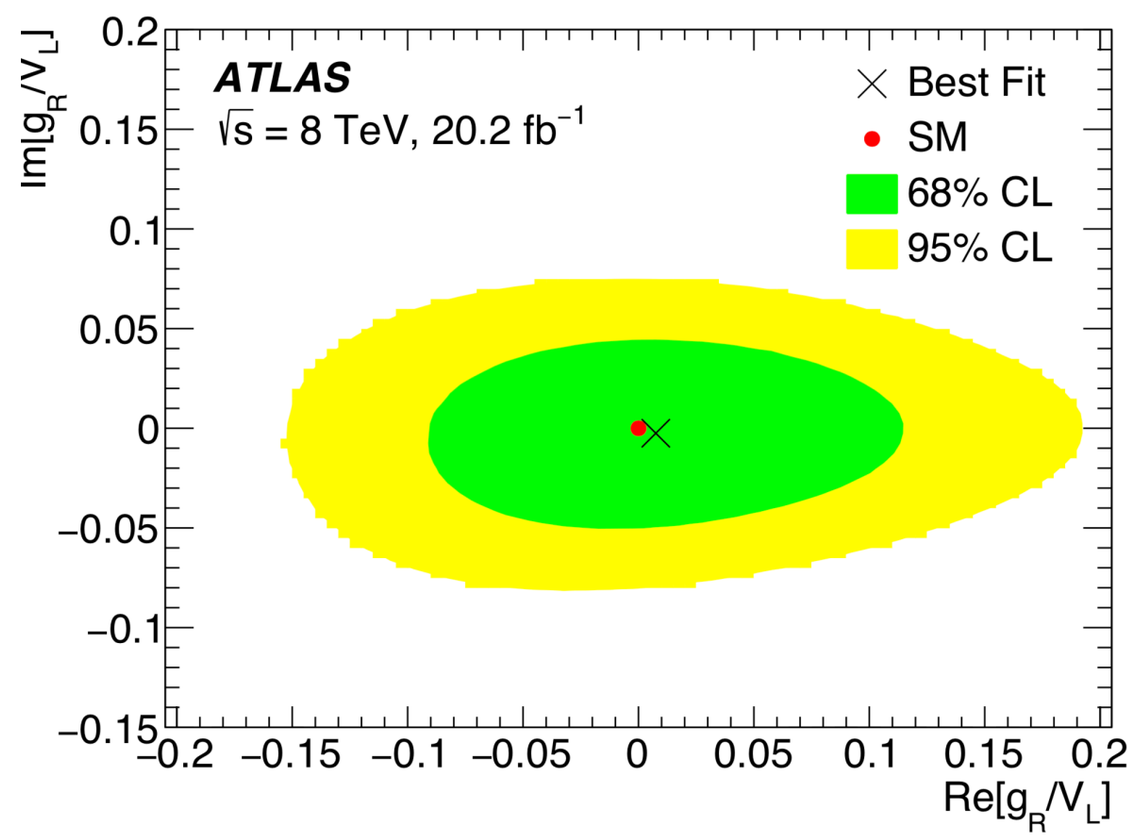
3-angle analysis

JHEP 1712 (2017) 017

Limits @95% C.L.:

- $|V_R/V_L| < 0.37$ $\quad |g_L/V_L| < 0.29$
  - tighter limits from $b \to s\gamma$ and W helicity with assumptions on other parameters
- $\mathrm{Re}[g_R]/V_L \in [-0.12, 0.17]$ $\quad \mathrm{Im}[g_R]/V_L \in [-0.07, 0.06]$





In agreement with SM predictions

conclusions

Wtb vertex carefully probed during Run I in top-quark production and decay

- BSM effects on Wtb vertex probed in the EFT framework

Left-handed vector coupling V_L extracted from single top-quark cross-sections

- most precise combination $\mathbf{|f_{LV}V_{tb}| = 0.998 \pm 0.041}$, Run I combination ongoing
- assumption: $V_R = g_L = g_R = 0$

Wtb anomalous couplings probed in W-helicity measurements

- assumption: 2 independent F, 4 (real) couplings

Wtb vertex probed through global fit (x-sec+helicity+asymmetries)

- ATLAS+CMS(+CDF+D0), quite general EFT approach
- **competitive constraints when V_L=1**

Wtb vertex tested via triple-differential angular decay rates

- most general approach, ability to separate F_0 into two components (f_0 and f_0^+)
- **no assumptions** on anomalous couplings

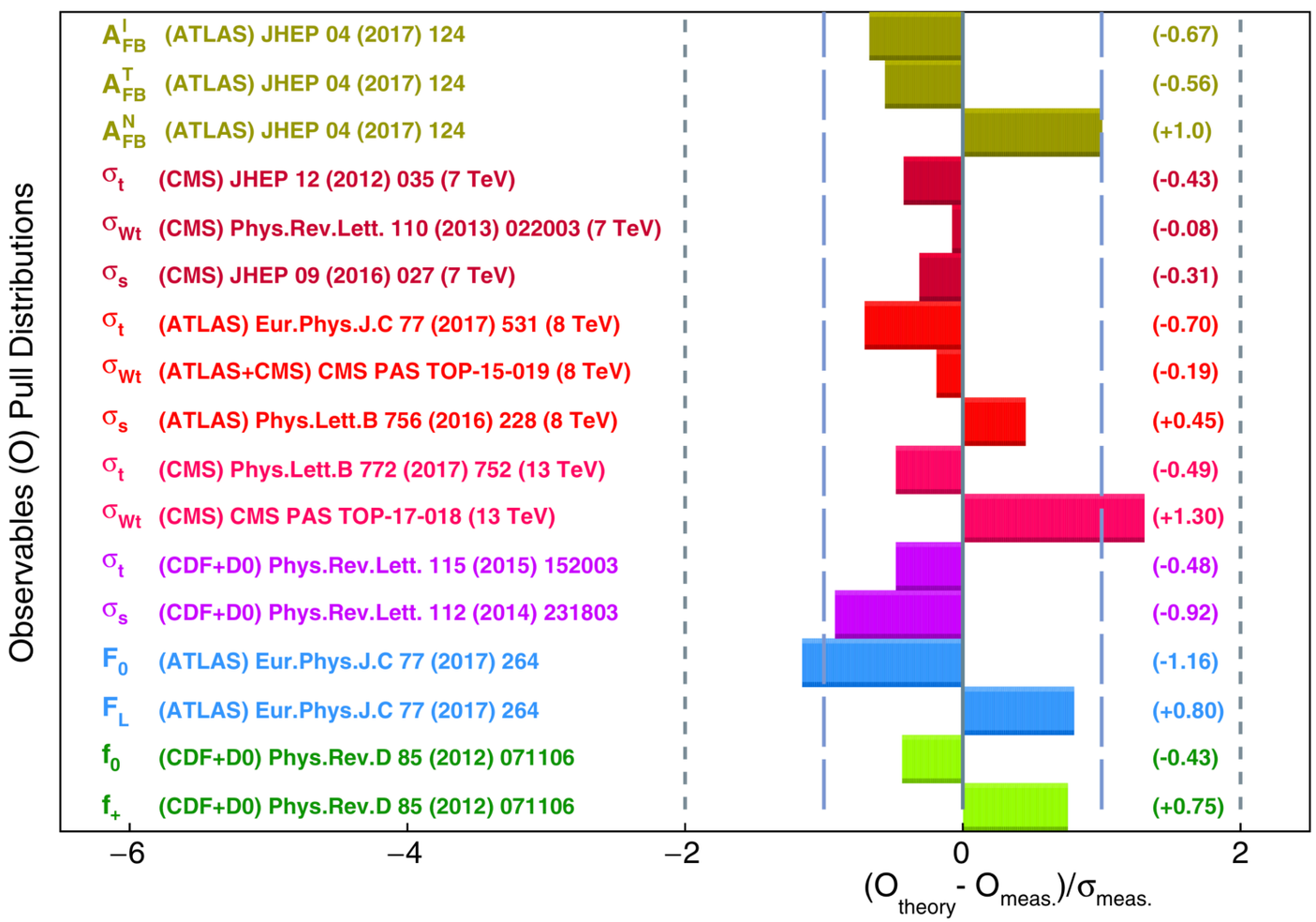
conclusions

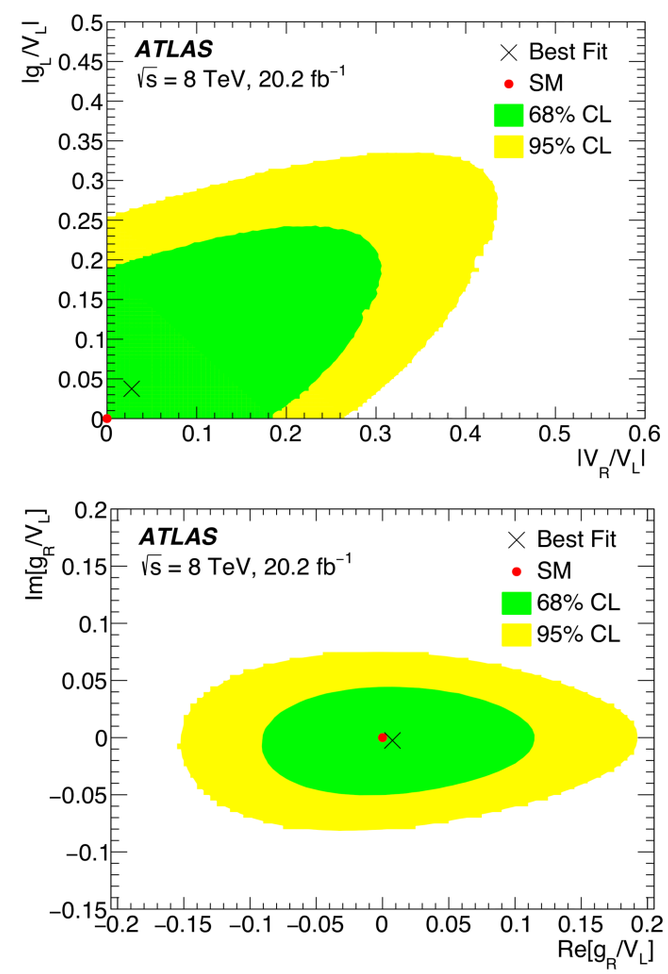
All measurements consistent with the SM predictions

- dominated by systematic uncertainties
- no sign of new physics BSM so far

Run II data being studied nowadays → even more interesting results soon!

Phys. Rev. D, 97, 013007 (2017)





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