Study for measuring $|V_{ts}|$ directly in dileptonic final state of top pair production at 13 TeV with the CMS detector

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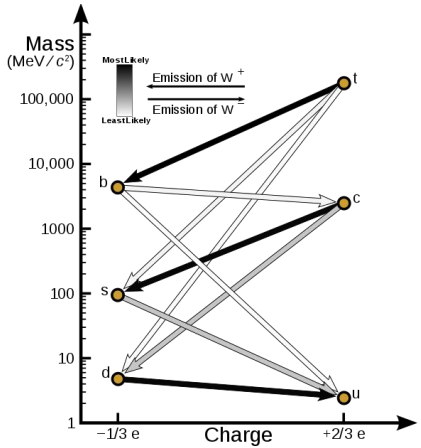
Introduction

- Quark mixing is described by the CKM matrix
  - 3 X 3 complex matrix including information on charged weak interaction
    - Unitarity is assumed in the Standard Model (SM) but it can be broken in the Beyond Standard Model (BSM) paradigm [1]
  - $|V_{ts}|$ is one of the elements of the matrix
    - The square of the component gives a branching ratio of t→sW decay

$$|V_{ts}|^2 = \frac{BR(t \to s)}{BR(t \to q)}$$

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{pmatrix}$$

- The goal of the analysis is to measure $|V_{ts}|$ directly
  - Test the SM and constrain the BSM models
  - Set a upper limits on the rare top decay process not yet been observed
- Current reported value based on global fit, taken from PDG [2]
  - $|V_{ts}| = 0.04110$ and $|V_{tb}| = 0.99912$



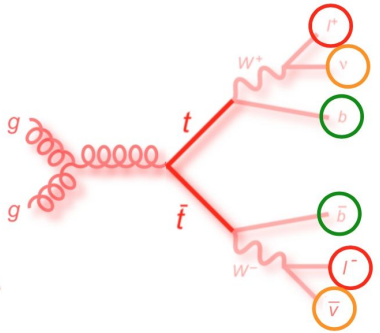
Charged current weak interaction between generations

[1] Vatsyayan, D., & Kundu, A. (2020). Constraints on the quark mixing matrix with vector-like quarks. *Nucl. Phys. B, 960, 115208.*

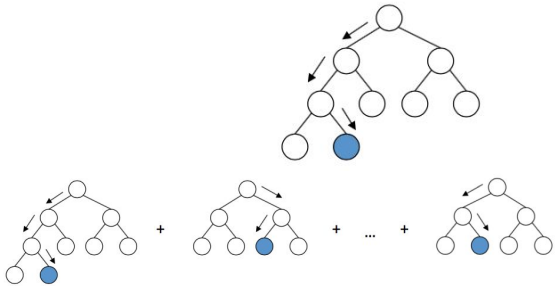
[2] Particle Data Group, et al. "Review of particle physics." *Progress of theoretical and experimental physics* 2022.8 (2022): 083C01.

Analysis Strategy

- Dilepton final state of top pair production
  - Less jet diversity than other channels
  - Still dominant background from t→bW
    - $|V_{tb}|^2 / |V_{ts}|^2 \sim 0.6 \times 10^3$
  - Other backgrounds from non-top process

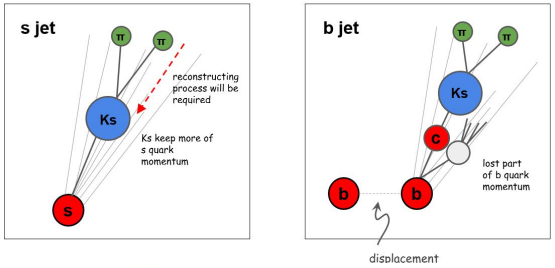


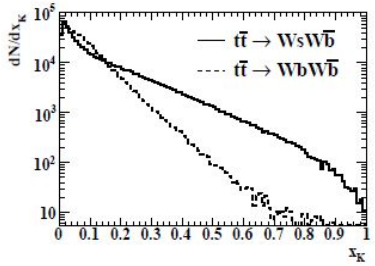
- Removing jet backgrounds is a major challenge
  - It is important to improve performance of discrimination of strange jet from top decays
  - We use the Boosted Decision Trees (BDT) as a jet discriminator
  - Extraction of $|V_{ts}|$ is performed by binned likelihood fit on model taken from jet discrimination output

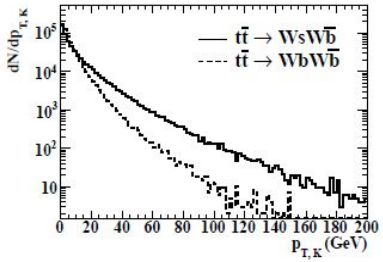


Information for Jet BDT Discriminator

- Jet information such as jet kinematics, jet shape
- Event topology such as lepton, p_T^{miss} for t→q / non t→q separation
- In addition, strange hadron information
  - Strange mesons such as K^0_S and Λ_0 can be produced from t→bW as well as t→sW
  - ⇒ Difference in several properties be like
    - Larger energy fraction hadron takes in s jet than in b jet
    - More charged leptons from B hadron decay in b jet
    - Different jet cone size, s jet narrower and b jet wider





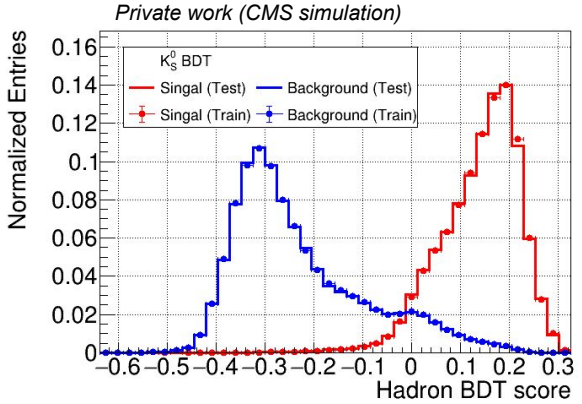


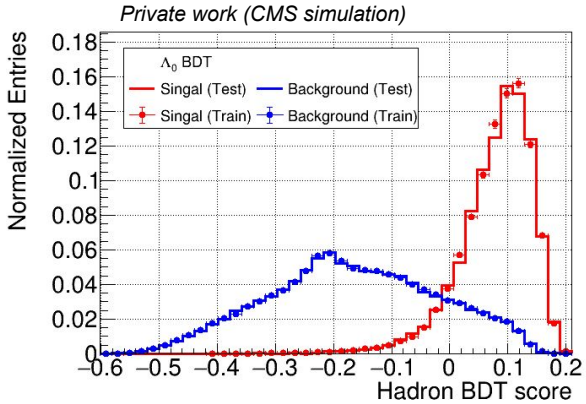
[3]

[3] Ali, Ahmed, Fernando Barreiro, and Theodota Lagouri. "Prospects of measuring the CKM matrix element |Vts| at the LHC." *Physics Letters B* 693.1 (2010): 44-51.

Hadron Reconstruction

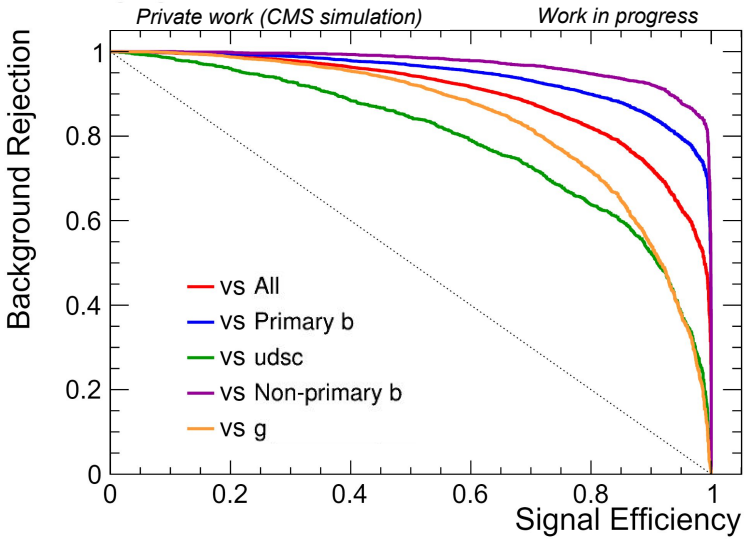
- All possible pairs of charged tracks in inner tracker
  - Opposite charge + assuming charged pion mass
  - Quality criteria are applied on pairs
- For excluding fake hadrons, hadron BDT is trained
  - Sample : tt→sWbW and tt→bWbW samples
    - Generated by MadGraph5_aMC@NLO and showering by Pythia8
  - Training variables
    - Basic hadron kinematics (p_T, η, ϕ)
    - Hadron vertex and track information
    - Hadron daughter track information (such as p_T, σ_{IP}, and χ^2)
  - Choose a hadron with ΔR(jet, hadron) < 0.4 and the highest BDT score satisfying greater than a working point





Jet BDT Discriminator

- Jets from top decays (Primary jets)
  - Jets with $\Delta R(\text{jet}, t \rightarrow q) < 0.4$ and the highest p_T among ΔR matched jets
- BDT-based signal jet discriminator
  - The same sample as the hadron BDT
  - Signal definition: Primary s jet with a real hadron
  - Background definition: All other jets with a real hadron
  - Training variables
    - Jet information
      - + DeepJet [4] b-tagging discriminant
    - Event-wise information
    - Hadron and its daughter variables
- In an event, one jet with the highest score is selected



[4] Bols, Emil, Jan, Kieseler, Mauro, Verzetti, Markus, Stoye, Anna, Stakia. "Jet Flavour Classification Using DeepJet". *JINST* 15. 12(2020): P12012.

Dataset and Event Selection

- CMS data collected during Run 2 period (2016-2018) in pp collisions at 13 TeV and corresponding simulation samples are studied
  - Dilepton channels (*ee*, *eμ*, and *μμ*) of top pair production are used in the analysis
  - tt→sWbW / tt→bWbW / single top (tW, t-channel, s-channel) / W+Jets / Drell-Yan jets / Diboson (WW, WZ, ZZ)
- Most of selection criteria used in CMS top analysis [5] are applied in this work

Object selection

	ID	p_T	$\|\eta\|$	Isolation / Clustering
Muon	Tight	> 25(20)* GeV	< 2.4	Tight ($\Delta R = 0.4$)
Electron	Tight	> 25(20)* GeV	$1.44 < \|\eta\|$ $1.56 < \|\eta\| < 2.4$	Tight ($\Delta R = 0.3$)
Jet	Tight	> 30 GeV	< 2.4	Anti-k_T ($\Delta R = 0.4$)
b-Jet	b-tagging from CMS DeepJet medium working point			

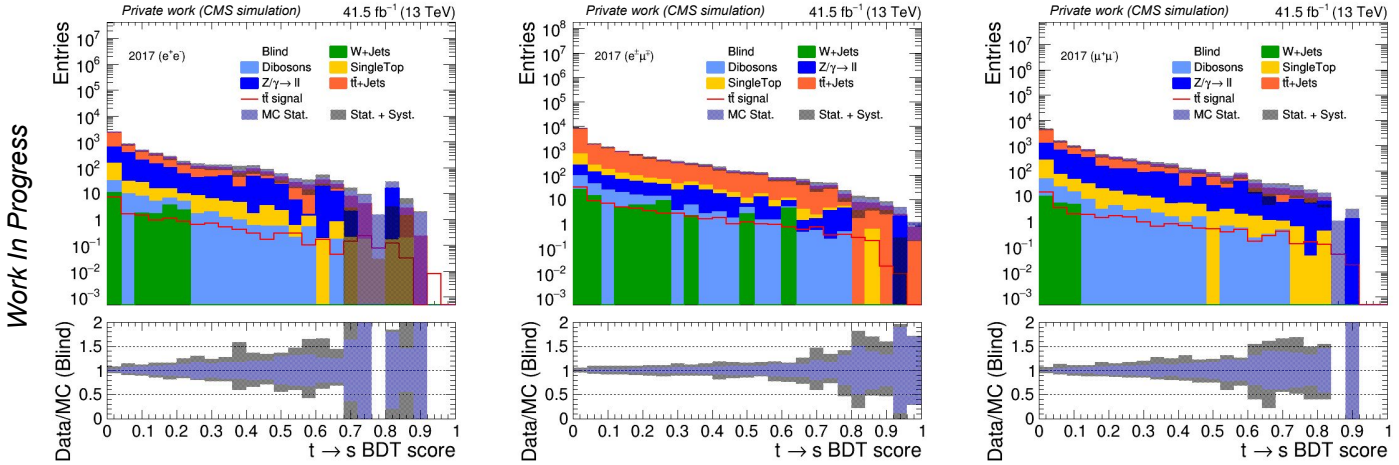
- * indicates leading(sub-leading) lepton
- Electron (muon) ID efficiency ~70 (95)%
- Jet ID efficiency > 98%
- DeepJet medium working point
  ⇒ b-tagging efficiency ~80% while mis-identification rate ~1%

Event selection

Description
Well reconstructed events with good primary vertex and triggers
Exactly one opposite charged lepton pair with $M_{ll} > 20$ GeV
Veto Z-boson in *ee* and *μμ* channel ($\|M_{ll} - M_Z\| < 15$ GeV)
$p_T^{miss} > 40$ GeV in *ee* and *μμ* channel
The number of selected jets ≥ 2
The number of selected b-tagged jets ≤ 1
Discrimination of signal jet

[5] Sirunyan, Albert M, others. "Measurement of the cross section for tt production with additional jets and b jets in pp collisions at sqrt(s)= 13 TeV". *JHEP* 07. (2020): 125.

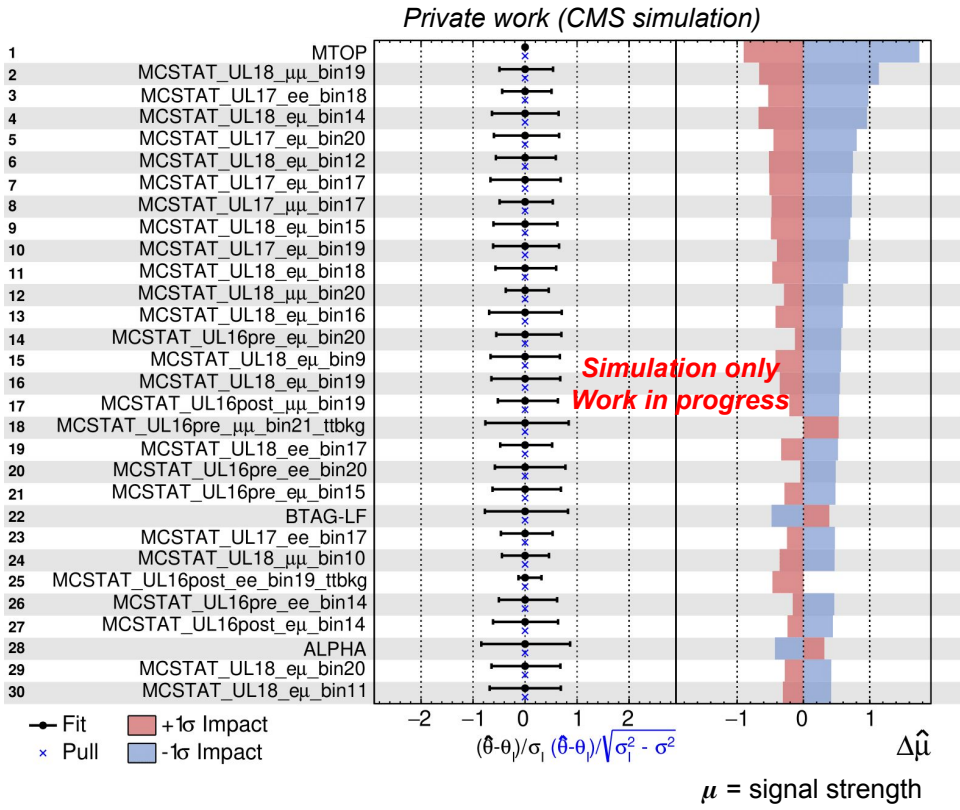
Jet BDT Score Distribution



- Signal process (tt→sWbW) is normalized by assuming $|V_{ts}^{CKM}| = 0.04110$
- Uncertainties
  - MC statistical error
  - Uncertainty from Drell-Yan background estimation
  - Systematics (Work in progress)
    - Experimental uncertainties
      - Luminosity, L1 prefiring, pile-up, trigger efficiency, lepton corrections and etc.
    - And theoretical uncertainties
      - Parton shower, underlying-event tune, QCD scales at matrix-level and etc.

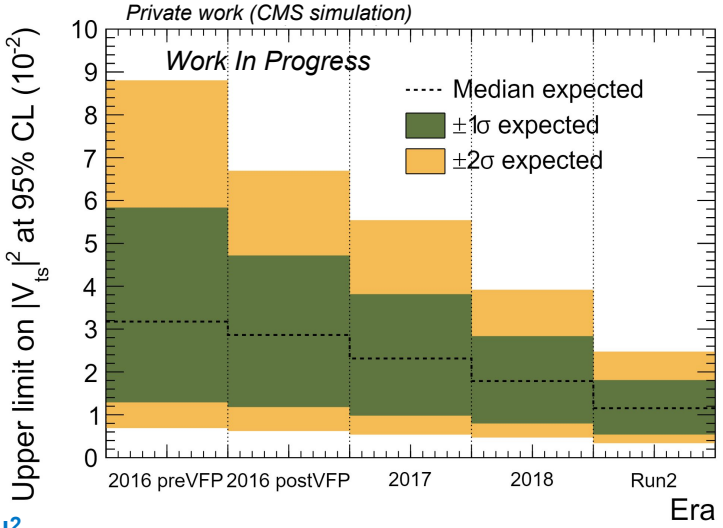
Simulation Results

- Run 2 (138 fb^{-1}) with currently implemented uncertainties
  - The final jet BDT score distribution as a model PDF and we perform binned likelihood fits
  - A-priori expected significance excluding $|V_{ts}| = 0$ from the Asimov dataset assuming $V_{ts} = 0.04110$
    - ~0.6σ
      - Need to improve some systematics fits → WIP
- Pull & Impacts (WIP)
  - In order of nuisance impact (Right)
    - Large impact by MC sample size (MTOP, MC stats., and etc.)



Simulation Results

- Run 2 (138 fb^{-1}) with currently implemented uncertainties
  - The final jet BDT score distribution as a model PDF and we perform binned likelihood fits
- Expected upper limits on $|V_{ts}|^2$ (WIP)
  - Median, ±1σ, and ±2σ expected limits for background-only hypothesis.



Expected upper limit on $|V_{ts}|^2$

Year	Median expected ($\times 10^{-2}$)	±1σ expected ($\times 10^{-2}$)	±2σ expected ($\times 10^{-2}$)
2016 preVFP	< 3.18	< [1.30 , 5.83]	< [0.69, 8.80]
2016 postVFP	< 2.86	< [1.19, 4.71]	< [0.63, 6.69]
2017	< 2.31	< [0.99, 3.81]	< [0.54, 5.54]
2018	< 1.79	< [0.80, 2.83]	< [0.47, 3.91]
Combined (Run2)	< 1.15	< [0.54, 1.80]	< [0.34, 2.47]

Summary and Plans

- This analysis aims to measure $|V_{ts}|$ directly
  - Its result will give testing on the SM and constraints on the BSM
  - Good discrimination of signal jet (s jet from top decays) is required
    - Currently, the BDT-based s-jet discriminator is developed
      - with jet, hadron properties and event topology information
    - There is also ongoing study for a deep learning based jet discriminator
- Analysis is performed on ttbar dilepton final state in pp collisions at 13 TeV with CMS
  - Applied object and event reconstructions used in CMS top analysis
  - The expected result using MC only is extracted using the CMS Run 2 samples
- Plan
  - Improving the discrimination and data-driven s-jet tagging efficiency scale factors across all years will be applied
  - Adding more systematics, improving implemented ones

Thank you for your attention