Limits on anomalous Wtb couplings in single top-quark events in the CMS experiment

Georgii Vorotnikov

SINP MSU

on behalf of the CMS Collaboration

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Anomalous coupling in Wtb vertex

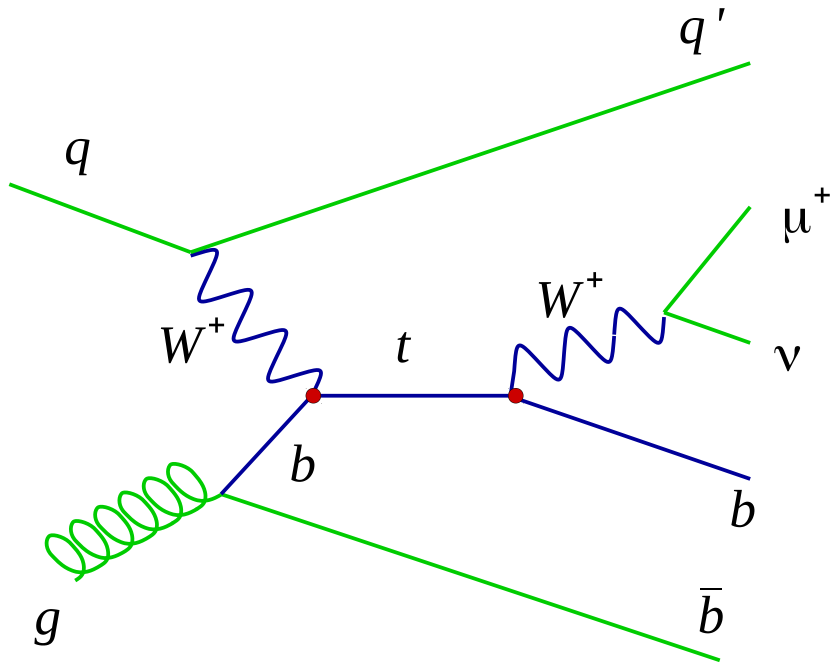
General form of the effective Wtb vertex lagrangian:

$$\mathfrak{L} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}\left(f_V^L P_L + f_V^R P_R\right) t W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}\partial_{\nu}W_{\mu}^{-}}{M_W}\left(f_T^L P_L + f_T^R P_R\right) t + h.c.$$

Where

f_V^L, f_V^R – Left and right vector couplings

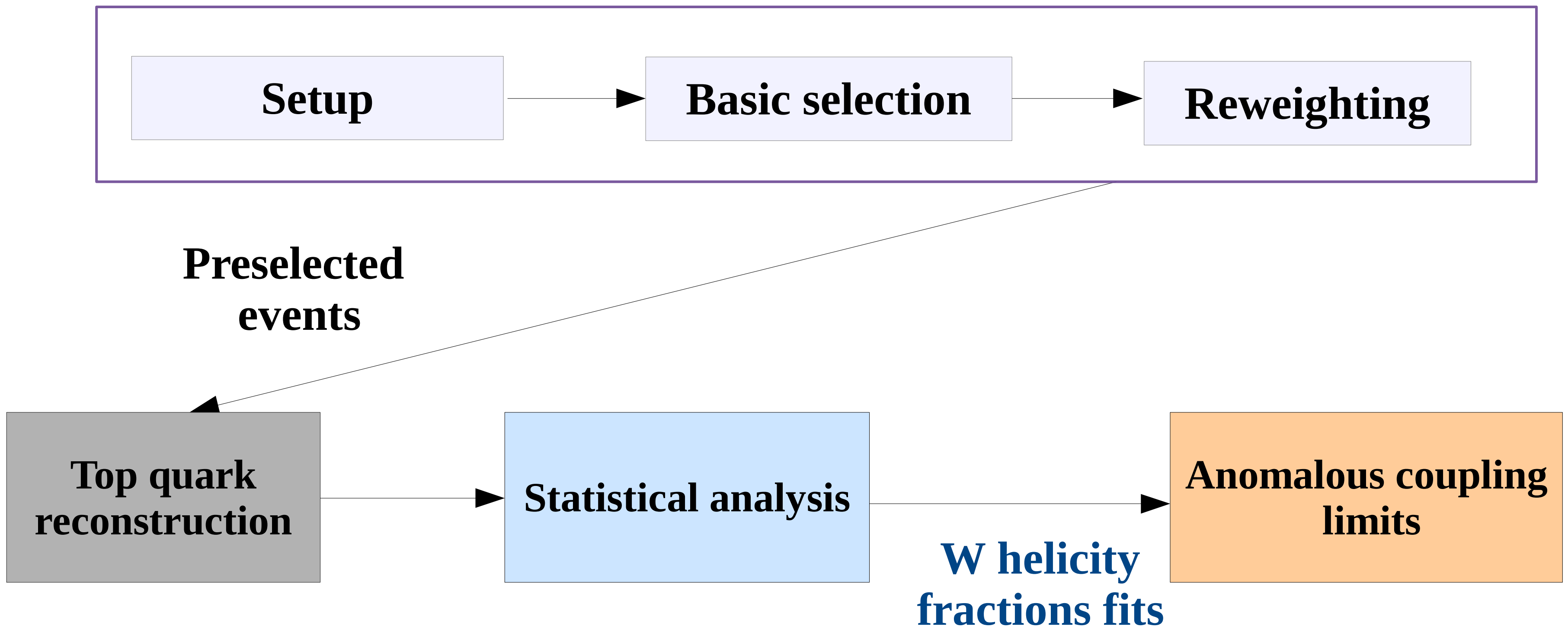
f_T^L, f_T^R – Left and right tensor couplings



SM values: $f_V^L = 1;$

$$f_V^R = f_T^L = f_T^R = 0$$

Measurement of the W boson helicity in events with a single reconstructed top quark in pp collisions at sqrt(s) = 8 TeV



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Analysis setup

Setup: Int. luminosity 19.7 /fb at $\sqrt{s}=8\,TeV$

MC Reweighting:

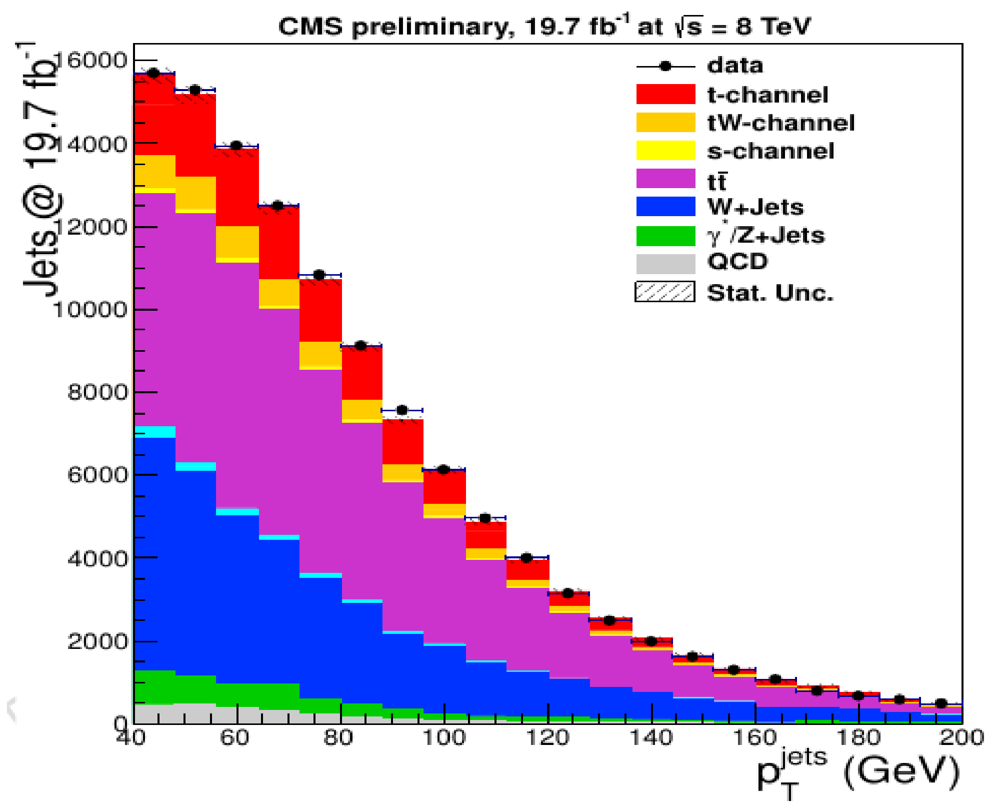
- **Pile-Up**
- **B-tag**
- **Triggers and lepton ID/Iso**

Selection:

- Objects definition and selection follows [CMS Top Group](#) recommendations;
- **e** and **μ channels**
- **Two jets** with **one b-tagged** and one untagged jet according to **TCHPT**
- ΔR(l,jet)>0.3 cut for jets
- m_T^W > 50 GeV/c

Triggers:

```
HLT_IsoEle27_v*
HLT_IsoMu24_eta2p1_v*
```



W boson helicity fractions

Expected distribution of the partial width of top quark decay:

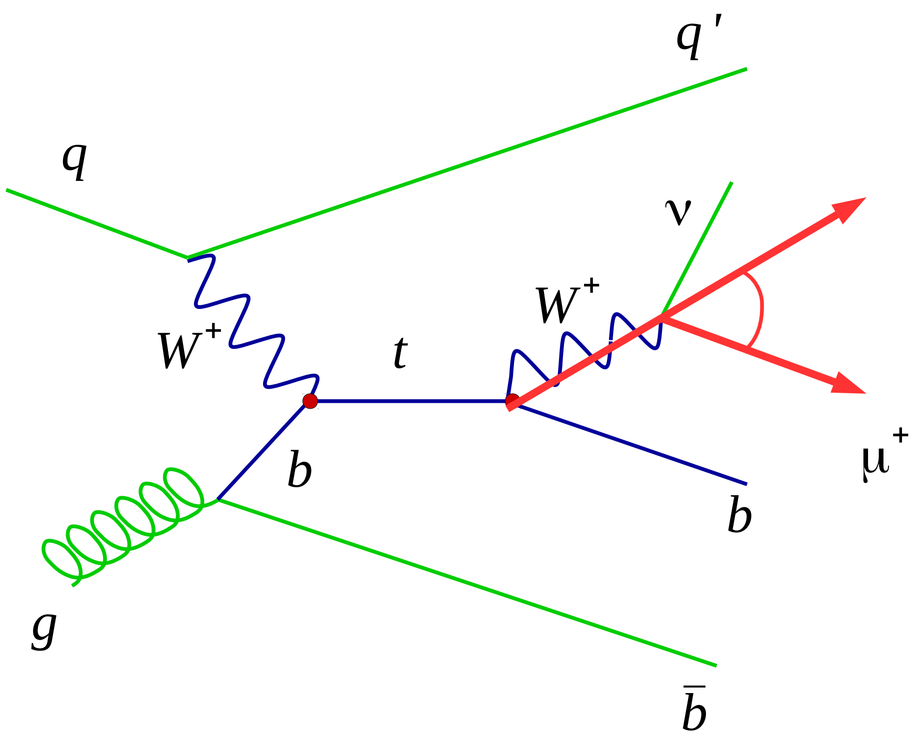
$$\rho(\cos\theta_l^*) \equiv \frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_l^*} = \frac{3}{8}(1-\cos\theta_l^*)^2 F_L + \frac{3}{8}(1+\cos\theta_l^*)^2 F_R + \frac{3}{4}\sin^2\theta_l^* F_0$$

Where

F_L, F_0, F_R – Left, longitudinal and right polarization fraction of the W-boson helicity

NNLO SM values:

$$F_L = 0.311 \pm 0.005,$$
$$F_0 = 0.687 \pm 0.005,$$
$$F_R = 0.0017 \pm 0.0001$$



θ_l^* – angle **in top quark rest frame** between the lepton 3-momentum in W-boson rest frame and the 3-momentum of W-boson

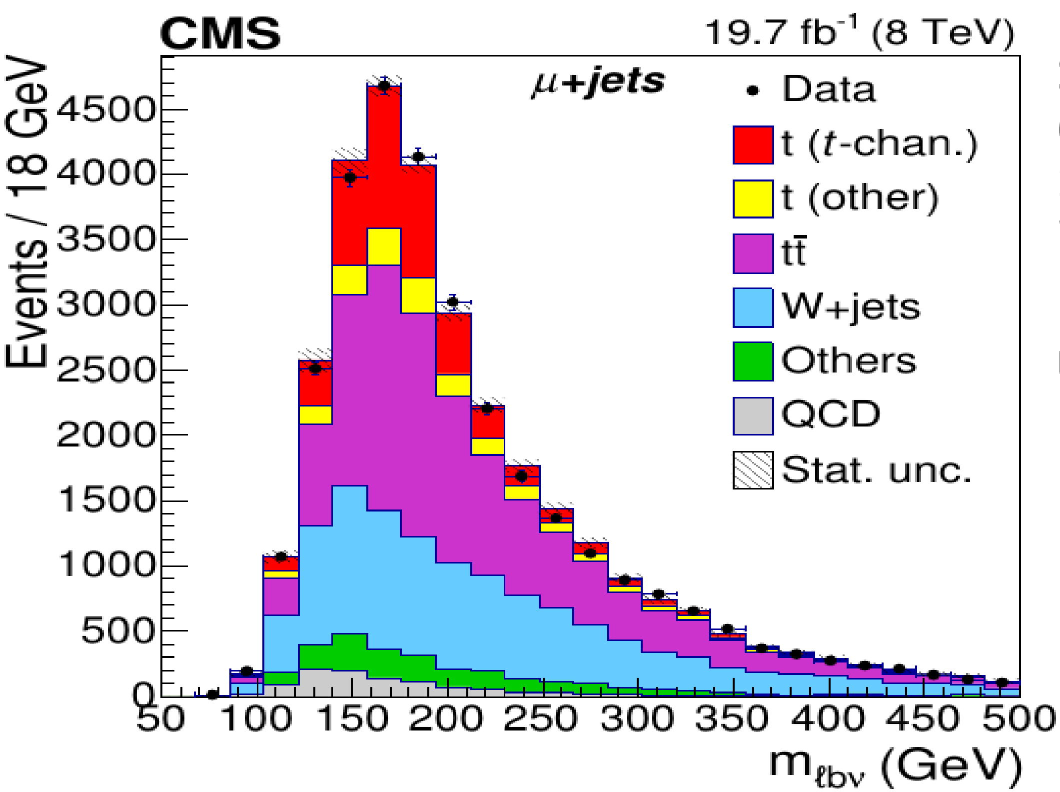
Top quark reconstruction

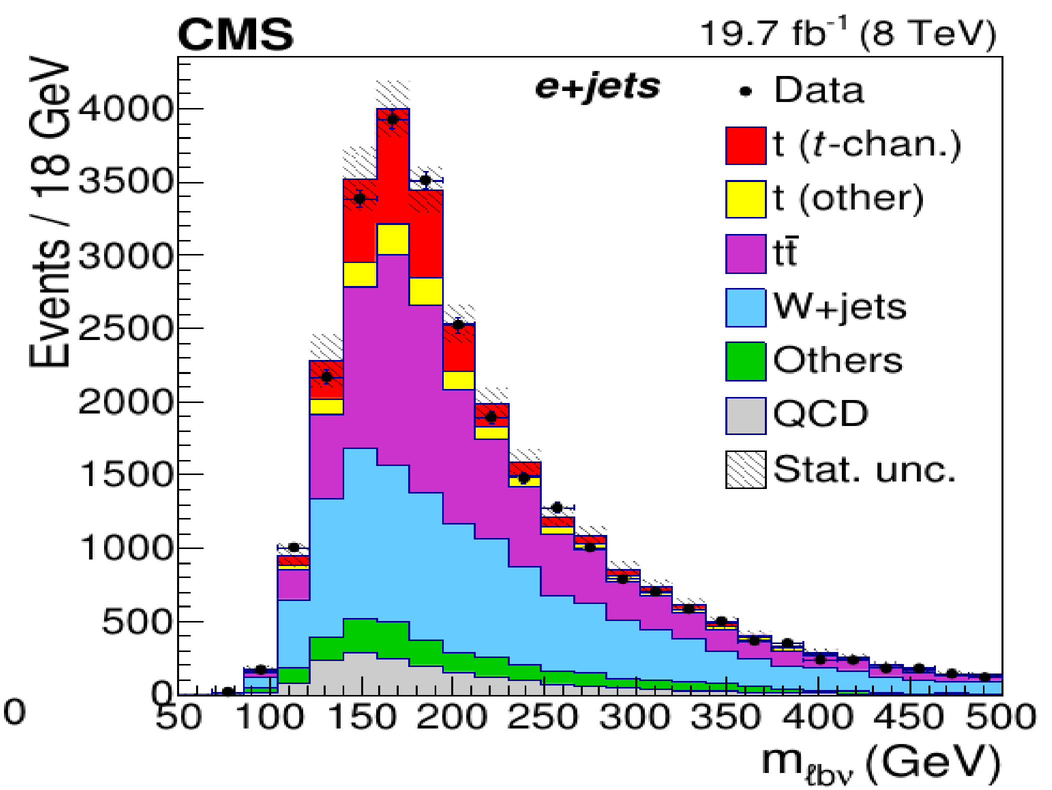
To calculate θ_l^*, top quark 4-momenta is needed. For this purpose neutrino longitudinal momentum will be found.

$$p_{z,\nu} = \frac{\Lambda \cdot p_{z,l}}{p_{T,l}^2} \pm \frac{1}{p_{T,l}^2}\sqrt{\Lambda^2 \cdot p_{z,l}^2 - p_{T,l}^2(E_l^2 \cdot \not{E}_T{}^2 - \Lambda^2)}$$

Where $\Lambda = \frac{m_W^2}{2} + \vec{p}_{T,l} \cdot \vec{\not{E}}_T$, $m_W^2 = (E_l + E_\nu)^2 - (p_T^l + p_T^\nu)^2 - (p_z^l + p_z^\nu)^2.$

Events with complex $p_{z,\nu}$ are excluded from the analysis

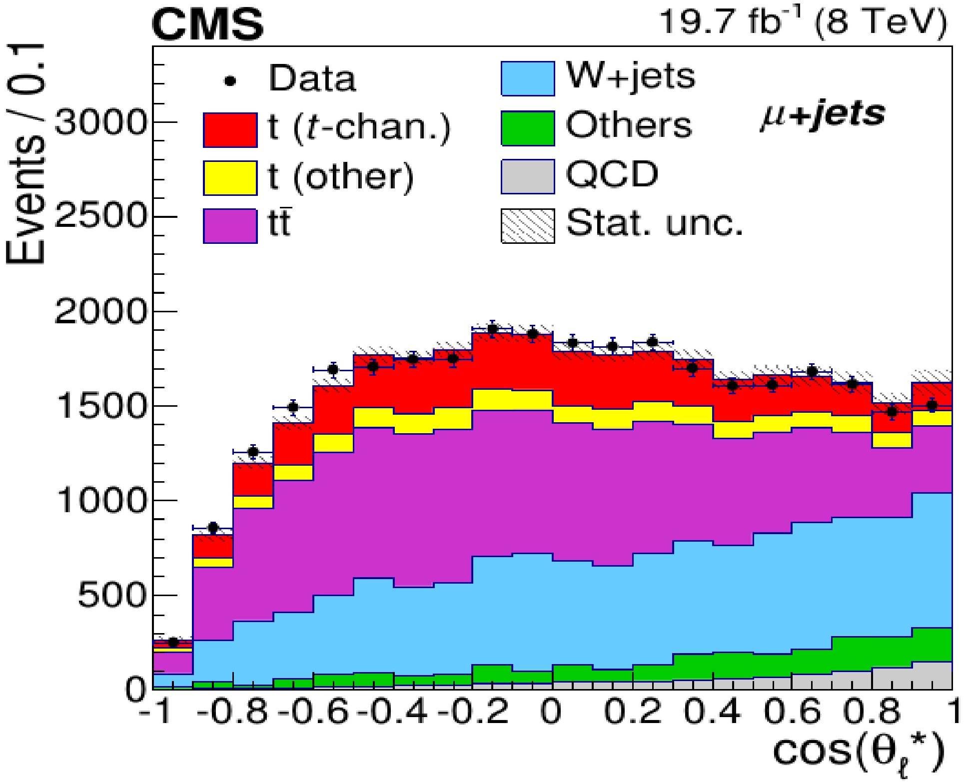




The fit method

The Poisson likelihood function

$$\mathcal{L}(\vec{F}) = \prod_{i\in \text{bins}} \frac{(\lambda_i^{\text{MC};\vec{F}})^{n_i^{\text{data}}}}{n_i^{\text{data}}!} \times \mathrm{e}^{-\lambda_i^{\text{MC};\vec{F}}}$$



Where

n_i^{data} – number of selected data events in the bin i

$\lambda_i^{MC;\vec{F}}$ – expected nubmer of simulated events

$$\lambda_i^{\text{MC};\vec{F}} = \lambda_i^{\text{bkg-other}} + \beta_{\text{W jets}} \times \lambda_i^{\text{W jets}} + f \times \lambda_i^{\text{signal};\vec{F}}$$

$\lambda_i^{signal}, \lambda_i^{Wjets}$ and $\lambda_i^{bkg-other}$ is the shapes of singnal, W+jets and other backgrounds sources and are defined from simulation,

f is signal normalization parameter (fixed to 1) and

β_{Wjets} is free parameter for normalization W+jets background

Taking into accout $\sum F_i = 1$, there are only three parameters in likehood function

Systematics

Sources of systematic uncertainties:

Experimental

- JEC / JER
- Unclustered MET
- PileUp
- B-tag / mistag
- Triggers SF
- Lepton Id / Iso
- Luminosity

Modelling

- Generator choise
- Scale
- Top quark mass
- PDF
- W+jets shape uncertainty

Normalization

- ttbar
- Single t quark
- QCD multijet
- Electroweak backgrounds

Method-specific:

- SM W helicities in MC
- Fixing signal normalization in the fit
- Finite MC statistic
- Wtb vertex bias from anomalous couplings

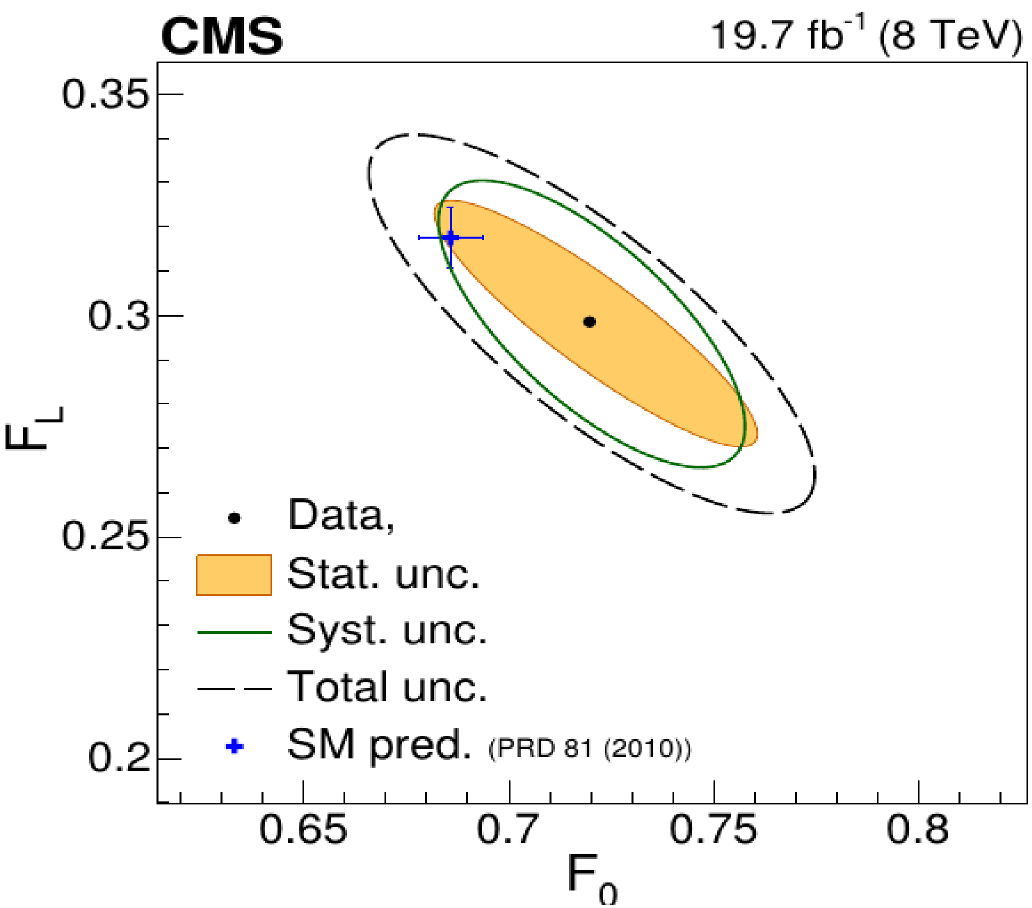
Standard Model results

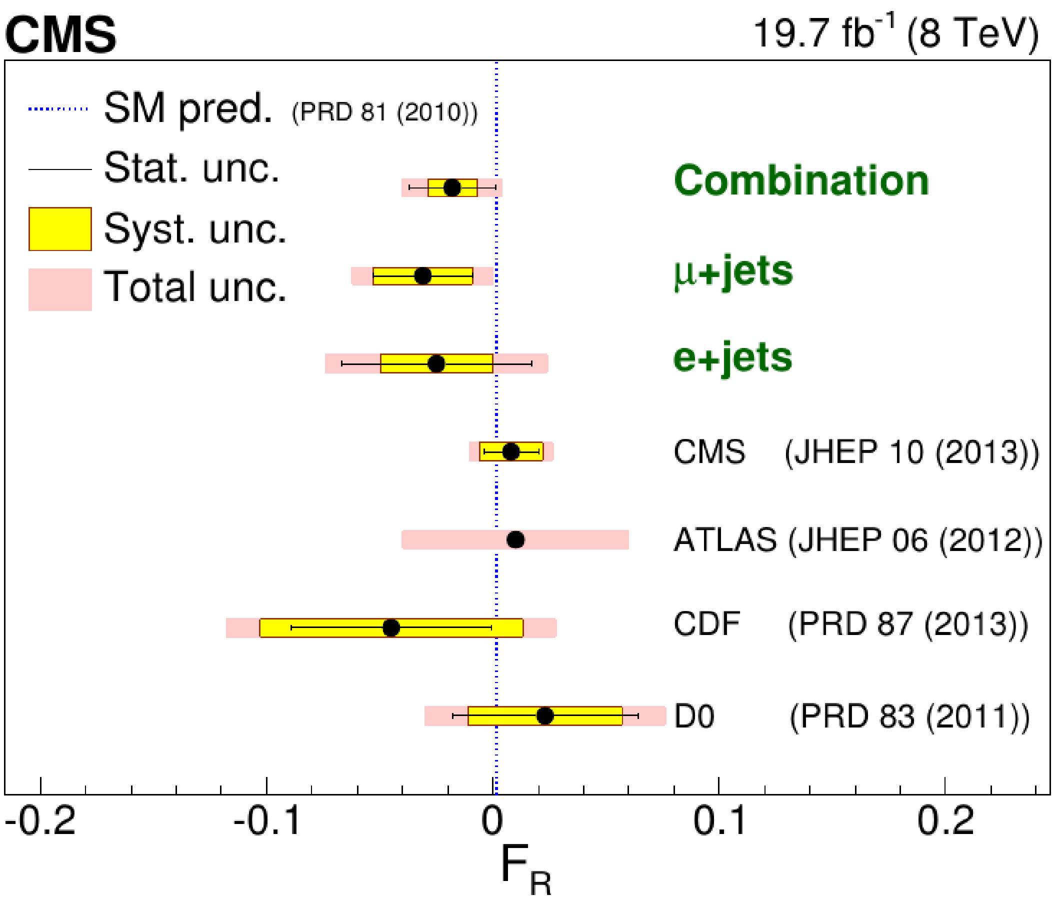
	Muon channel		Electron channel		Combination	
	ΔF_0	ΔF_L	ΔF_0	ΔF_L	ΔF_0	ΔF_L
Experimental	0.010	0.009	0.008	0.005	0.010	0.010
Modeling	0.025	0.017	0.025	0.022	0.025	0.020
Normalization	0.002	0.008	0.012	0.014	0.011	0.012
SM W helicities	0.007	0.004	0.005	0.003	0.007	0.004
MC sample size	0.026	0.012	0.025	0.015	0.020	0.012
tWb in prod.	0.014	0.016	0.010	0.018	0.011	0.014
Total	0.041	0.030	0.040	0.036	0.037	0.032

Muon and electron channels combination:

$$F_L = 0.298 \pm 0.028\,(\text{stat}) \pm 0.032\,(\text{syst}),$$
$$F_0 = 0.720 \pm 0.039\,(\text{stat}) \pm 0.037\,(\text{syst}),$$
$$F_R = -0.018 \pm 0.019\,(\text{stat}) \pm 0.011\,(\text{syst})$$

SM values (NNLO): $F_L = 0.311 \pm 0.005$, $F_0 = 0.687 \pm 0.005$, $F_R = 0.0017 \pm 0.0001$ [Czarnecki at al.]





Anomalous couplings in W helicity fractions

The anomalous couplings <u>can be obtained</u> from partial width for the top decay into a W boson with -1, 0 or +1 helicity:

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

$$\Gamma_i = W_i \cdot \Gamma$$

Where

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

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

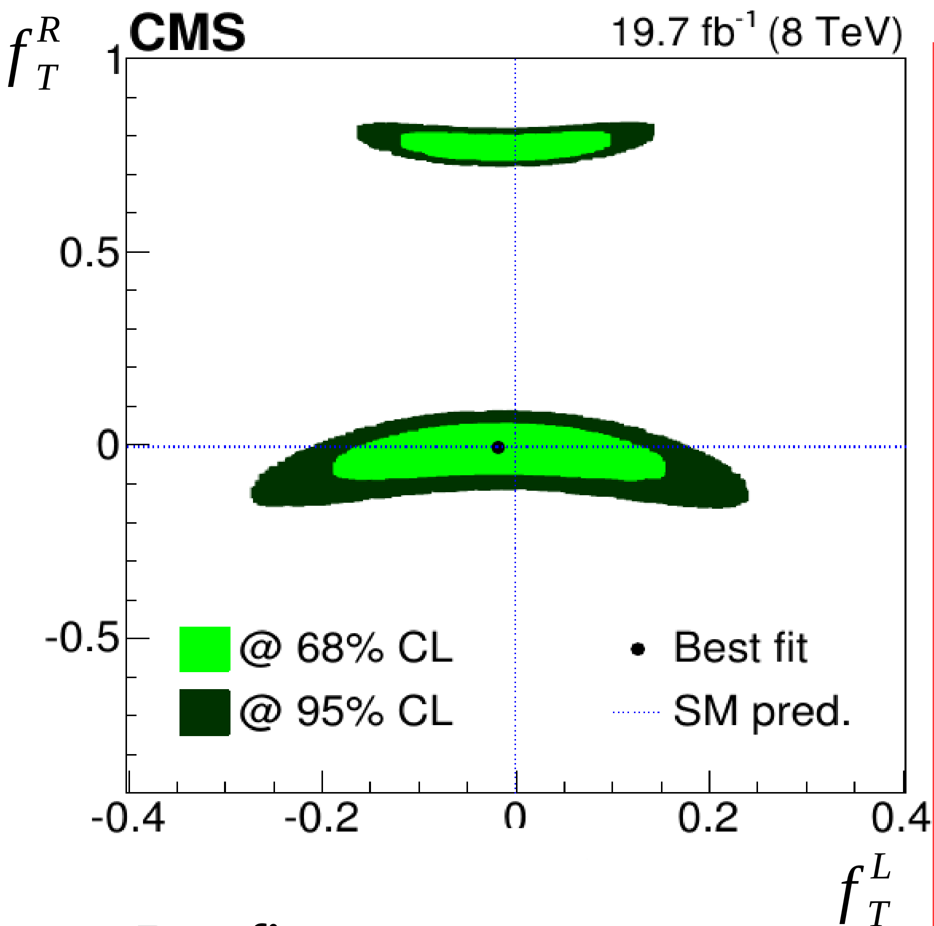
$$x_W = M_W/m_t, \qquad x_b = m_b/m_t$$

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

$$f_V^{L,R} = \mathrm{Re}\left(V_{L,R}\right)$$
$$f_T^{L,R} = \mathrm{Re}\left(g_{L,R}\right)$$

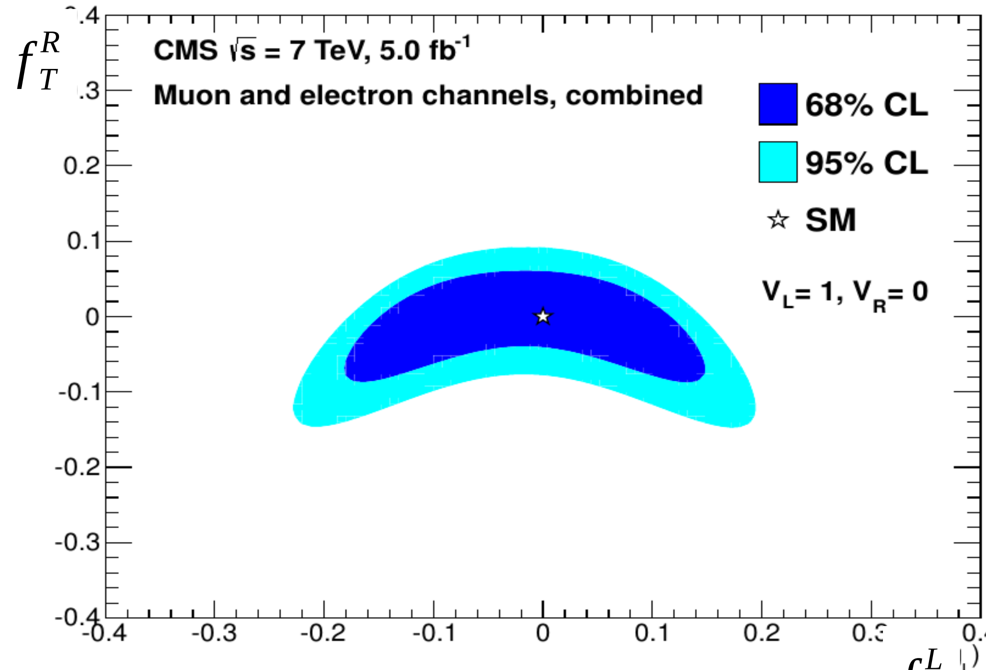
If CP is conserved, the couplings could be taken as real

Anomalous Wtb results

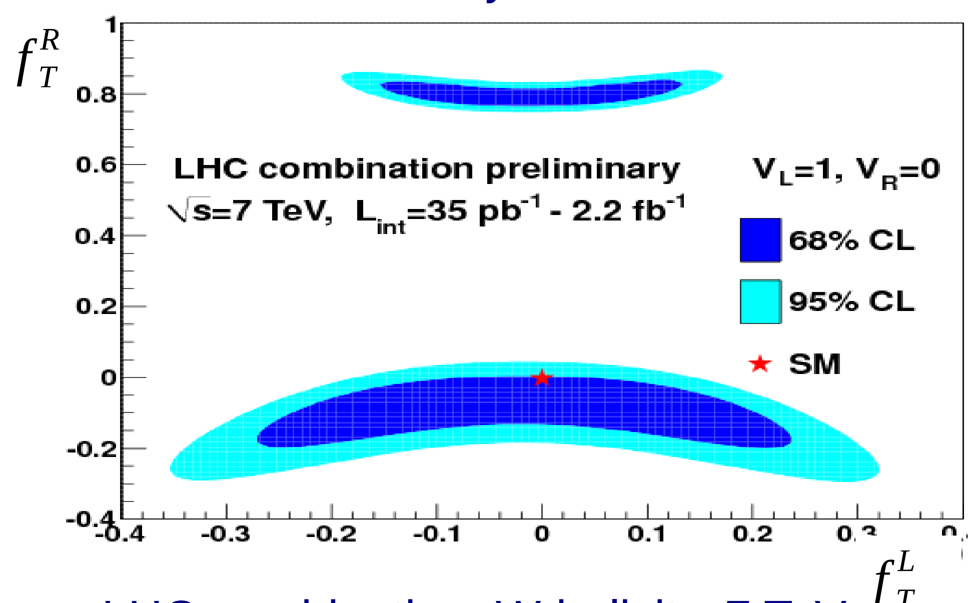


Best fit:

$$f_T^L = -0.017,$$
$$f_T^R = -0.008$$

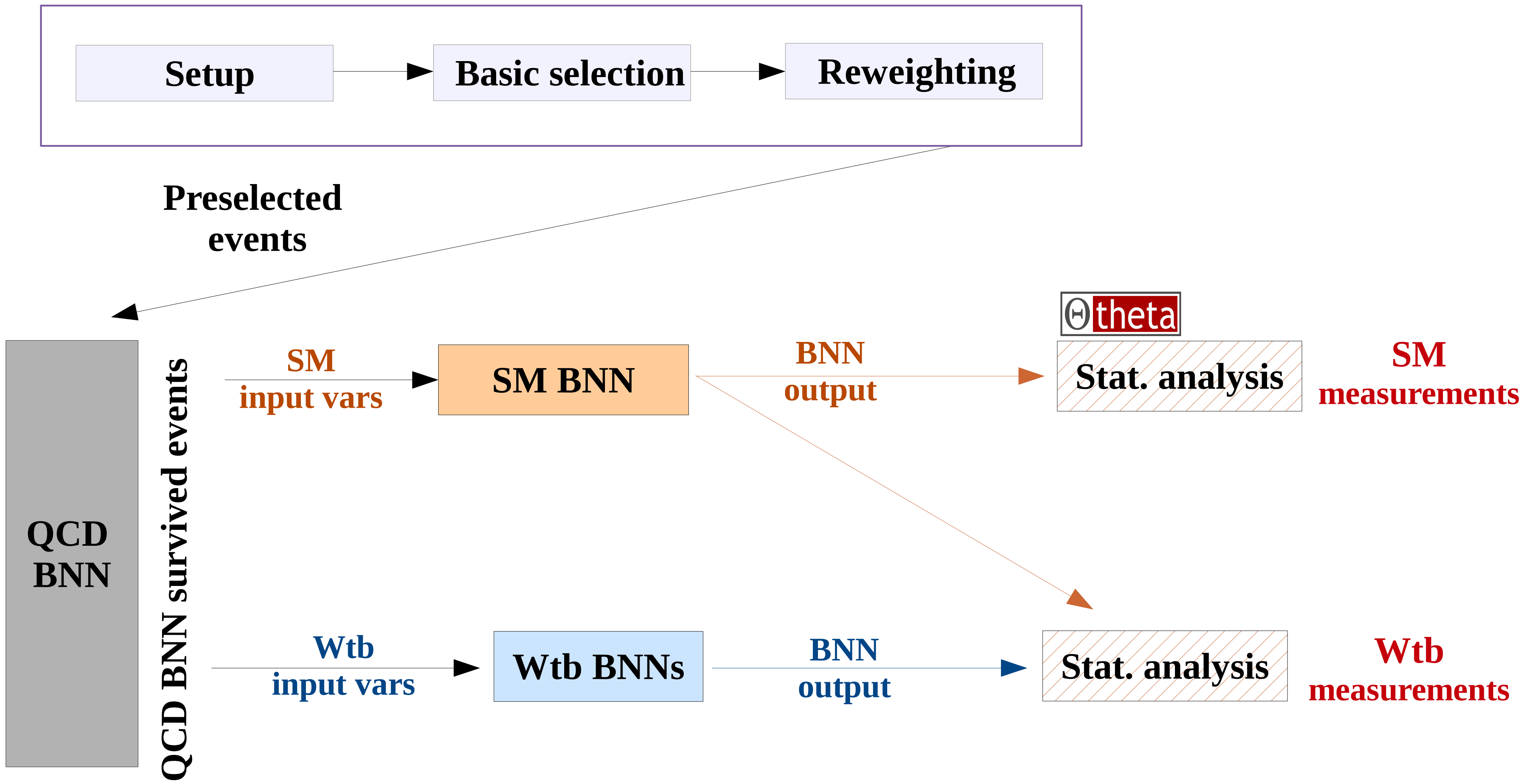


CMS, W helicity in ttbar, 7 TeV



LHC combination, W-helicity, 7 TeV

Search for anomalous Wtb couplings and FCNC in t-channel single-top-quark events



Published as CMS-PAS-TOP-14-007

Analysis setup

Setup: Int. luminosity 5 / fb at $\sqrt{s}=7\,TeV$

MC Reweighting:

- **Pile-Up**
- **B-tag**
- **Triggers and muon ID/Iso**
- **PDF**

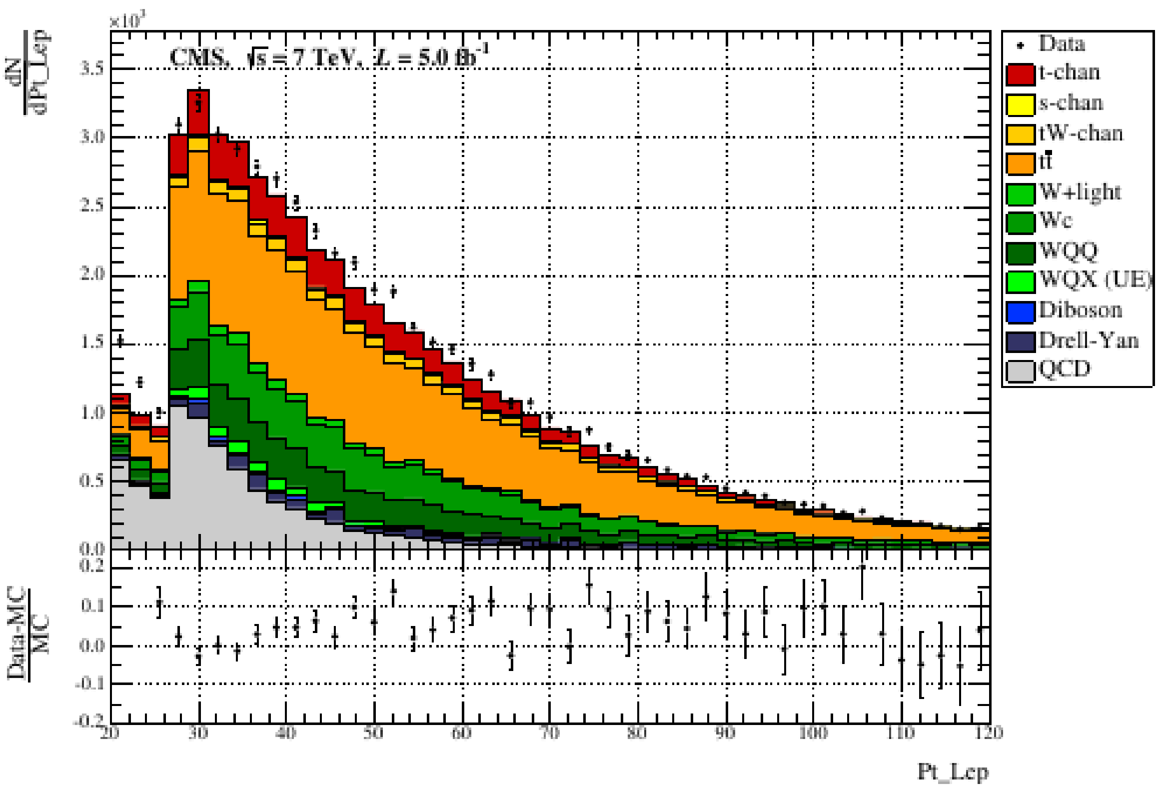
Selection:

Objects definition and selection follows CMS Top Group recommendations;

- **muon channel only**
- **Two or three jets**
- At least **one b-tagged** jet according to **CSVT**, at least **one untagged**

Triggers:

HLT_IsoMu17_v*
HLT_IsoMu24_v*
HLT_IsoMu24_eta2p1_v*

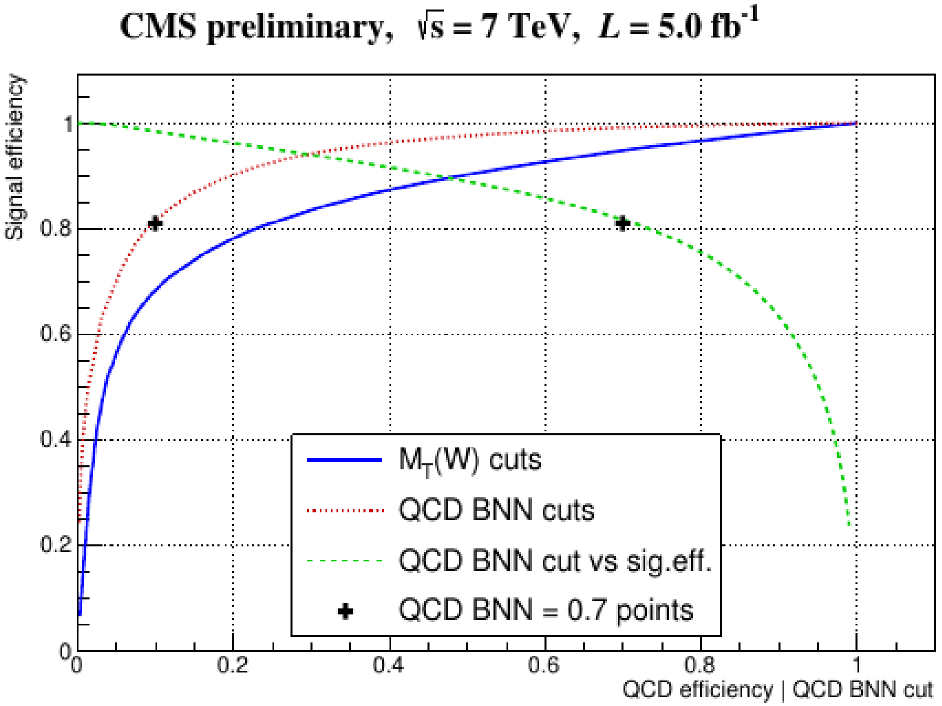


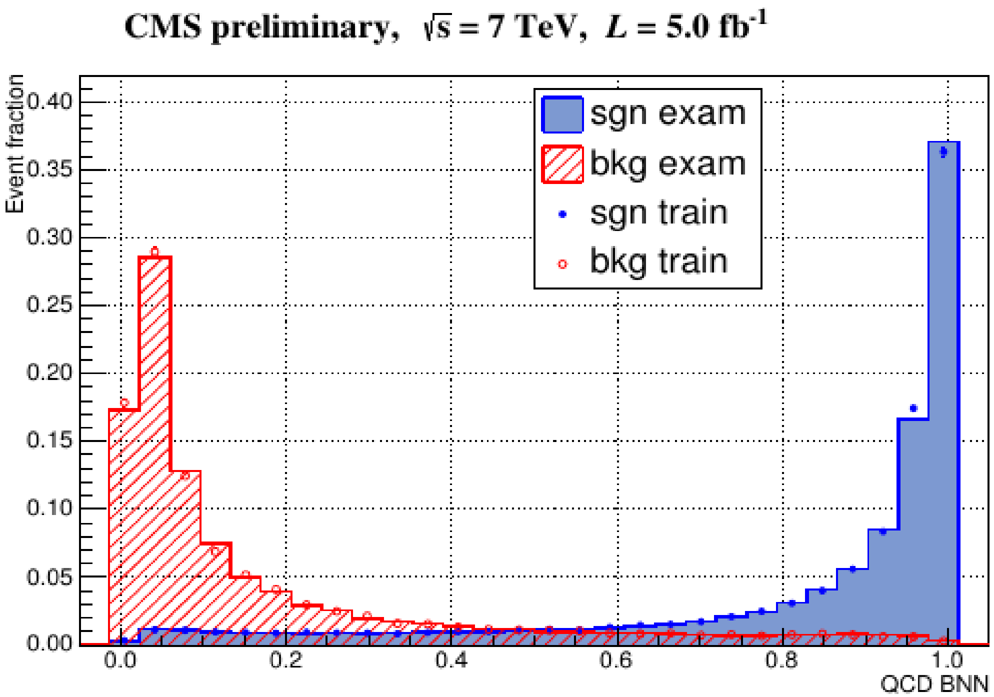
Multijet QCD suppression

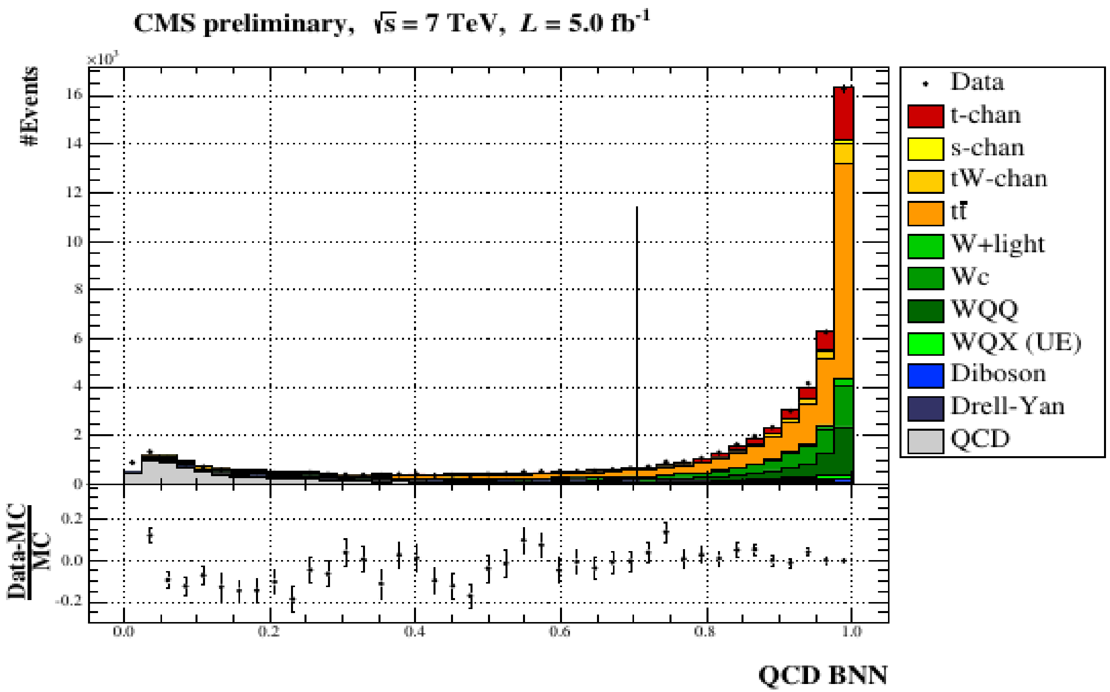
- **Estimation**
- Multijet QCD background is estimated from the data
- Modified event selection
- "Cleaning" procedure for jets, $\Delta R(l,jet)>0.5$ or removing jet

Suppression:

- Special neural network for QCD removing
- BNN_qcd > 0.7 cut







High level analysis

Input variables :

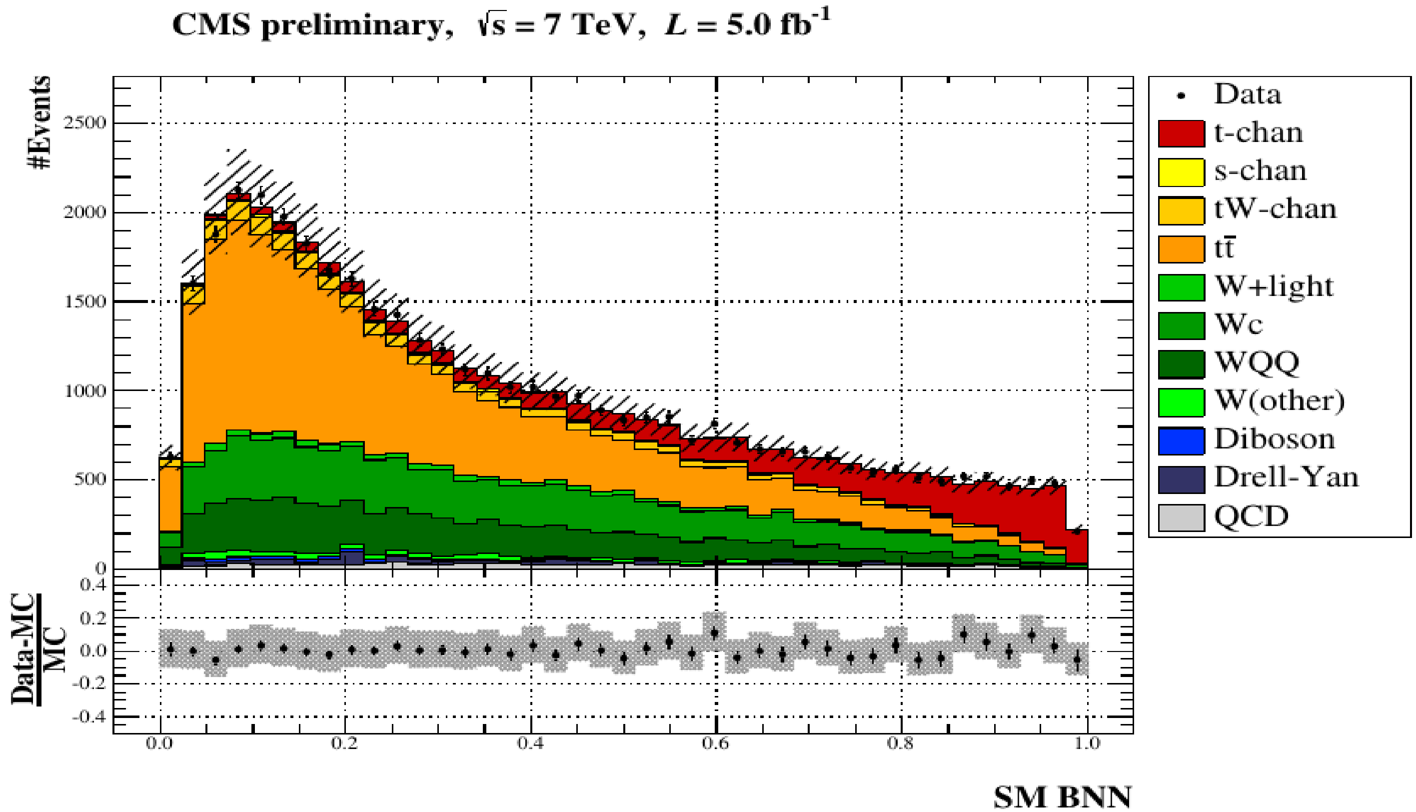
Optimal variables method: Feynman diagrams structure analysis

Signal:

t-channel production (SM analysis) **or** one of f_V^R or f_T^L coupling (Wtb analysis)

Background:

All other processes (SM analysis) **or** left vector coupling (f_V^L) (Wtb analysis)



Systematics

Sources of systematic uncertainties:

- **Finite MC statistics**
- **Luminosity**

Marginalized:

- Xsections
- JEC
- JER
- Unclustered MET
- PileUp
- B-tag /mistag
- Triggers SF
- Lepton Id
- Lepton Iso

Unmarginalized:

- Generator choise
- Scale
- Matching
- PDF

Unmarginalized uncertaintites are estimated with toy experiments. Pseudodata are constructed with a best-fit value for t-channel x-section, not SM value.

Standard Model results

Type of uncertainty	Down uncertainty	Up uncertainty
Scale	-1.51 %	+3.39 %
Matching	-4.06 %	+4.06 %
Triggers SFs	-0.0378 %	+0.171 %
PDF	-9 %	+9.05 %
Generator	-4.34 %	+4.34%
Total unmarginalized	-11.03 %	+11.16 %
Marginalized	-6.09 %	+6.27 %
Luminosity	-2.2 %	+2.2 %
Total	-12.79 %	+12.99 %

$$\sigma_{t-channel}^{observed} = 69.74^{+9.1}_{-8.9} \, {}^{(+13.0\%)}_{(-12.8\%)} \, pb$$

$$\sigma_{t-channel}^{theory, NLO} = 65.9^{+2.1}_{-0.7} \, {}^{+1.5}_{-1.7} \, pb$$ (Kidonakis)

$$\sigma_{t-ch.} = 67.2 \pm 6.1 \, pb$$ (JHEP12(2012)035)

Measured cross-section is used in anomalous Wtb couplings searches

Anomalous coupling searching

$$\mathfrak{L} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}\left(f_{\mathrm{V}}^{\mathrm{L}}P_{\mathrm{L}} + f_{\mathrm{V}}^{\mathrm{R}}P_{\mathrm{R}}\right)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}\partial_{\nu}W_{\mu}^{-}}{M_{\mathrm{W}}}\left(f_{\mathrm{T}}^{\mathrm{L}}P_{\mathrm{L}} + f_{\mathrm{T}}^{\mathrm{R}}P_{\mathrm{R}}\right)t + h.c.$$

For f_V^R or f_T^L anomalous coupling additional BNN is trained to separate it from f_V^L

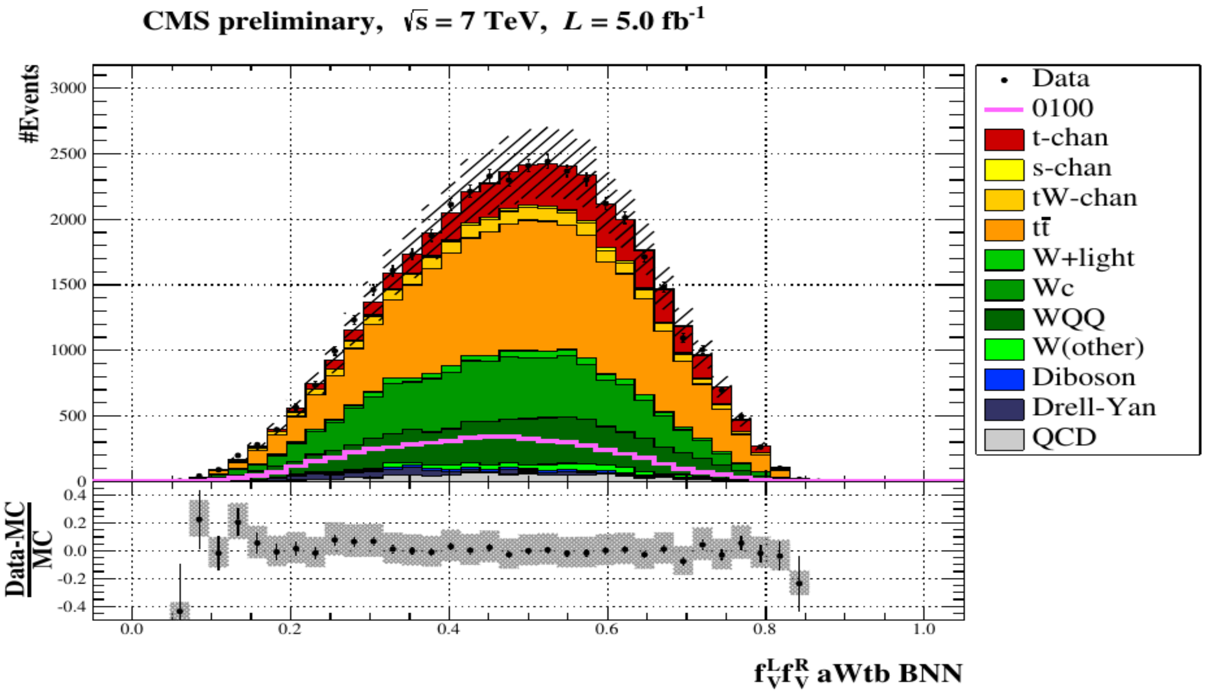
(i.e. from Standard Model t-channel events)

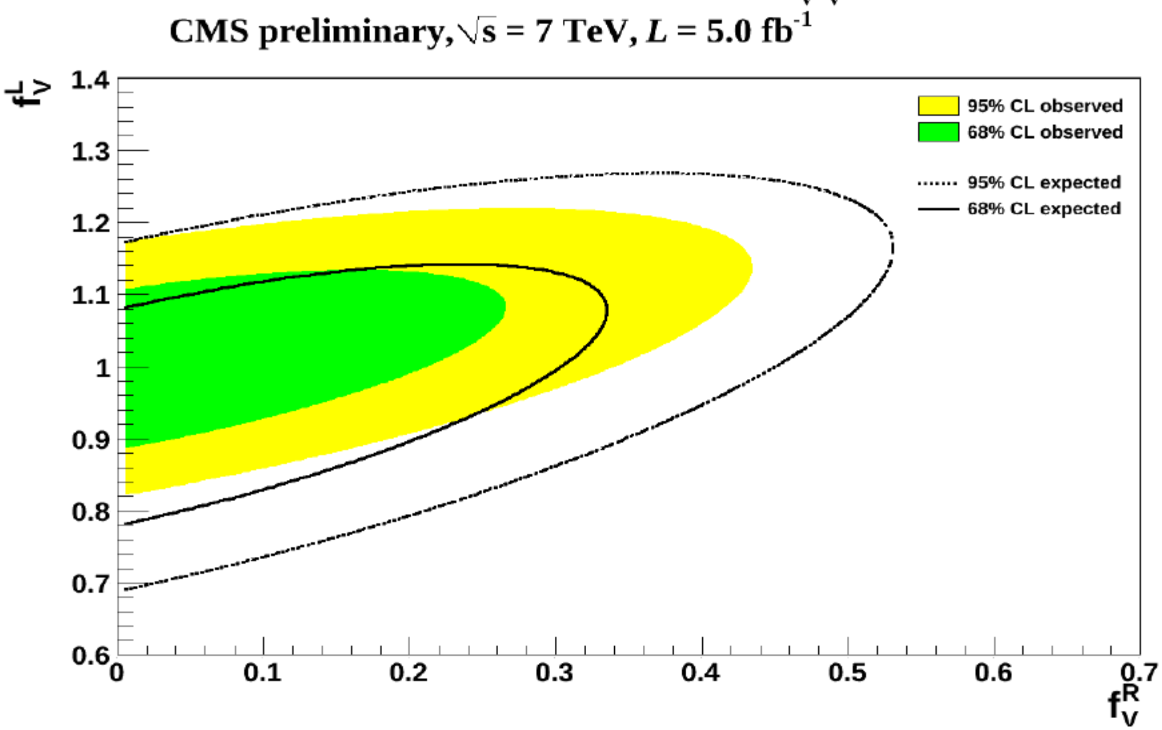
2 different scenarios:

- Searching for (f_V^L, f_V^R), while **LT** and **RT** couplings are fixed to SM values $(f_T^L = f_T^R = 0)$
- Searching for (f_V^L, f_T^L), while **RV** and **RT** couplings are fixed to SM values $(f_V^R = f_T^R = 0)$

Each scenario gives 1D limit for each coupling and 2D fit of couplings distribution

(LV,RV) scenario



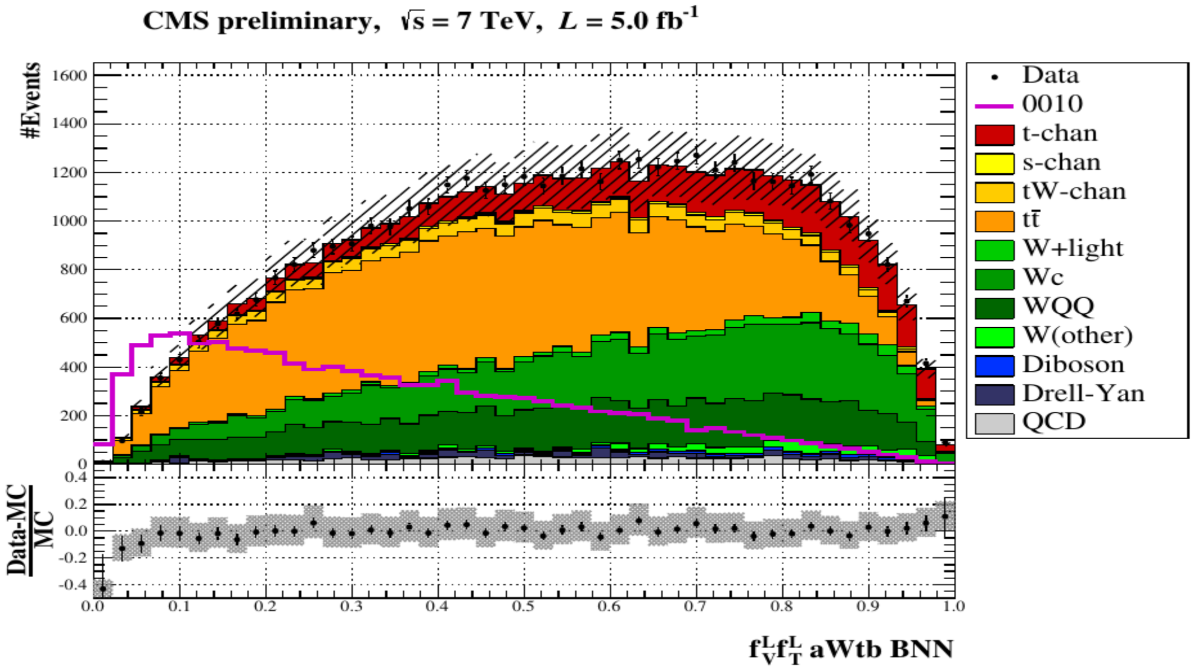


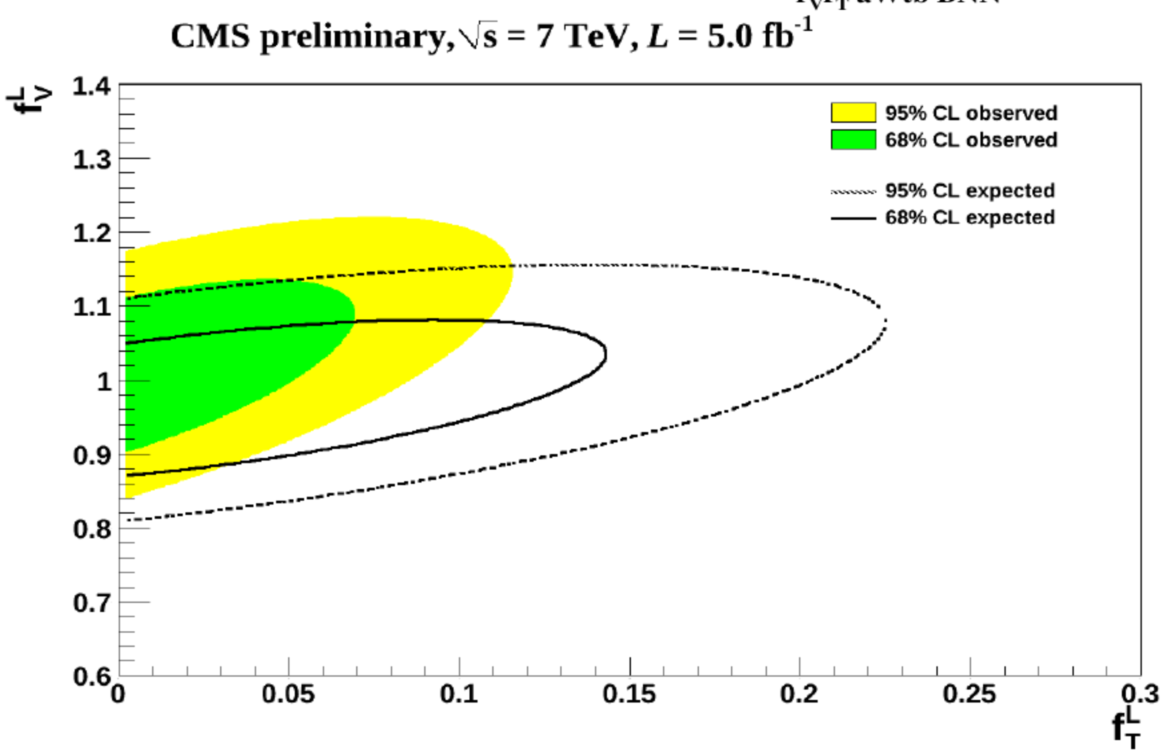
Observed (expected) 1D limits at 95% C.L.:

$$|f_V^L| > 0.90\ (0.88)$$

$$|f_V^R| < 0.34\ (0.39)$$

(LV,LT) scenario

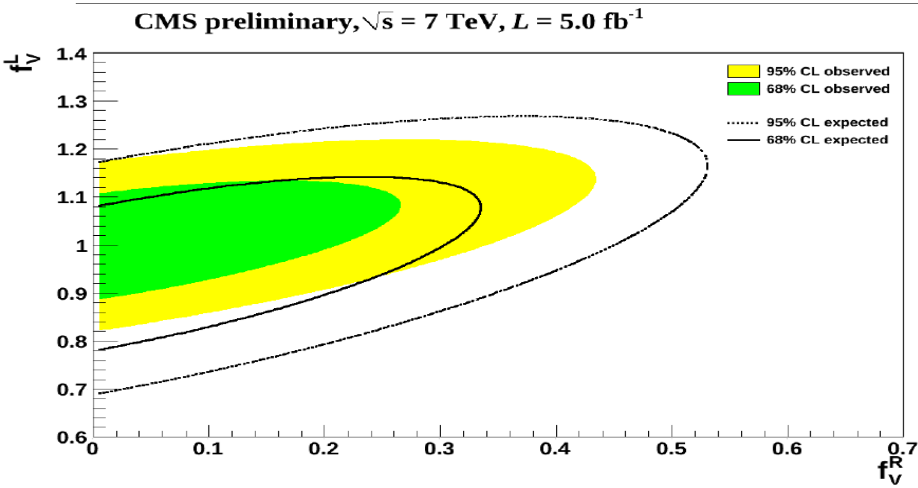


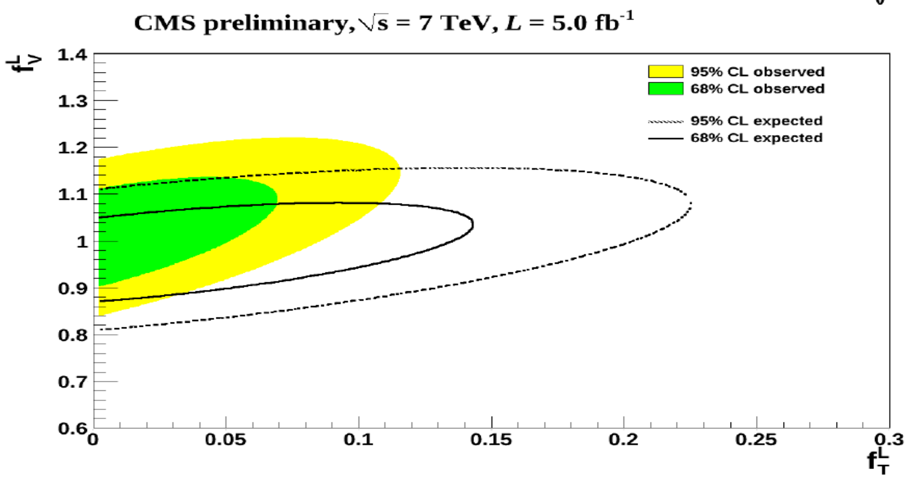


Observed (expected) 1D limits at 95% C.L.:

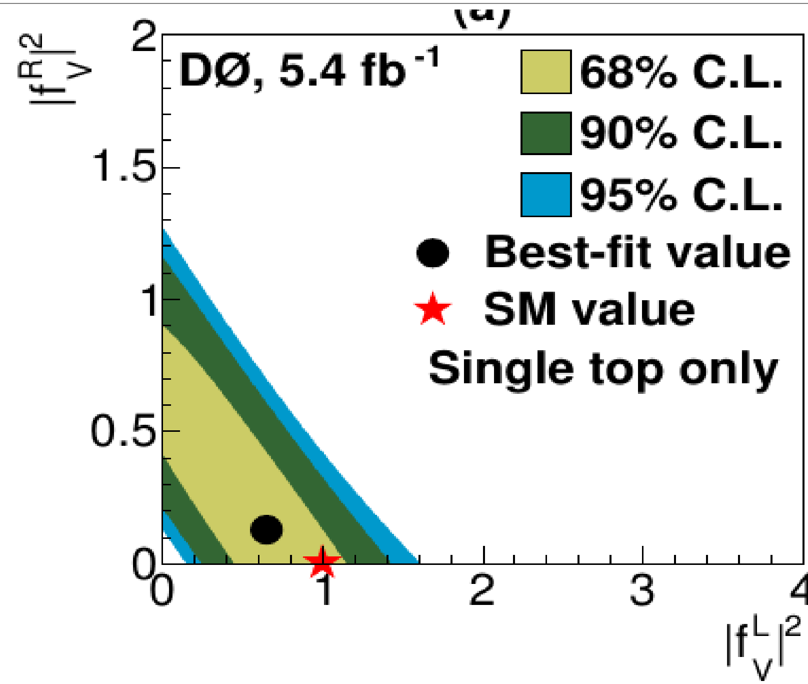
$$|f_V^L| > 0.92\ (0.88)$$
$$|f_T^L| < 0.09\ (0.16)$$

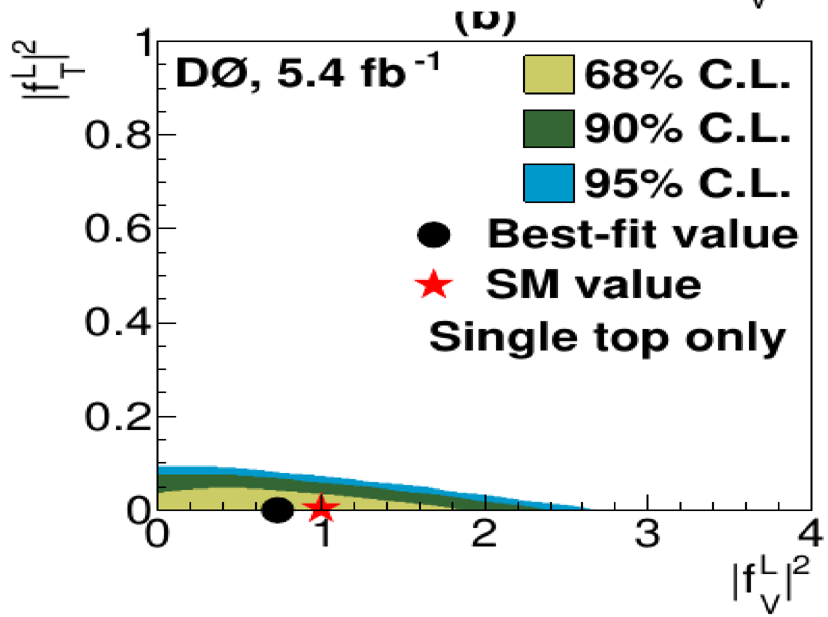
Anomalous Wtb searches results





$$\left|f_V^L\right| > 0.90,$$
$$\left|f_V^R\right| < 0.34,$$
$$\left|f_T^L\right| < 0.09$$

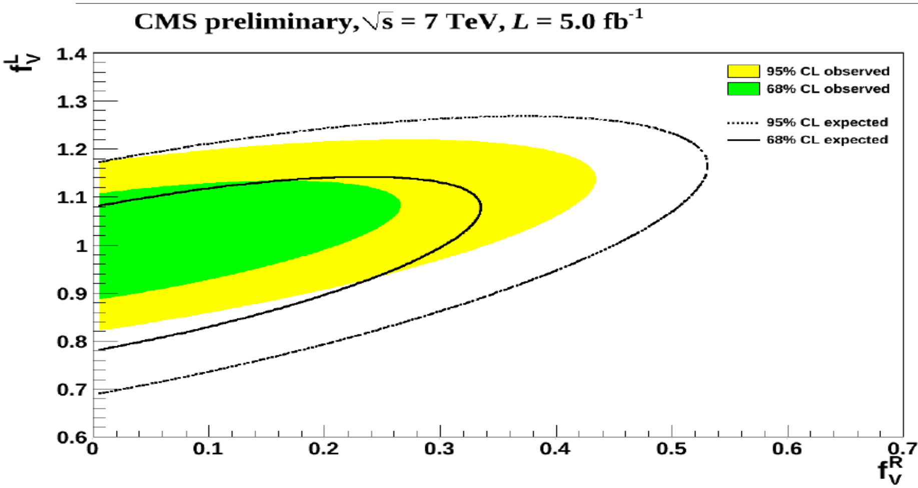


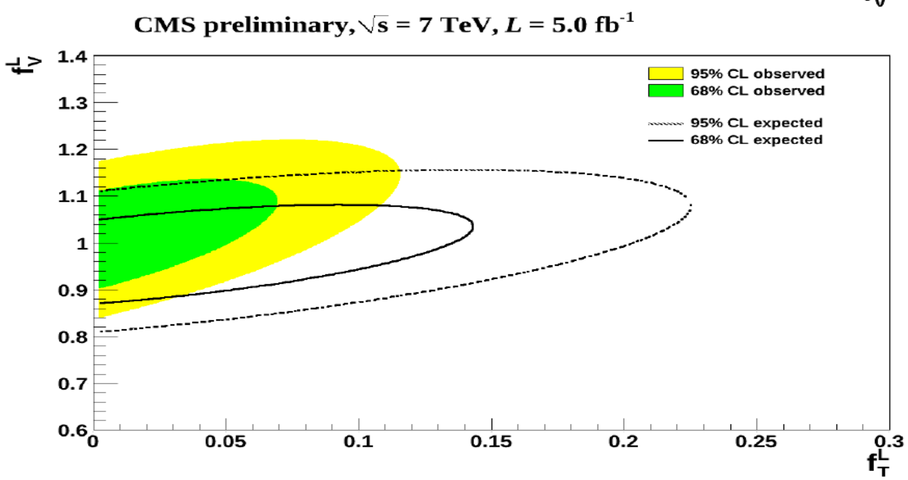


$$\left|f_V^R\right|^2 > 0.89,$$
$$\left|f_T^L\right|^2 < 0.07,$$
$$\left|f_T^R\right|^2 < 0.18$$

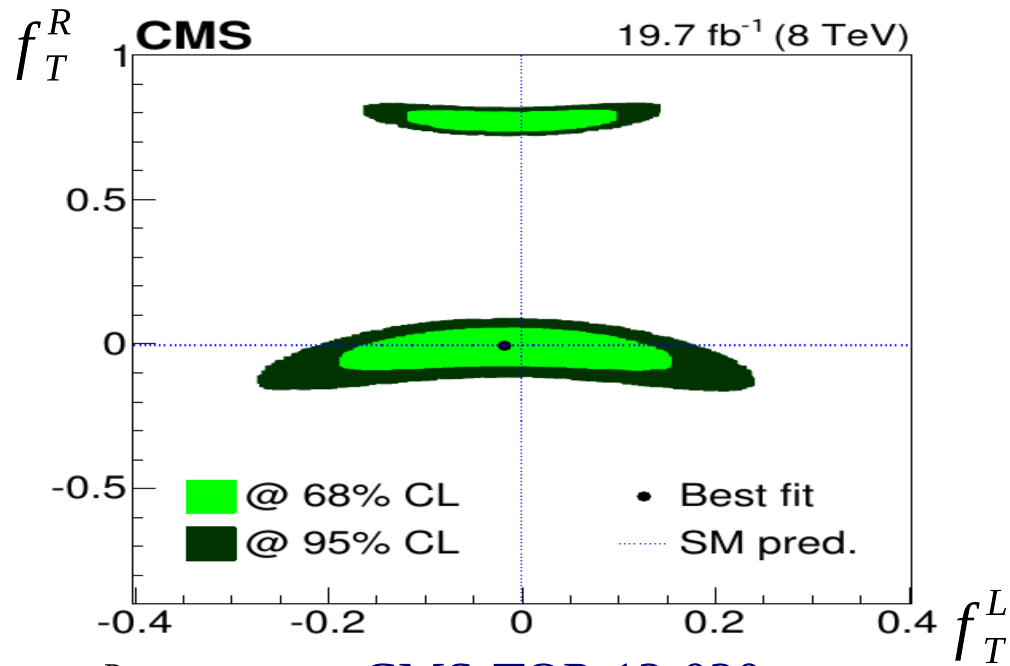
D0, single top only, 1,96 TeV

Anomalous Wtb searches results

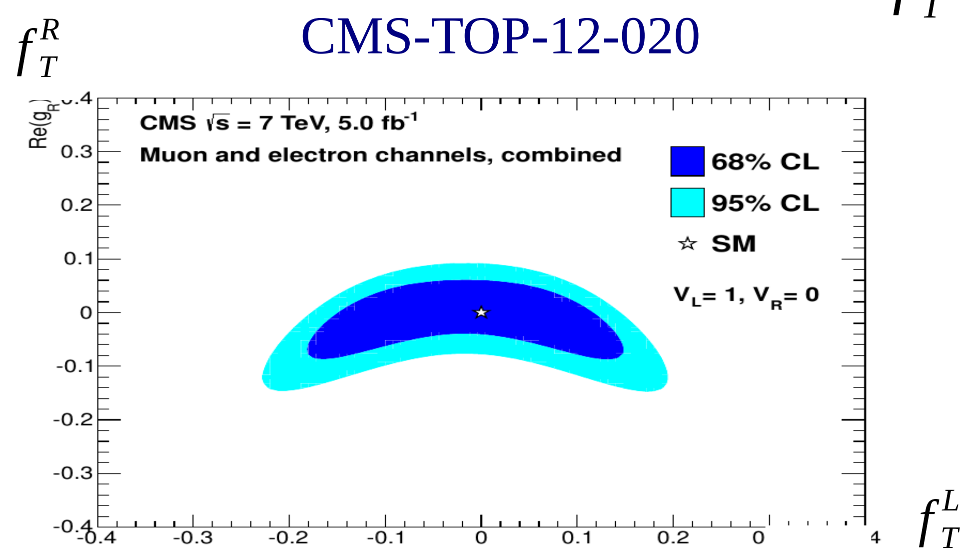




$$|f_V^L| > 0.90\,,$$
$$|f_V^R| < 0.34\,,$$
$$|f_T^L| < 0.09$$



CMS-TOP-12-020



$$f_T^R = -0.008 \pm 0.024\,(stat.)^{+0.029}_{-0.030}\,(syst.)$$

[CMS, W helicity in ttbar, 7 TeV]

Summary

- **W-boson helicity is measured for 8 TeV in e- and μ- channels simultaneously**

- **1D limits for LV, RV and LT couplings in Wtb vertex**
- **2D limits for (LV,RV), (LV,LT) and (LT,RT)**

- **CMS-12-020 is already published in JHEP**
- **CMS-PAS-TOP-14-007 is published as a Physics Analysis Summary,**

  updated results with 7+8 TeV full datasets, limit for RT coupling, ''3D'' scenarios will be published soon as CMS-TOP-14-007 paper

Thank you for attention!

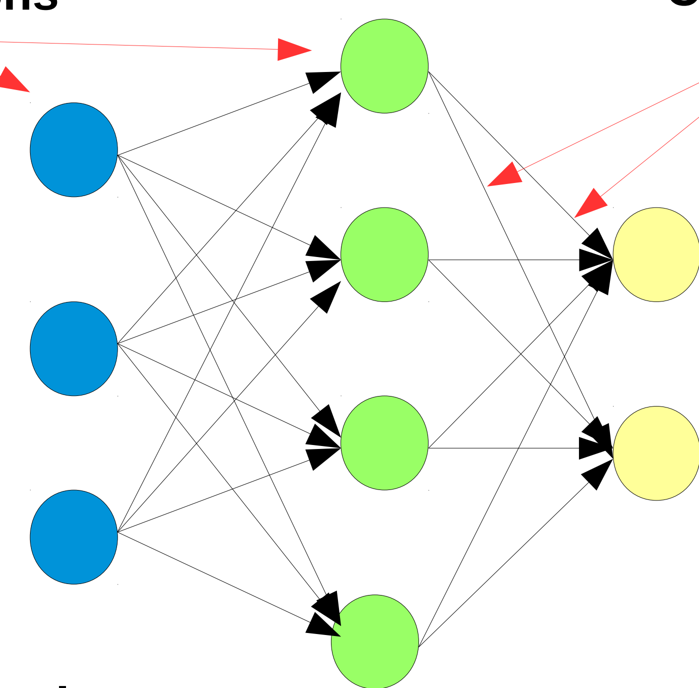
Backup

Artificial Neural Networks (ANN)

ANN analysis:

- Possibility for multi-dimentional analysis
- High efficiency
- Supervised learning

Single-layer perceptron:



Bayesian Neuron Networks (BNN):

- Bayesian treatment of probability:

  output is interpreted as degree of belief
- Ansambles of networks:
  overfitting protection