Electro-weak and top physics beyond the LHC

Mini-review of future collider top/EW prospects
Marcel Vos (IFIC, CSIC/UV, Valencia, Spain)
EPS-HEP, Venice, 2017
Future projects

Particle physics' new energy-frontier installation

HL-LHC program runs until 2037

Lead time is ~15 years. Need to approve a project soon to minimize the Ph.D. gap between the end of the HL-LHC and the start of the new project.

For consideration by funding agencies proposals must:
- a - be based on completed R&D and industrialization
- b - perform a detailed engineering design & costing

(a) excludes e.g. a muon collider from the current discussion
(b) is our homework towards the European strategy update in 2019
Linear $e^+e^-$ colliders

Accelerating cavities
SLC was built with 17 MV/m cavities (1989-1998)

Intense R&D and industrialization program to improve acceleration gradient

→ 35 MV/m super-conducting cavities  
   (mature & industrialized, XFEL/ILC)

→ 100 MV/m “warm” cavities  
   (concept proven in large-scale tests, CLIC)

→ Plasma wakefield (when?)

Excellent overview of the future of cold and warm technology
Note: there is more to a machine....positron source, final focus
Circular pp/e⁺e⁻ colliders

Bending magnets
Tevatron had 4 Tesla superconducting magnets (1990-95, 2001-11)
LHC has 8 Tesla superconducting double-channel magnets

Nb3Sn magnets are a key R&D program in current European strategy

16 T - as assumed for HL-LHC, HE-LHC, SPPC, FCChh - was achieved in short racetrack magnet, “accelerator-like” magnet to reach 14-15 T soon

Recent status update here and by F. Savary in session on accelerators
Top and EW physics at a lepton collider

**Lepton collider projects:**

- **ILC (TDR, negotiations):**
  250, 500, 1000 GeV
- **CLIC (CDR):**
  380, 1500, 3000 GeV
- **CEPC (pre-CDR, TDR ~2020):**
  250 GeV → no $t\bar{t}$ production
- **FCC-ee (CDR 2018):**
  90, 160, 240, 350, 370 GeV

*Detailed designs for ILC/CLIC CEPC/FCC-ee to provide CDR*

**Clear complementarity:**

*Circular is superior at low energy, linear is the only option at high energy*
Precision physics at lepton colliders

For precision there is nothing like $e^+e^-$

Machine: per mille level control over luminosity, polarization and beam energy calibration

Theory: no PDFs, small QCD corrections
Predictions at few per-mille level already today!

Selection: democratic cross sections allow for truly inclusive measurements (no trigger!)

Statistics: smaller samples (decreasing with energy for s-channel processes, increasing for t-channel)

Challenge: excellent detectors to make sure the experiment matches few per mille theory precision

See also: Chokoufè et al., arXiv:1609.03390
Top and EW physics at the next hadron collider?

Projects for the next very large hadron collider

16 Tesla magnets: $\sqrt{s}/L \sim 1$ TeV/km

- **SPPC** (China, conceptual design end 2016)
  100 km (TeV)

- **FCChh** (CERN, CDR ~2018)
  100 km (TeV)

- **High-E LHC**
  LEP/LHC tunnel 27 km (or TeV)
Physics at hadron colliders: HL-LHC

Hadron colliders are top quark factories

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- **Access to remote corners of phase space and rare processes**

  The increase in the high-energy tail is even more pronounced: analyses of boosted top quark pair production are on their way to become bread-and-butter physics

  For many rare processes (associated production of top and gauge bosons, ttH, FCNC decays, vector boson scattering) analyses are still statistics-limited. We’ll just let the machine do the dirty work and collect the benefits..

Still many areas where we probe top quark and gauge boson interactions in new ways. There might be surprises. Optimize analyses for BSM sensitivity (informed by EFT or concrete models)

HL-LHC prospect studies for top and EW physics are rare (but increasing).
Physics at hadron colliders: brute force

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Top and W/Z production rates of FCChh and SPPC are off the chart!
10 ab⁻¹ at 100 TeV yields $10^{12}$ top quark pairs

Access to $\sqrt{s} = 10-20$ TeV and processes you wouldn't dream of elsewhere
Physics at hadron colliders: brute force

Hadron colliders are top quark factories

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tt production

|             | 57 k | 2.6 M | 15.5 M | 155 M | 1.55 G |

FCChh and SPPC

Challenge (arXiv:1507.08169): “one of the key obstacles to exploiting the immense statics available at hadron colliders for precision measurements, is the intrinsic difficulty in performing accurate absolute rate predictions”

Work-arounds later in the talk
80-100 TeV pp collisions

Consequences of “top as a light quark”

Production much more forward → dedicated experiment a la LHCb?
M. Mangano, TOP2015

Must treat production differently: \( g \to t\bar{t} \) splitting, top quark PDF

Must deal with ultra-boosted decay topologies
Charged substructure, A. Larkoski, arXiv:1511.06495
Pushing calorimeter granularity, arXiv:1412.5951
Full simulation starting → Chekanov @ ICHEP

See: M. Selvaggi, in this track

FCChh BSM summary: arXiv:1606.00947

Mass reach (2.5-3 TeV today) expected to scale with center-of-mass energy
Direct searches vs. Indirect sensitivity

A new collider's primary aim: discovery → searches

Searches a $\bar{p}p$ colliders provide mass reach up to fraction of $\sqrt{s}$
Sp$\bar{p}$S (540 GeV) discovered W, but not top
Tevatron (1.96 TeV) discovered top, but not Higgs boson

Even lepton colliders cannot fully cover everything up to $m = \sqrt{s}$
LEP (208 GeV) missed the Higgs boson (125 GeV)

Indirect sensitivity can exceed $\sqrt{s}$ significantly
LEP EW fit felt the top quark and Higgs bosons, B-factories probe high scales

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2} \sum_i C_i O_i + \mathcal{O} \left( \Lambda^{-4} \right)$$

Express BSM sensitivity in terms of expected limits on anomalous form factors or D6/D8 operators coefficients in EFT
EW fit
EW fit

LEP/SLD legacy results completed by Tevatron/LHC:
precise measurements of W-boson and top quark mass
Discovery of the Higgs boson

Gfitter, arXiv:1407.3792
Snowmass EW, arXiv:1310.6708
New $e^+e^-$ machines exceed LEP and SLC luminosity by orders of magnitude (ILC GigaZ or FCC-ee TeraZ)

Higher-performance detectors and more sophisticated theory/Monte Carlo

**We can take EW fit to next level**

*TLEP physics case, arXiv:1308.6176*  
*Snowmass EW, arXiv:1310.6708*

Exactly how far we get depends on theory progress (see Piccinini, FCC week Berlin)
W-boson mass

W-boson mass extracted from transverse mass distribution of decay products at Tevatron/LHC

Lepton colliders: direct measurement or WW threshold

Prospects for W-boson mass measurements, according to TLEP study:
~ 5 MeV at hadron colliders, down to 1 MeV at lepton colliders

See: E. Locci in this track
Top quark mass

Experiment:
Tevatron/LHC direct measurements today $\sim$500 MeV.
HL-LHC can reach 200-300 MeV (CMS-FTR-13-007-PAS “optimistic, but not unrealistic”)

Theory:
Additional uncertainty for “interpretation” in mass scheme: Hoang et al., arXiv:1608.01318
Challenge: can pole or MS mass extractions reach competitive precision?

Ultimate top quark mass measurement $e^+e^- \rightarrow tt$ threshold scan

Stat. precision 1S/PS mass: $\sim$20 MeV
Experimental systematics: O(30 MeV)
Theory uncertainty: 50 MeV
Requires precise value of $\alpha_s$ (shape fit + 1S $\rightarrow$ MS conversion)
Beneke et al., 1506.06864 [hep-ph]
P. Marquard et al., arXiv:1502.01030
F. Simon, arXiv:1603.04764

See: N. v.d. Kolk in this track.
Recent review: arXiv:1604.08122
Rare EW processes
Vector boson scattering

The measurement that demanded a Higgs boson...

EWK process isolated during run I at the LHC using same-sign WW and WZ production

Forward “tag” jets, high-mass VV' system
ATLAS arXiv:1611.02428
CMS arXiv:1410.6315

Test Higgs-suppression of longitudinal VBS, constrain anomalous couplings (aTGC and aQGC), measure Higgs properties, Campbell, Ellis arXiv:1502.02990

Towards a global fit of a complete vector boson EFT, including all relevant aTGC and aQGCs, and Higgs operators

See: updates by ATLAS and CMS
Limits on anomalous quartic couplings: LHC vs. CLIC

ATLAS run-I, *from Green, Meade, Pleier, arXiv:1610.07572*

CLICdp prospects for 3 TeV, *see poster Matthias Weber*
Vector boson scattering – future hadron colliders

Prospects for HL-LHC: the precision in the measurement of the EWK component cross-section is 10% or better after 3 ab$^{-1}$. Isolate tiny longitudinal component. Limits on aTGCs and aQGC order of magnitude better.

*SMP-14-008-PAS*

Prospects for FCChh/SPPC, Probing high-mass VV production yields very competitive limits on D8 operators

*arXiv:1704.04911*
Top and QCD
Heavy gluon exchange represented by dimension-6 four-fermion operators

Cross-section and $A_C$ provide complementary constraints

LHC vs. Tevatron: use higher boost to produce tight constraints

M. Perelló, M.V., arXiv:1512.07542
Top and QCD

8 TeV fit: resolved and boosted category offer similar sensitivity
Englert et al., arXiv:1607.04304

Indeed, a measurement of the charge asymmetry with $m(tt)>1.2$ TeV and 0.5% precision shrinks the allowed region by a factor 10
arXiv:1512.07542

Inclusive measurement syst-limited
Boosted expected to improve quicker
Top and QCD

Aguilar-Saavedra et al., arXiv:1412.6654

Top quark chromomagnetic and chromoelectric dipole moments

\[ d_v = \frac{\sqrt{2} v m_t}{g_s \Lambda^2} \Re C_{uGq}^{33} \quad d_A = \frac{\sqrt{2} v m_t}{g_s \Lambda^2} \Im C_{uGq}^{33} \]

Ultra-boosted: \( m(\bar{t}t) > 10 \text{ TeV} \)
Top decay to \( b\mu\nu \)
Assume 5% systematic

Further studies would also be desirable to evaluate the complementarity of the measurements discussed in this paper, with those possible with \( e^+e^- \) collisions.

Order of magnitude improvement
Top and Higgs
Top quark Yukawa coupling

Prospects at lepton colliders

**ILC:** 3% with 4 ab\(^{-1}\) at 550 GeV

arXiv:1506.05992

**ILC:** 4% with 1 ab\(^{-1}\) at 1 TeV

arXiv:1409.7157

**CLIC:** 4% with 1.5 ab\(^{-1}\) at 1.4 TeV

arXiv:1608.07538

Prospects for full LHC programme:

\(K_u \to 14-15\% \ (300/fb)\)

Snowmass

\(K_u \to 7-10\% \ (3/ab)\)

Higgs report

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**Note:** 4% stat. from threshold scan (but: large theory uncertainty)
Top quark Yukawa coupling at hadron colliders

The $ttH$ cross section at 100 TeV is 60 times larger than at the LHC

**Relative** cross sections or ratios of processes $ttH/ttZ$ cancel theory uncertainty

<table>
<thead>
<tr>
<th></th>
<th>$\sigma(ttH)$ [pb]</th>
<th>$\sigma(ttZ)$ [pb]</th>
<th>$\frac{\sigma(ttH)}{\sigma(ttZ)}$</th>
</tr>
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<tbody>
<tr>
<td>13 TeV</td>
<td>$0.475^{+5.79%+3.33%}_{-9.04%-3.08%}$</td>
<td>$0.785^{+9.81%+3.27%}_{-11.2%-3.12%}$</td>
<td>$0.606^{+2.45%+0.525%}_{-3.66%-0.319%}$</td>
</tr>
<tr>
<td>100 TeV</td>
<td>$33.9^{+7.06%+2.17%}_{-8.29%-2.18%}$</td>
<td>$57.9^{+8.93%+2.24%}_{-9.46%-2.43%}$</td>
<td>$0.585^{+1.29%+0.314%}_{-2.02%-0.147%}$</td>
</tr>
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**Use data to gain confidence with (scale) uncertainties of ratios:**
Tevatron $A_{FB}$, recent ATLAS $tt/Z$ ratio (*arXiv:1612.03636*)

FCChh fast simulation study:
**1% precision on the top Yukawa coupling (20/ab, 100 TeV)**
*Mangano, Plehn, Reimitz, Schell, Shao, 2015*
Top and FCNC
FCNC interactions

\[
\begin{align*}
pp &\rightarrow t \quad (CDF/ATLAS) \\
pp &\rightarrow tj \quad (D0/CMS) \\
pp &\rightarrow t\gamma/ll \quad (CMS) \\
e^+e^- &\rightarrow tj \quad (LEP2) \\
ep &\rightarrow et \quad (HERA) \\
t &\rightarrow j\gamma/ll \quad (CDF/D0/ATLAS/CMS) \\
t &\rightarrow jh \quad (ATLAS/CMS)
\end{align*}
\]
FCNC interactions

\[ \begin{align*}
pp & \rightarrow t \quad (CDF/ATLAS) \\
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e^+e^- & \rightarrow et \quad (HERA) \\
t & \rightarrow j\gamma/ll \quad (CDF/D0/ATLAS/CMS) \\
t & \rightarrow jh \quad (ATLAS/CMS)
\end{align*} \]
FCNC at lepton colliders

Lepton colliders may provide complementary constraints:

\[ e^+e^- \to tj \text{ production, sensitive to } Ztq \text{ and } \gamma tq \]

Top physics below $t\bar{t}$ production threshold: limits from LEP2 in arXiv:1412.7166

Prospect studies for ILC (hep-ph/0102197) and FCC-ee (arXiv:1408.2090) indicate potential well beyond equivalent BR $< 10^{-4}$

Benign experimental environment for “hard” top decays

Expected limits on $\text{BR}(t \to ch) \times \text{BR}(h \to bb') \sim 10^{-5}$

Zarnecki, vd Kolk, preliminary parton-level study

Order of magnitude better than Snowmass expectation for LHC + lumi upgrade
FCNC at future hadron colliders

Searches for rare decays are an obvious strong point for a machine producing billions of top quarks/year

From FCChh SM physics summary (arXiv:1607.01831)

“Performing a naive rescaling of the LHC expectations [...] and assuming a luminosity of $10 \text{ ab}^{-1}$ for the FCC, one would expect an improvement of almost two orders of magnitude, reaching a sensitivity of $\text{Br}(t \to qZ; t \to q\gamma) \sim 10^{-7}$ However, at such a level of precision the systematic uncertainties in the background predictions will likely be dominant, and a more reliable estimation of the sensitivity requires a detailed analysis.”
Top EW couplings
Top EW couplings: LHC status

Simultaneous fit to Tevatron and LHC data

Single top production, ttZ, (top decay)
Associated production at 100 TeV

Analyses of still “rare” processes to profit most from increase in rate.

<table>
<thead>
<tr>
<th></th>
<th>$t\bar{t}$</th>
<th>$t\bar{t}t\bar{t}$</th>
<th>$t\bar{t}W^{\pm}$</th>
<th>$t\bar{t}Z^0$</th>
<th>$t\bar{t}WW$</th>
<th>$t\bar{t}W^{\pm}Z$</th>
<th>$t\bar{t}ZZ$</th>
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<tr>
<td>$\sigma (pb)$</td>
<td>3.2 $\cdot 10^4$</td>
<td>4.9</td>
<td>16.8</td>
<td>56.3</td>
<td>1.1</td>
<td>0.17</td>
<td>0.16</td>
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Rontsch & Schulze, arXiv:1501.05939
Schulze & Soreq, arXiv:1603.08911

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<tr>
<th></th>
<th>$C_{1,V}$</th>
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<th>$C_{2,V}$</th>
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</tr>
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<tbody>
<tr>
<td>SM value</td>
<td>0.24</td>
<td>-0.60</td>
<td>&lt; 0.001</td>
<td>$\ll$ 0.001</td>
</tr>
<tr>
<td>13 TeV, 3 ab$^{-1}$</td>
<td>[-0.4, +0.5]</td>
<td>[-0.5, -0.7]</td>
<td>[-0.08, +0.08]</td>
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</tr>
<tr>
<td>100 TeV, 10 ab$^{-1}$</td>
<td>[+0.2, +0.28]</td>
<td>[-0.63, -0.57]</td>
<td>[-0.02, +0.02]</td>
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arXiv:1607.01831
EPS-HEP, Venice, Jul.
Lepton colliders

The best laboratory to test γtt and Ztt vertices

Effect of four-fermion operators (i.e. new massive mediator) best felt at high energy

Effect of two-fermion operators (i.e. loop effects on ttX vertex) best probed at ~500 GeV

Fit of all operators on measurements of σ, A_{FB} needs two energy points
(Fiolhais et al., arXiv:1206.1033)
Top EW couplings at lepton colliders

\[ \Gamma^{\tau\tau X}(k^2, q, \bar{q}) = i e \left\{ \gamma_\mu \left( F_{1V}^X(k^2) + \gamma_5 F_{1A}^X(k^2) \right) - \frac{\sigma_{\mu\nu}}{2m_t} (q + \bar{q})^\nu \left( i F_{2V}^X(k^2) + \gamma_5 F_{2A}^X(k^2) \right) \right\} \]

Prospects for HL-LHC/ILC500/CLIC380


EPS-HEP, Venice, July 2017
Many directions to approach the problem

Top decay $t \rightarrow Wb$

Single top production $e^+ e^- \rightarrow \bar{t} t$

Associated production: $pp \rightarrow \bar{t} t Z$

Current and future constraints from different processes and colliders on CP violating electric dipole moments of the top quark $= f(\text{Im}(Ctw), \text{Im}(CtB))$

See also: contribution on ep by Christian Schwanenberger in this track
The future of EW and top physics: highlights

Lepton collider prospects:
= Z-pole: GigaZ, TeraZ to bring EW fit to the next level
= WW threshold for W mass
  Challenges: control of theory/modelling

= 250 GeV: W physics, searches for exotic single-top production

= 350 GeV: top mass measurement to 50 MeV precision
> 350 GeV: Unrivalled sensitivity to ttZ and ttγ vertices
> 550 GeV: direct top Yukawa coupling to 3-4%
>> 1-3 TeV: limits on anomalous top EW, TGC and QGC couplings
  Challenges: control of systematics to per mille level

100 TeV hadron collider targets:
Greatly enhanced mass reach for searches, access to rare processes
Constraint of ttg vertex improves by an order of magnitude
  (and qqtt 4-fermion operators)
Top Yukawa coupling to 1%
FCNC, top mass, W mass potential to be evaluated
  Challenges: control of systematics to % level, ultra-boosted production
Lessons and future work

Top and EW precision physics may deliver the transformative discovery that this field needs

Each of the future facilities offers exciting new possibilities, with quite complementary sensitivity to high-scale new physics

Comparison is hard! Take advantage of EFT machinery to compare the potential different processes/machines