Ideas for combinations of measurements constraining the Wtb vertex

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The Wtb vertex

Effective *Wtb* vertex from dim-6 operators

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

$V_L \equiv V_{tb} \sim 1$ (within SM)

$V_R, g_R, g_L \Rightarrow$ anomalous couplings

[EPJC50 (2007) 519, NPB804 (2008) 160, NPB812 (2009) 181]

How to probe anomalous couplings in the *Wtb* vertex?

- indirect limits from *B*-physics (☞ model dependent!)
- single *t* production: cross-section and angular distibutions
- $t\bar{t}$ production: angular distributions of *t* decays

The Wtb vertex

gauge-invariant effective operators

$$\mathcal{L} = \mathcal{L}_4 + \mathcal{L}_6 + \ldots$$

where

$\mathcal{L}_4 = \mathcal{L}_{\mathrm{SM}}$ ➜ SM Lagrangian

$\mathcal{L}_6 = \sum_x \frac{\alpha_x}{\Lambda^2} O_x$ ➜ O_x gauge-invariant building blocks

Parameterise effects of new physics at scale $\Lambda > v$

The following dim-6 operators are relevant to the Wtb vertex:

$$\delta V_L = \left(C_{\phi q}^{(3)*} + \frac{g}{2} \mathrm{Re}\, C_{qW} \right) \frac{v^2}{\Lambda^2} \,, \qquad \delta g_L = \sqrt{2} C_{dW}^{*} \frac{v^2}{\Lambda^2} \,,$$

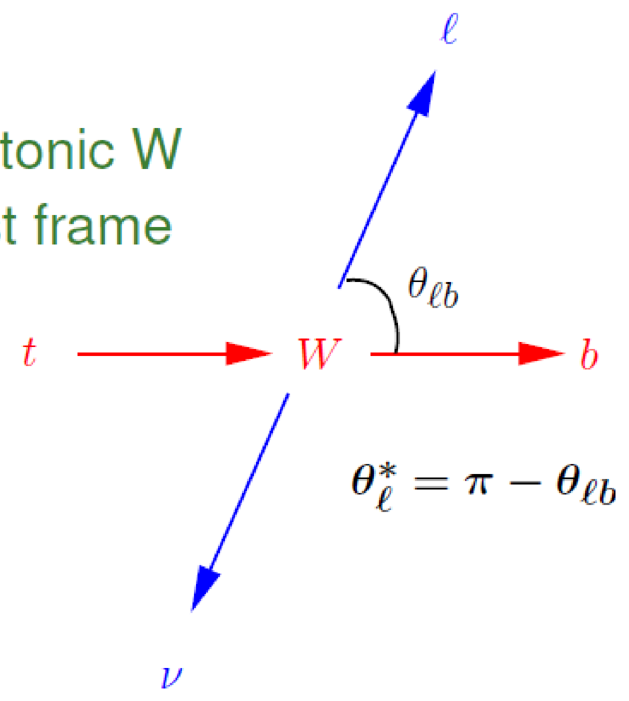
$$\delta V_R = \frac{1}{2} C_{\phi\phi}^{*} \frac{v^2}{\Lambda^2} \,, \qquad \delta g_R = \sqrt{2} C_{uW} \frac{v^2}{\Lambda^2} \,,$$

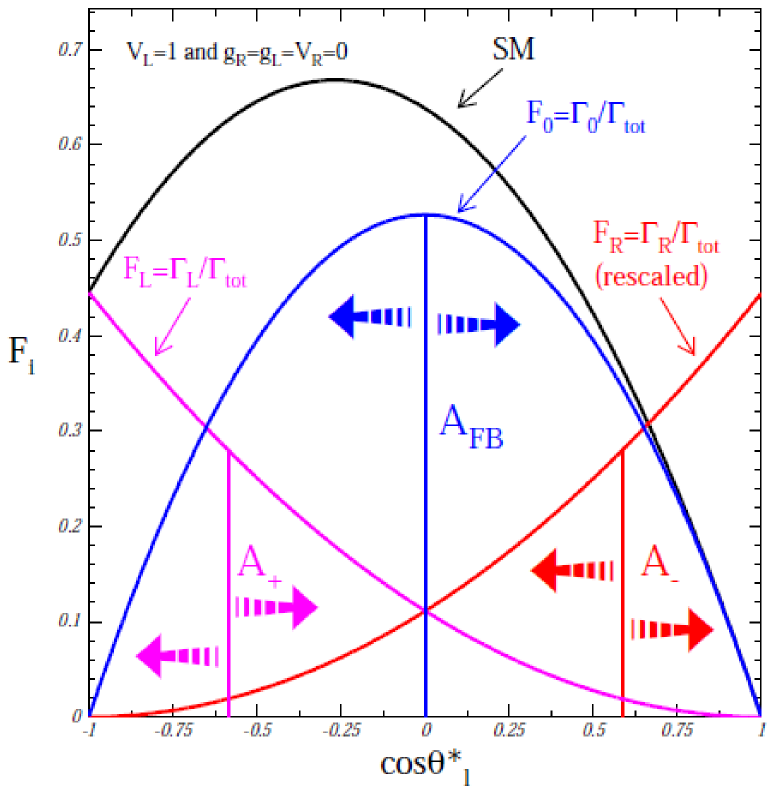
[Nucl.Phys.B 812 (2009) 181]

W polarization and the Wtb vertex

$$\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}\cos\theta_\ell^*} = \frac{3}{2}\left[F_0\left(\frac{\sin\theta_\ell^*}{\sqrt{2}}\right)^2 + F_L\left(\frac{1-\cos\theta_\ell^*}{2}\right)^2 + F_R\left(\frac{1+\cos\theta_\ell^*}{2}\right)^2\right]$$

leptonic W rest frame



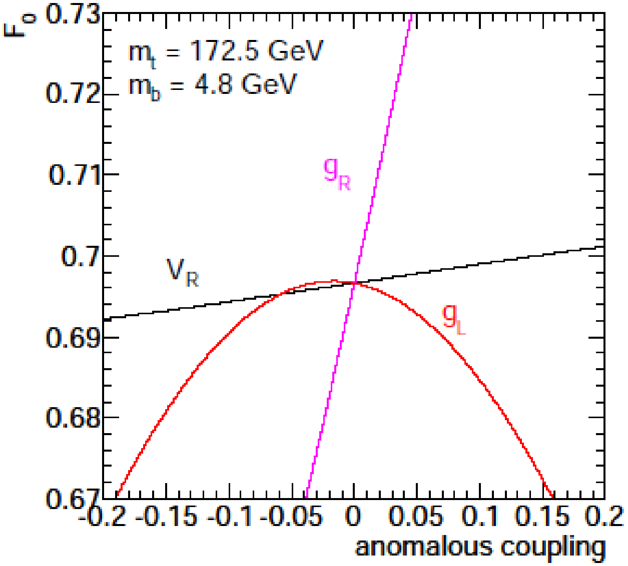


W polarization and the Wtb vertex

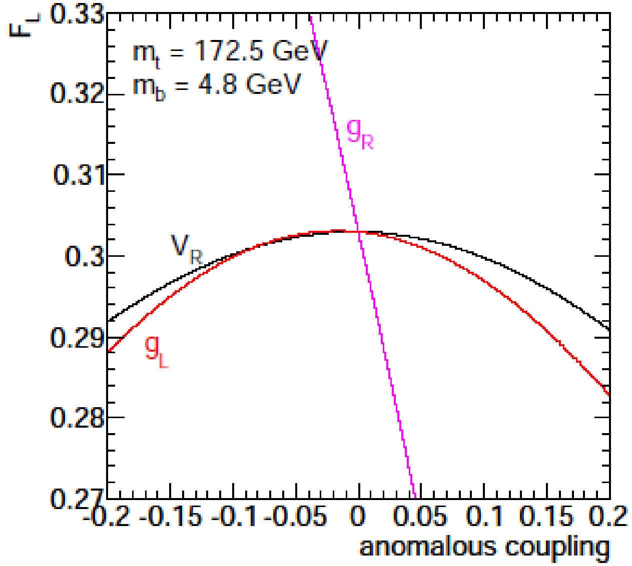
[EPJC50 (2007) 519]

anomalous couplings ⇒ deviations in *W* helicity fractions

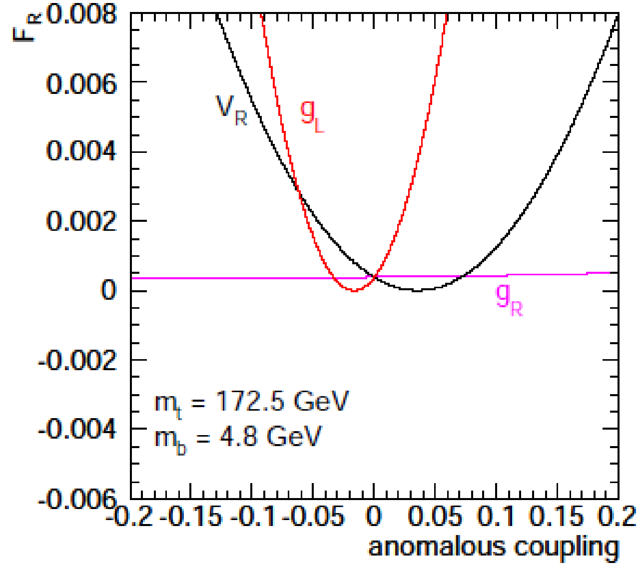
F_0



F_L



F_R



W polarization and the Wtb vertex

Measurement	F_0	F_L	F_R
ATLAS 2010 (single lepton) [Alj2010]	$0.652 \pm 0.134 \pm 0.092$	$0.359 \pm 0.088 \pm 0.056$	$-0.011 \pm 0.060 \pm 0.046$
ATLAS 2011 (single lepton) [Alj2011]	$0.642 \pm 0.030 \pm 0.071$	$0.344 \pm 0.020 \pm 0.042$	$0.014 \pm 0.014 \pm 0.055$
ATLAS 2011 (dilepton) [Adil2011]	$0.744 \pm 0.050 \pm 0.087$	$0.276 \pm 0.031 \pm 0.051$	$-0.020 \pm 0.026 \pm 0.065$
CMS 2011 (single lepton) [Clj2011]	$0.567 \pm 0.074 \pm 0.048$	$0.393 \pm 0.045 \pm 0.024$	$0.040 \pm 0.035 \pm 0.043$

TOPLHC NOTE

ATLAS-CONF-2013-033
CMS PAS TOP-12-025

March 13, 2013

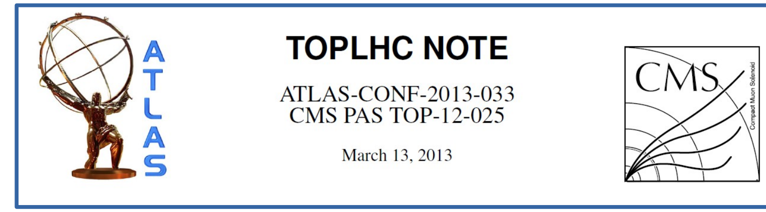
BLUE combination:

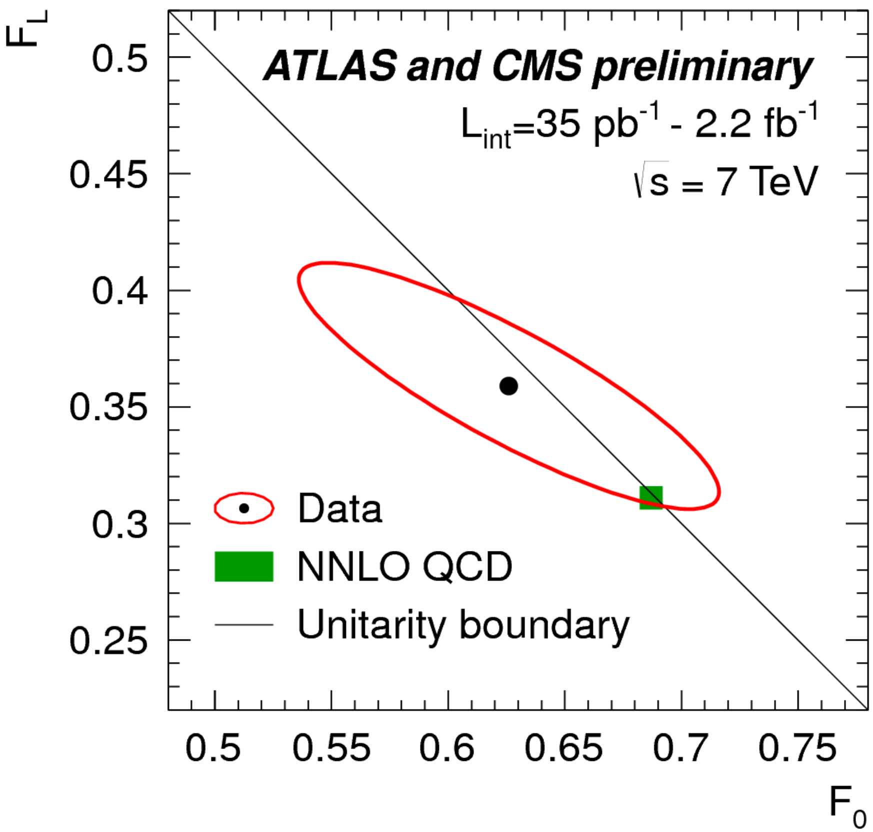
Measurement	Fraction	Alj2010 F_0	Alj2011 F_0	Adil2011 F_0	Clj2011 F_0
Alj2010	F_0	$+1$	$\rho_{exp}(F_0, F_0)$	$\rho_{exp}(F_0, F_0)$	$\rho_{LHC}(F_0, F_0)$
Alj2011	F_0	$\rho_{exp}(F_0, F_0)$	$+1$	$\rho_{exp}(F_0, F_0)$	$\rho_{LHC}(F_0, F_0)$
Adil2011	F_0	$\rho_{exp}(F_0, F_0)$	$\rho_{exp}(F_0, F_0)$	$+1$	$\rho_{LHC}(F_0, F_0)$
Clj2011	F_0	$\rho_{LHC}(F_0, F_0)$	$\rho_{LHC}(F_0, F_0)$	$\rho_{LHC}(F_0, F_0)$	$+1$
Alj2010	F_L	$\rho_{ATLAS}(F_0, F_L)$	$-\rho_{exp}(F_0, F_0)$	$-\rho_{exp}(F_0, F_0)$	$-\rho_{LHC}(F_0, F_0)$
Alj2011	F_L	$-\rho_{exp}(F_0, F_0)$	$\rho_{ATLAS}(F_0, F_L)$	$-\rho_{exp}(F_0, F_0)$	$-\rho_{LHC}(F_0, F_0)$
Adil2011	F_L	$-\rho_{exp}(F_0, F_0)$	$-\rho_{exp}(F_0, F_0)$	$\rho_{ATLAS}(F_0, F_L)$	$-\rho_{LHC}(F_0, F_0)$
Clj2011	F_L	$-\rho_{LHC}(F_0, F_0)$	$-\rho_{LHC}(F_0, F_0)$	$-\rho_{LHC}(F_0, F_0)$	$\rho_{CMS}(F_0, F_L)$

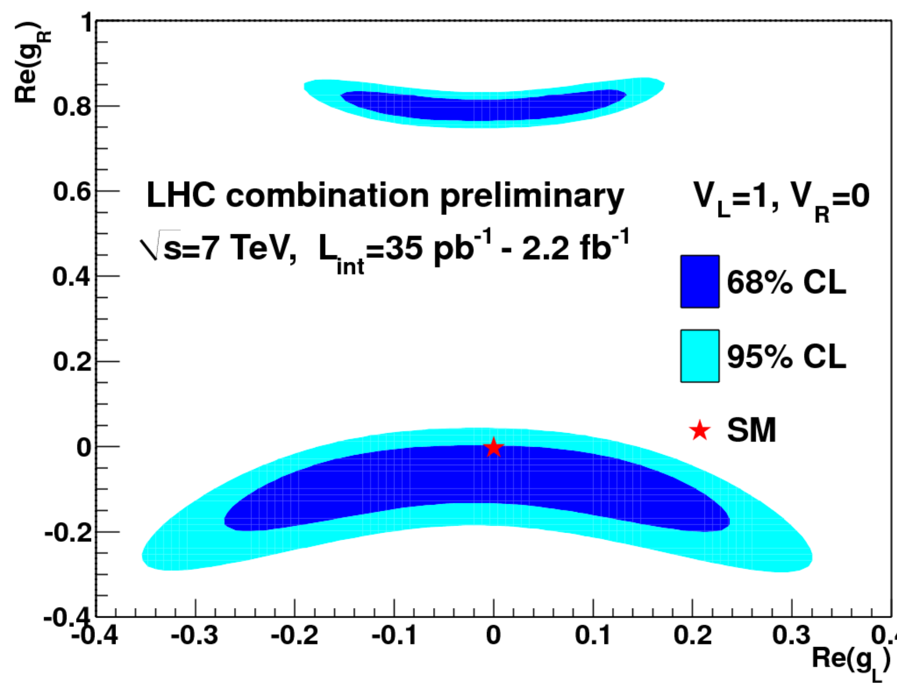
Measurement	Coefficient [%] w_{F_0}	w_{F_L}
F_0 ATLAS 2010 (single lepton)	12.2	7.4
F_L ATLAS 2010 (single lepton)	19.0	11.6
F_0 ATLAS 2011 (single lepton)	39.5	- 8.4
F_L ATLAS 2011 (single lepton)	-16.0	35.4
F_0 ATLAS 2011 (dilepton)	13.0	2.8
F_L ATLAS 2011 (dilepton)	4.9	15.2
F_0 CMS 2011 (single lepton)	35.4	- 1.8
F_L CMS 2011 (single lepton)	- 7.9	37.8
Total weight:	100.0	100.0

Category	LHC combination F_0	F_L
Detector modeling		
Detector model	0.019	0.011
Jet energy scale	0.020	0.012
Luminosity and pile-up	0.006	0.003
Signal and background modeling		
Monte Carlo	0.012	0.008
Radiation	0.024	0.012
Top-quark mass	0.019	0.012
PDF	0.008	0.004
Background (MC QCD)	0.003	0.001
Background (MC W + jets)	0.007	0.002
Background (MC other)	0.011	0.006
Background (data-driven)	0.013	0.008
Method-specific uncertainties		
Method	0.008	0.005
Total uncertainties		
Total systematic uncertainty	0.048	0.028
Statistical uncertainty	0.034	0.021
Total uncertainty	0.059	0.035

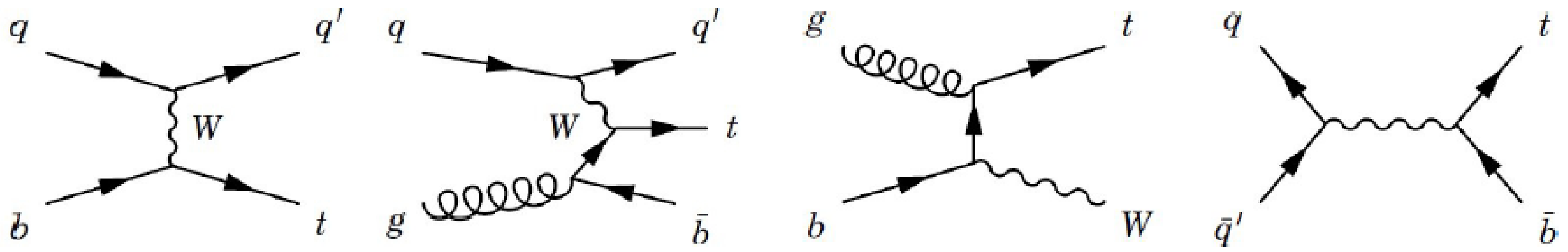
W polarization and the Wtb vertex







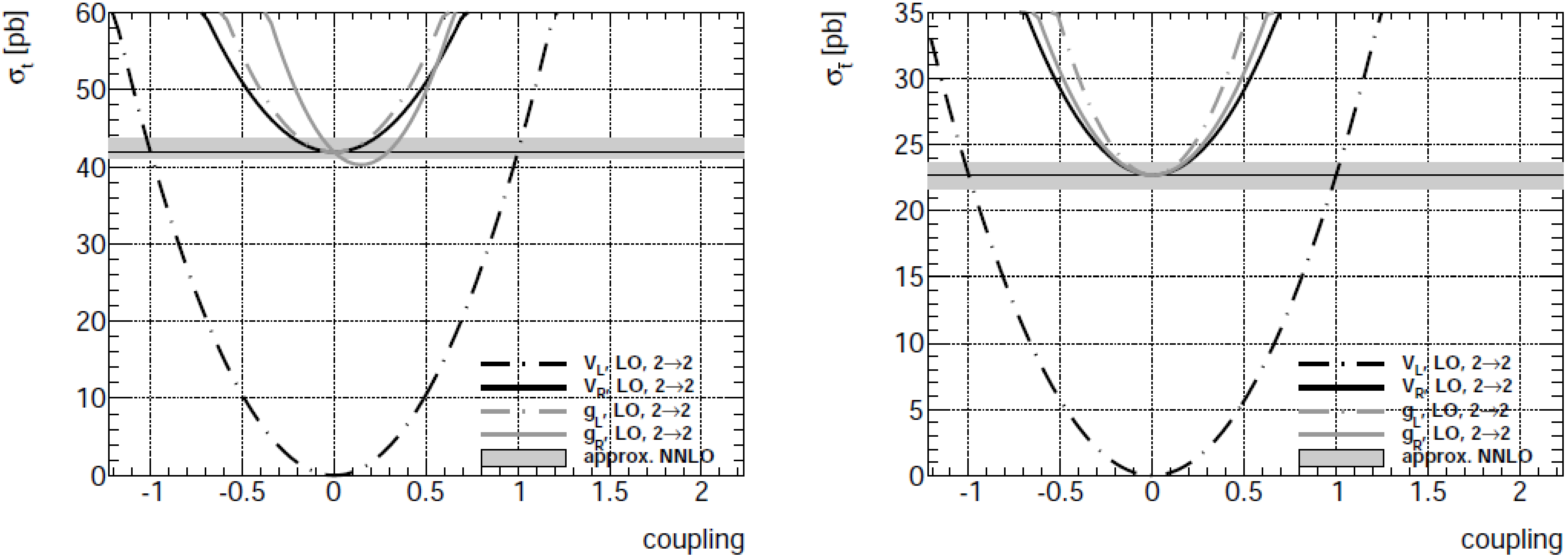
Single top production cross-section



$$\sigma = \sigma_{\mathrm{SM}} \left(V_L^2 + \kappa^{V_R} V_R^2 + \kappa^{V_L V_R} V_L V_R + \kappa^{g_L} g_L^2 + \kappa^{g_R} g_R^2 + \kappa^{g_L g_R} g_L g_R + \ldots \right)$$

- the κ factors determine the dependence on anomalous couplings
- the presence of anomalous couplings affect not only the cross-section but the event kinematics (effect on the signal efficiency which has to be determined at the analysis level)

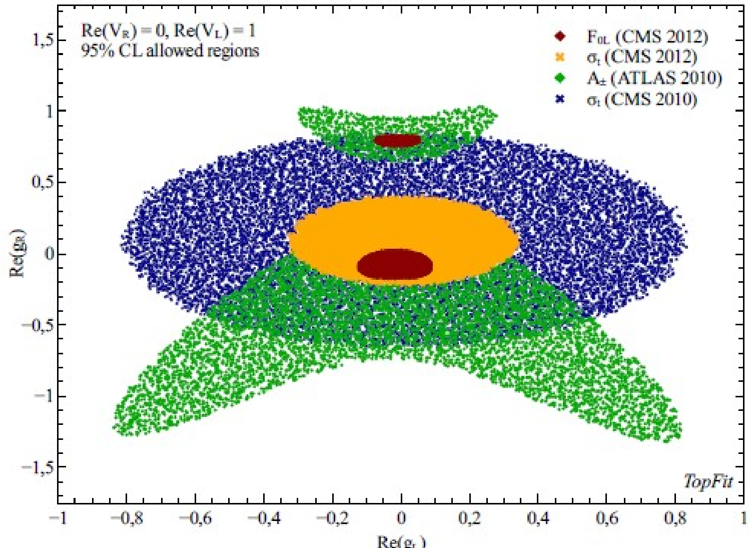
Single top production cross-section

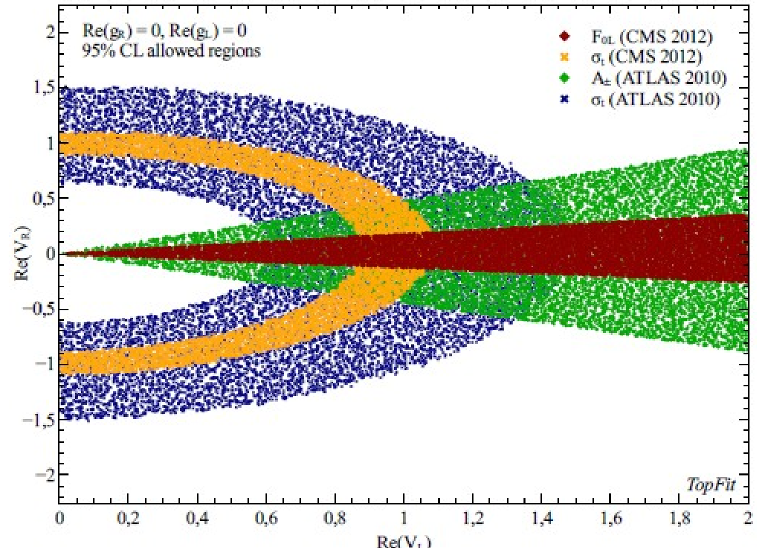


[Nils Rosien, MSc. thesis]

- Notice the difference in the dependence of g_R for top and anti-top production

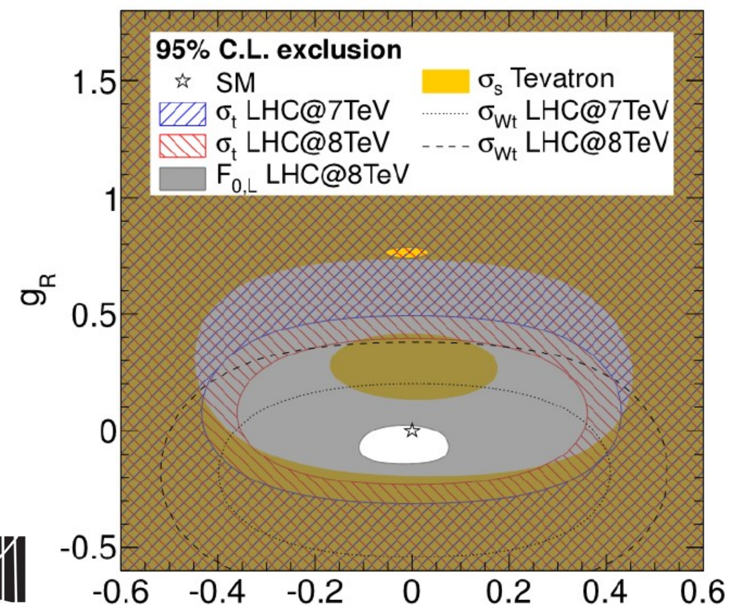
Single top production cross-section

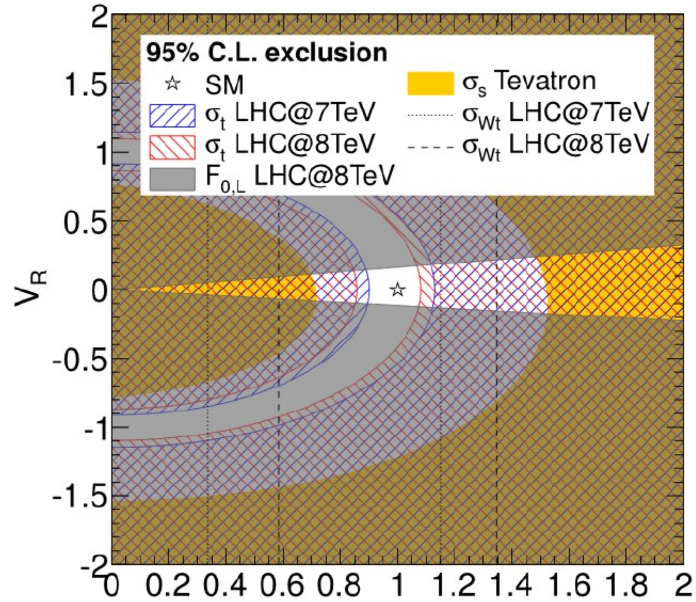




Phys.Rev. D90 (2014) 11, 113007

- Interpretations done outside the collaborations with the published information
- Very useful to know what to expect but a detailed study of the correlations can't be done





g_L Eur.Phys.J. C74 (2014) 12 V_L

Combining results at the observable level

- The Best Linear Unbiased Estimator (BLUE) method:
  - The combined result is a linear combination of the individual measurements
  - The combined result is unbiased
  - The combined result has a minimum variance

$$\hat{y} = \sum_i \alpha_i y_i$$

[NIM 270 1 (1988) 110]

  - Minimize $\sum_i \sum_j (y' - y_i) E^{-1}_{ij} (y' - y_j)$

error matrix

  - Full covariance matrix needed [Eur. Phys. J. C, 74 (2014) 2717]

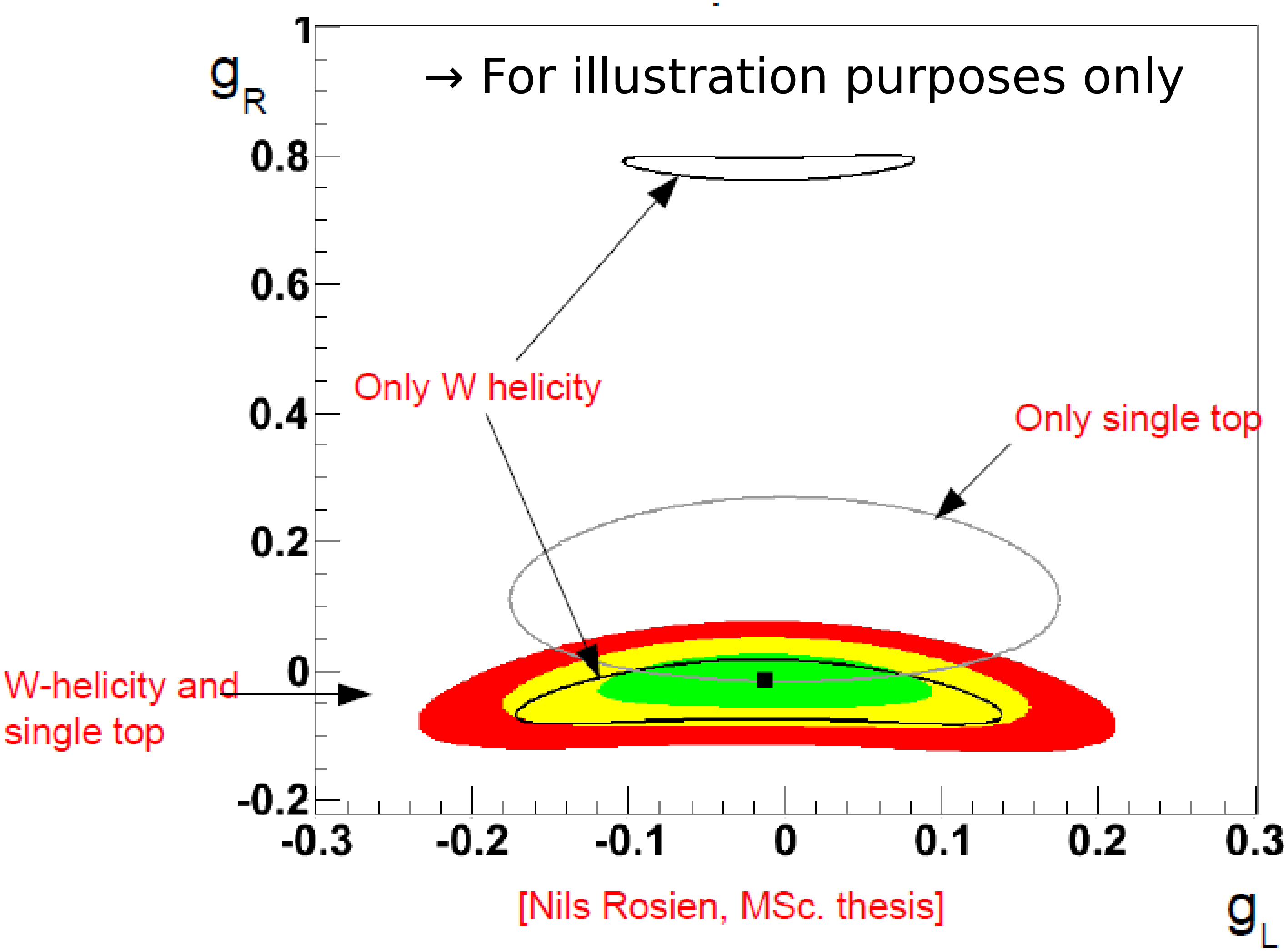
- In the present case, what we want is not a combined measurement (e.g. if the individual measurements are the W helicity fractions and the single top production cross-section) but rather the combined contraints on the anomalous Wtb couplings

$$y' = F(V_L, V_R, g_L, r_R)$$

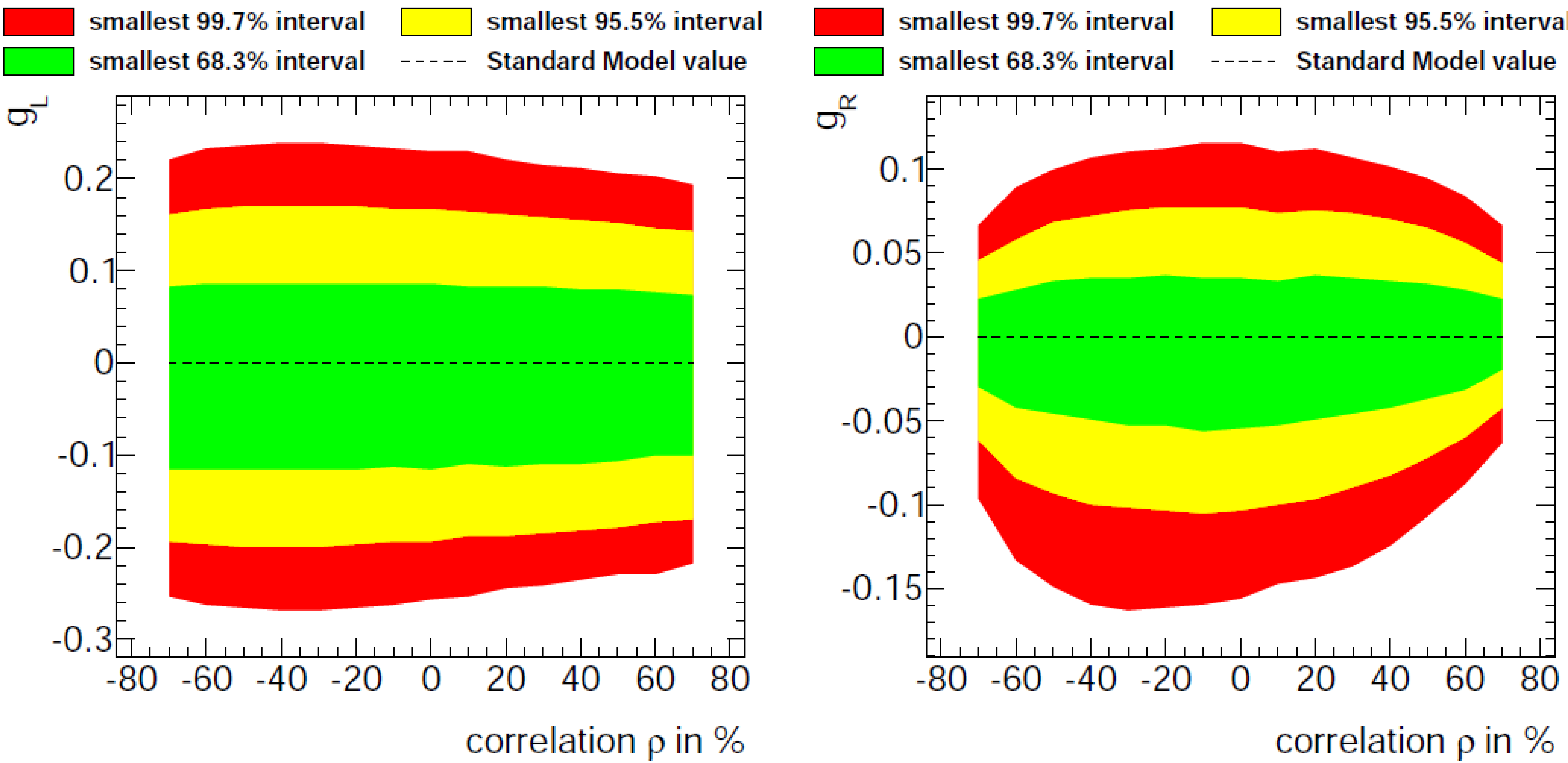
LIP

Combining results at the observable level

- It's crucial to apply the efficiency corrections when interpreting the measurements
- ***EFTfitter*** (developed by Kevin Kroeninger) can be used:



Combining results at the observable level



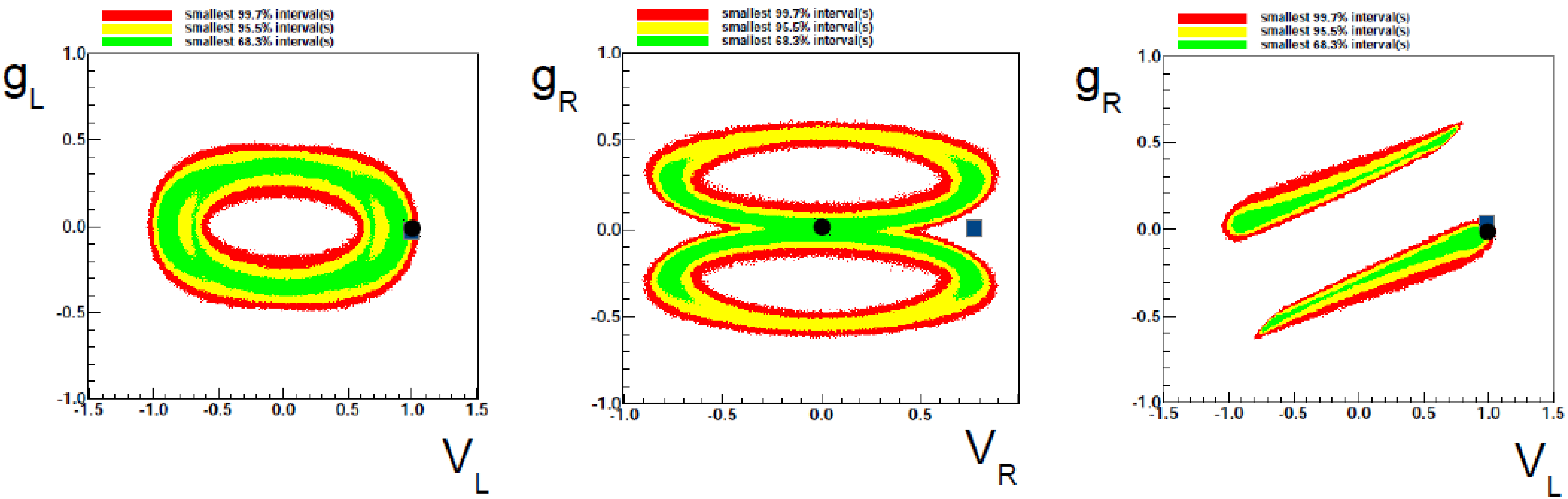
→ For illustration purposes only

[Nils Rosien, MSc. thesis]

	σ_t	$\sigma_{\bar{t}}$
F_0	ρ	ρ
F_L	$-\rho$	$-\rho$

Combining results at the observable level

Allowing all the (real part of the) anomalous couplings to vary simultaneously:



[Nils Rosien, MSc. thesis]

● Standard Model

■ This could be your favorite BSM model!

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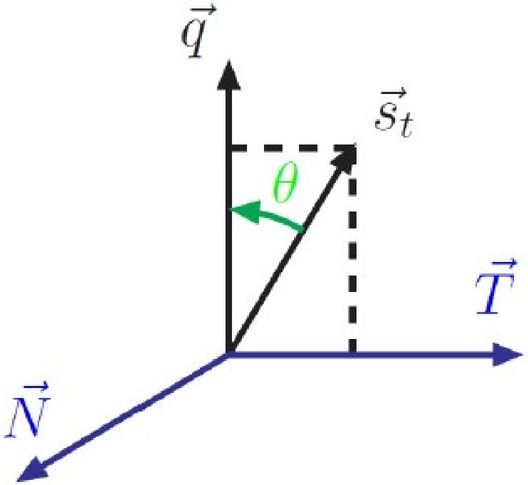
Accessing the imaginary part of the couplings

[NPB840 (2010) 349]

☞ consider transverse and normal directions



$\vec{q}$ → W mom in t rest frame

$\vec{s}_t$ → top spin

$$\vec{N} = \vec{s}_t \times \vec{q}$$

$$\vec{T} = \vec{q} \times \vec{N}$$

meaningful for polarised t decays

(e.g. in single top production)

θ_ℓ^* → angle between ℓ, $\vec{q}$

determine F_+, F_0, F_-

θ_ℓ^T → angle between ℓ, $\vec{T}$

determine F_+^T, F_0^T, F_-^T

θ_ℓ^N → angle between ℓ, $\vec{N}$

determine F_+^N, F_0^N, F_-^N

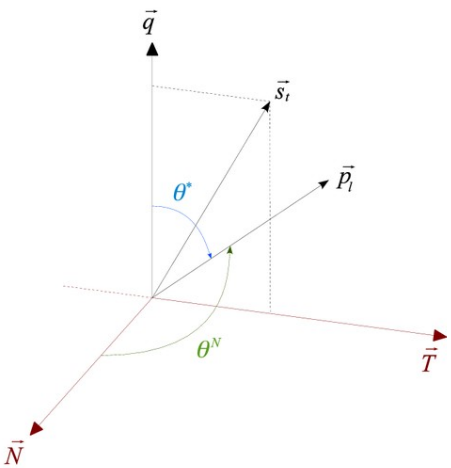
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_\ell^X} = \frac{3}{8}(1+\cos\theta_\ell^X)^2 F_+^X + \frac{3}{8}(1-\cos\theta_\ell^X)^2 F_-^X + \frac{3}{4}\sin^2\theta_\ell^X F_0^X$$

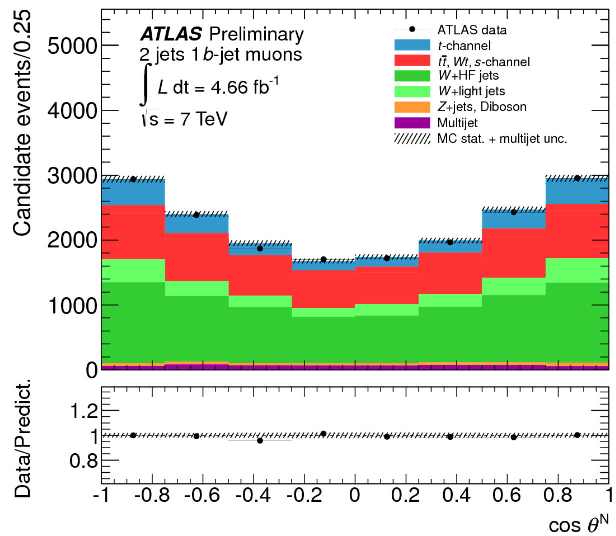
$$A_{\mathrm{FB}}^N = \frac{3}{4}\left[F_+^N - F_-^N\right]$$

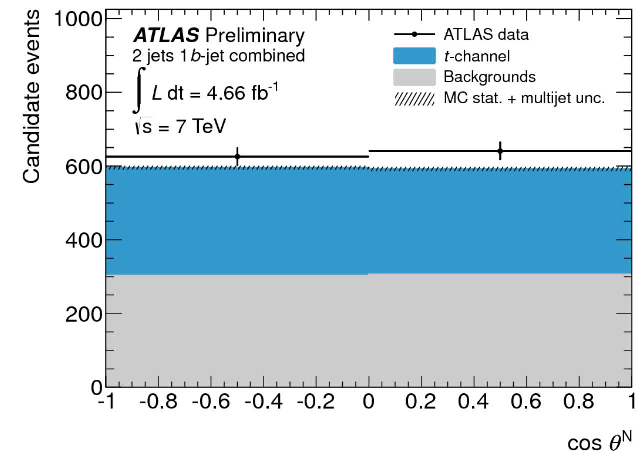
$$A_{\mathrm{FB}}^N \simeq 0.64\, P\, \mathrm{Im}\, g_R$$

Accessing the imaginary part of the couplings

ATLAS-CONF-2013-032

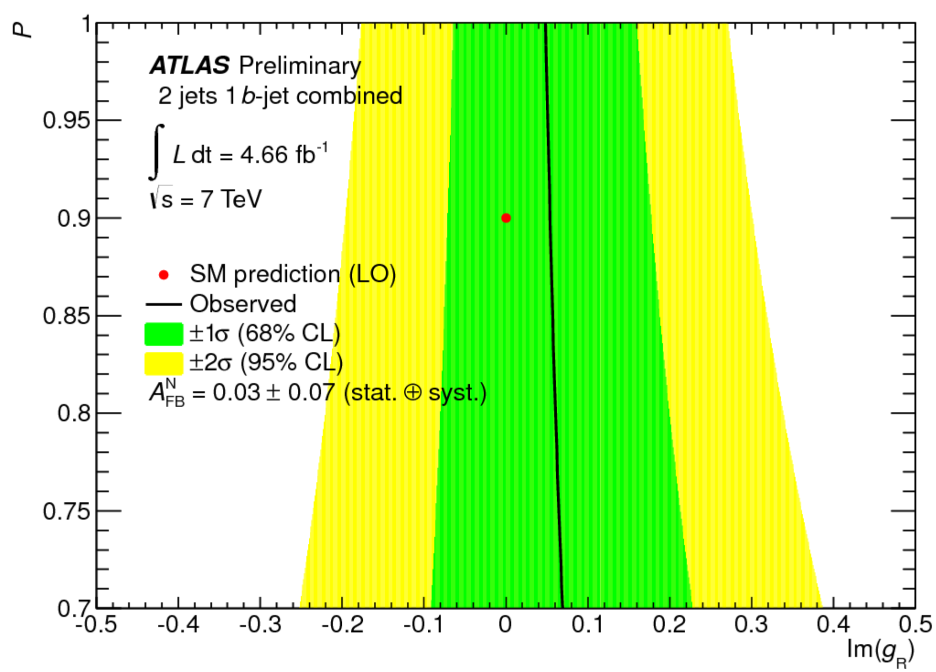




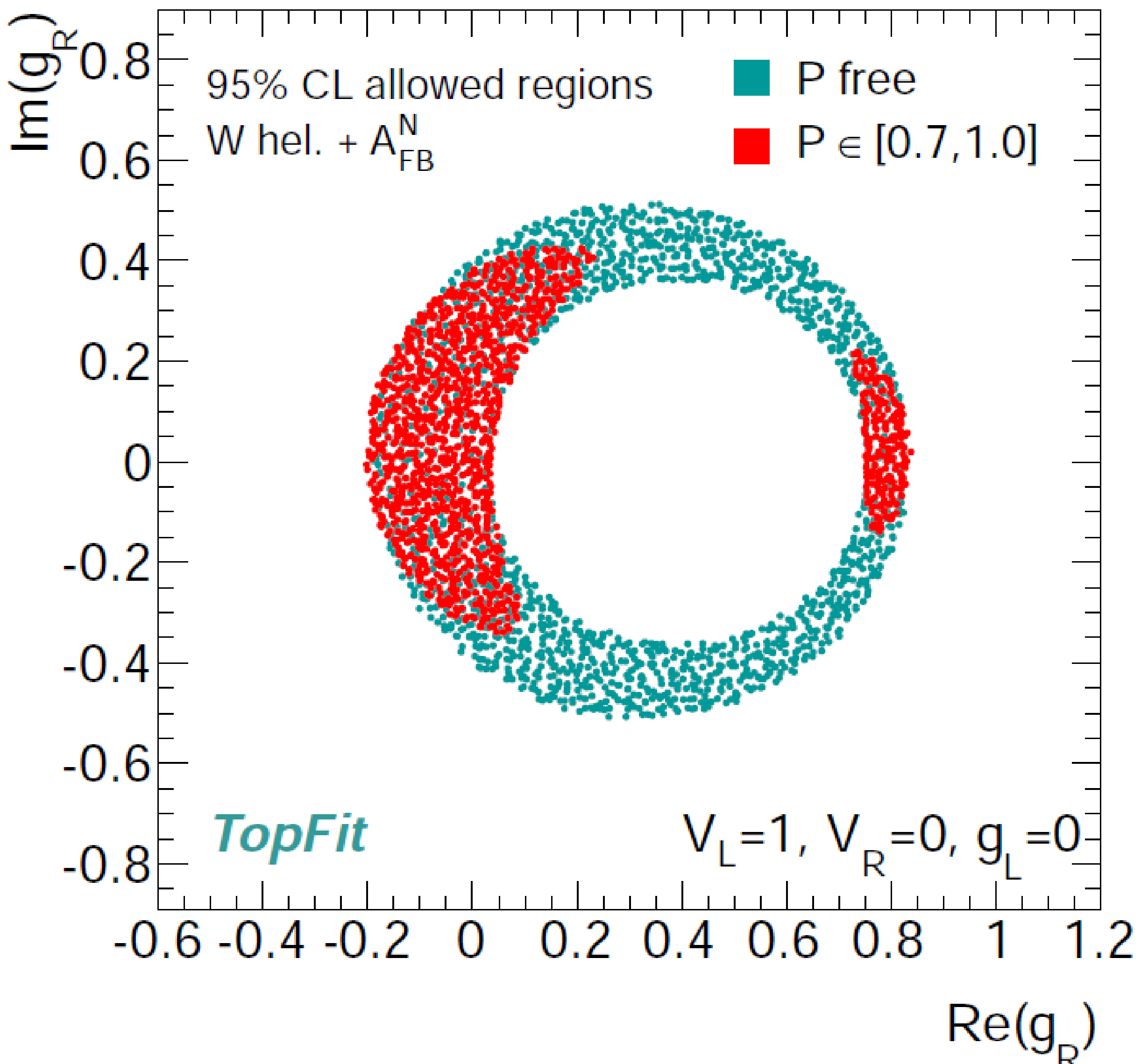


$$A_z \equiv \frac{N_{\rm evt}(\cos\theta > z) - N_{\rm evt}(\cos\theta < z)}{N_{\rm evt}(\cos\theta > z) + N_{\rm evt}(\cos\theta < z)}$$

$$A_{\rm FB}^N \simeq 0.64\, P\, {\rm Im}\, g_R$$



Accessing the imaginary part of the couplings



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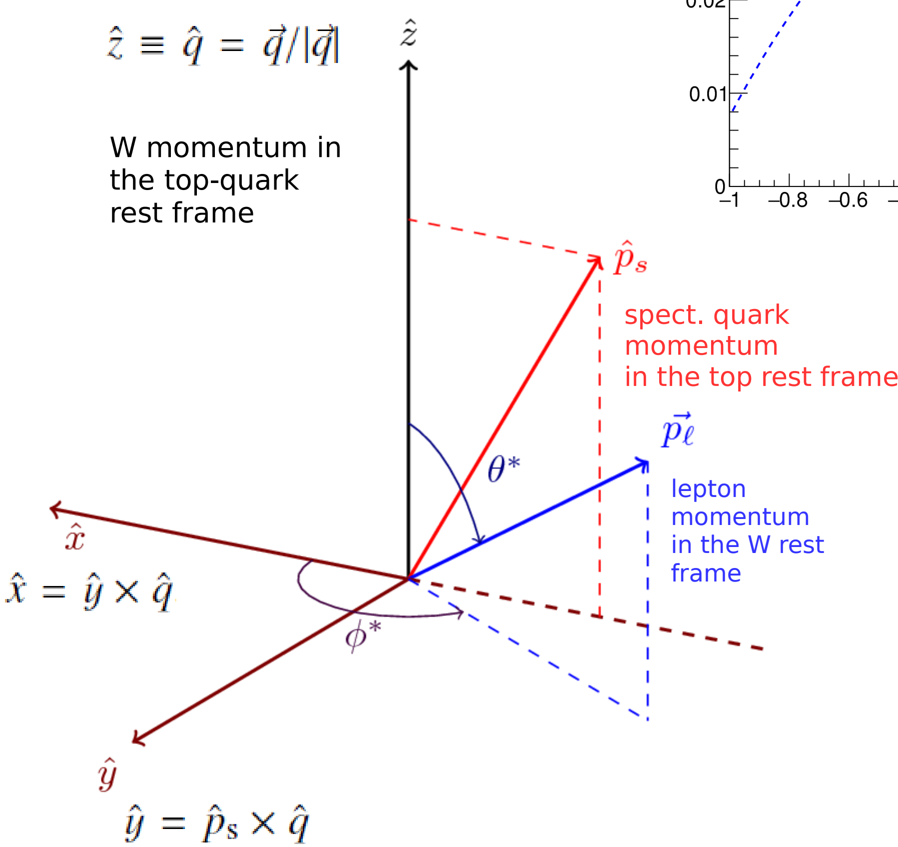
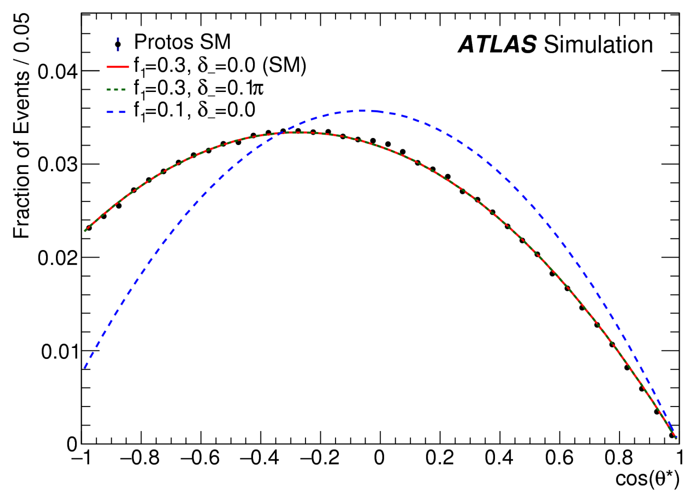
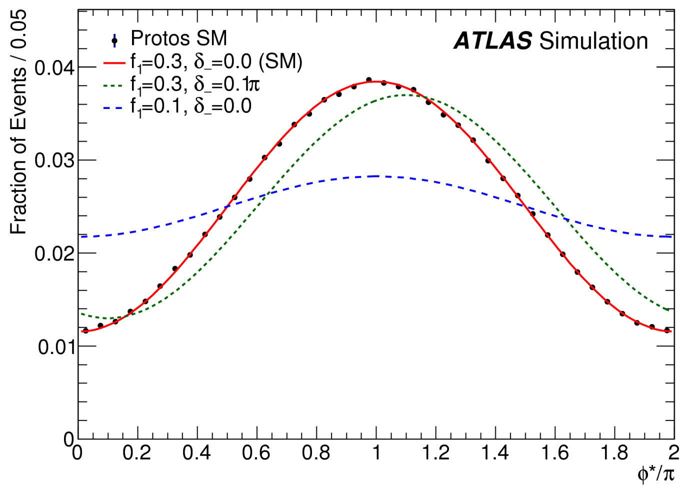
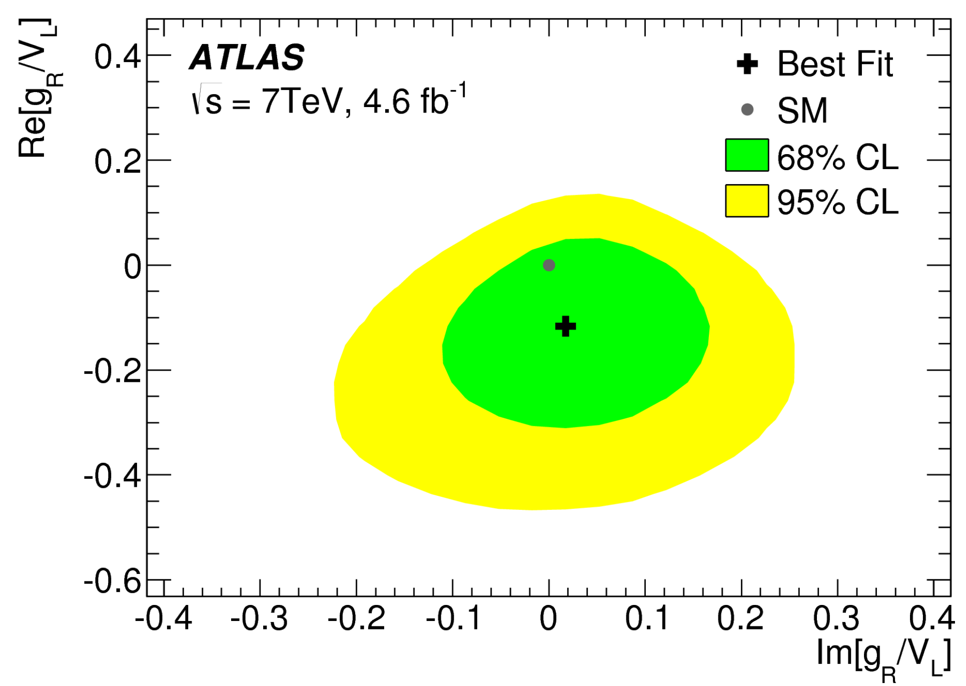
Accessing the imaginary part of the couplings

[arXiv:1510.03764]









Accessing the imaginary part of the couplings

[arXiv:1511.02138]

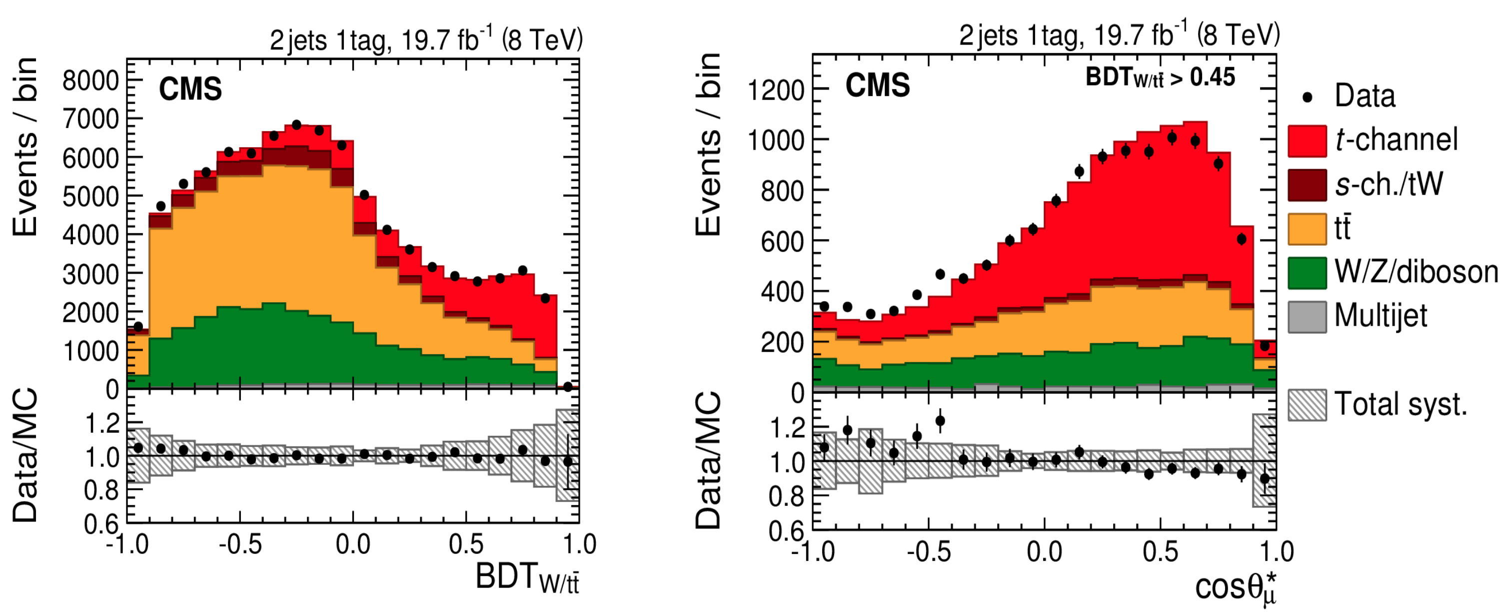
$$A_X \equiv \frac{1}{2} P_t \, \alpha_X = \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)}$$

$N(\uparrow)$ and $N(\downarrow)$ → defined, for each top ($t \to bW \to b\mu\nu$) as the number of times each decay product (μ) is aligned (or antialigned) w.r.t. the direction of the recoiling spectator quark

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_X^*} = \frac{1}{2}\left(1 + P_t^{(\vec{s})} \alpha_X \cos\theta_X^*\right) = \left(\frac{1}{2} + A_X \cos\theta_X^*\right)$$

t polarization

→ Polarization axis: defined along the untagged jet in the top rest frame



Accessing the imaginary part of the couplings

[arXiv:1511.02138]

injecting anomalous Wtb-vertex coupling events as pseudo-data

	$\delta A_\mu(\text{t})/10^{-2}$	$\delta A_\mu(\bar{\text{t}})/10^{-2}$	$\delta A_\mu(\text{t}+\bar{\text{t}})/10^{-2}$
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 $\not{E}_T$	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
$t\bar{t}$ renorm./fact. scales	2.2	3.4	2.7
$t\bar{t}$ 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

$$A_\mu(\text{t}) = 0.29 \pm 0.03\,(\text{stat}) \pm 0.10\,(\text{syst}) = 0.29 \pm 0.11,$$
$$A_\mu(\bar{\text{t}}) = 0.21 \pm 0.05\,(\text{stat}) \pm 0.13\,(\text{syst}) = 0.21 \pm 0.14,$$
$$A_\mu(\text{t}+\bar{\text{t}}) = 0.26 \pm 0.03\,(\text{stat}) \pm 0.10\,(\text{syst}) = 0.26 \pm 0.11,$$

(0.44 expected in the SM)

$$p(\text{data}|\text{SM}) = 4.6\%$$

Some concluding remarks

- In order to go further on the (general) Wtb vertex study we need a combination of different observables between experiments. This requires additional information to be properly done:
  - Type of uncertainties: gaussian (this would make our life simpler...)
  - Categories of uncertainties (stat., JES, b-tagging, etc): same categories between measurements / experiments
  - Correlation between uncertainties: one needs to remember to save the information on the sign of uncertainties $(\pm)$
  - MC samples with anomalous couplings needed to access the impact on the eff * accept
    - It's crucial not to assume the SM Wtb vertex in the measurements (e.g. when doing the unfolding)
  - Shall we also start thinking about a combination of fiducial measurements affecting related to the Wtb vertex?

Going even further: towards a global fit in the top sector

Dataset	$\sqrt{s}$ (TeV)	Measurements
Top pair production		
ATLAS	7 + 8	Total inclusive σ
	7 + 8	Differential $p_T(t), M_{t\bar{t}}, \lvert y(t\bar{t})\rvert$
CMS	7	Differential $p_T(t), M_{t\bar{t}}, y(t), \lvert y(t\bar{t})\rvert$
CDF	1.96	Differential $M_{t\bar{t}}$
DØ	1.96	Differential $M_{t\bar{t}}, p_T(t), \lvert y(t)\rvert$
Single top production		
ATLAS t-channel	7	Total inclusive σ
	7	Differential $p_T(t), \lvert y(t)\rvert$
CMS t-channel	7	Total inclusive σ
	8	Total inclusive σ
CDF s-channel	1.96	Total inclusive σ
DØ $s+t$-channel	1.96	Total inclusive σ

[arXiv:1506.08845]

4-fermion operators		Non 4-fermion operators	
O^1_{qq}	$(\bar{q}\gamma_\mu q)(\bar{q}\gamma^\mu q)$	$O^3_{\phi q}$	$i(\phi^\dagger \tau^I D_\mu \phi)(\bar{q}\gamma^\mu \tau^I q)$
O^3_{qq}	$(\bar{q}\gamma_\mu \tau^I q)(\bar{q}\gamma^\mu \tau^I q)$	O_{tW}	$(\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi}W^I_{\mu\nu}$
O_{uu}	$(\bar{u}\gamma_\mu u)(\bar{u}\gamma^\mu u)$	O_{tG}	$(\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi}G^A_{\mu\nu}$
O^8_{qu}	$(\bar{q}\gamma_\mu T^A q)(\bar{u}\gamma^\mu T^A u)$	O_G	$f_{ABC}\, G^{A\nu}_{\mu} G^{B\lambda}_{\nu} G^{C\mu}_{\lambda}$
O^8_{qd}	$(\bar{q}\gamma_\mu T^A q)(\bar{d}\gamma^\mu T^A d)$	$O_{\tilde{G}}$	$f_{ABC}\, \tilde{G}^{A\nu}_{\mu} G^{B\lambda}_{\nu} G^{C\mu}_{\lambda}$
O^8_{ud}	$(\bar{u}\gamma_\mu T^A u)(\bar{d}\gamma^\mu T^A d)$	$O_{\phi G}$	$(\phi^\dagger\phi)G^A_{\mu\nu}G^{A\mu\nu}$
		$O_{\phi\tilde{G}}$	$(\phi^\dagger\phi)\tilde{G}^A_{\mu\nu}G^{A\mu\nu}$