glueballs from gluon jets at the LHC

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status of glueballs: theory, experimental scenarios
leading systems in gluon jets, LEP results
proposals for LHC

with Peter Minkowski (Univ. Bern)

hadron2011, Munich, June 13, 2011
QCD expectations for glueballs

- early prediction: bound states of self-interacting gluons
- scenarios for glueball phenomenology
  - Fritzsch-Minkowski ’75

### Lattice QCD

- quenched approximation (only gluons)
  - lightest state $J^{PC} = 0^{++}$: mass $\sim 1600 \pm 200$ MeV

- unquenched results (including $q\bar{q}$)
  - lightest gluonic flavour singlet:
    - mass $\sim 1000$ MeV  
      - UKQCD ’06: Hart et al.
    - mass $\sim 1500$ MeV  
      - UKQCD ’10: Richards et al.

### Some problems:

- extrapolation to small lattice spacing, small $m_q$; decay to $\pi\pi$
QCD sum rules

- 2 gluonic resonances to satisfy sum rules for $0^{++}$
  \[ M_{gb1} \approx 1 \text{ GeV}, \quad M_{gb2} \approx 1.5 \text{ GeV} \]

  either 2 $gb$ states (NV) or a mixed $gb$-$q\bar{q}$ system (HKMS)

Narison-Veneziano '89 (broad $M_{gb1}$)
Harnett-Kleiv-Moats-Steele '08-'11

Experimental searches

- extra state in spectrum besides flavour nonets
- enhanced production in "gluon rich" processes
- suppression in $\gamma\gamma$ processes
glueball in scalar meson spectrum

possible solution:

\[ f_0(1710) \]
\[ f_0(1500) \]
\[ f_0(1370) \] 3 isoscalars: 2 nonet \( q\bar{q} \) states

one extra state: \[ \rightarrow \text{glueball } M \sim 1.5 \text{ GeV} \] Amsler, Close '96 ...

\[ f_0(980) \]
\[ f_0(600)/\sigma \] could be from light nonet: \( q\bar{q}, \, 4q, \, K\bar{K} \)

problem:
\[ f_0(1370) \] not seen in energy-independent analyses (\( \pi\pi \))

alternative possibility:

\[ f_0(1500) \]
\[ f_0(980) \] \( q\bar{q} \) nonet \( \text{(no } f_0(1370)) \) Minkowski, W.O. '98

\[ f_0(600)/\sigma \] glueball \( M_{BW} \sim 1 \text{ GeV} \) Narison

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gluon rich processes produce $gb = (gg)$ . . .

1. central production in pp collisions:
   double Pomeron exchange: $pp \rightarrow p_f \ gb \ p_f$

2. $J/\psi \rightarrow \gamma \ gb$

3. $p\bar{p} \rightarrow \pi \ gb$

4. $b \rightarrow sg$: $B \rightarrow K \ gb$

5. gluon jet at high energy: $e^+e^- \rightarrow q\bar{q}g$, $pp \rightarrow g + X$: $g \rightarrow gb + X$

reactions 1-4 proceed at low energies, role of gluon not obvious
example:
ALICE @ LHC: (double Pomeron): excess of $f_0(980)$ and $f_2(1270)$ ($q\bar{q}$)!
Pomeron structure at HERA:
   large $q\bar{q}$ singlet component at $z=1$.

⇒ only in reaction 5 a gluon can be identified

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leading systems in gluon jets

\[ u \rightarrow \pi^+ (u\bar{d}) + X: \] leading meson at large x carries initial quark

in analogy:

\[ g \rightarrow gb(gg) + X: \] leading meson is a glueball, carries initial gluon (?)

- nonperturbative jet model for flavour singlet object \((\eta, \eta', \omega, gb)\)
  (analogy to Field Feynman model) C.Peterson, T.F.Walsh, ’80

- fragmentation functions \(g \rightarrow gb\) at large \(x\) P. Roy, K. Sridhar ’97
  H. Spiesberger, P.M. Zerwas ’00

- rapidity gap analysis, study charge and mass of leading cluster
  W. O., P. Minkowski ’00

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different colour neutralization processes

colour charges separated beyond confinement radius $r \gtrsim R_c$:
$\Rightarrow$ colour neutralization by pair production

a) initial $q\bar{q}$:  
\[ \begin{array}{c}
q \quad \bar{q} \\
\bar{q} \quad q
\end{array} \]

b) initial $gg$

\[ \begin{array}{c}
\bar{q} \quad q \\
q \quad \bar{q}
\end{array} \]

\[ \begin{array}{c}
g \quad g \\
g \quad g
\end{array} \]

colour triplet neutralization \hspace{2cm} (P_3) colour triplet neutralization $Q = 0, \pm 1$

electric charge $Q = 0, \pm 1$ \hspace{2cm} (P_8) colour octet neutralization $Q = 0$

colour octet mechanism is precondition for leading glueballs
rapidity gap analysis

rapidity gap isolates leading cluster (charge $Q_{\text{lead}}$, mass $M_{\text{lead}}$)

\[ \Delta y > y \quad \text{rapidity: } y = \frac{1}{2} \ln \frac{E+p_\parallel}{E-p_\parallel} \]

for large rapidity gaps $\Delta y$:

- limiting distribution of charge $Q_{\text{lead}}$
  - $Q_{\text{lead}} = 0, \pm 1$ for $(q\bar{q})$
  - probabilities from fragmentation models
  - $Q_{\text{lead}} = 0$ for $(gg)$

- charges $|Q_{\text{lead}}| > 1$ are suppressed (multiquark exchanges)

⇒ Results from LEP on $Q_{\text{lead}}$ and $M_{\text{lead}}$ from DELPHI, OPAL, ALEPH
rapidity gap analysis: leading charge $Q_{lead}$

| Gluon Jet | Quark Jet | $\Delta y = 1.5$ DELPHI |
|-----------|-----------|--------------------------|

Excess $Q_{lead} = 0$ in gluon jet vs. MC (JETSET), excess 5-10% dependence on $\Delta y$
leading charge $Q_{\text{lead}}$ in gluon jets

identified $b\bar{b}g$ events

 gluon jet, no gap

 gluon jet, with gap

JETSET ok

$Q_{\text{lead}} = 0$ excess of $\sim 40\%$ (JETSET)

(GAL, AR refer to color reconnection models)
rapidity gap analysis: cluster mass for $Q_{lead} = 0$

**DELPHI**

- gluon jet
- gluon jet
- quark jet

**OPAL**

- gluon jet

charged + neutrals

**gluon jets:** excess of low mass $M_{lead} < 3$ GeV

excess at mass $< 2.5$ GeV (2σ)

no $\rho$ in $\pi^+\pi^-$, $f_0(1500)$ in 4π?

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Advantages at LHC

- higher energy of gluon jets → larger rapidity gaps
- quark and gluon jets at comparable energies in the same experiment
- higher statistics
separation of gluon and quark jets at LHC

1. leading order processes

quark jets in $\gamma +$ jet events ($qg \rightarrow \gamma q$)

 gluon jets in di-jet events (at small $x_T$)

rates from pdf’s and parton parton cross sections

| $p_T$ | $x_T$ | g in di-jet | q in $\gamma +$ jet |
|------|------|-------------|---------------------|
| 1.8 TeV (CDF) | 50 | 0.056 | 60% | 75 % |
| 7 TeV (G& S) | 200 | 0.057 | 60% | 80 % |
| 50 | 0.014 | 75% | 90 % |
| 800 | 0.229 | 25% | 75% |

J. Gallicchio and M.D. Schwartz, 4/2011

quark jets: an 80% purity is ok for the study of leading systems

(quarks fragment harder than gluons)

2. gluon bremsstrahlung

 gluon jets: from 3 jet events with high purity (> 90 %)

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selection of gluon jets

⇒ trigger on total transverse energy

select 3 jet events: soft gluon jet from bremsstrahlung: \( qqg \) or \( ggg \)

production of low energy jet:

\[
\frac{d\sigma}{dx_g dp_T} = \sigma_q \frac{\alpha_s}{2\pi p_T^2} P_{qg}(x_g) + \sigma_g \frac{\alpha_s}{2\pi p_T^2} P_{gg}(x_g)
\]

fraction of gluon jets:

\[
F_g(x_g) = \frac{\sigma_q P_{qg}(x_g) + \sigma_g P_{gg}(x_g)}{\sigma_q P_{qg}(x_g) + \sigma_g P_{gg}(x_g) + \sigma_g P_{gg}(x_g)}
\]

\( P_{qg}(x_g) = \frac{4}{3} \frac{1+(1-x_g)^2}{x_g} \), \( \ldots \)

for \( x_g \to 0 \):

\[
F_g(x_g) = \frac{1}{1+4x_g/(8+18 R_g)} ; \quad R_g = \frac{\sigma_g}{\sigma_q}
\]

examples: \( x_g = 0.2 ; \ R_g = 1 \quad \Rightarrow F_g \approx 95\% \)

\( x_g = 0.5 ; \ R_g = 1 \quad \Rightarrow F_g \approx 85\% \)
studies at LHC

1. Repeat rapidity gap studies at LEP in new environment:

   ⇒ larger rapidity gaps ($\Delta y \sim 4$) (factor 10 in energy, $\ln 10 = 2.3$);
   
   $Q = 0, \pm 1$ closer to asymptotics;

   learn more about colour neutralization of gluon $P_3, P_8$

   ⇒ mass peaks in $Q = 0$ system?

   problem: limited angular acceptance due to rapidity gap

2. alternative approach: resonance production directly

   ⇒ mass spectra $M(\pi\pi), M(K\bar{K}), M(4\pi)\ldots$ in jets

   study their $x$-dependence in quark and gluon jets

   ⇒ define reference $x$-distributions:

   "leading" (like $u \rightarrow \pi^+$) and "suppressed" (like $u \rightarrow \pi^-, g \rightarrow \pi$)
### large $x$ fragmentation

| meson          | quark jet     | gluon jet     |
|----------------|---------------|---------------|
| $q\bar{q}$: $\{\rho, f_2\}, f_0$  | leading       | suppressed    |
| $gb$: $f_0$    | suppressed    | leading       |
| $q\bar{q}$: $f_0$, strongly mixed | leading       | leading       |
| $4q$: $\sigma, f_0(980)$ (?) | suppressed    | suppressed    |
$x -$ dependent mass spectrum

Cluster mass spectrum for

$x_{\text{cluster}} \text{ small} \quad \text{(many combinations)}$

Glueballs among isoscalars

| Cluster | Scalar Meson |
|---------|--------------|
| $(\pi \pi)^0$ | $f_0(600)/\sigma, f_0(980), f_0(1500)$ |
| $(4\pi)^0$ | $f_0(1370)(?), f_0(1500)$ |
| $(K\bar{K})^0$ | $f_0(980), f_0(1500), f_0(1710)$ |

$x_{\text{cluster}} \text{ large} \quad \text{(one or few combinations)}$

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Summary

- glueballs predicted in QCD since the very beginning
  no clear evidence yet

- new chance finding glueballs in gluon jets at LHC
  - large rapidity gaps - increased $Q_{lead} = 0$ excess
  - $x$-dependence of mass spectra in $q$ and $g$ jets

- important hints from LEP
  ⇒ new fragmentation component beyond JETSET
  clear excess of $Q_{lead} = 0$ jets (up to 40%)
  not enough $\rho$?
  gluon jets may not be built from quark strings only