Measurement of the properties of top quarks in decays

(includes top quark and W polarisation, top quark charge and couplings)

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Outline

- W helicity in top decays
- Electroweak couplings:
  - associated tt+γ production
  - associated tt+Z and tt+W production
- Branching ratio: R=B(t→Wb)/B(t→Wq)
- FCNC

W helicity in top decays

- Very sensitive to additional contributions: (BSM or "anomalous") couplings - **important test of Wtb structure**
- W helicity fractions measured from angular distributions:
  - cos(θ*): in t rest frame - **angle between down-type fermion momentum in W rest frame and W momentum in top rest frame**

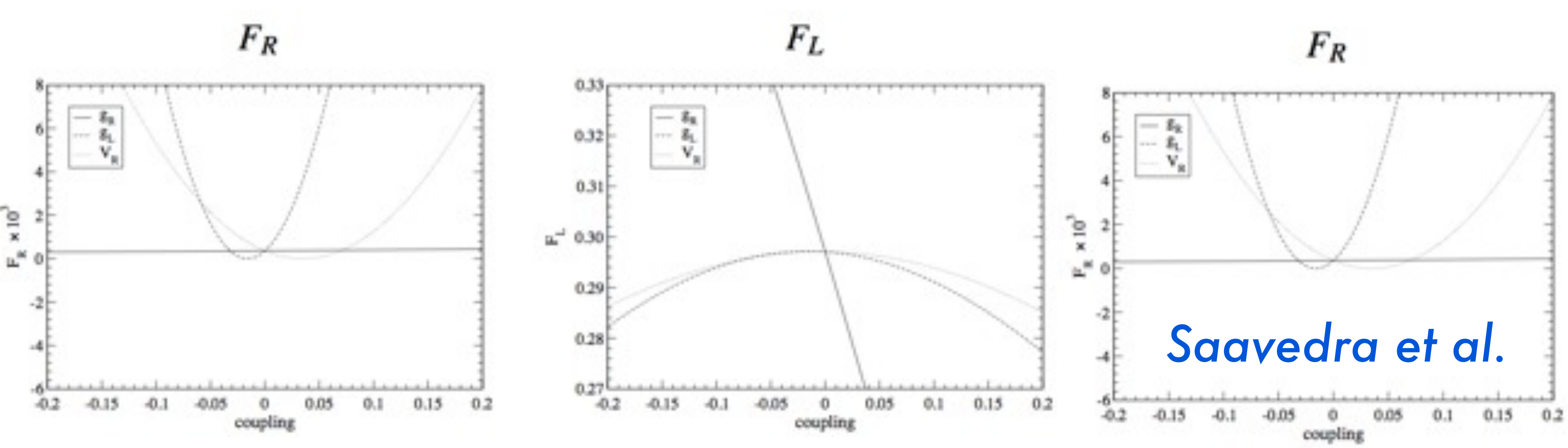
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = \frac{3}{8}(1-\cos\theta^*)^2 F_L + \frac{3}{8}(1+\cos\theta^*)^2 F_R + \frac{3}{4}\sin^2\theta^* F_0$$

in SM (LO):
F_0=0.6902
F_L=0.3089
F_R=0.0009

- General vertex langrangian:

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

In the SM: $V_L = V_{tb} \cong 1$ V_R, g_L, g_R are all =0

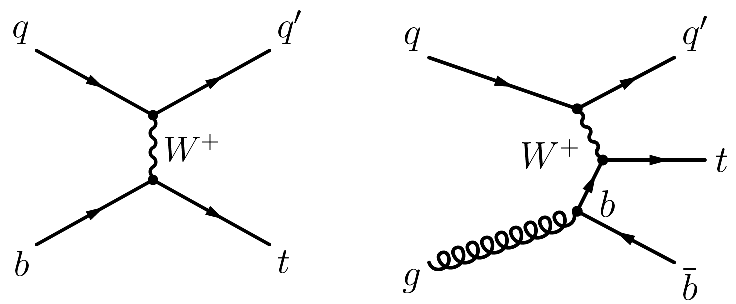


Straightforward to interpret fractions in terms of anomalous couplings:

simple polynomial dependence

W helicity in top decays

Single-top topology



Data: pp@ 7 TeV (1.14 fb^{-1}) / 8 TeV (5.3 fb^{-1})

Selection for 7 / 8 TeV:

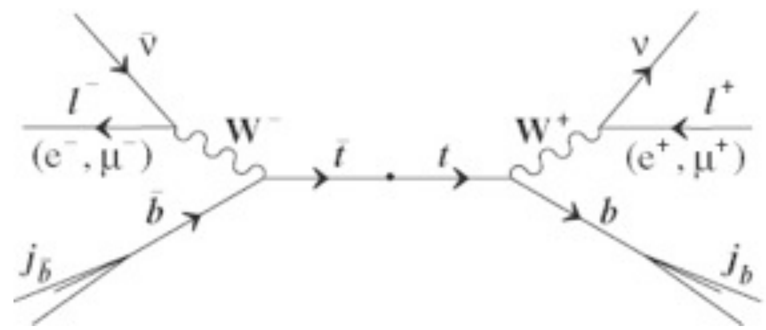
1 muon p_T>20 / p_T>26 GeV

Exactly *2 jets* p_T> 30 / p_T>60 GeV

Exactly 1 tagged as b

M_T>40 / M_T>50 GeV (W transverse mass)

ll+jets



Data: pp@ 7 TeV (4.6 fb^{-1})

2 isolated leptons (e/μ) p_T>20 GeV

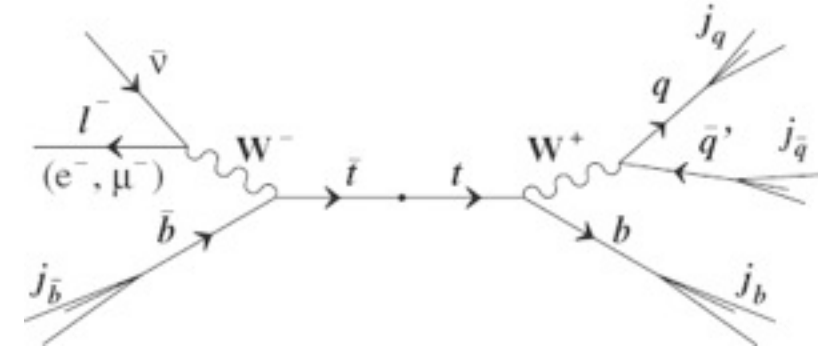
In ee and μμ channels: reject evt in Z mass window 76< M_{ll} <106 GeV

At least *2 jets* p_T> 30 GeV

At least 1 tagged as b

E_T^{miss}>30 (ee/μμ) or E_T^{miss}>20 (eμ) GeV

l+jets



Data: pp@ 7 TeV (5.0 fb^{-1})

Exactly *1 lepton*

p_T>26 (muon) or p_T>30 (electron channel) GeV

At least *4 jets* p_T> 30 GeV

At least 2 jets tagged as b

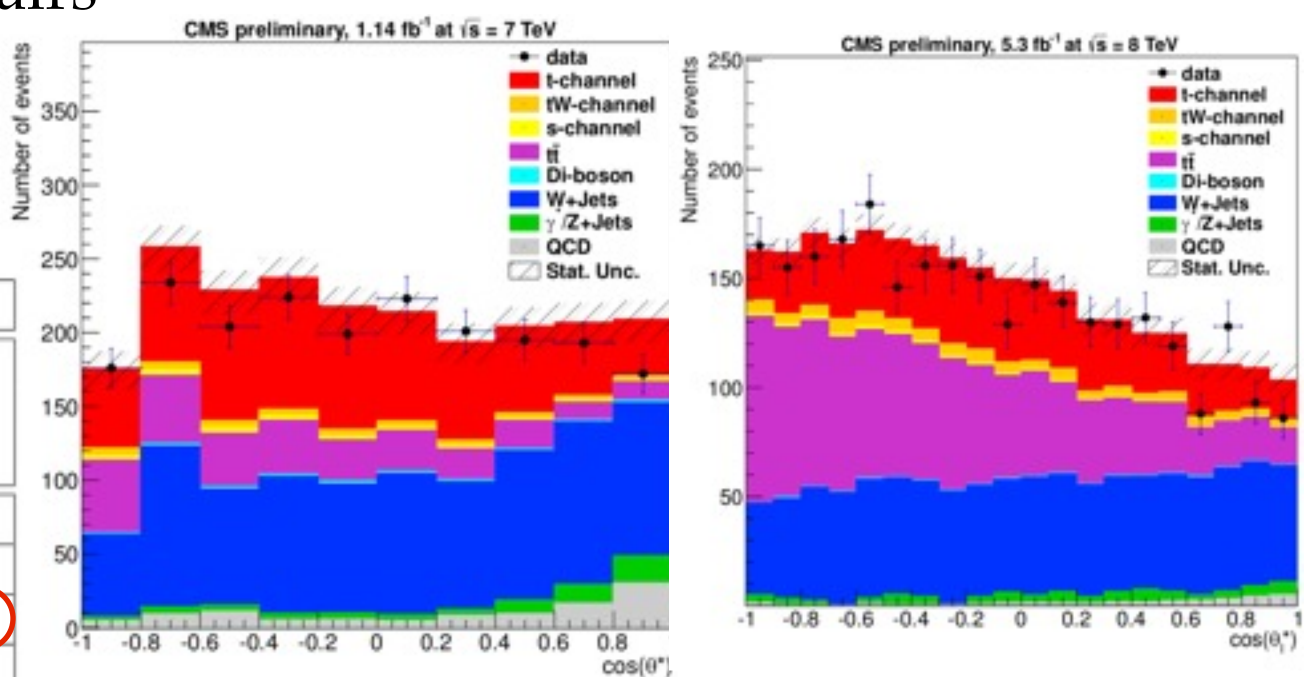
M_T>30 GeV

W helicity: single-top topology

- Large contribution from top pairs, specially at 8 TeV
- Measurement from both single-top and top pairs
- Shape and normaliz. of W+jets:

  data control samples

PAS:TOP-12-020



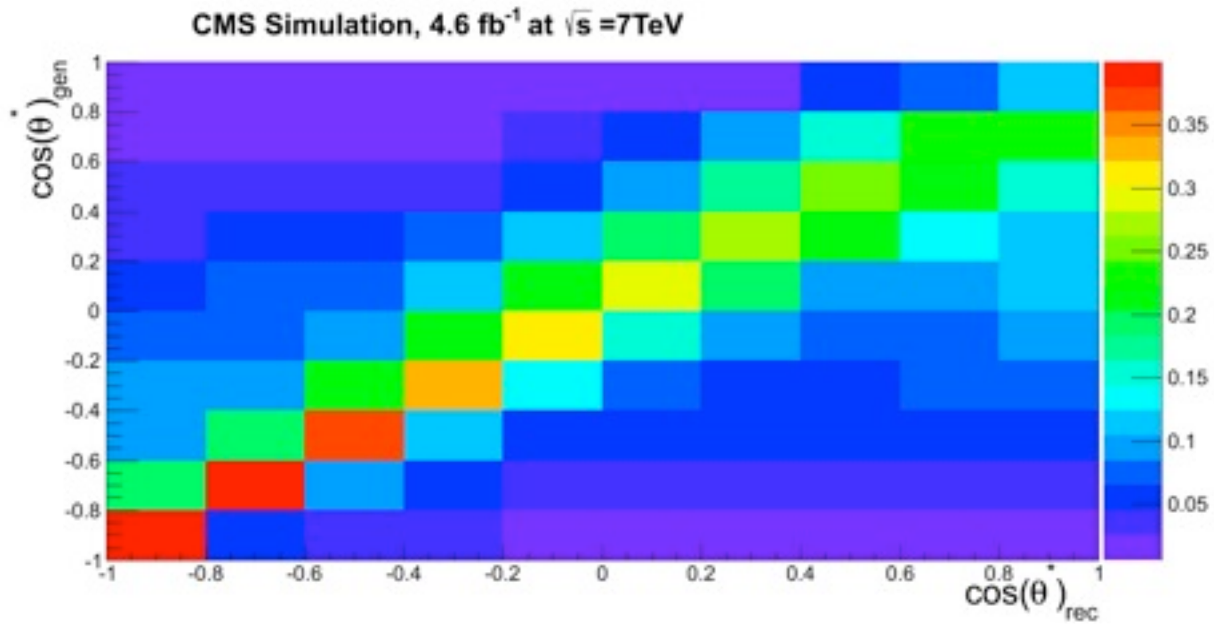
	$\sqrt{s} = 8$ TeV		$\sqrt{s} = 7$ TeV	
Systematic source	ΔF_L	ΔF_0	ΔF_L	ΔF_0
JES	0.006	0.006	0.020	0.020
JER	0.008	0.003	0.015	0.010
unclustered energy	0.013	0.003	0.015	0.015
pileup	0.002	0.003	0.004	0.000
b-flavored scale factor	0.004	0.006	0.009	0.009
non-b-flavored scale factor	0.004	0.007	0.002	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

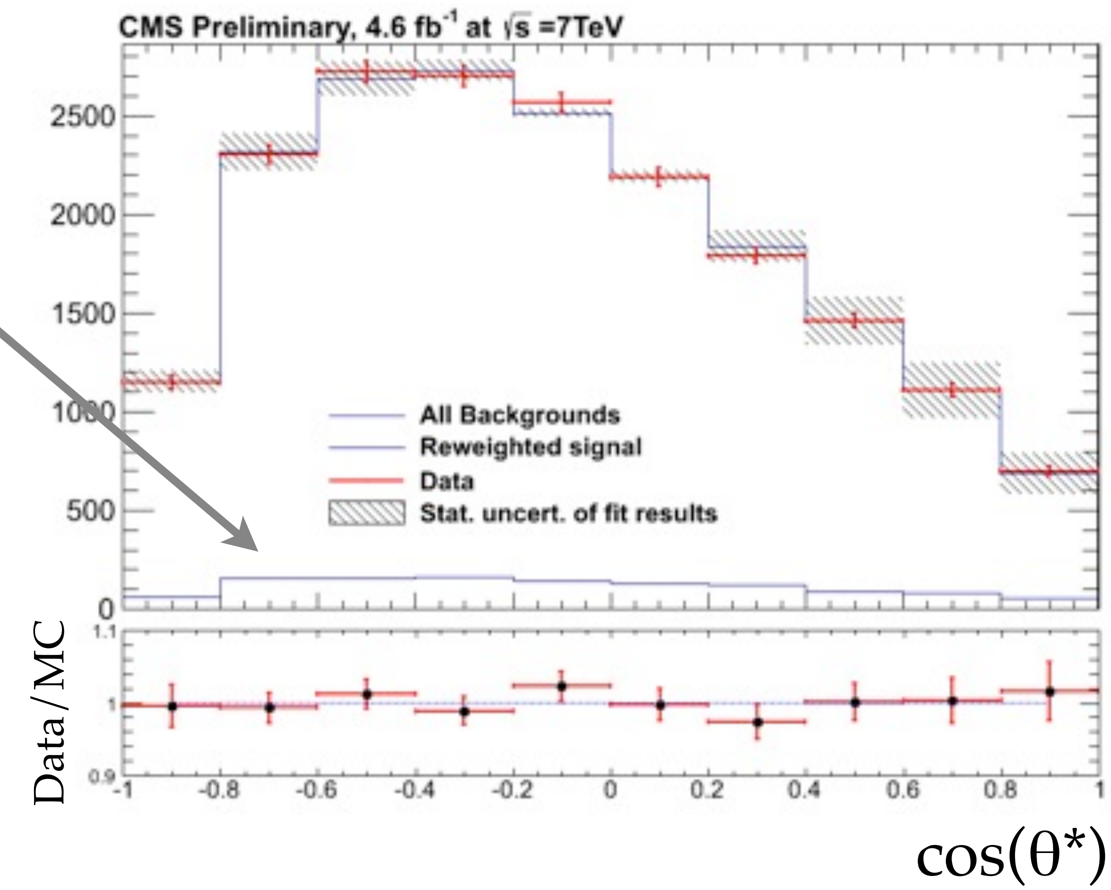
Combined results: 7 and 8 TeV

F_0=0.713±0.114±0.023
F_L=0.293±0.069±0.030
F_R=-0.006±0.057±0.027

W helicity in top decays (ll+jets):

- Measurement from $\cos(\theta^*)$ both sides
- Very low backgrounds: estimated using MC





Systematic Source	Fitting F_L, F_0 $\pm\delta F_L$	$\pm\delta F_0$
Top QScale	0.027	0.051
Top Mass	0.016	0.003
WZQScale	0.013	0.026
DY XSection	0.009	0.014
W XSection	0.000	0.002
SingleTopTW XSection	0.002	0.008
JES	0.01	0.006
Pile-up	0.014	0.017
PDF	0.004	0.005
Total	0.040	0.063

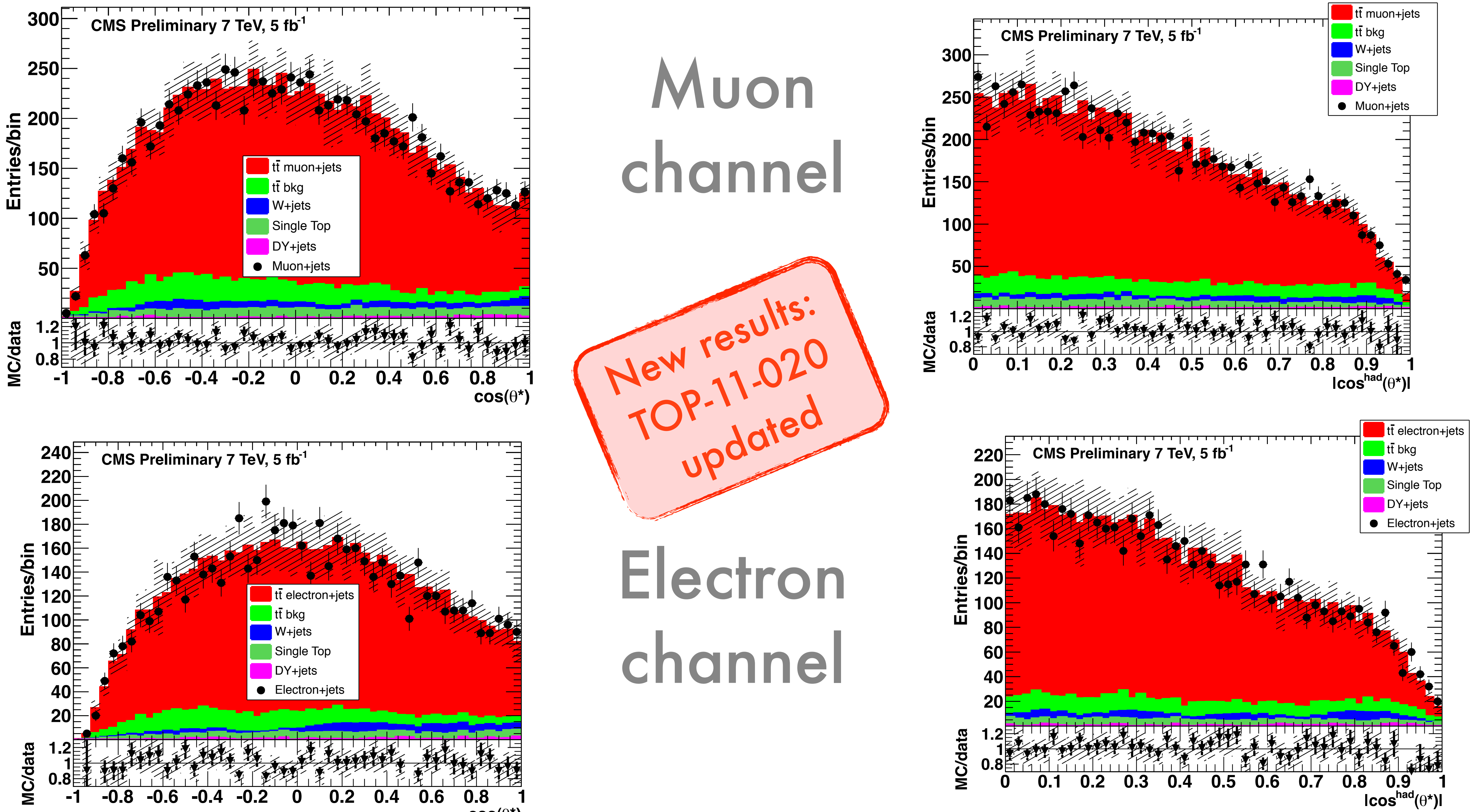
PAS: TOP-12-015

F_0=0.698±0.057±0.063
F_L=0.288±0.035±0.040
F_R=0.014±0.027±0.042

W helicity in top decays (l+jets)

TOP-11-020 updated, to be submitted to JHEP

- $\cos(\theta^*)$: needs to identify **down-type fermion**
- Leptonic branch: d-fermion = lepton (ok!)
- Hadronic branch: d-type quark can not be identified: only $|\cos^{had}(\theta^*)|$ information



W helicity in top decays (l+jets)

- Treating leptonic/hadronic branches independently
  - "3D": fit F_0, F_L, and tt normalization

    take F_R=1-F_0-F_L (as in single top and ll)
  - "2D": set F_R=0

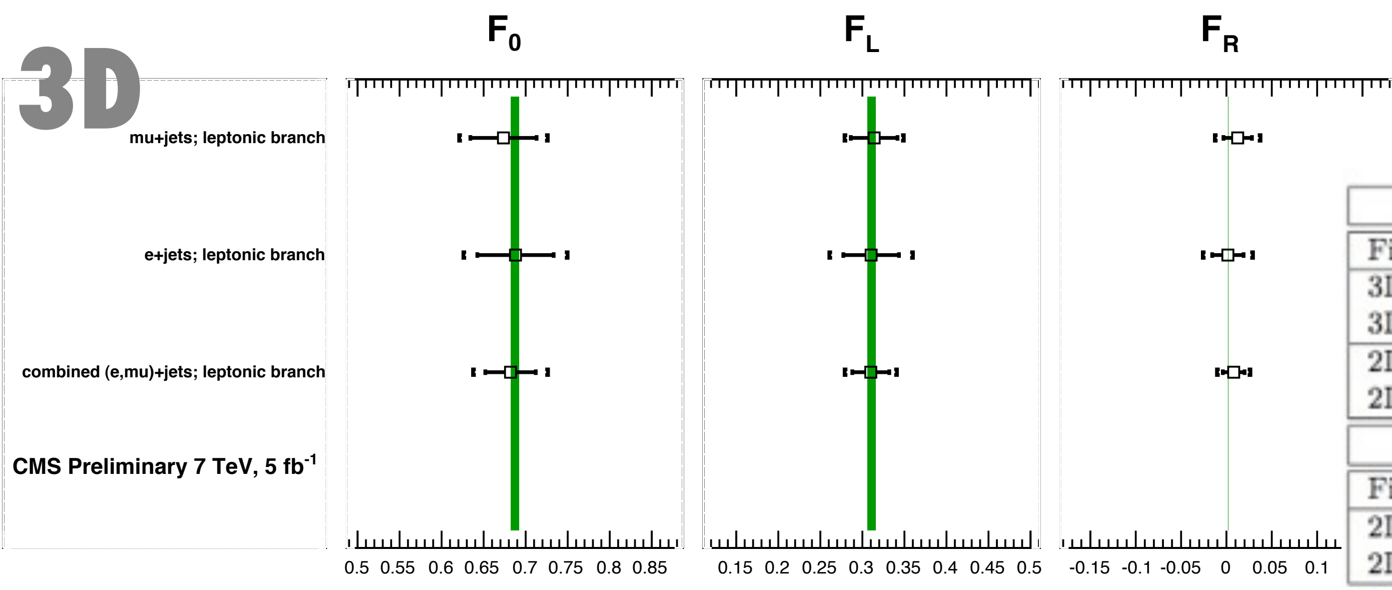
New results:
TOP-11-020
updated

- W+jets and DY+jets normalization and shape from control regions

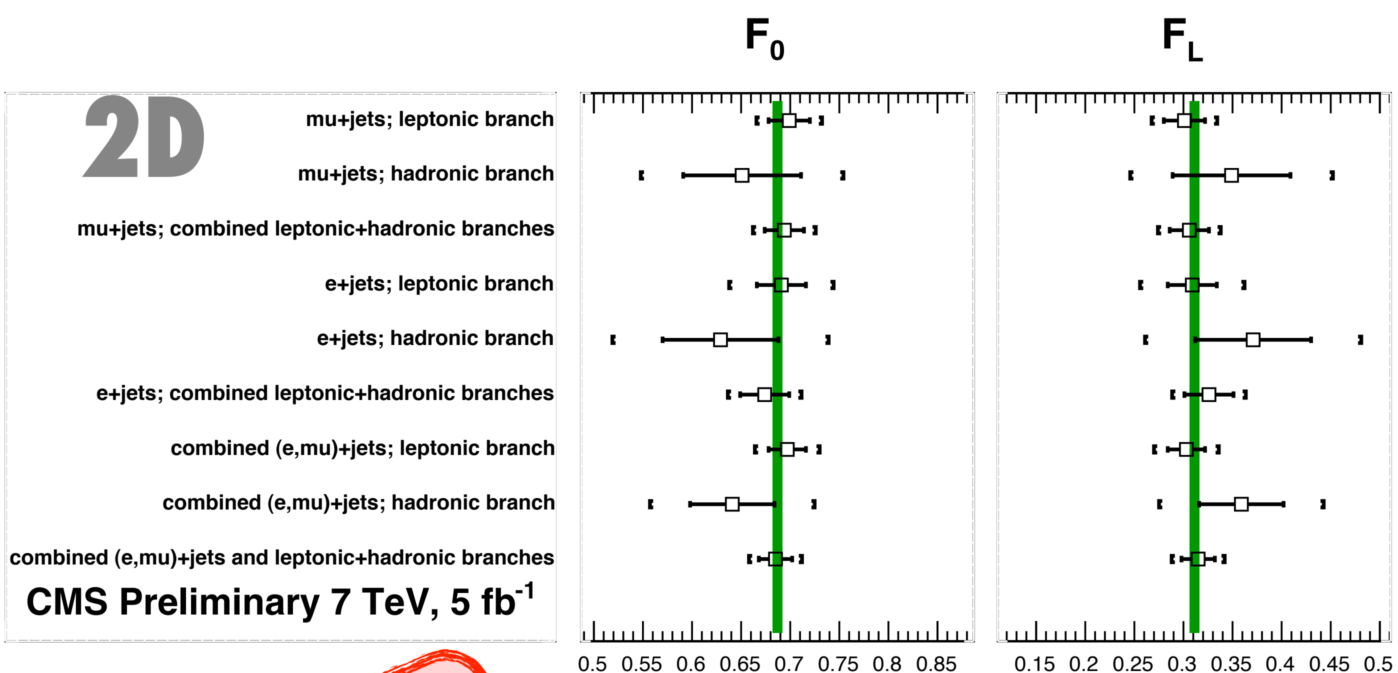
(estimated in data)

Systematics	μ+jets ($\cos\theta^*$) 3D fit $\pm\Delta F_0$	μ+jets ($\cos\theta^*$) 3D fit $\pm\Delta F_L$	μ+jets ($\cos\theta^*$) 2D fit $\pm\Delta F_0$	e+jets ($\cos\theta^*$) 3D fit $\pm\Delta F_0$	e+jets ($\cos\theta^*$) 3D fit $\pm\Delta F_L$	e+jets ($\cos\theta^*$) 2D fit $\pm\Delta F_0$	ℓ+jets ($\cos\theta^*$) 3D fit $\pm\Delta F_0$	ℓ+jets ($\cos\theta^*$) 3D fit $\pm\Delta F_L$	ℓ+jets ($\cos\theta^*$) 2D fit $\pm\Delta F_0$
b-tag eff.	0.001	0.001	$< 10^{-3}$	$< 10^{-3}$	$< 10^{-3}$	0.001	0.001	$< 10^{-3}$	$< 10^{-3}$
Single-t bkg.	0.004	$< 10^{-3}$	0.003	0.004	$< 10^{-3}$	0.004	0.004	0.001	0.003
DY+jets bkg.	0.002	0.001	0.001	0.001	$< 10^{-3}$	0.001	0.001	$< 10^{-3}$	0.001
W+jets bkg.	0.019	0.007	0.006	0.009	0.006	0.022	0.013	0.004	0.006
Lepton eff.	0.001	0.001	0.001	0.009	0.012	0.015	0.001	0.002	0.002
JES	0.005	0.003	0.001	0.006	0.002	0.003	0.006	0.003	0.001
$t\bar{t}$ scales	0.013	0.009	0.007	0.015	0.018	0.030	0.009	0.009	0.011
JER	0.009	0.005	0.001	0.014	0.009	0.003	0.011	0.007	0.001
Top-quark mass	0.011	0.008	0.007	0.025	0.018	0.014	0.016	0.011	0.019
Pileup	0.013	0.011	0.008	0.008	0.007	0.005	0.002	$< 10^{-3}$	0.008
$t\bar{t}$ match. scale	0.004	0.001	0.006	0.010	0.013	0.016	0.011	0.010	0.008
PDF	0.002	0.001	0.003	0.004	0.002	0.002	0.002	$< 10^{-3}$	0.003
MC statistics	0.016	0.012	0.009	0.019	0.015	0.012	0.016	0.012	0.010

W helicity in top decays (l+jets)



Fit	Channel	$F_0 \pm$ (stat.) $\pm$ (syst.)	$F_L \pm$ (stat.) $\pm$ (syst.)	$F_R \pm$ (stat.) $\pm$ (syst.)	ρ_{0L}^{stat}
Leptonic branch: $\cos\theta^*$					
3D	μ+jets	0.674 ±0.039±0.035	0.314 ±0.028±0.022	0.012 ±0.016±0.020	-0.95
3D	e+jets	0.688 ±0.045±0.042	0.310 ±0.033±0.037	0.002 ±0.017±0.023	-0.95
2D	μ+jets	0.698 ±0.021±0.019	0.302 ±0.021±0.019	fixed at 0	-1
2D	e+jets	0.691 ±0.025±0.047	0.309 ±0.025±0.047	fixed at 0	-1
Hadronic branch: $\lvert\cos^{had}\theta^*\rvert$					
2D	μ+jets	0.651 ±0.060±0.084	0.349 ±0.060±0.084	fixed at 0	-1
2D	e+jets	0.629 ±0.060±0.093	0.371 ±0.060±0.093	fixed at 0	-1



Fit	Channel(s)	Branch	Fraction $\pm$ (stat.) $\pm$ (syst.) [total]		ρ_{0L}^{total}
3D	ℓ+jets	l	F_0	0.682 ±0.030±0.033 [0.045]	-0.95
			F_L	0.310 ±0.022±0.022 [0.032]	
			F_R	0.008 ±0.012±0.014 [0.018]	
2D	μ+jets	l+h	F_0	0.694 ±0.020±0.025 [0.032]	
			F_L	0.306 ±0.020±0.025 [0.032]	-1
2D	e+jets	l+h	F_0	0.674 ±0.025±0.028 [0.037]	
			F_L	0.326 ±0.025±0.028 [0.037]	-1
2D	ℓ+jets	l+h	F_0	0.685 ±0.017±0.021 [0.027]	
			F_L	0.315 ±0.017±0.021 [0.027]	-1

New results: TOP-11-020 updated

World's most precise:

(with no F_R=0 assumption)

$F_0 = 0.682 \pm 0.030 \pm 0.033$

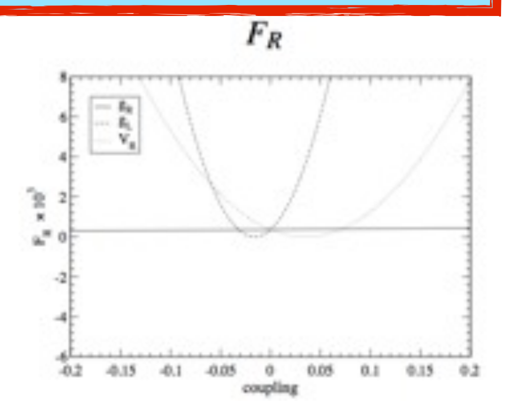
$F_L = 0.310 \pm 0.022 \pm 0.022$

$F_R = 0.008 \pm 0.012 \pm 0.014$

Anomalous couplings from W helicity

- Fix $V_L=1$ and $V_R=0$ to SM predictions

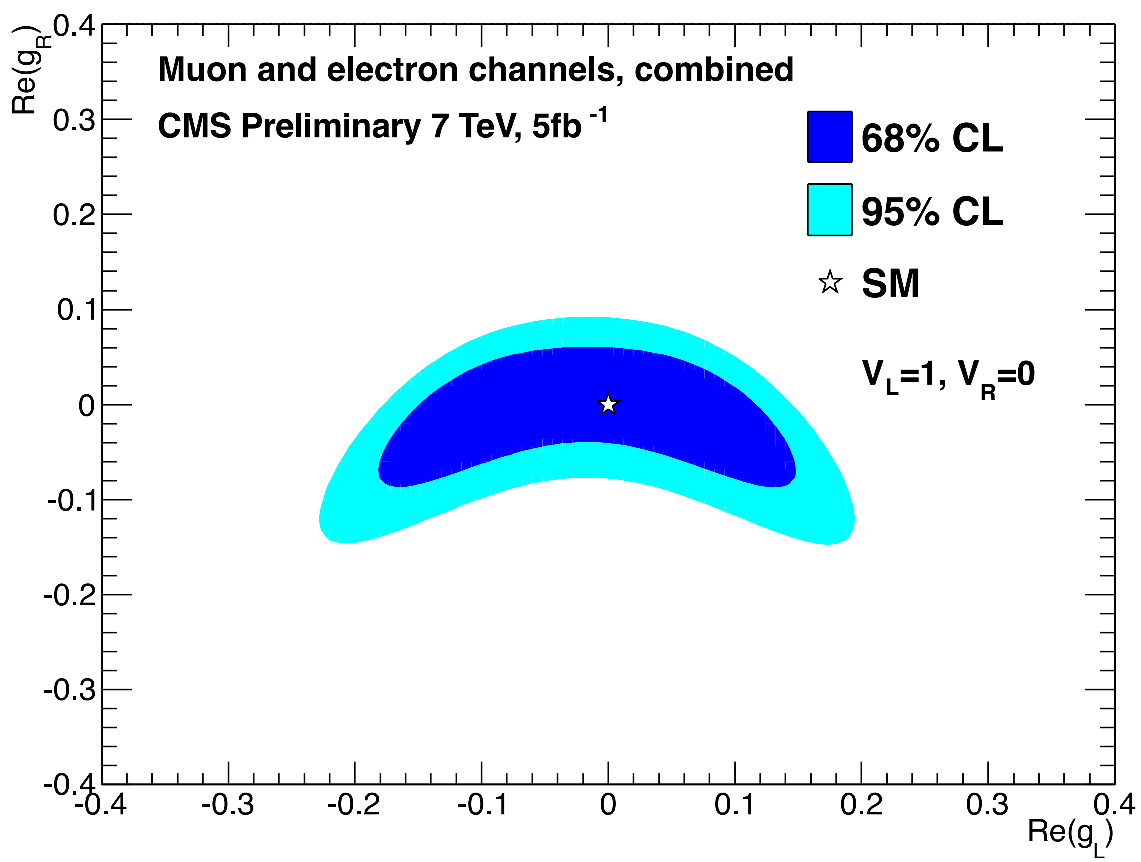
1) fix also $g_L=0$ ➙ set limits on g_R (independent on F_R): ☞



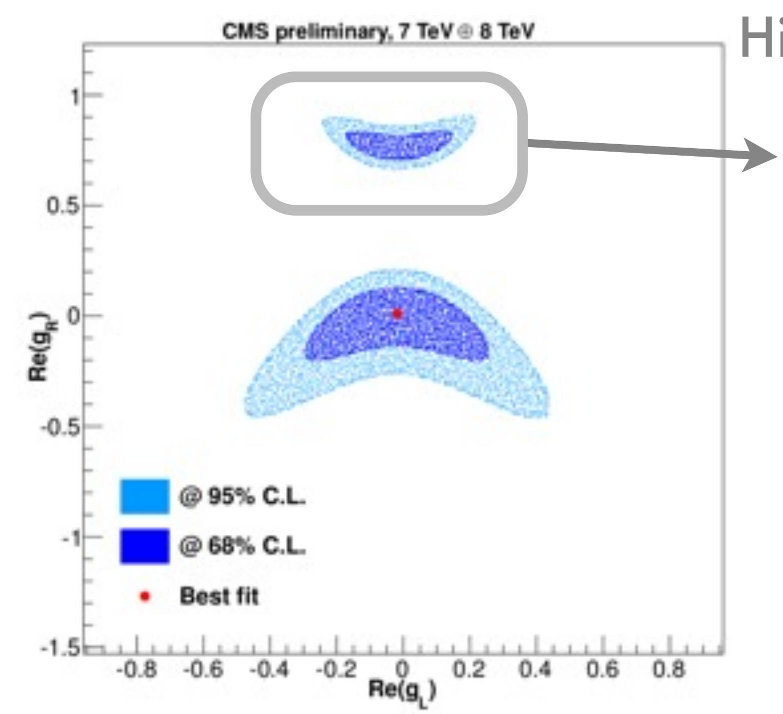
- Use measurement setting $F_R=0$, more precise F_0
- Limit: **$\mathrm{Re}(g_R) = -0.008 \pm 0.024(\mathrm{stat.})^{+0.029}_{-0.030}(\mathrm{syst.})$**

2) set limits on $\mathrm{Re}(g_R)$ vs $\mathrm{Re}(g_L)$

- Use most precise "3D" measurement:



From single-top (TOP-12-020):

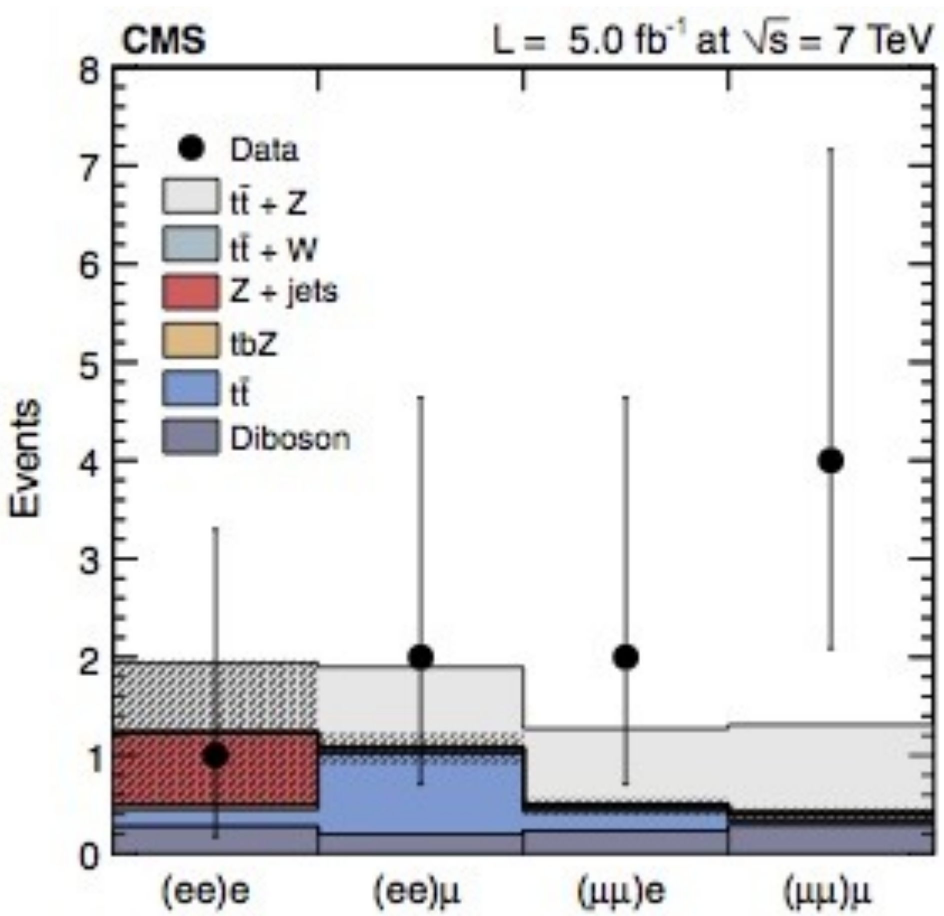


Highly disfavored by single-top cross sections measurements

ttZ cross-section

- LHC measurements are crucial: ttV cross section very low to be seen at Tevatron
- tt → l+jets and Z→ ll
- Three-lepton final state, event selection:

2 isolated leptons p_T>20 GeV in Z window
3rd lepton pT>10 GeV
at least 3 jets p_T>20 GeV , 2 b-tags
$H_T = \sum p_T(jets)$>120 GeV



PRL 110(2013) 172002 (TOP-12-014)

- Very low SM backgrounds
  - "fake lepton" (e.g. tt+jets, Z+jets with one jet misidentified as lepton), diboson
  - Use control regions with looser selection criteria to measure fakes/ estimate background
  - Single-top +Z (via virtual W, final state: tbZ): taken from simulation
- In the signal region:
  - 9 events (3.2±0.8 expected bkg only)

$\sigma_{ttZ} = 0.28^{+0.14}_{-0.11}(stat)^{+0.06}_{-0.03}(syst)$ pb

significance: 3.3 σ, (p-value 0.0004)
(NLO pred: 0.137 pb)

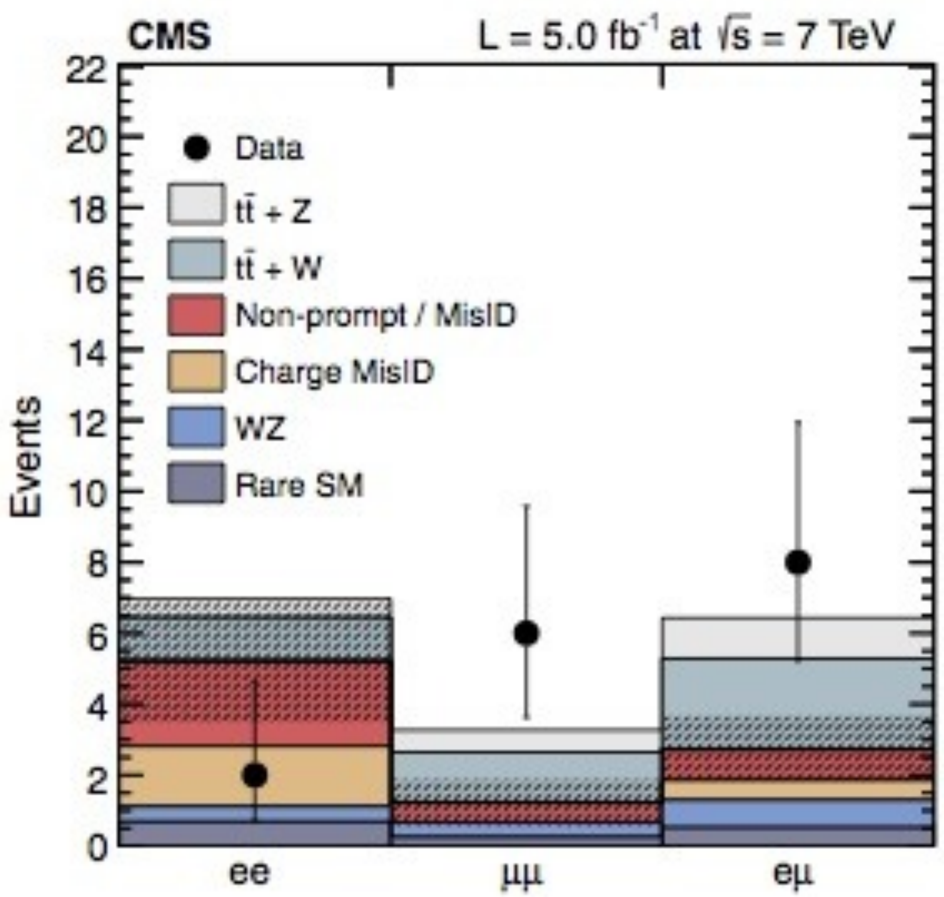
ttV cross-section (V=Z,W)

PRL 110(2013) 172002 (PAS:TOP 12-014)

- Selecting 2 same-sign leptons

$$pp \to t\bar{t}W \to (t \to b\ell^{\pm}\nu)(t \to bjj)(W \to \ell^{\pm}\nu)$$

$$pp \to t\bar{t}Z \to (t \to b\ell^{\pm}\nu)(t \to bjj)(Z \to \ell^{\pm}\ell^{\mp})$$



Background sources

Mis-reconstruction (charge id, fakes)

Rare SM: WZ, ZZ, Wγ, WW(++,--), VVV

Event selection

2 leptons p_T>55 (30) GeV

veto over ttZ selection (3 leptons)

3 jets p_T>20 GeV

1 btag

H_T>100 GeV

- 16 events (9.2±2.6 expected bkg only)

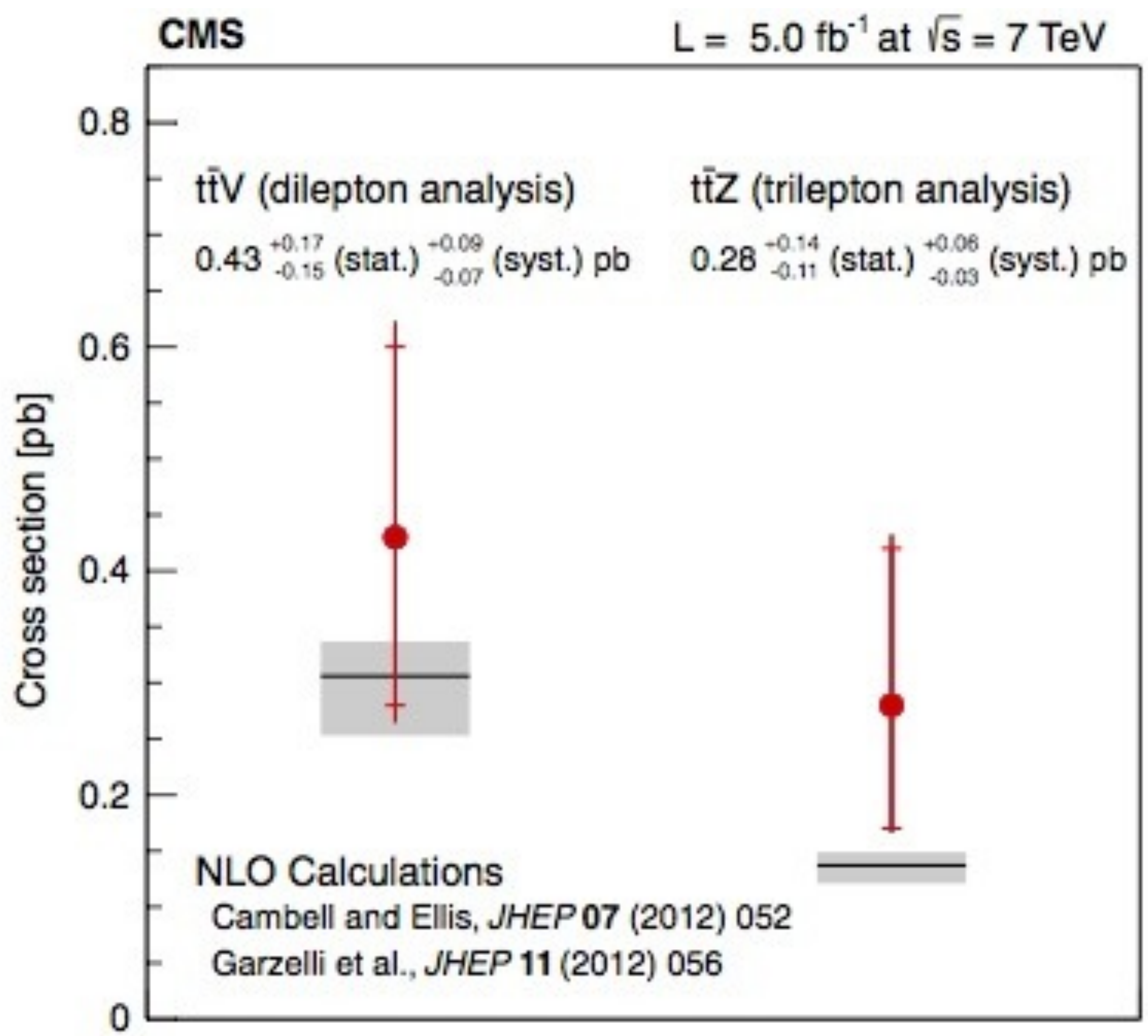
$$\sigma_{ttV} = 0.43^{+0.17}_{-0.15}(stat)^{+0.09}_{-0.07}(syst)\ pb$$

significance: 3.0 σ

(p-value 0.002)

(NLO pred: 0.306 pb)

ttV summary



Cross sections slightly above but consistent with the Standard Model predictions

Branching ratio:
$R=B(t\to Wb)/B(t\to Wq)$ $q=b,s,d$

PAS: TOP 12-035

* Key issues : correctly identify b/light–quark jets and its parent top *

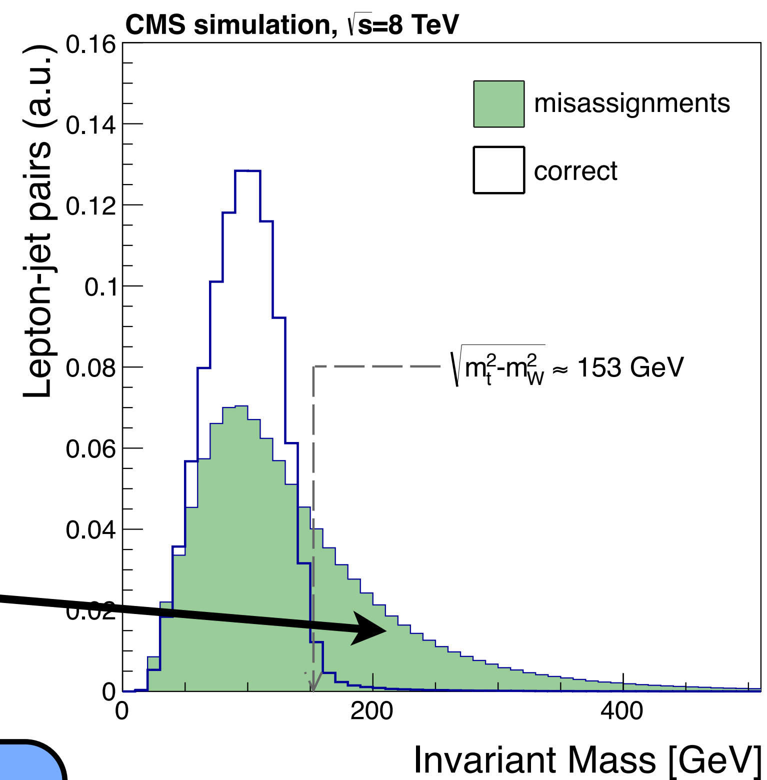
- Data: pp @ 8 TeV (2012), 16.7 fb^{-1}
- Dilepton channel, event selection:
  - *2 isolated leptons $p_T>20$ GeV*
    - *$|M_{ll}-M_Z|>15$ GeV (Z bkg removal) for ee/μμ*
    - *$M_{ll}>12$ GeV*
  - *$E_T^{miss} > 40$ GeV for ee/μμ*
  - *At least two jets separated from leptons $\Delta R\geq 0.3$*

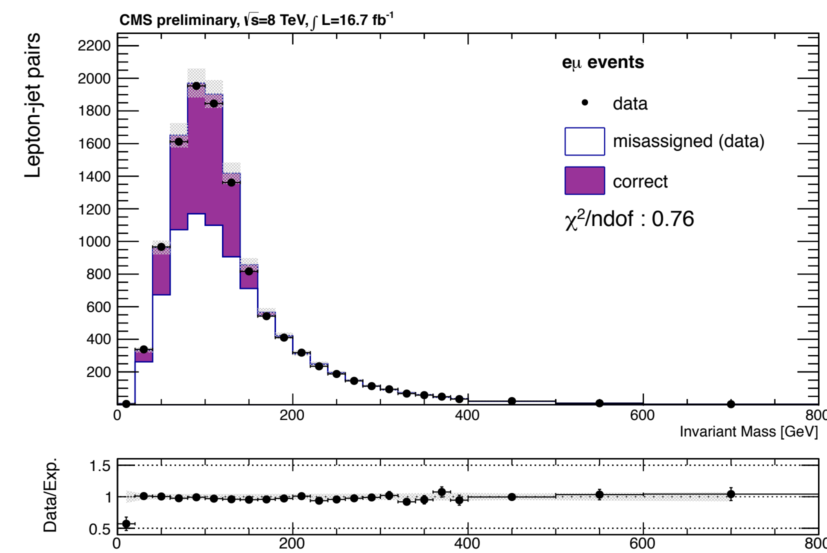
- b-tagging: for the analysis, crucial to know efficiency of
  - correctly identifying b-jets using btag (ε_b, ±~1-3%)
  - accepting light jets passing btag (mistags: ε_q ~14%,±~11%)

Measured in data

Branching ratio

- Jet assignment to its parent top:
  - use invariant mass (lepton-jet)
  - normalize at high mass region





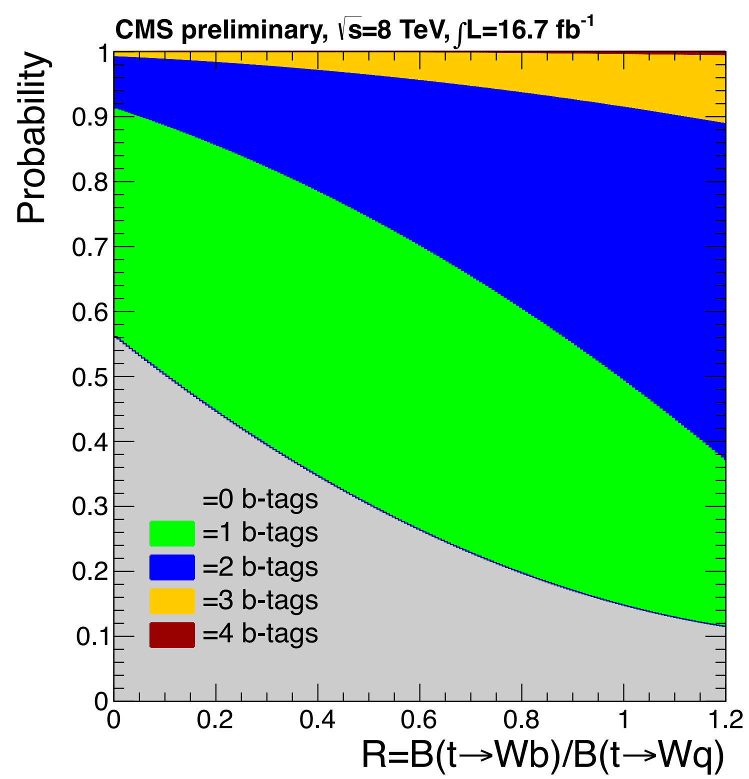
Measured in data

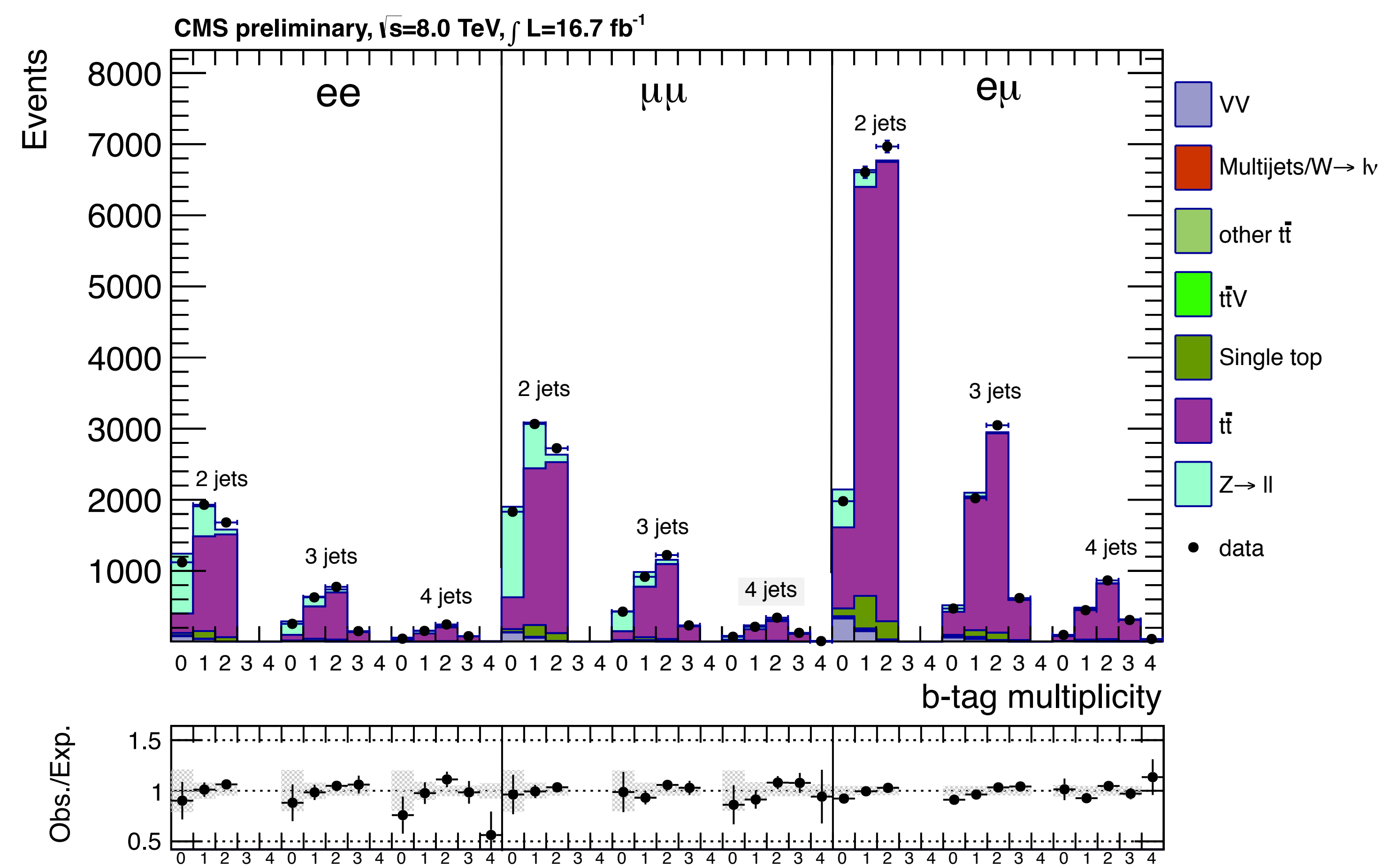
  - remove from data ☞ f_{corr}~0.25

Category		$f^{MC}_{correct}$	$f^{data}_{correct}$	data/MC
ee	2 jets	0.265 ± 0.002	$0.28 \pm 0.01 \pm 0.01$	$1.05 \pm 0.04 \pm 0.04$
	3 jets	0.211 ± 0.002	$0.21 \pm 0.02 \pm 0.01$	$0.99 \pm 0.09 \pm 0.05$
	4 jets	0.173 ± 0.002	$0.18 \pm 0.02 \pm 0.02$	$1.04 \pm 0.12 \pm 0.12$
$e\mu$	2 jets	0.3475 ± 0.0009	$0.35 \pm 0.01 \pm 0.01$	$1.00 \pm 0.02 \pm 0.02$
	3 jets	0.2539 ± 0.0008	$0.26 \pm 0.01 \pm 0.01$	$1.01 \pm 0.04 \pm 0.04$
	4 jets	0.2114 ± 0.0010	$0.20 \pm 0.01 \pm 0.01$	$0.94 \pm 0.05 \pm 0.05$
$\mu\mu$	2 jets	0.269 ± 0.001	$0.27 \pm 0.01 \pm 0.01$	$0.97 \pm 0.04 \pm 0.04$
	3 jets	0.214 ± 0.001	$0.22 \pm 0.01 \pm 0.01$	$1.05 \pm 0.05 \pm 0.05$
	4 jets	0.172 ± 0.002	$0.18 \pm 0.02 \pm 0.01$	$1.06 \pm 0.12 \pm 0.06$

Branching ratio

- From f_{corr} ⇒ get N, nr of correctly reconstructed and selected tops (thus, of bjets!)
- Given N, from ε_b, ε_q ⇒ model the nr expected events for each b-tag multiplicity





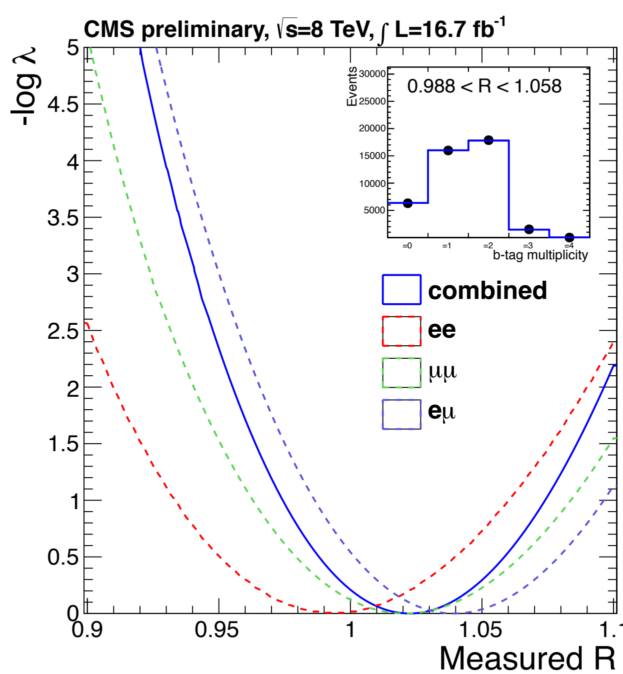
Extract R from a likelihood fit to the model entirely based on data

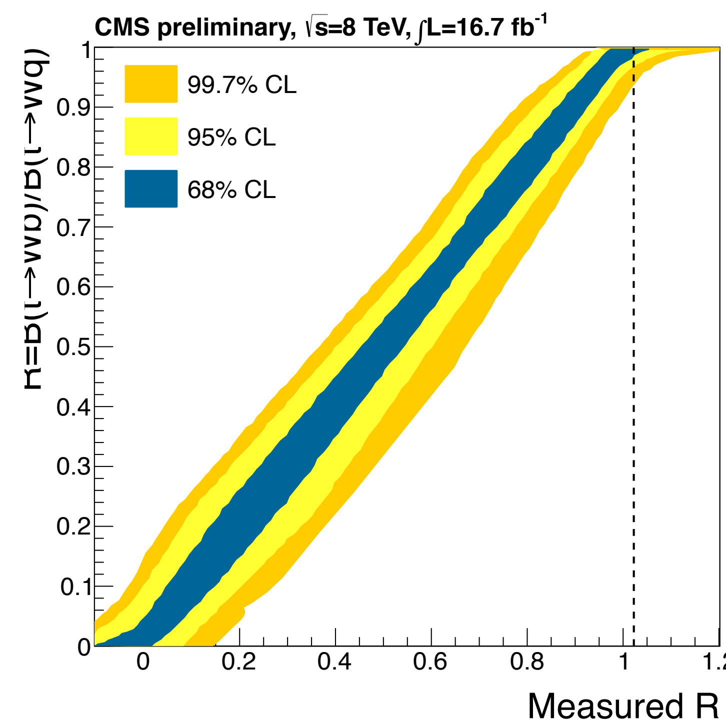
Branching ratio

- Systematic uncertainties

Source	Uncertainty (%)
Statistical	0.4
Systematic	3.4
Individual contributions:	
b-tagging efficiency	1.9
$f_{t\bar{t}}^{stat}$	0.5
Mistag rate	0.9
$B(W \to \ell\nu)$	0.2
DY	0.3
Fake leptons	0.1
JER	0.9
JES	1.0
Luminosity	0.2
ME-PS	1.2
Pileup	0.2
Q^2	1.1
Selection efficiency	0.2
Signal	0.2
Simulation stat.	0.2
Single top cross section	0.1
$f_{correct}^{stat}$	1.1
Extra sources of heavy flavors	0.9
Total	**3.4**

- Likelihood fit:





$R=1.023^{+0.036}_{-0.034}$

$R>0.945$ @95%CL

At 7 TeV (TOP 11-029) with 2.2 fb^{-1}:

$R:=0.98\pm0.04$, $R>0.85$ @95%CL

FCNC in top pairs

- SM: t→Wb ***almost 100%***
- Direct search for flavor changing neutral currents tt → Wb +Zq →lνb +llq
- t→Zq is highly suppressed (BF~10^{-14}), not visible at the LHC unless ***new physics occurs***
- Tri-lepton final state, event selection (**19.5 fb^{-1} pp @ 8 TeV**)

3 isolated leptons p_T>20 GeV
Z mass window: 78< M_{ll} <102 GeV
$p_T(Z)$ > 35 GeV
3rd lepton pT>10 GeV
at least 2 jets p_T>30 GeV
exactly 1 btag
E_T^{miss} >30 GeV

Selection	data-driven estimation	SM MC prediction
$t \to Zq$ ($\mathcal{B} = 0.1\%$)	—	$6.36 \pm 0.08 \pm 1.27$
WZ	$1.54 \pm 0.12 \pm 0.74$	$0.87 \pm 0.10 \pm 0.62$
ZZ		$0.07 \pm 0.01 \pm 0.05$
Drell-Yan		$0.00 \pm 0.03 \pm 0.02$
$t\bar{t}$	$1.60 \pm 4.96 \pm 0.44$	$0.74 \pm 0.70 \pm 0.52$
$Zt\bar{t}$		$1.09 \pm 0.13 \pm 0.77$
$Wt\bar{t}$		$0.09 \pm 0.05 \pm 0.06$
tbZ		$0.33 \pm 0.02 \pm 0.23$
Total background	$3.14 \pm 4.97 \pm 1.17$	$3.19 \pm 0.72 \pm 2.26$
Observed events	1	—
Expected limit	$\mathcal{B}(t \to Zq) < 0.10\%$	—
Observed limit	$\mathcal{B}(t \to Zq) < 0.07\%$	

- Backgrounds from data: classified by nr of b-tags
  - 0 b-tag: **diboson**, Drell-Yan, QCD
  - 1 b-tag: signal
  - 2 b-tags: **tt**,tbZ, Wtt, Ztt

1 event observed (3.14 expected)

BF<0.05% @95%CL

Summary and conclusions

- Important tests of the Standard Model validity on 2011 and 2012 LHC data:

- W helicity in top decays measured with unprecedented precision
  - Stringent constraints on anomalous couplings

- Measurements of ttV (V=Z,W) cross sections presented
  - ttV in hadron colliders: unique for LHC
  - first steps towards understanding structure of electroweak couplings to tops

- $R = B(t \to Wb)/B(t \to Wq) > 0.85$ at 95%CL

- Limits on FCNC in top pairs were set (BF<0.05% at 95%CL)

- Consistency with the Standard Model in all measurements

All results can be found in https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

Additional slides

Fitting method

- Likelihood fit with

$$\mathcal{L}(\vec{F}) = \prod_{bin\ i} \frac{N_{MC}(i;\vec{F})^{N_{data}(i)}}{(N_{data}(i))!} \exp\left(-N_{MC}(i;\vec{F})\right).$$

$$\begin{aligned} \mathrm{N_{MC}}(i,\vec{F}) &= \mathrm{N_{BKG}}(i) + \mathrm{N_{t\bar{t}}}(i;\vec{F}) \\ \mathrm{N_{t\bar{t}}}(i;\vec{F}) &= \mathcal{F}_{t\bar{t}} \left[\sum_{\mathrm{t\bar{t}\ events,\ bin}\ i} W(\cos\theta^*_{gen};\vec{F}) \right] \\ \mathrm{N_{BKG}}(i) &= \mathrm{N_{W+jets}}(i) + \mathrm{N_{Drell-Yan+jets}}(i) + \mathrm{N_{Single-Top}}(i) \end{aligned}$$

- Number of expected tt for different helicity configurations $\vec{\mathrm{F}}$ obtained by reweighting

$$W(\cos\theta^*_{gen};\vec{F}) \equiv \frac{\rho(\cos\theta^*_{gen})}{\rho^{SM}(\cos\theta^*_{gen})} = \frac{\frac{3}{8}F_L(1-\cos\theta^*_{gen})^2 + \frac{3}{4}F_0\sin^2\theta^*_{gen} + \frac{3}{8}F_R(1+\cos\theta^*_{gen})^2}{\frac{3}{8}F_L^{SM}(1-\cos\theta^*_{gen})^2 + \frac{3}{4}F_0^{SM}\sin^2\theta^*_{gen} + \frac{3}{8}F_R^{SM}(1+\cos\theta^*_{gen})^2}$$

Electroweak couplings: gauge-boson associated tt production

- Important Standard Model test: new physics modifies the structure of the electroweak couplings, described by

see e.g. U.Baur et al., PRD71 (2005) 054013

$$\Gamma_\mu^{ttV}(k^2, q, \bar{q}) = -ie\left\{\gamma_\mu\left(F_{1V}^V(k^2) + \gamma_5 F_{1A}^V(k^2)\right) + \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu\left(iF_{2V}^V(k^2) + \gamma_5 F_{2A}^V(k^2)\right)\right\}$$

$$F_{1V}^{\gamma,SM} = -\frac{2}{3}, \qquad F_{1A}^{\gamma,SM} = 0$$

$$F_{1V}^{Z,SM} = -\frac{1}{4\sin\theta_W\cos\theta_W}\left(1 - \frac{8}{3}\sin^2\theta_W\right), \qquad F_{1A}^{Z,SM} = \frac{1}{4\sin\theta_W\cos\theta_W},$$

$$F_{2V}^{\gamma,SM} = F_{2V}^{Z,SM} = 0 \qquad F_{2A}^{\gamma,SM} = F_{2A}^{Z,SM} = 0$$

Precision measurements on ttV final states sensitive to anomalous couplings

- tt production via intermediate V very difficult
  - small correction to a QCD dominated process
- Instead, measure *cross-sections:* ttZ, ttW production

- Tests of the electroweak sector in top physics specially interesting
- LHC measurements are crucial: ttV cross section very low to be seen at Tevatron

Top quark charge

- SM - electroweak isospin parter of b quark (of q=-1e/3) : **charge = +2e/3**
- Other possible decay to W and b quark: exotic particle charge -4e/3

* Key issue : to identify b–quark jet and its charge *

- **identification of b-initiated jets** (b-tagging): long lifetime of B hadrons, jets with large impact parameter; *soft* (low-p_T) muons from B decays
- **identification of b quark charge** ➨ more complicated! Methods:

1. from the charge of the soft muon (same sign as B-hadron in direct decays)
    - smeared by flavour oscillations of neutral B mesons
    - smeared by B-hadron cascades through charmed hadrons
2. from the momentum-weighted charge of all charged particles in the jet

$$Q_{b\,jet} = \frac{\sum_i q_i |\vec{j} \cdot \vec{p}_i|^\kappa}{\sum_i |\vec{j} \cdot \vec{p}_i|^\kappa},$$

K MC derived parameter =0.5
i runs over all tracks

Top quark charge

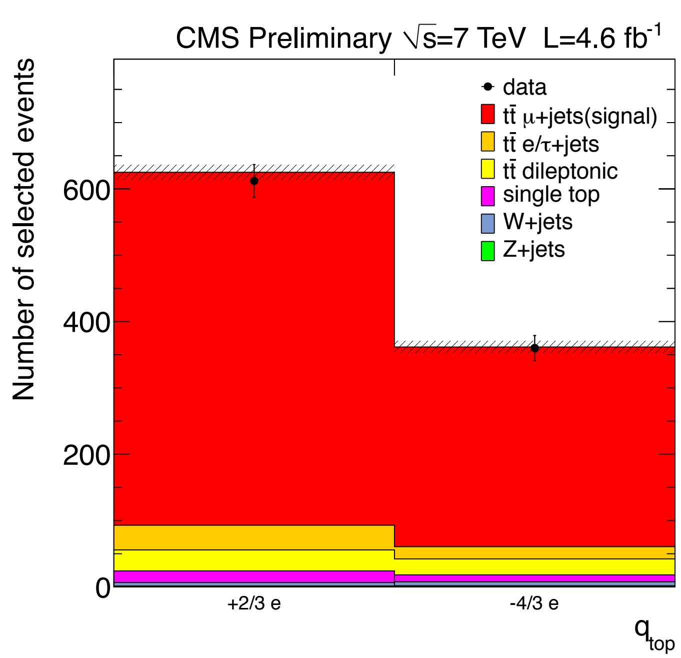
PAS: TOP 11-031
4.6 fb^{-1} $t\bar{t} \to \mu\,\nu$+jets

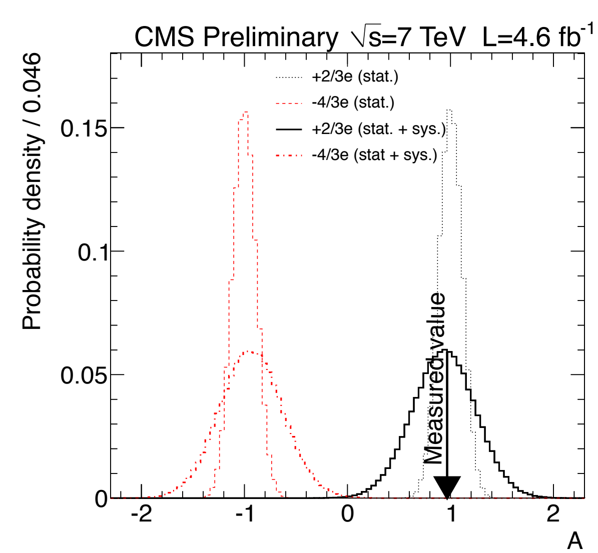
- Systematic uncertainties

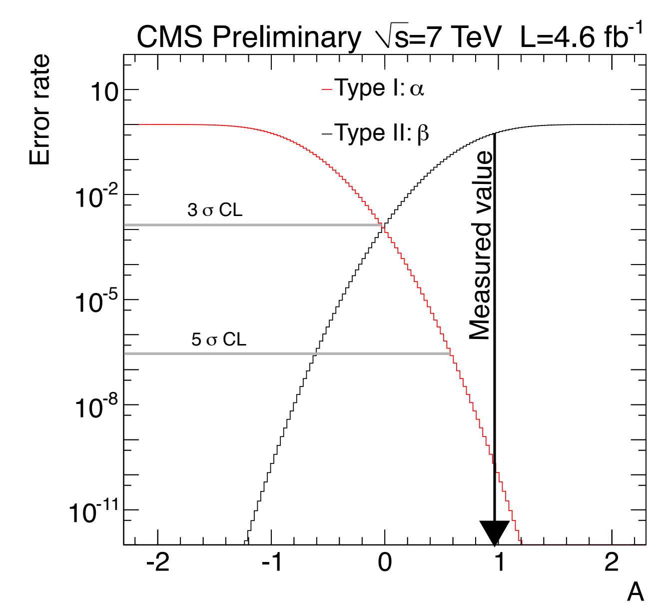
Category	Rel. Sys. Uncertainty on P_{signal}	Rel. Sys. Uncertainty on A
Matching Threshold	5%	23 %
b Charge MisID	2.5%	12%
Top Mass	2%	8%
JES	1%	7%
Q^2	0.5%	3%
Fragmentation Model	0.6%	3%
JER	0.1%	3%
b-tagging	0.2%	2%
Pileup	0.4%	2%

exactly 1 isolated muon p_T>26 GeV
>=4 jets p_T>30 GeV
2 btags

Soft lepton: +1 μ within jet (p_T>4 GeV)







* Exotic scenario excluded at 5 σ *