THE STANDARD MODEL AND BEYOND'19

DMITRY KAZAKOV
JINR(DUBNA)
### The Standard Model of Fundamental Interactions

#### Three Generations of Matter (Fermions)

<table>
<thead>
<tr>
<th></th>
<th>I</th>
<th>II</th>
<th>III</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mass (MeV)</td>
<td>charge</td>
<td>spin</td>
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<tr>
<td>I</td>
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<tr>
<td>II</td>
<td>1.24</td>
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<tr>
<td>III</td>
<td>172.5</td>
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<td>1/2</td>
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</table>

#### Quarks

- **d** (down): 6 MeV
- **s** (strange): 95 MeV
- **b** (bottom): 4.2 GeV

#### Leptons

- **e** (electron): 0.511 MeV
- **μ** (muon): 106 MeV
- **τ** (tau): 1.78 GeV

#### Bosons (Forces)

- **ν_e** (electron neutrino): ≤ 2 eV
- **ν_μ** (muon neutrino): ≤ 0.19 MeV
- **ν_τ** (tau neutrino): ≤ 18.2 MeV
- **Z^0** (weak force): 90.2 GeV
- **W^±** (weak force): 80.4 GeV

#### Forces

- Electromagnetic
- Strong
- Weak
- Gravity
THE PRINCIPLES
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Three gauged symmetries SU(3) x SU(2) x U(1)
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- Three gauged symmetries $SU(3) \times SU(2) \times U(1)$
- Three families of quarks and leptons $(3 \times 2, 3 \times 1, 1 \times 2, 1 \times 1)$
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The ST principles allow:
- Extra families of quarks and leptons
- Presence or absence of right-handed neutrino
- Majorana or Dirac nature of neutrino
- Extra Higgs bosons
THE LAGRANGIAN

\[ \mathcal{L} = \mathcal{L}_{gauge} + \mathcal{L}_{Yukawa} + \mathcal{L}_{Higgs}, \]
THE LAGRANGIAN

\[
L = L_{\text{gauge}} + L_{\text{Yukawa}} + L_{\text{Higgs}},
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L_{\text{gauge}} = -\frac{1}{4} G_{\mu\nu}^a G^{a}_{\mu\nu} - \frac{1}{4} W_i^\mu W_i^\nu - \frac{1}{4} B_{\mu\nu} B_{\mu\nu}
+ i\bar{L}_\alpha \gamma^\mu D_\mu L_\alpha + i\bar{Q}_\alpha \gamma^\mu D_\mu Q_\alpha + i\bar{E}_\alpha \gamma^\mu D_\mu E_\alpha
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\[ + i \overline{N}_\alpha \gamma^\mu \partial_\mu N_\alpha \]

possible right handed neutrino?
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\[ \mathcal{L}_{\text{Yukawa}} = y^L_{\alpha\beta} \bar{L}_\alpha E_\beta H + y^D_{\alpha\beta} \bar{Q}_\alpha D_\beta H + y^U_{\alpha\beta} \bar{Q}_\alpha U_\beta \tilde{H} + h.c., \]
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\[ + i \bar{N}_\alpha \gamma^\mu D_\mu \tilde{N}_\alpha + \lambda (H^\dagger H)^2 (H^\dagger H)^2, \]

\[ \mathcal{L}_{\text{Yukawa}} = \sum_{\alpha} \left( y_{\alpha \beta}^{L} \bar{L}_\alpha E_\beta H + y_{\alpha \beta}^{D} \bar{Q}_\alpha D_\beta H + y_{\alpha \beta}^{U} \bar{Q}_\alpha U_\beta \tilde{H} + \text{h.c.} \right), \]

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THE STANDARD MODEL: THE STATUS REPORT AND OPEN QUESTIONS

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All these parameters are not predicted by the SM and determined experimentally.

Three gauge couplings

Three or four Yukawa matrices
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Three gauge couplings

Possible right-handed neutrino?

Three or four Yukawa matrices

Two parameters
Quantum Numbers of Matter

➢ Quarks

\[ Q_L = \begin{pmatrix} up \\ down \end{pmatrix}_L \]

\[ U_R = up_R \]

\[ D_R = down_R \]

➢ Leptons

\[ L_L = \begin{pmatrix} \nu \\ e \end{pmatrix}_L \]

\[ N_R = \nu_R \]

\[ E_R = e_R \]

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<thead>
<tr>
<th>SU(3)_c</th>
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</tr>
</thead>
<tbody>
<tr>
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| 1       | 2       | -1     |
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<td>triplets</td>
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triplets

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Quantum Numbers of Matter

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V-A currents in weak interactions

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</tr>
<tr>
<td>1</td>
<td>1</td>
<td>-2</td>
</tr>
</tbody>
</table>
Quantum Numbers of Matter

➢ Quarks

\[ Q_L = \begin{pmatrix} up \\ down \end{pmatrix}_L \]

\[ U_R = up_R \]

\[ D_R = down_R \]

➢ Leptons

\[ L_L = \begin{pmatrix} \nu \\ e \end{pmatrix}_L \]

\[ N_R = \nu_R \]

\[ E_R = e_R \]

\[ SU(3)_c \quad SU(2)_L \quad U_Y(1) \]

\[ \begin{array}{ccc}
3 & 2 & 1/3 \\
3 & 1 & 4/3 \\
3 & 1 & -2/3 \\
\end{array} \]

\[ SU(3)_c \quad SU(2)_L \quad U_Y(1) \]

\[ \begin{array}{ccc}
1 & 2 & -1 \\
1 & 1 & 0 \\
1 & 1 & -2 \\
\end{array} \]

V-A currents in weak interactions

Electric charge

\[ Q = T_3 + Y / 2 \]
The Number of Colours

- The x-section of electron-positron annihilation into hadrons is proportional to the number of quark colours. The fit to experimental data at various colliders at different energies gives

\[ N_c = 3.06 \pm 0.10 \]
The Number of Generations

- The width of the Z-boson (LEP)

  Z-line shape obtained at LEP depends on the number of flavours and gives the number of (light) neutrinos or (generations) of the Standard Model

- The CMB spectrum (Planck)

  The shape of the CMB temperature fluctuations give the number of active neutrinos or generations of the Standard Model assuming the quark-lepton symmetry

\[ N_g = 2.982 \pm 0.013 \]
Quark’s Colour

Baryons are “made” of quarks

\[ \Delta^- (d \uparrow d \uparrow d \uparrow) \]

\[ \Omega^- (s \uparrow s \uparrow s \uparrow) \]

\[ \Delta^{++} (u \uparrow u \uparrow u \uparrow) \]
Quark’s Colour

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To avoid Pauli principle veto one can antisymmetrize the wave function introducing a new quantum number - “colour”, so that
Quark’s Colour

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$\Omega^- (s \uparrow s \uparrow s \uparrow)$

$\Delta^{++} (u \uparrow u \uparrow u \uparrow)$

To avoid Pauli principle veto one can antisymmetrize the wave function introducing a new quantum number - “colour”, so that

$\Delta^- = \epsilon^{ijk} (d_i \uparrow d_j \uparrow d_k \uparrow)$
The group structure of the SM

For SU(N)

\[ \sum_{a=1}^{N_A} (T^a T^{a*})_{ij} = \delta_{ij} C_F, \quad \sum_{i,j=1}^{N_F} T^a_{ij} T^{a*}_{jk} = \delta^{ab} T_F, \quad \sum_{a,b=1}^{N_A} f^{abc} f^{*abd} = \delta^{cd} C_A \]

Casimir Operators

\[ C_A = N_C, \quad C_F = \frac{N_C^2 - 1}{2N_C}, \quad T_F = 1/2 \]
The group structure of the SM Casimir Operators

For SU(N)

\[ \sum_{i,j}^N \left( T^a_i T^{\dagger a}_j \right) = \delta_{ij} C_F \]
\[ \sum_{i,j=1}^{N_F} T^a_{ij} T^{\dagger b}_{ji} = \delta^{ab} T_F \]
\[ \sum_{a,b=1}^{N_A} f^{abc} f^{*ab} = \delta^{cd} C_A \]

For SU(N)

\[ C_A = N_C, \quad C_F = \frac{N_C^2 - 1}{2N_C}, \quad T_F = 1/2 \]
The group structure of the SM

For SU(N)

QCD analysis definitely singles out the SU(3) group as the symmetry group of strong interactions

Casimir Operators

\[ \sum_{a=1}^{N_A} (T^a T^a)_{ij} = \delta_{ij} C_F \quad , \quad \sum_{i,j=1}^{N_F} T^a_{ij} T^b_{ji} = \delta^{ab} T_F \quad , \quad \sum_{a,b=1}^{N_A} f^{abc} f^{*ab} = \delta^{cd} C_A \]
Electro-weak sector of the SM

SU(2) x U(1)  versus  O(3)

3 gauge bosons  1 gauge boson  3 gauge bosons
Electro-weak sector of the SM

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After spontaneous symmetry breaking one has
Electro-weak sector of the SM

SU(2) x U(1) versus O(3)

3 gauge bosons  1 gauge boson  3 gauge bosons

After spontaneous symmetry breaking one has

3 massive gauge bosons
(W\(^+\), W\(^-\), Z\(^0\)) and 1 massless (γ)
Electro-weak sector of the SM

SU(2) x U(1) versus O(3)

3 gauge bosons 1 gauge boson 3 gauge bosons

After spontaneous symmetry breaking one has

3 massive gauge bosons
\((W^+, W^-, Z^0)\)
and 1 massless \((\gamma)\)

2 massive gauge bosons
\((W^+, W^-)\)
and 1 massless \((\gamma)\)
Electro-weak sector of the SM

\[ SU(2) \times U(1) \quad \text{versus} \quad O(3) \]

3 gauge bosons \quad 1 gauge boson \quad 3 gauge bosons

After spontaneous symmetry breaking one has

3 massive gauge bosons \((W^+, W^-, Z^0)\) and 1 massless \((\gamma)\)

2 massive gauge bosons \((W^+, W^-)\) and 1 massless \((\gamma)\)

- Discovery of neutral currents was a crucial test of the gauge model of weak interactions at CERN in 1973
- The heavy photon gives the neutral current without flavour violation
Flavour Sector

- Quarks: Up, Down, Charm, Strange, Top, Beauty
- Leptons: Electron, Neutrino, Muon, Neutrino Muon, Tau, Neutrino Tau
Electromagnetic Interactions
Electromagnetic Interactions

1. Performed via exchange of quanta of electromagnetic field - photon
Electromagnetic Interactions

1. Performed via exchange of quanta of electromagnetic field - photon
2. Electromagnetic field is described by Maxwell equations

\[ \partial_\mu F_{\mu\nu} + j_\mu = 0 \]
\[ \partial_\mu \tilde{F}_{\mu\nu} = 0 \]
\[ F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \]

\[ \partial_t \vec{E} - \nabla \times \vec{B} = -\vec{j} \]
\[ \vec{\nabla} \vec{E} = \rho \]
\[ \partial_t \vec{B} + \nabla \times \vec{E} = 0 \]
\[ \vec{\nabla} \vec{B} = 0 \]
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F_{\mu\nu} = \partial_{\mu} A_{\nu} - \partial_{\nu} A_{\mu} \\
\partial_t \tilde{E} - \nabla \times \tilde{B} = \tilde{j} \\
\nabla \tilde{E} = \rho \\
\partial_t \tilde{B} + \nabla \times \tilde{E} = 0 \\
\nabla \tilde{B} = 0
\]

3. Charged particles (quarks and leptons) obey Dirac equation

\[
(\hat{\partial} - m - e\hat{A}) \psi = 0 \\
\hat{\partial} = \gamma^\mu \partial_{\mu}
\]
Strong Interactions
Strong Interactions

1. Performed via exchange of quanta of gluon (color) field -gluon
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**Strong Interactions**

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   - mesons \( \bar{M} = \bar{qq} \) and baryons \( B = qqq \)
6. However, exotic hadrons are proved to exist
Weak Interactions
Weak Interactions

1. Performed via exchange of intermediate weak bosons W, Z
Weak Interactions

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2. The fields $W$ and $Z$ are described by Yang-Mills eqs
   (generalization of Maxwell eqs)
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Weak Interactions

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3. The fields W, Z carry weak charge (isospin) and interact with each other
4. W, Z can be observed in free state and are massive
5. Weak interactions involve quarks and leptons
6. Weak interactions are short-range $R \sim 1/M_W$
Quarks – “the building blocks of the Universe”
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Charm came as surprise but completed the picture
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The number of quarks increased with discoveries of new particles and have reached 6.

Charm came as a surprise but completed the picture.
Quarks – “the building blocks of the Universe”

Charm came as surprise but completed the picture.

For unknown reasons Nature created 3 copies (generations) of quarks and leptons.

The number of quarks increased with discoveries of new particles and have reached 6.
Leptons are from λεπτόσ - light

Electrons form atomic shells and define all chemistry of animated and unanimated nature

Neutrino are produced in hadron decay

\[ n(udd) \rightarrow p(uud) + e + \bar{\nu} \]

Muons are created from \( \pi^- \)-mesons decay in cosmic rays and decay into electrons and two neutrinos
Matter and Antimatter

The first generation is what we are made of.

Antimatter was created together with matter during the “Big bang”.

Antiparticles are created at accelerators in ensemble with particles but the visible Universe does not contain antimatter.
Five fundamental forces of Nature
Five fundamental forces of Nature

\[ V(r) = -\frac{e_1 e_2}{r} \]
Five fundamental forces of Nature

- Electromagnetic (El-Mag) force
  \[ V(r) = -\frac{e_1e_2}{r} \]

- Weak force
  \[ V(r) = -\frac{g^2}{r}e^{-Mw r} \]
Five fundamental forces of Nature

El-Mag:
\[ V(r) = -\frac{e_1 e_2}{r} \]

Weak:
\[ V(r) = -\frac{g^2}{r} e^{-M_W r} \]

Strong:
\[ V(r) = -\frac{g_s^2}{r} + br \]
Five fundamental forces of Nature

**El-Mag**

\[ V(r) = -\frac{e_1 e_2}{r} \]

**Weak**

\[ V(r) = -\frac{g^2}{r} e^{-M_W r} \]

**Strong**

\[ V(r) = -\frac{g_s^2}{r} + br \]

**Higgs**

\[ V(r) = -\frac{m_1 m_2}{v_H^2 r} e^{-M_H r} \]
Five fundamental forces of Nature

El-Mag

\[ V(r) = -\frac{e_1 e_2}{r} \]

Weak

\[ V(r) = -\frac{g^2}{r} e^{-M_W r} \]

Strong

\[ V(r) = -\frac{g_s^2}{r} + br \]

Higgs

\[ V(r) = -\frac{m_1 m_2}{v_H^2 r} e^{-M_H r} \]

Gravity

\[ V(r) = -\frac{m_1 m_2}{M_{PL}^2 r} \]
Five fundamental forces of Nature

El-Mag

Weak

Strong

Higgs

Gravity

Spin

\[
V(r) = -\frac{e_1 e_2}{r}
\]

\[
V(r) = -\frac{g^2}{r} e^{-M \omega r}
\]

\[
V(r) = -\frac{g_s^2}{r} + br
\]

\[
V(r) = -\frac{m_1 m_2}{r^2} e^{-M_H r}
\]

\[
V(r) = -\frac{M^2_{PL}}{r^2} e^{-M_H r}
\]
Gauge Invariance

Gauge transformation

\[ \psi_i(x) \rightarrow U_{ij}(x)\psi_j(x) = \exp[i\alpha^a(x)T_{ij}^a]\psi_j(x) \]

Matrix \[ U^+U = 1 \]

Parameter matrix

\[ \bar{\psi}_i(x) \rightarrow \bar{\psi}_j U_{ji}^+(x) \]

\[ a = 1, 2, \ldots, N \]
Gauge Invariance

Gauge transformation
\[ \psi_i(x) \rightarrow U_{ij}(x)\psi_j(x) = \exp[i\alpha^a(x)T_{ij}^a]\psi_j(x) \]
\[ \bar{\psi}_i(x) \rightarrow \bar{\psi}_jU^+_{ji}(x) \]

Fermion Kinetic term
\[ i\bar{\psi}(x)\gamma^\mu \partial_\mu \psi(x) \rightarrow i\bar{\psi}(x)U^+(x)\gamma^\mu \partial_\mu (U(x)\psi(x)) \]
\[ = i\bar{\psi}(x)\gamma^\mu \partial_\mu \psi(x) + i\bar{\psi}(x)\gamma^\mu U^+(x)\partial_\mu U(x)\psi(x) \]
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\[ \psi_i(x) \rightarrow U_{ij}(x)\psi_j(x) = \exp[i\alpha^a(x)T^a_{ij}]\psi_j(x) \]

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Fermion Kinetic term

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\[ a = 1, 2, \ldots, N \]
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matrix \quad U^+U = 1 \quad \text{parameter matrix}

Fermion Kinetic term

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Covariant derivative

\[ \partial_\mu \rightarrow D_\mu = \partial_\mu I + gA^a_\mu T^a = \partial_\mu I + gA_\mu \]

Gauge field
Gauge Invariance

Gauge transformation

\[ \psi_i(x) \rightarrow U_{ij}(x) \psi_j(x) = \exp[i \alpha^a(x) T^a_{ij}] \psi_j(x) \]

\[ \bar{\psi}_i(x) \rightarrow \bar{\psi}_j U^+_{ji}(x) \]

Matrix: \[ U^+ U = 1 \]

Parameter matrix: \[ a = 1, 2, \ldots, N \]

Fermion Kinetic term

\[ i \bar{\psi}(x) \gamma^\mu \partial_\mu \psi(x) \rightarrow i \bar{\psi}(x) U^+(x) \gamma^\mu \partial_\mu (U(x)\psi(x)) \]

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Covariant derivative

\[ \partial_\mu \rightarrow D_\mu = \partial_\mu I + g A^\mu T^a \equiv \partial_\mu I + g A_\mu \]

Gauge field

Gauge invariant kinetic term

\[ i \bar{\psi}(x) \gamma^\mu D_\mu \psi(x) \]
Gauge Invariance

Gauge transformation
\[ \psi_i(x) \rightarrow U_{ij}(x)\psi_j(x) = \exp[i\alpha^a(x)T^a_{ij}]\psi_j(x) \]
\[ \bar{\psi}_i(x) \rightarrow \bar{\psi}_j U^+_{ji}(x) \]

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\[ i\bar{\psi}(x)\gamma^\mu \partial_\mu \psi(x) \rightarrow i\bar{\psi}(x)U^+(x)\gamma^\mu \partial_\mu (U(x)\psi(x)) \]
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Covariant derivative
\[ \partial_\mu \rightarrow D_\mu = \partial_\mu I + gA_\mu^a T^a \equiv \partial_\mu I + gA_\mu \]

Gauge invariant kinetic term
\[ i\bar{\psi}(x)\gamma^\mu D_\mu \psi(x) \]

Field strength tensor
\[ [D_\mu, D_\nu] = G_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu + g[A_\mu A_\nu] \]
\[ G_{\mu\nu} \rightarrow U^+(x)G_{\mu\nu}U(x) \]
Gauge Invariance

Gauge transformation
\[ \psi_i(x) \rightarrow U_{ij}(x)\psi_j(x) = \exp[i\alpha^a(x)T^a_{ij}]\psi_j(x) \]
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Covariant derivative
\[ \partial_\mu \rightarrow D_\mu = \partial_\mu I + gA^a_\mu T^a \equiv \partial_\mu I + gA_\mu \]
\[ \text{Gauge field} \]

Gauge invariant kinetic term
\[ \bar{\psi}(x)\gamma^\mu D_\mu \psi(x) \]
\[ [D_\mu, D_\nu] = G_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu + g[A_\mu A_\nu] \]
\[ G_{\mu\nu} \rightarrow U^+(x)G_{\mu\nu}U(x) \]
\[ \text{Field strength tensor} \]

Gauge field kinetic term
\[ -\frac{1}{4} Tr G_{\mu\nu} G^{\mu\nu} \]
Fermion Masses in the SM

Direct mass terms are forbidden due to $SU(2)_L$ invariance!
Fermion Masses in the SM

Direct mass terms are forbidden due to SU(2)$_L$ invariance!

Dirac Spinors

$$\psi, \psi_L = \frac{1 - \gamma^5}{2} \psi, \quad \psi_R = \frac{1 + \gamma^5}{2} \psi, \quad \psi = \psi^+ \gamma^0, \quad \psi^c = C \gamma^0 \psi = i \gamma^2 \psi^*$$
Fermion Masses in the SM

Direct mass terms are forbidden due to SU(2)$_L$ invariance!

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Dirac Spinors

\[
\psi, \quad \psi_L = \frac{1 - \gamma^5}{2} \psi, \quad \psi_R = \frac{1 + \gamma^5}{2} \psi
\]

Dirac conjugated

\[
\bar{\psi} = \psi^+ \gamma^0, \quad \psi^c = C \gamma^0 \psi = i \gamma^2 \psi^*
\]
Fermion Masses in the SM

Direct mass terms are forbidden due to SU(2)$_L$ invariance!

Dirac Spinors

Left

$$\psi_L = \frac{1 - \gamma^5}{2} \psi, \quad \psi^R = \frac{1 + \gamma^5}{2} \psi$$

Right

Dirac conjugated

$$\psi^\dagger = \psi^+ \gamma^0$$

Charge conjugated

$$\psi^c = C \gamma^0 \psi = i \gamma^2 \psi^*$$
Fermion Masses in the SM

Direct mass terms are forbidden due to $SU(2)_L$ invariance!

Dirac Spinors

\[
\psi, \psi_L = \frac{1-\gamma^5}{2}\psi, \quad \psi_R = \frac{1+\gamma^5}{2}\psi
\]

Dirac conjugated

\[
\overline{\psi} = \psi^+\gamma^0, \quad \psi^c = C \gamma^0 \psi = i\gamma^2 \psi^*
\]

Lorenz invariant Mass terms
Fermion Masses in the SM

Direct mass terms are forbidden due to SU(2)$_L$ invariance!

\[
\begin{align*}
\psi, \quad \psi_L &= \frac{1 - \gamma^5}{2} \psi, \\
\psi_R &= \frac{1 + \gamma^5}{2} \psi, \\
\psi &= \psi^+ \gamma^0, \\
\psi^c &= C \gamma^0 \psi^* = i \gamma^2 \psi^* 
\end{align*}
\]

Lorenz invariant Mass terms

\[
\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L
\]
Fermion Masses in the SM

Direct mass terms are forbidden due to SU(2)$_L$ invariance!

Dirac Spinors

\[ \psi, \psi_L = \frac{1 - \gamma^5}{2} \psi, \quad \psi_R = \frac{1 + \gamma^5}{2} \psi \]

\[ \bar{\psi} = \psi^+ \gamma^0, \quad \psi^c = C \gamma^0 \psi = i \gamma^2 \psi^* \]

Lorenz invariant Mass terms

\[ \bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L \]

SU(2) doublet  SU(2) singlet
Fermion Masses in the SM

Direct mass terms are forbidden due to SU(2)$_L$ invariance!

\[ \psi, \, \psi_L = \frac{1 - \gamma^5}{2} \psi, \, \psi_R = \frac{1 + \gamma^5}{2} \psi, \psi = \psi^+ \gamma^0, \psi^c = C \gamma^0 \psi = i \gamma^2 \psi^* \]

Lorenz invariant Mass terms

SU(2) doublet \quad SU(2) singlet

\[ \psi_L \psi_R + \psi_R \psi_L \]
Fermion Masses in the SM

Direct mass terms are forbidden due to SU(2)$_L$ invariance!

Dirac Spinors

\[ \psi, \quad \psi_L = \frac{1 - \gamma^5}{2} \psi, \quad \psi_R = \frac{1 + \gamma^5}{2} \psi, \quad \bar{\psi} = \psi^+ \gamma^0, \quad \psi^c = C \gamma^0 \psi = i \gamma^2 \psi^* \]

Lorenz invariant Mass terms

\[ \psi_L \psi_R + \psi_R \psi_L \]

SU(2) doublet \quad SU(2) singlet

\[ \psi_L \psi_L = \psi_R \psi_R = 0 \]
Fermion Masses in the SM

Direct mass terms are forbidden due to SU(2)$_L$ invariance!

Dirac Spinors

$$\psi, \psi_L = \frac{1-\gamma^5}{2}\psi, \psi_R = \frac{1+\gamma^5}{2}\psi$$

Dirac conjugated

$$\psi = \psi^+\gamma^0, \psi^c = C\gamma^0\psi = i\gamma^2\psi^*$$

Lorenz invariant Mass terms

$$\psi_L\psi_R + \psi_R\psi_L^c = 0$$

SU(2) doublet

SU(2) singlet

$$\psi_L^c\psi_L^c + \psi_L^c\psi_L^c = 0$$
Fermion Masses in the SM

Direct mass terms are forbidden due to SU(2)$_L$ invariance!

Dirac Spinors

Left: $\psi_L = \frac{1-\gamma^5}{2}\psi$, $\psi^L = \frac{1+\gamma^5}{2}\psi$

Right: $\psi_R = \psi^R + \gamma^0\psi$

Dirac conjugated: $\psi^c = C\gamma^0\psi = i\gamma^2\psi^*$

Charge conjugated:

Lorenz invariant Mass terms

$\psi_L\psi_R + \psi_R\psi_L = 0$

$\psi_L^c\psi_L^c + \psi_L^c\psi_L^c = 0$

$\psi_R^c\psi_R^c + \psi_R^c\psi_R^c = 0$

SU(2) doublet

SU(2) singlet

SU(2)$_L$ & U$_Y$(1)

U$_Y$(1)
Fermion Masses in the SM

Direct mass terms are forbidden due to SU(2)\(_L\) invariance!

Dirac Spinors

- left: \(\psi_L\)
- right: \(\psi_R\)

\[
\psi, \psi_L = \frac{1 - \gamma^5}{2} \psi, \quad \psi_R = \frac{1 + \gamma^5}{2} \psi
\]

- Dirac conjugated: \(\psi^+\gamma^0\)
- Charge conjugated: \(\psi^c = C\gamma^0\psi = i\gamma^2\psi^*\)

Lorenz invariant Mass terms

\[
\psi_L\psi_R + \psi_R\psi_L = 0
\]

SU(2) doublet \(\psi_L\psi_R\)

SU(2) singlet \(\psi_R\psi_L\)

SU\(_L\)(2) & U\(_Y\)(1)

Majorana mass term

\[
\psi_L\psi_L + \psi_R\psi_R
\]

\[
\psi_R\psi_L + \psi_L\psi_R
\]

Unless \(Q=0, Y=0\)
Spontaneous Symmetry Breaking

$SU_c(3) \otimes SU_L(2) \otimes U_Y(1) \rightarrow SU_c(3) \otimes U_{EM}(1)$
Spontaneous Symmetry Breaking

\[ SU_c(3) \otimes SU_L(2) \otimes U_Y(1) \rightarrow SU_c(3) \otimes U_{EM}(1) \]

Introduce a scalar field with quantum numbers: (1,2,1)

\[ H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} \]

With potential

\[ V = -m^2 H^\dagger H + \frac{\lambda}{2} (H^\dagger H)^2 \]
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Unstable maximum

Stable minimum
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At the minimum

\[ H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} = \begin{pmatrix} \frac{H^+}{\sqrt{2}} \\ \nu + \frac{S+iP}{\sqrt{2}} \end{pmatrix} = \text{exp}(i \frac{\xi^a \sigma^a}{2}) \begin{pmatrix} 0 \\ S \end{pmatrix} \]

v.e.v.

v.

scalar

pseudoscalar

Unstable maximum

Stable minimum
Spontaneous Symmetry Breaking

\[ SU_c(3) \otimes SU_L(2) \otimes U_Y(1) \rightarrow SU_c(3) \otimes U_{EM}(1) \]

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\[ V = -m^2 H^\dagger H + \frac{i}{2} \left( H^\dagger H \right)^2 \]

At the minimum

\[ H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} = \begin{pmatrix} H^+ \\ \nu + \frac{S+iP}{\sqrt{2}} \end{pmatrix} = \exp(i \frac{\xi^a \sigma^a}{2}) \begin{pmatrix} 0 \\ \frac{S}{\sqrt{2}} \end{pmatrix} \]

Gauge transformation

\[ H \rightarrow H' = \exp(i \frac{\alpha^a \sigma^a}{2}) H \]

Higgs boson

\[ H' = \begin{pmatrix} 0 \\ \frac{h}{\sqrt{2}} \end{pmatrix} \]
**The Higgs Mechanism**

**Q:** What happens with missing d.o.f. (massless goldstone bosons P, H⁺ or $\xi^*$)?

**A:** They become longitudinal d.o.f. of the gauge bosons $W_\mu^i$, $i=1,2,3$

Gauge transformation

$$\hat{W}_\mu \rightarrow e^{i\alpha^a \sigma^a} \hat{W}_\mu e^{-i\alpha^a \sigma^a} - \frac{1}{g} \partial_\mu \left( e^{i\alpha^a \sigma^a} \right) e^{-i\alpha^a \sigma^a}$$

Longitudinal components

**Higgs field kinetic term**

$$\left| D_\mu H \right|^2 = \left| \partial_\mu H - \frac{g}{2} \hat{W}_\mu H - \frac{g'}{2} \hat{B}_\mu H \right|^2 \quad \text{↔} \quad H = \begin{pmatrix} 0 \\ v \end{pmatrix}$$

$$\rightarrow \frac{1}{4} (0 \ v) \begin{pmatrix} gW_\mu^3 + g'B_\mu & \sqrt{2}gW^-_\mu \\ \sqrt{2}gW^+_\mu & -gW^3_\mu + g'B_\mu \end{pmatrix} \begin{pmatrix} gW_\mu^3 + g'B_\mu & \sqrt{2}gW^-_\mu \\ \sqrt{2}gW^+_\mu & -gW^3_\mu + g'B_\mu \end{pmatrix} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

$$\Rightarrow \frac{g^2}{2} v^2 W_\mu^+ W_-^\mu + \frac{1}{4} v^2 (-gW^3_\mu + g'B_\mu)^2$$

$$M_W^2 = \frac{1}{2} g^2 v^2$$

$$M_Z^2 = \frac{1}{2} (g^2 + g'^2) v^2$$

$$\tan \theta_W = \frac{g'}{g}$$

$$M_\gamma = 0$$

$$W_\mu^\pm = \frac{W_\mu^1 \mp W_\mu^2}{\sqrt{2}}$$

$$Z_\mu = -\sin \theta_W B_\mu + \cos \theta_W W_\mu^3$$

$$\gamma_\mu = \cos \theta_W B_\mu + \sin \theta_W W_\mu^3$$
The Higgs Boson and Fermion Masses

\[ H = \begin{pmatrix} 0 \\ v + \frac{h}{\sqrt{2}} \end{pmatrix} \implies V = -m^2 H^\dagger H + \frac{\lambda}{2} (H^\dagger H)^2 \]

\[ V = -\frac{\lambda v^4}{2} + \lambda v^2 h^2 + \frac{\lambda v}{\sqrt{2}} h^3 + \frac{\lambda}{8} h^4 \quad \implies v^2 = \frac{m^2}{\lambda} \]

\[ m_h = \sqrt{2} m = \sqrt{2\lambda v} \]

\[ L_{\text{Yukawa}} = y^E_{\alpha\beta} \overline{L}_\alpha E_\beta H + y^D_{\alpha\beta} \overline{Q}_\alpha D_\beta H + y^U_{\alpha\beta} \overline{Q}_\alpha U_\beta \tilde{H} \]

\( \alpha, \beta = 1, 2, 3 \) - generation index

Dirac fermion mass

\[ M^u_i = \text{Diag}(y^u_{\alpha\beta}) \nu, \quad M^d_i = \text{Diag}(y^d_{\alpha\beta}) \nu, \quad M^l_i = \text{Diag}(y^l_{\alpha\beta}) \nu \]

\[ y^N_{\alpha\beta} \overline{L}_\alpha N_\beta H \rightarrow M^N_i = \text{Diag}(y^N_{\alpha\beta}) \nu \]  

Dirac neutrino mass
Quark/Lepton Mixing

• The mass matrix is non-diagonal in generation space
• It can be diagonalized by field rotation $Q \rightarrow Q' = V Q$

\[
\overline{U} M_U U \rightarrow \overline{U}' V_U^+ M_U V_U U' = \overline{U}' M_U^{\text{Diag}} U'
\]
\[
\overline{D} M_D D \rightarrow \overline{D}' V_D^+ M_D V_D D' = \overline{D}' M_D^{\text{Diag}} D'
\]

• Neutral Current:
\[
\overline{U} Z_\mu U \rightarrow \overline{U}' V_U^+ Z_\mu V_U U' = \overline{U}' Z_\mu U' V_U^+ V_U = \overline{U}' Z_\mu U'
\]

• Charged Current
\[
\overline{U} W_\mu D \rightarrow \overline{U}' V_U^+ W_\mu V_D D = \overline{U}' W_\mu V_U^+ V_D D'
\]

Cabibbo-Kobayashi-Maskawa mixing matrix

\[
K = V_U^+ V_D
\]

The (only) source of flavour mixing in the SM

Unitarity: $K^+ K = 1$
CKM Matrix and Unitarity Triangle

Two important properties

1. CP-violation due to a complex phase $\delta$!
2. Unitarity triangle

\[ K = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix} =
\begin{pmatrix}
c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{i\delta} \\
-s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\
s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13}
\end{pmatrix} \]

\[ V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \]

\[ \Rightarrow V_{ub}^* + V_{td} = s_{12}V_{cb}^* \]
The Unitarity Triangle: all constraints

A consistent picture across a huge array of measurements
**Flavor Physics**

- **CKM and CPV**
  - $|V_{cb}|$ puzzle resolved (not $|V_{ub}|$)
  - new $\gamma$ ($\varphi_3$) from LHCb

- CKM and CPV
  
  - $B \to \pi\pi, \rho\rho$
  - $B \to D^{(*)} K^{(*)}$
  - $B \to J/\psi K_s$
  - $B_s \to J/\psi \Phi$
  - $K \to \pi\nu$ anti-$\nu$

**P. Urquijo**

**E. Waheed**

**S. Rahatlou**

*ICHEP 2018, Seoul (7/11/18)*
Extraordinary agreement between measurements and SM predictions
• With the Higgs Boson discovery the Standard Model is completed!
• Why are we not satisfied and think that new physics exists and new discoveries will come?
• With the Higgs Boson discovery the Standard Model is completed!
• Why are we not satisfied and think that new physics exists and new discoveries will come?

• There are conceptional problems which require a critical view beyond the SM
• There are small discrepancies which might grow up to become a problem for the SM
• It is hard to believe that the quest for the miracle of Nature is over
THE OPEN QUESTIONS
THE OPEN QUESTIONS

Why’s?
THE OPEN QUESTIONS

Why’s?

why the SU(3) x SU(2) x U(1)?
THE OPEN QUESTIONS

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- why the SU(3) x SU(2) x U(1) ?
- why 3 generations ?
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- why $V-A$ weak interaction?
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### THE OPEN QUESTIONS

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- why the SU(3)×SU(2)×U(1)?
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- etc

#### How’s?
THE OPEN QUESTIONS

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- why the SU(3)xSU(2)xU(1)?
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- etc

How’s?

- how confinement actually works?
THE OPEN QUESTIONS

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How’s?

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Is it self consistent?
- Does it describe all experimental data?
- Are there any indications for physics beyond the SM?
- Is there another scale except for EW and Planck?
- Is it compatible with Cosmology? Where is dark matter?
The Standard Model of Fundamental Interactions

- Higgs Sector
- Neutrino Sector
- Flavour Sector
- Dark Matter

New particles and Interactions
Higgs bosons - entering precision era

Run-2 analyses with 80 fb$^{-1}$ for the first time – higher precision is coming!
The electroweak vacuum is unstable under radiative corrections.

The whole construction of the SM may be in trouble being metastable or even unstable.

The situation crucially depends on the top and Higgs mass values and requires severe fine-tuning and high accuracy of calculations (3 loops).
Muon anomalous magnetic moment

\[ \frac{ie\bar{u}_\ell(p')}{2m_\ell} \left[ \gamma^\mu - \frac{a_\ell}{2m_\ell} i\sigma^{\mu\nu} q_\nu \right] u_\ell(p) \epsilon^*_\mu, \quad q_\mu = (p - p')_\mu \]

Dirac equation predicts \( g = 2 \)

\[ a = \frac{(g - 2)}{2} \]

For electron \( a_e \) theory and experiment agrees!

\[ a^{th}_{\mu} - a^{exp}_{\mu} = -(3.06 \pm 0.76) \times 10^{-8} \quad 4\sigma \]

Theory: uncertainty in hadronic contributions to the muon \( g - 2 \), (Jägerlehner, 1802.08019). Lattice QCD great progress light-by-light study (RBC & UKQCD, 1801.07224).

Fermilab and J-Park experiments are expected to clarify existing discrepancy!
Discrepancy might dissolve and might as well grow up
A light boson could in principle rule its self-interaction and the Yukawa interactions with fermions in such a way that the theory could remain weakly coupled up to the Planck scale without any dynamics appearing beyond the EW scale. This would be in itself an outstanding discovery: for the first time we would have seen a phenomenon that could be described by the same theory over 15 orders of magnitude in energy.

POSSIBLE PHYSICS BEYOND THE STANDARD MODEL

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A 125GeV boson is a very special object.

**IS THERE ANOTHER SCALE EXCEPT FOR EW AND PLANCK?**

Planck

you are here

EW

would like to get to here

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\[ \Lambda_{QCD} \]

you are here

EW

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IS THERE ANOTHER SCALE EXCEPT FOR EW AND PLANK?

String scale ~ $10^{18}$ GeV

Planck scale ~ $10^{19}$ GeV

Planck
A light boson, could in principle rule its self-interaction and the Yukawa interactions with fermions in such a way that the theory could remain weakly coupled up to the Planck scale without any dynamics appearing beyond the EWK scale. This would be in itself an outstanding discovery: for the first time we would have seen a phenomenon that could be described by the same theory over 15 orders of magnitude in energy.

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$\Lambda_{QCD}$

you are here

EW

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Planck

GUT scale $\sim 10^{16}$ GeV

String scale $\sim 10^{18}$ GeV

Planck scale $\sim 10^{19}$ GeV

Possible Physics Beyond the Standard Model
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\[\text{you are here} \]
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**Planck**

**Planck scale ~ 10^{19} GeV**

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**Majorana scale ~ 10^{12} GeV**

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you are here

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would like to get to here

Planck

SUSY

IS THERE ANOTHER SCALE EXCEPT FOR EW AND PLANK?

\[ \text{Vacuum Stab} \sim 10^1 \text{GeV} \]

\[ \text{Majorana scale} \sim 10^{12} \text{GeV} \]

\[ \text{GUT scale} \sim 10^{16} \text{GeV} \]

\[ \text{String scale} \sim 10^{18} \text{GeV} \]

\[ \text{Planck scale} \sim 10^{19} \text{GeV} \]
THE WAYS BEYOND
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Extension of symmetry group of the SM: SUSY, GUT, new U(1)'s

-> may solve the problem of Landau pole, the problem of stability,
the hierarchy problem, may give the DM particle
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- Additional particles: Extra generations, extra gauge bosons, extra Higgs bosons, extra neutrinos, etc
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- New paradigm beyond local QFT: string theory, brane world, etc
  -> main task is unification with gravity and construction of quantum gravity
NEW SYMMETRIES

Supersymmetry is an extension of the Poincare symmetry of the SM
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**Poincare Algebra**

\[
\begin{align*}
[P_\mu, P_\nu] &= 0, \\
[P_\mu, M_\rho\sigma] &= i(g_{\mu\rho}P_\sigma - g_{\mu\sigma}P_\rho), \\
[M_{\mu\nu}, M_\rho\sigma] &= i(g_{\nu\rho}M_{\mu\sigma} - g_{\nu\sigma}M_{\mu\rho} - g_{\mu\rho}M_{\nu\sigma} + g_{\mu\sigma}M_{\nu\rho})
\end{align*}
\]
POSSIBLE PHYSICS BEYOND THE STANDARD MODEL

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SUPERSYMMETRY

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\end{align*}
\]

Super Poincare Algebra

\[
\begin{align*}
[Q^i_\alpha, P_\mu] &= [\bar{Q}^i_\dot{\alpha}, P_\mu] = 0, \\
[Q^i_\alpha, M_{\mu\nu}] &= \frac{1}{2}(\sigma_{\mu\nu})^\beta_\alpha Q^i_\beta, \\
[\bar{Q}^i_\dot{\alpha}, M_{\mu\nu}] &= -\frac{1}{2} \bar{Q}^i_\dot{\beta}(\bar{\sigma}_{\mu\nu})^\dot{\beta}_\dot{\alpha}, \\
\{Q^i_\alpha, Q^j_\beta\} &= 2\delta^{ij}(\sigma^\mu)^\alpha_\beta P_\mu, \\
\{Q^i_\alpha, \bar{Q}^j_\dot{\beta}\} &= 2\epsilon_{\alpha\dot{\beta}} Z^{ij}, \\
\{\bar{Q}^i_\dot{\alpha}, \bar{Q}^j_\dot{\beta}\} &= -2\epsilon_{\dot{\alpha}\dot{\beta}} Z^{ij}, \\
\{Z_{ij}, anything\} &= 0,
\end{align*}
\]

\(\alpha, \dot{\alpha} = 1, 2 \quad i, j = 1, 2, \ldots, N.\)
NEW SYMMETRIES

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[P_\mu, P_\nu] = 0, \\
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Super Poincare Algebra

\[
Q_i, \bar{Q}_i
\]

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[Q_\alpha, P_\mu] = [\bar{Q}_{\dot{\alpha}}, P_\mu] = 0, \\
[Q_\alpha, M_{\mu\nu}] = \frac{1}{2}(\sigma_{\mu\nu})_\beta^\alpha Q^i_\beta, \\
[\bar{Q}_{\dot{\alpha}}, M_{\mu\nu}] = -\frac{1}{2} \bar{Q}_{\dot{\beta}}^i (\bar{\sigma}_{\mu\nu})_{\dot{\alpha}}, \\
\{Q^i_\alpha, Q^j_\beta\} = 2\delta^{ij}(\sigma_\mu)^{\alpha\beta}P_\mu, \\
\{Q^i_\alpha, Q^j_\beta\} = 2\epsilon_{\alpha\beta}Z^{ij}, \quad Z^{ij} = Z^{ij}_+, \\
\{\bar{Q}_{\dot{\alpha}}, \bar{Q}_{\dot{\beta}}\} = -2\epsilon_{\dot{\alpha}\dot{\beta}}Z^{ij}, \quad [Z_{ij}, \text{anything}] = 0, \\
\alpha, \dot{\alpha} = 1, 2 \quad i, j = 1, 2, \ldots, N.
\]
Chiral multiplet $N = 1$, $\lambda = 0$

<table>
<thead>
<tr>
<th>helicity</th>
<th>-1/2</th>
<th>0</th>
<th>1/2</th>
</tr>
</thead>
<tbody>
<tr>
<td># of states</td>
<td>1</td>
<td>2</td>
<td>1</td>
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</table>

$(\varphi, \psi)$

SUSY MULTIPLETS
SUSY MULTIPLETS

Chiral multiplet $\mathcal{N} = 1, \, \lambda = 0$

Vector multiplet $\mathcal{N} = 1, \, \lambda = 1/2$
### SUSY MULTIPLETS

<table>
<thead>
<tr>
<th>Multiplet</th>
<th>$N$</th>
<th>$\lambda$</th>
<th>Helicity</th>
<th># of States</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chiral multiplet</td>
<td>$1$</td>
<td>$0$</td>
<td>$-1/2$</td>
<td>$1$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$0$</td>
<td>$2$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$1/2$</td>
<td>$1$</td>
</tr>
<tr>
<td>Vector multiplet</td>
<td>$1$</td>
<td>$1/2$</td>
<td>$-1$</td>
<td>$1$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$-1/2$</td>
<td>$1$</td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$1$</td>
<td>$1$</td>
</tr>
</tbody>
</table>

**Scalar**: $(\phi, \psi)$

**Spinor**: $(\lambda, A^\mu)$

**Spinor**: $(\lambda, A_\mu)$

**Vector**: $(\phi, \psi)$
**SUSY MULTIPLETS**

<table>
<thead>
<tr>
<th>Chiral multiplet</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Helicity</td>
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</tr>
<tr>
<td># of states</td>
<td>$1$, $2$, $1$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Vector multiplet</th>
<th>$\mathcal{N} = 1$, $\lambda = 1/2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helicity</td>
<td>$-1$, $-1/2$, $1/2$, $1$</td>
</tr>
<tr>
<td># of states</td>
<td>$1$, $1$, $1$, $1$</td>
</tr>
</tbody>
</table>

Members of a supermultiplet are called superpartners.
SUSY MULTIPLETS

Chiral multiplet \( N = 1, \lambda = 0 \)
- helicity: -1/2, 0, 1/2
- # of states: 1, 2, 1

Vector multiplet \( N = 1, \lambda = 1/2 \)
- helicity: -1, -1/2, 1/2, 1
- # of states: 1, 1, 1, 1

Members of a supermultiplet are called superpartners

Extended supersymmetry
SUSY MULTIPLETS

Chiral multiplet $N = 1, \lambda = 0$

Vector multiplet $N = 1, \lambda = 1/2$

Members of a supermultiplet are called superpartners

Extended supersymmetry

<table>
<thead>
<tr>
<th>$N=4$</th>
<th>SUSY YM</th>
<th>helicity</th>
<th>$-1$ $-1/2$ $0$ $1/2$ $1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda = -1$</td>
<td># of states</td>
<td>$1$ $4$ $6$ $4$ $1$</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$N=8$</th>
<th>SUGRA</th>
<th>helicity</th>
<th>$-2$ $-3/2$ $-1$ $-1/2$ $0$ $1/2$ $1$ $3/2$ $2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda = -2$</td>
<td># of states</td>
<td>$1$ $8$ $28$ $56$ $70$ $56$ $28$ $8$ $1$</td>
<td></td>
</tr>
</tbody>
</table>
SUSY MULTIPLETS

Chiral multiplet \( N = 1, \lambda = 0 \)

<table>
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<tr>
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Vector multiplet \( N = 1, \lambda = 1/2 \)

<table>
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<tr>
<th>helicity</th>
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<th>-1/2</th>
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Extended supersymmetry

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<th>( N=8 ) SUGRA</th>
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<th>-2</th>
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<th>-1/2</th>
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<td>56</td>
<td>28</td>
<td>8</td>
<td>1</td>
</tr>
</tbody>
</table>

\( N \leq 4 S \) spin

\( N \leq 4 \) For renormalizable theories (YM)

\( N \leq 8 \) For (super)gravity
Bosons and Fermions come in pairs

\[
(\varphi, \psi) \quad (\tilde{\lambda}, A_\mu) \quad (\tilde{g}, g)
\]

Spin 0 \quad Spin 1/2 \quad Spin 1/2 \quad Spin 1 \quad Spin 3/2 \quad Spin 2
Bosons and Fermions come in pairs

\[(\varphi, \psi) \quad (\tilde{\lambda}, A_\mu) \quad (\tilde{g}, g)\]

Spin 0 \quad Spin 1/2 \quad Spin 1/2 \quad Spin 1 \quad Spin 3/2 \quad Spin 2

scalar
Bosons and Fermions come in pairs

\[(\varphi, \psi) \quad (\tilde{\lambda}, A_\mu) \quad (\tilde{g}, g)\]

Spin 0  Spin 1/2  Spin 1/2  Spin 1  Spin 3/2  Spin 2

scalar  chiral  fermion
Bosons and Fermions come in pairs

\((\varphi, \psi)\)  \((\tilde{\lambda}, A_\mu)\)  \((\tilde{g}, g)\)

Spin 0  Spin 1/2  Spin 1/2  Spin 1  Spin 3/2  Spin 2

Scalar  Chiral Fermion  Majorana Fermion
Bosons and Fermions come in pairs

\[(\varphi, \psi) \quad (\tilde{\lambda}, A_\mu) \quad (\tilde{g}, g)\]

Spin 0 \quad Spin 1/2 \quad Spin 1/2 \quad Spin 1 \quad Spin 3/2 \quad Spin 2

scalar \quad chiral fermion \quad majorana fermion \quad vector
Bosons and Fermions come in pairs

\[(\varphi, \psi) \quad (\tilde{\lambda}, A_\mu) \quad (\tilde{g}, g)\]

Spin 0  Spin 1/2  Spin 1/2  Spin 1  Spin 3/2  Spin 2

scalar  chiral  majorana  vector  gravitino  fermion  fermion  fermion
Bosons and Fermions come in pairs

\[(\varphi, \psi) \quad (\tilde{\lambda}, A_\mu) \quad (\tilde{g}, g)\]

Spin 0  Spin 1/2  Spin 1/2  Spin 1  Spin 3/2  Spin 2

Scalar  Chiral fermion  Majorana fermion  Vector  Gravitino  Graviton
Supersymmetry is a dream of a unified theory of all particles and interactions
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Why SUSY?
Supersymmetry is a dream of a unified theory of all particles and interactions.

Why SUSY?

Unification with gravity!
Supersymmetry is a dream of a unified theory of all particles and interactions

**Why SUSY?**

- Unification with gravity!
- Unification of the gauge couplings
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- Provided the DM particle
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Why SUSY?

- Unification with gravity!
- Unification of the gauge couplings
- Solution of the hierarchy problem
- Explanation of the EW symmetry violation
- Provided the DM particle

Local supersymmetry = general relativity!
$R = (-)^{3(B-L)+2S}$

The Usual Particle: $R = +1$

SUSY Particle: $R = -1$

B - Baryon Number
L - Lepton Number
S - Spin
The R-parity

\[ R = (-1)^{3(B-L)+2S} \]

The Usual Particle: \( R = +1 \)
SUSY Particle: \( R = -1 \)

B - Baryon Number
L - Lepton Number
S - Spin

The consequences:

- The superpartners are created in pairs
- The lightest superparticle is stable
THE R-PARITY

The Usual Particle: \( R = +1 \)
SUSY Particle: \( R = -1 \)

\[ R = (-)^{3(B-L)+2S} \]

The consequences:

• The superpartners are created in pairs
• The lightest superparticle is stable

• The lightest superparticle (LSP) should be neutral - the best candidate \( \sim \) is neutralino (photino or higgsino) \( \chi_0 \)
• It can survive from the Big Bang and form the Dark matter in the Universe

B - Baryon Number
L - Lepton Number
S - Spin
THE INTERACTIONS IN THE MSSM
THE INTERACTIONS IN THE MSSM

SM \rightarrow \text{MSSM}

Vertices

$-ie_q \gamma_\mu$

$-ie_q (p + p')_\mu$

$-ie_q \frac{1 \pm \gamma_5}{\sqrt{2}}$
THE INTERACTIONS IN THE MSSM
THE INTERACTIONS IN THE MSSM

Vertices

SM \rightarrow MSSM

- $\gamma$: $-ie_g \gamma_\mu$
- $q \bar{q}$: $-ie_g (p + p')_\mu$
- $g$: $ig_s f^{abc}$
- $H_2$: $QL yU \rightarrow U_R$
- $\tilde{H}_2$: $QL \rightarrow U_R$

Rigid

Soft

Rigid
CREATION AND DECAY OF SUPERPARTNERS IN CASCADE PROCESSES @ LHC

 Typical SUSY signature: Missing Energy and Transverse Momentum
CREATION AND DECAY OF SUPERPARTNERS
IN CASCADE PROCESSES @ LHC

Typical SUSY signature: Missing Energy and Transverse Momentum
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Typical SUSY signature: Missing Energy and Transverse Momentum
THE DECAY OF SUPERPARTNERS

**squarks**

\[ \tilde{q}_{L,R} \rightarrow q + \chi_i \]
\[ \tilde{q}_L \rightarrow q' + \chi_i \]
\[ \tilde{q}_{L,R} \rightarrow q + g \]

**sleptons**

\[ \tilde{l} \rightarrow l + \chi_i \]
\[ \tilde{l}_L \rightarrow \nu_l + \chi_i \]

**chargino**

\[ \tilde{\chi}_i^{\pm} \rightarrow e + \nu_e + \chi_i \]
\[ \tilde{\chi}_i^{\pm} \rightarrow q + q' + \chi_i \]

**gluino**

\[ \tilde{g} \rightarrow q + q + \gamma \]
\[ \tilde{g} \rightarrow g + \gamma \]

**neutralino**

\[ \tilde{\chi}_i^0 \rightarrow \tilde{\chi}_1^0 + l^+ + l^- \]
\[ \tilde{\chi}_i^0 \rightarrow \tilde{\chi}_1^0 + q + q' \]
\[ \tilde{\chi}_i^0 \rightarrow \tilde{\chi}_1^0 + l^\pm + \nu_l \]
\[ \tilde{\chi}_i^0 \rightarrow \tilde{\chi}_1^0 + \nu_l + \nu_l \]

**Final states**

\[ l^+ l^- + E_T \]
\[ 2 \text{ jets } + E_T \]
\[ \gamma + E_T \]
\[ E_T \]
SOFT BUSY BREAKING

MSSM

Messengers

Gravitons, gauge, gauginos, etc

Breaking via F and D terms in a hidden sector
SOFT BUSY BREAKING

Hidden sector

SUSY

Messengers

Gravitons, gauge, gauginos, etc

Breaking via F and D terms in a hidden sector

\[-L_{\text{Soft}} = \sum_{\alpha} M_i \tilde{\lambda}_i \tilde{\lambda}_i + \sum_i m_{0i}^2 \left| A_i \right|^2 + \sum_{ijk} A_{ijk} A_i A_j A_k + \sum_{ij} B_{ij} A_i A_j\]

gauginos
.scalar fields
SOFT BUSY BREAKING

**MSSM**

Hidden sector

Messengers

Gravitons, gauge, gauginos, etc

Breaking via F and D terms in a hidden sector

\[-L_{\text{Soft}} = \sum_{\alpha} M_i \tilde{\lambda}_i \tilde{\lambda}_i + \sum_i m_{0i}^2 |A_i|^2 + \sum_{ijk} A_{ijk} A_i A_j A_k + \sum_{ij} B_{ij} A_i A_j\]

Over 100 of free parameters!
SUSY Models and Signatures

usual\ mSUGRA
\[ m_0 \ m_{1/2} \ A_0 \]
\[ \tan \beta \ \text{sign}(\mu) \]

- generic squarks and gluinos
- sbottom and stop might be light
- gauginos $\rightarrow$ leptons

split SUSY
- gluino metastable

mSUGRA RPV
- R-parity violated

- stopping gluinos, gluinos $\tilde{g}$ long lived
- form `R hadrons`
- lepton-lepton couplings
- lepton-quark couplings

GMSB
- LSP = light gravitino

- photons + missing energy

- AMSB
- mass degeneracies

- long lived heavy charged particles
- decay inside detector
- Mirage unification
SUSY Models and Signatures

- **usual** mSUGRA:
  - $m_0$, $m_{1/2}$, $A_0$
  - $\tan \beta$, sign($\mu$)

- **split SUSY**
  - gluino metastable

- **NMSSM = MSSM + Singlet**
  - 3 light Higgses around 125 GeV
  - Heavy Higgs decay $H \rightarrow h_1 h_2$

- **GMSB**
  - LSP = light gravitino

- **AMSB**
  - mass degeneracies

Generic squarks and gluinos

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Gauginos $\rightarrow$ leptons

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Gluinons $\tilde{g}$ long lived

Form $\tilde{R}$ hadrons

- 3 light Higgses around 125 GeV
- Heavy Higgs decay $H \rightarrow h_1 h_2$

- Photons $+$ missing energy

- NLSP $= \tilde{\chi}^0_1 \rightarrow \gamma \tilde{G}$

- Long lived heavy charged particles

Decay inside detector

Mirage unification
Particle Phys
Direct production at colliders at high energies
Direct production at colliders at high energies
Indirect manifestation at low energies
Direct production at colliders at high energies
Indirect manifestation at low energies
Rare decays (\( B_s \rightarrow s\gamma, \ B_s \rightarrow \mu^+\mu^-, \ B_s \rightarrow \tau\nu \))
Direct production at colliders at high energies
Indirect manifestation at low energies
Rare decays (\( B_s \rightarrow s\gamma \), \( B_s \rightarrow \mu^+\mu^- \), \( B_s \rightarrow \tau\nu \))
g-2 of the muon
**SEARCH FOR SUSY MANIFESTATION**

- **Direct production at colliders at high energies**
- **Indirect manifestation at low energies**
  - Rare decays: $B_s \rightarrow s\gamma$, $B_s \rightarrow \mu^+\mu^-$, $B_s \rightarrow \tau\nu$
  - $g$-2 of the muon
- **Search for long-lived SUSY particles**
Rare decays (\(g-2\) of the muon)

Direct production at colliders at high energies

Indirect manifestation at low energies

Rare decays (\(B_s \rightarrow s\gamma, B_s \rightarrow \mu^+\mu^-, B_s \rightarrow \tau\nu\))

g-2 of the muon

Search for long-lived SUSY particles

SEARCH FOR SUSY MANIFESTATION
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Particle Phys

- Direct production at colliders at high energies
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Astro Phys (if SUSY DM)

- Relic abundance of Dark Matter in the Universe
### SEARCH FOR SUSY MANIFESTATION

#### Particle Phys
- Direct production at colliders at high energies
- Indirect manifestation at low energies
- Rare decays ($B_s \rightarrow s\gamma$, $B_s \rightarrow \mu^+\mu^-$, $B_s \rightarrow \tau\nu$)
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- Relic abundancy of Dark Matter in the Universe
- DM annihilation signal in cosmic rays
SEARCH FOR SUSY MANIFESTATION

**Particle Phys**
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- Direct production at colliders at high energies
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  - Rare decays ($B_s \rightarrow s\gamma$, $B_s \rightarrow \mu^+\mu^-$, $B_s \rightarrow \tau\nu$)
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- Search for long-lived SUSY particles

Astro Phys (if SUSY DM)

- Relic abundancy of Dark Matter in the Universe
- DM annihilation signal in cosmic rays
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Nothing so far ...
WHAT IS THE LHC REACH NOW?
WHAT IS THE LHC REACH NOW?

Universal parameters
WHAT IS THE LHC REACH NOW?

Universal parameters

$\tilde{t}\tilde{t}$

Masses of superpartners

$M_{\tilde{t}, \tilde{g}} > 950$ GeV

$\tilde{g} \rightarrow t\bar{t} \tilde{\chi}_1^0$

$\tilde{g} \rightarrow tt \tilde{\chi}_1^0$
Gluino decays to $qq+$LSP

**Summary of decays to light quarks + LSP**

- **ATLAS-CONF-2016-078**
- **CMS-SUS-16-014**
- **CMS-SUS-16-015**

**Other results**
- **ATLAS-CONF-2016-037**

**Top squarks - summaries**

- **ATLAS summary**
- **CMS summary**
- **ATLAS multi-b**
  - **ATLAS-CONF-2016-052**
Gluino decays to qq+LSP

Summary of decays to light quarks + LSP

Gluino decays to tt+LSP

CMS summary

ATLAS multi-b

Top squarks - summaries

• SUSY limits for strong int’s are pushed above 1 TeV
Gluino decays to $qq+\text{LSP}$

Summary of decays to light quarks + LSP

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Top squarks - summaries

- SUSY limits for strong int’s are pushed above 1 TeV
- This already requires fine tuning - little hierarchy prob
Gluino decays to $qq+\text{LSP}$

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**CMS-SUS-16-014**

**CMS-SUS-16-015**

**Top squarks - summaries**

• SUSY limits for strong int’s are pushed above 1 TeV

• This already requires fine tuning - little hierarchy prob

• No guiding lines

**SUPERSYMMETRY @ LHC**
Chargino / neutralino production

Direct production of “electroweakino” pairs

• decays via sleptons / sneutrinos
• using benchmarks to illustrate different scenarios
  (depend on mixings and nature of lightest slepton)

Effect of change in intermediate slepton mass

3l + same-sign 2l
Chargino / neutralino production

Direct production of “electroweakino” pairs
- decays via sleptons / sneutrinos
- using benchmarks to illustrate different scenarios
  (depend on mixings and nature of lightest slepton)

No light EWkinos

Effect of change in intermediate slepton mass

3l + same-sign 2l
WHERE ARE WE NOW?

Strong production (gluinos, squarks)

EWK production (charginos, neutralinos, sleptons)
SUSY is certainly a compelling candidate of BSM physics, so we should keep searching for her without leaving any stone unturned.

* Taking the gauge coupling unification seriously, SUSY may have some chance to be seen at LHC, and a good chance at the FCC:

**FUTURE SUSY SEARCHES**

High luminosity LHC

[Graph 1: Susy discovery at 100 TeV collider](image)

100 TeV collider

Kiwoon Choi (ICHEP 2016, Chicago)
Unification of strong, weak and electromagnetic interactions within Grand Unified Theories is a new step in unification of all forces of Nature.

Creation of a unified theory of everything based on string paradigm seems to be possible.
POSSIBLE PHYSICS BEYOND THE STANDARD MODEL

NEW SYMMETRIES

GRAND UNIFICATION
Grand Unification is an extension of the Gauge symmetry of the SM
**NEW SYMMETRIES**

**GRAND UNIFICATION**

Grand Unification is an extension of the Gauge symmetry of the SM

\[
\begin{array}{ccc}
SU_c(3) & SU_L(2) & U_Y(1) \\
gluons & W, Z & photon \\
quarks & leptons & \\
g_3 & g_2 & g_1 \\
\Rightarrow & \Rightarrow & \Rightarrow \\
G_{GUT} \text{ (or } G^n + \text{discrete symmetry)} & \text{gauge bosons} & g_{GUT}
\end{array}
\]
NEW SYMMETRIES


GRAND UNIFICATION

Grand Unification is an extension of the Gauge symmetry of the SM

\[
SU_c(3) \otimes SU_L(2) \otimes U_Y(1) \Rightarrow G_{GUT} \quad (or \quad G^n + \text{discrete symmetry})
\]

Low energy

\[
\begin{align*}
g_3 \\
g_2 \\
g_1
\end{align*}
\]

⇒ High energy

\[
\begin{align*}
g_{GUT}
\end{align*}
\]

Unification of gauge couplings

\[
\frac{1}{\alpha_i(t)} = \frac{1}{\alpha_3(t)} + \frac{1}{\alpha_2(t)} + \frac{1}{\alpha_1(t)}
\]

\[
t = \ln\left(\frac{Q^2}{M_Z^2}\right)
\]

\[
\text{GeV}
\]

\[
10^2 \quad 10^6 \quad 10^9
\]
GRAND UNIFICATION

Grand Unification is an extension of the Gauge symmetry of the SM

\[ SU_c(3) \otimes SU_L(2) \otimes U_Y(1) \Rightarrow G_{GUT} \quad (\text{or } G^n \text{ + discrete symmetry}) \]

\[ g_3 \quad g_2 \quad g_1 \Rightarrow g_{GUT} \]

\[ SU(3) \times SU(2) \times U(1) \subset G_{GUT} \]

\[ Ex: SU(5), SO(10), E(6), SU(5) \times U(1), SU(4) \times SU(2) \times SU(2), SO(10) \times U(1) \]
SU(5) - Minimal GUT

Gauge fields

\[ 24 = \begin{pmatrix} 8, 1 \\ 1 \end{pmatrix} + \begin{pmatrix} 1, 3 \\ 3 \end{pmatrix} + \begin{pmatrix} 3, 2 \\ 2 \end{pmatrix} + \begin{pmatrix} 3, 2 \\ 2 \end{pmatrix} \]

- Gluons
- W and Z
- Leptoquarks

\[ SU(5) : \bar{5} + 10 + 1 \]

\[ \bar{5}^* = (d_1^c, d_2^c, d_3^c, e^-, \nu_e)_{Left} \]

\[ 10 = \begin{pmatrix} 0 & u_3^c & -u_2^c & u_1 & d_1 \\ 0 & u_1^c & u_2 & d_2 \\ 0 & u_3 & d_3 & e^+ \\ 0 & 0 & 0 & 1 \end{pmatrix} \]

\[ 1 = \nu_L^c \]
SU(5) - Minimal GUT

Gauge fields

\[ 24 = (8,1) + (1,3) + (3,2) + (3,2) \]

Glueons, W and Z, leptoquarks

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0 & 0
\end{pmatrix} \]

1 = \nu^c_L

SO(10) - Optimal GUT
GUT MODELS

SU(5) - Minimal GUT

Gauge fields

\[ \begin{align*}
24 &= (8,1)_{\text{gluons}} + (1,3)_{\text{W and Z}} + (3,2)_{\text{leptoquarks}} \\
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\end{align*} \]

\[ \overline{5}^* = (d^c_1, d^c_2, d^c_3, e^-, \nu_e)_{\text{Left}} \quad 10 = \begin{pmatrix}
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0 & u^c_1 & u^c_2 & u_2 & d_2 \\
0 & u_3 & d_3 & e^+ & 0
\end{pmatrix}_{\text{Left}} \]

SO(10) - Optimal GUT

Matter fields - just one representation

\[ \begin{align*}
16 &= (u_1 \ u_2 \ u_3 \ d_1 \ d_2 \ d_3 \ \nu_e \ e^- \ u^c_1 \ u^c_2 \ u^c_3 \ d^c_1 \ d^c_2 \ d^c_3 \ \nu^c_e \ e^+)_{\text{Left}} \\
SU(5) \text{ decomposition:} \quad &16 = \overline{5}^* + 10 + 1 \quad \text{fermions,} \\
&45 = 24 + 10 + 10^* + 1 \quad \text{gauge bosons}
\end{align*} \]
GUT symmetry is broken spontaneously by Brout-Englert-Higgs Mechanism
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SU(5)
GUT SYMMETRY BREAKING

GUT symmetry is broken spontaneously by Brout-Englert-Higgs Mechanism

**SU(5)**

Higgs Multiplets

\[
\begin{array}{c}
SU(5) \xrightarrow{\Sigma} SU(3) \times SU(2) \times U(1) \xrightarrow{H} SU(3) \times U(1)
\end{array}
\]

\[
< \Sigma_{24} >= \begin{pmatrix}
V & V \\
V & V \\
-3/2 V & -3/2 V
\end{pmatrix}
\]

\[
V \sim 10^{15} \text{ GeV}
\]

\[
< H_5 >= \begin{pmatrix}
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v/\sqrt{2}
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\[ v \sim 10^2 \text{ GeV} \]

SO(10)

Higgs Multiplets

16 or 126; 45 or 54 or 210

\[ SO(10) \xrightarrow{M_1} SU(5) \xrightarrow{M_2} SU(3) \otimes SU(2) \otimes U(1) \xrightarrow{M_W} SU(3) \otimes U(1) \]

\[ SO(6) \otimes SO(4) \sim SU(4) \otimes SU_L(2) \otimes SU_R(2) \]

\[ M_1 \gg M_2 \gg \cdots M_W \]
Solves many problems of the SM:

- absence of Landau pole
- Decreases the number of parameters
- All particles in a single representation (16 of SO(10))
- Unifies quarks and leptons -> spectrum and mixings from «textures»
- A way to B and L violation
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- Proton decay $P \to e^+\pi$, $P \to \bar{\nu}K^+$
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mean life time $> 10^{31} - 10^{33}$ years
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GRAND UNIFICATION

Solves many problems of the SM:
- absence of Landau pole
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- All particles in a single representation (\(16\) of \(SO(10)\))
- Unifies quarks and leptons -> spectrum and mixings from «textures»
- A way to \(B\) and \(L\) violation

\[
\begin{array}{cc}
p^+ & \{d, u, u\} \rightarrow d^+e^+ \pi^0 \\
\chi & \{d, d, u\} \rightarrow \tau^0 \\
\end{array}
\]

- Unification of the gauge couplings
- Stabilization of the hierarchy

Create new problems:
- Hierarchy of scales \(M_W/M_G \sim 10^{-14}\)
- Large Higgs sector is needed for GUT symmetry breaking

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- Proton decay \(P \rightarrow e^+\pi, \quad P \rightarrow \bar{\nu}K^+\)
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- \(|\Delta(B - L)| = 1 (|\Delta(B - L)| = 2)\) processes

Experiment:
mean life time > \(10^{31} - 10^{33}\) years

\[
\tau_{proton} \sim 10^{32} years
\]
\[
\tau_{Universe} \approx 1.4 \times 10^9 years
\]
Crucial points:

- SUSY leads to unification
- SUSY solves the hierarchy problems for GUTs
- No GUT without SUSY
SUSY GUT

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New properties:
- Later unification - higher GUT scale
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- New modes of proton decay
**SUSY GUT**

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---

**SUSY GUTS - Nucleon decay**

(a) Dimension 6.

\[
p \rightarrow \pi^0 + e^+ \quad \tau_{p \rightarrow e^+\pi^0} > 1 \times 10^{34} \text{ yrs}, \quad M_X > 10^{16} \text{ GeV}
\]

(b) Dimension 5.

\[
p \rightarrow K^+ + \bar{\nu} \quad \tau_{p \rightarrow K^+\bar{\nu}} > 3.3 \times 10^{33} \text{ yrs}
\]
NEW SYMMETRIES

- Appear in some GUT models
- Inspired by string models
NEW SYMMETRIES

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- Inspired by string models

Used as possible BSM signal with energetic single jet or dijet events

EXTRA U(1)', SU(2)'

- Extra symmetries that may signal physics beyond the Standard Model.
- Inspired by GUT models and string theory.
- Can manifest as energetic single jets or dijets in high-energy experiments.
NEW SYMMETRIES

- Appear in some GUT models
- Inspired by string models

Used as possible BSM signal with energetic single jet or dijet events

EXTRA U(1)', SU(2)'

Used as possible Dark matter candidate - Dark photon

Mixture of a usual EM U(1) photon and a new U(1)' one

\[ \mathcal{L} \sim F_{\mu \nu} F'_{\mu \nu} \]

Dedicated experiment to look for conversion of a usual photon into a dark one
NEW SYMMETRIES

Experiment

• Search for Z’ (Di-muon events)
• Search for W’ (single muon/ jets)
• Search for resonance decaying to t-tbar
• Search for diboson resonances
• Monojets + invisible
NEW SYMMETRIES

Experiment

**Same Flavor Opposite Sign (ee, μμ, ττ)**

![Graph showing ee data with limits](image1)

**Same Sign (ee, μμ)**

- $Z_{SM} (3\%$ width) $>4$ TeV
- $Z' (0.5\%$ width) $>3.36$ TeV

![Graph showing ee data with limits](image2)

**Additional Gauge Bosons**

- Search for $Z'$ (Di-muon events)
- Search for $W'$ (single muon/ jets)
- Search for resonance decaying to $t\bar{t}$
- Search for diboson resonances
- Monojets + invisible
NEW SYMMETRIES

ADDITIONAL GAUGE BOSONS

- Search for Z’ (Di-muon events)
- Search for W’ (single muon/ jets)
- Search for resonance decaying to t-tbar
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POSSIBLE PHYSICS BEYOND THE STANDARD MODEL

NEW SYMMETRIES

Experiment

<table>
<thead>
<tr>
<th>Same Flavor Opposite Sign (ee, μμ, ττ)</th>
<th>ATLAS CONF-2016-045</th>
<th>CMS PAS EXC-16-031</th>
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<tbody>
<tr>
<td>ee</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2016

Same Sign (ee, μμ) | Z_{3SM} (3% width) > 4 TeV | Z' (0.5% width) > 3.36 TeV |
<table>
<thead>
<tr>
<th></th>
<th></th>
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<tbody>
<tr>
<td>ATLAS CONF-2016-051</td>
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2016

- Search for Z’ (Di-muon events)
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No indication so far - experimental limits on Z’ and W’ masses around few TeV
NEW PARTICLES

EXTENDED HIGGS SECTOR
NEW PARTICLES

Is it the SM Higgs boson or not?

EXTENDED HIGGS SECTOR
NEW PARTICLES

Is it the SM Higgs boson or not?
What are the alternatives?
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EXTENDED HIGGS SECTOR

A. Singlet extension
B. Higgs doublet extension
C. Higgs triplet extension
POSSIBLE PHYSICS BEYOND THE STANDARD MODEL

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Custodial symmetry as guiding principle for extensions

\[ \rho = \frac{M_W^2}{M_Z^2 \cos^2 \theta_W} = 1 \]

indicates that an approximate global symmetry exists,
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Thus the Higgs field transforms under

\[ SU(2)_L \times SU(2)_R : \quad \Phi \rightarrow L\Phi R^\dagger \]

For both SU(2)-singlet with \( Y=0 \)

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\[ \rho = \frac{\sum_{i=1}^{n} [I_i(I_i + 1) - \frac{1}{4} Y_i^2]v_i}{\sum_{i=1}^{n} \frac{1}{2} Y_i^2 v_i} \sim 1 \]

For both SU(2)-singlet with $Y=0$
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Any number of singlets and doublets respects custodial
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EXTENDED HIGGS SECTOR

<table>
<thead>
<tr>
<th>Model</th>
<th>Particle content</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM</td>
<td>h CP-even</td>
</tr>
<tr>
<td>2HDM/MSSM</td>
<td>h, H CP-even</td>
</tr>
<tr>
<td></td>
<td>A CP-odd</td>
</tr>
<tr>
<td>NMSSM</td>
<td>H1, H2, H3 CP-even</td>
</tr>
<tr>
<td></td>
<td>A1, A2 CP-odd</td>
</tr>
<tr>
<td>Composite</td>
<td>h CP-even + excited</td>
</tr>
<tr>
<td></td>
<td>states</td>
</tr>
</tbody>
</table>
How to probe?
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- Probe deviations from the SM Higgs couplings
EXTENDED HIGGS SECTOR

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We may have found one of these states
How to probe?

- Probe deviations from the SM Higgs couplings
- Perform direct search for additional scalars

The mass spectrum of the Higgs bosons (GeV)

We may have found one of these states

One has to check the presence or absence of heavy Higgs bosons
ee → HZ  diff. decay channels

→ $b\bar{b}q\bar{q}$

→ $W^+W^- q\bar{q}$

$\Delta m_H = 40$ MeV

$\Delta m_H = 70$ MeV
ee $\rightarrow$ HZ  diff. decay channels

Int Linear Collider

$\rightarrow$ $W^+ W^- q\bar{q}$

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$\rightarrow$ $q\bar{q}\ell^+\ell^-$

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$W^+W^- q\bar{q}$

$W^+W^- e^+e^-$

$\Delta m_H = 40$ MeV

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Coupling Precision

LHC $300$ fb$^{-1} \times 2$

ILC

SUSY or 2HDM
Resonant 95% CL on $\sigma \times \text{BR}(h h \rightarrow \tau \tau)$ \[10^{-2} \text{pb}\]

Resonant $H \rightarrow ZZ \rightarrow 4l$, $m_H = 125 \text{GeV}$

Non-Resonant $H \rightarrow ZZ \rightarrow 4l$, $m_H = 125 \text{GeV}$

Resonant $H \rightarrow ZZ \rightarrow 4l$, $m_H = 125 \text{GeV}$

Non-Resonant $H \rightarrow ZZ \rightarrow 4l$, $m_H = 125 \text{GeV}$

Charged Higgs

Search for $H \rightarrow tb$ $300 < m_H < 1000 \text{ GeV}$

Search for $H \rightarrow WZ$

Heavy Higgs $\rightarrow \tau \tau$

Heavy Higgs $\rightarrow ZZ \rightarrow 4l$
NEW PARTICLES

AXION OR AXION-LIKE PARTICLES

- CP violation in QCD sector: CKM angle $\delta_{13} = 1.2 \pm 0.1$ rad
- AND flavour-neutral phase $\theta = \theta_{QCD} + N_f \delta$

$$\mathcal{L}_{SM} \in -\overline{q}_L \begin{pmatrix} m_u e^{i\delta/2} & 0 & \cdots \\ 0 & m_d e^{i\delta/2} & \cdots \\ 0 & 0 & \cdots \end{pmatrix} \begin{pmatrix} u \\ d \end{pmatrix}_R - \frac{\alpha_s}{8\pi} G \tilde{G} \theta_{QCD}$$

Axial anomaly
NEW PARTICLES

AXION OR AXION-LIKE PARTICLES

Javier Redondo, EPS HEP 2017

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AND flavour-neutral phase $\theta = \theta_{QCD} + N_f \delta$

The $\theta$-angle produces flavour-neutral CP violation like Electric Dipole Moments

- Neutron EDM (Guo 1502.02295)

$d_n = -4 \times 10^{-3} \times \theta$ [e fm]

- Experimental upper limit (Grenoble hep-ex/0602020)

$|d_n| < 3 \times 10^{-13}$ [e fm]

- Why is $\theta < 10^{-10}$?
PECCEI-QUINN MECHANISM - AXION

- Any theory promoting $\theta$ to a dynamical field, $\theta(t, \mathbf{x})$, will dynamically set $\theta \to 0$ after some time...

\[ V(\theta) \]

Potential energy density

- PQ Mechanism: Global $U(1)$ axial symmetry, spontaneously broken, colour anomalous $\rightarrow$ Goldstone boson

\[ \mathcal{L}_\theta = \frac{1}{2} (\partial_\mu \theta) (\partial^\mu \theta) f_a^2 - \frac{\alpha_s}{8\pi} G_{\mu\nu} \tilde{G}^{\mu\nu} \theta \]

New Spontaneous symmetry breaking [energy] scale $f_a$

Canonically normalised $\theta$ field is the QCD AXION! $a(x) = \theta(x) f_a$

generated by QCD non-perturbative dynamics (instantons)

WW Axion
WHAT IS THE MASS TO GET

\[ \Omega_{CDM} h^2 = 0.12 \]

Excluded by Labs+ Astro

Excluded (too much DM)

\[ \theta_I \sim O(1) \]

\[ \sim n \]

\[ m_a [\text{eV}] \]

\[ 10^{-7} \quad 10^{-6} \quad 10^{-5} \quad 10^{-4} \quad 10^{-3} \quad 10^{-2} \quad 10^{-1} \quad 1 \quad 10 \quad 10^2 \quad 10^3 \quad 10^4 \quad 10^5 \quad 10^6 \]

\[ 10^7 \quad 10^8 \quad 10^9 \quad 10^{10} \quad 10^{11} \quad 10^{12} \quad 10^{13} \quad 10^{14} \]

\[ f_a [\text{GeV}] \]

- Less minimal axion models have further possibilities...
Neutrino Physics

<table>
<thead>
<tr>
<th>parameter</th>
<th>best fit ± 1σ</th>
<th>3σ range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m_{21}^2 \times 10^{-5}$ eV$^2$</td>
<td>$7.55^{+0.20}_{-0.16}$</td>
<td>7.05–8.14</td>
</tr>
<tr>
<td>$</td>
<td>\Delta m_{31}^2</td>
<td>\times 10^{-3}$ eV$^2$ (NO)</td>
</tr>
<tr>
<td>$</td>
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<td>\times 10^{-3}$ eV$^2$ (IO)</td>
</tr>
<tr>
<td>$\sin^2 \theta_{12} / 10^1$</td>
<td>$3.20^{+0.20}_{-0.16}$</td>
<td>2.73–3.79</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23} / 10^1$ (NO)</td>
<td>$5.47^{+0.20}_{-0.30}$</td>
<td>4.45–5.99</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23} / 10^1$ (IO)</td>
<td>$5.51^{+0.18}_{-0.30}$</td>
<td>4.53–5.98</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13} / 10^{-2}$ (NO)</td>
<td>$2.160^{+0.083}_{-0.069}$</td>
<td>1.96–2.41</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13} / 10^{-2}$ (IO)</td>
<td>$2.220^{+0.074}_{-0.076}$</td>
<td>1.99–2.44</td>
</tr>
<tr>
<td>$\delta / \pi$ (NO)</td>
<td>$1.32^{+0.21}_{-0.15}$</td>
<td>0.87–1.94</td>
</tr>
<tr>
<td>$\delta / \pi$ (IO)</td>
<td>$1.56^{+0.13}_{-0.15}$</td>
<td>1.12–1.94</td>
</tr>
</tbody>
</table>

de Salas et al, 1708.01186
Neutrino Physics

- Absolute value of neutrino masses?
- Mass hierarchy?
- Dirac or Majorana?
- Fourth sterile neutrino?
- Neutrino dark matter?

---

de Salas et al, 1708.01186
Neutrino Physics

- Absolute value of neutrino masses?
- Mass hierarchy?
- Dirac or Majorana?
- Fourth sterile neutrino?
- Neutrino dark matter?

\[ 0.06 \text{ eV} < \sum m_\nu < 0.12 \text{ eV} \]

PMNS-matrix parameters are measured with high accuracy of few %

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\[ 0.06 \text{ eV} < \sum m_\nu < 0.12 \text{ eV} \]

PMNS-matrix parameters are measured with high accuracy of few %

- Normal hierarchy favoured at 3.1 \( \sigma \)
- Nonzero CP phase favoured
- Upper octant favoured
\[ \nu_D = \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix} \quad \nu_{M_1} = \begin{pmatrix} \xi_1 \\ \xi_1^* \end{pmatrix}, \quad \nu_{M_2} = \begin{pmatrix} \xi_2 \\ \xi_2^* \end{pmatrix} \]
DIRAC OR MAJORANA?

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\nu_D = \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}, \quad \nu_{M_1} = \begin{pmatrix} \xi_1 \\ \xi_1^* \end{pmatrix}, \quad \nu_{M_2} = \begin{pmatrix} \xi_2 \\ \xi_2^* \end{pmatrix}
\]

Mass matrix

\[
\mathcal{M} = \begin{pmatrix} L & R \\ 0 & m_D^* \end{pmatrix} \begin{pmatrix} L \\ m_D \end{pmatrix} = \begin{pmatrix} L & 0 \\ m_D^* & M \end{pmatrix} \begin{pmatrix} L \\ R \end{pmatrix}
\]

Majorana term
**DIRAC OR MAJORANA?**

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\nu_D = \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}, \quad \nu_{M_1} = \begin{pmatrix} \xi_1 \\ \xi_1^* \end{pmatrix}, \quad \nu_{M_2} = \begin{pmatrix} \xi_2 \\ \xi_2^* \end{pmatrix}
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**Mass matrix**

\[
\mathcal{M} = \begin{pmatrix} L & R \\ 0 & m_D \\ m_D^* & M \end{pmatrix}
\]

**Majorana term**

**Mass eigenvalues**

\[
m_1 \approx \frac{m_D^* m_D}{M} \\
m_2 \approx M
\]

Light \quad Heavy
DIRAC OR MAJORANA?

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Light \quad Heavy

\[ \nu_D \neq \nu_D^* \quad m_{\nu_L} = m_{\nu_R} \]
DIRAC OR MAJORANA?

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DIRAC OR MAJORANA?

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\]

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\[\nu_D \neq \nu_D^* \]
\[m_{\nu_L} = m_{\nu_R} \]

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\[m_{\nu_{M1}} \neq m_{\nu_{M2}} \]
BEYOND THE STANDARD MODEL: THE MASS SPECTRUM AND MIXINGS

- Mass spectrum?

\[
\begin{align*}
m_{\text{quark}} &= y_{\text{quark}} \cdot v \\
m_{\text{lepton}} &= y_{\text{lepton}} \cdot v \\
m_{W} &= g/\sqrt{2} \cdot v \\
m_{Z} &= \sqrt{g^2 + g'^2}/\sqrt{2} \cdot v \\
m_{H} &= \sqrt{\lambda} \cdot v \\
m_\gamma &= 0 \\
m_{\text{gluon}} &= 0
\end{align*}
\]

SM

- Mixing Matrices?

- Quark-Lepton Symmetry
- Strong difference in parameters

CKM vs. PMNS

\[
\begin{align*}
\text{CKM} &
\begin{array}{ccc}
d & s & b \\
u_e & & \\
u_\mu & & \\
u_\tau & & \\
\end{array}
\end{align*}
\]

\[
\begin{align*}
\text{PMNS} &
\begin{array}{ccc}
v_1 & v_2 & v_3 \\
u_e & & \\
u_\mu & & \\
u_\tau & & \\
\end{array}
\end{align*}
\]

Why these values? Are the two related? Are they related to masses?

For reference:

- Proton 0.938 GeV
- Originally thought to be massless but now not

These are relative masses not size – they have no measurable size
BEYOND THE STANDARD MODEL: THE MASS SPECTRUM AND MIXINGS

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SM

- Mixing Matrices?

\begin{itemize}
  \item Quark-Lepton Symmetry
  \item Strong difference in parameters
\end{itemize}

- Why these values? Are the two related? Are they related to masses?

- What are the CKM and PMNS phases?

- Where lies the source of CP violation: in quark or lepton sector?
BEYOND THE STANDARD MODEL: THE MASS SPECTRUM AND MIXINGS

• Mass spectrum?

\[ m_{\text{quark}} = y_{\text{quark}} \cdot \nu \]
\[ m_{\text{lepton}} = y_{\text{lepton}} \cdot \nu \]
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• Mixing Matrices?

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• Strong difference in parameters

CKM vs. PMNS

Why these values? Are the two related? Are they related to masses?

• What are the CKM and PMNS phases?

• Where lies the source of CP violation: in quark or lepton sector?

\[ J_{CP} = \frac{1}{8} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos \theta_{13} \sin \delta \]
Looking for new physics we are looking for new Symmetry of Nature!
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Symmetry might be tricky
Is it just the SM or requires New physics?

Three Types of Seesaw Mechanisms

Require the existence of new degrees of freedom (particles) beyond those present in the SM

Type I seesaw mechanism: $\nu_{IR} - RH \text{ vs' (heavy)}$.

Type II seesaw mechanism: $H(x)$ - a triplet of $H^0, H^-, H^{--}$ Higgs fields.

Type III seesaw mechanism: $T(x)$ - a triplet of fermion fields.
Is it just the SM or requires New physics?

Three Types of Seesaw Mechanisms

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Type II seesaw mechanism: $H(x)$ - a triplet of $H^0, H^-, H^{--}$ Higgs fields.

Type III seesaw mechanism: $T(x)$ - a triplet of fermion fields.

- Possible Sterile Neutrino?
  - New MiniBooNE consistent with LSND (but low energy excess?)
  - Reactor anomaly questioned by Daya Bay/RENO time dependence
  - New SBL and source experiments
  - Conflict with $\nu_\mu$ disappearance

M. Weber ICHEP2018
No evidence for sterile neutrinos

Various exps interpreted within 4 neutrino framework

Oscillation channels are related:

\[ P_{\nu_e \rightarrow \nu_e} \approx 1 - 2|U_{e4}|^2(1 - |U_{e4}|^2) \]
\[ P_{\nu_\mu \rightarrow \nu_\mu} \approx 1 - 2|U_{\mu4}|^2(1 - |U_{\mu4}|^2) \]
\[ P_{\nu_\mu \rightarrow \nu_e} \approx 2|U_{e4}|^2|U_{\mu4}|^2 \]

for \( 4\pi E/\Delta m_{41}^2 < L << 4\pi E/\Delta m_{31}^2 \)
0\beta\beta\nu  NEUTRINOLESS DOUBLE BETA DECAY
0\nu\beta\beta \text{ decay}

\[ n \{ \begin{array}{ccc} u & d & d \\ d & u & u \\ d & u & u \end{array} \} \rightarrow p \]
0νββ decay

$0^\beta_\beta^n$ NEUTRINOLESS DOUBLE BETA DECAY

\[ n \{ \begin{array}{c} u \\ d \\ d \\ d \\ u \\ u \end{array} \} \rightarrow p \{ \begin{array}{c} u \\ u \\ d \\ u \\ e \\ W \end{array} \} \]

\[ n \{ \begin{array}{c} d \\ d \\ u \\ u \\ u \end{array} \} \rightarrow p \{ \begin{array}{c} d \\ d \\ d \\ u \\ e \\ W \end{array} \} \]
0νββ decay

\[ n \{ u, d, u \} \rightarrow p \]

Only Majorana

\[ n \{ d, d, d \} \rightarrow p \]
$0\nu\beta\nu$ decay

$n \{ \begin{array}{c} u \\ d \\ d \\ d \\ u \\ u \\ u \\ u \end{array} \} \rightarrow p$

$0\nu\beta\nu$ decay

$n \{ \begin{array}{c} d \\ d \\ d \\ u \\ u \\ u \end{array} \} \rightarrow p$

Only Majorana

\[ (\beta\beta)_{0\nu} \]

\[ (\beta\beta)_{2\nu} \]
### Experimental Highlights

**P. Sphicas**

**Rencontres de Moriond, EWK session**

**$0^\nu\beta\beta$ decay**

- **$n \{ u, d, d \} \rightarrow p**
- **Only Majorana**

- **$n \{ d, d, u \} \rightarrow p**

**NEUTRINOLESS DOUBLE BETA DECAY**

<table>
<thead>
<tr>
<th>Candidate Isotope</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}$Ca</td>
<td>Candles</td>
</tr>
<tr>
<td>$^{76}$Ge</td>
<td>Gerda, Majorana</td>
</tr>
<tr>
<td>$^{82}$Se</td>
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</tr>
<tr>
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<td>SNO+</td>
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</tbody>
</table>

**$T_{1/2}^{2\nu\beta\beta} (^{136}\text{Xe}) \times 10^{21} \text{ yr} = 2.23 \pm 0.017 \text{ stat} \pm 0.22 \text{ sys}$**

**$T_{1/2}^{0\nu\beta\beta} (^{136}\text{Xe}) \times 10^{25} \text{ yr} > 1.6 (90\% \text{ CL})$**
**0νββ decay**

\[
\begin{align*}
0 \left\{ 
\begin{array}{c}
\text{nucleon} \\
\text{quarks:} u & d & d \\
\text{lepton:} e
\end{array}
\right\} 
\rightarrow 
\begin{array}{c}
\text{nucleon} \\
\text{quarks:} u & u & u \\
\text{lepton:} e
\end{array}
\end{align*}
\]

\[W \rightarrow v + v + e + e\]

Only Majorana

\[
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\begin{array}{c}
n \left\{ 
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d \\
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u
\end{array}
\right\} 
\rightarrow 
\begin{array}{c}
p \\
u
\end{array}
\end{array}
\end{align*}
\]

**Experimental highlights**

- **GERDA**

Rencontres de Moriond, EWK session

\[\nu_{\beta\beta} \rightarrow \nu_{\beta\beta}\]

Mar 09, 2013

\[\frac{Q_{\beta\beta}}{Q_{e^{-}e^{+}}} = \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} \]

\[
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- **KAMLAND-Zen**

- **NEUTRINOLESS DOUBLE BETA DECAY**

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NEW PARTICLES

The Dark Matter is made of:

- Macro objects – Not seen
- New particles – right heavy neutrino

Not from the SM

- axion (axino)
- neutralino
- sneutrino
- gravitino
- heavy photon
- heavy pseudo-goldstone
- light sterile higgs

DARK MATTER

might be invisible (?)
detectable in 3 spheres
less theory favorable
might be undetectable (?)
possible, but not related to the other models
POSSIBLE PHYSICS BEYOND THE STANDARD MODEL

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mSUGRA

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DARK MATTER

WIMP

Annihilation in the halo
\[ \sigma_A \Rightarrow \Omega_X \]
\[ X \xrightarrow{\sigma_A} q \bar{q} \]
\[ \bar{X} \xrightarrow{\sigma_A} q \bar{q} \]
\[ X + \bar{X} \rightarrow q + \bar{q} \]

Scattering on a target
\[ \Omega_X \Rightarrow \sigma_s \]
\[ X \xrightarrow{\Omega_X} X + q \]
\[ q \xrightarrow{\sigma_s} X \]
\[ q \xrightarrow{\sigma_s} X + \bar{X} \]

Creation at the LHC
\[ \Omega_X \Rightarrow \sigma_p \]
\[ q \xrightarrow{\Omega_X} X + \bar{X} \]
\[ q + \bar{q} \rightarrow X + \bar{X} \]
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WIMP is our chance!

Annihilation in the halo

Scattering on a target

Creation at the LHC

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DARK MATTER

WIMP is our chance!

But we have to look elsewhere!
**DARK MATTER: DIRECT DETECTION**

**LZ's Reach**

- Turning on by 2020 with 1,000 initial live-days plan
- 10 tons total, 7 tons active, ~5.6 ton fiducial mass

**GOALS:**

\[ < 3 \times 10^{-48} \text{ cm}^2 \]

- Clip shoulder at 40 GeV
- 6 keVnr threshold with at least 99.5% discrimination

*Plot and models from LZ's Conceptual Design Report, arXiv:1509.02910*

**DARK MATTER: DIRECT DETECTION**

**Mark Boulay**

- Recent result from CRESST-II (arxiv:1509.01515)
- CRESST-III Run starting August 2016
- Expect x100 increase in sensitivity (arxiv:1503.08065)
- Several other projects planning increase in low-mass sensitivity, many good ideas.

**CRESST-II**

- Our best, lowest exclusion is at 50 GeV:
  \[ 2.2 \times 10^{-46} \text{ cm}^2 \]

- That's 0.22 zeptobarns in s!

- 1 order of magnitude off XENON1T

- Within < 2 orders of LZ projection

- Comparable to LUX 2015 re-analysis of 3 months' worth of data at low mass but FOUR TIMES better at high mass. (Final G1?)

- ~2x below PandaX curve

- Paper coming quite soon

**Within (log) spitting distance of coherent neutrino scattering**

*NOT preliminary. Analysis/limit is final. Text under internal review.*

**25 (the 1 TeV Higgsino half-dead)**

*Zeplin III (2011)*

**Many Higgs-mediated models killed**

- 1 event
- \( N \) coherent, \( 3 \sigma \) significance
- 1,000 Tonne-years

- Neutrinos

- Neutrons

- DARWIN

\[ m_{WIMP} \text{ (GeV/c}^2) \]

- WIMP-nucleon cross section (cm^2)

- 10^-50 to 10^-30

- WIMP Mass [GeV/c^2]
DARK MATTER: DIRECT DETECTION

Recent result from CRESST-II (arxiv 1509.01515)

CRESST-III Run LNGS starting August 2016

Expect x100 increase in sensitivity (arxiv 1503.08065)

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(1 TeV Higgsino half-dead)

(LUX. zepto = $10^{-21}$)
DARK MATTER: DIRECT DETECTION

- All available experimental data combined (LHC, LUX, Planck) are still consistent with even the simplest versions of SUSY (cMSSM, NUHM).
- Remaining parameter space is directly probed by direct WIMP searches with tonne scale detectors: DEAP-3600, XENON1T, LUX/LZ.
- Complementarity with LHC (cMSSM/NUHM are mostly out of reach of the 14 TeV run!)

Within (log) spitting distance of coherent neutrino scattering

~2x below PandaX curve

Within (log) spitting distance of coherent neutrino scattering

Paper coming quite soon

Within (log) spitting distance of coherent neutrino scattering

Scientific text under internal review.
• Dark matter may pair annihilate or decay in our galactic neighborhood to:
  • positrons
  • high-energy photons
  • neutrinos
  • antiprotons
  • antideuterons

• Rapid improvements in recent years, Fermi-LAT now excludes WIMP makes up to ~100 GeV for certain annihilation channels
• The future is the Cherenkov Telescope Array, which will extend the reach by two orders in mass up to masses ~ 10 TeV
DARK MATTER: INDIRECT DETECTION

- Dark matter may pair annihilate or decay in our galactic neighborhood to:
  - positrons
  - high-energy photons
  - neutrinos
  - antiprotons
  - antideutrons

INDIRECT DM: POSITRON RESULTS

- Rapid improvements in recent years, Fermi-LAT now excludes WIMP makes up to ~100 GeV for certain annihilation channels

- The future is the Cherenkov Telescope Array, which will extend the reach by two orders in mass up to masses ~10 TeV
**SIMPs** (strong interacting massive particle)

- Dark matter is strongly interacting under the **other SU(N) gauge interactions**.
- DM may be pion/Baryon/gluball of the new strong interactions or couple to new scalar by large Yukawa coupling.

**Dark photon**

- U(1) gauge boson is relatively easy going object “gauge invariant $F_{\mu\nu}$”
- Sequestering U(1)$_D$ dark sector from SM sector,
- Interaction with SM may arises from kinetic mixing $F_{\mu\nu}F'^{\mu\nu}$
- Dark matter couple to U(1)$_D$ can have very small coupling, and also very light U(1)$_D$ $\alpha' \rightarrow 3\gamma$ has very long lifetime. Both can be dark matter.

---

**Nature of Dark matter** is one of the big questions that particle physics should answer.

- Success of LHC and dark matter searches and we are wondering over next steps to go.
NEW DIMENSIONS

Motivations
1. String theory
2. Interesting possibility that opens wide opportunities

• String theory suffers conformal anomalies that make it inconsistent.
• Conformal anomaly cancels at D=26 for a bosonic string and D=10 for a fermionic string
NEW DIMENSIONS

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- String theory suffers conformal anomalies that make it inconsistent.
- Conformal anomaly cancels at $D=26$ for a bosonic string and $D=10$ for a fermionic string

Why don't we see extra dimensions

EXTRA SPACE DIM
$1 + 3 \rightarrow 1 + n, \ n > 3$
NEW DIMENSIONS

Motivations

1. String theory
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- String theory suffers conformal anomalies that make it inconsistent.
- Conformal anomaly cancels at $D=26$ for a bosonic string and $D=10$ for a fermionic string

Why don’t we see extra dimensions

- discovery of D-brane
  - matter fields restricted to lower dimensional brane
  - external bulk felt only through gravity
  - extra dimension bigger

conventional Kaluza-Klein idea:
internal extra dimension too small to be seen
EXTRA SPACE-TIME DIMENSIONS

- Very large XDim accesible only to gravity
- Requires two or more XDim
- Black holes at colliders?

- TeV scale XDim (several hundred GeV?)
- Pair production, $\mathcal{E}_T$ (SUSY-like)
- Interesting DM candidate (non SUSY-like)
- Additional nice features in 6D

- Field localization
- Theories of flavor?
- KK resonances at few TeV
- Relatively broad resonances

RS1

Narrow spin-2 resonances?

Bulk gravity only

Many bulk fields

UED's

- Field localization
- Theories of flavor?
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ADD

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EXTRA SPACE-TIME DIMENSIONS
NEW PARADIGM

Particle

World-line

World-line action:

\[ S = -m \int d\tau \sqrt{-\frac{dX^\mu}{d\tau} \frac{dX^\nu}{d\tau} \eta_{\mu\nu}} \rightarrow \frac{d^2 X^\mu}{d\tau^2} = 0 \]

Open string

String tension

\[ l_S \quad \text{string length} \]

Closed string

World-surface

World-sheet action:

\[ S = -\frac{1}{2\pi l_S^2} \int d^2\sigma \sqrt{-\det \left( \frac{dX^\mu}{d\sigma^\alpha} \frac{dX^\nu}{d\sigma^\beta} \eta_{\mu\nu} \right)} \]
There are five types of string theories (IIA, IIB, I, two Heterotic).

All five string theories are only consistent in 10 space-time dimensions.

All five string theories have world-sheet supersymmetry and lead to space-time-supersymmetry in 10 dimensions.

All five string theories are related and part of a single “theory”: M-theory.

M-theory is a patchwork of the constituent theories plus many “rules”.

It seems unclear, at present, what its fundamental degrees of freedom are.
STRING THEORY AND THE “REAL” WORLD

Need to compactly six or seven dimensions to obtain $d=4$ theory

$d=10/11$
string/M theory

on $d=6/7$ dimensional space $X$

$d=4$
theory

Two-fold degeneracy in space $X$: continuous one in size and shape (moduli) and discrete one topology

Topology determines the structure of $d=4$ theory

Moduli appearing as scalar fields determine values of couplings in $d=4$

in $D=10/11$: gravity… ... and a p-brane

\[
S_D = \frac{1}{l_S^{D-2}} \int d^D x \sqrt{-g} R + \cdots + \frac{1}{l_S^{p-3}} \int d^{p+1} x \sqrt{-\gamma} \text{tr}(F_{\alpha\beta} F^{\alpha\beta}) + \cdots
\]

in $D=4$:

\[
S_4 = \frac{\frac{1}{16\pi G_N} V}{l_S^{D-2}} \int d^D x \sqrt{-g_4} R_4 + \cdots + \frac{\frac{1}{16\pi g_Y^2}}{l_S^{p-3}} \int d^{p+1} x \sqrt{-g_4} \text{tr}(F_{\mu\nu} F^{\mu\nu}) + \cdots
\]
String theory contains not just strings but extended objects - branes - of all dimensions.
NEW PARADIGM

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- branes - of all dimensions

Q: Do we really live on a brane?
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A: We believe in BIG deal

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The world according to string/M-theory
THE STANDARD MODEL: CONCEPTUAL PROBLEMS

Baryon Asymmetry of the Universe

SM expectation:

\[ \frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-18} \quad \text{vs.} \quad \frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-10} \]

Sakharov criteria

1. Baryon number violation
2. C and CP violation
3. Thermal non-equilibrium

* Observations are from WMAP
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Baryon Asymmetry of the Universe

SM expectation: \( \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 10^{-18} \)

Observed*: \( \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 10^{-10} \)

Sakharov criteria
1. Baryon number violation
2. C and CP violation
3. Thermal non-equilibrium

• Baryon number is conserved in the SM with exponential accuracy

• Violation of baryon number occurs in Grand Unified Theories and in Lepton=fourth color models (Pati-Salam model)

New particles = Leptoquarks, Extended Highs sector

\[ B = \frac{N_q - N_{\bar{q}}}{3} \]

• Violation of CP invariance in the SM achieved via phase factors in the CKM and PMNS mixing matrices

BAU requires larger CP than in the SM Possible Baryogeneses via Leptogeneses

The presence of new phase factors in extended models (2HDM, SUSY, etc)
Collectivity in small systems

Sharp increase in multiplicity at high centrality in XeXe - not seen in PbPb
WHAT MAKES US THINK THAT THERE IS PHYSICS BEYOND THE STANDARD MODEL?
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- New era in gravity due to discovery of gravitational waves and black holes might change the landscape
IDEAS (CONVENTIONAL AND NOT)

- Symmetries
  - Supersymmetry, family, ...
- Compositeness
  - Higgs, fermions, ...
- Extra dimensions
  - Large, warped, ...
- Dark or hidden sectors
  - Dark, SUSY-breaking, random, ...
- Unification
  - GUT, string, ...
- New dynamical ideas
  - Relaxion, nnaturalness, clockwork, string instantons, ...
- Random or environmental
  - Multiverse
- String remnants
  (need not solve SM problem)
  - Z’, vector fermions, extended Higgs, dark, moduli, axions, ...

BEYOND THE STANDARD MODEL: CONCLUSIONS
Which way to go?
Which way to go?
Which way to go?
How Will We Make Progress?
How Will We Make Progress?

- The energy frontier
How Will We Make Progress?

- The energy frontier
- The precision frontier and neutrinos
How Will We Make Progress?

- The energy frontier
- The precision frontier and neutrinos
- Cosmology and astrophysics
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