SPECTRUM OF HADRONS WITH STRANGENESS

The first DSE-based calculation of the spectrum of strange and nonstrange hadrons.

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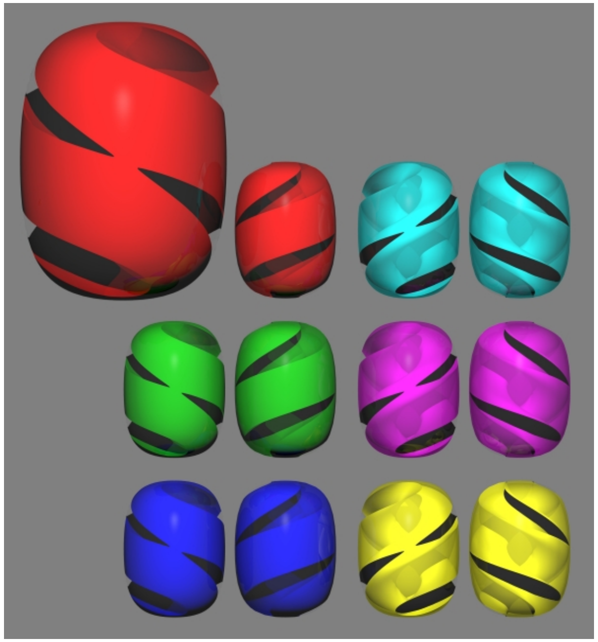


Spectrum of hadrons with strangeness
Chen Chen, Lei Chang, Craig D. Roberts, Shaolong Wan and David J. Wilson
[arXiv:1204.2553 [nucl-th]], Few Body Syst. *in press*

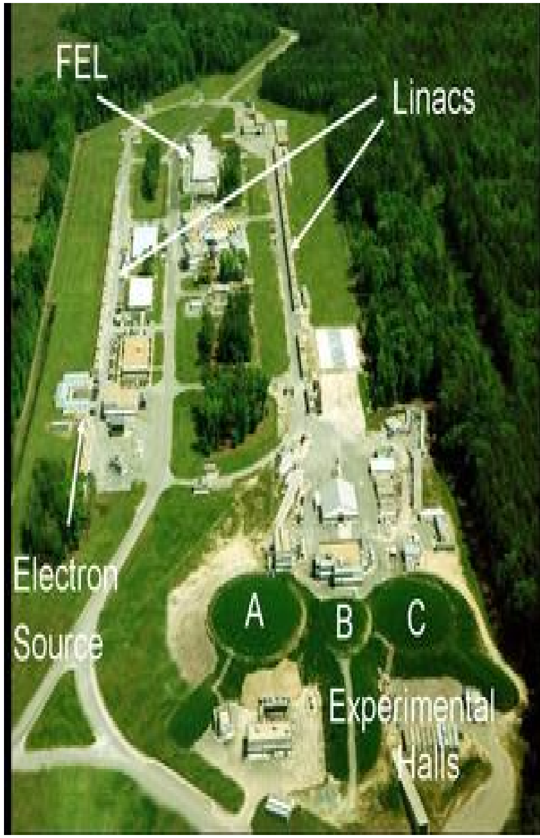
Universal Truths

- Spectrum of hadrons, and hadron elastic and transition form factors provide unique information about long-range interaction between light-quarks and distribution of hadron's characterising properties amongst its QCD constituents.
- Dynamical Chiral Symmetry Breaking (DCSB) is most important mass generating mechanism for visible matter in the Universe.
- Running of quark mass entails that calculations at even modest Q2 require a Poincaré-covariant approach.
- Confinement is expressed through a violent change of the propagators for coloured particles & can almost be read from a plot of a states’ dressed-propagator.

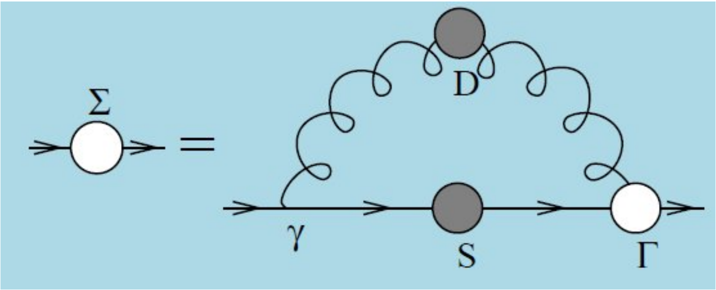
Motivations

The quest to understand these phenomena from first-principles is the driving force behind an upgrade of the Thomas Jefferson National Accelerator Facility (TJNAF), the World's premier hadron physics facility.

AND other facilities worldwide.



The only nonperturbative continuum approach:



Dyson-Schwinger Equations

General Form

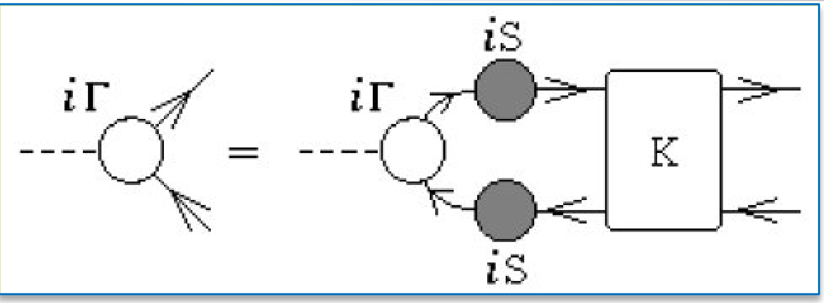
$$S(p)^{-1} = i\gamma\cdot p + m + \Sigma(p)\,,$$

$$\Sigma(p) = \int \frac{d^4\ell}{(2\pi)^4}\, g^2\, D_{\mu\nu}(p-\ell)\,\gamma_\mu \frac{\lambda^a}{2}\frac{1}{i\gamma\cdot\ell A(\ell^2)+B(\ell^2)}\,\Gamma^a_\nu(\ell,p).$$

NonPerturbative, Continuum approach to QCD

$D_{\mu\nu}(k)$ – dressed-gluon propagator

$\Gamma_\nu(q,p)$ – dressed-quark-gluon vertex



Bethe-Salpeter Equation Bound-State

$$[\Gamma_\pi^j(k;P)]_{tu} = \int_q^\Lambda [S(q+P/2)\Gamma_\pi^j(q;P)S(q-P/2)]_{sr} K_{tu}^{rs}(q,k;P)$$

K(q,k;P) – fully amputated, two-particle irreducible, quark-antiquark scattering kernel

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Diquarks

- Rainbow-ladder gap and Bethe-Salpeter equations

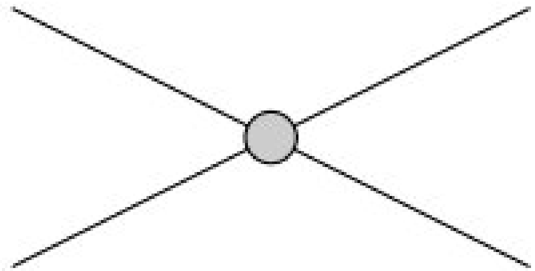
$$S(p)^{-1} = i\gamma \cdot p + m + \int \frac{d^4 q}{(2\pi)^4} g^2 D_{\mu\nu}(p-q) \frac{\lambda^a}{2} \gamma_\mu S(q) \frac{\lambda^a}{2} \gamma_\nu(q,p),$$

$$\Gamma(k;P) = -\int \frac{d^4 q}{(2\pi)^4} g^2 D_{\mu\nu}(p-q) \frac{\lambda^a}{2} \gamma_\mu S(q+P) \Gamma(q;P) S(q) \frac{\lambda^a}{2} \gamma_\nu \,.$$

- In this truncation, colour-anti triplet quark-quark correlations (diquarks) are described by a very similar homogeneous Bethe-Salpeter equation

$$\Gamma_{qq}(k;P)C^\dagger = -\frac{1}{2} \int \frac{d^4 q}{(2\pi)^4} g^2 D_{\mu\nu}(p-q) \frac{\lambda^a}{2} \gamma_\mu S(q+P) \Gamma_{qq}(q;P) C^\dagger S(q) \frac{\lambda^a}{2} \gamma_\nu$$

- Only difference is factor of ½
- Hence, an interaction that describes mesons also generates diquark correlations in the colour-antitriplet channel



Interaction Kernel

Vector-vector contact interaction

$$g^2 D_{\mu\nu}(p-q) = \delta_{\mu\nu} \frac{4\pi\alpha_{\rm IR}}{m_G^2}$$

2 parameters:

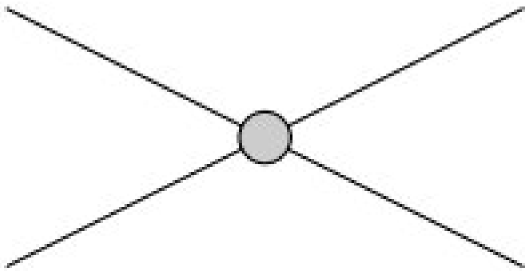
m_G = 0.8 GeV & αIR = 0.93π

Gap Equation:

$$M = m + \frac{M}{3\pi^2 m_G^2} \int_0^\infty ds\, s \frac{1}{s+M^2}$$

m_u	m_s
0.007	0.17

M_0	M_u	M_s
0.36	0.37	0.53

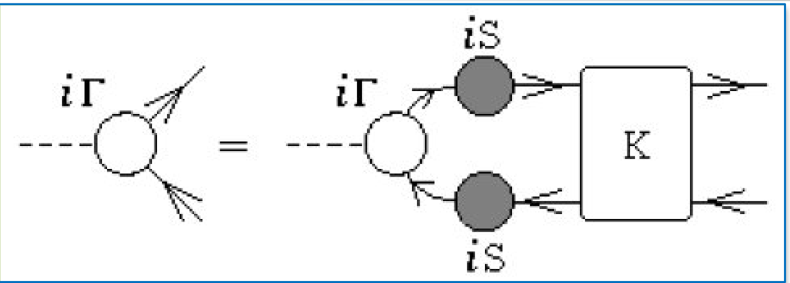


Interaction Kernel
- Regularisation Scheme

- Contact interaction is not renormalisable
- Must therefore introduce regularisation scheme
  - Use confining proper-time definition

$$\frac{1}{s+M^2} = \int_0^\infty d\tau\, \mathrm{e}^{-\tau(s+M^2)} \to \int_{\tau_{\mathrm{uv}}^2}^{\tau_{\mathrm{ir}}^2} d\tau\, \mathrm{e}^{-\tau(s+M^2)} = \frac{\mathrm{e}^{-(s+M^2)\tau_{\mathrm{uv}}^2} - e^{-(s+M^2)\tau_{\mathrm{ir}}^2}}{s+M^2}$$

  - $\Lambda_{ir} = 0.24$GeV, $\tau_{ir} = 1/\Lambda_{ir} = 0.8$fm
    a confinement radius, which is not varied
  - Two parameters:
    $m_G=0.8$GeV, $\Lambda_{uv}=0.905$GeV



Bethe-Salpeter Equation for ρ-meson

$$1+K^{\rho}(-m_{1^-}^2)=0,\ K^{\rho}(P^2)=\frac{1}{3\pi^2 m_G^2}\int_0^1 d\alpha\,\alpha(1-\alpha)P^2\,\overline{\mathcal{C}}_1^{iu}(\omega(M^2,\alpha,P^2))$$

$$\overline{C}_1^{iu}(\omega)=\Gamma(0,M^2r_{uv}^2)-\Gamma(0,M^2r_{ir}^2),\ C_1^{iu}(\omega)=\omega\overline{C}_1^{iu}(\omega)$$

$\omega(M^2,\alpha,P^2)= M^2 + \alpha(1- \alpha)P^2$

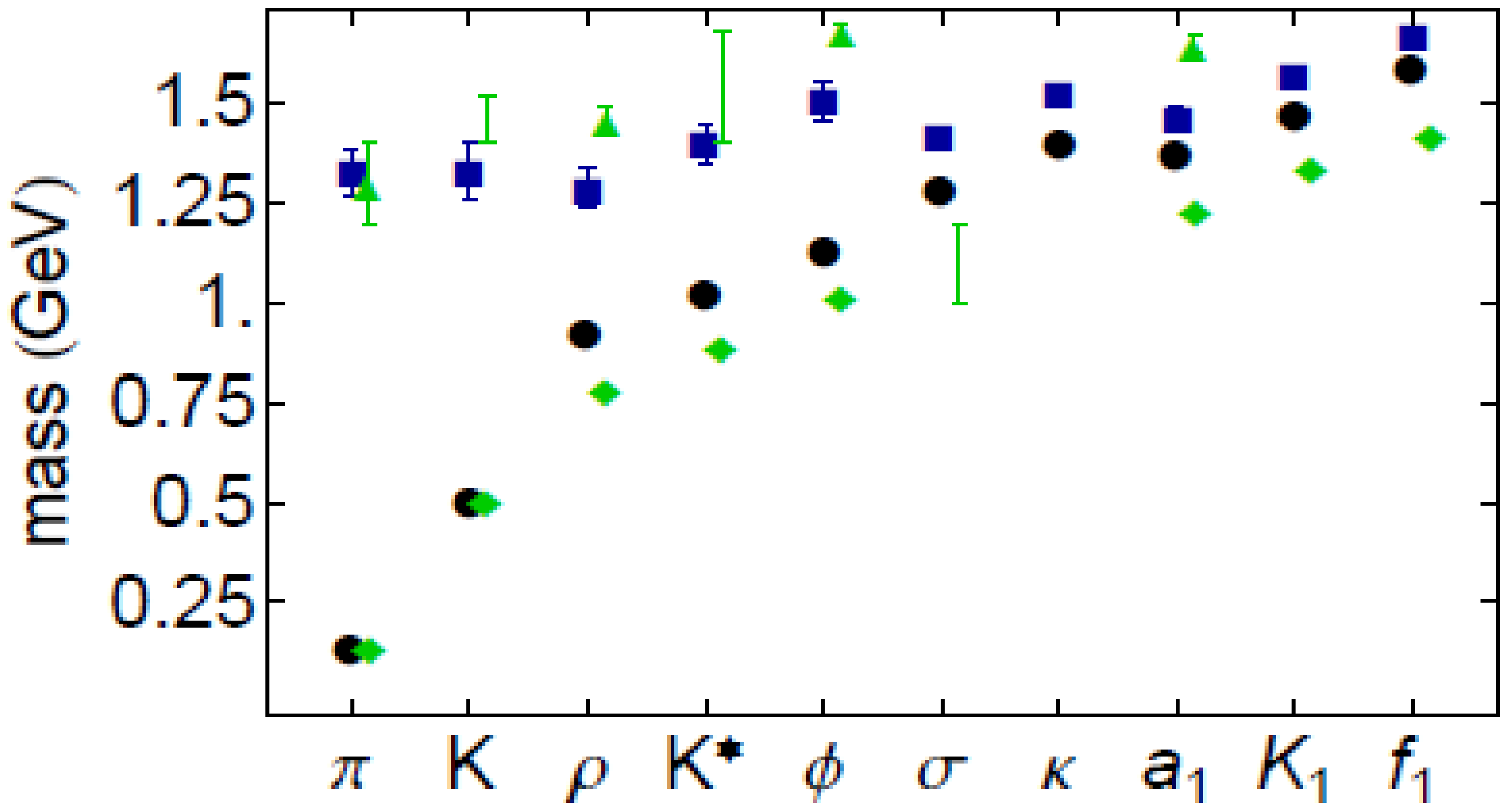
- *Contact interaction, properly regularised, provides a practical simplicity & physical transparency*

- All BSEs are one- or –two dimensional eigenvalue problems, eigenvalue is P^2= - (mass-bound-state)^2

Meson Spectrum

	m_π	m_K	m_ρ	m_{K^*}	m_ϕ	m_σ	m_κ	m_{a_1}	m_{K_1}	m_{f_1}
n=0 DSE	0.14	0.50	0.93	1.03	1.13	1.29	1.40	1.38	1.48	1.59
expt.	0.14	0.50	0.78	0.89	1.02	1.0 - 1.2		1.23	1.34	1.42
n=1 DSE	$1.33_{\pm 0.06}$	$1.33_{\pm 0.07}$	$1.29_{\pm 0.05}$	$1.40_{\pm 0.05}$	$1.51_{\pm 0.05}$	$1.42_{\pm 0.02}$	$1.53_{\pm 0.02}$	$1.47_{\pm 0.02}$	$1.57_{\pm 0.01}$	$1.67_{\pm 0.02}$
expt.	$1.3_{\pm 0.1}$	1.46*	$1.46_{\pm 0.03}$	1.68*	$1.68_{\pm 0.02}$			$1.65_{\pm 0.02}$		

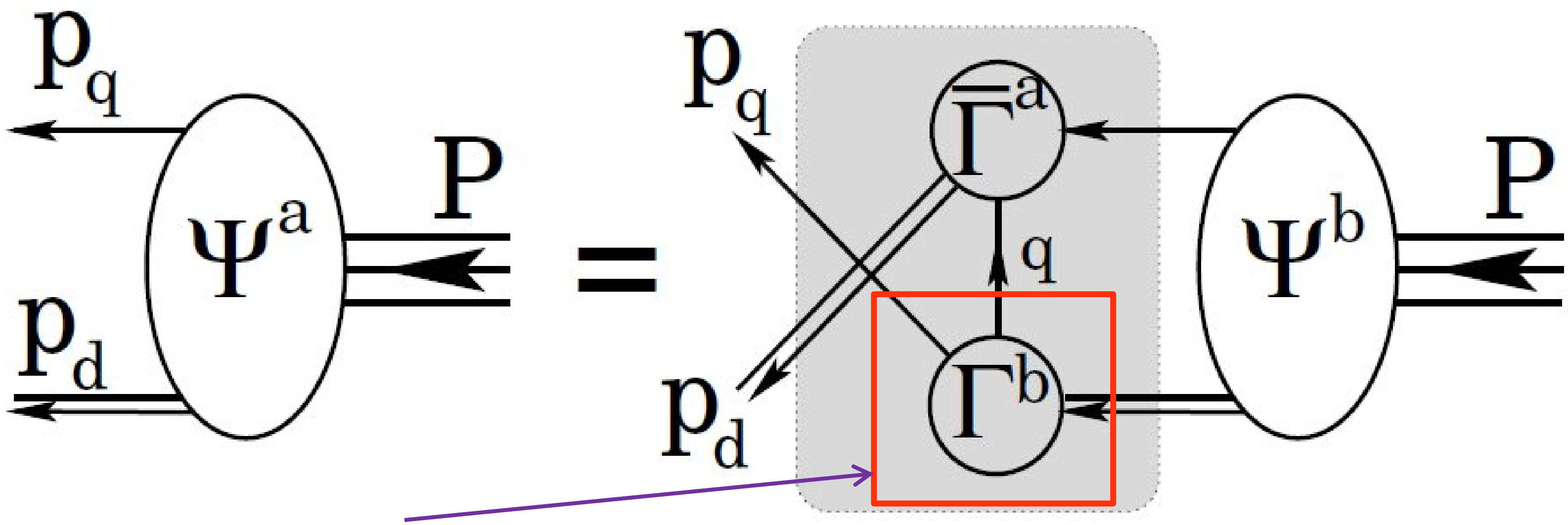
Meson Spectrum



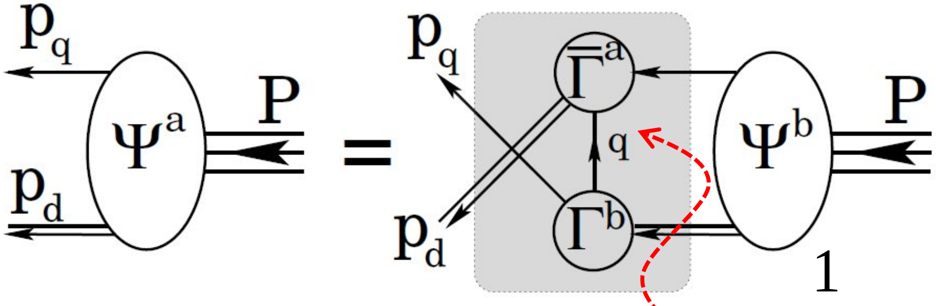
Diquark Spectrum

		$[u,d]_{0+}$	$[s,u]_{0+}$	$\{u,u\}_{1+}$	$\{s,u\}_{1+}$	$\{s,s\}_{1+}$	$[u,d]_{0-}$	$[s,u]_{0-}$	$\{u,u\}_{1-}$	$\{s,u\}_{1-}$	$\{s,s\}_{1-}$
n=0	qq	0.78	0.93	1.06	1.16	1.26	1.37	1.47	1.45	1.55	1.65
	$q\bar{q}$	0.14	0.50	0.93	1.03	1.13	1.29	1.40	1.38	1.48	1.59
n=1	qq	$1.34_{\pm 0.05}$	$1.35_{\pm 0.05}$	$1.32_{\pm 0.04}$	$1.42_{\pm 0.04}$	$1.53_{\pm 0.04}$	$1.48_{\pm 0.03}$	$1.57_{\pm 0.02}$	$1.52_{\pm 0.01}$	$1.62_{\pm 0.02}$	$1.71_{\pm 0.01}$
	$q\bar{q}$	$1.33_{\pm 0.06}$	$1.33_{\pm 0.07}$	$1.29_{\pm 0.05}$	$1.40_{\pm 0.05}$	$1.51_{\pm 0.05}$	$1.42_{\pm 0.02}$	$1.53_{\pm 0.02}$	$1.47_{\pm 0.02}$	$1.57_{\pm 0.01}$	$1.67_{\pm 0.02}$

Faddeev Equation



Diquark's amplitude

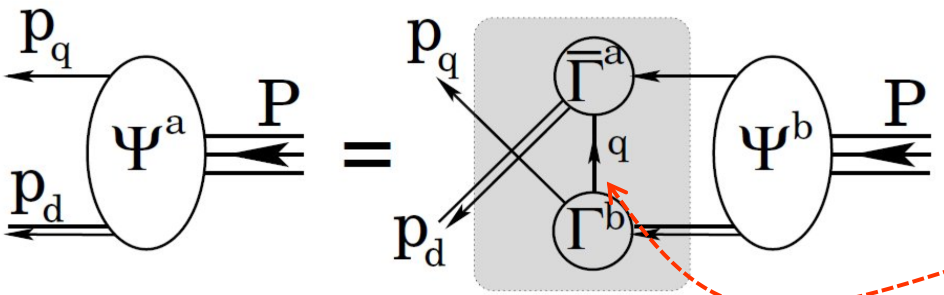


Spectrum of Baryons

$$\frac{1}{i\gamma\cdot p+M}\rightarrow\frac{g_B^2}{M}$$

- Static “approximation”
  - Implements analogue of contact interaction in Faddeev-equation
- In combination with contact-interaction diquark-correlations, generates Faddeev equation kernels which themselves are momentum-independent
- The merit of this truncation is the *dramatic simplifications* which it produces
- Used widely in hadron physics phenomenology

Spectrum of Baryons



$$\frac{1}{i\gamma\cdot p+M}\rightarrow\frac{g_B^2}{M}$$

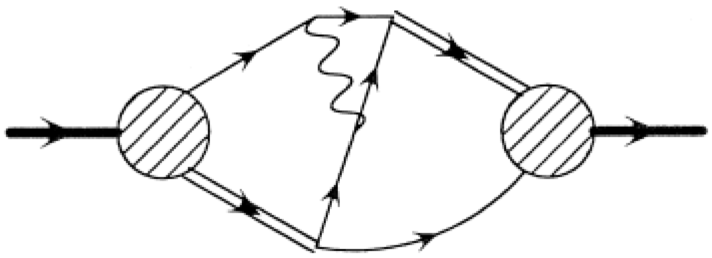
- Faddeev equation for Δ-baryon

$$1=8\frac{g_\Delta^2}{M}\frac{E_{qq_1+}^2}{m_{qq_1+}^2}\int\frac{d^4\ell'}{(2\pi)^4}\int_0^1 d\alpha\,\frac{(m_{qq_1+}^2+(1-\alpha)^2m_\Delta^2)(\alpha m_\Delta+M)}{[\ell'^2+\sigma_\Delta(\alpha,M,m_{qq_1+},m_\Delta)]^2}$$
$$=\frac{g_\Delta^2}{M}\frac{E_{qq_1+}^2}{m_{qq_1+}^2}\frac{1}{2\pi^2}\int_0^1 d\alpha\,(m_{qq_1+}^2+(1-\alpha)^2m_\Delta^2)(\alpha m_\Delta+M)\overline{\mathcal{C}}_1^{\mathrm{iu}}(\sigma_\Delta(\alpha,M,m_{qq_1+},m_\Delta))$$

- *One-dimensional eigenvalue problem, to which only axial-vector diquark contributes. All the Decuplet baryons only have axial-vector diquark components.*
- *All the Octet baryons have scalar & axial-vector diquarks. It is a three-dimensional eigenvalue problem*

Pion-loops and Baryon Masses

- Pion-loops: meson exchange between two distinct dressed-quarks within the bound states.
- For example:

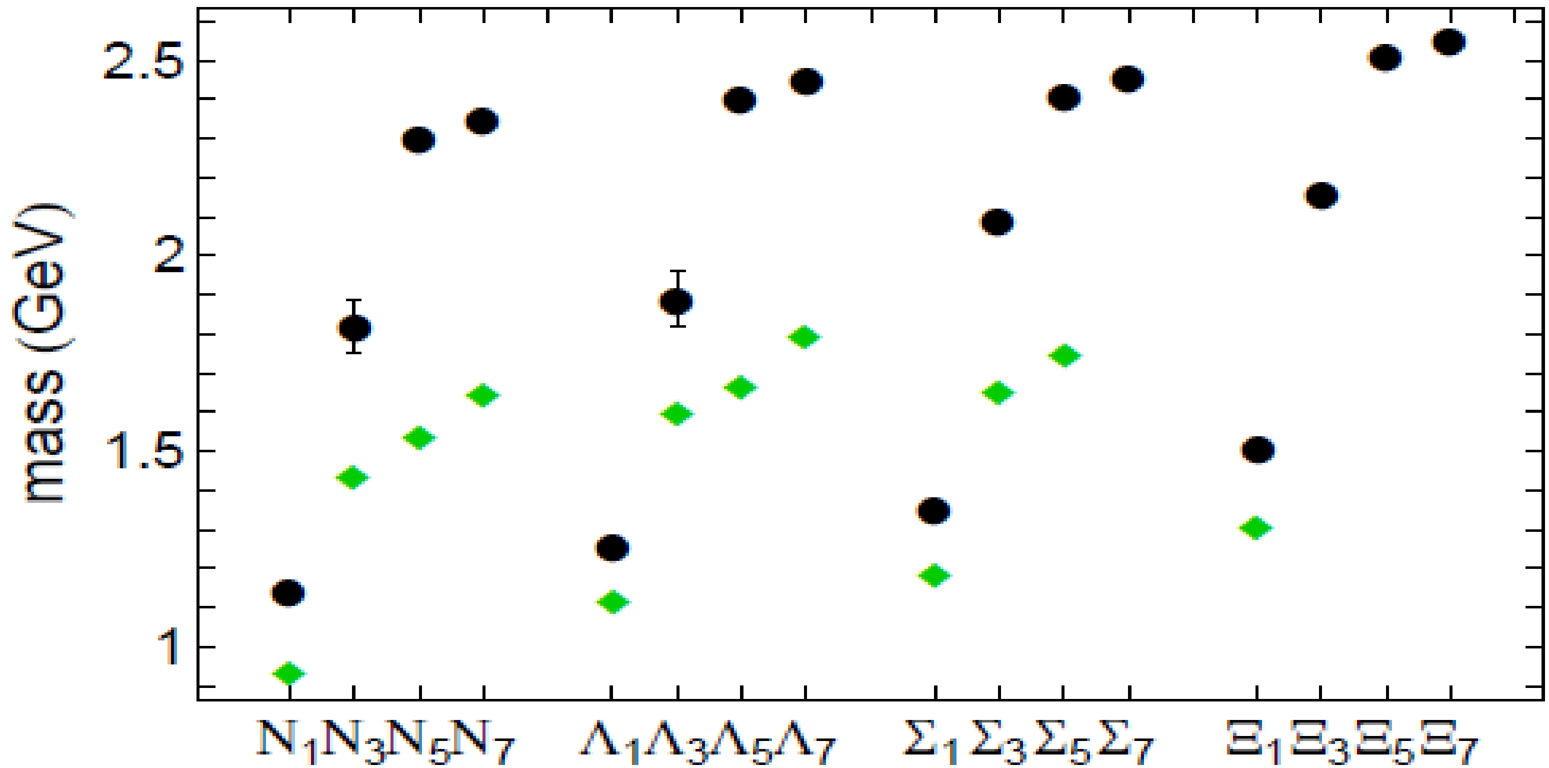


- *Achieved with $g_{B:}$ g_8=1.18 & g_{10}=1.56*

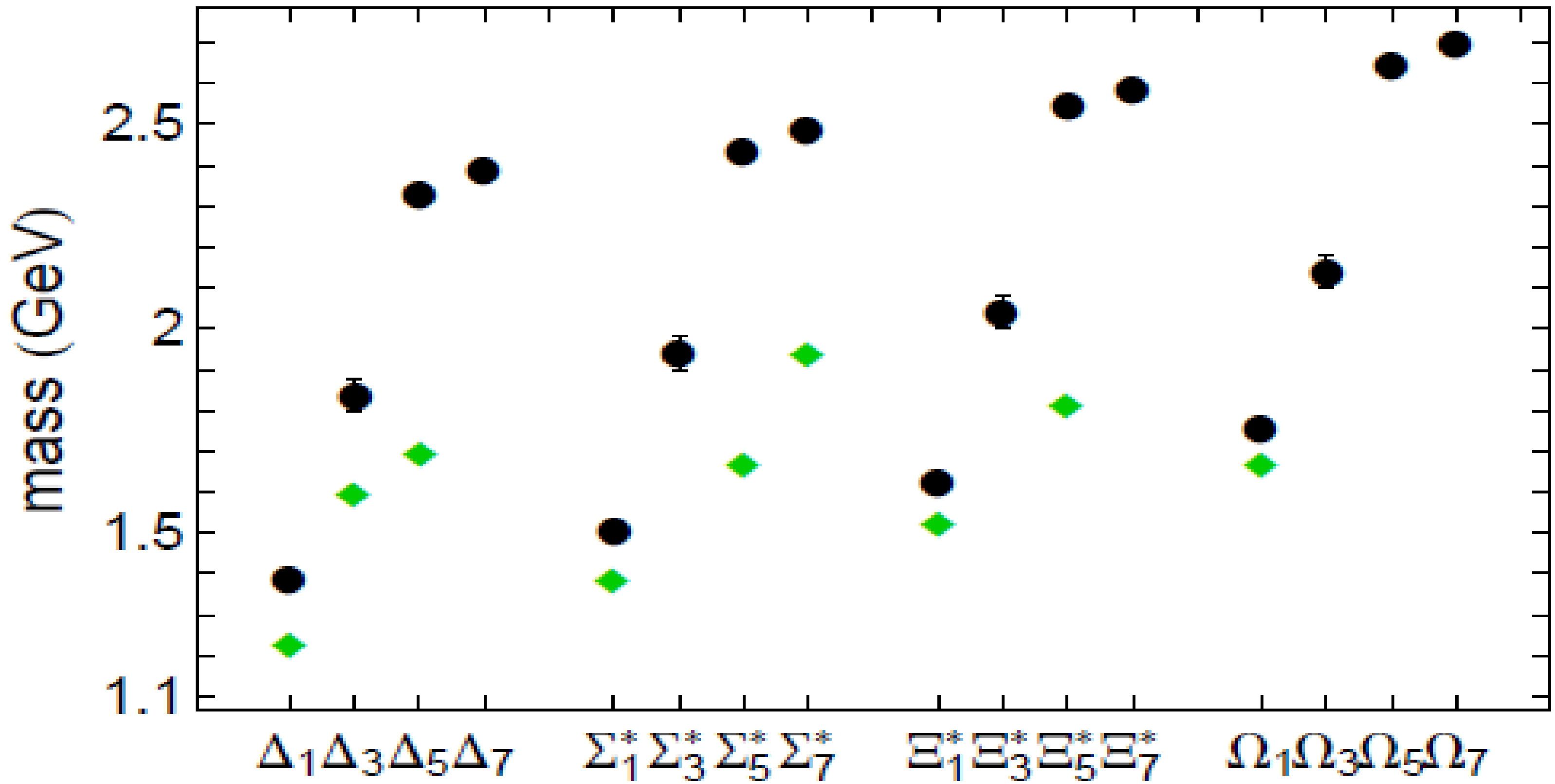
Baryon Spectrum

			N	Λ	Σ	Ξ	Δ	Σ^*	Ξ^*	Ω
$P=+$	n=0	DSE	1.14	1.26	1.35	1.51	1.39	1.51	1.63	1.76
		expt.	0.94	1.12	1.19	1.31	$1.23_{P_{33}}$	$1.39_{P_{13}}$	$1.53_{P_{13}}$	1.67
$P=+$	n=1	DSE	$1.82_{\pm 0.07}$	$1.89_{\pm 0.07}$	$2.09_{\pm 0.01}$	$2.16_{\pm 0.01}$	$1.84_{\pm 0.04}$	$1.94_{\pm 0.04}$	$2.04_{\pm 0.04}$	$2.14_{\pm 0.04}$
		expt.	$1.44_{P_{11}}$	$1.60_{P_{01}}$	$1.66_{P_{11}}$	-	$1.60_{P_{33}}$	-	-	-
$P=-$	n=0	DSE	2.30	2.40	2.41	2.51	2.33	2.44	2.55	2.65
		expt.	$1.54_{S_{11}}$	$1.67_{S_{01}}$	$1.75_{S_{11}}$	-	$1.70_{D_{33}}$	$1.67_{D_{13}}$	$1.82_{D_{13}}$	-
$P=-$	n=1	DSE	$2.35_{\pm 0.01}$	$2.45_{\pm 0.01}$	$2.46_{\pm 0.01}$	$2.55_{\pm 0.01}$	$2.39_{\pm 0.01}$	$2.49_{\pm 0.01}$	$2.59_{\pm 0.01}$	$2.70_{\pm 0.01}$
		expt.	$1.65_{S_{11}}$	$1.80_{S_{01}}$	-	-	-	$1.94_{D_{13}}$	-	-

Baryon Spectrum (Octet)



Baryon Spectrum (Decuplet)



Baryon Spectrum - Discussion

- Our computed baryon masses lie uniformly above the empirical values.
- We view this as a success because our results are those for the baryons’ dressed-quarkcores, whereas the empirical values include effects associated with meson-cloud effects, which typically produce sizable reductions.
- Our values may reasonably be viewed as bare-mass inputs appropriate for dynamical coupled-channels analyses of the hadron spectrum.

Summary & Perspective

- The first DSE-based calculation of the spectrum of strange and nonstrange hadrons.
- Our computed level ordering matches that of experiment. In particular, the parity-partner for each ground-state is always more massive than its first radial excitation.
- Our results further strengthen the claim that a symmetry-preserving treatment of a vector×vector contact interaction is a useful tool for the study of phenomena characterised by probe momenta less-than the dressed-quark mass.
- It is being used in the computation of elastic and transition form factors involving baryons with strangeness.

Thank you!