Search for the associated production of a single top quark with a Z boson in pp collisions at 8TeV

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Introduction

- Top quarks arise predominantly from top-antitop pair production (ttbar production) via strong interaction.
- They are also produced singly from EW processes (single top production) through three different production mechanisms, categorised by the virtuality of the W boson involved:
  - t-Channel
  - s-Channel
  - tW associated production

- Increasing luminosity and COM energy at LHC motivate the search for rare SM single top production, such as the production of a single top in association with a Z boson.
  - Standard Model tZq production (tZq-SM)
  - Flavour changing neutral current (FCNC) production (tZ-FCNC) subdivided into
    - single top FCNC
    - ttbar FCNC
tZq production within the SM

- Predominantly occurs when the Z boson is radiated off one of the quark lines in the t-channel (sensitive to tZ-coupling).

- It is also related to the WZ production by crossing, therefore also sensitive to the WWZ coupling.

- The observation of tZq-SM production and the subsequent measurement of the production cross-section represent an important test of the SM.

- Search for tZq-SM using two complementary approaches that cross-check each other:
  - Shape analysis using a boosted decision tree (BDT).
  - Simple and robust cut and count analysis.
FCNC tZ production

- Flavour changing neutral currents are processes in which the flavour of the fermion changes while its electrical charge is not altered.

- Within the SM, the FCNC of the top quark to the Z boson is forbidden at tree level and is suppressed at higher orders because of the GIM mechanism.

- Some extensions to the SM predict enhancements of the FCNC branching fractions. tZ searches are sensitive to \( tZq \) and \( tgg \) anomalous couplings (\( tZq \)-SM irreducible background).

**Production modes**

- **Single top FCNC**: pp\( \rightarrow tZ \)
- **ttbar-FCNC**: ttbar production via SM, but with one \( t \rightarrow Zq \)

\( tZ \)-FCNC search consists on a shape analysis using a BDT (shared tools and strategy with \( tZq \)-SM shape analysis).
skip this slide and say something like CMS is really cool and blah blah, but google has enough information

REMEMBER TO REMOVE THIS SLIDE
Event topology and backgrounds

Two different channels, depending on the decay of the W boson coming from the top quark:

- **Di-lepton channel**: hadronic decay of the top quark (t -> W(qq)b)
- **Tri-lepton channel**: leptonic decay of the top quark (t -> W(lnu)b)

Analyses are conducted **only in the trilepton final state at 8TeV** (dilepton search addressed only at 13TeV)

- Smaller branching ratio, but clearer signal.

**Event topology**

- Three isolated high p_T leptons, two of them compatible with coming from a Z boson (OSSF)
- Two or three jets, at least one of them originating from a b-quark.
- Missing transverse energy.
Event topology and backgrounds

**Backgrounds**

- Processes with prompt leptons originating from a W or a Z:
  - ttZ
  - WZ
  - (tZq-SM for FCNC search)
- Processes with non-prompt (fake) leptons that pass the **tight selection criteria**:
  - ttbar
  - DY(Z) + jets

*Set of cuts applied on selected leptons (kinematic requirements, isolation, etc).*
Analysis strategy and background estimation

- **Baseline selection** is applied.
- A **fit** is then applied simultaneously to the **signal region** and the **WZ (background enriched) control region**, in order to extract the tZq cross section and calculate the significance of the measurement:
  - **BDT discriminant** in the signal region
  - **Transverse mass of the W boson (MTW)** in the control region (high sensitivity to fake lepton background)

\[ m_{T,W} = \sqrt{2 \cdot E_{T, \text{miss}} \cdot p_{T, \text{lepton}} (1 - \cos(\phi_{\text{MET}} - \phi_{\text{lepton}}))} \]

- Peaks at around W mass for leptons and MET from a W boson
- For non-prompt lepton backgrounds in maximum close to zero
A BDT is used in the signal region to discriminate
  - tZq-SM search: tZq-SM events from the dominant main backgrounds (ttZ, WZ)
  - tZ-FCNC search: tZ-FCNC from tZq-SM

A set of input variables is selected based on their discriminating power.

The output discriminant distribution is then fitted to determine whether there are any signal events present in the data.

Prior to the fitting, the templates for each background process are scaled to the predicted SM cross section and integrated luminosity of the data sample used for the analysis.
Systematic uncertainties

- **Luminosity measurement**: experimental uncertainty of ±2.6%

- **Pile-up estimation**: the uncertainty in the average number of additional interactions per bunch crossing is ±5%

- **Lepton trigger, reconstruction and identification efficiency**:
  - A set of data to MC scale factors (SF) are applied to ensure that the efficiencies observed in data are correctly reproduced in the simulation, these are varied by their corresponding uncertainties
  - 4% uncertainty for lepton trigger SFs
  - 2% uncertainty for lepton reconstruction and identification SFs
Systematic uncertainties

- **Jet energy scale (JES), resolution (JER) and missing $E_T$**
  - jets 4-momenta are varied by the uncertainties associated to the jet energy scale and resolution (this also affects MET measurement)
  - contribution to MET that does not come from leptons, photons or jets is varied by ±10%

- **B-tagging**
  - b-tagging and misidentification efficiencies estimated using control samples
  - the SF thus obtained are varied by their corresponding uncertainties

- **Background normalisation**
  - non-prompt processes and WZ: estimated from data during final fit
  - backgrounds estimated from simulation: uncertainty taken to be ±30%
Systematic uncertainties

- **Z boson \( p_T \)**
  - uncertainty coming from Z boson \( p_T \) reweighting
  - accounted by applying twice, or not applying, the reweighting

- **Physics process modelling**
  - renormalisation and factorization scales are multiplied or divided by a factor 2

- **Parton Distribution Function (PDF) choice**
  - all simulated events are reweighted by each of the associated eigenvalues of the PDF set

- **Simulated event size**

For each source of systematic (\( u \)), a nuisance parameter (\( \theta_u \)) is introduced in the fit.
Results

Search for $tZq$-SM production

Shape analysis

<table>
<thead>
<tr>
<th>Channel</th>
<th>Signal strength [1 sigma band]</th>
<th>Cross section (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ee\epsilon$</td>
<td>0.0 [0.0 - 1.0]</td>
<td>$0.0^{+8.5}_{-0.7}$</td>
</tr>
<tr>
<td>$ee\mu$</td>
<td>1.4 [0.2 - 2.8]</td>
<td>$11^{+13}_{-10}$</td>
</tr>
<tr>
<td>$\mu\mu\epsilon$</td>
<td>2.9 [1.4 - 4.5]</td>
<td>$24^{+16}_{-12}$</td>
</tr>
<tr>
<td>$\mu\mu\mu$</td>
<td>0.6 [0.0 - 1.6]</td>
<td>$5.0^{+8.5}_{-5.7}$</td>
</tr>
<tr>
<td>combination</td>
<td>1.2 [0.6 - 1.9]</td>
<td>$10^{+8.2}_{-7.0}$</td>
</tr>
</tbody>
</table>

Combined cross section compatible with SM prediction

$\sigma(tlq)_{SM} = 8.2^{+0.59}_{-0.03}$ fb

Observed signal exclusion limit at 95%CL

$\sigma_{tZq} < 20.97$ fb

Observed (expected) significance: 2.4 (1.8). Expected 1sigma band i: 0.4 - 2.7
Search for tZq-SM production

Cut and count analysis

<table>
<thead>
<tr>
<th>Channel</th>
<th>Cross section (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>eee</td>
<td>(29^{+32}_{-24}) (stat.) (+8) (syst.)</td>
</tr>
<tr>
<td>ee(\mu)</td>
<td>(6^{+23}_{-6}) (stat.) (+4) (syst.)</td>
</tr>
<tr>
<td>(\mu\mu\epsilon)</td>
<td>(19^{+24}_{-19}) (stat.) (+5) (syst.)</td>
</tr>
<tr>
<td>(\mu\mu\mu)</td>
<td>(20^{+19}_{-15}) (stat.) (+4) (syst.)</td>
</tr>
<tr>
<td>combination</td>
<td>(18^{+11}_{-9}) (stat.) (+4) (syst.)</td>
</tr>
</tbody>
</table>

Combined cross section compatible with SM prediction and with shape analysis results.
Results

Search for tZ-FCNC production

- No excess over background is observed
- Exclusion limits on top FCNC calculated using theta with a Bayesian method
- Calculated for different values of couplings, but shown as a function of Br(t→Zq)
Conclusions

- The search for a single top quark produced in association with a Z boson, in both SM and FCNC events, has been presented.

- The tZq SM cross section has been measured for the first time by a shape analysis and a cut and count cross check. Both methods agree well with each other and the SM prediction.
  - The tri-lepton tZq cross section was measure to be $\sigma_{tZq} = 10^{8.7} \text{ fb}$

- No evidence for new physics has been found. The limits on FCNC tZq coupling are set to $\text{Br}(t\rightarrow Zu) < 0.017\%$ and $\text{Br}(t\rightarrow Zc) < 0.020\%$. These are the best current limits.

Ongoing analysis at 13 TeV... Stay tuned!