Top FCNC searches at HL-LHC with the CMS experiment

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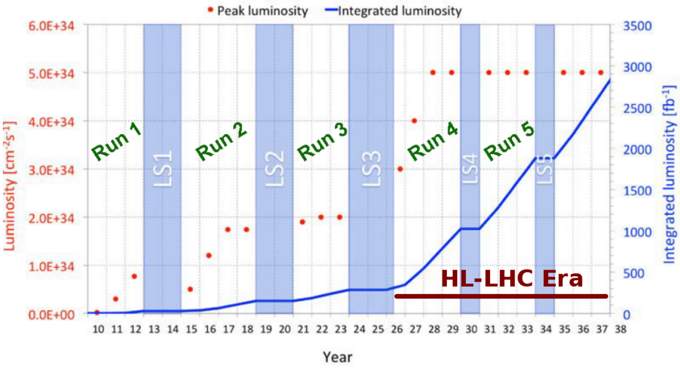
High-Luminosity LHC

The High-Luminosity LHC (HL-LHC) is the planed upgrade of the LHC:

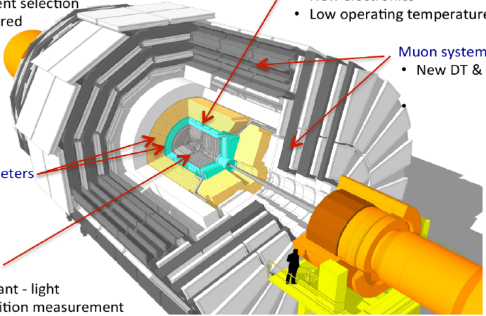
	LHC Run II	HL-LHC
$\sqrt{s}$	13 TeV	14 TeV
Integrated luminosity	50 fb^{-1} per year 300 at the end of Run III	300 fb^{-1} per year 3000 fb^{-1} in total
Pileup	27-36	140-200

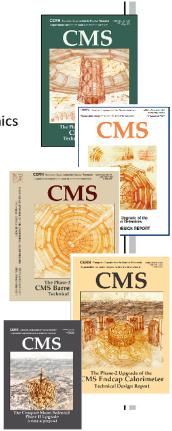


Phase-II Upgrade of the Compact Muon Solenoid

Significant upgrades of CMS for HL-LHC conditions:

- Radiation hardness
- Mitigate physics impact of high pileup

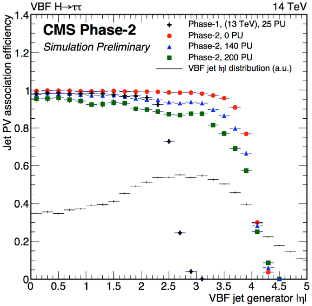


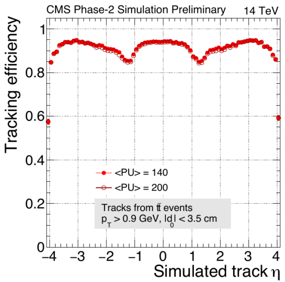


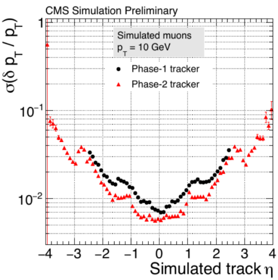
- addition of hardware trigger capabilities
- extended acceptance of the tracker and granularity of the calorimeters (HGCAL) in the forward region:

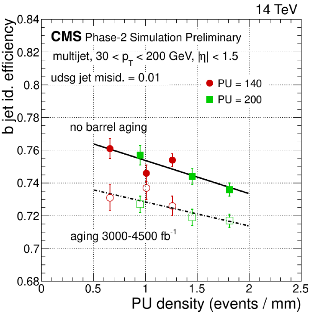
  inner tracker $|\eta| < 2.4 \rightarrow |\eta| < 4.0$

  muon system $|\eta| < 2.4 \rightarrow |\eta| < 2.8$
- pileup mitigation with PileUp Per Particle approach (PUPPI) algorithm





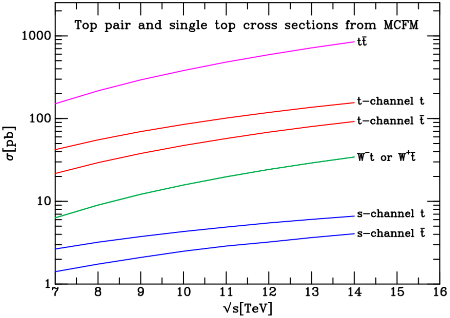




Large number of tops @ LHC ⇒ 10x more @ HL-LHC for:

- mass, width measurement
- kinematics, asymmetry study
- (anomalous) couplings measurement
- **FCNC rare decays search**
- direct BSM search

Adelman et. al [1309.1947]



	14 TeV - 3000 fb^{-1}
$t\bar{t}$	$3 \cdot 10^9$ events
$t\bar{t}$, fiducial,	$155 \cdot 10^6$ events
$t\bar{t}$, fiducial, $M_{t\bar{t}} > 1$ TeV	$3 \cdot 10^6$ events
$t\bar{t}$, fiducial, $M_{t\bar{t}} > 2$ TeV	$48 \cdot 10^3$ events
t-channel	$600 \cdot 10^6$
tW-channel	$200 \cdot 10^6$
s-channel	$30 \cdot 10^6$

Flavour changing neutral current in $t-$quark sector

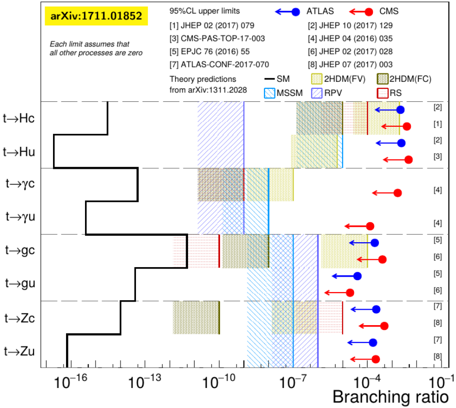
- In the SM, top quark FCNC decays are forbidden at tree level and have much smaller BR than the dominant decay mode $t \to bW$ at one loop level
- BSM models predict higher BR for top FCNC decays:

Process	SM	2HDM(FV)	2HDM(FC)	MSSM	RPV	RS
$t \to Zu$	7×10^{-17}	–	–	$\le 10^{-7}$	$\le 10^{-6}$	–
$t \to Zc$	1×10^{-14}	$\le 10^{-6}$	$\le 10^{-10}$	$\le 10^{-7}$	$\le 10^{-6}$	$\le 10^{-5}$
$t \to gu$	4×10^{-14}	–	–	$\le 10^{-7}$	$\le 10^{-6}$	–
$t \to gc$	5×10^{-12}	$\le 10^{-4}$	$\le 10^{-8}$	$\le 10^{-7}$	$\le 10^{-6}$	$\le 10^{-10}$
$t \to \gamma u$	4×10^{-16}	–	–	$\le 10^{-8}$	$\le 10^{-9}$	–
$t \to \gamma c$	5×10^{-14}	$\le 10^{-7}$	$\le 10^{-9}$	$\le 10^{-8}$	$\le 10^{-9}$	$\le 10^{-9}$
$t \to hu$	2×10^{-17}	6×10^{-6}	–	$\le 10^{-5}$	$\le 10^{-9}$	–
$t \to hc$	3×10^{-15}	2×10^{-3}	$\le 10^{-5}$	$\le 10^{-5}$	$\le 10^{-9}$	$\le 10^{-4}$

arXiv:1311.2028

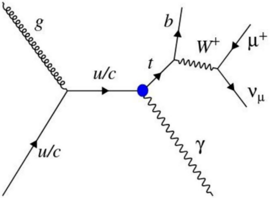
- Powerful probe for new physics

- No indication of FCNC transitions in $t-$quark sector:



Sensitivity to $tq\gamma$ FCNC transition

Single top quark **production** in association with photon:



⇒ distinctive event final-state signature of top quark decay with single muon or electron, neutrino and photon

⇒ enhanced FCNC production with an up-quark → differentiate between up and charm-type FCNC couplings

⇒ the photon is expected to have large transverse momentum, because of its recoil from the heavy top quark

Signals:

- FeynRules model in MadGraph: TopFCNCmode
- Official MC generation of datasets with MadGraph

Backgrounds:

- $t\bar{t}^1$, $t\bar{t}+\gamma^2$
- W + jets^2, $W+\gamma$ + jets^2
- Single top^1, Single top $+\gamma^3$

Generated with ^{1}Powheg, ^{2}MadGraph, ^{3}aMCatNLO.
Showered and hadronized with PYTHIA 8.

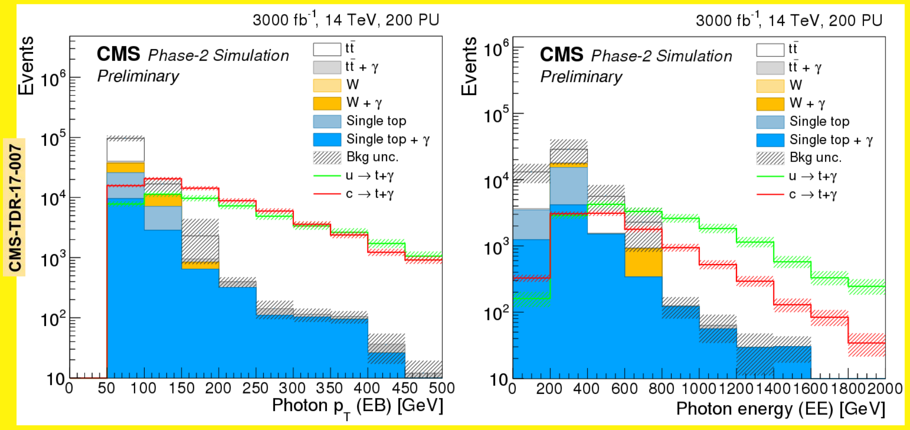
⇒ Full simulation of the upgraded CMS detector for signals and most of the backgrounds. Fast Delphes simulation of Single top $+\gamma$

⇒ Pile-Up $<\mu>= 200$ scenario is assumed

Selections:

- **Exactly one tight lepton** (e or μ) with $p_T > 25$ GeV, $|\eta| < 2.8$, relative isolation < 0.15 (electrons in the overlap region $1.4 < |\eta| < 1.6$ are removed)
- No additional leptons with $p_T > 10$ GeV, $|\eta| < 2.8$, relative isolation < 0.10
- **Exactly one b-tagged jet** with $p_T > 30$ GeV, $|\eta| < 2.8$ (cMVA algorithm for $|\eta| < 1.5$, DeepCSV algorithm for $|\eta| > 1.5$, PUPPI jets clustered with anti-k_T $R = 0.4$)
- **At least one photon** with $p_T > 50$, $|\eta| < 2.8$ (photons in the overlap region $1.4 < |\eta| < 1.6$ are removed)
- $E_T^{miss} > 30$ GeV
- Reconstructed t-quark mass in the range from 130 to 220 GeV

High photon p_T and Energy regions are populated by signal events:



combination of this distributions is used in statistical analysis for limit settings with the asymptotic CL_S method.

Systematic scenario:

$\Rightarrow$ 1.5% luminosity uncertanty

$\Rightarrow$ 1% JES uncertainty

$\Rightarrow$ 5% b-tagging uncertainty for the used working point

$\Rightarrow$ Run II normalization uncertainties (Single top $+\gamma$, $t\bar{t}$)

$\Rightarrow$ 50% variation of the renormalization and factorization scales (rest of the backgrounds)

single top $+\gamma$ **and** $t\bar{t} + \gamma$ **cross section uncertainties are dominated!**

Limits:

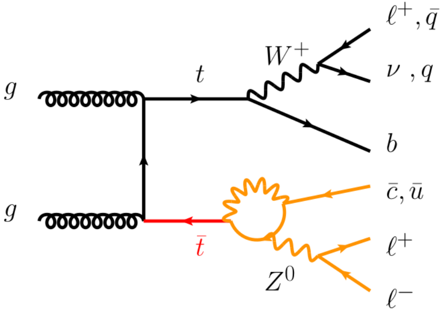
- **14 TeV 3000 fb^{-1} preliminary**
  CMS-TDR-17-007
  - $Br(t \to \gamma + u) < 1.16 \cdot 10^{-5}$
  - $Br(t \to \gamma + c) < 9.12 \cdot 10^{-5}$
- **8 TeV 19.7 fb^{-1}**
  JHEP 0 2 (2017) 028
  - $Br(t \to \gamma + u) < 1.3 \cdot 10^{-4}$
  - $Br(t \to \gamma + c) < 1.7 \cdot 10^{-3}$
- **14 TeV 3000 fb^{-1}** (fast simulation based)
  CMS-PAS-FTR-16-006
  - $Br(t \to \gamma + u) < 2.7 \cdot 10^{-5}$
  - $Br(t \to \gamma + c) < 2.0 \cdot 10^{-4}$

Sensitivity to tqZ FCNC transition

Top-quark pair with one top quark FCNC decay:

$\Rightarrow$ final-state signature with three isolated leptons (μ or e), neutrino and photon

- backgrounds: $t\bar{t} + jets$, $t\bar{t} + Z/W + jets$, $t + Z/W + jets$, $Z/W + jets$, $WW/WZ/ZZ + jet$
- fast Delphes simulation for signals and backgrounds
- pile-up $<\mu>= 140$ scenario is assumed



$\Rightarrow$ signals and backgrounds events are generated with MadGraph 5, showering and hadronization with Pythia 6,

Selections:

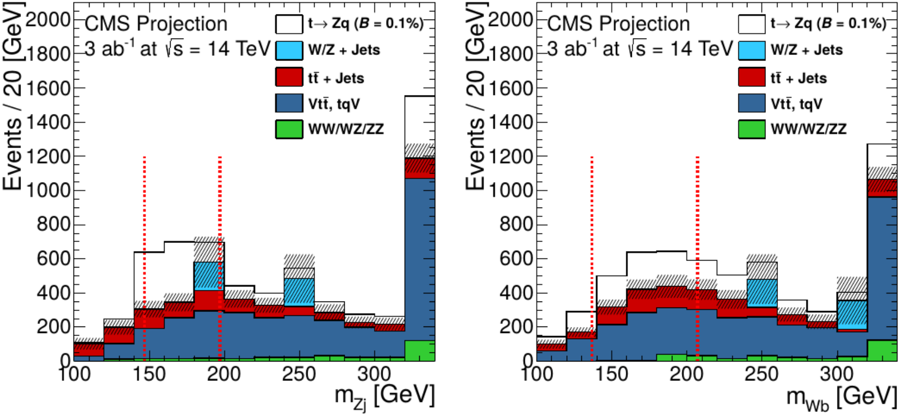
- Three isolated leptons with $p_T > 30$ GeV, $|\eta| < 2.5$ for electron and $|\eta| < 2.4$ for muon
- Invariant mass of two opposite-signed leptons $\in [78, 102]$ GeV
- At least two jets with $p_T > 50$ GeV, $|\eta| < 2.4$, one b-tagged jet
- $E_T^{miss} > 30$ GeV
- Reconstructed t-quark mass from SM decay $\in [137.5, 207.5]$

The expected number of events after selectios:

Process	Cross section (pb)	Expected @ 3000 fb^{-1}
top FCNC signal	1.91	578 ± 13
vector boson + jet	338×10^3	< 55
di-boson + jets	412	40 ± 31
top pair + jets	954	70 ± 57
single top + jets	323	< 8
boson + top + jets	97.3	15 ± 15
boson + top pair + jets	3.97	144 ± 14

Reconstructed m_{Zj} and m_{Wb} distributions of the simulated signal and background events for an integrated luminosity of 3000 fb^{1}:

CMS PAS FTR-13-016



The open histogram is the expected $Br(t \to Zq)$ is equal to 0.1%. The statistical uncertainties of these simulated background events are shown as shadowed area.

Systematic scenario:

- based on the study done with 8 TeV CMS-PAS-TOP-12-037
- rescaled as $\sqrt{19.5 fb/\mathcal{L}}$ by 0.25

Uncertainty (%)	$3000\,\mathrm{fb}^{-1}$ @ 14 TeV
Jet energy scale	3.4
$\not{E}_T$ resolution	3.2
MC Statistics	1.3
$\sigma(\mathrm{tqZ})/\ \sigma(\mathrm{Vt\bar{t}})$	0.8
b-tagging	4.2
Total	7

⇒ Simple counting experiment using the number of events after selections

⇒ Modified frequentist approach (CL_s method)

CMS PAS FTR-13-016

$\mathcal{B}(\mathrm{t} \to \mathrm{Zq})$	$19.5\,\mathrm{fb}^{-1}$ @ 8 TeV	$300\,\mathrm{fb}^{-1}$ @ 14 TeV	$3000\,\mathrm{fb}^{-1}$ @ 14 TeV
Exp. bkg. yield	3.2	26.8	268
Expected limit	$< 0.10\%$	$< 0.027\%$	$< 0.010\%$
1 σ range	$0.06 - 0.13\%$	$0.018 - 0.038\%$	$0.007 - 0.014\%$
2 σ range	$0.05 - 0.20\%$	$0.013 - 0.051\%$	$0.005 - 0.020\%$

Conclusions:

- The High-Luminosity LHC will deliver up billions of tops $\rightarrow$ great opportunity to challenge the SM by searching for FCNC with upgraded CMS detector
- Search for FCNC in $t \rightarrow q\gamma$ and $t \rightarrow qZ$ events are projected into the HL-LHC conditions and shows the possibility of improving existing constraints on the branchings by about one order of magnitude.
- Several studies for different FCNC in top quark sector are in an ongoing state:
  1. tqg transition in a single top quark production in association with u or c quark
  2. tHq and tqZ transition based on a full detector simulation
- Systematic uncertainty will play a dominant role in such analyzes $\rightarrow$ efforts to improve the accuracy of calculations of the cross sections of processes