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Review of top and EW physics at future colliders

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In this contribution I review the potential for top and EW physics of future colliders. Prospects for key measurements in the top and electroweak sector are presented. An extensive bibliography provides an up-to-date inventory of published studies. I also make a first (and only partly successfull) attempt to compare the relative merits of planned facilities on the basis of existing material and identify key areas where further studies are needed.

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1. Introduction

The Large Hadron Collider (LHC) at CERN is taking the study of hadroproduction of top quarks and electro-weak (EW) gauge bosons to the next level. Future runs, including the high-luminosity LHC phase or HL-LHC, are envisaged to collect a sample of 3 ab^{-1} by the year 2037. Several options exist for a new large-scale particle-physics facility:

- **A new hadron collider:** a machine based on 16 Tesla magnets in the existing LEP-LHC tunnel, the high-energy LHC or HE-LHC, can double the energy reach of the LHC. A new 100 km ring equiped with the same magnets could reach a center-of-mass energy of 100 TeV. Two such projects are being developed, the FCC at CERN [1, 2, 3, 4] and the SPPC in China [5].
- **A circular lepton collider:** a 100 km e^+e^- ring with a continuous top-up injection scheme to compensate for beam current loss due to synchrotron radiation can provide excellent luminosity at 250 GeV, where Higgsstrahlung production reaches maximum cross section. A circular e^+e^- collider may also reach the top quark pair production threshold. This possibility is under study in China (CEPC [5]) and in Europe (FCCee [6]).
- **A linear e^+e^- collider** based either on super-conducting cavities (the ILC [7]) or cavities at room temperature powered by a drive beam (CLIC [8]) cover the energy regime between 250 GeV and 500 GeV (1 TeV), or 350 GeV to 3 TeV, respectively. Both projects have prepared complete designs and a detailed staging scheme [9, 10, 11].

For the field to make an informed decision, detailed design reports of all these facilities are required, as well as reliable cost estimates and thorough studies of the scientific potential. In this contribution I focus on the latter.

In the following I briefly review the impact that each of these future projects may have on top quark and electro-weak physics. Given the limited space, the text is primarily meant as a starting point for further reading. An extensive bibliography is included. The reader may find more detailed accounts on behalf of each of the projects in the contributions by Hosseinabadi (HL-LHC), Locci (FCCee), Selvaggi (FCChh) Schwanenberger (LHeC/FCCeh) and van der Kolk (ILC/CLIC). A more extensive write-up on top physics beyond the LHC is found in Ref. [12].

2. The electro-weak fit: W-boson and top quark mass

New e^+e^- colliders operated at the Z-pole (FCC-ee TeraZ or the ILC GigaZ option) can exceed LEP and SLC luminosity by orders of magnitude. This data would take the electro-weak fit [13] to a new level of precision [6, 14, 15]. The ultimate precision that can be achieved is likely to depend ultimately on theory progress.

The mass of the W-boson is a key ingredient of the fit. Together with precise determinations of the top quark and Higgs boson mass it yields a stringent test of the internal consistency of the SM. The world average today, $m_W = 80.385 \pm 0.015$ GeV, is dominated by extractions from the reconstructed transverse mass distribution of $W \rightarrow l\nu_l$ decays at the Tevatron. The Tevatron experiments are still in the process of finalizing the legacy measurement based on the complete data set, which is expected to reach $\sim$ 10 MeV precision.

The first LHC measurements reach similar precision as the Tevatron measurements. The prospects for future W-boson mass measurements are evaluated in Refs. [6, 14]. Both studies envisage an improvement to a precision of 5 MeVat the HL-LHC, where the most important uncertainty is expected to come from parton density functions. At future lepton colliders the W-boson mass can be extracted from a scan of the beam energy through the W-boson pair production threshold, or from a kinematic reconstruction of the $q\bar{q}l\nu_l$ final state at higher energy. Both methods require excellent control over the beam energy calibration and detector systematics. The expected precision is 1-3 MeV [6, 14].

Measurements of the top quark mass at the LHC currently have a precision of approximately 500 MeV. The experimental uncertainty is expected to improve to 200-300 MeV after the HL-LHC collects 3 ab^{-1} [16]. The evolution of the theory uncertainty is unclear. A better understanding of the interpretation and the uncertainties related to parton shower and hadronization is required to match the experimental precision [17, 18, 19]. For this reason, the ultimate potential of high-energy hadron colliders remains to be understood [4].

A scan through the top quark pair production threshold at an e^+e^- collider is the most promising way of reaching a precision [20] below 100 MeV. The threshold “line shape” can be predicted with very good precision using a NNNLO NRQCD calculation [21]. Detailed studies show that the top quark mass can be determined precisely in a multi-parameter fit [22, 23, 24, 25]. The luminosity spectra of the different machines lead to small differences in the statistical precision that can be attained with a given integrated luminosity [26]. These are, however, irrelevant in the total uncertainty, that is likely dominated by the theory uncertainty, with important contributions from the line-shape prediction itself and from the conversion to the $\bar{M}S$ mass [26]). The determination of the $\bar{M}S$ mass can reach $\sim$ 50 MeV precision, including theory uncertainties. A precise value of the strong coupling constant α_s is needed to achieve this precision [27].

3. Rare electro-weak processes

Vector-boson scattering, isolated for the first time in LHC run-I [28, 29, 30], remains an intriguing process. The HL-LHC may achieve a precision in the measurement of the electro-weak component of the cross section of 10% or better after collecting 3 ab^{-1} [31]. Limits on anomalous triple and quartic gauge couplings are thus expected to improve by an order of magnitude at the HL-LHC.

The prospects for probing anomalous couplings in high-mass vector-boson pair production at future colliders are very promising [32]. The high-energy stage of CLIC, with a center-of-mass energy of 3 TeV, can yield very competitive limits on quartic couplings, two orders of magnitude better than the current constraints [33]. High-energy pp colliders, such as the FCChh and SPPC, can study vector-boson scattering at even higher mass. These projects can therefore derive very competitive constraints on anomalous couplings whose impact grows with energy, especially on dimension-8 operators [34].

4. Strong interactions of the top quark

The LHC top physics programme offers new opportunities to characterize the strong interactions of the top quark with high precision. Boosted production of top quark pairs provides good sensitivity to beyond-the-Standard-Model physics, in particular to chromo-magnetic and chromo-electric dipole moments of the top quark [35] and to the effect of very massive new mediators [36]. In the fit to current Tevatron and LHC data by the TopFitter collaboration [37] high-mass measurements and inclusive measurements yield roughly equally powerful constraints on the relevant operators in effective field theory.

Measurements on boosted top quark pair production are expected to improve rapidly as the LHC experiments collect more data. The constraints on four-fermion operators may improve by an order of magnitude [36]. At a 100 TeV pp collider top quark pairs are produced with an invariant mass of up to 20 TeV. The isolation of these final states with highly collimated top jets poses stringent constraints on the detector design and requires the development of new top-tagging techniques [38]. An exploratory analysis show that the limits on the chromo-magnetic and chromo-electric dipole moments of the top quark are expected to improve by an order of magnitude with respect to the HL-LHC [35].

5. The top quark and the Higgs boson

Observation of associated $t\bar{t}H$ production - due soon at the LHC if the Higgs boson behaves as expected in the SM [39, 40, 41] - provides a direct probe of the interactions between the two heaviest particles of the Standard Model. At the HL-LHC the direct measurement of the top quark Yukawa coupling is expected to reach a precision of 7-10% [42]. Therefore, a direct and precise determination of the top quark Yukawa coupling remains an excellent target for future colliders.

At linear e^+e^- colliders with a center-of-mass energy greater than 500 GeV the $e^+e^-t\bar{t}H$ process can be isolated. The estimated precision of the Yukawa coupling measurement is approximately 3-4 % [9, 43, 44] for center-of-mass energies in the range $\sqrt{s} = 0.55$-1.5 TeV. A 100 TeV pp collider can produce a large sample of $t\bar{t}H$ events. The potential of the Yukawa coupling measurement at FCChh/SPPC depends crucially on the control of systematic uncertainties. Ref. [45] shows that the theory uncertainty can be significantly reduced by the construction of cross-section ratios for very similar processes (i.e. $t\bar{t}H$ and $t\bar{t}Z$). The experimental strategy of the same authors relies on boosted Higgs boson production. With these ingredients the direct measurement of the Yukawa coupling may reach 1 % precision.

6. Top-quark FCNC interactions

The discovery of flavour-changing neutral-current interactions of the top quark, highly suppressed in the SM, would be clear evidence of physics beyond the SM. The constraints are expressed as limits on branching ratios for top quark decays through flavour-changing neutral currents, $BR(t \to qX)$. The limits combining LHC, Tevatron, LEP and HERA data have surpassed the 10^{-3} mark [46]. They will continue to evolve at the HL-LHC [47] as the top quark sample grows, reaching the $10^{-4} - 10^{-5}$ level for most branching ratios.

Future colliders further enhance the sensitivity. Searches for $e^+e^- \to tq$ production [48, 49] are possible also below the top quark pair production threshold (i.e. at $\sqrt{s} = 250$ GeV). They provide competitive constraints on the top quark FCNC couplings to a photon or a Z boson for integrated luminosity of several inverse ab. Important complementary constraints can be derived from such searches in a global analysis [50]. High-energy e^+e^- colliders operating above the $t\bar{t}$ threshold can provide limits on the $t \to cH$ and $t \to c\gamma$ branching ratios well below 10^{-4} [22, 51].

Experiments at 100 TeV pp collider may collect 10^{12} $t\bar{t}$ pairs [52]. Thus, one can potentially access branching ratios as low as 10^{-7} [4]. A detailed study, however, of the FCChh and SPPC potential remains to be performed.

7. Top quark electro-weak couplings

The interactions of the top quark with electro-weak gauge bosons are constrained by measurements of top quark decay, single top quark production and associated production ($t\bar{t}\gamma$, $t\bar{t}Z$, $t\bar{t}W$). While current constraints are quite weak [53], the significant progress is expected towards the HL-LHC, especially for the rare, associated production processes [54, 55, 56]. At at future 100 TeV pp collider the cross sections for $t\bar{t}V$ production reach several tens of *pb*. Provided theory and experimental systematic uncertainties can be controlled to the few-% level the limits on EW dipole moments are expected to increase by a factor 3-4 with respect to the HL-LHC [4].

The $e^+e^- \to t\bar{t}$ production process is an ideal laboratory to characterize the couplings of the top quark to neutral EW gauge bosons. Polarized beams (at linear colliders) allow to disentangle photon and Z-boson contributions [57, 58, 59, 60]. The combination of low-energy and high-energy operation helps to constrain all effective operators in a global fit [61]. The precision on the electric and weak dipole moments of the top quark that can be achieved in realistic initial running scenarios of ILC or CLIC exceeds that of the HL-LHC by more than an order of magnitude and exceeds the potential of the SPPC and FCChh projects. The study on the potential of circular colliders of Ref. [59] finds that reconstruction of the top quark polarization can take over the role of beam polarization to some extent. Operation at a center-of-mass energy slightly above the $t\bar{t}$ threshold then yields similar precision to CLIC or ILC runs at higher energy.

8. Summary and Outlook

Top and EW processes at future colliders have excellent sensitivity to physics beyond the Standard Model. A precise characterization of these processes may deliver the transformative discovery that this field needs. Energy-frontier e^+e^- colliders and a 100 TeV pp machine both offer exciting new possibilities, with excellent sensitivity to high-scale new physics.

The prospects of the HL-LHC and two main classes of future colliders are collected in Table 1. The level of detail of prospect studies varies across the table, from detailed full-simulation analyses to exploratory parton-level studies. A systematic comparison with uniform assumptions for theory and systematic uncertainties is still missing in most areas. However, even in its current incomplete form the table provides a clear illustration of the complementarity of the different projects. Circular e^+e^- colliders are clearly superior for low-energy precision physics (EW fit, W-boson mass), while linear e^+e^- colliders are the only option to reach higher energies ($t\bar{t}$ EW couplings, $t\bar{t}H$

Table 1: The current precision of several key measurement in top and electro-weak physics is compared to the projected evolution at the HL-LHC and two categories of future facilities. The HL-LHC prospects and the expected precision at future facilities are based on a highly non-uniform collection of studies, that include extrapolations, parton-level studies and full simulation studies. A more detailed description and references for the HL-LHC prospects and the expected precision at future facilities are given in the text.

	today	2037	e^+e^- collider	new pp collider
project	LEP/Tev/ LHC8	HL-LHC	ILC/CLIC/ FCCee/CEPC	FCChh/SPPC
$\sqrt{s}$	8 TeV	14 TeV	0.25-3 TeV	100 TeV
$\int \mathscr{L}$	20 fb^{-1}	3 ab^{-1}	0.5-4 ab^{-1}	20-30 ab^{-1}
m_W [MeV]	16	5	1-3	?
m_t, exp. $\oplus$ theo. [MeV]	$500 \oplus 1000$	$200 \oplus ?$	$20 \oplus 50$	?
top QCD $\|d_V\|$,$\|d_A\|$	< 0.02, < 0.09	< 0.01, < 0.02	?	< 0.003
top Yukawa (direct)	O (100%)	7-10 %	~ 4 %	1 %
FCNC $BR(t \to qX)$	$\sim 10^{-3}$	$10^{-5} - 10^{-4*}$	$t \to cH/c\gamma \sim 10^{-4}$	$\sim 10^{-7}$?
$t\bar{t}Z$ form factors	-	0.03-0.3	0.002-0.005	0.01-0.07

production). Also between hadron and e^+e^- colliders, strengths and weaknesses can be identified: as expected a hadron collider is a superior laboratory to study QCD couplings and to constrain operators with a strong energy dependence. Electro-weak couplings are best characterized at e^+e^- colliders, with the superior precision making up for the lower energy reach.

Today, a summary such as Table 1 is necessarily incomplete. Many caveats make comparison far from straightforward, as a result of the fragmented nature of the effort. Much more work is needed to fully understand the opportunities and limitations of each of the proposed facilities. The advent of global analyses in an effective-field-theory framework in the top and electro-weak sectors may facilitate a more systematic comparison of the sensitivity of different measurements, channels and machines.

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