Triangulating the Standard Model with the top quark, $W$ boson and Higgs boson
The Standard Model (SM) of Particle Physics

Matter particles: 3 generations of quark and lepton doublets

Force carriers: $Z^0$, $W^\pm$, $\gamma$ and octet of color-charged gluons

AND: a single spin 0 Higgs boson that gives mass to all the others (and itself)

The 2012 discovery of the Higgs boson completed the roster of SM particles. The SM has withstood 1000’s of experimental tests.

SM has 26 arbitrary parameters (masses, quark and lepton mixing, couplings) whose values we do not understand. But if they were different, our universe would be a very different place (or non-existent).

Measuring these parameters tells us something about the model, and about the way the SM will be extended in nature.

Much more can be learned from the relationships among the SM particles.

Today we will examine the relations among the top quark, $W$ boson and Higgs boson
Of course relationships among all the particles illuminate the way that the SM should be extended, but the top, W and Higgs are special ...
The Tevatron

2 TeV collisions of counter-rotating protons and antiprotons in a single 2 km diameter ring of superconducting magnets.

Two complementary detectors, CDF and DØ, study the interactions between the partonic constituents of the protons – quarks and gluons. First collisions in 1987; Tevatron shutdown in 2011.
The 8.6 km diameter Large Hadron Collider has collided protons and protons since 2009 at 7 or 8 TeV in two superconducting magnet rings, going up in June 2015 to 13 TeV, ultimately to 14 TeV (B=8.4T).

Two general purpose detectors, ATLAS and CMS, with more specialized experiments, LHCb, ALICE, Totem.
The $W$ boson

The $W^\pm$ bosons (and $Z$ boson) are the carriers of the short range Weak Interaction responsible for $\beta$ decay. Short range $\rightarrow$ large boson mass.

Neutron $\beta$ decay proceeds by a $d$ quark emitting a virtual $W$ boson and changing to a $u$ quark.

The $W$ boson was discovered in 1983 at CERN in 546 GeV $p\bar{p}$ collisions. Very large samples ($>10^6$) of $W$’s were accumulated at the Tevatron, and used to make very precise measurements of its mass and properties.

$W$ decays to $l\nu$ ($l = e, \mu, \tau$) with branching ratio 33% or $q\bar{q}$ (BR=67%). The quarks appear in an experiment as jets of hadrons. The energies of the jets (and $\tau$’s) are not precisely measured, so only the $e$ and $\mu$ decays are used to measure the mass.
The W boson

The mass measurement (use $W \rightarrow \ell \nu$) is complicated since the $\nu$ is unseen, but is sensed by imbalance in transverse momentum in the final state (MET). Use the Jacobian edge in transverse momentum of lepton ($p_T^\ell$) or $m_T = \sqrt{2p_T^e p_T^\nu(1-\cos \phi_{e\nu})}$. Compare data with templates prepared with different $M_W$.

Solid black line for $p_T^W=0$
Blue shaded for for $p_T^W \neq 0$
Dotted with detector smearing

For lepton $p_T$, $p_T^W$ dominates
For $m_T$ detector resol. dominates

Must calibrate absolute lepton energy response to $10^{-4}$ level; control event pileup, precisely determine the up and down quark distributions in the proton …

**World average (dominated by Tevatron)**
$M_W = 80,385 \pm 15$ MeV (<2x10^{-4} !!)

(It will be a long time before LHC gets this precision)
The top quark

With the discovery of the 3rd fermion generation (τ, b) the search for the the q=+2/3 partner of b-quark was on. Various e⁺e⁻ colliders & CERN SppS failed to find it. In 1995, CDF and DØ both published observation, with 10-20 top anti-top pairs each, produced by the strong interaction.

Produce top and anti-top pairs by the strong interaction. Each top decays ≈ 100% of the time to Wb. The W decays either to ℓν or qq. Can measure top mass for all combinations of final states.

1995 discovery paper top mass distributions
Fit the reconstructed mass of top decay products and compare to templates to determine top mass.

Though a pointlike elementary fermion, the top quark mass of ~175 GeV is nearly the mass of a gold atom! The most massive known elementary particle.
The top quark

Now Tevatron experiments have \( \sim 2000 \) events.

2014 CDF/D0 combination:

\[ M_t = 174.34 \pm 0.64 \text{ GeV} \ (0.38\%) \]

LHC exp’ts have larger statistics (\( \sim 10^5 \) evts) but larger systematic uncertainties so comparable total uncertainty.

The top quark is unique in that it decays before the strong interaction can bind it into resonances, so is a laboratory for studying ‘bare’ quarks.

The top quark properties have been well measured: lifetime (1/3 yoctosec), charge = +2/3e, polarization and spin correlations, couplings to other particles, single top production by EW interaction – all are as in SM.

No observed resonances of top antitop mass spectrum.
The Higgs mechanism

Without new elements, weak interaction cross section processes (e.g. WW scattering) would violate unitarity at $E_{\text{cm}} > 1$ TeV. Also since weak and EM interactions have similar structure, it is desirable to unify them. But the photon has no mass whereas W and Z masses ~ 100 GeV. Enter the Higgs (& Brout, Englert and Guralnik, Hagen, Kibble) mechanism.

Postulate a renormalizable unified Electroweak theory that in the symmetry limit has massless spin 1 gauge bosons: singlet $b$ and triplet $w = (w^+, w^0, w^-)$

Introduce a new complex doublet scalar Higgs field $\phi = (\phi^+, \phi^0)$ (four real fields) that permeate space and contribute a potential energy term to the Lagrangian of form $V = \mu^2 \phi^2 + \lambda \phi^4$.

If $\mu^2 > 0$, the equilibrium point is $\phi = 0$, but if $\mu^2 < 0$, the minimum of $V$ is at $\langle \phi \rangle_0 = v/\sqrt{2} = \sqrt{-\mu^2/2\lambda} = 174$ GeV. ($v \sim G_F$ so is known.) In this ‘Mexican hat’ potential, the ground state is shifted and the symmetry is spontaneously broken.

Note the intriguing fact: top mass $\approx$ vacuum exp. value, $v$
The Higgs mechanism in a picture

The primordial gauge boson and scalar fields mix to produce massive $W$ and $Z$. 3 of the scalar fields are converted to longitudinal helicity states of $W$ and $Z$ and the remaining scalar field survives as the Higgs boson.

- Before symmetry breaking: $12 \text{ d.o.f}$ (4x2 gauge boson plus 4 Higgs)
- After EWSB, $12 \text{ d.o.f}$. (3x3 for $W^\pm/Z$, 2 for $\gamma$ and 1 Higgs). We are left with an observable Higgs boson whose mass is not predicted by the theory.

The Higgs boson couples to mass. The Higgs mechanism gives mass to $W/Z$, all the fermions, and to the Higgs itself: $M_H^2 = -2\mu^2$. We know $v^2 = -\mu^2/\lambda$, but need $M_H$ to obtain $\mu$ and $\lambda$ separately.
July 4, 2012: ATLAS and CMS experiments jointly announced discovery of a “Higgs boson” with $M_H = 125 \text{ GeV}$; $>5\sigma$ from bknd only.

2014 results on the 2 cleanest channels:

- $H \rightarrow \gamma\gamma$
- $H \rightarrow ZZ^* \rightarrow 4 \ell$

The Tevatron found $3\sigma$ evidence for the dominant Higgs decay to fermions (bb) and confirmed the method by observing WZ in same final state.

With $M_H = 125 \text{ GeV}$, get $|\mu| = 88 \text{ GeV}$ and $\lambda = 0.13$
Higgs boson production

Four distinct production processes for Higgs bosons at LHC.

Gluon-gluon fusion (via intermediate top quark loop) dominates because of the large $ttH$ coupling. (The top quark determines Higgs boson production!)

The ggF, VBF, VH processes have been observed. The evidence for $ttH$ process is not yet firm.
Higgs boson decays

The 125 GeV Higgs boson has a rich set of decays. The mass chosen by Nature is serendipitous as there are a large number of accessible decay modes.

The $H \rightarrow ZZ$ decay angular distribution tells us that $J^P = 0^+$, consistent with SM.

In the SM, Higgs couplings are exactly proportional to mass. Any deviations from this proportionality indicate new physics beyond the SM.

But the current precision on BRs is too low to give tests of Beyond the SM (BSM) effects.
The masses of $W$, top and Higgs are related to each other (and to well-known constants $M_Z$, $G_F$ and $\alpha_{EM}$).

The measured values of $M_W$ and $M_t$, assuming SM, give a prediction of the Higgs mass. The presence of new physics like supersymmetry would modify the relation.

To the extent that Higgs line intersects the $M_t$–$M_W$ ellipse, SM is valid.
Putting the top, W and Higgs mass measurements together, including also precision measurements of the Z boson, one can look at the consistency of the SM. The agreement is good at the $1\sigma$ level. Improved precision on the W mass is the most critical ingredient.

Recent LHC combined result: $M_H = 125.09\pm0.24$ GeV
Testing the SM at very high energy scales

What you see depends on the magnification. A simple process at low resolution becomes more complex at high resolution (high momentum transfer, \( Q^2 \)). Thus “constants” like \( \alpha_{\text{EM}} \), \( \alpha_{\text{strong}} \) etc. vary with \( Q^2 \). This also occurs for the self-coupling term \( \lambda \) in the Higgs potential \( V = \mu^2 \phi^2 + \lambda \phi^4 \) and as \( Q^2 \to \infty \), \( \lambda \) decreases.

If \( \lambda < 0 \) at high \( Q^2 \), the Mexican hat potential turns over, and the absolute minimum in the potential may no longer be at the location that gave us the observed \( W, Z \) bosons and the Higgs boson but at very high \( Q^2 \).

The variation of \( \lambda \) depends (mainly) on the masses of the top quark and the Higgs boson.
Interplay of top and Higgs masses

For a fixed Higgs mass, raising the top mass leads to a region where no EW vacuum exists (pink). Between that and the stable (green) region where \( \lambda \) stays positive, there is a metastable region (yellow) where a local EW minimum exists but is not the lowest potential at high \( Q^2 \). In that region, it is possible to tunnel from the EW state to the new absolute minimum (with disastrous consequences for our known universe).

Current top and Higgs masses put us in the metastable region (but with lifetime \( \ll \) age of universe). Few GeV shift in \( M_t \) or \( M_H \) makes a big difference.

Caveats: (1) This picture assumes SM is good up to the Planck scale, but NP will modify the picture. (2) The theoretical meaning of the measured \( M_t \) is uncertain to \( \sim 1 \) GeV. Need a more robust method.

But it is odd that we live in a (SM) universe on the edge of stability!
Flaws of the SM

Besides the indication that the Higgs potential is unstable, there are many other reasons to expect new physics beyond the SM.

- There is no place for dark matter particles in the SM
- It is mighty odd to have the Higgs boson at 125 GeV and no new physics before the Planck scale of $10^{19}$ GeV (“the desert”). Tremendous fine tuning of parameters is needed to keep $M_H$ small.
- The SM does not give enough CP violation to explain the matter – antimatter asymmetry in the universe.
- CP symmetry in the strong interaction is not assured in the SM
- SM is incompatible with unification of Strong and EW forces
- The 26 parameters of the SM (fermion masses varying by 13 orders of magnitude, mixing angles, Higgs potential etc.) are arbitrary
- The scalar Higgs vacuum energy is $10^{120} \times$ the cosmological constant

Our job is to find how the SM breaks down
Beyond the SM

There are several proposed models for New Physics (NP) beyond the SM.

For years Supersymmetry has been the most popular candidate for new space-time (broken) symmetry between fermions and bosons. It solves many problems in understanding the vacuum, and the occurrence of particle states with mass $\ll$ Planck mass.

SUSY in its simplest form introduces a new fermion with same quantum #s as each SM boson, and a new bosons for each SM fermion. (There are many SUSY variants of differing complexity, all with added Higgs.)

SUSY has dark matter candidates, could give the CP violation needed for baryon asymmetry and protects the TeV EW scale particles from being corrected to high mass.
Beyond the SM

The SM, without SUSY, does not give unification of strong, weak and EM coupling constants. With SUSY, all can become the same at some high energy scale $\sim 10^{16}$ GeV.

Is that where New Physics lives?

Remember: couplings vary with $Q^2$ (coupling$^{-1}$ is plotted here)

Other models for new physics have been invented – e.g. new strong interactions with new particles coupling to 3$^{rd}$ generation fermions, composite Higgs, extra spatial dimensions with some forces extending into the new dimensions, etc. But most models of NP have a Higgs-like surrogate to be the observed new 125 GeV boson.

A small flaw! No hint of SUSY partners or other new physics has been seen at LHC (8 TeV) – Maybe this year at 13 TeV ??
Higgs couplings as probe of BSM

The SM Higgs boson couples to quarks and bosons in proportion to their mass. NP alters this relationship; the pattern of departure depends on the nature of NP. The size of the change depends on the scale of NP (shown here for ~1 TeV) at few% level.

In the absence of new observed particles, precise study of the couplings of the new Higgs boson to other SM particles can reveal the presence, and nature, of the New Physics.

At present, the LHC coupling measurements are not sufficiently precise (and necessarily make assumptions) to test the couplings at the required precision.

(Here, plot ratio of observed cross section x BR to the SM value.)
Measuring Higgs couplings

Typically experiments measure cross sections $X$ branching ratios to specific final state.

For Higgs production by interaction of $A\bar{A}$ and decay $H \rightarrow B\bar{B}$

$$\sigma(A\bar{A} \rightarrow H) \times BR(H \rightarrow B\bar{B}) \sim g_A^2 \left( g_B^2 / \Gamma_{tot} \right)$$

g_A and $g_B$ are Higgs couplings to $A\bar{A}$ and $B\bar{B}$ and $\Gamma_{tot}$ is the total Higgs decay width.

In principle, measurements in different production and decay modes allow untangling the individual couplings, if $\Gamma_{tot}$ is known. But if there is New Physics, there can be additional decay modes (e.g. dark matter) that alter $\Gamma_{tot}$.

For SM Higgs, $\Gamma_{tot} = 4$ MeV, unmeasurably small at LHC, so either must assume its value, or be content with measurements of ratios of couplings. Moreover the dominant $H \rightarrow bb$ decay is swamped with background and thus is very difficult to measure. (Tevatron did manage to get evidence.)

We are unlikely to get good sensitivity to NP at LHC
Enter the $e^+ e^-$ Collider

- In an $e^+ e^-$ collider, the interacting electrons have known fixed energy (interacting quarks in protons have a broad distribution of energies)
- Initial quantum $\#s$ known ($J^P=1^-$)
- Can polarize $e^+$ and $e^-$ and suppress or enhance specific subprocesses
- Collision events are very clean; can reconstruct the whole event
- Low backgrounds/event pileup – can simplify detectors and reduce material

Electrons in circular orbits emit synchrotron radiation, limiting practical machines to $< \sim 350$ GeV. Thus for high energy go to two long, opposing single pass linear accelerators. Squeeze the beams to a few nm at collision pt.

Schematic of subsystems of a linear collider
In 2013, an international team completed the ILC Technical Design Rept. for a 500 GeV $e^+ e^-$ collider, upgradable to 1000 GeV.

**VALUE** cost $7.8 B + 22.6M person hrs labor.

Japan has expressed serious interest in hosting ILC as an international project, and is conducting an evaluative process aimed at concluding in 2017. A site in northern Japan has been identified.

A global consortium has been formed for planning the accelerators and two detectors (led by Lyn Evans, ex-head of the LHC project).

The key challenge of making 1m long RF cavities with 31.5 MV/m accelerating gradient has now been met (15K of them needed).
**ILC physics program**

ILC can make Higgs analogously to LHC ("Higgstrahlung"). Cleanliness of $e^+ e^-$ collisions allows one to ‘see’ the Higgs from the Z boson recoiling against it and directly measure BRs.

The ability to ‘observe’ the Higgs without seeing its decay enables measurement of invisible decays (e.g. $H \rightarrow$ dark matter).

The clean environment and higher resolution detectors with lower mass also permit more precise measurements than at the LHC.

$\Gamma_{tot}$ is measureable: The $WW$ fusion $\sigma \times BR(H \rightarrow x\bar{x})$ ($x = b, W, t ...$) is proportional to $BR_W BR_x \Gamma_{tot}$. With the precise ILC measurements of $W$ and $x$ BRs and the observed rate, one can obtain $\Gamma_{tot}$ to $\pm 6\%$, removing a major limitation at the LHC.
Recall the possible deviations from the SM Higgs couplings of a few %. To measure such deviations, need precision at sub % level in a model independent measurement.

The ILC measurements will take us into the sub percent level for many of the Higgs couplings, and thus give incisive information on the character of New Physics.
The ILC physics program extends well beyond Higgs:

- $W$ mass to 3x better than current world average (remember the top vs. $W$ vs. Higgs constraints on the SM needed better $M_W$)

- Measure top quark mass 5x better than current world average and at ILC, we will know what this mass means theoretically.

ILC top and $W$ measurements shown at the current central values. Lack of intersection of top–$W$ ellipse with Higgs mass line would signal New Physics.
ILC measurements

Remember the role of top mass in the metastablility of the vacuum (Higgs potential).

At the ILC, one measures a well-defined theoretical mass. The ILC measurement (here plotted at the current world average) will further constrain the stability of the vacuum.

- Measure detailed properties of any SUSY (or other new) particles within reach. Illuminate the character of Supersymmetry breaking. Precision measurements can sense new physics to 5-10 TeV.

- Sensitive tests of EW symmetry breaking, and anomalous couplings

- Production cross section and mass of Dark Matter particles
The Standard Model has survived the test of 1000’s of measurements, but has severe flaws as a fundamental theory.

Observation of the Higgs boson at LHC was a major triumph of the SM.

No new particles or phenomena beyond the SM have yet been seen, despite myriad theoretical conjectures of New Physics.

Progress can be made through higher precision measurements of the top quark, W boson and Higgs boson. These are intricately interlocked and these measurements can indicate the nature of New Physics.

LHC has the potential to directly view the New Physics in its high energy, high luminosity running starting this year.

A future e+ e− linear collider has the potential to add precision where we need it most. Japan is seriously considering to host the ILC.
Studies of the Higgs boson, top quark and W boson at the Tevatron, LHC and ILC have a bright prospect to show us the nature of the breaking of Electroweak symmetry.
We stand at the end of two eras – the first run of the LHC at 7 – 8 TeV that discovered the Higgs boson, and the end of the Tevatron program that discovered the top quark and provided a precision profile of the W boson.

At this moment, the Standard Model of particle physics reigns supreme, but we do not understand why. But in the SM, three particles -- the Higgs, top and W are locked into a tightly constrained triangle. Measuring the properties of each with increasing precision should lead to new discoveries.