Measuring CKM Matrix element Vtx at the Electron-Proton collider

Hao Sun (孙昊)
Dalian University of Technology
Outline

• Motivation

• introduce a related study at the LHC

• study at the ep colliders

• summary
Motivation

The first two rows of $V$ are precisely measured, by, for example, B-physics, etc.

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

few direct measurement exit
Motivation

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A global CKM fit

$$|V_{tb}| = 1 - 8.81^{+0.12}_{-0.24} \times 10^{-3}$$

$$|V_{ts}| = 41.08^{+3.0}_{-5.7} \times 10^{-3}$$

$$|V_{td}| = 8.575^{+0.076}_{-0.098} \times 10^{-3}$$

Few direct measurement exit

These predictions for $V_{tq}$, ($q=d,s,b$), are derived from:

1. The CKM unitarity considerations
2. The measurement of the decay and oscillations of the B-mesons where the $V_{tq}$ elements enter in loops that involve top quarks.
Motivation

The first two rows of $V$ are precisely measured, by, for example, B-physics, etc.

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1. The CKM unitarity considerations
2. The measurement of the decay and oscillations of the B-mesons where the $V_{tq}$ elements enter in loops that involve top quarks.

It is of interest to confirm the $V_{tq}$ measurements using direct/indirect experiments.

Here we concentrate on $V_{td}$ and $V_{ts}$.

A global CKM fit

$$|V_{tb}| = 1 - 8.81^{+0.12}_{-0.24} \times 10^{-3},$$
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$$|V_{td}| = 8.575^{+0.076}_{-0.098} \times 10^{-3}.$$
Motivation

The current machine to directly measure $V_{tb}$ is the LHC, through top productions or decay.

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

But the searching potential is limited by

1. Overwhelming backgrounds like top pair or multi-jets
2. Systematic uncertainties

Furthermore, in our case, the remaining $V_{td}$ and $V_{ts}$ elements are very small. At the LHC, it is difficult to measure $t$-$d$ and $t$-$s$ transitions.

A global CKM fit

$$|V_{tb}| = 1 - 8.81^{+0.12}_{-0.24} \times 10^{-3}$$
$$|V_{ts}| = 41.08^{+3.0}_{-5.7} \times 10^{-3}$$
$$|V_{td}| = 8.575^{+0.076}_{-0.098} \times 10^{-3}$$

We suggest to extract $V_{td}$ and $V_{ts}$ elements through single top related production at the ep colliders.

At the ep colliders, the situation is much better:

1. the suppression of the top-pair background
2. SM QCD backgrounds small since there is suppressed gluon exchange progresses
3. Dominant CC single top signal production
Recent study on Vtd at the (HL)-LHC

key idea: due to the imbalance of the valence d(dbar)-partons in the proton, there arise obvious charge asymmetries in the final state products, while in contrary, the main backgrounds have almost vanishing charge asymmetries.

Recent study on $V_{td}$ at the (HL)-LHC

key idea: due to the imbalance of the valence $d$($d$-bar)-partons in the proton, there arise obvious charge asymmetries in the final state products, while in contrary, the main backgrounds have almost vanishing charge asymmetries.

$R_d = \frac{V_{td}^{\text{dev.}}}{V_{td}^{\text{fit}}}$

3sigam $R_d \sim 13.75$

Current study at the (HL)-LHC

Exp. Limits from Branch Ratio measurement

\[ \frac{\text{Br}(t \rightarrow Wb)}{\sum_{q=d,s,b} \text{Br}(t \rightarrow Wq)} > 0.955 \text{@95\%C.L.} \]

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

current constraints:

\[ \begin{cases} |V_{td}| < 0.2080 \\ |V_{ts}| < 0.211562 \end{cases} \]

current direct limit (2\sigma)

\[ R_d = \frac{V_{\text{dev.}}}{V_{\text{fit}}} \]

3sigam \quad R_d \sim 13.75

Exp. Limits from Branch Ratio measurement
\[ \frac{\text{Br}(t \to Wb)}{\sum_{q=d,s,b} \text{Br}(t \to Wq)} > 0.955 @ 95\% \text{C.L.} \]

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current constraints:
\[ \begin{cases} |V_{td}| < 0.2080 \\ |V_{ts}| < 0.211562 \end{cases} \]

Advantage:
Reduce the sys. uncertainties

Disadvantage:
1. Still face the ttbar background
   [see dashed lines]
2. Only work for \( V_{td} \) but not \( V_{ts} \)

\[ R_d = \frac{V_{\text{dev.}}}{V_{\text{fit}}} \]

3sigam \( R_d \sim 13.75 \)
The main background $tw$ associated SM production mediated by Vtb vertex

Following the previous idea, I want to see whether it can be performed at the ep projects?

**Advantage:**
1. Reduce the systematic uncertainties: define a similar charge asymmetry
2. Much suppressed ttbar background

**Disadvantage:**
1. Production rate become small: gluon change to photon
2. Only work for Vtd but not Vts
We can find obvious difference between the lepton eta distributions for signal but not background.
study at the ep collider

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

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

\[ A(\eta) = \frac{N(\Delta |\eta(\ell)| > 0) - N(\Delta |\eta(\ell)| < 0)}{N(\Delta |\eta(\ell)| > 0) + N(\Delta |\eta(\ell)| < 0)} \]
study at the ep collider

$$R_d = \frac{V_{\text{dev.}}}{V_{\text{fit}}}$$

$$A(\eta) = \frac{N (\Delta|\eta(\ell)| > 0) - N (\Delta|\eta(\ell)| < 0)}{N (\Delta|\eta(\ell)| > 0) + N (\Delta|\eta(\ell)| < 0)}$$

<table>
<thead>
<tr>
<th>process</th>
<th>$\sigma_{\text{ini}}$ [fb]</th>
<th>$A_i$</th>
<th>$\sigma_{\text{ini}} \cdot A_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>signal</td>
<td>0.01$r^2$</td>
<td>0.473</td>
<td>0.00473$r^2$</td>
</tr>
<tr>
<td>bak1</td>
<td>12.25</td>
<td>0.00368</td>
<td>0.0451</td>
</tr>
</tbody>
</table>
study at the ep collider

\[ SS = \frac{|A(\eta) - A^{SM}|}{\sqrt{(N^+ + N^-)^{-1} + \Delta^2_{sys}}} \]

\[ R_d = \frac{V_{td}^{dev.}}{V_{td}^{fit}} \]

FCC-eh, 2 ab^-1, 3sigma \( R_d \sim 7.48 \)

Parton Level, detector effective should be included.
study at the ep collider

DIS

Disadvantage:
1. di-lepton final state turns to “tri-lepton” final state. Not good.
2. di-muon final state, production too small, 10 times smaller than rp production
3. bad charge asymmetry

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<th>$A_i$</th>
<th>$\sigma_{ini} \cdot A_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>signal</td>
<td>0.0014$r^2$</td>
<td>0.38</td>
<td>0.000532$r^2$</td>
</tr>
<tr>
<td>bak1</td>
<td>2.43</td>
<td>0.12</td>
<td>0.29</td>
</tr>
</tbody>
</table>

It is not efficient to separate the signal and background by the asymmetries.

Anyway, not recommended.
study at the ep collider

Why not directly using the CC single top production?

Advantage:
1. Production rates are much larger
2. Much suppressed ttbar background
3. Work not only for Vtd but also Vts

Disadvantage:
1. Systematic uncertainties should be included.
Current progress in $V_{td}/V_{ts}$ measurement

Signal.I: $p e^{-} \rightarrow \nu_{e} \bar{t} \rightarrow \nu_{e} W^{-} \bar{b} \rightarrow \nu_{e} \ell^{-} \nu_{\ell} \bar{b}$

Signal.II: $p e^{-} \rightarrow \nu_{e} W^{-} \bar{b} \rightarrow \nu_{e} \ell^{-} \nu_{\ell} \bar{b}$

Signal.III: $p e^{-} \rightarrow \nu_{e} \bar{t} \rightarrow \nu_{e} W^{-} j \rightarrow \nu_{e} \ell^{-} \nu_{\ell} j$

In this case we have two $V_{tx}$ vertex contribute.

Signal.IV: $p e^{-} \rightarrow \nu_{e} W^{-} j \rightarrow \nu_{e} \ell^{-} \nu_{\ell} j$

We study the CKM vertex in four channels.
study $V_{td}$ and $V_{ts}$ at the ep colliders

Here is our simulation chain

- Lagrangian
- FeynRules
- MadGraph
- Pythia
- Delphes
- ROOT-analysis

For LHeC and FCC-he
study $V_{td}$ and $V_{ts}$ at the ep colliders

B1: $pe^{-} \rightarrow \nu_{e} \bar{t} \rightarrow \nu_{e} W^{-} \bar{b} \rightarrow \nu_{e} \ell^{-} - \nu_{\ell} \bar{b}$

B2: $pe^{-} \rightarrow \ell^{-} E_{T}^{\text{miss}} b/b$

B3: $pe^{-} \rightarrow \ell^{-} E_{T}^{\text{miss}} j$
Signal I:
\[pe^- \rightarrow \nu_e t \rightarrow \nu_e W^- b \rightarrow \nu_e \ell^- \nu_\ell b\]
Signal.I:
\[ pe^- \rightarrow \nu_e \bar{t} \rightarrow \nu_e W^{-} \bar{b} \rightarrow \nu_e \ell^- \nu_\ell \bar{b} \]

<table>
<thead>
<tr>
<th>( P_{e^-} = 80% )</th>
<th>( \sigma_x \cdot \text{Br}(t) \cdot \text{Br}(W) )</th>
<th>( B_{\text{initial}} )</th>
<th>optimized cut</th>
<th>( B_{\text{optimized}} )</th>
<th>( \epsilon_{\text{signal}}[%] )</th>
<th>( SS_{100fb^{-1}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHeC Rd = 10</td>
<td>11.73fb</td>
<td>0.657pb</td>
<td>( \ell^- + \geq 1 ) b-jet(s) ( M_{\ell b} &lt; 160\text{GeV} )</td>
<td>93fb</td>
<td>21.17</td>
<td>3.44</td>
</tr>
<tr>
<td>LHeC Rs = 5</td>
<td>33.04fb</td>
<td>0.657pb</td>
<td>( \ell^- + \geq 1 ) b-jet(s) ( M_{\ell b} &lt; 160\text{GeV} )</td>
<td>93fb</td>
<td>21.21</td>
<td>9.63</td>
</tr>
<tr>
<td>FCC-eh Rd = 10</td>
<td>67.23fb</td>
<td>4.51pb</td>
<td>( \ell^- + \geq 1 ) b-jet(s) ( M_{\ell b} &lt; 160\text{GeV} )</td>
<td>2pb</td>
<td>54.84</td>
<td>11.01</td>
</tr>
<tr>
<td>FCC-eh Rs = 5</td>
<td>224.8fb</td>
<td>4.51pb</td>
<td>( \ell^- + \geq 1 ) b-jet(s) ( M_{\ell b} &lt; 160\text{GeV} )</td>
<td>2pb</td>
<td>56.5</td>
<td>37.65</td>
</tr>
</tbody>
</table>
Signal II:
\[ pe^- \rightarrow \nu_e W^b \rightarrow \nu_e \ell^- \nu_\ell b \]
Signal II:

\[ p e^- \rightarrow \nu_e W^- \bar{b} \rightarrow \nu_e \ell^- \nu_\ell \bar{b} \]

<table>
<thead>
<tr>
<th></th>
<th>( \sigma \times \text{Br}(W \rightarrow \ell \nu_\ell) )</th>
<th>( B_{\text{initial}} )</th>
<th>( \text{optimized cut} )</th>
<th>( B_{\text{optimized}} )</th>
<th>( \epsilon_{\text{signal}}[%] )</th>
<th>( \text{SS}_{\text{lab}}^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_{e^-} = 80% )</td>
<td>( 0.16 \text{fb} )</td>
<td>0.657pb</td>
<td>( \ell^- + \geq 1 \text{ Bjet(s)} ) ( M_{T_{\ell \bar{b}}} &gt; 300 \text{GeV} )</td>
<td>0.048fb</td>
<td>4.34</td>
<td>1.28</td>
</tr>
<tr>
<td>LHC ( R_d = 10 )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>LHC ( R_s = 5 )</td>
<td>0.135fb</td>
<td>0.657pb</td>
<td>( \ell^- + \geq 1 \text{ Bjet(s)} ) ( M_{T_{\ell \bar{b}}} &gt; 220 \text{GeV} ) ( p_T^b &gt; 140 \text{GeV} )</td>
<td>0.127fb</td>
<td>5.74</td>
<td>0.91</td>
</tr>
<tr>
<td>FCC-eh ( R_d = 10 )</td>
<td>2.75fb</td>
<td>4.51pb</td>
<td>( \ell^- + \geq 1 \text{ Bjet(s)} ) ( M_{T_{\ell \bar{b}}} &gt; 380 \text{GeV} )</td>
<td>5.58fb</td>
<td>22.47</td>
<td>10.91</td>
</tr>
<tr>
<td>FCC-eh ( R_s = 5 )</td>
<td>3.1fb</td>
<td>4.51pb</td>
<td>( \ell^- + \geq 1 \text{ Bjet(s)} ) ( M_{T_{\ell \bar{b}}} &gt; 260 \text{GeV} )</td>
<td>12.58fb</td>
<td>26.24</td>
<td>9.7</td>
</tr>
</tbody>
</table>
To be updated soon!
study at the ep collider

\[
SS = \frac{|A(\eta) - A^{\text{SM}}|}{\sqrt{(N^+ + N^-)^{-1} + \Delta_{\text{sys}}^2}}
\]

\[
R_d = \frac{V_{\text{dev.}}^{\text{td}}}{V_{\text{fit}}^{\text{td}}}
\]

1ab-1, LHeC, Rd \sim 4.4; FCC-eh, Rd \sim 2.4

1ab-1, LHeC, Rs \sim 1.58; FCC-eh, Rs \sim 1.1

Parton Level, detector effective should be included.
study at the ep collider

\[ SS = \frac{|A(\eta) - A^{SM}|}{\sqrt{(N^+ + N^-)^{-1} + \Delta^2_{sys}}} \]

\[ R_d = \frac{V_{td}^{dev.}}{V_{fit}^{td}} \]

1ab-1, LHeC, Rd \sim 4.4; FCC-eh, Rd \sim 2.4

3sigam, Rd \sim 13.75

FCC-eh, 2 ab-1, 3sigma, Rd \sim 7.48

Parton Level, detector effective should be included.

To be updated soon!
1. In this talk we present a phenomenological study on $V_{tx}$, $(x=d,s)$ measurement in top sector at the $ep$ colliders.

2. This work is still updating, comments are welcomed and results will be revised.

3. More studies in top physics at the $ep$ colliders are welcomed.