A Composite Fermion Approach to Heavy Pentaquarks.

A. Bhattacharya and R. Ghosh
Department of Physics
Jadavpur University , Kolkata.
India.

Paper presented at
22nd International Spin Symposium (SPIN-2016)
25-30 September 2016
University of Illinois and Indiana University
Urbana - Champaign, USA.

Aim of the Work

- Heavypentaquarks are described as diquark-diquark-antiquark system. The Composite Fermion (CF) Model has been employed to obtain diquark mass.
- The higher state masses of heavy pentaquarks θ_c^0, N_c^0, Ξ_c^0 and θ_b^+, N_b^+, Ξ_b^+ have been investigated in the mass loaded flux tube model.
- Regge Trajectories (RTs) for heavy pentaquarks have been analyzed to get regge slope (α) and the string tension (σ)
- The ground state masses of pentaquark have been extracted from RT plots.
- The results are compared and found to be in good agreement with results available in literature.

Why Diquarks

- Diquark is low energy configuration of two strongly correlated quarks .
- At low energies the quark dynamics can be revisited in the light of new results of baryon and exotics spectroscopy.
- The **regularities in hadron spectroscopy , parton distribution function** , **spin dependent structure function of hadrons**, etc hint at the existence of diquark correlation[1]. In QCD both the gluon exchange interaction and Instanton Induced Interaction [2] favour the spin singlet and colour anti-symmetric diquark combination.

Ref: [1] A.S.Castro et al.,Z. Phys. C 57(1997) 315 ; D.B. Lichtenberg et al., Z. Phys. C 17 (1983) 57; E.V.Shuryak, Nucl.Phys.B 50 (1982) 93; T. Schafer et al., Rev.Mod.Phys. 70 (1998) 323.

[2] E.V.Shuryak, Nucl. Phys. B 50 (1982) 93; T.Schafer etal., Rev. Mod. Phys. 70 (1998) 323.

Why Diquarks.

- A deeply bound diquark system is one of the most important candidate for describing the baryonic and exotic system.
- The quark-quark correlation or a diquark can be assumed to be a fundamental entity behaving like an independent body inside hadron.
- They are hypothetical particles.
- The exact nature of the diquark correlation is under extensive study.

Quasiparticles.

- Quasi particles are particle like entities arising in system of interacting particles. They are low-lying excited states representing the properties of the system simulating many body interaction.
- Hypothetical particles.
- Quasiparticle concept is most important in condensed matter physics and one of the few known ways to simplify the quantum mechanical many-body problem.
- Example: electrons in crystal lattice.

Quasiparticles

- More specialized examples are “Composite fermions” and “Bogoluibov quasiparticle” in superconductors.
- Superconductivity arises due to cooper pairs. A broken cooper pair is known as bogoluibov quasiparticle.
- Behave independently — properties different from the original particle.

The Composite Fermion (CF)

- Composite Fermion (CF) bound state of an electron and an even number of quantized vortices in two dimension showing Fractional Quantum Hall Effect [FQHE] [3].
- They can be fractionally charged and neither fermion nor boson (anyon, an exotic type of particle.)
- CF is described in gauge invariant way in the system of gauge interaction of two dimensional electron gas in high magnetic field [4-5].
- CF spin is frozen and described as the stable quasi particles in the system.

[3] J.K.Jain; Physics TodayApril 2000, 39. [4]B.I.Helperin et al., Phys. Rev.B 47 (1993) 7312.

[5] A.Raghavchari et al., arXiv:cond.matt./9707055.

Composite Fermion Model of Diquark

- In analogy with CF model of a quasiparticle model for diquark has been suggested where it is described as Composite Fermion in presence of chromomagnetic nature of the vacuum.
- With CF model for diquark the masses of diquarks for different flavors are computed.
- Heavy pentaquark masses have been estimated in diquark - diquark – anti-quark configuration.

Compsite Fermion Model for diquark.

- Starting from Hamiltonian of composite fermion with cut off Λ , the expression of quasiparticle mass in a gauge invariant system can be obtained as: [5],

$$\frac{1}{m^*} = \frac{1}{m}(1 + \frac{\Lambda^4}{2p_F^4})..............................(1)$$

- m^*; effective mass of composite fermion, m ;constituent Mass , p_F is fermi momentum.
- Considering the diquark behaving like a CF in presence of chromo-magnetic field, effective mass represented as:

$$\frac{1}{m_D^*} = \frac{1}{m_{q1} + m_{q2}}(1 + \frac{\Lambda^4}{2p_F^4})...........................(2)$$

- m_D^* diquark mass; m_{q1}, m_{q2} mass of quark flavor of diquark, p_F Fermi momentum of diquark.

Composite Fermion Model for diquark.

- The Fermi momentum (p_F) - estimated using the work of Bhattacharya et al [6,7]. With input of radii of diquarks from existing literature and cut off 'Λ' as 0.573 Gev [8], the diquark masses estimated using the expression (2) .

- Masses obtained as m_{ud} = 0.4898 GeV, m_{us} = 0.6331 GeV for scalar diquark and m_{ud} = 0.5293 GeV, m_{us} = 0.7221 GeV for vector diquark.

- **Ref. [6] A.Bhattacharya et al., Int.J.Mod.Phys.A 15 (2003) 2053. [7] A.Bhattacharya et al.,Eur. Phys. J. C 2 (1998) 671, [8] S.Pepin et al; arXiv:hep-ph/9912475(1999).**

Mass Loaded Flux Tube Model

- In the semi-classical mass loaded flux tube model two masses are connected by a relativistic string tention "T", rotating with angular momentum **L**.
- Considering the heavy pentaquark in the diquark-diquark-antiquark picture, system represented as heavy antiquark at rest and the two diquarks connected by flux tube.
- Mass Formula Runs as:

$$E = M_{c,b} + \sqrt{\sigma L / 2} + 2^{1/4} k L^{-1/4} \mu_D^{3/2} + a \vec{L}.\vec{S} \ldots\ldots\ldots\ldots\ldots\ldots(3)$$

- Diquark masses computed using (2) and the energy of the heavy pentaquark system have been estimated for different J^P states.

Regge Trajectories.

- The orbital excitation of the particle can be described by Regge trajectories and has been expressed by:

$$E^2 = \alpha J \text{.............................}(4)$$

- E the energy at the higher states ; J is the total angular momentum .
- Regge slope runs as:

$$\alpha = 1/2\pi\sigma \text{ ....}(5)$$

E –J Graph plotted for charm and bottom pentaquarks (Fig-1 and Fig-2). The Regge slope (α) and the string tension (σ) have been estimated from Fig-1 and Fig-2 and displayed in Table –3.

Table1:Mass of higher states of charm pentaquarks

L	J^P	Mass (GeV) θ_c^0 $[ud][ud]\bar{c}$ Our results	Expt.results	Mass (GeV) N_C^0 $[ud][us]\bar{c}$ Our results	Expt.results	Mass (GeV) Ξ_C^0 $[us][us]\bar{c}$ Our results	Expt.results
1	$\frac{1}{2}^-$	3.200	-	3.426	-	3.653	-
	$\frac{3}{2}^-$	3.299	-	3.526,3.621	-	3.847	-
2	$\frac{3}{2}^+$	3.3198	-	3.509	-	3.699	-
	$\frac{5}{2}^+$	3.449	-	3.639,3.719	-	3.909	-
3	$\frac{5}{2}^-$	3.446	-	3.6183	-	3.790	-
	$\frac{7}{2}^-$	3.6115	-	3.783,3.855	-	4.027	-
4	$\frac{7}{2}^+$	3.565	-	3.725	-	3.885	-
	$\frac{9}{2}^+$	3.767	-	3.927,3.994	-	4.154	-

Table 2: Mass of higher states of bottom pentaquarks

L	J^P	Mass θ_b^+ $[ud][ud]\bar{b}$ Our results	(GeV) Expt.results	Mass N_b^+ $[ud][us]\bar{b}$ Our results	(GeV) Expt. results	Mass Ξ_b^+ $[us][us]\bar{b}$ Our results	(GeV) Expt.results
1	$\frac{1}{2}^-$	5.850	-	6.076	-	6.303	-
	$\frac{3}{2}^-$	5.949	-	6.176,6.271	-	6.497	-
2	$\frac{3}{2}^+$	5.969	-	6.159	-	6.349	-
	$\frac{5}{2}^+$	6.099	-	6.289,6.369	-	6.559	-
3	$\frac{5}{2}^-$	6.096	-	6.268	-	6.440	-
	$\frac{7}{2}^-$	6.261	-	6.433,6.505	-	6.677	-
4	$\frac{7}{2}^+$	6.215	-	6.375	-	6.535	-
	$\frac{9}{2}^+$	6.417	-	6.577,6.644	-	6.804	-

Figure 1: The regge trajectories $(J - E^2)$ for charm pentaquarks

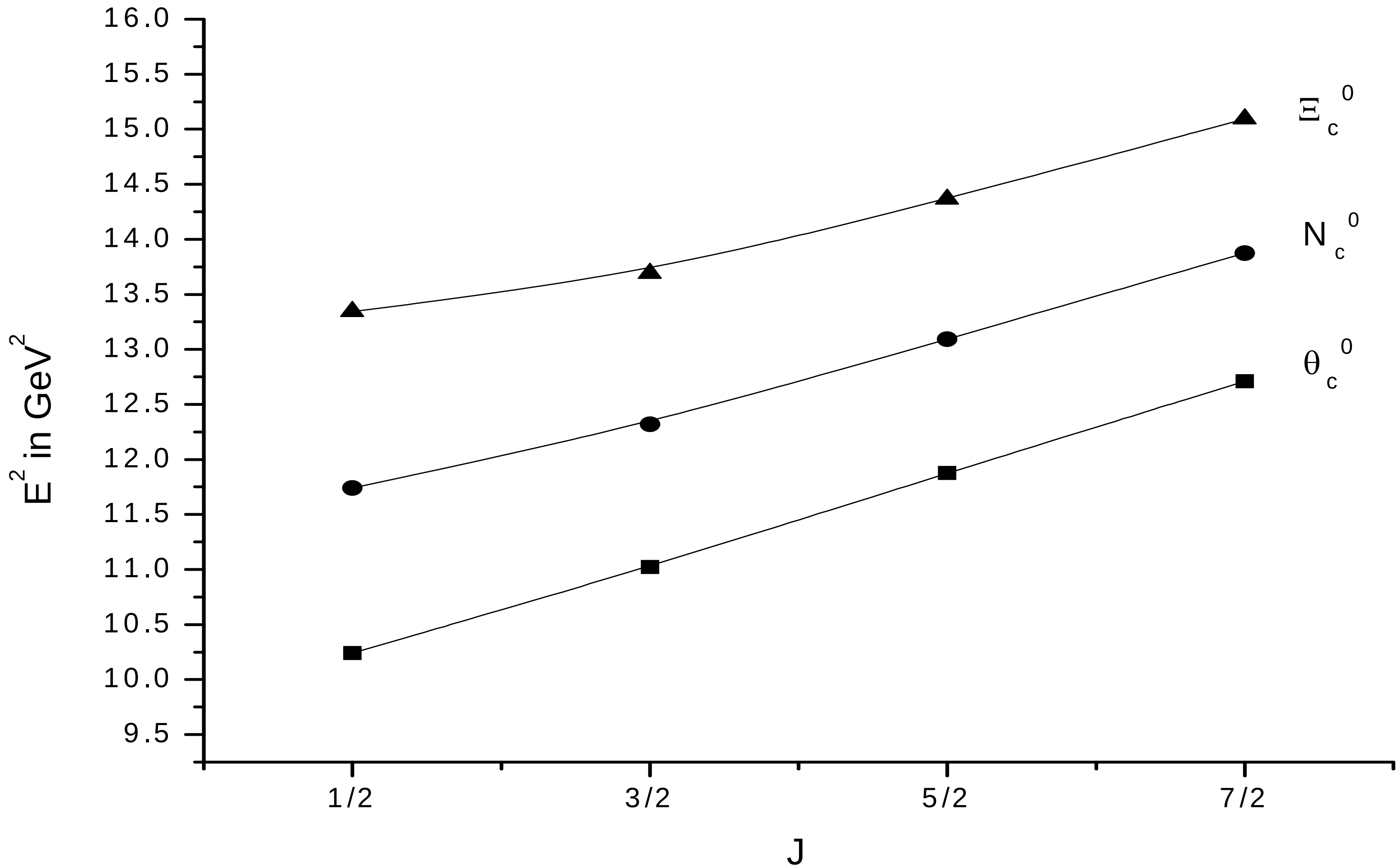

Figure 2: The regge trajectories $(J - E^2)$ for bottom pentaquarks

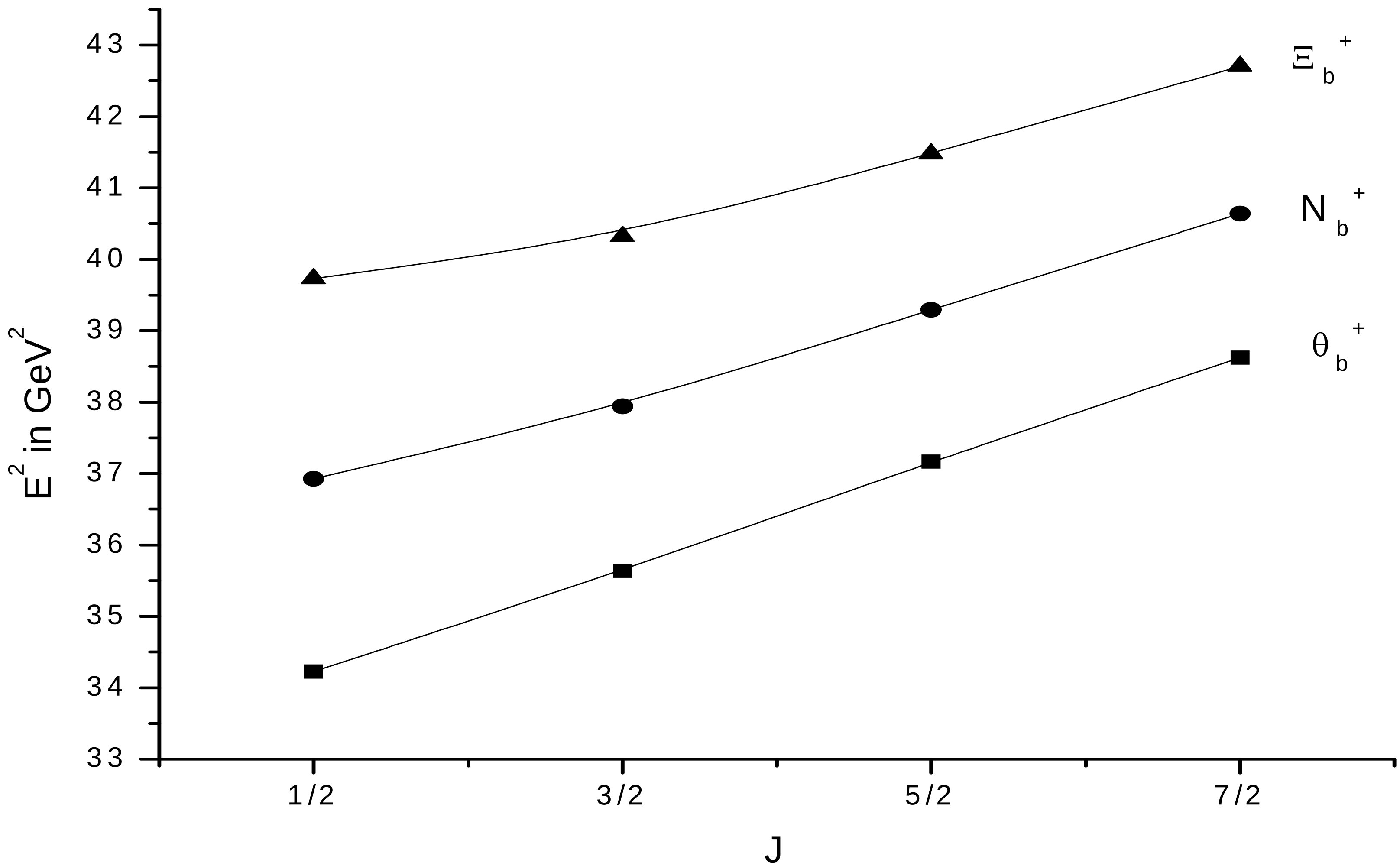

Table 3:Regge slope$(\alpha)$and string tension$(\sigma)$for heavy pentaquarks extracted from Fig.1 and Fig.2

Heavy pentaquark	α in GeV^{2}	σ in GeV^{-2}
θ_c^0	0.831	0.191
N_c^0	0.783	0.203
Ξ_c^0	0.726	0.219
θ_b^+	1.46	0.109
N_b^+	1.349	0.118
Ξ_b^+	1.228	0.129

Figure 3: Energy variation (E^2) with angular momentum (l) for charm pentaquark

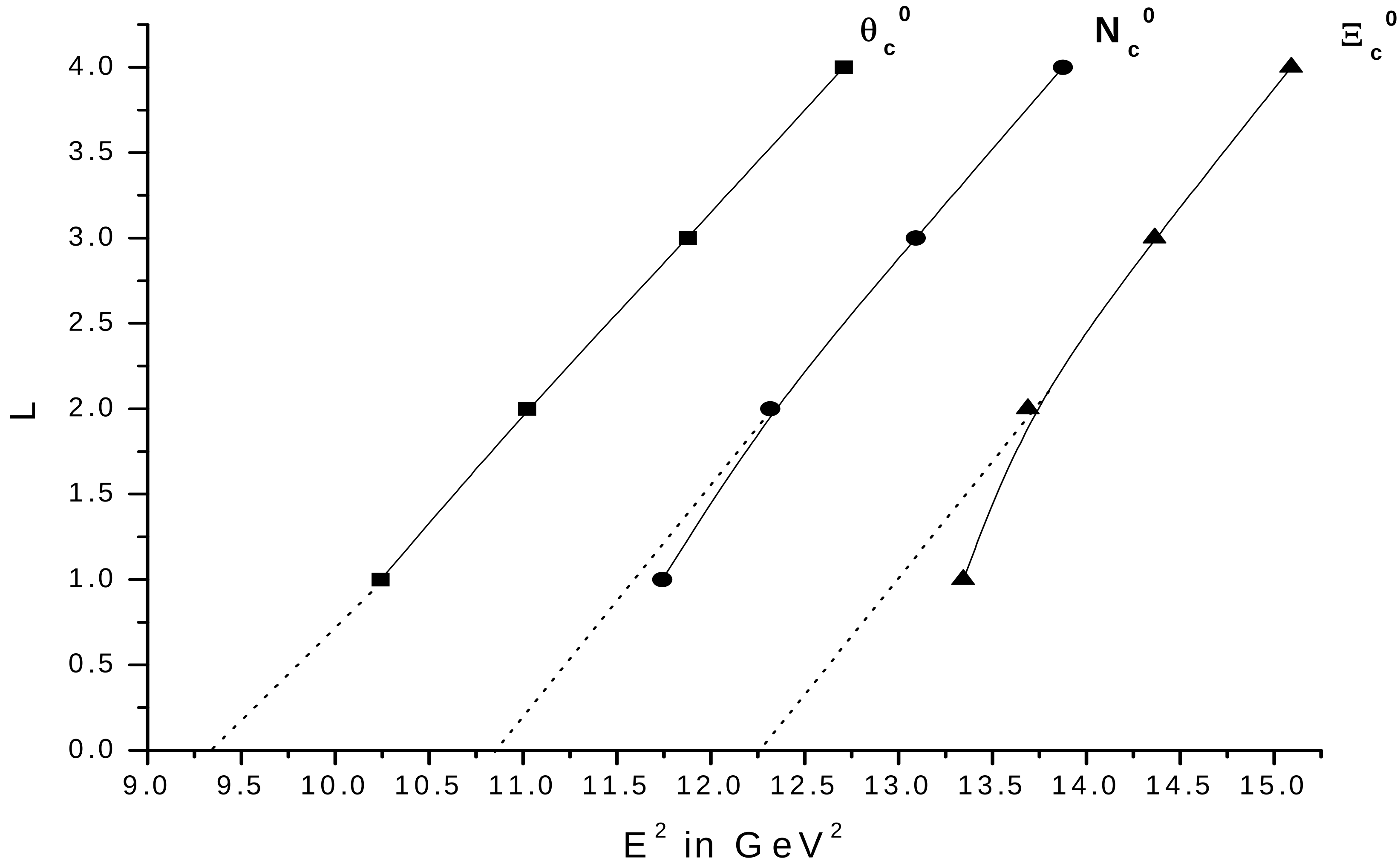

Figure 4: Energy variation (E^2) with angular momentum (l) for bottom pentaquark

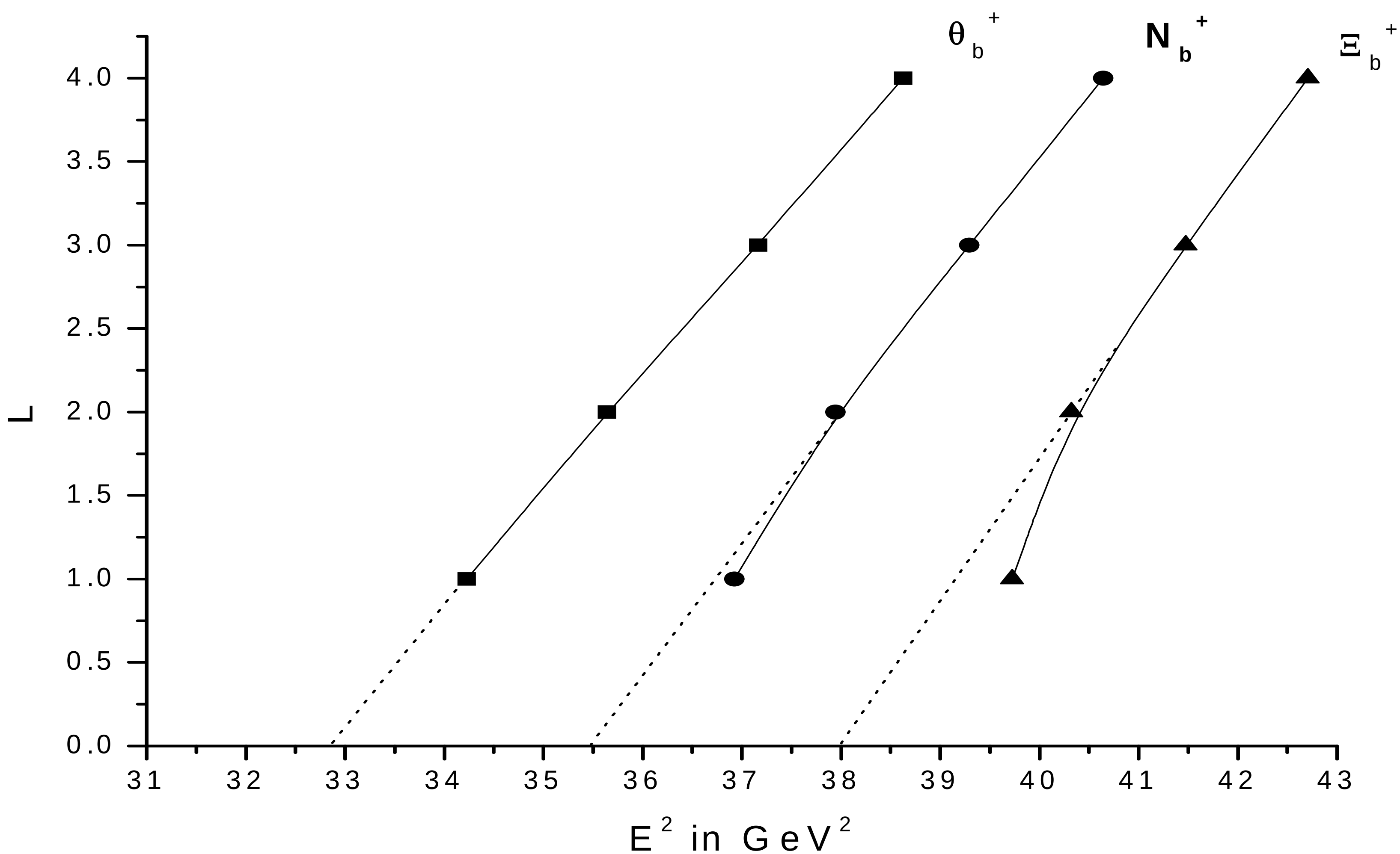

Table 4: Ground state (l=0) mass of heavy pentaquarks extracted from Fig.3 and Fig.4

Heavy pentaquark	Content $[qq][qq]\overline{Q}$	Our-work in GeV	Other works in GeV [9,10,11,12,13]
θ_c^0	$[ud][ud]\overline{c}$	3.061	2.710 [9], 2.990 [10], 2.902 [11], 2.938-2.997 [12]
N_c^0	$[ud][us]\overline{c}$	3.297	2.870 [9], 3.165 [10], 3.161 [11], 2.860 [13]
Ξ_c^0	$[us][us]\overline{c}$	3.5	3.135 [9], 3.340 [10], 3.403 [11], 3.014 [13]
θ_b^+	$[ud][ud]\overline{b}$	5.733	6.050 [9], 6.400 [10] 6.176 [11], 6.370-6.422 [12]
N_b^+	$[ud][us]\overline{b}$	5.958	6.210 [9], 6.570 [10] 6.442 [11], 6.199 [13]
Ξ_b^+	$[us][us]\overline{b}$	6.164	6.351 [9], 6.740 [10] 6.683 [11], 6.351 [13]

References

[9]. R. L. Jaffe et al., Phys. Rev. Lett. 91, Iss. 23, 232003 (2003).

[10]. M. Karliner et al., arXiv:hep-ph/0307343 (2003).

[11]. Fl. Stancu, arXiV:hep-ph/0504283 (2005).

[12]. K. Cheung, Phys. Rev. D 69, Iss. 9-1, 094029 (2004).

[13]. H. Y. Cheng et al., Phys. Rev. D 70, Iss. 3-1, 034007 (2004).

Conclusions

- Masses of exotic particles and excited states predicted theoretically. Results in agreement other theoretical predictions.
- Regge Trajectories (RT) give important information on hadron dynamic, production and High energy scattering.
- RT show deviation from linear behavior attributed to color screening, relativistic effect of current quark mass and high rotational speed.
- Diquark in CF model are found to be successful in predicting masses.
- Composite fermion model of diquarks incorporates effect of vacuum. It appears that vacuum plays important roll in exotic dynamics.
- All these particles await experimental detection…expected to be detected in post LHC era.

Thank you.