Minimal Matter at the Large Hadron Collider

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Abstract

We classify all possible new $U(1)_Y \otimes SU(2)_L \otimes SU(3)_c$ multiplets that can couple to pairs of SM particles. Assuming that production of such new particles is dominated by their gauge interactions we study their signals at LHC, finding the following five main classes: i) lepto-quark $2\ell 2q$ signals; ii) di-lepton $4\ell$ signals; iii) di-quarks $4j$ signals, iv) heavy-lepton $2\ell 2V$ signals and v) heavy quarks $2j 2V$ signals, where $V$ denotes heavy SM vectors (with $W$ being associated to exotic fermions). In each case we outline the most promising final states, the SM backgrounds and propose the needed searches.

1 Introduction

The Higgs mass hierarchy puzzle suggests new physics around the electroweak scale. It is usually assumed that new particles carry a new conserved quantum number, such that the lightest new particle is a stable Dark Matter candidate, and such that new physics affects electroweak precision data only at loop level. The main scenario is supersymmetry with conserved $R$-parity, where all new particles are odd under a $Z_2$ matter parity. Little-Higgs with $T$-parity could be a possible alternative \cite{1}. Some authors also consider extra dimensions with a $Z_2$ orbifold symmetry \cite{2}. These scenarios introduce a lot of new particles with unknown masses
and consequently suggest a huge variety of possible manifestations at LHC. Their common feature relevant for LHC signatures is the lack of $Z_2$-odd couplings of the form

$$\lambda \text{ (SM particle)} \cdot \text{ (SM particle)} \cdot \text{ (new particle)}. \quad (1)$$

In section 2 we consider a different scenario that suggests well-defined signatures: we add to the SM one electroweak multiplet with a mass term and renormalizable couplings to SM particles of the form of eq. (1). The Lagrangian is restricted only by imposing the SM gauge and Lorentz symmetries, not by new symmetries. We find that 28 possible new multiplets can have such couplings: 13 fermions (table 1) plus 15 scalars (listed in table 2); or equivalently 18 colored (shaded in red) plus 10 uncolored (shaded in blue).

We assume that the couplings $\lambda$ are small enough that production of new particles is dominated by their SM gauge interactions (weak or strong), and $\lambda$ is only relevant for decays of new particles, discussed in section 3. In this limit precision and flavor data are satisfied [3], and one obtains well-defined scenarios of new physics, allowing us to study their well-defined signals at LHC, that can be computed in terms of $M$, up to a minor dependence on $\lambda$ and on its flavor structure. LHC is the main probe because the smallness of $\lambda$ suppresses the width of these new particles, not their production cross section. This is unlike the case of new $Z'$ vectors, that gives signals both at LHC and in precision data (which did not show deviations from the SM) only if its coupling constant is large enough.

As well known, dedicated searches are usually necessary to discover new phenomena among the huge backgrounds present at hadron colliders. These 28 new-physics scenarios give rise to five main classes of signatures with well defined peaks in appropriate invariant-mass variables that we discuss in five dedicated sections: 4$q$ signatures (discussed in section 4), 4$\ell$ (section 5), 2$\ell 2V$ (section 6), 2$q 2V$ (section 7), 2$\ell 2q$ (section 8), where $q$ denotes SM quarks, $\ell$ denotes SM leptons and $V = \{W^\pm, Z, h\}$. Section 9 contains our conclusions.

## 2 New matter and its production

We denote the SM fermions as $L, E, Q, U, D$ and the SM Higgs doublet as $H$. The $L', E', Q', U', D'$ multiplets in table 1 denote new fermions with the same gauge quantum numbers of the SM.
Table 1: List of new fermions that can couple to two SM particles. $L', E', Q', U', D'$ denote new fermion-antifermions with quantum numbers equal to the corresponding unprimed chiral SM fermions. Colored (uncolored) particles in red (blue). The last four multiplets involve exotic electric charges.

| Name   | spin $|U(1)_Y|$ | SU(2)$_L$ | SU(3)$_C$ | $|Q| = |T_3 + Y|$ | couplings to type          |
|--------|-----------|-----------|-----------|-----------------|-----------------------------|
| $N'$   | $\frac{1}{2}$ | 0         | 1         | 1               | 0                          | $LH$ type-I see-saw          |
| $L'$   | $\frac{1}{2}$ | -1        | 2         | 1               | 0,1                        | $EH^*$ $LH$                  |
| $E'$   | $\frac{1}{2}$ | 1         | 1         | 1               | 1                          | $LH^*$ $LH$                  |
| $N_3$  | $\frac{1}{2}$ | 0         | 3         | 1               | 0,1                        | $LH$ type-III see-saw        |
| $E_3$  | $\frac{1}{2}$ | 1         | 3         | 1               | 0,1                        | $LH^*$ $LH$                  |
| $L_{3/2}$ | $\frac{1}{2}$ | $\frac{3}{2}$ | 2         | 1               | 1,2                        | $EH^*$ $LH$                  |
| $Q'$   | $\frac{1}{2}$ | $\frac{3}{2}$ | 2         | 3               | 1/3, 2/3                   | $HU, H^*D$ $QH$              |
| $U'$   | $\frac{1}{2}$ | $\frac{3}{2}$ | 1         | 3               | 2/3                        | $HQ$ $QH$                    |
| $D'$   | $\frac{1}{2}$ | $\frac{3}{2}$ | 3         | 3               | 1/3                        | $H^*Q$ $QH$                  |
| $U_3$  | $\frac{1}{2}$ | $\frac{3}{2}$ | 3         | 3               | 1/3, 2/3, 3/5/3            | $QH^*$ $QH$                  |
| $D_3$  | $\frac{1}{2}$ | $\frac{3}{2}$ | 3         | 3               | 1/3, 2/3, 3/4/3            | $QH^*$ $QH$                  |
| $Q^{5/6}$ | $\frac{1}{2}$ | $\frac{5}{6}$ | 2         | 3               | 1/3, 4/3                   | $DH^*$ $QH$                  |
| $Q^{7/6}$ | $\frac{1}{2}$ | $\frac{7}{6}$ | 2         | 3               | 2/3, 5/3                   | $UH^*$ $QH$                  |

Table 2: List of new scalars that can couple to two SM particles. Colored (uncolored) particles in red (blue).

| Name   | spin $|U(1)_Y|$ | SU(2)$_L$ | SU(3)$_C$ | $|Q| = |T_3 + Y|$ | couplings to type          |
|--------|-----------|-----------|-----------|-----------------|-----------------------------|
| $H'$   | 0         | $\frac{1}{2}$ | 2         | 1               | 0,1                        | $LE, QU, QD$ second Higgs   |
| $\tilde{E}$ | 0         | 1         | 1         | 1               | 1                          | $LL$ $LL$                   |
| $\tilde{E}^2$ | 0         | 2         | 1         | 1               | 2                          | $EE$ $LL$                   |
| $\tilde{E}_3$ | 0         | 1         | 3         | 1               | 0,1, 2                     | $LL, H^*H^*$ type-II see-saw|
| $\tilde{Q}$ | 0         | $\frac{1}{2}$ | 2         | 3               | 1/3, 2/3                   | $LD$ $LQ$                   |
| $\tilde{Q}^{5/6}$ | 0         | $\frac{5}{6}$ | 2         | 3               | 2/3, 5/3                   | $LU, \tilde{E}^2Q$ $LQ$     |
| $\tilde{D}$ | 0         | $\frac{1}{2}$ | 1         | 3               | 1/3                        | $LQ, \tilde{E}^2U, UD, \tilde{Q}Q$ $LQ/QQ$ |
| $\tilde{D}_3$ | 0         | $\frac{1}{2}$ | 3         | $\bar{3}$       | 1/3, 2/3, 3/4/3            | $LQ, \tilde{Q}^2Q$ $LQ/QQ$  |
| $\tilde{D}_6$ | 0         | $\frac{1}{2}$ | 1         | 6               | 1/3                        | $UD, \tilde{Q}Q$ $QQ$       |
| $\tilde{D}_{36}$ | 0         | $\frac{1}{2}$ | 3         | 3               | 1/3, 2/3, 3/4/3            | $\tilde{Q}^2Q$ $QQ$         |
| $\tilde{U}$ | 0         | $\frac{1}{2}$ | 1         | 3               | 2/3                        | $DD$ $QQ$                   |
| $\tilde{U}_6$ | 0         | $\frac{1}{2}$ | 1         | 6               | 2/3                        | $DD$ $QQ$                   |
| $\tilde{q}^{4/3}$ | 0         | $\frac{1}{2}$ | 1         | $\bar{3}$       | 4/3                        | $UU, ED$ $QQ$               |
| $\tilde{q}^{4/3}_6$ | 0         | $\frac{1}{2}$ | 1         | 6               | 4/3                        | $UU$ $QQ$                   |
| $H_8$ | 0         | $\frac{1}{2}$ | 2         | 8               | 0,1                        | $QU, QD$ $QQ$               |
Table 3: Color factors $C$ that enter in $d\sigma/d\hat{t}$, defined as $\text{Tr}T^aT^b = C\delta^{ab}$.

| SU(3) representation | dimension $d$ | Casimir $C$ |
|----------------------|--------------|-------------|
| singlet              | 1            | 0           |
| triplet              | 3            | 1/2         |
| sextet               | 6            | 5/2         |
| octet                | 8            | 3           |

ones plus the corresponding conjugated representations in order to make them non-chiral allowing for a gauge-invariant Dirac mass term $M$. Similarly the first row of table 2 presents $H'$, i.e. a second Higgs doublet. The other rows list the new exotic particles (i.e. they have quantum numbers different from SM particles) that can have cubic couplings with the SM particles. In order to denote these new particles in a systematic way, a tilde denote the 15 scalars (so that, in MSSM-like notation, $E, L, Q, U, D$ have the same quantum numbers as the corresponding untilted SM leptons and quarks). When new particles have SU(2)$_L$ interactions different than SM particles, a subscript 3 denotes that they form a triplet under SU(2)$_L$: for example $\tilde{E}_3$ is a scalar triplet with the same couplings as the one that appears in type-II see-saw. When new particles have non-standard color interactions, a subscript 6 and 8 denotes they are sextet or octet under color SU(3)$_c$. When new multiplet have a non-standard hypercharge, it is added as superscript.

Up to a few more cubic and quartic scalar couplings involving the Higgs doublet this makes the full list of possible renormalizable interactions between SM multiplets and one new multiplet. We do not consider the possibility of adding new massive vectors, because they should be accompanied by new gauge groups broken by new higgses, giving rise to many new non-minimal possibilities, already studied as extra $Z'$, etc.

The partonic processes that lead to pair production of new particles $X$ (either fermions $\psi$ or scalars $A$) in $pp$ collisions are

$$q\bar{q} \to g, \gamma, Z \to XX \quad u\bar{d} \to W^+ \to X_1X_2, \quad gg \to XX.$$  \hspace{1cm} (2)

Figure 1 shows the corresponding Feynman diagrams. The partonic production cross sections, summed over final state colors and polarizations, and averaged over initial state colors and polarizations, are

$$\frac{d\sigma}{dt}(q_1\bar{q}_2 \to \psi_1\bar{\psi}_2) = \frac{V_L^2 + V_R^2}{144\pi s^2} (2M_1^2M_2^2 + s^2 - 2(M_1^2 + M_2^2)\hat{t} + 2\hat{t}^2 + \hat{s}(2\hat{t} - (M_1 - M_2)^2)), \hspace{1cm} (3a)$$

$$\frac{d\sigma}{dt}(q_1\bar{q}_2 \to A_1A_2^*) = \frac{V_L^2 + V_R^2}{144\pi s^2} (M_1^2M_2^2 - (M_1^2 + M_2^2)\hat{t} + \hat{t}^2 + \hat{s}), \hspace{1cm} (3b)$$

$$\frac{d\sigma}{dt}(gg \to \psi\bar{\psi}) = \frac{g_3^2C}{8\pi d\hat{s}^2} \left[ C - \frac{3d}{8\hat{s}^2}(\hat{t} - M^2)(\hat{u} - M^2) \right] f_{\psi\psi}, \hspace{1cm} (3c)$$

$$\frac{d\sigma}{dt}(gg \to AA^*) = \frac{g_3^2C}{8\pi d\hat{s}^2} \left[ C - \frac{3d}{8\hat{s}^2}(\hat{t} - M^2)(\hat{u} - M^2) \right] f_{AA}. \hspace{1cm} (3d)$$
The CDF and D0 experiments published bounds down to few fb on various processes.

1 Given the new particles listed in tables 1 and 2, pair production of real scalars or fermions is never relevant for us. In such cases the cross sections must be divided by 2, and with this specification our formulas are fully general, allowing e.g. to compute production of an electro-weak neutral color octet scalar or fermion, such as the supersymmetric Majorana gluino.

2 Should LHC reach only a fraction \( r \sim 1/2 \) of its planned energy, the reduced cross section are roughly obtained modifying the masses \( M \) on the horizontal axis of fig. 2a as \( M \rightarrow r \cdot M \).
Figure 2: Cross sections for pair production via gauge interactions at leading order in hadronic collisions of new particles $X\bar{X}$ labelled as $P^Q_{T_3}$ where $Q$ is the electric charge, $T_3$ is weak isospin and $P = F$ ($S$) for a fermion (scalar). Cross sections of colored particles (in red) negligibly depend on their electroweak interactions, so we adopted the simplified notation $P_d$ where $d = \{3, 6, 8\}$ for color triplets, sextets and real color octets. Couplings and MSTW 2008 pdf are renormalized at $Q^2 = \hat{s}$. 

\[ \text{LHC at } \sqrt{s} = 14 \text{ TeV} \]

\[ \text{TeVatron at } \sqrt{s} = 1.96 \text{ TeV} \]
We ignore higher order QCD processes, that lead to pair production of new particles together with jets. Furthermore, if \( \lambda \) is large enough, at very large masses \( M \) the cross section for single production \( X \) via the cubic coupling \( \lambda \) (possibly at one loop) becomes larger than the cross section for pair \( XX \) production via SM gauge interactions. We do not explore this possibility, that leads to different signatures.

3 Mass spectra and decays

We first need to compute the mass spectrum of the new particles. The mass term \( M \) gives a common mass \( M \) to all components of the new weak multiplet. If it is a scalar multiplet, it can have a quartic coupling \( (X^\dagger T^a X)(H^\dagger T^a H) \) to the Higgs doublet \( H \) that splits the \( X \) components according to their \( T^3 \). For both scalars and fermions, electroweak corrections generate a mass splitting among the components of SU(2)_L multiplets. Specializing eq. (6) of [11] to the case \( M \gg M_W \), the mass difference between two components with electric charge \( Q \) and \( Q + 1 \) is

\[
\Delta M = M_{Q+1} - M_Q = (1 + 2Q + \frac{2Y}{\cos \theta_W})\alpha_2 M_W \sin^2 \frac{\theta_W}{2} = 166 \text{MeV}(1 + 2Q + \frac{2Y}{\cos \theta_W}). \tag{7}
\]

This means that the lightest component is the one with the smallest electric charge. (The neutron is instead heavier than the proton because they are composite of quarks with different masses; we here consider new elementary particles).

Therefore two competing effects lead to decays of the new particles. The \( \lambda \) couplings give rise to their decays into SM particles. Furthermore, heavier components of the multiplets have electroweak decays into the lighter components, with rates suppressed by the small phase space. Since \( \Delta M > m_\pi \) two-body decays into pions are open, and for both scalars and fermions one has

\[
\Gamma(X_{Q+1} \rightarrow X_Q \pi^+) = c G_F V_{ud}^2 \frac{\Delta M^3 f_\pi^2}{\pi} \sqrt{1 - \frac{m_\pi^2}{\Delta M^2}} \sim \frac{1}{\text{mm}}, \tag{8}
\]

where \( c = 2 \) for a weak triplet and \( c = 1 \) for a weak doublet. If \( \Delta M > \text{GeV} \) one must consider decays into two \( \pi \) and ultimately compute the decay at the quark level.

The couplings \( \lambda \) generically lead to a decay rate

\[
\Gamma \sim \frac{M \lambda^2}{4\pi} \sim \frac{1}{3 \text{cm}} \frac{M}{\text{TeV}} \frac{\lambda^2}{10^{-16}}. \tag{9}
\]

For a new fermion coupled to a SM fermion (either Q or L) and to the SM Higgs doublet, a generic simple result holds in the \( M \gg M_W \) SU(2)_L invariant limit: all components of the multiplet have the same decay rate. Furthermore, when two channels are allowed (one involving the upper component \( H^+ \) and the other the lower \( H^0 \) component of the Higgs doublet), their relative widths are fixed by SU(2)_L group theory to be 1 or 0, as easily read from the Yukawa Lagrangian in the gauge-less limit.
Taking into account gauge interactions adds corrections suppressed by \( M_W^2/M^2 \): indeed, once that the Higgs gets a vev, \( H^0 = v + (h + i\eta)/\sqrt{2} \) and the \( V = \{ Z, W^\pm \} \) vectors become massive by ‘eating’ the Goldstones \( \eta \) and \( H^+ \) in the Higgs doublet \( H \), decays into \( H^\pm \) are replaced by decays into \( W^\pm \), and decays into \( H^0 \) by decays into \( h, Z \) with equal BR. Concretely, this arises because inserting the Higgs vev in the Yukawa couplings \( FHf \) generates a mass mixing between the new fermions \( F \) and the SM fermions \( f \), such that gauge interactions of \( F \) and of \( f \) become gauge interactions of \( F \) with \( f \). Fermions with exotic electric charges cannot mix with SM fermions and thereby they always lie in weak multiplets together with non-exotic new fermions that can mix.

Notice that experimentalists searched for ‘excited leptons’ or ‘excited quarks’ that decay into leptons or quarks plus a photon. Photons are not generated by our ‘heavy leptons’ or ‘heavy quarks’, because they couple to the Higgs doublet which is ‘eaten’ by \( Z \) and \( W \) but not by photons. Ignoring photons and the physical Higgs boson \( h \) (just because its phenomenology depends on its still unknown mass) we list the decays of new heavy particles into pairs of SM particles allowed by electric charge conservation and by Lorentz invariance:

| charge | if scalar | if fermion |
|--------|----------|------------|
| 0      | \( f\bar{f}, W^+W^- \), ZZ | \( \nu Z, W^\pm\ell^\mp \) |
| 1/3    | \( u\ell^+, \bar{d}\nu, ud \) | \( d\bar{Z}, \bar{u}W^+ \) |
| 2/3    | \( d\ell^+, ud \), \( u\bar{d}, W^+Z \) | \( uZ, dW^+ \) |
| 1      | \( \ell^+\nu, ud \), \( W^+Z \) | \( \ell^+Z, \nu W^+ \) |
| 4/3    | \( uu \) | \( dW^+ \) |
| 5/3    | \( u\ell^+ \) | \( uW^+ \) |
| 2      | \( \ell^+\ell^+, W^+W^+ \) | \( \ell^+W^+ \) |

where \( f \) denotes any SM fermion.

In the following we will discuss all these possibilities, except the decay of a scalar into a pair of vectors which is not present in our scenario. This kind of decay appears however in other contexts as discussed in [13].

When \( \lambda \) is such that the gauge decay width eq. (8) is not negligible the decay length could be macroscopically large, leading to the usual associated extra signatures. This is a bonus selection criterion for all the signatures discussed in the following sections. However the experimental resolution on displaced vertexes is about 100 \( \mu \)m which means that for small values of \( \lambda \) the displacement is undetectable. As such detectably displaced vertex arise only in a small range within the allowed range for \( \lambda \) from current experimental limits. Furthermore for decays mediated by gauge interactions the displaced vertex is likely to be undetectable because (at least for new fermions) \( \Delta M \) is so small that the \( \pi^\pm \) emitted in the decay are too soft. A possibility to see this kind of decays could be a dedicated trigger thought to infer a kink in a charged track to the change in the electric charge of the heavy particle \( X \) that decays in the detector magnetic field. However if \( X \) is colored it hadronizes before decaying, forming \( X \)-hadrons with various possible electric charges (even changing during its interactions with the detector material) and washing out the effect [12]. In the case where electroweak decays cannot
be seen and dominate over λ decays, one effectively has production of the lightest component of the weak multiplet with cross section equal to production of all multiplet components. In the following we will focus on the opposite case of prompt λ decays, that dominate over electroweak decays, so that each multiplet gives rise to a set of different signatures.

We can divide the signals into five main classes, discussed in the next five sections. In all cases we consider the standard set of isolation and detection cuts needed to make the leptons and jets identifiable:

\[ p_T > 20 \text{ GeV}, \quad \Delta R > 0.4, \quad |\eta| < 2.5. \]

for all particles. Here \( p_T \) is the momentum orthogonal to the beam axis, \( \eta \) is the pseudo-rapidity and \( \Delta R = (\Delta \phi_T^2 + \Delta \eta^2)^{1/2} \), with \( \Delta \phi_T \) being the angular separation in the plane Transverse to the beam.

All our signals have been computed using a MonteCarlo code written by us in Mathematica and using MSTW 2008 PDFs [4]. Some of them have also been computed using MADGRAPH [5] where the new particles interactions were added using FeynRules [6]. All SM backgrounds are computed using either MADGRAPH or ALPGEN [7] using PDFs CTEQ6L1 and CTEQ5L respectively [8]. In the cases where showering has been considered it has been performed with PYTHIA 8.1 [9].

4 4q di-quark signals

We here consider scalars that couple to two quarks. One possibility is a second Higgs doublet, which has a complex and well explored phenomenology that we will not discuss here. All other possibilities involve colored scalars, that can transform under SU(3)_c as an octet (a ‘colored higgs’ [14]), sextet or triplet: in all cases their production cross sections are large and dominated by strong interactions. The color representation affects the total signal rate (triplets
have lower production cross sections than octets or sextuplets) and mildly affects the shape of \( \frac{d\sigma}{d\ell} \). Various weak multiplets are possible, containing electric charges which are either 0 and 1 (second higgs or colored higgs) or various combinations of 1/3, 2/3 and 4/3. They cannot be discriminated as long as each new particle decays into two light quarks, so that the only observable signal is \( 4j \). The main main background to this signal are the QCD \( 4j \) events. We perform the following cuts:

i) \( |\eta| < 2.5 \) for all jets and \( \Delta R > 0.4 \) for all jet pairs;

ii) we select among the \( 4j \) the couple of pairs with ratio \( R \) of their effective masses closer to 1, and accept the event if \( R \) deviates from 1 by less than 25%, determining the \( M_{\text{eff}} \) associated to the event;

iii) \( p_T > \max(rM_{\text{eff}}, 100 \text{ GeV}) \) for each jet with \( r = 0.2 \) or \( r = 0.3 \);

iv) \( H_T \equiv \sum_j p_{Tj} > 2M_{\text{eff}} \).

Fig. 3a shows the resulting background as function of \( M_{\text{eff}} \), choosing bins of 25% size such that the signal is a peak entirely concentrated in a single bin, corresponding to the mass \( M \) of the new scalar. The curves show the total signal cross section as function of \( M \); the acceptance of the signal after these cuts is 30% for \( r = 0.2 \) and 12% for \( r = 0.3 \). Even if the signal is somewhat below the background, event rates are so large that the statistical significance of the signal peak, \( N_{\text{ev}}/\sqrt{N_{\text{bck}}} \), can allow its detection, provided that the background rate can be independently computed. This can be done by relying on the larger sample of QCD \( 4j \) events such that \( 2j \) pairs do not have the same invariant mass. The signal/background ratio can be enhanced by devising cuts that optimize the discrimination of the signal from the background: for example taking into account that QCD jets tend to be forward and hierarchical in \( p_T \) while the signal tends to give central jets paired in cones.

Although the discovery by event counting described above seems pretty reasonable the existence of new resonances in multi-jet final states can be established in a more robust way looking for a peak in the invariant mass of suitably chosen jet pairs. This would allow to make a discovery without any theoretical input about the background shape and normalization. To exemplify how to achieve this goal, we consider one scalar octet with mass \( M = 400 \text{ GeV} \) such that the signal cross section computed with \textsc{madgraph} and CTEQ6L1 PDFs is \( \sigma = 8 \text{ pb} \) after the basic cuts of eq. (10). Besides performing the cuts described above, we also require

v) \( p_T^j > 250 \text{ GeV} \) and \( \Delta \eta_{jj} < 1.7 \).

The distribution of the retained jet pair invariant mass is shown in fig. 3b assuming 100/pb of integrated luminosity: a clear peak above the background is present at the mass \( M \) of the new particle. Additionally, in figure 4 we present the result for the same analysis in the case of 1/fb of integrated luminosity for the LHC running at 7 TeV.
We verified that along the same lines, a heavier $M = 1$ TeV scalar gives a clear peak with an integrated luminosity of $100/fb$.

If one or more of the four signal quarks is a top quark, a different and easier signal is obtained. In our scenario the production cross section is entirely due to QCD gauge interactions. A somewhat related $4j$ signal was previously studied in [14], where production can be mediated by a new particle, such that the invariant mass of all $4j$ is around its mass, and a larger cross section can be obtained.

5 **4ℓ di-lepton signals**

We consider scalars that couple to two leptons. There are four possible complex scalars. Two of them have already been studied as ‘type II see-saw’ [15] and ‘second Higgs doublet’: in both cases they can also couple to the Higgs or to quarks, so that the name ‘di-lepton’ is not fully appropriate for them. The pure di-leptons are the remaining two cases:

i) the singlet $\tilde{E}$ with $Y = 1$ and Yukawa coupling $\tilde{E}L_iL_j = \tilde{E}(\ell_i\nu_j - \ell_j\nu_i)$ and

ii) the singlet $\tilde{E}^2$ with $Y = 2$ and Yukawa coupling $\tilde{E}^2EE$.

They have different signatures.

5.1 **4 charged leptons**

The $\tilde{E}^2$ singlet couples to right-handed leptons as $\tilde{E}^2EE$: its signal is 4 charged leptons $\ell^+\ell^+\ell^-\ell^-$ with equal invariant mass of the same-sign lepton pairs. This signature gets lost
Figure 5: **scalar di-leptons signals vs backgrounds:** $pp \to \mu^+\mu^-\mu^+\mu^-$ (left) and $pp \to \ell^+\nu\ell^-\bar{\nu}$ (right).

if one of the leptons is a $\tau$ (in such a case the $\mu$ and $e$ spectra from its decays allow in principle to test its polarization), and in the worst case where $4\tau$ are produced the signatures are similar to the ones discussed in [16]. In the best case one has $\mu^+\mu^+e^-e^-$ states that violate lepton flavor. We here focus on the $\mu^+\mu^+\mu^-\mu^-$ case, showing that SM backgrounds are well below the total signal cross-section, plotted in fig. 2. In the SM $\sigma(pp \to \mu^+\mu^-\mu^+\mu^-) = 6.8$ fb.

Fig. 5a shows, as function of $M_{\text{eff}}$, the cross section of such events with the further requirement that $M_+ \equiv M_{\text{eff}}(\mu^+,\mu^-) \text{ and } M_- \equiv M_{\text{eff}}(\mu^-,\mu^-)$ differ by less than 25%. We see that despite the loose requirement in the difference $|M_- - M_+|$, the signal is already clean. Thus at this stage the luminosity for discovery is set by the signal rate only and no tightening of this requirement seems needed. Furthermore, one can remove the $Z \to \ell^+\ell^-$ background by demanding that opposite-sign lepton pairs do not reconstruct the $Z$ mass, suppressing the irreducible SM backgrounds by a factor $\sim 10^3$ with respect to fig. 5a. Before concluding that the signal is background-free, one should also consider fake leptons or backgrounds (such as $\mu$ from $\pi$ decays), that can be suppressed by demanding isolation criteria. This was achieved by the D0 collaboration, that searched for similar signals [17], finding that at TeVatron the $\ell^+\ell^+\ell^-\ell^-$ signal must have cross section below about 20 fb, which implies scalars heavier than about $130 \div 150$ GeV [17]. As such this kind of signature seems visible at the LHC as soon as the luminosity collected is sufficient to produce an handful of signal events.

### 5.2 2 charged leptons and 2 neutrinos

The $\tilde{E}$ singlet couples to left-handed leptons with flavour anti-symmetric couplings $\tilde{E}L_iL_j = \tilde{E}(\ell_i\nu_j - \ell_j\nu_i)$ and thereby is somewhat similar to a heavier leptonically-decaying $W^\pm$, produced with a smaller cross-section. Thereby the signal of $\tilde{E}$ is more elusive: two opposite-sign leptons accompanied by missing energy. The signal cross section is the lowest one in fig. 2.

The SM background process is $pp \to \ell_i\bar{\ell}_j\nu_i\nu_j$ with a total cross section of about 2 fb.
this background is mostly due to two-body processes like $pp \rightarrow W^+W^-$ and $pp \rightarrow ZZ$ it can be reduced requiring final state leptons and missing transverse energy that force the vector bosons to be off-shell. This can be done requiring

$$M_{\text{eff}}(\ell_i \bar{\ell}_j) > M_Z$$

and

$$m_T^2(\ell \nu) \equiv 2E_T \phi_{T_{\ell \nu}} > M_W^2.$$  \hspace{1cm} (12)

Here $E_T$ and $E_T'$ are the missing transverse momentum of the neutrino and of the lepton and $\phi_{T_{\ell \nu}}$ is the angle between the components of their momenta transverse to the beam.

In this kind of events $m_T$ cannot be directly computed because there is more than one source of missing transverse energy. However the cut in eq. (12) can be enforced using the variable $m_{T2}$ of [18] and requiring

$$m_{T2}^2 \equiv \min \max(m_T^2(\ell_1 \nu_1), m_T^2(\ell_2 \nu_2)) > M_W^2.$$ \hspace{1cm} (13)

The cuts of eq.s (11), (13) have a mild effect on the signal because leptons and missing transverse energy are generated by an heavy particle which can be on-shell and still pass the cuts. As such, even though the signal rate is not very high, it can result in an excess of event after $\sim 10/fb$ of luminosity have been collected.

Fig. 5b shows an example of the $\tilde{E}$ signal (computed for $M = (150) \ 200$ GeV such that $\sigma \approx 12(7) fb$ times a 60% acceptance) compared to the backgrounds after the requirement $p_T > 40$ GeV and those of eq.s (10), (11), (13). Background tails are even smaller for a lepton-flavor violating signal such as $e^- \mu^+ E_T$.

Finally we note that from the distribution in $m_{T2}$ one could in principle measure the mass of $\tilde{E}$ looking at the endpoint of the distribution.

6 2$\ell$2$\nu$ heavy lepton signals

We consider fermions coupled to a lepton and to the Higgs doublet. Lepton number is violated if the fermion has a Majorana mass: the two possible cases are well known as type-I and type-III see-saw; the latter case has LHC manifestations that have already been studied in [19].

We therefore focus on the Dirac case and there are two possibilities$^3$.

i) the SU(2) triplet $E_3 + \text{h.c.}$ coupled as $E_3 LH^*$ with components of electric charge 0, 1, 2 that can decay as

$$E^0 \rightarrow \nu Z, \quad E^+ \rightarrow \nu W^+, \ell^+ Z, \quad E^{++} \rightarrow \ell^+ W^+$$ \hspace{1cm} (14)

$^3$An early study of the phenomenology of such kind of particles is found in [20].
with equal total widths in the $M \gg M_Z$ limit. Notice that $E^0$ does not decay into $\ell^\pm W^\mp$. Notice also that although $E^0$ is not a stable DM-like particle, it looks like that when its decay is invisible, $E^0 \to \nu\bar{\nu}$.

ii) the SU(2) doublet $L^{3/2} + \text{h.c.}$ coupled as $L^{3/2}\bar{E}H^*$, with components of electric charge 1, 2 that can decay as

$$L^+ \to \ell^+ Z, \quad L^{++} \to \ell^+ W^+$$

with equal widths ($L^+$ does not decay into $\bar{\nu}W^+$).

The primary final states with only charged leptons and heavy vectors are $\ell^+ W^+ \ell^- W^-$, $\ell^+ Z\ell^- Z$, $\ell^+ W^- \ell^- Z$. Other similar channels involve neutrinos and higgses. Lepton flavor can be violated, while lepton number is conserved. We assume that the leptons $\ell$ produced in heavy-lepton decays are $e$ or $\mu$ rather than $\tau$.

6.1 Production of $pp \to W^+ \to E^{++} E^-$

This production mechanism has the larger cross-section. $E^{++}$ decays into $W^+\ell^+$, and we assume that $E^-$ decays into $\ell^- \bar{E}_T$ giving rise to a $W^+\ell^+ \bar{E}_T$ state, such that this signal exists for both the heavy lepton triplet $E$ and doublet $L$. If the $W$ decays leptonically and $Z \to \nu\bar{\nu}$, the final state is $\ell^+\ell^+\ell^- \bar{E}_T$ with BR $\approx 4(2)%$ for the heavy triplet $E$ (doublet $L$). If instead $E^- \to Z\ell^-, h\ell^-$ and the $Z$ or $h$ decays hadronically, or if there are jets from QCD initial state radiation, the signal is

$$pp \to \ell^+\ell^+\ell^- \bar{E}_T X$$

where $X$ denotes extra particles.

In the case the heavy lepton is light enough that a large number of signal events is present, we can restrict to the cleaner state where $X$ is empty:

$$pp \to \ell^+\ell^+\ell^- \bar{E}_T .$$

The production of leptons in the SM is mainly given by vector bosons decays. Hence the dominant contribution to the background arise from two-body processes like $pp \to Z\bar{W}^+$ which can be efficiently suppressed requiring opposite-sign leptons with invariant mass $m_{OS}$ well above $M_Z$, leaving only 3-body backgrounds with smaller cross sections:

1. $pp \to \ell^+\ell^- W^+$ from off-shell $Z$ or $\gamma$ which gives $\approx 9(1) \text{ fb}$ after demanding $m_{OS} > 100(200) \text{ GeV}$ and a leptonic $W^+$ decay.

2. $\sigma(pp \to W^+W^+W^-) \approx 1 \text{ fb}$ after demanding that all $W$ decay into $e$ or $\mu$.

The exclusive signal of eq. (17) has no hard jets. However we expect that some hadronic activity will be present due to initial state radiation (ISR). This activity will produce jets that
This signal is characterized by same sign leptons whose invariant mass is a fraction of the mass of the new particle. The mass of the new particle also sets the scale for the missing transverse energy $E_T$ and for the invariant mass of opposite signs leptons, $m_{OS}$. Therefore we look for the signal in the distribution of the invariant mass of same-sign leptons, $m_{SS}$, in events with large $m_{OS}$ and large $E_T$. Figure 6 shows the result for a $M = 600$ GeV resonance such that the signal eq. (17) has a cross-section of 0.5 fb with the cuts

$$E_T > 200 \text{GeV}, \quad m_{OS} > 150 \text{GeV}. \quad (18)$$

The signal extends up to $m_{SS} < M$ and the signal/background ratio is large, allowing for discovery as soon as a handful of signal events can be produced, after that an integrated luminosity of about 10/fb is collected.

Figure 6: Heavy lepton signal+background and background-only distributions of the invariant mass of same-sign leptons for the $pp \to E^{++} \cdot E^- \to W^+ \ell^+ \cdot \ell^- Z \to \ell^+ \ell^- E_T$ heavy lepton signal of eq. (17).
For higher masses $M$ the signal cross section of eq. (17) drops quickly. Hence it would be interesting to study the less clean final states where $X$ is non empty. In this case the evaluation of backgrounds where jets appear from ISR and leptons arise from meson decays would be necessary. We do not perform this study, however Ref. [10] examined some similar case in the context of supersymmetric signatures like eq. (17) and found that a cut in missing transverse energy like eq.(18) provides good rejection of this kind of background where leptons are not generated together with $\not{E_T}$.

Production of $pp \rightarrow W^+ \rightarrow E^+E^0$ has the same rate of the production of $E^{++}E^{-}$ studied above in this section, and its experimental signatures are a subset of the ones already considered in the type-III see-saw context [19].

6.2 Production of $pp \rightarrow Z, \gamma \rightarrow E^{++}E^{--}$

The signal is $\ell^+W^+ \ell^-W^-$ with equal invariant masses for the first and second pair. The possible final states are:

- The $\ell^+\ell^-4j$ signal has the highest BR $\approx 46\%$ but also a huge background of about 10 pb if the two leptons have the same flavor. Given that the full event can be reconstructed various cuts and selections on invariant masses can be performed.

- The $\ell^+\ell^-\ell^+\ell^-\not{E_T}$ signal has the smallest BR $\approx 4.5\%$. The backgrounds are: $\sigma(pp \rightarrow ZWW) \approx 200 \text{ fb}$ reduced down to 0.2 fb after restricting to leptonic decays, $\sigma(pp \rightarrow ZZ) \approx 10 \text{ pb}$ reduced down to 1 fb after restricting to $Z \rightarrow \tau^+\tau^-$ and leptonic $\tau$ decays, $\sigma(pp \rightarrow t\bar{t}) \approx 700 \text{ pb}$ reduced by a large amount by leptonic BR and jet veto and lepton isolation cuts. These backgrounds can be further suppressed demanding that the invariant mass of opposite sign leptons is above $M_Z$, or if the signal violates lepton flavor.
• The $\ell^+\ell^-\ell^+E_T2j$ signals have BR $\approx 14.4\%$ each. The main background is $\sigma(pp \to t\bar{t}W) \approx 320$ fb, that becomes $\approx 3$ fb after imposing the appropriate decay modes; it can be suppressed exploiting the kinematical features of the signal (large invariant masses of same-sign leptons, $M_{\text{eff}}(jj) = M_W$). The $\sigma(pp \to ZW^+W^-) \approx$ 100 fb background can be eliminated imposing $M_{\ell^+\ell^-} > 100$ GeV. With this cut one is left with the $pp \to \ell^+\ell^-W^+W^-$ background; its cross section is $\sigma \approx 0.4$ fb (0.06 fb) before (after) imposing the appropriate $W$ decays.

Another background is $pp \to t\bar{t}$, with $t \to bW \to cWW$ followed by leptonic $W$ decays; devising cuts that reduce its large cross section by a large enough factor is mainly an experimental issue that we do not address.

This signal allows to measure the mass of the heavy lepton in two different ways: as the endpoint of the same-sign leptons invariant mass distribution (fig. 5a); and as a peak in the invariant mass of the two jets with the opposite-sign lepton (fig. 5b). In both variables the signal is well above the backgrounds.

7 2j 2V heavy-quark signals

The new particles are SU(3) triplets, that decay into a quark and a $W$ or $Z$ or $h$. The flavor of the quark is unknown, and again we will consider a generic light quark rather than a $b$ or a $t$.

If both $W$s decay hadronically, it seems feasible with appropriate cuts to identify the resulting 6j signal in the QCD multi-jet background. If instead one $W$ decays leptonically and the other hadronically, the resulting 4j $\ell E_T$ signature (with invariant masses $M_{jj} = M_W$ and $M_{jW} = M$) emerges over the $t\bar{t}+$ jets and $W^+$ jets backgrounds, as previously studied for the analogous 4th-generation signal in [21]. In such a scenario the new particle, called $t'$, decays as $t' \to Wb$, while $t' \to Zu$ decays are not present at tree level, as the $t'$ gets its mass from the same Yukawa couplings that give rise to its decay, so that $Z$ couplings are flavor conserving.

In order to avoid problems with precision data and flavor, we instead consider new non-chiral heavy quarks, that therefore have a mass term invariant under SU(2)$_L \otimes U(1)_{Y}$ as well as small Yukawa couplings: decays into $Zq$ and $hq$ are necessarily present, with a branching ratio of about 25% each. Ignoring the still unknown Higgs boson, we obtain in our scenario the cleaner $jjWZ$ and $jjZZ$ events. The best signature is $4j2\ell$, produced in about 1% of the signal events, when $W,Z \to jj$ and $Z \to \ell^+\ell^-$ with $\ell = \{e,\mu\}$. The main SM backgrounds are:

1. $\sigma(pp \to 4jZ \to 4j2\ell) \approx 10$ pb.
2. $\sigma(pp \to jjWZ \to 4j2\ell) \approx 0.4$ pb.
3. $\sigma(pp \to t\bar{t}jj \to 4j2\ell) \approx 10$ pb and $\sigma(pp \to 4j2W \to 4j2\ell) \sim 0.2$ pb become subdominant with respect to the previous backgrounds after imposing $M_{\ell\ell} = M_Z$. 

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We select the events imposing the standard isolation and detection cuts of eq. (10) (the acceptance is $\approx 20\%$ for the signal) and that some combination of jets satisfies $M_{jj} = M_W \pm 10 \text{GeV}$ and $M_{\ell\ell j} = M_{jW}$ within 10%. In fig. 8 we plot the background [7] and the signal as function of this latter invariant mass variable, such that the signal is a peak at the heavy-quark mass. The signal events are generated for the case of an SU(2)$_L$ singlet quark. Bigger SU(2)$_L$ multiplet will result in bigger cross sections due to the possibility to produce further weak-isospin replicas.

Table 1 lists 7 different ‘heavy quarks’ (3 SM-like and 4 with exotic quantum numbers), so that one wonders which LHC observable could discriminate among them. A partial discrimination can be done measuring their mass and their production cross section: as already pointed out heavy quarks can be singlet, doublet or triplet under SU(2)$_L$, and one doublet (triplet) has a production cross section 2 (3) times larger than one singlet. Furthermore heavy quarks with exotic charges can only decay into $W^\pm q$, so that their presence leads to an enhanced ratio between $jjWW \div jjWZ \div jjZZ$ signals. Discriminating $W$ from $Z$ presumably can only be done observing the signals from their leptonic decays. Observing all the three signals above would therefore allow to probe the presence of exotic heavy quarks. The presence of top or bottom quarks (which give rise to extra specific signatures) would provide an extra handle.

8 2$\ell$ 2$q$ lepto-quark signals

New scalars that couple to a lepton and a quark (and thereby commonly called Lepto-Quarks, LQ) give rise to final states containing 2 leptons and 2 quarks. The resulting LHC signals and capabilities have been already extensively explored [22], so that we will not focus on such topic.

We notice that according to our classification some particles both give rise to LQ signals together with the QQ signals (as well as possible violation of baryon-number) discussed in section 4.
9 Conclusions

We classified all new scalar or fermion multiplets of the SM gauge group such that one new particle can couple to a pair of SM particles (either the Higgs boson or quarks or leptons) in a gauge and Lorentz invariant way. Such ‘Minimal Matter’ scenario is orthogonal to the standard ideology, that instead assumes a sector of new particles supplemented with an ad-hoc discrete symmetry that forbids all the above couplings such that new particles can only couple in pairs to the SM sector and the lightest new particle can be a stable Dark Matter candidate. However this symmetry is not necessary; automatically stable ‘Minimal’ Dark Matter candidates were proposed in [11].

Assuming that the new couplings are small avoids all current indirect constraints leaving direct production at LHC as the main probe: indeed new particles are produced in pairs via their gauge interactions, so that we computed their production rate (fig. 2), while the smallness of their couplings to SM particles only adds a small decay width. We obtained a set of well defined new-physics signatures and presented the dedicated searches that can allow to see such new physics among the huge backgrounds present at LHC. These signatures fall into five main classes:

1. The well known scalar lepto-quarks, that couple to leptons and quarks.
2. Scalar di-quarks couple to two quarks and lead to $4j$ signatures with peaks in the two $jj$ invariant masses; we explored how they could be discovered as a small excess as well as isolated as a clean peak (fig. 3).
3. Scalar di-leptons couple to two leptons and lead to $4\ell$ signatures: either $\ell^+\ell^-\ell^+\ell^-$ (which easily emerges over the SM backgrounds, fig. 5a) or $\ell^+\ell^-E_T$ (which emerges over the SM backgrounds after considering a dedicated transverse mass $m_T^2$ of the system, fig. 5b).
4. Heavy leptons couple to leptons and to the Higgs boson and lead to $\ell\ellVV$ states, where $V$ is either a $W$ or a $Z$ or a higgs, giving rise to various signatures: we exemplified the observability of the $\ell^+\ell^+\ell^-E_T$ (fig. 6) and $\ell^+\ell^+\ell^-E_Tjj$ (fig. 7) signals.
5. Heavy quarks couple to quarks and to the Higgs boson leading to $jjVV$ states, that are best seen as $4j\ell E_T$ or $4j2\ell$ (fig. 8) final states. Their ratio indicates the $W$ fraction in $V$: a high $W$ fraction indicates the presence of heavy quarks with exotic electric charges $4/3$ or $5/3$, that can therefore decay only into $Wq$.

A few multiplets (such as the scalar triplets of type-II see-saw) can have couplings of different types, violating the conserved global symmetries of the SM and leading to special signatures [15, 3].

Final states involving no missing energy $E_T$ and the lack of edges in observable related to $E_T$ allow to discriminate this scenario from the standard scenarios where a DM LSP-like particle carries away $E_T$. 

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They seem equal, but look at the scale below:

\[ \sigma(M, \sqrt{s}) \approx \sigma(\frac{M}{2}, \frac{\sqrt{s}}{2}) \]

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Figure 9: Cross sections for pair production via gauge interactions at leading order in hadronic collisions of new particles \( XX \) labelled as \( P^Q_{T3} \) where \( Q \) is the electric charge, \( T_3 \) is weak isospin and \( P = F \) (S) for a fermion (scalar). Cross sections of colored particles (in red) negligibly depend on their electroweak interactions, so we adopted the simplified notation \( P_d \) where \( d = \{3, 6, 8\} \) for color triplets, sextets and real color octets. Couplings and MSTW 2008 pdf are renormalized at \( Q^2 = \hat{s} \).

**Addendum: Minimal Matter at the LHC at 7 TeV**

LHC is running at reduced \( \sqrt{s} = 7 \text{ TeV} \) with the hope of accumulating an integrated luminosity of at least \( 1/\text{fb} \) by the end of 2012. Compared to the design \( \sqrt{s} = 14 \text{ TeV} \) considered in the main text, the partonic luminosities are reduced by a factor 2 to 10 for a partonic center of mass energy between 100 GeV and 1 TeV, however there is still a significant increase compared the Tevatron. Therefore LHC is expected to superseed Tevatron to make discoveries and in placing bounds even in this “preliminary” run. In the following we discuss the signals of minimal matter that can be searched for in the ongoing LHC run.

The total leading-order cross-sections for the LHC running at 7 TeV are given in figure 9 with the same notation of figure 2. Neglecting the logarithmic variation of parton distributions with energy we have \( \sigma(M, s) \propto f(s/M^2)/s \), and consequently the following scaling: \( \sigma(M, s) \approx \sigma(M/2, s/4)/4 \). This roughly means that reducing the energy of LHC \( \sqrt{s} \) by a factor of 2, reduces its reach in mass by a factor 2. In a precise analysis, one needs to take into account also the factor of 4 (less important than the stronger variation of the function \( f \)), the luminosity
of the collider, and the variation in the background rate.

The on-going run of LHC aims at collecting 1/fb of integrated luminosity: therefore it will be sensitive to processes with cross-section larger that 10-100 fb. Using the cross sections of figure 9, one can see the reach in the mass of the new particles. For a more detailed analysis, we selected 4 representative cases, one for each type of signals discussed in this paper. Namely we will discuss: i) one diquark: the scalar color octet $S_8$ (4j signal); ii) one heavy quark: the fermionic color triplet $F_3$ (2j 2$V$ signals); iii) one dilepton: the scalar weak singlet of hypercharge 2 called $S_2^0$ (4$\ell$ signals); iv) one heavy lepton: the weak triplet of hypercharge 2 called $F_1^2$ (2$\ell$ 2$V$ signals).

Our results for the four relevant signatures at the LHC running at 7 TeV are shown in figure 10. The relevant variables are the particle mass $M$ on the horizontal axis and the collected integrated luminosity at LHC on the vertical axis. When comparing with TeVatron, we fix its integrated luminosity at 10/fb, a realistic value. To assess the reach we estimate that, depending on how clean the signature is, a minimum number of events, $N_{\text{disc}}$, must be produced for the discovery. For the cases of $S_2^0$ and $F_3$ we also show current bounds from TeVatron [17, 23]. From the same bounds we estimate that, once the backgrounds are taken into account, the number of signal event needed for a discovery are about 10 for $S_2^0$ and about 500 for $F_3$. For $F_1^2$ we do not have found a specific search and we assume that 10 events are needed for the discovery. For the case of di-jet resonances the results of section 4 allow us to estimate that order 500 event should be enough for a discovery.

The coloured areas in figure 10 have the following meaning:

- In the red area, no discovery can be done at the LHC, either because the number of signal events at LHC is less than one (at high mass), or because TeVatron would have more events (at low mass).

- In the yellow region, a discovery at LHC is unlikely. More precisely, in the low mass part of the yellow region both LHC and TeVatron would have more than $N_{\text{disc}}$ events. Therefore this part of the yellow region represents the cases where the experiments on the two accelerators can compete for a discovery. In the high mass part of the yellow region LHC can see more events than TeVatron, but less than $N_{\text{crit}}$, as such in this region we expect the discovery to not be possible due to lack of statistics.

- A discovery at LHC is expected in the green region. Indeed LHC experiments would collect more than $N_{\text{disc}}$ events, while TeVatron experiments would have less than $N_{\text{disc}}$ events and therefore not enough statistics for discovery.

We see that, for colored particles, LHC starts to explore new regions of parameter space once $\sim$100/pb of integrated luminosity is reached. For uncolored minimal matter particles, LHC starts to superseed TeVatron once a luminosity of $\sim$1/fb is accumulated. Fig. 4 exemplifies how a di-quark signal would appear.
Figure 10: The reach of LHC running at $\sqrt{s} = 7$ TeV for the discovery of representative examples of minimal matter candidates. The upper row is for the colored particles $S_8$ (left) and $F_3$ (right). The lower row is for non-colored particles $S_0^2$ (left) and $F_1^2$ (right). The continuous (dashed) contours show the number of signal events at LHC (TeVatron). In all the panels the green area is the regions where LHC has enough luminosity for a discovery that is not accessible to TeVatron. The red regions are those where LHC is either not competitive with TeVatron or has less than 1 event. In the low mass part of the yellow region both LHC and TeVatron can go for a discovery, while in the high mass part of the yellow region both TeVatron and LHC lack events, but LHC has more.