Some top partners at the LHC

Stefano Porto
University of Padova

Munich, July 18, 2011

Supervisor: Donal O'Connell (Niels Bohr International Academy)

Outline

The Standard Model of particle physics

- It's our theoretical framework
- Electroweak and strong interactions $\rightarrow$ from $\Lambda_{EW} \approx 10^2$ GeV to $\Lambda_{Pl} \approx 10^{18}$ GeV
- Foresaw several particles, eventually seen: b, t, ν_τ, $W^\pm$, Z
- Great accord with experiment

The Standard Model of particle physics

- It's our theoretical framework
- Electroweak and strong interactions $\rightarrow$ from $\Lambda_{EW} \approx 10^2$ GeV to $\Lambda_{Pl} \approx 10^{18}$ GeV
- Foresaw several particles, eventually seen: b, t, ν_τ, $W^\pm$, Z
- Great accord with experiment

BUT

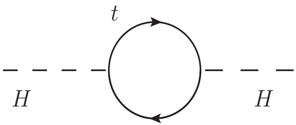
There are many open questions:

- Dark Matter?
- Matter-Antimatter asymmetry?
- Gravity?
- Hierarchy Problem?
- ...

The Hierarchy Problem

Higgs (mass)^2: quadratically divergent 1-loop corrections.

$$\mathscr{L}_{Yuk} \supset -\frac{y_t}{\sqrt{2}} H\bar{t}t$$



$\longleftrightarrow$

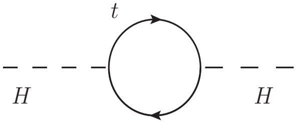
$$\delta m_H^2 \propto \int_0^\infty dk_E \, k_E$$

A counterterm is needed!

The Hierarchy Problem

Higgs (mass)^2: quadratically divergent 1-loop corrections.

$$\mathscr{L}_{Yuk} \supset -\frac{y_t}{\sqrt{2}} H\bar{t}t$$



$\longleftrightarrow$

$$\delta m_H^2 \propto \int_0^\infty dk_E\, k_E$$

A counterterm is needed!

Renormalization $\rightarrow$ momentum cut off up to Λ_{Pl}

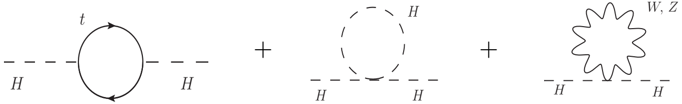
$$\downarrow$$

$$\delta m_H^2|_t = -\frac{3m_t^2}{4\pi^2 v^2}\left[\Lambda_{Pl}^2 + \ldots\right] \approx 10^{36}\,(\mathrm{GeV})^2$$

From phenomenological and experimental constraints we expected $m_H \sim 120$ GeV!

The Hierarchy Problem

Considering all 1-loop quadratic divergent corrections:



$+ \ \ldots \ \simeq m_H^2$?

A huge fine tuning is needed, due to the Big Desert $\Lambda_{EW} < \cdots < \Lambda_{Pl}$.

Hypotheses:

- A not-yet observed low energy scale between Λ_{EW} and Λ_{Pl}.
- There must be some kind of symmetry that tames the 1-loop corrections.

Supersymmetry

Fermion and boson loops $\longrightarrow$ relative sign $\longrightarrow$ Let's relate fermions and bosons.

Supersymmetry, that's what we wanted:

$$Q|Boson\rangle = |Fermion\rangle, \quad Q|Fermion\rangle = |Boson\rangle$$

Supersymmetry algebra:

$$\{Q, Q^\dagger\} = P^\mu,$$
$$\{Q, Q\} = \{Q^\dagger, Q^\dagger\} = 0,$$
$$[P^\mu, Q] = [P^\mu, Q^\dagger] = 0.$$

(P^μ generator of Poincaré translations)

Single particle states fall into supermultiplets, with $\#_{fermionic} d.o.f. = \#_{bosonic} d.o.f.$:

- Chiral supermultiplet: 1 complex scalar field, 1 spin-$\frac{1}{2}$ Weyl fermion
- Vector supermultiplet: 1 spin-$\frac{1}{2}$ Weyl fermion, 1 massless gauge boson

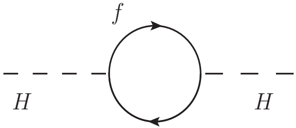
$[Q, P^2] = 0 \rightarrow$ superpartners have the same mass.

$[Q, T^a] = 0 \rightarrow$ same gauge quantum numbers, same representation.

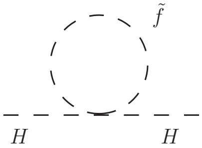
Example

Chiral supermultiplet $(\tilde{f}, f)$ interacting with H:

$$-\lambda_f H\bar{f}f - \lambda_{\tilde{f}}^2|H|^2|\tilde{f}|^2$$



$$\delta m_H^2|_f = -\frac{\lambda_f^2}{16\pi^2}[\Lambda^2 + \ldots]$$



$$\delta m_H^2|_f = \frac{\lambda_{\tilde{f}}^2}{16\pi^2}[\Lambda^2 + \ldots]$$

Supersymmetry imply that $\lambda_f^2 = \lambda_{\tilde{f}}^2$ so the quadratic divergences neatly cancel!

The MSSM

Each SM particle has a superpartner.

Chiral supermultiplets

- spin-$\frac{1}{2}$ quarks: $Q_f = (u_L, d_L)_f, u_{Rf}, d_{Rf}$ $\longleftrightarrow$ spin-0 *squarks*: $\tilde{Q}_f = (\tilde{u}_L, \tilde{d}_L), \tilde{u}_{Rf}, \tilde{d}_{Rf}$
- spin-$\frac{1}{2}$ leptons: $L_f = (\nu, e_L), e_{Rf}$ $\longleftrightarrow$ spin-0 *sleptons*: $\tilde{L}_f = (\tilde{\nu}, \tilde{e}_L)_f, \tilde{e}_{Rf}$
- spin-0 Higgs doublets (**2**!): H_u, H_d $\longleftrightarrow$ spin-$\frac{1}{2}$ *Higgsinos*: $\tilde{H}_u, \tilde{H}_d$

The MSSM

Each SM particle has a superpartner.

Chiral supermultiplets

- spin-$\frac{1}{2}$ quarks: $Q_f = (u_L,\, d_L)_f,\, u_{R\,f},\, d_{R\,f}$ $\longleftrightarrow$ spin-0 *squarks*: $\tilde{Q}_f = (\tilde{u}_L,\, \tilde{d}_L), \tilde{u}_{R\,f}, \tilde{d}_{R\,f}$
- spin-$\frac{1}{2}$ leptons: $L_f = (\nu,\, e_L),\, e_{R\,f}$ $\longleftrightarrow$ spin-0 *sleptons*: $\tilde{L}_f = (\tilde{\nu},\, \tilde{e}_L)_f,\, \tilde{e}_{R\,f}$
- spin-0 Higgs doublets (**2**!): $H_u,\, H_d$ $\longleftrightarrow$ spin-$\frac{1}{2}$ *Higgsinos*: $\tilde{H}_u,\, \tilde{H}_d$

Vector supermultiplets

- spin-1 gauge bosons $g,\, W,\, B$ $\longleftrightarrow$ spin-$\frac{1}{2}$ *gauginos* $\tilde{g},\, \tilde{W},\, \tilde{B}$

MSSM described by $W_{MSSM} = \bar{u}\mathbf{y_u} Q H_u - \bar{d}\mathbf{y_d} Q H_d - \bar{e}\mathbf{y_e} L H_d + \mu H_u H_d$.

The MSSM

Each SM particle has a superpartner.

Chiral supermultiplets

- spin-$\frac{1}{2}$ quarks: $Q_f = (u_L,\, d_L)_f,\, u_{R\,f},\, d_{R\,f}$ $\longleftrightarrow$ spin-0 *squarks*: $\tilde{Q}_f = (\tilde{u}_L,\, \tilde{d}_L), \tilde{u}_{R\,f}, \tilde{d}_{R\,f}$
- spin-$\frac{1}{2}$ leptons: $L_f = (\nu,\, e_L),\, e_{R\,f}$ $\longleftrightarrow$ spin-0 *sleptons*: $\tilde{L}_f = (\tilde{\nu},\, \tilde{e}_L)_f,\, \tilde{e}_{R\,f}$
- spin-0 Higgs doublets (**2**!): $H_u,\, H_d$ $\longleftrightarrow$ spin-$\frac{1}{2}$ *Higgsinos*: $\tilde{H}_u,\, \tilde{H}_d$

Vector supermultiplets

- spin-1 gauge bosons $g,\, W,\, B$ $\longleftrightarrow$ spin-$\frac{1}{2}$ *gauginos* $\tilde{g},\, \tilde{W},\, \tilde{B}$

MSSM described by $W_{MSSM} = \bar{u}\mathbf{y_u}QH_u - \bar{d}\mathbf{y_d}QH_d - \bar{e}\mathbf{y_e}LH_d + \mu H_u H_d$.

None of superpartners observed $\longrightarrow$ SUSY must be broken!

The CCT model: idea

H. Cai, H. C. Cheng, J. Terning, *A spin-1 top quark superpartner*, `arXiv:0806.0386v3 [hep-ph]`

Idea: find a model with a spin-1 stop instead of a spin-0 one.

The CCT model: idea

H. Cai, H. C. Cheng, J. Terning, *A spin-1 top quark superpartner*, `arXiv:0806.0386v3 [hep-ph]`

Idea: find a model with a spin-1 stop instead of a spin-0 one.

How? $SU(5)$ group: $\mathbf{24} \quad \rightarrow \quad (\mathbf{8}, \mathbf{1}, 0) + (\mathbf{1}, \mathbf{3}, 0) + (\mathbf{1}, \mathbf{1}, 0) + (\mathbf{3}, \mathbf{2}, \frac{1}{6}) + (\bar{\mathbf{3}}, \mathbf{2}, -\frac{1}{6})$

The CCT model: idea

H. Cai, H. C. Cheng, J. Terning, *A spin-1 top quark superpartner*, `arXiv:0806.0386v3 [hep-ph]`

Idea: find a model with a spin-1 stop instead of a spin-0 one.

How? $SU(5)$ group: $\mathbf{24} \quad \rightarrow \quad (\mathbf{8}, \mathbf{1}, 0) + (\mathbf{1}, \mathbf{3}, 0) + (\mathbf{1}, \mathbf{1}, 0) + (\mathbf{3}, \mathbf{2}, \frac{1}{6}) + (\bar{\mathbf{3}}, \mathbf{2}, -\frac{1}{6})$

The broken generators have the same quantum numbers of $t_L, \bar{t}_L$.

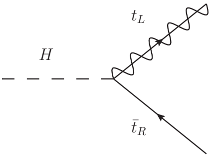
The CCT model: idea

H. Cai, H. C. Cheng, J. Terning, *A spin-1 top quark superpartner*, `arXiv:0806.0386v3 [hep-ph]`

Idea: find a model with a spin-1 stop instead of a spin-0 one.

How? $SU(5)$ group: $\mathbf{24} \quad \rightarrow \quad (\mathbf{8},\mathbf{1},0)+(\mathbf{1},\mathbf{3},0)+(\mathbf{1},\mathbf{1},0)+(\mathbf{3},\mathbf{2},\frac{1}{6})+(\bar{\mathbf{3}},\mathbf{2},-\frac{1}{6})$

The broken generators have the same quantum numbers of $t_L, \bar{t}_L$.



$\longleftrightarrow$

The top yukawa term becomes a gaugino interaction term

$\rightarrow$ $\bar{t}_R$ still in a chiral supermultiplet.

Unified with the Higgs, in a **5** of $SU(5)$:

$\bar{I} \supset (\bar{\tilde{T}}, H_d) + \theta(\overline{T}, \tilde{H}_d), \quad I \supset (\bar{\tilde{T}}^c, H_u) + \theta(\overline{T}^c, \tilde{H}_u)$

The CCT model: realization

Gauge group: $\mathscr{G} = SU(3) \times SU(2) \times U(1)_H \times U(1)_V \times SU(5)$

Fields	SU(3)	SU(2)	$U(2)_H$	$U(1)_V$	SU(5)	$Y = H + V + \frac{1}{\sqrt{15}} T_{24}$
Q_i	$\square$	$\square$	$\frac{1}{6}$	0	**1**	$\frac{1}{6}$
$\bar{u}_i$	$\bar{\square}$	**1**	-$\frac{2}{3}$	0	**1**	-$\frac{2}{3}$
$\bar{d}_i$	$\bar{\square}$	**1**	$\frac{1}{3}$	0	**1**	$\frac{1}{3}$
L_i	**1**	$\square$	$-\frac{1}{2}$	0	**1**	$-\frac{1}{2}$
$\bar{e}_i$	**1**	**1**	1	0	**1**	1
I	**1**	**1**	$\frac{1}{2}$	$\frac{1}{10}$	$\square$	$\left(\frac{2}{3}, \frac{1}{2}\right)$
$\bar{I}$	**1**	**1**	$-\frac{1}{2}$	$-\frac{1}{10}$	$\bar{\square}$	$\left(-\frac{2}{3}, -\frac{1}{2}\right)$
Φ_3	$\bar{\square}$	**1**	-$\frac{1}{6}$	$\frac{1}{10}$	$\square$	$\left(0, -\frac{1}{6}\right)$
Φ_2	**1**	$\bar{\square}$	0	$\frac{1}{10}$	$\square$	$\left(\frac{1}{6}, 0\right)$
$\bar{\Phi}_3$	$\square$	**1**	$\frac{1}{6}$	$-\frac{1}{10}$	$\bar{\square}$	$\left(0, \frac{1}{6}\right)$
$\bar{\Phi}_2$	**1**	$\square$	0	$-\frac{1}{10}$	$\bar{\square}$	$\left(-\frac{1}{6}, 0\right)$

$$
\begin{aligned}
W_{CCT} = & y_1 Q_3 \Phi_3 \bar{\Phi}_2 + \mu_3 \Phi_3 \bar{\Phi}_3 + \mu_2 \Phi_2 \bar{\Phi}_2 + y_2 \bar{u}_3 I \bar{\Phi}_3 + \mu_I I \bar{I} \\
& + Y_{Uij} Q_i \bar{u}_j \bar{\Phi}_2 I + Y_{Dij} Q_i \bar{d}_j \Phi_2 \bar{I} + Y_{Eij} L_i \bar{e}_j \Phi_2 \bar{I}.
\end{aligned}
$$

The CCT model: realization

Gauge group: $\mathscr{G} = SU(3) \times SU(2) \times U(1)_H \times U(1)_V \times SU(5)$

Fields	SU(3)	SU(2)	U(2)$_H$	U(1)$_V$	SU(5)	$Y = H + V + \frac{1}{\sqrt{15}} T_{24}$
Q_i	$\square$	$\square$	$\frac{1}{6}$	0	**1**	$\frac{1}{6}$
$\bar{u}_i$	$\bar{\square}$	**1**	$-\frac{2}{3}$	0	**1**	$-\frac{2}{3}$
$\bar{d}_i$	$\bar{\square}$	**1**	$\frac{1}{3}$	0	**1**	$\frac{1}{3}$
L_i	**1**	$\square$	$-\frac{1}{2}$	0	**1**	$-\frac{1}{2}$
$\bar{e}_i$	**1**	**1**	1	0	**1**	1
I	**1**	**1**	$\frac{1}{2}$	$\frac{1}{10}$	$\square$	$\left(\frac{2}{3}, \frac{1}{2}\right)$
$\bar{I}$	**1**	**1**	$-\frac{1}{2}$	$-\frac{1}{10}$	$\bar{\square}$	$\left(-\frac{2}{3}, -\frac{1}{2}\right)$
Φ_3	$\bar{\square}$	**1**	$-\frac{1}{6}$	$\frac{1}{10}$	$\square$	$\left(0, -\frac{1}{6}\right)$
Φ_2	**1**	$\bar{\square}$	0	$\frac{1}{10}$	$\square$	$\left(\frac{1}{6}, 0\right)$
$\bar{\Phi}_3$	$\square$	**1**	$\frac{1}{6}$	$-\frac{1}{10}$	$\bar{\square}$	$\left(0, \frac{1}{6}\right)$
$\bar{\Phi}_2$	**1**	$\square$	0	$-\frac{1}{10}$	$\bar{\square}$	$\left(-\frac{1}{6}, 0\right)$

$$W_{CCT} = y_1 Q_3 \Phi_3 \bar{\Phi}_2 + \mu_3 \Phi_3 \bar{\Phi}_3 + \mu_2 \Phi_2 \bar{\Phi}_2 + y_2 \bar{u}_3 I \bar{\Phi}_3 + \mu_I I \bar{I}$$
$$+ Y_{Uij} Q_i \bar{u}_j \bar{\Phi}_2 I + Y_{Dij} Q_i \bar{d}_j \Phi_2 \bar{I} + Y_{Eij} L_i \bar{e}_j \Phi_2 \bar{I}.$$

The CCT model: realization

Gauge group: $\mathscr{G} = SU(3) \times SU(2) \times U(1)_H \times U(1)_V \times SU(5)$

Fields	SU(3)	SU(2)	$U(2)_H$	$U(1)_V$	SU(5)	$Y = H + V + \frac{1}{\sqrt{15}} T_{24}$
Q_i	$\square$	$\square$	$\frac{1}{6}$	0	**1**	$\frac{1}{6}$
$\bar{u}_i$	$\bar{\square}$	**1**	$-\frac{2}{3}$	0	**1**	$-\frac{2}{3}$
$\bar{d}_i$	$\bar{\square}$	**1**	$\frac{1}{3}$	0	**1**	$\frac{1}{3}$
L_i	**1**	$\square$	$-\frac{1}{2}$	0	**1**	$-\frac{1}{2}$
$\bar{e}_i$	**1**	**1**	1	0	**1**	1
I	**1**	**1**	$\frac{1}{2}$	$\frac{1}{10}$	$\square$	$\left(\frac{2}{3}, \frac{1}{2}\right)$
$\bar{I}$	**1**	**1**	$-\frac{1}{2}$	$-\frac{1}{10}$	$\bar{\square}$	$\left(-\frac{2}{3}, -\frac{1}{2}\right)$
Φ_3	$\bar{\square}$	**1**	$-\frac{1}{6}$	$\frac{1}{10}$	$\square$	$\left(0, -\frac{1}{6}\right)$
Φ_2	**1**	$\bar{\square}$	0	$\frac{1}{10}$	$\square$	$\left(\frac{1}{6}, 0\right)$
$\bar{\Phi}_3$	$\square$	**1**	$\frac{1}{6}$	$-\frac{1}{10}$	$\bar{\square}$	$\left(0, \frac{1}{6}\right)$
$\bar{\Phi}_2$	**1**	$\square$	0	$-\frac{1}{10}$	$\bar{\square}$	$\left(-\frac{1}{6}, 0\right)$

$$
\begin{aligned}
W_{CCT} =& y_1 Q_3 \Phi_3 \bar{\Phi}_2 + \mu_3 \Phi_3 \bar{\Phi}_3 + \mu_2 \Phi_2 \bar{\Phi}_2 + y_2 \bar{u}_3 I \bar{\Phi}_3 + \mu_I I \bar{I} \\
&+ Y_{Uij} Q_i \bar{u}_j \bar{\Phi}_2 I + Y_{Dij} Q_i \bar{d}_j \Phi_2 \bar{I} + Y_{Eij} L_i \bar{e}_j \Phi_2 \bar{I}.
\end{aligned}
$$

The CCT model: realization

After SUSY breaking, $\mathscr{G}$ is diagonally broken by the VEVs of $\Phi_2, \Phi_3, \bar{\Phi}_2, \bar{\Phi}_3$ into

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

The CCT model: realization

After SUSY breaking, $\mathscr{G}$ is diagonally broken by the VEVs of $\Phi_2, \Phi_3, \bar{\Phi}_2, \bar{\Phi}_3$ into

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

The following fields have the quantum numbers of t_L (and $\bar{t}_L$)

$$\begin{array}{ccccc}
Q_3 & \rightarrow & (\mathbf{3}, \mathbf{2}, \frac{1}{6}) & \rightarrow & Q_3 \\
\mathbf{24} & \rightarrow & (\mathbf{8}, \mathbf{1}, 0) + (\mathbf{1}, \mathbf{3}, 0) + (\mathbf{1}, \mathbf{1}, 0) + (\mathbf{3}, \mathbf{2}, \frac{1}{6}) + (\bar{\mathbf{3}}, \mathbf{2}, -\frac{1}{6}) & \rightarrow & \lambda, \bar{\lambda} \\
\bar{\Phi}_3 & \rightarrow & (\mathbf{1}, \mathbf{1}, 0) + (\mathbf{8}, \mathbf{1}, 0) + (\mathbf{3}, \mathbf{2}, \frac{1}{6}) & \rightarrow & \bar{\Phi}_{3\,t} \\
\Phi_2 & \rightarrow & (\mathbf{3}, \mathbf{2}, \frac{1}{6}) + (\mathbf{1}, \mathbf{1}, 0) + (\mathbf{1}, \mathbf{3}, 0) & \rightarrow & \Phi_{2\,t}
\end{array}$$

and of $\bar{t}_R$

$$\begin{array}{ccccc}
\bar{u}_3 & \rightarrow & (\bar{\mathbf{3}}, \mathbf{1}, -\frac{2}{3}) & \rightarrow & \bar{u}_3 \\
\bar{I} & \rightarrow & (\mathbf{3}, 1, -\frac{2}{3}) + (1, \mathbf{2}, -\frac{1}{2}) & \rightarrow & \overline{T}
\end{array}$$

The CCT model: realization

After SUSY breaking, $\mathscr{G}$ is diagonally broken by the VEVs of $\Phi_2, \Phi_3, \bar{\Phi}_2, \bar{\Phi}_3$ into

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

The following fields have the quantum numbers of t_L (and $\bar{t}_L$)

$$\begin{array}{lcccl}
Q_3 & \to & (\mathbf{3}, \mathbf{2}, \frac{1}{6}) & \to & Q_3 \\
\mathbf{24} & \to & (\mathbf{8}, \mathbf{1}, 0) + (\mathbf{1}, \mathbf{3}, 0) + (\mathbf{1}, \mathbf{1}, 0) + (\mathbf{3}, \mathbf{2}, \frac{1}{6}) + (\bar{\mathbf{3}}, \mathbf{2}, -\frac{1}{6}) & \to & \lambda, \bar{\lambda} \\
\bar{\Phi}_3 & \to & (\mathbf{1}, \mathbf{1}, 0) + (\mathbf{8}, \mathbf{1}, 0) + (\mathbf{3}, \mathbf{2}, \frac{1}{6}) & \to & \bar{\Phi}_{3\,t} \\
\Phi_2 & \to & (\mathbf{3}, \mathbf{2}, \frac{1}{6}) + (\mathbf{1}, \mathbf{1}, 0) + (\mathbf{1}, \mathbf{3}, 0) & \to & \Phi_{2\,t}
\end{array}$$

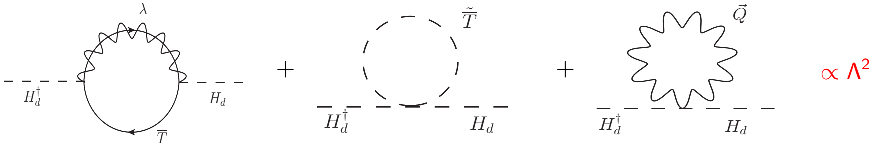
and of $\bar{t}_R$

$$\begin{array}{lcccl}
\bar{u}_3 & \to & (\bar{\mathbf{3}}, \mathbf{1}, -\frac{2}{3}) & \to & \bar{u}_3 \\
\bar{I} & \to & (\mathbf{3}, 1, -\frac{2}{3}) + (1, \mathbf{2}, -\frac{1}{2}) & \to & \overline{T}
\end{array}$$

With a certain choice of parameters (couplings, gaugino masses, VEVs) $\to$ t_L mainly λ, $\bar{t}_R$ mainly $\overline{T}$.

CCT: quadratic divergences

Do quadratic divergences due to top/stop loops cancel each other?



No, we need to consider all the scalar particles of the $SU(5)$ multiplet of the Higgs.

Why? probably because of the previous $\mathscr{G}$ symmetry breaking.

Consequence: It's hard to place strict mass bounds on $\vec{Q}$

$\downarrow$

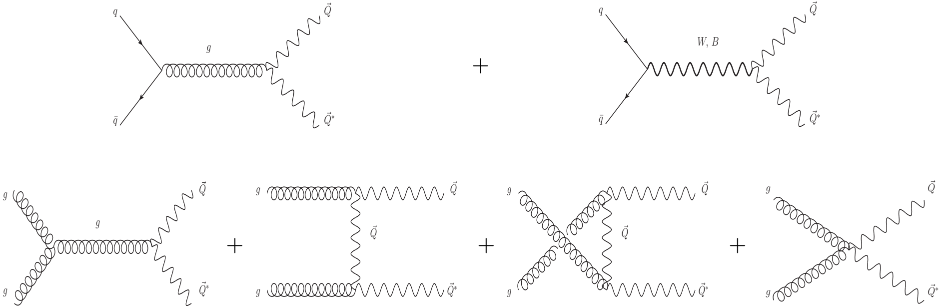
Let's consider $m_{\vec{Q}}$ as a free parameter (expected between 100 GeV and 1 TeV)

Effective theory at the LHC: SM + $\vec{Q}, \vec{Q}^*$

$$\mathscr{L}_{\vec{Q}} = -(D_\mu \vec{Q}_\nu)^\dagger [D^\mu \vec{Q}^\nu - D^\nu \vec{Q}^\mu] + m^2_{\vec{Q}} \vec{Q}_\mu \vec{Q}^{*\,\mu} + g'^2 \vec{Q}\vec{Q}^* |H|^2 + \text{decay operators}$$

with $D_\mu \vec{Q}_\nu = \left(\partial_\mu + i g_2 W_{a\mu} \frac{\sigma^a}{2} + i g_1 B_\mu \frac{\mathbb{1}}{6} + i \frac{g_S}{2} \lambda^b g^b_\mu\right) \vec{Q}_\nu$

Production modes at the LHC (L.O.):



Production cross section of $\vec{Q}$, $\vec{Q}^*$

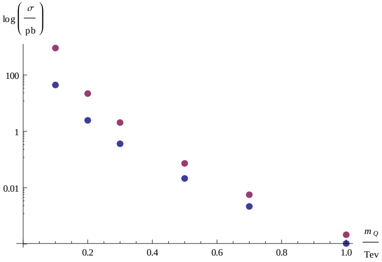


Figure: $\sigma(pp \to \vec{Q}\vec{Q}^*)$ from quarks (blue points) and gluons (purple points) vs $m_{\vec{Q}}$ at $\sqrt{s} = 7$ TeV

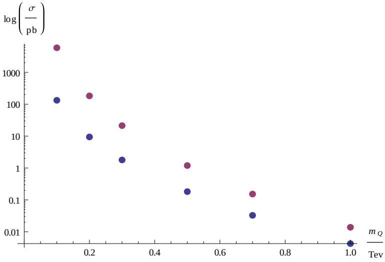


Figure: $\sigma(pp \to \vec{Q}\vec{Q}^*)$ from quarks (blue points) and gluons (purple points) vs $m_{\vec{Q}}$ at $\sqrt{s} = 14$ TeV

$$\hat{\sigma}(q\bar{q} \to \vec{Q}\vec{Q}^*) = \frac{2\pi}{9}\alpha_s^2 \frac{1}{\hat{s}^2}\left[\frac{\hat{s}^2}{3m_{\vec{Q}}^2} - \frac{\hat{s}}{3} - 4m_{\vec{Q}}^2\right]$$

$$\hat{\sigma}(gg \to \vec{Q}\vec{Q}^*) = \frac{\alpha_s^2}{8\hat{s}}\frac{\pi}{64}\frac{2}{3}\left(\frac{13\hat{s}^2}{m_{\vec{Q}}^4} - \frac{52\hat{s}}{m_{\vec{Q}}^2}\right)$$

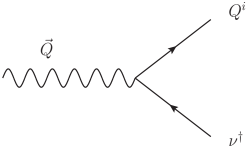
Leading contribute from $gg \to \vec{Q}\vec{Q}^*$ process.

Decay scenarios

With this particle spectrum, we have different scenarios, depending on the charges we assign $\vec{Q}$:

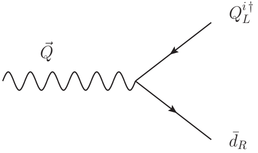
- $\vec{Q}$ has R-charge -1 and we introduce a lighter goldstino ν with R-charge -1. If $\vec{Q}$ has Barion number the following lagrangian term is allowed

$$gQ_L^{i\,\dagger}\epsilon\vec{Q}\sigma\nu \qquad \rightarrow$$



- $\vec{Q}$ has R-charge $+1$ and doesn't have Barion number. It's permitted the operator:

$$gQ_L^i\epsilon\vec{Q}\sigma d_R^j \qquad \rightarrow$$



Conclusions

- A model with a top left in a vector supermultiplet is available.
- At low energies, the structure of loop cancellation is delicate, involving many particles.
- At the LHC energies we have that the most important contribute to production cross section comes from $gg \to \vec{Q}\vec{Q}^*$ process.
- Depending on the R-charge of $\vec{Q}$, we have different scenarios.

Thank you very much!

The MSSM

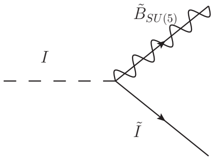
Chiral supermultiplets		Spin 0	Spin 1/2	$SU(3)_C \times SU(2)_L \times U(1)_Y$
Squarks-Quarks	Q_f	$\begin{pmatrix} \tilde{u}_L \\ \tilde{d}_L \end{pmatrix}$	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$(\mathbf{3}, \mathbf{2}, \frac{1}{6})$
(one for each $f = u, c, t$)	$\bar{u}$	$\tilde{u}_R^*$	$u_R^\dagger$	$(\bar{\mathbf{3}}, \mathbf{1}, -\frac{2}{3})$
	$\bar{d}$	$\tilde{d}_R^*$	$d_R^\dagger$	$(\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3})$
Sleptons-Leptons	L_ϕ	$\begin{pmatrix} \tilde{\nu} \\ \tilde{e}_L \end{pmatrix}$	$\begin{pmatrix} \nu \\ e_L \end{pmatrix}$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$
(one for each $\phi = e, \mu, \tau$)	$\bar{e}$	$\tilde{e}_R^*$	$e_R^\dagger$	$(\mathbf{1}, \mathbf{1}, 1)$
Higgses-Higgsinos	H_u	$\begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$	$\begin{pmatrix} \tilde{H}_u^+ \\ \tilde{H}_u^0 \end{pmatrix}$	$(\mathbf{1}, \mathbf{2}, +\frac{1}{2})$
	H_d	$\begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$	$\begin{pmatrix} \tilde{H}_d^0 \\ \tilde{H}_d^- \end{pmatrix}$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$

Vector supermultiplets	Spin $\frac{1}{2}$	Spin 1	$SU(3)_C \times SU(2)_L \times U(1)_Y$
Gluinos-Gluons	$\tilde{g}$	g	$(\mathbf{8}, \mathbf{1}, 0)$
Winos-Ws	$\tilde{W}^\pm, \ \tilde{W}^0$	$W^\pm, \ W^0$	$(\mathbf{1}, \mathbf{3}, 0)$
Bino-B	$\tilde{B}^0$	B^0	$(\mathbf{1}, \mathbf{1}, 0)$

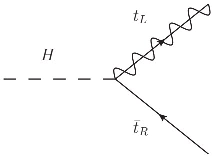
Described by $W_{MSSM} = \bar{u}\mathbf{y_u}QH_u - \bar{d}\mathbf{y_d}QH_d - \bar{e}\mathbf{y_e}LH_d + \mu H_u H_d$.

The CCT model: gaugino coupling

SUSY permits:



Then, after SUSY and $\mathscr{G}$ breaking



$\longleftrightarrow$

The top yukawa term becomes a gaugino interaction term

$\downarrow$

t_R still has a scalar partner.

Unified in a supermultiplet containing the Higgs, **5** under $SU(5)$:

$$\bar{I} = (\bar{T}, H_d),\ I = (\bar{T}^c, H_u)$$

The CCT model: realization

After SUSY breaking, the potential for $\Phi_2, \Phi_3, \bar{\Phi}_2, \bar{\Phi}_3$ is assumed to be unstable so that they gets VEVs:

$$\langle \Phi_3 \rangle = \begin{pmatrix} f_3 & 0 & 0 & 0 & 0 \\ 0 & f_3 & 0 & 0 & 0 \\ 0 & 0 & f_3 & 0 & 0 \end{pmatrix}, \qquad \langle \overline{\Phi}_3 \rangle^T = \begin{pmatrix} \bar{f}_3 & 0 & 0 & 0 & 0 \\ 0 & \bar{f}_3 & 0 & 0 & 0 \\ 0 & 0 & \bar{f}_3 & 0 & 0 \end{pmatrix},$$

$$\langle \Phi_2 \rangle = \begin{pmatrix} 0 & 0 & 0 & f_2 & 0 \\ 0 & 0 & 0 & 0 & f_2 \end{pmatrix}, \qquad \langle \overline{\Phi}_2 \rangle^T = \begin{pmatrix} 0 & 0 & 0 & \bar{f}_2 & 0 \\ 0 & 0 & 0 & 0 & \bar{f}_2 \end{pmatrix},$$

$$\downarrow$$

$\mathscr{G}$ is diagonally broken by the VEVs into

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

The CCT model: realization

After the breaking of $\mathscr{G}$ into $SU(3)_C \times SU(2)_L \times U(1)_Y$:

these fields have the quantum numbers of t_L (and $\bar{t}_L$)

$$
\begin{array}{lclcl}
Q_3 & \to & (\mathbf{3},\mathbf{2},\frac{1}{6}) & \to & Q_3 \\
\mathbf{24} & \to & (\mathbf{8},\mathbf{1},0)+(\mathbf{1},\mathbf{3},0)+(\mathbf{1},\mathbf{1},0)+(\mathbf{3},\mathbf{2},\frac{1}{6})+(\bar{\mathbf{3}},\mathbf{2},-\frac{1}{6}) & \to & \lambda,\bar{\lambda} \\
\bar{\Phi}_3 & \to & (\mathbf{1},\mathbf{1},0)+(\mathbf{8},\mathbf{1},0)+(\mathbf{3},\mathbf{2},\frac{1}{6}) & \to & \bar{\Phi}_{3\,t} \\
\Phi_2 & \to & (\mathbf{3},\mathbf{2},\frac{1}{6})+(\mathbf{1},\mathbf{1},0)+(\mathbf{1},\mathbf{3},0) & \to & \Phi_{2\,t}
\end{array}
$$

and of $\bar{t}_R$

$$
\begin{array}{lclcl}
\bar{u}_3 & \to & (\bar{\mathbf{3}},\mathbf{1},-\frac{2}{3}) & \to & \bar{u}_3 \\
\bar{I} & \to & (\mathbf{3},1,-\frac{2}{3})+(1,\mathbf{2},-\frac{1}{2}) & \to & \overline{T}
\end{array}
$$

The CCT model: realization

With a certain choice of parameters (couplings, gaugino masses, VEVs):

$\hat{g}_5 = 1.2,\ y_1 = 1.5,\ y_2 = 1.5,\ M_5 = 0.7\,\text{TeV},\ \mu_3 = 2\,\text{TeV},\ \mu_2 = 5\,\text{TeV}, \mu_H = 0.3\,\text{TeV},$
$\bar{f}_2 = 1.5\,\text{TeV},\ f_2 = 1.7\,\text{TeV},\ \bar{f}_3 = 0.6\,\text{TeV}$

Mass matrices

	λ	$\Phi_{2\,t}$	$\overline{\Phi}_{3\,t}$	Q_3
$\overline{\lambda}$	M_5	$\hat{g}_5 f_2$	$\hat{g}_5 \bar{f}_3$	0
$\overline{\Phi}_{2\,t}$	$\hat{g}_5 \bar{f}_2$	μ_2	0	$y_1 f_3$
$\Phi_{3\,t}$	$\hat{g}_5 f_2$	0	μ_3	$y_1 \bar{f}_2$
$\overline{Q}_3$	0	0	0	0

$\rightarrow$ t_L is mainly λ

	$\overline{T}$	$\bar{u}_3$
$\overline{T}^c$	μ_H	$y_2 \bar{f}_2$
u_3	0	0

$\rightarrow$ $\bar{t}_R$ is mainly $\overline{T}$

Eigenvector of zero mass

$\rightarrow$ yukawan vertex is mainly $\hat{g}_5 H_d^\dagger \lambda \overline{T}$.