HELMHOLTZ ZENTRUM
DRESDEN ROSSENDORF

Octet masses from Poincaré-covariant three-body Faddeev equation

Zhao-Qian Yao

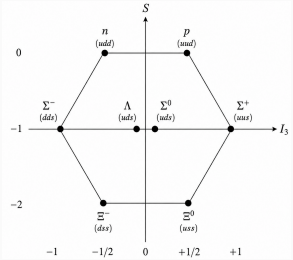
Institute of Theoretical Physics, HZDR

The 15th International Workshop on the Physics of Excited Nucleons (Nstar 2026)
Seville, Spain, September 7, 2026

Nucleons and hyperons

HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

Octet



Baryon octet

$$N, \quad \Lambda, \quad \Sigma, \quad \Xi$$

- Nucleons: $N = (p, n)$, composed of light quarks u, d.
- Hyperons: baryons containing at least one strange quark:

$$\Lambda, \quad \Sigma, \quad \Xi.$$

- Current-quark masses:

$$m_u \sim 2\,\mathrm{MeV}, \qquad m_d \sim 5\,\mathrm{MeV}, \qquad m_s \sim 95\,\mathrm{MeV}.$$

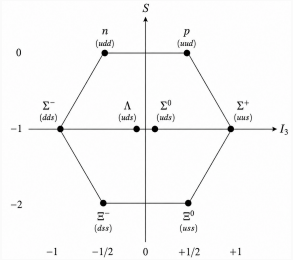
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E-mail: z.yao@hzdr.de

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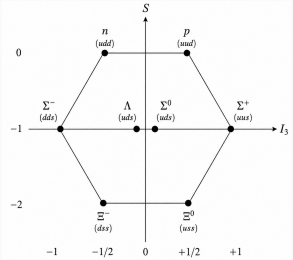
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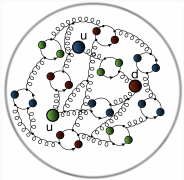
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Nucleons and hyperons

Octet



Proton



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Dyson-Schwinger Equations

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Dyson-Schwinger Equations (DSEs) are a system of infinitely coupled equations for Schwinger functions.

DSEs provide a widely used approach to hadron structure.

[Craig D. Roberts et al., Prog. Part. Nucl. Phys. 33 (1994) 477-575]

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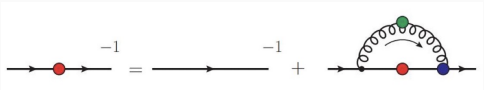
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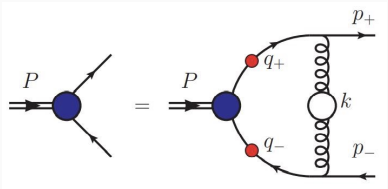
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- Gap Equation: DSEs for quark propagator: $S(p)$

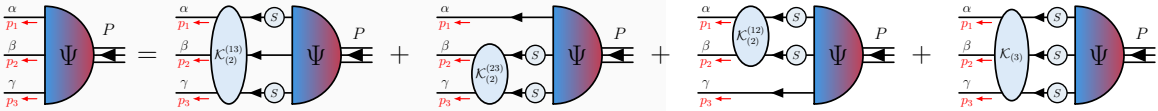


- Bethe-Salpeter Equations: DSEs for two quark bound state: $\Gamma(q, P)$



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Three-body Faddeev equation

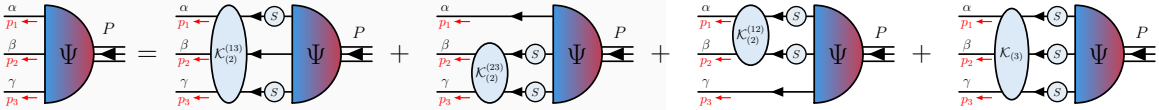


Full three-body kernel: $K_3 = K_2^{(1)} + K_2^{(2)} + K_2^{(3)} + K_3^{\rm irr}$

- $K_2^{(1)}$: interaction of quarks $2, 3$, with quark 1 as spectator;
- $K_2^{(2)}$: interaction of quarks $1, 3$, with quark 2 as spectator;
- $K_2^{(3)}$: interaction of quarks $1, 2$, with quark 3 as spectator;
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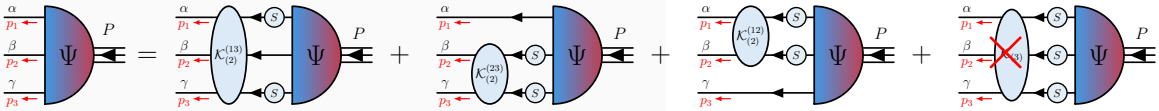
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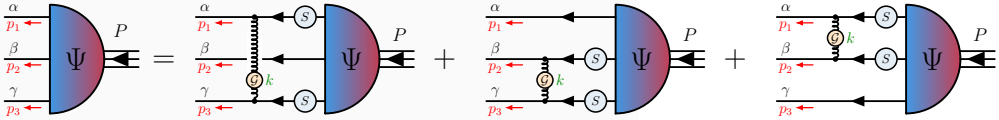
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The spectator is not dynamically inactive.
The genuine three-body kernel is neglected $K_3^{\text{irr}} \approx 0$

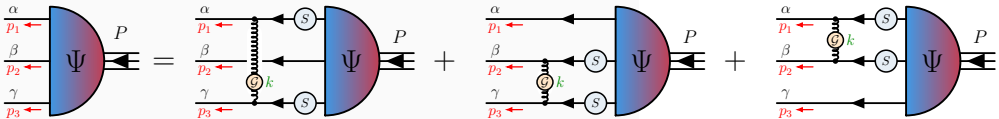
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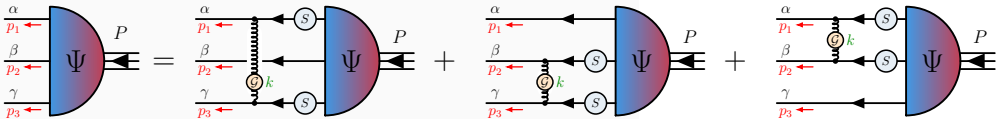


Faddeev amplitude:

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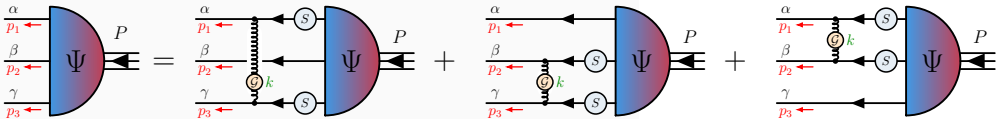


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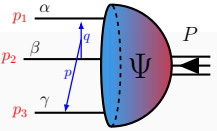


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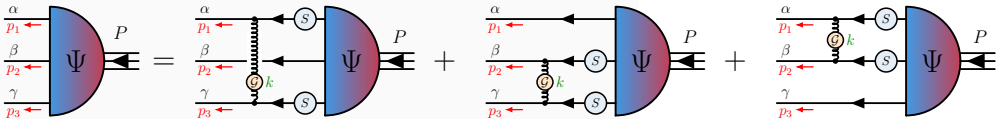
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Jacobi coordinates momenta:



$q = \frac{p_2 - p_1}{2}, p = \frac{2p_3 - p_1 - p_2}{3}$,
$P = p_1 + p_2 + p_3$.
Five Lorentz-invariant variables:
$p^2,\ q^2,\ z_0 = \widehat{p}_T \cdot \widehat{q}_T,$
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T : the projection transverse to P

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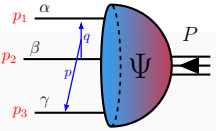


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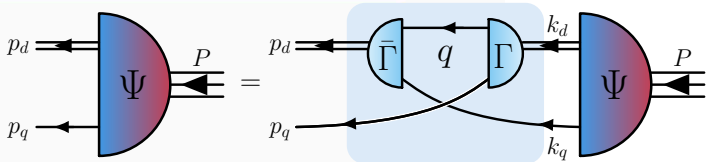
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Quark–diquark approximation

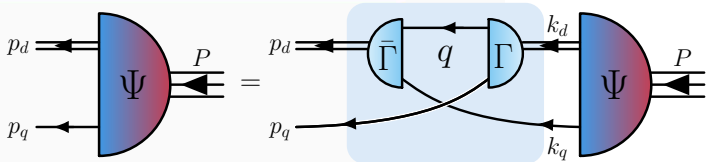


Quark–diquark approximation:

$$qqq \longrightarrow q + (qq).$$

- The two-quark scattering matrix is approximated by diquark correlations.
- The baryon is described as a bound state of one dressed quark and one diquark.
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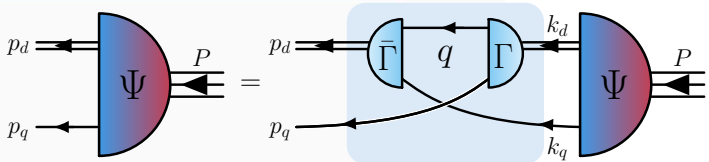


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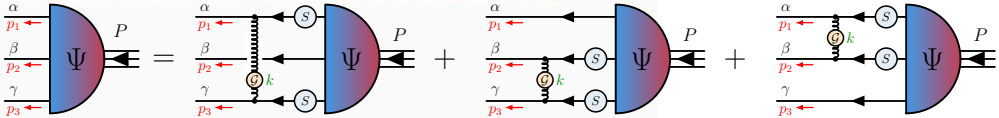
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Phenomenological ansatz or robust baryon structure?

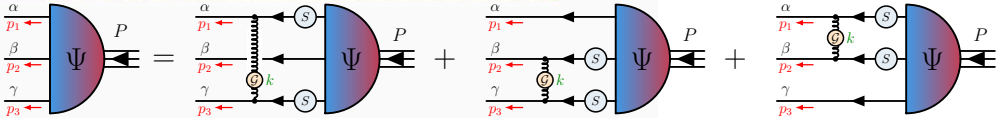
Three-body Faddeev equation: Permutation symmetry



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G. Eichmann, Phys. Rev. D **84**, *014014 (2011)*

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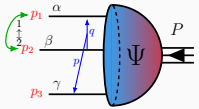
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Nucleon Flavor Amplitudes

	$\mathrm{F}^0(\mathcal{M}_\mathcal{A})$	$\mathrm{F}^1(\mathcal{M}_\mathcal{S})$
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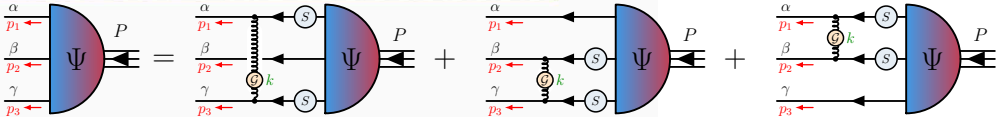
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For the Jacobi momenta, $q \to -q$

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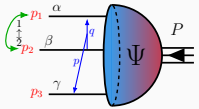
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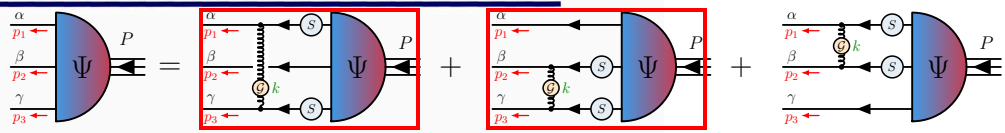


For the Jacobi momenta, $q \to -q$
System of three identical particles:

$$\psi^{0}_{\alpha\beta\gamma\mathcal{I}}(p,q,P) \longrightarrow -\psi^{0}_{\beta\alpha\gamma\mathcal{I}}(p,-q,P)$$
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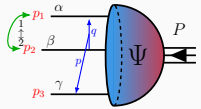
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Diagrams **1** and **2** are reconstructed by permutation:

$$\Psi = \mathcal{P}_1\Psi^{(3)} + \mathcal{P}_2\Psi^{(3)} + \Psi^{(3)}.$$

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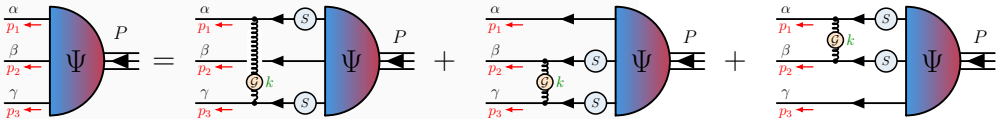
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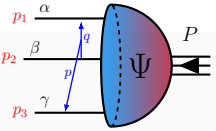


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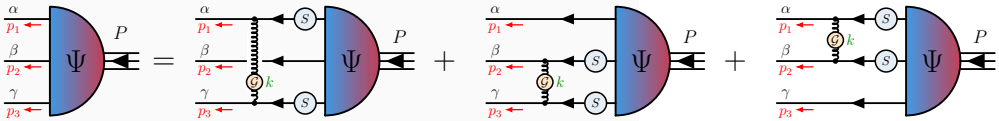
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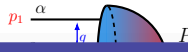
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$P = p_1 + p_2 + p_3$.
Five Lorentz-invariant variables:
$p^2,\ q^2,\ z_0 = \widehat{p}_T \cdot \widehat{q}_T,$
$z_1 = \widehat{p} \cdot \widehat{P},\ z_2 = \widehat{q} \cdot \widehat{P}.$
T : the projection transverse to P

Three-body Faddeev equation



Faddeev amplitude:

Jacobi coordinates momenta:



Key challenge

48 CPUs: one eigenvalue iteration $\sim$ 2–8 h.

How can we solve the full unequal-flavor Faddeev equation efficiently?

$\psi^\rho(p,q,P) = \sum_m^{64} f_m^\rho(p^2,q^2,z_0,z_1,z_2)\, X_m(p,q,P)$

- Numerical size: $2 \times 64 \times N_p\, N_q\, N_{z_0}\, N_{z_1}\, N_{z_2}$
  $\sim 10^7$ numbers for the Faddeev amplitude,
  $\sim 10^{14}$ numbers for kernel matrix.

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Unequal flavor Faddeev equation: nucleon degeneracy

HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

Nucleon Flavor Amplitudes

	$\mathrm{F}^0(\mathcal{M}_\mathcal{A})$	$\mathrm{F}^1(\mathcal{M}_\mathcal{S})$
p	$\frac{1}{\sqrt{2}}(udu - duu)$	$\frac{1}{\sqrt{6}}(2uud - udu - duu)$
n	$\frac{1}{\sqrt{2}}(udd - dud)$	$\frac{1}{\sqrt{6}}(udd + dud - 2ddu)$

Isospin symmetry

$$m_u = m_d, \qquad S_u(p) = S_d(p).$$

In the symmetry-preserving case, they must yield exactly the same mass:

$$\boxed{M_{\mathcal{M}_A} = M_{\mathcal{M}_S}}$$

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HZDR HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

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Numerically Result:

	$\mathcal{M}_A$	$\mathcal{M}_S$
2010	0.99	0.97
This work	**0.937**	**0.937**

[G. Eichmann et al., Phys. Rev. Lett. **104**, *201601 (2010)]*

Omit angel dependent: $z_0 = \widehat{p}_T \cdot \widehat{q}_T$

Two degenerate masses:

$$\boxed{M_{\mathcal{M}_A} = M_{\mathcal{M}_S} = 0.937 \text{ GeV}}$$

These two solutions do **not** correspond to the proton and neutron.

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Hyperon Flavor Amplitudes

	$\mathrm{F}^0(\mathcal{M}_\mathcal{A})$	$\mathrm{F}^1(\mathcal{M}_\mathcal{S})$
Σ^+	$\frac{1}{\sqrt{2}}(usu - suu)$	$\frac{1}{\sqrt{6}}(2uus - usu - suu)$
Σ^0	$\frac{1}{2}(usd + dsu - sud - sdu)$	$\frac{1}{\sqrt{12}}(2uds + 2dus - usd - dsu - sud - sdu)$
Σ^-	$\frac{1}{\sqrt{2}}(dsd - sdd)$	$\frac{1}{\sqrt{6}}(2dds - dsd - sdd)$
Ξ^0	$\frac{1}{\sqrt{2}}(uss - sus)$	$\frac{1}{\sqrt{6}}(uss + sus - 2ssu)$
Ξ^-	$\frac{1}{\sqrt{2}}(dss - sds)$	$\frac{1}{\sqrt{6}}(dss + sds - 2ssd)$
Λ^0	$\frac{1}{\sqrt{12}}(2uds - 2dus + sdu - dsu + usd - sud)$	$\frac{1}{2}(usd + sud - dsu - sdu)$

Isospin symmetry

$$\Xi^0 \longleftrightarrow \Xi^-, \qquad \Sigma^- \longleftrightarrow \Sigma^0 \longleftrightarrow \Sigma^+.$$

Hence, they cannot be distinguished at the Faddeev-equation level.

Hyperons

Flavor-resolved Faddeev kernel

The homogeneous Faddeev equation can be written schematically as

$$\Psi = \mathcal{K}\, G_0\, \Psi, \qquad G_0^{abc} = S_a \otimes S_b \otimes S_c.$$

The baryon amplitude is expanded in flavor and Dirac spaces:

$$\Psi = \sum_{i=0,1} F^i\, \psi^i, \qquad \psi^i = \sum_m f_m^i\, X_m,$$

X_m is the Dirac-momentum basis. m is the sum of all sample points and Dirac basis.

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The projected Faddeev kernel is therefore

$$K_{ij}^{mn} = \langle F^i \bar{X}_m |\, \mathcal{K} G_0\, | X_n F^j \rangle.$$

For a fixed flavor ordering abc, define

$$\omega_{abc}^{mn} \equiv \langle \bar{X}_m | \mathcal{K}_D\, (S_a \otimes S_b \otimes S_c)\, | X_n \rangle.$$

Hence,

$$K_{ij}^{mn} = \sum_{abc} (F^i)^*_{abc} (F^j)_{abc}\, \omega_{abc}^{mn}$$

$$f_i^{\,m} = \sum_{j,n} K_{ij}^{mn}\, f_j^{\,n}$$

Hyperons

	$\mathrm{F}^0(\mathcal{M}_\mathcal{A})$	$\mathrm{F}^1(\mathcal{M}_\mathcal{S})$
Σ^0	$\frac{1}{2}(usd+dsu-sud-sdu)$	$\frac{1}{\sqrt{12}}(2uds+2dus-usd-dsu-sud-sdu)$
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Ξ^0	$\frac{1}{\sqrt{2}}(uss-sus)$	$\frac{1}{\sqrt{6}}(uss+sus-2ssu)$

With isospin symmetry $S_u = S_d$,

$$\mathbb{A}^{mn} \equiv \omega^{mn}_{usd} = \omega^{mn}_{dsu}, \quad \mathbb{B}^{mn} \equiv \omega^{mn}_{sud} = \omega^{mn}_{sdu}, \quad \mathbb{C}^{mn} \equiv \omega^{mn}_{uds} = \omega^{mn}_{dus}.$$

$$K^{mn}_{\Sigma} = \begin{pmatrix} \frac{\mathbb{A}+\mathbb{B}}{2} & \frac{\mathbb{B}-\mathbb{A}}{\sqrt{12}} \\ \frac{\mathbb{B}-\mathbb{A}}{\sqrt{12}} & \frac{4\mathbb{C}+\mathbb{A}+\mathbb{B}}{6} \end{pmatrix}^{mn}$$

$$K^{mn}_{\Lambda} = \begin{pmatrix} \frac{4\mathbb{C}+\mathbb{A}+\mathbb{B}}{6} & \frac{\mathbb{A}-\mathbb{B}}{\sqrt{12}} \\ \frac{\mathbb{A}-\mathbb{B}}{\sqrt{12}} & \frac{\mathbb{A}+\mathbb{B}}{2} \end{pmatrix}^{mn}$$

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Ground-state hadron spectrum

HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

Same interaction, different bound-state equations

The following meson and baryon results are obtained using the **same model parameters**.

Mesons from BSE

	π	K	ρ	K^*	ϕ
$m_{\text{calc.}}$	0.140	0.500	0.740	0.950	1.090
$m_{\text{exp.}}$	0.140	0.494	0.775	0.892	1.019
$f_{\text{calc.}}$	0.094	0.110	0.150	0.180	0.190
$f_{\text{exp.}}$	0.092	0.110	0.153	0.159	0.168

Baryons from the Faddeev equation

	N	Λ^0	Σ^0	Ξ^0	Δ	Ω
$m_{\text{calc.}}$	0.937	1.090	1.115	1.300	1.200	1.670
$m_{\text{exp.}}$	0.939	1.116	1.193	1.315	1.232	1.672

$$m_{\Sigma^0} - m_{\Lambda^0} = \begin{cases} \mathbf{25\ MeV}, & \text{This work,} \\ \mathbf{76.96\ MeV}, & \text{Experiment.} \end{cases}$$

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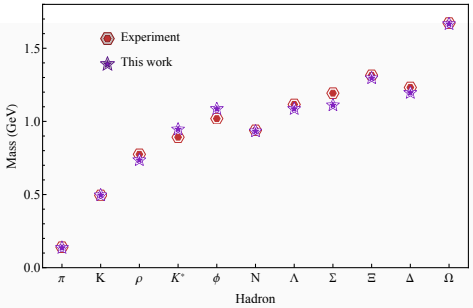
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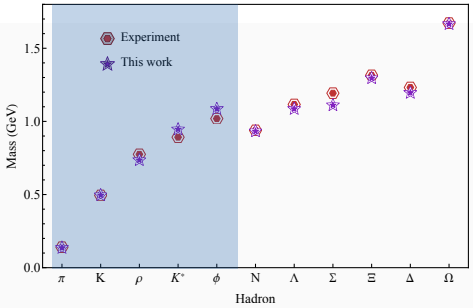
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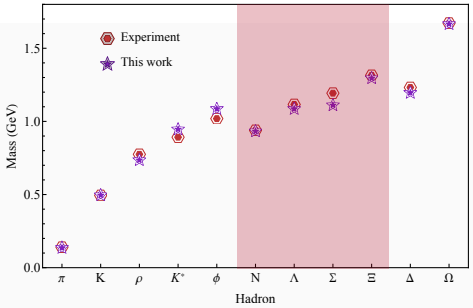
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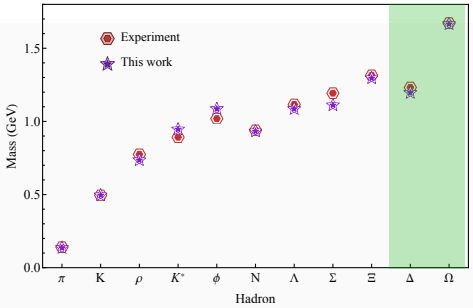
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Summary and outlook

HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

Summary

- A full three-body, Poincaré-covariant Faddeev equation is solved for ground-state baryons.
- CSMs with BSE + Faddeev equations give a good description of ground-state hadron masses.
- Extend the calculation to electromagnetic form factors of hyperons.
- Extend the framework to spin-$\frac{3}{2}$ baryons.
- Go beyond rainbow–ladder kernels to improve the Λ–Σ splitting.

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Appendix: RL

- The key element is the quark+quark scattering kernel, for which the RL truncation is obtained by writing:

$$\mathcal{K}^{rs}_{tu}(k) = \mathcal{G}_{\mu\nu}(k)[i\gamma_\mu \frac{\lambda^a}{2}]_{ts}[i\gamma_\nu \frac{\lambda^a}{2}]_{ur}\,, \tag{1a}$$

$$\mathcal{G}_{\mu\nu}(k) = \tilde{\mathcal{G}}(y) T_{\mu\nu}(k)\,, \tag{1b}$$

$k^2 T_{\mu\nu}(k) = k^2\delta_{\mu\nu} - k_\mu k_\nu$, $y = k^2$.r, s, t, u represent colour, spinor, and flavour matrix indices (as necessary).

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Appendix: iteration

$$\tilde{\mathcal{G}}(y) = \frac{8\pi^2}{\omega^4} D e^{-y/\omega^2} + \frac{8\pi^2 \gamma_m \mathcal{F}(y)}{\ln\left[\tau + (1 + y/\Lambda_{\rm QCD}^2)^2\right]}\,, \tag{2}$$

where $\gamma_m = 12/25$, $\Lambda_{\rm QCD} = 0.234\,{\rm GeV}$, $\tau = {\rm e}^2 - 1$, and
$\mathcal{F}(y) = \{1 - \exp(-y/\Lambda_I^2)\}/y$, $\Lambda_I = 1\,{\rm GeV}$.
We employ a mass-independent (chiral-limit) momentum-subtraction renormalisation scheme.
Contemporary studies employ $\omega = 0.5\,{\rm GeV}$. With $\omega D = (0.8\,{\rm GeV})^3$.

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