Outlook for Supersymmetry

• Successful prediction for Higgs mass
  – Should be < 130 GeV in simple models
• Successful predictions for Higgs couplings
  – Should be within few % of SM values
• Could explain the dark matter
• Naturalness, GUTs, string, … (???)
• July 4th 2012
• The discovery of a new particle
That’s great, but …

- The LHC paradox:
  - Light Higgs + nothing else?
- If something light, why no indirect evidence?
- If nothing light, is light Higgs unnatural?

Electroweak and Higgs coupling measurements complement searches for New Physics.
Theoretical Confusion

- High mortality rate among theories
- \((M_H, M_t)\) close to stability bound
- Split SUSY? High-scale SUSY?
- Is Nature natural?
- String landscape?
- SUSY anywhere better than nowhere!
- SUSY could not explain the hierarchy
- **New ideas needed?**
Some Theoretical Views

M the

$M_{\text{uni}}$

$\tilde{m}_s$

Theory

Kane

Hall

Isidori

Ibanez
Theoretical Constraints on Higgs Mass

• Large $M_h \rightarrow$ large self-coupling $\rightarrow$ blow up at

$$\lambda(Q) = \lambda(v) - \frac{3m_t^4}{2\pi^2v^4} \log \frac{Q}{v}$$

• Small: renormalization due to $t$ quark drives quartic coupling $< 0$ at some scale $\Lambda$ $\rightarrow$ vacuum unstable

• Vacuum could be stabilized by Supersymmetry

Instability @ $10^{10} - 10^{13}$ GeV

Vacuum Instability in the Standard Model

- Very sensitive to $m_t$ as well as $M_H$

- Present vacuum probably metastable with lifetime $>>$ age of the Universe

How to Stabilize a Light Higgs Boson?

- Top quark destabilizes potential: introduce stop-like scalar:
  \[ \mathcal{L} \supset M^2 |\phi|^2 + \frac{M_0}{v^2} |H|^2 |\phi|^2 \]
- Can delay collapse of potential:
- But new coupling must be fine-tuned to avoid blow-up:
- Stabilize with new fermions:
  – just like Higgsinos
- Very like Supersymmetry!
MSSM Higgs Masses & Couplings

Lightest Higgs mass up to ~ 130 GeV

Heavy Higgs masses quite close

Consistent With LHC
Couples like Higgs of Standard Model

No indication of any significant deviation from the Standard Model predictions
Global Analysis of Higgs-like Models

- Rescale couplings: to bosons by $a$, to fermions by $c$

- Standard Model: $a = c = 1$
It Walks and Quacks like a Higgs

- Do couplings scale ~ mass? With scale = v?

\[ \lambda_f = \sqrt{2} \left( \frac{m_f}{M} \right)^{1+\epsilon} \quad \text{g}_V = 2 \left( \frac{m_V^{2(1+\epsilon)}}{M^{1+2\epsilon}} \right) \]

Global fit

- Red line = SM, dashed line = best fit
Supersymmetric Models

- Global fits within simplified models
  (universal soft supersymmetry-breaking masses, CMSSM NUHM1)
  suggest ~ SM couplings
- How to probe?
  - HL-LHC, Higgs factory?
Limits on Heavy MSSM Higgses
Maybe it is a Supersymmetric Duck?

- Fits with lighter/heavier scalar Higgs at 125 GeV

Bechtle et al., arXiv:1211.1955
Maybe it is a Supersymmetric Duck?

- Fits with lighter/heavier scalar Higgs at 125 GeV

Bechtle et al., arXiv:1211.1955
Data

- Electroweak precision observables
- Flavour physics observables
- $g_\mu - 2$
- Higgs mass
- Dark matter
- LHC

Deviation from Standard Model: Supersymmetry at low scale, or …?

$M_H = 125.6 \pm 0.3 \pm 1.5$ GeV

MasterCode: O. Buchmueller, JE et al.
Searches with 8 TeV Data

Multiple searches including b, leptons
Scan of CMSSM

Impacts of searches with full 2012 data

Red and blue curves represent $\Delta \chi^2$ from global minimum, located at ★

p-value of simple models < 10%


Mastercode Fit July 2012

χ² minimum
Δχ² = 2.30
Δχ² = 5.99
Obs. Atlas 20 fb⁻¹ @8TeV 0 lepton 2-6 jets
Obs. Atlas 20 fb⁻¹ @8TeV 0-1 lepton 3 b jets
Obs. Atlas 5 fb⁻¹ @8TeV 0 lepton
Obs. Atlas 5 fb⁻¹ @8TeV 0 lepton extrapolation

Post-LHC, Post-XENON100

2012 ATLAS + CMS with 5 fb⁻¹ of LHC Data
Favoured values of gluino mass significantly above pre-LHC, > 1.5 TeV
Favoured values of stop mass significantly below gluino, other squarks


Stop mass

CMSSM

$\chi^2$
Favoured values of stau mass:
Several hundred GeV


Stau mass

ATLAS + CMS with 5 fb⁻¹ of LHC Data
What remains for the CMSSM?

- Favoured regions of parameter space

- Focus on the coannihilation strip

- Small mass difference – long-lived stau?

Search for long-lived Staus?

- Small $\Delta m$ favoured in $\chi^2$ analysis
- May decay inside or outside the detector

Long-lived Gluinos in Split SUSY?
SUSY in the Sky: Inflation, Dark Matter?
Inflationary Models in Light of Planck

- Planck CMB observations consistent with inflation
- Tilted scalar perturbation spectrum:
  \[ n_s = 0.9585 \pm 0.070 \]
- **BUT** strengthen upper limit on tensor perturbations: \( r < 0.10 \)
- Challenge for simple inflationary models
  - Starobinsky \( R^2 \) to rescue?
  - Supersymmetry to rescue?

Croon, JE & Mavromatos: arXiv:1303.6253
Supersymmetric Inflation in Light of Planck

- Supersymmetric Wess-Zumino (WZ) model consistent with Planck data

Croon, JE, Mavromatos: arXiv:1303.6253
No-Scale Supergravity Inflation

- The only good symmetry is a local symmetry
- Early Universe cosmology needs gravity
- **Supersymmetry + gravity = Supergravity**
- **BUT**: potentials in generic supergravity models have potential ‘holes’ with depths $\sim -M_P^4$
- Exception: **no-scale supergravity**
- Appears in compactifications of string
- Flat directions, scalar potential $\sim$ global model + controlled corrections

No-Scale Supergravity Inflation

- Good inflation for $\lambda \approx \mu/3$

Looks like $R^2$ model

Accessible to PRISM

Strategies for Detecting Supersymmetric Dark Matter

• Scattering on nucleus in laboratory
  \[ \chi + A \rightarrow \chi + A \]

• Annihilation in core of Sun or Earth
  \[ \chi - \chi \rightarrow \nu + \ldots \rightarrow \mu + \ldots \]

• Annihilation in galactic centre, dwarf galaxies
  \[ \chi - \chi \rightarrow \gamma + \ldots ? \]

• Annihilation in galactic halo
  \[ \chi - \chi \rightarrow \text{positrons, antiprotons, …?} \]
Best limit: XENON100 with 225 days of data

Confusion at low WIMP masses?

New CDMS result

LHC monojet exclusion at Low masses model-dependent

Aprile et al.
Global Fit to Supersymmetric Model

Excluded by LHC

Excluded by XENON100

Favoured values of dark matter scattering cross section significantly below XENON100

Spin-independent Dark matter scattering

--- 1/fb
— 5/fb

Prospective Future Sensitivity

L. B., Physics of the Dark Universe 1, 94 (2012)

Spin-independent cross section (at $M_\chi \sim 50-100$ GeV) [cm$^2$]

-1 event kg$^{-1}$yr$^{-1}$
Gamma Rays from Galactic Centre?

Galactic centre is a complicated place

Time variation in black hole Sgr A*?
BUT: Fermi Collaboration also sees bump in control sample of γ’s from Earth’s limb

Presumably a systematic effect
Positron Fraction Rising with E

A new phenomena has occurred

8% of total Data to 2028

Dark Matter? Galactic cosmic rays? Local sources?
Can find good fit: $\chi^2 \sim 18$ with annihilation to $\tau^+\tau^-$ by modifying cosmic ray parameters

JE, Olive & Spanos, in preparation
Dark Matter Fit to AMS Positron Data

- **BUT:** very large annihilation cross section
  \[ \sim 3 \times 10^{-23} \text{ cm}^2 \gg \text{ required for relic density} \]
- **OR:** very large boost from halo density fluctuation(s)

JE, Olive & Spanos, in preparation
Assume Local Source: Constrain any extra Dark Matter Contribution

Dark Matter annihilation could give feature above otherwise smooth distribution

Bergstrom et al, arXiv::1306.3983
To study the ‘Higgs’ in detail:

- The LHC
  - Rethink LHC upgrades in this perspective?
- A linear collider?
  - ILC up to 500 GeV
  - CLIC up to 3 TeV
  (Larger cross section at higher energies)
- A circular $e^+e^-$ collider: LEP3, TLEP
  - A photon-photon collider: SAPPHiRE
- A muon collider
# Higgs Factory Summary

<table>
<thead>
<tr>
<th>Accelerator</th>
<th>LHC 300fb(^{-1}) /exp</th>
<th>HL-LHC 3000fb(^{-1}) /exp</th>
<th>ILC (250) 250 fb(^{-1})</th>
<th>ILC (250+350+1000)</th>
<th>LEP3 240 4 IP</th>
<th>TLEP 240 +350 4 IP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Approx. date</td>
<td>2021</td>
<td>2030</td>
<td>2035</td>
<td>2045</td>
<td>2035</td>
<td>2035</td>
</tr>
<tr>
<td>(N_H)</td>
<td>1.7 \times 10^7</td>
<td>1.7 \times 10^8</td>
<td>(5 \times 10^4) ZH</td>
<td>((1.5 \times 10^5) ZH) ((1.4 \times 10^5) Hvv)</td>
<td>4 \times 10^5 ZH</td>
<td>2 \times 10^6 ZH</td>
</tr>
<tr>
<td>(m_H) (MeV)</td>
<td>100</td>
<td>50</td>
<td>35</td>
<td>35</td>
<td>26</td>
<td>7</td>
</tr>
<tr>
<td>(\Delta \Gamma_H/\Gamma_H)</td>
<td>--</td>
<td>--</td>
<td>10%</td>
<td>3%</td>
<td>4%</td>
<td>1.3%</td>
</tr>
<tr>
<td>(\Delta \Gamma_{inv}/\Gamma_H)</td>
<td>Indirect (30%?)</td>
<td>Indirect (10% ?)</td>
<td>1.5%</td>
<td>1.0%</td>
<td>0.35%</td>
<td>0.15%</td>
</tr>
<tr>
<td>(\Delta g_{HH}/g_{HH})</td>
<td>6.5 – 5.1%</td>
<td>5.4 – 1.5%</td>
<td>--</td>
<td>5%</td>
<td>3.4%</td>
<td>1.4%</td>
</tr>
<tr>
<td>(\Delta g_{Hgg}/g_{Hgg})</td>
<td>11 – 5.7%</td>
<td>7.5 – 2.7%</td>
<td>4.5%</td>
<td>2.5%</td>
<td>2.2%</td>
<td>0.7%</td>
</tr>
<tr>
<td>(\Delta g_{Hww}/g_{Hww})</td>
<td>5.7 – 2.7%</td>
<td>4.5 – 1.0%</td>
<td>4.3%</td>
<td>1%</td>
<td>1.5%</td>
<td>0.25%</td>
</tr>
<tr>
<td>(\Delta g_{Hzz}/g_{Hzz})</td>
<td>5.7 – 2.7%</td>
<td>4.5 – 1.0%</td>
<td>1.3%</td>
<td>1.5%</td>
<td>0.65%</td>
<td>0.2%</td>
</tr>
<tr>
<td>(\Delta g_{HHH}/g_{HHH})</td>
<td>&lt; 30% (2 exp.)</td>
<td>&lt; 30%</td>
<td>&lt; 30%</td>
<td>~30%</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>(\Delta g_{HWW}/g_{HWW})</td>
<td>&lt;30</td>
<td>&lt;5</td>
<td>--</td>
<td>--</td>
<td>14%</td>
<td>7%</td>
</tr>
</tbody>
</table>

**Best precision**

ICFA Higgs Factory Workshop
Fermilab, Nov. 2012
Possible TLEP Locations around Geneva
Comparison of Possible Higgs Factory Measurements

TLEP SG (al et JE et al), arXiv:1308.6176
Impact of Higgs Factory?

- Predictions of current best fits in simple SUSY models
- Current uncertainties in SM calculations [LHC Higgs WG]
- Comparisons with
  - LHC
  - HL-LHC
  - ILC
  - TLEP
- Don’t decide before LHC 13/4

**Best Fit Predictions**

- $h \rightarrow \gamma\gamma$
- $h \rightarrow ZZ$
- $h \rightarrow WW$
- $h \rightarrow gg$

<table>
<thead>
<tr>
<th>Supersymmetric model fits</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC</td>
</tr>
<tr>
<td>HL-LHC</td>
</tr>
<tr>
<td>ILC</td>
</tr>
<tr>
<td>TLEP</td>
</tr>
</tbody>
</table>

$\frac{(BR_{SM} - BR_{SM})}{BR_{SM}} (%)$
Part of a Vision for the Future

- A large circular tunnel
  - Circumference ~ 80 to 100 km
- Could accommodate TLEP and VHE-LHC
  - $E_{CM}$ up to 100 TeV with 15 Tesla magnets
- Could be sited around Geneva
  - Interest in China, …
- TLEP study under way:  
  [TLEP SG (al et JE et al), arXiv:1308.6176](http://tlep.web.cern.ch/)
- VHE-LHC study now starting
Let us be patient …

- If you have a problem, postulate a new particle:
  - QM and Special Relativity: Antimatter
  - Nuclear spectra: Neutron
  - Continuous spectrum in β decay: Neutrino
  - Nucleon-nucleon interactions: Pion
  - Absence of lepton number violation: Second neutrino
  - Flavour SU(3): Ω⁻
  - Flavour SU(3): Quarks
  - FCNC: Charm
  - CP violation: Third generation
  - Strong dynamics: Gluons
  - Weak interactions: W⁺, Z⁰
  - Renormalizability: H (48 years)
  - Naturalness: Supersymmetry? (40 years)