Standart Model Ötesi Fenomenoloji : Supersimetri

Part 1: The Standard Model

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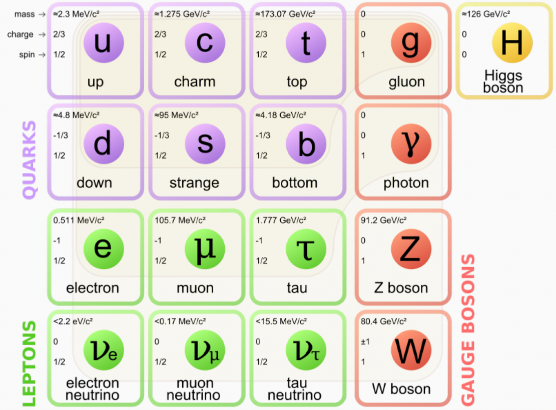
Outline

Standard Model

$$SU(3) \times SU(2) \times U(1)$$



- Fermion: 1/2 spin

  Madde parçacıkları,

  Quark - Lepton.

- Ayar Bozonları - 1 spin,

  Etkileşim taşıyıcıları.

- Higgs Bozon - 0 Spin,

  parçacıkların kütlesi.

Sürekli Simetri	**Korunumlu Nicelik**	
Zamanda Öteleme	Enerji	Uzayzaman (Kinematics)
Uzayda Öteleme	Lineer Momentum	Uzayzaman (Kinematics)
Rotasyon	Açısal Momentum	Uzayzaman (Kinematics)
$U(1)_{EM}$ Ayar Dönüşümü	Elektrik Yükü	Elektromagnetik Etkileşim
$U(1)_Y$ Ayar Dönüşümü	Hiperyük	Hiperyük Etkileşim
$SU(2)_L$ Ayar Dönüşümü	Zayıf Isospin	Zayıf Etkileşim
$SU(3)_C$ Ayar Dönüşümü	Renk Yükü	Güçlü Etkileşim (QCD)

The Standard Model: Group Teori & QFT

SM: Grup Teori + Relativistik Alan Teorisi

$$G_{\mathrm{SM}} = SU(3)_C \times SU(2)_L \times U(1)_Y$$

Group Teori & Etkileşimler

- $SU(3)_C$ **(QCD):** Non-Abelian Ayar Simetrisi $\rightarrow$ 8 gluon .
- $SU(2)_L \times U(1)_Y$ **(EW):** Electrozayıf etkileşimler $\rightarrow W^{\pm}, Z^0, \gamma$.

Kuantum Alan Theorisi (QFT)

- vakum etrafında perturbasyon
- Simetrik Lagrangian

Standard Model Parçacık Representasyonları & Quantum Sayıları

Sector / Field	Symbol	Chiral	$SU(3)_C$	$SU(2)_L$	Hypercharge (Y)	Isospin (T_3)	Charge (Q)
Fermions (Quarks)							
Left-handed Quarks	Q_L	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	**3**	**2**	$+1/3$	$+1/2, -1/2$	$+2/3, -1/3$
Right-handed Up Quark	u_R	u_R	**3**	**1**	$+4/3$	0	$+2/3$
Right-handed Down Quark	d_R	d_R	**3**	**1**	$-2/3$	0	$-1/3$
Fermions (Leptons)							
Left-handed Leptons	L_L	$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	**1**	**2**	-1	$+1/2, -1/2$	$0, -1$
Right-handed Electron	e_R	e_R	**1**	**1**	-2	0	-1
Right-handed Neutrino*	ν_R	ν_R	**1**	**1**	0	0	0
Gauge Bosons							
Gluons (Strong)	G_μ^a	—	**8**	**1**	0	0	0
Weak Isospin	W_μ^i	—	**1**	**3**	0	$+1, 0, -1$	$+1, 0, -1$
Weak Hypercharge	B_μ	—	**1**	**1**	0	0	0
Scalar Field							
Higgs Doublet	Φ	$\begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$	**1**	**2**	$+1$	$+1/2, -1/2$	$+1, 0$

*Note: Sağ-elli nötrinoların tüm kuantum sayıları sıfırdır.
Eelktrik Yükü: $Q = T_3 + \frac{Y}{2}$

The Standard Model Lagrangian

$$\mathcal{L}_{\text{SM}} = \underbrace{-\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu}}_{\text{Gauge Sector}} + \underbrace{i\bar{\psi}\gamma^\mu D_\mu\psi}_{\text{Fermion Sector}} + \underbrace{|D_\mu\Phi|^2 - V(\Phi)}_{\text{Higgs Sector}} - \underbrace{\left(y_{ij}\bar{\psi}_i\Phi\psi_j + \text{h.c.}\right)}_{\text{Yukawa Sector}}$$

1. Gauge Sector ($\mathcal{L}_{\text{gauge}}$)

Ayar bozonlarının dinamiği

2. Fermion Sector ($\mathcal{L}_{\text{fermion}}$)

Fermiyonlar - Ayar bozonları etkileşimleri

$$D_\mu = \partial_\mu - ig_s T^a G^a_\mu - ig\tau^b W^b_\mu - ig' Y B_\mu.$$

3. Higgs Sector ($\mathcal{L}_{\text{Higgs}}$)

Skaler potensiyel: $V(\Phi) = -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$.

Kendiliğinden Simetri Kırılması

4. Yukawa Sector ($\mathcal{L}_{\text{Yukawa}}$)

Ayar-invaryant skaler-fermion etkileşimleri.

The Higgs Mekanizması: Ayar Bozon Kütleleri

$$SU(2)_L \times U(1)_Y \xrightarrow{\langle\Phi\rangle} U(1)_{\text{EM}}$$

1. The Higgs Alanı & VEV

- Kompleks skaler dublet:
  $\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}.$
- Vakum Beklenen Deger (VEV)

$$\langle\Phi\rangle_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad v = \sqrt{\frac{-\mu^2}{\lambda}} \approx 246 \text{ GeV}$$

2. Gauge Boson Mass Formulas

- $|D_\mu \Phi|^2$:

$$M_W = \frac{1}{2} g v \quad (\approx 80.4 \text{ GeV})$$

$$M_Z = \frac{1}{2} \sqrt{g^2 + g'^2}\, v \quad (\approx 91.2 \text{ GeV})$$

$$M_\gamma = 0 \quad (\text{Unbroken } U(1)_{\text{EM}})$$

$$\mathcal{L}_{\text{Yukawa}} = -y_d \bar{Q}_L \Phi d_R - y_u \bar{Q}_L \tilde{\Phi} u_R - y_e \bar{L}_L \Phi e_R + \text{h.c.}$$

- $\Phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$:

$$\mathcal{L}_{\text{Yukawa}} \supset -\frac{y_f v}{\sqrt{2}} \bar{\psi}_f \psi_f - \frac{y_f}{\sqrt{2}} h \bar{\psi}_f \psi_f$$

- Kütle:

$$m_f = \frac{y_f v}{\sqrt{2}}$$

2. Key Physical Consequences

- **Hiyerarşik Yukawa:** $m_f \propto y_f$.
- **Higgs Etkileşimleri:** $g_{hff} = \frac{m_f}{v}$.
- Flavor karışımları

  (CKM and PMNS matrisleri)

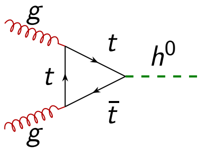
Higgs Bozon Üretim & Bozunum Kanalları

Üretim Kanalları ($\sqrt{s} = 13$ TeV)

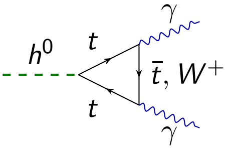
- **Gluon Fusion (*ggF*):** $\sim 85\%$ ($\sigma \approx 48.6$ pb)
- **Vector Boson Fusion (*VBF*):** $\sim 7\%$ (3.8 pb)
- **Associated *VH* (*W*/*ZH*):** $\sim 4\%$ (2.3 pb)
- **Associated $t\bar{t}H$:** $\sim 1\%$ (0.5 pb)

Bozunum Kanalları ($m_h \approx 125$ GeV)

- $h^0 \to b\bar{b}$ (**58.2**%): Dominant, high QCD bkg.
- $h^0 \to WW^*$ (**21.4**%): Broad width.
- $h^0 \to \tau^+\tau^-$ (**6.3**%): Leptonic mode.
- $h^0 \to ZZ^* \to 4\ell$ (**2.6**%): "Golden Channel".
- $h^0 \to \gamma\gamma$ (**0.23**%): Discovery peak at LHC!



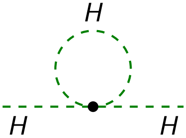
Gluon Fusion ($gg \to h^0$)



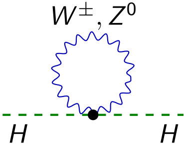
Deneysel Gözlemler

- **Hassasiyet:**
  - Anomal magnetik moment
  - W, Z ve Higgs bozon kütleleri, bozunum genişlikleri, etkileşim sabitleri
  - charm, top ve güçlü etkileşim sabiti
- **Nadir B$-$mezon bozunumları:** $B_s \to \mu\mu$, $B \to X_s\gamma$
- **Flavor Karışımları:** CKM matris, yüklü lepton flavor ihlalleri

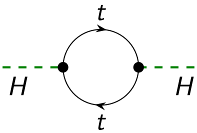
Hierarşi Problemi



$$\sim \int \frac{d^4 k}{(2\pi)^4} \frac{1}{k^2 - M_H^2} \sim \frac{1}{16\pi^2} \lambda^2 \Lambda^2$$



$$\sim \int \frac{d^4 k}{(2\pi)^4} \frac{1}{k^2 - M_G^2} \sim \frac{1}{16\pi^2} g^2 \Lambda^2$$



$$\sim \int \frac{d^4 k}{(2\pi)^4} \frac{i}{\not{k} - m_f} \frac{i}{(\not{k} - \not{p}) - m_f} \sim -\frac{3}{8\pi^2} y_t^2 \Lambda^2$$

İnce Ayar

$$\begin{aligned}\delta m_H^2 &\sim \frac{\Lambda^2}{16\pi^2}\left(\lambda^2+g^2-6y_t^2\right)\\ &\sim \frac{\Lambda^2}{16\pi^2 v^2}\left(3m_H^2+6m_W^2+3m_Z^2-12m_t^2\right)\end{aligned}$$

- **Bozonik Katkılar (+):**

  $m_H^2 + 2m_W^2 + m_Z^2 \approx (125)^2 + 2(80.4)^2 + (91.2)^2 \approx 3.69 \times 10^4 \ \text{GeV}^2$

- **Fermiyonik Katkı (−) :**

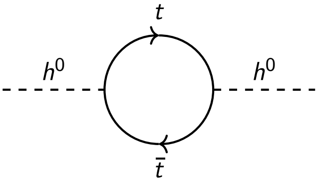
  $4m_t^2 \approx 4(173.1)^2 \approx 1.20 \times 10^5 \ \text{GeV}^2$

$$\Lambda \simeq ?$$

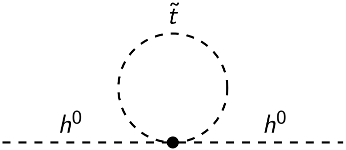
Standart Model'in Temel Eksiklikleri ve Sınırları

- **Nötrino Kütleleri & Salınımları:** SM nötrinoları kütlesiz öngörür, ancak salınım gözlemleri nötrinoların kütleli olduğunu kanıtlamıştır.
- **Karanlık Madde ve Karanlık Enerji:** Evrenin %95'ini oluşturan karanlık bileşenleri açıklayacak kararlı bir SM parçacığı veya mekanizması yoktur.
- **Madde - Anti-Madde Asimetrisi:** SM CKM matrisindeki CP ihlali, evrendeki baryon asimetrisini açıklamak için son derece yetersizdir.
- **Flavor Hiyerarşisi:** Fermiyon kütleleri arasındaki devasa mertebe farkları (elektron ile top kuark arası 10^5 kat) açıklanamaz.
- **Güçlü CP Problemi:** QCD Lagrangian'ındaki CP ihlali parametresinin (θ_{QCD}) deneysel olarak neden sıfıra yakın olduğu bilinmemektedir.
- **Kuantum Kütleçekimi:** Kütleçekim kuvveti $SU(3)_C \times SU(2)_L \times U(1)_Y$ ayar grubuna ve renormalize edilebilir QFT yapısına dahil edilemez.

Süpersimetri: Fermiyon $\longleftrightarrow$ Bozon



$+$



$$\Delta m_h^2 \propto -\frac{3y_t^2}{8\pi^2}\Lambda^2$$

$$\Delta m_H^2 \propto +\frac{3\lambda_S}{16\pi^2}\Lambda^2$$

$$Q\,|fermiyon\rangle = |bozon\rangle\,, \quad Q\,|bozon\rangle = |fermiyon\rangle$$

Wess-Zumino Model: Serbest Alanlar

$$\mathcal{S} = \int d^4x(\mathcal{L}_{\text{skaler}} + \mathcal{L}_{\text{fermiyon}}) : \begin{cases} \mathcal{L}_{\text{skaler}} & = -\partial_\mu \phi^* \partial^\mu \phi \\ \mathcal{L}_{\text{fermiyon}} & = i\psi^\dagger \bar{\sigma}^\mu \partial_\mu \psi \\ \hline \mathcal{L}_{\text{serbest}} & = -\partial^\mu \phi^* \partial_\mu \phi + i\psi^\dagger \bar{\sigma}^\mu \partial_\mu \psi \end{cases}$$

Alan	**Spin**	**On-Shell**	**Off-Shell**
Karmaşık Skaler (ϕ)	0	2	2
Weyl Spinörü (ψ)	1/2	2	4
Yardımcı Alan ($\mathcal{F}$)	0	0	2

$$\mathcal{L}_{\text{serbest}} = -\partial^\mu \phi^* \partial_\mu \phi + i\psi^\dagger \bar{\sigma}^\mu \partial_\mu \psi + \mathcal{F}^* \mathcal{F}$$

Wess-Zumino Model: Serbest Alanlar

$$
\begin{aligned}
\phi &\to \phi' \simeq \phi + \delta\phi \\
\psi' &\to \psi' \simeq \psi + \delta\psi \\
\mathcal{F} &\to \mathcal{F}' \simeq \mathcal{F} + \delta\mathcal{F}
\end{aligned}
\quad , \quad
\left\{
\begin{aligned}
\delta\phi &= \epsilon\psi \\
\delta\psi_\alpha &= -i(\sigma^\mu \epsilon^\dagger)_\alpha \partial_\mu \phi + \epsilon_\alpha \mathcal{F} \\
\delta\mathcal{F} &= -i\epsilon\bar{\sigma}^\mu \partial_\mu \psi
\end{aligned}
\right.
$$

$$
[\delta_{\epsilon_2}, \delta_{\epsilon_1}]\phi = -i(\epsilon_1 \sigma^\mu \epsilon_2^\dagger - \epsilon_2 \sigma^\mu \epsilon_1^\dagger)\partial_\mu \phi
$$

Wess-Zumino Model: Etkileşimli Alanlar

$$\underline{\textbf{Ansatz}}\textbf{:}\ \mathcal{L}_{\rm int} = \left(\frac{1}{2}\mathcal{W}^{ij}\psi_i\psi_j + \mathcal{W}^i\mathcal{F}_i + \text{c.c}\right)$$

Süperpotansiyel: $\mathcal{W} \equiv \mathcal{W}(\phi_i, \phi_j^*) = M^{ij} + y^{ijk}\phi_k + Y^{ijk}\phi_k^*$

$$\mathcal{W}^{ij} \equiv \frac{\partial^2\mathcal{W}}{\partial\phi_i\partial\phi_j},\ \mathcal{W}^{ij} \equiv \frac{\partial\mathcal{W}}{\partial\phi_i}$$

$$\begin{aligned}
\delta\mathcal{L}_{\rm int}\,\big|_{\phi,\phi^*} &= -\frac{1}{2}\frac{\delta\mathcal{W}^{ij}}{\delta\phi_k}\delta\phi_k\psi_i\psi_j - \frac{1}{2}\frac{\delta\mathcal{W}^{ij}}{\delta\phi_k^*}\delta\phi_k^*\psi_i\psi_j \\
&= -\frac{1}{2}\frac{\delta\mathcal{W}^{ij}}{\delta\phi_k}(\epsilon\psi_k)\psi_i\psi_j - \frac{1}{2}\frac{\delta\mathcal{W}^{ij}}{\delta\phi_k^*}(\epsilon^\dagger\psi_k^\dagger)\psi_i\psi_j \\
&= -\frac{1}{2}\frac{\delta\mathcal{W}^{ij}}{\delta\phi_k}(\epsilon\psi_k)\psi_i\psi_j = 0
\end{aligned}$$

Holomorfi: $\mathcal{W}$ Skaler alanlarin kompleks eşleniklerine bağlı olamaz! $(Y^{ijk} = 0)$

Wess-Zumino Model: Yardımcı Alanlar

$$\mathcal{L}_{\mathcal{F}} = \mathcal{F}^{*i}\mathcal{F}_i + \mathcal{W}^i\mathcal{F}_i \Rightarrow \delta\mathcal{L}_{\mathcal{F}} = \mathcal{F}^{*i} + \mathcal{W}^i = 0 \rightarrow \mathcal{F}^{*i} = -\mathcal{W}^i$$

$$\mathcal{L} = -\partial^\mu\phi^*\partial_\mu\phi + i\psi^\dagger\bar{\sigma}^\mu\partial_\mu\psi + \frac{1}{2}\left(\mathcal{W}^{ij}\psi_i\psi_j + \mathcal{W}^*_{ij}\psi^\dagger_i\psi^\dagger_j\right) + \mathcal{W}^i\mathcal{W}^*_i$$

- Süpersimetrik modellerde skaler potansiyel: $V(\phi_i, \phi^*_i) = \mathcal{F}_i\mathcal{F}^{*i} = \mathcal{W}^i\mathcal{W}^*_i$
- On shell: $\mathcal{F} = 0 \Longrightarrow V(\phi_i, \phi^*_i) = 0$
- **Vakumun sıfırdan farklı bir enerjiye sahip olması için SUSY kırılmak zorunda!**

$$\mathcal{W} = \frac{1}{2}M^{ij}\phi_i\phi_i + \frac{1}{6}y^{ijk}\phi_i\phi_j\phi_k$$

Part II: MSSM

Standard Model Ötesi Fenomenoloji

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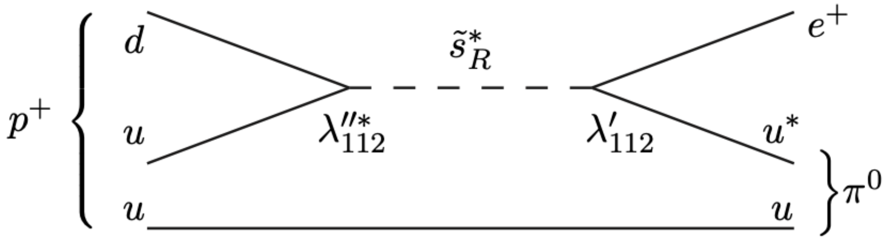
Süperçoklu	SM	Süpereş	$SU(3)_C, SU(2)_L$	Y
Q	$q_L = (u_L, d_L)^T$	$\tilde{q}_L = (\tilde{u}_L, \tilde{d}_L)^T$	$(\mathbf{3}, \mathbf{2})$	$+1/3$
$\bar{u}$	$u_R^\dagger$	$\tilde{u}_R^*$	$(\bar{\mathbf{3}}, \mathbf{1})$	$-4/3$
$\bar{d}$	$d_R^\dagger$	$\tilde{d}_R^*$	$(\bar{\mathbf{3}}, \mathbf{1})$	$+2/3$
L	$l_L = (\nu_L, e_L)^T$	$\tilde{l}_L = (\tilde{\nu}_L, \tilde{e}_L)^T$	$(\mathbf{1}, \mathbf{2})$	-1
$\bar{e}$	$e_R^\dagger$	$\tilde{e}_R^*$	$(\mathbf{1}, \mathbf{1})$	$+2$
H_u	$(H_u^+, H_u^0)^T$	$(\tilde{H}_u^+, \tilde{H}_u^0)^T$	$(\mathbf{1}, \mathbf{2})$	$+1$
H_d	$(H_d^0, H_d^-)^T$	$(\tilde{H}_d^0, \tilde{H}_d^-)^T$	$(\mathbf{1}, \mathbf{2})$	-1
G	g	$\tilde{g}$	$(\mathbf{8}, \mathbf{1})$	0
W	$W^\pm, W^0$	$\tilde{W}^\pm, \tilde{W}^0$	$(\mathbf{1}, \mathbf{3})$	0
B	B^0	$\tilde{B}^0$	$(\mathbf{1}, \mathbf{1})$	0

MSSM Yukawa ve μ Terimleri

$$\mathcal{W}_{\text{MSSM}} = y_u Q H_u \bar{u} - y_d Q H_d \bar{d} - y_e L H_d \bar{e} + \mu H_u H_d$$

$$\mathcal{W}_{\text{RPV}} = \frac{1}{2}\lambda^{ijk} L_i L_j \bar{e}_k + \lambda'^{ijk} L_i Q_j \bar{d}_k + \mu'^{i} L_i H_u + \frac{1}{2}\lambda''^{ijk} \bar{u}_i \bar{d}_j \bar{d}_k$$

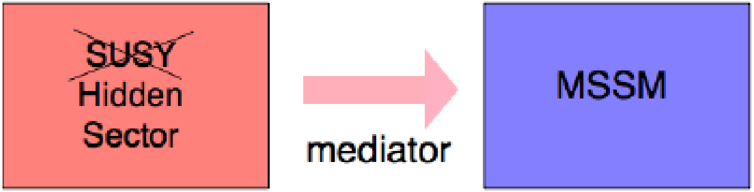


R-Parite

- Hem λ' $(\Delta L \neq 0)$ hem de λ'' $(\Delta B \neq 0)$ bağlaşımları aynı anda sıfırdan farklı olursa, skaler kuark (squark) değişimi üzerinden hızlı proton bozunumu $(p^+ \to e^+\pi^0)$ gerçekleşir.
- R parite:

$$P_R = (-1)^{3(B-L)+2S}$$

- Standart Model parçacıkları için: $P_R = +1$
- Süperparçacıklar (S-particles) için: $P_R = -1$
- Süperparçacıklar çarpıştırıcılarda daima **çiftler halinde** üretilir.
- En Hafif Süperparçacık (**LSP**): Karanlık Madde.

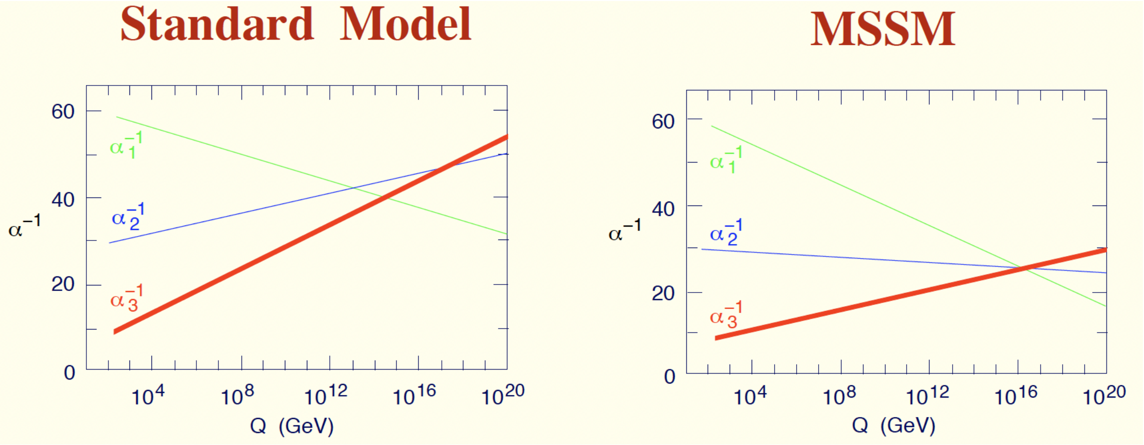


- Gravity Mediated SUSY Breking ($\Lambda \gtrsim M_{\mathrm{GUT}}$)
- Gauge Mediated SUSY Breaking ($\mathcal{O}(\mathrm{TeV}) \leq \Lambda \leq M_{\mathrm{GUT}}$)
- Anomaly Mediated SUSY Breaking ($\Lambda \gtrsim M_{\mathrm{GUT}}$)

SUSY Breaking

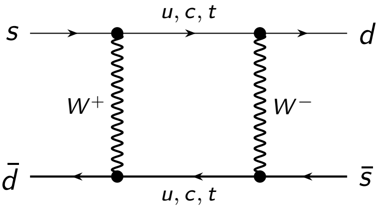
$$
\begin{aligned}
\mathcal{L}_{\cancel{\mathrm{SUSY}}} = & -\frac{1}{2}(M_1 \tilde{B}\tilde{B} + M_2 \tilde{W}\tilde{W} + M_3 \tilde{g}\tilde{g}) + \mathrm{h.c.} \\
& - m_{H_u}^2 h_u^\dagger H_u - m_{H_d}^2 H_d^\dagger H_d - (bH_u H_d + \mathrm{h.c.}) \\
& - m_Q^2 \tilde{Q}^\dagger \tilde{Q} - m_L^2 \tilde{l}^\dagger \tilde{l} - m_u^2 \tilde{u}_R^\dagger \tilde{u}_R - m_d^2 \tilde{d}_R^\dagger \tilde{d}_R - m_e^2 \tilde{e}_R^\dagger \tilde{e}_R \\
& - (A_u \tilde{u}_R \tilde{q} H_u + A_d \tilde{d}_R \tilde{q} H_d + A_e \tilde{e}_R \tilde{l} H_d) \\
& {\color{red} - (A_u \tilde{u}_R \tilde{q} H_d^* + A_d \tilde{d}_R \tilde{q} H_u^* + A_e \tilde{e}_R \tilde{l} H_u^*)} \longleftarrow \text{Non-Holomorphy}
\end{aligned}
$$

Büyük Birleşim



$K^0 - \bar{K}^0$ Karışımı

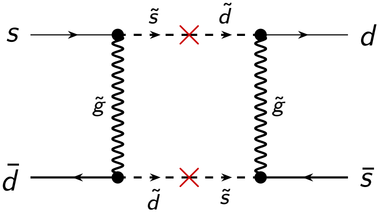
SM



Zayıf Etkileşim ($W^\pm$)

GIM mekanizması ile bastırılır.

MSSM

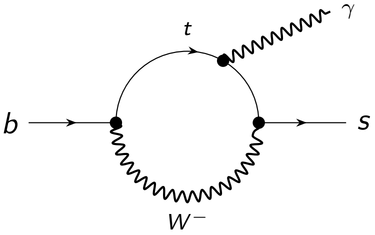


Güçlü Etkileşim ($\tilde{g}$ ve $\tilde{q}$)

- Cross: $(\delta^d_{12})_{AB} \equiv \dfrac{(\Delta m^2_{\tilde{q}})_{12}}{m^2_{\tilde{q}}} \ll 1$
- $\Delta m_K^{\text{exp}} = (3.484 \pm 0.006) \times 10^{-15}$ GeV, $\quad |\epsilon_K|^{\text{exp}} = (2.228 \pm 0.011) \times 10^{-3}$

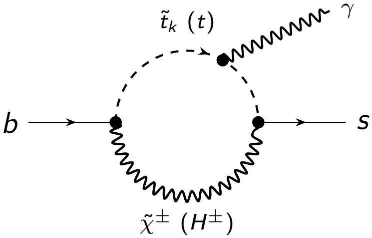
Nadir B Bozunumları: $B \to X_s\gamma$

SM



$$\mathrm{BR}_{\mathrm{SM}} \approx (3.36 \pm 0.23) \times 10^{-4}$$

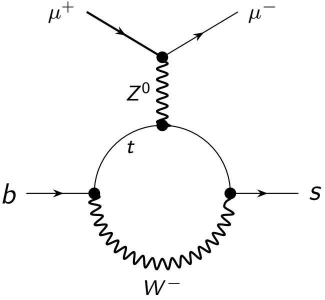
MSSM ($H^\pm$ / $\tilde{\chi}^\pm$ Katkısı)



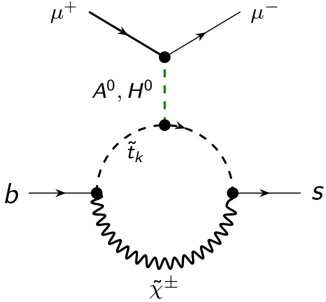
Yüklü Higgs ($H^\pm$) ve Chargino ($\tilde{\chi}^\pm$)

Skaler kuark Sol-Sağ karışımı

SM



MSSM



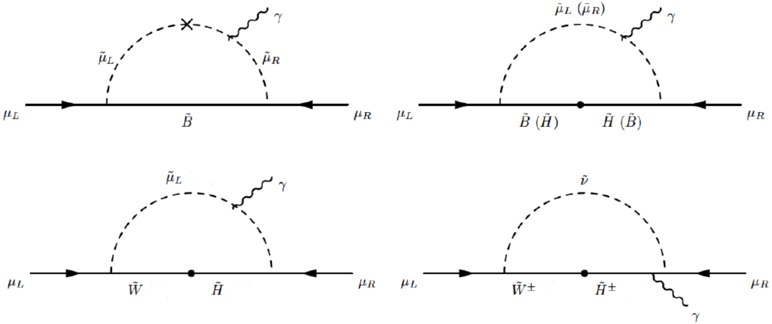
Helisite Bastırması: $\propto m_\mu$

FCNC bastırması

$\mathrm{BR}_{\mathrm{SM}} = (3.64 \pm 0.12) \times 10^{-9}$

$\mathrm{BR}_{\mathrm{MSSM}} \propto \frac{\tan^6\beta}{M_A^4}$

muon $g-2$



$$\Delta a_\mu^{\tilde{B}\tilde{\mu}_L\tilde{\mu}_R} \simeq \frac{g_1^2}{16\pi^2}\frac{m_\mu^2 M_{\tilde{B}}\left[(\mu + A'_\mu)\tan\beta - A_\mu\right]}{m_{\tilde{\mu}_L}^2 m_{\tilde{\mu}_R}^2} F_N\left(\frac{m_{\tilde{\mu}_L}^2}{M_{\tilde{B}}^2}, \frac{m_{\tilde{\mu}_R}^2}{M_{\tilde{B}}^2}\right)$$

muon $g-2$

$$
\begin{aligned}
\Delta a_\mu &= (28.6 \pm 8.0) \times 10^{-10} \quad (2006) \\
\Delta a_\mu &= (28.7 \pm 8.0) \times 10^{-10} \quad (2009) \\
\Delta a_\mu &= (25.1 \pm 5.9) \times 10^{-10} \quad (2021) \\
\Delta a_\mu &= (24.5 \pm 4.9) \times 10^{-10} \quad (2024) \\
\Delta a_\mu &= 3.8(6.6) \times 10^{-10} \quad (2025)
\end{aligned}
$$

Temel Teorik Motivasyonlar

- **Hiyerarşi Problemi:** Higgs kütlesindeki kuadratik sonsuzluklar ortadan kalkar ve elektrozayıf ölçeği kararlı kılar.
- **Ayar Birleşimi:** g_1, g_2, g_3 ayar sabitlerini GUT skalasında ($\sim 10^{16}$ GeV) birleştirir.
- **Doğal Karanlık Madde:** R-parite korunumu en hafif süperparçacığı (LSP, genelde Nötralino $\tilde{\chi}_1^0$) kararlı bir WIMP adayı yapar.
- **Radyatif EWSB:** Radyatif katkılarla Elektrozayıf Simetri Bozulmasını tetikler.

- 125 GeV Higgs Kütlesi
- **Direct Searches ($m_{\tilde{g}}, m_{\tilde{q}} > 2$ TeV)**
  - Elektrozayif sektör ($\tilde{\chi}^0, \tilde{\chi}^{\pm}$) ve sıkışık spectrum (compressed spectra) senaryoları
- **Karanlık Madde (LZ / XENONnT) Kısıtları**

HL-LHC ve Gelecek Çarpıştırıcılar (FCC/ILC)