Search for associated production of a Z boson with a single top quark and for tZ flavour-changing interactions in pp collisions at √s = 8 TeV

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Second China LHC Physics workshop, 16-19 Dec 2016, Beijing, China.

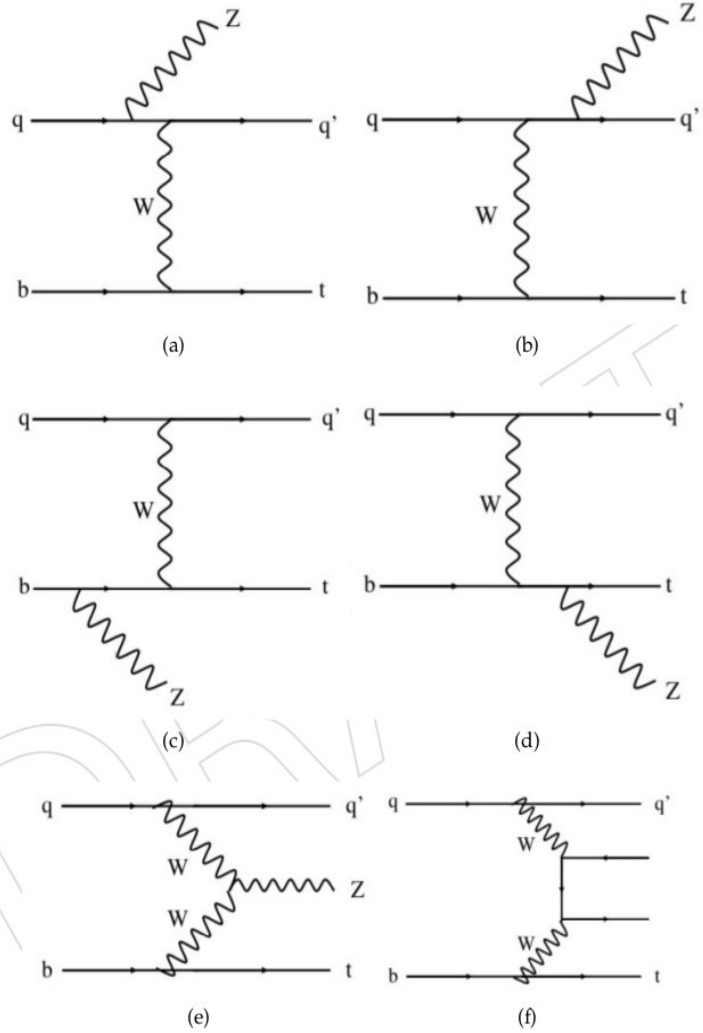
Introduction

- Top quark, massive particle in SM.
- At hadron colliders top quarks arise predominantly from the production of top quark-antiquark(tt) pairs through the strong interaction.
- May also produce singly through the electroweak process categorized as t-channel, s-channel and associated tW.
- At the CERN LHC, the t- and tW channel production have been observed and studied by the ATLAS and CMS collaborations. [PhysRevD.90.112006, PhysRevLett.107.091802]
- The high luminosity and centre-of-mass energy at the LHC motivate the search for rare SM single top quark production processes, such as the production of a single top quark in association with a Z boson and thus provides ground for the test of the SM.
- A search for tZq-SM production and a search for tZ-FCNC production from
- anomalous couplings.
- Any flavour-changing neutral current (FCNC) involving the top quark and the Z boson is forbidden at tree level and is suppressed at higher orders in SM.
- Some SM extensions, such as R-parity violating supersymmetric models(1), top-colour assisted technicolour models(2) and singlet quark models(3) predict enhancements of the FCNC branching fraction.
  [PhysRevD.58.055001,(2)PhysRevD.68.015002 (3)Phys.Rev.D69(2004)099901]

tZq-SM Production

Via t-channel and radiated Z

- Predominantly occurs when t channel radiates a Z boson, but also includes 3 gauge coupling between W and Z
- $\sigma(tZq) = 160^{+7}_{-2}(\text{scale})^{+11}_{-11}(\text{PDF})$ fb
- $\sigma(tZq) = 76^{+4}_{-1}(\text{scale})^{+5}_{-5}(\text{PDF})$ fb
- Phys.Rev.D: 87(2013)11406
- $\sigma(tl^+l^-q) = 8.2^{+0.59}_{-0.03}(\text{scale})$ fb
- based on leptonic top decay, and $m_{ll} > 50$ GeV using MC@NLO
- Search for associated production of a single top quark with a Z boson, with one recoiling quark
  - Search conducted in tri-lepton final state



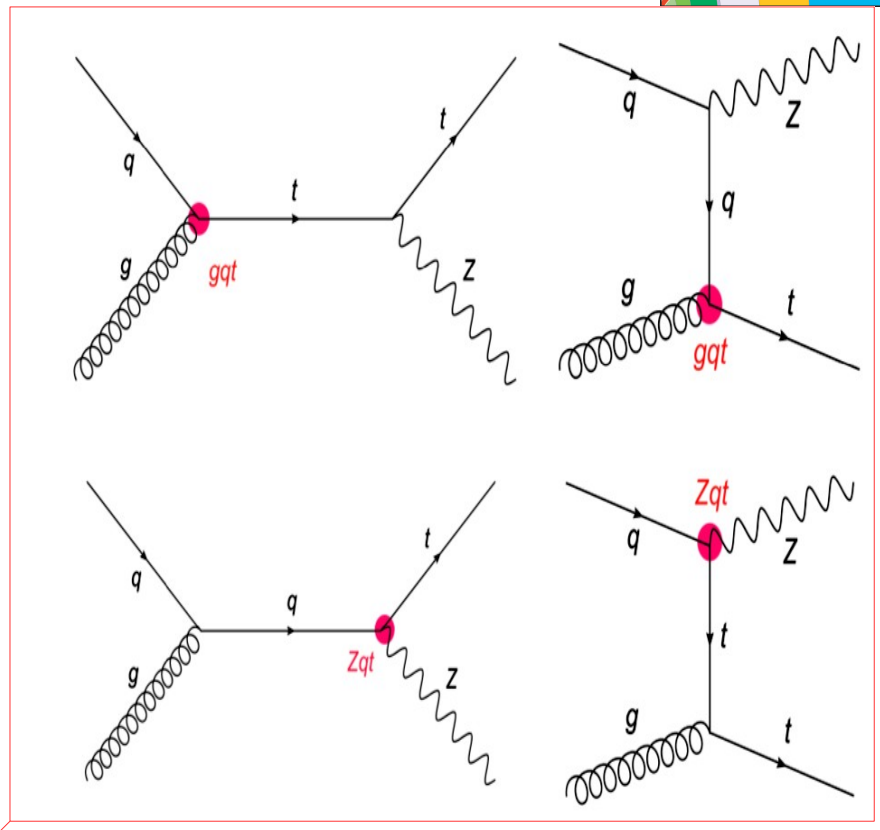
Includes coupling of W to a Z boson or ll pair

TZ-FCNC production

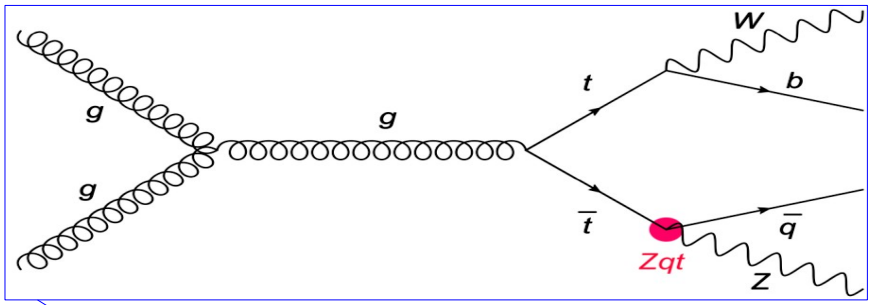
- The search for tZ-FCNC is performed by combining the single top quark and tt production modes.
- tZ-FCNC processes can be produced both via strong ggt and weak Zqt couplings.
- SM Lagrangian using effective operators.

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

- The interference between single top quark and tt-FCNC processes is neglected



production of tZ in tZ-FCNC channels.



production of tZq in the tt-FCNC channel

Event Topology and Backgrounds

- **Event topology**
  - Three isolated, high-p_T leptons, two of which are consistent with a Z decay (same flavour, opposite sign)
  - A bottom quark jet that arises from the hadronisation of the b quark produced in the top quark decay
  - for tZq-SM production, or for tt-FCNC, there is an additional jet. Thus we will have 2-3 jets in final state.
  - Missing transverse energy (from W decay)
- For tZ-FCNC production, two different signal selections are considered.
- Single-top-quark- FCNC selection: Exactly one b Jet is required
- tt-FCNC selection: At least two jets one which should be b Jet.
- **Backgrounds**
  - Processes with prompt leptons from real W and Z decays
    - ttZ, WZ
  - Processes with nonprompt leptons that fake the W or Z decays
    - tt, Z+jets

Event Selection

- Lepton selection:
  - 3 leptons, 2 consistent with a Z decay
  - Same flavour, oppositely charged, p T > 20 GeV, | η |<2.5(2.4) for electrons(Muons) and 76<m_{ll}<*106*GeV
  - Must be isolated with I_{rel}<0.15(0.12) with a cone size ΔR = 0.3(0.4) for electrons(muons) where $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$
  - Events with additional loose leptons are vetoed
- Jets:
- For the tZ-FCNC: p T > 30 GeV and | η | < 2.4
- For tZq-SM: | η | has been relaxed to 4.7 to increase the signal acceptance.
- Jets Closed to lepton have been removed with ΔR < 0.5.
- Combined secondary vertex algorithm used to identify b jets.
- MET and m_T^W cuts optimized based on expected significance of fit, applied to signal region only.
  - Optimal was to apply no MET cut and m_T^W > 10 GeV for tZq-SM.
  - $\not{E}_T$ > 40 GeV and m_T^W >10GeV for tZ-FCNC
  - Signal region requires 2-3 jets, at least one passing b-tagging where
  - “WZ control region” requires 1 or 2 jets, with no b-tags.

Analysis Strategy

- Baseline selection applied.
- A fit is then applied simultaneously to the signal and WZ control regions to extract the tZq cross section and calculate the significance of the measurement
- To increase the the separation between signal and background
  - BDT discriminant used in the signal region
  - m_T^W distribution used in the control region, chosen for its sensitivity to fake lepton backgrounds
  - BDT_{tZq-SM} is used to discriminate between the tZq-SM signal and the dominating $t\bar{t}Z$ and WZ background processes.
  - For the FCNC searches, the $BDT_{tZ-FCNC}$ and $BDT_{tt-FCNC}$ are used to discriminate FCNC processes from the SM background processes.

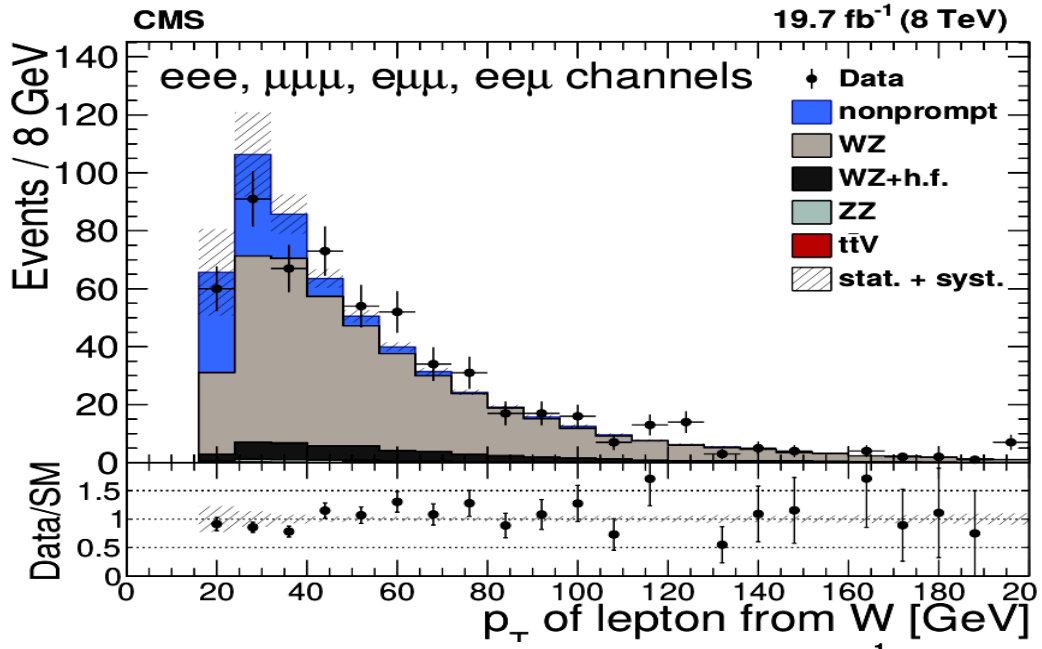
Background Estimation

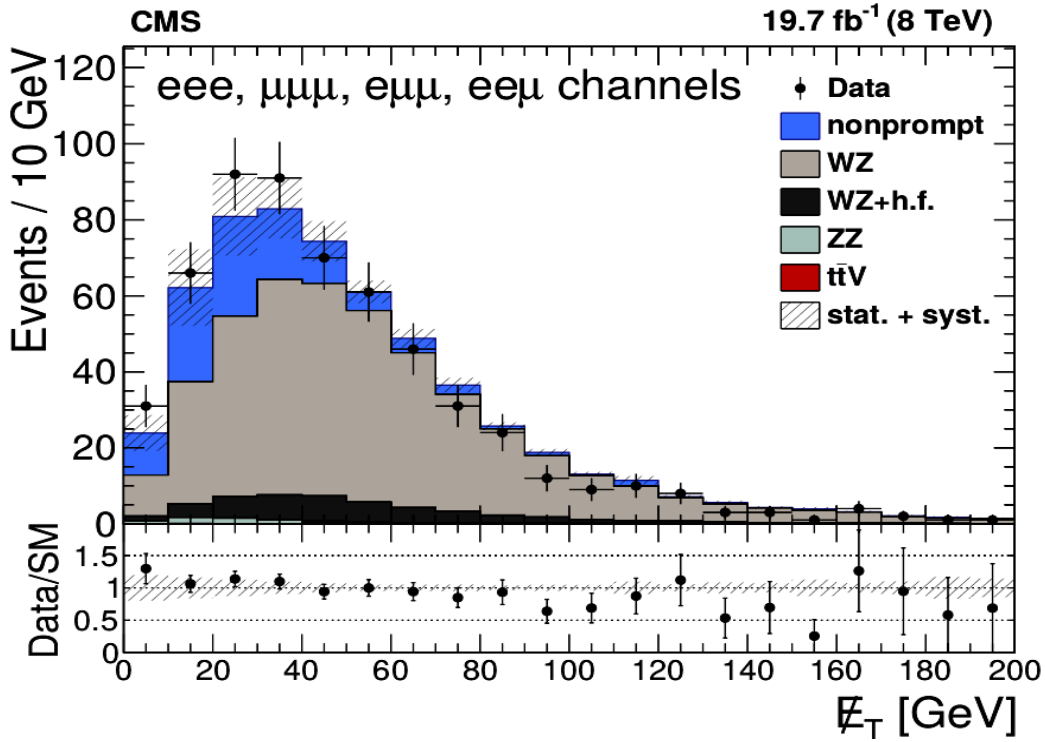
- Data driven methods are used to calculate the WZ normalization and nonprompt lepton backgrounds.
- WZ background is constrained by fitting the m_T^W distribution in the WZ control region

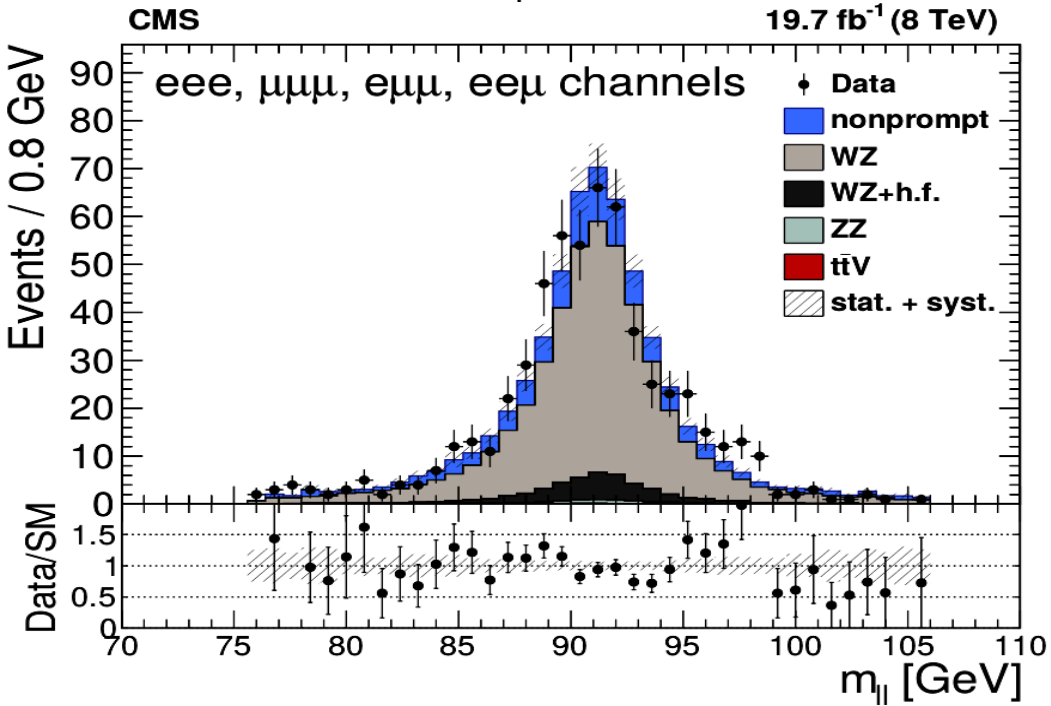
$$m_{T,W} = \sqrt{2 \cdot E_{T,miss} \cdot p_{T,l} \left(1 - \cos(\phi_{E_{T,miss}} - \phi_l)\right)}$$

  - As the flavour composition might not be well modeled in the WZ sample, the sample is split into WZ plus light and heavy (c,b) jet samples with independent normalizations
- Fit templates for prompt lepton backgrounds (i.e. WZ, ttZ, ZZ et al) are taken from simulation
  - ttW found to be negligible
- Templates for the nonprompt lepton backgrounds (Z+jets, tt) are extracted from data by inverting the lepton isolation.

Data/MC comparison in Background Enriched Samples



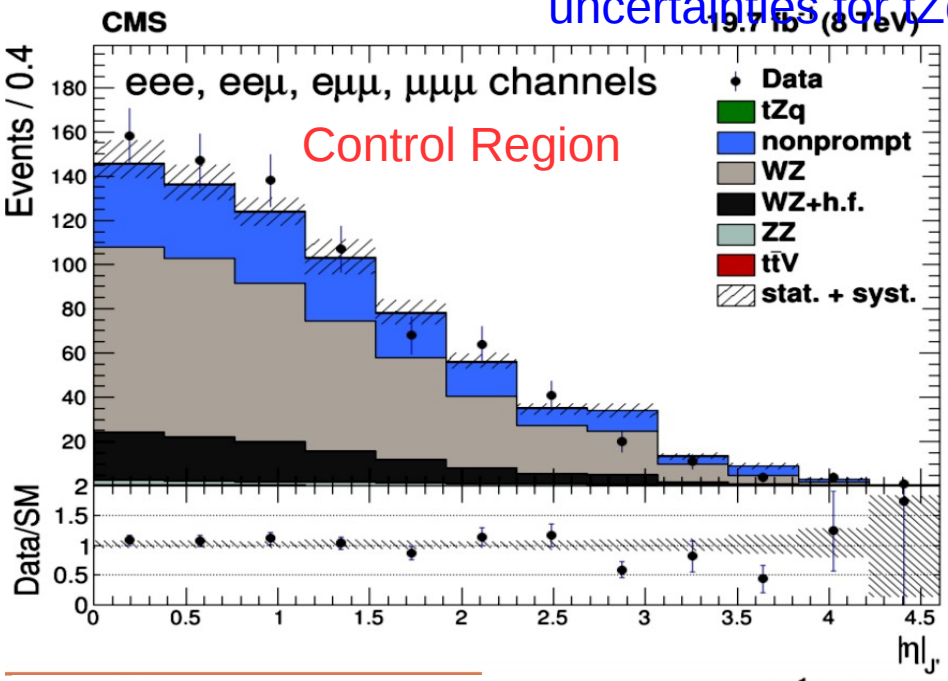


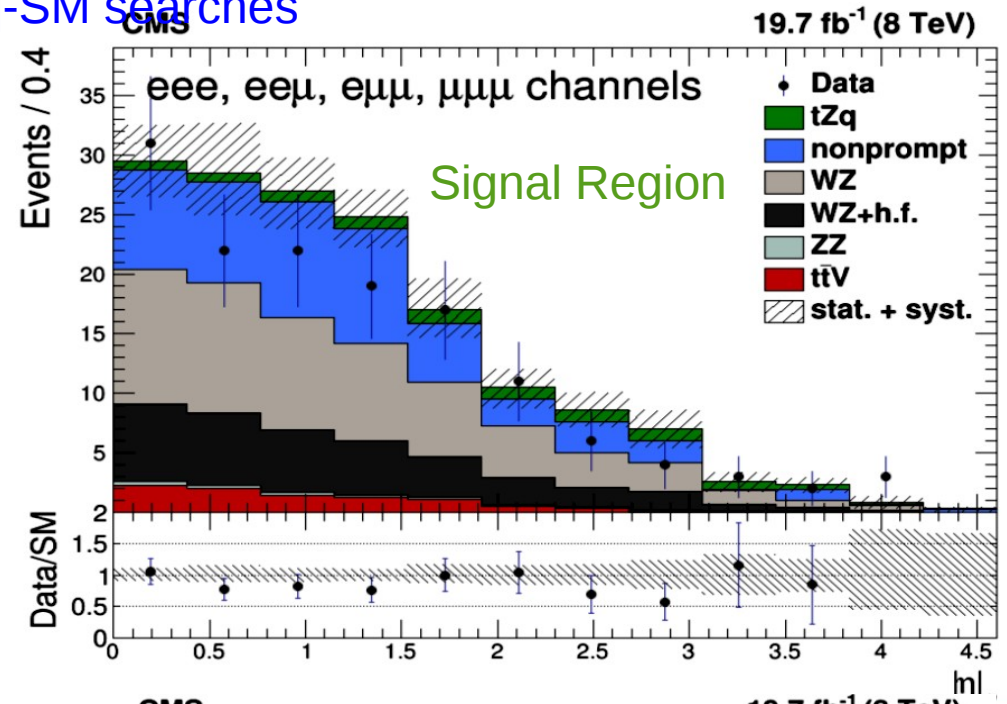


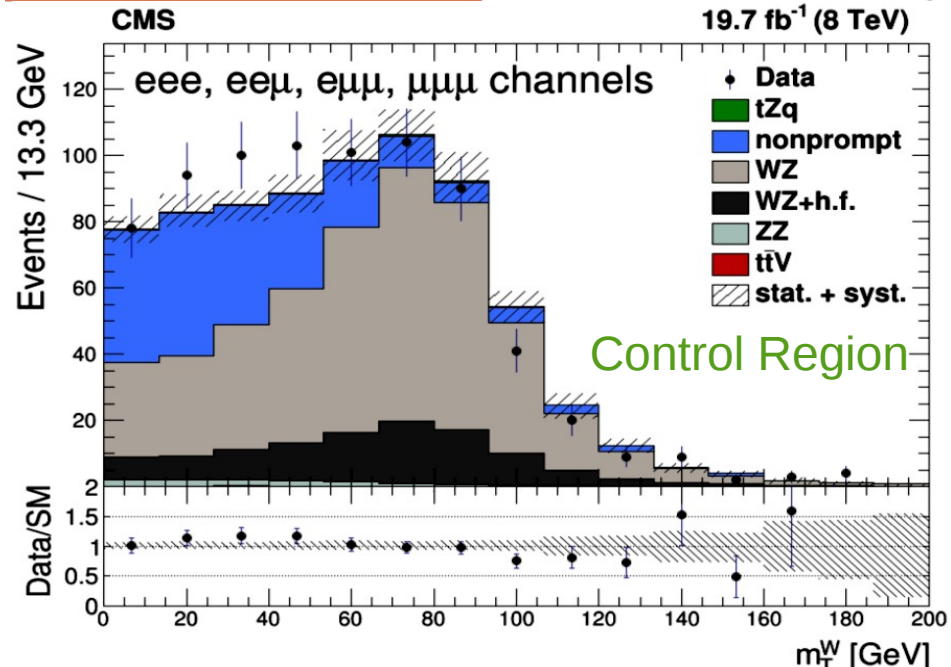
Data-to-prediction comparisons in the background-enriched samples has been shown for tZ-FCNC search where WZ + h.f. denotes WZ + heavy flavour.

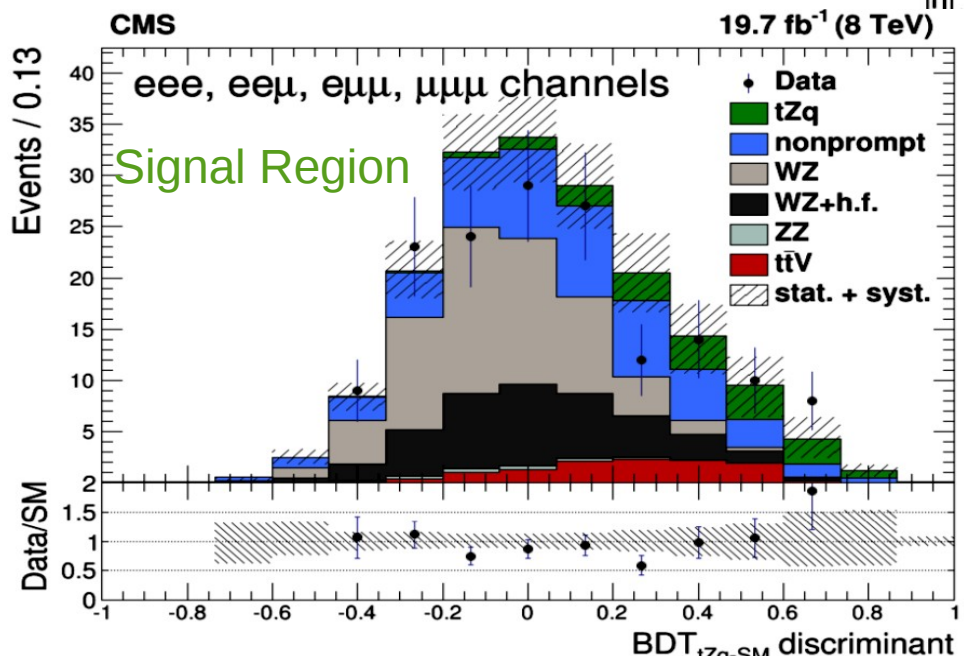
Data-prediction Comparison

The post-fit data-to-prediction comparisons, including the post-fit uncertainties for tZq-SM searches

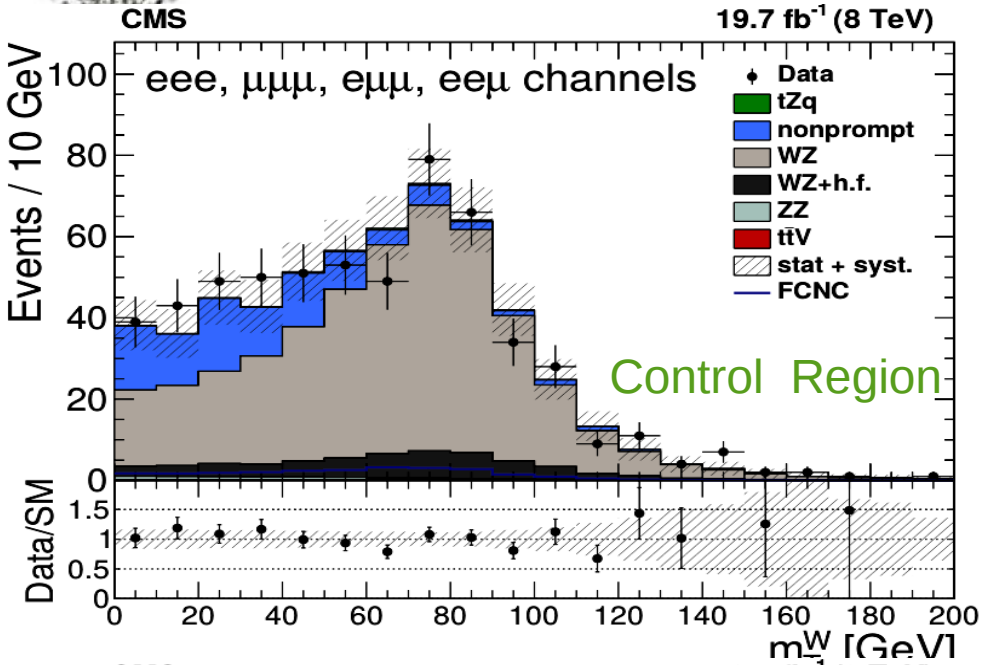


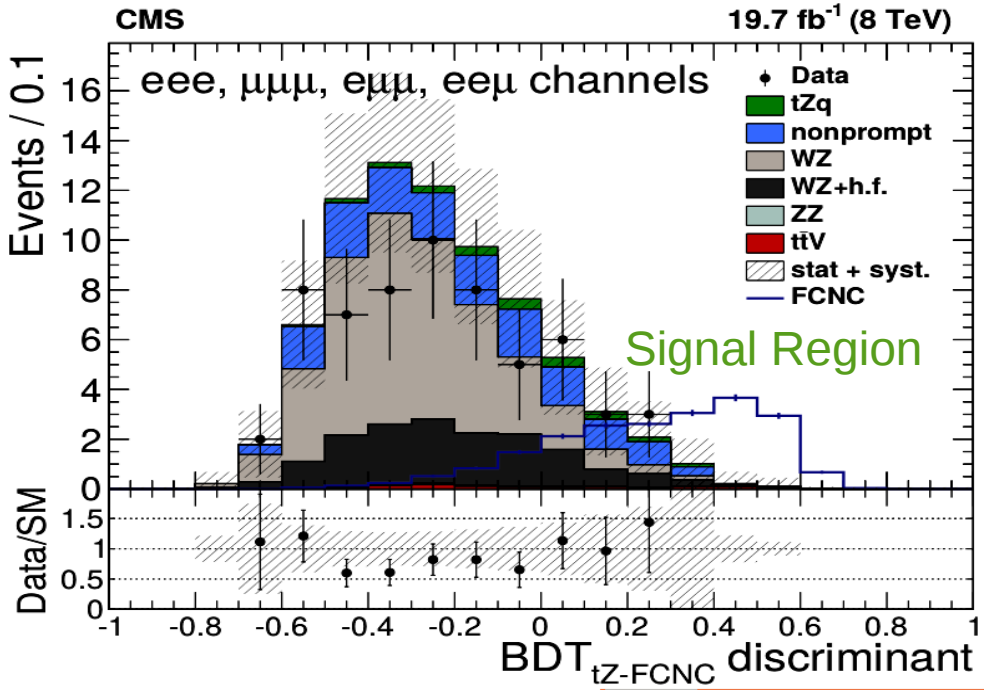


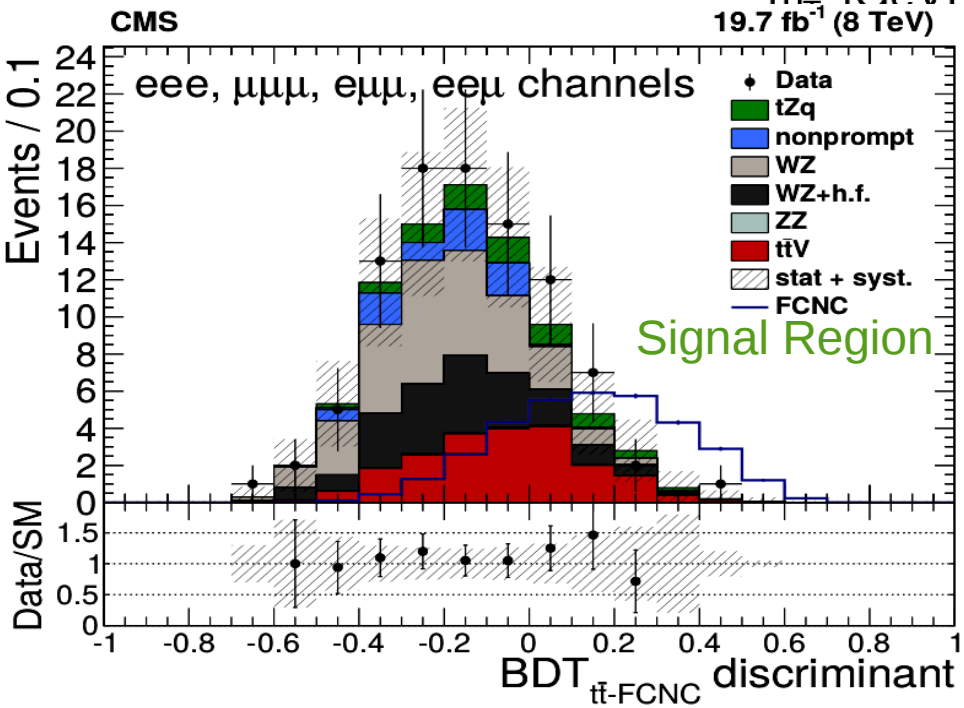




Data-prediction Comparison







Data-to-prediction comparisons for the tZ-FCNC search after performing the fit

Nuisance parameters and uncertainties

- Cross section measurement and significance calculation performed using theta
- Rate and shape changing systematics both accounted for
- Most systematics included as nuisance parameters
- Some externalized: scale, matching, PDF
- Nuisance parameters have 0 prior with 1 uncertainty

Systematic source	Amplitude (%)	Type
Z+jets, $t\bar{t}$	30 %	norm.
Muon fake rate	floating in the fit	norm.
Electron fake rate	floating in the fit	norm.
Z p_T	$\pm 1\sigma$	shape
WZ+l jets norm.	floating in the fit	norm.
WZ+l jets matching	$\pm 1\sigma$	shape
WZ+l jets scale	Q^2 $\times 2, /2$	shape
WZ+hf jets norm.	floating in the fit	norm.
WZ+hf jets matching	$\pm 1\sigma$	shape
WZ+hf jets scale	Q^2 $\times 2, /2$	shape
tZq	30 %	norm.
tZq scale	Q^2 $\times 2, /2$	norm.+shape
ZZ	30%	norm.
single top	30%	norm.
$t\bar{t}$ V	30%	norm.
Trigger (signal+(OB))	$\pm 1\sigma$	norm.
Lept. sel.(signal+(OB))	1%	norm.+shape
JES	$\pm 1\sigma(p_T, \eta)$	norm.+shape
JER	$\pm 1\sigma(p_T, \eta)$	norm.+shape
unc. $\not{E}_T$	$\pm 10\%$	norm.+shape
b-tagging	$\pm 1\sigma(p_T, \eta)$	norm.+shape
pileup	$\pm 1\sigma$	norm.+shape
pdf	$\pm 1\sigma$	norm.+shape
tZ-FCNC scale	Q^2 $\times 2, /2$	norm.+shape
lumi	2.6	norm.

Results

- Combined cross section:
  - $\sigma_{tZq} = 10^{+8}_{-7}$ fb (measured)
  - $\sigma(tl^+l^-q)_{SM} = 8.2^{+0.59}_{-0.03}$(scale) fb
- Observed (expected) significance: 2.4 (1.8)
  - Expected one sigma band: 0.4 – 2.7

BDT-based

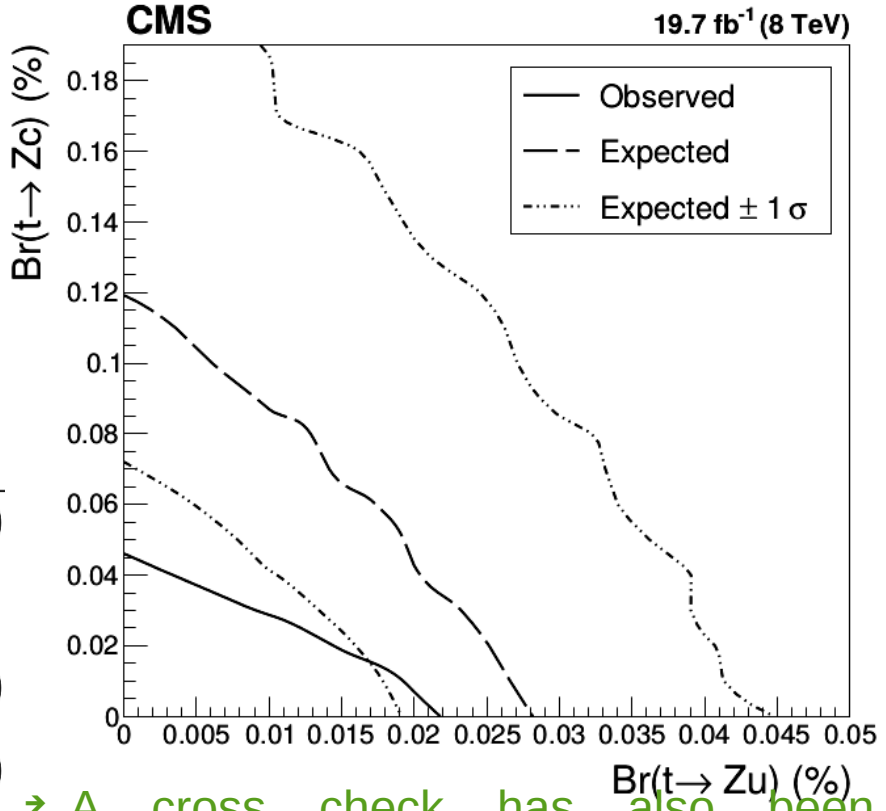
Channel	Cross section (fb)
eee	0^{+9}_{-0}
eeμ	11^{+13}_{-10}
$\mu\mu$e	24^{+19}_{-16}
$\mu\mu\mu$	5^{+9}_{-6}
Combination	10^{+8}_{-7}

counting

Channel	Cross section (fb)
eee	$29^{+32}_{-24}(\text{stat})^{+8}_{-7}(\text{syst})$
eeμ	$6^{+23}_{-6}(\text{stat})^{+4}_{-3}(\text{syst})$
$\mu\mu$e	$19^{+24}_{-18}(\text{stat})^{+5}_{-5}(\text{syst})$
$\mu\mu\mu$	$20^{+19}_{-15}(\text{stat})^{+4}_{-3}(\text{syst})$
Combination	$18^{+11}_{-9}(\text{stat})^{+4}_{-4}(\text{syst})$

limits on the branching fraction of the tZ-FCNC couplings

Branching fraction	Expected	1σ range	2σ range	Observed
$\mathcal{B}$(t→ Zu) (%)	0.027	0.018–0.042	0.014–0.065	0.022
$\mathcal{B}$(t→ Zc) (%)	0.118	0.071–0.222	0.049–0.484	0.049



- A cross check has also been perfomed using counting experiment for tZq-SM searches with I_{rel}<0.1, and a tighter m_{ll} selection, 78–102 GeV.
- WZ background is estimated by counting the number of events in a region enriched in WZ events, defined by inverting the b tagging requirements.

Conclusion

- A search for the associated production of a top quark and a Z boson, as predicted by the standard model (SM) was performed with the full CMS 8 TeV data set.
- A moderate excess of events over the background was observed.
- tZq cross section was measured to be 10^{+8}_{-7} fb, in good agreement with the SM expectation.
- The corresponding observed and expected significances are 2.4 and 1.8 standard deviations, respectively.
- A search for tZ production produced via flavour-changing neutral current (FCNC) interactions has also been performed(single-top-quark or tt production modes).
- Standard model tZq process was considered as a background.
- No evidence for tZ-FCNC interactions is found and limits at 95% confidence limit are set on the branching fraction for the decay of a top quark into a Z boson and a quark.
- Improve the previous limits set by the CMS Collaboration by about a factor of two.[Phys. Rev. Lett. 112 (2014) 171802]

BACKUP