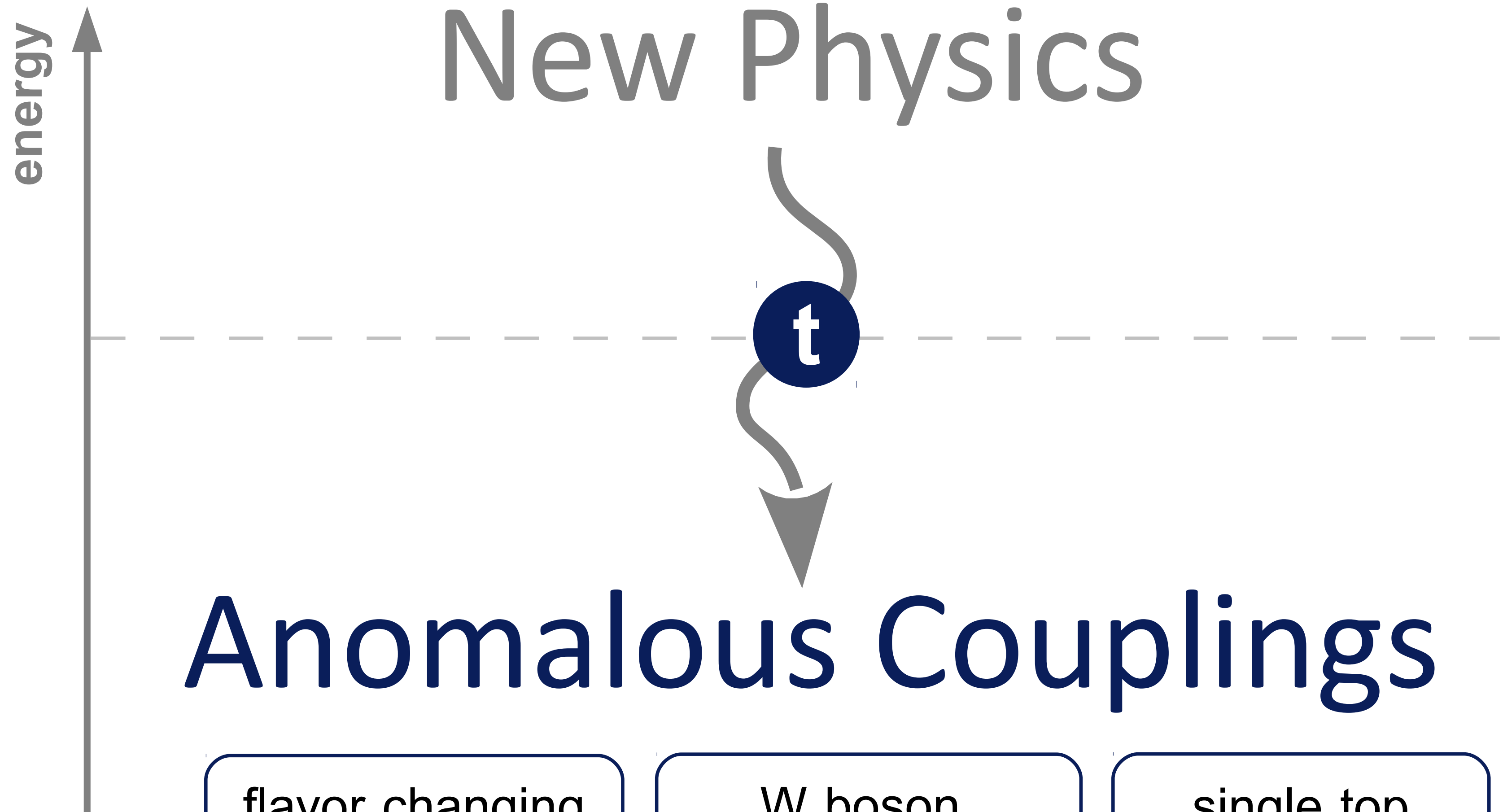


New Physics

Anomalous Couplings

flavor changing neutral currents	W boson helicity fractions	single top polarization
CMS-PAS-TOP-12-020	CMS-PAS-TOP-12-020	CMS-PAS-TOP-13-001

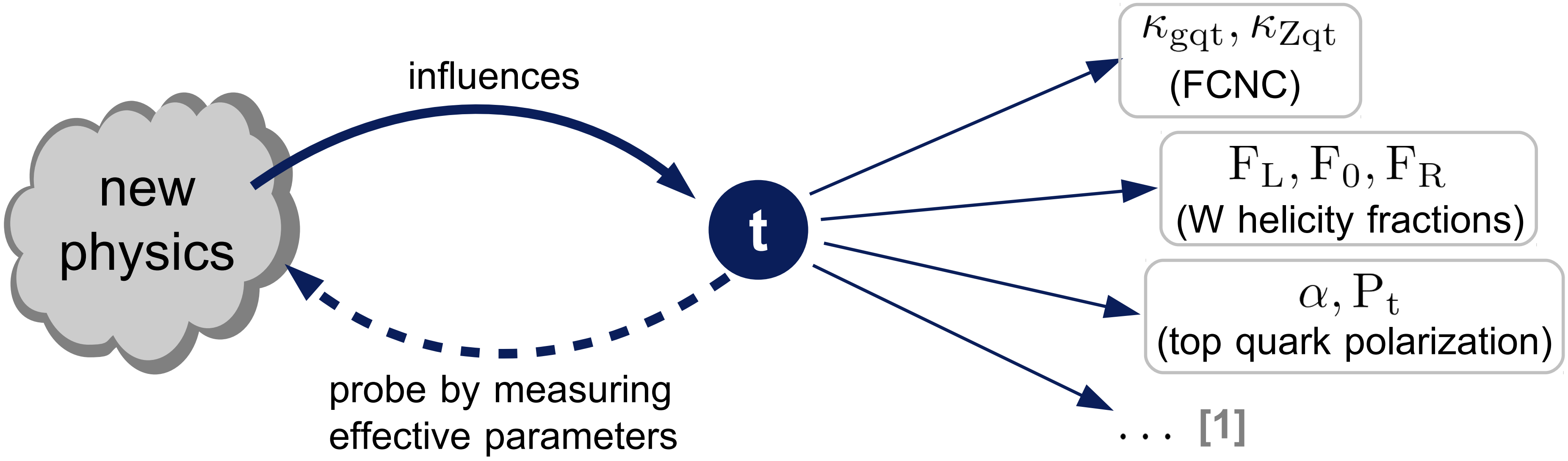
➢ **Matthias Komm**

UCL
Université catholique de Louvain

Motivation

- **effective approach**

$$\mathcal{L}_{\mathrm{SM}} \rightarrow \mathcal{L}_{\mathrm{eff.}} = \lim_{q \rightarrow 0} \mathcal{L}_{\mathrm{BSM}}(\Lambda)$$



  - BSM physics at scale Λ can lead to "anomalous couplings"

- **idea**
  - measure / test for anomalous coupling as a model independent probe for new physics (e.g. exotic quarks, SUSY, technicolor,...)

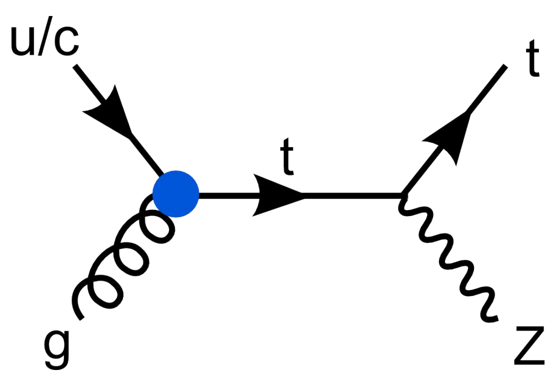
[1] J. A. Aguilar-Saavedra, *A minimal set of top anomalous couplings*, arXiv:0811.3842 [hep-ph]

Search for FCNC in tZ Final State

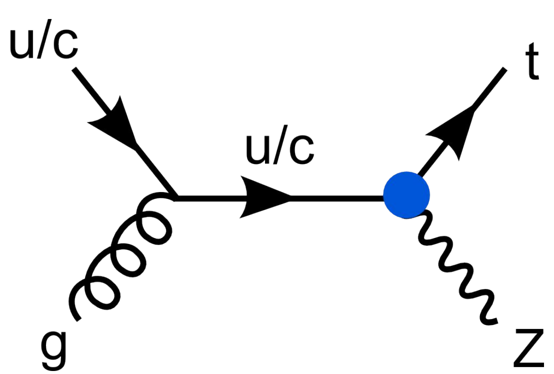
CMS-PAS-TOP-12-021

- **motivation**
  - detection would be a direct hint for new physics
  - complementary to FCNC search in $t\bar{t}$ events

- **signal process**



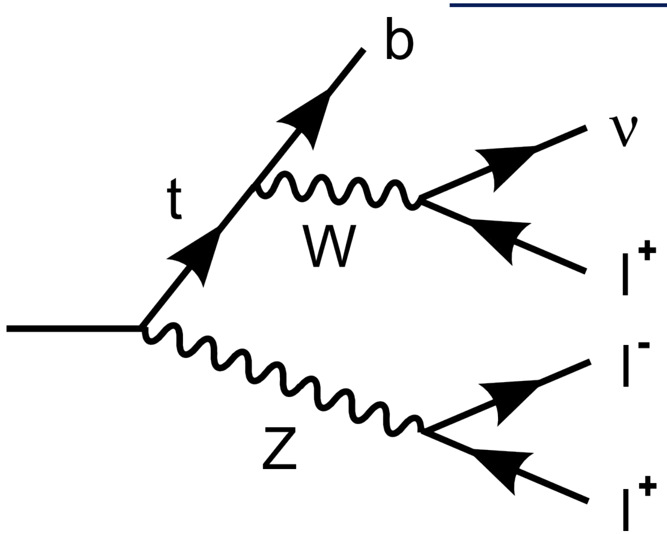
$$\mathcal{L} = \sum_{q=u,c} \left[\sqrt{2} g_s \frac{\kappa_{gqt}}{\Lambda} \bar{t} \sigma^{\mu\nu} T_a P_L G^a_{\mu\nu} \right] + \text{h.c.}$$



$$\mathcal{L} = \sum_{q=u,c} \left[\frac{g}{\sqrt{2} c_W} \frac{\kappa_{Zqt}}{\Lambda} \bar{t} \sigma^{\mu\nu} P_L q Z_{\mu\nu} \right] + \text{h.c.}$$

Analysis Strategy

- **selection of tZ events**



$p_T > 30$ GeV, $|\eta| < 4.5$
b-tagging with MVA ("combined secondary vertex")

$m_T(W) > 20$ GeV to reject Z+jets events

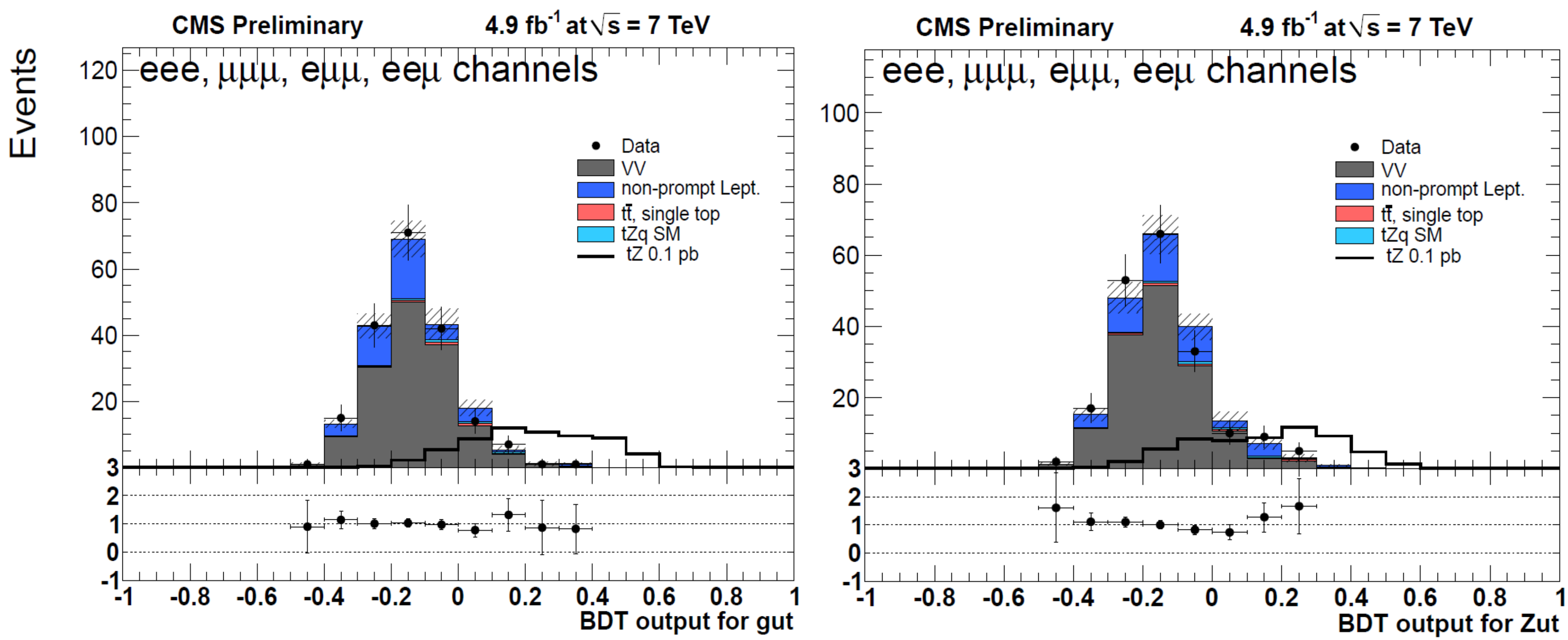
3 isolated leptons ($\mu\mu\mu, \mu\mu e, ee\mu, eee$)
- $p_T > 20$ GeV $|\eta| < 2.4(\mu), 2.5(e)$
- OS leptons within Z mass window ($76 < m_{ll} < 106$ GeV)

- **analyzed data**: $5\ fb^{-1}$ at 7 TeV using di-lepton triggers

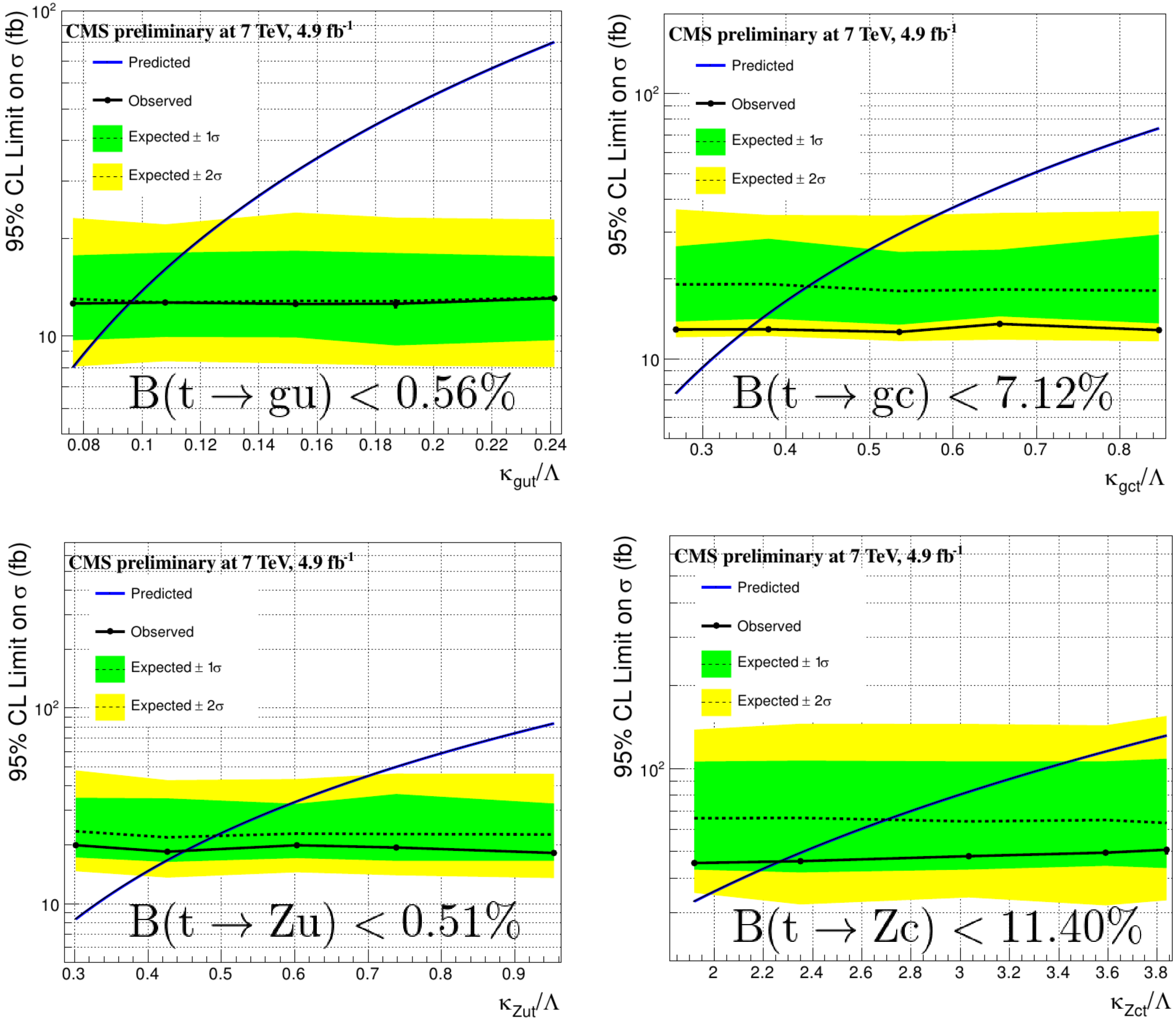
- **Z+jets & WZ+jets background estimation**
  - idea: use $m_T(W)$ to estimate the Z+jets yield from data
    - orthogonal Z+jets template by inverting the non-Z lepton isolation
    - systematics: varied isolation veto, WZ+jets renormalization/factorization & matching scale, 30% cross section uncertainty (di-boson, ttbar, single top, tZq)
  - result: $\sigma^{data}_{Z+jets}/\sigma^{MadGraph}_{Z+jets} = 2.57 \pm 0.73$ (all channels combined)

Analysis Strategy (2)

- **signal extraction**
  - remaining main background after $m_T(W) > 20\ \mathrm{GeV}$ → WZ+jets
  - idea: train Boosted Decision Tree (BDT) to enhance signal to background ratio
    - input variables: top quark mass, $\Delta\phi(l-b)$, $q \cdot |\eta|$ of W boson, Z boson kinematics, b-tagger value, …
    - train dedicated BDT for all four FCNC couplings: $\kappa_{gut}, \kappa_{gct}, \kappa_{Zut}, \kappa_{Zct}$



Results: Search for FCNC in tZ Events



brief summary:

- FCNC in single top complementary to $t\bar{t}$
- κ_{Zqt} 7 TeV limits competitive with $t\bar{t}$ & combination planned
- update to 8 TeV foreseen

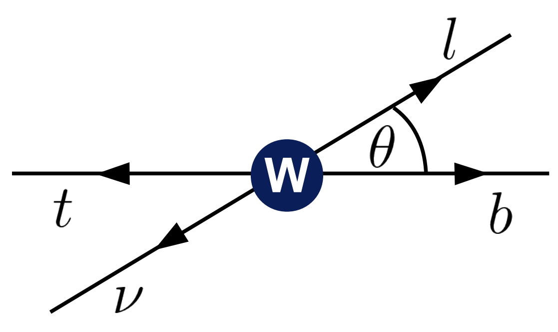
Measurement of W helicity Fractions

CMS-PAS-TOP-12-021

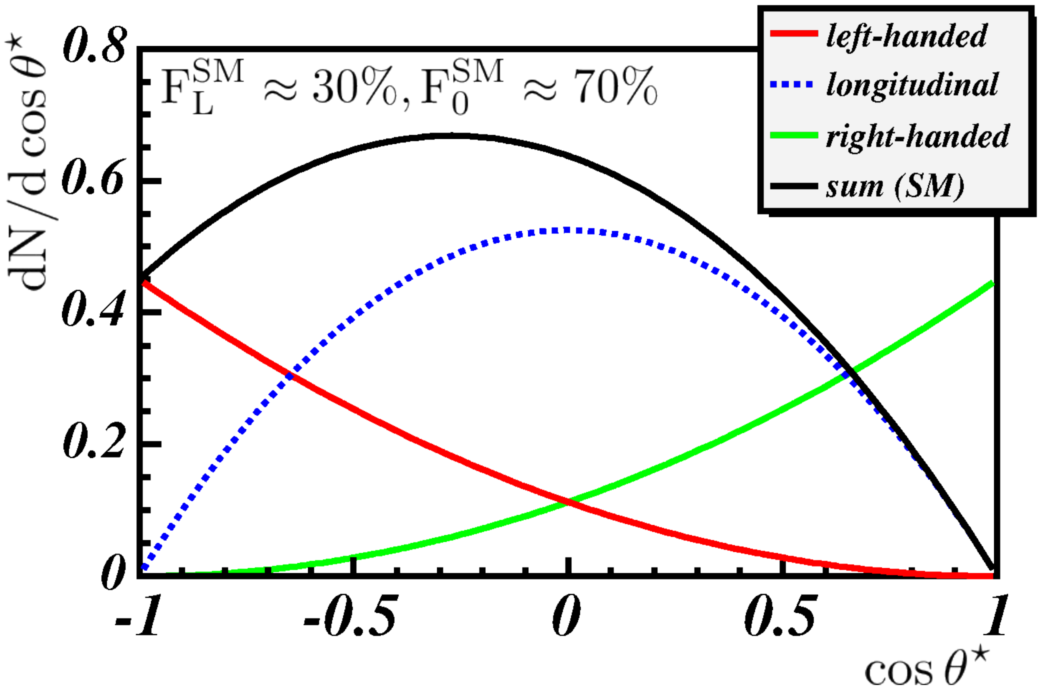
- **motivation**
  - top quark does not hardonize → angular distribution of decay products determined by $\mathcal{L}_{\mathrm{Wtb}}$ coupling structure (SM: V-A)
  - complementary to measurement in $\mathrm{t\bar{t}}$

- **definition:**
  - decompose top quark decay width

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

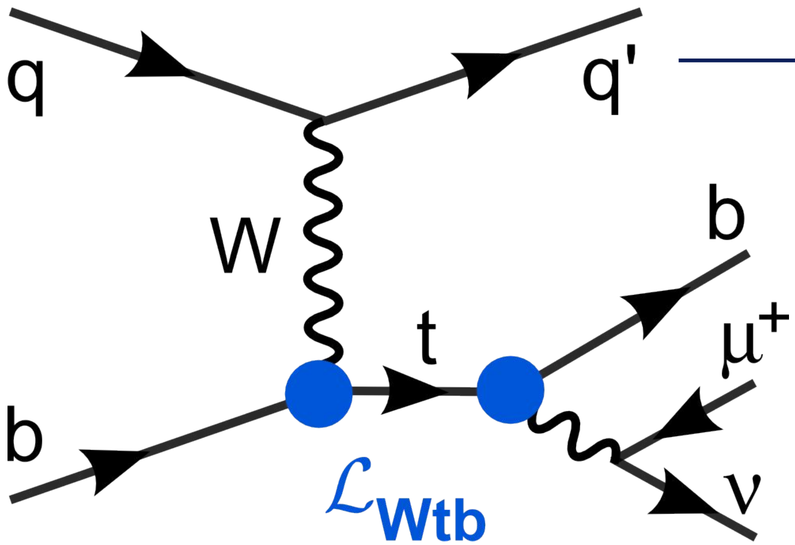


$$\cos\theta^{\star} = \frac{\vec{p}_{\mathrm{W}}^{\,(\mathrm{top})}\cdot\vec{p}_{\mathrm{l}}^{\,(\mathrm{W})}}{|\vec{p}_{\mathrm{W}}^{\,(\mathrm{top})}|\cdot|\vec{p}_{\mathrm{l}}^{\,(\mathrm{W})}|}$$



Analysis Strategy

- **selection of single top t-channel events**



→ jets: $p_T > 30\ (60)\ \mathrm{GeV}$ for 7 (8) TeV, $|\eta| < 4.5$

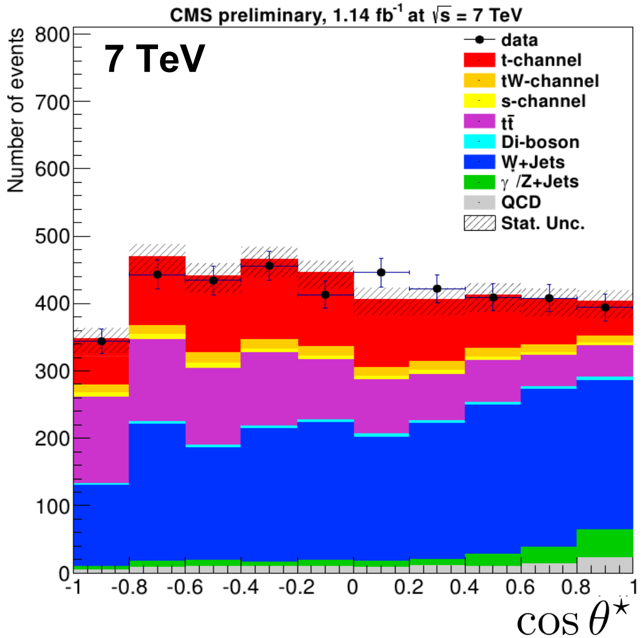
→ btagging: "track counting high purity"

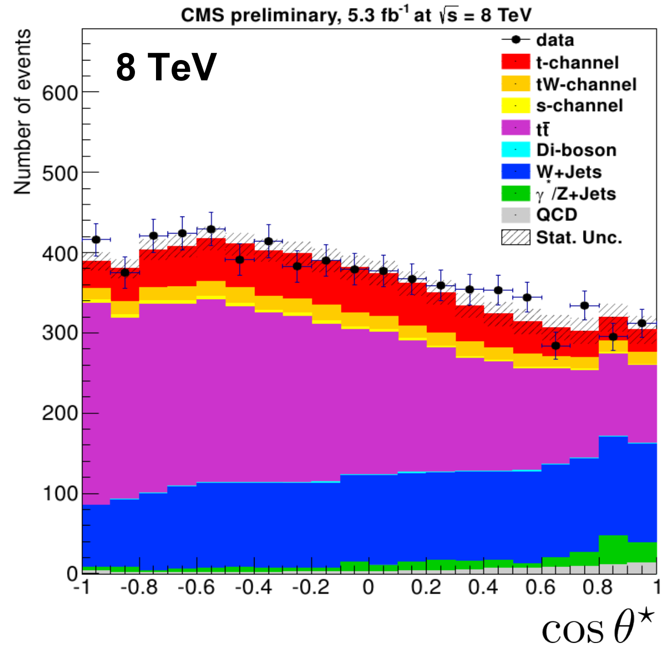
→ $p_T > 20\ (26)\ \mathrm{GeV}$ for 7 (8) TeV, $|\eta| < 2.1$

→ $m_T(W) > 40\ (50)\ \mathrm{GeV}$ to reject QCD

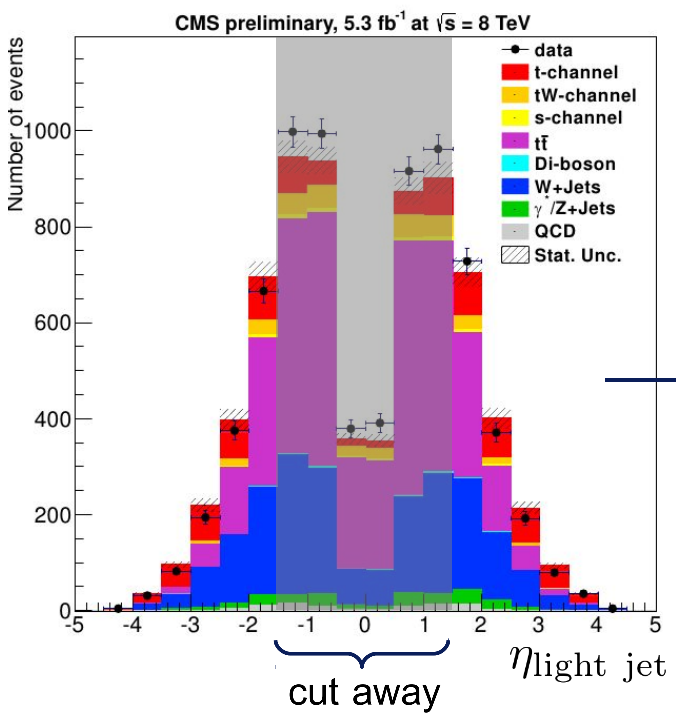
- **analyzed data**: $1.1\ \mathrm{fb}^{-1}$ at $7\ \mathrm{TeV}$ + $5.3\ \mathrm{fb}^{-1}$ at $8\ \mathrm{TeV}$ using isolated muon triggers

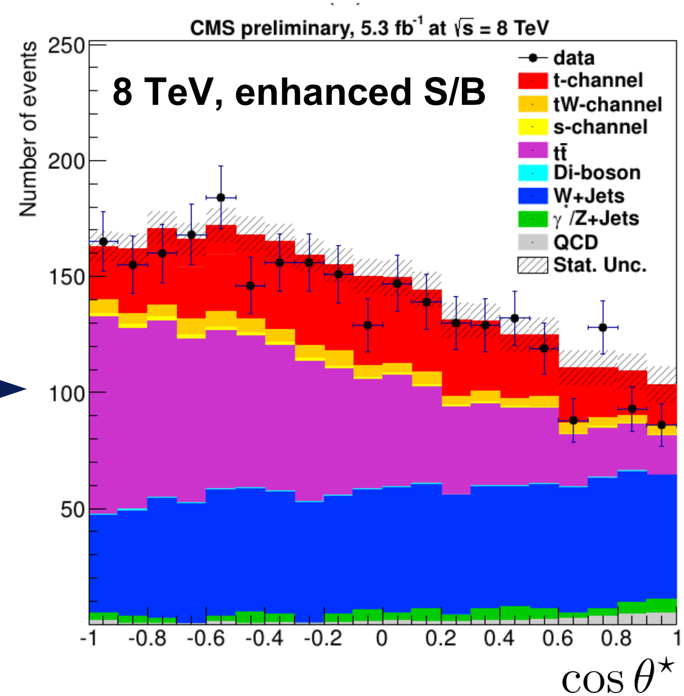
After Event Selection





- good agreement between data & MC
- W+jets and $t\bar{t}$ replace each other as the dominant systematic from 7 to 8 TeV





- specialty of single top t-channel production: very forward light jet

→ a cut can enhance the S/B ratio

→ not done by this analysis due to statistical limitations

Estimation of W Helicity Fractions

- **idea: fit signal, background contributions & $\vec{\mathrm{F}}$ simultaneously**
  - reweight signal to arbitrary W helicity fractions $\vec{\mathrm{F}} = (\mathrm{F_L}, \mathrm{F_0}, \mathrm{F_R})$

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

- **construct likelihood**
  - assume Poisson distribution per bin in $\cos\theta^\star$

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

with expected number of events depending per bin on

$$n_i^{MC;\vec{F}} = n_i^{bkg-other} + N_{Wjets} \times \beta_i^{Wjets} + f \times n_{i,rw}^{signal}$$

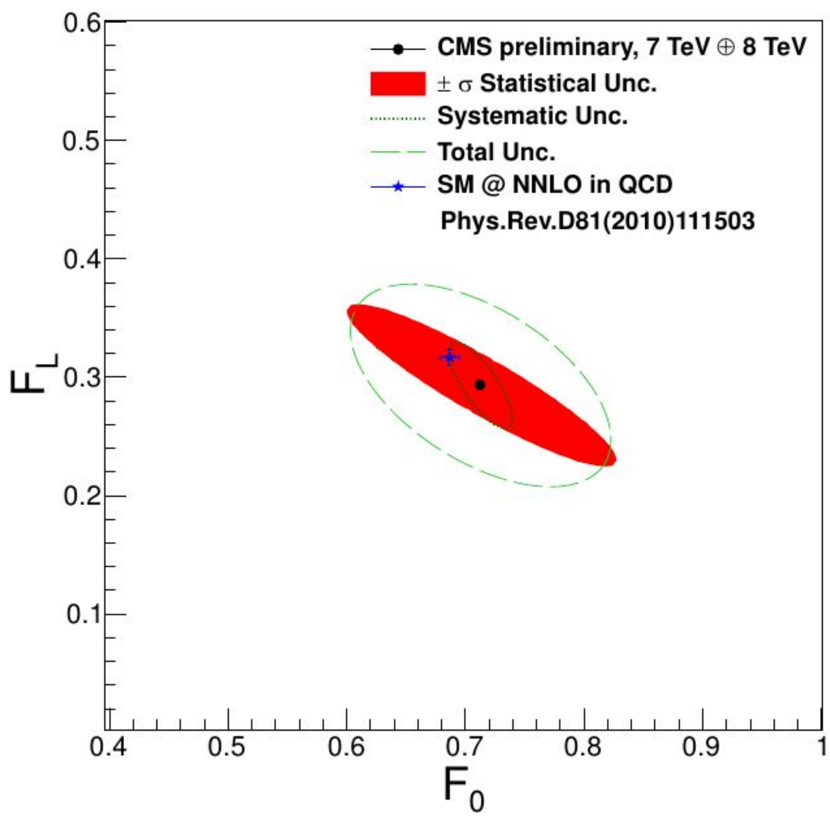
- $n_i^{bkg-other}$: expected background
- N_{Wjets}: expected W+jets contribution
- β_i^{Wjets}: W+jets template by inverting b-tag
- f: signal fraction
- $n_{i,rw}^{signal}$: reweighted signal

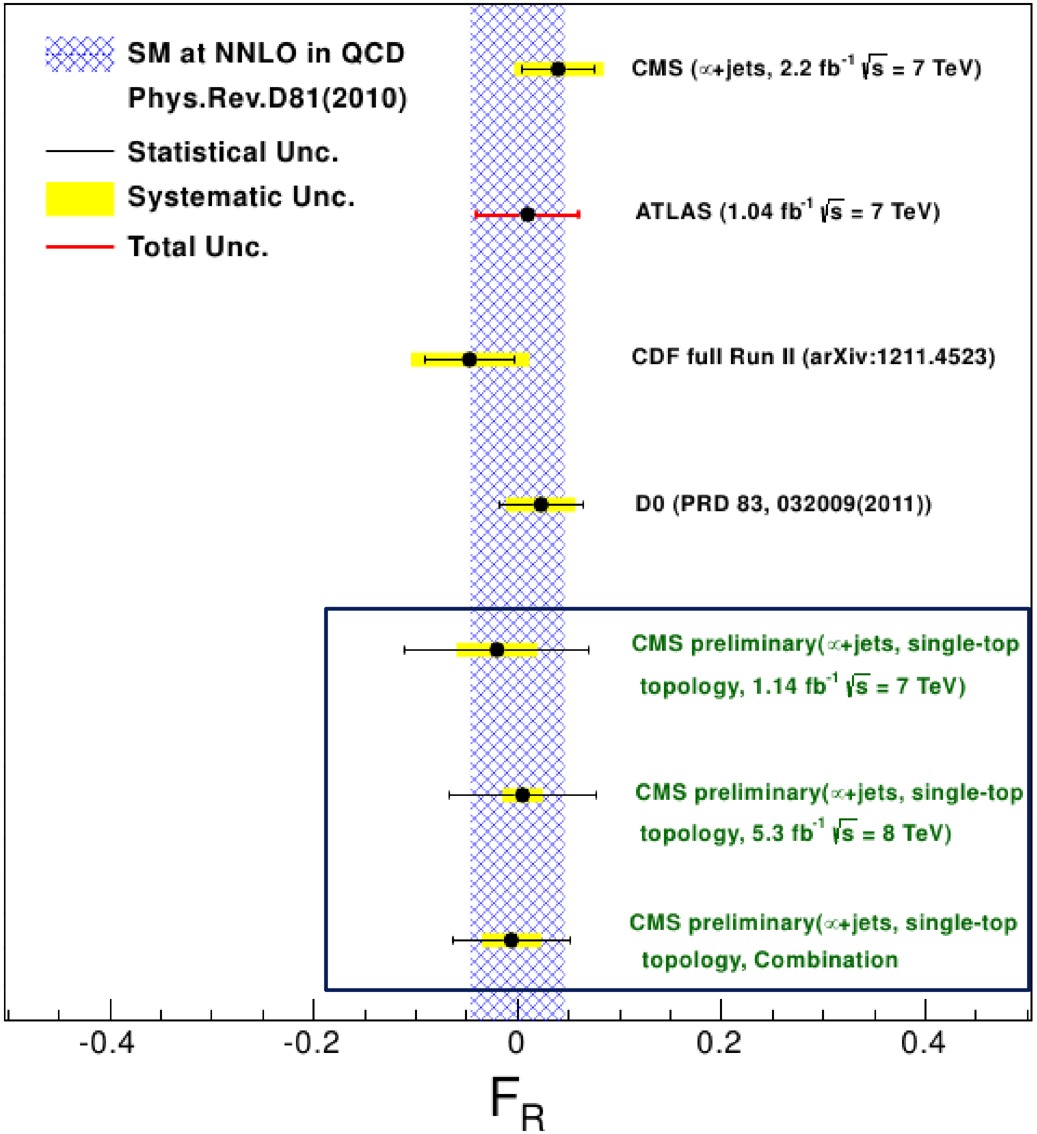
Result: W Helicities in Single Top

- **combined result:**

$$\mathcal{L}_{\mathrm{comb.}} = \mathcal{L}_{7\ \mathrm{TeV}} \cdot \mathcal{L}_{8\ \mathrm{TeV}}$$

$$F_L = 0.293 \pm 0.069(\mathrm{stat.}) \pm 0.030(\mathrm{syst.}),$$
$$F_0 = 0.713 \pm 0.114(\mathrm{stat.}) \pm 0.023(\mathrm{syst.}),$$
$$F_R = -0.006 \pm 0.057(\mathrm{stat.}) \pm 0.027(\mathrm{syst.})$$
$$\rho = -0.92$$





→ result in agreement with previous analyses in $t\bar{t}$ topology from CMS, ATLAS, CDF, and D0

Limits on Anomalous Couplings

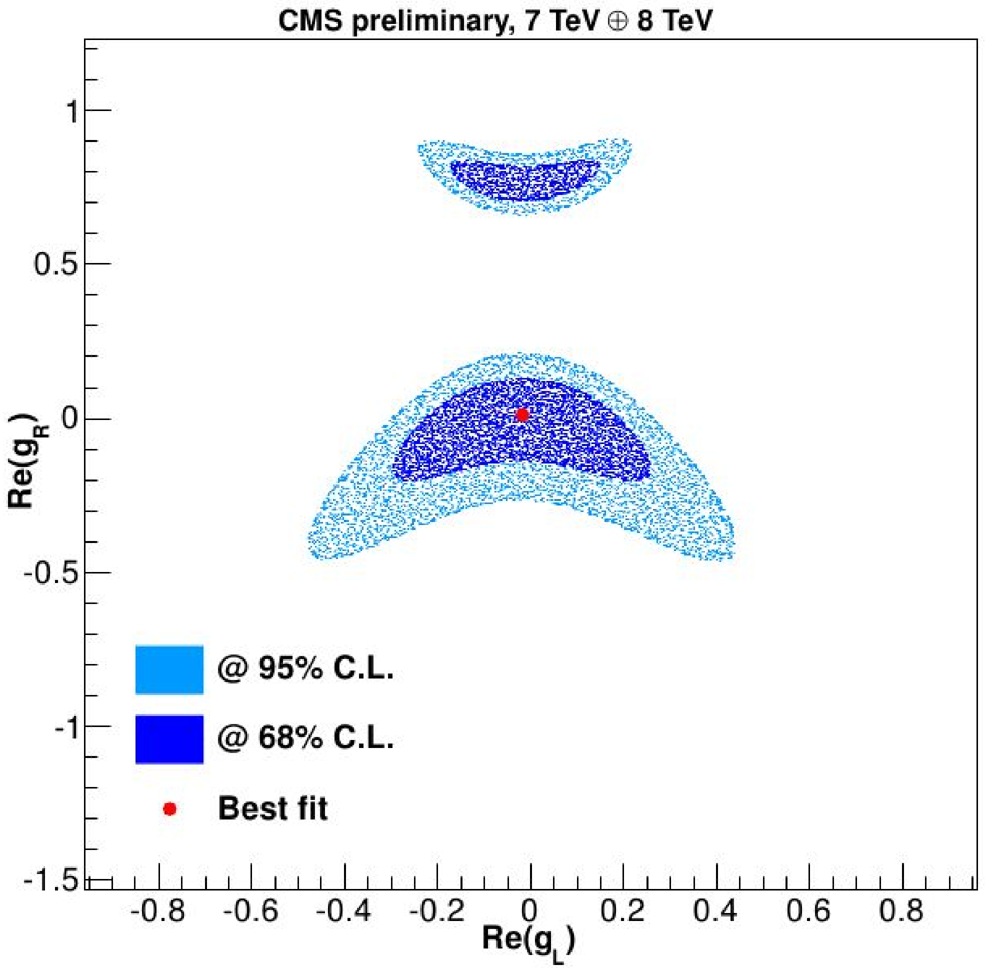
- **definition**
  - interpret result in terms of anomalous Wtb couplings

$$\mathcal{L}_{\mathrm{Wtb}} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}\Big(V_L P_L + V_R P_R\Big)tW_{\mu} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}^{W}}{m_W}\Big(g_L P_L + g_R P_R\Big)tW_{\mu} + \mathrm{h.c.}$$

    - vector-like couplings: V_L, V_R
    - tensor-like couplings: g_L, g_R

- **result**
  - W helicity measurement has highest sensitivity on tensor-like couplings
  - limits compatible with SM prediction: $g_L^{SM} = g_R^{SM} = 0$

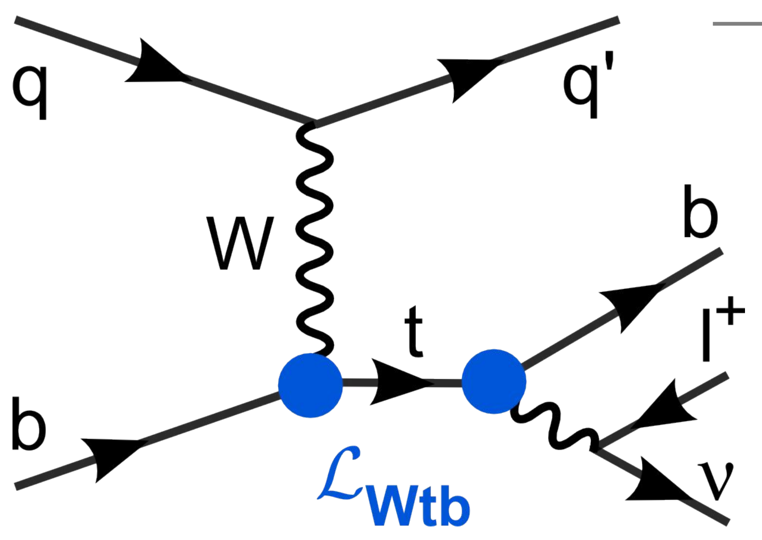
- **future**
  - paper in preparation including:
    - $20\ \mathrm{fb}^{-1}$ at $8\ \mathrm{TeV}$ data
    - electron channel will be added



Top Quark Polarization

CMS-PAS-TOP-13-001

- **top quark are polarized in t-channel single top production**



SM: top highly polarized along light quark $(\mathrm{P}_{\mathrm{t}}^{\mathrm{Powheg}} = 0.863)$

Wtb coupling structure encoded in kinematics of decay products (SM: V-A coupling structure)

- **analysis of coupling structure**
  - extract distribution of angle between light quark & lepton (electron, muon) in top quark rest frame
  - calculate asymmetry to probe coupling structure [1]

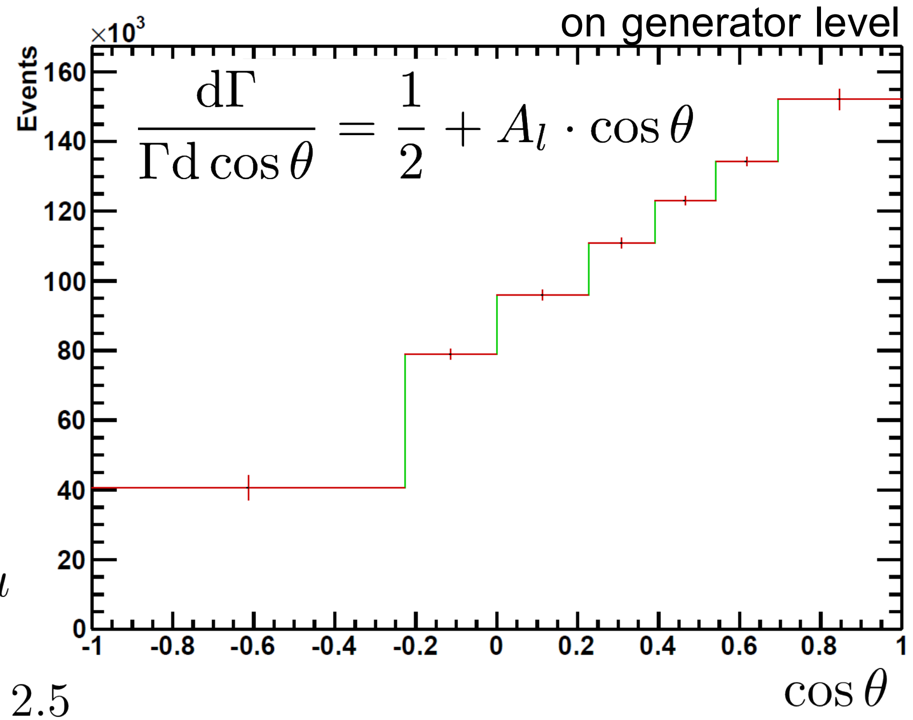
$$\mathrm{A} = \frac{N_{\uparrow} - N_{\downarrow}}{N_{\uparrow} + N_{\downarrow}} = \frac{1}{2}\mathrm{P}_{\mathrm{t}} \cdot \alpha_l \quad \text{where} \quad \alpha_l \equiv \alpha_l(\mathrm{V_L}, \mathrm{V_R}, \mathrm{g_L}, \mathrm{g_R})$$

[1] J. A. Aguilar-Saavedra et. al., *W polarisation beyond helicity fractions in top quark decays*, arXiv:1005.5382 [hep-ph]

Analysis Strategy

- **definition**

$$\cos\theta = \frac{\vec{p}_l^{\,(\mathrm{top})} \cdot \vec{p}_{\mathrm{lightquark}}^{\,(\mathrm{top})}}{|\vec{p}_l^{\,(\mathrm{top})}| \cdot |\vec{p}_{\mathrm{lightquark}}^{\,(\mathrm{top})}|}$$

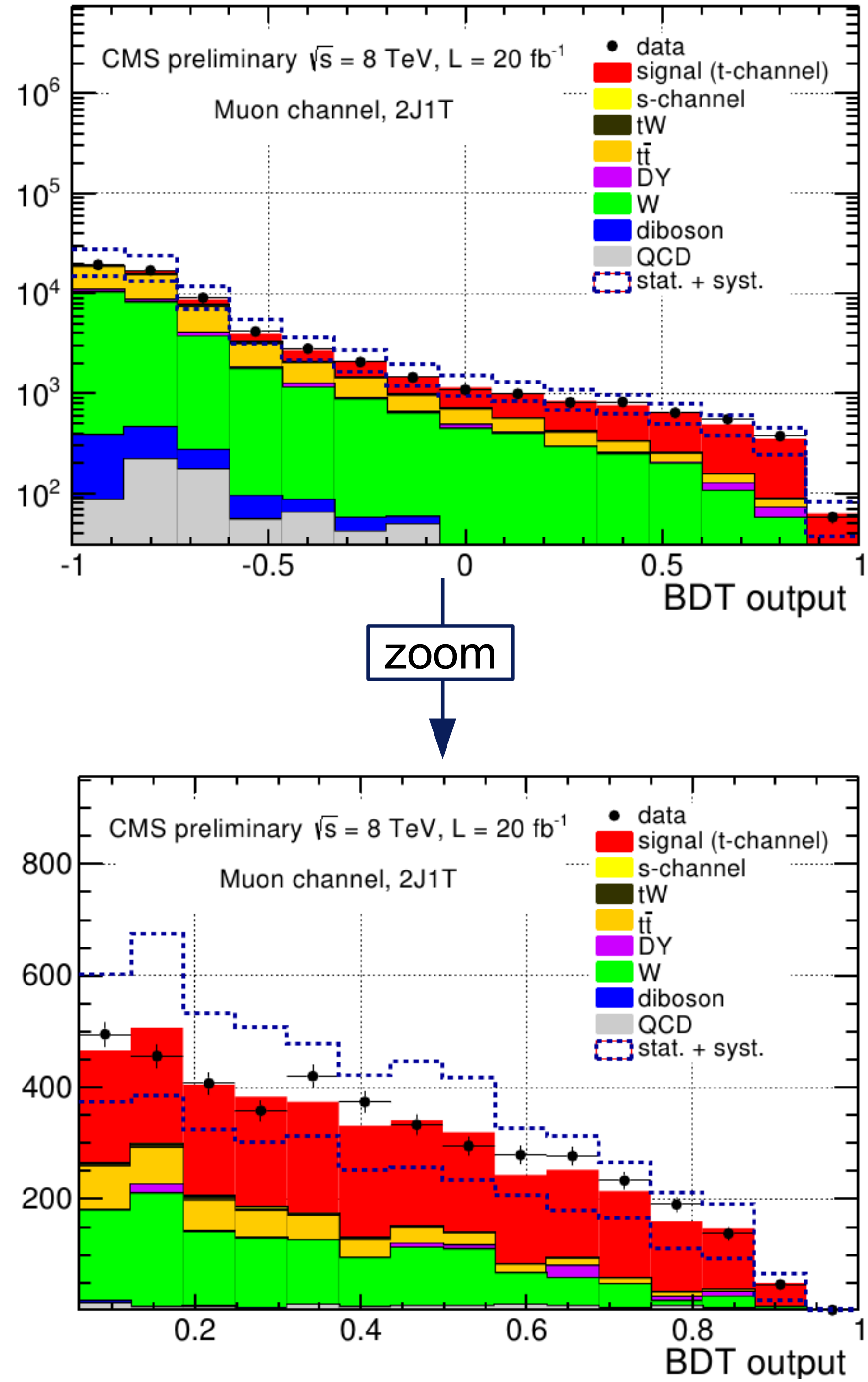


- **analysis overview**
  - event selection
    - similar to W helicity analysis for $\mathrm{W} \to \nu\mu$
    - $\mathrm{W} \to \nu\mathrm{e}$ events: $\mathrm{E}_{\mathrm{T}}^{\mathrm{mis}} > 45\mathrm{GeV}$
      isolated electron with: $\mathrm{p_T} > 30\ \mathrm{GeV}, |\eta| < 2.5$
  - selection of signal enhanced phase space using BDT
  - estimation of signal and background fractions
    → extraction of $\cos\theta$ from data from high S/B phase space region
  - unfolding of $\cos\theta$
  - calculate asymmetry

- **analyzed data:** $20\ \mathrm{fb}^{-1}$ at $8\ \mathrm{TeV}$ using single isolated lepton triggers

Analysis Strategy (2)

- **select signal enhanced phase space**
  - train BDT and select event with high output
  - input variables were selected not to bias $\cos\theta^{\star}$
    - top quark mass, η_{lightjet}, event shape C, jet masses, $\mathrm{p_T^{bjet}}$, $\mathrm{p_T^{lepton}}$ $\mathrm{m_T(W)}$, $\mathrm{E_T^{mis}}$

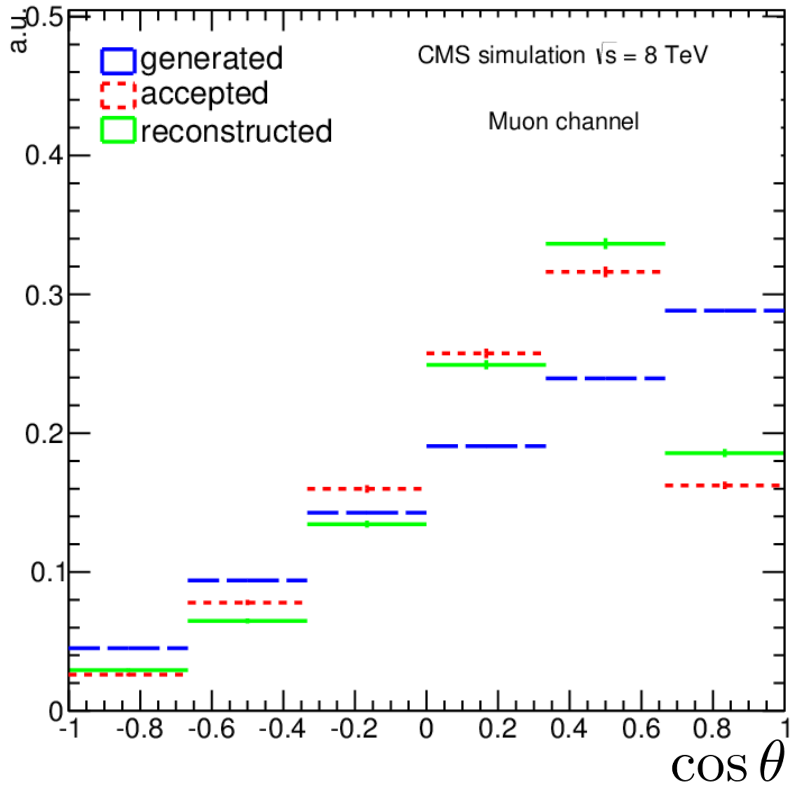


- **estimate signal & background fractions**
  - template fit of BDT output shape
  - no bias on $\cos\theta^{\star}$ by construction

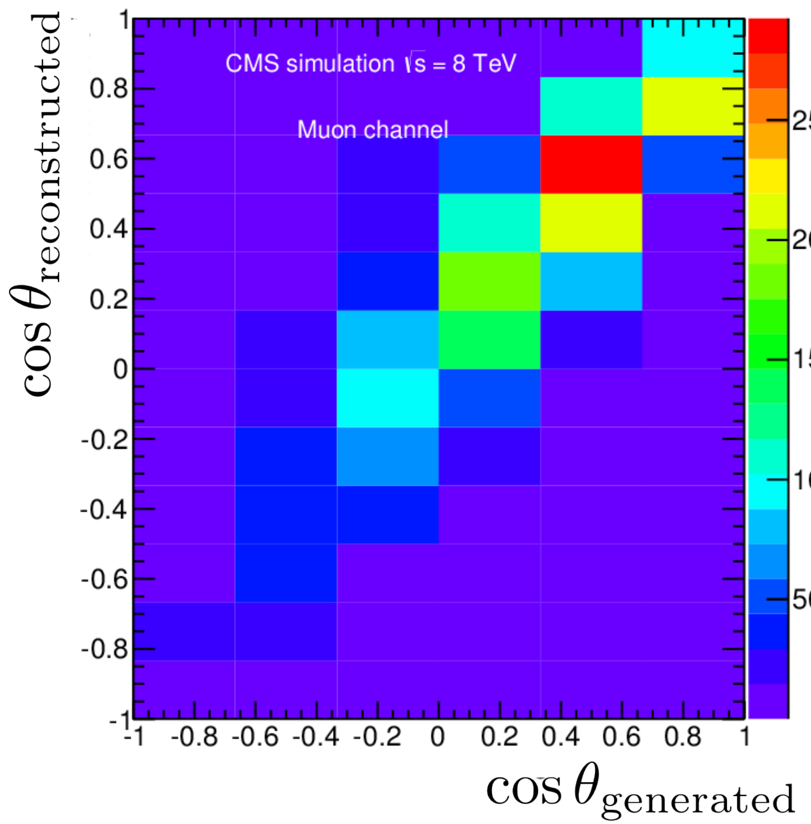
Unfolding

- to compare asymmetry with theory
  → invert detector reconstruction and acceptance
- unfolding algorithm based on regularized inversion of response matrix (“TUnfold” [1])

shape comparison between various stages



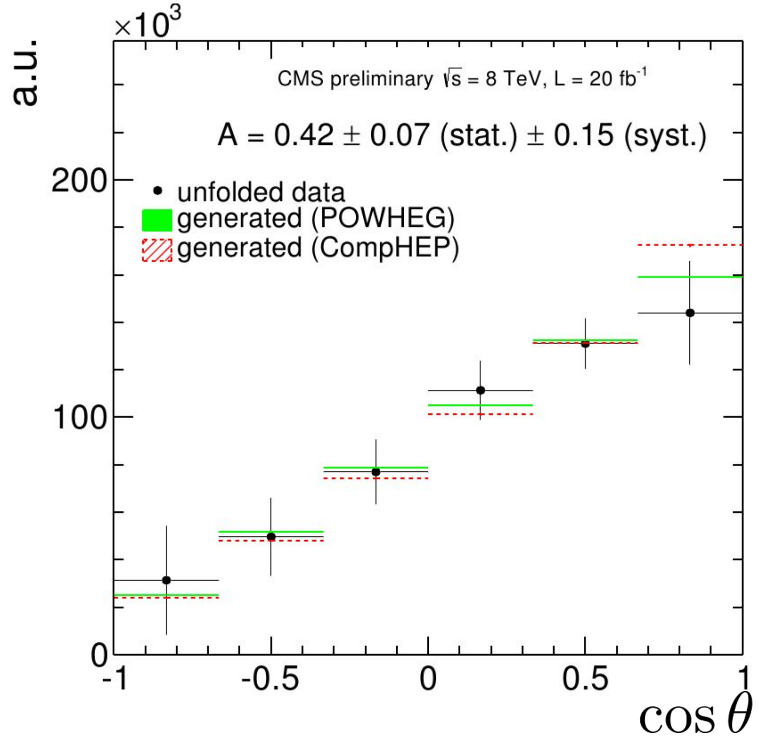
derived response matrix

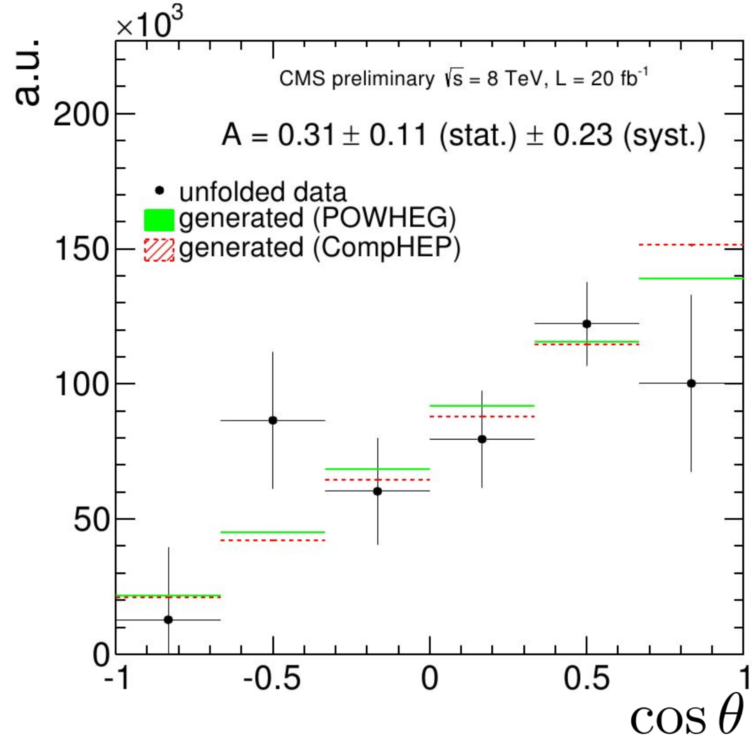


[1] Stefan Schmitt, *Tunfold: An algorithm for correcting migration effects in high energy physics*, arXiv:1205.6201 [physics.data-an]

Result

- **unfolded distributions**





- **combination with BLUE**

$$\mathrm{A_l} = 0.41 \pm 0.06(\mathrm{stat.}) \pm 0.16(\mathrm{sys.}) = 0.41 \pm 0.17$$

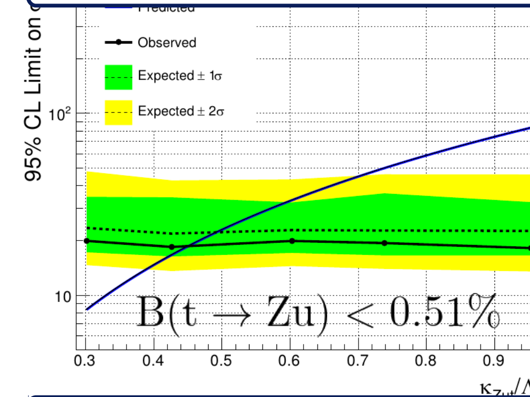
corresponds to a polarization of $\mathrm{P_t} = 2\alpha_\mathrm{l} \cdot \mathrm{A_l} = \boxed{0.82 \pm 0.34}$ assuming $\alpha_\mathrm{l} = 1$

- **future**
  - drop $\alpha_\mathrm{l} = 1$ assumption and combine with results from W helicitiy & cross section measurements in a very model-independent way

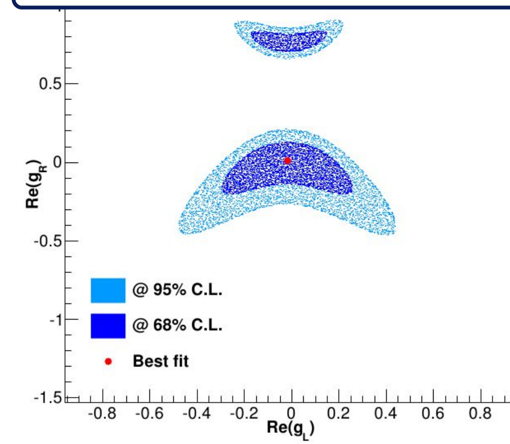
Conclusion

- **anomalous couplings**
  - parameterizes effects of BSM physics through effective parameters
  - model-independent probe for new physics
- **FCNC & W boson helicity fraction**
  - single top topology as orthogonal category to $t\bar{t}$
  - combination of results possible
- **top polarization measurement**
  - only in single top topology possible
  - shows possibility of performing differential measurements
- **future**
  - updates on all three analysis coming soon

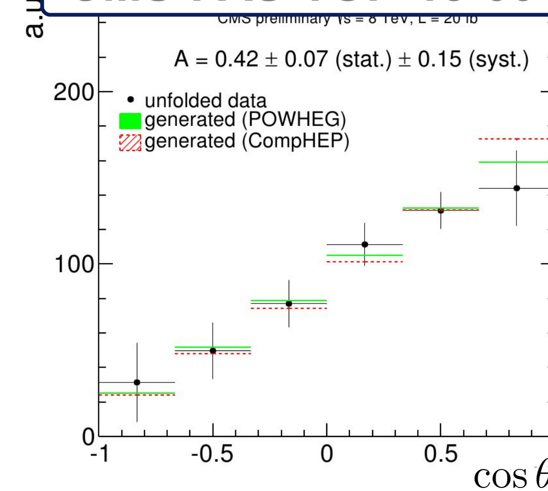
CMS-PAS-TOP-12-021



CMS-PAS-TOP-12-020

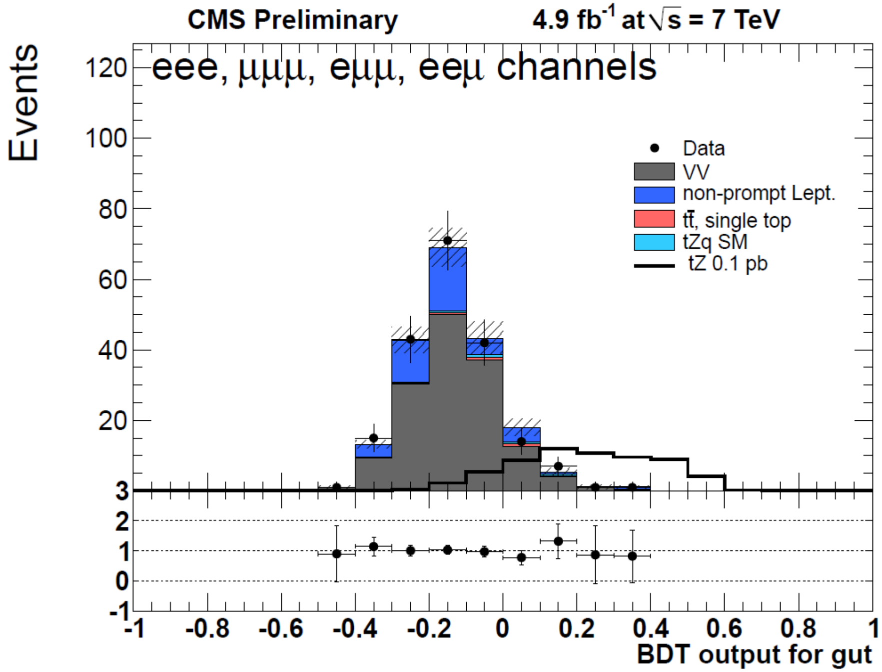


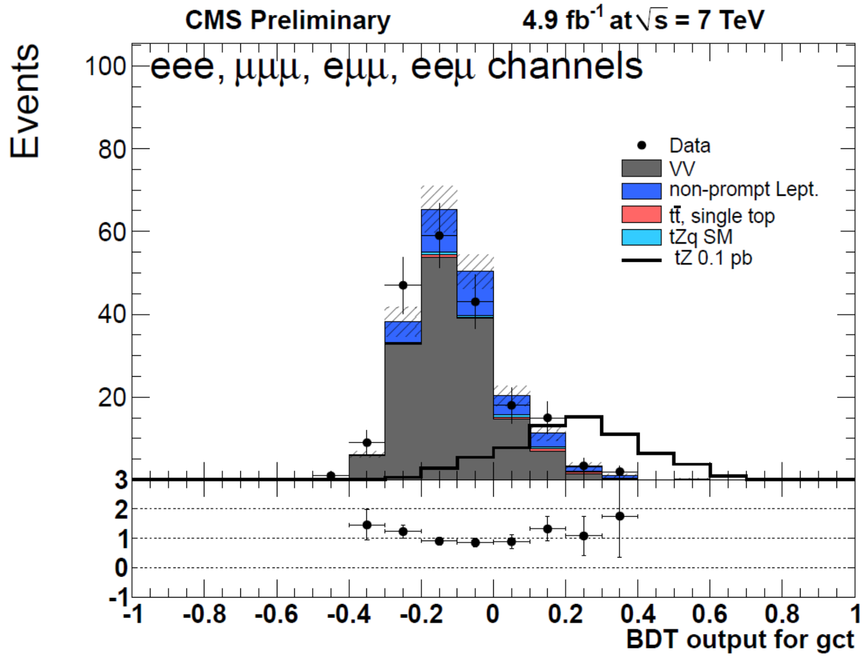
CMS-PAS-TOP-13-001

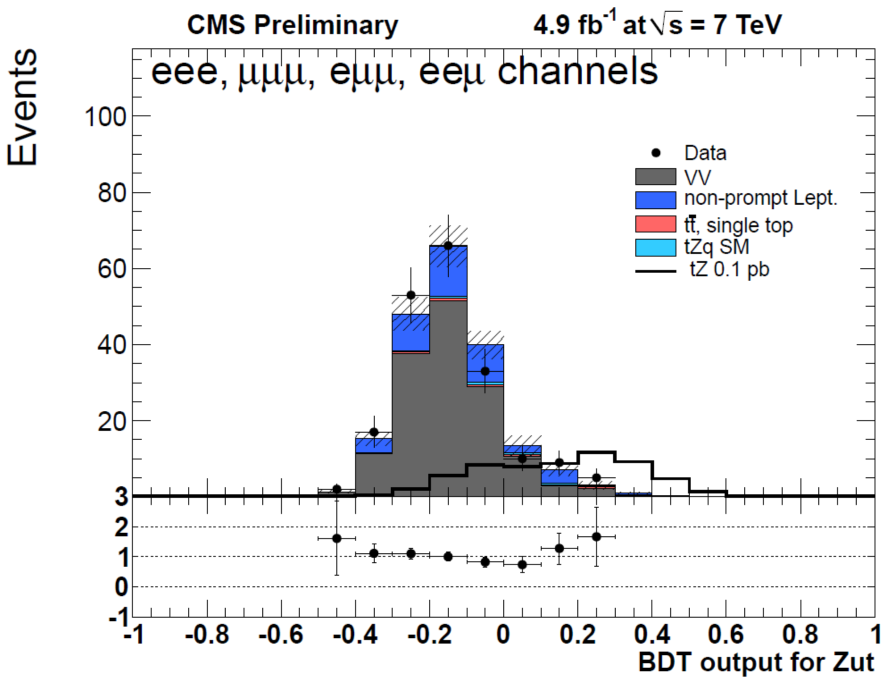


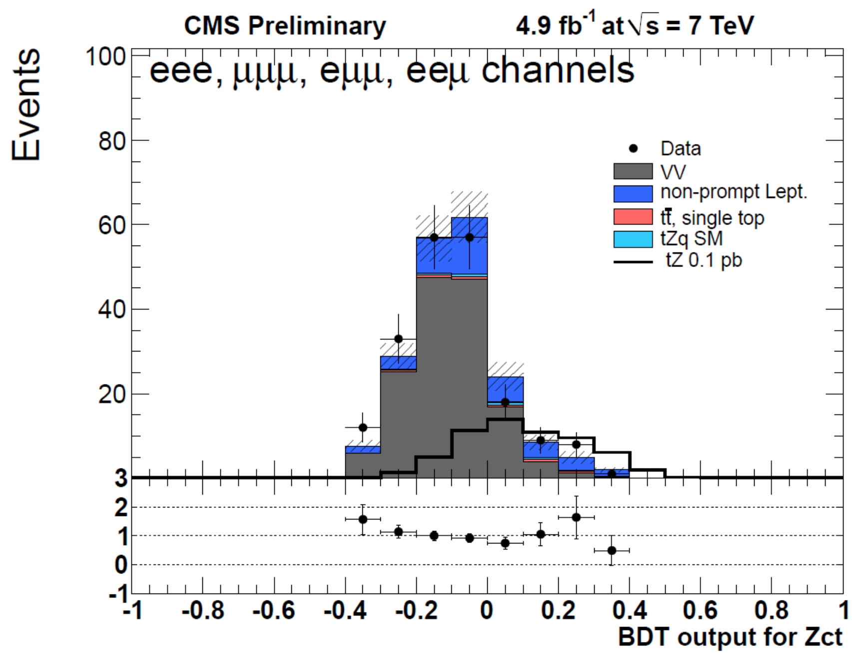
Backup

All BDTs for FCNC



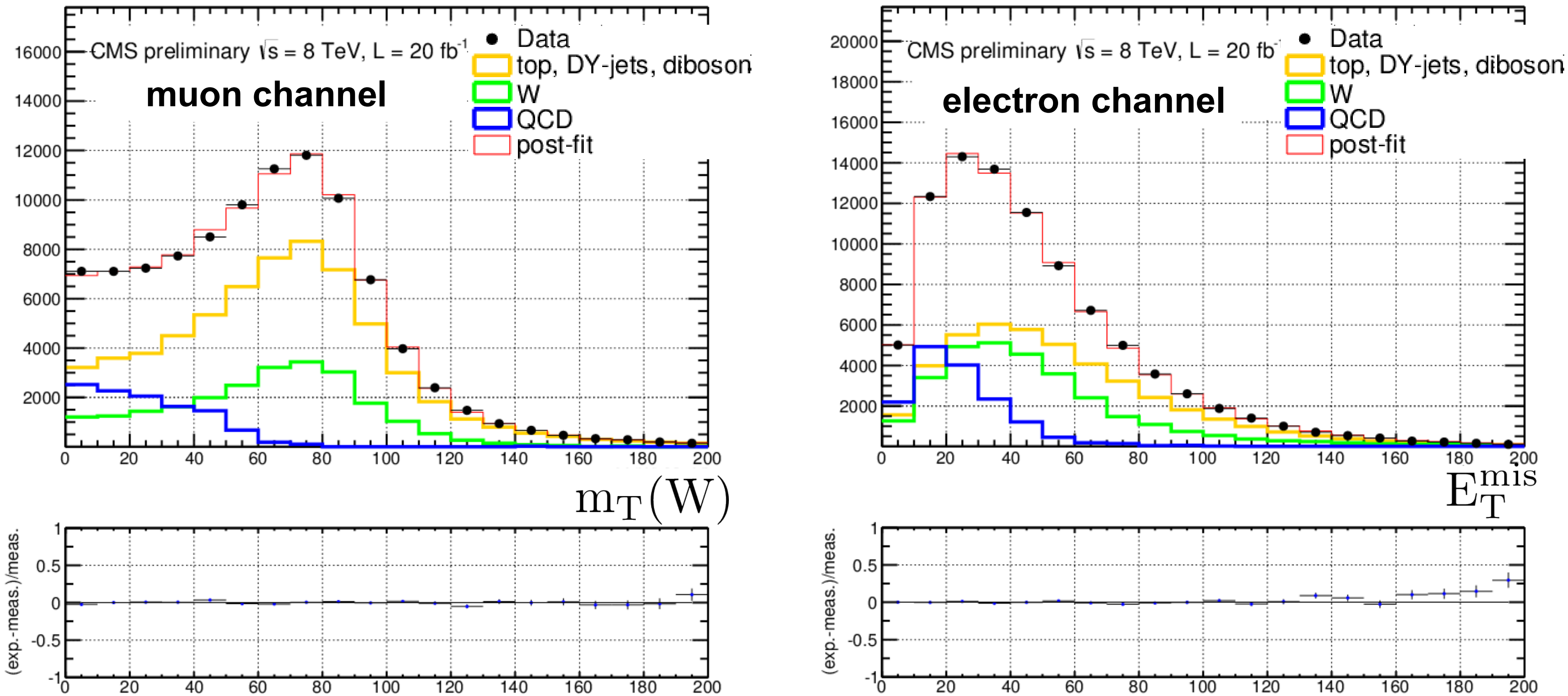






Estimation of QCD in Top Polarization

- **template fit**
  - input: W+jets, QCD template from anti-isolated region,
    other (top processes, DY+jets, di-boson)



→ good agreement after fit

→ to suppress QCD in final selection: $m_T(W) > 50\ \mathrm{GeV}$ for muon channel,
$E_T^{mis} > 45\ \mathrm{GeV}$ for electron channel

FCNC Uncertainties

- trigger & lepton selection efficiencies
- 30% on normalization of ZZ+jets
- LO tZq cross section uncertainty: 50%
- isolation veto window for Z+jets: ±0.1
- pT modeling of Z bosons in WZ/ZZ+jets
- JES, b-tagging, CSV-shape
- matching, renormalization & factorization scale
- tZq top quark mass ±2 GeV
- PDF
- 2.5% on luminosity
- 5% on minimum-bias cross section for pileup description

W Helicity Fraction Uncertainties

	$\sqrt{s} = 8\,\text{TeV}$		$\sqrt{s} = 7\,\text{TeV}$	
Systematic source	ΔF_L	ΔF_0	ΔF_L	ΔF_0
JES	0.006	0.006	0.020	0.020
JER	0.008	0.003	0.015	0.010
unclustered energy	0.013	0.003	0.015	0.015
pileup	0.002	0.003	0.004	0.000
b-flavored scale factor	0.004	0.006	0.009	0.009
non-b-flavored scale factor	0.004	0.007	0.002	0.001
single-top generator	0.008	0.014	0.004	0.004
Q^2 scale	0.009	0.012	0.040	0.007
m_{top}	0.005	0.006	0.010	0.010
PDF	0.005	0.005	0.000	0.000
$t\bar{t}$ normalization	0.002	0.003	0.008	0.008
QCD shape	0.002	0.002	0.004	0.004
W+jets shape	0.008	0.010	0.010	0.010
integrated luminosity	0.003	0.003	0.007	0.007
SM W-helicity reference	0.004	0.003	0.001	0.002
total systematic uncertainty (w/o generator)	0.022	0.021	0.054	0.035
total systematic uncertainty	0.024	0.026	0.054	0.035

Top Polarization Uncertainties

Uncertainty source	δA_l^{μ}	δA_l^{e}
generator	0.025	0.009
Q^2 scale t-channel	0.024	0.055
Q^2 scale, $t\bar{t}$	0.015	0.005
Q^2 scale, W+jets	0.036	0.038
top quark mass	0.058	0.042
W+jets shape	0.016	0.007
W+jets flavour	0.005	0.008
top p_T, $t\bar{t}$	0.010	0.025
matching, $t\bar{t}$	0.028	0.052
matching, W+jets	0.025	0.038
PDF	0.013	0.014
JES	0.074	0.074
JER	0.016	0.179
unclustered $\not{E}_T$	0.013	0.006
lepton ID and isolation	0.001	0.002
lepton trigger	0.001	0.002
pileup	0.015	0.002
b tagging	0.007	0.009
mistagging	0.001	0.003
lepton weight	0.001	0.009
anti-isolation range of QCD	0.010	0.053
QCD fraction	0.092	0.028
background fractions	0.007	0.018
unfolding bias	0.002	0.003
total systematics	0.15	0.23
statistical	0.07	0.11
total	0.17	0.26

Product Operator Expansion

- Lagrangian

$$\mathcal{L}^{\mathrm{OS}}_{Vf_if_j} = \bar{f}_j\,\gamma^\mu\,(\mathcal{A}_L P_L + \mathcal{A}_R P_R)\,f_i\,V_\mu + \bar{f}_j\,i\sigma^{\mu\nu}q_\nu\,(\mathcal{B}_L P_L + \mathcal{B}_R P_R)\,f_i\,V_\mu + \mathrm{H.c.}$$

- expansion

$$\mathcal{L}^{\mathrm{eff}} = \sum \frac{C_x}{\Lambda^2} O_x + \ldots$$

- dimension-six gauge-invariant operators

$$O^{(3,ij)}_{\phi q} = i(\phi^\dagger \tau^I D_\mu \phi)(\bar{q}_{Li}\gamma^\mu \tau^I q_{Lj})\,,$$
$$O^{(1,ij)}_{\phi q} = i(\phi^\dagger D_\mu \phi)(\bar{q}_{Li}\gamma^\mu q_{Lj})\,,$$
$$O^{ij}_{\phi\phi} = i(\tilde{\phi}^\dagger D_\mu \phi)(\bar{u}_{Ri}\gamma^\mu d_{Rj})\,,$$
$$O^{ij}_{\phi u} = i(\phi^\dagger D_\mu \phi)(\bar{u}_{Ri}\gamma^\mu u_{Rj})\,,$$
$$O^{ij}_{uW} = (\bar{q}_{Li}\sigma^{\mu\nu}\tau^I u_{Rj})\tilde{\phi}\,W^I_{\mu\nu}\,,$$
$$O^{ij}_{dW} = (\bar{q}_{Li}\sigma^{\mu\nu}\tau^I d_{Rj})\phi\,W^I_{\mu\nu}\,,$$
$$O^{ij}_{uB\phi} = (\bar{q}_{Li}\sigma^{\mu\nu} u_{Rj})\tilde{\phi}\,B_{\mu\nu}\,,$$
$$O^{ij}_{Du} = (\bar{q}_{Li}\,D_\mu u_{Rj})\,D^\mu\,\tilde{\phi}\,,$$
$$O^{ij}_{\bar{D}u} = (D_\mu \bar{q}_{Li}\,u_{Rj})\,D^\mu\,\tilde{\phi}\,,$$
$$O^{ij}_{Dd} = (\bar{q}_{Li}\,D_\mu d_{Rj})\,D^\mu\,\phi\,,$$
$$O^{ij}_{\bar{D}d} = (D_\mu \bar{q}_{Li}\,d_{Rj})\,D^\mu\,\phi\,,$$
$$O^{ij}_{qW} = \bar{q}_{Li}\gamma^\mu \tau^I D^\nu q_{Lj} W^I_{\mu\nu}\,,$$
$$O^{ij}_{qB} = \bar{q}_{Li}\gamma^\mu D^\nu q_{Lj} B_{\mu\nu}\,,$$
$$O^{ij}_{uB} = \bar{u}_{Ri}\gamma^\mu D^\nu u_{Rj} B_{\mu\nu}\,,$$

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Effective FCNC Couplings

- effective Lagrangian

$$\begin{aligned}\mathcal{L}_{Ztc} &= -\frac{g}{2c_W}\bar{c}\,\gamma^\mu\left(X^L_{ct}P_L + X^R_{ct}P_R\right)t\;Z_\mu \\ &\quad -\frac{g}{2c_W}\bar{c}\,\frac{i\sigma^{\mu\nu}q_\nu}{M_Z}\left(\kappa^L_{ct}P_L + \kappa^R_{ct}P_R\right)t\;Z_\mu + \mathrm{H.c.}\end{aligned}$$

- originates from operators

$$\delta X^L_{ct} = \frac{1}{2}\left[C^{(3,23)}_{\phi q} + C^{(3,32)*}_{\phi q} - C^{(1,23)}_{\phi q} - C^{(1,32)*}_{\phi q}\right]\frac{v^2}{\Lambda^2}\,,$$

$$\delta X^R_{ct} = -\frac{1}{2}\left[C^{23}_{\phi u} + C^{32*}_{\phi u}\right]\frac{v^2}{\Lambda^2}\,,$$

$$\delta\kappa^L_{ct} = \sqrt{2}\left[c_W C^{32*}_{uW} - s_W C^{32*}_{uB\phi}\right]\frac{v^2}{\Lambda^2}\,,$$

$$\delta\kappa^R_{ct} = \sqrt{2}\left[c_W C^{23}_{uW} - s_W C^{23}_{uB\phi}\right]\frac{v^2}{\Lambda^2}\,.$$

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Effective Wtb Couplings

- effective Lagrangian

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

- originate from operators

$$\delta V_L = C_{\phi q}^{(3,33)*}\frac{v^2}{\Lambda^2}\,, \qquad \delta g_L = \sqrt{2}C_{dW}^{33*}\frac{v^2}{\Lambda^2}$$

$$\delta V_R = \frac{1}{2}C_{\phi\phi}^{33}\frac{v^2}{\Lambda^2}\,, \qquad \delta g_R = \sqrt{2}C_{uW}^{33}\frac{v^2}{\Lambda^2}$$

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