Status and Phenomenology of the Standard Model

- The new standard model
- Experimental tests, unique features, anomalies, hints of new physics
  - Precision tests
  - Higgs
  - Heavy quarks
  - Neutrinos
  - FCNC and EDMs
  - Astrophysics and cosmology
- Theoretical problems
- Perspective

Physics at LHC (July 16, 2004) Paul Langacker (Penn)
The New Standard Model

- Standard model, supplemented with neutrino mass (Dirac or Majorana):

  \[ SU(3) \times SU(2) \times U(1) \times \text{classical relativity} \]
  
  focus of talk

- Mathematically consistent field theory of strong, weak, electromagnetic interactions

- Correct to first approximation down to \(10^{-16}\) cm

- Complicated, free parameters, fine tunings \(\Rightarrow\) must be new physics
Many special features *usually not* maintained in BSM

- $m_\nu = 0$ in *old* standard model (need to add singlet fermion and/or triplet Higgs and/or higher dimensional operator (HDO))
- Yukawa coupling $h \propto gm/M_W \Rightarrow$ flavor conserving and small for light fermions (partially maintained in MSSM and simple 2HDM)
- No FCNC at tree level ($Z$ or $h$); suppressed at loop level (SUSY loops; $Z'$ from strings, DSB)
- Suppressed off-diagonal CP; highly suppressed diagonal (EDMs) (SUSY loops, soft parameters, exotics)
- $B, L$ conserved perturbatively ($B - L$ non-perturbatively) (GUT (string) interactions, $R_p$)
- New TeV scale interactions suggested by top-down ($Z'$, exotics, extended Higgs)
Fermi Theory incorporated in SM and made renormalizable

CKM matrix for $F = 3$ involves 3 angles and 1 $CP$-violating phase (after removing unobservable $q_L$ phases) (new interactions involving $q_R$ could make observable)

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{td} & V_{td} \end{pmatrix}$$

Extensive studies, especially in $B$ decays, to test unitarity of $V$ as probe of new physics and test origin of $CP$ violation

Need additional source of $CP$ breaking for baryogenesis
- Overconstrain unitarity triangle as test of SM

- Babar, Belle: \( \sin 2\beta = 0.736 \pm 0.049 \) from \( B^0_d(t) \rightarrow J/\psi K_S \) (little theory error)

- \( \alpha, \gamma \) harder

- Anomalies in electroweak penguins?
$\Delta m_d$ 
$\Delta m_s$ \& $\Delta m_d$ 

$|V_{ub}/V_{cb}|$ 

$\sin 2\beta$ 

$\epsilon_K$ 

$\epsilon_K$ 

$\alpha$ 

$\beta$ 

$\Delta m_d$ 

$B \rightarrow \rho \rho$ 

$B \rightarrow \rho \rho$ 

$\sin 2\beta$ 

$\alpha$ 

$\beta$ 

$\Delta m_d$ 

$\Delta m_s$ \& $\Delta m_d$ 

$\epsilon_K$ 

excluded area has $\text{CL} < 0.05$

Winter 2004
The Weak Neutral Current

Prediction of $SU(2) \times U(1)$

WNC discovered 1973: Gargamelle at CERN, HPW at FNAL

Tested in many processes: $\nu e \rightarrow \nu e$, $\nu N \rightarrow \nu N$, $\nu N \rightarrow \nu X$; $e^+ \downarrow D \rightarrow eX$; atomic parity violation; $e^+ e^-$, $Z$-pole reactions

WNC, $W$, and $Z$ are primary test/prediction of electroweak model
The LEP/SLC Era

- **Z Pole:** $e^+e^- \rightarrow Z \rightarrow \ell^+\ell^-$, $q\bar{q}$, $\nu\bar{\nu}$
  - LEP (CERN), $2 \times 10^7 Z'$s, unpolarized (ALEPH, DELPHI, L3, OPAL);
    SLC (SLAC), $5 \times 10^5$, $P_{e^-} \sim 75\%$ (SLD)

- **Z pole observables**
  - lineshape: $M_Z, \Gamma_Z, \sigma$
  - branching ratios
    - $e^+e^-, \mu^+\mu^-, \tau^+\tau^-$
    - $q\bar{q}, c\bar{c}, b\bar{b}, s\bar{s}$
    - $\nu\bar{\nu} \Rightarrow N_\nu = 2.9841 \pm 0.0083$ if $m_\nu < M_Z/2$
  - asymmetries: FB, polarization, $P_\tau$, mixed
  - lepton family universality
\[ \nu = 2.9841(83) \]

(2 \sigma, cf \sigma_{\text{had}})
LEP averages of leptonic widths

\[ \Gamma_e = 83.92 \pm 0.12 \text{ MeV} \]

\[ \Gamma_\mu = 83.99 \pm 0.18 \text{ MeV} \]

\[ \Gamma_\tau = 84.08 \pm 0.22 \text{ MeV} \]

\[ \Gamma_1 = 83.98 \pm 0.09 \text{ MeV} \]

\[ m_Z = 91.188 \pm 0.002 \text{ GeV} \]

\[ m_t = 174.3 \pm 0.5 \text{ GeV} \]
### Winter 2004

#### Measurement Fit

<table>
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<th>Parameter</th>
<th>Value (uncertainty)</th>
<th>Value (uncertainty)</th>
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<td>$m_Z$ [GeV]</td>
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<td>$2.4952 \pm 0.0023$</td>
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<td>$\sigma_0^\text{had}$ [nb]</td>
<td>$41.540 \pm 0.037$</td>
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<td>$A_l(P_{\tau})$</td>
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<td>$0.1480$</td>
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<td>$R_b$</td>
<td>$0.21638 \pm 0.00066$</td>
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<td>$R_c$</td>
<td>$0.1720 \pm 0.0030$</td>
<td>$0.1723$</td>
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<tr>
<td>$A_{\text{fb}}^{0,c}$</td>
<td>$0.0706 \pm 0.0035$</td>
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<td>$0.935$</td>
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<tr>
<td>$A_c$</td>
<td>$0.670 \pm 0.026$</td>
<td>$0.668$</td>
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<td>$A_l$(SLD)</td>
<td>$0.1513 \pm 0.0021$</td>
<td>$0.1480$</td>
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<td>$\sin^2 \theta_{\text{eff}}^{\text{lept}}(Q_{\text{fb}})$</td>
<td>$0.2324 \pm 0.0012$</td>
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<td>$m_W$ [GeV]</td>
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<tr>
<td>$\Gamma_W$ [GeV]</td>
<td>$2.133 \pm 0.069$</td>
<td>$2.094$</td>
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<tr>
<td>$m_t$ [GeV]</td>
<td>$178.0 \pm 4.3$</td>
<td>$178.1$</td>
</tr>
</tbody>
</table>
Gauge Self-Interactions

Three and four-point interactions predicted by gauge invariance

Indirectly verified by radiative corrections, \( \alpha_s \) running in QCD, etc.

Strong cancellations in high energy amplitudes would be upset by anomalous couplings

Tree-level diagrams contributing to \( e^+e^- \rightarrow W^+W^- \)
The Precision Program

- WNC, Z, Z-pole, W, $m_t$

- Implications
  - SM correct and unique to zeroth approx. (gauge principle, group, representations)
  - SM correct at loop level (renorm gauge theory; $m_t$, $\alpha_s$, $M_H$)
  - TeV physics severely constrained (unification vs compositeness)
  - Precise gauge couplings (gauge unification)
Problems with the Standard Model

Lagrangian after symmetry breaking:

\[
\mathcal{L} = L_{\text{gauge}} + L_{\text{Higgs}} + \sum_{i} \bar{\psi}_{i} \left( i \varphi - m_{i} - \frac{m_{i} H}{\nu} \right) \psi_{i} - \frac{g}{2\sqrt{2}} \left( J_{W}^{\mu} W_{\mu}^{\nu} + J_{W}^{\mu\nu} W_{\mu}^{\nu} \right) - eJ_{Q}^{\mu} A_{\mu} - \frac{g}{2\cos \theta_{W}} J_{Z}^{\mu} Z_{\mu}
\]

Standard model: \(SU(2) \times U(1)\) (extended to include \(\nu\) masses) + QCD + general relativity

Mathematically consistent, renormalizable theory

Correct to \(10^{-16}\) cm
However, too much arbitrariness and fine-tuning: $O(27)$ parameters (+ 2 for Majorana $\nu$), and electric charges

- **Gauge Problem**
  - complicated gauge group with 3 couplings
  - charge quantization ($|q_e| = |q_p|$) unexplained
  - Possible solutions: strings; grand unification; magnetic monopoles (partial); anomaly constraints (partial)

- **Fermion problem**
  - Fermion masses, mixings, families unexplained
  - Neutrino masses, nature?
  - CP violation inadequate to explain baryon asymmetry
  - Possible solutions: strings; brane worlds; family symmetries; compositeness; radiative hierarchies. New sources of CP violation.
• Higgs/hierarchy problem
  – Expect $M_H^2 = O(M_W^2)$
  – higher order corrections:
    $$\delta M_H^2 / M_W^2 \sim 10^{34}$$

Possible solutions: supersymmetry; dynamical symmetry breaking; large extra dimensions; Little Higgs

• Strong CP problem
  – Can add $\frac{\theta}{32\pi^2} g_s^2 F \tilde{F}$ to QCD (breaks, P, T, CP)
  – $d_N \Rightarrow \theta < 10^{-9}$
  – but $\delta \theta |_{\text{weak}} \sim 10^{-3}$
  – Possible solutions: spontaneously broken global $U(1)$ (Peccei-Quinn) $\Rightarrow$ axion; unbroken global $U(1)$ (massless $u$ quark); spontaneously broken CP + other symmetries
• Graviton problem
  – gravity not unified
  – quantum gravity not renormalizable
  – cosmological constant: \( \Lambda_{SSB} = 8\pi G_N \langle V \rangle > 10^{50} \Lambda_{obs} \) (\( 10^{124} \) for GUTs, strings)
  – Possible solutions:
    * supergravity and Kaluza Klein unify
    * strings yield finite gravity.
    * \( \Lambda \)?
(Nearly) Unique Features of the old Standard Model

\( m_\nu = 0 \) in old standard model (need to add singlet fermion and/or triplet Higgs and/or higher dimensional operator (HDO))

- Oscillation experiments confirm non-zero masses, LMA, SSM (also helioseismology)
  - Excluded sterile, RSPF, new interactions as dominant
  - Oscillation dip observed (further constrains/excludes alternatives)
3 $\nu$ Patterns

- **Solar:** LMA (SNO, Kamland)

- $\Delta m^2_{\odot} \sim 8 \times 10^{-5}$ eV$^2$ for LMA

- **Atmospheric:** $\Delta m^2_{\text{Atm}} \sim 3 \times 10^{-3}$ eV$^2$, near-maximal mixing

- **Reactor:** $U_{e3}$ small
Physics at LHC (July 16, 2004)  

Paul Langacker (Penn)
Mixings: let $\nu_{\pm} \equiv \frac{1}{\sqrt{2}} (\nu_{\mu} \pm \nu_{\tau})$:

\[
\begin{align*}
\nu_3 & \sim \nu_+ \\
\nu_2 & \sim \cos \theta \nu_- - \sin \theta \nu_e \\
\nu_1 & \sim \sin \theta \nu_- + \cos \theta \nu_e
\end{align*}
\]

Hierarchical pattern

- Analogous to quarks, charged leptons
- $\beta\beta_{0\nu}$ rate very small

Inverted quasi-degenerate pattern

- $\beta\beta_{0\nu}$ if Majorana
- May be radiative unstable
Outstanding issues

- Dirac or Majorana

- Distinguish by $\beta\beta_{0\nu}$, at least for inverted, degenerate. Observation?

Dirac Mass

- Connects distinct Weyl spinors (usually active to sterile):
  $$(m_D \bar{\nu}_L N_R + h.c.)$$

- 4 components, $\Delta L = 0$

- $\Delta I = \frac{1}{2} \rightarrow$ Higgs doublet

- Why small? LED? HDO?

\[\nu_L \quad v = \langle \phi \rangle \]
\[h \quad m_D = h v \]

Physics at LHC (July 16, 2004)  Paul Langacker (Penn)
Majorana Mass

- Connects Weyl spinor with itself:
  \[ \frac{1}{2}(m_T \bar{\nu}_L \nu_R^c + h.c.) \] (active);
  \[ \frac{1}{2}(m_S \bar{N}_L^c N_R + h.c.) \] (sterile)

- 2 components, \( \Delta L = \pm 2 \)

- Active: \( \Delta I = 1 \rightarrow \text{triplet or seesaw} \)

- Sterile: \( \Delta I = 0 \rightarrow \text{singlet or bare mass} \)
• Scale of neutrino masses: $0.05 \text{ eV} < m_\nu < O(0.3 \text{ eV})$. Probe by $\beta$ decay (KATRIN), cosmology, $\beta\beta_{0\nu}$

• Type of hierarchy: $\beta\beta_{0\nu}$

• $U_{e3}$, leptonic $CP$

• LSND? $\Rightarrow$ Additional (sterile) neutrino(s) which mix with ordinary. MiniBooNE.

• Leptogenesis?
Flavor Changing Neutral Currents

- In SM: Yukawa coupling $h \propto gm/M_W \Rightarrow$ flavor conserving and small for light fermions (partially maintained in MSSM and simple 2HDM)

- In SM: no FCNC at tree level ($Z$ or $h$); suppressed at loop level

- Violated in almost all extensions, including SUSY loops; $Z'$ from strings, DSB

- Hard to give precise expectations, but critical to search

- Third family transitions (rare $B$, $\tau$) often largest, but small induced effects in first two families ($\mu$, $K$ decays) may be more sensitive (MEG at PSI, MECO at BNL, PRIME at JHF)
History of Lepton Flavor Violation Searches

- $\mu^+ \rightarrow e^+\gamma$
- $\mu^- \rightarrow e^-N$
- $K^0 \rightarrow \mu^+ e^-$
- $K^+ \rightarrow \pi^+ \mu^+ e^-$

MECO Goal

SINDRUMII
What might we expect?

**Supersymmetry**

Predictions at $10^{-15}$

**Compositeness**

$\Lambda_c = 3000 \text{ TeV}$

**Heavy Neutrinos**

$$\left| U_{\mu N} U_{eN} \right|^2 = 8 \times 10^{-13}$$

**Second Higgs**

$g_{H\mu\mu} = 10^{-4} \times g_{H\mu\mu}$

**Leptoquarks**

$$M_L = 3000 \sqrt{\lambda_{\mu d} \lambda_{ed}} \text{ TeV/c}^2$$

**Heavy Z', Anomalous Z coupling**

$$M_Z = 3000 \text{ TeV/c}^2$$

$$B(Z \to \mu e) < 10^{-17}$$

*After W. Marciano*
- SM: suppressed off-diagonal $\mathcal{CP}$; highly suppressed diagonal (EDMs)

- Larger in SUSY (loops, soft parameters) unless tuning or cancellations

- Larger in other extensions, e.g., singlet scalars in $Z'$ models (but may be hidden)

- $B$ decays, leptonic $\mathcal{CP}$, EDMs

- Need additional $\mathcal{CP}$ for baryogenesis
Electron EDM in various SM extensions

\[ \mathcal{L}_d = \frac{d_e}{2} \bar{\psi} \gamma_5 \sigma_{\mu\nu} \psi F_{\mu\nu} \]

not renormalizable

⇒ loop diagrams

| Physics model                      | $|d_e|$      |
|-----------------------------------|------------|
| Standard Model                    | \(\sim 10^{-41} \text{ e}\cdot\text{cm}\) |
| Left-right symmetric              | \(10^{-26}-10^{-28} \text{ e}\cdot\text{cm}\) |
| Lepton flavor-changing            | \(10^{-26}-10^{-29} \text{ e}\cdot\text{cm}\) |
| Multi-Higgs                       | \(10^{-27}-10^{-28} \text{ e}\cdot\text{cm}\) |
| Technicolor                       | \(10^{-27}-10^{-29} \text{ e}\cdot\text{cm}\) |
| Supersymmetry                     | \(< 10^{-25} \text{ e}\cdot\text{cm}\) |

Experimental limit:

$|d_e| < 1.6 \times 10^{-27} \text{ e}\cdot\text{cm}$

B. Regan, E. Commins, C. Schmidt, D. DeMille, PRL 88, 071805 (2002)

Models assume new physics at \(\sim 100 \text{ GeV}\) & CP-violating phases \(\sim 1\)
(D. DeMille)
Baryon and Lepton Number Violation

- **SM**: $B, L$ conserved perturbatively ($B - L$ non-perturbatively)

- Violated in BSM, e.g., by GUT (string) interactions or $\mathcal{R}_p$

- Proton decay expected at some level in many extensions, especially Planck scale

- $\mathcal{L}$ needed for Majorana neutrino masses $\Rightarrow \beta\beta_{0\nu}$

- New $B$ and/or $L$ invoked in some baryogenesis schemes
<table>
<thead>
<tr>
<th>mode</th>
<th>exposure (kt\cdot yr)</th>
<th>εBm (%)</th>
<th>observed</th>
<th>B.G. event</th>
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<td>40</td>
<td>0.2</td>
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<td>92</td>
<td>34</td>
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<td>K^0 \rightarrow π^+ μ^+ (spectrum)</td>
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</table>

**Diagram:**

The diagram shows the lifetime limit for different decay modes. The axes represent the lifetime limit in years, with ranges from 10^2 to 10^4 years. The decay modes are color-coded, with each mode represented by a different symbol (e.g., stars, squares, circles) to distinguish between SK, IMB3, KAM, and Soudan2 experiments.
• New TeV scale interactions suggested by top-down

• \( Z' \) or other new interactions
  – Implications for highly non-standard Higgs, FCNC, CDM, baryogenesis

• Exotics
  – Extra Higgs doublets and singlets
  – Exotic quarks and leptons
  – Fractional charges

• Quasi-hidden sectors
Hints and Anomalies

- Gauge unification in supersymmetric extension
  - If not accident or compensation, severely limits new TeV scale physics

- Precision data suggests light Higgs
• Precision data suggests light Higgs

• $M_H = 113^{+56}_{-40} \text{ GeV}$ (< 246 GeV at 95% including indirect)

• Consistent with SUSY (but does not prove)

• Has increased due to new D0 $m_t$ value and lower $M_W$

• $A_{FB}^b$ pulls up, $A_L$ down

$\Delta \chi^2$

Excluded Preliminary

$\Delta \alpha_{\text{had}} = \Delta \alpha_{\text{had}}^{(5)}$

$0.02761 \pm 0.00036$

$0.02747 \pm 0.00012$

incl. low $Q^2$ data

Theory uncertainty

Physics at LHC (July 16, 2004)

Paul Langacker (Penn)
- Tension between lepton and quark asymmetries
- $A_{FB}(b)$ and $A_l$
- New physics in 3rd family?
• Atomic parity violation? Now in agreement after complete radiative corrections.

• NuTeV? Unresolved. Likely QCD or structure function issue.

• Electroweak penguins in $B \rightarrow \phi K_S, K\pi$?
  – Experimental situation uncertain
  – SUSY loops for large $\tan \beta$ or tree effects, e.g. FCNC $Z'$

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Physics at LHC (July 16, 2004)  Paul Langacker (Penn)
• Anomalous magnetic moment of muon
  
  – Hadronic vacuum polarization \((e^+e^- \text{ vs } \tau \text{ decay}); \text{ light by light}\)
  – If real, then SUSY with large \(\tan \beta\) and low masses is possibility

\[
\Delta a_\mu(ee) = (23.9 \pm 9.9) \times 10^{-10} \quad 2.4 \text{ s.d.}
\]

\[
\Delta a_\mu(\tau) = (7.6 \pm 8.9) \times 10^{-10} \quad 0.9 \text{ s.d.}
\]

Physics at LHC (July 16, 2004)  
Paul Langacker (Penn)
CKM Universality

- $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 \sim |V_{ud}|^2 + |V_{us}|^2 = 1 - \Delta$

  - PDG 2002: $\Delta = 0.0042 \pm 0.0019$
  - New physics? Constrains $\nu - \nu_{\text{heavy}}$ explanations of NuTeV
  - Problem in $V_{ud}$?
    - Superallowed: $|V_{ud}| = 0.9740(5)$, many checks
    - Neutron: $0.9745$ (16) (common structure-independent rad corr)
    - Pion beta decay: $0.9716(39)$ (new)
  - Problem in $V_{us}$?
    - BNL E685, KTEV, KLOE but not CERN NA 48
• Dark Matter
  - $\sim 30\%$ matter, mainly dark
  - No SM candidates; SUSY LSP if $R_P$ conserved (MSSM tightly constrained); axions

• $\sim 70\%$ dark energy
  - Higgs VeV, QCD vacuum energy in SM, but too large by $\sim 10^{50}$; new fields? quintessence?
  - JDEM (SNAP)
Physics at LHC (July 16, 2004)

Paul Langacker (Penn)
• Baryogenesis

- Baryon asymmetry $n_B/n_\gamma \sim 6 \times 10^{-10}$

• Possible mechanisms

  – GUT baryogenesis (wiped out by sphalerons for $B - L = 0$)
  – Leptogenesis (for heavy right-handed Majorana neutrino in seesaw)
  – Electroweak baryogenesis
EB requires strong first order transition, $v(T_c)/T_c \gtrsim 1 - 1.3$ and adequate CP violation in expanding bubble wall

- Absent in SM
- Narrow parameter range in MSSM
- Possible in $Z'$

(W. Bernreuther, hep-ph/0205279)
Conclusions

- Standard Model is spectacularly successful, but has many parameters, tunings, and unexplained features
- Must be new physics

- Theoretical ideas
  - Strings
  - Grand Unification (canonical or modified)
  - Supersymmetry
  - Top-down remnants ($Z'$, exotics)
  - Large extra dimensions, deconstruction
  - Dynamical symmetry breaking, compositeness, Little Higgs
• **Experimental probes**
  
  – Hadron colliders: Tevatron, LHC
  – Linear collider/CLIC
  – FCNC, EDM, heavy quark, precision, neutrino, $p$ decay
  – Cosmology/astrophysics

• **Tremendous opportunities in particle physics, to develop standard theory valid to the Planck scale**