Facts and Phantoms at the High Energy Frontier

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Present Energy Frontier
Large Hadron Collider @ CERN
Situation

• The structure of the Standard Model (SM) was sufficient to define experimental stepping stones leading to the recent discovery of the Higgs scalar boson (July 2012), considered to be the ‘last’ SM particle
  – This is a stunning success!

• A number of questions are left unanswered:
  – Is the particle discovered really the SM Higgs or does it have other scalar partners?
  – Can the SM really describe all high energy phenomena up to the Planck scale?
  – What about SUSY? Hidden Sectors? U(1) A’?
  – Where do the fermion mixing (CKM) and CP parameters come from?
  – What constitutes Dark Matter and Dark Energy?
The Standard Model of EW Interactions

- SU(2)$_L$ x U(1)$_Y$ Gauge Group + Higgs Mechanism

- EM \[ e = (4\pi\alpha)^{1/2} \]
- CC \[ g = 2(\sqrt{2}Gf)^{1/2} M_w \]
- NC \[ g' = g \tan\theta_w \]

\[ \tan\theta_w = \frac{g'}{g} \quad \text{and} \quad e = \frac{g'g}{\sqrt{g'^2 + g^2}} \]

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Higgs Particle & Couplings

\[ <v> = \left( G_\mu \sqrt{2} \right)^{-1/2} \approx 246 \text{ GeV} \]

\[-\text{im}_f (G_F \sqrt{2})^{1/2} \]

\[-\text{ig}_M_{w} g_{\mu\nu} \]

\[-\frac{\text{ig}_M_{z}}{\cos \theta_w} g_{\mu\nu} \]

\[-6i|\lambda| v = -3i M_H^2 (G_F \sqrt{2})^{1/2} \]

Couplings depends on Mass by design
SM with Radiative Corrections

• Running $\alpha(0) \rightarrow \alpha(M_Z^2)$ by QED & $\langle v \rangle = (G_\mu \sqrt{2})^{-1/2} \approx 246$ GeV
  - Contributions to $\gamma$ self energy term

$$\frac{1}{\alpha(0)} - \frac{1}{\alpha(M_Z^2)} = \sum_f Q_f^2 \ln\left(\frac{m_f^2}{M_Z^2}\right)$$

• Vector gauge boson mass relations

$$M_Z^2 = \frac{\pi \alpha_{em}}{\sqrt{2} G_\mu \sin^2 \theta_W \cos^2 \theta_W \zeta_Z}$$

$$M_W^2 = \frac{M_Z^2}{2} \left(1 + \sqrt{1 - \frac{4\pi \alpha_{em}}{\sqrt{2} G_F \zeta_W M_Z^2}}\right)$$

• Vector gauge boson partial widths

$$\Gamma_{ff} = \frac{\sqrt{2} G_m M_Z^3}{12\pi} N_c \left(g_{Vf}^2 + g_{Af}^2\right) \zeta_{ff}$$

Correction Terms

~ $M_{top}^2$
~ $\ln(M_{higgs})$
Standard Model Stepping Stones

EW-SM (NC/CC), $\alpha_{em}$, Gf, $\theta_w$: $M_w$, $M_z$

Known Predicted

EW-SM (NC/CC), $\alpha_{em}$, Gf, $\theta_w$, $M_w$, $M_z$, radiative corrections: $M_t$

EW-SM (NC/CC), $\alpha_{em}$, Gf, $\theta_w$, $M_w$, $M_z$, radiative corrections, $M_t$: $M_h$

EW-SM (NC/CC), $\alpha_{em}$, Gf, $\theta_w$, $M_w$, $M_z$, radiative corrections, $M_t$, $M_h$: (? SUSY ?)
The large value of $M_T$ makes it play a big role. $M_H$ plays a smaller role.

\[ \delta_H \approx g^2 \left[ \ln \left( \frac{M_H}{M_W} \right) + g^2 \left( \frac{M_H}{M_W} \right)^2 \right] \approx g^2 \ln \left( \frac{M_H}{M_W} \right) \]

“The Screening Theorem and Higgs System”: Veltman XXXIV
Cracow School of Theoretical Physics, Zakopane, Poland, June 1-10, 1994
The next to the last stepping Stone

- Summer 2010 EW Working Group before LHC data

\[ \Delta r \sim \ln \left( \frac{M_{Higgs}}{M_W} \right) \]

CERN-PH-EP-2010-095

- \( M_h = 89 \pm 35/-26 \) GeV EW precision
- \( M_h > 114 \) GeV LEP II
- \( M_h < 158 \) GeV Tevatron
- \( M_h > 175 \) GeV Tevatron

We had a pretty good idea on where to look for the Higgs!
SM Higgs Cross Sections & Branching Ratios

Production

Decay

$\sqrt{s} = 8\text{TeV}$

proton - (anti)proton cross sections

Tevatron LHC

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ATLAS

$M_{4\mu} = 123 \text{ GeV}$
$M_{Higgs}$ Detection @ LHC - ATLAS
SM-Like Higgs Properties

<table>
<thead>
<tr>
<th>Process</th>
<th>Mass [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMS $H \to \gamma\gamma$</td>
<td>$125.4 \pm 0.5 \pm 0.6$</td>
</tr>
<tr>
<td>CMS $H \to ZZ^{(*)} \rightarrow ll\ell\ell$</td>
<td>$125.8 \pm 0.5 \pm 0.2$</td>
</tr>
<tr>
<td>CMS Combined</td>
<td>$125.7 \pm 0.3 \pm 0.3$</td>
</tr>
<tr>
<td>ATLAS $H \to \gamma\gamma$</td>
<td>$126.8 \pm 0.2 \pm 0.7$</td>
</tr>
<tr>
<td>ATLAS $H \to ZZ^{(*)} \rightarrow ll\ell\ell$</td>
<td>$124.3 \pm 0.6 \pm 0.5 \pm 0.5 \pm 0.3$</td>
</tr>
<tr>
<td>ATLAS Combined</td>
<td>$125.5 \pm 0.2 \pm 0.5 \pm 0.6$</td>
</tr>
<tr>
<td>Combination</td>
<td>$125.6 \pm 0.3$</td>
</tr>
</tbody>
</table>

Width $\sim 4.2$ MeV (Theory)

CMS measurement
$\Gamma/\Gamma_{SM} < 4.2$ @ 95% CL
Updated Today at La Thuille

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Higgs Couplings \approx F(\text{mass})
Higgs Signal Strength vs. Theory
Mass, Spin, CP, Branching Ratios, Production Cross Section are all consistent with the SM Higgs

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Radiative corrections to the Higgs mass as a function of energy scale $\Lambda$:

$$M_H^2 = M_0^2 + \frac{3A^2_C}{8\pi^2v^2} \left[ M_H^2 + 2M_W^2 + M_Z^2 - 4m_t^2 \right] + \ldots$$

Note that Bosons enter the series with opposite sign of the Fermions. It would seem that a fine tuning (cancelation of terms) is needed to keep the Higgs mass finite up to the Planck scale.

Supersymmetry provides a natural solution – for every fermion there is a corresponding supersymmetric boson partner & vice versa.
To paraphrase George Santayana: “Those who fail to confirm or reject the theories of the past are condemned to repeat the search”

Supersymmetry is a candidate theory to solve this dilemma
### ATLAS SUSY Searches* - 95% CL Lower Limits

**Status:** SUSY 2013

\[ \int_{\mathcal{L}} d\mathcal{L} = (4.6 - 22.9) \text{ fb}^{-1} \quad \sqrt{s} = 7, 8 \text{ TeV} \]

<table>
<thead>
<tr>
<th>Model</th>
<th>( e, \mu, \tau, \gamma ) Jets</th>
<th>( E_{\text{miss}}^T )</th>
<th>( f \times 10^{-3} ) fb |</th>
<th>Mass limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSUGRA/CMSSM</td>
<td>0, 2 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>1.7 TeV</td>
</tr>
<tr>
<td>MSUGRA/CMSSM</td>
<td>1, 3 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>1.2 TeV</td>
</tr>
<tr>
<td>MSU1</td>
<td>1, 2 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>1.1 TeV</td>
</tr>
<tr>
<td>GMSB (LNLSP)</td>
<td>1, 2 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>1.24 TeV</td>
</tr>
<tr>
<td>GGM (bino NLSP)</td>
<td>2, 3 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>1.4 TeV</td>
</tr>
<tr>
<td>GGM (higgsino, NLSP)</td>
<td>2, 3 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>1.6 TeV</td>
</tr>
<tr>
<td>Gravitino LSP</td>
<td>0, 3 jets</td>
<td>Yes</td>
<td>10.5</td>
<td>1.7 TeV</td>
</tr>
<tr>
<td>3rd gen. &amp; med.</td>
<td>0, 2 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>1.3 TeV</td>
</tr>
<tr>
<td>3rd gen. squarks</td>
<td>0, 2 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>1.3 TeV</td>
</tr>
<tr>
<td>EW effect</td>
<td>2, 3 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>1.3 TeV</td>
</tr>
<tr>
<td>Direct &amp; indirect</td>
<td>2, 3 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>1.3 TeV</td>
</tr>
<tr>
<td>RPV</td>
<td>2, 3 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>1.3 TeV</td>
</tr>
<tr>
<td>Scalar gluon pair, gluin+aq̄q̄</td>
<td>2, 3 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>1.3 TeV</td>
</tr>
</tbody>
</table>

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1\( \sigma \) theoretical signal cross section uncertainty.
<table>
<thead>
<tr>
<th>Extra dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large ED (ADD): monojet + $E_{\text{miss}}$</td>
</tr>
<tr>
<td>Large ED (ADD): monophoton + $E_{\text{miss}}$</td>
</tr>
<tr>
<td>Large ED (ADD): diphoton &amp; dilepton, $m_{\gamma\gamma}$, $m_{\ell\ell}$</td>
</tr>
<tr>
<td>UED: diphoton + $E_{\text{miss}}$</td>
</tr>
<tr>
<td>S'/Z', ED: dilepton, $m_{\ell\ell}$</td>
</tr>
<tr>
<td>RS1': WW resonance, $m_{WW}$</td>
</tr>
<tr>
<td>Bulk RS: ZZ resonance, $m_{\ell\ell}$</td>
</tr>
<tr>
<td>RS g+ → ttf (BR=0.925): tt → l+jets, $m_{t}$</td>
</tr>
<tr>
<td>ADD BH ($M_{\text{TH}}/M_{\text{TH}}=3$): SS dimuon, $N_{\ell\ell}$, $m_{\ell\ell}$</td>
</tr>
<tr>
<td>ADD BH ($M_{\text{TH}}/M_{\text{TH}}=3$): leptons + jets, $\gamma,p$</td>
</tr>
<tr>
<td>Quantum black hole: dijet, $f$ (m)</td>
</tr>
<tr>
<td>qqqq contact interaction: $\hat{x}$ (m)</td>
</tr>
<tr>
<td>uutt CI: SS dilepton + jets + $E_{\text{miss}}$</td>
</tr>
<tr>
<td>Z' (SSM): $m_{\ell\ell}$</td>
</tr>
<tr>
<td>Z' (leptophobic topcolor): $t\bar{t} → l+jets, m_{t}$</td>
</tr>
<tr>
<td>W' (SSM): $m_{\ell\ell}$</td>
</tr>
<tr>
<td>W' (→ $t\bar{q}$, $g=1$): $m_{\ell\ell}$</td>
</tr>
<tr>
<td>W' (→ $tb$, LRSM)</td>
</tr>
</tbody>
</table>

| Scalar LQ pair (β=1): kin. vars. in $e\bar{e}$, $e\nu$, $e\nu$ |
| Scalar LQ pair (β=1): kin. vars. in $\mu\bar{\nu}$, $\mu\nu$, $\mu\bar{\nu}$ |
| Scalar LQ pair (β=1): kin. vars. in $\tau\bar{\nu}$, $\tau\nu$, $\tau\bar{\nu}$ |

| 4th generation: b'→ WbWb |
| Vector-like quark: $T\rightarrow H+X$ |
| Vector-like quark: $C\ell, m_{\ell\ell}$ |
| Excited quarks: $\gamma$-jet resonance, $m_{\gamma\gamma}$ |
| Excited quarks: dijet resonance, $m_{\ell\ell}$ |
| Excited b: W resonance, $m_{W}$ |
| Excited leptons: $\ell$ resonance, $m_{\ell}$ |

| Techni-hadrons (LSTC): dilepton, $m_{\ell\ell}$ |
| Techni-hadrons (LSTC): WZ resonance (tH), $m_{WZ}$ |
| | |
| Major. neutr. (LRSM, no mixing): 2-lep + jets |
| Heavy lepton N: (type III seesaw): Z-l resonance, $m_{N}$ |
| H^{+} (DY prod., BR(H^{+}→l+ll)): SS ee (μμ), $m_{\ell\ell}$ |
| Color octet scalar: dijet resonance, $m_{\ell\ell}$ |
| Multi-charged particles (DY prod.): highly ionizing tracks |
| Magnetic monopoles (DY prod.): highly ionizing tracks |

*Only a selection of the available mass limits on new states or phenomena shown*
The SM Higgs Potential

- $M_H$ is light - therefore there is the possibility that its potential could be finite up to the Planck scale
  - Examine the Higgs potential quartic coupling, $\lambda$, as a function of energy scale
    $$V = -m^2 |H|^2 + \lambda |H|^4$$
  - Find that $\lambda$ goes negative (meta-stable) but with some spread in parameters within errors goes to 0 at Planck scale (extrapolation only 16 orders of magnitude !)

Degrassi, et al., arXiv:1205.6497v2
The minimum $M_h$ value that ensures vacuum stability is where the Higgs potential quartic coupling goes to 0. Note that this point is only a few orders of magnitude away from the Planck scale given experimental errors.

$$M_h \ [\text{GeV}] > 129.4 + 1.4 \left( \frac{M_t \ [\text{GeV}] - 173.1}{0.7} \right) - 0.5 \left( \frac{\alpha_s(M_Z) - 0.1184}{0.0007} \right) \pm 1.0_{\text{th}} \ .$$ for stability
Near Term Physics Program

• More precise measurements of the Higgs properties
  – Better mass and BR determinations
  – Width (?) by interference with $\gamma\gamma$ background
  – Search for multi-Higgs production

• Search for violations of the SM
  – A cross section that does not agree, for example

• Search for physics beyond the standard model
  – $Z'$, SUSY, Extra dimensions, Black holes, Dark Matter

• Detector upgrades are underway to better trigger and withstand the expected pileup at high $L$
LHC Luminosity Projections to 2027

Run 1: $\sqrt{s}=7-8 \text{ TeV}$, $\int L dt=25 \text{ fb}^{-1}$, pileup $\mu \approx 20$

$L_{\text{peak}} = 0.7 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$

LS1: **phase 0** upgrade

Run 2: $\sqrt{s} \approx 13-14 \text{ TeV}$, $\int L dt \approx 120 \text{ fb}^{-1}$, pileup $\mu \approx 43$

$L_{\text{peak}} = 1.6 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$

LS2: **phase 1** upgrade

Run 3: $\sqrt{s} \approx 14 \text{ TeV}$, $\int L dt \approx 350 \text{ fb}^{-1}$, pileup $\mu \approx 50-80$

$L_{\text{peak}} \approx 2-3 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$

LS3: **phase 2** upgrade

HL-LHC: $\sqrt{s} \approx 14 \text{ TeV}$, $\int L dt \approx 3000 \text{ fb}^{-1}$, pileup $\mu \approx 140-200$

$L_{\text{peak}} = 20 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$ leveled to $L_{\text{peak}} = (5-7.5) \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$

*LS=“long shutdown”*
The main 2013-14 LHC consolidations

1. 1695 Openings and final reclosures of the interconnections
2. Complete reconstruction of 1500 of these splices
3. Consolidation of the 10170 13kA splices, installing 27000 shunts
4. Installation of 5000 consolidated electrical insulation systems
5. 300 000 electrical resistance measurements
6. 10170 orbital welding of stainless steel lines
7. 18 000 electrical Quality Assurance tests
8. 10170 leak tightness tests
9. 4 quadrupole magnets to be replaced
10. 15 dipole magnets to be replaced
11. Installation of 612 pressure relief devices to bring the total to 1344
12. Consolidation of the 13 kA circuits in the 16 main electrical feedboxes
Longer Term Upgrade: High Energy-LHC

- HE-LHC
  - 20-T dipole magnets
  - $\sqrt{s} \approx 33$ TeV

- SPS+
  - Higher energy transfer lines

- 2-GeV Booster

- Linac4

- $\sqrt{s}$
LHC Results

• So far the LHC physics program has beautifully confirmed the predictions of the SM!
  – The Higgs is consistent with a single scalar particle of mass 126 GeV
  – Branching ratios agree with the predictions of the SM
  – Data in the future will refine these results

• What about the phantoms?
  – SUSY and Extra Dimensions and Black Holes and Dark Matter not yet observed
  – Given the (near) meta-stability of the vacuum SUSY really needed (?) (Bardeen, Lykken, Iso, ... )

• LHC running in 2015 will have $\sqrt{s} \approx 13$ TeV and that factor of 1.6 increase in energy may (?) uncover another energy threshold.
  – At $\sqrt{s} = 8$ TeV no new energy thresholds have been observed
Summary

• We high energy physicists have been very privileged to work in the era of the SM of the EW sector during the last 40 years. We had guidance of the energy required for the next machine
  – In a sense all the energy scales were derived from theory, prior discovery and the values of \( G_F, \theta_W & \alpha_{em} \) - the stepping stones
  – This is a remarkable achievement!

• The future is not so certain but if history is any guide probing the highest energies will uncover new phenomena
  – There are many possibilities but no clear theoretical guidance
  – There are examples of physics proposed where the energy scale was not known but eventually discovered - example
    • Neutrino oscillations discovered long after paper by B. Pontecorvo
  – What about SUSY – forever a phantom or to become a fact?
Backup Slides
ATLAS Detector

Muon Detectors
Tile Calorimeter
Liquid Argon Calorimeter

24 m

45 m

7000 T

Toroid Magnets
Solenoid Magnet
SCT Tracker
Pixel Detector
TRT Tracker
100 TeV FCC 80-100 km tunnel: Geneva option

«Pre-Feasibility Study for an 80-km tunnel at CERN»
John Osborne and Caroline Waaijer,
CERN, ARUP & GADZ, submitted to ESPG

~15 T ⇒ 100 TeV in 100 km
~20 T ⇒ 100 TeV in 80 km

even better 100 km?

LEGEND

- LHC tunnel
- HE_LHC 80km option
- Site location

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Superconductors

Current Density Across Entire Cross-Section

- YBCO: Parallel to tape plane, 4.2 K
- YBCO: Perpendicular to tape plane, 4.2 K
- 2212: Round Wire, 4.2 K
- Nb₃Sn: High Energy Physics
- Nb-Ti (LHC) 1.9 K (‘‘+3 T shift over 4.2 K)
Physics Prospectus @ 100 TeV

FCC/TLEP Physics in a Nutshell

- $10^{12}$ Z, $10^8$ WW, $2 \times 10^6$ ZH, $10^6$ tt
- Sensitivity to BSM physics through precision Z, W, H, t processes
  - Higgs invisible width to .16%, $g_{HYY}$ to 1.4%, $g_{HZZ}$ to .05%, $g_{H\tau\tau}$ to .49%
  - $\Delta M_W = < .5$ MeV, $\Delta M_Z < 100$ KeV
- Search for rare processes

Sally Dawson,
BNL Dec-2013

[TLEP physics, arXiv:1308.6176]