Signals of single particle production at the earliest LHC

Riccardo Torre

University of Pisa and INFN

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   - The reference Lagrangian
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Some “simple” questions

1. Can the LHC discovery new physics in its early stage?

Our “simple” answers

1. Yes… if we are lucky
The early LHC: the criterion of “simplicity”

Some “simple” questions

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2. How new physics can show up?

Our “simple” answers

1. Yes... if we are lucky
2. E.g. in the single resonant production of new particles
Some “simple” questions

1. Can the LHC discover new physics in its early stage?
2. How new physics can show up?
3. What kind of “new physics” is accessible to the LHC in its early stage ($\sqrt{s} = 7$ TeV and $\int \mathcal{L} = 1$ fb$^{-1}$)?

Our “simple” answers

1. Yes... if we are lucky
2. E.g. in the single resonant production of new particles
3. Charge, spin, SM representation are constrained by the required production rates and by general principles (simplicity at first!)
How to bring out the best from the early LHC

The early LHC: the criterion of “simplicity”

Some “simple” questions

1. Can the LHC discover new physics in its early stage?
2. How new physics can show up?
3. What kind of “new physics” is accessible to the LHC in its early stage ($\sqrt{s} = 7$ TeV and $\int L = 1 \text{ fb}^{-1}$)?
4. What is the best way to present the experimental data in order to quickly test many new physics models and understand if a signal is there?

Our “simple” answers

1. Yes... if we are lucky
2. E.g. in the single resonant production of new particles
3. Charge, spin, SM representation are constrained by the required production rates and by general principles (simplicity at first!)
4. The data have to be presented with a minimum of biases coming from model building: simple phenomenological Lagrangians can be the guiding line for the experimental analysis making a signal of new physics to simply emerge
Our approach

- We base our considerations on simple phenomenological Lagrangians, fulfilling reasonable consistency conditions.
- We are generally guided by the possible existence of composite states produced by a putative strong dynamics responsible for ElectroWeak Symmetry Breaking.
- We aim also at a neat and simple definition of the interactions responsible for the signals under discussion, to be used as a possible guide for the presentation of the data.
- The interpretation of a possible positive signal in terms of more elaborate and more defined theoretical models is eased by this way of presenting the data.

The goal of my talk

Apply this approach to the single resonant production of new particles
What kind of new particles?

**A matter of parton luminosities**

- Single production of a relatively narrow resonance is the most obvious candidate for a copious production at the LHC also in its early stage.

- One of the most studied cases (mostly in the leptonic channel) is the vector resonance, either neutral or charged, produced in the $q\bar{q}$ channel. See the *Review on $Z'$ searches* in PDG and for recent results see E. Salvioni, A. Strumia, G. Villadoro and F. Zwirner, arXiv:0911.1450 [hep-ph].

- In competition with the Tevatron (with its high integrated luminosity) the $q\bar{q}$ channel at the LHC is definitely less favorable relative to the $gg$, $qg$ and $qq$ channels in view of the corresponding parton luminosities.

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We concentrate our attention to the $gg$, $ug$ and $uu$ production mechanisms.
The nature of the new particles

- Considering for simplicity the lowest possible spin and QCD representation of the new particles candidates the $gg$, $qg$ and $qq$ production mechanisms suggest a small set of possible new states

The possibilities

1. **$gg$-channel**: a spin-less totally neutral scalar $S$;
2. **$qg$-channel**: a $J = 1/2$ color-triplet "heavy quark”, either "U” or "D”;
3. **$qq$-channel**: a spin-less color-triplet or color-sextet scalar $\phi$, with various possible charges.

- We assume that one single new particle is available at a time, which therefore can only decay into SM particles
- We concentrate our attention to the first two cases since the scalar triplet or sextet (see C. W. Bauer et al., arXiv:0909.5213 [hep-ph]) can only decay into a pair of jets, whereas we find relatively more promising the final states containing at least one photon
- The resonances in the $qq$ channel suffer also of problems with flavor physics
A reasonable reference Lagrangian for a scalar singlet $S$ is given by

$$\mathcal{L}_S = c_3 \frac{g_S^2}{\Lambda} G^a_{\mu \nu} G^{\mu \nu \ a} S + c_2 \frac{g^2}{\Lambda} W^{i \mu \nu} W^{\mu \nu \ i} S + c_1 \frac{g'^2}{\Lambda} B_{\mu \nu} B^{\mu \nu} S + \sum_f c_f \frac{m_f}{\Lambda} \bar{f} f S, \quad (1)$$

- A coupling to the SM Higgs of the form $m_S S H^\dagger H$ could also be present, as it would actually be induced by radiative corrections. In a wide range of $M_S$ and $\Lambda$ it is however consistent to assume that such coupling is irrelevant.
- NDA suggests $c_i \approx \frac{1}{4\pi}$ but can easily be larger
- We take as reference values $\Lambda = 3$ TeV (reminiscent of a possible strong interaction responsible for EWSB at $\Lambda \approx 4\pi v$) and $c_i = 1$
- Our results can be simply generalized to different values of the parameters
Scalar resonance: decay widths and branching ratios

The phenomenology of the new particle is now a function of the production rate and of the decay branching ratios (for a fixed mass $M_S$)

### Partial widths

\[
\Gamma(S \rightarrow gg) = \frac{2g_S^4 M_S^3}{\pi \Lambda^2}
\]

\[
\Gamma(S \rightarrow W^+ W^-) = \frac{g^4 \sqrt{M_S^2 - 4M_W^2} \left( M_S^4 - 4M_S^2 M_W^2 + 6M_W^4 \right)}{2\pi M_S^2 \Lambda^2}
\]

\[
\Gamma(S \rightarrow ZZ) = \frac{(g^2 \cos^2 \theta_W + g' \sin^2 \theta_W)^2 \sqrt{M_S^2 - 4M_Z^2} \left( M_S^4 - 4M_S^2 M_Z^2 + 6M_Z^4 \right)}{4\pi M_S^2 \Lambda^2}
\]

\[
\Gamma(S \rightarrow Z\gamma) = \frac{\sin^2 \theta_W \cos^2 \theta_W \left( g'^2 - g^2 \right)^2 \left( M_S^2 - M_Z^2 \right)^2}{2\pi M_S^3 \Lambda^2}
\]

\[
\Gamma(S \rightarrow \gamma\gamma) = \frac{e^4 M_S^3}{\pi \Lambda^2},
\]

\[
\Gamma(S \rightarrow t\bar{t}) = \frac{3m_t^2 \left( M_S^2 - 4m_t^2 \right) \sqrt{M_S^2 - 4m_t^2}}{8\pi M_S^2 \Lambda^2}
\]
Scalar resonance: decay widths and branching ratios

The phenomenology of the new particle is now a function of the production rate and of the decay branching ratios (for a fixed mass $M_S$).

- The total width scales as $1/\Lambda^2$ and the results can be simply generalized to different values of $\Lambda$.
- We made a preliminary phenomenological study of the di-jet, $\gamma\gamma$ and $\gamma Z$ decay channels.
The discovery in the di-jet channel with a small statistics ($\lesssim 1 \text{ fb}^{-1}$) seems strongly disfavored by the high SM background.
The discovery in the di-jet channel with a small statistics ($\lesssim 1 \text{ fb}^{-1}$) seems strongly disfavored by the high SM background and by the large Jet Energy Scale systematic uncertainty.
Scalar resonance in the $\gamma\gamma$ channel

The $\gamma\gamma$ channel is much more promising due to the low SM background.

The graph shows the distribution of the invariant mass $M(\gamma,\gamma)$ in the range 400 to 1400 GeV. The signal is compared to the background, with cuts on $M_{\gamma\gamma} > 100$ GeV and $|\eta_{\gamma}| < 2.4$. The curves indicate the presence of a signal for a scalar singlet with a mass $M_S > 1$ TeV, which is possible with a modest luminosity of about $10$ to $100$ pb$^{-1}$. For a given integrated luminosity, the absence of a signal in the $\gamma\gamma$ channel translates into a lower bound on the scale $\Lambda$ of $3$ TeV. The collider energy is $\sqrt{s} = 7$ TeV.
Scalar resonance in the $\gamma\gamma$ channel

The $\gamma\gamma$ channel is much more promising due to the low SM background.

- A discovery for a scalar singlet with a mass in the range $500 \text{ GeV} \lesssim M_S \lesssim 1 \text{ TeV}$ seems possible with a modest luminosity of about $10$ to $100 \text{ pb}^{-1}$.
- Obviously for a given integrated luminosity the absence of a signal in the $\gamma\gamma$ channel is easily translated in a lower bound on $\frac{\Lambda}{c_1 + c_2}$.

$\Lambda = 3 \text{ TeV}$

$M_S = 0.5 \text{ TeV}$

$\sqrt{s} = 7 \text{ TeV}$

$M_{\gamma\gamma} > 100 \text{ GeV}$

$|\eta_{\gamma}| < 2.4$
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The reference Lagrangian for an heavy quark $U$ is given by

$$\mathcal{L}_U = c_G \frac{g_S}{\Lambda} \bar{U}_L \sigma^{\mu\nu} T^a u_R G^a_{\mu\nu} + c_B \frac{g'}{\Lambda} \bar{U}_L \sigma^{\mu\nu} u_R B_{\mu\nu} + h.c., \quad (2)$$

- The $U$ field transforms as a $(3, 1)_{2/3}$ representation of the SM group.
- Problem with the flavor if we pretend that the $U$ couples to the physical $u$-quark but has no (significant) coupling to the $c$-quark (not to cause unobserved $\Delta C = 2$ flavor changing effects).
- Possible solution to this problem: introduce three $U$ fields, one per generation and assume that the Lagrangian (2) respects a global $SU(3)_R$ acting on the standard three $u$-type quarks.
- These considerations don't affect the phenomenology we are interested in.
- As in the case of the scalar we have done a preliminary phenomenological study with the reference values $\Lambda = 3$ TeV and $c_G = c_B = 1$. 
As in the case of the scalar, the phenomenology depends only on the production rate and on the decay branching ratios (for a fixed mass $M_U$)

### Partial widths

\[
\begin{align*}
\Gamma(U \to ug) &= \frac{4\alpha_SM_U^3}{3\Lambda^2} \\
\Gamma(U \to uZ) &\approx \frac{\alpha M_U^3 \tan^2 \theta_W}{\Lambda^2} \\
\Gamma(U \to u\gamma) &= \frac{\alpha M_U^3}{\Lambda^2}
\end{align*}
\]

### Total width

\[
\Gamma_U \approx \frac{M_U^3 \alpha S}{\Lambda^2} \left( \frac{4}{3} + \frac{\alpha}{\alpha_S \cos^2 \theta_W} \right)
\]

- With our choice of the parameters $2 \lesssim \Gamma_U \lesssim 30$ GeV for $0.5 \lesssim M_U \lesssim 1.5$ TeV
- $\text{BR}(U \to ug) \approx 92\%$, $\text{BR}(U \to u\gamma) \approx 6\%$ and $\text{BR}(U \to uZ) \approx 2\%$
The discovery in the di-jet channel with a small statistics ($\lesssim 1 \text{ fb}^{-1}$) seems strongly disfavored by the dominant SM background and by the large Jet Energy Scale systematic uncertainty.
Heavy quark in the $\gamma + jet$ channel

The $\gamma + jet$ channel is much more promising due to the low SM background.
A discovery for an heavy quark with a mass in the range $500 \text{ GeV} < M_S < 1.5 \text{ TeV}$ seems possible with a modest luminosity of about $5$ to $10 \text{ pb}^{-1}$.

Obviously for a given integrated luminosity the absence of a signal in the $\gamma + \text{jet}$ channel is easily translated in a bound on $\frac{\Lambda}{cB}$. 

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The $\gamma + \text{jet}$ channel is much more promising due to the low SM background.

<table>
<thead>
<tr>
<th>$M(\gamma, j)$ (GeV)</th>
<th>$\sigma(M(\gamma, j) &gt; M(\gamma, j))$ (pb)</th>
</tr>
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<tbody>
<tr>
<td>$300$</td>
<td>$1 \times 10^1$</td>
</tr>
<tr>
<td>$400$</td>
<td>$1 \times 10^2$</td>
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<td>$500$</td>
<td>$1 \times 10^3$</td>
</tr>
<tr>
<td>$600$</td>
<td>$1 \times 10^4$</td>
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<tr>
<td>$700$</td>
<td>$1 \times 10^5$</td>
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</table>

$\sqrt{s} = 7 \text{ TeV}$

$M_{\gamma j} > 150 \text{ GeV}$

$|\eta_j| < 1.3$, $|\eta_{\gamma}| < 2.4$

$\Lambda = 3 \text{ TeV}$

$M_U = 0.5 \text{ TeV}$
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### Heavy quark in the $\gamma + \text{jet}$ channel

The $\gamma + \text{jet}$ channel is much more promising due to the low SM background.

**diagram:**

- Signal (pp->qg->U->γj) + background
- Background (pp->γj), j=light jet (g,u,d,s,c,ubar,dbar,sbar,cbar)

<table>
<thead>
<tr>
<th>$M_{0(\gamma,j)} (\text{GeV})$</th>
<th>$\sigma(M(\gamma,j) &gt; M_{0(\gamma,j)}) (\text{pb})$</th>
</tr>
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<tbody>
<tr>
<td>700</td>
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</table>

- $\sqrt{s} = 7 \text{ TeV}$
- $M_{\gamma j} > 150 \text{ GeV}$
- $|\eta_{j}| < 1.3$, $|\eta_{\gamma}| < 2.4$

- $\Lambda = 3 \text{ TeV}$
- $M_{U} = 1 \text{ TeV}$
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- Obviously for a given integrated luminosity the absence of a signal in the $\gamma + jet$ channel is easily translated in a bound on $\frac{\Lambda}{c_B}$.
In view of the lack so far of a thorough experimental exploration of the energy range at or well above the Fermi scale, an open attitude is best to take in the expectation for possible signals of new physics at the LHC.

We have studied the possibility to observe at the early LHC relatively narrow resonances that can have, in a wide region of the parameters, important production rates.

These particles could be composite particles arising from a strong dynamics responsible for EWSB. They might be visible in $\gamma\gamma$ or in $\gamma + jet$ channels at 7 TeV with less than 100 pb$^{-1}$.

We have at least defined simple single interactions responsible for their production, useful to guide (without prejudices) the experimental analysis and the presentation of the experimental results.

I would like to thanks Riccardo Barbieri and Michelangelo Mangano.