CKM Physics with Top

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Outline

- CKM Physics with Single Top
  - Single top measurements at CMS & ATLAS
    - Cross section
    - CKM matrix element \( V_{tb} \)
    - Ratio of cross section in t-channel \( (R_{t-ch}) \)
- CKM Physics with Top pairs
  - Top pair production at CMS
    - \( \text{Br}(t \to Wb)/\text{Br}(t \to Wq) \) where \( q = d, s, b \) & indirect determination of CKM matrix element \( V_{tb} \)
- Summary
Single top quarks are produced via **electroweak interaction**: 

- **t-channel**
- **s-channel**
- **tW-channel**
Interesting features of single top

The production of single top quarks provides a unique testing ground for the study of electroweak processes:

- Single top production cross section is proportional to the strength of $W_{tb}$ interaction
  - Probe anomalous $W_{tb}$ couplings
- Direct measurement of the Cabibbo–Kobayashi–Maskawa (CKM) matrix element $|V_{tb}|$
- Provide additional handle to constrain PDFs
  - The cross-section ratio top-quark/top-antiquark production is sensitive to the $u/d$-quark ratio in the PDF sets.
- Polarized sample:
  - Allows study of top quark polarization
- Sensitive to FCNC with top quarks
- Looking for signs of new physics:
  - Sensitive to new physics via $s$-channel (new resonances like $H^\pm$, $W'$)
t-channel Single top

Final state signature

- Light jet in forward region
- Missing Energy
- Isolated lepton
- Signal Region: 2 jets & 1 b-tagged jet (2jet 1tag)
- b-tagged jet
- Out of acceptance

Control/Validation Regions:
- CMS: ttbar (3jet 2tag, 3jet 1tag), QCD & W+jets (2jet 0tag)
- ATLAS: ttbar (3jet 2tag), W+jets (2jet 1loose-tag)
Cross section @ 13 TeV

Signal discrimination:
artificial neural network is trained in 2jet 1tag
Important inputs:
light jet $|\eta|$, reconstructed top mass

Events with non-isolated lepton and low $m_T(W)$ are used in QCD estimation

Analysis Strategy:
simultaneous fit in 3 regions
2jet 1tag, 3jet 1tag, 3jet 2tag

arXiv:1610.00678,
Submitted to Phys.Lett.B

$\sigma (t +t^\rightarrow) = 232 \pm 13 \; (\text{stat}) \pm 12 \; (\text{exp}) \pm 26 \; (\text{theo}) \pm 6 \; (\text{lumi}) = 232 \pm 31 \; \text{pb}$
The charge of the top quark is connected to the type of the incoming light-flavour quark → top-quark/top-antiquark production is sensitive to d/u-quark ratio

All PDF predictions are in agreement with the measurement


\[ \sigma_{t-ch, t} = 150 \pm 8 \text{ (stat)} \pm 9 \text{ (exp)} \pm 18 \text{ (theo)} \pm 4 \text{ (lumi)} \text{ pb} = 150 \pm 22 \text{ pb} \]

\[ \sigma_{t-ch, \bar{t}} = 82 \pm 10 \text{ (stat)} \pm 4 \text{ (exp)} \pm 11 \text{ (theo)} \pm 2 \text{ (lumi)} \text{ pb} = 82 \pm 16 \text{ pb} \]

\[ R_{t-ch} = 1.81 \pm 0.18 \text{(stat)} \pm 0.15 \text{(syst)} \]

CKM matrix element \( V_{tb} \) ( |\( V_{tb} \) | >> |\( V_{ts} \) | >> |\( V_{td} \) |):

\[ |f_{LV} V_{tb} | = 1.03 \pm 0.07 \text{(exp)} \pm 0.02 \text{(theo)} \]
Cross section @ 13 TeV

Signal discrimination
Neural Network is trained in 2jet 1tag

Important inputs:
reconstructed top mass, jet pair mass $m(jb)$, transverse W boson mass, light jet $|\eta|$

Analysis regions are separated into + and – lepton charge
$tt\bar{t}$ normalisation is controlled by using 3jet 2tag events
$W$+jets normalisation is estimated using 2jet 1loose-tag

arXiv:1609.03920
Submitted to JHEP

$$\sigma(tq + \bar{t}q) = 247 \pm 6 \text{ (stat)} \pm 45 \text{ (syst)} \pm 5 \text{ (lumi)} \text{ pb} = 247 \pm 46 \text{ pb}$$
The charge of the top quark is connected to the type of the incoming light-flavour quark

→ top-quark/top-antiquark production is sensitive to d/u-quark ratio

All PDF predictions are in agreement with the measurement

arXiv:1609.03920
Submitted to JHEP

\[ \sigma(tq) = 156 \pm 5 \text{ (stat)} \pm 27 \text{ (syst)} \pm 3 \text{ (lumi)} \text{ pb} = 156 \pm 28 \text{ pb} \]

\[ \sigma(fq) = 91 \pm 4 \text{ (stat)} \pm 18 \text{ (syst)} \pm 2 \text{ (lumi)} \text{ pb} = 91 \pm 19 \text{ pb} \]

\[ R_t = 1.72 \pm 0.09 \text{ stat} \pm 0.18 \text{ syst} \]

CKM matrix element $V_{tb}$ ($|V_{tb}| >> |V_{ts}| >> |V_{td}|$):

\[ |f_{LV} V_{tb}| = 1.07 \pm 0.01 \text{ (stat.)} \pm 0.09 \text{ (syst.)} \pm 0.02 \text{ (theor.)} \pm 0.01 \text{ (lumi.)} \]
tW-channel Single top @ 13TeV

- Dilepton (ee, eμ, μμ) Channel
- Signal Regions: 1jet 1tag, 2jet 1tag
- Two BDTs are trained tW and ttbar for the two signal regions:
  - 1jet 1tag (1j1b) region:
    - pTsys(ℓ1 ℓ2 ETmiss j1),
    - ΔpT(ℓ1 ℓ2 ETmiss j1)
  - 2jet 1tag (2j1b) region:
    - pTsys(ℓ1, ℓ2)
    - Δ R(ℓ1 ℓ2, ETmiss j1 j2)

ATLAS-CONF-2016-065
tW-channel Single top @ 13TeV

Measured cross section: $\sigma(Wt) = 94 \pm 10_{-23}^{+28}$ stat pb

SM: $\sigma(Wt) = 71.1 \pm 3.9$ pb

Significance: 4.5 $\sigma$
tW-channel Single top observation @ 8TeV

- Dilepton (ee, eμ, μμ) Channel
- Signal Region: 1jet 1tag
- BDT is trained tW and ttbar for the signal region

$$\sigma_{\text{meas}} = 23.4 \pm 5.4 \text{ pb}$$

6.1σ significance, First observation

$$|V_{tb}| = 1.03 \pm 0.12 \text{ (exp.)} \pm 0.04 \text{ (th.)}$$

tW-channel Single top @ 8TeV

- Dilepton (ee, eμ, μμ) Channel
- Signal Region: 1jet 1tag
- BDT used to discriminate signal and background
- Profile likelihood fit to BDT discriminant simultaneously in 1jet 1tag, 2jet 1tag and 2jet 2tag regions

\[ \sigma_{tW} = 23.0 \pm 1.3 \text{ (stat.)}^{+3.2}_{-3.5} \text{ (syst.)} \pm 1.1 \text{ (lumi.)} \text{ pb} \]

7.7\( \sigma \) observed significance

\[ |f_{LV} V tb| = 1.01 \pm 0.1 \]

JHEP01(2016)064
Combination of tW cross-section measurements @ 8TeV

ATLAS+CMS Preliminary
LHCtopWG
May 2016

Data 2012, √s = 8 TeV, m_t = 172.5 GeV

- NLO+NNLL (PRD82 (2010) 054018)
- MSTW2008_{NNLO}
- scale uncertainty
- scale ⊕ PDF uncertainty

\( \sigma_{Wt} \pm \text{(stat)} \pm \text{(syst)} \pm \text{(lumi)} \)

ATLAS, \( L_{\text{int}} = 20.3 \text{ fb}^{-1} \)
arXiv:1510.03752

23.0 ± 1.3 ± 3.5 ± 1.1 pb

CMS, \( L_{\text{int}} = 12.2 \text{ fb}^{-1} \)
PRL 112 (2014) 231802

23.4 ± 2.0 ± 4.6 ± 0.7 pb

LHC combined (May 2016)
ATLAS-CONF-2016-023,
CMS-PAS-TOP-15-019

23.1 ± 1.1 ± 3.3 ± 0.8 pb

Effect of LHC beam energy uncertainty: 0.38 pb (not included in the figure)
s-channel Single top evidence @ 8TeV

- Signal Region: 2jet 2tag
- Matrix element method to separate signal and background
- Profile likelihood fit of the signal and background templates of signal probability $P(S|X)$

$$\sigma(tb) = 4.8 \pm 0.8 \text{ (stat)} ^{1.6}_{-1.3} \text{ (syst)} \text{ pb}$$

SM: $\sigma = 5.2 \pm 0.2 \text{ pb}$

Significance: $3.2 \sigma$

s-channel Single top @ 7 & 8TeV

Signal extraction Strategy
- For electron & muon at 7 & 8TeV, BDTs trained in 2jet 1tag (2J2T), 2jet 1tag (2J1T) and 3jet 2tag (3J2T)
  - In 2J2T: s-channel vs rest
  - In 3J2T: t\bar{t} vs rest
  - In 2J1T: W+jets vs rest
- Simultaneous fit in signal and control regions

\[ \sigma_s = 7.1 \pm 8.1 \text{ (stat + syst) } \text{pb}, \text{ muon channel, 7 TeV;} \]
\[ \sigma_s = 11.7 \pm 7.5 \text{ (stat + syst) } \text{pb}, \text{ muon channel, 8 TeV;} \]
\[ \sigma_s = 16.8 \pm 9.1 \text{ (stat + syst) } \text{pb}, \text{ electron channel, 8 TeV;} \]
\[ \sigma_s = 13.4 \pm 7.3 \text{ (stat + syst) } \text{pb}, \text{ combined, 8 TeV.} \]

JHEP 09 (2016) 027
Summary of single top cross section measurements

From CMS PhysicsResultsTOPSummaryFigures
Summary of single top cross section measurements

From ATLAS CombinedSummaryPlotsTOP
Summary of cross-section measurements

FROM LHCTopWGSummaryPlots
Summary of CKM matrix element $V_{tb}$

- Cross section is proportional to $|V_{tb}|^2$
  - In the Standard Model with 3 quark generations
  - One expects $V_{tb} \sim 1$ (unitarity):

$$|V_{tb}^{obs}| = \sqrt{\frac{\sigma^{obs}}{\sigma^{theo}}}$$

- Assumptions for the extraction:
  - Independence of 3 quark generations
  - Left-handed weak interaction
  - Top quark decays only into $b$ quarks: ($V_{td}, V_{ts} \ll V_{tb}$)

- Can be done with all three single top processes

From LHCTopWGSummaryPlots
CKM Physics with Top Pairs @8TeV

- Measure the flavor content of quarks/jets in top pairs
- Indirect measurement of $|V_{tb}|$: Under the assumption of the unitarity of the $3 \times 3$ CKM matrix, $R = |V_{tb}|^2$
- Long history of measurements:

$$R = \frac{B(t \rightarrow Wb)}{\sum B(t \rightarrow Wq)}$$

where $q = d, s, b$


$$R = 1.023^{+0.036}_{-0.034}$$

CDF Note 10887 (2012)

CMS-PAS-SUS-12-029 (2012)

$D\bar{O}$ PRL 107, 121802 (2011)

$D\bar{O}$ PRL 100, 192003 (2008)

$D\bar{O}$ PLB 639, 616 (2006)

$CDF$ PRL 93, 102002 (2005)

$CDF$ PRL 86, 3233 (2001)

$95\% \text{ CL}$
Strategy

- Top pairs: We select dilepton events in data
  - Lower branching ratio (≈0.065) but cleaner signature (S/S+B≈70-90%)
  - ≥ 2 isolated prompt leptons with op. sign + ≥ 2 jets + ETmiss >40 GeV for ee/μμ channels

- Count N(t → Wb) and compare to the total N(t → Wq)

  ![Diagram]

  - Estimate main background (DY)
  - fit the signal strength
  - assume tW/τt ratio from simulation
  - How many t → lvj decays were actually reconstructed?
    - Estimate using M_τ kinematics
    - Categorize according to 0, 1 or 2 selected jets from top decay
    - Measure b-tag efficiency
    - Count number of b-tags
    - Compare with data-driven probability functions
  - How many jets are from b’s?

  \[ R = \frac{B(t \rightarrow Wb)}{B(t \rightarrow Wq)} \]
  - Corresponding to dilepton channel x number of jets x number of b-tagged jets
b-tagged jet multiplicity in dilepton channels

CMS, $\sqrt{s} = 8$ TeV, $\int L\, dt = 19.7$ fb$^{-1}$

Observation/Expected ratio

Extraction of $R$ & $V_{tb}$

- By counting the number of $b$ jets per event, an unconstrained value of
  \[ R = 1.014 \pm 0.003 \text{ (stat)} \pm 0.032 \text{ (syst)} \]
  is measured.

- Measured $R$ is in good agreement with the standard model prediction.

- A lower limit $R > 0.955$ at the 95% confidence level is obtained after requiring $R$ lower than one, and a lower limit on the Cabibbo-Kobayashi-Maskawa matrix element
  \[ | V_{tb} | > 0.975 \]
  is set at 95% confidence level when assuming the unitarity of the three-generation CKM matrix.

Summary of V_{tb} from single top and top pairs @ 7 & 8TeV

From CMS PhysicsResultsTOPSummaryFigures
Summary

- Direct measurement of CKM matrix element $V_{tb}$ using single top production channels with CMS and ATLAS is presented.

- Indirect measurement of $V_{tb}$ by measuring the ratio of top quark branching fractions in top pairs dilepton final state at CMS is presented.

- Stay tuned to more results from already collected 13TeV data!
Thanks