Collider Searches for Leptogluons

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Matter to the Deepest, *Ustroń*

Outline

1. Introduction on Compositeness and Leptogluons

2. Leptogluons in Dimuon Production at the LHC

3. Conclusion

Introduction on Compositeness and Leptogluons

Motivation for physics beneath lepton-quark level

Indications on possible nonfundamentality of the SM fermions

- Large number of them: $\{e^-, \nu, u, d$ and their antiparticles$\} \times 3$ generations
- Fractional electric charge of quarks
- Arbitrary fermion masses and mixing parameters
- Similarity between leptons and quarks in the SM flavor and gauge structure
- Absence of gravity in the SM
- Fermion spin 1/2 (spinning gravitating solution, circular current?)
- Dark matter, cosmic-ray anomalies, etc.

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GUT, SUSY, superstrings, etc.

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Some of these issues are addressing in models with elementary ℓ and q, and external relationships or symmetries:
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Alternative possibility with non-elementary ℓ and q is investigated in
models of particle compositeness

Although so many names of particle subcomponents are used in various theories: *subquarks, maons, alphons, quinks, rishons, tweedles, helons, haplons, Y-particles, primons, (..?)*
most commonly the fermion subcomponents are called **preons** [Pati, Salam, 1974].

Typically models of fermion compositeness predict **new heavy composites**, which can be constructed using their sets of preons.

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Current mass bounds for new composite fermions

- Excited ℓ^* and q^* differ from the SM ℓ and q only by larger values of masses. Lower limits on their masses: $m^* > 100 - 1000\,\text{GeV}$ [PDG2014]
- Color (anti)sextet quarks q_6: $m_{q_6} > 84\,\text{GeV}$ [CDF: Abe, PRL 63, 1447]
  $(\bar{3} \times \bar{3} = 3 + \bar{6})$
- Leptoquarks LQ: $m_{LQ} > 845\,\text{GeV}$ [CMS PAS EXO-12-041]
  (1st generation)
- Color octet neutrinos ν_8: $m_{\nu_8} > 110\,\text{GeV}$ [CDF: Barger, PL B220, 464]
  $(3 \times \bar{3} = 1 + 8)$
- Color octet charged leptons ℓ_8: $m_8 > 86\,\text{GeV}$ [CDF: Abe, PRL 63, 1447]
- **New bound on ℓ_8 mass:** $\mathbf{m_8 > 1.2\,TeV}$ [Goncalves-Netto et al., 2013]

Quark and lepton compositeness should manifest itself at low energies in **contact interactions** (lowest dim. interactions with 4 fermions)

$$L = \frac{g^2}{2\Lambda^2}[\eta_{LL}\bar{\psi}_L\gamma_\mu\psi_L\bar{\psi}_L\gamma^\mu\psi_L + \eta_{RR}\bar{\psi}_R\gamma_\mu\psi_R\bar{\psi}_R\gamma^\mu\psi_R + \eta_{LR}\bar{\psi}_L\gamma_\mu\psi_L\bar{\psi}_R\gamma^\mu\psi_R],$$

where Λ is the scale of compositeness, and $\eta_{\alpha\beta}$ can be selected as either ±1 or 0, e.g., $\Lambda = \Lambda_{LL}^{\pm}$ for $(\eta_{LL}, \eta_{RR}, \eta_{LR}) = (\pm1, 0, 0)$.

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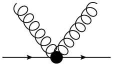
Present limits on $\Lambda_{\psi\psi\psi\psi}$ [PDG 2014]

$\Lambda_{\psi\psi\psi\psi}$	Bound on Λ^+_{LL} (Λ^-_{LL}), TeV	Experiment
Λ_{eeee}	> 8.3 (> 10.3)	RVUE - LEP2
$\Lambda_{ee\mu\mu}$	> 8.5 (> 9.5)	L3 (ALEPH)
$\Lambda_{ee\tau\tau}$	> 7.9 (> 7.2)	ALEPH, DLPHI (OPAL)
$\Lambda_{\ell\ell\ell\ell}$	> 9.1 (> 10.3)	DLPHI (ALEPH)
Λ_{eeqq}	> 23.3 (> 26.4)	LEP2, etc.
$\Lambda_{\mu\mu qq}$	> 9.6 (> 13.1)	ATLAS (CMS)
$\Lambda_{\ell\nu\ell\nu}$	> 3.1 [for $\Lambda^\pm_{LR}$]	SPEC - TRIUMF
$\Lambda_{e\nu qq}$	> 2.81	CDF
Λ_{qqqq}	> 9.9	CMS

However dominant effects of compositeness may come from $\psi\psi$**gg interactions**.

Similarity between quarks and leptons in the SM gauge and flavor structure suggests that composite leptons likely contain $SU(3)$ colored constituents.
At low energies such substructure of a lepton should slightly affect its intrinsic properties. Relevant lowest order effective interaction among the SM particles is $\boldsymbol{\ell}$-$\mathbf{g}$-$\mathbf{g}$-$\boldsymbol{\ell}'$ (dim.5)



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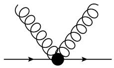
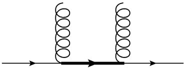




This vertex may originate from an **intermediate state $\boldsymbol{\ell_8}$** between emission (absorption) of the "first" and the "second" gluon by a lepton ℓ.

The effective interaction of ℓ_8 with the lepton and gluon can be written as

$$\mathcal{L} = \frac{g_s}{2\Lambda} \overline{\ell_8^A} \sigma^{\mu\nu} G^A_{\mu\nu} (a_{\ell L} P_L + a_{\ell R} P_R)) \ell + \mathrm{H.c.}$$

In the following we consider long-lived **leptogluons $\boldsymbol{\ell_8}$** with the decay width

$$\Gamma_{\ell_8 \to g\ell} = \alpha_s (a^2_{\ell L} + a^2_{\ell R}) \frac{m_8^3}{4\Lambda^2} \ll m_8.$$

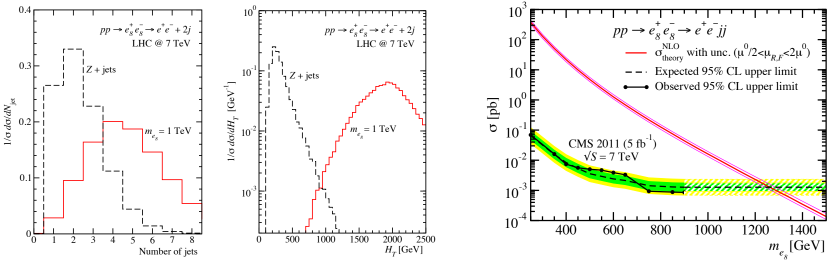
Selected papers on collider searches for leptogluons (LG)

- M. A. Abolins, *et al.*, eConf C **8206282** (1982) 274
  discussed single production of LG in lepton-proton collisions
- A. Celikel, M. Kantar and S. Sultansoy, Phys. Lett. B **443** (1998) 359
  pair production of LG at LHC at LO (some misprints in cross-sections)
- A. N. Akay, *et al.*, Europhys. Lett. **95** (2011) 31001 [arXiv:1012.0189]
  indirect production of LG at LC at LO (misprint in diff. cross-sect.)
- J. L. Abelleira Fernandez, *et al.* [LHeC Study Group Collaboration], J. Phys. G **39** (2012) 075001 [arXiv:1206.2913 [physics.acc-ph]]
  prospects for the searches at LHeC
- T. Mandal and S. Mitra, Phys. Rev. D **87** (2013) 9, 095008 [arXiv:1211.6394 [hep-ph]]
  pair, single and indirect prod. of LG at LHC at LO
  (expectations for 14 TeV LHC)
- D. Goncalves-Netto, *et al.*, Phys. Rev. D **87** (2013) 094023
  (see next slide)

Recent search for LG at the LHC at next-to-leading order

- D. Goncalves-Netto, *et al.*, Phys. Rev. D **87** (2013) 094023 [arXiv:1303.0845 [hep-ph]]

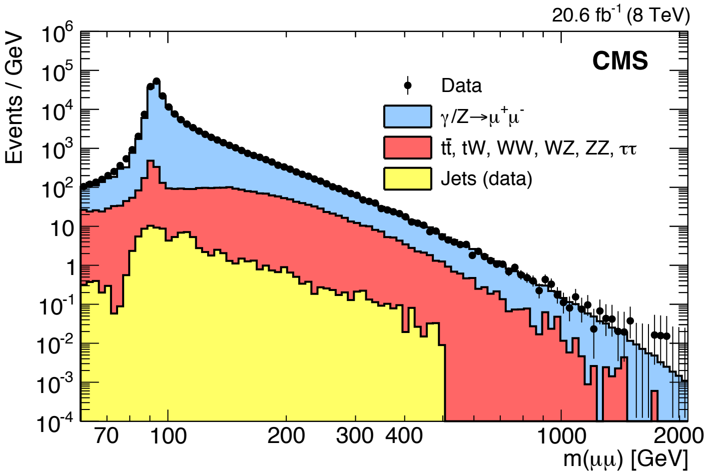
  NLO calculation of LG pair production at LHC.
  Based on $pp \to \ell_8^+ \ell_8^- \to \ell^+ \ell^- jj$ and the CMS leptoquark searches they derived lower bound of **1.2-1.3 TeV** for the mass of charged LG



Leptogluons in Dimuon Production at the LHC

Dimuon mass spectrum measured by the CMS so far agrees with the SM

[JHEP 04 (2015) 025 [arXiv:1412.6302]]



However the trend at the high-energy tail is clear: new physics may effect data points at $m_{\mu\mu} \gtrsim 1.5\,\mathrm{TeV}$. Coming LHC run-2 will address this possibility.

Table from JHEP 04 (2015) 025 [arXiv:1412.6302] by CMS Collaboration.

Table 2: The number of dimuon events in various invariant mass ranges for an integrated luminosity of 20.6 fb^{-1}. The total background is the sum of the events for the standard model processes listed. The yields from simulation are normalized relative to the expected cross sections, and overall the simulation is normalized to the data using the number of events in the mass window 60–120 GeV acquired using a prescaled low threshold trigger. Uncertainties include both statistical and systematic components, summed in quadrature. A dash (—) is used to indicate negligibly small contributions.

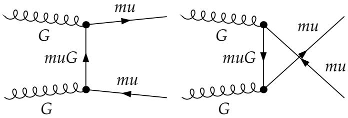
$m_{\mu\mu}$ range (GeV)	Data	Total background	Z/γ^*	$t\bar{t}$ + other prompt bkgd	Jet mis-reconstruction
120–400	96299	96800 ± 4300	86800 ± 3800	9900 ± 420	147 ± 18
400–600	1367	1460 ± 80	1180 ± 60	276 ± 13	3 ± 3
600–900	273	283 ± 19	246 ± 16	37 ± 4	—
900–1300	55	46 ± 4	40 ± 4	5 ± 1	—
1300–1800	8	6.1 ± 0.8	5.7 ± 0.8	0.4 ± 0.2	—
>1800	2	0.8 ± 0.2	0.8 ± 0.2	—	—

How much may leptogluons with mass 1-2 TeV contribute to these data?

Possible effect of muonic leptogluon $\mu_8 \equiv muG$

Indirect production of LG

$\mu^+\mu^-$ pairs can be produced though t-channel exchange of $\mu_8^{\pm}$



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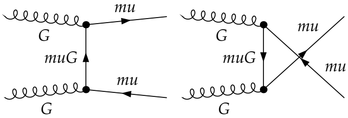
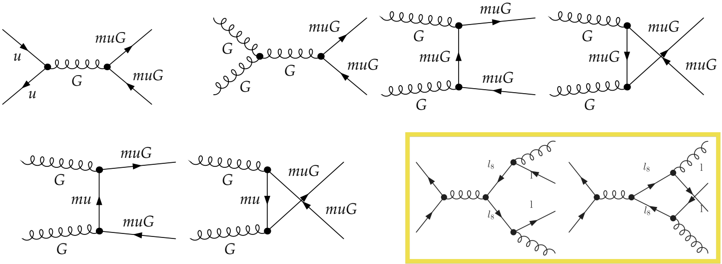


Compare with **pair production of LG**



Bottom-left: LG pair production with a subsequent radiative decay

Analytical results

$$\sigma_{gg\to\mu^+\mu^-}(m_{\mu\mu}^2) = \frac{\pi\alpha_s^2}{12}\xi^4 m_8^2\ F\left(\frac{m_8^2}{m_{\mu\mu}^2}\right),$$

where $\xi = \frac{a_{\mu L}}{\Lambda}$ is coupling-to-scale ratio, and we neglected the terms of $\mathcal{O}(\Gamma/m_8)$,

$$F(r) = \frac{1 - 6\,r - 24\,r^2}{2\,r} + 3\,r(3+4r)\ln\left(\frac{1+r}{r}\right).$$

The total cross section for the process $pp \to ggX \to \mu^+\mu^- X$ can be written as

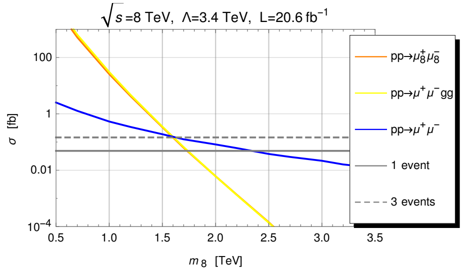
$$\sigma_{pp\to\mu^+\mu^- X} = \int\limits_{y_0}^{1}\frac{dy}{y}\int\limits_{y}^{1}\frac{dx}{x}\,p_g(x,\mu_F^2)\,p_g\left(\frac{y}{x},\mu_F^2\right)\sigma_{gg\to\mu^+\mu^-}(ys)$$

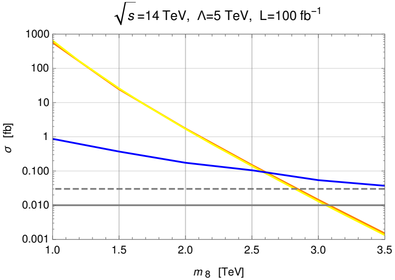
where $y_0 = 4m_\mu^2/s$, $\sqrt{s}$ is the total energy of the pp collisions, μ_F is the factorization scale, and $p_g(x,Q^2) = x\,g(x,Q)$ is a gluon PDF.

We do not show here the analytical results for $\sigma_{pp\to\mu_8^+\mu_8^- X}$ and differential cross-sections (including the diagrams with t-channel exchange of $\mu^\pm$) for short.

Full comparison with MadGraph5 (including the dependence on α_s, PDFs and LQ decay widths) is on the way.

Using MadGraph5 [Alwall, *et al.* '11] we have got the cross-sections





The indirect production of $\mu_8^\pm$ dominates over their pair production for

- $m_8 \gtrsim 1.5\,\text{TeV}$ for $\sqrt{s} = 8\,\text{TeV}$ and $\Lambda = 3.4\,\text{TeV}$
- $m_8 \gtrsim 2.5\,\text{TeV}$ for $\sqrt{s} = 14\,\text{TeV}$ and $\Lambda = 5\,\text{TeV}$

Hence indirect production of LG is of particular importance for 8 TeV LHC. (Relevant signature is two hard muons without alongside jets.)

PRELIMINARY

We have found that the effect of indirect production of LQ may reduce the deviations of the central values of the CMS data points from the SM background for $\mu^+\mu^-$ production at 8 TeV LHC in region of large $m(\mu^+\mu^-)$

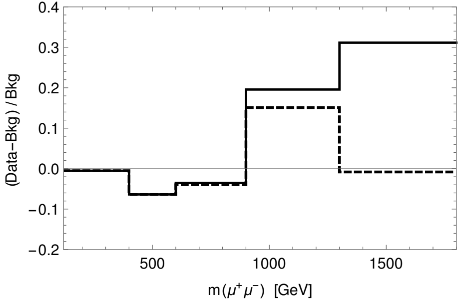


Figure : Weighted difference between # of CMS data and background events in the given ranges of the invariant mass $m(\mu^+\mu^-)$ for $\sqrt{s} = 8$ TeV and $L = 20.6\ \text{fb}^{-1}$.
Solid line represents pure SM background.
Dashed line represents the combination of the SM background and the effect of indirect production of $\mu_8^{\pm}$ with the mass $m_8 = 2$ TeV and coupling-to-scale ratio $\xi = (2.1\ \text{TeV})^{-1}$, which corresponds to $\chi^2_{\text{min}} = 2.06$.

Wolfram Mathematica and CTEQ5 PDFs were used

Conclusion

We have derived the differential and full cross-sections for indirect and pair production of leptogluons in pp collisions including the diagrams with the t-channel exchange of leptons.

We have found that **indirect production** of LG dominates at 8 TeV LHC for the leptogluon masses $m_8 > 1.5\,\mathrm{TeV}$.

For **dimuon production** at 8 TeV LHC we have shown that the effect of indirect production of leptogluons reduces the deviations of the central values of the CMS data points from the SM background.

Our analysis shows great prospects of further searches for the lepton colored compositeness in the modern collider experiments. In particular, combination of 8 TeV LHC data with coming results of 13 TeV LHC run would be useful for these searches.

It is my pleasure to thank
Henryk Czyż, **Janusz Gluza** and **Tomasz Jelinski**
for useful discussions and collaborative work.

THANK YOU FOR YOUR ATTENTION!

Backup Slides

Historical excurse

When the electron spin was discovered, Uhlenbeck and Goudsmit proposed (in 1925) that it comes from rotation of the electron charge sphere. However Lorentz argued that the surface of the sphere would have a tangential speed $v = 137c$ *to produce the accurate spin angular momentum.*

However in the picture of rotating wavepacket [Chuu, Chang, Niu, 2010] the minimum intrinsic radius of the electron wavepacket is 137 times larger than the classical electron radius used in Lorentz's argument. Hence even tightest possible electron wavepacket does not have to rotate faster than the speed of light.

May spin of the SM electron (and other fermions) have similar origin?

For this to happen e^- should be a composite object.

Indeed, intrinsic structure can be responsible for the rotation and, in particular, provides a preferred axis of rotation.

Brief introduction to preons

By **preons** I mean subcomponents of leptons, quarks, etc.

Historically word "preon" originates from "pre-quark".
However it can be understood more generically as "pre-particle".

Other names, used in the literature: subquarks, maons, alphons, quinks, rishons, tweedles, helons, haplons, Y-particles, primons, and (?)

Problem is that simple assignment of preons violates Heisenberg's uncertainty principle, giving the *mass paradox*: sum of the masses of preons, which compose a SM fermion, should exceed the mass of this fermion.

Possible solutions of mass paradox

- Classical limit ($\hbar \to 0$, $N_c \to \infty$, etc.)
- Confined preons with either small or zero mass [Yu. P. Goncharov, 1312.4049]
- Nonlocality (includes application of SUSY and string theory methods)
- Large binding force between preons, cancelling their mass-energies

Particles from gravity site

"It is commonly recognized now that black holes are akin to elementary particles" [A. Burinskii, 1212.2920]

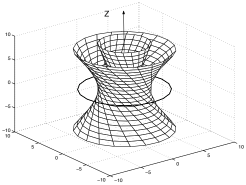
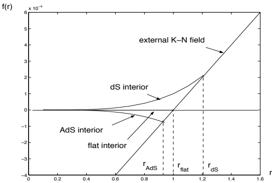


Figure 1: Congruence of the lightlike lines $k^\mu(x)$ is focused on singular ring, creating twosheeted Kerr space.

Matching of metrics:

$$g_{\mu\nu} = \eta_{\mu\nu} + 2Hk_\mu k_\nu,$$
$$H = \frac{mr - e^2/2}{r^2 + a^2\cos^2\theta}$$



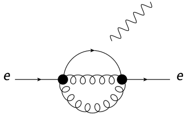
Electron may be explained by a regular solution (charged, spinning and gravitating) of Kerr-Newman geometry (in the thin-wall approximation).

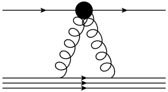
In non-abelian case this solution predicts a disk-like core of e^- formed by the Higgs field, which is spinning and oscillating, and is bounded by a closed circular current of the Compton radius. [A. Burinskii, 1003.2928]

KN solution has gyromagnetic ratio $g = 2$ as of the Dirac electron, and the gravitational field as expected for e^- from asymptotics.

Other possible directions for the searches

- Very soft scattering of the polarized e^- may probe the disk-like form of the electron's core (testing of this shape was discussed already by Compton in 1919) [Burinskii 1003.2928]
- Effect of lepton colored substructure in AMM of e and μ





- Effect in μ-e conversion on N (flavor-changing μegg vertex)
- Search for colored substructure of neutrinos in neutrino-nucleus scattering
- $\ell\ell'$ production at high L and E colliders: LHC, Belle II, ILC, CLIC, etc.
- Search for "leptonization" - jets from destroyed leptons (at Roman pots)
- New global fits to neutrino data, etc.

Contribution to muon $g-2$

The lowest order contribution to the lepton AMM from the lepton color excitation $\tilde{\ell}$ can be represented by the diagram

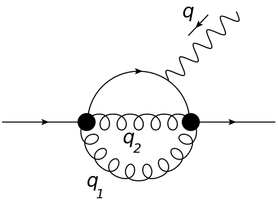


Figure : Feynman diagram for the considered contribution to lepton AMM

The two limiting cases for the decay width of $\tilde{\ell}$ may generate the expressions for the vertex ℓ-ℓ'-g-g, which differ by the factor i, depending on the values of $\tilde{m}$ and Γ. This can switch the sign of the considered contribution to the lepton AMM.