The Standard Model of Particle Physics
  - And the Higgs boson…

Looking for the Higgs
  - A new boson at ≈ 126 GeV!
  - Update since the discovery (properties)

Searching for New Physics
  - Supersymmetry?

Outlook
Standard Model of Particle Physics

The main ideas
Intermediate vector bosons and their masslessness
The Higgs mechanism
Nature: “forces” between particles?

- Gravity == action-at-a distance: separated objects, in the vacuum, act on each other!
- The “charge” of gravity: mass – the substance of matter!

What about electricity and magnetism? Same as gravity; except two charges (like ones repel, opposite ones attract). But same spooky “action-at-a-distance, through the vacuum”
Nature: “forces”?!?

- Maxwell and electromagnetism: the concept of a field; charges generate fields which (can) permeate all of space… Other “charges” feel this field – and thus they feel a force.
- The incredible discovery: the E/B fields can exist alone – they propagate in waves in the vacuum! Thus are radio, TV and cell-phones made possible.
20th century: two more forces at work

- But nuclei are held together – against the electrostatic repulsion. So there is yet another type of force! And it must be very, very strong.

- And nuclei break up! Radioactivity! Neutrons become protons. So there is yet another type of force! And it is very, very weak.

There are, in total FOUR different forces in nature

All forces in the world can be attributed to these four interactions!
FOUR???

What makes them different?
Are all of them “needed”?
Why not just one?

The two scientific revolutions of the 20\textsuperscript{th} century (Relativity and Quantum mechanics) provide (most of) the answers
20th century physics: quantum mechanics and relativity

- **Relativity**: action can only travel at speed \( c \)
  - Localization
  - Communication between space-time points only as long as within light-cone
  - Thus: operators (that finally yield observables) are a function of \( x,t \); i.e. they are fields

- **Quantum Mechanics**
  - **Dicretization**
    - e.g. of absorption or emission
  - **Wave-particle duality**
    - demonstrated beyond all doubt:

Electron density waves are seen breaking around two atom-size defects on the surface of a copper crystal
Quantum mechanics + Relativity

- A system is described by a wavefunction $\psi(x,t)$
  - Wavefunction: a complex number
    - Probability $\sim |\psi(x,t)|^2$
  - Changing the phase of the wavefunction by some angle $\omega$, changes nothing:
    - $\psi(x,t) \rightarrow \psi(x,t)e^{i\omega}$ still means $|\psi(x,t)e^{i\omega}|^2 = |\psi(x,t)|^2$
  - We are thus free to select this phase freely. [As long as it is the same phase everywhere…]

- Relativity: we should, in principle, be able to do locally, i.e. $\omega \rightarrow \omega(x)$!!!
  - For it takes a while to communicate to other points that we have changed this phase!
The “derivation” of electromagnetism:

- e⁺e⁻ interactions: spin-1/2 fields. Dirac Lagrangian:

\[
L = \bar{\psi} \left( i \gamma^\mu \frac{\partial}{\partial x^\mu} - m \right) \psi = \bar{\psi} \left( i \gamma^\mu \partial_\mu - m \right) \psi
\]

- It is NOT invariant under “rotations in U(1)”, i.e. under \( \psi(x) \rightarrow \psi(x) \, e^{i q \theta(x)} \)...

  - because of the derivative

- Insist on invariance! So restore it.

- Requires adding a field \( A_\mu(x) \) that cancels derivatives, i.e.

\[
L = \bar{\psi} \left[ i \gamma^\mu \left( \partial_\mu + i q A_\mu \right) - m \right] \psi; \quad A_\mu \rightarrow A_\mu - \partial_\mu \theta
\]
The fields $A$ and $\psi$ now interact:

$$L_{\text{int}} = -q \overline{\psi} \gamma^\mu A_\mu \psi$$

- Which is precisely the interaction term in the Maxwell Lagrangian:

$$L = -\frac{1}{16\pi} F^{\mu\nu} F_{\mu\nu} - J^\mu A_\mu \quad \text{(with } J^\mu = q \overline{\psi} \gamma^\mu \psi \text{)}$$

- Thus: matter-$A$-matter interaction with Force Law:

$$\vec{F} = q \left( -\vec{\nabla} A^0 + \frac{\partial \vec{A}}{\partial t} \right) + q \vec{v} \times \left( \vec{\nabla} \times \vec{A} \right)$$

- “Discovery” of electro-magnetism (!) from the demand that the phase can be set locally.
Quantum Electrodynamics (III)

- The interaction:

\[ L_{\text{int}} = -q \bar{\psi} \gamma^\mu A_\mu \psi \]

- And the quantum excitation of the A field will be particles (photons!)
Relativity Theory + Quantum mechanics: a new picture of what is a “force”

\[ L_{\text{int}} = -q \overline{\psi} \gamma^{\mu} A_{\mu} \psi \]

FORCE IS THE EXCHANGE OF PARTICLES!
Weak interaction

Beta decay $n \rightarrow p + e^- + \bar{\nu}_e$

Mediated by charged $W$ exchange
Quantum Field theory:
- Matter particles (spin-1/2) interact via the exchange of force particles (spin-1)

- Forces: interactions, so need (a) charge(s). Which should be conserved. Which implies some new symmetry…
- Standard Model: internal symmetry (SU(3)xSU(2)xU(1))
Invariance of the world under phase changes in $SU(2) \otimes U(1)$ results in four bosons, $W^\pm, Z, \gamma$

Thus the unification of Electromagnetism and the Weak interaction into the “Electroweak”

Except that it gets a basic issue wrong. Because the range of the weak force is very small. Which means the carrier must be massive. Very massive!
Yet, the Standard Model symmetry (SU(2)xU(1)) MUST be broken:

- $M(\gamma)=0$; $M(W)=80 \text{ GeV}/c^2$; $M(Z)=90 \text{ GeV}/c^2$
  - And we cannot add mass terms by hand (gauge invariance)
- How can we end up with an asymmetric world when the laws are symmetric?

Take potential with two minima

- “Laws of nature”
  (potential $\rightarrow$ Lagrangian $\rightarrow$ equations of motion) right-left symmetric
- Equilibrium state is not
- Particle chooses one of the two minima $\rightarrow$ left-right symmetry is “broken”

Laws are LR symmetric; but low-energy world need not be!
The Higgs Mechanism

- With two independent (complex) fields
- Two “motions” in the potential
  - One on the plane; “massless” mode that is lost (once a direction is chosen). The degree of freedom appears as additional degree of freedom of the gauge boson
    - Extra polarization state
    - The boson becomes massive!
  - One up/down on potential; massive
    - Higgs boson; for which we know everything, except one parameter: its mass!

Thus were the W/Z masses born in theory; and discovered (at the right value) @ CERN in 1984.
The Standard Model up until 2012

### Measurement vs. Fit

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Fit</th>
<th>( \Delta \alpha^{(5)}_{\text{had}}(m_Z) ) 0.02758 ± 0.00035</th>
<th>0.02768</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>( m_Z ) [GeV] 91.1875 ± 0.0021</td>
<td>91.1874</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( \Gamma_Z ) [GeV] 2.4952 ± 0.0023</td>
<td>2.4959</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( \sigma_0^0_{\text{had}} ) [nb] 41.540 ± 0.037</td>
<td>41.476</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( R_i ) 20.767 ± 0.025</td>
<td>20.750</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( A_{0,l} ) 0.01714 ± 0.00008</td>
<td>0.01721</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( A_l(P_{\tau}) ) 0.1465 ± 0.0005</td>
<td>0.1465</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( R_b ) 0.21623</td>
<td>0.21623</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( R_c ) 0.13772</td>
<td>0.13772</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( A_{0,b} ) 0.9742</td>
<td>0.9742</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( A_{0,c} ) 0.935</td>
<td>0.935</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( A_c ) 0.668</td>
<td>0.668</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( A_l(SLD) ) 0.1513 ± 0.0021</td>
<td>0.1481</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( \sin^2 \theta_{\text{lep}} ) 0.1324 ± 0.0012</td>
<td>0.2314</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( m_W ) [GeV] 80.399 ± 0.023</td>
<td>80.379</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( \Gamma_W ) [GeV] 2.085 ± 0.042</td>
<td>2.092</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( m_t ) [GeV] 173.3 ± 1.1</td>
<td>173.4</td>
</tr>
</tbody>
</table>

### Graph

- **First Generation**
  - Top quark
- **Second Generation**
  - Charm quark
  - Bottom quark
- **Third Generation**
  - Tau neutrino
  - Muon neutrino
  - Down quark
  - Up quark
  - Muon
  - Electron

### Notes

- Only missing piece: Higgs
- Confirmed to better than 1% precision by 100's of precision measurements

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P. Sphicas  
The Standard Model and Beyond  
CERN Accelerator School  
Nov 04, 2013
LHC($t_0+\Delta t=2.5\text{yrs}$):

Foundations established a “tour de force” of SM measurements

and, of course, the hunt for the Higgs boson...
The LHC: signals much smaller than “bkg”

- General event properties
- Heavy flavor physics
- Standard Model physics
  - QCD jets
  - EWK physics
  - Top quark
- Higgs physics
- Searches for SUSY
- Searches for ‘exotica’
To probe the hard scatter:

- The hard scatter: jet $P_T$ and $\eta$, dijet correlations, dijet mass, ...

Excellent agreement with QCD

$M_{jj} = 4.04$ TeV
$P_T^1 = 1850$ GeV, $\eta = 0.32$
$P_T^2 = 1840$ GeV, $\eta = -0.53$
W/Z at 7 TeV: (still) clean & beautiful

Z → electron + positron

W → electron + neutrino
Standard model in pp collisions @ 7 TeV

- Understanding of SM processes at level of Tevatron experiments – and beyond.
  - Let the search begin.

**Diagram:**

- Production Cross Section, $\sigma_{tot}$ [pb]
- CMS

- $W$ production
- $Z$ production
- $W\gamma$, $Z\gamma$
- $WW$, $WZ$, $ZZ$

- $E_T > 30$ GeV
- $|\eta|^\leq 2.4$
- $\Delta R(y,I) > 0.7$

- JHEP1(2011)132
- JHEP01(2012)010
- CMS-PAS-SMP-12-011 (WZ 8 TeV)
- PLB701(2011)535
- CMS-PAS-EWK-11-010 (WZ)
- CMS-PAS-SMP-12-005, 007, 013, 014 (WW ZZ)

- 36, 19 pb$^{-1}$
- 36 pb$^{-1}$
- 4.9 fb$^{-1}$
- 3.5 fb$^{-1}$
- 1.1 fb$^{-1}$
- 4.9 fb$^{-1}$
- 5.3 fb$^{-1}$
What about the Higgs boson?

Some “signatures”
$p_T(\mu) = 36, 48, 26, 72 \text{ GeV}; \quad m_{12} = 86.3 \text{ GeV}, m_{34} = 31.6 \text{ GeV}$

15 reconstructed vertices

$H \rightarrow ZZ \rightarrow 4\mu$ candidate with $m_{4\mu} = 125.1 \text{ GeV}$
8 TeV DATA

4-lepton Mass : 126.9 GeV

$\mu^+(Z_1) \ p_T$: 43 GeV
$e^-(Z_2) \ p_T$: 10 GeV
$m^-(Z_1) \ p_T$: 24 GeV
$e^+(Z_2) \ p_T$: 21 GeV

$H \to ZZ \to \mu\mu ee$ candidate with $m_{4\mu} = 125.1$ GeV

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$p_T(e,e,\mu,\mu)$: 19, 76, 20, 8 GeV; $m_{e^+e^-} = 88$ GeV, $m_{\mu^+\mu^-} = 20$ GeV

12 reconstructed vertices
H → WW → lνl'ν signature

$\mu P_T$ 32 GeV

$e P_T$ 34 GeV

$\Delta \phi (ll)$

Signature: 2 high $p_T$
leptons
large
missing $E_T$

qq → WW +

gg → WW

- Non-resonant

H → WW

- Large BR

- Small $\Delta \phi (ll)$

Main backgrounds:
WW, top

Other backgrounds:
$W$+jet, $Z/\gamma^*$, $WZ$, $ZZ$, $W\gamma$
Are these events “significant”?

- Searches for the SM Higgs boson
- Discovery of a new boson
Mass peaks: $H(\gamma \gamma)$ & $H(\gamma \gamma)$

Despite the low branching fraction to the final state, the mass resolution of these two channels enables the siting of a “peak”. The ZZ peak has a Z calibration as well(!)
Putting it all together...
And thus was born, on July 4\textsuperscript{th} 2012, “a new boson”: it decayed to two bosons (two $\gamma$; two $Z$; two $W$).

It is not spin-1: it decays to two photons (Landau-Yang theorem).

It is either spin-0 or spin-2 (could also be higher spin, but this is really disfavored).
So, is it THE Higgs boson?

- Can we call the “new boson” the “Higgs boson”? Let alone a “Standard Model Higgs boson”…
  - Foremost: it must have spin 0 (to call it a “Higgs boson”)
  - Also:
    - neutral CP-even component of complex $SU(2)_L$ doublet with $Y=1$
    - couplings to SM fermions proportional to masses

- The “new boson” can have many non-SM properties and still be the Higgs boson of electroweak symmetry breaking:
  - CP mixture, mixture of two or more weak doublets!
  - Composite!
  - Nonstandard decay to $gg$ or $\gamma\gamma$ from other colored/charged exotic particles in loops
Does it behave like the Higgs boson?

- Does it couple like a H-boson? (i.e. to mass?)
  - Measure couplings to fermions and bosons, and see if they come out right
- What is its spin & CP?

**Decay Modes available**

<table>
<thead>
<tr>
<th>Mode</th>
<th>Exp Sig (CMS)</th>
<th>$\sigma_{M}/M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b\bar{b}$</td>
<td>2.2σ</td>
<td>10%</td>
</tr>
<tr>
<td>$\tau\tau$</td>
<td>2.7σ</td>
<td>10%</td>
</tr>
<tr>
<td>$WW$</td>
<td>5.1σ</td>
<td>20%</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>7.1σ</td>
<td>1-2%</td>
</tr>
<tr>
<td>$\gamma\gamma$</td>
<td>4.2σ</td>
<td>1-2%</td>
</tr>
</tbody>
</table>

5 decay modes exploited

- $bb$ @125.7
- $\tau\tau$ @125.7
- $WW$ @125.7
- $ZZ$ @125.7
- $\gamma\gamma$ @125.7

Very rare:
- $cc$ & $gg$

'Challenging':
- $cc$ & $gg$
Since the discovery...

- The existence of a new particle has been established beyond any doubt; it is a $0^{++}$ boson responsible for EWSB, as evident from its relative couplings to $W/Z$ vs. $\gamma$.
- Its properties are consistent with those of the SM Higgs boson within (sizable) uncertainties.
- There is mounting evidence (Tevatron, CMS), that it couples to at least the third generation fermions.

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**Higgs Boson Signal Strength**

Consistency with the SM Higgs boson:

- ATLAS: $\mu = 1.30 \pm 0.20$ @ 125.5 GeV
- CMS: $\mu = 0.80 \pm 0.14$ @ 125.7 GeV

Has not been updated to the latest result of $1.00 \pm 0.50$.

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**ATLAS** Preliminary

$\sqrt{s} = 8$ TeV, $\int L dt = 13-20.7$ fb$^{-1}$

**CMS** Preliminary

$\sqrt{s} = 8$ TeV, $L \leq 19.6$ fb$^{-1}$
Couplings to particles

\[ \lambda_f = \frac{m_f}{v} \]

\[ g_v = 2 \frac{m_v^2}{v} \]
H→ZZ→4leptons: angular analysis

Matrix Element Likelihood Analysis:
uses kinematic inputs for signal to background discrimination
\{m_1, m_2, \theta_1, \theta_2, \theta^*, \Phi, \Phi_1\}

\[
MELA = \left[ 1 + \frac{P_{\text{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{P_{\text{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})} \right]^{-1}
\]
Scalar or pseudoscalar? Spin 2 or 0?

- Test angular distributions under both the $0^+$ and $0^-$ hypotheses
- Test angular distributions under both the $2^+$ and $0^+$ hypotheses

$CL_S(0^-/0^+) = 0.16\%, CL_S(2^+/0^+) = 1.5\%$
Summary (and where it was – in mass…)

- So it is a Higgs boson; and in fact one that looks very (as in very) much like the one of the Standard Model
- And its mass? That “one unknown parameter”?

<table>
<thead>
<tr>
<th>Collaboration</th>
<th>channel</th>
<th>mass (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>$\gamma\gamma$</td>
<td>$126.8 \pm 0.2 \pm 0.7$</td>
</tr>
<tr>
<td>CMS</td>
<td>$\gamma\gamma$</td>
<td>$125.4 \pm 0.5 \pm 0.6$</td>
</tr>
<tr>
<td>ATLAS</td>
<td>$4\ell$</td>
<td>$124.3^{+0.6}<em>{-0.5}^{+0.5}</em>{-0.3}$</td>
</tr>
<tr>
<td>CMS</td>
<td>$4\ell$</td>
<td>$125.8 \pm 0.5 \pm 0.2$</td>
</tr>
<tr>
<td>ATLAS</td>
<td>combination</td>
<td>$125.5 \pm 0.2^{+0.5}_{-0.6}$</td>
</tr>
<tr>
<td>CMS</td>
<td>combination</td>
<td>$125.7 \pm 0.3 \pm 0.3$</td>
</tr>
</tbody>
</table>

$M_H \approx 126$ GeV! A farce?
So is this it?

What about new physics?

In a world of an SM Higgs, is there any room for new physics?
Scale of New Physics = $F(M_H)$

\[ \lambda(Q^2) = \frac{\lambda(Q_0^2)}{1 - \lambda(Q_0^2) / 16\pi^2 \log \left( \frac{Q^2}{Q_0^2} \right)} \]

\[ Q^2 \to \infty, \lambda \to \infty! \quad \Lambda \leq M_H \exp \left( \frac{4\pi^2 \nu^2}{3M_H^2} \right) \]
Zooming in: some good (?) news

- At 95% CL: there is new physics at a scale below the GUT scale 😊
  - Or vacuum is not stable…

Thankfully, best estimate of time we still have ~15 Gyr!
Living at the edge...

- Perhaps even more important than originally thought
Plenty of room for new physics

Some real and some virtual reasons to believe in new physics

Real reasons: dark matter & $\nu$ masses
Virtual reasons: naturalness
Real reason(s): dark matter

Probably the biggest mystery in nature (as we speak)
New type of matter?
New forces?
New dimensions?
Virtual reasons: Higgs mass

- Foremost, the issue of “naturalness”: how can the mass of the Higgs boson be anything “small”?
  - It should “resist” itself (since it couples to mass, it should couple to itself as well); Its mass should be almost infinite:

\[
m^2(p^2) = m_0^2 + \frac{1}{p^2} \phi^J + \frac{1}{J=1/2} + \frac{1}{J=0}
\]

- Quadratic divergence in the Higgs mass
  
  \[
m^2(p^2) = m^2(\Lambda^2) + C g^2 \int_{p^2}^{\Lambda^2} dk^2
\]

- Why is the Higgs mass so low? What is the mechanism?
- Strong dependence of Physics(\(\Lambda_{EWK}\)) on Physics(\(\Lambda_{PL}\))
  - It’s like saying that to describe the Hydrogen atom one needs to know about the quarks inside the proton (not true!)
  - Implies extreme fine-tuning (ETF) of parameters
Bringing gravity into the game...

- If cut off at $\Lambda_{PL}$, why $m_W \ll M_{Pl}$? Or, why is gravity ($G \sim 1/M_{Pl}$) so very very weak?
  - And by the way, the mighty SM ignores gravity (too weak)

- Interestingly, beyond the Higgs, the biggest problems come from gravity-related measurements:
  - Dark matter, Dark Energy, and a non-matter-dominated universe

- Where is all this vacuum energy?
  - We would expect a tremendous energy density, $> \text{Googol} (10^{100})$ times larger than observed! ("Cosmological constant too small")
  - Size of the universe if the Higgs, as we expect it was there (ALONE): a football (soccer) ball

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Supersymmetry (and Naturalness)
**Supersymmetry (SUSY)**

- SUSY (super-symmetry) premise: for every particle in the SM, there is a super-partner with spin-$\frac{1}{2}$ difference
  - Can now speak of a “super-particle” which has two possible states: fermion and boson – much like the proton and the neutron can be seen as two isospin states of one particle, the “nucleon”!

With SUSY, infinities disappear: As long as $M_p = M_{sp}$

---

**Isotopic symmetry**
Proton and Neutron: different states of a generalized particle (Nucleon)

**Supersymmetry:**
Fermion and Boson: different states of a generalized entity (Superparticle)
Supersymmetry (SUSY)

- SUSY (super-symmetry) premise: for every particle in the SM, there is a super-partner with spin-$\frac{1}{2}$ difference
SUSY? What it could look [looks?] like

\[
\begin{align*}
\text{MHT} &= 693 \text{ GeV} \\
\text{HT} &= 1132 \text{ GeV} \\
\text{M}_{\text{eff}} &= \text{MHT} + \text{HT} = 1.83 \text{ TeV}
\end{align*}
\]
No signs of SUSY yet

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SUSY with ME_T: signatures and bkgds

- Searches distinguished by the number of leptons
  - In all cases, demand “(high-P_T) jets + (high) ME_T”
  - 0\(\ell\) (all-hadronic); 1\(\ell\); 2\(\ell\) (and break down into OS and SS)

QCD multijets
\(Z(\rightarrow \nu\nu)+\) jets
\((W,t)+\) jets; \(W\rightarrow \tau\nu\)

QCD: small
\(W/Z(\rightarrow \ell\nu)+\) jets
\(W/W, W/Z\)

\(t(\rightarrow \ell\nu)+\) jets
\(t t(\rightarrow \ell\ell\nu)+\) jets

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### ATLAS SUSY Searches - 95% CL Lower Limits

<table>
<thead>
<tr>
<th>Model</th>
<th>e, μ, τ Jets</th>
<th>Ptmiss</th>
<th>Int.L x10^{-3} fb^{-1}</th>
<th>Mass Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSUGRA1GMSM 0</td>
<td>2-6 jets</td>
<td>Yes</td>
<td>70.3</td>
<td>1.2 TeV</td>
</tr>
<tr>
<td>MSUGRA1GMSM 1</td>
<td>4 jets</td>
<td>Yes</td>
<td>5.8</td>
<td>1.1 TeV</td>
</tr>
<tr>
<td>MSUGRA1GMSM 2</td>
<td>7-10 jets</td>
<td>Yes</td>
<td>26.3</td>
<td>740 GeV</td>
</tr>
<tr>
<td>MSUGRA1GMSM 3</td>
<td>0 jets</td>
<td>Yes</td>
<td>19.8</td>
<td>1.3 TeV</td>
</tr>
<tr>
<td>GMSB (NLSP) 0</td>
<td>2 jets</td>
<td>Yes</td>
<td>4.0</td>
<td>1.1 TeV</td>
</tr>
<tr>
<td>GMSB (NLSP) 2</td>
<td>4 jets</td>
<td>Yes</td>
<td>4.7</td>
<td>900 GeV</td>
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<tr>
<td>GMSB (NLSP) 4</td>
<td>0 jets</td>
<td>Yes</td>
<td>4.7</td>
<td>1.1 TeV</td>
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<tr>
<td>GMSB (NLSP) 6</td>
<td>0 jets</td>
<td>Yes</td>
<td>5.8</td>
<td>650 GeV</td>
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<tr>
<td>GMSB (NLSP) 8</td>
<td>0 jets</td>
<td>Yes</td>
<td>10.5</td>
<td>560 GeV</td>
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<td>GMSB (NLSP) 10</td>
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<td>Yes</td>
<td>10.5</td>
<td>560 GeV</td>
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<td>GMSB (NLSP) 12</td>
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<td>Yes</td>
<td>10.5</td>
<td>560 GeV</td>
</tr>
</tbody>
</table>

**Spring 2013**

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus a theoretical signal cross section uncertainty.*
Supersymmetry

- The LHC has placed very severe constraints on Supersymmetry
  - In fact, the more “constrained” models of SUSY are now almost excluded
  - So, is it dead? [it seems the press loves to declare this…]

- There is a lot of room still left. But if SUSY is the answer to the “naturalness” problem, then there must exist light colored particles
  - Leading hypothesis: a relatively light (~TeV) top squark (partner of the top quark)
Searches for top squarks

- Dedicated searches for both direct and indirect production of top squarks; no signs of them (yet):

  - But still room left for naturalness: e.g. $M(\text{gluino}) \sim 1.5 \text{ TeV}$; $m(\text{stop}) \sim 300 \text{ GeV}$; $m(\text{LSP}) \sim 150 \text{ GeV}$

- Really need more energy!
Outlook
(LHC at 13-14 TeV & at very high luminosity)
&
Summary
LHC running in at higher energy

- Enhances physics reach in two ways:
  - Higher cross sections for new physics over full mass range

![Graph showing luminosity ratios and mass scales for different particles and processes.](image)

- Ratios of LHC parton luminosities:
  - $8 \text{ TeV} / 7 \text{ TeV}$, $10 \text{ TeV} / 7 \text{ TeV}$
  - and $14 \text{ TeV} / 7 \text{ TeV}$

- SUSY squarks/Gluino
  - ~1.5 TeV
  - or
  - Z$'$
  - ~3.0 TeV

- Enhances physics reach in two ways:
  - Higher cross sections for new physics over full mass range
Very significant new reach to SUSY (stop)

Gluino ($l + b$) Search – Result

Sensitive to gluino masses up to 2.2 TeV and LSP masses up to 1.2 GeV

Gain of ~300 GeV in gluino mass discovery reach when going from 300 fb$^{-1}$ to 3000 fb$^{-1}$!

about half of the interesting mass range will be covered!

Limit on stop mass can be extended by 200 GeV when going from 300 fb$^{-1}$ to 3000 fb$^{-1}$!

most interesting mass range will be covered!
Summary

- The Standard Model of particle physics is actually much more: it’s the Standard Theory of particle physics
  - An elegant description of “interactions”, based on Quantum Field Theory (special relativity and quantum mechanics)
  - One tricky issue: symmetry breaking. Needed a truly new mechanism – BEH? There should be a left-over boson
    - For decades, one missing element – the Higgs boson

- A new boson with mass 125-126 GeV has been found
  - We are probing its properties. It’s a Higgs boson! Is it the SM Higgs boson? Need to study it in more detail

- Even if this turns out to be the very Higgs boson of the Standard Model, there are huge reasons to believe that new physics is within reach;
  - A gigantic amount of work on searches for SUSY, extra dimensions, etc…; Null so far, but, the best has yet to come!

- The increase in energy in 2015 will give very significant new physics reach to the experiments. Stay tuned!
Backups
FAQ: how to make a universe

- **Strong**
  - Gluons (8)
  - Quarks
  - Mesons Baryons
  - Nuclei

- **Electromagnetic**
  - Photon
  - Atoms
  - Light
  - Chemistry
  - Electronics

- **Gravitational**
  - Graviton ?
  - Solar system
  - Galaxies
  - Black holes

- **Weak**
  - Bosons (W,Z)
  - Neutron decay
  - Beta radioactivity
  - Neutrino interactions
  - Burning of the sun

Quarks: u, d, s

Proton: u d

Neutron: u d d

Nucleus: Quarks

Electron

Nuclei

Molecule

Atom

Solar system

Galaxies

Black holes

Neutron decay

Beta radioactivity

Neutrino interactions

Burning of the sun