Minimal matter at the LHC
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with E. Del Nobile, D. Pappadopulo and A. Strumia

Roberto Franceschini

EPFL Lausanne

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Outline

1. Introduction
2. Gauge decays
3. Signatures
4. LHC
5. Di-quarks
6. Di-leptons
7. Heavy leptons
8. Early birds
9. Conclusions
popular "motivated" BSM

- Supersymmetry
- Kaluza-Klein
- Little Higgs

Experiments $\Rightarrow$ Matter Parity

no $\varphi_{NP}\Phi_{SM}\Phi_{SM}$ interactions

Matter Parity

- symmetry to provide a DM candidate
- easy-to-hide new physics

Minimal "useless" Matter

$$\mathcal{L} \supset \lambda \varphi_{NP}\Phi_{SM}\Phi_{SM}$$

- Lorentz invariance
- SM gauge $G_{SM}$ invariance

Experiments $\Rightarrow \lambda \ll 1$

"effective parity"

and ...

- DM candidate through higher reps of $G_{SM}$
\begin{align*}
\mathcal{L} &\supset \lambda \varphi_{NP} \Phi_{SM} \Phi_{SM} + \mathcal{L}_{mass}
\end{align*}

**Framework**
- neglect higher dimensional operators ok because of weak coupling
- no new interactions i.e. no new vectors
  
- add only one spin 0 or $\frac{1}{2}$ particle

**Predictive scenario: gauge production**

**model independent searches**
- quantum numbers are the only assumption
- the pheno of a set of new multiplets could be very different
## Scalars: couplings and decays

| 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 | 1         | 2         | 3         | $1/3, 2/3$    | $LD$       | LQ               |
| $\tilde{Q}^{7/6}$ | 0 | 1         | 3         | 3         | $2/3, 5/3$    | $LU, \tilde{E} \tilde{Q}$ | LQ |
| $\tilde{D}$ | 0 | 1         | 3         | 1         | $1/3$        | $LQ, E \tilde{U}, UD, \tilde{Q} \tilde{Q}$ | LQ/QQ   |
| $\tilde{D}_3$ | 0 | 3         | 3         | 3         | $1/3, 2/3, 4/3$ | $LQ, \tilde{Q} \tilde{Q}$ | LQ/QQ   |
| $\tilde{D}_6$ | 0 | 1         | 6         | 1         | $1/3$        | $U \tilde{D}, \tilde{Q} \tilde{Q}$ | QQ       |
| $\tilde{D}_{36}$ | 0 | 3         | 6         | 1         | $1/3, 2/3, 4/3$ | $\tilde{Q} \tilde{Q}$ | QQ       |
| $\tilde{U}$ | 0 | 1         | 3         | 2         | $2/3$        | $D \tilde{D}$ | QQ       |
| $\tilde{U}_6$ | 0 | 1         | 6         | 2         | $2/3$        | $D \tilde{D}$ | QQ       |
| $\tilde{q}^{4/3}$ | 0 | 1         | 3         | 4         | $4/3$        | $U \tilde{U}, \tilde{E} \tilde{D}$ | QQ |
| $\tilde{q}_6^{4/3}$ | 0 | 1         | 6         | 4         | $4/3$        | $UU$        | QQ       |
| $H_8$ | 0 | 2         | 8         | 0         | 1             | $QU, Q \tilde{D}$ | QQ       |

### Signatures of new scalars
- **QQ**: heavy quarks
- **LL, EE**: heavy leptons
- **LQ**: leptoquarks

### Old and new friends
Leptoquarks, See-Saw mediators, supermodel candidates, ...

### Only quantum numbers matter
No heavy flavors involved in the decay, i.e. in some model the search could be easier.
List of new fermions that can couple to two SM particles.

| Name | spin | U(1)Y | SU(2)L | SU(3)c | |Q| = |T₃ + Y| | couplings to | type |
|------|------|-------|--------|--------|----------------|-----------------|
| N    | ½    | 0     | 1      | 1      | 0              | LH              | type-I see-saw |
| L'   | −½   | 2     | 1      | 0, 1   | EH*            | LH              |                |
| E'   | 1     | 1     | 1      | 1      | LH*            | LH              |                |
| N₃   | 0     | 3     | 1      | 0, 1   | LH              | type-III see-saw|
| E₃   | 1     | 3     | 1      | 0, 1, 2| LH*            | LH              |                |
| L₃/2 | 2     | 1     | 1, 2   |        | EH*            | LH              |                |
| Q'   | 2     | 3     | 1/3, 2/3| HU, H*D  | QH              |                |
| U'   | 1     | 3     | 2/3    |        | HQ              | QH              |                |
| D'   | 1     | 3     | 1/3    |        | H*Q            | QH              |                |
| U₃   | 3     | 3     | 1/3, 2/3, 5/3| QH*  | QH              |                |
| D₃   | 3     | 3     | 1/3, 2/3, 4/3| QH*  | QH              |                |
| Q⁵/₆ | 2     | 3     | 1/3, 4/3| DH*  | QH              |                |
| Q⁷/₆ | 2     | 3     | 2/3, 5/3| UH*  | QH              |                |

**signatures of new fermions**
- QH: heavy quarks
  - jet + V
- LH: heavy leptons
  - ℓ + V
  - mET + V

**sources of SM vectors**
- exotic charges

**old and new friends**
- exotic fermions, fourth vectorial generation, fermionic see-saw mediators, etc.

**only quantum numbers matter**
- no heavy flavors involved in the decay, i.e. in some model the search could be easier
Tevatron: with $\mathcal{L} \sim 10/\text{fb}$ the generic bound is $\sigma \lesssim 1 - 10 \text{ fb}$
small splittings: soft is hard to detect

On top of the gauge invariant mass term $M \bar{\psi} \psi$ or $M^2 |\phi|^2$ a mass splitting arises at loop level:

$$\Delta M = M_{Q+1} - M_Q = (1 + 2Q + \frac{2Y}{\cos \theta_W})\alpha_2 M_W \sin^2 \frac{\theta_W}{2} = 166 \text{ MeV} \cdot (1 + 2Q + \frac{2Y}{\cos \theta_W})$$

without other sources of splitting this poses serious experimental issues (track algorithm, fakes, QCD longlived ...)

$$\Gamma(X_{Q+1} \rightarrow X_Q \pi^+) = c \frac{G_F^2 V_{ud}^2 \Delta M^3 f^2_{\pi}}{\pi} \sqrt{1 - \frac{m_{\pi}^2}{\Delta M^2}} \sim \frac{1}{\text{mm}}$$

$$\Gamma \sim \frac{M \chi^2}{4\pi} \sim \frac{1}{3 \text{ cm}} \frac{M}{\text{TeV}} \frac{\chi^2}{10^{-16}}$$

1 \neq \text{many}

$$\mathcal{L} = M \bar{\psi} \psi + m \bar{\chi} \chi + \kappa \bar{\chi} \psi + ...$$

significant mixing can produce decay chains with hard visible particles
EWSB: eating a Goldstone boson

\[ \lambda H \bar{\Psi} \psi_{SM} \rightarrow \lambda v \bar{\Psi} \psi \] and the mass matrix

\[
\begin{pmatrix}
M & \lambda v \\
\lambda v & 0
\end{pmatrix}
\]

is made diagonal with

\[ \psi_{SM} \rightarrow \psi_{SM} + \frac{\lambda v}{M} \psi, \quad \psi \rightarrow \psi - \frac{\lambda v}{M} \psi_{SM} \]

obtaining a interaction

\[
\frac{\lambda g v}{M} W^\mu \bar{\psi} \gamma_\mu \psi_{SM}
\]

- definite prediction for the BR of fermions into states with \( W^\pm, Z^0, h \)
- no decay into photons
- electroweak symmetry still visible in the absence of some vertex i.e. the interaction \( L^{3/2} EH^* \) do not generate the decay \( L^{3/2, +} \rightarrow \nu W^+ \)
Signatures summary

- scalar di-quark resonances
  \[ 4j \]
- scalar di-lepton resonances
  \[ \ell\ell\ell\ell, \ell\ell \text{ mET} \]
- heavy leptons
  \[ \ell\ell VV (\ell^+\ell^+\ell^- \text{ mET}, \ell^+\ell^+\ell^- \text{ mET}jj, \ldots) \]
- heavy quarks
  \[ 2j2V (4j\ell \text{ mET}, 4j2\ell, \ldots) \]
- leptoquarks
**Introduction**

**LHC**

- **Gauge decays**
- **Signatures**
- **Di-quarks**
- **Di-leptons**
- **Heavy leptons**
- **Early birds**
- **Conclusions**

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**pp collisions at design regime**

- C.o.M. Energy = 14 TeV
- \( \mathcal{L} = 10^{34} \cdot cm^{-2} s^{-1} \)
- \( \sim 10^4 \) protons per bunch
- \( \sim 25 \) \( pp \) interactions per crossing
- Bunch crossed each 25 ns

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**scheduled and unscheduled**

**European Organization for Nuclear Research**

**News: 6 November 2009**

**LHC "bird-bread" strike**

On Tuesday 3 November, a bird carrying a baguette bread caused a short circuit in an electrical outdoor installation that serves sectors 7-8 and 8-1 of the LHC. The knock-on effects included an interruption to the operation of the LHC cryogenics system. The bird escaped unharmed but lost its bread.

The standard failsafe systems came into operation and after the cause was identified, re-cooling of the machine began and the sectors were back at operating temperature last night. The incident was similar in effect to a standard power cut, for which the machine protection systems are very well prepared.

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**European Organization for Nuclear Research**

**News: 9 November 2009**

**Particles have gone half way round the LHC**

Splash event recorded by the CMS experiment on 7 November. The electromagnetic calorimeter is in red, the hadronic calorimeter in blue, the muon system is yellow and magenta. The barrel muon detector was on standby and the inner tracking detector was off.

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Roberto Franceschini

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General Purpose Detector (CMS)

\[ \vec{p} = (p_T, \eta, \phi) \]

\[ p_T = \sqrt{p_x^2 + p_y^2} = p \cdot \sin \theta \]

\[ \eta = \ln \cot \frac{\theta}{2} \]

\[ \Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2} \]
General Purpose Detector (CMS)

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General Purpose Detector (CMS)

\[
\vec{p} = (p_T, \eta, \phi)
\]

\[
p_T = \sqrt{p_{x}^2 + p_{y}^2} = p \cdot \sin \theta
\]

\[
\eta = \ln \cot \frac{\theta}{2}
\]

\[
\Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2}
\]
**Introduction**

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**pp → X \bar{X} → 4j**

- large cross section
- inclusive search (only Q#s)
- no clues to determine the charge
- 4 hard QCD jets (Madgraph)
- $\Delta R > 0.4$, $|\eta| < 2.5$
- $p_T > \text{max}(100 \text{ GeV}, r \cdot M)$
- $H_T > 2M$
- $|m(j_a, j_b)/m(j_c, j_d) - 1| < 0.25$

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**Feynman diagrams for gauge-production of new fermions or scalars**

- $X$ in table 2 presents $H'$; i.e. 2 new matter and its production
- We denote the SM fermions as $L, E, Q, U, D$
- We assume that the couplings $\lambda_j$ are small enough that production of new particles is dominated by their SM gauge interactions (weak or strong), and
- $H$ is only relevant for decays of new particles, not their production cross section. This is unlike the case of new $Z$ and $\text{W}$ vectors, that obtain well-defined scenarios of new physics, allowing us to study their well-defined signals at LHC, that can be computed in terms of $M_{\text{eff}}$:
  - $M_{\text{eff}}(j_1, j_2) = M_{\text{eff}}(j_3, j_4)$ within 25%
Give a shape to the background if you do not like it!

**a 400 GeV example**

$$\int L \, dt = 100/\text{pb}$$

<table>
<thead>
<tr>
<th>$M_{jj}$ in TeV</th>
<th>events per 75 GeV bin</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>200</td>
<td>4</td>
</tr>
<tr>
<td>400</td>
<td>10</td>
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<tr>
<td>600</td>
<td>20</td>
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<tr>
<td>800</td>
<td>30</td>
</tr>
<tr>
<td>1000</td>
<td>35</td>
</tr>
</tbody>
</table>

**SM background:**

$pp \rightarrow 4j$

**$4j$ signal for $M = 400$ GeV**

- $\Delta R > 0.4, \eta < 2.5$
- $p_T > 0.6M = 250$ GeV
- $\Delta\eta_{jj} < 1.7$

$$m^2(j_a, j_b) \simeq p_T^{(a)} p_T^{(b)} \Delta R^2$$

The BG is incoherent hence it has no reason to have jet pairs with invariant mass much smaller than the hard $p_T^{(j)}$.

The signal emerges out of a low-tail of the BG (slight changes from parton-shower are expected).

**applicable to other searches**

- $h \rightarrow WW$ under examination with A. Wulzer

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(1, 1)_2 \text{ that is to say } \mathcal{L} \supset \lambda \tilde{E}_2 EE

\begin{align*}
pp &\rightarrow E^+ E^- \rightarrow \ell \bar{\ell} \ell \bar{\ell}
\end{align*}

- low production $\sigma$
  (only mediated by hypercharge)

- very clean final state
- discovery only suffers lack of events
- Tevatron type-II-SS dedicated search says $M > 130$ GeV

- easy discovery, interesting with $\mathcal{L} \gtrsim 100$/pb

- negligible BG (mostly from ZZ)
- $|1 - m(\ell, \ell)/m(\bar{\ell}, \bar{\ell})| < 0.25$

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\[(1, 1)_1 \quad \text{that is to say} \quad \mathcal{L} \supset \mathcal{L} \tilde{E}LL\]

\[pp \rightarrow \ell_i \bar{\ell}_j \quad \text{mET}\]

\[m_{T2} \equiv \min_{p_T^{\nu_2} - p_T^\nu_1} \max \left[ m_T(\bar{\ell}, \nu_2), m_T(\ell, \nu_1) \right]\]

- low production $\sigma$
- (only mediated by hypercharge)

- end-point feature in the region $m_{T2} > m_W$

- clean despite neutrinos, interesting for $\mathcal{L} \gtrsim 1/\text{fb}$

- BG mostly from WW
- $p_T^\ell > 40$ GeV

- all sorts of rare lepton fakes must be considered
  (mostly detector effects)
(1, 3)\subscript{1} coupled as $\lambda E_3 L H^*$
(1, 2)\subscript{3/2} coupled as $\lambda L^{3/2} E H$

$$pp \rightarrow E^{++} E^- \rightarrow W^+ e^+ e^- Z \rightarrow e^+ e^+ e^- \text{ mET}$$

The same final state is available for $L^{3/2}$ as well.

- $m_{OS} > 100$ GeV
- $\ell^+ \ell^- W^- \sim 10$ fb
- $W^+ W^+ W^- \sim 1$ fb
- $\bar{t}t W^+ \sim 0.1$ fb using jet veto

- mET $> 200$ GeV
- $m_{SS} > 150$ GeV

- showering is included (Pythia 8)
  - visible with at least 10/fb
  - $d\sigma/dm_{SS}$ in fb/GeV
  - background
  - heavy lepton signal $M = 600$ GeV
Early birds (preliminar and not complete)

- Detector effects are desperately needed to say s.t. meaningful

- While we talk Tevatron sets new limits

100/pb (the whole 2010 data-take?)

- 4j signal with di-jet resonaces with $M \sim 400$ GeV
- $\ell^+ \ell^+ \ell^- jj$ mET from heavy leptons with charge two $M \sim 300$ GeV
- $\ell^+ \ell^+ \ell^- \ell^-$ from scalar di-leptons of charge two $M \sim 150$ GeV

roughly same discovery potential despite the very different rates

1/fb (at least 2012)

- $\ell_i \ell_j$ mET from scalar leptons $M \sim 150$ GeV
Conclusions: Just assuming quantum numbers a lot of collider physics!

- generic experimental difficulties for the gauge decays (though unlikely to be relevant)
- many "minimal" signatures have been studied
- rough discovery reach applicable to a yet-to-formulate BSM ... if any
- resonant signatures for the first year of data-taking: 4j, ℓℓℓℓ, ℓℓ mETjj
- many particles with degenerate signatures (yet another hint that LHC can’t write a $\mathcal{L}$agrangian)
- events of new physics without mET (how to disprove matter parity?)
- indirect effects can be important as well (change UV sensitive couplings like the loop-generated $ggH$; change the running of SM couplings)
heavy flavor is always better

Not a theorem ... but close to

handswaiving proof for b quarks

- b quarks can be tagged (and mistagged ... of course)
- single-flavor background has to be less than many-flavor background
- b can be produced in top decay (typically subdominat)

\[ BR(t \rightarrow b\ell m\text{ET}) \approx 0.2 \]

trading a light quark for a top always gives back a jet, though softer because \( p_b \sim p_t / 2 \) and in 20% of cases gives also a lepton.

- \( \sigma(BG + 1t) < \sigma(BG + g) \) (plus you typically must produce \( \bar{t}t \))
- \( \sigma(BG + 1\ell) \sim \alpha_{ew} \cdot \sigma(BG) \)

for hadronic top could be more delicate to establish
other signatures

\[ pp \rightarrow E^{++} E^{--} \rightarrow \ell^{+} \ell^{+} \ell^{-} jj \text{ mET} \]

- \( t\bar{t} W^+ \sim 3 \text{ fb} \)
- \( t\bar{t} \) need a hard lepton from a \( b \) (tail effect, computer-intensive)

- as it is it can give a handful of events already with \( \sim 200/\text{pb} \)
we focus on $VV=ZZ$ or $ZW$ (WW is well studied)

$m(j,j) - m_W < 10$ GeV

$|m(\ell^+, \ell^-, j)/m(3j) - 1| < 0.1$

$Z4j \sim 10$ pb

$ZW2j \sim 0.4$ pb

$\bar{t}tjj$ and $4j2W$ are eliminated by $m(\ell^+, \ell^-) = m_Z$
Pair production at ‘weakened’ LHC

They seem equal, but look at the scale below:

$$\sigma(M, \sqrt{s}) \approx \sigma(M/2, \sqrt{s}/2)$$