Study of linearity of hadronic Regge Trajectories based solely upon the experimental data

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INTRODUCTION

- QCD generates an enormous richness and complexity of phenomena and of forms of matter.
- They range from the spectrum of strongly interacting hadrons and nuclei which make our present Universe to the quark gluon plasma, a state of matter in the early Universe.
- It was discovered that the spectrum of both stable and short lived particles follow a symmetry pattern.
- It was found empirically that spin quantum number grows linearly with the squared mass, leading to the so called Regge trajectories, that is diagrams showing spin as a function of squared mass .
- Regge theory, a phenomenological theory of strong interaction at high energies was initially introduced by Tullio Regge in the year 1959-1960 [1,2].
- RTs evidently describe high energy hadronic processes and spectrum of hybrid mesons.
- Ordering of hadronic states on approximately linear RTs manifests the underlying non-perturbative QCD dynamics leading to confinement.

- In particular, a linear potential between a quark and antiquark for mesons (quark and diquark for baryons) and the linearly rising Regge trajectories are immediate consequences of the string picture.

- The confinement potential amongst the quarks at different length scales is estimated by Cornell potential which is

$$V(R) \approx -(4/3)(\alpha_s/R) + \sigma R$$

- The past few decades witnessed the proliferation of a large number of theoretical quark models, some of which clearly in favour of the linearity of RTs[3,4] while the others claim non-linearity [5,11].

- The RT phenomenology is often attacked to investigate whether the RTs are actually straight lines in the entire energy interval or whether this is only valid partially.

- Also, questions are raised whether trajectories for mesons, baryons, glueballs and hybrids have the same slope and thereby obey universality.

- Furthermore, the availability of large amount of new data posed several challenges regarding the behaviour of linearity of the RTs.

❖These contradictions merely lead to a shear mix of confusions and at this stage the only rescue is the hadronic data which projects out the finest image of the hadronic world.

❖We have analyzed the spectrum of hadrons by the latest data available through the Particle Data Group-2008 [12], with the aim of pinpointing trajectories with which hadronic resonances can be associated [13].

❖We have extracted a number of inherent parameters of these RTs such as slopes, variance, string tension among quarks and have deduced results which are both in coherence as well as in sharp contrast to the conventional ones.

❖We have plotted a of total 66 plotted trajectories, 64.81% are essentially non-linear, 27.78% are essentially linear, while 7.41% are fairly linear.

❖Existence of 15 new resonance particles has been predicted along with some of their intrinsic parameters.

❖The flavour dependence of RTs is also interrogated.

Analysis Of Experimental Hadronic Data

❖The entire data of the spectrum of bound states of light quarks is well described by linear, fairly linear as well as non-linear Regge trajectories both in the (N_R,M^2) and in the (J,M^2) plane.

❖The most appropriate parameters describing the essential deviations of RTs from linearity and parallelism are variance and the average value of slope for a particular given RT.

❖For the case of essentially linear RTs, we evaluated their slopes and also calculated the string tension among the constituent quarks.

❖Both these parameters exhibit essential deviations from the standard universal values (0.93$GeV^{-2}$for slope and 1GeV/fm for string tension).

❖A universal value of slope is plausible only if the strings joining the quarks have constant string tension $\alpha=1/(2\pi\sigma)$ (where σ is the string tension).

❖The variance V~ 0 indicate that there is no deviation from the standard value for slope.

❖Some of the RTs(doublets) are too short to judge non-linearity because of scarcity of data.

❖This analysis is of importance since its results can be compared with the predictions of the theoretical models.

❖Our inspection is somewhat self explanatory and is subjected to minimal bias in the interpretation of results.

❖Moreover, it is of interest in itself since the parameters of the RTs for the light and heavy quarkonia can be compared on its basis.

Mesonic Sector

❖We have constructed all possible orbital and radial RT for this sector.

❖Out of the plotted 35 mesonic RTs, 66.67% are EN while 26.67% are EL and 6.67% are FL.

❖Our entire analysis spans over a mass spectra range below 2,500 MeV, but the radial RTs covered for charm ($J/\psi(1^{--})$) and the bottom sector ($\gamma(1^{--})$) witness the inclusion of higher mass scales (up to 11020MeV).

❖By analyzing these figures 2-6 for EL and FL RTs, we have predicted the existence of 7 new resonance particles in the mesonic sector along with their spin and parity.

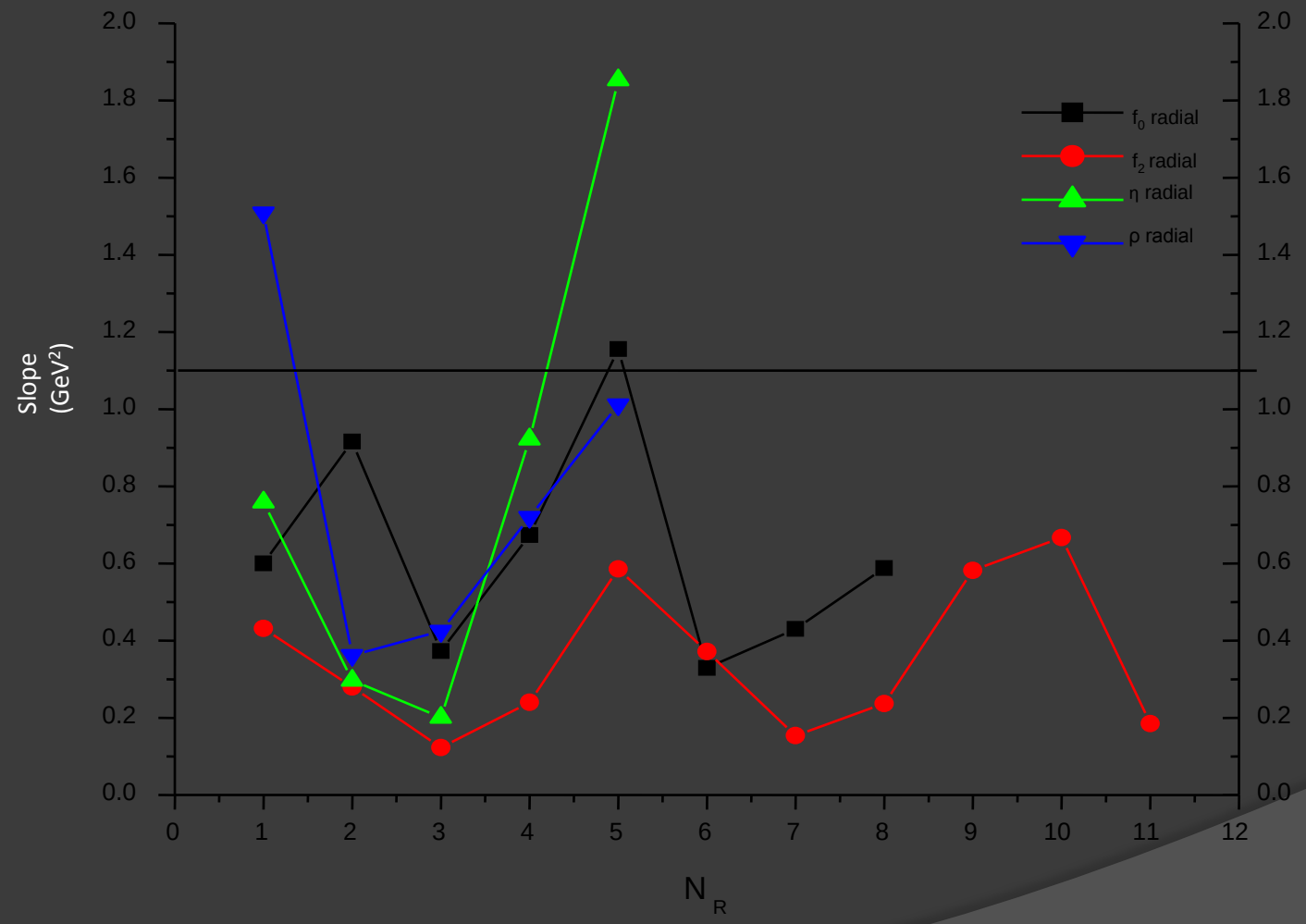
1) $f_2(1735)$ $J^{PC}=2^{++}$
2) $\omega_3(2000)$ $J^{PC}=3^{--}$
3) $a_0(1070)$ $J^{PC}=0^{++}$
4) $\varphi_3(1770)$ $J^{PC}=3^{--}$
5) $\varphi_5(2290)$ $J^{PC}=5^{--}$
6) K(1325) $J^{P}=0^{-}$
7) K(2265) $J^{P}=3^{+}$

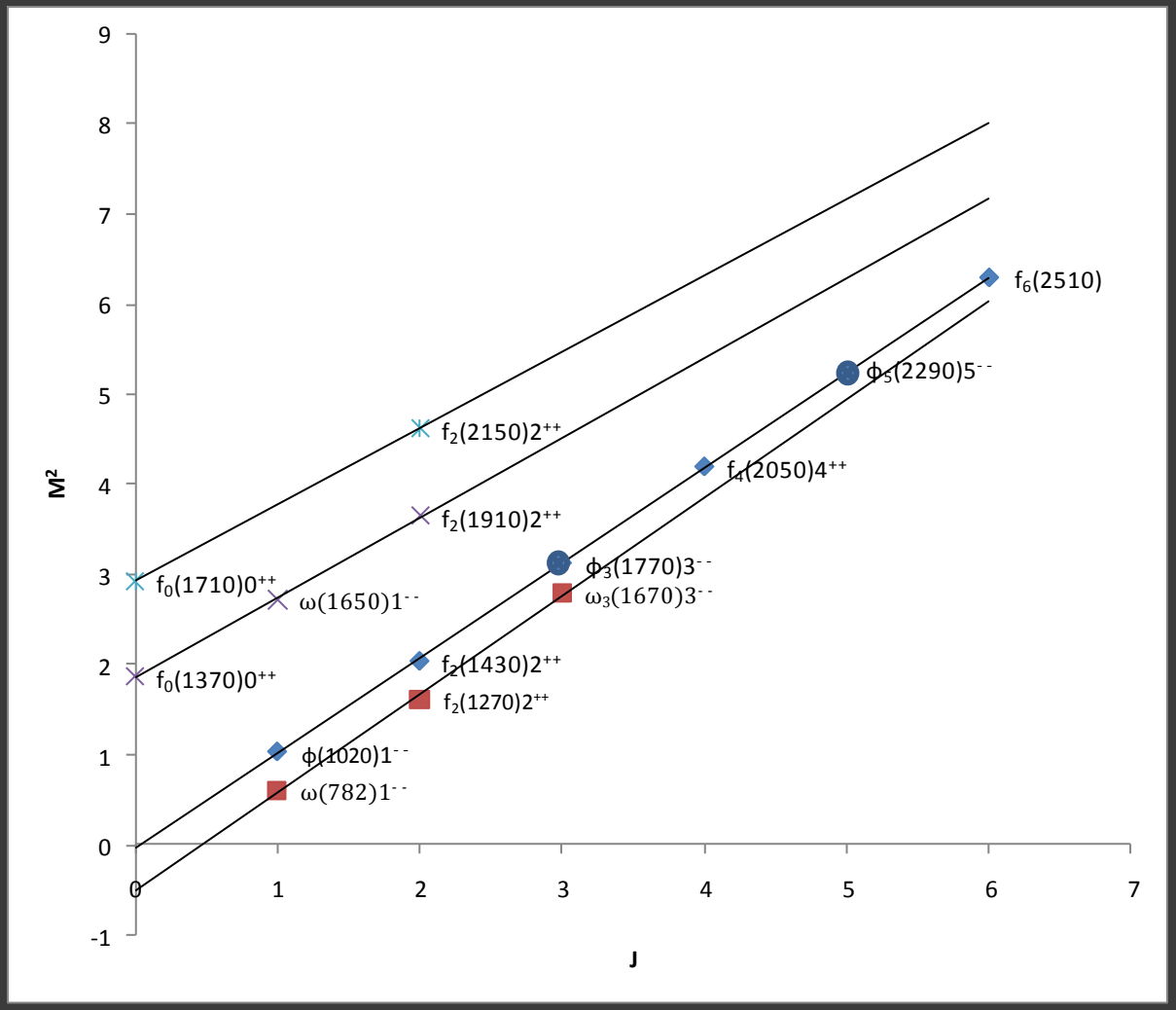
Table 1:- Various parameters for Essentially Nonlinear Mesonic RTs

Mesonic RT	Slopes for neighbouring pairs in GeV^2	Average Slope $<\alpha>$ in GeV^2	Variance V in GeV^2
$f_0(0^{++})$orbital	0.572, 0.980,1.487, 0.712	0.938	0.349
$f_0(0^{++})$radial	0.6,0.916,0.373,0.674,1.156, 0.329, 0.43,0.588	0.633	0.353
$f_1(1^{++})$radial	0.365,0.263	0.314	0.051
$f_2(2^{++})$radial	0.432,0.280,0.123,0.24,0.586,0.372,0.154,0.237,0.582,0.667,0.185	0.351	0.182
$f_4(4^{++})$radial	0.725,0.361	0.543	0.226
$a_0(0^{++})$orbital	1.504,0.224,0.732	0.82	0.526
$\rho(1^{--})$ radial	1.509,0.362,0.425,0.72,1.012	0.806	0.421
$\rho_3(3^{--})$ radial	1.104,1.102	1.103	0.001
$\eta(0^{-+})$ radial	0.759,0.297,0.201,0.922,1.853	0.806	0.593
$h_1(1^{+-})$ radial	0.535,0.639	0.587	0.052
$\pi_2(2^{-+})$ radial	0.745,0.875	0.81	0.065
$\omega(1^{--})$ radial	1.404,0.706	1.055	0.349

Mesonic RT	Slopes for neighbouring pairs in GeV^2	Average Slope <α> in GeV^2	Variance V in GeV^2
$K_0^*(0^+)$orbital	1.348,1.180	1.264	0.084
$K_0^*(0^+)$radial	1.404,1.757	1.581	0.177
$K(1^+)$radial	0.347,0.762	0.555	0.208
$K^*(1^-)$radial	1.192,0.834	1.013	0.623
$K(2^-)$radial	0.636,0.179,1.75	0.855	0.660
$J/\psi(1^{--})$ radial	0.633,2.108,0.984,2.186	1.478	0.681
$\gamma(1^{--})$ radial	10.96,6.765,4.71,6.003,3.5	6.388	11.055

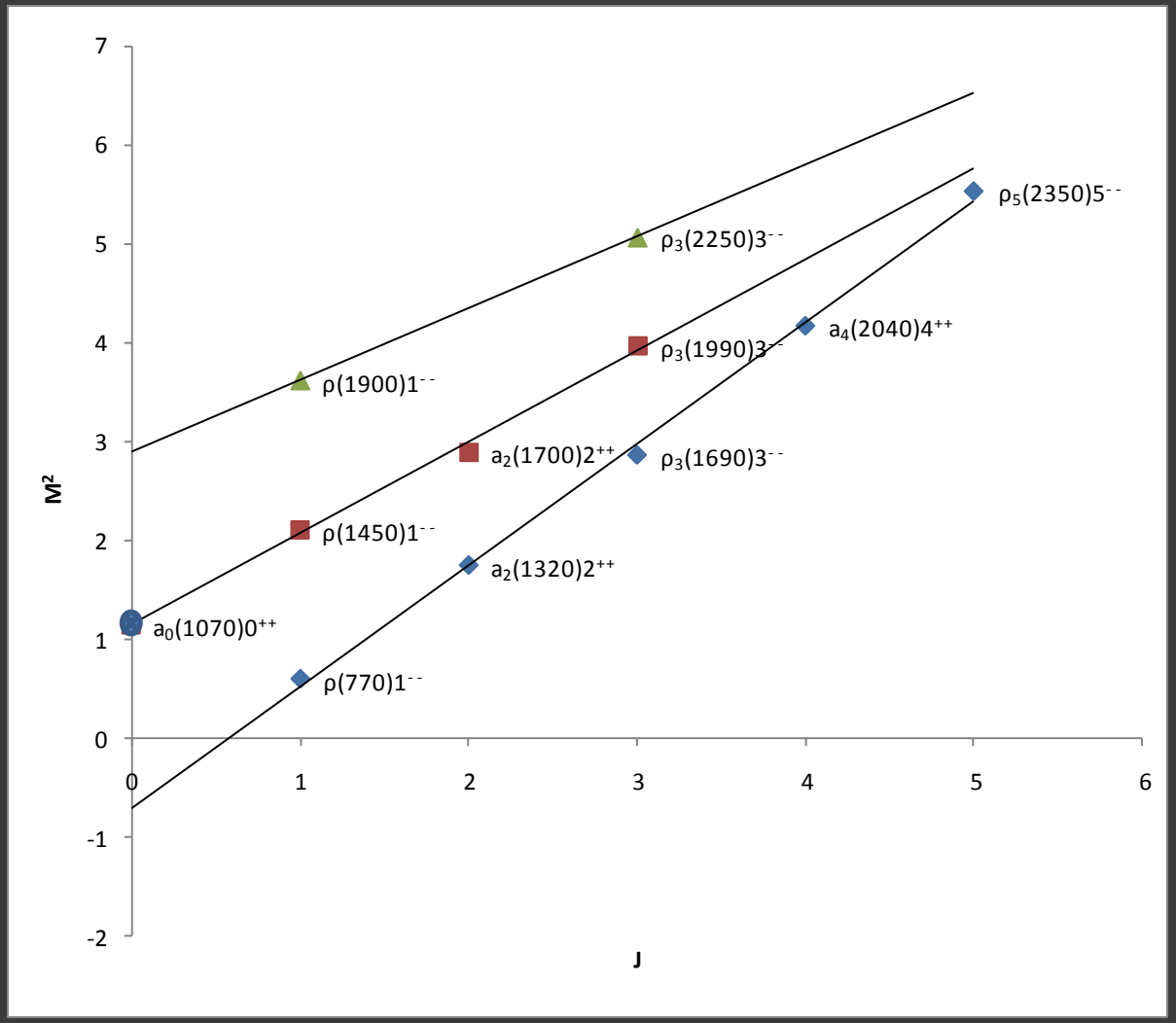
Figure 1:-Variation of slopes with radial quantum number N_R for the prominent f_0,f_2,η and ρ radial RTs. The straight horizontal line denotes the standard universal value of slope.





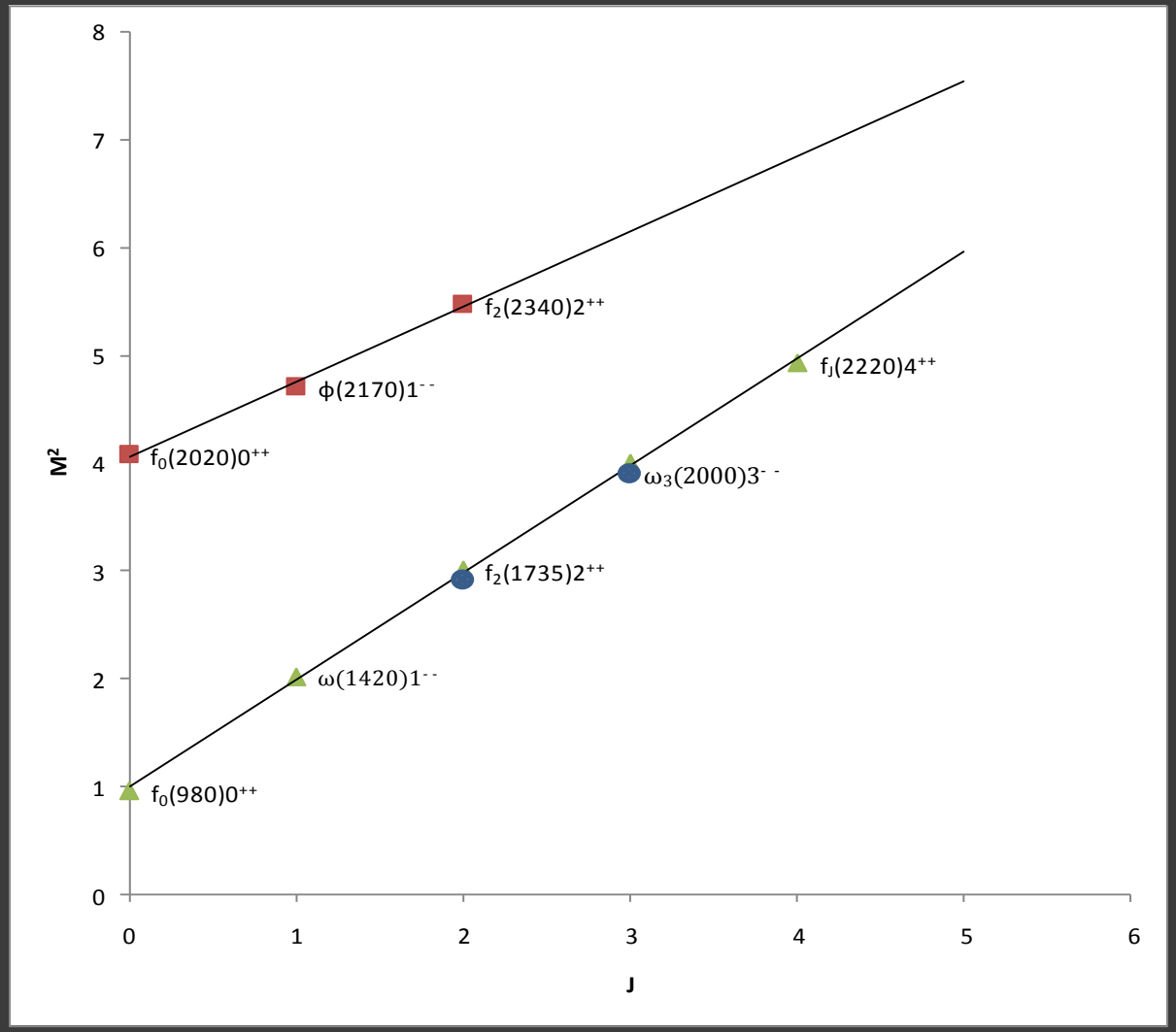
M^2=0.849J+2.924 ; String Tension=0.187 GeV^{-2}
M^2=0.885J+1.863 ; String Tension=0.180 GeV^{-2}
M^2=1.056J-0.035 ; String Tension=0.151 GeV^{-2}
M^2=1.088J-0.506 ; String Tension=0.146 GeV^{-2}

Figures 2:-Regge trajectories for four separate series of unflavoured (u-d) mesons along with their straight line equations and the string tensions. Resonance particles $\varphi_3(1770)$ at J=3 and $\varphi_5(2290)$ at J=5 are predicted to exist and are denoted by the symbol ● .



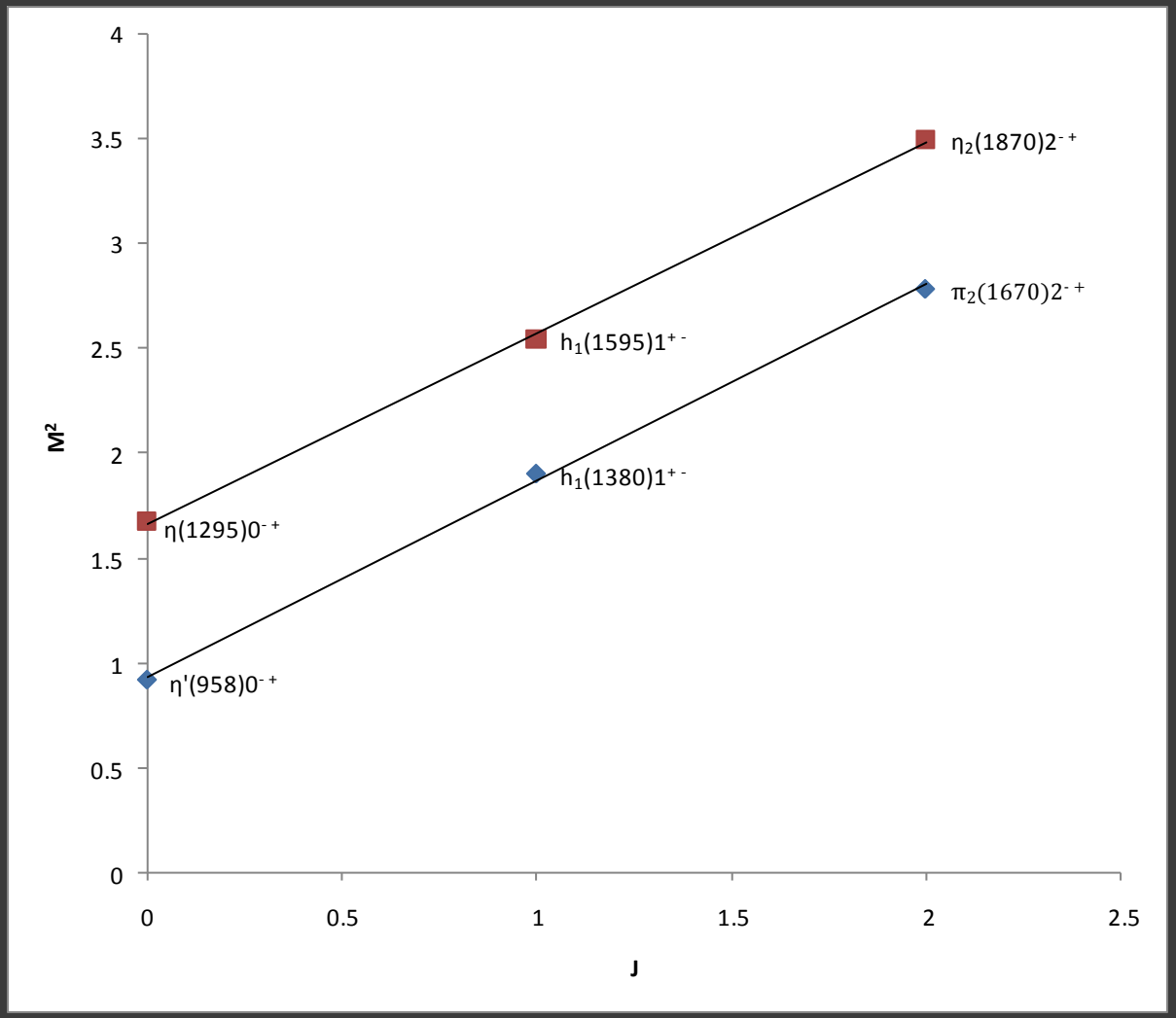
M^2=0.726J+2.883 ; String Tension=0.22 GeV^{-2}
M^2=0.928J+1.126 ; String Tension=0.172 GeV^{-2}
M^2=1.227J-0.708 ; String Tension=0.13 GeV^{-2}

Figure 3 :- RTs for three separate series of unflavoured (u-d) mesons along with their straight line equations and the string tensions. Resonance particle $a_0(1070)$ at J=0 is predicted to exist and is denoted by the symbol ●.



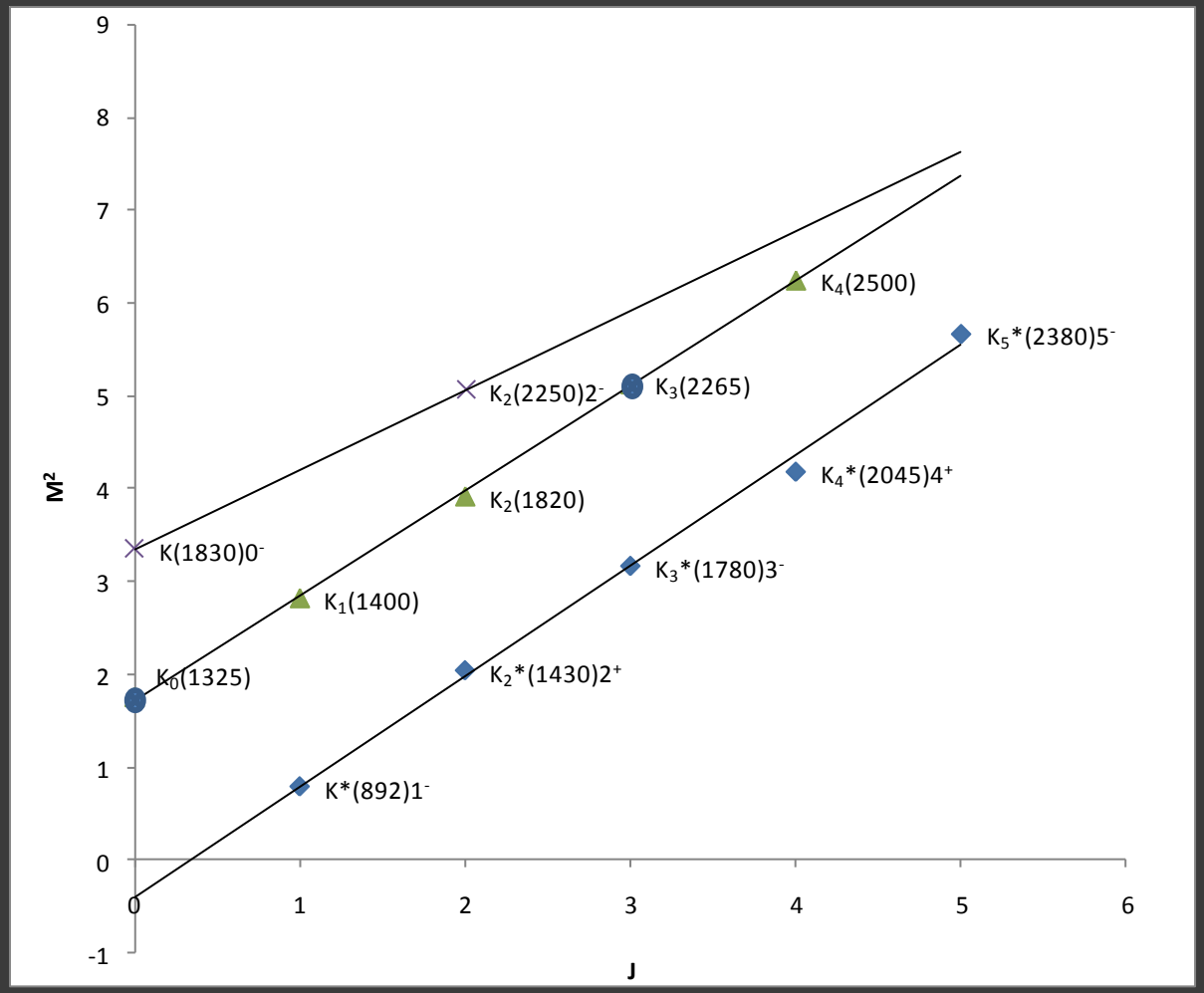
M^2=0.697J+4.057 ; String Tension =0.697 GeV^{-2}
M^2=0.987J+0989 ; String Tension =0.161 GeV^{-2}

Figure 4:- RTs for two separate series of unflavoured (u-d) mesons along with their straight line equations and the string tensions. Two resonance particles, f_2 (1735) at J=2 and ω_3(2000)at J=3 are predicted to exist and are denoted by the symbol



M^2=0.909J+1.662 ; String Tension=0.175 GeV^{-2}
M^2=0.935J+0.934 ; String Tension=0.170 GeV^{-2}

Figure 5:- RTs for two separate series of unflavoured (u-d) mesons along with their straight line equations and the string tensions.



M^2=0.856J+3.348 ; String Tension=0.186 GeV^{-2}
M^2=1.145J+1.657; String Tension=0.139 GeV^{-2}
M^2=1.187J-0.391; String Tension=0.134 GeV^{-2}

Figure 6:- RTs for three separate series of K-mesons along with their straight line equations and string tensions. Two resonance particles $K_0(1325)$ at J=0 and $K_3(2265)$ at J=3 are predicted to exist and are denoted by the symbol ●.

Baryonic Sector

❖We have plotted a total of 31 orbital and radial RTs in the baryonic sector.

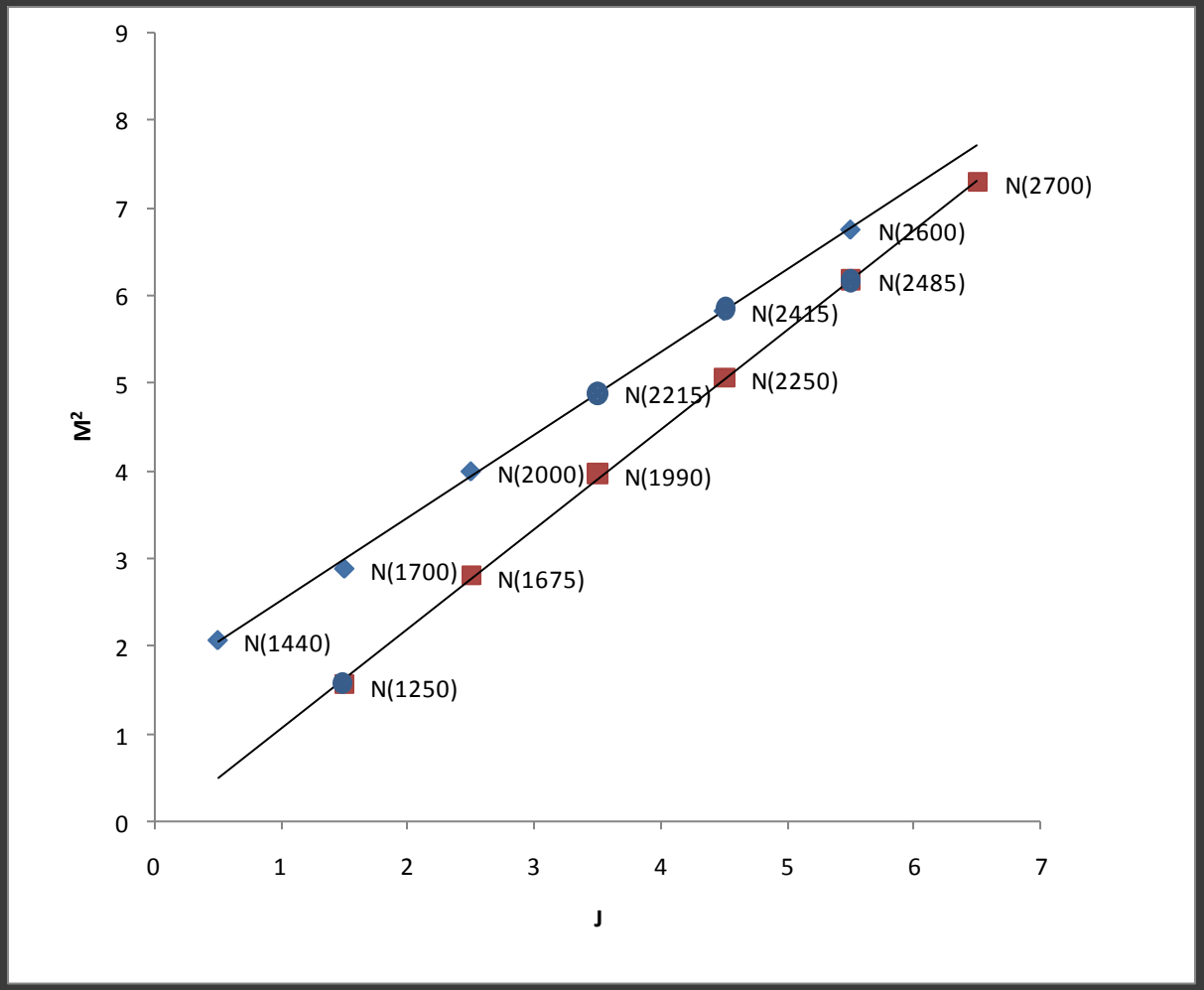
❖It was found that 62.5% are EN, 29.17% are EL and 8.33% are FL.

❖An analysis of figures 7-11 for EL and FL RTs, we have predicted the existence of 8 new resonance particles in the baryonic sector along with their spin and isospin.

1) $\Delta(2180)$ J=2.5,I=1.5
2) $\Delta(1145)$ J=0.5,I=1.5
3) N(1250) J=1.5,I=0.5
4) N(2215) J=3.5,I=0.5
5) N(2415) J=4.5,I=0.5
6) N(2485) J=5.5,I=0.5
7) $\Lambda(1050)$ J=0.5,I=0
8) $\Sigma(1385)$ J=0.5, I=1

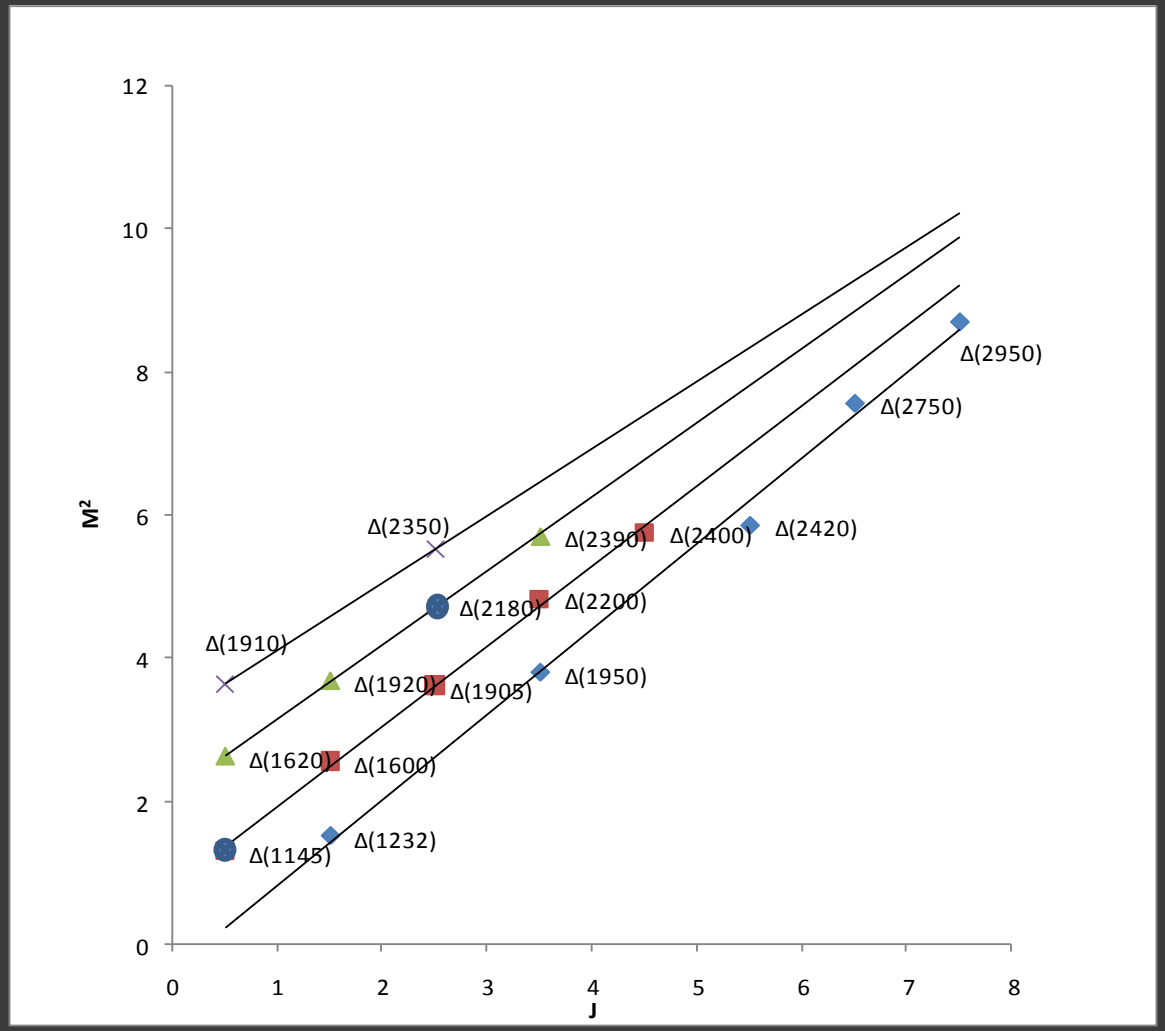
Table 2:- Various parameters for Essentially Nonlinear Baryonic RTs

Baryonic RT	Slopes for neighbouring pairs	Average Slope <α> in GeV^2	Variance V in GeV^2
N orbital	1.402,0.469,0.132	0.668	0.537
N orbital	0.235,1.881	1.058	0.823
$N^{1/2-}$radial	0.366,1.645	1.006	0.639
$N^{1/2+}$radial	0.850,1.485	1.168	1.003
$N^{3/2-}$radial	0.579,1.436	1.008	0.428
Δ orbital	0.701,0.236,1.29	0.742	0.431
Δ orbital	0.834,0.077	0.456	0.379
$\Delta^{1/2-}$radial	0.985,1.012	0.999	0.014
$\Delta^{3/2+}$radial	1.042,1.126	1.084	0.042
Λ orbital	0.296,0.492	0.394	0.098
$\Lambda^{1/2-}$radial	0.814,0.451	0.633	0.182
$\Lambda^{3/2-}$radial	0.545,2.549	1.547	1.002
$\Sigma^{1/2-}$radial	0.438,0.937	0.688	0.25
$\Sigma^{1/2+}$radial	0.377,0.401	0.389	0.012
$\Sigma^{3/2-}$radial	0.292,0.974	0.633	0.341



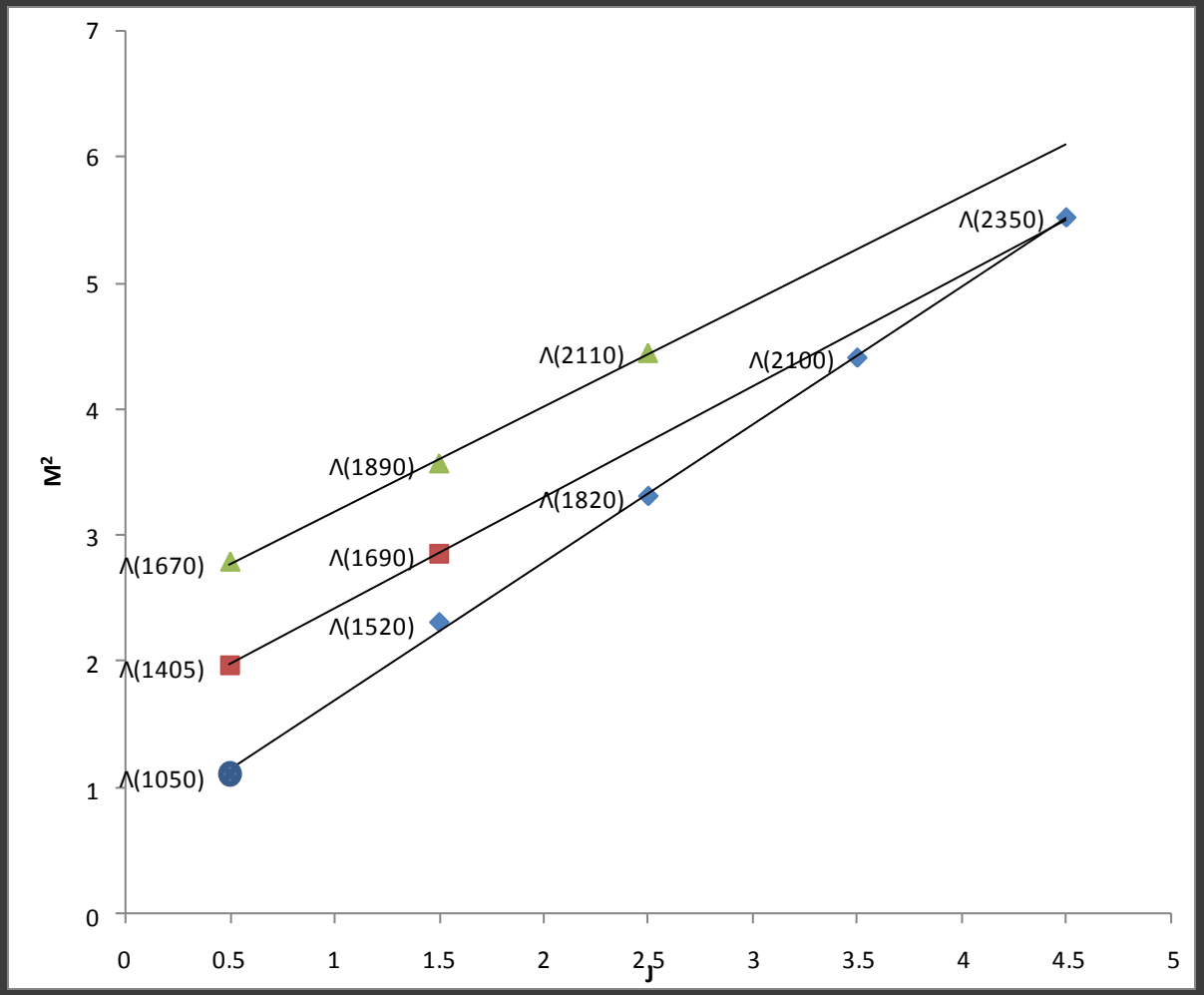
M^2=0.945J+1.566 ; String Tension=0.168 GeV^{-2}
M^2=1.118J+0.025 ; String Tension=0.014 GeV^{-2}

Figure 7:- RTs for two separate series of N-baryons along with their with straight line equations and string tensions . Resonance particles N(1250) at J=3/2, N(2215) at J=7/2, N(2415) at J=9/2 and N(2485) at J=11/2 are predicted to exist and are denoted by the symbol .



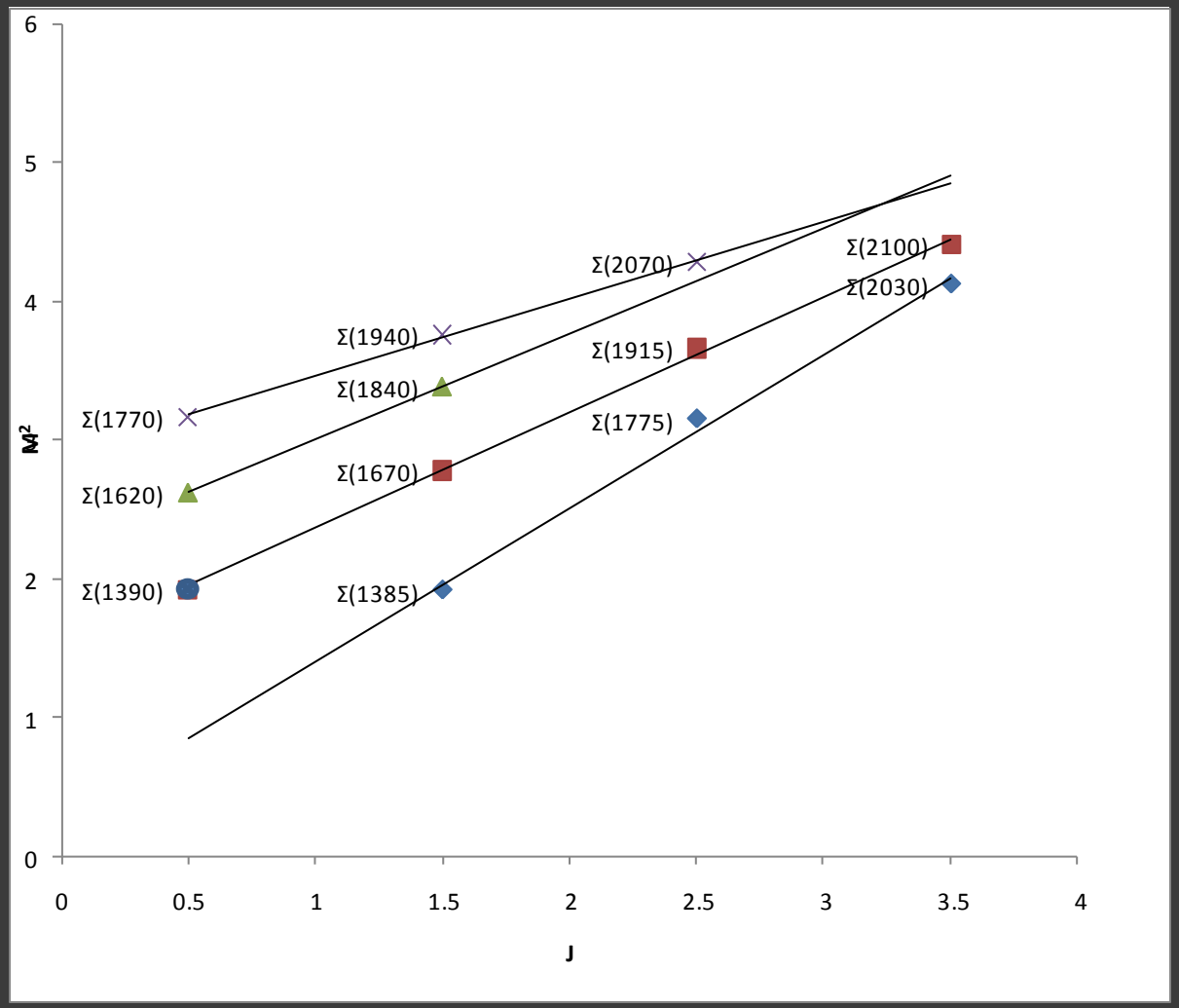
M^2=0.937J+3.179 ; String Tension=0.170 GeV^{-2}
M^2=1.026J+2.125 ;String Tension=0.155 GeV^{-2}
M^2=1.081J+0.954 ; String Tension=0.147 GeV^{-2}
M^2=1.196J-0.374 ; String Tension=0.133 GeV^{-2}

Figure 8 :- RTs for four separate series of Δ baryons along with their straight line equations and string tensions. Resonance particles Δ(1145) at J=1/2 and Δ(2180) at J=5/2 are predicted to exist and are denoted by the symbol ●.



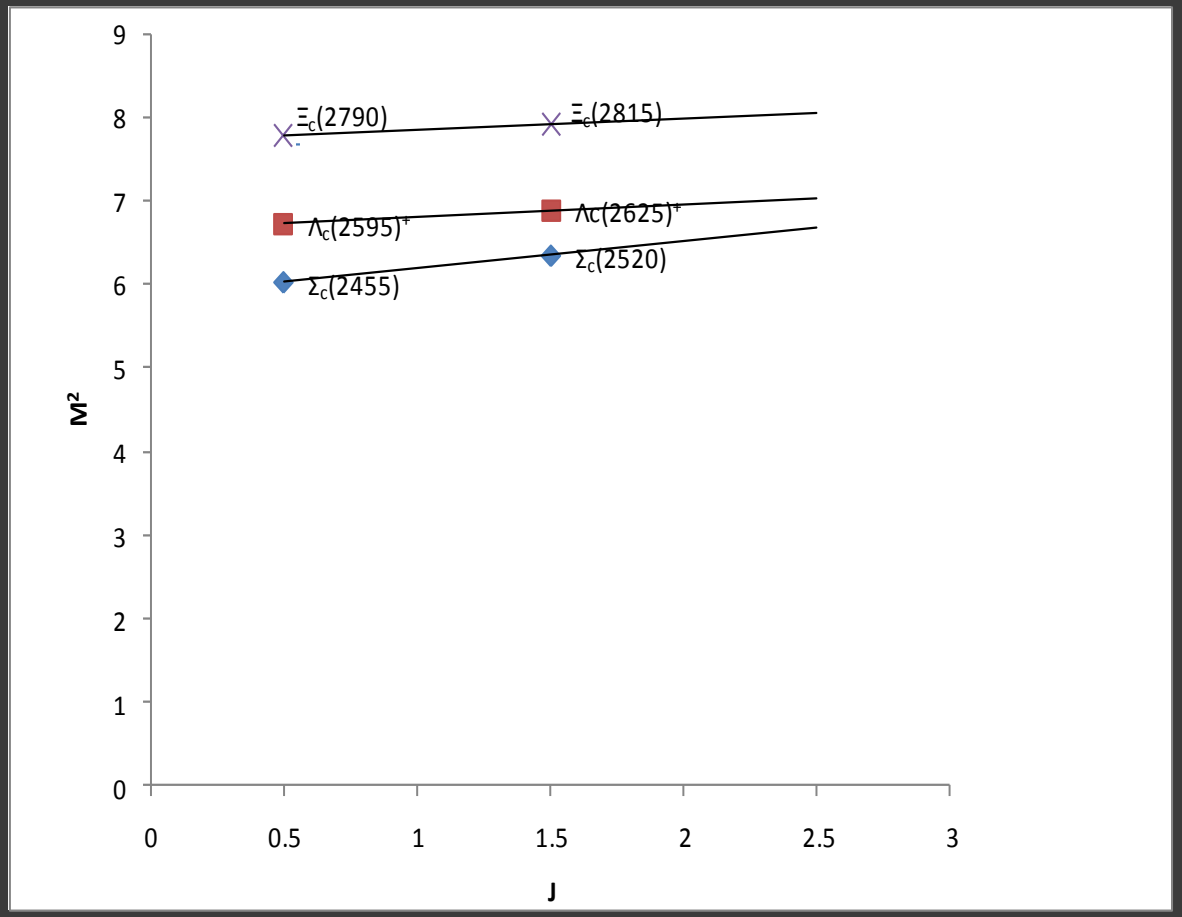
M^2=0.831J+2.357 ; String Tension=0.192 GeV^{-2}
M^2=0.882J+1.533 ; String Tension=0.180 GeV^{-2}
M^2=1.073J+0.668 ; String Tension=0.148 GeV^{-2}

Figure 9 :- RTs for three separate series of Λ baryons along with their straight line equations and string tensions. A single resonance particle Λ(1050) at J=1/2 is predicted to exist and is denoted by the symbol .



M^2=0.556J+2.906 ; String Tension=0.286 GeV^{-2}
M^2=0.761J+2.243 ; String Tension=0.209 GeV^{-2}
M^2=0.81J+1.595 ; String Tension=0.196 GeV^{-2}
M^2=1.101J+0.309 ; String Tension=0.145 GeV^{-2}

Figure 10 :- RTs for four separate series of Σ baryons along with their straight line equations and string tensions. A single resonance particle Σ(1390) at J=1/2 is predicted to exist and is denoted by the symbol ● .



M^2=0.140J+7.714 ; String Tension= 1.137 GeV^{-2}
M^2=0.156J+6.655 ; String Tension=1.02 GeV^{-2}
M^2=0.323J+5.865 ; String Tension=0.493 GeV^{-2}

Figure 11:- RTs for three separate series of charmed baryons along with their straight line equations and the string tensions .

Flavour dependence of RT

- The flavour dependence of RTs is a very interrogatory feature and has been widely investigated theoretically and we have tried to investigate this feature on the experimental front.

- A number of theoretical quark models [14,15,16], such as the potential quark model revealed decreasing slope with increasing quark mass for RTs in u, d, s, c and b sector.

- We have plotted the parent and daughter RTs for the different flavour contents and have calculated the average value of slopes for them.

- Due to scarcity of experimental data, we were unable to plot daughter RTs for the charm and the bottom sector.

Table 3:- Average value of slopes in GeV^2 for mesonic trajectories with N_R=0,1,2

N_R	Up-down	Strange	Charm	Bottom
0	1.0814	1.2595	0.43	0.34
1	0.787	1.763		
2	0.8395			

- Table 3 clearly depicts a decrease in average value of slopes as the quark mass increases with flavour.
- It is interesting to note that the average values of slopes are almost independent of N_R both for the u-d and s family.
- Our results clearly match with the theoretical values calculated by other physicists under the non-relativistic quark model [14].
- Correspondingly, the string tension among quarks increases with decreasing slope.
- Thus, as the masses of the constituent quarks comprising the hadrons increases, there is an increase in the energy per unit length among these quarks.
- The exact dynamics of the hadron interior is yet unclear, we can possibly comment that either energy between the constituent quarks increases or the separation between these quarks decreases with higher flavour mass hadrons.

CONCLUSIONS

- Analysis of pure experimental data in the current resonance region reveals a distinctive feature that RTs in many cases are non-linear functions of J.

- The appropriate variance for the non-linear hadronic RTs span the range 0.001-1.003 GeV^2 and the average value of slopes $<\alpha>$ span the range 0.314-1.581 GeV^2 for hadronic masses less than 2500MeV.

- However, for the charm and bottom sector which correspond to much higher mass scale (up to11020MeV) we obtain the highest average value of slope (6.388 GeV^2) and the highest variance (11.055 GeV^2).

- The entire slope range for EL RTs lies between (0.140-1.196) GeV^2 and the string tensions among the constituent quarks comprising the hadrons lies between (0.0142-1.137)GeV^{-2}.

- Around 12% EL RTs have values o slopes almost equal to the universal value (1.1GeV^2).

- Deviations from this universal value can be interpreted by the fact that string tensions among quarks keeps altering in contrast to the orthodox notion.

- Flavour dependence projects out as an essential ingredient upon which the value of slope parameter relies.

- Decrease in the value of slope of RTs is evident with subsequent increase in mass of corresponding hadrons referring to higher massed flavours.

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