To 350 GeV, and Beyond: Physics Case for High Energy e+e- Collisions

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Higgs and Top, Together

- ~350 GeV is the minimum energy required to pair-produce top quarks in e+e- collisions

- Top is special in the SM, due to its large Yukawa coupling to the Higgs:

\[ \mathcal{L} = -\mu^2 |H|^2 + \lambda |H|^4 + y_t Q_3 H t_R + \ldots \]

- Understanding electroweak (-breaking) sector of the SM requires a precision top program, complementary to (and of equal importance with) precision Higgs.
Standard Model Breakdown?

- Key parts of the SM were constructed by noticing and fixing theoretical inconsistencies in predictions of earlier theories at energies >> experiment at the time

- SM itself might have a similar inconsistency:
  \[
  \frac{d\lambda}{d\mu^2} = \frac{1}{16\pi^2} \left( 12\lambda^2 + 6\lambda y_t^2 - 3y_t^4 + \ldots \right) < 0
  \]
  unbounded negative energy if quartic < 0!

- However, this high-energy behavior depends very sensitively on the value of top Yukawa!
Top Mass: LHC

- Direct measurement of top Yukawa to required precision ($<10^{-3}$) appears out of reach
- Within SM: $m_t = y_t v$ → precision top mass measures Yukawa
- LHC: reconstruct “kinematic” top mass from decay products. Need to model soft-gluon radiation/exchanges to relate it to “Lagrangian” mass
- Challenging: non-perturbative effects
- Not clear how/if required level of precision can be reached
Top Mass: e+e- Threshold Scan

- Threshold scan in e+e- collisions provides a theoretically clean, precision observable: cross section
- State-of-the-art: NNNLO+NNLL resummation
- Expect $\Delta m_{\text{stat}} \approx 20$ MeV, $\Delta m_{\text{syst}} \approx 50$ MeV
- This is sufficient to resolve the issue of possible SM inconsistency, and if it is present, to determine the required scale of new physics
- May control the fate of the universe: instability implies that our vacuum is unstable
Top Mass with Energy Correlators

- A new alternative approach in QCD theory is to study energy correlation functions, rather than S-matrix for quarks and gluons.
- Similar to temperature correlations in cosmic microwave background!
- 3-pt correlation fn. in boosted top jets is very sensitive to top mass, clean.
- e+e- collisions at 500-1000 GeV will produce a large, clean sample of boosted tops.
Top Couplings

• At 500 GeV and above, e+e- colliders provide a uniquely precise measurement of top electroweak couplings, especially to the Z

\[
\begin{align*}
&O_{\psi\gamma}^{\text{y}} &\equiv & q \gamma^\mu q & \phi \bar{q} D_\mu \phi', \\
&O_{\psi\gamma}^{\text{Z}} &\equiv & q \gamma^\mu q & \phi \bar{q} D_\mu \phi', \\
&O_{\psi\gamma}^{\text{W}} &\equiv & q \gamma^\mu q & \phi \bar{q} D_\mu \phi', \\
&O_{\psi\gamma}^{\text{H}} &\equiv & q \gamma^\mu q & \phi \bar{q} D_\mu \phi', \\
&O_{\psi\gamma}^{\text{V}} &\equiv & q \gamma^\mu q & \phi \bar{q} D_\mu \phi', \\
&O_{\psi\gamma}^{\text{A}} &\equiv & q \gamma^\mu q & \phi \bar{q} D_\mu \phi', \\
&O_{\psi\gamma}^{\text{B}} &\equiv & q \gamma^\mu q & \phi \bar{q} D_\mu \phi'.
\end{align*}
\]

• Coupling deviations can be parametrized by effective contact operators - “SMEFT”

• Global fits demonstrate e+e- sensitivity 10-100 times above HL-LHC for some operators
Example: Little Higgs

- As a benchmark model, consider “Little Higgs” theory:

\[ \mathcal{L} = -f (\lambda_1 u_R + \lambda_2 U_R) U_L - \lambda_1 u_R^\dagger \tilde{H} Q_L + \frac{\lambda_1}{2f} (H^\dagger H) u_R^\dagger U_L + \text{h.c.} + \ldots \]

- At tree level, Higgs is a massless Goldstone boson

- At loop level, top + top partner loops generate a negative Higgs mass^2, triggering EWSB (i.e. EWSB is predicted, as opposed to the SM!)

- Direct searches for top partners at the LHC:

\[ T \rightarrow Wb, tZ, th \]
Example: Little Higgs

- After EWSB, “our” top quark is an admixture of states with different SU(2)×U(1) quantum numbers

- This results in shifts in this particle’s couplings to gauge bosons:

\[ g_{HL} = \frac{e}{c_w s_w} \left( \frac{\cos^2 \beta}{2} - \frac{2 s_w^2}{3} \right); \quad g_{HR} = -\frac{2 e s_w}{3 c_w}; \quad \sin \beta \approx \tan \alpha \frac{m_t}{m_T}. \]

- These shifts can also be expressed as dim-6 SMEFT operators generated by integrating out the top partner:

\[ O_{\varphi \gamma} = \frac{y_{t \gamma}}{\sqrt{2}} \bar{\varphi} \gamma^\mu q \varphi^\dagger \not{D}_\mu \varphi, \quad C_{\varphi \gamma}^1 = \frac{\lambda^2 y_t^2}{4 M_U^2}, \quad C_{\varphi \gamma}^3 = -\frac{\lambda^2 y_t^2}{4 M_U^2}. \]

- Precision top program in e+e- probes regions in parameter space inaccessible to the HL-LHC via either precision-top or direct top-partner searches

[Durieux, Perello, Vos, Zhang]
Composite Higgs/Top

• Elementary scalar fields generically have masses of order the highest physical scale in the theory: \( m \sim \max M_i \)

• But \( m_h \ll M_{Pl} \) - “hierarchy problem”

• A possible resolution is for the Higgs to be a bound state, like a meson

• Top may be another bound state of the same constituents, like a baryon

• If other quarks are NOT composite, it would explain why the top Yukawa is \( >> \) all other Yukawas
Higgs/Top in Extra Dimension

- Some of such composite models are “dual” (i.e. equivalent in some respects) to models with extra dimensions

- All SM particles have “doubles” at Kaluza-Klein mass ~ size of extra dimension ~ compositeness scale

- Contact operators=form-factors are generated by integrating out KK excitations of Z, photon

\[ \frac{C_{lq}}{\Lambda^2} = \begin{cases} \frac{-0.022}{m_{KK}^2} & \text{for } Z, \\ \frac{-0.032}{m_{KK}^2} & \text{for } \gamma, \\ \frac{-0.004}{m_{KK}^2} & \text{for } e, \\ \frac{-0.064}{m_{KK}^2} & \text{for } \mu. \end{cases} \]

- Sensitivity up to 5-15 TeV KK mass can be reached in e+e- colliders

[Randall, Sundrum, ...]
FCNC Top Couplings

- Flavor-non-diagonal operators can also be induced in new physics models, possibly inducing FCNC’s that are negligible in the SM.

- e+e- colliders improve HL-LHC sensitivity by up to 3 orders of magnitude for some FCNC operators (such as 4-fermion llqq).

![Figure 10.5: The projected 95% C.L. bounds on the EFT operator coefficients that give rise to the FCNC e+e- production process. The bounds are given in units of TeV for the LHC run 2 (dark red arrows), for the HL-LHC (purple arrows) and for the three nominal ILC stages: 250 GeV (green bars), 500 GeV (orange bars) and 1 TeV (blue bars). The round markers of the same color represent the expected bounds without beam polarization.]

Number of Higgs bosons produced at ILC-500 will be similar to the number at ILC-250, providing comparable statistical power as at ILC-250 for all the measurements at 250 GeV discussed in Sec. 8.1. The experimental techniques and background composition are different at the different energies, production methods and beam polarizations, providing a range of systematic checks by comparing measurements of related observables made under different conditions, before combining the measurements to achieve optimal sensitivity while also testing the internal consistency of the measurements when interpreted within the Standard Model.

The comparison of Higgs production in the Zh and WW-fusion processes, enabled respectively by the hZZ and hWW couplings, with the measured decay branching ratio to WW* and ZZ* will allow independent checks of the Higgs couplings to V (W/Z). The experimental sensitivity to anomalous HVV couplings, whose effects typically grow with energy, will be significantly enhanced at ILC-500. The impact of ILC-500 data on the understanding of the Higgs sector is clearly demonstrated later in this report, for example in Fig. 12.1.
Higgs Self-Coupling

• At 500 GeV, e+e- collisions allow a direct measurement of Higgs cubic self-coupling through ZHH production (~25% precision)

• At 1 TeV, the same coupling can be measured through HH production in WW fusion (~10% precision)

• SM makes an unambiguous prediction for $h^3$ once Higgs vev and mass are measured ➡️ excellent test of new physics in the Higgs sector!
Higgs Self-Coupling

- The two cross sections have opposite behavior as $h^3$ coupling deviates from the SM: constructive interference in ZHH, destructive in WW fusion.

- Combining the two measurements allows for a $<20\%$ precision in $h^3$, even if it deviates from the SM by 50-100%!

- At LHC, gluon fusion has destructive interference - suffers for enhanced $h^3$. 
Electroweak Phase Transition

• In the early universe, electroweak symmetry is restored

• Higgs “plasma mass” decreases with temperature, resulting in EW-breaking phase transition at $T \sim$ weak scale ($t \sim$ nsec)

• SM predicts a gradual, adiabatic transition (“crossover”), but in BSM theories a first-order transition may occur

• First-order EWPT can generate matter-antimatter asymmetry (“electroweak baryogenesis”), create gravity waves
First-Order PT and Higgs Couplings

- First-order EWPT requires BSM fields, with significant coupling to Higgs and mass \( \sim \) weak scale

- A singlet scalar is the simplest benchmark:
  \[
  V = m_S^2 S^2 + \frac{\kappa}{2} S^2 |H|^2
  \]

- Invisible to the LHC as long as \( m_S > m_h/2 \)

- Models with first-order EWPT typically predict \( \sim 20-120\% \) enhancement in \( h^3 \)

[Huang, Long, L-T. Wang]
New Physics: Supersymmetry

- LHC has put strong constraints on SUSY models with superpartners below TeV

- Loopholes remain: electroweak couplings, small splittings (e.g. Higgsino) are difficult to constrain

- For example, recent muon g-2 anomaly was interpreted in terms of SUSY models with such features

- e+e- collisions provide robust, model-independent sensitivity for such scenarios, probing SUSY masses up to kinematic threshold
New Physics: Extra Gauge Bosons

- Extra U(1) gauge groups are ubiquitous in BSM physics: grand unification, string-inspired models, ...

- Predict Z' bosons, with specific pattern of couplings to SM fermions depending on the model

- Study of e+e- -> fermions at 500 GeV/1 TeV provides a window into Z' far above the LHC reach
New Physics: Dark Photon/Z

- An alternative possibility is a U(1) symmetry that no SM field is charged under
- Could be part of “dark sector” along with dark matter particles
- Dominant coupling to SM is via kinetic mixing, typically a loop effect
  \[ \mathcal{L}_{\text{gauge}} = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} + \frac{\varepsilon}{2c_W} B_{\mu\nu} A'^{\mu\nu} - \frac{1}{4} A'_{\mu\nu} A'^{\mu\nu} \]
- Sub-GeV DP is interesting [see next talk by Y. Sakaki] but could be much heavier - “dark Z”

If Dark Z is within kinematic reach of an e+e- collider, regions inaccessible at the HL-LHC can be probed [San, Tanedo, MP]
Dark Z Couplings

- If a dark Z is discovered, e+e- collider can be turned into a “dark Z factory” by running on resonance
- Similar to LEP-1, but dark Z is very narrow (< MeV width)
- Mass can be pinpointed accurately with an “inverse line-shape” scan
- Dark Z couplings can then be determined, model discrimination, ...

[San, Tanedo, MP]
Highlights

- Understanding EWSB requires precision measurements of top mass and couplings, due to large top Yukawa coupling

- e+e- collisions at threshold (~350 GeV) and at 500 GeV provide unique sensitivity to top mass and couplings

- Higgs cubic coupling can be measured for the first time in e+e- collisions at 500-1000 GeV, deviations predicted by models with first-order electroweak phase transitions can be probed

- High precision in e+e- collisions provides indirect sensitivity to new physics far above the LHC reach, e.g. Z’ bosons

- New physics can be within kinematic reach of e+e- collisions at 500-1000 GeV and escape LHC detection (e.g. Higgsinos, dark Z, ...) - discovery potential