Experimental review on single top FCNC searches

Kirill Skovpen

Institut Pluridisciplinaire Hubert Curien (IPHC), Strasbourg

Top LHC-France meeting
IPNL

2014-04-08

FCNC and GIM mechanism

- Flavour-changing neutral current (FCNC) transition is an interaction process where a fermion undergoes the change of flavour without alternation of its charge
- FCNC amplitudes at tree level are forbidden by the Glashow-Iliopoulos-Maiani (GIM) mechanism in the Standard Model (SM)
- However, GIM-highly suppressed FCNC transitions are possible in the SM in the higher orders via penguin and box diagrams
- Some extensions of the SM could introduce FCNC decays at tree level including new particles

Effective FCNC Lagrangian:

FCNC couplings

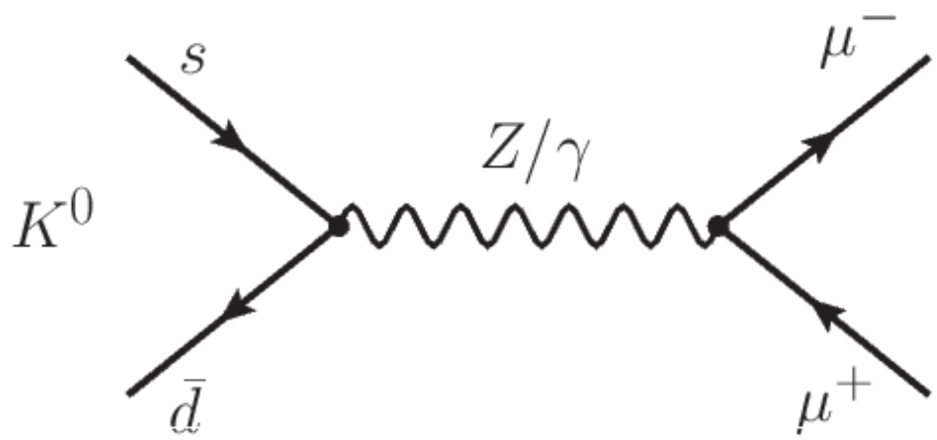
$$\Delta\mathcal{L}_{\text{eff}} = e\ e_t\ \bar{t}\frac{i\sigma_{\mu\nu}p^{\nu}}{\Lambda}\kappa_{\gamma}u\ A^{\mu} + \frac{g}{2\cos\theta_W}\ \bar{t}\gamma_{\mu}v_Z uZ^{\mu}\ + \text{h.c.}$$

***GIM mechanism**: S. L. Glashow, J. Iliopoulos and L. Maiani, Phys. Rev. D 2 (1970) 1285*

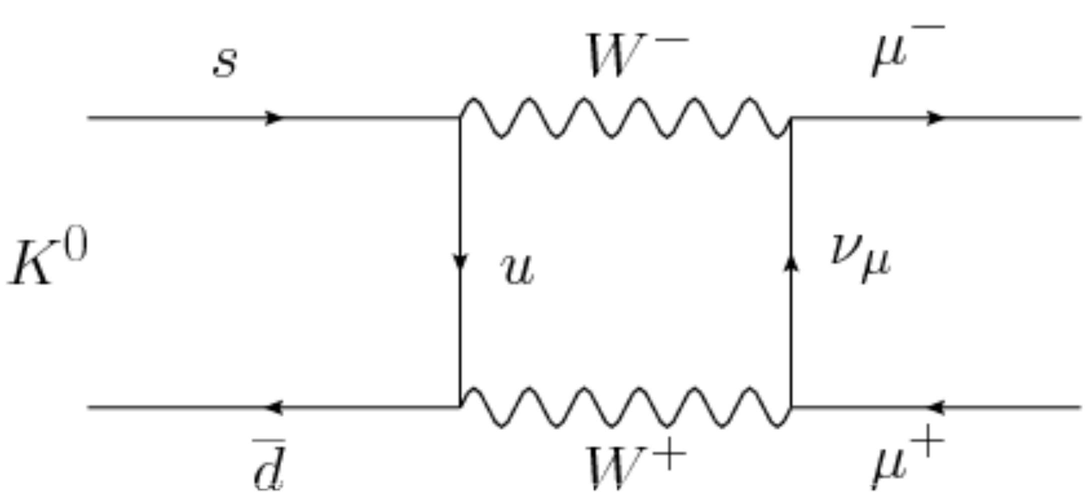
FCNC in SM

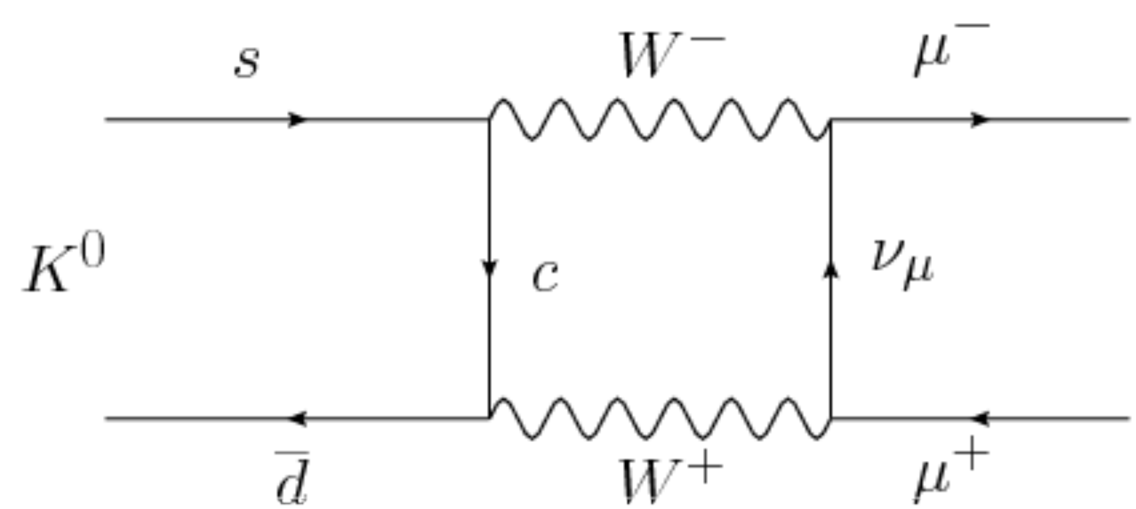
Example of SM FCNC process: **$K_L \to \mu^+\mu^-$**

Forbidden:



Observed but highly suppressed (Br ≈ 10^{-9}):





Phys.Rev.Lett. 63 (1989) 2185 (AGS, BNL)

Search for FCNC in BSM

Higher rates for FCNC processes are predicted by many extensions of the SM:

- Fourth-generation models
- Extended technicolor models
- Leptoquark models
- Extra dimensions
- Extra quark models
- Supersymmetry
- Two-Higgs-Doublet models
- …

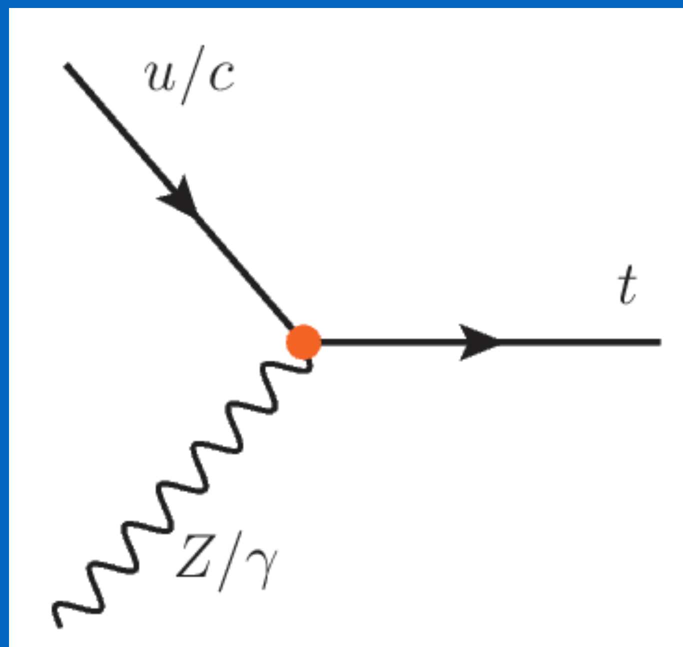
Model	Br ($t \rightarrow Z/\gamma\ q$)
SM	~ 10E-12
SUSY	~ 10E-6
Two-Higgs-Doublet	~ 10E-7

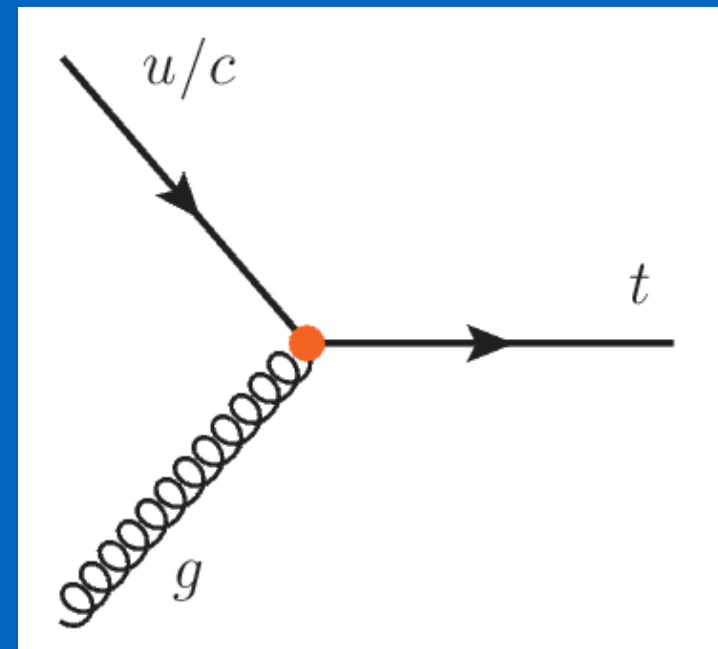
Why look for FCNC with t-quark at the LHC ?

Search for FCNC in t-quark decays is promising because of the several important properties of t-quark:

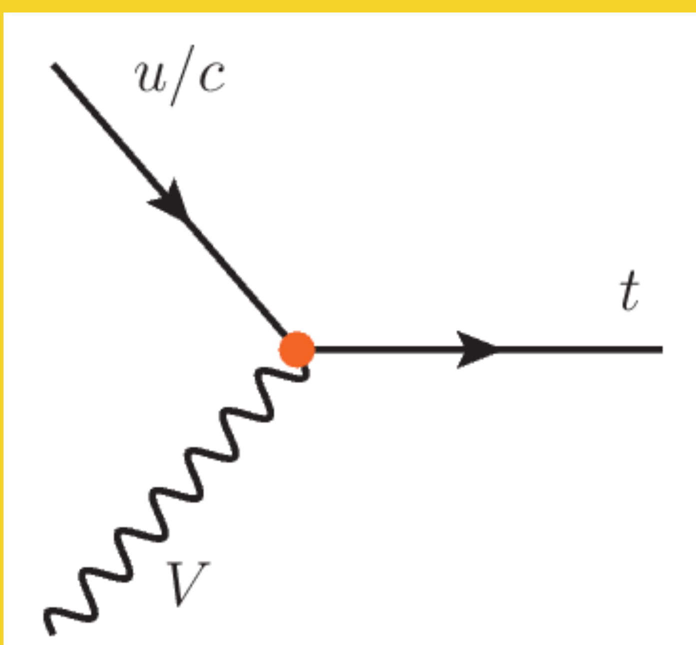
- The formation of strong bound states occurs much slower than the decay of t-quark which results in a clean event signature
- Yukawa coupling for t-quark is close to unity which makes it an interesting candidate to study EW symmetry breaking mechanism
- t-quark is the heaviest elementary particle known - sensitivity to new physics searches

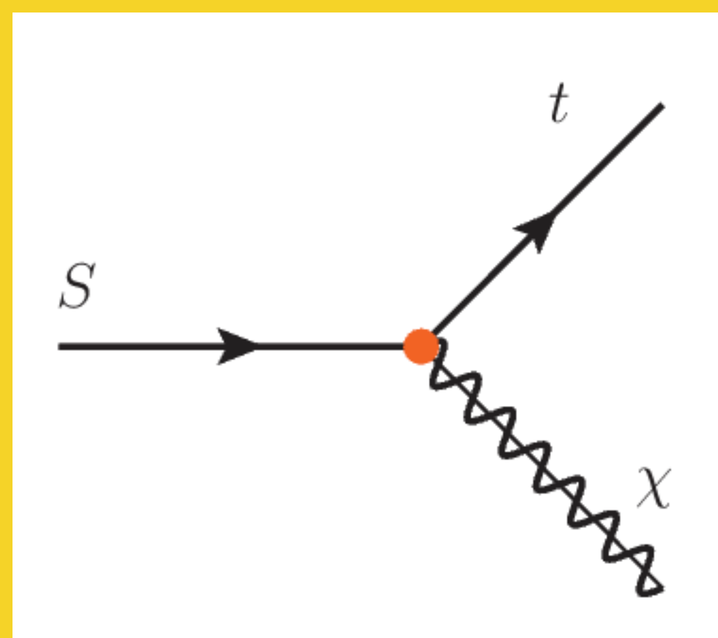
Single top FCNC interaction vertices





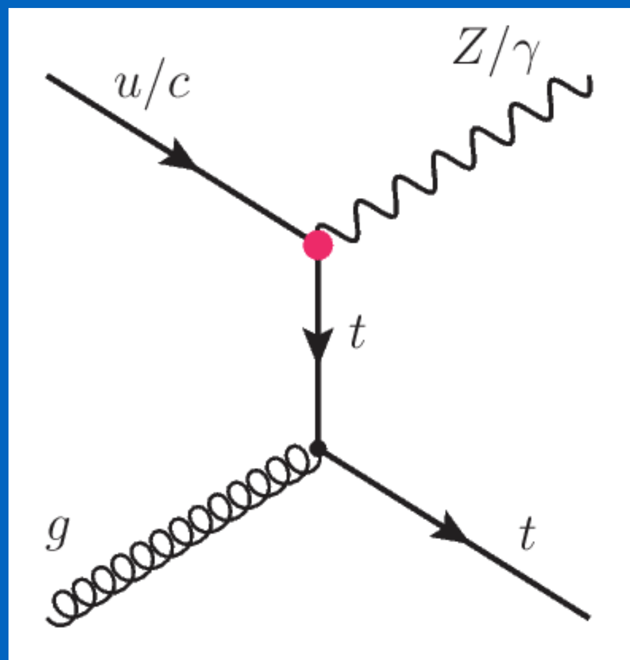
transitions u/c to t-quark with radiation of Z/γ or gluon via anomalous couplings

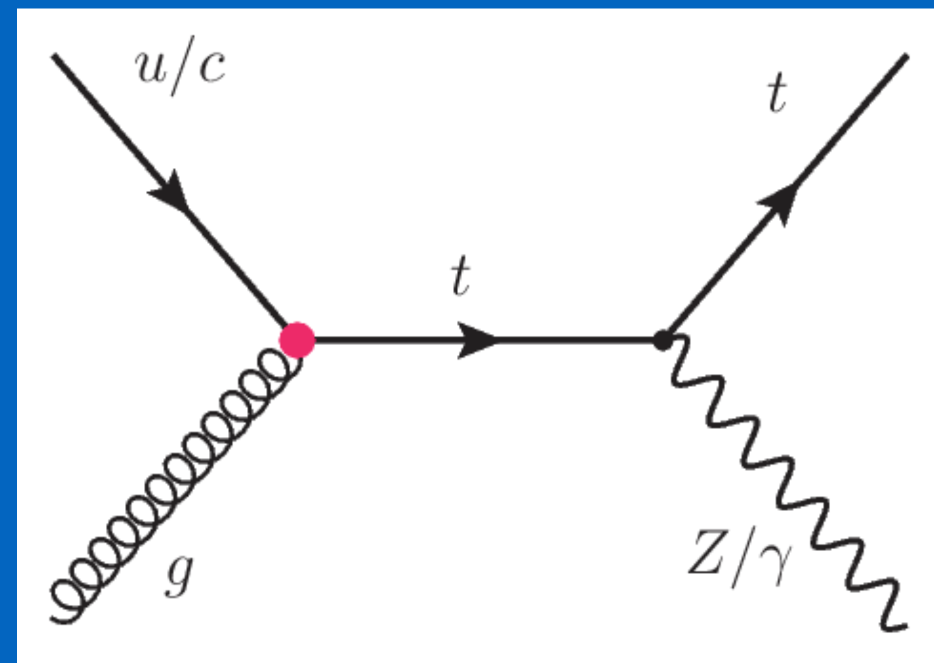




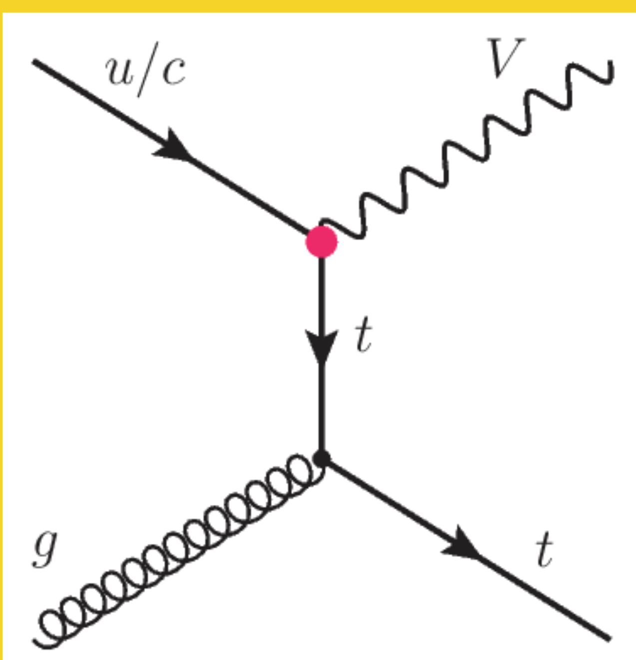
coupling to hypothetical weakly interacting particles

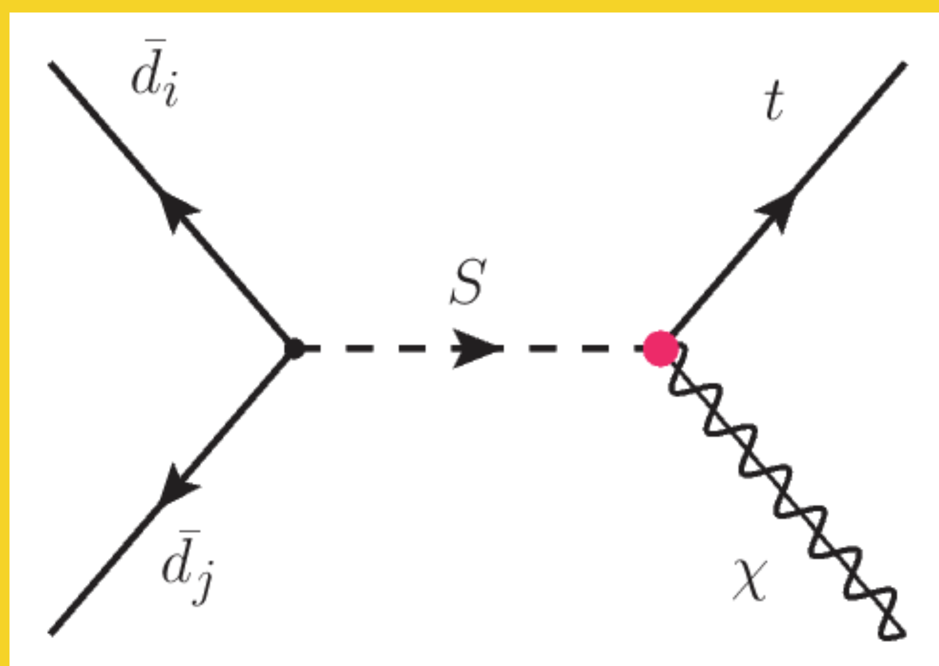
Search for single top FCNC processes





qg → t + Z/γ





qg → t + V

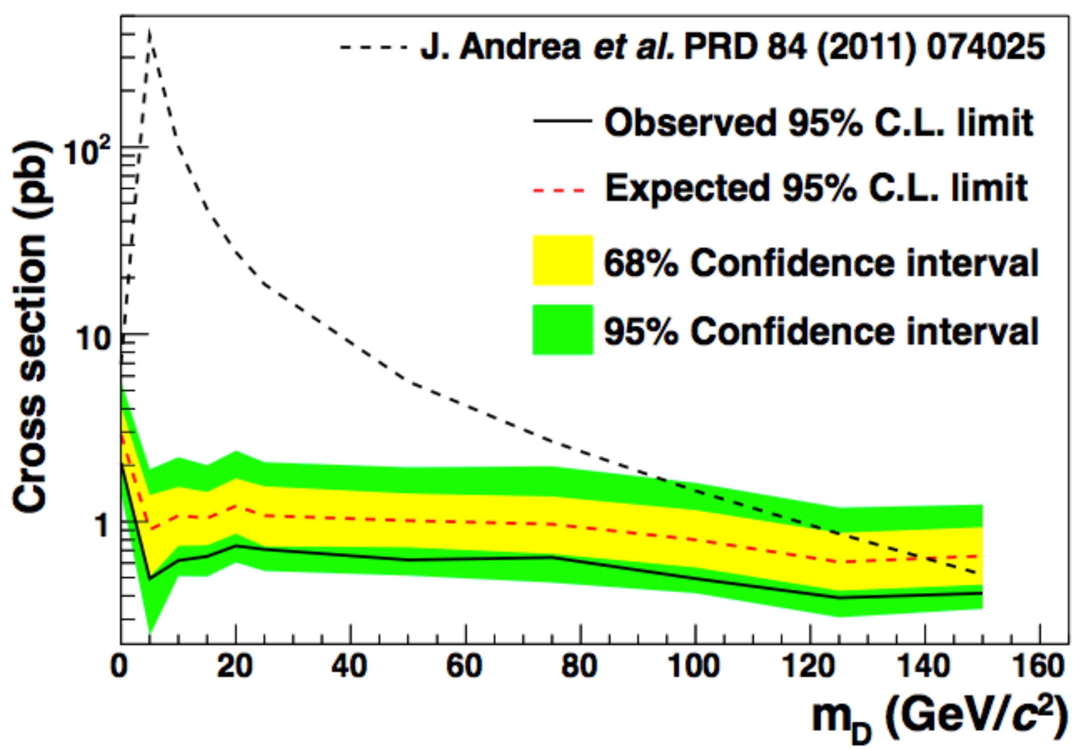
qq → t + X

Monotop searches at CDF

7.7/fb at 1.96 TeV

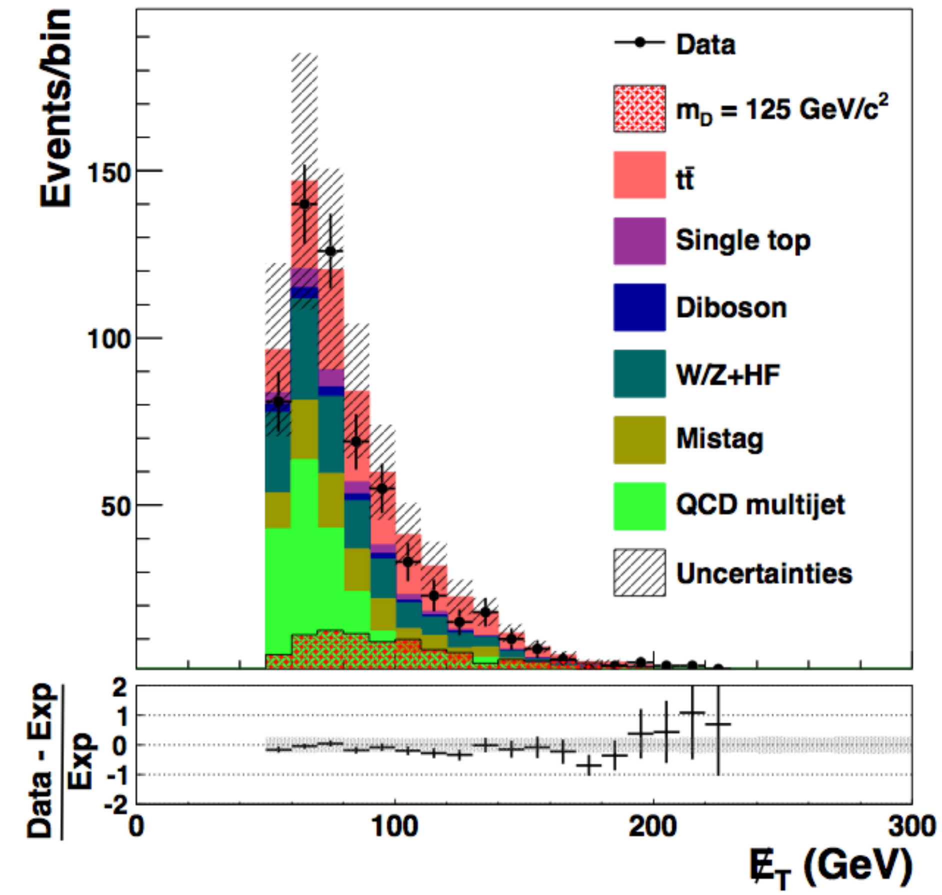
ppbar → t + D → qqbar b D

D is a new WIMP, coupling set to 0.1



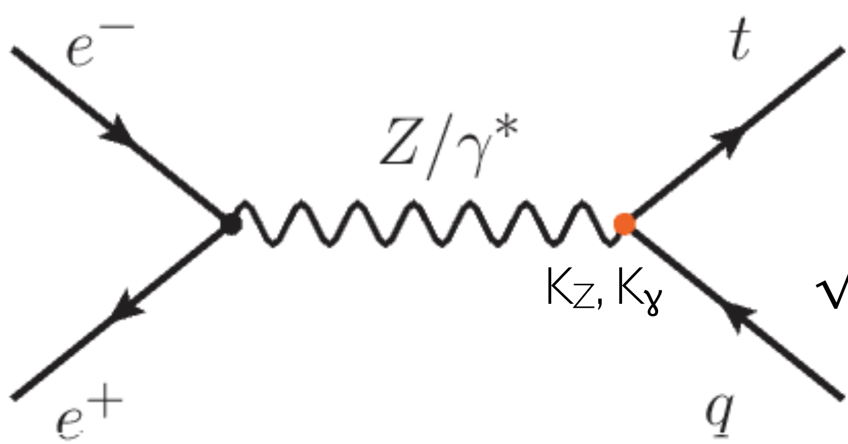
m_D < 150 GeV (95% CL) excluded

Phys. Rev. Lett. 108 (2012) 201802

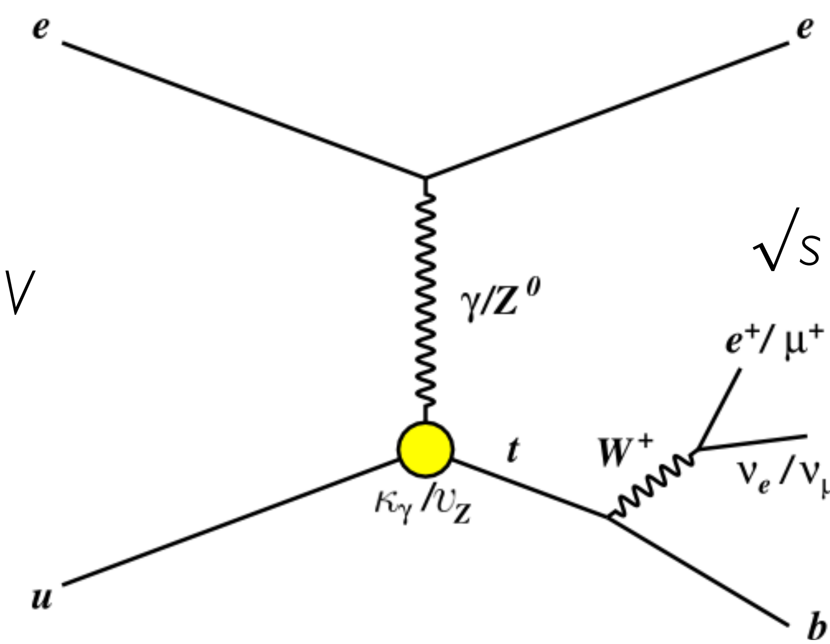


Processes	Events
$p\bar{p} \to t + D$	
$m_D = 20$ GeV/c^2	2116.9 ± 121.4
$m_D = 75$ GeV/c^2	232.3 ± 22.9
$m_D = 100$ GeV/c^2	129.8 ± 12.5
$m_D = 125$ GeV/c^2	94.5 ± 9.3
$t\bar{t}$	182.8 ± 20.2
Single top	24.3 ± 4.5
Diboson	15.7 ± 2.7
W/Z+HF	130.5 ± 33.8
Mistag	96.9 ± 39.4
QCD multijet	210.2 ± 54.5
Total background	660.2 ± 78.1
Data	592

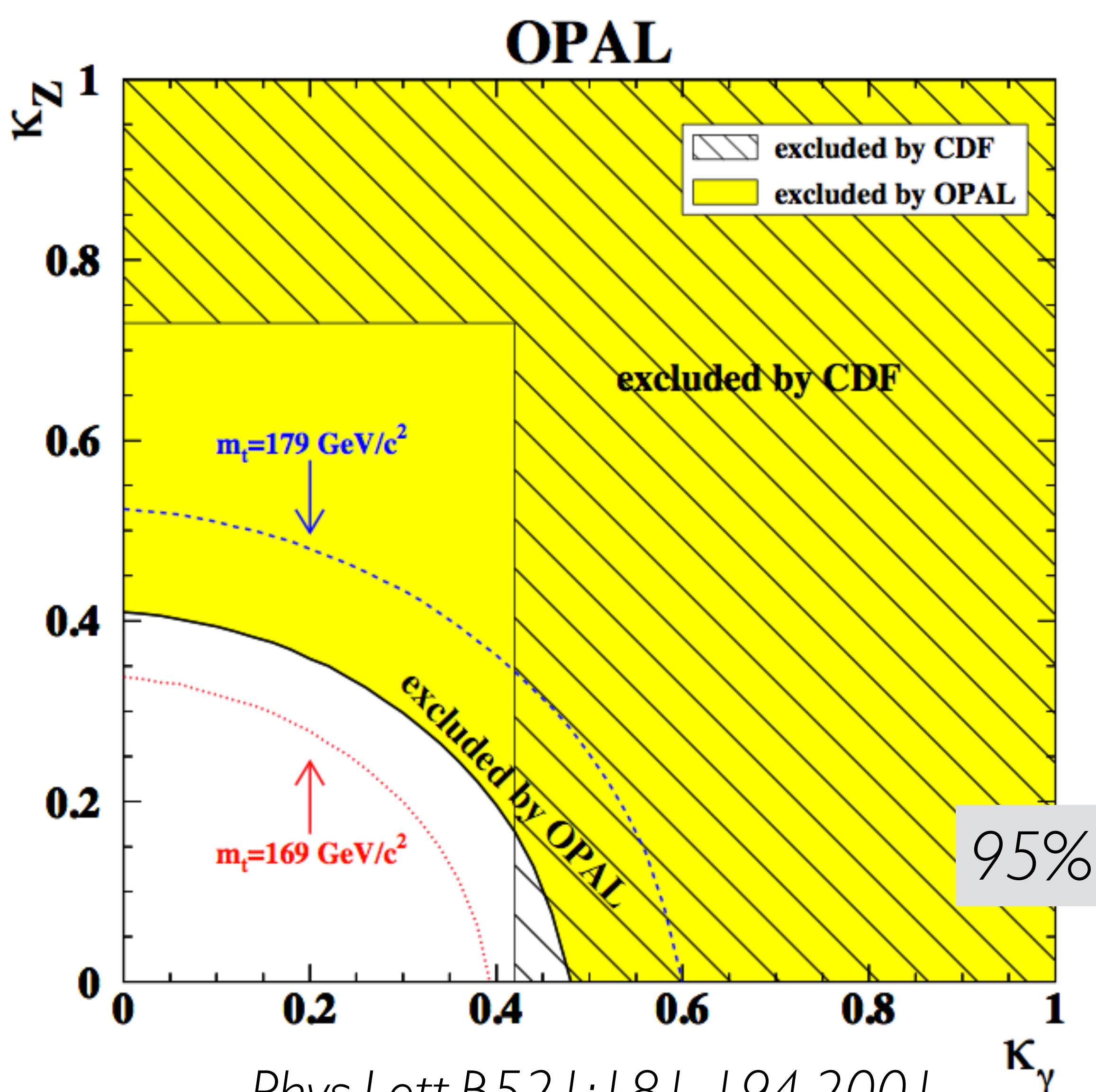
FCNC single top searches from OPAL and ZEUS



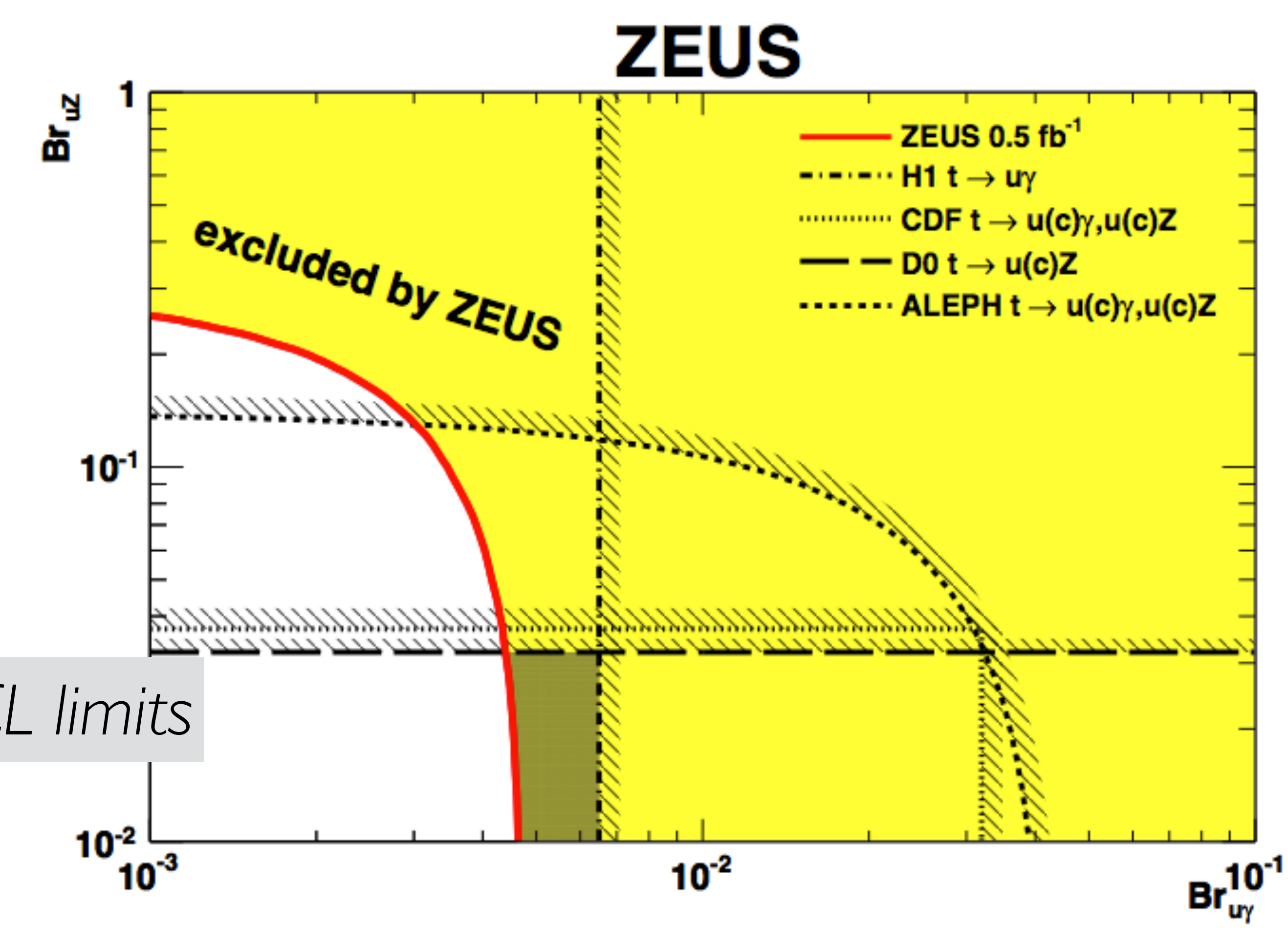
LEP2
0.6/fb at
$\sqrt{s}$ = 189-209 GeV



HERA
0.5/fb at
$\sqrt{s}$ = 315 GeV



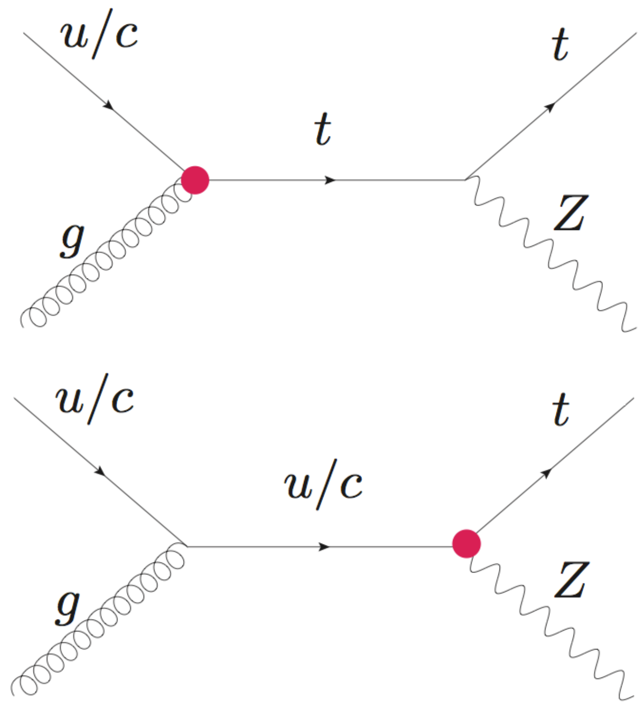
95% CL limits



Phys.Lett.B521:181-194,2001
L3 results: Phys.Lett.B549:290-300,2002

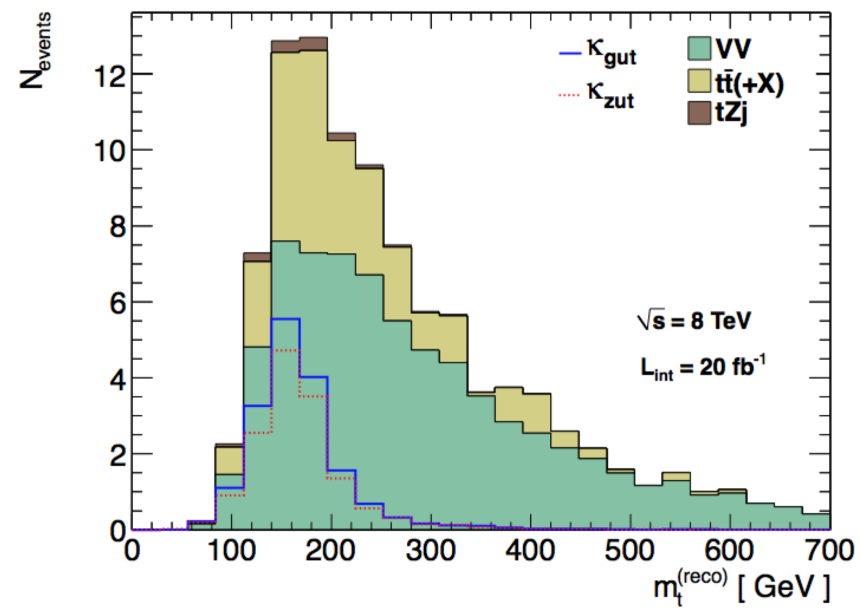
CDF limits are shown from ttbar searches
Phys.Lett.B708:27-36,2012

Anomalous couplings with trilepton signatures



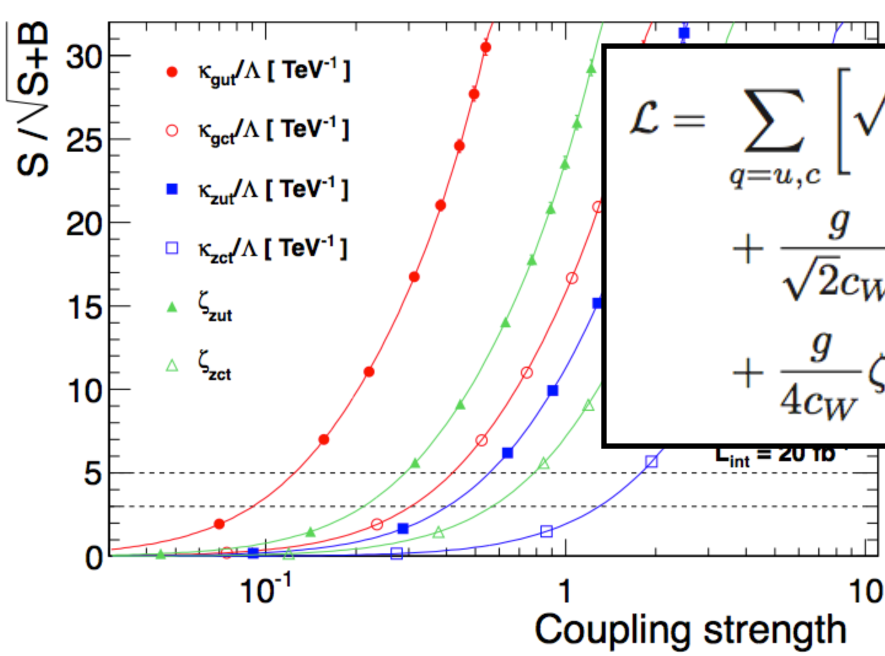
Probing gqt and Zqt at the same time

Phenomenological study of single top production in association with Z-boson at LHC for 20/fb at 8 TeV



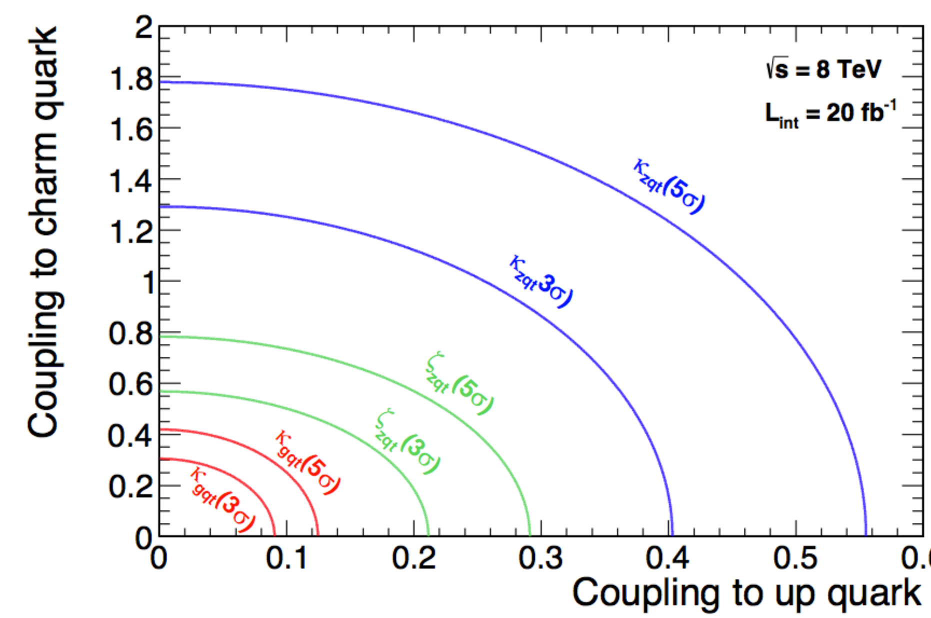
single non-vanishing coupling case, discovery for 3σ (5σ):

$$\mathcal{BR}(t \to gu) \leq 0.47\% \ (0.25\%)$$
$$\mathcal{BR}(t \to gc) \leq \ 5.1\% \ (2.8\%) \ ,$$
$$\mathcal{BR}(t \to Zu) \leq 0.39\% \ (0.20\%)$$
$$\mathcal{BR}(t \to Zc) \leq \ 3.8\% \ (2.1\%)$$
$$\mathcal{BR}(t \to Zu) \leq 1.07\% \ (0.56\%)$$
$$\mathcal{BR}(t \to Zc) \leq \ 7.2\% \ (4.0\%)$$



$$\mathcal{L} = \sum_{q=u,c} \Bigg[\sqrt{2} g_s \frac{\kappa_{gqt}}{\Lambda} \ \bar{t} \sigma^{\mu\nu} T_a (f_q^L P_L + f_q^R P_R) q \ G^a_{\mu\nu} + \frac{g}{\sqrt{2} c_W} \frac{\kappa_{zqt}}{\Lambda} \ \bar{t} \sigma^{\mu\nu} (\hat{f}_q^L P_L + \hat{f}_q^R P_R) q \ Z_{\mu\nu} + \frac{g}{4 c_W} \zeta_{zqt} \ \bar{t} \gamma^\mu (\tilde{f}_q^L P_L + \tilde{f}_q^R P_R) q \ Z_\mu \Bigg] + \text{h.c.} \ .$$

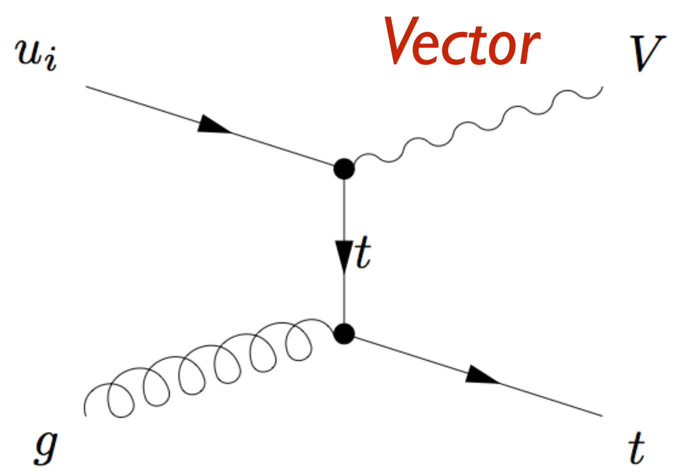
two non-vanishing couplings (u and c quarks):

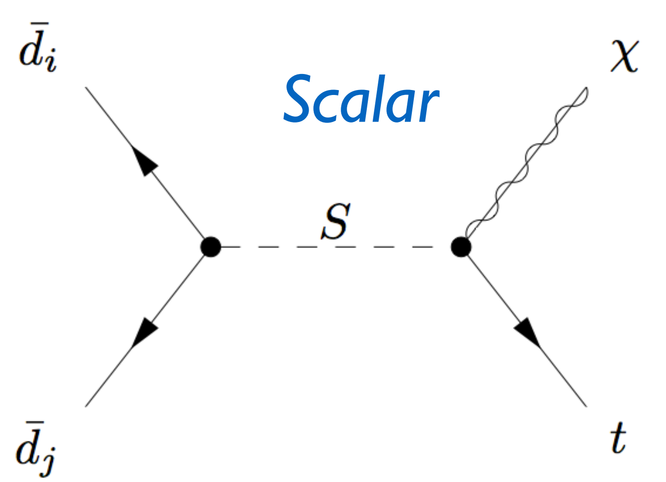


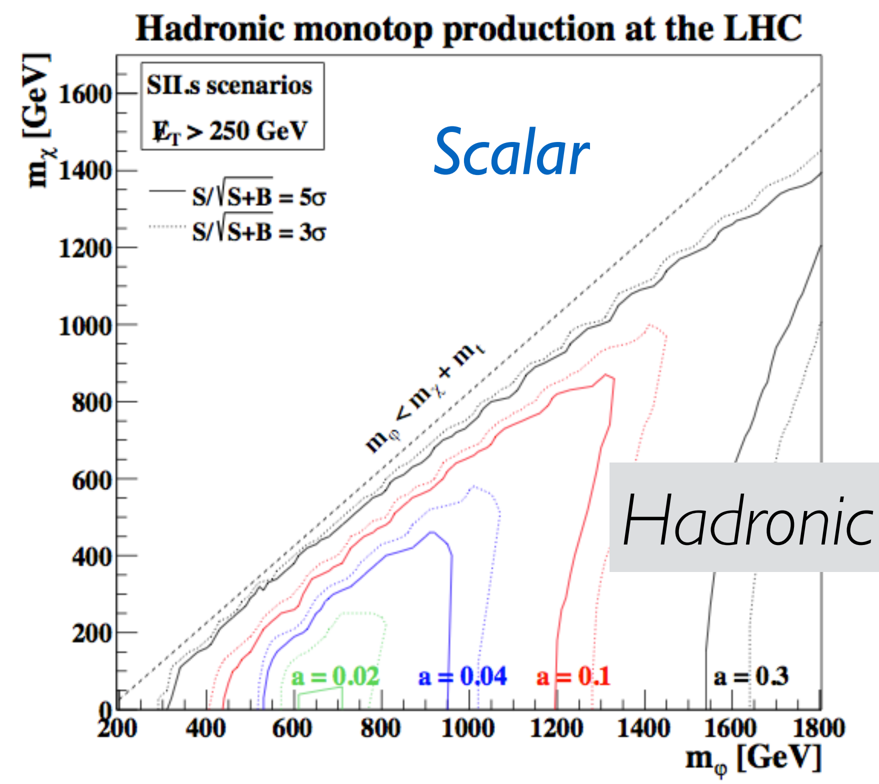
Contributions from IPHC and GRPHE

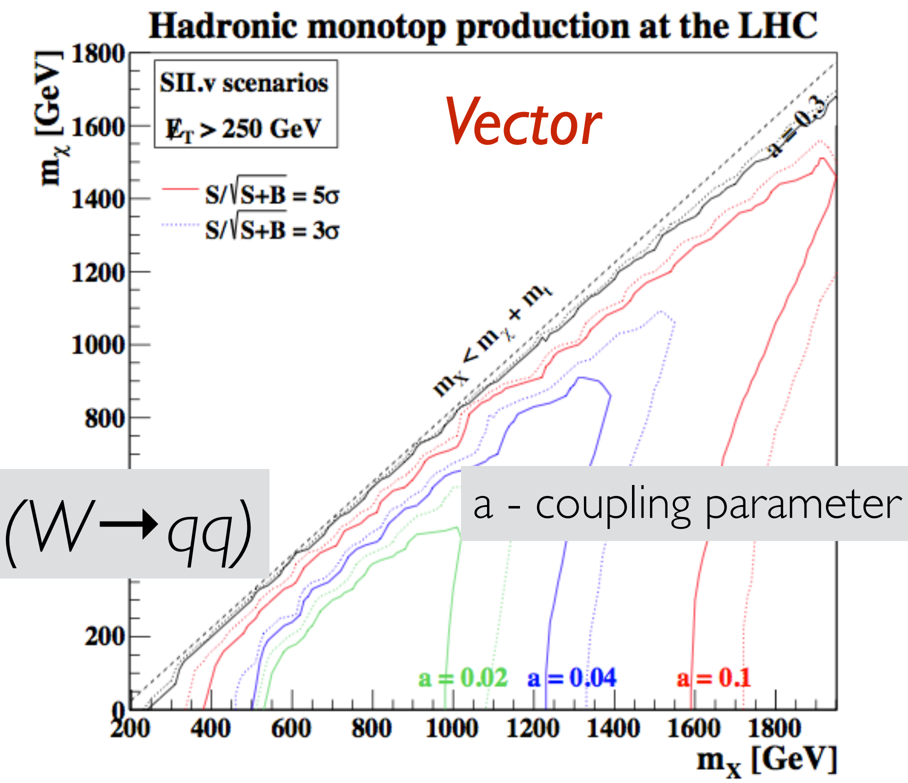
Phys. Lett B725 (2013) 123-126

Monotop phenomenology at LHC



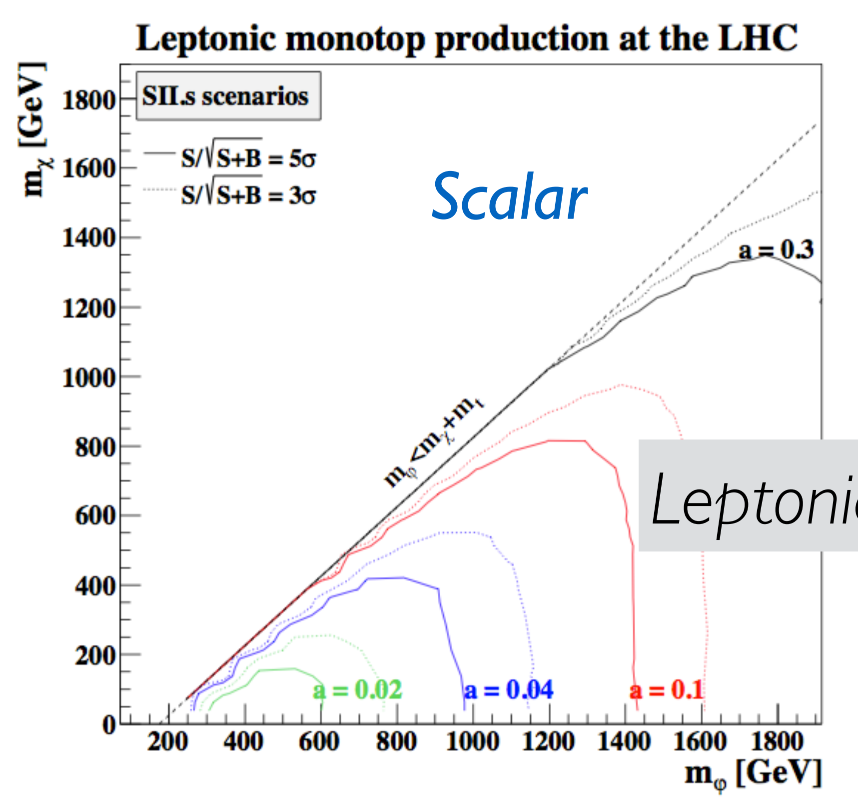


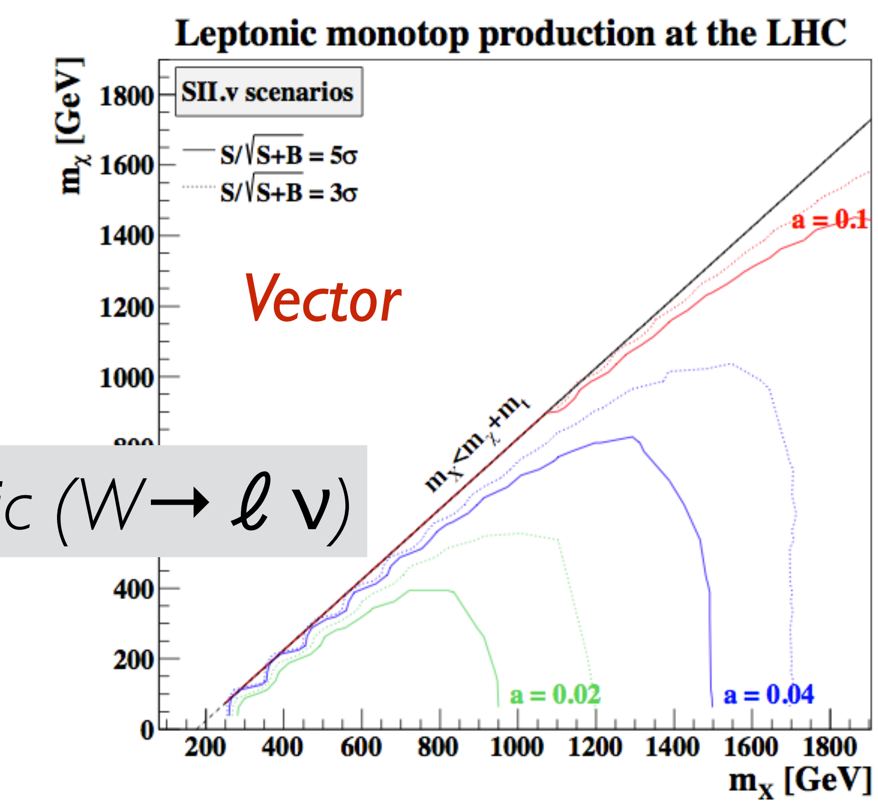




Hadronic ($W \rightarrow qq$)

a - coupling parameter





Leptonic ($W \rightarrow \ell\,\nu$)

Monotop sensitivity studies for LHC, 20/fb at 8 TeV

Considered both leptonic and hadronic W decay modes

Monotop phenomenology work by A. Deandrea and G. Cacciapaglia (IPNL) is in progress

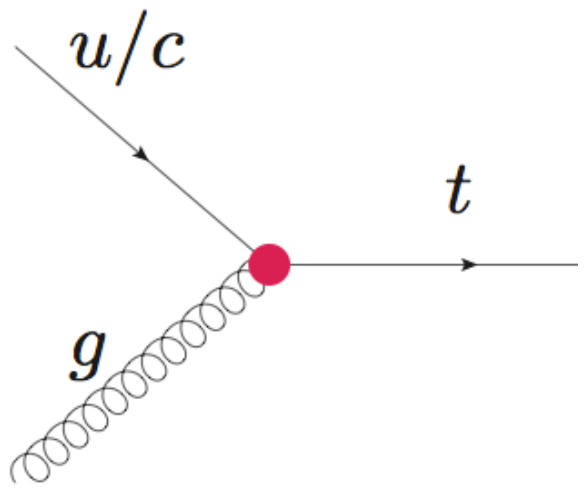
Contributions from IPHC and GRPHE

Phys. Rev. D89 (2014) 014028

FCNC at ATLAS: Overview

ATLAS-CONF-2013-063

14.2 fb^{-1} at 8 TeV



Probe gqt anomalous couplings

- t-quark produced singly: W and b-quark are back-to-back
- higher momenta of decay products compared to W/Z +jets background

Process:

qg → t → ℓ ν b

Signature:

one isolated lepton+ b-tagged jet + missing energy

Main background:

W/Z+(b/c)+jets,
SM top,
WW/ZZ/WZ+jets,
QCD

Discriminant:

Neural Network

FCNC at ATLAS: Selection criteria

- **Exactly one isolated lepton with P_T > 25 GeV**
  electron with $|\eta_{clus}| < 2.47$ vetoing crack region
  E_T-dependent isolation using $\Delta R < 0.2$ and 0.3
  muon with $|\eta| < 2.5$
  relative mini-isolation (< 0.05) using cone radius of
  R_{iso} = 10 GeV / $P_T(\mu)$

- **Exactly one b-tagged jet with P_T > 30 GeV**
  Using AntiKt4 Topo jets
  Reject closest jet to electron in $\Delta R(e,j) < 0.2$
  Remove all electrons close to jets in $\Delta R(e,j) < 0.4$
  Suppress pileup jets with JVF > 0.5

- **Missing E_T > 30 GeV** (Additional suppression of Z+jets background)

  signal region (SR): same as above
  W+jets control region: looser b-tagging requirement + SR b-tag veto

- **$m_T(W)$ > 50 GeV** (Additional suppression of QCD background)

FCNC at ATLAS: Background estimation

All background except QCD is estimated from MC

QCD background measurement (no cut on missing E_T is applied):

- **Electron channel**: *Jet-electron method* with template fit:

  - Measure missing E_T shape templates in multi-jet MC with SR selection criteria applied where jet is selected in place of an electron (jet mis-reconstructed as electron = jet-electron object)

  - A bin maximum likelihood fit to the observed data in missing E_T distribution using multi-jet and other SM background templates

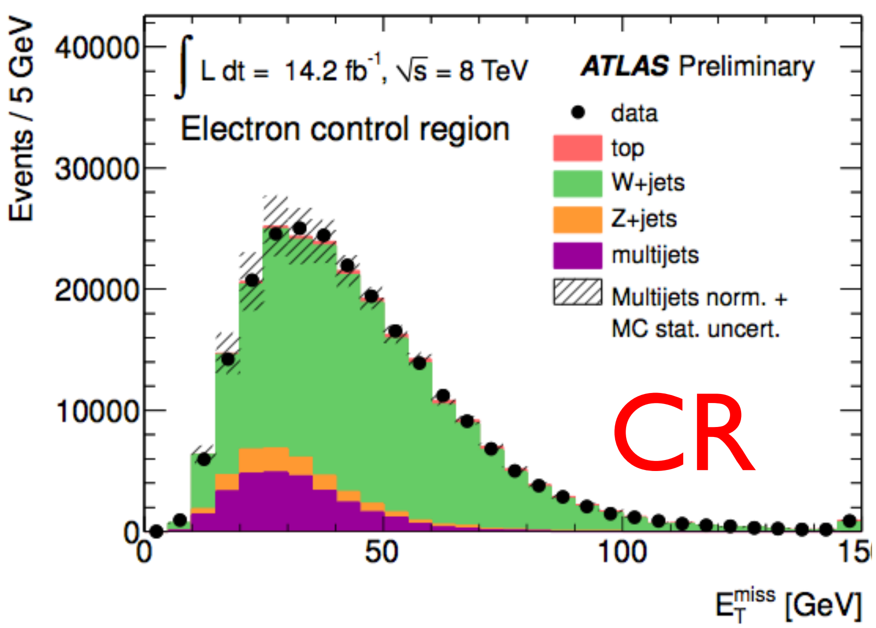
- **Muon channel**: *Matrix Method*

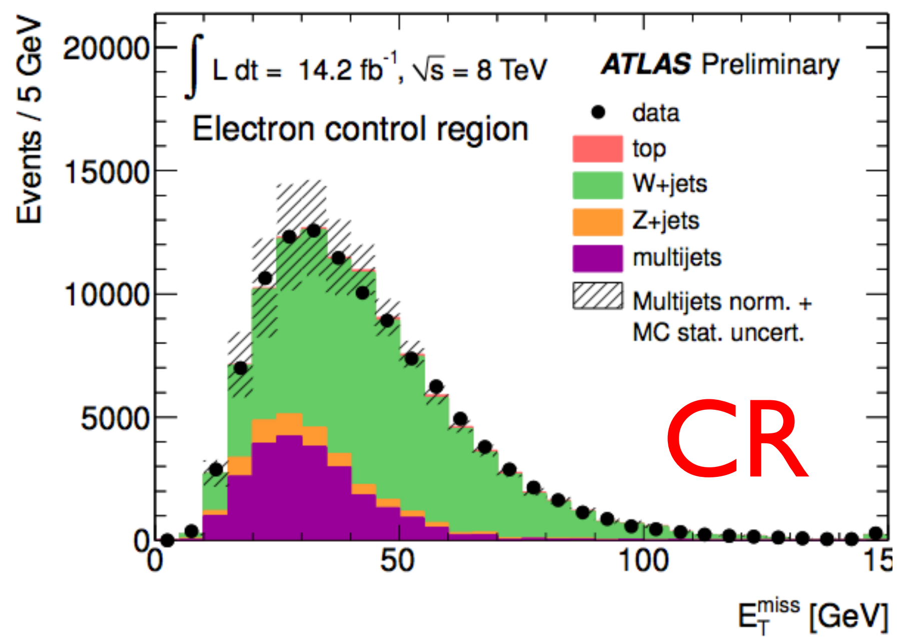
  - Fake efficiencies measured in high impact parameter significance region
  - Real efficiencies measured with $m_T(W) > 100$ GeV

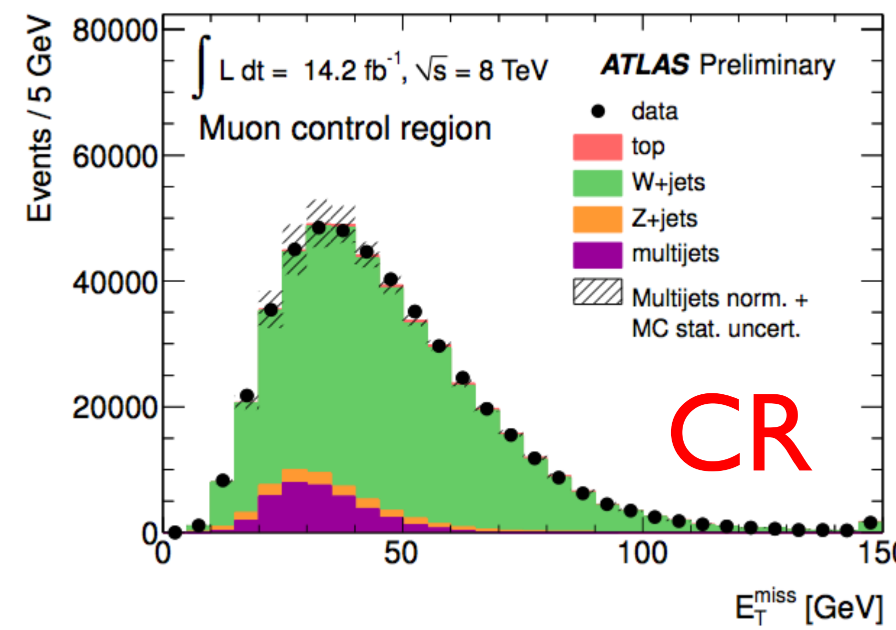
Systematics (50%) are assessed by switching the two methods for electron and muon channels, and switching missing E_T and $m_T(W)$ variables to extract multi-jet background normalisation from the fit

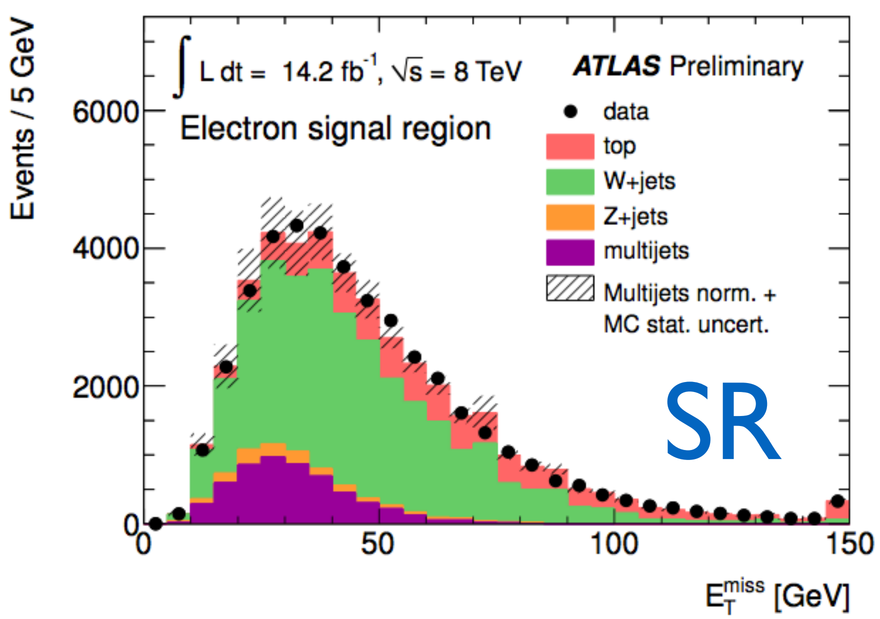
FCNC at ATLAS: Background validation

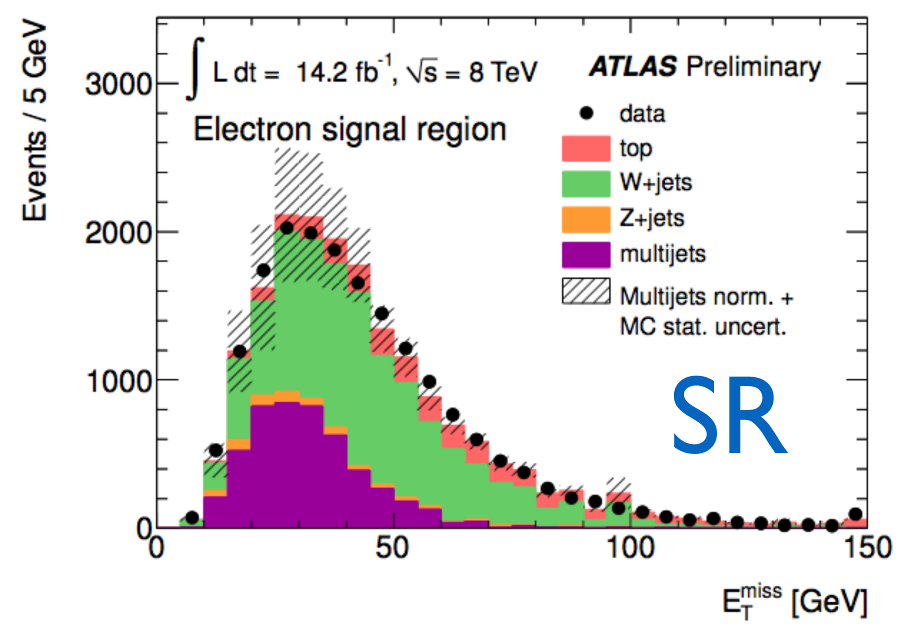
electron channel (|η| < 1.5) electron channel (|η| > 1.5) muon channel

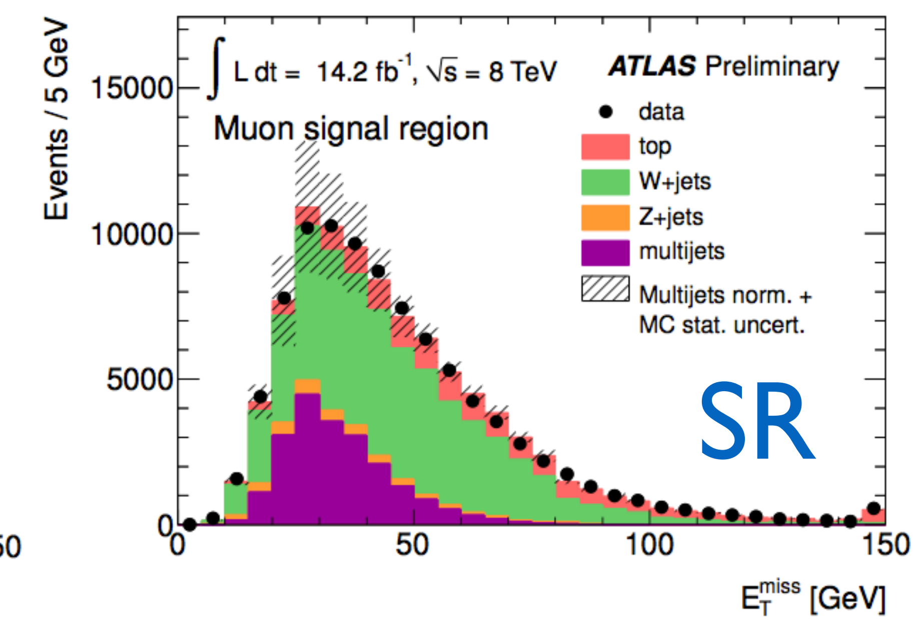








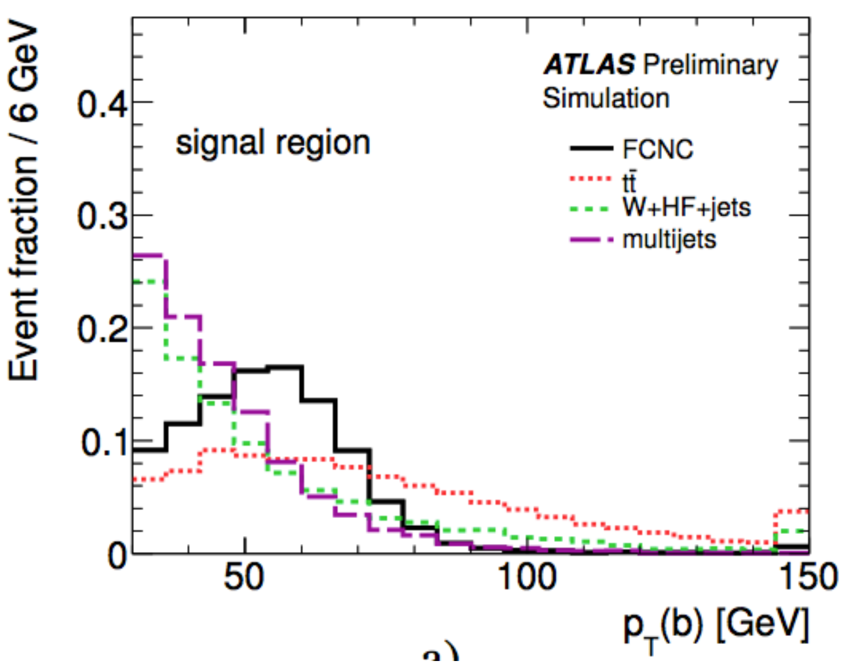




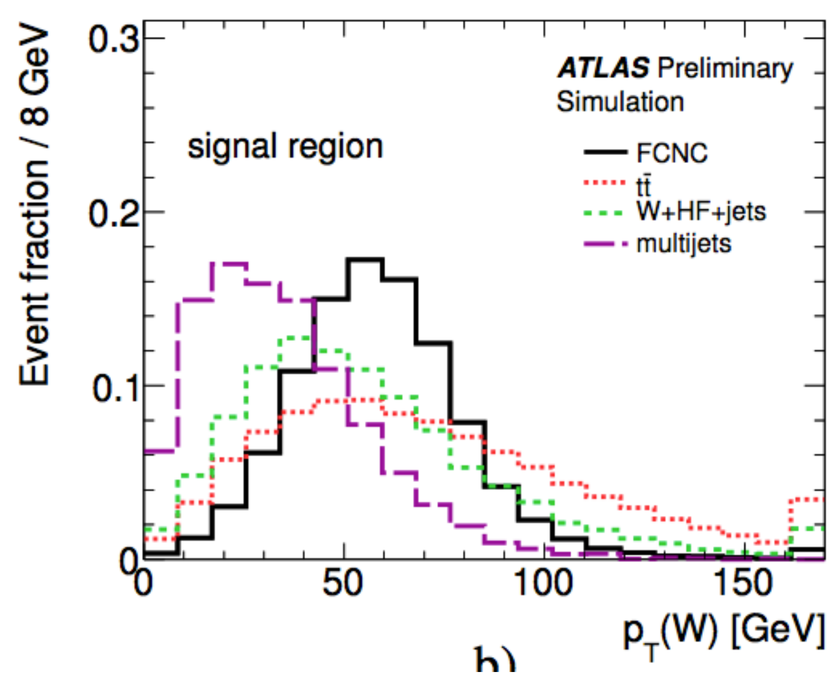
FCNC at ATLAS: Neural Network inputs

- No single discriminating variable to separate signal from background
- Total 13 input variables used by Neural Network:
  momenta, relative angles, pseudorapidity, reconstructed particles masses, lepton electric charge, etc.
- Most discriminating variables: P_T(b-jet), P_T(W), $\Delta\phi(W,\nu)_{t\text{-rest}}$

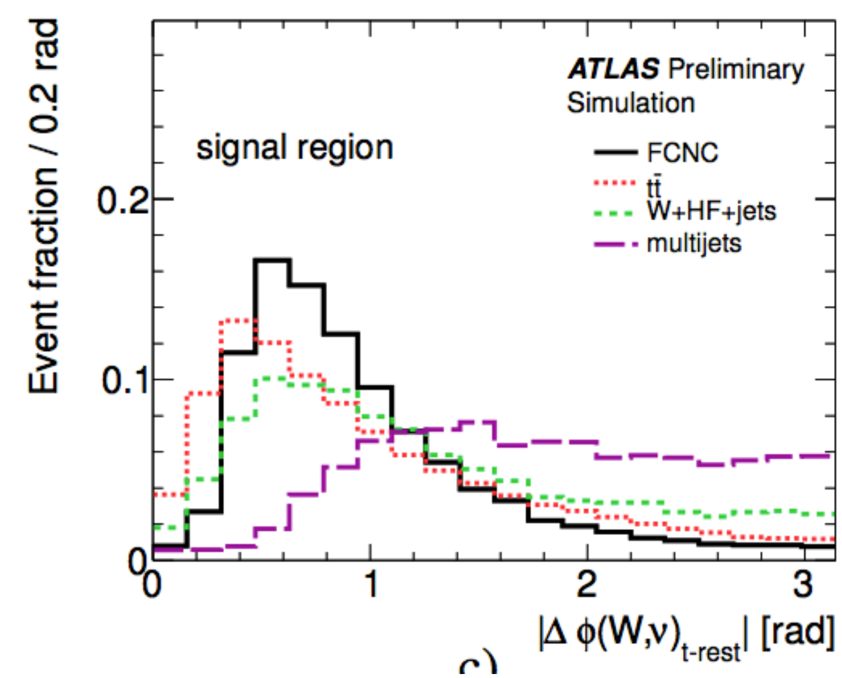
SR



P_T(b-jet)

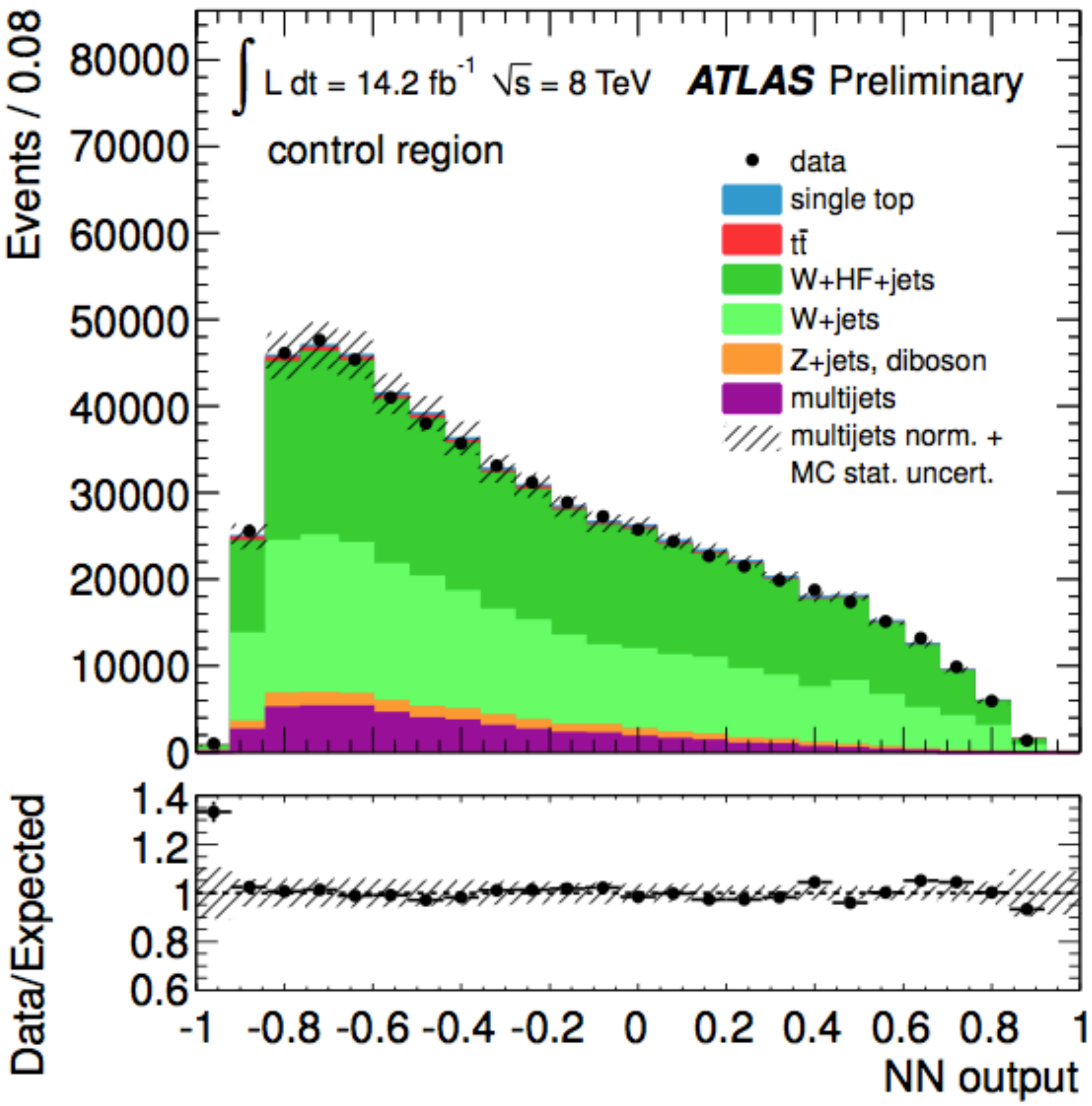


P_T(W)

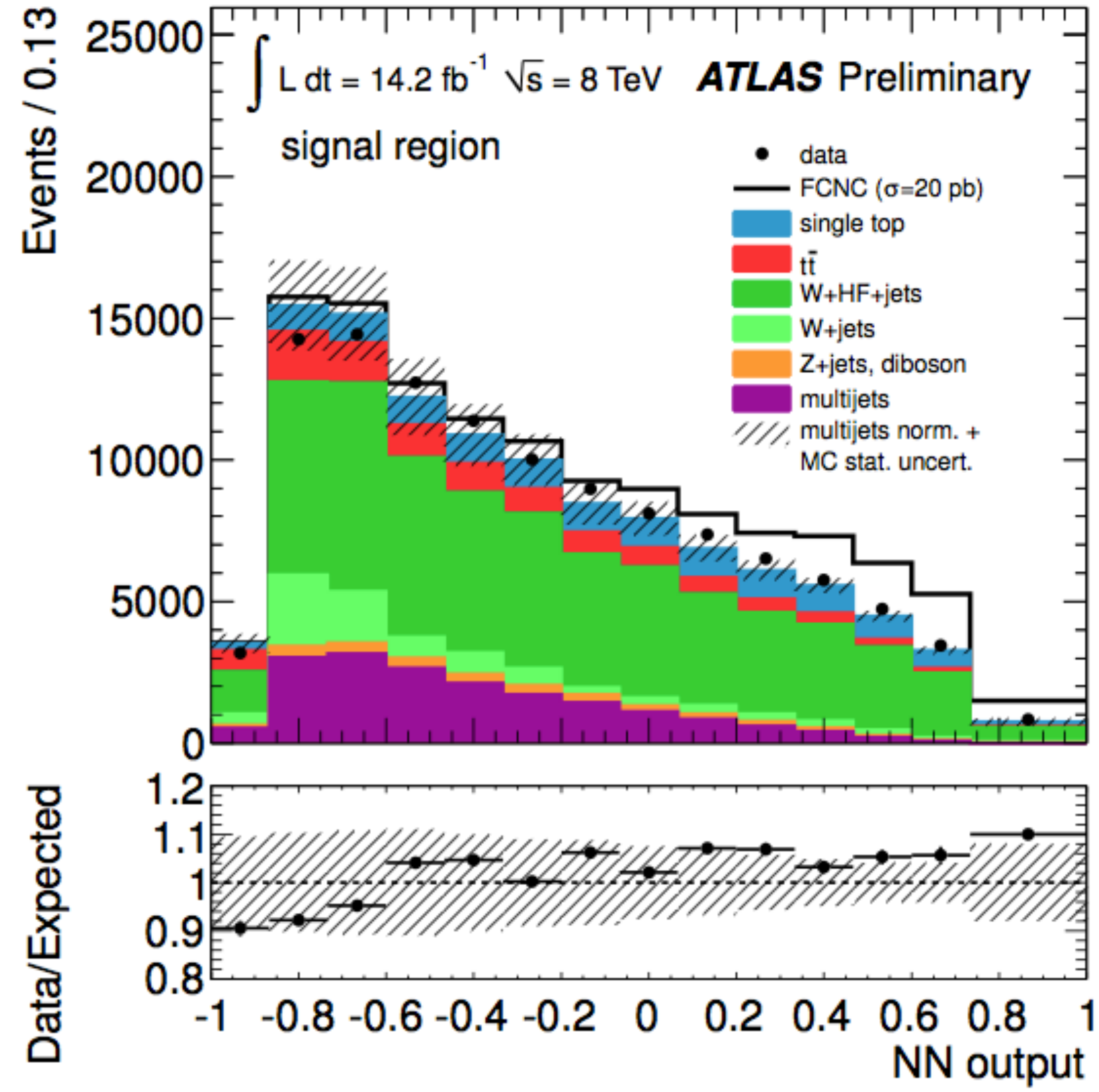


$\Delta\phi(W,\nu)_{t\text{-rest}}$

FCNC at ATLAS: Neural Network results

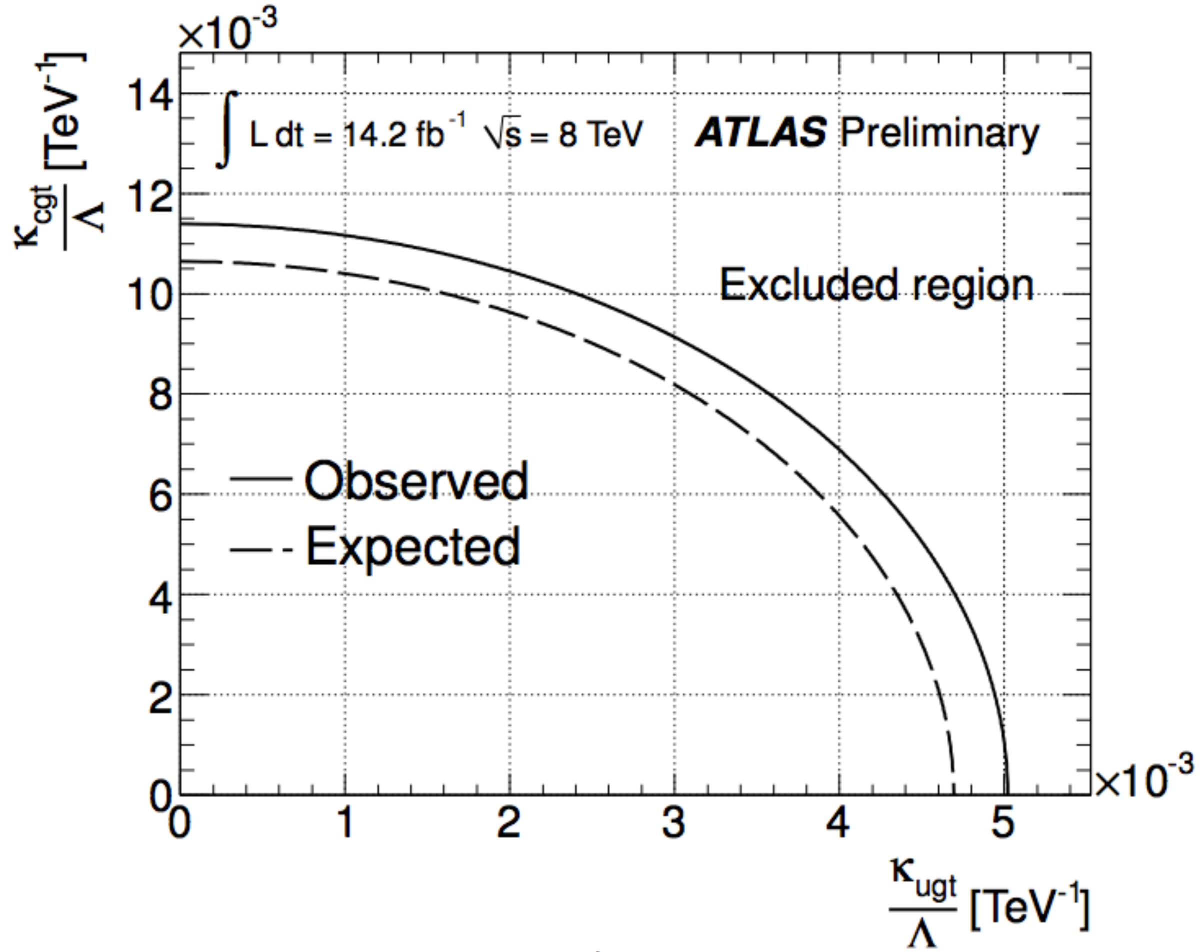


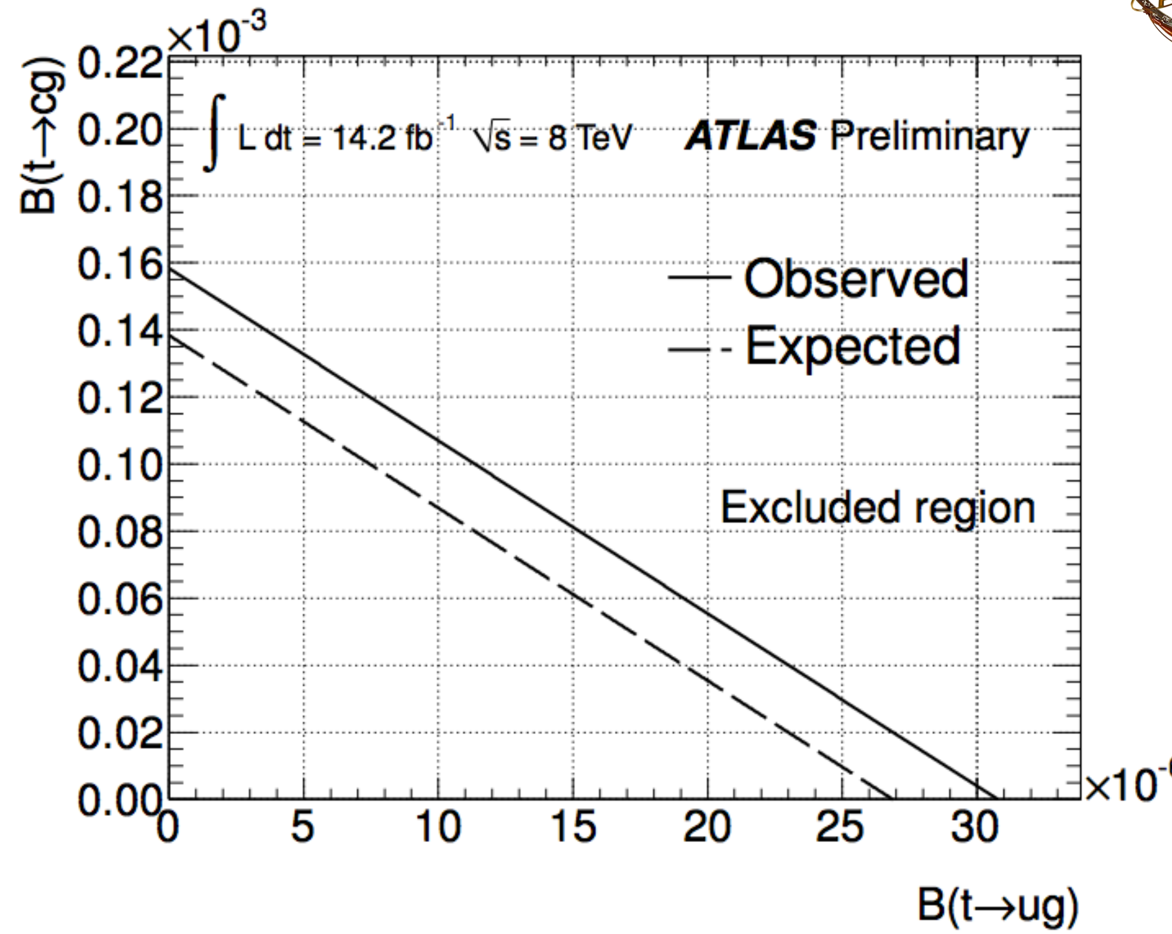
CR



SR

Overall good agreement between data and background prediction



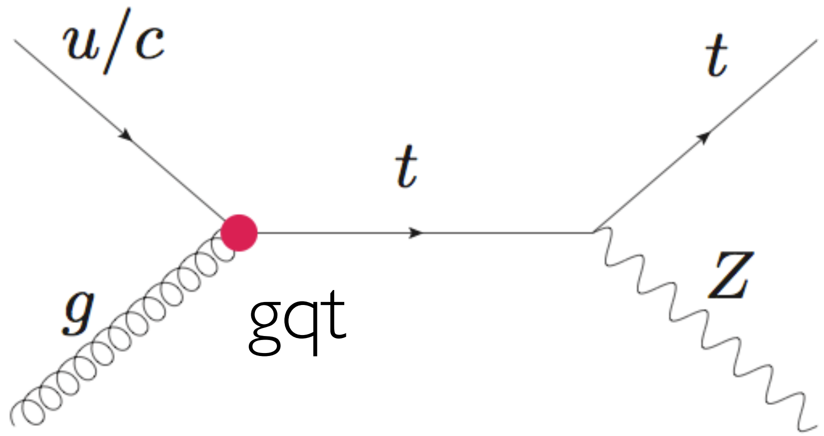


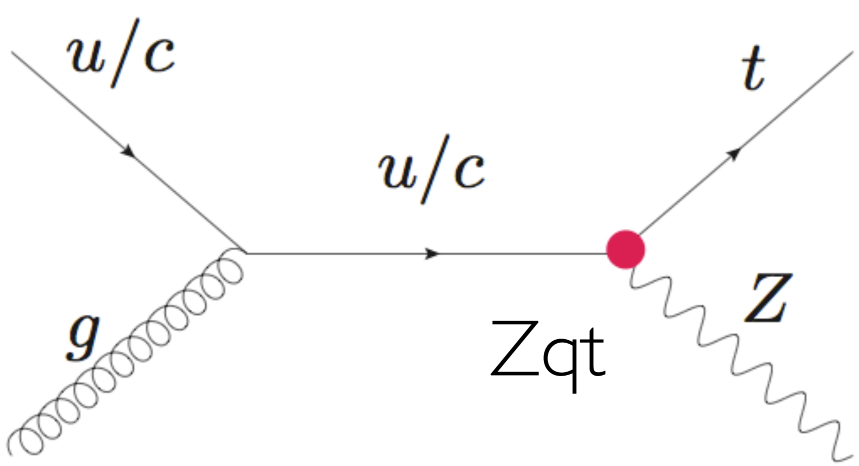
- No evidence for FCNC strong interaction in single top production
- 95% CL upper limits are set with Bayesian approach

FCNC in tZ events at CMS: Overview

CMS PAS TOP-12-021

5 fb^{-1} at 7 TeV





Probing both Zqt and gqt anomalous couplings

Process:

qg→t(q)→tZ→ 3ℓ b ν

Signature:

three isolated leptons + b-tagged jet + missing energy

Main background:

WZ/ZZ+jets
tZq+jets
Z+jets, ttbar+jets,
single top, tW,
WW+jets

Discriminant:

BDT

Contributions from: IPHC and GRPHE

Analysis at 8 TeV with 20/fb in progress !

FCNC in tZ events at CMS: Selection criteria

- Analysis is performed in the following tri-lepton channels:
  μμμ, μμe, eeμ and eee

- At least three leptons with P_T > 20 GeV
  electrons with $|\eta| < 2.5$ with relative energy isolation (0.17) in $\Delta R < 0.2$
  muons with $|\eta| < 2.4$ with relative Pt isolation (0.20) in $\Delta R < 0.2$

- Invariant mass of two same flavour and opposite-sign leptons is required to lie within [76,106] GeV window, the remaining lepton is treated as the one from W decay

- Up to one b-tagged jet with P_T > 30 GeV and $|\eta| < 2.5$
  AntiKt5 jets reconstructed from Particle Flow objects with pileup suppression
  If no b-tagged jets, the highest-P_T jet is considered as b-jet candidate

- $m_T(W)$ > 20 GeV (Additional suppression of Z+jets background)

- No explicit selection on missing E_T but this variable is used in BDT

FCNC in tZ events at CMS: Background estimation

Non-prompt lepton background is estimated from $m_T(W)$ template fit in data:

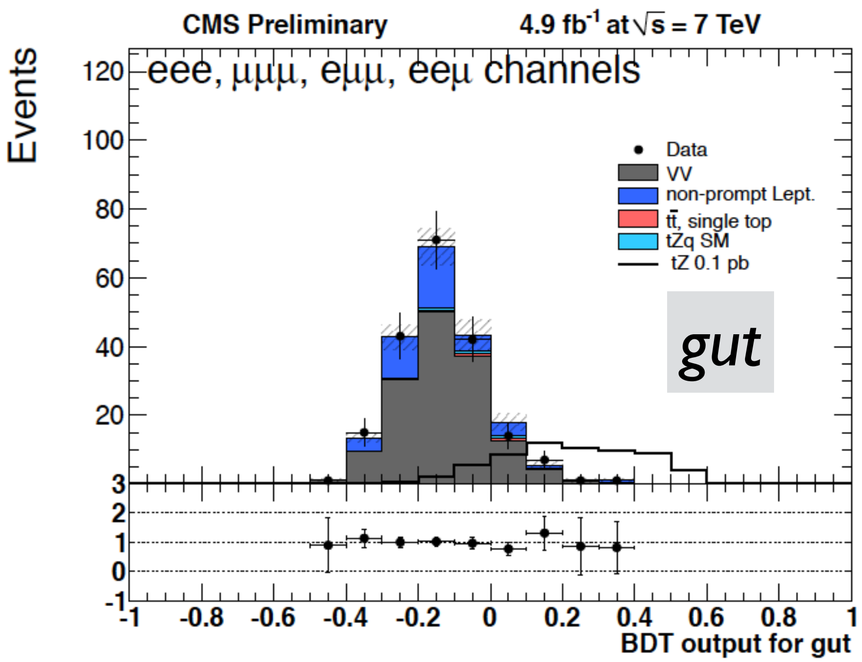
- No b-jet tagging and $m_T(W)$ selection cuts applied
- Three templates:
  Z+jets (from data, non-Z-decay-associated lepton is non-isolated)
  WZ+jets (from MC, also accounts for signal)
  All other processes summed

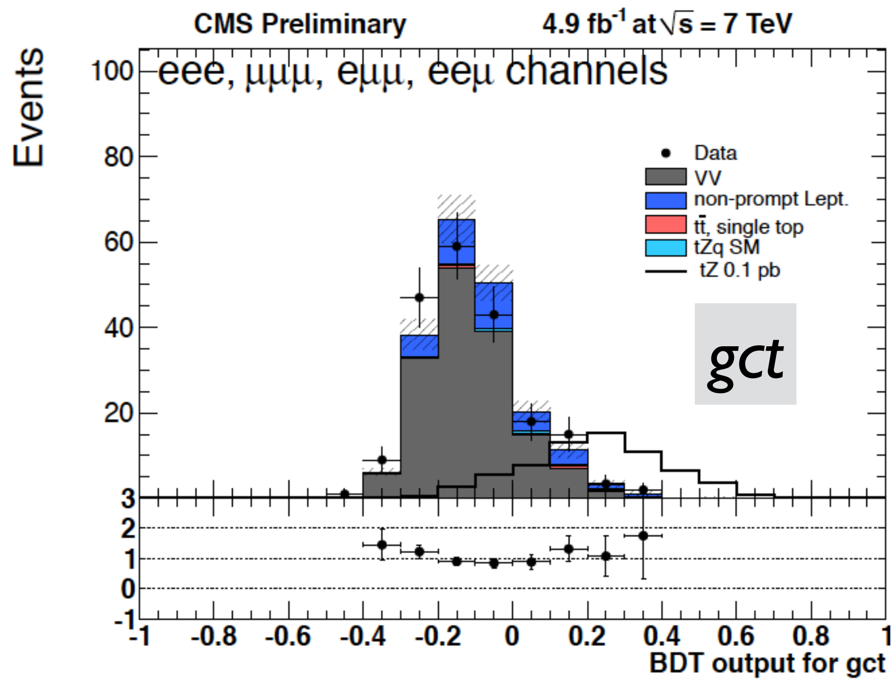
Boosted Decision Tree (BDT) is used to discriminate signal and background events with the following variables:

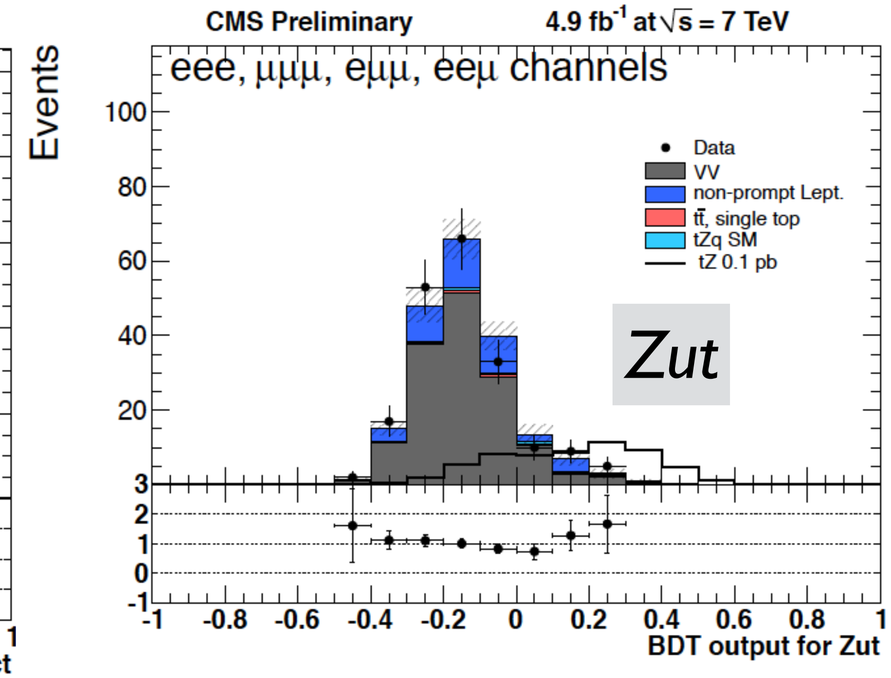
- reconstructed t-quark mass
- $\Delta\phi(\ell_W, b)$, $\Delta\phi(Z, \text{missing } E_T)$, $\Delta\phi(\ell_W, Z)$
- P_T and η of Z candidate
- total and b-tagged jet multiplicities
- CSV b-tagging discriminator
- charge and η of W candidate
- η of the leading jet
- …

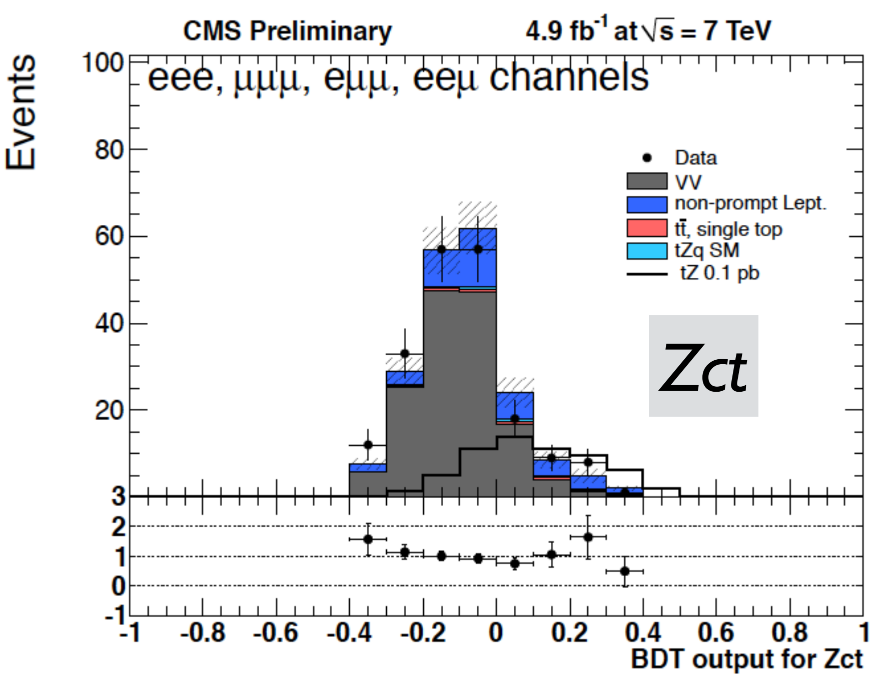
BDT is trained on WZ+jets and signal events

FCNC in tZ events at CMS: BDT results





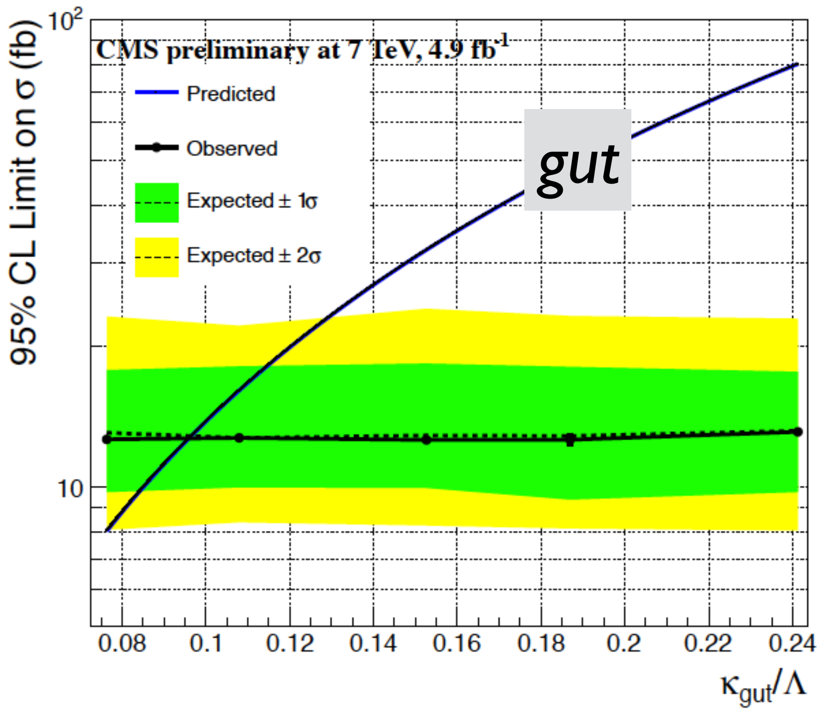


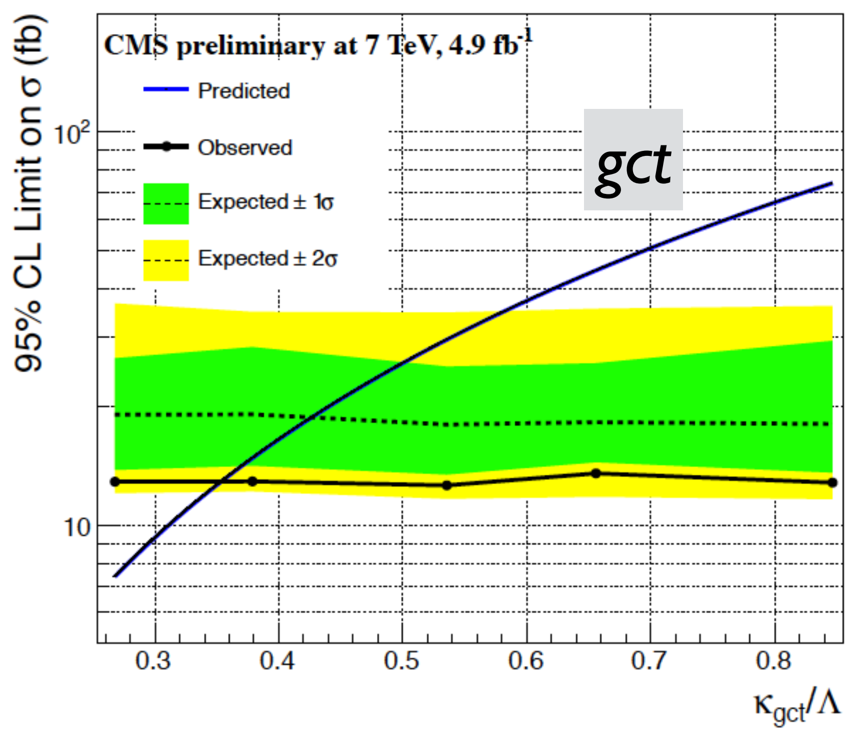


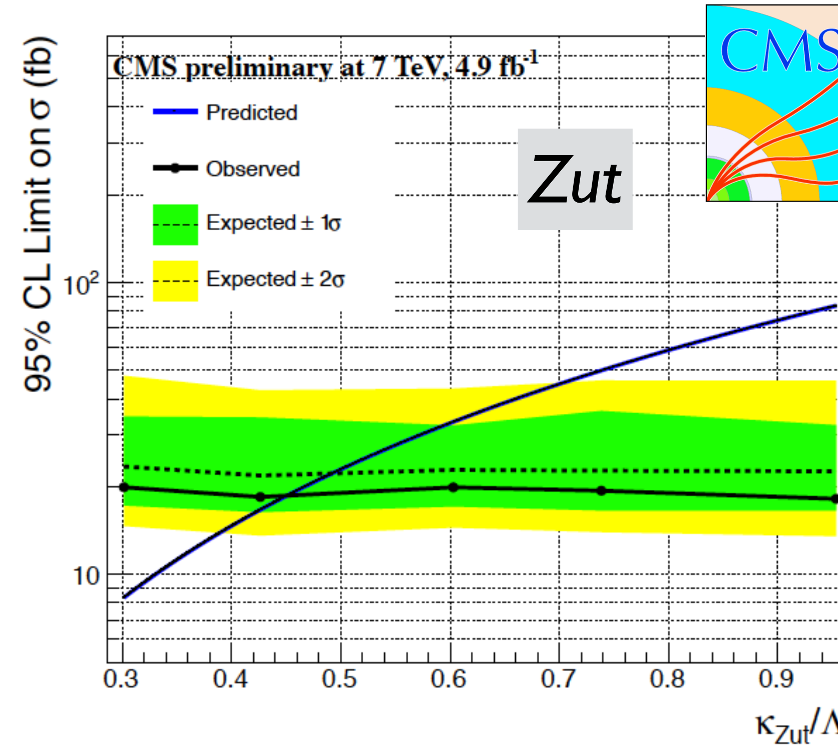
Cut	signal (0.1 pb)	$t\bar{t}$	SingleTop	DY
lepton selection	98.6 ± 3.6	12.0 ± 0.5	0.9 ± 0.3	233.0 ± 12.8
Z mass cut	89.7 ± 3.5	3.8 ± 0.3	0.4 ± 0.2	187.8 ± 8.2
jet multiplicity	78.6 ± 3.3	3.5 ± 0.3	0.3 ± 0.2	55.6 ± 4.5
b-jet multiplicity	73.8 ± 3.2	3.1 ± 0.3	0.3 ± 0.2	55.6 ± 4.5
m_T^W	62.4 ± 2.9	2.8 ± 0.2	0.2 ± 0.2	40.2 ± 3.8

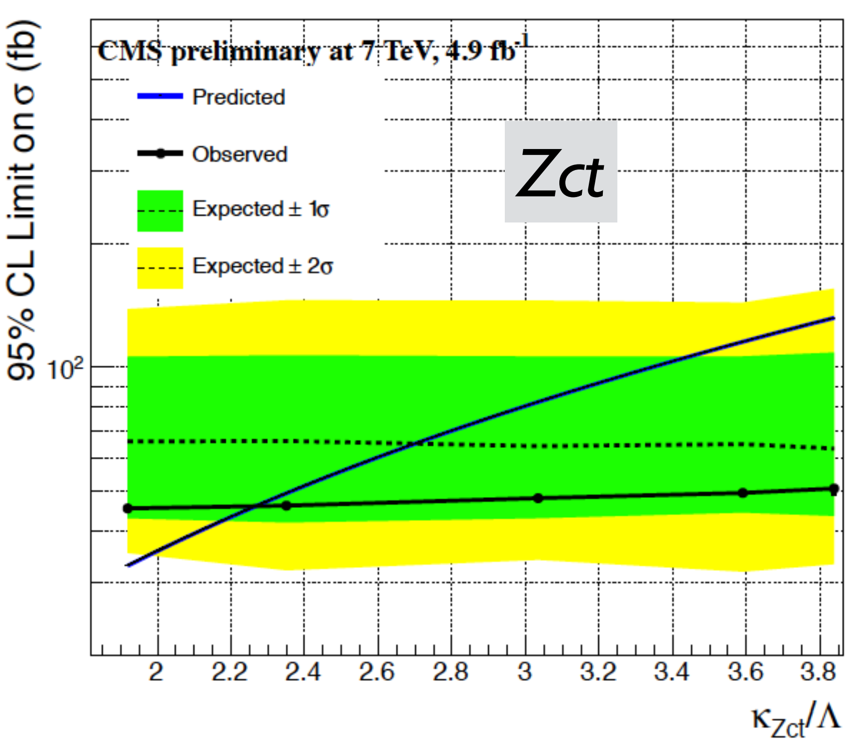
Cut	Diboson	tZq	total Background	Data
lepton selection	775.9 ± 2.2	5.0 ± 0.2	1026.7 ± 13.0	891.0 ± 29.8
Z mass cut	471.1 ± 2.1	4.4 ± 0.2	667.6 ± 8.4	667.0 ± 25.8
jet multiplicity	197.6 ± 1.4	4.4 ± 0.2	261.4 ± 4.7	245.0 ± 15.7
b-jet multiplicity	179.3 ± 1.3	3.1 ± 0.1	241.5 ± 4.7	231.0 ± 15.2
m_T^W	157.1 ± 1.3	2.8 ± 0.1	203.2 ± 4.0	195.0 ± 14.0

FCNC in tZ events at CMS: Upper limits









95% CL upper limits are computed with profile likelihood ratio (PLR) method using Theta

couplings	Expected	Observed	$\mathcal{B}(t \to gq/Zq)$
κ_{gut}/Λ	0.096	0.096	0.56 %
κ_{gct}/Λ	0.427	0.354	7.12 %
κ_{Zut}/Λ	0.492	0.451	0.51 %
κ_{Zct}/Λ	2.701	2.267	11.40 %

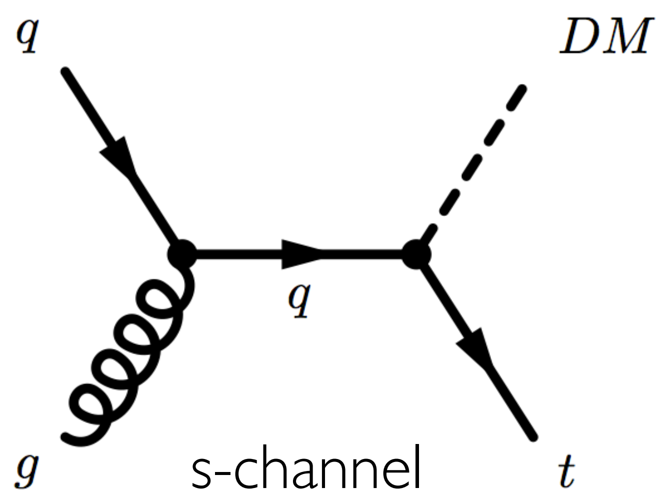
Best limit for Br(t→Zq) !

$$Br(t \to gq/Zq) = \frac{\Gamma_{t\to gq/t\to Zq}}{\Gamma_{t\to gq/t\to Zq} + \Gamma_{top}}$$

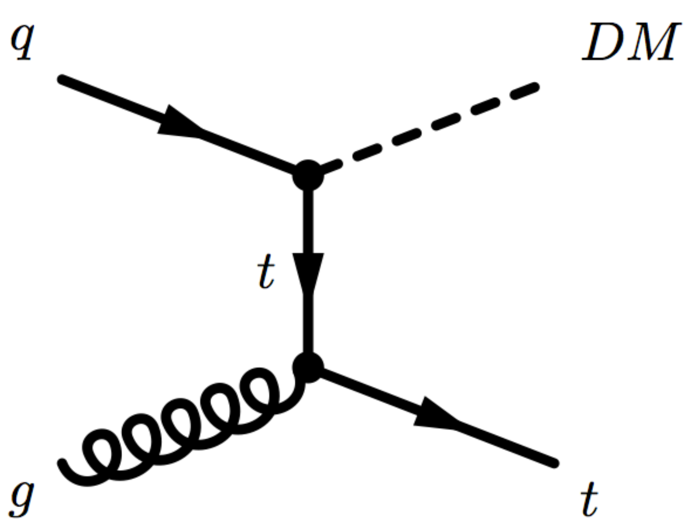
Monotop search at CMS: Overview

New Result !

CMS PAS B2G-12-022



s-channel



t-channel

20/fb at 8 TeV

Contributions from: IPHC

Process:

qg→t+V(S)→bqq+V(S)

Signature:

large ETmiss + two jets
+ one b-tagged jet

Main background:

ttbar
W+jets
QCD multijet
Z(Z→νν)+3j

Discriminant:

Invariant mass of
three jets

signal cross-sections

Mass (GeV)	$\sigma \times BR(t \to 3j)$(pb)	
	scalar DM	vector DM
1	6.320	184590
50	5.072	110.0
100	3.406	36.36
150	2.227	19.29
200	1.447	9.357
300	0.624	3.215
400	0.290	1.304
500	0.149	0.607
600	0.079	0.298
700	—	0.158
800	—	0.087
900	—	0.050
1000	—	0.030

coupling constants are set at 0.1

Probing new couplings
with new scalar and
vector fields

Monotop search at CMS: Selection criteria

- Two jets with P_T > 60 GeV and one jet with P_T > 40 GeV, $|\eta|$ < 2.4
  AntiKt5 jets reconstructed from Particle Flow objects with pileup suppression
- Invariant mass of three leading jets has to be less than 250 GeV
- Events with additional jets with P_T > 35 GeV are rejected
- One of the jets is required to be b-tagged by CSV algorithm
- Events with isolated electrons (P_T > 20 GeV) or muons (P_T > 10 GeV) are rejected (relative isolation of 0.2 in ΔR < 0.3 for electrons and ΔR < 0.4 for muons)
- Missing E_T > 350 GeV (optimised on best expected limit)

Monotop search at CMS: Background estimation

Z+jets background

observed number of events

non-Drell-Yan number of events from MC

$$N(Z \to \nu\nu) = \frac{N^{obs}(\mu\mu) - N^{MC}(non - Z)}{A \times \epsilon(\mu\mu)} \cdot \frac{BR(Z \to \nu\nu)}{BR(Z \to \mu\mu)}$$

W+jets background

observed number of events

non-W number of events from MC

$$N(W \to lost\ \ell\nu) = \frac{N^{obs}(\mu) - N^{MC}(non - W)}{A \times \epsilon(\mu)} \cdot \sum_{\ell=e,\mu,\tau} \frac{BR(W \to \ell\nu)}{BR(W \to \mu\nu)}\, p(lost\ \ell)$$

probability for a lepton to pass loose lepton veto (for tau: hadronic tau to pass jet selection)

Monotop search at CMS: QCD background

Likelihood approach

$$\begin{cases} N^{0b} = p^{0b}_{sig} \cdot N_{sig} + p^{0b}_{QCD} \cdot N_{QCD} + N^{0b}_{other\ bg} \\ N^{1b} = p^{1b}_{sig} \cdot N_{sig} + p^{1b}_{QCD} \cdot N_{QCD} + N^{1b}_{other\ bg} \end{cases}$$

tagging probabilities

contribution from non-QCD background

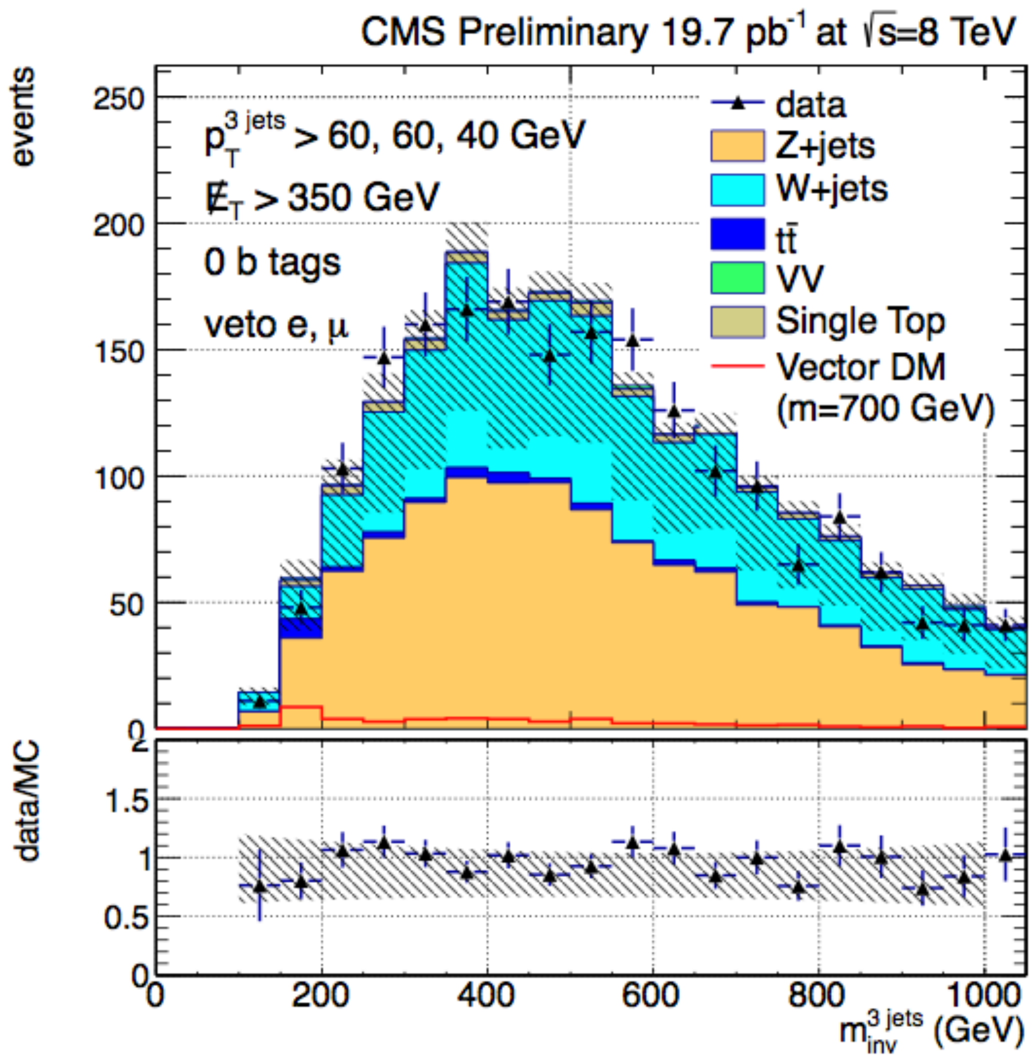
$$\mathcal{L}_{\mathrm{S+B}}(\sigma_{sig}, \nu) = Poisson\left(N^{0b}_{observed} | N^{0b}\right) \times Poisson\left(N^{1b}_{observed} | N^{1b}\right)$$

systematic uncertainties are treated as nuisance parameters

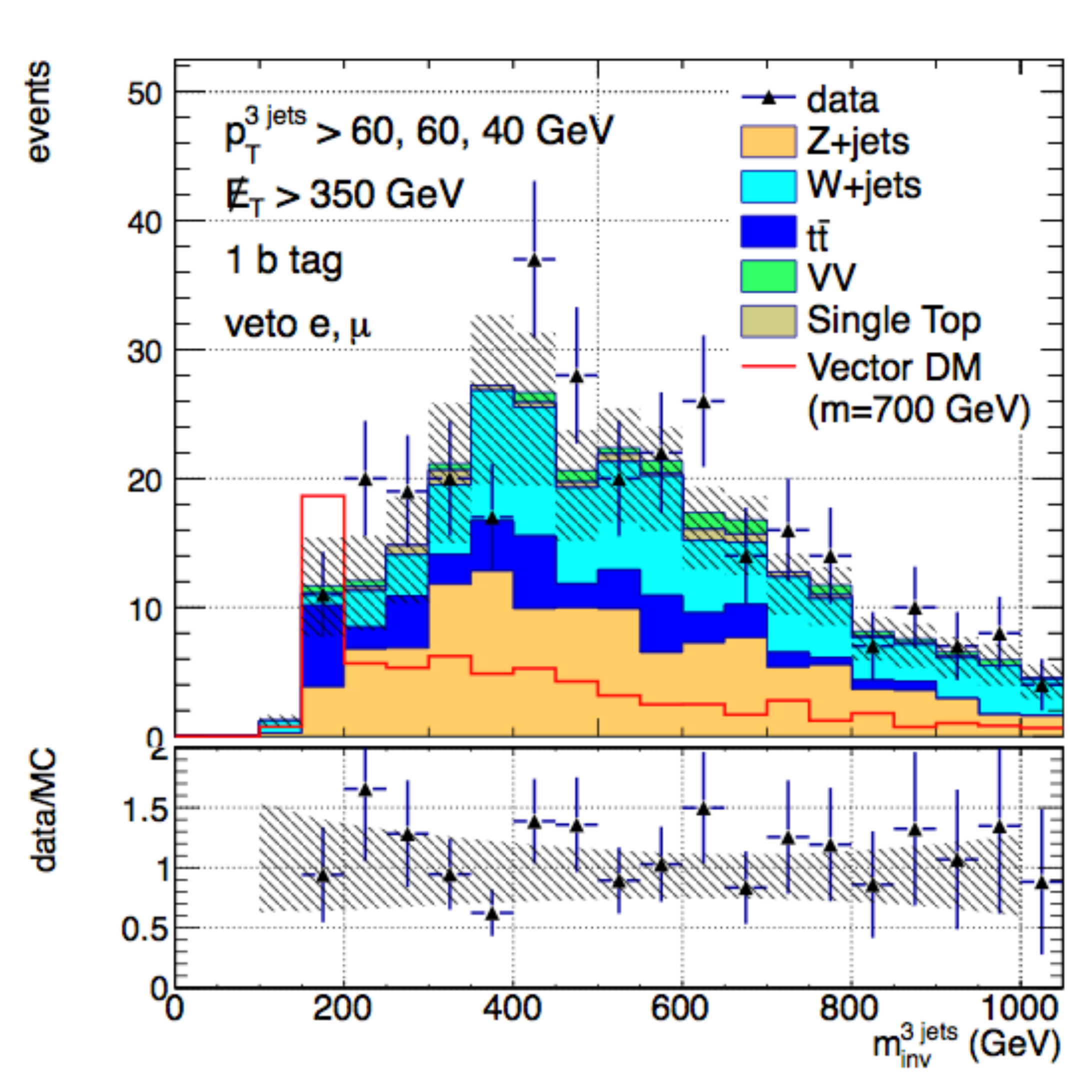
Parameter	p^{0b}_{QCD}	p^{1b}_{QCD}	p^{0b}_{sig}	p^{1b}_{sig}
Value	0.80	0.18	0.32	0.56
Uncertainty	0.03	0.03	0.05	0.05

Result QCD background prediction in the signal region is negligible

Monotop search at CMS: Results



0 b-tag jets



1 b-tag jet

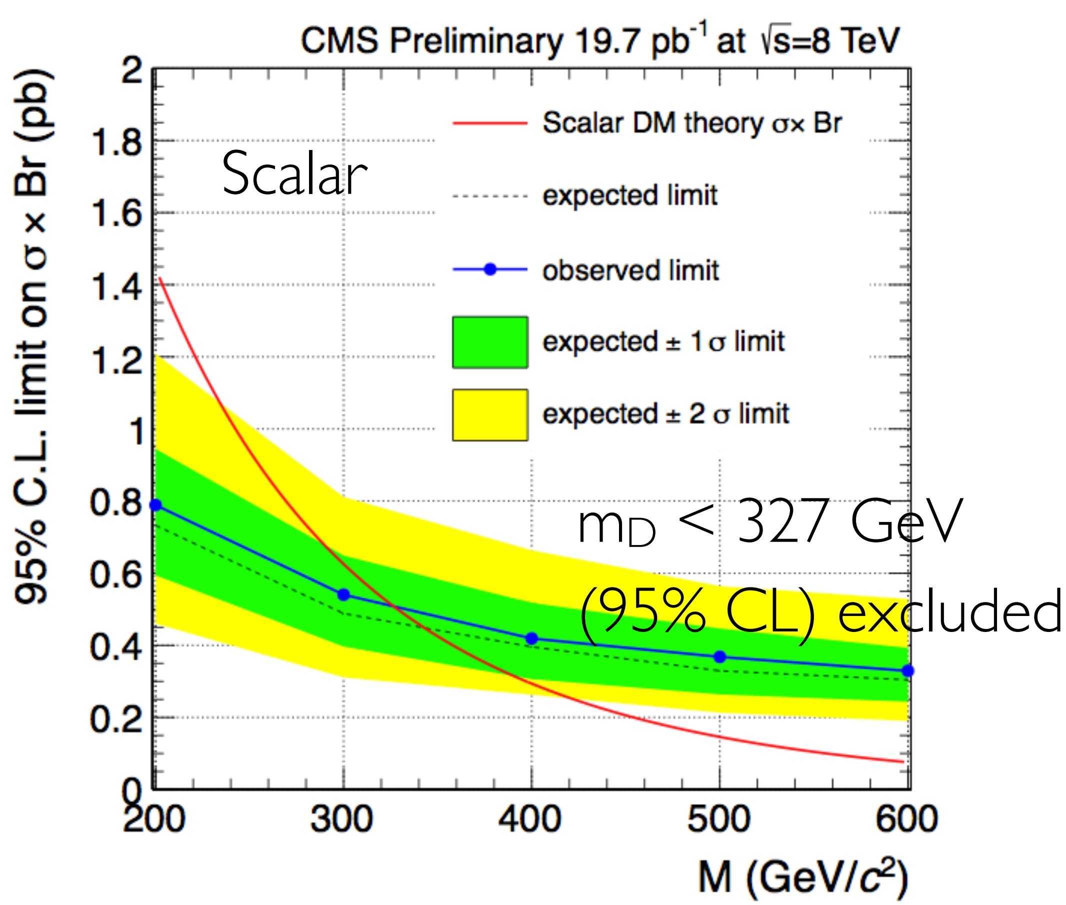
# of b tags	$Z \rightarrow \nu\nu$+jets	W+jets	$t\bar{t}$	Single top	VV	Sum	Data
zero b tags	103±34	18±12	5.9±4.5	2±0.5	5±0.4	134±36	143
one b tag	11±11	2.6±2.2	12±12	1±0.6	0±0	27±16	30

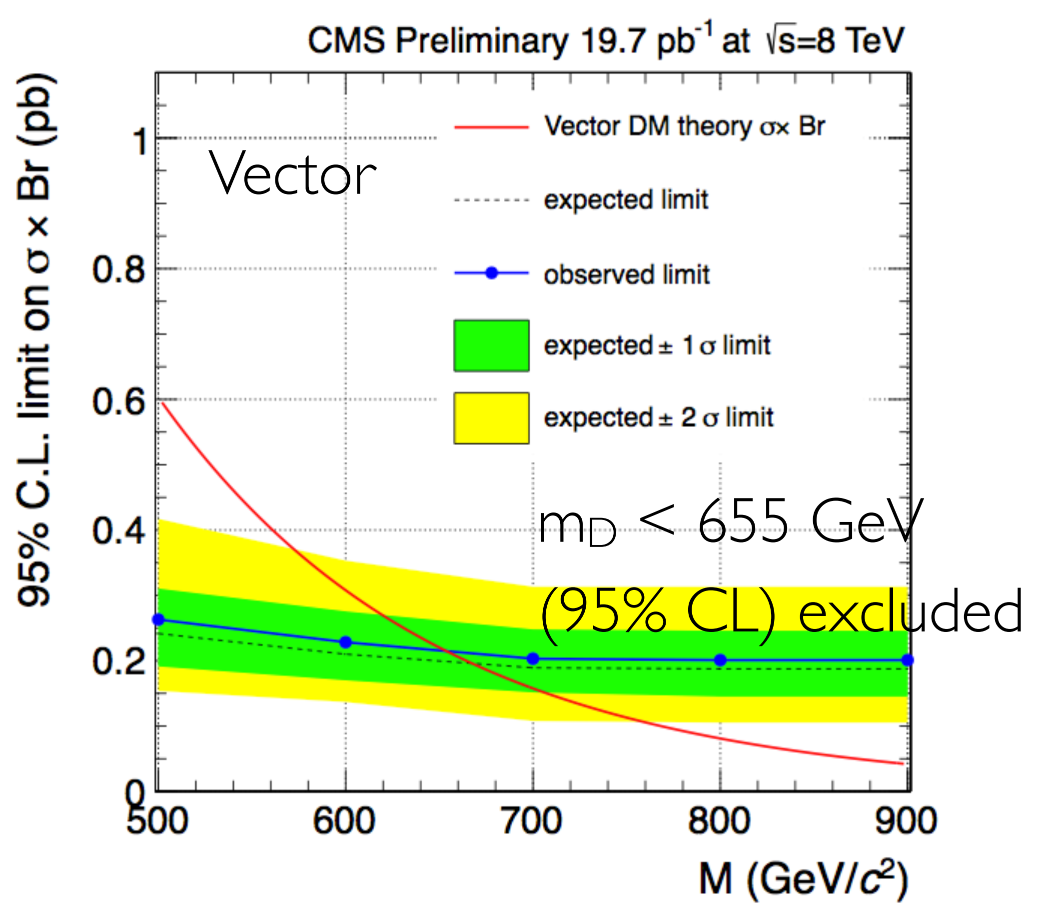
Monotop search at CMS: Results

# of b tags	Zero CSVm b tag	One CSVm b tag
$t\bar{t}$	$6\pm0\pm5$	$12\pm0\pm12$
W+jets	$18\pm9\pm7$	$3\pm1\pm2$
Z+jets	$103\pm33\pm9$	$11\pm10\pm1$
Single top	$2\pm1\pm1$	$1\pm1\pm1$
VV	$5\pm0\pm0$	$0\pm0\pm0$
QCD	6	1
sum	140 ± 36	28 ± 16
Data	143	30

No significant excess above the SM expectation is found

95% CL exclusion limits are computed with CLs (RooStats)





Conclusion

- The study of FCNC processes is important for precise tests of the SM as well as probing new physics
- With the LHC experiments the most stringent limits on the processes with FCNC anomalous couplings in single top production have been set
- Anticipating new results soon on monotop search (Clermont-Ferrand, ATLAS) and FCNC tZ at 8 TeV (IPHC, CMS)
- Run II would improve the sensitivity to FCNC even further

Eur.Phys.J. C57 (2008) 183-308