Measurement of top quark properties with CMS

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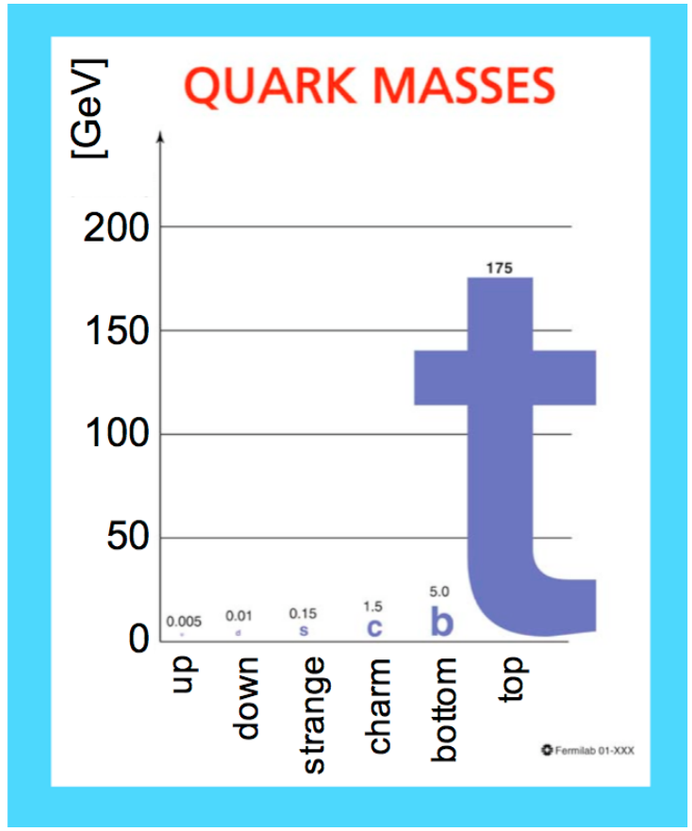
for the
CMS collaboration

Introduction: Study of Top Properties

Heaviest quark in the standard model

- Produced at the LHC predominantly through gluon-gluon fusion
- Decays predominantly through t→bW
- Consequence of being heavier than W mass: top decays before hadronization and spin de-correlation
  - **Bare quark properties are accessible** (mass, spin, charge, …)
  - **Spin effects are passed on to decay products**.



Test Standard Model (SM) predictions

- Top quark has the largest coupling to the Higgs boson

Search for new physics

- Top quarks could be produced from decay of new particles
- Top quarks could decay into new particles
- Top quarks can be backgrounds to new physics processes

Outline:

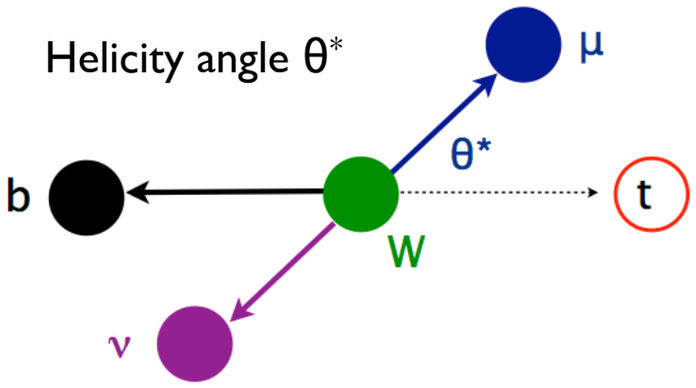
- W helicity in top decays
- Top pair asymmetry
- TTbar spin correlations
- Flavor changing neutral currents

W helicity in top decays: Introduction

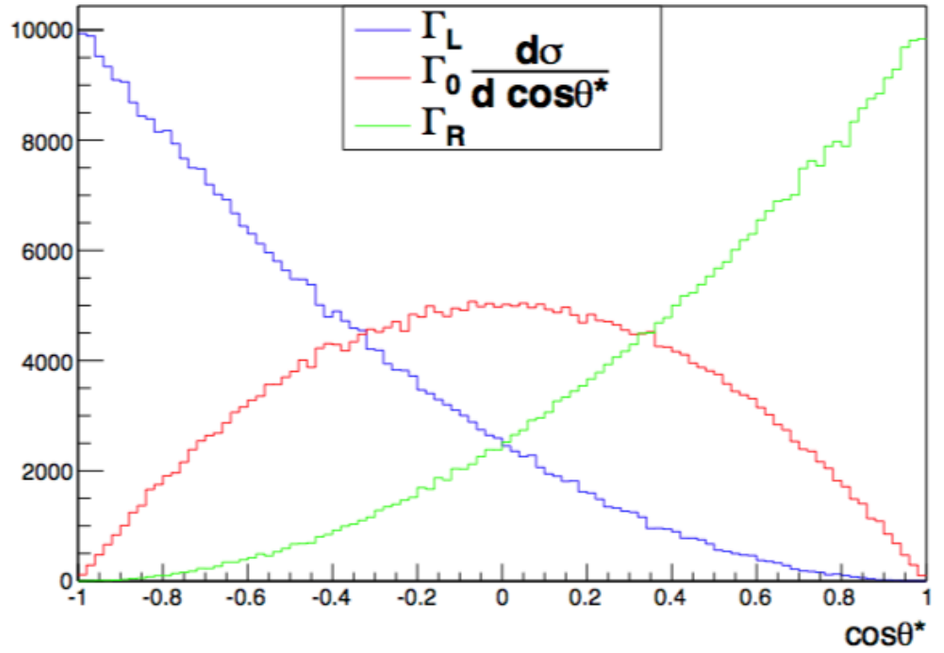
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = \frac{3}{8}\left(1-\cos\theta^*\right)^2 F_L + \frac{3}{8}\left(1+\cos\theta^*\right)^2 F_R + \frac{3}{4}\left(\sin\theta^*\right)^2 F_0$$

$$F_L + F_R + F_0 = 1 \qquad F_X \equiv \frac{\Gamma_X}{\Gamma}$$

- Measure W helicity fractions (FR, FL, and F0) using cos(θ*) distribution in ttbar events



Direction of charged lepton in W rest frame with respect to W direction in top rest frame



- Results based on reweighting MC using likelihood techniques to find fractions F_i preferred in data

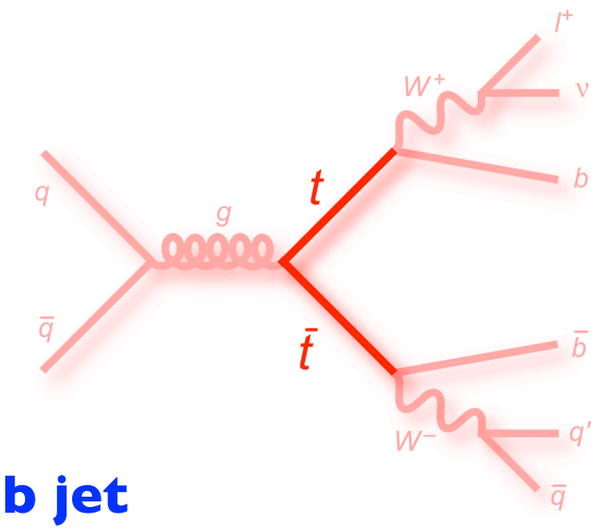
W helicity in top decays: CMS overview

	7 TeV	8 TeV
NNLO	FL = 0.311 ± 0.005, FR = 0.0017 ± 0.0001, F0 = 0.687 ± 0.005 Phys. Rev. D 81 (2010) 111503	
Lepton+jets	FL = 0.310 ± 0.022 (stat.) ± 0.022 (syst.), FR = 0.008 ± 0.012 (stat.) ± 0.014 (syst.), F0 = 0.682 ± 0.030 (stat.) ± 0.033 (syst.) JHEP JHEP 10 (2013) 167	NEW
Dilepton	FL = 0.288 ± 0.035(stat) ± 0.040(sys), FR = 0.014 ± 0.027(stat) ± 0.042(sys), F0 = 0.698 ± 0.057(stat) ± 0.063(sys) CMS PAS TOP-12-015	
Single top	FL = 0.293 ± 0.069(stat.) ± 0.030(syst.), FR = −0.006 ± 0.057(stat.) ± 0.027(syst.), F0 = 0.713 ± 0.114(stat.) ± 0.023(syst.) CMS PAS TOP-12-020	
Atlas+CMS combination Lepton+jets and dilepton	FL = 0.359 ± 0.021 (stat.) ± 0.028 (syst.), FR = 0.015 ± 0.034, F0 = 0.626 ± 0.034 (stat.) ± 0.048 (syst.) CMS PAS TOP-12-025	

The different helicity fraction measurements are in agreement with NNLO QCD

New: W helicity in lepton+jets

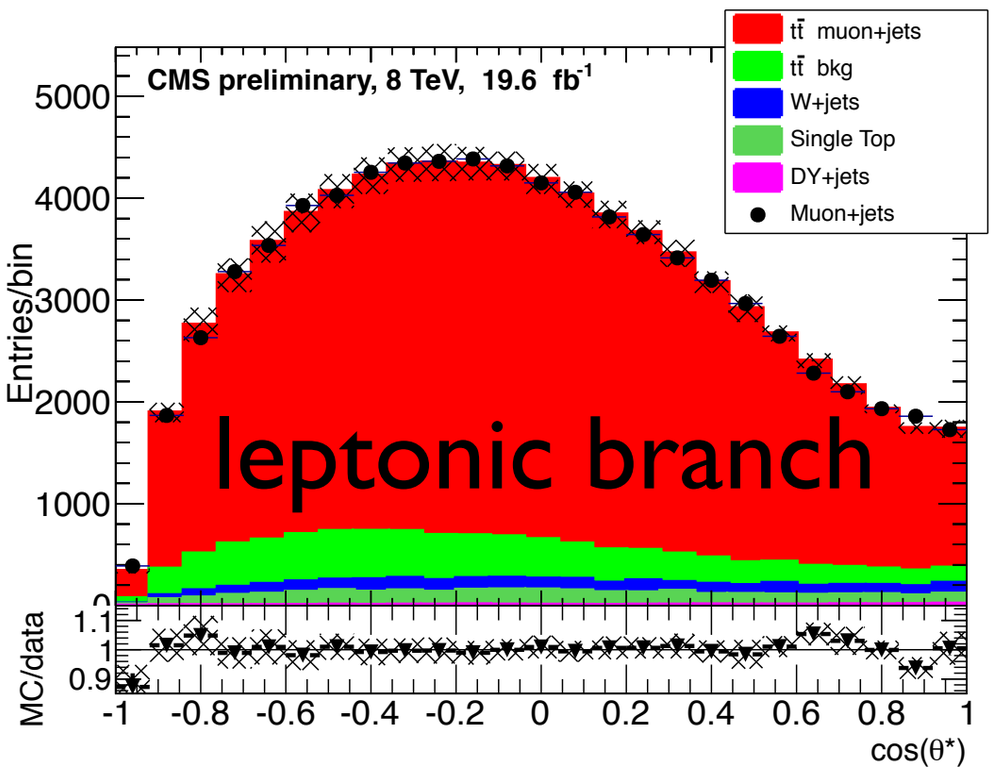
- CMS PAS TOP-13-008 : Measurement of the W-boson helicity in top decays from TTbar production in lepton+jets events at the LHC at $\sqrt{s}$ = 8 TeV

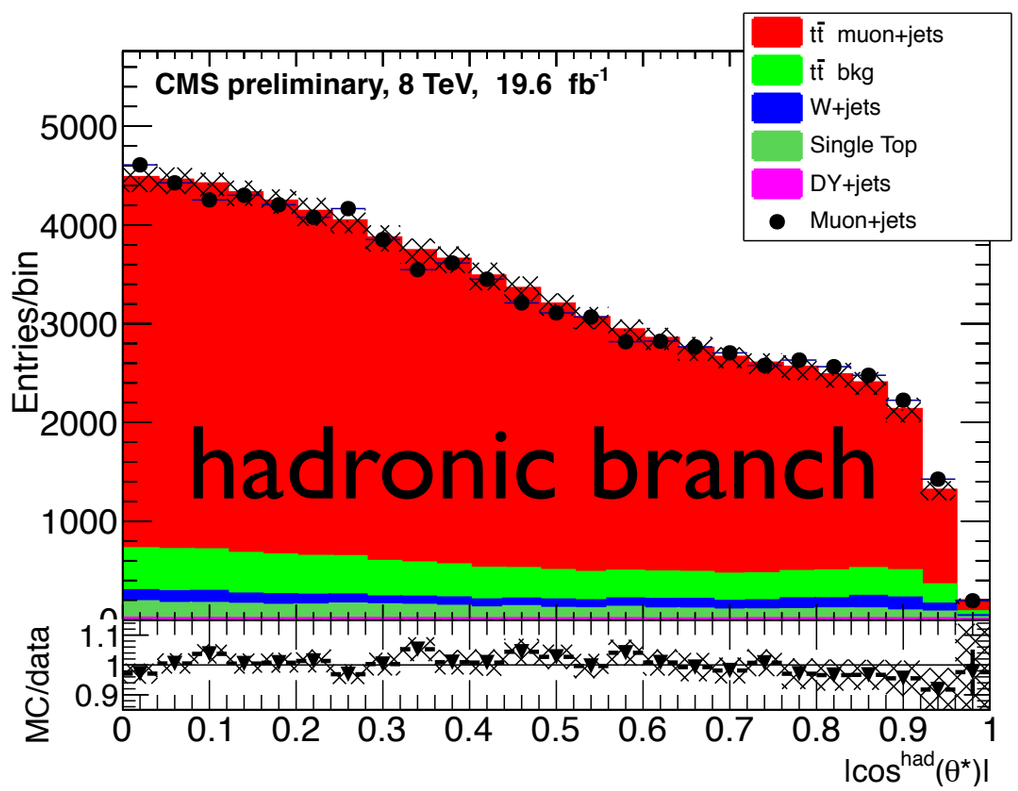


- **Full 2012 dataset at $\sqrt{s}$ = 8 TeV: 19.6/fb**
  - Single muon trigger
- **Muon+jets event selection**
  - At least **1 isolated muon**, at least **4 jets**, at least **2 jets tagged as a b jet**
  - Cut on transverse mass of W to reduce QCD multijet background and suppress dilepton ttbar events
- **TTbar system reconstruction**
  - Groups of 4 jets, together with the lepton and $p_{T,miss}$, are tested for their compatibility with decay products of the **hadronic** ($\bar{t} \rightarrow W^{-}\bar{b} \rightarrow q\bar{q}\bar{b}$) and **leptonic** ($t \rightarrow W^{+}b \rightarrow l\nu_{l}b$) **branches**, taking into account b tagged jets
- **W helicity measurement:** reweighting method to maximize a binned Poisson likelihood function
  - Constructed using the numbers of observed $N_{data}(i)$ and expected $N_{MC}(i,F)$ events in each $\cos(\theta^{*})$ bin i
- **Dominant systematic uncertainties:**
  - Top mass, ttbar renormalisation and factorization scales, ttbar matching scale

New: W helicity in lepton+jets

CMS PAS TOP-13-008





Measurement of the W helicity fractions using the helicity angle $\cos(\theta^*)$ from the **leptonic branch** of semileptonic ttbar decays fitting F0 and FL simultaneously.:

$$F0 = 0.659 \pm 0.015(\text{stat.}) \pm 0.023(\text{syst.}),$$
$$FL = 0.350 \pm 0.010(\text{stat.}) \pm 0.024(\text{syst.}),$$

The right-handed helicity fraction is calculated from the unitarity condition, FL + F0 + FR = 1

$$FR = -0.009 \pm 0.006(\text{stat.}) \pm 0.020(\text{syst.}).$$

The measured fractions are consistent with the predictions from SM.

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The different helicity fraction measurements are in agreement with NNLO QCD

Limits on anomalous couplings

- The combined helicity fractions are in agreement with NNLO QCD predictions and can be used to set limits on new physics contributing to the tWb vertex.
- Start with most general tWb vertex:

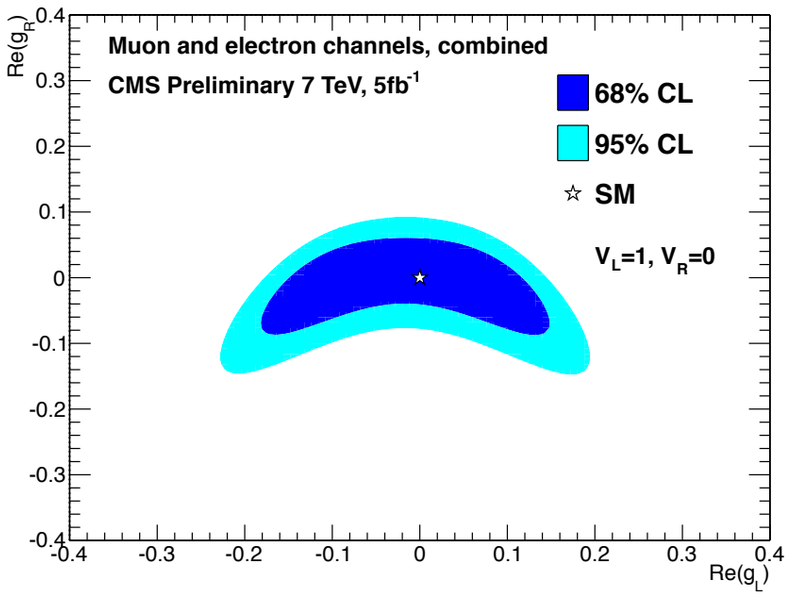
left and right handed vector couplings — left and right handed tensor couplings

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

SM part, $V_L = V_{tb}$ — anomalous couplings (zero in SM)

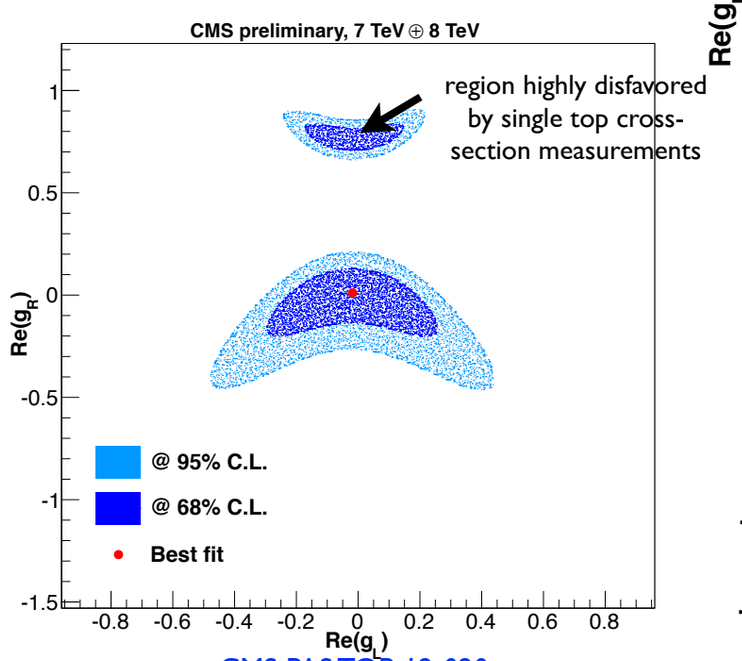
- Assuming $V_L = 1$ and $V_R = 0$, set limits on real parts of g_L and g_R

7 TeV lepton+jets



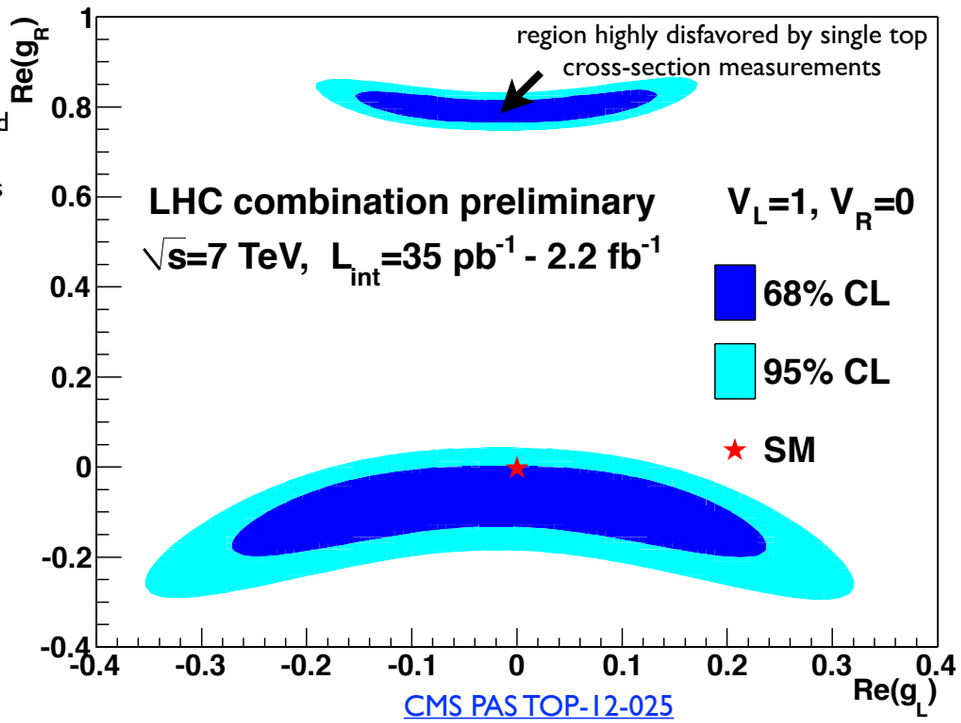
JHEP 10 (2013) 167

7 TeV single top



CMS PAS TOP-12-020

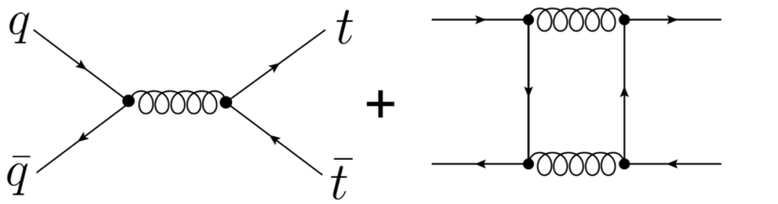
7 TeV lepton+jets and dilepton Atlas+CMS combination



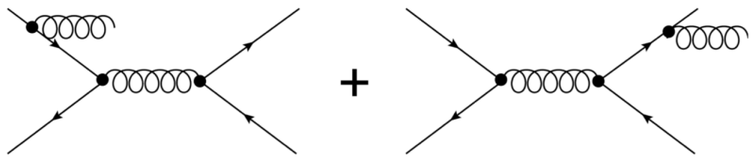
CMS PAS TOP-12-025

Top pair asymmetry

Tevatron



Top quark emitted in the direction of the proton



Top quark emitted in the opposite direction of the proton

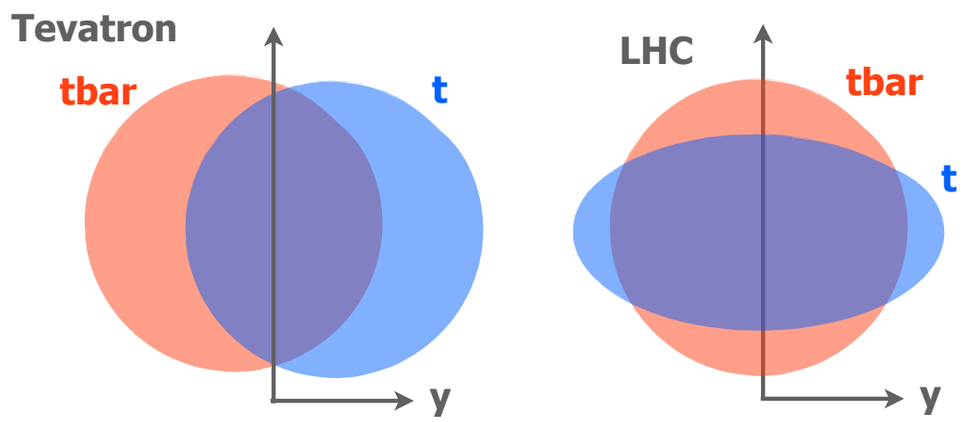
- Interference causes the (anti)top direction to be correlated to the initial state (anti)quark
- Forward-Backward asymmetry:

$$A_{\mathrm{FB}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

$$\Delta y = y_t - y_{\bar{t}}$$

- **Deviation (>2σ) from SM in inclusive measurement**
  - Considerable increase of asymmetry with m(ttbar)
  - Phys. Rev. D 87, 092002 (2013)

- Tevatron A_{FB} variable not useful at **LHC**
  - Initial state is forward-backward symmetric (pp)
    - Quark (mainly valence quark) and anti-quark (sea quark) parton distributions inside the protons are not symmetric
    - Quarks carry more momentum than the anti-quarks → **rapidity distribution of tops broader than of anti-tops when a charge asymmetry is present.**
      - i.e. $|y_t| > |y_{tbar}|$



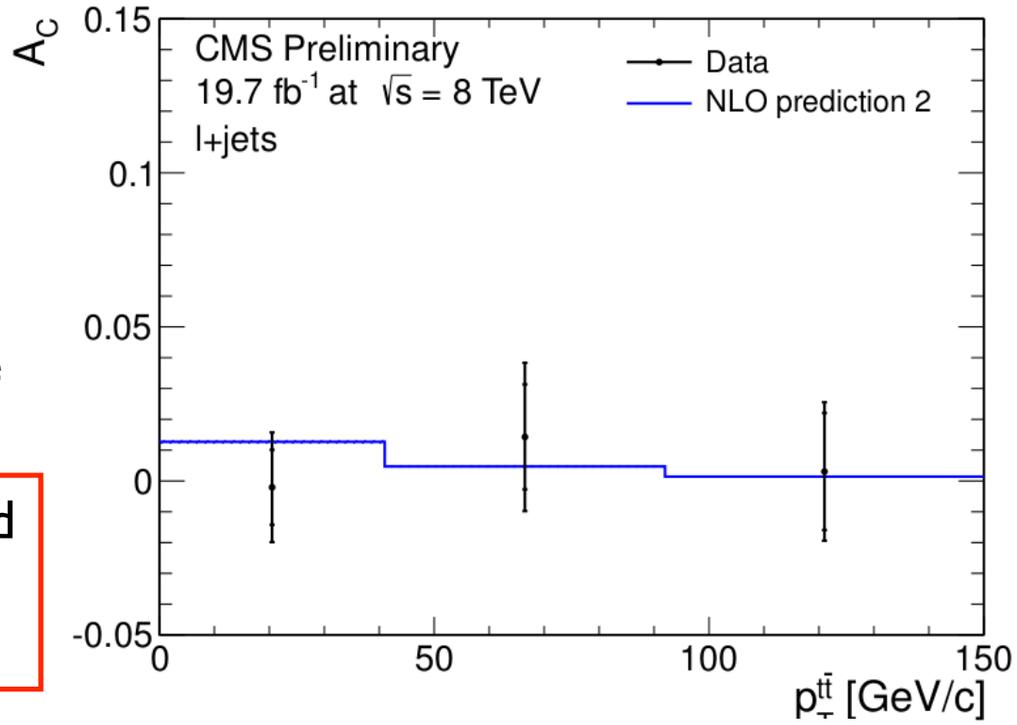
- Charge asymmetry:

$$A_C = \frac{N(|y_t| > |y_{\bar{t}}|) - N(|y_t| < |y_{\bar{t}}|)}{N(|y_t| > |y_{\bar{t}}|) + N(|y_t| < |y_{\bar{t}}|)}$$

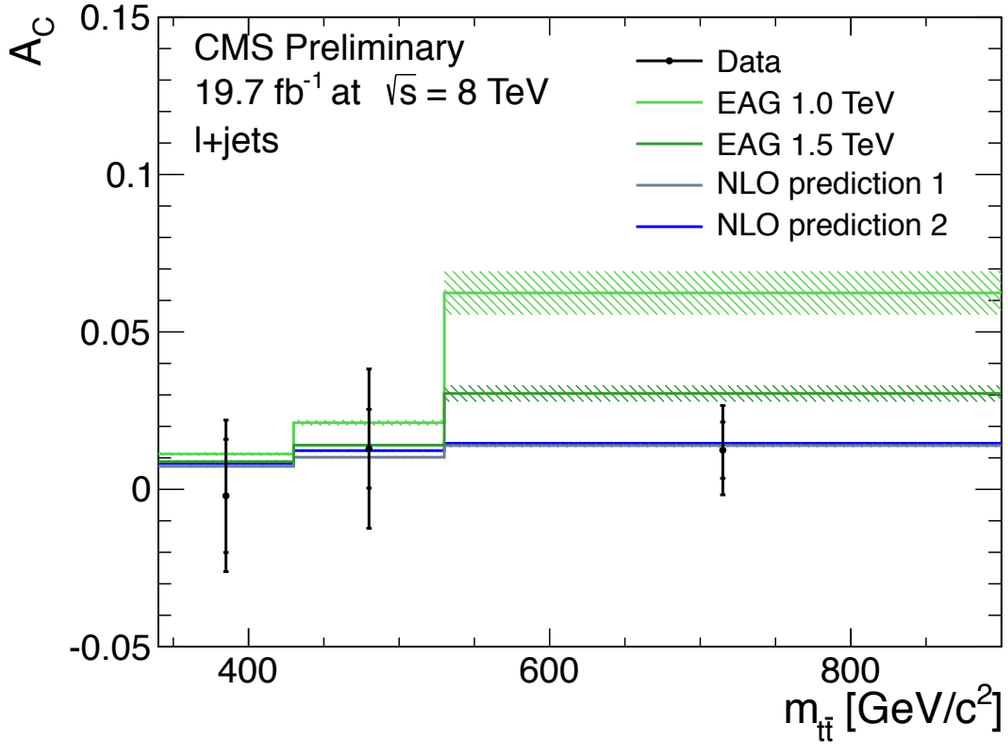
New: Top pair charge asymmetry in lepton+jets

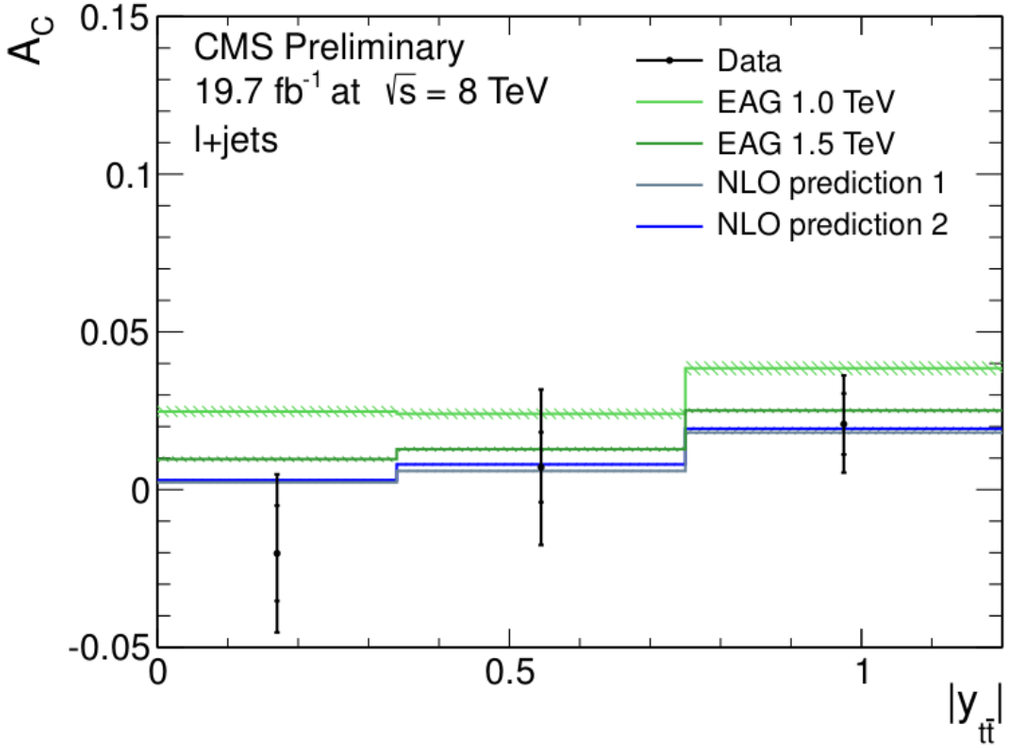
- **Full 2012 dataset at $\sqrt{s}$ = 8 TeV: 19.7/fb**
  - Single lepton trigger selections for electrons and muons
- Event selection
  - **1 isolated electron or muon**, at least **4 jets**, at least **1 jet tagged as b**
- Major backgrounds are W+Jets and Multijet QCD events, charge asymmetries are unfolded to parton level

Measurements are consistent with the predictions of the Standard Model and no hints for deviations due to new physics contributions have been observed.



CMS PAS TOP-12-033





EAG: Model featuring an effective axial-vector coupling of the gluon: Phys. Rev. D 85 (2012) 074021

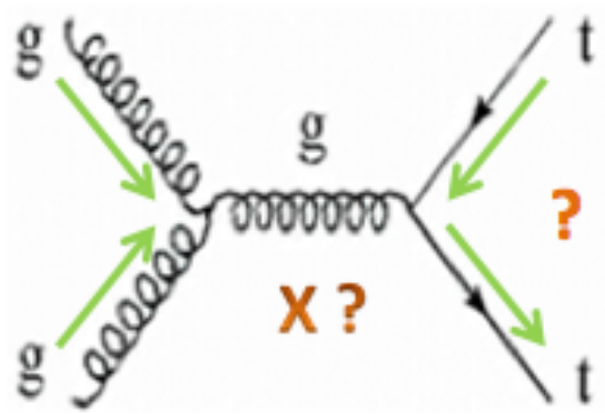
Top pair asymmetry at the LHC

	NLO	Lepton+jets	Dileptons
7 TeV	0.0115 ± 0.0006 Phys. Rev. Lett. 81 (1998) 49	0.004 ± 0.010 (stat.) ± 0.011 (syst.) [5/fb] Phys. Lett. B717 (2012) 129	0.010 ± 0.015 (stat.) ± 0.006 (syst.) [5/fb] CMS PAS TOP-12-010
8 TeV	0.0111 ± 0.0004 Phys. Rev. D **86** (2012) 034026	0.005 ± 0.007 (stat.) ± 0.006 (syst.) NEW [19.7/fb] CMS PAS TOP-12-033	

Measurements are consistent with the predictions of the Standard Model

Top spin correlations and polarization in dileptons

- We measure the top polarization and TTbar spin correlations and compare to SM predictions
  - New physics could alter polarization and spin correlation Phys. Rev. D 84, 074034 (2011)



- **Top polarization:**

$$P = 2 * A \qquad A_P = \frac{N(\cos(\theta_\ell) > 0) - N(\cos(\theta_\ell) < 0)}{N(\cos(\theta_\ell) > 0) + N(\cos(\theta_\ell) < 0)}$$

  - A_P: measured in the helicity basis (angle θ_l of lepton measured in parent top's rest frame, relative to direction of the top in the ttbar center of mass frame)

- **TTbar spin correlation:**

$$A_{\Delta\phi} = \frac{N(\Delta\phi_{\ell^+\ell^-} > \pi/2) - N(\Delta\phi_{\ell^+\ell^-} < \pi/2)}{N(\Delta\phi_{\ell^+\ell^-} > \pi/2) + N(\Delta\phi_{\ell^+\ell^-} < \pi/2)}$$

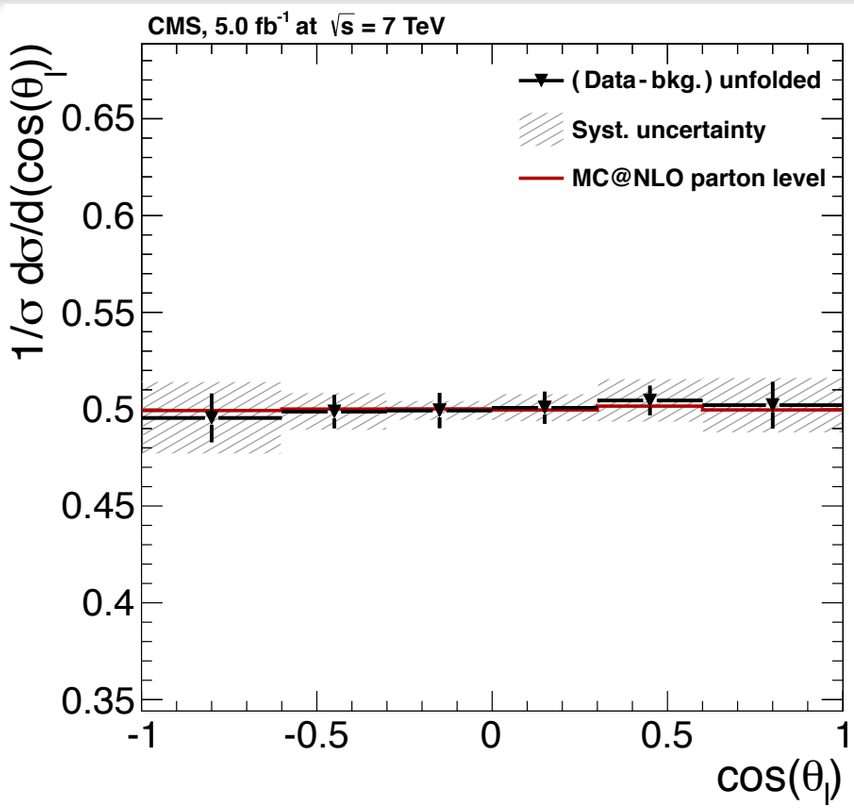
  - $A_{\Delta\varphi}$: excellent discrimination at the LHC between correlated and anti-correlated top and tbar spins

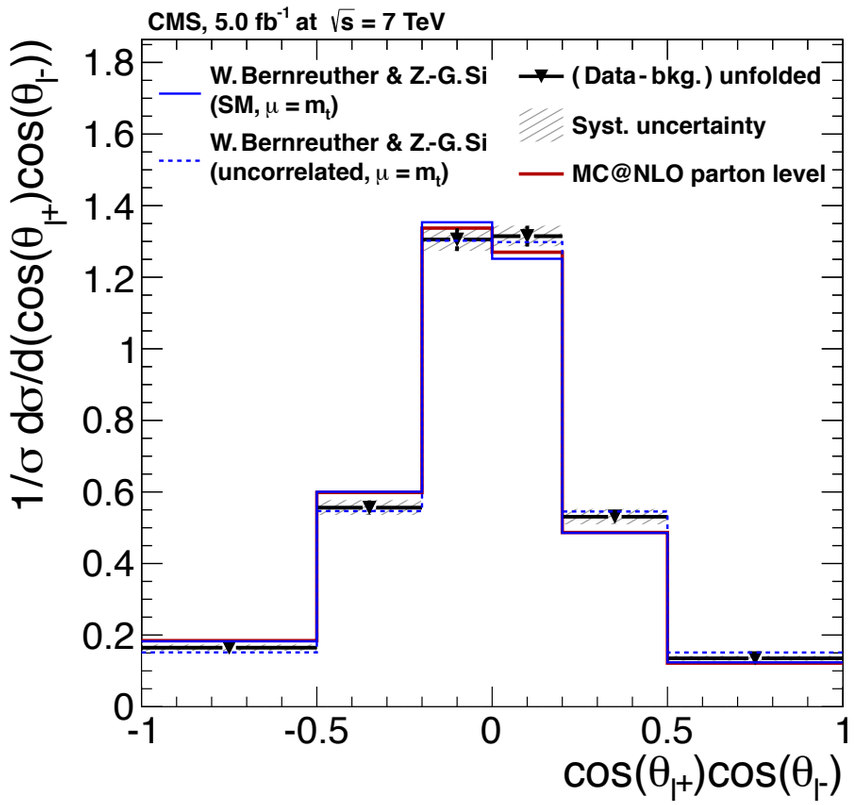
$$A_{c_1c_2} = \frac{N(c_1 \cdot c_2 > 0) - N(c_1 \cdot c_2 < 0)}{N(c_1 \cdot c_2 > 0) + N(c_1 \cdot c_2 < 0)}$$

  - A_{c1c2}: where c1 = cos(θ_{l+}) and c2 = cos(θ_{l-}), provides a direct measure of the spin correlation coefficient C_{hel} using the helicity angles of the two leptons in each event: $C_{hel} = -4A_{c1c2}$

Top spin correlations and polarization in dileptons

- **Full 2011 dataset at $\sqrt{s}$ = 7 TeV: 5/fb**
  - Dilepton trigger selections for electrons and muons
- Top dilepton selection
  - **2 opposite sign isolated leptons** and at least **2 jets** , at least **1 jet tagged as a b**
  - MET cut in ee and μμ channels to suppress Drell-Yan background
- **Top kinematics reconstructed** using analytical matrix weighting technique (**AMWT**)
- An "**unfolding**" procedure is employed to correct acceptance and resolution effects based on the singular value decomposition (**SVD**) method
- Main systematic uncertainty is coming from top p_T reweighting
  - CMS studies have shown the top quark p_T distribution in data to be softer than in the NLO simulation, this is corrected by reweighting the MC
    - For details, please refer to S. Costantini talk about "Top quark pair cross section measurements with CMS" in the Parallel Sessions 24B2: BSM/Top1

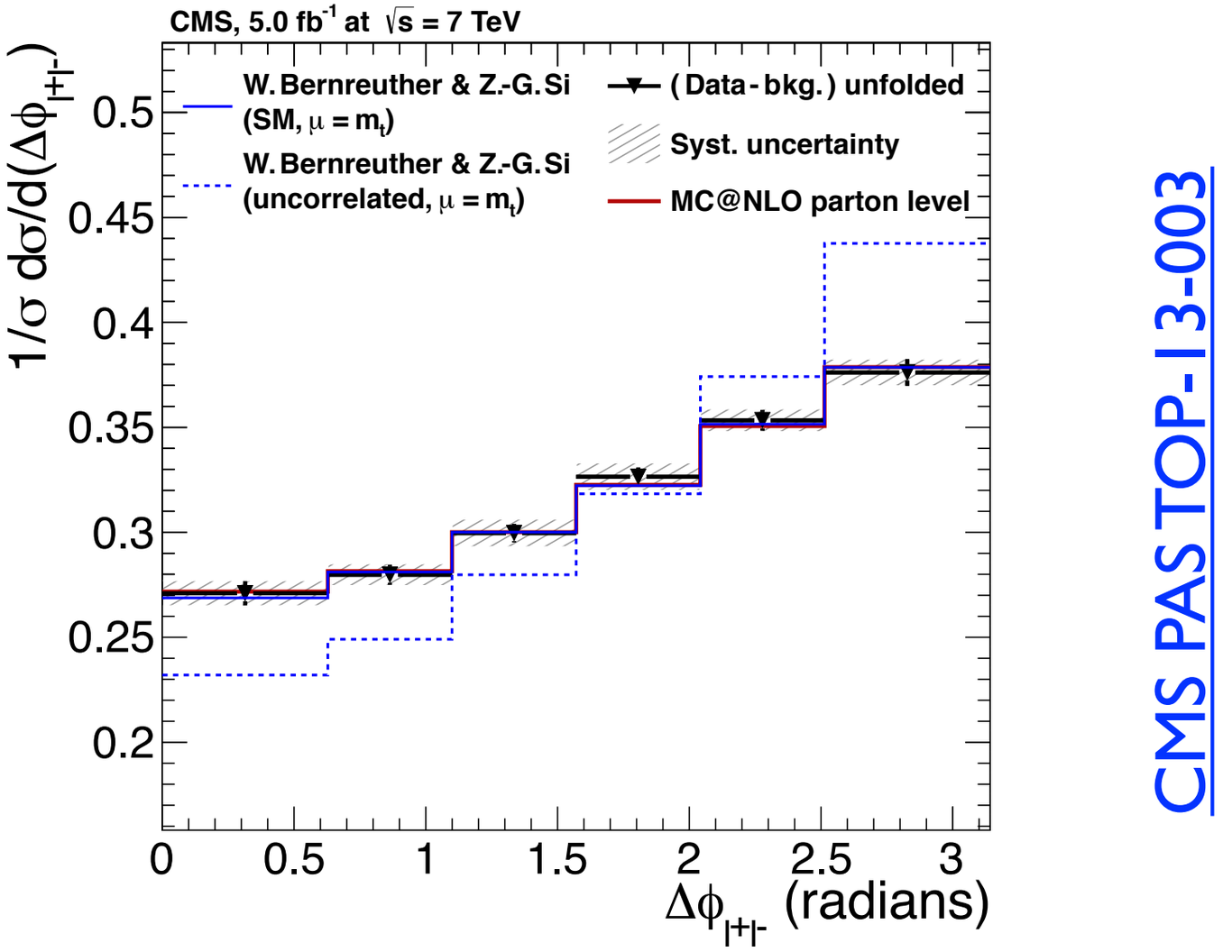




CMS PAS TOP-13-003

Top spin correlations and polarization in dileptons

- **In good agreement with the standard model predictions for all three measured variables**
  - **$A_{\Delta\varphi}$ result indicates the presence of ttbar spin correlations**, and strongly disfavors the uncorrelated case.



Asymmetry	Data (unfolded)	MC@NLO	NLO (SM, correlated)	NLO (uncorrelated)
$A_{\Delta\phi}$	$0.113 \pm 0.010 \pm 0.007 \pm 0.012$	0.110 ± 0.001	$0.115^{+0.014}_{-0.016}$	$0.210^{+0.013}_{-0.008}$
$A_{c_1c_2}$	$-0.021 \pm 0.023 \pm 0.027 \pm 0.010$	-0.078 ± 0.001	-0.078 ± 0.006	0
A_P	$0.005 \pm 0.013 \pm 0.020 \pm 0.008$	0.000 ± 0.001	N/A	N/A

stat. syst. top p_T reweighting

FCNC in top decays

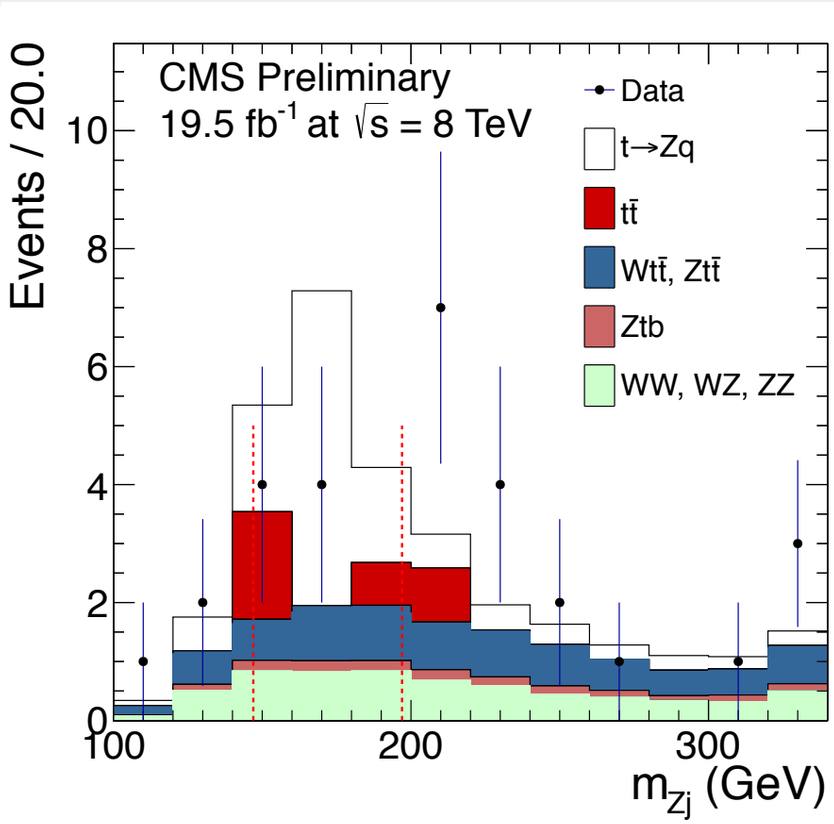
- **Search for flavor changing neutral currents**: t→Zq suppressed in SM but can be enhanced in new physics models

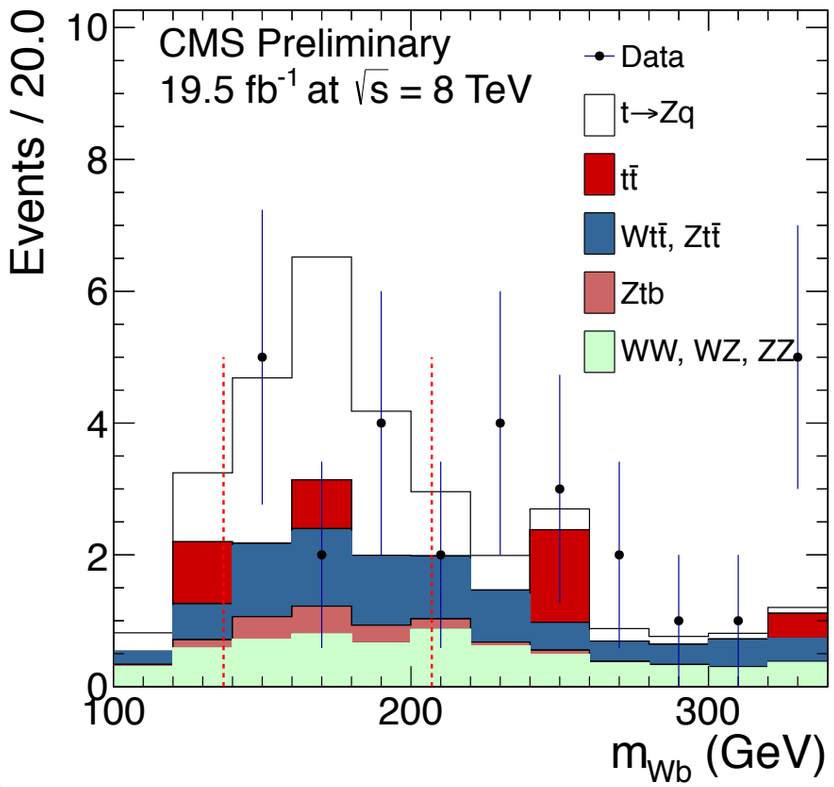
- **Full 2012 dataset at √s = 8 TeV: 19.5/fb**
  - Single lepton trigger

- Event selection
  - **3 isolated leptons (e or μ)**, of which two opposite-sign and consistent with a Z, at least **2 jets**, exactly **1 b tagged jet**

- Backgrounds are estimated from data using b tagging information:

Total background	$3.14 \pm 4.97 \pm 1.17$
Observed events	1
Expected limit	$\mathcal{B}(t \to Zq) < 0.10\%$
Observed limit	$\mathcal{B}(t \to Zq) < 0.07\%$





TOP-12-037

- **No excess of events over the SM background is observed** and a **B(t → Zq) branching fraction larger than 0.07% is excluded at the 95% confidence level**
  - **3 times better than 7 TeV result**
  - For comparison:
    - Model with Q=2/3 quark singlets (QS) predicts a BR of ~10E-4
    - MSSM predicts ~10E-6
      - Acta Phys. Pol. B35 (2004) 2527-2811

Conclusions

- The LHC is a top factory and allows precision measurements of many top properties
  - Allows to test SM predictions and search for new physics

- CMS latest results of top property measurements have been presented for
  - W helicity in top decays, Top pair asymmetry, TTbar spin correlations, Flavor changing neutral currents

- All presented results are in good agreement with SM predictions, no hints for deviations due to new physics contributions have been observed