Search for FCNC in Top Quark Production and Decays

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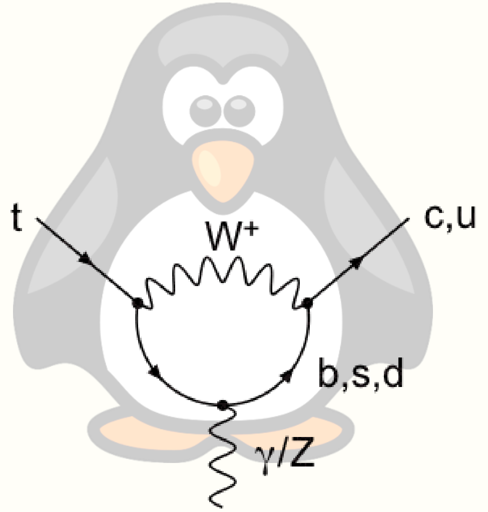
On behalf of the ATLAS, CDF, DO and CMS Collaborations

Top2014: 7th International Workshop On Top Quark Physics

2 October 2014 Cannes, France

Introduction



- Flavor changing neutral currents (FCNC) allow for transitions between quarks of different flavor but same electric charge.
- FCNC processes are highly suppressed in the Standard Model (SM) due to the GIM mechanism and smallness of the related CKM elements.
- Small contributions appear at one loop level.
- Many extensions of the SM predict the presence of FCNC and give rise to detectable FCNC amplitude.

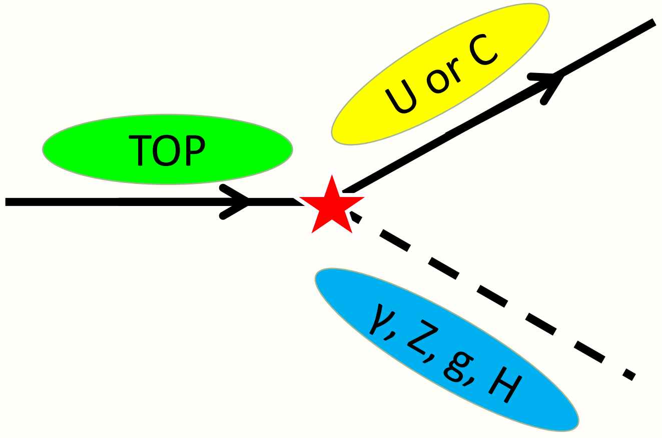
Any evidence of FCNC will indicate the existence of new physics

	SM	QS	2HDM	FC 2HDM	MSSM	$\not R$ SUSY
$t \to uZ$	8×10^{-17}	1.1×10^{-4}	—	—	2×10^{-6}	3×10^{-5}
$t \to u\gamma$	3.7×10^{-16}	7.5×10^{-9}	—	—	2×10^{-6}	1×10^{-6}
$t \to ug$	3.7×10^{-14}	1.5×10^{-7}	—	—	8×10^{-5}	2×10^{-4}
$t \to uH$	2×10^{-17}	4.1×10^{-5}	5.5×10^{-6}	—	10^{-5}	$\sim 10^{-6}$
$t \to cZ$	1×10^{-14}	1.1×10^{-4}	$\sim 10^{-7}$	$\sim 10^{-10}$	2×10^{-6}	3×10^{-5}
$t \to c\gamma$	4.6×10^{-14}	7.5×10^{-9}	$\sim 10^{-6}$	$\sim 10^{-9}$	2×10^{-6}	1×10^{-6}
$t \to cg$	4.6×10^{-12}	1.5×10^{-7}	$\sim 10^{-4}$	$\sim 10^{-8}$	8×10^{-5}	2×10^{-4}
$t \to cH$	3×10^{-15}	4.1×10^{-5}	1.5×10^{-3}	$\sim 10^{-5}$	10^{-5}	$\sim 10^{-6}$

Branching ratios for top FCN decays in the SM, models with $Q = 2/3$ quark singlets (QS), a general 2HDM, a flavour-conserving (FC) 2HDM, in the MSSM and with R parity violating SUSY.

Aguilar-Saavedra, ACTA Phys. Pol. B 35(2004)

Introduction



- top-quark anomalous couplings to Z boson, photon, gluon and Higgs boson are parameterized by means of effective operators independent of the underlying theory.

$$
\begin{aligned}
-\mathcal{L}^{\text{eff}} = &\ \frac{g}{2c_W} X_{qt}\, \bar{q}\gamma_\mu (x_{qt}^{\text{L}} P_{\text{L}} + x_{qt}^{\text{R}} P_{\text{R}}) t Z^\mu + \frac{g}{2c_W} \kappa_{qt}\, \bar{q}(\kappa_{qt}^v + \kappa_{qt}^a \gamma_5) \frac{i\sigma_{\mu\nu}q^\nu}{m_t} t Z^\mu \\
&+ e\lambda_{qt}\, \bar{q}(\lambda_{qt}^v + \lambda_{qt}^a \gamma_5) \frac{i\sigma_{\mu\nu}q^\nu}{m_t} t A^\mu + g_s \zeta_{qt}\, \bar{q}(\zeta_{tq}^v + \zeta_{qt}^a \gamma_5) \frac{i\sigma_{\mu\nu}q^\nu}{m_t} T^a q G^{a\mu} \\
&+ \frac{g}{2\sqrt{2}} g_{qt}\, \bar{q}(g_{qt}^v + g_{qt}^a \gamma_5) t H + \text{H.c.}\,,
\end{aligned}
$$

Aguilar-Saavedra, ACTA Phys. Pol. B 35(2004)

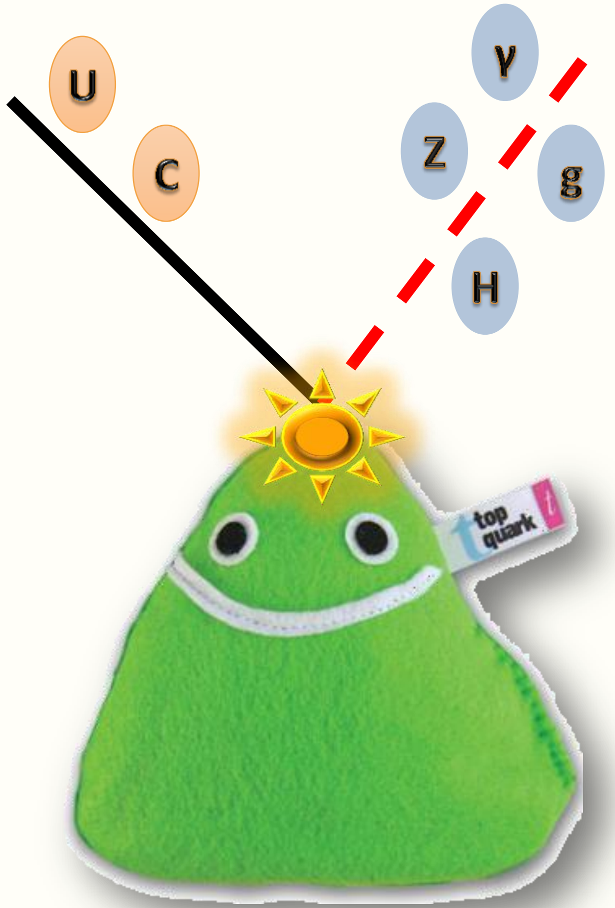
- Different measurements use different normalization of coupling constants in $\mathcal{L}^{eff}$.
- Different parameterizations were used, making the comparison of the couplings not straightforward. Results on the branching ratios are more easily comparable.

Outline

Search for FCNCs

Anomalous decays of top quark in $t\bar{t}$ events

pp → $t\bar{t}$ → Wb qH (ATLAS)	JHEP06 (2014) 008
pp → $t\bar{t}$ → Wb qH (CMS)	CMS PAS HIG 13-034
pp → $t\bar{t}$ → Wb qZ (ATLAS)	JHEP 90 (2012) 139
pp → $t\bar{t}$ → Wb qZ (CMS)	PRL 112 (2014) 171802
$p\bar{p}$ → $t\bar{t}$ → Wb qZ (CDF)	PRL 101 (2008) 192002
$p\bar{p}$ → $t\bar{t}$ → Wb qZ (D0)	PRL 701 (2011) 313



Anomalous production of single top events

pp → tZ (CMS)	CMS PAS TOP-12-021
pp → tγ (CMS)	CMS PAS TOP-14-003
pp → tg/q (CMS)	CMS PAS TOP-14-007
$p\bar{p}$ → t (CDF)	PRL 102 (2009) 151801
pp → t (ATLAS)	ATLAS-CONF-2013-063
$p\bar{p}$ → tg/q (D0)	PLB 693 (2010) 81

ep → et X (ZEUS)	PLB 708 (2012) 27
ep → et X (H1)	PLB 678 (2009) 450
$e^+e^- \to t\bar{c}(\bar{u})$(DELPHI)	PLB 590 (2004) 21

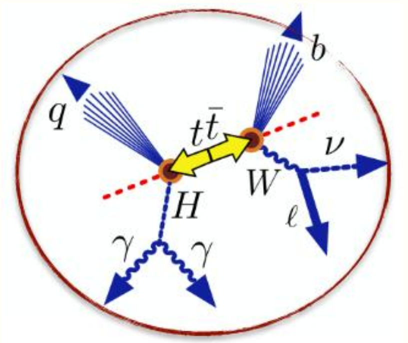
Anomalous decays of top quark in $t\bar{t}$ events

$4.7\,\text{fb}^{-1}$ of $\sqrt{s} = 7$ TeV $+ 20.3\,\text{fb}^{-1}$ of $\sqrt{s} = 8$ TeV

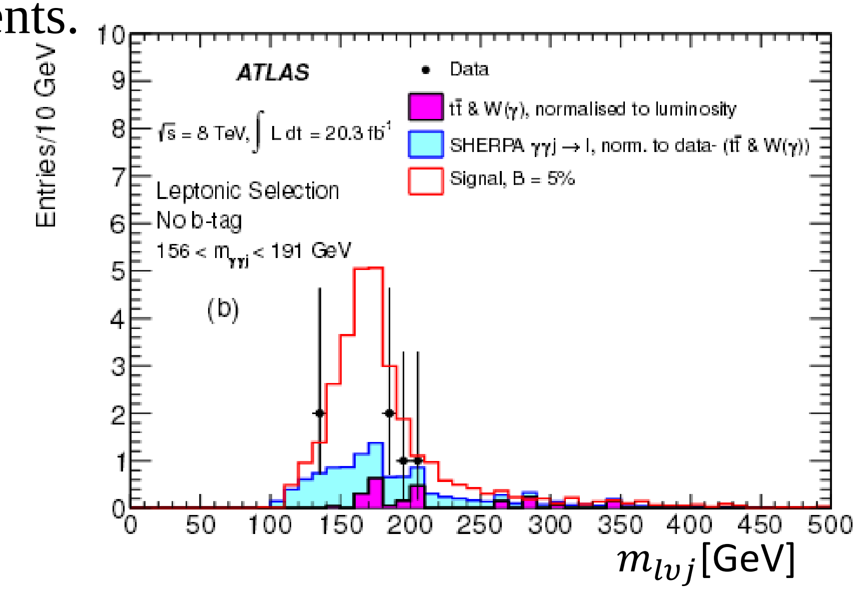
$pp \to t\bar{t} \to Wb\, qH$ (ATLAS)

JHEP06 (2014) 008

- A search for FCNC in top quarks decays $t \to Hq$ (q= u or c) in $t\bar{t}$ events.



Only one lepton.
2 jets or more, One b-tag
m_T of W > 30 GeV
$156 < m_{\gamma\gamma j} < 191$ (GeV)
$135 < m_{l\upsilon j} < 205$ (GeV)



Leptonic channel (8 TeV)

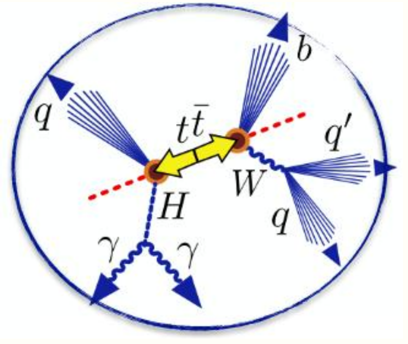
$l\nu b$ $q\gamma\gamma$

2 well identified isolated photons.
Leading photon: $E_T > 40$ GeV
Sub-leading photon: $E_T > 30$ GeV

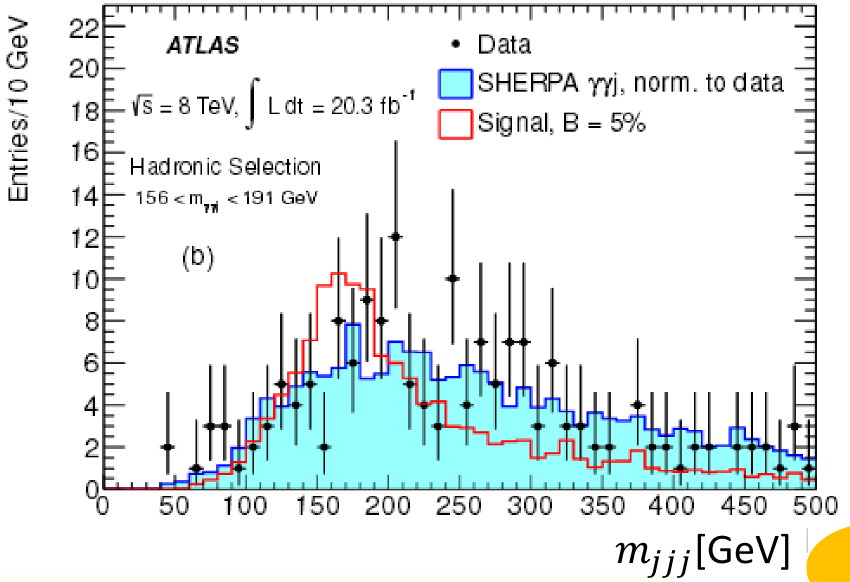
$pp \to t\bar{t} \to Wb\, qH$

Hadronic channel

$q\bar{q}b$ $q\gamma\gamma$



No leptons.
At least four jets.
One b-tag between 4 selected jets.
$156 < m_{\gamma\gamma j} < 191$ (GeV)
$130 < m_{jjj} < 210$ (GeV)



Anomalous decays of top quark in $t\bar{t}$ events

$pp \to t\bar{t} \to Wb\, qH$ (ATLAS)

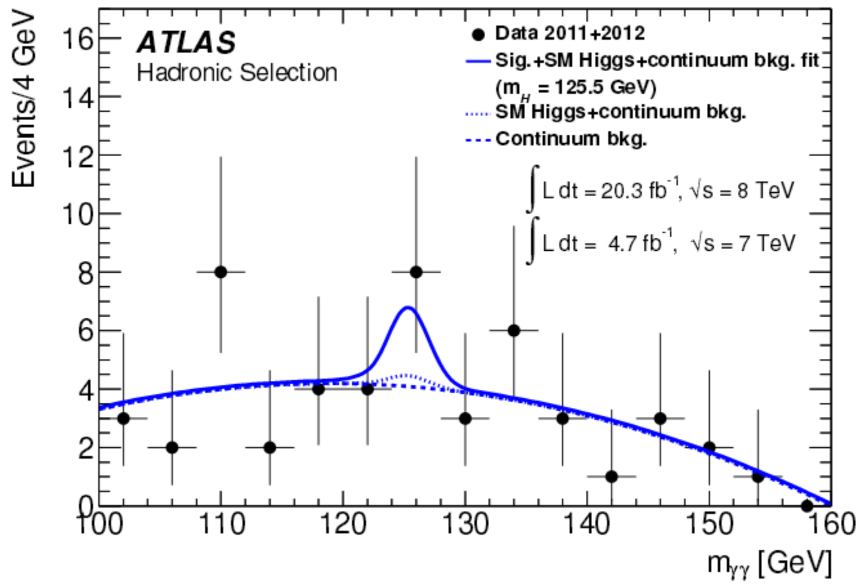
JHEP06 (2014) 008

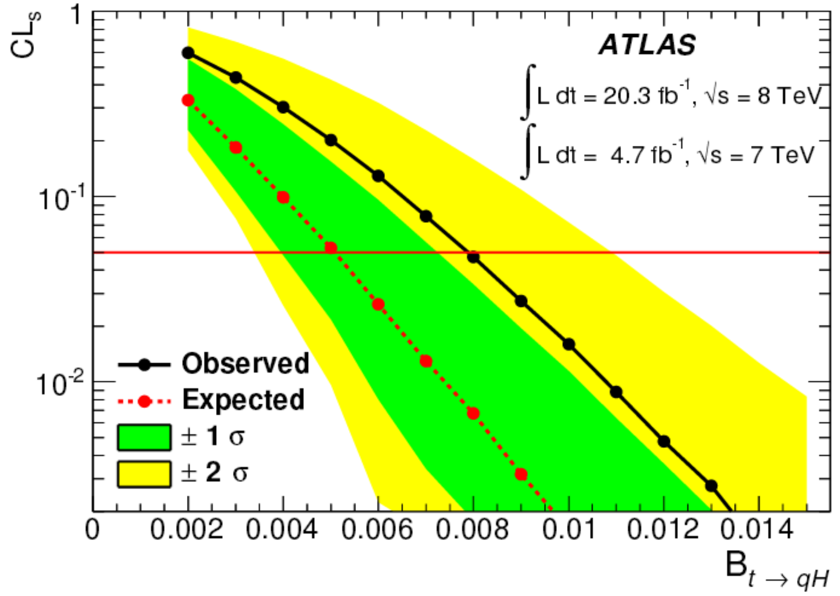
- Signal generated with PROTOS.
- Backgrounds:
  - Non resonant : $\gamma\gamma j$ normalized to data
  - SM Higgs: ggF, VBF, WH, ZH, $t\bar{t}H$, tH.
- Hadronic channel: Fit on $m_{\gamma\gamma}$ distribution. 7 and 8 TeV data are combined.
- Leptonic channel: event counting in two $m_{\gamma\gamma}$ bins.

NO EXCESS OVER SM BKG

$$\lambda_{tqH} = 1.91\sqrt{\mathcal{B}R\,(t \to qH)}$$

95% CL upper limit	Expected	Observed
$\sqrt{\lambda_{tcH}^2 + \lambda_{tuH}^2}$	0.14	0.17
$\mathcal{B}R\,(t \to qH)$	0.51%	0.79%





Main systematic uncertainties:
Photon identification, JES, b-tagging and ISR/FSR.

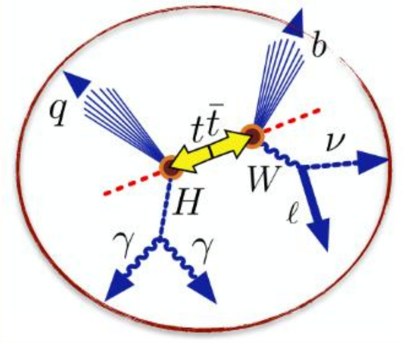
Anomalous decays of top quark in $t\bar{t}$ events

$pp \to t\bar{t} \to Wb\ qH$ (CMS)

CMS-PAS-HIG-13-034
CMS-PAS-HIG-13-025
PRD 90 (2014) 032006

$19.5\ \mathrm{fb}^{-1}$ of $\sqrt{s} = 8$ TeV

- Interpretation of two CMS searches in the context of top quark FCNC decay to a Higgs boson and c quark.



Diphotons + lepton

$H \to \gamma\gamma$

Highest sensitivity and lowest backgrounds

Leading photon: $E_T > 40$
Sub-leading photon: $E_T > 25$
1 lepton of any flavor: $P_T > 10$
$120 < m_{\gamma\gamma} < 130$ (GeV)

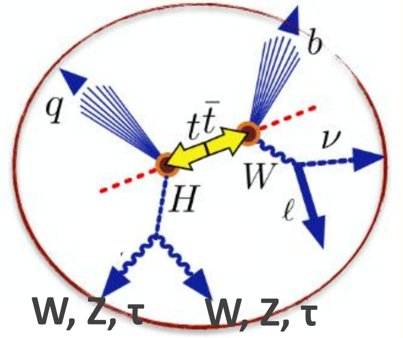
$pp \to t\bar{t} \to Wb\ qH$

$H \to WW^* \to l\upsilon l\upsilon$

multileptons

$H \to \tau\tau$

At least 3 lepton, where at most one of them is a hadronic τ
Leading e or μ: $P_T > 20$
Sub-leading e or μ: $P_T > 10$
Additional charge lepton: (e or μ: $P_T > 10$, τ: $P_T > 20$)



$H \to ZZ^* \to jjll, \upsilon\upsilon ll, llll$

Dominated background: Z+jets (Z boson decays leptonically + a third misidentified lepton from a jet)
Estimated from data.

Dibosons and $t\bar{t}$ contribution is estimated from simulation

Anomalous decays of top quark in $t\bar{t}$ events

$pp \to t\bar{t} \to Wb\, qH$ (CMS)

CMS-PAS-HIG-13-034

- Counting experiment with several channels to set limit.
- The significant nuisance parameters are the luminosity uncertainty, trigger efficiency, lepton identification efficiencies and background uncertainties.
- Categorization of low and high background channels to maximize search sensitivity.

Events in diphoton + lepton channel are classified by

The presence of τ_h
The presence of $b-jet$
E_T^{miss} (4 bins)

Events in multilepton channel are classified by

The presence of τ_h
The presence of $b-jet$
The presence of OSSF
(on-Z, above-Z, bellow-Z)
H_T (> or < 200 GeV)
E_T^{miss} (5 bins)

The signal predominantly populates channels:
No τ_h , no OSSF pair or an OSSF pair off Z,
a b-jet, E_T^{miss} < 100

NO EXCESS OVER SM BKG

Higgs Decay Mode	observed	expected	1σ range
$H \to WW^*$ ($\mathcal{B} = 23.1\,\%$)	1.58 %	1.57 %	(1.02–2.22) %
$H \to \tau\tau$ ($\mathcal{B} = 6.15\,\%$)	7.01 %	4.99 %	(3.53–7.74) %
$H \to ZZ^*$ ($\mathcal{B} = 2.89\,\%$)	5.31 %	4.11 %	(2.85–6.45) %
combined multileptons ($WW^*, \tau\tau, ZZ^*$)	1.28 %	1.17 %	(0.85–1.73) %
$H \to \gamma\gamma$ ($\mathcal{B} = 0.23\,\%$)	0.69 %	0.81 %	(0.60–1.17) %
combined multileptons + diphotons	0.56 %	0.65 %	(0.46–0.94) %

$BR\,(t \to cH) \sim 0.29 \left(|\lambda^H_{tc}|^2 + |\lambda^H_{ct}|^2 \right)$

$\sqrt{|\lambda^H_{tc}|^2 + |\lambda^H_{ct}|^2} < 0.14$

Anomalous decays of top quark in $t\bar{t}$ events

$p\bar{p} \to t\bar{t} \to Wb\ qZ$ (CDF)	PRL 101 (2008) 192002
$p\bar{p} \to t\bar{t} \to Wb\ qZ$ (D0)	PRL 701 (2011) 313
$pp \to t\bar{t} \to Wb\ qZ$ (ATLAS)	JHEP 90 (2012) 139
$pp \to t\bar{t} \to Wb\ qZ$ (CMS)	PRL 112 (2014) 171802

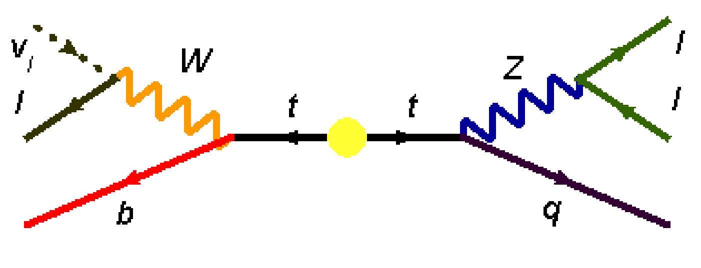
CDF: 1.9 fb^{-1} of $\sqrt{s} = 1.96$ TeV, D0: 4.1 fb^{-1} of $\sqrt{s} = 1.96$ TeV

ATLAS: 2.1 fb^{-1} of $\sqrt{s} = 7$ TeV, CMS: $(5 + 19.7\ fb^{-1})$ of $\sqrt{s} = (7 \,\&\, 8)$ TeV

- A search for FCNC in top quarks decays $t \to Zq$ in ttbar events.
- Signal generated by PYTHIA (CDF and D0), TopRex (ATLAS) and MadGraph (CMS).

This mode provide a distinct signature with low background, albeit at the cost of statistical power.

D0, CMS, ATLAS



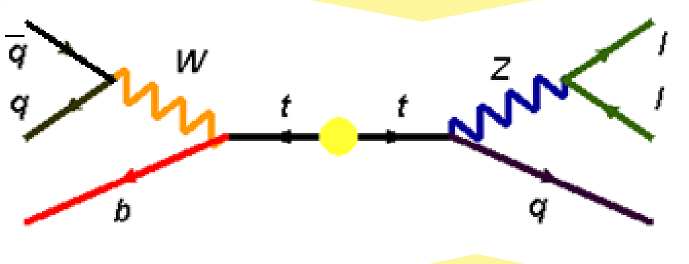
Three charged leptons (muon or electron).
MET
jets

Backgrounds

With 3 final state charged leptons (real leptons). WZ, ZZ, $t\bar{t}$ W and $t\bar{t}$ Z
With at least one fake lepton. Z+jets, $t\bar{t}$, WW

This signature suffers from large background, but profit from more statistics comparing to leptonic decay of W.

CDF



Two oppositely charged lepton (muon or electron).
4 or more jets

Backgrounds

Dominant: Z+jets,
Smaller contributions from: $t\bar{t}$ and Dibosons

Anomalous decays of top quark in $t\bar{t}$ events

pp $\rightarrow t\bar{t} \rightarrow$ Wb qZ (CMS)

PRL 112 (2014) 171802

Processes are categorized on the number of b-quark:

No b-quark: Diboson, Drell-Yan

Only one b-quark: signal

At least 2 b-quark: $t\bar{t}$, $t\bar{t}Z$, $t\bar{t}W$, tbZ

Two opposite sign same flavor lepton (e or μ)

$78 < m_{ll} < 102$(GeV)

One extra charged lepton

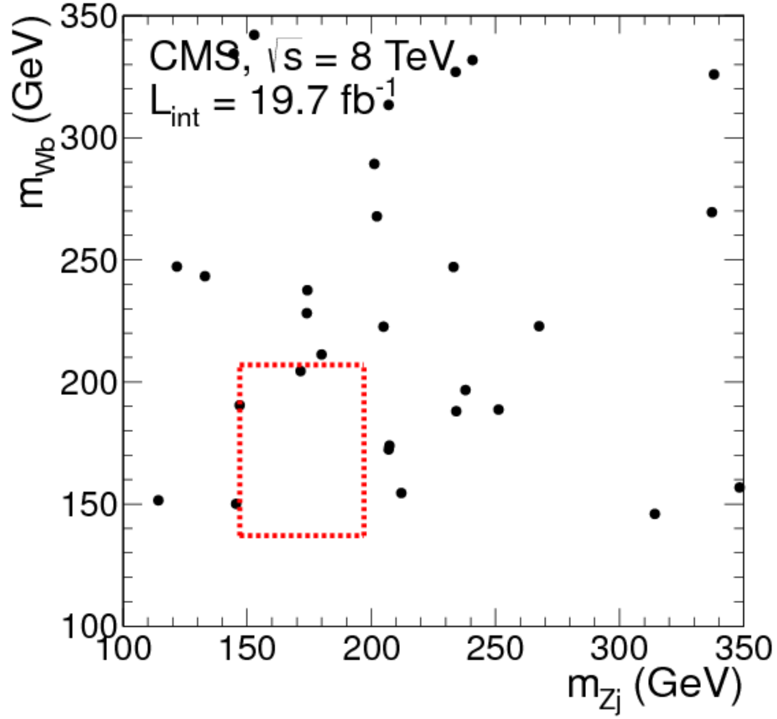
No 4th lepton

MET>30

Only one b-jet

$147.5 < m_{Zj} < 197.5$(GeV)

$137.5 < m_{Wb} < 207.5$(GeV)



EXP.	Dominant systematics uncertainties
CDF	JES, b-tagging and $\sigma_{t\bar{t}}$
D0	ZZ and WZ modelling, JES, lepton identification and $\sigma_{t\bar{t}}$.

EXP.	Dominant systematics uncertainties
ATLAS	ZZ and WZ modelling, JES, electron reconstruction and $\sigma_{t\bar{t}}$.
CMS	Factorization and renormalization scales, PDFs and $\sigma_{t\bar{t}}$.

NO EXCESS OVER SM BKG

EXP.	$\sqrt{s}$	Lumi .	$\mathcal{B}(t \rightarrow qZ)$ %
CDF	1.96 TeV	1.9 fb^{-1}	3.7
D0	1.96 TeV	4.1 fb^{-1}	3.2

EXP.	$\sqrt{s}$	Lumi .	$\mathcal{B}(t \rightarrow qZ)$ %
ATLAS	7 TeV	2.1 fb^{-1}	2.73
CMS	7&8 TeV	$(5 + 19.7)fb^{-1}$	0.05

Anomalous production of single top events

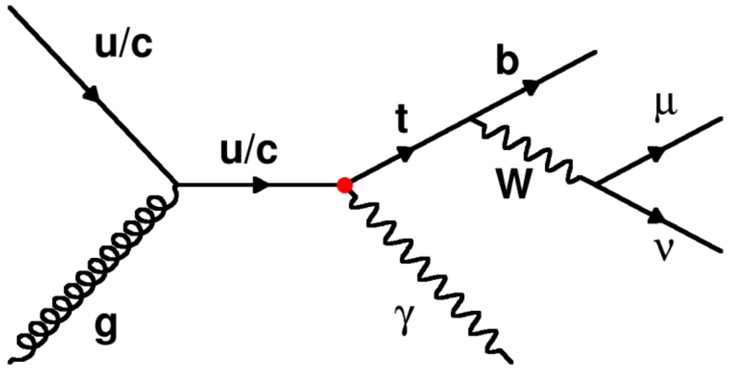
pp $\rightarrow$ tγ (CMS)

CMS PAS TOP-14-003

19.1 fb^{-1} of $\sqrt{s} = 8$ TeV

- A search for FCNC in production of single top quark in association with a photon.
- Signal generated with PROTOS.
- 8 variables are combined using BDT to separate signal from backgrounds.
- W+jets and Wγ+jets (main backgrounds) contribution are estimated from data.
- Other backgrounds from simulation.

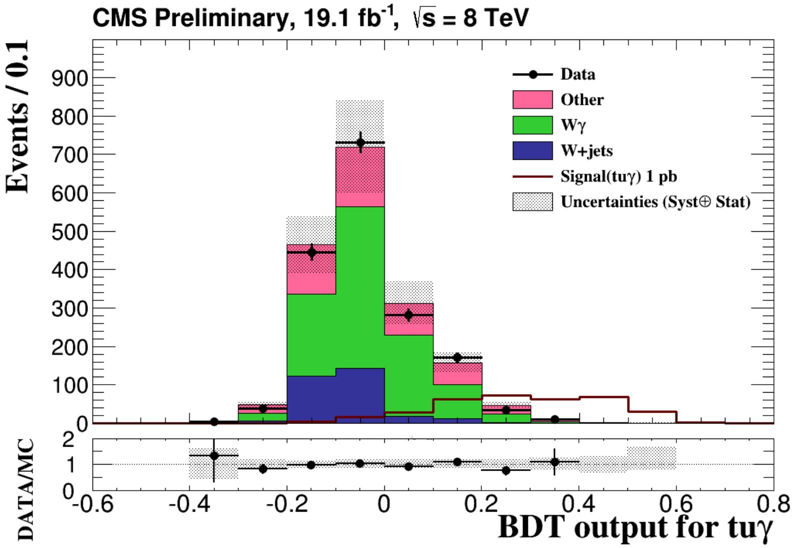
one photon: $E_T > 50$
one muon
0 or 1 btag jets.
MET > 30 GeV
$\Delta R(l,\gamma)>0.7$
$\Delta R(b\text{-}jet,\gamma)>0.7$
$130 < m_{top} < 220$(GeV)



Backgrounds:
With prompt photon:
w+γ+jet, z+ γ +jet, Single top+γ, $t\bar{t}\gamma$, wwγ, γjets.
with fake photon:
Single top, $t\bar{t}$, Dibosons, wjets, Zjets.

NO EXCESS OVER SM BKG

	Exp. limit (LO)	Obs. limit (LO)
$\sigma_{tu\gamma} \times Br(W \rightarrow l\nu_l)$	0.0404 pb	0.0234 pb
$\sigma_{tc\gamma} \times Br(W \rightarrow l\nu_l)$	0.0411 pb	0.0281 pb
$\kappa_{tu\gamma}$	0.0367	0.0279
$\kappa_{tc\gamma}$	0.113	0.094
$Br(t \rightarrow u\gamma)$	0.0279%	0.0161%
$Br(t \rightarrow c\gamma)$	0.261%	0.182%



Dominant systematic uncertainties are related to the data driven background estimations

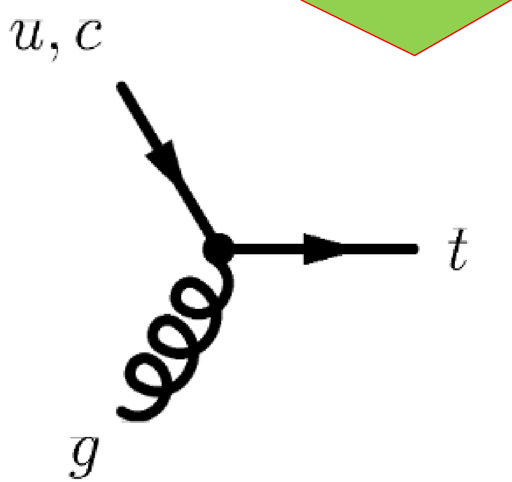
Anomalous production of single top events

CDF: 2.2fb^{-1} of $\sqrt{s} = 1.96$ TeV, ATLAS: 14.2 fb^{-1} of $\sqrt{s} = 8$ TeV

$p\bar{p} \rightarrow t$ (CDF)	PRL 102 (2009) 151801
$pp \rightarrow t$ (ATLAS)	ATLAS-CONF-2013-063

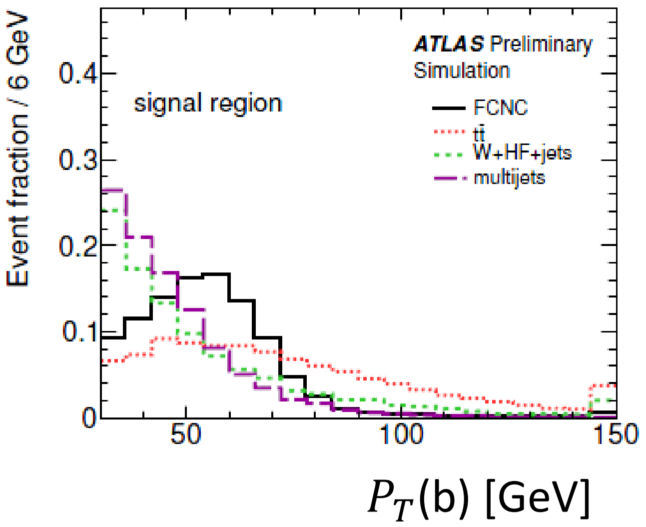
- Signal generated by TOPREX (CDF) and METOP (ATLAS).
- Neural network is used to separate signal from backgrounds.

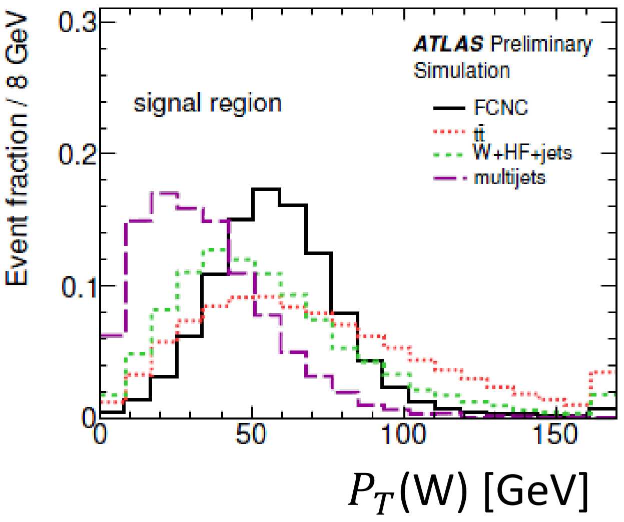
The $t \rightarrow qg$ decay mode is nearly indistinguishable from the overwhelming background of QCD multijets. A much better sensitivity can be achieved by searching for anomalous single top production.



Exactly one muon or electron.
Missing Transverse Energy
Exactly one b-jet

Backgrounds:
w+jets, z+jets, Dibosons, SM Single top, $t\bar{t}$.





Signal characterization

W and b from top decay tend to be back to back in the azimuthal plane.
W is boosted and its decay products have smaller opening angle.
Top is produced three times more than antitop.

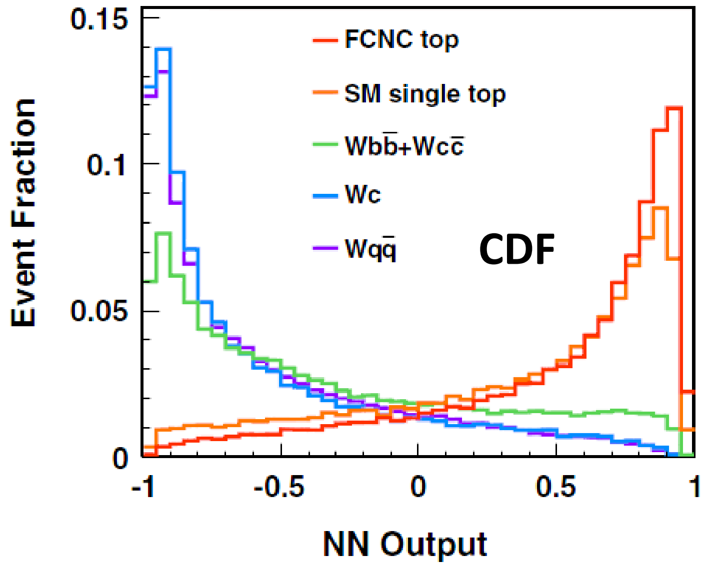
Anomalous production of single top events

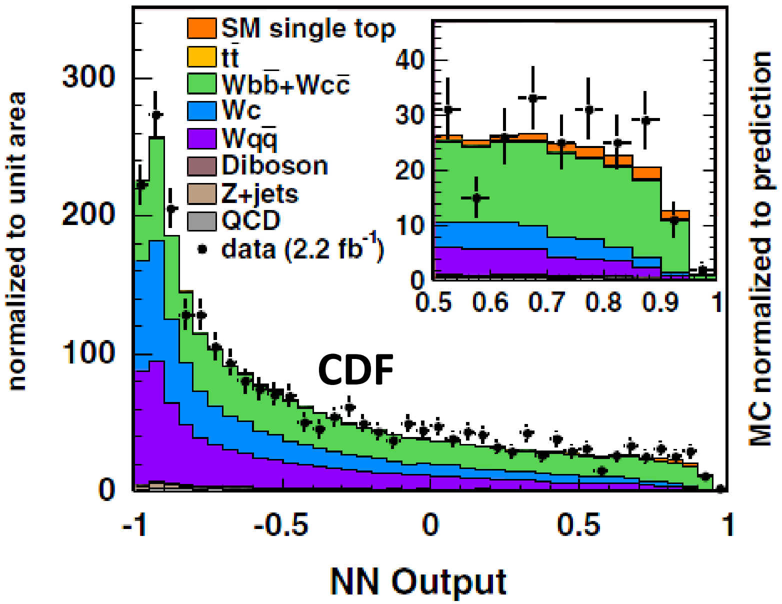
$p\bar{p} \to t$ (CDF)

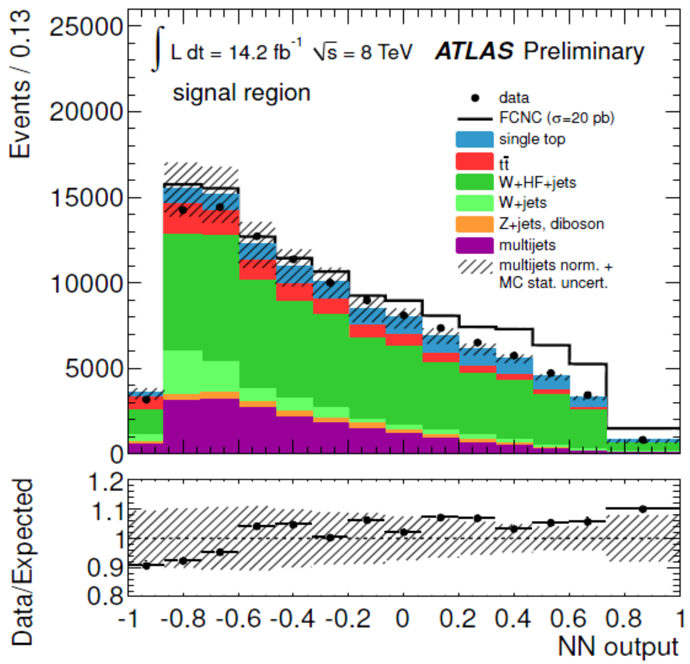
$pp \to t$ (ATLAS)

PRL 102 (2009) 151801

ATLAS-CONF-2013-063







NO EXCESS OVER SM BKG

NO EXCESS OVER SM BKG

Dominant systematics uncertainties: JES/JER, b-tag efficiency, PDFs.

CDF	tgu	tgc
κ_{tgq}/Λ	$0.018\ \mathrm{TeV}^{-1}$	$0.069\ \mathrm{TeV}^{-1}$
$\mathcal{B}R\ (t \to gq)$	0.039%	0.57%

ATLAS	tgu	tgc
κ_{tgq}/Λ	$0.0051\mathrm{TeV}^{-1}$	$0.011\ \mathrm{TeV}^{-1}$
$\mathcal{B}R\ (t \to gq)$	0.0031%	0.016%

Anomalous production of single top events

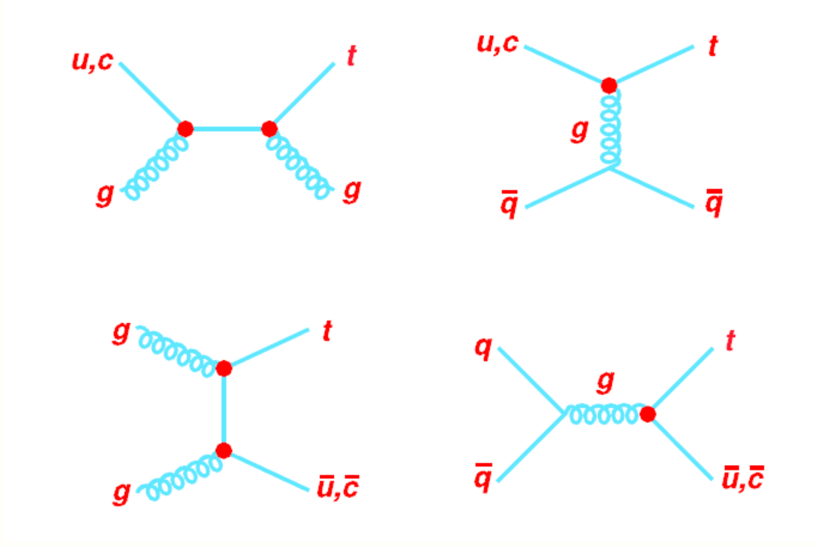
$p\bar{p} \rightarrow tg/q$ (D0)

$pp \rightarrow tg/q$ (CMS)

PLB 693 (2010) 81

CMS PAS TOP-14-007

D0: $2.3 fb^{-1}$ of $\sqrt{s} = 1.96$ TeV, CMS: $5 fb^{-1}$ of $\sqrt{s} = 7$ TeV

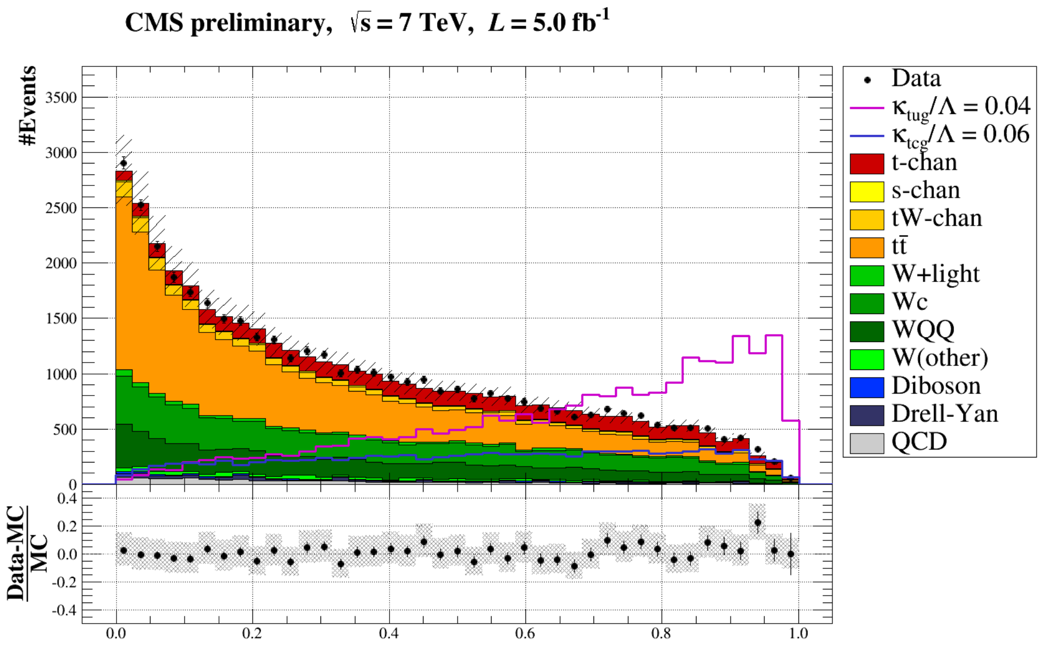


- The single top quark final state is sensitive to tqg FCNC couplings.
- The final state contains a top quark and a light quark or gluon, a topology similar to SM t-channel single top quark production.
- Signal generated by CompHEP .
- Different variables are combined using Bayesian Neural Networks to separate signal from backgrounds.

Backgrounds:
w+jets, z+jets, Dibosons, SM Single top, $t\bar{t}$, QCD.

CMS
one isolated muon
No additional muon or electron
2 or 3 jets $P_T > 30$, $|\eta|<4.7$
At least 1 b-tag jet

D0
Only one isolated muon or electron
2 to 4 jets $P_T > 15$, $|\eta|<3.4$
Only 1 b-tag jet



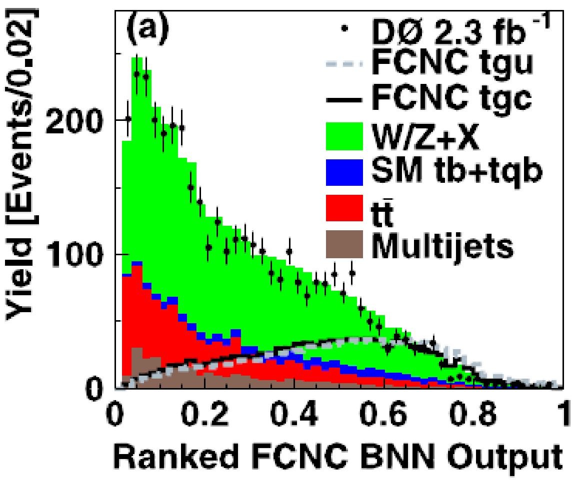
tug FCNC BNN

Anomalous production of single top events

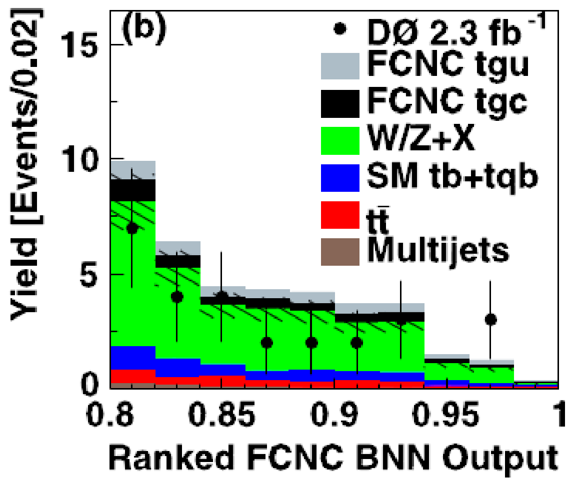
$p\bar{p} \rightarrow tg/q$ (D0) — PLB 693 (2010) 81

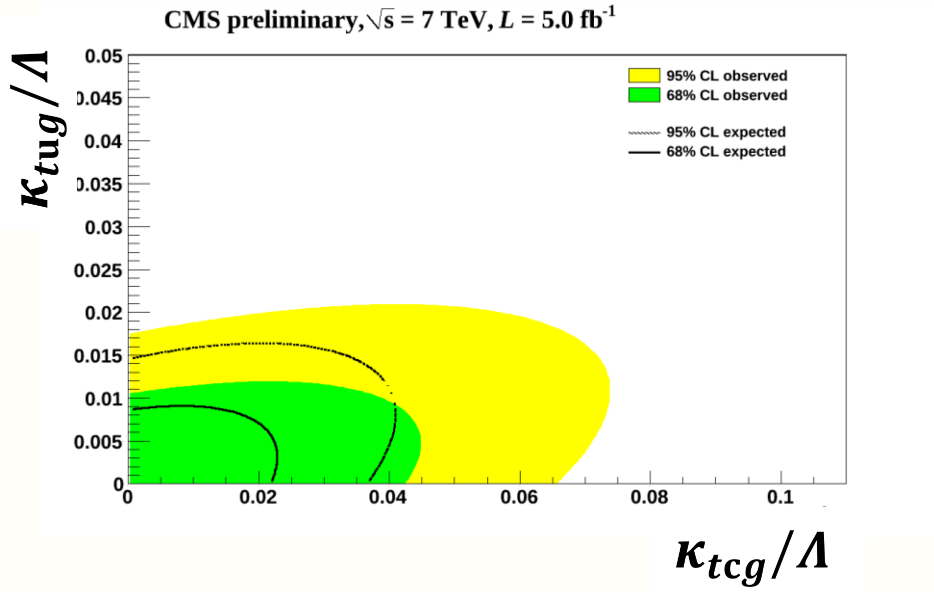
$pp \rightarrow tg/q$ (CMS) — CMS PAS TOP-14-007

Signal normalized to 5 pb



Signal normalized to observed limits





Dominant uncertainties: jet energy scale and b-tag modeling.

Dominant systematics uncertainties: PDFs, renormalization and factorization scale, signal generator

NO EXCESS OVER SM BKG

NO EXCESS OVER SM BKG

D0	**tgu**	**tgc**
κ_{tgf}/Λ	$0.013\ TeV^{-1}$	$0.057\ TeV^{-1}$
$\mathcal{BR}\ (t \rightarrow gq)$	0.020%	0.39%

CMS	**tgu**	**tgc**
κ_{tgf}/Λ	$0.018\ TeV^{-1}$	$0.056\ TeV^{-1}$
$\mathcal{BR}\ (t \rightarrow gq)$	0.035%	0.34%

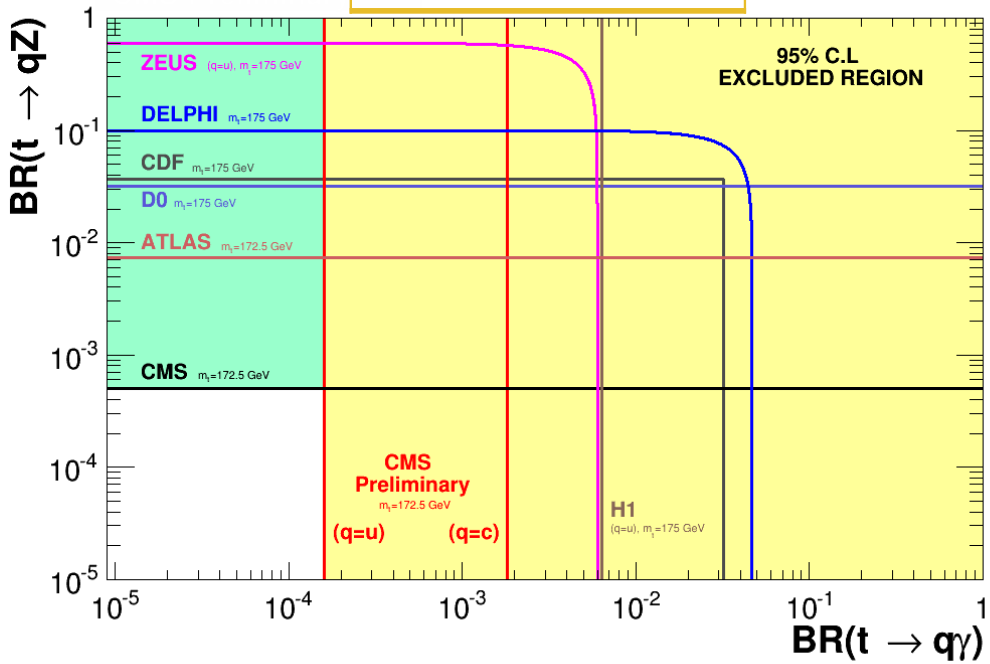
FCNC search results

EXP.	$\sqrt{s}$	Lumi .	$\mathcal{B}(t \to u\gamma)$ %	$\mathcal{B}(t \to c\gamma)$ %	Ref .
CDF	1.8 TeV	110 pb^{-1}	3.2		PRL 80 (1998) 2525
CMS	8 TeV	19.1 fb^{-1}	0.0161	0.182	CMS PAS TOP-14-003
			$\mathcal{B}(t \to uZ)$ %	$\mathcal{B}(t \to cZ)$ %	
CDF	1.96 TeV	1.9 fb^{-1}	3.7		PRL 101 (2008) 192002
D0	1.96 TeV	4.1 fb^{-1}	3.2		PRL 701 (2011) 313
CMS	7 TeV	4.9 fb^{-1}	0.51	11.40	CMS PAS TOP-12-021
ATLAS	7 TeV	2.1 fb^{-1}	2.73		JHEP 90 (2012) 139
CMS	7&8 TeV	$(5 + 19.7)fb^{-1}$	0.05		PRL 112 (2014) 171802
			$\mathcal{B}(t \to ug)$ %	$\mathcal{B}(t \to cg)$ %	
CDF	1.96 TeV	2.2 fb^{-1}	0.039	0.57	PRL 102 (2009) 151801
D0	1.96 TeV	2.3 fb^{-1}	0.02	0.39	PLB 693 (2010) 81
CMS	7 TeV	4.9 fb^{-1}	0.56	7.12	CMS PAS TOP-12-021
CMS	7 TeV	4.9 fb^{-1}	0.035	0.34	CMS PAS TOP-14-007
ATLAS	8 TeV	14.2 fb^{-1}	0.0031	0.016	ATLAS CONF -2013-063
			$\mathcal{B}(t \to uH)$ %	$\mathcal{B}(t \to cH)$ %	
ATLAS	7&8 TeV	$(4.7 + 20.3)fb^{-1}$	0.79		JHEP 06 (2014) 008
CMS	8 TeV	19.5 fb^{-1}	0.56		CMS PAS HIG-13-034

Summary

- FCNC are suppressed at SM ($\mathcal{B} \sim \mathbf{10^{-10} - 10^{-14}}$), far beyond the current experimental sensitivity. Therefore, any evidence for FCNC in the top-quark sector will be a signal of physics beyond the SM.
- Two complementary channels have been considered in order to search for anomalous top couplings to the SM neutral gauge bosons.
  - First, top-anti-top pair production followed by one or two FCN top-decays.
  - Second, anomalous single top production.
- No excess over the SM expectation is found. Therefore, 95% CL exclusion limits are set on the signal cross section and then translated to anomalous couplings and top quark FCNC decay branching ratios.
- Although the SM predicts top quark anomalous branching ratios many order of magnitude below the current experimental limits experiments are closing to the regions which are predicted by some beyond SM models.

CMS PAS TOP-14-003

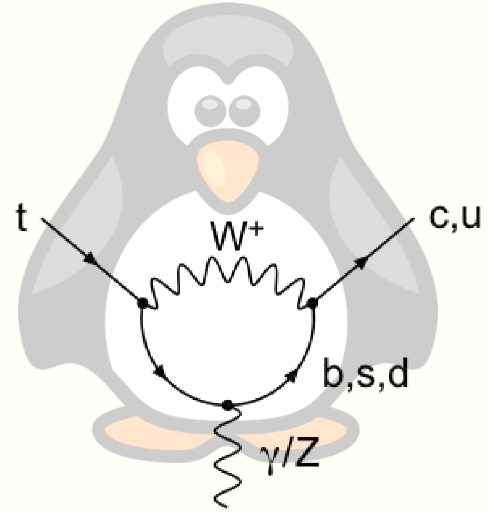


BACKUP

Tevatron and LHC Public Results

CMS	https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP
	https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG
	https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS
ATLAS	https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
	https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults
CDF	http://www-cdf.fnal.gov/physics/new/top/top.html
D0	http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/top_public.html

Introduction



In the Standard Model (SM) Flavor Changing Neutral Currents (FCNC) are forbidden at tree level and heavily suppressed at loop level.

Suppression mechanism 1: GIM

Penguin matrix element depends on universal functions of single parameter.

$$x_i = \frac{m_i^2}{m_W^2}$$

$$\mathscr{M} \propto F(x_\mathrm{d})\, V_{\mathrm{cd}}^* V_{\mathrm{td}} + F(x_\mathrm{s})\, V_{\mathrm{cs}}^* V_{\mathrm{ts}} + F(x_\mathrm{b})\, V_{\mathrm{cb}}^* V_{\mathrm{tb}}$$

Compare to CKM unitarity relation: $V_{\mathrm{cd}}^* V_{\mathrm{td}} + V_{\mathrm{cs}}^* V_{\mathrm{ts}} + V_{\mathrm{cb}}^* V_{\mathrm{tb}} = 0$

Exact cancellation if masses of b, s, and d quarks were the same.

Suppression mechanism 2: smallness of relevant CKM matrix elements

$$|V_{\mathrm{cd}}^* V_{\mathrm{td}}| \approx 0.002,\ |V_{\mathrm{cs}}^* V_{\mathrm{ts}}| \approx 0.04,\ |V_{\mathrm{cb}}^* V_{\mathrm{tb}}| \approx 0.04$$

http://www.hep.upenn.edu/HEP_website_09/Talks/Seminars/talks/2007_husemann.pdf

Introduction

The most general effective Lagrangian describes FCNC integrations in top sector, containing terms up to dimension 5.

$$
\begin{aligned}
-\mathcal{L}^{\mathrm{eff}} \; = \; & \frac{g}{2c_W} X_{qt}\, \bar{q}\gamma_\mu (x_{qt}^{\mathrm{L}} P_{\mathrm{L}} + x_{qt}^{\mathrm{R}} P_{\mathrm{R}}) t Z^\mu + \frac{g}{2c_W} \kappa_{qt}\, \bar{q}(\kappa_{qt}^v + \kappa_{qt}^a \gamma_5) \frac{i\sigma_{\mu\nu} q^\nu}{m_t} t Z^\mu \\
& + e\lambda_{qt}\, \bar{q}(\lambda_{qt}^v + \lambda_{qt}^a \gamma_5) \frac{i\sigma_{\mu\nu} q^\nu}{m_t} t A^\mu + g_s \zeta_{qt}\, \bar{q}(\zeta_{tq}^v + \zeta_{qt}^a \gamma_5) \frac{i\sigma_{\mu\nu} q^\nu}{m_t} T^a q G^{a\mu} \\
& + \frac{g}{2\sqrt{2}} g_{qt}\, \bar{q}(g_{qt}^v + g_{qt}^a \gamma_5) t H + \mathrm{H.c.}\,,
\end{aligned}
$$

Aguilar-Saavedra, ACTA Phys. Pol. B 35(2004)

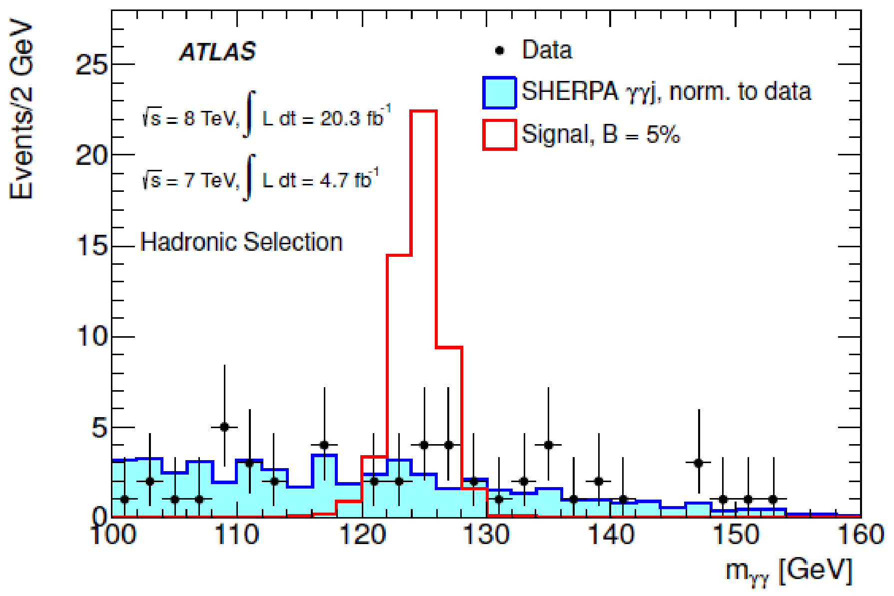
$$
\begin{aligned}
\Gamma(t \to bW^+) &= \frac{\alpha}{16\, s_W^2} |V_{tb}|^2 \frac{m_t^3}{M_W^2} \left[1 - 3\frac{M_W^4}{m_t^4} + 2\frac{M_W^6}{m_t^6} \right], \\
\Gamma(t \to qZ)_\gamma &= \frac{\alpha}{32\, s_W^2 c_W^2} |X_{qt}|^2 \frac{m_t^3}{M_Z^2} \left[1 - \frac{M_Z^2}{m_t^2} \right]^2 \left[1 + 2\frac{M_Z^2}{m_t^2} \right], \\
\Gamma(t \to qZ)_\sigma &= \frac{\alpha}{16\, s_W^2 c_W^2} |\kappa_{qt}|^2 m_t \left[1 - \frac{M_Z^2}{m_t^2} \right]^2 \left[2 + \frac{M_Z^2}{m_t^2} \right], \\
\Gamma(t \to q\gamma) &= \frac{\alpha}{2} |\lambda_{qt}|^2 m_t\,, \\
\Gamma(t \to qg) &= \frac{2\alpha_s}{3} |\zeta_{qt}|^2 m_t\,, \\
\Gamma(t \to qH) &= \frac{\alpha}{32\, s_W^2} |g_{qt}|^2 m_t \left[1 - \frac{M_H^2}{m_t^2} \right]^2 .
\end{aligned}
$$

Anomalous decays of top quark in $t\bar{t}$ events

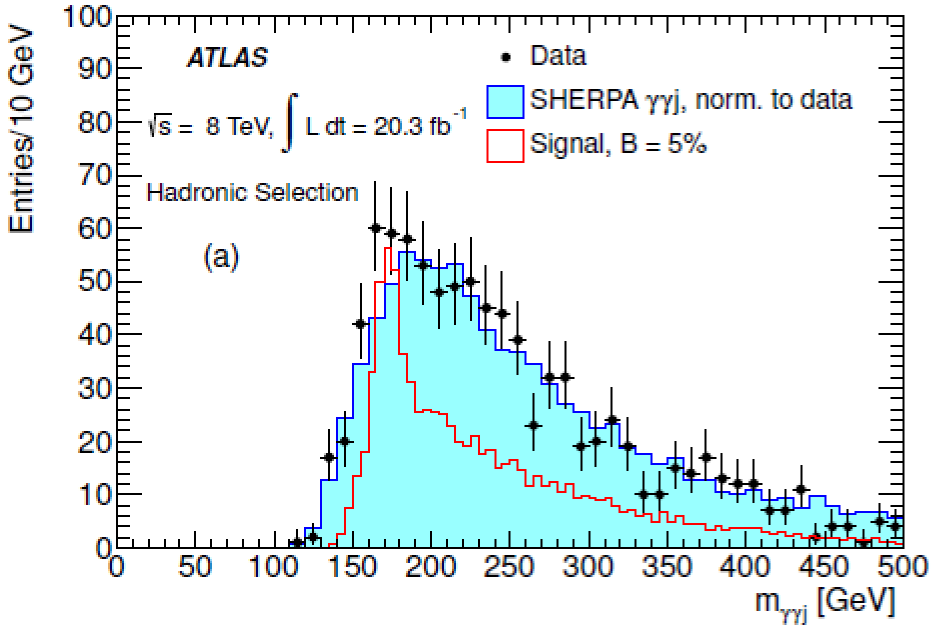
$pp \to t\bar{t} \to Wb\, qH$ (ATLAS)

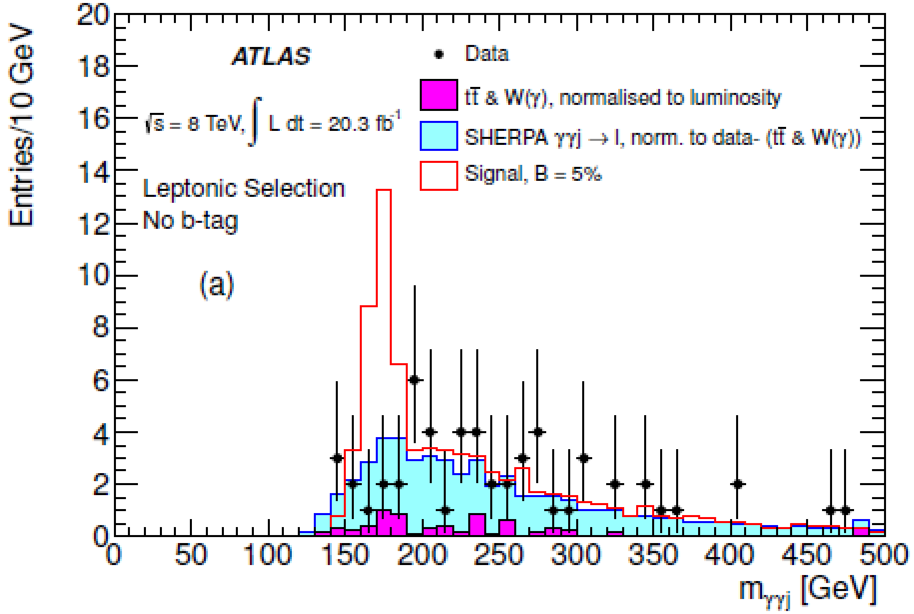
JHEP06 (2014) 008

- Signal events are generated by PROTOS assuming $m_H = 126.8$ GeV.
- Fit to data is performed for signal and background estimation.



Control region:
$100 < m_{\gamma\gamma} < 123$ (GeV) and $129 < m_{\gamma\gamma} < 160$ (GeV)
Signal region:
$123 < m_{\gamma\gamma} < 129$ (GeV)





Anomalous decays of top quark in $t\bar{t}$ events

$pp \rightarrow t\bar{t} \rightarrow Wb\, qH$ (CMS) | CMS-PAS-HIG-13-034

- Signal events are generated by MadGraph assuming $m_H = 126$ GeV.
- The expected signal events are shown these two tables for the sensitive channels assuming $\mathcal{B}$R (t→cH)=1%

The ten most sensitive signal regions for t →cH where H → γγ.

$N_{\tau_{had}}$	E_T^{miss} [GeV]	$N_{b\text{-jets}}$	data	background	signal	efficiency [10^{-5}]
0	50–100	≥ 1	1	2.3 ± 1.2	2.88 ± 0.39	3.1 ± 0.4
0	30–50	≥ 1	2	1.1 ± 0.6	2.16 ± 0.30	2.4 ± 0.3
0	0–30	≥ 1	2	2.1 ± 1.1	1.76 ± 0.24	1.9 ± 0.3
0	50–100	0	7	9.5 ± 4.4	2.22 ± 0.31	2.4 ± 0.3
0	> 100	≥ 1	0	0.5 ± 0.4	0.92 ± 0.14	1.0 ± 0.2
0	> 100	0	1	2.2 ± 1.0	0.94 ± 0.17	1.0 ± 0.2
0	30–50	0	29	21 ± 10	1.51 ± 0.22	1.6 ± 0.2
1	30–50	≥ 1	2	2.1 ± 1.2	0.43 ± 0.09	0.5 ± 0.1
1	0–30	≥ 1	6	6.4 ± 3.3	0.48 ± 0.12	0.5 ± 0.1
1	50–100	≥ 1	1	1.5 ± 0.8	0.30 ± 0.08	0.3 ± 0.1

The ten most sensitive signal regions for t →cH where H →WW,ττ, or ZZ.

OSSF pair	$N_{\tau_{had}}$	E_T^{miss} [GeV]	H_T [GeV]	$N_{b\text{-jets}}$	data	background	signal	efficiency [10^{-5}]
below Z	0	50–100	0–200	≥ 1	48	48 ± 23	9.5 ± 2.3	10.3 ± 2.5
n/a	0	50–100	0–200	≥ 1	29	26 ± 13	5.9 ± 1.3	6.4 ± 1.4
below Z	0	0–50	0–200	≥ 1	34	42 ± 11	5.9 ± 1.2	6.4 ± 1.3
n/a	0	0–50	0–200	≥ 1	29	23 ± 10	4.3 ± 1.1	4.7 ± 1.2
below Z	0	50–100	> 200	≥ 1	10	9.9 ± 3.7	3.0 ± 1.1	3.3 ± 1.2
below Z	0	0–50	> 200	≥ 1	5	10 ± 2.5	2.8 ± 0.8	3.1 ± 0.9
below Z	0	50–100	0–200	0	142	125 ± 27	9.7 ± 2.1	10.6 ± 2.3
n/a	1	0–50	0–200	≥ 1	237	240 ± 113	13.1 ± 2.6	14.3 ± 2.8
n/a	0	50–100	0–200	0	35	38 ± 15	4.3 ± 1.1	4.7 ± 1.2
above Z	0	0–50	0–200	≥ 1	17	18 ± 6.7	2.8 ± 0.8	3.1 ± 0.9

Anomalous decays of top quark in $t\bar{t}$ events

pp $\rightarrow t\bar{t} \rightarrow$ Wb qZ (ATLAS)

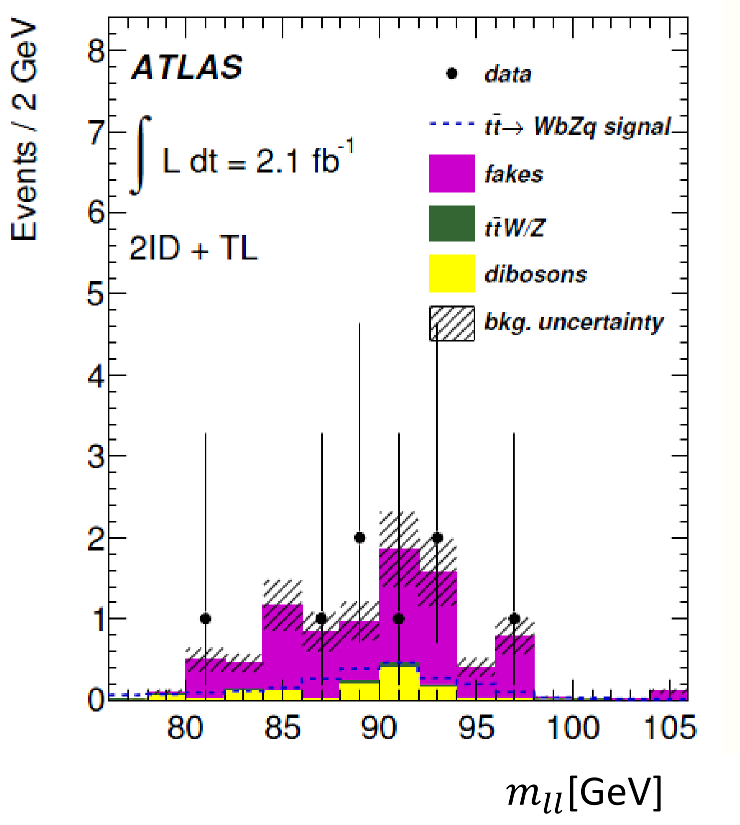
JHEP 90 (2012) 139

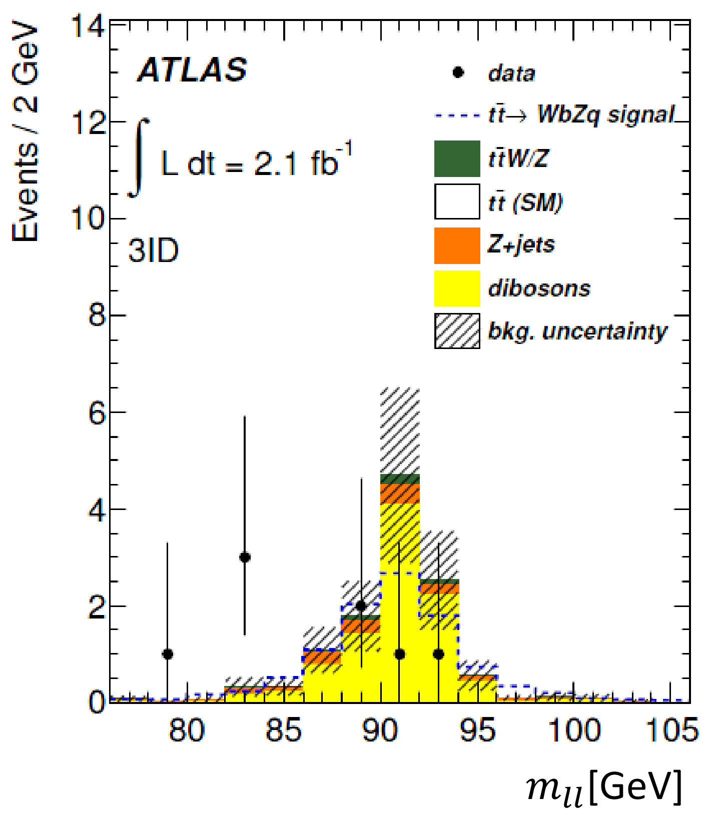
3 ID or 2 ID + 1 track lepton (TL).
ID → track and calorimeter information used in reconstruction.
TL → only track information used.
≥2 jets (≥1 b-jet in 2ID+1TL events).
MET > 20 GeV and $|m_{ll} - m_Z| < 15$ GeV

Reconstruction of top anti-top system through a $\chi 2$ minimization.

$$\chi^2 = \frac{\left(m^{reco}_{j_a l_a l_b} - m_t\right)^2}{\sigma_t^2} + \frac{\left(m^{reco}_{j_b l_c \nu} - m_t\right)^2}{\sigma_t^2} + \frac{\left(m^{reco}_{l_c \nu} - m_W\right)^2}{\sigma_W^2} + \frac{\left(m^{reco}_{l_a l_b} - m_Z\right)^2}{\sigma_Z^2}$$

$$m_t = 172.5 \text{ GeV}, m_W = 80.4 \text{ GeV}, m_Z = 91.2 \text{ GeV}$$
$$\sigma_t = 15 \text{ GeV}, \sigma_W = 10 \text{ GeV}, \sigma_Z = 3 \text{ GeV}$$



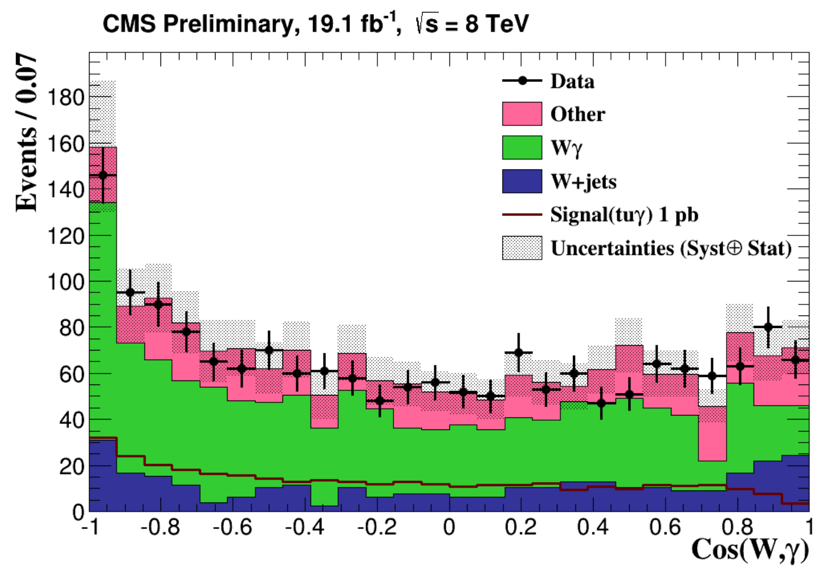


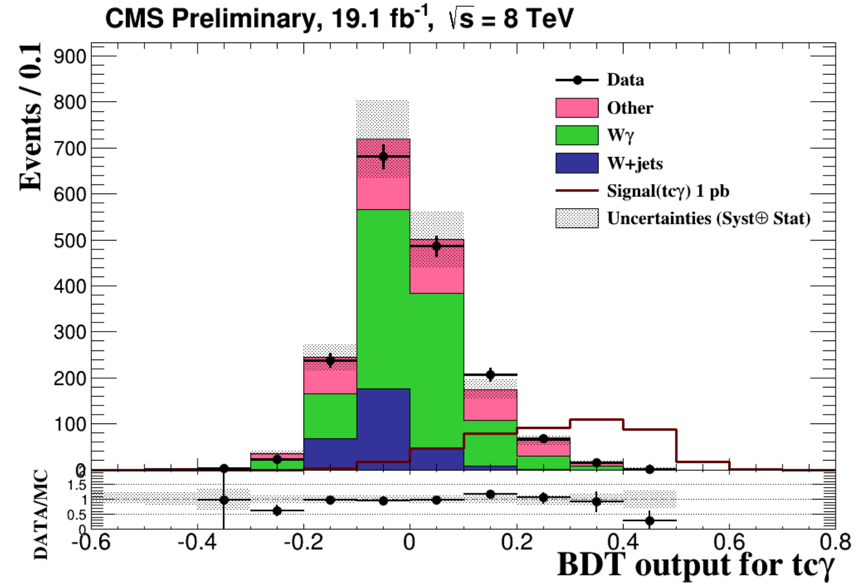
Anomalous production of single top events

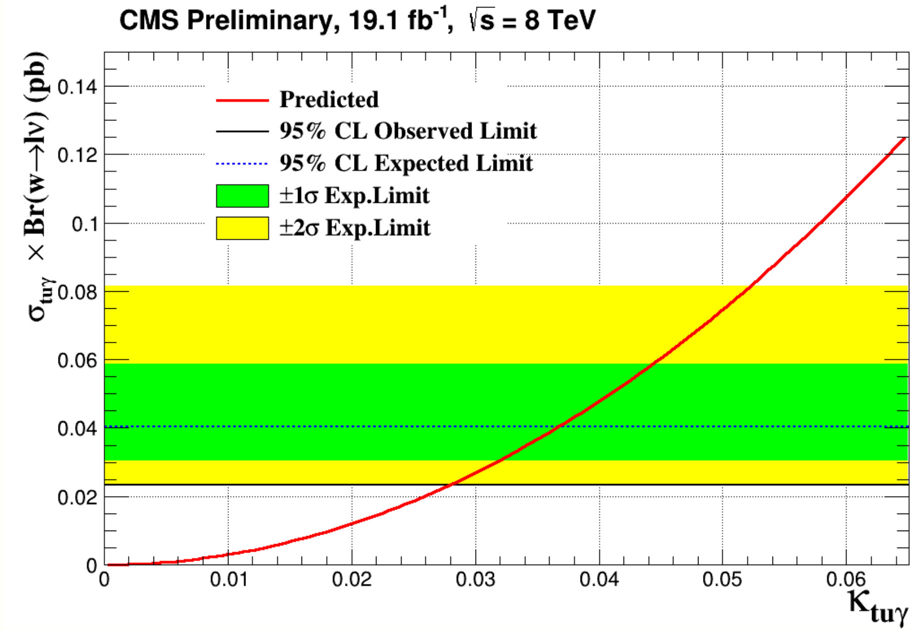
pp → tγ (CMS)

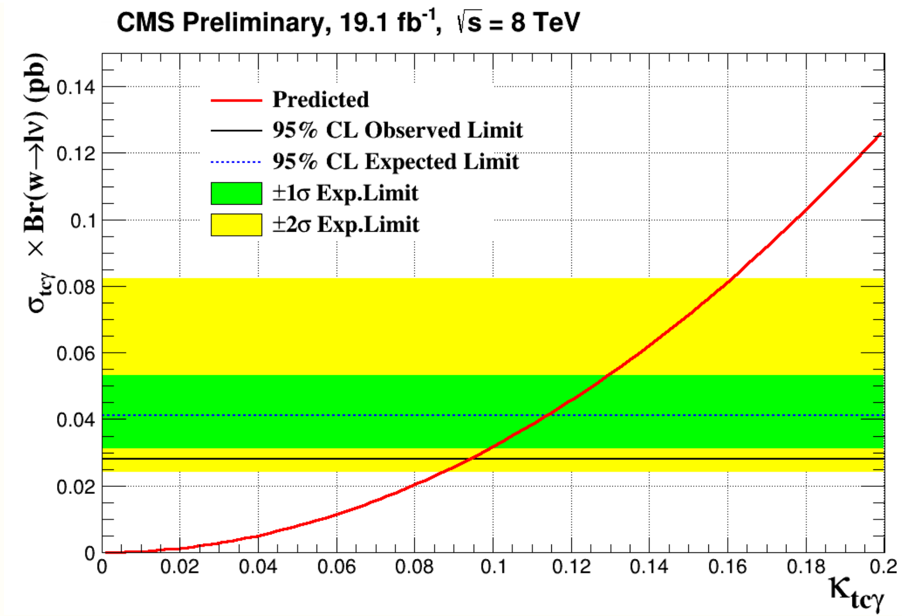
CMS PAS TOP-14-003

- Data sample including a photon with wide electromagnetic shower and zero btag is used to estimate W+jets.
- Wγ+jets is estimated from data outside top mass window.









Anomalous production of single top events

pp $\to$ tZ (CMS)

CMS PAS TOP-12-021

4.9 fb^{-1} of $\sqrt{s}$ =7 TeV

- A search for FCNC in production of single top quark in association with a Z boson to probe tqz and tqg anomalous couplings..
- Signal generated with MadGraph.
- Main background from fake leptons (Z+jets)
- Other backgrounds : ZZ+jets, $t\bar{t}$, tZq.