Scalar gluons at the LHC

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Introduction

2010-2011 run of the LHC is very successful - over 2 fb$^{-1}$ of data per experiment has been gathered

great accomplishments

- very fast data analyses
- "rediscovered" SM
- new exclusion limits on the Higgs boson (but no discovery)
- new limits on BSM physics

despite new constrains all the arguments in favour of SUSY are still valid

new exclusion limits on Higgs boson matches perfectly MSSM lightest "higgs" mass window

troubles: constraints from flavour put MSSM under stretching

- barion- and lepton-number violating vertices
- flavour alignment

many theoretical propositions (non-minimal versions of the SUSY)
Motivation

- if one discovers SUSY particles, the next step should be to determine their nature
- important example
  - gluinos in MSSM are pure Majorana particles
  - if experiments determine Dirac nature of gluinos, SUSY would require additional color-charged, electroweak-singlet particle - so-called sgluon ($\sigma$)
- LHC is a "hadron machine" - enhancement of color charged particle’s production
- scalar $SU(3)_C$ octets have been proposed in many different contexts
  - neutrino’s mass generation: Fileviez - Perez, P. and Wise, Mark - On the Origin of Neutrino Masses
  - sgluons in the context of SU(5) GUT: Fileviez - Perez, P. and others - Grand Unification and Light Color-Octet Scalars at LHC
  - R-symmetric models
  - $N = 1/N = 2$ hybrid models
  - many other purely phenomenological analyses
- we assume the framework of the $N = 1/N = 2$ hybrid model
Sgluon sector

- as was advertised in J. Kalinowski talk I will focus on phenomenology of sgluons
- relevant part of the low-energy, SUSY-broken lagrangian

\[ \mathcal{L} \ni (D_{\mu} \sigma^a)^\dagger (D_{\mu} \sigma^a) - m_{\tilde{g}} \frac{\lambda_{ij}^a}{\sqrt{2}} \sigma^a \sum_q (\bar{q}_{L,i} \tilde{q}_{L,j} - \bar{q}_{R,i} \tilde{q}_{R,j}) \]

- second term comes from the SUSY-breaking D-term
- left and right squark contributions come with opposite signs
- tree level sgluon couplings to squarks and gluinos are unimportant from the point of view of production but are important for its decays
- no \( \sigma \bar{q} q \) and \( \sigma gg \) vertices at the tree level, however R-parity (R-symmetry) allows them and they can be generated at the one-loop level
Single sgluon’s coupling to quarks

- relevant diagrams

\[ \sigma \bar{q} \tilde{g} \quad \tilde{q} \quad \tilde{q} \quad \sigma \]

- effective \( \sigma q \bar{q} \) coupling

\[
\imath \Gamma_{\sigma q \bar{q}} = \frac{3 \imath m_{\tilde{g}_D} m_q \lambda^a}{32 \sqrt{2} \pi^2} \int_0^1 dx \int_0^{1-x} dy \left\{ (1-x-y) \left[ \frac{1}{C_L} - \frac{1}{C_R} \right] + \frac{x+y}{9} \left[ \frac{1}{D_L} - \frac{1}{D_R} \right] + \left[ \frac{1}{C_L} - \frac{1}{C_R} \right] \gamma^5 \right\}
\]

\[
C_\alpha = (x+y)m_{\tilde{g}_D}^2 + (1-x-y)m_{\tilde{q}_\alpha}^2 - xym_\sigma^2 - (x+y)(1-x-y)m_q^2
\]

\[
D_\alpha = (1-x-y)m_{\tilde{g}_D}^2 + (x+y)m_{\tilde{q}_\alpha}^2 - xym_\sigma^2 - (x+y)(1-x-y)m_q^2
\]
Single sgluon’s coupling to quarks continued

- coupling proportional to quark mass due to chiral structure, relevant only for tops
- negligible cross section for $\sigma$ production through $q\bar{q}$ interaction but important decay channel
- width generally very small, of the order of $10^{-5}$ GeV
Single sgluon’s coupling to gluons

- **relevant diagrams**

- there is also a tri-gluino triangle diagram which gives zero due to group structure

- **effective $\sigma gg$ coupling**

\[
\Gamma_{\sigma gg}^{\mu\nu} = \frac{\sqrt{s} m_{\tilde{q}}}{8 \sqrt{2} \pi^2} \left( g_{\mu\nu} - \frac{2 p_1^\mu p_2^\nu}{m_\sigma^2} \right) \sum_{q, \alpha} (-1)^\alpha m_{\tilde{q} \alpha}^2 C_0 (m_\sigma^2, 0, 0, m_{\tilde{q} \alpha}^2, m_{\tilde{q} \alpha}^2, m_{\tilde{q} \alpha}^2)
\]

- the only relevant channel for resonant $\sigma$ production and an important decay channel

- width generally also very small, of the order of $10^{-5}$ GeV
Model parameters

- experimental constrains

![Diagram showing gluino decay through on-shell stop (left) and off-shell stop (right).](image)

**Figure:** Gluino decay through on-shell stop (left) and off-shell stop (right) - Henri Bachacou, Lepton-Photon 2011, Mumbai

- model parameters: \( m_{\tilde{g}_D} = 0.75 \text{ TeV}, \ m_{\tilde{q}_L} = 1.2 \text{ TeV}, \ m_{\tilde{q}_R} = 0.95 m_{\tilde{q}_L}, \ m_{\tilde{t}_L} = 0.9 m_{\tilde{q}_L}, \ m_{\tilde{t}_R} = 0.5 m_{\tilde{q}_L}. \)
Cross sections and branching ratios

Figure: Cross section for single (left, blue line) and double (left, purple line) sgluon production. On the right plot is sgluon branching ratios.
Sgluon’s resonant production and decay

- exciting possibility of resonant sgluon production and decay to top quarks or gluons
- right plot shows search for s-channel color-octet scalar resonance in $jj$ channel assuming tree-level couplings
- assuming full strength $S_8$ tree level coupling to gluons, as proposed by Tao Han in arXiv:1010.4309, Atlas excludes sgluon mass below $\sim 2$ TeV
- in our model this process is generated at one-loop level
- for $m_\sigma > 0.5$ TeV the cross section is below 1 fb
- there are no limits from the Atlas on that process

Figure: Atlas Collaboration, arXiv 1108.6311
Production of 2 sgluons and their decays

- production of $\sigma\sigma^*$ pair at tree level through standard kinetic term
- if $m_\sigma < 2m_t$ it decays only to gluons
- 4 gluons in the final state
- detailed analysis was done by S. Schumann, A. Renaud, D. Zerwas in arXiv:1108.2957 (see plot)
- applied cuts
  - four jets with $p_T > 50$ GeV
  - minimize $|\Delta R_{ij} - 1| + |\Delta R_{kl} - 1|$, veto on $\Delta_{ij} = 1.6$ (usual separation of signal jets is $\Delta R \approx 1$)
  - reconstructed masses $|M_1 - M_2|/(M_1 + M_2) < 0.075$
Production of 2 sgluons and their decays continued

- for $m_\sigma > 2m_t$ the $t\bar{t}$ decay channel opens
- such a process hasn’t been analysed in details yet
- as an example we take $m_\sigma = 500$ GeV
- cross section for production of sgluons pair of mass $m_\sigma = 500$ GeV is
  $\sigma(pp \rightarrow \sigma\sigma^*) = 635$ fb
- cross section for pair production and subsequent decay to top’s is
  $\sigma(pp \rightarrow \sigma\sigma^* \rightarrow 2t\bar{t}) = 236$ fb
- we assume that one $t\bar{t}$ decays leptonically and the second one hadronically
- expected cross section is 1.7 fb
- almost 50 events for predicted integrated luminosity of the 7 TeV LHC run ($\approx 30$ fb$^{-1}$)
- interesting possibility to use $\mu^+\mu^-$ from top’s decays as spin analysers
Background cross section

- one looks for high multiplicity events with pair of top quarks of an invariant mass $m_{t\bar{t}} = (500 \pm 50)$ GeV, two opposite-sign muons and a missing energy

<table>
<thead>
<tr>
<th>process</th>
<th>$\sigma$ (fb, no cuts)</th>
<th>$\sigma$ (fb, $m_{t\bar{t}} = (500 \pm 50)$ GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pp \to t\bar{t}\mu^+\mu^-\nu\bar{\nu}$</td>
<td>0.056</td>
<td>0.013</td>
</tr>
<tr>
<td>$pp \to t\bar{t}\mu^+\mu^-\nu\bar{\nu}b\bar{b}$</td>
<td>0.017</td>
<td>-</td>
</tr>
</tbody>
</table>

- main background comes from production of $t\bar{t} + jj$ system with parton shower
- the analysis seems feasible to see the signal
- studies of spin correlations are under way
Summary

- the LHC has stimulated the community to consider strongly interacting BSM particles
- here we have discussed well motivated R-symmetric/hybrid SUSY model
- production of single sgluon would be spectacular but in the viable parameter range it is indistinguishable from background
- sgluons pair production accompanied by decay to $t\bar{t}t\bar{t}$ looks very promising
- studies of spin correlations are under way
- we encourage experimentalists to make detailed phenomenological studies of such a model

Thank you for your attention!
Any Question?

from Mihoko Nojiri

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