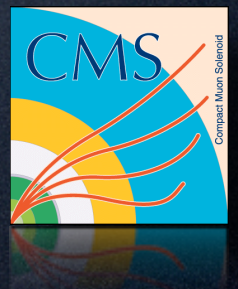
Observation of single top tW production and search for FCNC in tZ events

Outline:

- Single Top at the LHC
- tW-channel results
- Search for FCNC in tZ events
- Conclusions

Gabriele Benelli
On behalf of the CMS Collaboration



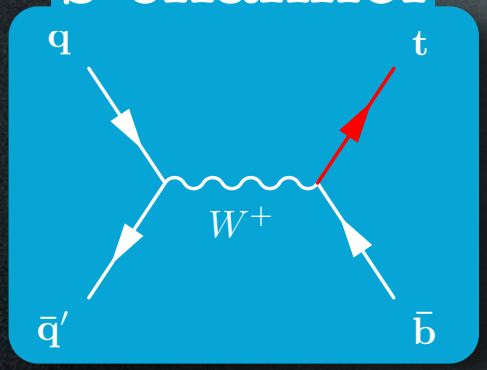
Gabriele.Benelli@cern.ch

EPS HEP 2013 Stockholm, July 19th 2013

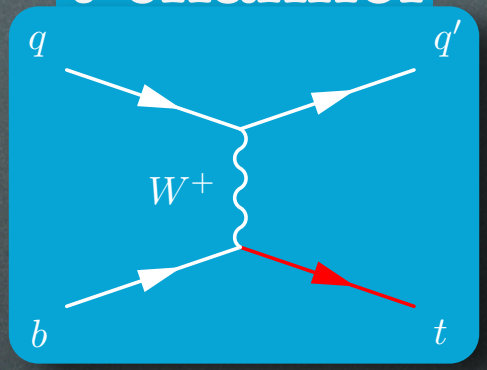
Introduction

- Three single top production channels:

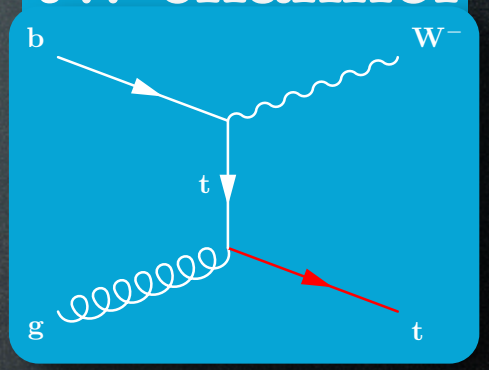
s-channel



t-channel



tW channel



- Weak interaction production (Wtb, btW) and decay vertices (tWb)
- Access to CKM matrix element V_{tb}
- Sensitive to new physics
- Top cross-sections at the LHC (and Tevatron)

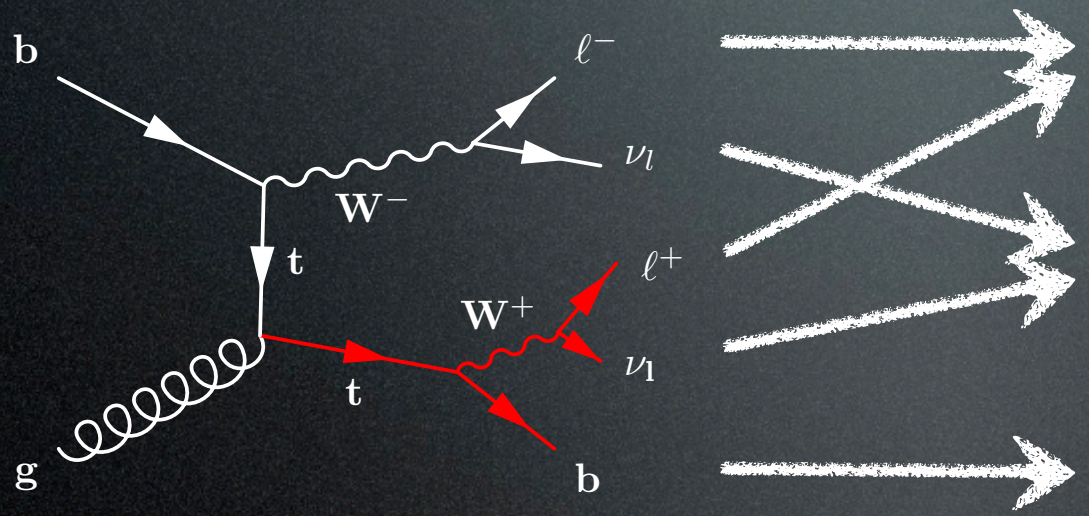
Top mass = 173 GeV

N. Kidonakis arxiv.org/pdf/1205.3453v1 (2012)

Cross sections (pb)	s-channel	t-channel	tW channel	top pairs
Tevatron: ppbar@1.96TeV	1.05	2.08	0.22* *arxiv.org/pdf/0909.0037	7.08
LHC: pp @ 7 TeV	4.56	65.9	15.6	163
LHC: pp @ 8 TeV	5.55	87.2	**22.2**	**234**

Single top tW channel

- tW associated production observable at LHC for the first time!
- Interesting topology (background to Higgs->WW searches)
- Only leptonic (e, μ) decays of W considered:
  - **Di-lepton** topology:



Two isolated leptons (ee, μμ, eμ)

E_t^{miss} from the two neutrinos

One b-jet from top decay b quark

- Full reconstruction of W or top not possible
- Main backgrounds:
  - Top pairs, Z+jets, all other processes easily reducible
- tW mixing with top pair at NLO:
  - Diagram Removal vs. Diagram Subtraction (DR/DS)

tW channel Event Selection I

- Dileptonic Triggers:
  - Two leptons (e or μ: ee, eμ, μμ)
  - Leading lepton p_t > 17GeV, second lepton p_t > 8GeV
- Object selection:
  - Electrons:
    - p_t>20GeV
    - $|\eta|$<2.5
    - IP<0.04cm from beamspot
    - RelIso<0.15 in a cone of ΔR<0.3
  - Muons:
    - p_t>20GeV
    - $|\eta|$<2.4
    - RelIso<0.20 in a cone of ΔR<0.4
  - Jets:
    - Anti-k_t
    - p_t>30GeV
    - $|\eta|$<2.4
    - Energy and p_t corrected
- Particle Flow corrected missing transverse energy (E_t^{miss}) used
- B tagging information:
  - Tracking-based multivariate tagging algorithm
  - Data-driven pt dependent b-tagging scale factors applied

tW channel Event Selection I

- Dileptonic Triggers:
  - Two leptons (e or μ: ee, eμ, μμ)
  - Leading lepton p_t > 17GeV, second lepton p_t > 8GeV
- Object selection:
  - Electrons:
    - p_t>20GeV
    - $|\eta|$<2.5
    - IP<0.04cm from beamspot
    - RelIso<0.15 in a cone of ΔR<0.3
  - Loose Electrons:
    - p_t>10GeV
    - $|\eta|$<2.5GeV
  - Muons:
    - p_t>20GeV
    - $|\eta|$<2.4
    - RelIso<0.20 in a cone of ΔR<0.4
  - Loose Muons:
    - p_t>10GeV
    - $|\eta|$<2.5GeV
  - Jets:
    - Anti-k_t
    - p_t>30GeV
    - $|\eta|$<2.4
    - Energy and p_t corrected
  - Loose Jets:
    - Not “tight”
    - p_t>20GeV
    - $|\eta|$<4.9GeV
    - $|\eta|$<2.4GeV (central)
- Particle Flow corrected missing transverse energy (E_t^{miss}) used
- B tagging information:
  - Tracking-based multivariate tagging algorithm
  - Data-driven pt dependent b-tagging scale factors applied

tW channel Event Selection II

- Selection (3 final states ee, μμ, eμ):
  - Exactly 2 isolated, oppositely charged leptons
  - Leptons invariant mass m_{ll} >20 GeV

All states

  - Z mass veto (m_{ll} < 81 GeV, m_{ll} > 101 GeV)
  - E_T^{miss} > 50 GeV

ee/μμ

- Signal and control regions defined by jet multiplicity and b-tagging:
  - 1 jet 1 b-tag (**1j1t**): signal region (15-20% tW, 75% top pairs, 5% Z+Jets)
  - 2 jets 1 b-tag (**2j1t**) and 2 jets 2 b-tags **(2j2t**) control regions to constrain top pair cross-section
- Analysis strategy:
  - Data-driven normalization of Z+jets MC (reverse Z mass veto control region)
  - Kinematic variables used to disentangle tW from top pairs
  - Multivariate Boosted Decision Tree (BDT) analysis to extract signal

tW Boosted Decision Tree

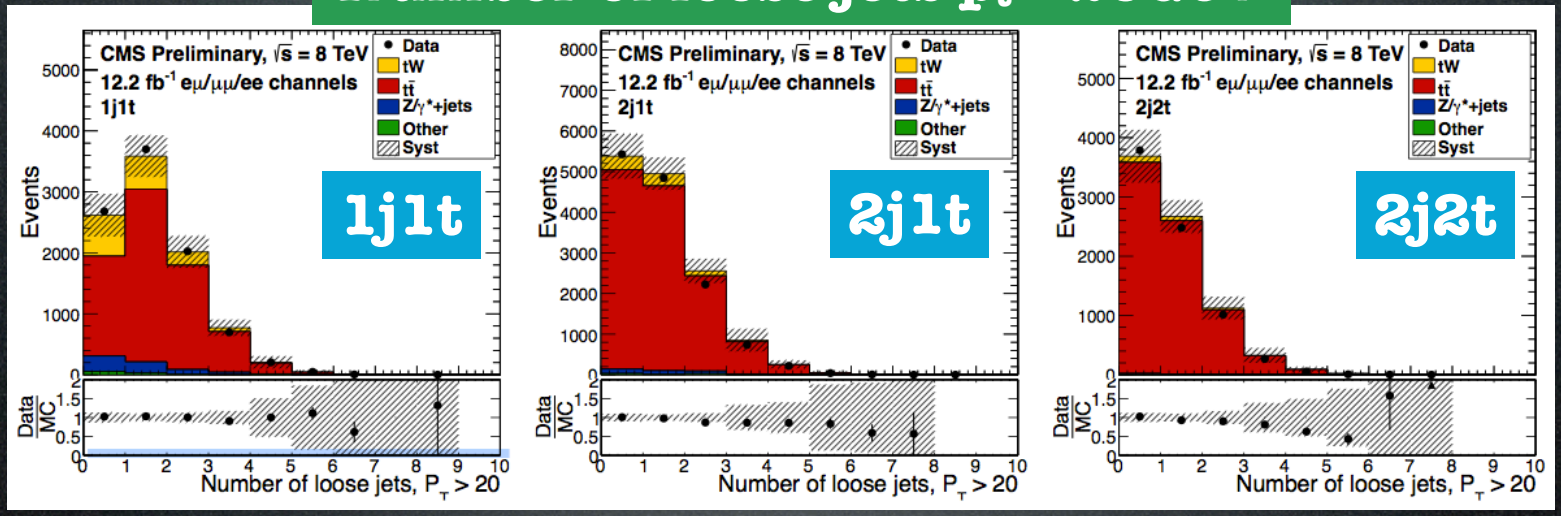
- Training on 200k exclusive tW and top pair dilepton events (after selection and in the 1j1t region)
  - MC generators:
    - Single Top: POWHEG
    - Top pairs/V+jets: MadGraph
    - VV et al: Pythia
- 13 kinematic input variables chosen based on:
  - signal/background separation
  - data/MC agreement in several control regions (2j1t, 2j2t, 2j0t,1j0t)

Variable	Description
Nloosejets	Number of loose jets, $p_T > 20$ GeV, $\|\eta\| < 4.9$
NloosejetsCentral	Number of loose jets, $p_T > 20$ GeV, $\|\eta\| < 2.4$
NbtaggedLoosejets	Number of loose jets, $p_T > 20$ GeV, CSVM btagged
$p_{T,sys}$	Vector sum of p_T of leptons, jet, and E_T^{miss}
H_T	Scalar sum of p_T of leptons, jet, and E_T^{miss}
Jet p_T	p_T of the leading, tight, b-tagged jet
Loose jet p_T	p_T of leading loose jet, defined as 0 for events with no loose jet present
$p_{T,sys}/H_T$	Ratio of $p_{T,sys}$ to H_T for the event
Msys	Invariant mass of the combination of the leptons, jet, and E_T^{miss}
centralityJLL	Centrality of jet and leptons
$H_{T,leptons}/H_T$	Ratio of scalar sum of p_T of the leptons to the H_T of full system
p_T-jll	Vector sum of p_T of jet and leptons
E_T^{miss}	Missing transverse energy in the event

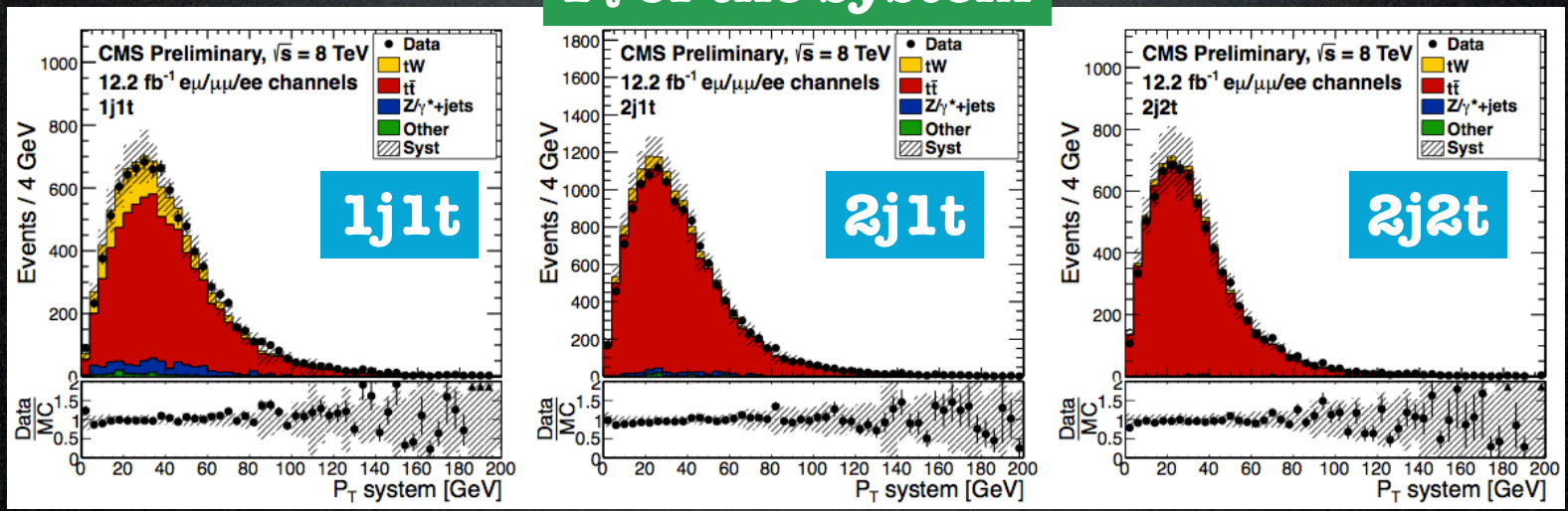
tW BDT Input Variables

- Sample input variable distributions in the control and signal regions:

Number of loose jets p_t > 20GeV



P_t of the system

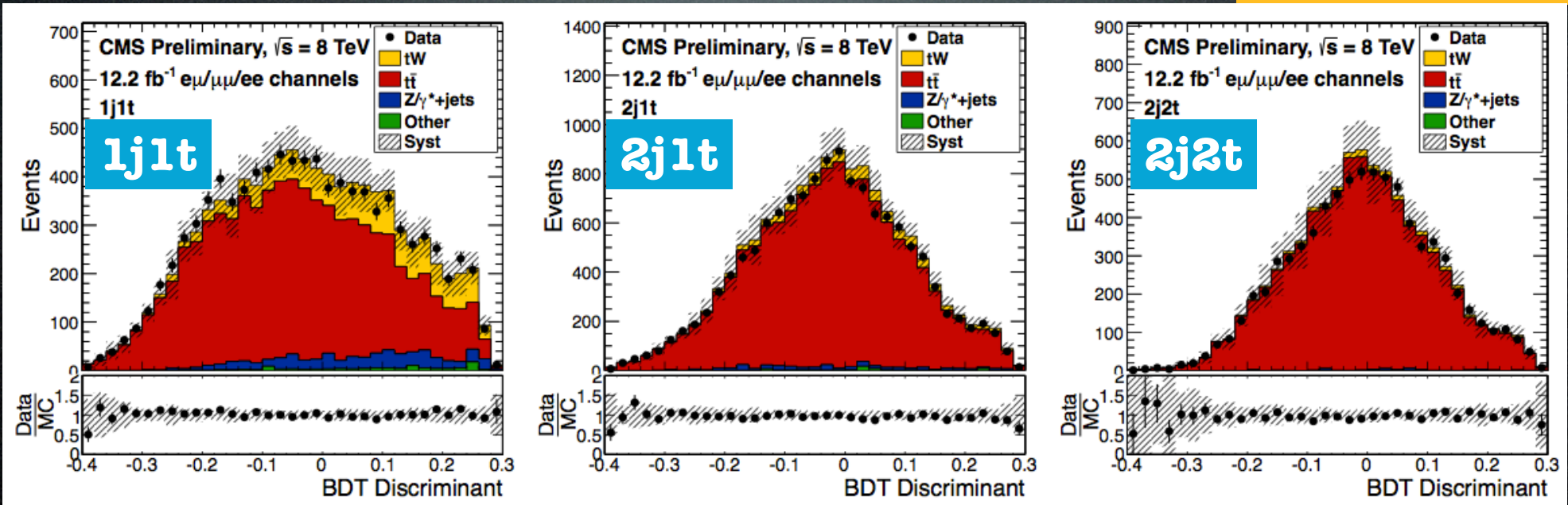


12.2 fb^{-1} @8 TeV

tW BDT Discriminant

- BDT discriminant for each event:
  - Signal-like events positive values
  - Background-like events negative values

12.2 fb^{-1} @8 TeV



- Likelihood fit to BDT discriminant:
  - Simultaneous in all channels and all regions
  - Signal and background templates from MC
  - Systematics shape and rate effects accounted for as nuisance parameters

tW Systematic Uncertainties

- Several sources of systematic uncertainties considered in both significance and cross-section estimate
- The 68%C.L. interval evaluated using profile likelihood
- Theory shape uncertainties estimated as the central value difference from value obtained setting nuisance parameters to +/-1σ
- Externalized in the significance calculation
- For other sources nuisance parameters fixed to central value and confidence level interval change used as estimate
- "Statistical" uncertainty from fixing all other sources to central value

Systematic Uncertainty	$\Delta\sigma$ (pb)	$\frac{\Delta\sigma}{\sigma}$
ME/PS matching thresholds	3.25	14%
Q^2 scale	2.68	11%
Top quark mass	2.28	10%
Statistical	2.13	9%
Luminosity	1.13	5%
JES	0.91	4%
$t\bar{t}$ cross section	0.87	4%
Z+jet data/MC scale factor	0.56	2%
tW DR/DS scheme	0.45	2%
PDF	0.33	1%
Lepton identification	0.31	1%
JER	0.27	1%
B-tagging data/MC scale factor	0.20	< 1%
$t\bar{t}$ Spin Correlations	0.12	< 1%
Top Pt Reweighting	0.12	< 1%
Event pile up	0.11	< 1%
E_T^{miss} modeling	0.07	< 1%
Lepton energy scale	0.02	< 1%
Total	5.58	24%

tW Results

- Significance estimated using binned likelihood fit with pseudo-experiments (lots of them!):
  - Excess of events with respect to the background-only hypothesis
  - Observed significance in 12.2 fb^{-1} of 8 TeV data: **6.0 σ**
  - Expected significance from MC: **$5.4^{+1.5}_{-1.4}\sigma$**
- Cross-section estimated using profile likelihood:
  - **$\sigma_{tW} = 23.4^{+5.5}_{-5.4}$ pb at 8TeV**
  - Theoretical value (m_{top}=173GeV):
    - σ_{tW} = 22.2 ± 0.6(scale) ±1.4(PDF) pb

(Approximate NNLO) N. Kidonakis arxiv.org/pdf/1210.7813 (2012)

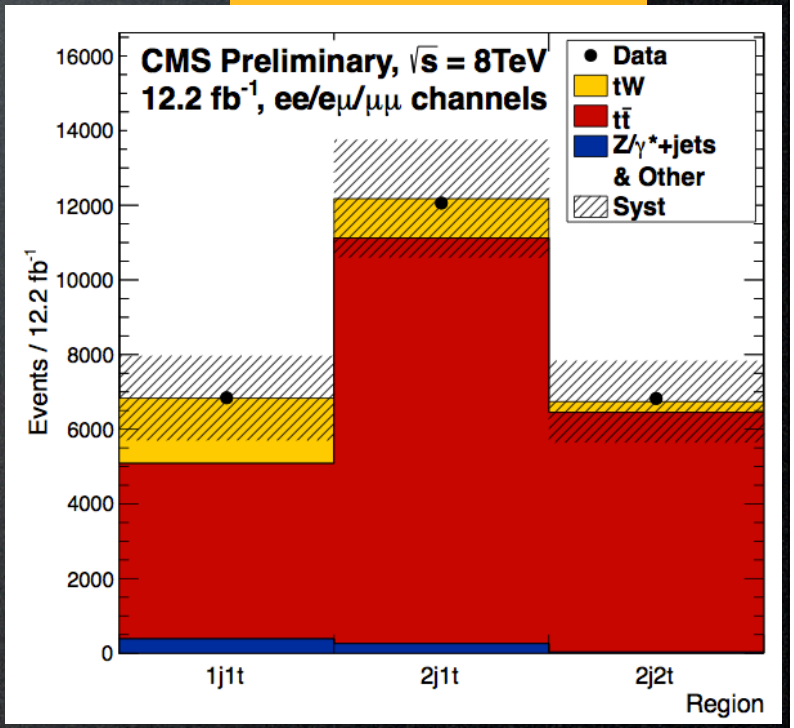
- V_{tb} matrix element estimate ($|V_{tb}| >> |V_{td}|, |V_{ts}|$):
  - $$|V_{tb}| = \sqrt{\frac{\sigma_{tW}}{\sigma_{tW}^{th}}} = 1.03 \pm 0.12(exp.) \pm 0.04(th.)$$
  - $|Vtb| > 0.78$ at 95% C.L. ($0 \leq |V_{tb}|^2 \leq 1$)

12.2 fb^{-1} @8 TeV

tW Cross-check analyses

- Two cross-check analyses performed, using the same event selection and the same signal and control regions with the following exceptions:
  - $p_{T,sys}$ Fit:
    - Veto extra b–tagged loose jets events
    - Cut on H_t in eμ channel (H_t>160GeV)
    - Same fit as BDT but to the $p_{T,sys}$ distribution
    - Results:
      - Observed significance **4.0** sigma
      - Expected significance $\mathbf{3.2^{+0.4}_{-0.9}}$ sigma
      - Cross section: $\mathbf{24.3^{+8.6}_{-8.8}}$ pb
  - Cut and Count:
    - Veto extra b–tagged loose jets events
    - Cut on H_t in eμ channel (H_t>160GeV)
    - Fit to the event counts only in each region
    - Results:
      - Observed significance **3.6** sigma
      - Expected significance $\mathbf{2.8^{+0.9}_{-0.8}}$ sigma
      - Cross section: $\mathbf{33.9^{+8.6}_{-8.6}}$ pb

12.2 fb^{-1} @8 TeV

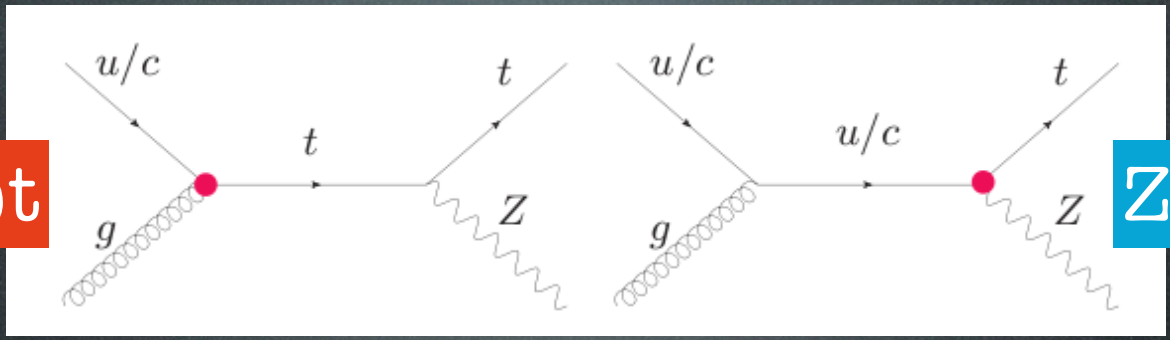


CMS PAS TOP-12-021

Search for FCNC in tZ events

- tZ final state sensitive to 2 types of anomalous couplings

gu(c)t



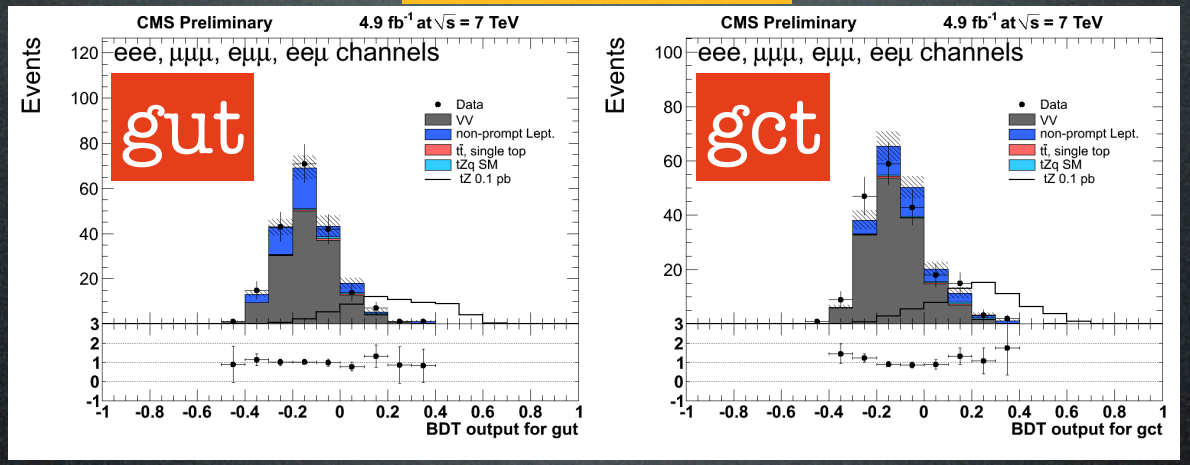
Zu(c)t

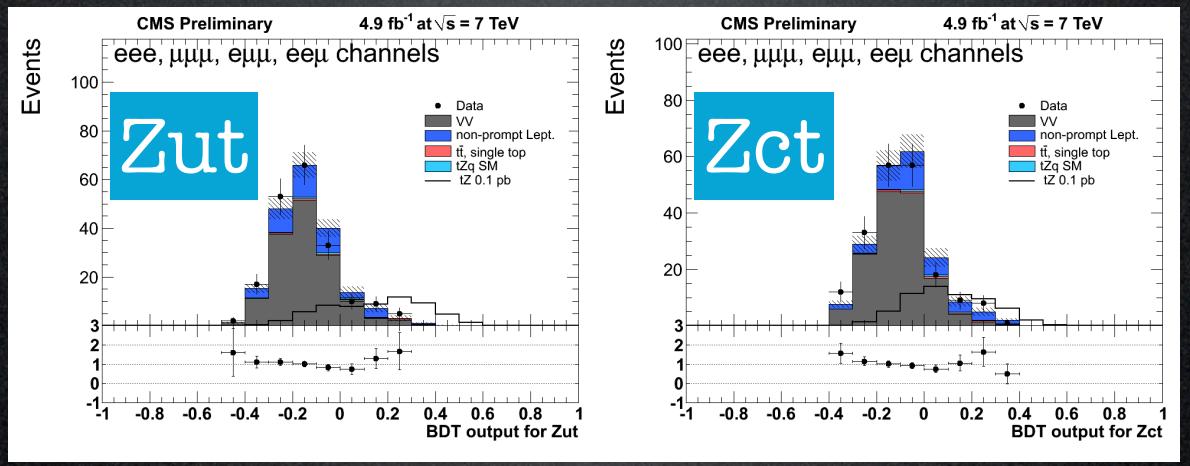
- Final state:
  - 3 leptons (leptonic Z and W decay)
  - 1 b-jet (top Wb decay)
- Low statistics: 4 channels (eee, μμμ, eeμ, μμe) summed up
- After event selection, Boosted Decision Tree (BDT) discriminants used
- Main backgrounds:
  - Fake lepton (Z+jets) : normalization from a template fit of the m_T^W distribution. Shapes extracted from data for Z+jets.
  - WZ+jets normalization is left free in the calculation of the limit.
  - Other sub-dominant backgrounds : ZZ+jets, top pairs, tZq

tZ FCNC BDT strategy

- 4 separate BDTs trained on each of the anomalous couplings signal MC (gut, gct, Zut, Zct) and the main WZ+jets background
- Likelihood fits to extract 95%C.L. cross-section limit

4.9 fb^{-1} @7 TeV



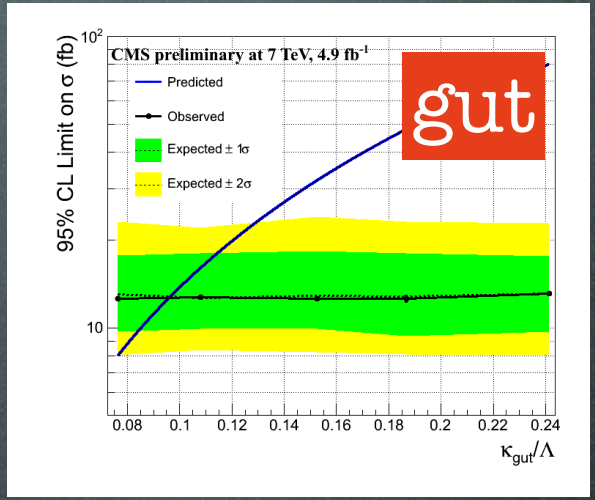


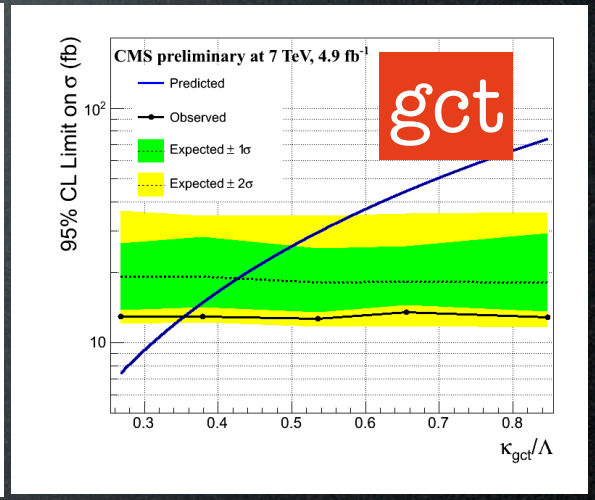
FCNC results

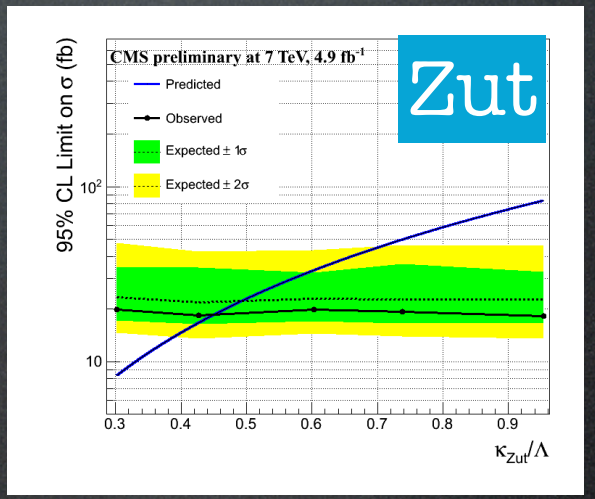
- Results do not show anomalous couplings signal
- Exclusion limits at 95% C.L. determined using a likelihood based technique
- Coupling strength results translated into top decay branching fractions

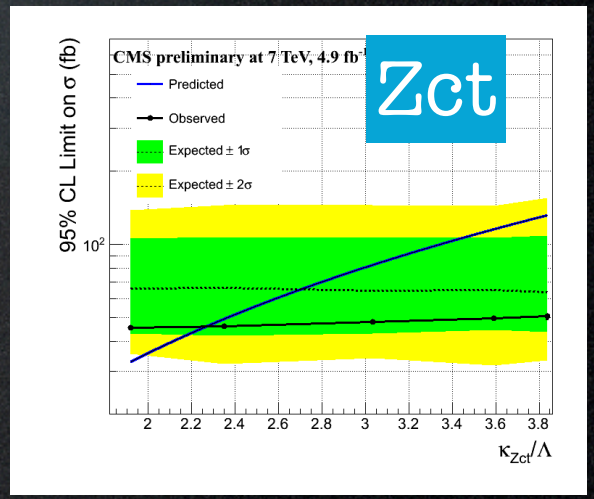
couplings	Expected	Observed	$\mathcal{BR}(t \to gq/Zq)$
κ_{gut}/Λ	0.100	0.099	0.60%
κ_{gct}/Λ	0.440	0.361	7.40%
κ_{Zut}/Λ	0.514	0.463	0.53%
κ_{Zct}/Λ	2.766	2.286	11.57%

- Complementary results to top pair FCNC analyses
- Improvement expected with 8TeV analysis (coming soon!)









Conclusions

- First > 5 σ observation of Single Top tW production in pp collisions:
  - Expected significance: **$5.4^{+1.5}_{-1.4}$ σ**
  - Observed: **6.0 σ**
- New measurement of tW cross-section:
  - **$\sigma_{tW} = 23.4^{+5.5}_{-5.4}$ (stat⊕sys) pb**
- $|V_{tb}|$ measurement from tW-channel analysis:

$$|V_{tb}| = \sqrt{\frac{\sigma_{tW}}{\sigma_{tW}^{th}}} = 1.03 \pm 0.12(exp.) \pm 0.04(th.)$$

- Two cross-check analyses confirm robustness of event selection
- **Another rare process confirmation of the standard model!**

A new discovery for EPS!

12.2 fb^{-1} @8 TeV
CMS PAS TOP-12-040
http://cds.cern.ch/record/1563135

4.9 fb^{-1} @7 TeV
CMS PAS TOP-12-021

- A search for FCNC in Single Top tZ was carried out on 7 TeV data
- Anomalous couplings limits are derived:

couplings	Expected	Observed	$\mathcal{BR}(t \to gq/Zq)$
κ_{gut}/Λ	0.100	0.099	0.60%
κ_{gct}/Λ	0.440	0.361	7.40%
κ_{Zut}/Λ	0.514	0.463	0.53%
κ_{Zct}/Λ	2.766	2.286	11.57%

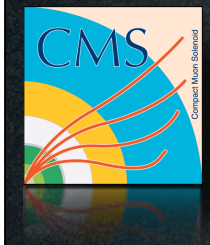
- Both results are in agreement with standard model predictions :)

Thank you!

Public results links

- Single Top tW:
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP12040
  - http://cds.cern.ch/record/1563135

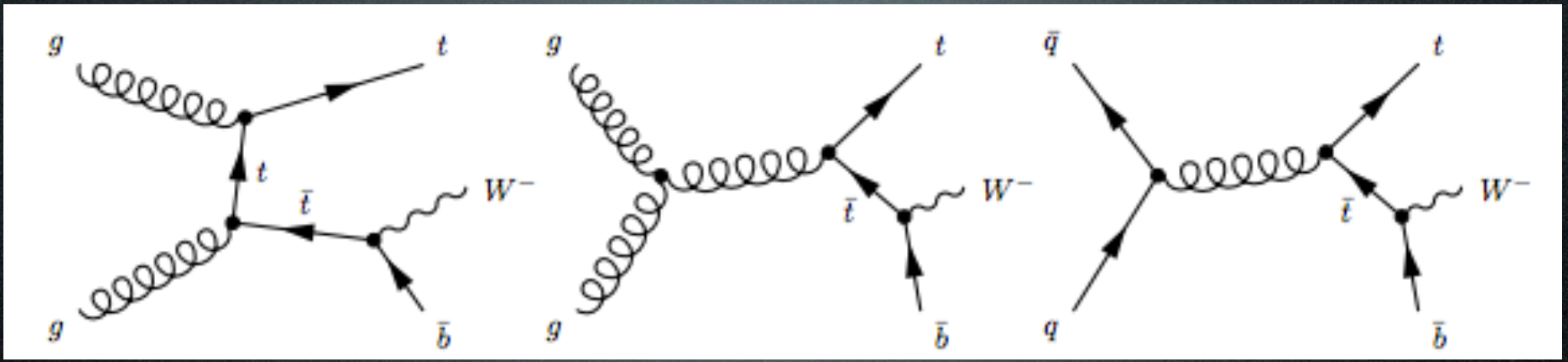
- Single Top tZ, search for FCNC:
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP12021
  - CDS entry coming soon!



Back-up

tW NLO QCD mixing

- tW mixes with top pair production at NLO:



  - Diagram Removal (DR): remove double resonant diagrams
  - Diagram Subtraction (DS): subtract gauge-invariant term to cancel contribution from top pair production
- DR scheme is used as the signal in the analysis
  - DR and DS are consistent within statistical uncertainty
  - Difference accounted for as a theory systematic uncertainty

tW Lepton Selection

- Electrons:
  - p_t>20GeV
  - $|\eta|$<2.5
  - IP<0.04cm from beamspot
  - 0.5<MvaTrigV0<1.0
  - RelIso<0.15 in a cone of ΔR<0.3
- Muons:
  - p_t>20GeV
  - $|\eta|$<2.4
  - RelIso<0.20 in a cone of ΔR<0.4
- Loose Electrons:
  - p_t>10GeV
  - $|\eta|$<2.5GeV
- Loose Muons:
  - p_t>10GeV
  - $|\eta|$<2.5GeV

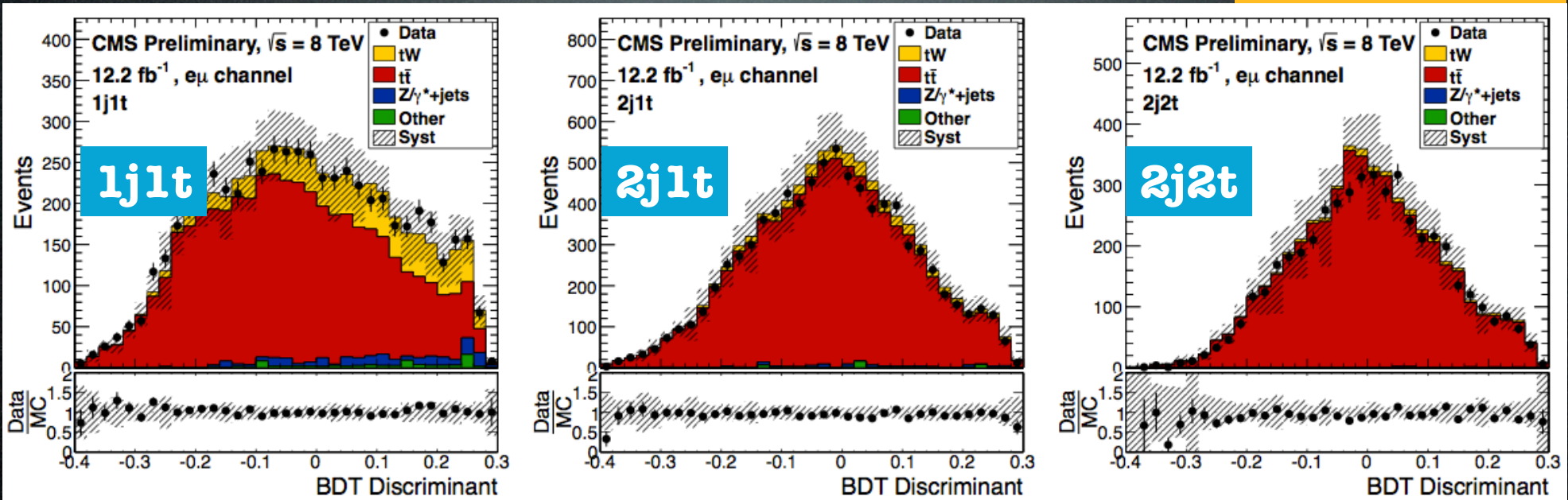
tW Jet and MET Selection

- Jets:
  - Anti-k_t algorithm
  - Corrected p_t>30GeV
  - $|\eta|$<2.4
  - Jet Energy Correction (JEC) applied
- Loose Jets:
  - Failing Tight requirements above
  - p_t>20GeV
  - $|\eta|$<4.9GeV
  - $|\eta|$<2.4GeV (central)
- B-tagged Jets:
  - Combined Secondary Vertex tagging algorithm
  - Medium Working point
  - Re-weighted with pt dependent b-tagging scale factors
- Missing Transverse Energy (MET)
  - Particle Flow MET
  - Type I corrections applied

tW BDT discriminant eμ channel

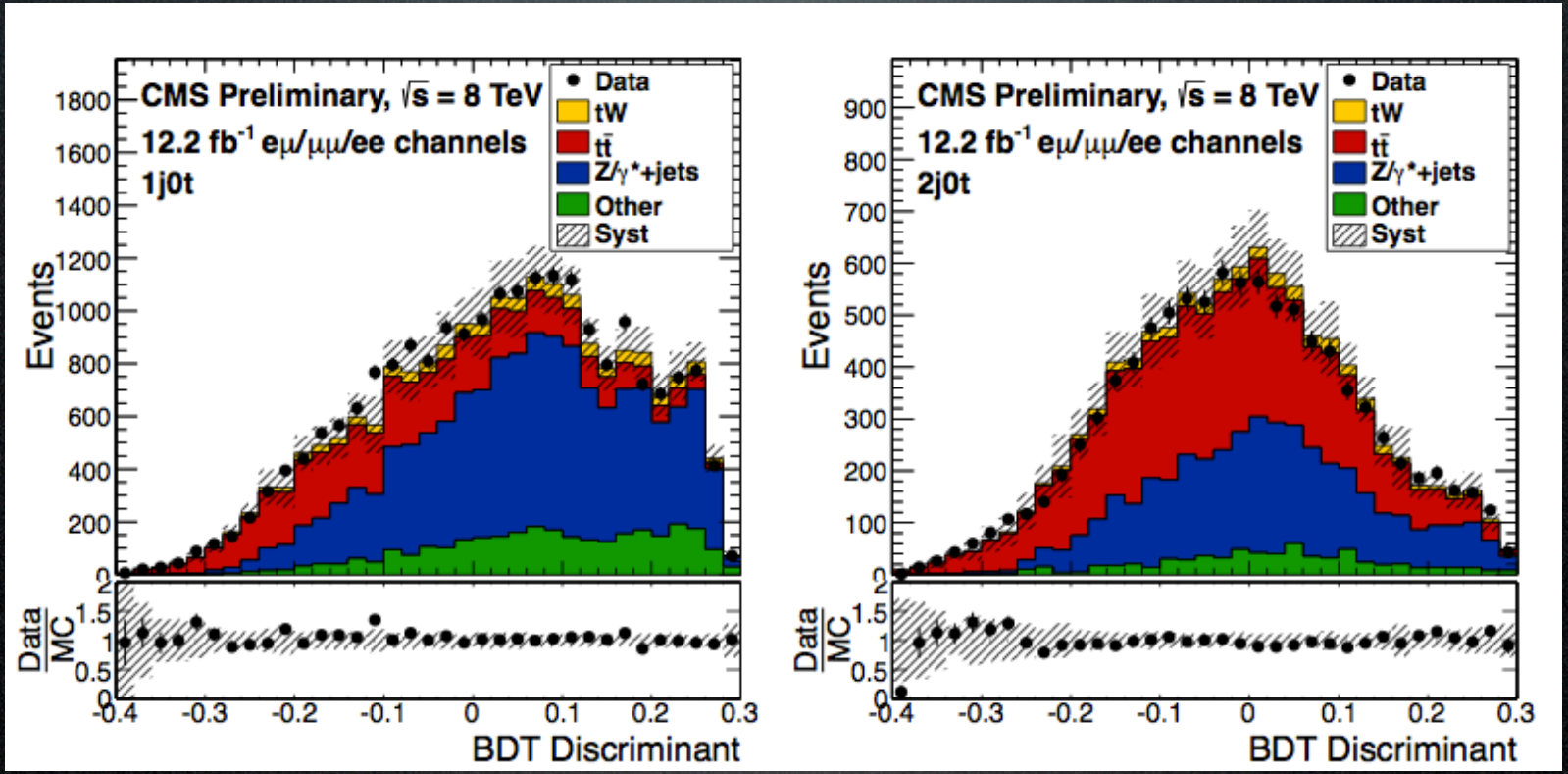
- BDT discriminant for the eμ channel alone in the signal and 2 control regions:

12.2 fb^{-1} @8 TeV



BDT discriminant data/MC

- In order to check for data/MC agreement 2 extra control regions were studied:
  - 1j0t
  - 2j0t
- Example BDT discriminant (all channels) distributions:



tW Variable definitions

$$\vec{p}_T^{\,system} = \vec{p}_{T,\ell 1} + \vec{p}_{T,\ell 2} + \vec{p}_{T,jet} + \overrightarrow{E_T}^{miss}$$

$$H_T = p_{T,\ell 1} + p_{T,\ell 2} + p_{T,jet} + E_T^{miss}$$

Cross-section table

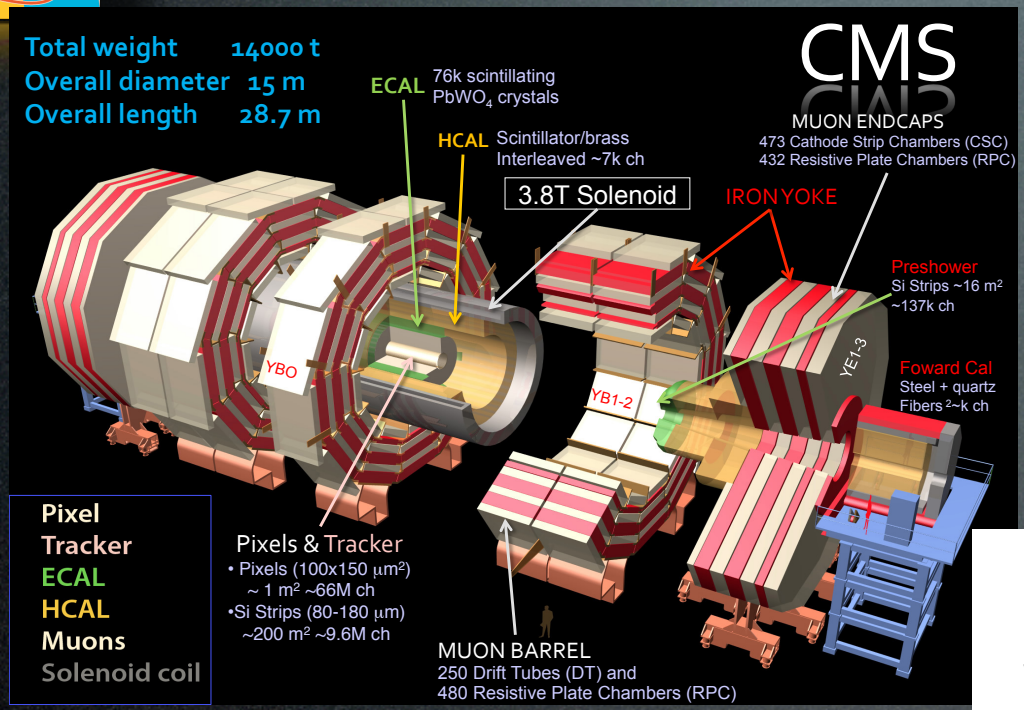
- With all uncertainties (first due to renormalization/factorization scale, second due to the parton distribution function)

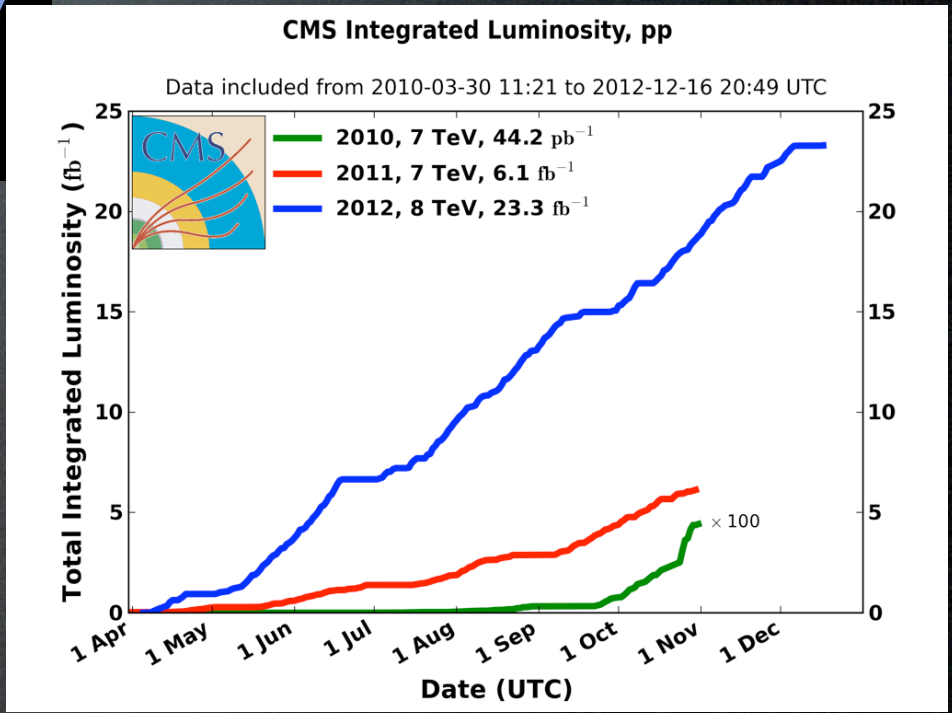
Cross sections (pb) [m_{top} = 173 GeV]	s-channel	t-channel	tW channel	top pair
Tevatron: ppbar@1.96TeV	$1.046^{+0.002}_{-0.01}{}^{+0.06}_{-0.056}$	$2.08^{+0.00}_{-0.04} \pm 0.12$	0.22 ± 0.08	$7.08^{+0.00}_{-0.24}{}^{+0.36}_{-0.27}$
LHC: pp @ 7 TeV	$4.56 \pm 0.07^{+0.18}_{-0.17}$	$65.9^{+2.1}_{-0.7}{}^{+1.5}_{-1.7}$	$15.6 \pm 0.4^{+1.0}_{-1.2}$	$163^{+7}_{-5} \pm 9$
LHC: pp @ 8 TeV	$5.55 \pm 0.08 \pm 0.21$	$87.2^{+2.8}_{-1.0}{}^{+2.0}_{-2.2}$	$22.2 \pm 0.6 \pm 1.4$	$234^{+10}_{-7} \pm 12$

N. Kidonakis arxiv.org/pdf/0909.0037 (2009)

N. Kidonakis arxiv.org/pdf/1205.3453v1 (2012)

CMS detector and data sample





- Total Integrated luminosity recorded:
  - 7 TeV (2011): 6.1 fb^{-1}
  - 8TeV (2012): 23.3 fb^{-1}
- Analyses presented today based on a fraction of the data:
  - tZ FCNC: 4.9fb^{-1} @7TeV
  - tW-channel: 12.2 fb^{-1} @8TeV

Anomalous Coupling tZ Lagrangian

- The effective Lagrangian added to the Standard Model with the two terms involving the anomalous couplings considered in the analysis:

gu(c)t

$$\mathcal{L} = \sum_{q=u,c} \left[\sqrt{2} g_s \frac{\kappa_{gqt}}{\Lambda} \bar{t} \sigma^{\mu\nu} T_a (f_q^L P_L + f_q^R P_R) q \, G^a_{\mu\nu} + \frac{g}{\sqrt{2} c_W} \frac{\kappa_{zqt}}{\Lambda} \bar{t} \sigma^{\mu\nu} (\hat{f}_q^L P_L + \hat{f}_q^R P_R) q \, Z_{\mu\nu} \right] + \text{h.c.}$$

Zu(c)t

Phenomenology described in arXiv:1304.5551, accepted by PLB

tZ objects and event selection

- Object Selection:
  - PF Electrons : pT > 20 GeV, $|\eta|<2.5$, 2011 recipe for electron ID, PF based RelIso < 0.17
  - PF Muons : pT > 20 GeV, $|\eta|<2.4$, 2011 recipe for muon ID, PF base RelIso < 0.20
  - PF Jets pT >30 GeV, $|\eta|<2.5$, loose jet ID
  - PF MET => no cut but used for the reconstruction of top-quarks and other variables
- Event Selection:
  - Dilepton triggers : ee for eee, mumu for mumumu, emu for eemu and mumue
  - 2 leptons with opposite signs with $|M_{ll}-91| < 15$ GeV. Select the lepton pairs with the invariant mass the closest to the Z mass
  - Exactly 1 additional lepton
  - ≥1 selected jets
  - Veto on events with 2 b-tagged (CSVHE loose) jets
  - Transverse mass of the W (mTW) > 20 GeV
- Transverse mass of the W (mTW) and the top candidate are reconstructed from the 3rd lepton, the met and the b-tagged jet (or leading jet if no b-tag).

tZ FCNC BDT input variables

- Reconstructed top mass
- $\Delta\phi(l_W\text{-}b)$
- $q|\eta_W|$,
- p_T and η of the Z boson,
- Jet multiplicity,
- B-tagged jet multiplicity,
- $\Delta\phi(Z\text{-}E_t^{miss})$,
- B-tagging discriminant (CSV),
- η of the leading jet,
- $\Delta\phi(l_W\text{-}Z)$