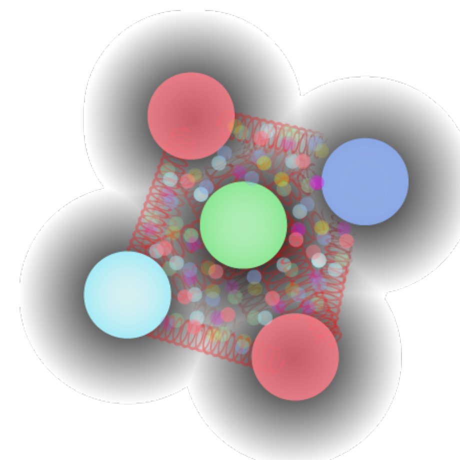
Pentaquark spectroscopy for the LHC



Raul Torres *(Raul D. Torres)*

With G. Eichmann and T. Peña

The 15th International Workshop on the Physics of Excited Nucleons, Sevilla, Spain, September 9th, 2026

GE, Torres, PRD 111 (2025)

GE, Peña, Torres, PLB 866 (2025)

TÉCNICO LISBOA

FCT Fundação para a Ciência e a Tecnologia

LIP

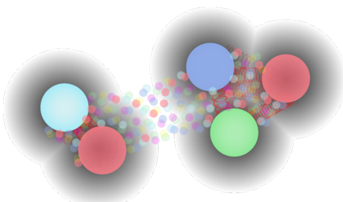
REPÚBLICA PORTUGUESA

NAWI Graz Natural Sciences

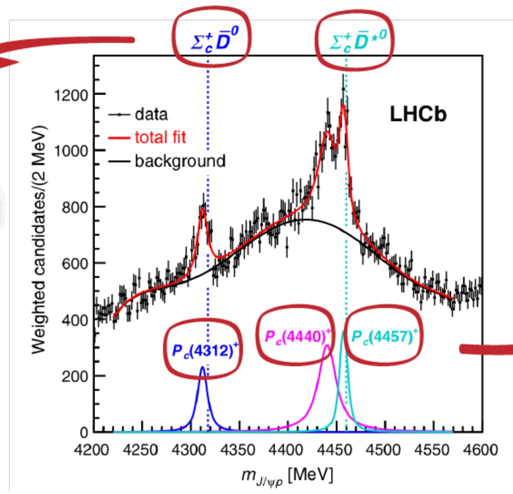
UNI GRAZ

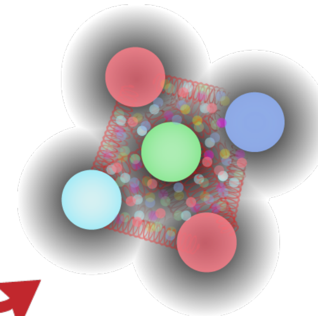
Motivation

We investigate the mass spectra and internal structure of heavy-light pentaquarks in the charm and light sectors.



Molecule





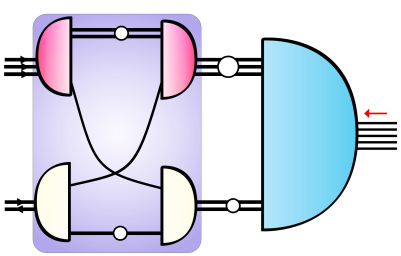
Five-Body System

$P_c(4312)^+$ $P_c(4337)^+$
$P_c(4440)^+$ $P_c(4380)^+$
$P_c(4457)^+$
$P_{cs}(4338)^0$ $P_{cs}(4459)^0$

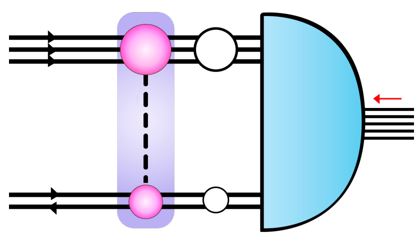
LHCb Collaboration,
PRL 122 (2019) 22, 22201
PRL 131 (2023) 3, 031901

Molecule

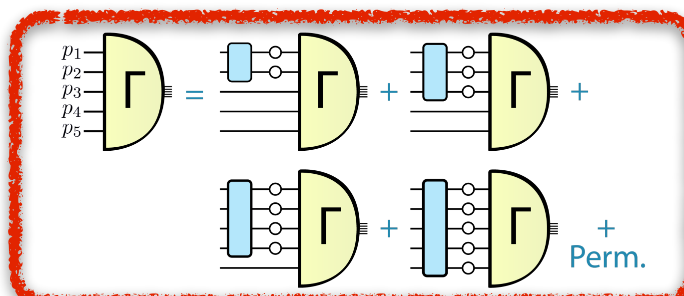
Quark exchange



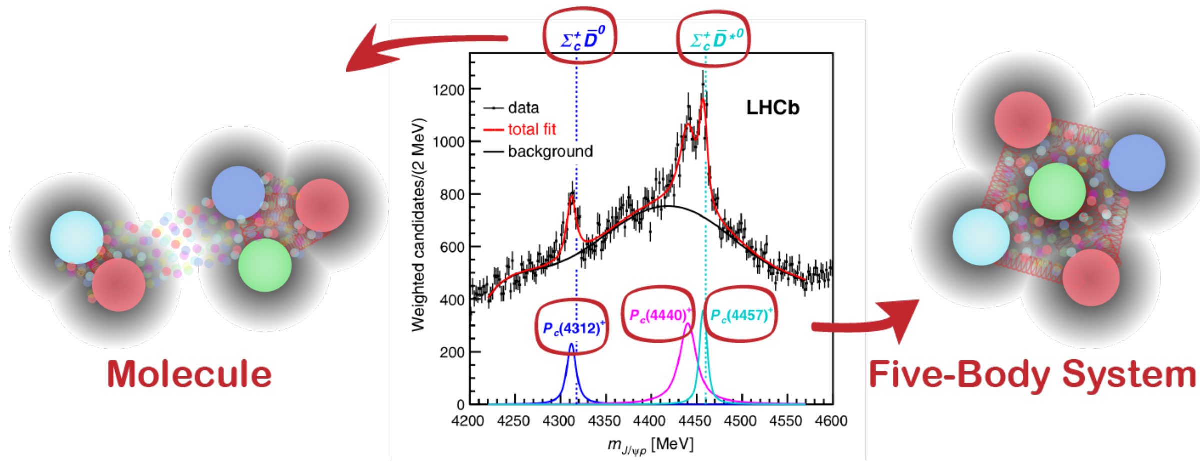
Hadronic exchange



Five-Body Equation

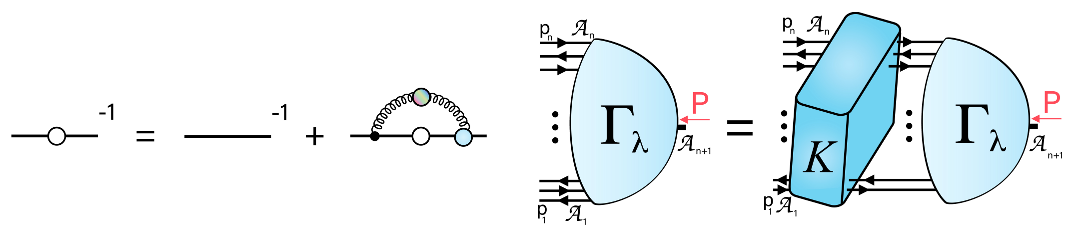


Different theoretical approaches



- **Quark models**
- **QCD Sum Rules**
- **Amplitude analyses**
- **Effective Field Theories**
- **Lattice QCD**

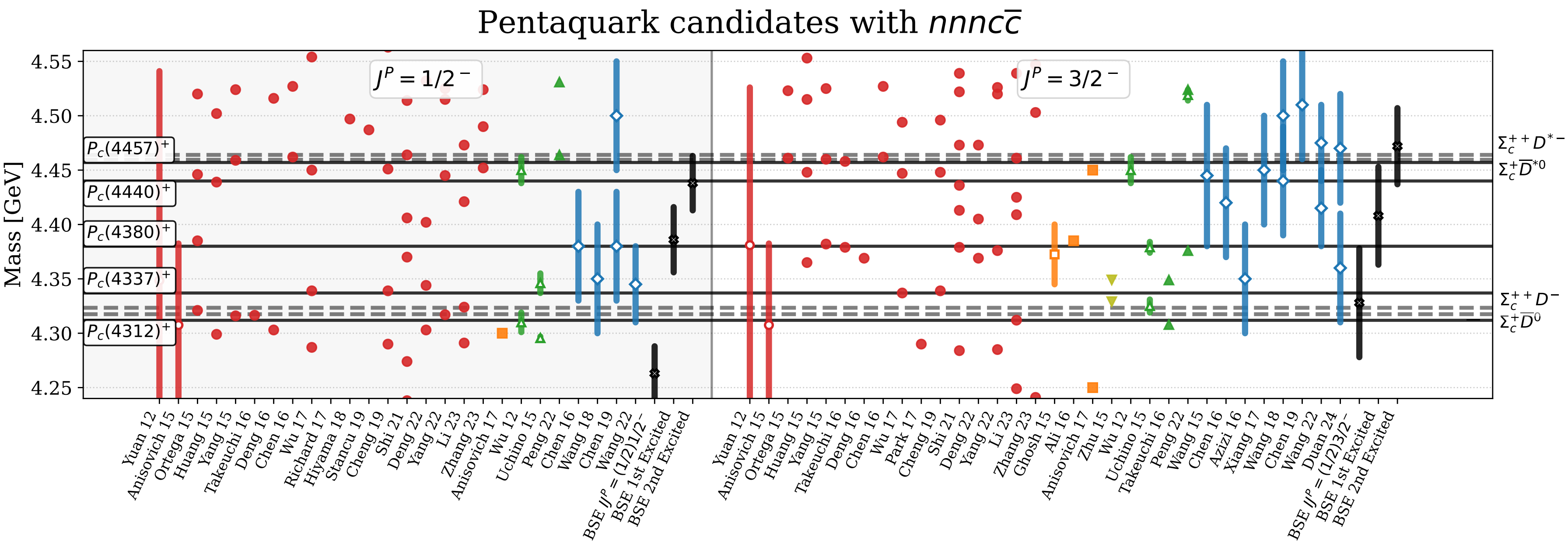
- Functional methods like ***Dyson Schwinger*** and ***Bethe Salpeter Equations:***

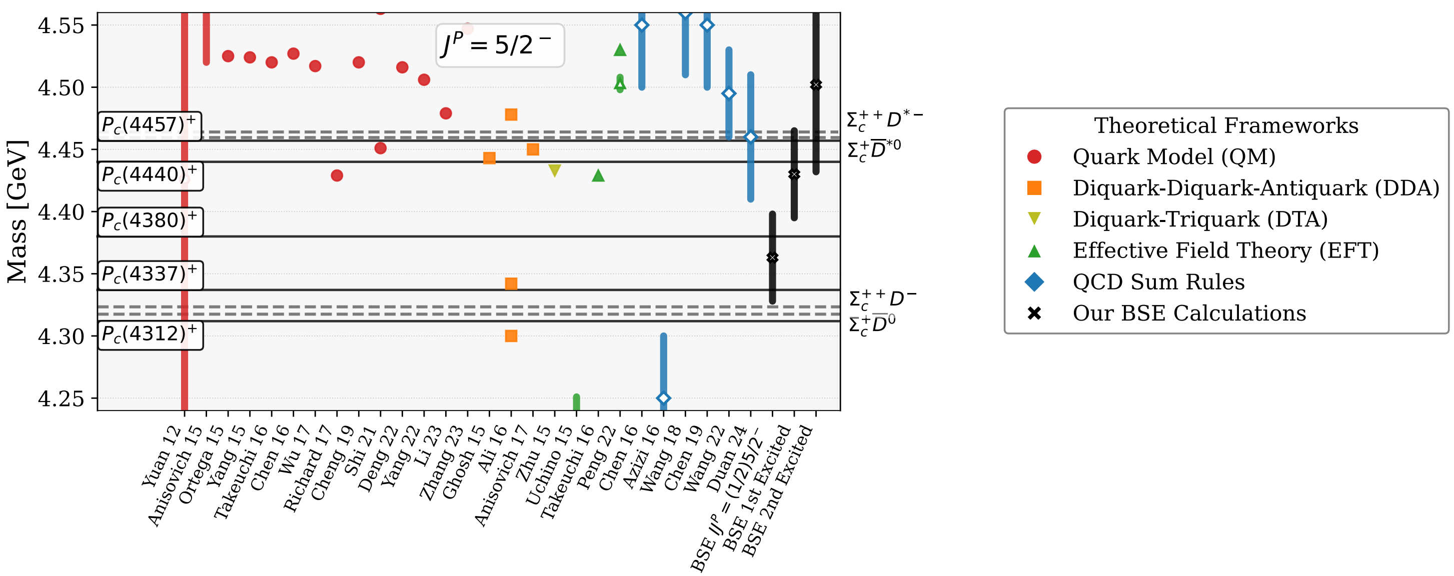


Chen, Chen, Liu, Zhu,
Phys. Rept. 639 (2016), 1601.02092.
Esposito, Pilloni, Polosa,
Phys. Rept. 668 (2017), 1611.07920.
Chen, Chen, Liu, Zhu,
Phys. Rept. 86 (2023), 2204.02649.

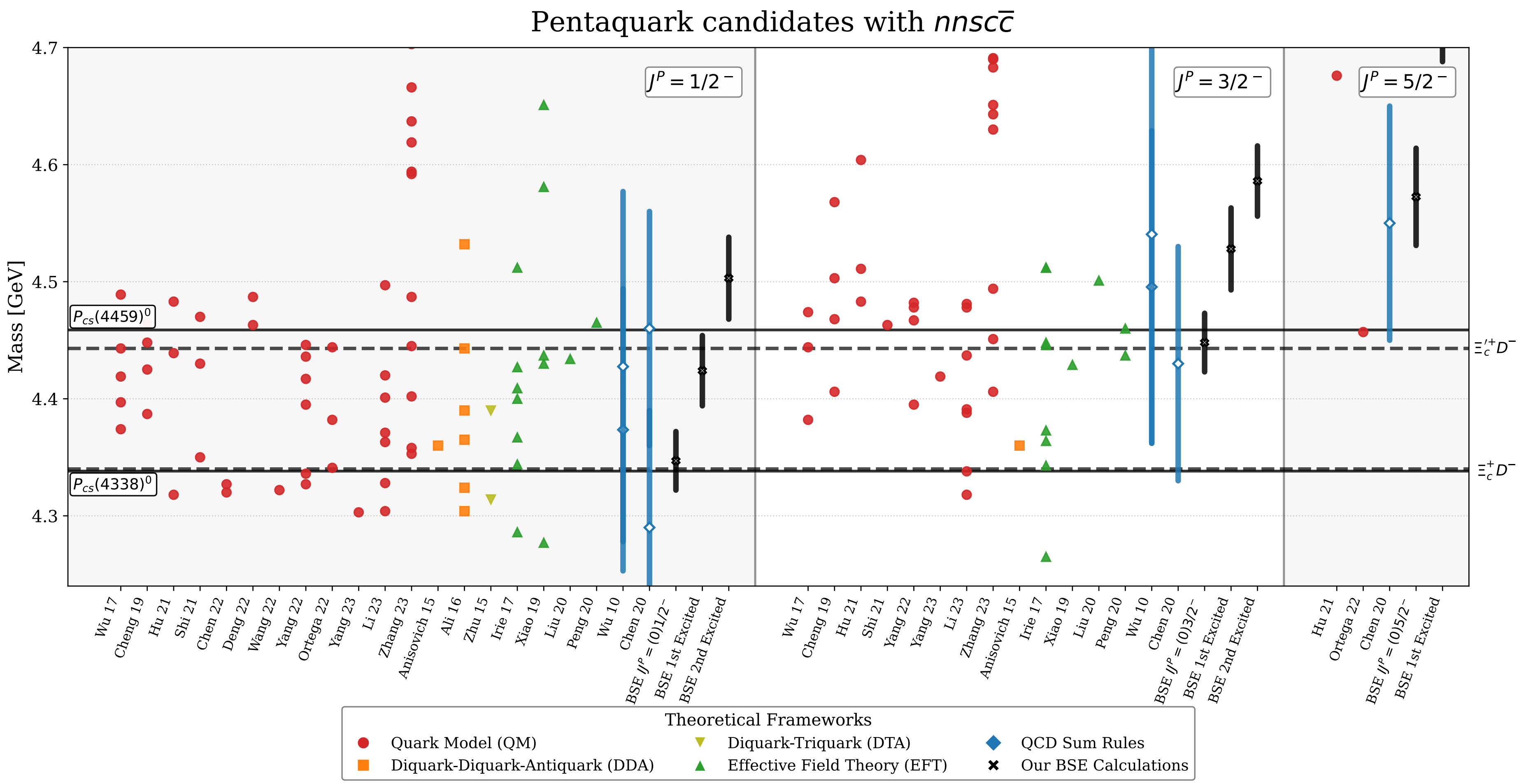
GE, Sanchis-Alepuz, Williams, Alkofer, Fischer,
Prog. Part. Nucl. Phys. 91 (2016), 1606.09602.
Qin, Roberts, Chin. Phys. Lett. 38 (2021).
Huber, PRD 101 (2020).
GE, Palowski, Silva, PRD 104 (2021).

Pentaquarks in LHCb





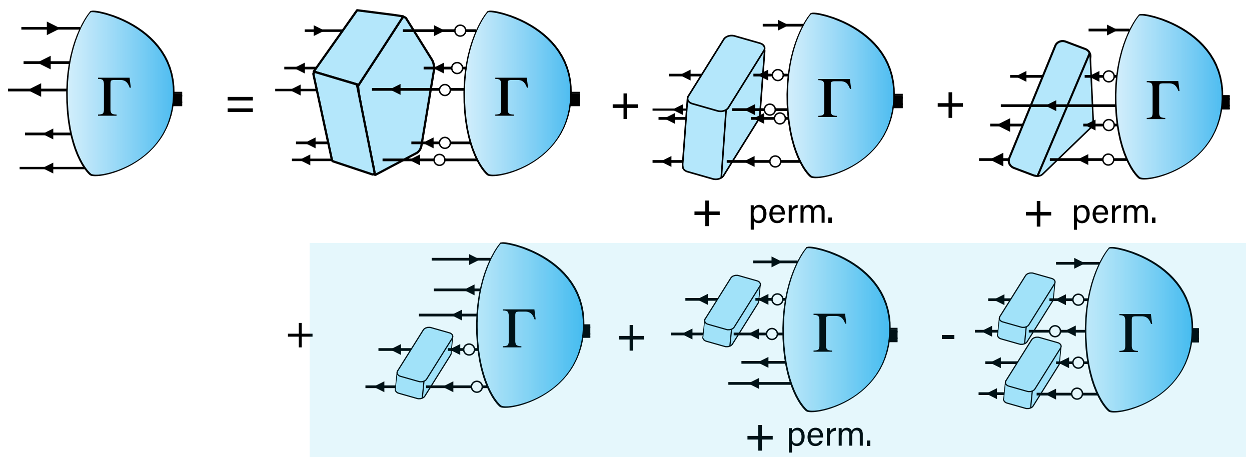
Pentaquarks in LHCb



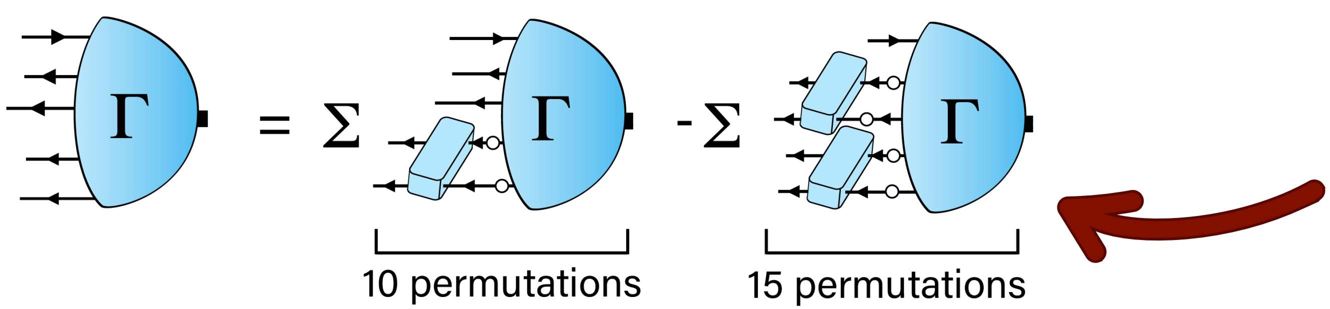
Five-body systems

Our starting point is the homogeneous BSE for a **five-body system:**

$$\Gamma = K G_0 \Gamma.$$



We restrict ourselves to a ***two-body kernel***. In a five-body system there are **ten possible two-body kernels** and **15 independent double-kernel** configurations:



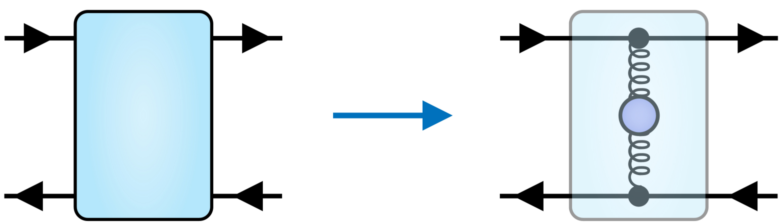
Avoids overcounting in $T^{(10)}$ — matrix

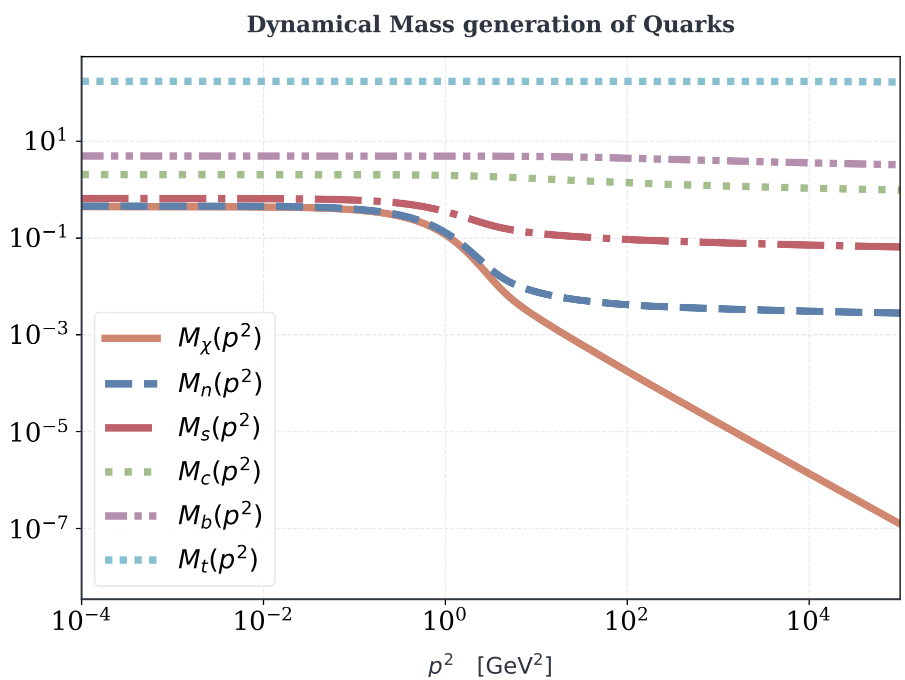
GE, Fischer, Heupel, PLB 753 (2016), Wallbott, GE, Fischer, PRD 102 (2020), Hoffer, GE, Fischer, PRD 109 (2024).

Five-body systems

<u>In practice</u>, we restrict ourselves to *Rainbow-ladder truncation:*

$$\Gamma^{qgv}(q,k,\mu) = t_a f(k^2,\mu)\gamma^\mu$$

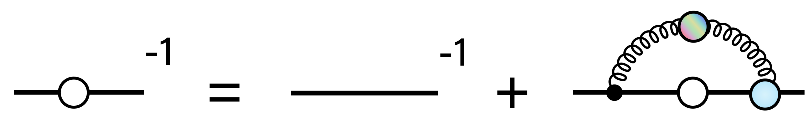




We implement a widely used and very successful parametrization known as the Maris-Tandy (Roberts) model:

$$\alpha(k^2) = \pi\eta_{MT}^7 x^2 e^{-\eta_{MT}^2 x} + UV, \quad x = \frac{k^2}{\Lambda_{MT}^2}$$

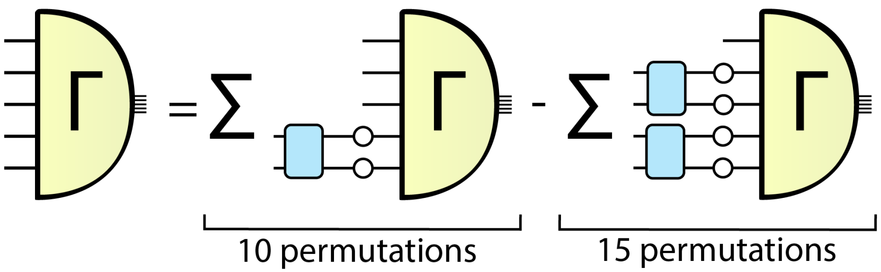
Maris, Tandy, PRC 60 (1999),
Qin, Chang, Liu, Roberts, Wilson, PRC 84 (2011)



The quark dressing function $M(p^2)$ computed for various current-quark masses $m_n(p^2)$, ranging from the chiral limit (χ) to the heavy-quark regime (3740 MeV).

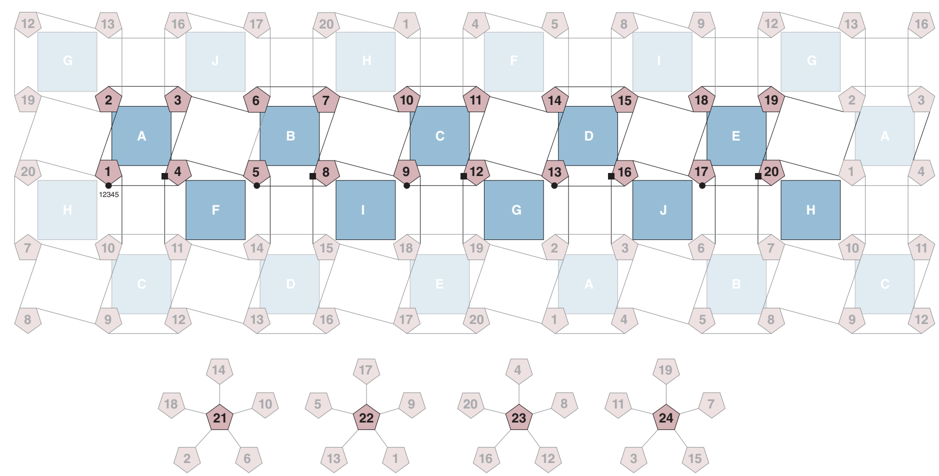
Five-body systems

We solve the Bethe-Salpeter equation for the massive Wick-Cutkosky model to study the kinematics of a five-body system.



GE, Peña, Torres, PLB 866 (2025)

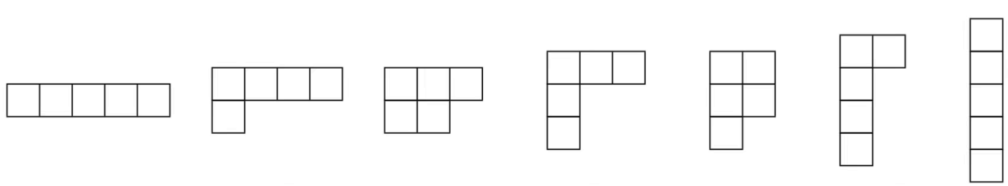
Cayley graph of S_5



One can group the 15 Lorentz-invariant momentum variables $\Omega = \{p^2, q^2, \cdots\}$ in multiples of S_5.

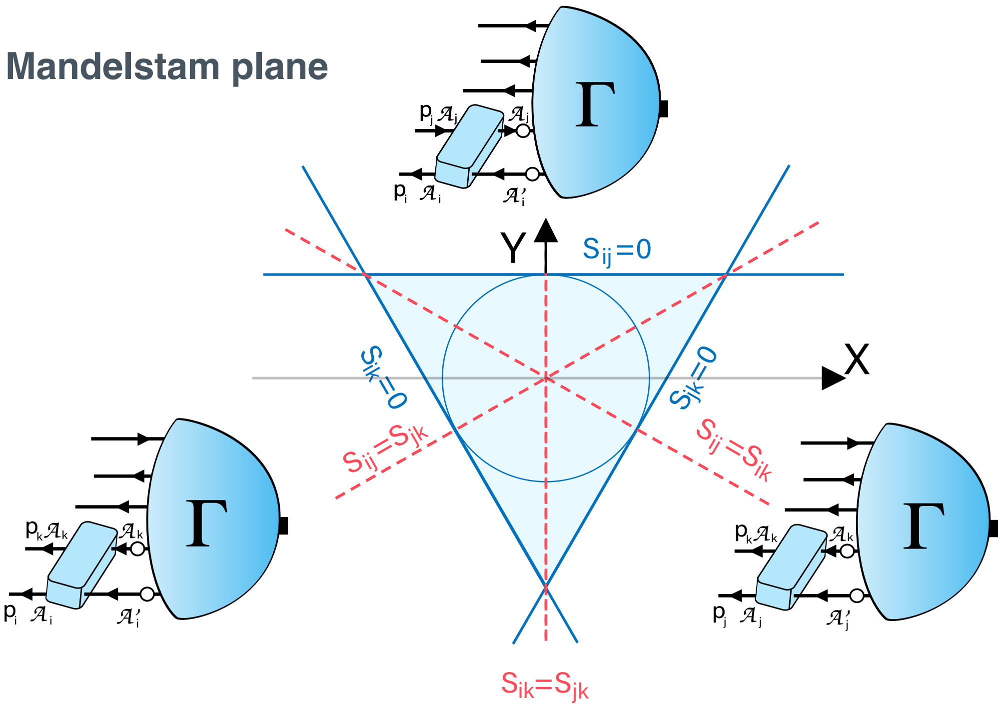
GE, Torres, PRD 111 (2025)

$\mathbf{1}$	$\mathbf{4}$	$\mathbf{5}$	$\mathbf{6}$	$\bar{\mathbf{5}}$	$\bar{\mathbf{4}}$	$\bar{\mathbf{1}}$
$\mathcal{S}$	$\mathcal{Q}_i^+$	$\mathcal{V}_j^+$	$\mathcal{W}_k$	$\mathcal{V}_j^-$	$\mathcal{Q}_i^-$	$\mathcal{A}$



Five-body systems

Mandelstam plane



The leading momentum dependent beyond the singlet variable $\mathcal{S}_0$ comes from the two-body clusters.

GE, Torres, PRD 111 (2025)

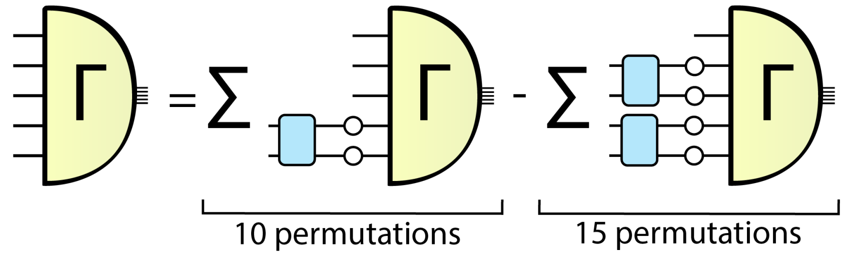
$$\Gamma^{phys.}(\cdots) \approx \sum_{i \in \{MB, DDA\}} f_i(\mathcal{S}_0) \mathrm{P}_i^{aa'} \tau_i^{Dirac} \otimes \tau_i^{Color} \otimes \tau_i^{Flavor}$$

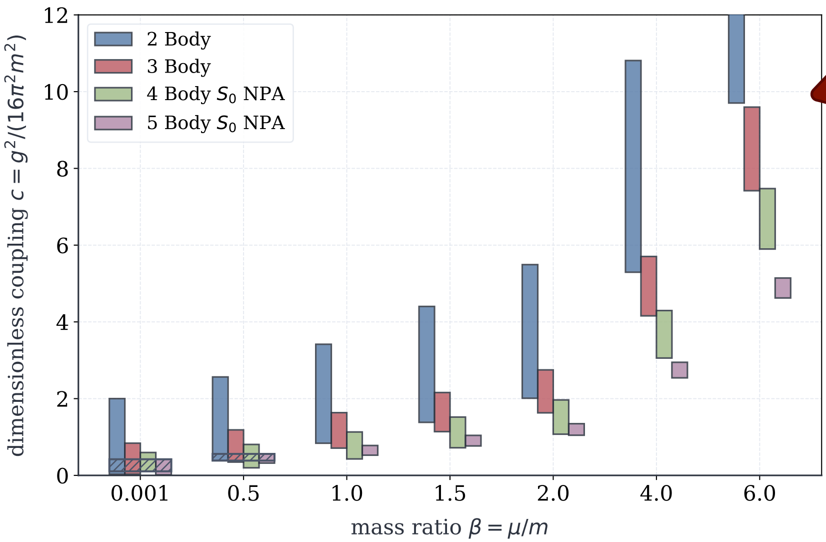
Example *MB:*

$$\mathrm{P}_{(12)(345)} = \frac{1}{(p_1+p_2)^2 + M_M^2} \frac{1}{(p_3+p_4+p_5)^2 + M_B^2}$$

Five-body systems

Parameters are the coupling strength c, and exchange particle ratio $\beta = \mu/m$.



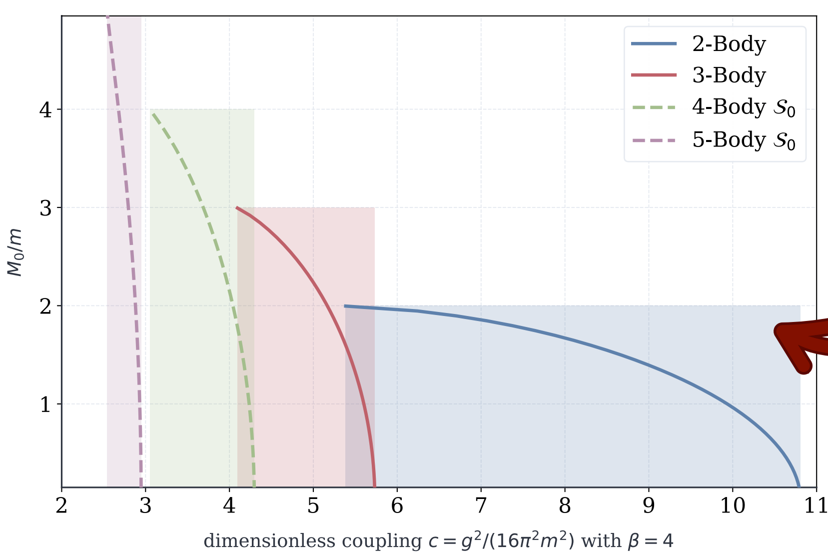


Coupling ranges where n-body ground states are possible for different values of β.

n-body: Full solution

$\mathcal{S}_0$: Only singlet + Pole Ansatz

$\mathcal{S}_0$ NPA: Only singlet



Ground-state masses obtained from the n-body BSEs for $\beta = 4$ and different values of the coupling c.

For highest values of β the five-body system becomes **Borromean.**

GE, Peña, Torres, PLB 866 (2025)

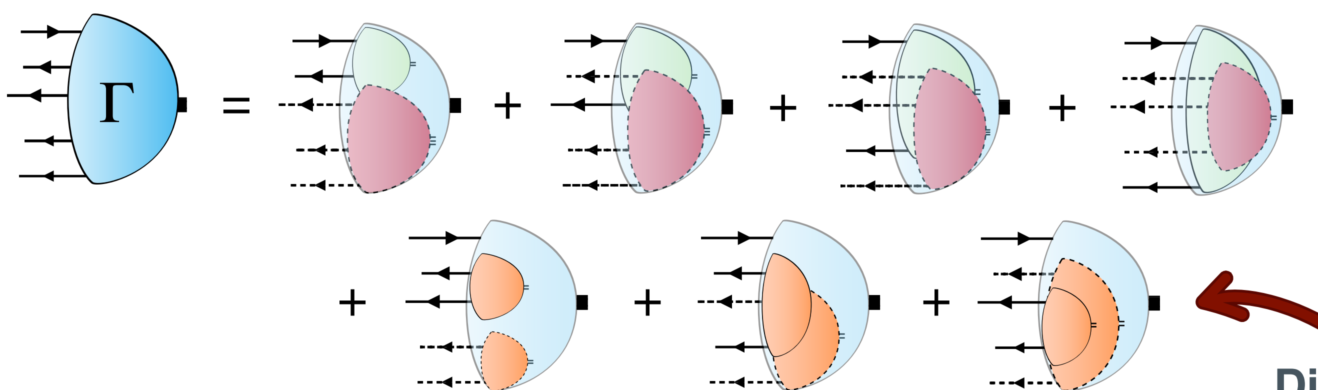
Five-body systems

We construct a physical motivated basis by projecting onto a subset of two body dominant clusters based in their dominant decay channels, meson-baryon or diquark-diquark-antiquark.

$$\Gamma^{phys.}(\cdots) \approx \sum_{i \in \{MB,DDA\}} f_i(\mathcal{S}_0)\tau_i^{Dirac} \otimes \tau_i^{Color} \otimes \tau_i^{Flavor}$$

$$(\mathbf{3} \otimes \mathbf{3} \otimes \mathbf{3}) \otimes (\mathbf{3} \otimes \bar{\mathbf{3}}) = \mathbf{1}_{\mathbf{1}\otimes\mathbf{1}} \oplus \mathbf{1}_{\mathbf{8}\otimes\mathbf{8}} \oplus \mathbf{1}_{\mathbf{8}\otimes\mathbf{8}\oplus} \cdots$$

Attractive **Repulsive**



Meson-baryon sub-clusters

Diquark-diquark-Antiquark sub-clusters

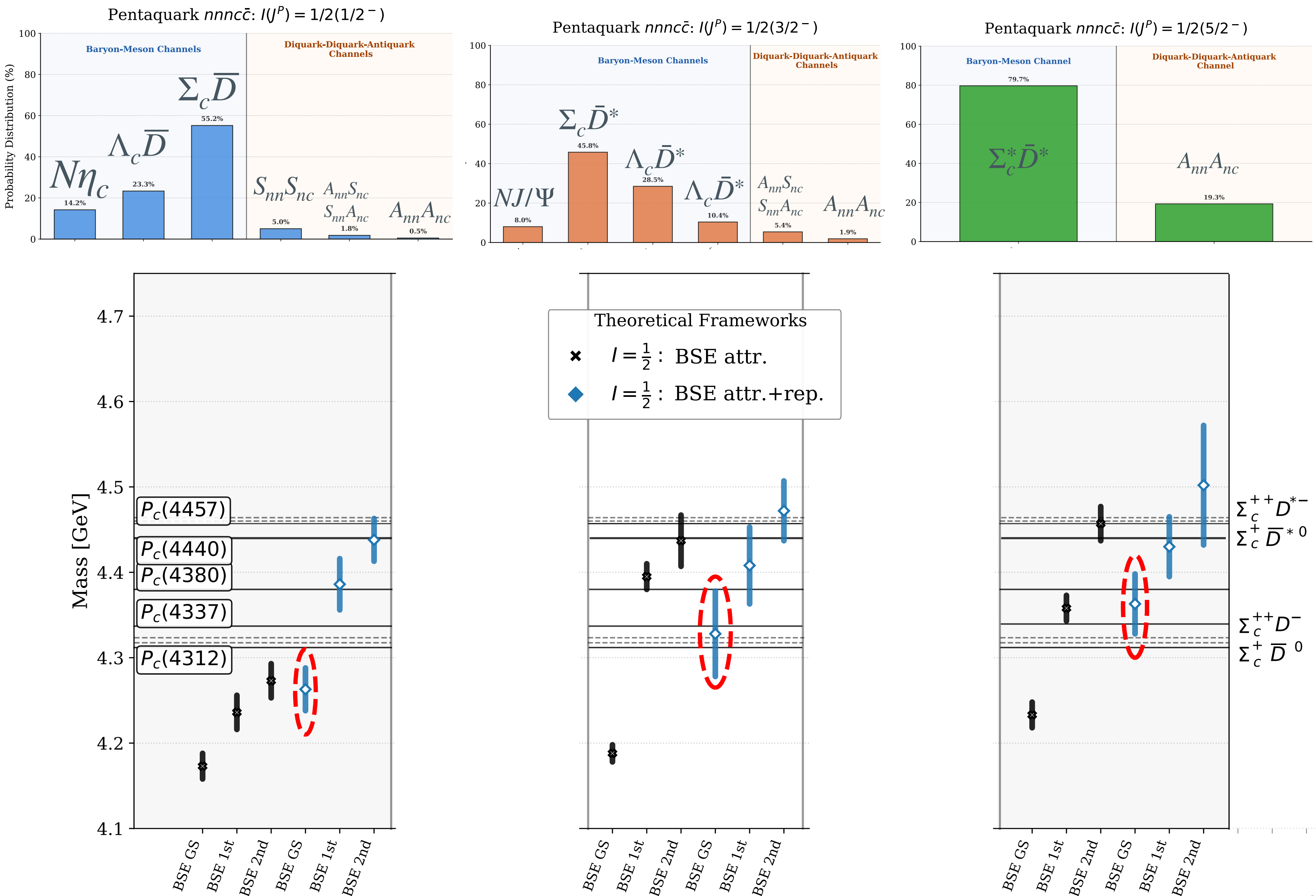
Pentaquarks $nnnc\bar{c}$

$I(J^P)$	$\Sigma_c D$	$\Sigma_c D^*$	$\Sigma_c^* D$	$\Sigma_c^* D^*$	$\Lambda_c D$	$\Lambda_c D^*$	$N\eta_c$	NJ/ψ	$\Delta\eta_c$	$\Delta J/\psi$	S_{nn} S_{nc}	A_{nn} S_{nc}	S_{nn} A_{nc}	A_{nn} A_{nc}
$\frac{1}{2}\left(\frac{1}{2}^-\right)$	✓	✗		✗	✓	✗	✓	✗			✓	✓	✓	✓
$\frac{3}{2}\left(\frac{1}{2}^-\right)$	✓	✗		✗						✗			✓	✓
$\frac{1}{2}\left(\frac{3}{2}^-\right)$		✓	✓	✗		✓		✓				✓	✓	✓
$\frac{3}{2}\left(\frac{3}{2}^-\right)$		✓	✓	✗					✓	✗			✓	✓
$\frac{1}{2}\left(\frac{5}{2}^-\right)$				✓										✓
$\frac{3}{2}\left(\frac{5}{2}^-\right)$				✓						✗				✓

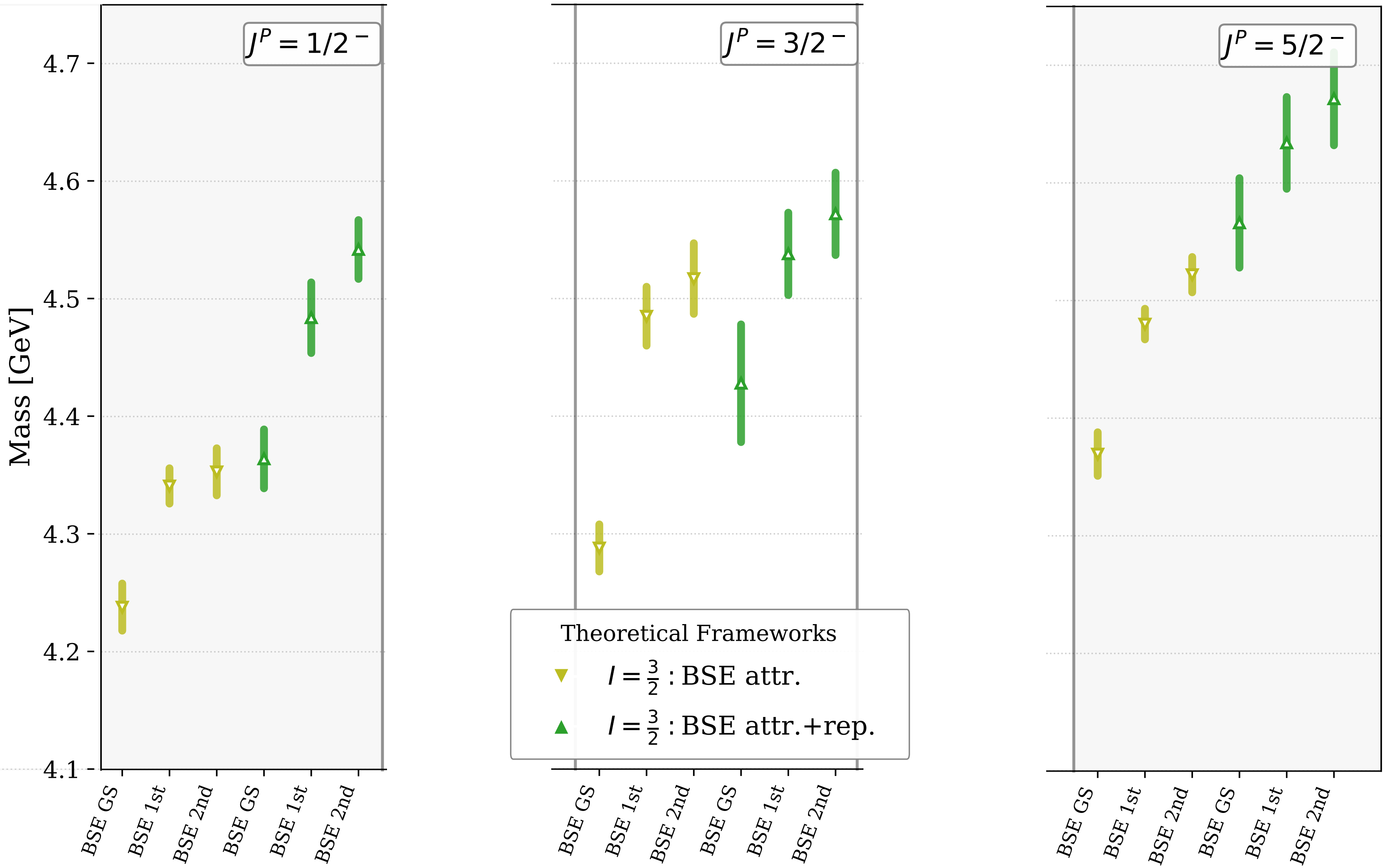
✓ States included in BSE

✗ Possible states but not included in BSE

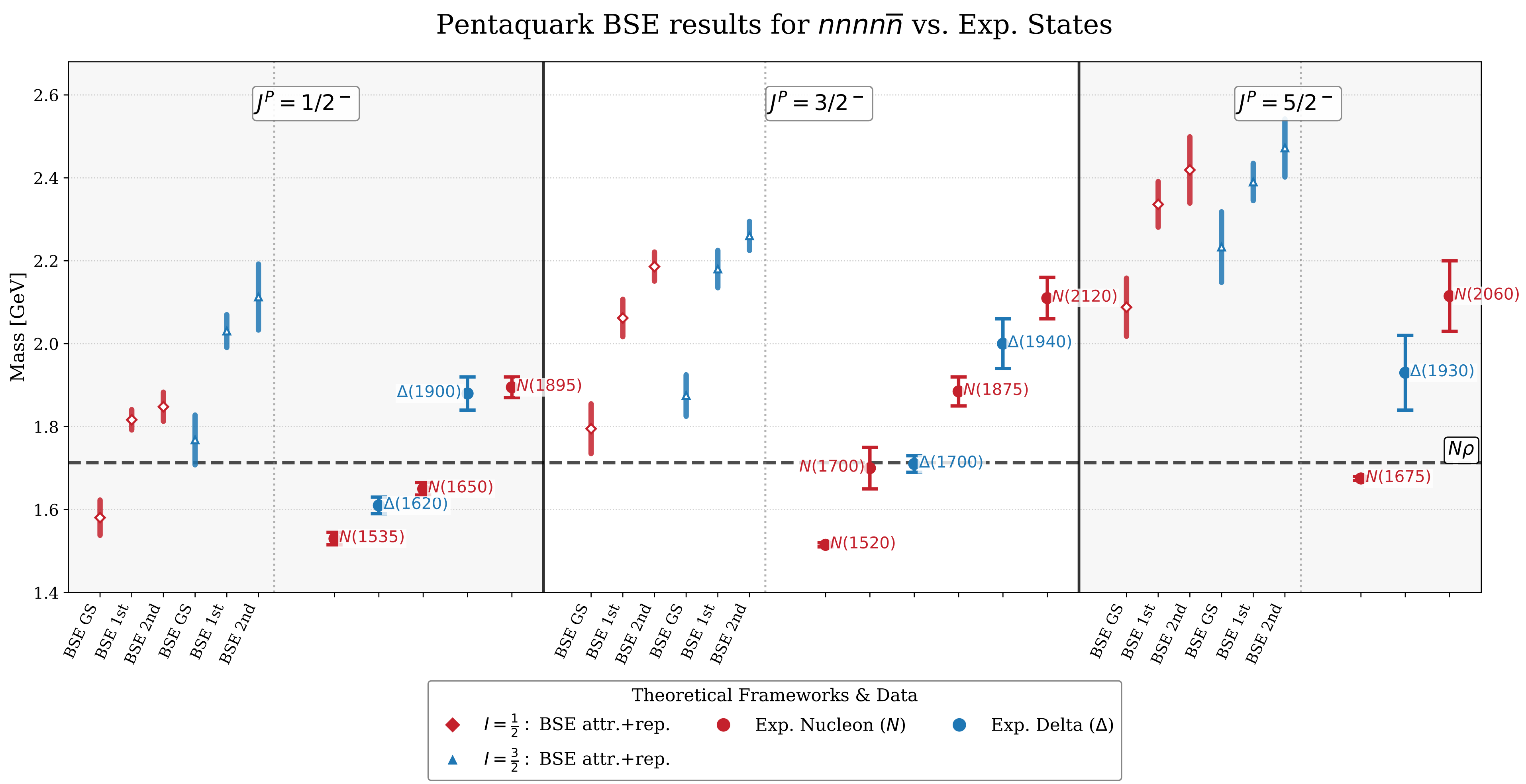
Pentaquarks $nnnc\bar{c}$ - preliminary



Pentaquarks $nnnc\bar{c}$ - preliminary



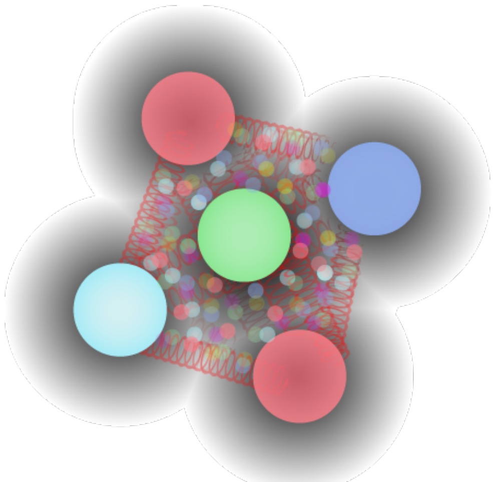
Pentaquarks $nnnn\bar{n}$ - preliminary

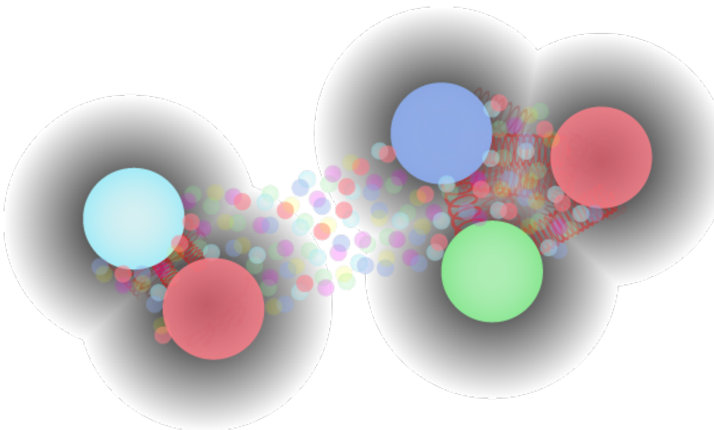


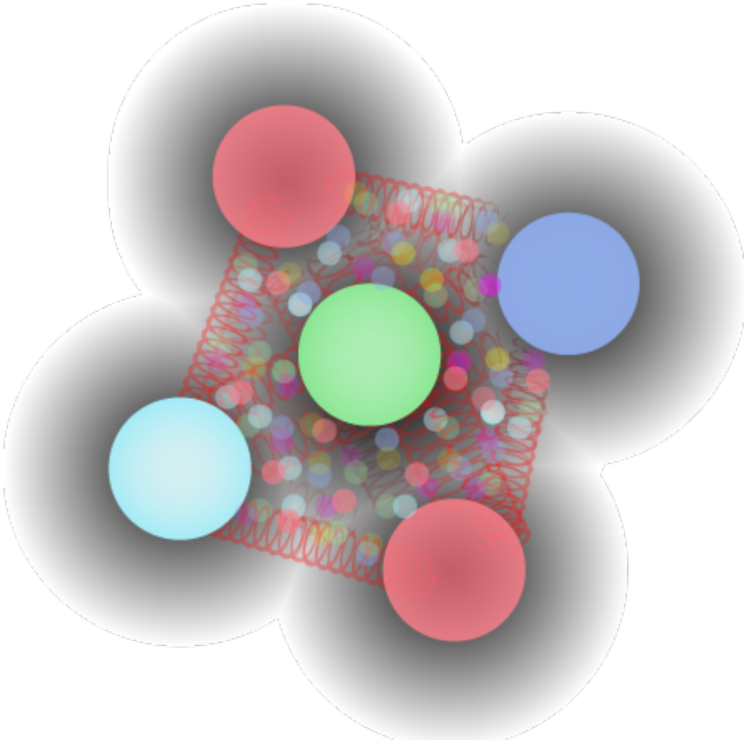
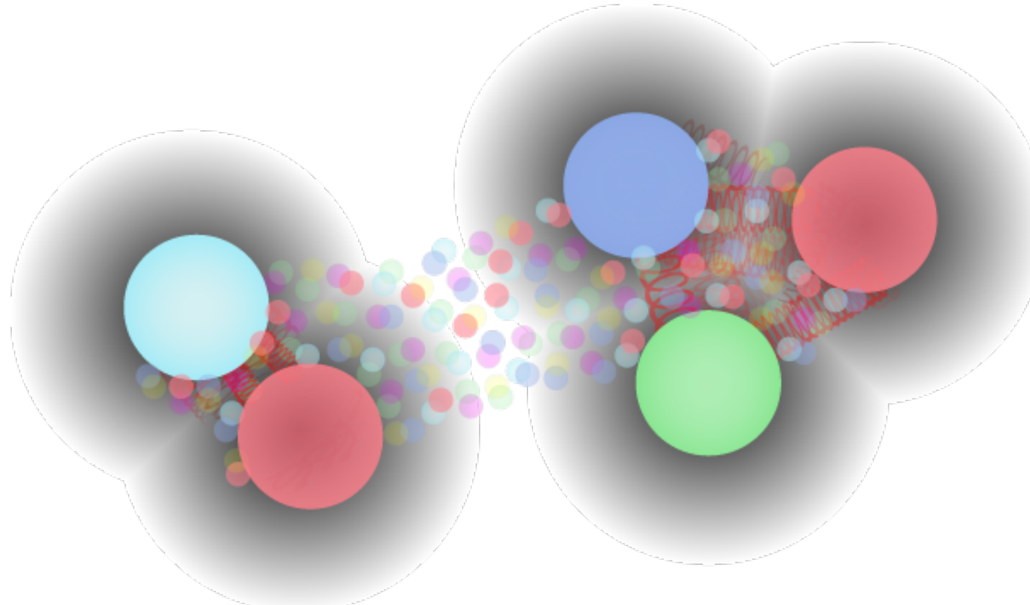
Conclusion and future

- **First calculation of five-body Bethe-Salpeter Equation in QCD.**
- **Assigned quantum numbers for P_c pentaquark candidates.**
- **Lightest pentaquark mass spectra.**

- **We can calculate the Heavy-light sector:** $nnsc\bar{c}$, $nssc\bar{c}$, $sssc\bar{c}$, etc.
- **We can calculate the Light sector:** $\Lambda(1405)$, Θ^+, $P_{c\bar{c}}$, etc.



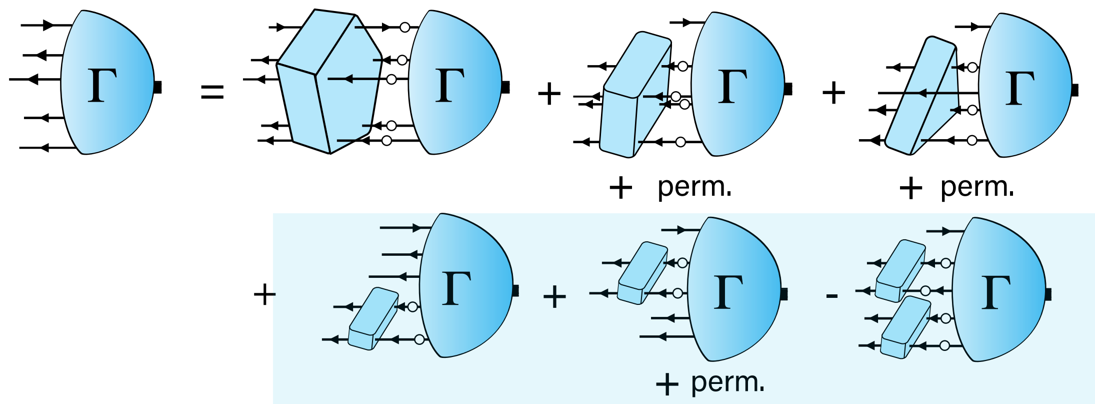


Thank you

Backup slides

Dirac basis



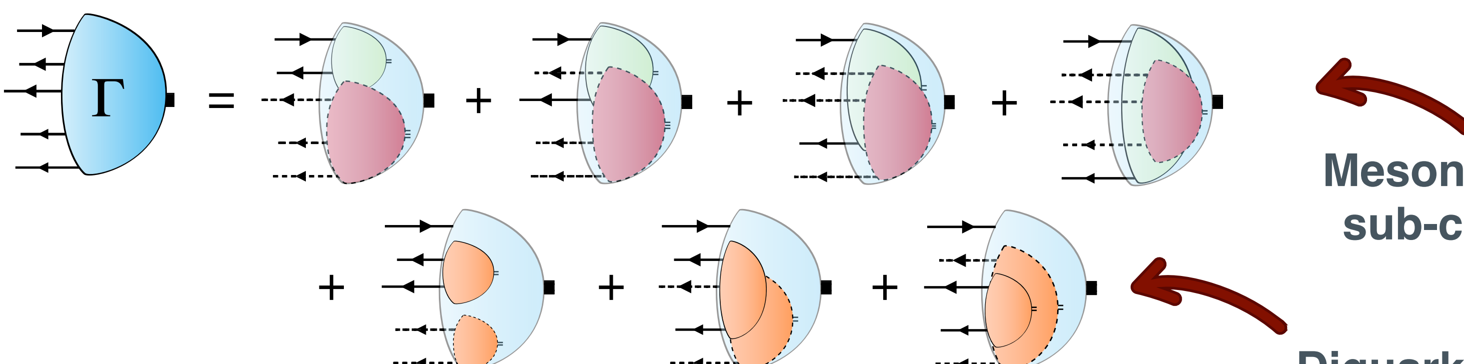
The Dirac basis elements

$$\tau_i^{(\mu\nu)}(p,k,q,l) = \Gamma_i^{(\mu\nu)}\Omega_\omega\Lambda_\lambda\gamma_5(C)\otimes\Gamma_j^{(\mu\nu)}\Omega_{\omega'}\Lambda_{\lambda'}\gamma_5(C)\otimes\Gamma_k^{(\mu\nu)}\Omega_{\omega''}\Lambda_{\lambda''}\gamma_5(C)$$

- $\Gamma_i, \Gamma_j, \Gamma_k \in \{\mathbf{1}, n_1^\mu\gamma^\mu, n_2^\mu\gamma^\mu, n_3^\mu\gamma^\mu, n_4^\mu\gamma^\mu\}$,
- n_i^μ the four orthonormal basis,
- $\Omega_\omega, \Omega_{\omega'}, \Omega_{\omega''} \in \{\mathbf{1}, \varepsilon\gamma_5\}$ with $\varepsilon \in \{-1,1\}$,
- Positive/negative energy projector $\Lambda_\pm = (\mathbf{1} \pm n_4^\mu)/2$
- $J = \dfrac{1}{2}$ contains 4096 Dirac tensor basis

Dirac basis

d	$J^P = 1/2^\lambda$	$J^P = 3/2^\lambda$	$J^P = 5/2^\lambda$
	Meson-Baryon Topology		
$\mathcal{M}$	$(\Lambda_\pm \gamma_5 C) \otimes \Lambda_+ \otimes (\gamma_5 \Omega_\lambda)$	$(\Lambda_\pm \gamma_5 C) \otimes \Lambda_+ \otimes (\gamma_\perp^\rho \Omega_\lambda)$	—
$\mathcal{M}$	$(\gamma_5 \gamma_\perp^\mu \Lambda_\pm \gamma_5 C) \otimes (\gamma_5 \gamma_\perp^\mu \Lambda_+) \otimes (\gamma_5 \Omega_\lambda)$	$(\gamma_5 \gamma_\perp^\nu \Lambda_\pm \gamma_5 C) \otimes (\gamma_5 \gamma_\perp^\nu \Lambda_+) \otimes (\gamma_\perp^\rho \Omega_\lambda)$	—
$\mathcal{M}$	—	$(\Lambda_\pm \gamma_\perp^\rho C) \otimes \Lambda_+ \otimes (\gamma_5 \Omega_\lambda)$	$(\Lambda_\pm \gamma_\perp^\rho C) \otimes \Lambda_+ \otimes (\gamma_\perp^\sigma \Omega_\lambda)$
	Diquark-Diquark-Antiquark Topology		
$\mathcal{D}$	$(\Lambda_\pm \gamma_5 C) \otimes (\Lambda_\pm \gamma_5 C) \otimes (\gamma_5 \Omega_\lambda)$	—	—
$\mathcal{D}$	$(\Lambda_\pm \gamma_5 C) \otimes (\Lambda_\pm C \gamma_\perp^\mu) \otimes (\gamma_\mu^\perp \Omega_\lambda)$	$(\Lambda_\pm \gamma_5 C) \otimes (\Lambda_\pm \gamma_\perp^\rho C) \otimes (\gamma_5 \Omega_\lambda)$	—
$\mathcal{D}$	$(\Lambda_\pm \gamma_\perp^\mu C) \otimes (\Lambda_\pm \gamma_\perp^\mu C) \otimes (\gamma_5 \Omega_\lambda)$	$\varepsilon_\perp^{\rho\mu\nu} (\Lambda_\pm \gamma_\perp^\mu C) \otimes (\Lambda_\pm \gamma_\perp^\nu C) \otimes (\gamma_5 \Omega_\lambda)$	$(\Lambda_\pm \gamma_\perp^\rho C) \otimes (\Lambda_\pm \gamma_\perp^\sigma C) \otimes \Omega_\lambda$



Meson-baryon sub-clusters

Diquark-diquark-Antiquark sub-clusters

Color basis

Meson-baryon clusters

$$\mathcal{M}_1^{\mathbf{1}}:\ [\Gamma_1^{\mathcal{C}}]_{ABCDE}=\frac{\varepsilon_{ABC}\,\delta_{DE}}{N_c\sqrt{(N_c-1)!}},\quad \mathcal{M}_2^{\mathbf{1}}:\ [\Gamma_2^{\mathcal{C}}]_{ABCDE}=\frac{\varepsilon_{ABD}\,\delta_{CE}}{N_c\sqrt{(N_c-1)!}},$$

$$\mathcal{M}_3^{\mathbf{1}}:\ [\Gamma_3^{\mathcal{C}}]_{ABCDE}=\frac{\varepsilon_{ADC}\,\delta_{BE}}{N_c\sqrt{(N_c-1)!}},\quad \mathcal{M}_4^{\mathbf{1}}:\ [\Gamma_4^{\mathcal{C}}]_{ABCDE}=\frac{\varepsilon_{DBC}\,\delta_{AE}}{N_c\sqrt{(N_c-1)!}}. \tag{4.50}$$

$$\mathcal{M}_1^{\mathbf{8}}:\ [\Gamma_5^{\mathcal{C}}]_{ABCDE}=\frac{N_c\Gamma_2^{\mathcal{C}}-\Gamma_1^{\mathcal{C}}}{\sqrt{N_c^2-1}},\quad \mathcal{M}_2^{\mathbf{8}}:\ [\Gamma_6^{\mathcal{C}}]_{ABCDE}=\frac{N_c\Gamma_1^{\mathcal{C}}-\Gamma_2^{\mathcal{C}}}{\sqrt{N_c^2-1}},$$

$$\mathcal{M}_3^{\mathbf{8}}:\ [\Gamma_7^{\mathcal{C}}]_{ABCDE}=\frac{N_c\Gamma_1^{\mathcal{C}}-\Gamma_3^{\mathcal{C}}}{\sqrt{N_c^2-1}},\quad \mathcal{M}_4^{\mathbf{8}}:\ [\Gamma_8^{\mathcal{C}}]_{ABCDE}=\frac{N_c\Gamma_1^{\mathcal{C}}-\Gamma_4^{\mathcal{C}}}{\sqrt{N_c^2-1}}, \tag{4.52}$$

$$\mathcal{M}_1^{\mathbf{8'}}:\ [\Gamma_9^{\mathcal{C}}]_{ABCDE}=\frac{N_c\Gamma_3^{\mathcal{C}}-\Gamma_1^{\mathcal{C}}}{\sqrt{N_c^2-1}},\quad \mathcal{M}_2^{\mathbf{8'}}:\ [\Gamma_{10}^{\mathcal{C}}]_{ABCDE}=\frac{N_c\Gamma_3^{\mathcal{C}}+\Gamma_2^{\mathcal{C}}}{\sqrt{N_c^2-1}},$$

$$\mathcal{M}_3^{\mathbf{8'}}:\ [\Gamma_{11}^{\mathcal{C}}]_{ABCDE}=\frac{N_c\Gamma_2^{\mathcal{C}}+\Gamma_3^{\mathcal{C}}}{\sqrt{N_c^2-1}},\quad \mathcal{M}_4^{\mathbf{8'}}:\ [\Gamma_{12}^{\mathcal{C}}]_{ABCDE}=\frac{N_c\Gamma_2^{\mathcal{C}}+\Gamma_4^{\mathcal{C}}}{\sqrt{N_c^2-1}}, \tag{4.53}$$

Color basis

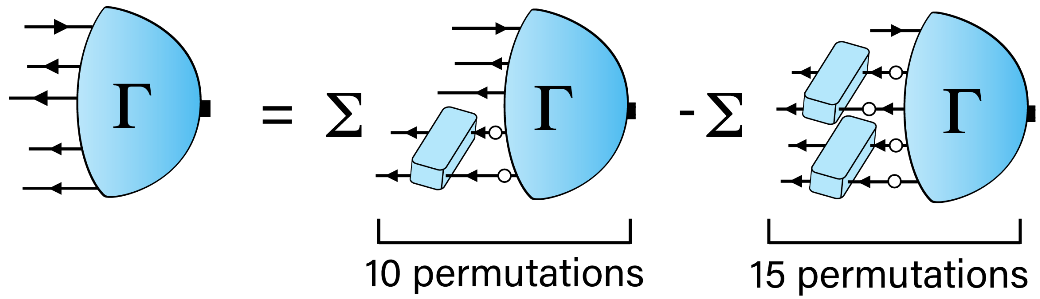
Diquark-Diquark-antiquark clusters

$$\mathcal{D}_1^{\overline{\mathbf{33}}}:\ [\Gamma_{13}^{\mathcal{C}}]_{ABCDE}=\frac{\Gamma_1^{\mathcal{C}}-\Gamma_2^{\mathcal{C}}}{\sqrt{2-\frac{2}{N_c}}},\quad \mathcal{D}_2^{\overline{\mathbf{33}}}:\ [\Gamma_{14}^{\mathcal{C}}]_{ABCDE}=\frac{\Gamma_1^{\mathcal{C}}-\Gamma_3^{\mathcal{C}}}{\sqrt{2-\frac{2}{N_c}}},$$
$$\mathcal{D}_3^{\overline{\mathbf{33}}}:\ [\Gamma_{15}^{\mathcal{C}}]_{ABCDE}=\frac{\Gamma_1^{\mathcal{C}}-\Gamma_4^{\mathcal{C}}}{\sqrt{2-\frac{2}{N_c}}}. \tag{4.54}$$

$$\mathcal{D}_1^{\overline{\mathbf{3}}\mathbf{6}}:\ [\Gamma_{16}^{\mathcal{C}}]_{ABCDE}=\frac{\Gamma_3^{\mathcal{C}}-\Gamma_4^{\mathcal{C}}}{\sqrt{2+\frac{2}{N_c}}},\quad \mathcal{D}_2^{\overline{\mathbf{3}}\mathbf{6}}:\ [\Gamma_{17}^{\mathcal{C}}]_{ABCDE}=\frac{\Gamma_2^{\mathcal{C}}-\Gamma_4^{\mathcal{C}}}{\sqrt{2+\frac{2}{N_c}}},$$
$$\mathcal{D}_3^{\overline{\mathbf{3}}\mathbf{6}}:\ [\Gamma_{18}^{\mathcal{C}}]_{ABCDE}=\frac{\Gamma_1^{\mathcal{C}}+\Gamma_4^{\mathcal{C}}}{\sqrt{2+\frac{2}{N_c}}}, \tag{4.55}$$

$$\mathcal{D}_1^{\mathbf{6}\overline{\mathbf{3}}}:\ [\Gamma_{19}^{\mathcal{C}}]_{ABCDE}=\frac{\Gamma_1^{\mathcal{C}}+\Gamma_2^{\mathcal{C}}}{\sqrt{2+\frac{2}{N_c}}},\quad \mathcal{D}_2^{\mathbf{6}\overline{\mathbf{3}}}:\ [\Gamma_{20}^{\mathcal{C}}]_{ABCDE}=\frac{\Gamma_1^{\mathcal{C}}+\Gamma_3^{\mathcal{C}}}{\sqrt{2+\frac{2}{N_c}}},$$
$$\mathcal{D}_3^{\mathbf{6}\overline{\mathbf{3}}}:\ [\Gamma_{21}^{\mathcal{C}}]_{ABCDE}=\frac{\Gamma_2^{\mathcal{C}}-\Gamma_3^{\mathcal{C}}}{\sqrt{2+\frac{2}{N_c}}}. \tag{4.56}$$

Explicit BSE



$$\Gamma(\{p_i\},P)_{\mathcal{A}_1\mathcal{A}_2\mathcal{A}_3\mathcal{A}_4\mathcal{A}_5} = \sum_{a}^{10} \Gamma_{(a),\mathcal{A}_{(a)}}(\{p_i\},P) - \sum_{a\neq b}^{15} \Gamma_{(a,b),\mathcal{A}_{(a)}\mathcal{A}_{(b)}}(\{p_i\},P),$$

Where

$$\Gamma_{(a),\mathcal{A}_{(a)}}(\{p_i\};P) = \int \frac{\mathrm{d}^4 r}{(2\pi)^4} \left[K(p_{a_1},k_{a_1},p_{a_2},k_{a_2};P)\right]^{\mathcal{A}_{a_1}\mathcal{A}_{a_2}}_{\mathcal{A}'_{a_1}\mathcal{A}'_{a_2}}$$
$$\{S^{(\lambda_{a_1})}_{\mathcal{A}'_{a_1}\mathcal{A}''_{a_1}}(k_{a_1})\Gamma_{\mathcal{A}_1\ldots\mathcal{A}''_{a_1}\ldots\mathcal{A}''_{a_2}\ldots\mathcal{A}_n}(p_1,\ldots,k_{a_1},\ldots,k_{a_2},\ldots,p_5;P)S^{(\lambda_{a_2})}_{\mathcal{A}'_{a_2}\mathcal{A}''_{a_2}}(k_{a_2})\}$$
$$\Gamma_{(a,b),\mathcal{A}_{(a)}}(\{p_i\};P) = \int \frac{\mathrm{d}^4 r}{(2\pi)^4} \left[K(p_{a_1},k_{a_1},p_{a_2},k_{a_2};P)\right]^{\mathcal{A}_{a_1}\mathcal{A}_{a_2}}_{\mathcal{A}'_{a_1}\mathcal{A}'_{a_2}} \tag{4.6}$$
$$\{S^{(\lambda_{a_1})}_{\mathcal{A}'_{a_1}\mathcal{A}''_{a_1}}(k_{a_1})\Gamma_{(b),\mathcal{A}_1\ldots\mathcal{A}''_{a_1}\ldots\mathcal{A}''_{a_2}\ldots\mathcal{A}_5}(p_1,\ldots,k_{a_1},\ldots,k_{a_2},\ldots,p_5;P)S^{(\lambda_{a_2})}_{\mathcal{A}'_{a_2}\mathcal{A}''_{a_2}}(k_{a_2})\},$$