Extended Higgs sectors and high-energy flavour dynamics: what we can expect from experiments

Philipp Roloff (CERN)
14/05/2019
Granada Conference Center
Topics of this presentation

This talk: prospects of future collider facilities in the following areas

Extended Higgs sectors:

• Standard Model + real scalar singlet: can lead to a strong 1\textsuperscript{st} order EW phase transition
• Two-Higgs doublet models: heavy MSSM Higgs bosons as example
• Doubly-charged Higg bosons: exist in type-II seesaw models
→ connection to neutrino masses

High-energy flavour dynamics:

• FCNC effects in top-quarks physics: decays and EFT analysis of high-energy processes
• Leptoquarks: renewed interest triggered by flavour anomalies

→ see the next talk by Veronica Sanz for the theoretical context
A few caveats

• The topics listed on the previous slide were chosen to well represent the input provided to the strategy process by the various future collider communities.

• Results shown in the following are based on very different levels of sophistication: from generator-level estimates up to full detector simulations → differences will be mentioned if relevant.

• In some cases projections were not available from all collider options → physics capabilities typically most dependent on centre-of-mass energy and integrated luminosity (especially for lepton colliders).

• Unless stated explicitly, HL-LHC projections are for one experiment (3 ab⁻¹).

• Invisible and exotic Higgs decays (e.g. to new scalars), flavour physics at the Z pole covered in other presentations.
**Reminder: collider parameters**

<table>
<thead>
<tr>
<th>Collider</th>
<th>Type</th>
<th>( \sqrt{s} )</th>
<th>Call to ( P ) [%]</th>
<th>N(Det.)</th>
<th>( \mathcal{L}_{\text{inst}} ) [10^{34} cm^{-2} s^{-1}]</th>
<th>( \mathcal{L} ) [ab⁻¹]</th>
<th>Time [years]</th>
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<td>20</td>
</tr>
<tr>
<td>FCC-hh</td>
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<td>25</td>
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<tr>
<td>FCC-ee</td>
<td>( ee )</td>
<td>( M_Z )</td>
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<td>100/200</td>
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<td>4</td>
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<td></td>
<td></td>
<td>( 2M_W )</td>
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<td>240 GeV</td>
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<td>2</td>
<td>7</td>
<td>5</td>
<td>3</td>
</tr>
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<td></td>
<td>( 2m_{top} )</td>
<td>0/0</td>
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<td>0.8/1.4</td>
<td>1.5</td>
<td>5</td>
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<td></td>
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<td></td>
<td></td>
<td>(±1)</td>
</tr>
<tr>
<td>ILC</td>
<td>( ee )</td>
<td>250 GeV</td>
<td>±80/±30</td>
<td>1</td>
<td>1.35/2.7</td>
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<td>350 GeV</td>
<td>±80/±30</td>
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<td>1.8/3.6</td>
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<tr>
<td>CEPC</td>
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<td>17/32</td>
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<td>( 2M_W )</td>
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<td>2</td>
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<td>1</td>
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<td></td>
<td></td>
<td>240 GeV</td>
<td>0/0</td>
<td>2</td>
<td>3</td>
<td>5.6</td>
<td>7</td>
</tr>
<tr>
<td>CLIC</td>
<td>( ee )</td>
<td>380 GeV</td>
<td>±80/0</td>
<td>1</td>
<td>1.5</td>
<td>1.0</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.5 TeV</td>
<td>±80/0</td>
<td>1</td>
<td>3.7</td>
<td>2.5</td>
<td>7</td>
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<td></td>
<td></td>
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<td>±80/0</td>
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<td>6.0</td>
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<td>8</td>
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<td></td>
<td>(±4)</td>
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<td>LHeC</td>
<td>( ep )</td>
<td>1.3 TeV</td>
<td>-</td>
<td>1</td>
<td>0.8</td>
<td>1.0</td>
<td>15</td>
</tr>
<tr>
<td>HE-LHeC</td>
<td>( ep )</td>
<td>2.6 TeV</td>
<td>-</td>
<td>1</td>
<td>1.5</td>
<td>2.0</td>
<td>20</td>
</tr>
<tr>
<td>FCC-eh</td>
<td>( ep )</td>
<td>3.5 TeV</td>
<td>-</td>
<td>1</td>
<td>1.5</td>
<td>2.0</td>
<td>25</td>
</tr>
</tbody>
</table>

**Notes:**
- pp colliders
- e⁺e⁻ colliders
- ep colliders

*arXiv:1905.03764*
Potential for SM Higgs and a single real scalar:

\[ V_0 = -\mu^2 |H|^2 + \lambda |H|^4 - \frac{1}{2} \mu_s^2 S^2 + \frac{1}{4} \lambda_s S^4 + \lambda_{HS} |H|^2 S^2 \]

Higgs-singlet mixing:

\[ h = h_0 \cos \gamma + S \sin \gamma \]
\[ \phi = S \cos \gamma - h_0 \sin \gamma \]

Equivalence theorem:

\[ \text{BR}(\phi \to hh) = \text{BR}(\phi \to ZZ) = 25\% \]

Indirect sensitivity:

EFT fit by ECFA WG on Higgs at future colliders

arXiv:1905.03764
Potential for SM Higgs and a single real scalar

\[ V_0 = -\mu^2 |H|^2 + \lambda |H|^4 - \frac{1}{2} \mu_S S^2 + \frac{1}{4} \lambda_S S^4 + \lambda_{HS} |H|^2 S^2 \]

Higgs-singlet mixing:
\[ h = h_0 \cos \gamma + S \sin \gamma \]
\[ \phi = S \cos \gamma - h_0 \sin \gamma \]

Sensitivity from Higgs couplings:
\( c_H \) is overall scaling of the Higgs couplings (using sensitivity for this individual operator)

Sensitivity from EW precision observables:
S and T parameters derived from from \( c_{\phi_{WB}} \) and \( c_T \) (simultaneous fit of both operators)

Equivalence theorem:
\[ \text{BR}(\phi \rightarrow hh) = \text{BR}(\phi \rightarrow ZZ) = 25\% \]

<table>
<thead>
<tr>
<th>Facility</th>
<th>95% C.L. limit on ( \sin^2 \gamma )</th>
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<tr>
<td>HL-LHC</td>
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<td>HE-LHC</td>
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<td>ILC 250 GeV</td>
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<td>ILC 500 GeV</td>
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<td>CLIC 380 GeV</td>
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<td>CLIC 1.5 TeV</td>
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<tr>
<td>FCC-ee/-eh/-hh</td>
<td>0.0034</td>
</tr>
</tbody>
</table>
SM + singlet: direct searches

Lepton colliders:

• CLIC study of $e^+e^- \rightarrow \nu\bar{\nu}\phi$ (Delphes) at 1.5 and 3 TeV: $\phi \rightarrow hh \rightarrow b\bar{b}b\bar{b}$ most powerful channel

• $\mu^+\mu^- \rightarrow \nu\bar{\nu}\phi; \phi \rightarrow hh$ studied on generator level for 5 ab$^{-1}$ at $\sqrt{s} = 6$ and 20 ab$^{-1}$ at 14 TeV (also valid for an $e^+e^-$ collider based on novel accelerator techniques)

Sec. 4.2 of CERN-2018-009-M
JHEP 11,144 (2018)

Hadron colliders:

• Current LHC sensitivity dominated by $\phi \rightarrow ZZ$ search (36 ab$^{-1}$ at 13 TeV)

JHEP 06, 127 (2018)

• Extrapolation using quark parton luminosities to HL-LHC (3 ab$^{-1}$ at 14 TeV), HE-LHC (15 ab$^{-1}$ at 27 TeV), FCC-hh (30 ab$^{-1}$ at 100 TeV)

Sec. 6.1.4 of CERN-LPCC-2018-005
JHEP 11,144 (2018)
**SM + singlet: precision Higgs**

- $e^+e^-$ colliders provide significant improvement compared to hadron colliders
- NB: The lines for FCC-ee and CEPC are identical
SM + singlet: S and T

- Higgs couplings are better than S and T for all collider options
- NB: The EPWO curves for HL-LHC and LHeC are identical
At HL-LHC, HE-LHC and CLIC direct and indirect searches provide complementary information.

NB: FCC-hh and the muon collider will follow on the next slide.
SM + singlet: high-mass region

• Direct reach at FCC-hh better than precision Higgs couplings below 12 TeV
No mixing limit

Potential for SM Higgs and a single real scalar:

\[ V_0 = -\mu^2 |H|^2 + \lambda |H|^4 - \frac{1}{2} \mu_S^2 S^2 + \frac{1}{4} \lambda_S S^4 + \lambda_{HS} |H|^2 S^2 \]

Unbroken \( Z_2 \) symmetry:
no Higgs-singlet mixing → new scalar escapes undetected

Sensitivity from Higgs couplings: limit on \( \lambda_{HS} \) from \( c_H \)

Direct sensitivity:

Hadron colliders:
FCC-hh study of \( pp \rightarrow \phi \phi jj \) using VBF jets (Delphes)

Lepton colliders:
No projection for \( e^+e^- \rightarrow \phi \phi e^+e^- \) or \( \mu^+\mu^- \rightarrow \phi \phi \mu^+\mu^- \) available yet

JHEP 11, 127 (2014)
Sec. 11 of CERN-ACC-2018-0056
No mixing: direct vs. indirect

NB: The lines for FCC-ee and CEPC are identical
Scalar searches using recoil method

- A lepton collider could search for new scalars with a small (but non-vanishing) coupling to the Z boson using the recoil technique:

\[ M_{\text{recoil}}^2 = (\sqrt{s} - E_Z)^2 - |\vec{p}_Z|^2 \]

→ independent of new scalar decay

- Studied for ILC at 250 and 500 GeV, but also possible at CEPC, FCC-ee and 380 GeV CLIC

- Less powerful at high energy (lower cross section, detector resolution, ISR & linear collider luminosity spectra)

\[ \sin^2(\theta): \text{cross section limit normalised to the cross section for a SM Higgs of the same mass} \]

arXiv:1903.01629
Heavy MSSM Higgs bosons

Lepton colliders: mass reach generally close to $\sqrt{s}/2$ independent on $\tan \beta$, e.g. using $e^+e^- \rightarrow H^+H^-$ or $e^+e^- \rightarrow AH$

Hadron colliders: access to the highest possible masses, benchmarks discussed in the following:

- $A/H \rightarrow \tau^+\tau^-$ at HL-LHC
- $pp \rightarrow A \rightarrow ZH$ at HL-/HE-LHC
- MSSM Higgs bosons at FCC-hh
**A/H → \(\tau^+\tau^-\) at HL-LHC**

- Combination of CMS and ATLAS Projections (6 ab\(^{-1}\) in total)
- Direct access to heavy Higgs bosons of 2.5 TeV for \(\tan \beta > 50\)
- Region of low \(\tan \beta\) could be improved by \(A/H \rightarrow \tau^+\tau^-\)

**M\(_h^{125}\) scenario:**
- \(\tan \beta < 6 \rightarrow\) light Higgs below 122 GeV
- \(M_A < 900\) excluded by Higgs signal strengths
(dependent on the benchmark scenario used)

Sec. 9.5 of CERN-LPCC-2018-04
**Benchmark points:**

- Type-I and Type-II 2HDM in the alignment limit (lighter CP-even Higgs h has SM couplings)
- $m_A - m_H = 100$ GeV and 200 GeV

Extrapolation of $A \rightarrow ZH; \ Z \rightarrow \ell^+\ell^-; \ H \rightarrow b\bar{b}$

search from ATLAS


For Type-II 2HDM the region of low $\beta$ and and large $m_H$ could be covered by:

$A \rightarrow ZH; \ Z \rightarrow \ell^+\ell^-; \ H \rightarrow tt$

- "gg": gluon fusion
- "bb": bb-associated production

Sec. 9.4 of CERN-LPCC-2018-04
MSSM Higgs bosons at FCC-hh

pp → bbH⁰/A → bbττ (large tanβ)
pp → bbH⁰/A → ttbb (int. tanβ)
pp → ttH⁰/A → tttt (low tanβ)

• Exclusion limits better than 5 TeV for H⁰/A (20 TeV at low tan β)
• Exclusion limits in the range 10 - 15 TeV for H⁺

95% C.L. exclusion limits

JHEP 01, 018 (2017)
JHEP 11, 124 (2015)
Sec. 6.7 of CERN-TH-2016-113
Doubly-charged Higgs bosons

• Type II seesaw: hadron colliders
• Type II seesaw: lepton colliders
Type II seesaw: hadron colliders

- **Type II seesaw**: new scalar triplet couples to SM leptons to produce the light neutrino masses (no sterile neutrinos)

- Doubly charged Higgs production in hadron collisions:
  \[ pp \rightarrow Z^*/\gamma^* \rightarrow H^{++}H^{--} \quad \text{and} \quad pp \rightarrow W^* \rightarrow H^{++/-}H^{-+/+} \]

- **Benchmark**: \[ H^{++}H^{--} \rightarrow \tau^+_h \ell^+/-\ell^-/\pm; \quad \tau^{\pm} \rightarrow \pi^{\pm} \nu \]
  → tau polarisation can help to discriminate between different heavy scalar mediated neutrino mass mechanisms

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JHEP 09, 079 (2018)
Sec. 5.1 of CERN-LPCC-2018-005

\[ M(H^{\pm\pm}) > 1930 \text{ GeV} / 2070 \text{ GeV for NH / IH using } 3 \text{ ab}^{-1} \text{ at } 100 \text{ TeV} \quad (3 \text{ sigma}) \]
Type II seesaw: lepton colliders

- Pair production cross section almost flat up to the kinematic limit: \( e^+e^- \rightarrow H^+H^- \)

**Benchmark:** triplet vev \( v_\Delta = 10^{-2} \) GeV

\( \rightarrow \text{BR}(H^+ \rightarrow W^+W^-) = 100\% \)
(cross section in VBF at LHC very small)

- CLIC study for 380 GeV and 3 TeV (Delphes) shows sensitivity almost up to the kinematic limit
(also expected for other e\(^+\)e\(^-\) colliders)

\[ \sqrt{s} = 380 \text{ GeV:} \]

<table>
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<tr>
<th>Mass (GeV)</th>
<th>( n_s )</th>
<th>( \mathcal{L} ) (fb(^{-1}))</th>
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<tr>
<td>121</td>
<td>1.54</td>
<td>1054.14</td>
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<tr>
<td>137</td>
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<td>159</td>
<td>10.48</td>
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<td>172</td>
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<tr>
<td>184</td>
<td>2.69</td>
<td>345.48</td>
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</table>

\[ \sqrt{s} = 3 \text{ TeV:} \]

<table>
<thead>
<tr>
<th>Masses (GeV)</th>
<th>( n_s ) (2,3-tagged ( \mathcal{L} = 500 \text{ fb}^{-1} ))</th>
<th>( \mathcal{L} ) (fb(^{-1})) (with 2.3-tagged)</th>
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<td>17.96(2-tag)</td>
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<td>1000</td>
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<td>1400</td>
<td>3.95(3-tag)</td>
<td>801.15</td>
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</table>

\( \rightarrow \text{Luminosity for 5}\sigma \text{ discovery smaller than expectation at CLIC} \)

NB: FCC-hh would be sensitive to \( H^+H^- \rightarrow W^+W^+W^-W^- \) below \( \approx 1.7 \text{ TeV} \) for \( v_\Delta > 10^{-4} \) GeV

\[ \sqrt{s} = 380 \text{ GeV:} \]

\( \sigma(e^+e^- \rightarrow H^+H^-) \) (380 GeV)

\( \sigma(e^+e^- \rightarrow H^+H^-) \) (3 TeV)

\( \sigma(pp \rightarrow H^+H^-) \) (13 TeV)

\[ \sqrt{s} = 3 \text{ TeV:} \]

\( \text{BR}(H^+ \rightarrow W^+W^+) \)

\( \text{BR}(H^+ \rightarrow W^+W^+) \)

\nb\text{NB: M}(H^{++}) < M(H^+) \)

JHEP 01, 101 (2019)

Sec. 7.1 of CERN-2018-009-M
High-energy flavour dynamics

• Top-quark FCNC: branching ratios
• Top-quark FCNC: Effective Field Theory
• Leptoquarks
Top-quark FCNC: $t \rightarrow Hq$ branching ratios

**FCC-e**h and **LHeC:**
BR($t \rightarrow Hu$) from the process $ep \rightarrow \nu_e Hb$; $H \rightarrow b\bar{b}$

**500 GeV ILC and 380 GeV CLIC:**
A few million top decays near threshold, $H \rightarrow b\bar{b}$ decays used, best suited for decays with charm quarks

**HL-LHC:**
Based on ATLAS studies using $H \rightarrow b\bar{b}$ and $H \rightarrow \gamma\gamma$

**FCC-hh:**
Large statistics allows usage of clean $H \rightarrow \gamma\gamma$ decays, combination of semi-leptonic and fully hadronic final states

**HL-/HE-LHC:** Sec. 8.1 of CERN-LPCC-2018-06
**ILC:** Sec. 10.3 of arXiv:1903.01629
**CLIC:** Sec. 10 of arXiv:1807.02441
**LHeC:** EPPSU submission #159
**FCC-hh/-eh:** Sec. 6 of CERN-ACC-2018-0056
Top-quark FCNC: $t \rightarrow Zq$ branching ratios

FCC-ee:
BR$(t \rightarrow Zq)$ from anomalous single top production: $e^+e^- \rightarrow Z^*/\gamma^* \rightarrow t\bar{q} \ (t\bar{q})$
$\rightarrow$ further improvement from combination of both energy stages possible

FCC-eh and LHeC:
BR$(t \rightarrow Zq)$ from NC DIS production of single top quarks

HL-LHC:
Based on ATLAS study for $tt \rightarrow bWqZ \rightarrow b\ell\nuq\ell\ell$

FCC-hh:
Estimate using HL-LHC projection

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HL-/HE-LHC: Sec. 8.1 of CERN-LPCC-2018-06
ILC: Sec. 10.3 of arXiv:1903.01629
CLIC: Sec. 10 of arXiv:1807.02441
LHeC: EPPSU submission #159
FCC-hh/-eh: Sec. 6 of CERN-ACC-2018-0056
Top-quark FCNC: $t \rightarrow \gamma q$ branching ratios

**FCC-ee:**
BR($t \rightarrow Z q$) from anomalous single top production: $e^+ e^- \rightarrow Z^*/\gamma^* \rightarrow t \bar{q}$ ($t \bar{q}$)

**FCC-eh and LHeC:**
BR($t \rightarrow Z q$) from NC DIS production of single top quarks

**500 GeV ILC and 380 GeV CLIC:**
A few million top decays near threshold, $H \rightarrow b \bar{b}$ decays used, best suited for decays with charm quarks

**HL-LHC:**
BR($t \rightarrow \gamma u$) and BR($t \rightarrow \gamma u$) from CMS study of single top production in association with a photon

**FCC-hh:**
Delphes study focussing on the boosted top regime ($p_T > 400$ GeV)

**HL-/HE-LHC:** Sec. 8.1 of CERN-LPCC-2018-06

**ILC:** Sec. 10.3 of arXiv:1903.01629

**CLIC:** Sec. 10 of arXiv:1807.02441

**LHeC:** EPPSU submission #159


**FCC-hh/-eh:** Sec. 6 of CERN-ACC-2018-0056
Top-quark FCNC: $t \to gq$ branching ratios

**HL-LHC:**
BR$(t \to gu)$ and BR$(t \to gu)$ from CMS study of single top production

**HE-LHC:**
BR$(t \to gu)$ and BR$(t \to gu)$ from CMS study of single top production

**HL-/HE-LHC:** Sec. 8.1 of CERN-LPCC-2018-06
**ILC:** Sec. 10.3 of arXiv:1903.01629
**CLIC:** Sec. 10 of arXiv:1807.02441
**LHeC:** EPPSU submission #159
**FCC-hh/-eh:** Sec. 6 of CERN-ACC-2018-0056

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Top-quark FCNC: $t \rightarrow gq$ branching ratios

**Conclusions:**
- Complementary set of possible measurements in $e^+e^-, ep$ and $pp$ colliders
- Not all possibilities explored yet
- Generally improvements by 1-2 orders of magnitude compared to HL-LHC possible

**HL-LHC:**
BR($t \rightarrow gu$) and BR($t \rightarrow gu$) from CMS study of single top production

**HE-LHC:**
BR($t \rightarrow gu$) and BR($t \rightarrow gu$) from CMS study of single top production

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**HL-/HE-LHC:** Sec. 8.1 of CERN-LPCC-2018-06

**ILC:** Sec. 10.3 of arXiv:1903.01629

**CLIC:** Sec. 10 of arXiv:1807.02441

**LHeC:** EPPSU submission #159


**FCC-hh/-eh:** Sec. 6 of CERN-ACC-2018-0056
Sensitivity to top-quark FCNC effects can be studied using EFT

**Input:** limits on FCNC branching ratios, limits on $e^+e^- \rightarrow tj$ from LEP II

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**White marks:** individual limits

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Sec. 8.1 of CERN-LPCC-2018-06
Top-quark FCNC: $e^+e^- \rightarrow tj$ at CLIC

95% C.L. limits on top-quark FCNC operator coefficients

Black arrows: decays at CLIC (see slide X)
Red arrows: current LHC
Magenta arrows: HL-LHC projections
Dots: CLIC without beam polarisation

- The high-energy runs significantly improve the sensitivity for “four-fermion” operators
- $e^+e^- \rightarrow tj$ much more powerful than the decays at high-energy lepton colliders
Leptoquarks decaying to $\tau$ and $b$ (1)

- CMS study of single and double leptoquark production (Delphes)

- 5σ discovery significance for masses below 1.5 TeV (double production) and 1 TeV (single production)

CMS-PAS-FTR-18-028
Sec. 5.2.3 of CERN-LPCC-2018-005
Leptoquarks decaying to $\tau$ and $b$ (2)

Triplet $S_3 = (\bar{3},3,-1/3)$:

**U**$_\mu$ = $\bar{3},1,2/3$:

- $b \rightarrow c\tau\nu$ anomaly suggests rather light LQ that couples predominantly to the third generation fermions of the SM → see talk by Veronica Sanz
- LQ pair production and $pp \rightarrow \tau^+\tau^-$ complementary
- Small improvement in mass reach for $S_3$ at from CLIC up to $g_3 \approx 1.5$
- HE-LHC improves the direct mass reach by more than a factor 2 compared to HL-LHC

Sec. 3.3 of CERN-2018-009-M

NB: Background negligible in multi-TeV $e^+e^-$ collisions ($2b2\tau$ final states)

Sec. 5.3.2 of CERN-LPCC-2018-005
More projections

**HL-/HE-LHC, FCC-hh:** \( gg \rightarrow S_3 S_3^* \rightarrow (\mu^- j)(\mu^+ j) \)
and \( Z' \rightarrow \mu^+ \mu^- \) motivated by anomaly in \( b \rightarrow s \ell \ell \)

**Example:** scalar LQ coupling to d-quark and electron

- If accessible, FCC-eh could measure the LQ properties (fermion number, spin, coupling, ...)

Sec. 5.2 of CERN-LPCC-2018-005
Sec. 14.3 of CERN-ACC-2018-0056
Some observations

- **Substantial improvement** with respect to HL-LHC possible for all discussed physics topics

- **Large amount of complementarity:**
  - Direct and indirect sensitivity (e.g. SM + heavy singlet, heavy MSSM Higgs bosons)
  - Hadron and lepton collisions (e.g. doubly charged Higgs)
  - Different energy stages of a lepton collider (e.g. top-quark FCNC effects)

Thank you!
Backup slides
Lepton colliders

• Generally, mass reach close to $\sqrt{s}/2$ for all values of $\tan \beta$

• Beam polarisation and threshold scans might help to constrain the underlying theory

• **Example:** $e^+e^- \rightarrow HA$ at 3 TeV CLIC

• Combination of the $b\bar{b}b\bar{b}$, $b\bar{b}t\bar{t}$ and $t\bar{t}t\bar{t}$ final states

• Similar reach for $e^+e^- \rightarrow H^+H^-$

Sec. 1 of CERN-2012-003
## FCNC top branching ratios: input

<table>
<thead>
<tr>
<th>BR $\times 10^5$</th>
<th>HL-LHC</th>
<th>HE-LHC</th>
<th>ILC</th>
<th>CLIC</th>
<th>LHeC</th>
<th>FCC-ee</th>
<th>FCC-ee</th>
<th>FCC-hh</th>
<th>FCC-eh</th>
</tr>
</thead>
<tbody>
<tr>
<td>95% C.L.</td>
<td>14 TeV</td>
<td>27 TeV</td>
<td>500 GeV</td>
<td>380 GeV</td>
<td>1.3 TeV</td>
<td>240 GeV</td>
<td>365 GeV</td>
<td>100 TeV</td>
<td>3.5 TeV</td>
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<tr>
<td>t $\rightarrow$ Hc</td>
<td>$\approx$ 3</td>
<td>15</td>
<td></td>
<td></td>
<td>1.6</td>
<td></td>
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<tr>
<td>t $\rightarrow$ Hu</td>
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<tr>
<td>t $\rightarrow$ Hq</td>
<td>10</td>
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</tr>
<tr>
<td>t $\rightarrow$ Zq</td>
<td>2.4</td>
<td>4</td>
<td>3</td>
<td>5</td>
<td>$\approx$ 0.1</td>
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<td>- 5.8</td>
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<td></td>
</tr>
<tr>
<td>t $\rightarrow$ γc</td>
<td>7.4</td>
<td>$\approx$ 1</td>
<td>2.6</td>
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<td>0.024</td>
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<td>t $\rightarrow$ γu</td>
<td>0.86</td>
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<td>0.018</td>
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<td>0.085</td>
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<td>t $\rightarrow$ g_c</td>
<td>3.2</td>
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<td>t $\rightarrow$ g_u</td>
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<td>0.056</td>
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</table>

### Comments:
- $q = u, c$ inclusive
- FCC-ee numbers for 240 GeV and 365 GeV will be combined in the future

### References:
- HL-/HE-LHC: Sec. 8.1 of CERN-LPCC-2018-06
- ILC: Sec. 10.3 of arXiv:1903.01629
- CLIC: Sec. 10 of arXiv:1807.02441
- LHeC: EPPSU submission #159
- FCC-hh/-eh: Sec. 6 of CERN-ACC-2018-0056
Strong first-order EW phase transition

- $h_2 \rightarrow h_1 h_1$
- $4\tau$ and bb$\gamma\gamma$ final states (generator level)
- Benchmark points minimising and maximising the cross section

Comments:
- The $e^+e^-$ numbers in this plot are outdated

\[ h_1 = h \cos \theta + s \sin \theta \]
\[ h_2 = -h \sin \theta + s \cos \theta \]
Direct vs. indirect constraints

- Doubly-charged scalar which is a singlet under the SU(2) weak symmetry of the SM

Sec. 7.3 of CERN-2018-009-M

Direct: $e^+e^- \rightarrow S^{++}e^-e^-$

Indirect: $e^+e^- \rightarrow e^+e^-$ and $\mu^+\mu^-$
$W' \rightarrow \tau \nu$ at HL-LHC

CMS-PAS-FTR-18-030
LQ search strategy

\[ L \supset y_{q\ell} \bar{q} \ell \Phi + \text{h.c.} \]

\[ p p \rightarrow \Phi \Phi \]

\[ p p \rightarrow \ell \ell \]

JHEP 05, 126 (2018)