$|V_{tx}|$ mixing (at the LHC)

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-- Physics of HL-LHC and perspectives at HE-LHC --

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Overview

- Very brief overview of $|V_{tx}|$ at the LHC. (where we stand)

- Measuring $\sqrt{|V_{ts}|^2 + |V_{td}|^2}$ at HL/HE-LHC.
  
  Light-quark-jet tagger! Based on D.F, Kamenik, Patra, Zupan 1807.XXXXX

- Improving limits for $|V_{td}|$ at HL-LHC. Based on Alvarez, Da Rold, Estevez, Kamenik 1709.07887

- Conclusions

Disclaimer: LHC = LHC as a top-factory (ATLAS/CMS)
\[ |V_{tx}| \text{ mixing} \]

- **Global CKM fit:**
  
  \[ |V_{tb}| = 1 - 8.81^{+0.12}_{-0.24} \times 10^{-3} \]
  
  \[ |V_{ts}| = 41.08^{+3.0}_{-5.7} \times 10^{-3} \]
  
  \[ |V_{td}| = 8.575^{+0.076}_{-0.098} \times 10^{-3} \]

  Charles et al. [1501.05013]

- **|V_{tx}|:** indirect determination (loop level) and model dependant!!

- **Top-philic** New Physics could spoil unitarity in 3rd row of CKM.

  e.g. Vector-like top partner \( T \) (\( Q=2/3 \))

  \[ T \text{ mixes with SM right-handed top quark} \sum_{x=d,s,b} |V_{tx}|^2 < 1 \]

  Alwall et al. [0607115]

  Aguilar-Saavedra et al. [1306.0572]

- Important to extract \( V_{tx} \) with a **direct measurement**!

  and confront unitarity hypothesis.

  \[ \sum_{x=d,s,b} |V_{tx}|^2 = 1 \]
| $V_{tx}$ | at LHC

- t-channel Single-top production  
  \[ pp \rightarrow tj \quad \sigma_{tj}^{\text{SM}} \propto |V_{tb}|^2 \]

- A measurement on $|V_{tb}|$ can be extracted from x-section  
  \[ |V_{tb}| = 1.07 \pm 0.09 \quad \text{assuming} \quad |V_{tb}| \gg |V_{ts}|, |V_{td}| \]

- See also Lacker et al. [1202.4694]

- What can the LHC say about $|V_{ts}|, |V_{td}|$ ?
Measure top-decay branching ratios

\[ \mathcal{B}(t \rightarrow bW^\pm) \sim 1 \]
\[ \mathcal{B}(t \rightarrow sW^\pm) \sim \mathcal{O}(10^{-3}) \]
\[ \mathcal{B}(t \rightarrow dW^\pm) \sim \mathcal{O}(10^{-4}) \]

Count fraction of b-jets in top-decays:

8 TeV CMS [1404.2292]

\[ \mathcal{R} = \frac{\mathcal{B}(t \rightarrow bW)}{\sum_i \mathcal{B}(t \rightarrow d_iW)} \]

\[ \mathcal{R} > 0.995 \text{ at } 95\% \text{ CL} \]

\[ \sqrt{|V_{ts}|^2 + |V_{td}|^2} < 0.217 |V_{tb}| \]

No sign yet of large hierarchy in 3rd row of CKM matrix...

Soon limited by systematics at the LHC..
Not much gain from higher-lumi...

New approach is necessary!
CKM section PDG 2016

\[ |V_{ts}|^2 + |V_{td}|^2 \] at LHC

DF, Kamenik, Patra, Zupan [1807.0xxx]

12.2.7. \( |V_{td}| \) and \( |V_{ts}| \):

The CKM elements \( |V_{td}| \) and \( |V_{ts}| \) are not likely to be precisely measurable in tree-level processes involving top quarks, so one has to rely on determinations from \( B^- \bar{B} \) oscillations mediated by box diagrams with top quarks, or loop mediated rare \( K \) and \( B \) decays.

- Why not? Strange and Down quark jets are indistinguishable at ATLAS/CMS.

\[ K^\pm \sim \pi^\pm \] since no particle ID

- Can we measure \( \sqrt{|V_{ts}|^2 + |V_{td}|^2} \) at the LHC?

- \( t \rightarrow s(d)W^\pm \) vs \( t \rightarrow bW^\pm \)

- We need a light-quark jet tagger! \((u,d,s)\)

- Jet-tagging technology: b-jets, tau-jets, quark/gluon jets, jet substructure techniques, etc...
Light-quark tagging

- Require all tracks in jet to be prompt.
  
  All tracks in jets: \( d_0(\text{track}) < 30 \mu\text{m} \)

  \( d_0 \) : Transverse Impact Parameter

- light-quark tagger should be a quark-tagger.

  Many powerful discriminators in literature...

  Gallicchio, Schwartz [1106.3076]
  Larkowski, Salam, Thaler [1305.0007]

  - Multiplicity of (charged) particles in jet.
  - 2-point Energy Correlation Functions (ECF)

\[
U_1 = \sum_{i,j \in \text{jet}} p_T^i p_T^j (R_{ij})^\beta
\]

\[
R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2
\]
- Fraction of jet momentum carried by the hardest track.

\[ z \equiv \frac{\max_{i \in \text{jet}}(p_i)}{p_{\text{jet}}} \]

- \( z \) is related to the fragmentation function of \( K^\pm, \pi^\pm \)

- Observable has been studied at ATLAS and CMS. Good agreement with Pythia
MC results: Excellent bottom rejection, good charm and gluon rejection!
- 1) Select pair of candidate jets $j_1 j_2$ from first stage top-decays. $t\bar{t} \rightarrow j_1 j_2 W^+W^-$

- 2) Tag pair with light-quark and bottom tagger.

**Signal Region:** $j_1 j_2$ are $s\bar{b} -$ jets

- 1) Select 2 isolated leptons.

- 2) Select $j_1 j_2$ candidates:

  leading & sub-leading jets $p_T(j_1, j_2) > 100\text{GeV}$

  $|\eta(j_1, j_2)| < 1$

- 3) Tag $j_1 j_2$ as bottom or light-quark jets.

**Cleanest environment at LHC.**

**Irreducible background:** $pp \rightarrow t\bar{t} j \quad j=u,d \quad $ valence quark ISR
Results from MC: MadGraph 5 @ LO + Pythia 8

13 TeV LHC, Resolved leptonic tops

Luminosity (fb⁻¹)

13 TeV LHC, Boosted semi-leptonic tops

Luminosity (fb⁻¹)

LHC 95% CL limits, Resolved leptonic tops

Luminosity (fb⁻¹)

13 TeV

27 TeV

HE-LHC

HL-LHC

D.F. J.F. Kamenik, M. Patra, J. Zupan 1807.XXXXX

Boosted Analysis! (in backup slide)
Proposal: $tW$ associated production at the LHC \[ dg \rightarrow tW^- , \quad \bar{d}g \rightarrow tW^+ \propto |V_{td}|^2 \]

Alvarez, Da Rold, Estevez, Kamenik [1709.07887]

13 TeV LHC:
\[
\sigma(dg \rightarrow tW^-) \simeq 20 \text{ fb} \\
\sigma(\bar{d}g \rightarrow tW^+) \simeq 6 \text{ fb}
\]

Signal Features:
- Charge asymmetry from *valence* $d$-quark vs *sea* anti-$d$-quark.
- $W^-$ is more forward than $W^+$

Most backgrounds are charge-symmetric \[ bg \rightarrow tW^- , \quad \bar{b}g \rightarrow \bar{t}W^+ \]

Total x-section \[ \sigma_{tW}^{SM} \simeq 28 \text{ pb} \]

Top-pairs have a small charge-asymmetry at NLO \[ \sigma_{t\bar{t}}^{SM} \simeq 680 \text{ pb} \]
Purely Leptonic channel \( pp \rightarrow tW \rightarrow \ell^+ \ell^- b \nu \)

Motivates the kinematical variables:

\[
\Delta |\eta(\ell)| = |\eta(\ell^+)| - |\eta(\ell^-)| \quad \quad \Sigma |\eta(\ell)| = |\eta(\ell^+)| + |\eta(\ell^-)|
\]
\[
\Delta p_T(\ell) = p_T(\ell^+) - p_T(\ell^-) \quad \quad \Sigma p_T(\ell) = p_T(\ell^+) + p_T(\ell^-)
\]

Alvarez, Da Rold, Estevez, Kamenik [1709.07887]
Signal Region: 1st quadrant.

Background Region: symmetric.

Construct the **dilepton charge-asymmetry observable**:

\[
A(\eta, p_T) = \frac{N^+ - N^-}{N^+ + N^-}
\]

Event count in 1st and 3rd quadrants:

\[
N^\pm = N (\Delta|\eta(\ell)| \geq 0 \& \Delta p_T(\ell) \geq 0)
\]
- Analysis performed on MC samples with detector effects included (Delphes)

- Search Strategy:
  
  - Select events with $\ell^+ \ell^- b$, $|\eta| < 2.5$ & $p_T > 20$ GeV
  
  - Veto events with extra jets within $|\eta| < 5$
  
  - Z-mass veto $|m_{\ell\ell} - m_Z| < 15$ GeV and $E_T^{\text{miss}} > 30$ GeV

- Sensitivity at the HL-LHC $3000 \text{ fb}^{-1}$

  *Estimation of total unc. $\sim 0.2\%$*

  *Top-pair background reduced by half.*

  *Anticipating Multi-variate analysis (Boosted decision trees, etc...)*
HL-LHC reach

Alvarez, Da Rold, Estevez, Kamenik [1709.07887]
Conclusions

- We discussed the HL-HE LHC prospects of measuring directly $|V_{tx}|$ mixing elements.

- Current measurements of single-top and top-decays provide $|V_{tb}| \approx 1$ $|V_{td}|, |V_{ts}| < 0.2$. These will soon be limited by systematics.

- We showed that with help of a light-quark tagger the HL/HE - LHC can potentially measure directly in top-decays the quantity:

  $$\sqrt{|V_{ts}|^2 + |V_{td}|^2}$$

  This would confirm the large hierarchy in the 3rd row of the CKM matrix obtained indirectly from low-energy experiments.

- We showed that $|V_{td}|$ can be constrained using W-associated single-top production. Dilepton charge asymmetry is in particular sensitive to this CKM element. HL-LHC could establish that: $|V_{td}| < |V_{ts}|$

Thank you for your attention!
- 1) Selection:
  - 1 isolated lepton.
  - 1 Fat-Jet with $R = 1.5$, $p_T > 250$ GeV
  - Tag the top-jet (John Hopkins Top tagger).
- 2) Select $\hat{j}_1$ as top subjet.
- 3) Tag $\hat{j}_1$ as bottom or light-quark jet.
- 4) Remove top-jet from event and Re-cluster jets with $R = 0.4$ $p_T > 100$ GeV
- 5) Select $\hat{j}_2$ best reconstructs leptonic top
- 6) Tag $\hat{j}_2$ as bottom or light-quark jet.

This category provides a tag and probe environment.
- The **Jet tagging industry** is currently booming!

- **Bottom-taggers:**
  - Image: Displaced vertex (DV) from B-meson decays

- **Quark/gluon taggers:**
  - Image: Exploits observables sensitive to difference in QCD radiation pattern of parton (jet shape, angularities...)

- **Fat-jet-taggers:**
  - Image: $R \sim 2m_t/p_t \sim \mathcal{O}(1)$
    - Jet-substructure:
      - 3-prong: Tops
      - 2-prongs: W, Z, Higgs