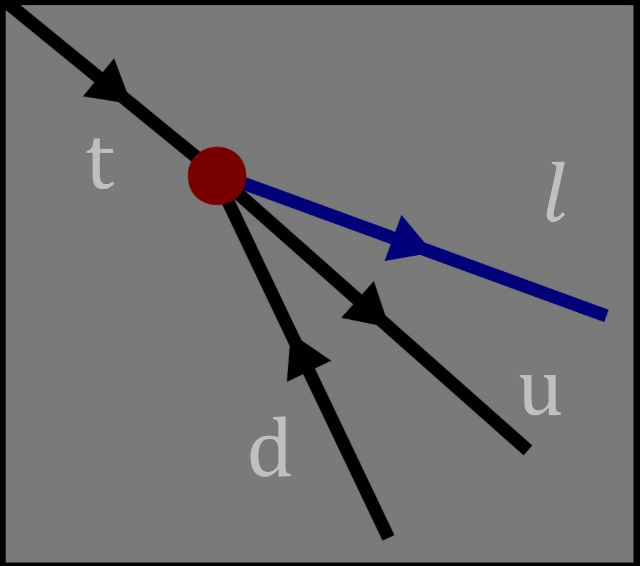
Search for Baryon Number Violation in top quark production and decay using proton-proton collisions at 13 TeV

ARXIV:2402.18461



UNIVERSITY OF NOTRE DAME

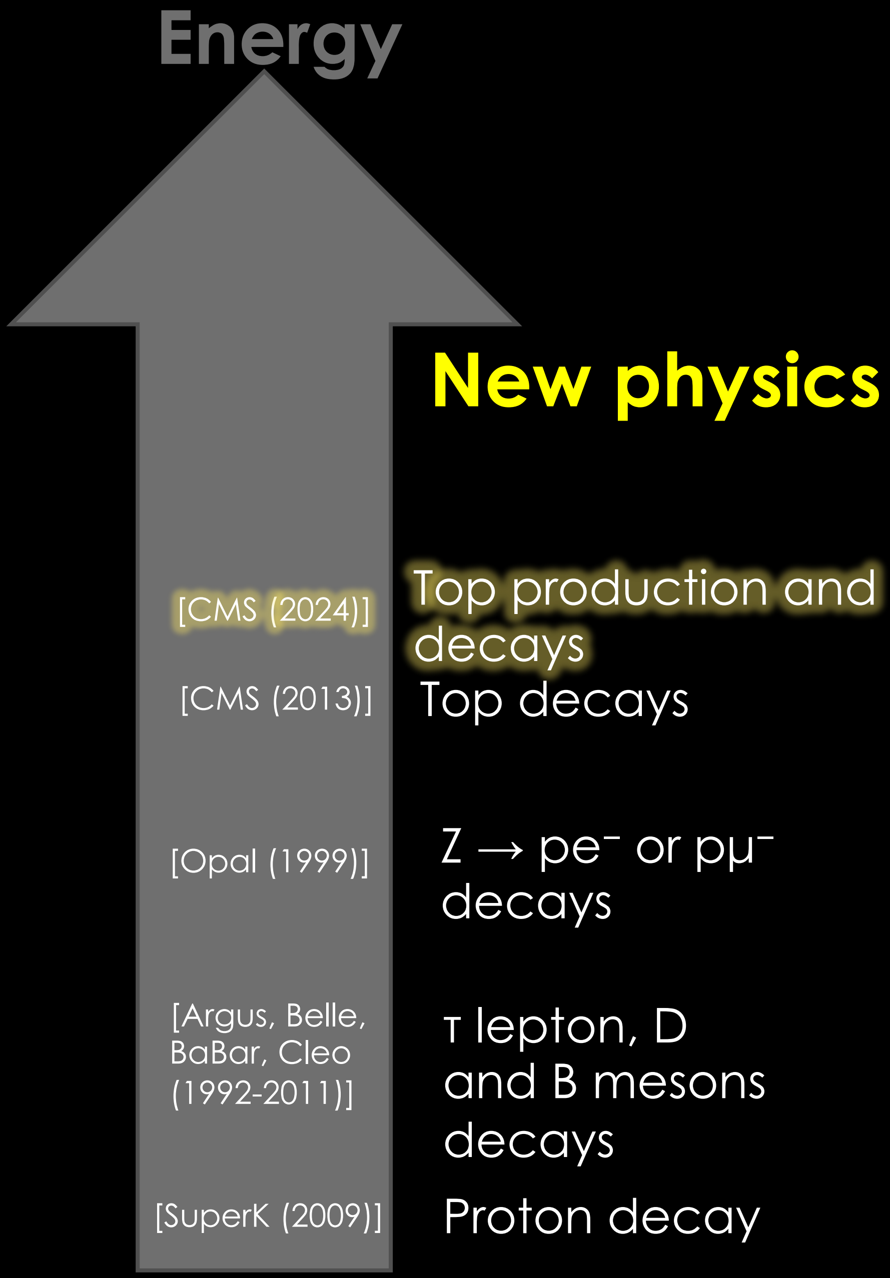
LHCtopWG2024
24-26 April
2024

Reza Goldouzian

On behalf of the
CMS Collaboration

Motivations

- In the standard model (SM), the baryon number is a conserved quantum number
    - Not from a fundamental symmetry in the SM
- Baryon number can be violated by non-perturbative effects in the SM
    - Too small to explain the observed matter-antimatter asymmetry in the universe
- Certain scenarios of physics beyond the SM naturally include Baryon Number Violation (BNV)
    - Such as grand unified theories and supersymmetry
- Various low-energy direct searches for BNV signatures are performed
    - LHC provide the highest sensitivity for potential high-energy BNV processes involving the top quark
- I present the results of our recent search for BNV in top quark production and decay at the LHC
    - https://arxiv.org/abs/2402.18461



Energy

New physics

[CMS (2024)] Top production and decays

[CMS (2013)] Top decays

[Opal (1999)] Z → pe⁻ or pμ⁻ decays

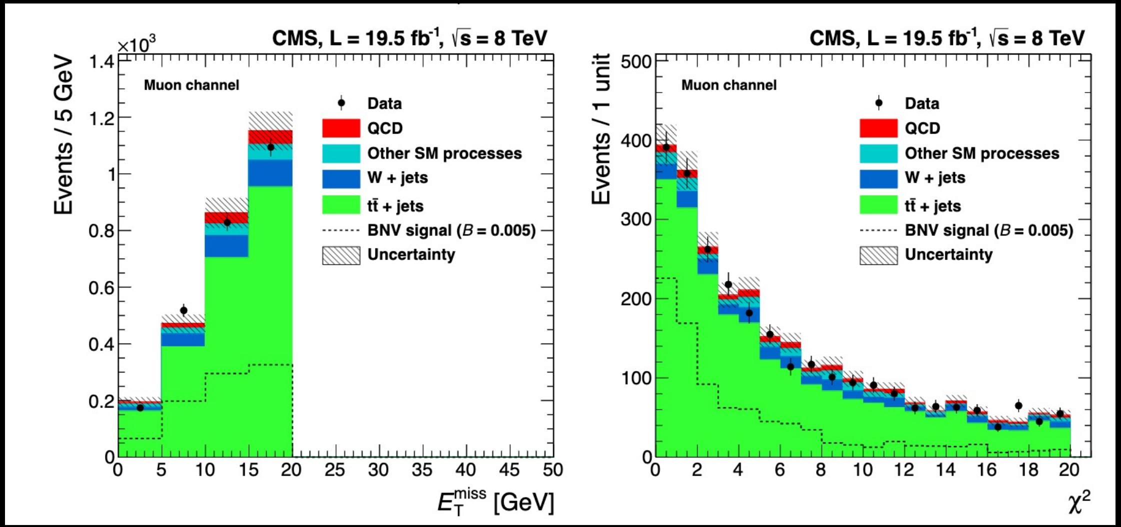
[Argus, Belle, BaBar, Cleo (1992-2011)] τ lepton, D and B mesons decays

[SuperK (2009)] Proton decay

state of the art

- Phenomenological studies for the top quark BNV search at the LHC are done in 2011
  - PhysRev D85 (2012) 016006 [arXiv:1107.3805]

- CMS collaboration performed a search for top quark BNV signatures at 8 TeV in lepton+jets final state
  - Phys. Lett. B 731 (2014) 173 [arXiv:1310.1618]
  - Only BNV contribution to top quark decay is included
  - Upper limits are set on the top quark BNV decay branching fraction



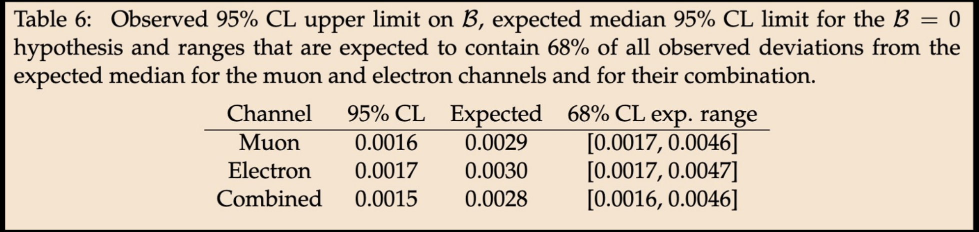


Table 6: Observed 95% CL upper limit on $\mathcal{B}$, expected median 95% CL limit for the $\mathcal{B} = 0$ hypothesis and ranges that are expected to contain 68% of all observed deviations from the expected median for the muon and electron channels and for their combination.

Channel	95% CL	Expected	68% CL exp. range
Muon	0.0016	0.0029	[0.0017, 0.0046]
Electron	0.0017	0.0030	[0.0017, 0.0047]
Combined	0.0015	0.0028	[0.0016, 0.0046]

- Our new search for top quark BNV signatures at 13 TeV is performed in dilepton final states
  - BNV contribution to single top quark production is included for the first time
  - Various quark flavour combinations are considered for the first time
  - Most stringent limits are set on the branching fraction of top quark BNV decays

Signal modeling

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \sum_x \frac{C_x}{\Lambda^2} O_x + \dots ,$$

$$O^{(s)} \equiv \epsilon^{\alpha\beta\gamma}[\overline{t^c_\alpha}(aP_L + bP_R)D_\gamma][\overline{U^c_\beta}(cP_L + dP_R)E],$$

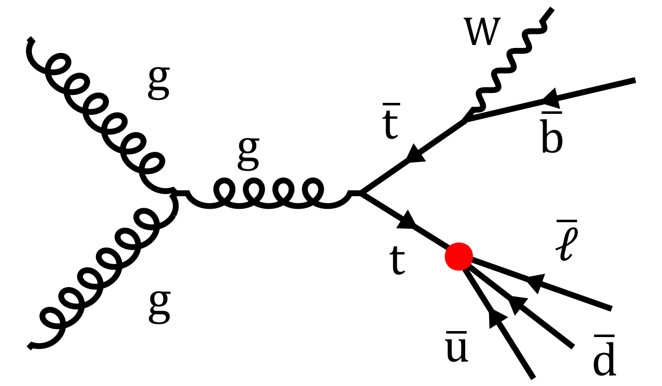
$$O^{(t)} \equiv \epsilon^{\alpha\beta\gamma}[\overline{t^c_\alpha}(a'P_L + b'P_R)E][\overline{U^c_\beta}(c'P_L + d'P_R)D_\gamma]$$

- A model independent effective field theory approach is followed
- Two independent operators can describe the BNV interactions
  - The s and t labels denote that the mass of a heavy mediator exchanged in the s or t channels
- No specific chirality is assumed for the BNV interactions
  - a=b=c=d= $\sqrt{C_s}$ and a'=b'=c'=d'= $\sqrt{C_t}$

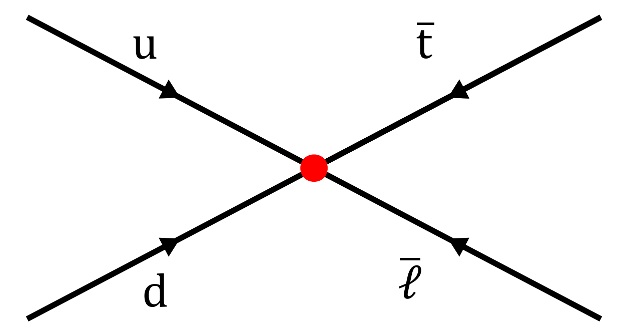
$$\mathcal{L}_{\mathrm{eff}} = \frac{C_s}{\Lambda^2}\epsilon^{\alpha\beta\gamma}[\overline{\mathrm{t}^c_\alpha}\mathrm{d}_\gamma][\overline{\mathrm{u}^c_\beta}\ell] + \frac{C_t}{\Lambda^2}\epsilon^{\alpha\beta\gamma}[\overline{\mathrm{t}^c_\alpha}\ell][\overline{\mathrm{u}^c_\beta}\mathrm{d}_\gamma] + \mathrm{h.c.},$$

- BNV vertices open new top quark decay and production channels
- Various quark flavor combinations can contribute to the BNV signal
  - tlud, tlus, tlub, tlcd, tlcs,and tlcb (l = electron or muon)
- Signal events are generated at LO with MadGraph5_aMC@NLO using TopBNV model (https://feynrules.irmp.ucl.ac.be/wiki/TopBNV)
- Independent signal samples are generated for various quark flavor combinations in production and decay channels

Top quark decay (TT mode)



Single top quark production (ST mode)



Signal features

- Signal cross sections for the production and decay modes are as the following;

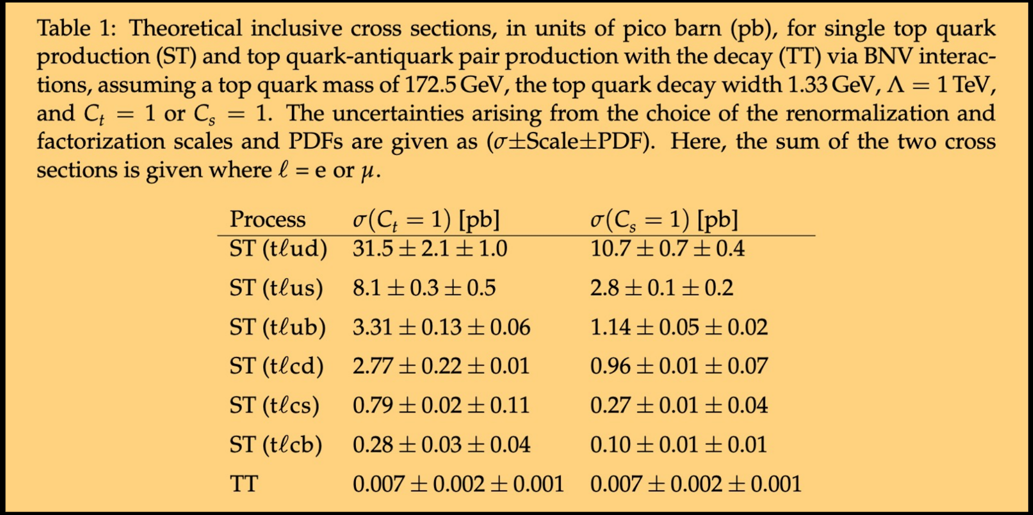


Table 1: Theoretical inclusive cross sections, in units of pico barn (pb), for single top quark production (ST) and top quark-antiquark pair production with the decay (TT) via BNV interactions, assuming a top quark mass of 172.5 GeV, the top quark decay width 1.33 GeV, $\Lambda = 1$ TeV, and $C_t = 1$ or $C_s = 1$. The uncertainties arising from the choice of the renormalization and factorization scales and PDFs are given as (σ±Scale±PDF). Here, the sum of the two cross sections is given where ℓ = e or μ.

Process	$\sigma(C_t = 1)$ [pb]	$\sigma(C_s = 1)$ [pb]
ST ($t\ell ud$)	$31.5 \pm 2.1 \pm 1.0$	$10.7 \pm 0.7 \pm 0.4$
ST ($t\ell us$)	$8.1 \pm 0.3 \pm 0.5$	$2.8 \pm 0.1 \pm 0.2$
ST ($t\ell ub$)	$3.31 \pm 0.13 \pm 0.06$	$1.14 \pm 0.05 \pm 0.02$
ST ($t\ell cd$)	$2.77 \pm 0.22 \pm 0.01$	$0.96 \pm 0.01 \pm 0.07$
ST ($t\ell cs$)	$0.79 \pm 0.02 \pm 0.11$	$0.27 \pm 0.01 \pm 0.04$
ST ($t\ell cb$)	$0.28 \pm 0.03 \pm 0.04$	$0.10 \pm 0.01 \pm 0.01$
TT	$0.007 \pm 0.002 \pm 0.001$	$0.007 \pm 0.002 \pm 0.001$

PhysRev D85 (2012) 016006 [arXiv:1107.3805]

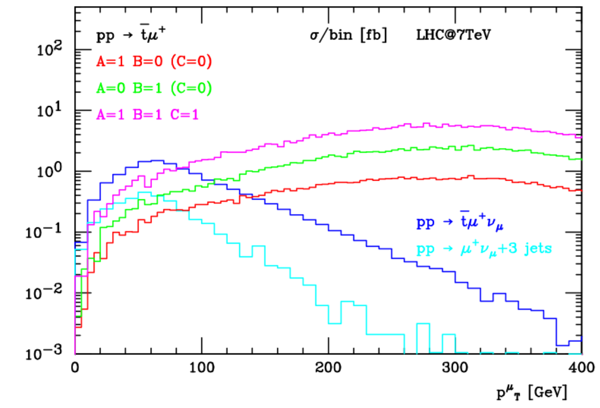
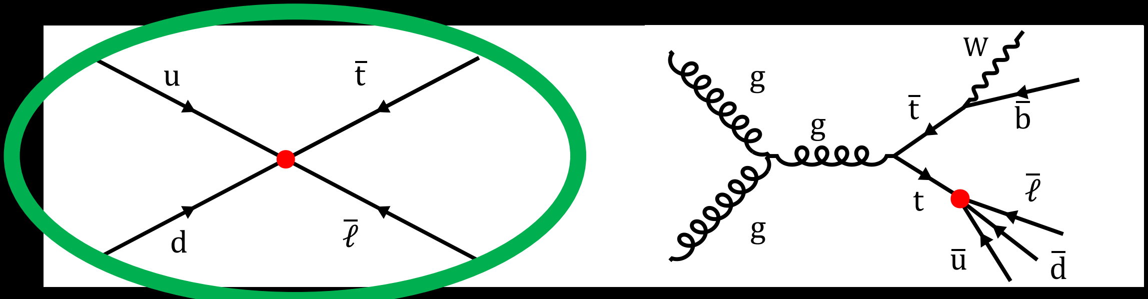


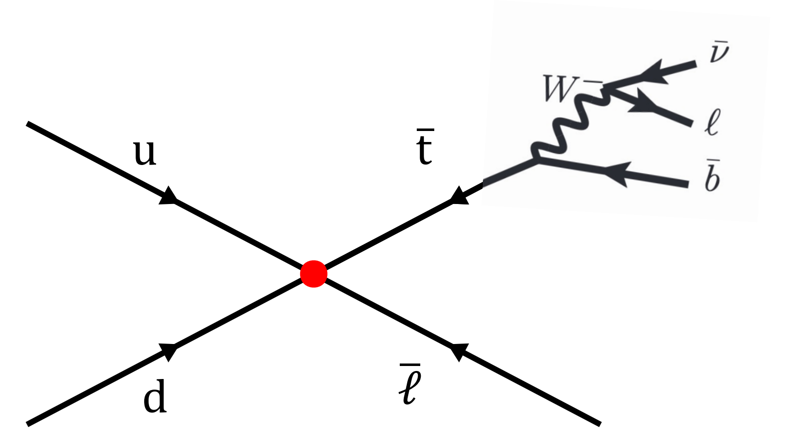
FIG. 2. Transverse momentum for the charged lepton in the BNV production signal $\bar{t}\,\mu^+$ (from ud initial state) and in the W^++3-jet and $\bar{t}W^+$ backgrounds. Top quarks are decayed hadronically. Selection cuts on the three jets and the muon are given in the text.

- The dominant signal process is the ST mode because
  - It has larger cross section compared to the TT mode
  - Its final-state particles have a harder pT spectrum compared to SM processes and the TT mode
- We optimize our analysis based on the production mode features and add the decay mode just for completeness



Datasets, final states and selections

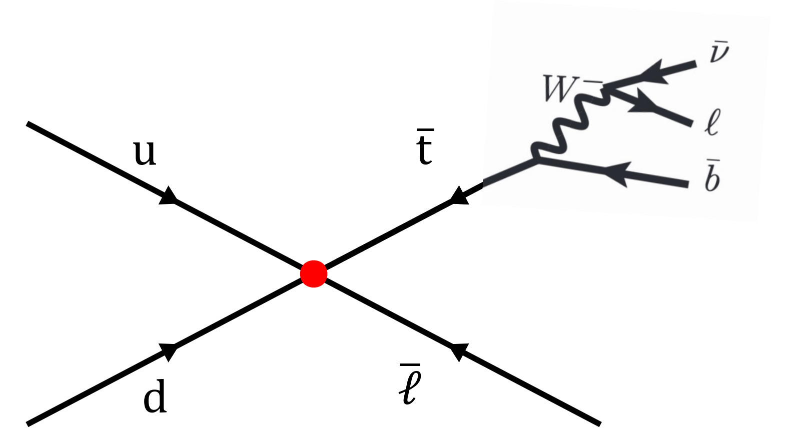
- Datasets
  - Full run2 datasets corresponding to an integrated luminosity of 138/fb
- Final states
  - Dilepton (e^+e^-, $e^\pm\mu^\mp$, and $\mu^+\mu^-$)
- BG processes are estimated by Monte Carlo simulation
  - $t\bar{t}, tW$: POWHEG v2.0
  - $t\bar{t}W, t\bar{t}Z, DY + jets, W + jets, WW, WZ, ZZ$: MadGraph5_aMC@NLO
- Trigger
  - A combination of single lepton and dilepton triggers
- Object selections
  - Electron (muon) candidates are selected with pt>35 (53) GeV and $|\eta| < 2.4$
  - AK4 jet candidate are selected with pt> 30 GeV and $|\eta| < 2.4$
  - DEEPJET algorithm is used to tag b-jets with an average of ~70% efficiency
- Event selections
  - Exactly one opposite-sign lepton pair
  - Invariant mass of dilepton system > 106 GeV and MET> 60 GeV
  - Exactly one b-tagged jet irrespective of the number of untagged jets
- Background combination after event selection
  - $t\bar{t}\,(\sim 89\%), tW\,(\sim 9\%), DY\,(\sim 1\%)$



Signal discrimination

- Signal events in the ST mode have specific features
  - The lepton and top quark are produced directly from the annihilation of the incoming quarks and are Lorentz-boosted and approximately back-to-back
  - The subleading lepton in the ST mode is primarily from the top quark decay chain

- To benefit from these features, we reconstruct the top quark candidate in the ST mode
  - The four-momentum vectors of the top quarks are reconstructed from the subleading lepton, the neutrino, and the b jet candidate
  - The neutrino pt is inferred from MET and its pz component is calculated using the W mass constraint
- A boosted decision tree is employed to separate signal from background events with 10 input variables
  - Pt of the leading lepton (ℓ1), subleading lepton (ℓ2), and the top quark candidate (t); ΔR(ℓ1, ℓ2), and ΔR(ℓ1, t); Δϕ(ℓ1, ℓ2), and Δϕ(ℓ1, t), the invariant mass and pt of the dilepton system; and $|p^{t}_{T} - p^{\ell 1}_{T}|/|p^{t}_{T} + p^{\ell 1}_{T}|$
- Different quark flavor combination signal show similar shapes for the input variables
  - We combine all signal events of the ST mode and train them against the SM backgrounds



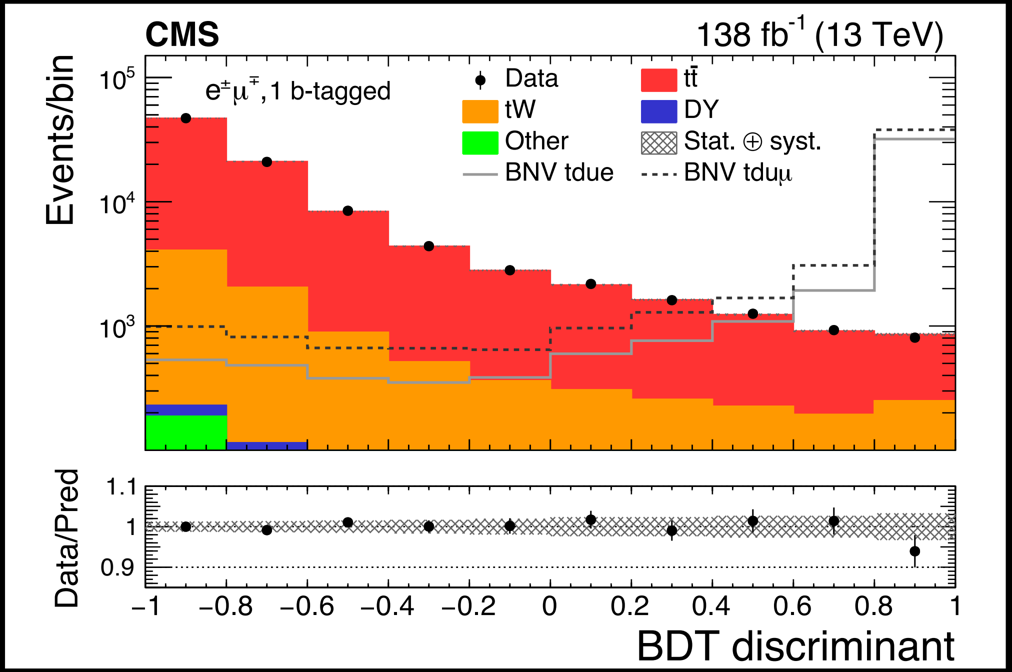
Uncertainties

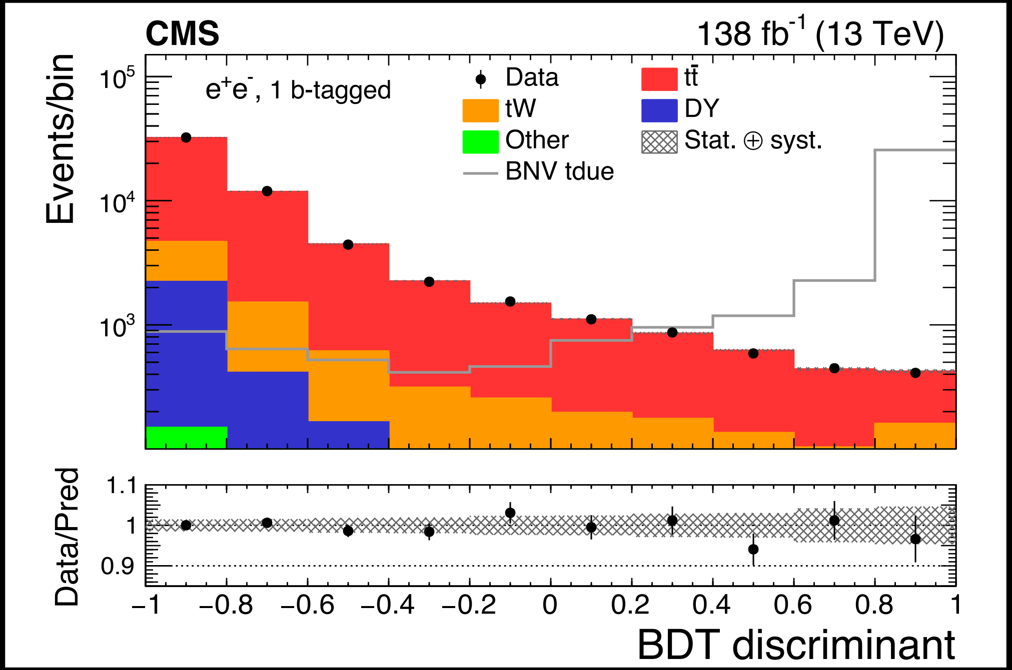
- We have considered the following uncertainty sources
  - Uncertainties on the lepton reconstruction identification, isolation and trigger scale factors
  - Uncertainties in the integrated luminosity
  - Uncertainties on the modeling of pileup effects
  - Uncertainties on the jet energy scale and resolution
  - Uncertainties in the calculation of the MET
  - Uncertainties on the normalization of the background processes
  - Uncertainties on the $t\bar{t}$ and signal modeling
    - PDFs, renormalization and factorization scales, and initial- and final-state QCD radiation
  - More $t\bar{t}$ modeling uncertainties
    - Uncertainties from the matching of the matrix element level calculation to the parton shower
    - Uncertainties on the modeling of the underlying event defined in PYTHIA tunes
    - Uncertainties on the models of color reconnection

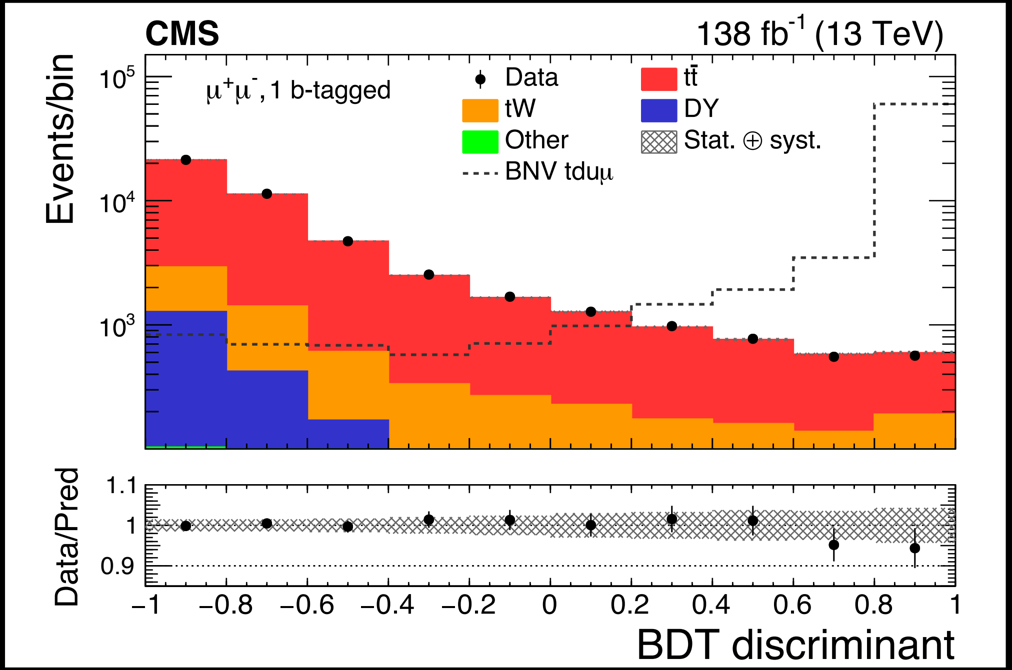
- To improve the modeling of the pt spectrum of the top quark in POWHEG, simulated SM tt events are weighted as a function of the pt of the top quark to match the expectations at NNLO QCD accuracy, including electroweak corrections
  - Uncertainties from this correction is evaluated by the renormalization and factorization scales at NNLO QCD

BDT output distributions

- BDT discriminant distributions for events in three channels are shown
  - Signal distributions are well separated from the background distributions
- To extract the signal contribution, a simultaneous binned maximum-likelihood is performed in all three signal channels
  - The best fit for the BNV effective couplings is consistent with zero and no significant excess over the background expectations is observed

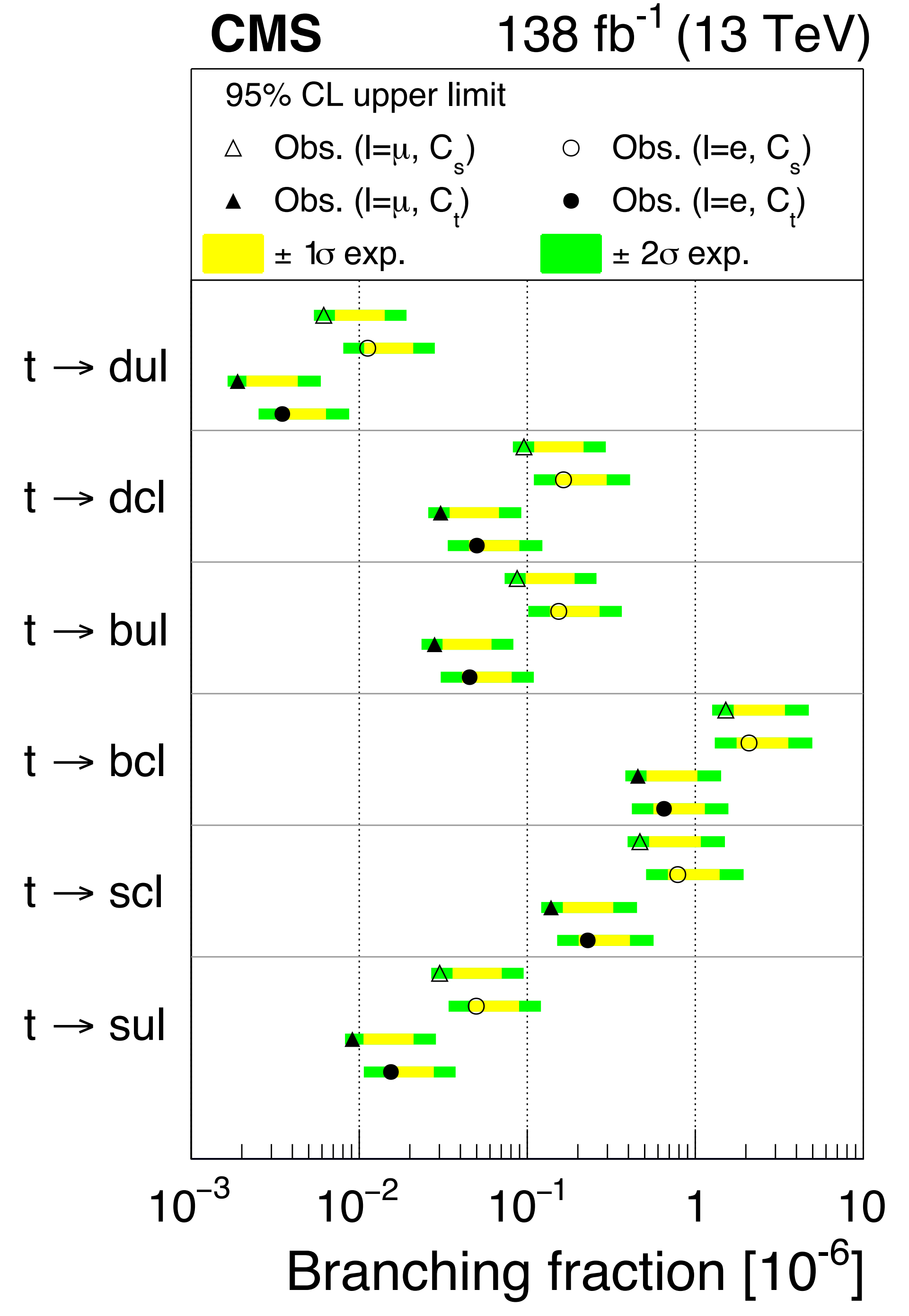






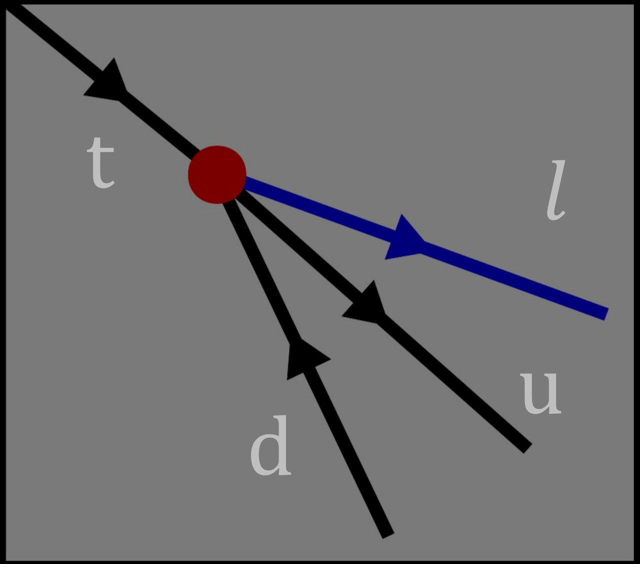
Results

- 95% CL exclusion limits are calculated
- The limit-setting is performed for each individual BNV coupling while setting the other BNV couplings to zero
- All described sources of uncertainties are treated as nuisance parameters
- The importance of the uncertainties in the limit setting procedure depends on the signal shape (quark flavor combination)
  - Three main common sources of uncertainty the normalization of the SM tW process, muon energy scale, and modeling of the top quark pt
- The limits on the strengths of the BNV couplings are translated to limits on the branching fractions for the BNV top quark decays
- The differences between different quark flavor combination stems mainly from the different PDFs involved in the production mode
- The results improve the previous bounds by three to six orders of magnitude based on the fermion flavor combination of the baryon number violating interactions



Summary

- A search for baryon number violation (BNV) in events with top quarks is performed using the LHC pp collision data collected by the CMS experiment in 2016-2018
- A model independent EFT approach is followed for modeling the BNV signal
  - All relevant quark flavor combinations are probed
- Dilepton events are selected for this search
- The analysis explores baryon number violating effects in single top quark production for the first time
- BDT is used to discriminate between signal and background events
- No significant excess of events over the background prediction is observed
- Expected upper limit are set on the 24 Wilson coefficients and then translated to the limits on the branching fractions of top quark BNV decays
- Upper limits on the branching fractions of top quark BNV decays are multiple orders of magnitude more stringent than the previous limits



Thanks for your attention