Whither Colliders after LHC 7/8?

Rohini M. Godbole

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8-12 December 2014, IIT Guwahati
Whither Colliders after LHC 7/8?

Plan

- Hurrah for the SM!

- How did colliders help us on this journey?

- What are the next steps? Whither/Whether [Wither?] Colliders?

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$L = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \overline{FD} \gamma^\mu D_\mu + h.c.$
$+ \overline{X_i} Y_{ij} X_j \phi + h.c.$
$+ |\overline{D\phi}|^2 - V(\phi)$
The SM Lagrangian consists of **Gauge sector** and the **Scalar** sector:

\[
\mathcal{L} = -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + i\bar{\psi} \not{D} \psi + f_e^*(\bar{\nu}, \bar{e}) L \Phi e_R + f_u^*(\bar{\nu}, \bar{d}) L \Phi^C u_R \\
+ \ldots + h.c. + |D_\mu \Phi|^2 - \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2
\]
Gauge sector in very good shape Given that the Strong interaction part as well as idea of Spontaneous Symmetry breaking AND EW unified model all got the Nobel prizes before July 4, 2012.

But the EW gauge theory needs the Scalar sector for it to be consistent!
2013 Update of the PDG!

We found it where we expected it.

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The SM rocks!

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SM rocks! LOOP Level!
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The Yuakwa sector

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To steal from ’Tale of two cities’

It is the **BEST** of the times ; it is the **WORST** of the times!

**WHY?**

Found the ’light’ Higgs but *as yet NO* evidence for the physics that we *think* *must* exist to keep it so!
Peeping through the Higgs window!

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Constraints from the LHC

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Gian's summary of LHC/BSM

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LHC:

Seems to have found the light Higgs

BUT

So far no evidence/indication for the different BSM particles.

The mass and the couplings of this light state might be the window through which we can get a view of BSM at present!
'Anticipating' the scale of BSM physics is a bit like anticipating the Higgs mass in the SM. We had no prediction for it, but then there were precision constraints.

Can we probe BSM like this: through the mass of the Higgs and through the Higgs couplings, through vacuum stability?
Statement number 1:

"In the present state of physical science, therefore, a question of extreme interest arises: Is there any principle on which an absolute thermometric scale can be founded?"

Statement number 2:

"There is nothing new to be discovered in physics now, All that remains is more and more precise measurement."
1. **Existence of a EW scale** stable under radiative corrections **revealed.** Is there a guiding principle on which the stability can be founded? We ’thought’ we knew!...may be our thinking is right but...may be not!

2. **All that remains is more and more precise measurement** of the Higgs and top properties! **OR Higher and higher energies?**
It is not as though we are only agonising over non discovery of a beautiful theory which we think must be realised in nature because of its aesthetic beauty!

MANY pragmatic reasons to expect physics: either interactions or particles beyond what we have found!
• Existence of a light Higgs!

• Direct evidence for the nonzero $\nu$ masses

• Quantitative explanation of the Baryon Asymmetry in the Universe!

• Dark Matter makes up 30% of the Universe.!

• Cosmological puzzles! Dark Energy! + understanding CMBR!

----------------------------------------------------------------------

• Instability of the EW scale under radiative corrections.

• Unification of couplings

• Need to get a basic understanding of the flavour issue

• Inclusion of Gravity in the picture?
DM : the direct detection experiments and astrophysics both are challenging usual DM folklores just as much as LHC 'paradox' is challenging the 'hierarchy' folklore or 'fine tuning' folklore!

DM at the colliders is throwing out results that too we do not seem to understand!
May be we are at a cusp and some people are asking the question whether it is time for a paradigm shift!

What is the way forward?

Before discussing and thinking about these things better to take stock of things as they are!

How we came to be here?
The baton at the frontier has passed from one type of machine to another back and forth.

Hadronic colliders make broad sweep measurements

Leptonic colliders offered precision measurements

Both necessary for development
**Whither Colliders after LHC 7/8?**

**How did we get here?**

---

**Flow of Physics info. between Colliders**

<table>
<thead>
<tr>
<th><strong>$e^+e^-$ Colliders</strong></th>
<th><strong>$p\bar{p}$ Colliders</strong></th>
<th><strong>$e^-$ Colliders</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>SPEAR</td>
<td>ISR (CERN)</td>
<td>Fermilab CERN</td>
</tr>
<tr>
<td>J/ψ</td>
<td>Jets + evidence for quarks, $W/Z$ discovery of EW Theory</td>
<td>Revealed</td>
</tr>
<tr>
<td>Third generation</td>
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<tr>
<td>PEP/PETRA</td>
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<tr>
<td>gluons</td>
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<tr>
<td>(Strong Int. gauge bosons)</td>
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</tbody>
</table>

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Whither Colliders after LHC 7/8?  
How did we get here?

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What have the Colliders taught us?

- μ decay, ν expts used to predict Mω and Mζ in the Standard Model.
- DIS expt info impacts Collider design.
- CERN SppS discovered W and Z as per prediction.
- LEP, Tevatron
  - Precision Z phys. at LEP & Tevatron
  - Top observation
- LEP Prediction of top mass agrees with value measured at Tevatron
- Tested formalism accurately
- LEP-II, Tevatron
- Further precision measurements of Mω, Mζ
- Predict Mh
- LHC to look for Higgs

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Whither Colliders after LHC 7/8?

Intensity frontier

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At present we do not quite know the answer to the question 'Whither next'?

Following the 'discovery ' of the Higgs at the LHC, next logical step is to make precision studies of the properties of the Higgs.

Just like precision study of all the other particles in the SM gave information on the missing piece the Higgs, now one can learn about Beyond the SM(BSM) physics.

Can LHC offer high enough precision in the studies of the properties (mass, spin, parity) of the Higgs.

The energy scale for BSM seems to be high (initial LHC results) 😞

Historically baton has passed from hadronic to leptonic colliders and vice versa. So then may be it is the turn of high energy $e^+e^-$ colliders.

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• The days of “guaranteed” discoveries or of no-lose theorems in particle physics are over, at least for the time being ....

• .... but the big questions of our field remain wild open (hierarchy problem, flavour, neutrinos, DM, BAU, ....)

• This simply implies that, more than for the past 30 years, future HEP’s progress is to be driven by experimental exploration, possibly renouncing/reviewing deeply rooted theoretical bias
Experiments with these machines helped us discover the physics at the heart of matter.

LHC has given us our latest fundamental particle.

Is this now the end of the journey?

We needed results from LHC to help us answer this query as well. Now we have some answers and weak pointers where to go ahead!
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Exciting and worrying things!

The mass of the observed state very very interesting from a lot of points of view!

Small enough to keep us still thinking of a mechanism like SUSY to stabilize it (case for a higher energy $pp$ machine?)

and

Large enough to make us wonder whether SM is the ONLY thing all the way to the Planck Scale! (strengthened by absence of any BSM signal!) case for precision measurement?

and

A unique value where decays into almost all final states are substantial Good for precision measurement
Whither Colliders after LHC 7/8?

Moving energy frontier

[Graph depicting the energy frontier with Hadron Colliders and e+e- Colliders.]
Hadronic colliders can make precision measurements too!

Example: $M_W$ (Tevatron)

Case for High Luminosity LHC!

Make use of the precision of $e^+e^-$ colliders to study Higgs and top sector with high precision!

Should we push to increase the energy frontier of hadronic colliders further?
13/14 TeV LHC!

High Luminosity HL 13/14 TeV : 3000 fb$^{-1}$

Far future: HE 100 TeV?

ILC: 250 GeV, 500 GeV and 1 TeV: Interesting developments in Japan!

FCC: future circular colliders: FCC(ee) upto 350 GeV

Same tunnel : 100 TeV pp and also high energy eP?

Chinese: thinking seriously about the FCC!

On the intensity front : Super Belle. Will provide precision information on flavor physics!
Colliders:

Current knowledge provides the physics justification, motivation for the next machine. The physics case as one would like to call it.

a) It provides the goals for the accelerators in terms of energy and luminosity

b) It provides goals for the measurements that the detectors must be capable of
There has been a world wide process over last 10 years

Americas, Asia and Europe made Road Maps.

Now we need to decide which fork in those road maps will be most useful!

European Strategy Group had many Asian and American members (global effort)

We heard about the ILC project yesterday!
The Physics Case for an e⁺e⁻ Linear Collider

James E. Brau, Rohini M. Godbole, Francois R. Le Diberder, M. A. Thomson, Harry Weerts, Georg Weiglein, James D. Wells, Hitoshi Yamamoto

This document presents an overview of the physics potential of a future electron-positron linear collider. It represents a common input from the CLIC and ILC communities.

Comments: Submitted to the Open Symposium of the European Strategy Preparatory Group, 10-12 September 2012, Krakow, Poland, 15 page limit.

arXiv:1210.0202 [hep-ex]

Now various 'white papers' have come out of the US Snowmass papers.
Europe, Japan seems strongly in favor of a staged, $e^+e^-$ at present with possibilities of CLIC, $\gamma\gamma$ colliders etc. to be decided by physics discoveries of the next decades.

Japanese Government has sanctioned in its budget 'ILC designated' budget to evaluate feasibility of an International project. (Sachio's talk)

USA, China, Europe: studying the possibilities of a circular electron-positron collider: FCC

Support for ILC in the HEPAP report as well as in European Strategy report!
FCC Study (Future Circular Colliders)
CDR and cost review for the next ESU (2018)

- 80-100 km tunnel infrastructure in Geneva area
- design driven by pp-collider requirements
- with possibility of e+e- (TLEP) and p-e (VLHeC)
- CERN-hosted study performed in international collaboration

15 T $\Rightarrow$ 100 TeV in 100 km
20 T $\Rightarrow$ 100 TeV in 80 km
Whither Colliders after LHC 7/8? European thinking?

FCC (hh) is the goal, FCC(ee) on the way!

What is required:

A 80-100 km Tunnel

(Talk at ICHEP by R. Tenchini, 1412.2928): Requires 1/4 RF power of LEP with an increase in radius by a factor 3 and total power consumption 5 times that of LEP for energy of 240 GeV.

A Working group formed to discuss, compare and contrast the capabilities of different machines!

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Centre for Future High Energy Physics: CFHEP Design and physics potential studies for future circular colliders. A Higgs factor with $\sqrt{s} = 240$ GeV and then a high energy pp machine.

Regular workshops: so far two have taken place.

See for details the webpage and talk by Yifang Wang at the ICFA seminar in Beijing in October 2014.
We want precision in the SM sector: why? If there are anomalies hiding in tall 'elephant grass' we need to have pinpointed search lights! A very tough ask to decide whether the deviations are statistically significant!

We want precision determination in the Higgs sector: Not just the signal strengths $\mu$, but also the tensor structure of the vertices. The latter can provide model independent studies of the BSM in terms of effective operators! (remember talk by J. Wudka)

We want precision determination of the top sector! mass and the strength and the structure of Yukawa coupling of the top!
Precision determination of $m_t$ and $m_h$ necessary to conclude about possible scale of ’BSM’!

We want precision prediction for the Higgs mass: recent progress has a big effect on analyzing implications of observed Higgs mass for SUSY. ’Invisible’ decays of the Higgs!

Precision determination of the $B, D$ physics and probing the BSM through these effects! LHCB, Super Belle.
Light Higgs still keeps one hopeful of seeing some new physics which should stabilize the Higgs mass without too much 'fine tuning'.

How much fine tuning is too much? *somewhat subjective*

How does reach (for example) for SUSY increase with increasing Energy and increasing luminosity?
Increase the energy by a factor 2 and luminosity by a factor 4, reach in M by a factor 2.

At a given energy increase luminosity by a factor 10, reach seems to go up by $\Delta m = 0.07 \sqrt{s}$
Increase luminosity by factor 10
\[ \rightarrow \text{reach increases by constant} \]
\[ \Delta m \approx 0.07\sqrt{s} \]
i.e. for \( \sqrt{s}=14 \) TeV, reach goes by up 1 TeV

No deep reason — a somewhat random characteristic of large-x PDFs.
Only holds for \( 0.15 \leq M/\sqrt{s} \leq 0.6 \)

From a slide from G. Salam for a FCC workshop
Flavour physics constraints and precision study may push scale of new physics very high! Then a higher energy hh machine would be the only option!

Arkani Hamed argues that for him the expected SUSY reach at a 100 TeV collider will be at the edge of fine tuning he thinks is ’natural’!
US: Snowmass studies.

Comparisons of HL LHC, FCC(ee), ILC and CLIC!

FCC(ee): Lower energy than ILC, can cover precision study of Higgs and $t\bar{t}$ in the second stage. Extension to higher energy to cover $t\bar{t}h$ seems a bit too expensive for the circular option.

Higher luminosity, so precisions for FCC(ee) almost always better than even ILC.

FCC (hh) requires magnetic fields of about 15-20 Tesla. This is about twice the current values.

Chinese option for FCC is looking at (right now) only the option with energy unto 240 GeV.
I want to remind us of Sachio’s slide from yesterday;

More than two decades required to achieve the performance for the beam and acceleration gradient that is required for the ILC to deliver!

Typical time scale!

LHC: 13 TeV: current

SuperBelle : certain.

LHC(HL): Quite certain

ILC: Technology available and can be undertaken once money is available

FCC (ee) and FCC(hh) seem more the 'future' machines: two or three decades in future.
Whither Colliders after LHC 7/8?

One way of discovery of BSM!

Inclusive “SM” cross sections

Examples

<table>
<thead>
<tr>
<th></th>
<th>( \sigma (pp \rightarrow W^+ W^- + X) ) [pb]</th>
<th>SM NLO [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.6 fb(^{-1}) ATLAS 7 TeV</td>
<td>51.9 ± 2.0 ± 3.9 ± 2.0</td>
<td>44.7 \pm 2.1</td>
</tr>
<tr>
<td>4.6 fb(^{-1}) CMS 7 TeV</td>
<td>52.4 ± 2.0 ± 4.5 ± 1.2</td>
<td>44.7 ± 2.1</td>
</tr>
<tr>
<td>3.5 fb(^{-1}) CMS 8 TeV</td>
<td>69.9 ± 2.8 ± 5.6 ± 3.1</td>
<td>57.3 \± 2.4</td>
</tr>
</tbody>
</table>

Exptl syst’s is theory dominated (jet veto efficiencies, PDFs, ....)

\(\sim2\sigma\) off  
\(>3\sigma\) if combined

- How far can we take similar discrepancies, should they increase to the 3\(\sigma\) level and be confirmed at 14 TeV? They could be hiding charginos, sleptons, ....

- They appear to be syst limited: what more can be done to reduce the syst?
For the first time some information on the fermion higgs coupling. 
\[ \lambda_x = \frac{m_x}{v} \] (in the SM)

Is it the Higgs?
Whither Colliders after LHC 7/8? Help from ILC!

1207.2516 : M. Peskin

$\frac{g(hAA) - g(hAA)_{SM}}{1}$ LHC/ILC1/ILC/ILC TeV

W Z b g γ τ c t inv
The knowledge of theory effects essential in deciding whether we have a smoking gun signal for BSM, especially when it is indirect.

Assumption about theoretical systematic aggressive. Would require NNNLO and above calculations.
Whither Colliders after LHC 7/8? Correlation of Higgs data with invisible decay

Light Higgs raises the possibility that $\lambda_{eff}$ becomes less than zero at high scale where $\lambda_{eff}$ is the self coupling!

De Grassie et al (1205.6497) Complete NNLO analysis. Major progress. Theoretical error on the obtained bounds due to missing higher order corrections reduced to 1 GeV. $m_t$ dependence is significant.

With the given value of $m_h, m_t$, we MAY be living in a metastable vacuum OR there MAY be some BSM around $10^{10}$ GeV!
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Whither Colliders after LHC 7/8? The fate of vacuum

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Moch et al: extract the $\overline{MS}$ mass of the top quark from the measurement of the top quark cross-sections at the Tevatron and the NNLO calculation.

Estimate: $m_t^{pole} = 173.3 \pm 2.8$ GeV.

Results in diluting the Vacuum stability constraint $m_h > 129.4 \pm 5.6$ GeV.
Whither Colliders after LHC 7/8?

The fate of vacuum
Whither Colliders after LHC 7/8? ILC can help?

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Earlier one thought that determination of $J^{CP}$ of the boson will be a long term prospect.

But existence of the $h \rightarrow ZZ^*$ allowed this determination.
Determination of the $J^{PC}$ quantum numbers about as 'certain' as India losing test series abroad!

What is important and difficult is to find if there is a CP mixing!

This is where perhaps the Linear Collider can really score!

Of course one wants to find out what LHC can do too!

In more detail:

$$V_{HV}^{\mu\nu} = \frac{igmZ}{\cos\theta_W} \left[ aV g_{\mu\nu} + bV \left( \frac{p \cdot q g_{\mu\nu} - p_{\mu} q_{\nu}}{m_V^2} \right) + cV \epsilon_{\mu\nu\alpha\beta} \frac{p^\alpha q^\beta}{m_V^2} \right] ,$$
Significance of the asymmetries about 3σ for CP odd couplings similar in strength to CP even. Consistent with the current 3σ discrimination against a pure CP odd Higgs! (JHEP 0712 (2007) 031)
In general $e^+e^-$ colliders can do well here.

For establishing the $J^{PC} = 0^{++}$ as well as for measuring the CP mixing if it is not a CP eigenstate.

At electron-positron colliders using polarisation one can do even better.
\( L = 500 \text{ fb}^{-1}, \text{ at } 3\sigma \text{ significance; } \) PRD. 73, D73 (2006) 035001, PRD79 (2009) 035012: Biswal, Singh, R.G.

<table>
<thead>
<tr>
<th>Coupling</th>
<th>Limit</th>
<th>Observable used</th>
</tr>
</thead>
<tbody>
<tr>
<td>(</td>
<td>\Delta a_Z</td>
<td>)</td>
</tr>
<tr>
<td>(</td>
<td>\Re (b_Z)</td>
<td>)</td>
</tr>
<tr>
<td>(</td>
<td>\Im (b_Z)</td>
<td>)</td>
</tr>
<tr>
<td>(</td>
<td>\Re (\tilde{b}_Z)</td>
<td>)</td>
</tr>
<tr>
<td>(</td>
<td>\Im (\tilde{b}_Z)</td>
<td>)</td>
</tr>
</tbody>
</table>

20\% efficiency : \(|\Im (b_Z)| \leq 0.050, \ |\Re (\tilde{b}_Z)| \leq 0.049|

30\% efficiency : \(|\Im (b_Z)| \leq 0.041, \ |\Re (\tilde{b}_Z)| \leq 0.046|

\(\tilde{b}_Z\) related to \(c\) of the earlier plot!
In the units mentioned in the effective Lagrangian approach these will correspond to sometimes $\Lambda \lesssim 1.5 \text{TeV}$ and the LHC numbers to about $\Lambda \sim 400 - 500 \text{ GeV}$.


With HL option one can reach $\Lambda \sim 800 \text{GeV}$
$ttH$ coupling the most unambiguous way of studying CP violation in the Higgs sector.

At LHC rates give weak constraints: assume the coupling to be $\bar{t}(a + ib\gamma_5)t\phi$ Kirtimaan Mohan, R.G, F. Boudjema.
Can measure also $t\bar{t}h$ coupling directly including the $CP$ structure unambiguously! $e^+e^- \rightarrow t\bar{t}H$ has a different threshold rise for scalar and pseudoscalar: ZPC 71, 1681 (R.G. M. Muhellkleitner, etal) Can even measure/bound CP mixing in Higgs without ambiguity!

![Graph showing cross-section vs. sqrt(s) for CP-even and CP-odd states for M_\phi=120 GeV](image)
Whither Colliders after LHC 7/8? \( t\bar{t}H \) and CLIC


R.G. et al, EPJC 71, 1681 (2011)
Possibilities with LHC too! (Ellis et al, Boudjema, R.G. K. Mohan et al)

More detailed studies needed to see what can be really done!

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Is this then the END?

It is not even beginning of the end!

If at all only the end of a beginning

😊
Connections with Cosmology : Some can be tested through precision measurements at the Colliders! for example the **Invisible branching ratio** of the Higgs.

The Higgs mass and (in)stability of the Vacuum may say something about high scale physics and MAY have connections to some Planck Scale physics ideas!

The progress has to come through the joint investigations on the earth and in the sky!

So Colliders will do their bit! By precision measurements: either at hadronic colliders or at leptonic colliders!
LHC: 13 TeV: current

SuperBelle: certain.

LHC(HL): Quite certain

ILC: Technology available and can be undertaken once money is available. CLIC technology studies in advanced stage. (Linear Collider Board: LCB)

FCC (ee) and FCC(hh) seem more the 'future' machines: two or three decades in future.

Results form LHC 13 will play a role in deciding what we do! May be in a few months we will have forgotten that we were agonizing over this 'absence' of new physics at LHC!
One thing for sure: we need precision calculations and precision measurements!

The road may be very long but colliders are not 'withering' just yet!
\[ L = \sqrt{g} \left\{ R - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} + \Theta F^{\mu\nu} \right. \\
\quad + \bar{\Psi} \partial \Psi + Y_{ij} H \Psi_i \Psi_j + h.c. \\
\left. + |D_m H|^2 - V(H) \right\} \]

\[ \equiv \text{Our Universe... so far} \]
Backup slides
Example

Partons and QCD:

1) SLAC 'discovered' partons at the fixed target $eP$ experiment

2) Fixed target $\nu N, \mu N$ experiments provided quantitative information on parton content of the proton. Also provided information which eventually led to formulation of QCD.

3) $pp$ experiments at ISR/SPS provided evidence for partons in a different environment altogether.

4) PETRA and PEP ($e^+e^-$) provided 'direct' evidence for gluons.
5) HERA $ep$ collider provided **precision** information on proton structure and provided precision tests of QCD.

6) $\bar{p}p$ experiments at the S $pp\bar{S}$ and the Tevatron added to this

7) **Precision** measurements at LEP ($e^+e^-$) of $\alpha_s$ and $\sin^2 \theta_W$:

   a) Provided a big step towards establishing QCD as THE gauge theory

   b) Provided **precise** enough information to pose questions on unification of couplings and pointers to **BSM** physics.
With Fixed target experiments goal for the $S^p\bar{p}S$ was set because theory predicted $M_W/M_Z$

With measurements from LEP-I amd LEP-II the target for $M_t$ was set.

In the SM there is no 'pure' theoretical prediction for the Higgs mass but only upper and lower limits: theoretical bounds.

The luminosity and the energy of the LHC was fixed to cover this entire mass range where the Higgs could be in the SM.
With discovery of $t$ at Tevatron told us where the higgs mass aught to lie, in the SM, given the precision measurements at LEP-I, LEP-II. INDIRECT bounds.

Comparing results of direct searches with these indirect bounds can give now information about the SM and physics beyond the SM (BSM).
Higgs Measurements of the Future

Higgs boson $\mu$ values

- CMS results from 7-8 TeV 10 fb$^{-1}$ and extrapolated to 300 fb$^{-1}$ with fixed systematic uncertainties with or w/o theory uncertainties

- Achieve 10-15% precision with 300 fb$^{-1}$ for these main channels

Note sensitivity to $\mu\mu$, and tthH with 3000 fb$^{-1}$

ATLAS Simulation

$\sqrt{s} = 14$ TeV: $L_{\text{data}} = 300$ fb$^{-1}$; $L_{\text{data}} = 3000$ fb$^{-1}$

$\Delta \mu / \mu$
### Theoretical uncertainties on inclusive production rates

<table>
<thead>
<tr>
<th>Process</th>
<th>$\delta$(pert. theory)</th>
<th>$\delta$(PDF, $\alpha_s$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$gg \rightarrow H$</td>
<td>$\pm 10%$</td>
<td>$\pm 7%$</td>
</tr>
<tr>
<td>VBF ($WW \rightarrow H$)</td>
<td>$\pm 1%$</td>
<td>$\pm 2%$</td>
</tr>
<tr>
<td>$qq \rightarrow WH$</td>
<td>$\pm 0.5%$</td>
<td>$\pm 4%$</td>
</tr>
<tr>
<td>$(qq,gg) \rightarrow ZH$</td>
<td>$\pm 2%$</td>
<td>$\pm 4%$</td>
</tr>
<tr>
<td>$(qq,gg) \rightarrow ttH$</td>
<td>$\pm 8%$</td>
<td>$\pm 9%$</td>
</tr>
</tbody>
</table>

*Improve with higher-loop calculations: $gg \rightarrow H$ at NNNLO, $ttH$ at NNLO*

*Petriello*

*Huston*
Even without including the additional EFT uncertainty, the procedure reduces the excess from $\sim 2\sigma$ to $\sim 1\sigma$. 
Whither Colliders after LHC 7/8?

Including the theory error linearly

Conclusion: For discovery perhaps it was not so relevant, but for the studies of couplings (unless we use ratio of ratios OR ratio of different observed rates!) a discussion of how these errors should be treated in extraction of couplings is important!
The success of the LHC is proof of the effectiveness of the European organizational model for particle physics, founded on the sustained long-term commitment of the CERN Member States and of the national institutes, laboratories and universities closely collaborating with CERN. Europe should preserve this model in order to keep its leading role, sustaining the success of particle physics and the benefits it brings to the wider society.

The scale of the facilities required by particle physics is resulting in the globalisation of the field. The European Strategy takes into account the worldwide particle physics landscape and developments in unrelated fields and should continue to do so.
The European Strategy for Particle Physics:

- The discovery of the Higgs boson is the start of a major programme of work to measure this particle's properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to pursue this programme. Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.
To stay at the forefront of particle physics, Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when physics results from the LHC running at 14 TeV will be available. CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide.
• There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded. The Technical Design Report of the International Linear Collider (ILC) has been completed, with large European participation. The initiative from the Japanese particle physics community to host the ILC in Japan is most welcome, and European groups are eager to participate. Europe looks forward to a proposal from Japan to discuss a possible participation.
• Rapid progress in neutrino oscillation physics, with significant European involvement, has established a strong scientific case for a long-baseline neutrino programme exploring CP violation and the mass hierarchy in the neutrino sector. CERN should develop a neutrino programme to pave the way for a substantial European role in future long-baseline experiments. Europe should explore the possibility of major participation in leading neutrino projects in the US and Japan.
On the basis of these developments and following the subcommittee's recommendation on ILC, JAHEP proposes that ILC be constructed in Japan as a global project with the agreement of and participation by the international community in the following scenario:

Physics studies shall start with a precision study of the "Higgs Boson", and then evolve into studies of the top quark, "dark matter" particles, and Higgs self-couplings, by upgrading the accelerator. A more specific scenario is as follows:

- **Staging**
  - A Higgs factory with a CM energy of ~250 GeV to start
  - Upgraded in stages to ~500 GeV (ILC baseline)
  - Technical expandability to ~1 TeV to be secured
Is this a pipe dream?

- There is a lot of momentum in Japan:
  - Community
  - Industry & local regions
  - National Politics
- It crucially depends on international interest & support on its scientific case
- European Strategy supports the proposal for Japan to host an ILC, already helping
A 5-year plan formed through town hall meetings in 2007
- Endorsed by Japan Association of HE Physicists
- ILC at the top of the pyramid
KEK takes an initiative to start an international preparatory organization to host ILC in Japan, engage in detailed designs of equipments, facilities, laboratory organization etc., and aims at starting the construction under international framework within the duration of this roadmap (5 years from 2014). (my translation)
JAHEP
Subcommittee on Future Projects in HEP

- A report on large projects (March 2012)
  - ILC and neutrino experiment at highest priority.
  - On ILC:
    Should a new particle such as a Higgs boson with a mass below approximately 1−1 TeV be confirmed at LHC, Japan should take the leadership role in an early realization of an $e^+e^-$ linear collider. In particular, if the particle is light, experiments at low collision energy should be started at the earliest possible time.

(Now, Higgs-like particle has been found and it is ‘light’)

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CHEP, IISc