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pΩ Bound State via the Pomeron Exchange Model

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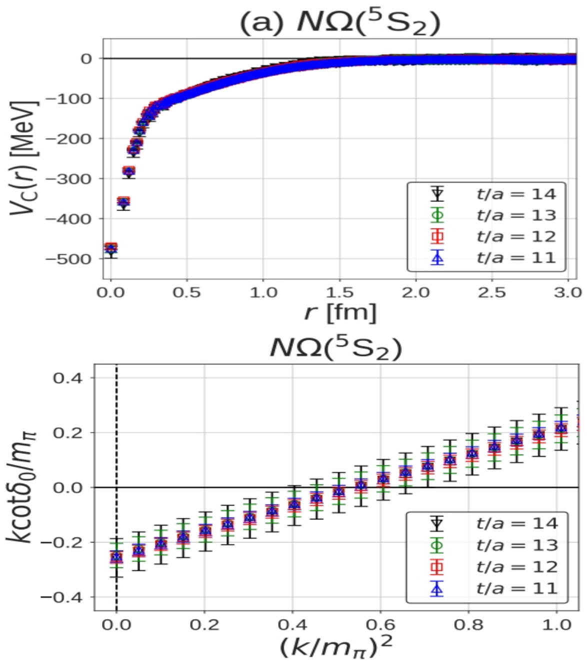
Outline

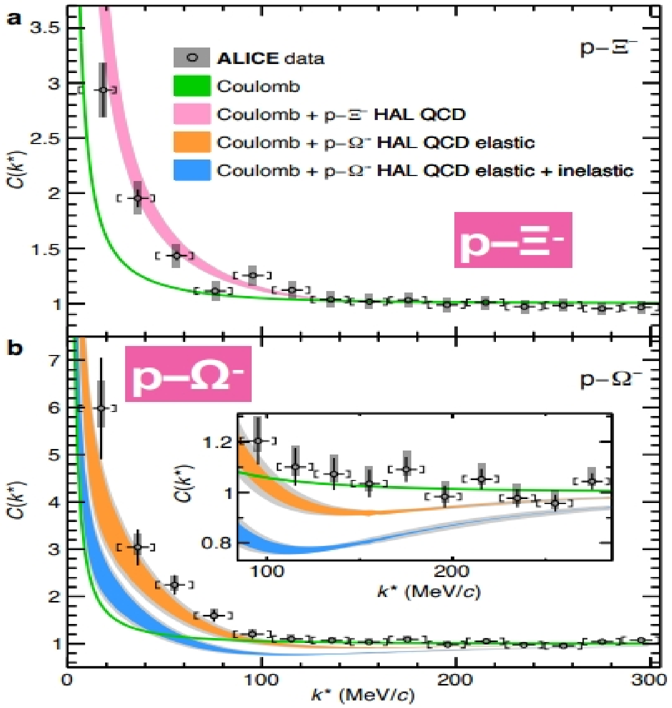
- **Background and motivation**
- **Framework**
- **Results**
- **Summary**

1. Background and motivation

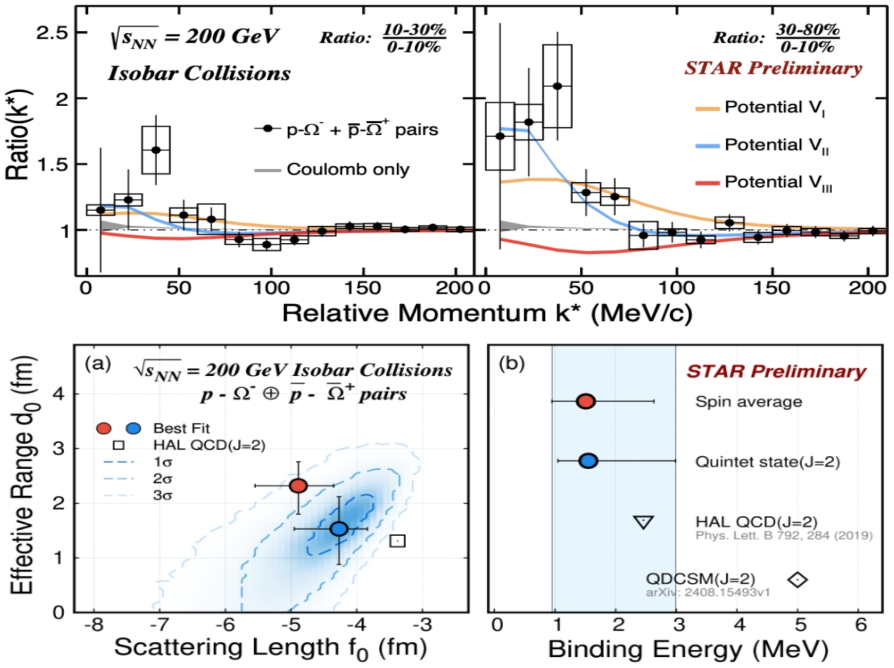
Some results from experiment and lattice



HAL QCD Collaboration, *Phys.Lett.B*,792 (2019) 284-289



ALICE, *Nature Physics* 588 (2020) 232



STAR Collaboration, *arxiv* 2512.09452

- Potential is attractive at all distance.
- A quasi-bound state with

$$a_0 = 5.30(0.44)^{+0.16}_{-0.01}\ \text{fm},$$
$$r_{\text{eff}} = 1.26(0.01)^{+0.02}_{-0.01}\ \text{fm},$$
$$B = 1.54(0.30)^{+0.04}_{-0.10}\ \text{MeV},$$
$$\sqrt{\langle r^2\rangle} = 3.77(0.31)^{+0.11}_{-0.01}\ \text{fm}.$$

- p-Ω bound state is not observed in data.

- First experimental evidence of Strange Dibaryon.

- Calculated BE are consistent with HAL QCD prediction.

Theoretical works

$N\Omega$ interaction: meson exchanges, inelastic channels, and quasibound state

Takayasu Sekihara,[1,*] Yuki Kamiya,[2,†] and Tetsuo Hyodo[2,‡]

[1] *Advanced Science Research Center, Japan Atomic Energy Agency, Shirakata, Tokai, Ibaraki, 319-1195, Japan*
[2] *Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan*

(Dated: May 11, 2018)

Based on a baryon–baryon interaction model with meson exchanges, we investigate the origin of the strong attraction in the $N\Omega(^5S_2)$ interaction, which was indicated by recent lattice QCD simulations. The long range part of the potential is constructed by the conventional mechanisms, the exchanges of the η meson and of the correlated two mesons in the scalar-isoscalar channel, denoted by "σ" in the literature. The short range part is represented by the contact interaction. We find that the meson exchanges do not provide sufficient attraction. This means that most of the attraction is attributed to the short range contact interaction. We then evaluate the effect of

To reproduce the HAL QCD results, T. Sekihara et al introduced **contact term**:

$$V_C = -cF(q)^2 \bar{u}_N(\boldsymbol{p}', \lambda'_N) u_N(\boldsymbol{p}, \lambda_N) \times \bar{u}_{\Omega\mu}(-\boldsymbol{p}', \lambda'_\Omega) u^{\mu}_{\Omega}(-\boldsymbol{p}, \lambda_\Omega).$$

What is the dynamical origin of the extra contact term?

- Quark model

J.T. Goldman et al, *Phys.Rev.Lett.* 59 (1987) 627

M. Oka, *Phys.Rev.D* 38 (1988) 298

Q.B. Li and P.N. Shen, *Eur.Phys.J.A* 8 (2000) 417-421

H.R. Pang et al, *Phys.Rev.C* 69 (2004) 065207

M. Chen, H.X. Huang, J.L. Ping and F. Wang, *Phys.Rev.C* 83 (2011) 015202

H.X. Huang, J.L. Ping and F. Wang, *Phys.Rev.C* 92 (2015) 065202

T. Sekihara and T. Hashiguchi, *Phys.Rev.C* 108 (2023) 6, 065202

…

- Femtoscopic correlation functions

K. Morita, A. Ohnishi, F. Etminan and T. Hatsuda, *Phys.Rev.C* 94 (2016) 3, 031901

M. Piquer i Méndez, A. Parreño García and J. Torres-Rincon, *arxiv*:2409.16747

Y. Yan et al, *Sci.China Phys.Mech.Astron.* 68 (2025) 3, 232012

- QCD sum rule

X.H. Chen, Q.N. Wang, W. Chen, and H.X. Chen, *Phys.Rev.D* 103 (2021) 9, 094011

- Effective field theory

J. Haidenbauer et al, *Eur.Phys.J.C* 77 (2017) 11, 760

T. Sekihara, Y. Kamiya and T. Hyodo, *Phys.Rev.C* 98(2018) 1,015205

2. Framework

Pomeron exchange model

- Pomeoron (vacuum quantum number 0^{++}) Dominates high-energy hadron collisions and the diffractive behavior of vector meson photoproduction on nucleons.
- Regge condition: high s, small $|t| \sim s \gg |t|$
- Pomeron-photon analogy: Pomeron couples with a quark in hadron like a photon with $J^{PC} = 1^{-+}$.
- For A + B → A + B scattering at high s :

P.V. Landshoff, J.C. Polkinghorne, *Nucl. Phys. B* **32**, 541 (1971)
G.A. Jaroszkiewicz, P.V. Landshoff, *Phys. Rev. D* **10**, 170 (1974)
A. Donnachie and P. V. Landshoff, *Nucl. Phys. B* 244 (1984) 322.
A. Donnachie and P. V. Landshoff, *Phys. Lett. B* 185 (1987) 403.
Q. Zhao, J. P. Didelez, M. Guidal and B. Saghai, *Nucl. Phys. A* 660, 323-347 (1999)
T.-S.H. Lee, S. Sakinah, Yongseok Oh, *Eur.Phys.J.A* 58 (2022) 12, 252.
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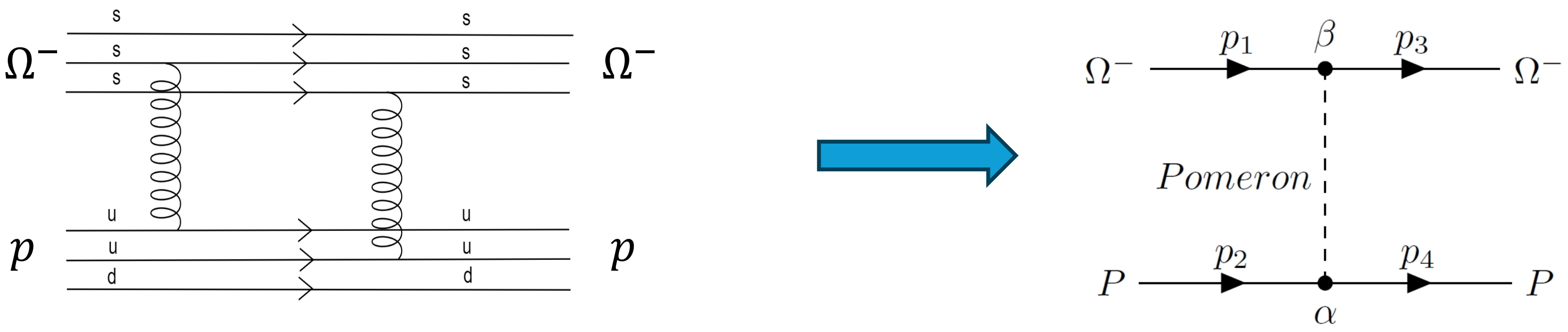
$$T(s,t) = \left[\beta_{q_A} n_A F_A(t)\right]\left[\beta_{q_B} n_B F_B(t)\right] \frac{e^{-i\frac{\pi}{2}(\alpha_p(t)-1)}}{2\sin\left(\frac{\pi}{2}\alpha_p(t)\right)} \times (\alpha_{1,p} s)^{\alpha_p(t)}$$

$$\alpha_p(t) = \alpha_{0,p} + \alpha_{1,p} t = 1.08 + 0.25t$$



$$\mathcal{M}_{\Omega N} = i\bar{u}^{\mu}(\vec{p}',\lambda_3)\left[3\beta_s\left(F_1^*(t)g_{\mu\nu} + F_3^*(t)\frac{q_\mu q_\nu}{4M_\Omega^2}\right)\right]\gamma_\beta u^{\nu}(\vec{p},\lambda_1)\bar{u}(-\vec{p}',\lambda_4)\left[3\beta_{u/d}f_1(t)\right]\gamma^{\beta}u(-\vec{p},\lambda_2)G_p(t)$$

$$\beta_{u/d} = 2.07GeV^{-1}, \quad \beta_s = 1.38GeV^{-1}$$

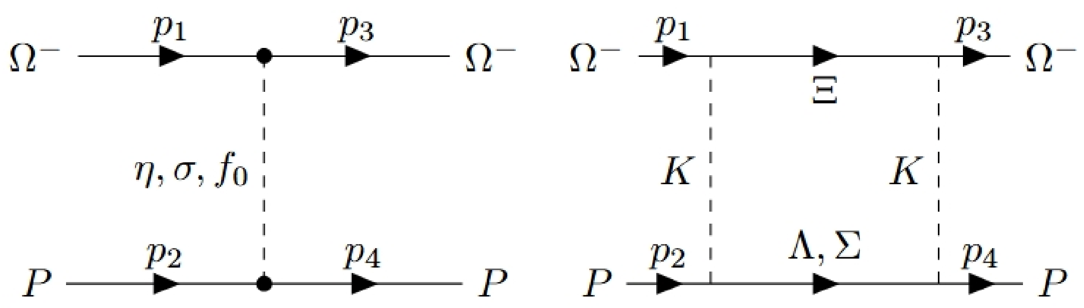
Couplings are obtained by fitting the data of vector meson photoproduction.

$$F_1 = \frac{-1}{(1+\frac{Q^2}{\Lambda^2})^2}, F_3 = \frac{-3.36}{(1+\frac{Q^2}{\Lambda^2})^3}$$

G. Ramalho. *Phys. Rev. D*, 103(7):074018 (2021).
G. Ramalho and M. T. Pena. *Phys. Rev. D*, 83:054011(2011).

2. Framework

One boson exchange model



(b) One meson exchange (c) Box-loop diagram

Isospin conservation ⟶ Only isoscalar neutral meson

Ideal mixing of ϕ and ω ⟶ OZI suppressed

The leading effective Lagrangian based on chiral symmetry and SU(3) flavor symmetry:

$$\mathcal{L}_{PBB} = \frac{D}{2}\left\langle \bar{B}\gamma^\mu\gamma_5\{u_\mu, B\}\right\rangle + \frac{F}{2}\left\langle \bar{B}\gamma^\mu\gamma_5[u_\mu, B]\right\rangle$$

$$\mathcal{L}_{PBD} = -\frac{f_{PBD}}{m_\pi}\left\langle (\bar{T}_\mu \cdot \partial^\mu\Phi)B + h.c.\right\rangle$$

$$\mathcal{L}_{PDD} = -\frac{f_{PDD}}{m_\pi}\left\langle (\bar{T}^\mu \cdot \gamma^\nu\gamma^5 T_\mu)\partial_\nu\Phi\right\rangle$$

$$\mathcal{L}_{\sigma NN} = -g_{\sigma NN}\sigma(p\bar{p} + n\bar{n})$$

$$\mathcal{L}_{f_0 NN} = -g_{f_0 NN} f_0(p\bar{p} + n\bar{n})$$

$$\mathcal{L}_{\sigma\Omega\Omega} = +g_{\sigma\Omega\Omega}\Omega^-\bar{\Omega}^+\sigma$$

$$\mathcal{L}_{f_0\Omega\Omega} = +g_{f_0\Omega\Omega}\Omega^-\bar{\Omega}^+ f_0.$$

All coupling constants are taken from references or extracted via SU(3) symmetry.

$$\mathcal{B} = \begin{pmatrix} \frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & \Sigma^+ & p \\ \Sigma^- & -\frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & n \\ \Xi^- & \Xi^0 & -\frac{2}{\sqrt{6}}\Lambda \end{pmatrix} \qquad \Phi = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta \end{pmatrix}$$

$$T^{111} = \Delta^{++}, \quad T^{112} = \frac{1}{\sqrt{3}}\Delta^+, \; T^{113} = \frac{1}{\sqrt{3}}\Sigma^{*+},$$

$$T^{122} = \frac{1}{\sqrt{3}}\Delta^0, \; T^{123} = \frac{1}{\sqrt{6}}\Sigma^{*0}, \; T^{133} = \frac{1}{\sqrt{3}}\Xi^{*0},$$

$$T^{222} = \Delta^-, \quad T^{223} = \frac{1}{\sqrt{3}}\Sigma^{*-}, \; T^{233} = \frac{1}{\sqrt{3}}\Xi^{*-},$$

$$T^{333} = \Omega^-.$$

Formfactor: $F(q^2, \Lambda_m) = \frac{\Lambda_m^2}{\Lambda_m^2 + |q^2|}$, $\Lambda_m = 0.8\text{GeV}$ fixed as a typical scale.

Avoid singularities in the unphysical kinematic region: $|q^2| = -q^2$

T. A. Rijken, M.M. Nagels, Y. Yamamoto, *Prog.Theor.Phys.Suppl.* 185 (2010) 14-71

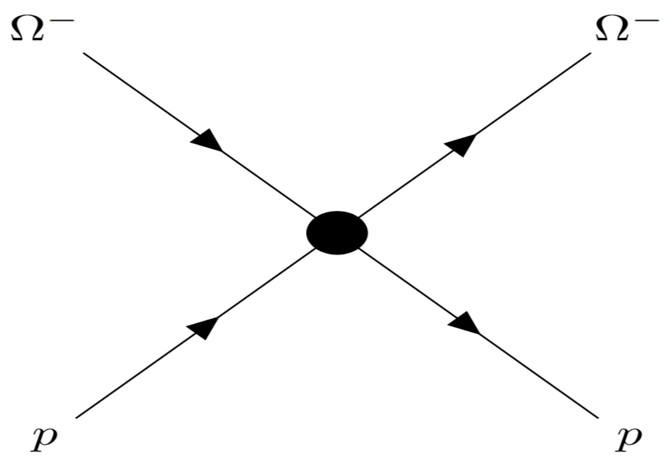
T. Sekihara, Y. Kamiya and T. Hyodo, *Phys.Rev.C* 98(2018) 1,015205

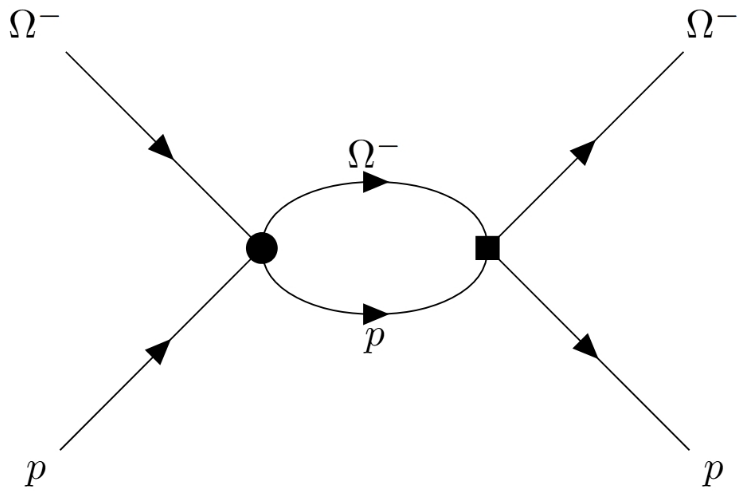
B. Wu, X.H. Cao, X.K. Dong and F.K. Guo, *Phys.Rev.D* 109.3(2024).

L.L. Lopes, K.D. Marquez and D.P. Menezes, *Phys.Rev.D* **107**, (2023) 036011

2. Framework

The scattering amplitude and transition matrix T





The leading-order scattering amplitude:

$$\mathcal{M} = \mathcal{M}^{\mathrm{OBE}} + \mathcal{M}^{\mathrm{Loop}} + \mathcal{M}^{\mathrm{Pom}}$$

The non-relativistic interaction potential:

$$\mathrm{V}_{\mathrm{fi}} = -\frac{\mathcal{M}_{\mathrm{fi}}}{\sqrt{\prod_{\mathrm{f}} E_{\mathrm{f}}/m_{\mathrm{f}} \prod_{\mathrm{i}} E_{\mathrm{i}}/m_{\mathrm{i}}}}.$$

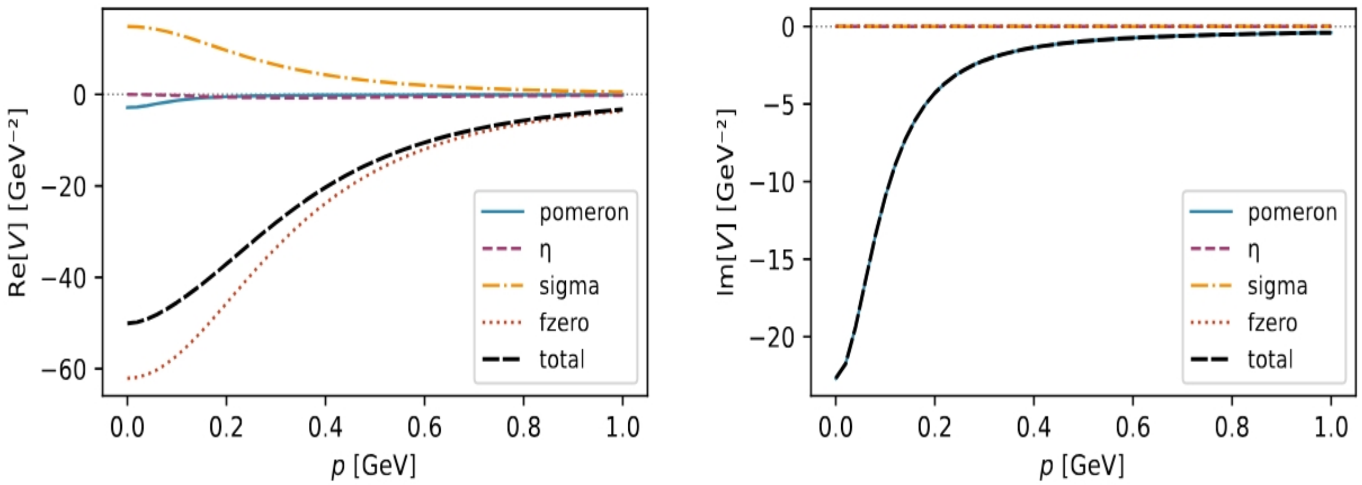
The transition matrix of p$\Omega \to$ pΩ is obtained with the LS equation:

$$T(E;p',p) = V(E;p',p) + \int_0^\infty \frac{\mathrm{d}^3\vec{p}''}{(2\pi)^3} \frac{V(E;p',p'')T(E;p'',p)}{E - \epsilon - \frac{p''^2}{2\mu} + i\varepsilon}$$

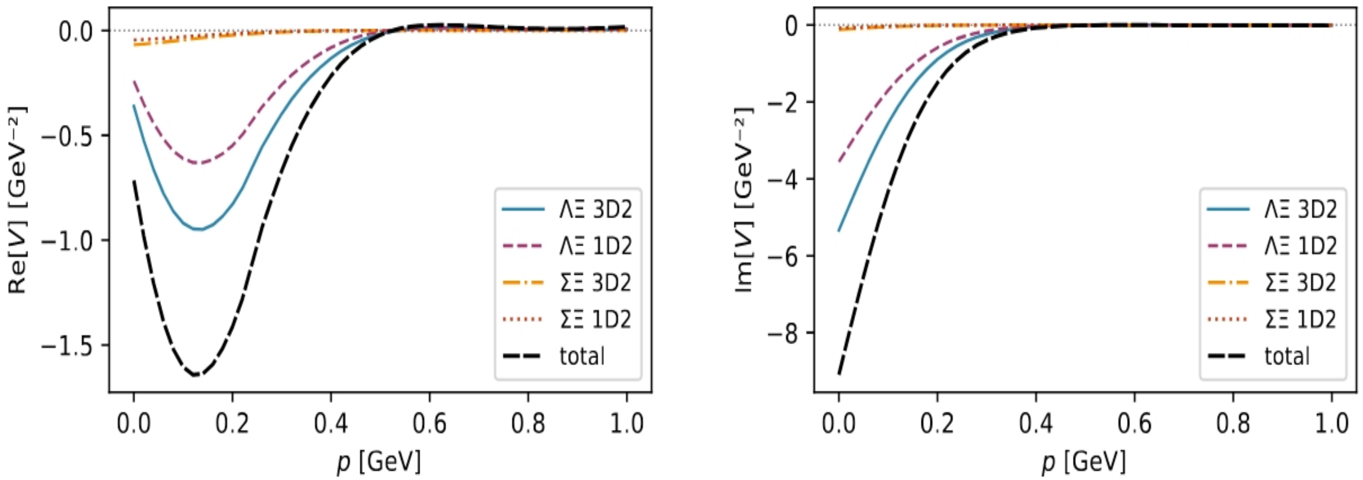
The only free parameter is Λ in the Pomeron exchange potential.

3. Results

The interaction potential of $p\Omega^-({}^5S_2)$



(a)

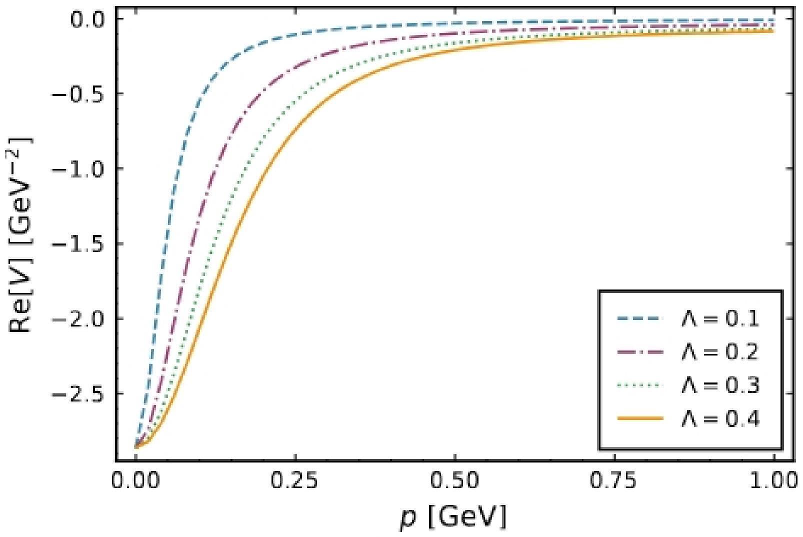


(b)

- The Pomeron exchange contributes mainly to the **imaginary part** of the interaction potential, and its contribution is **comparable** to that of the conventional meson exchange.
- The absorption effects from open channels are relatively **weak**.

3. Results

Behavior of Pomeron potential under different cut-off



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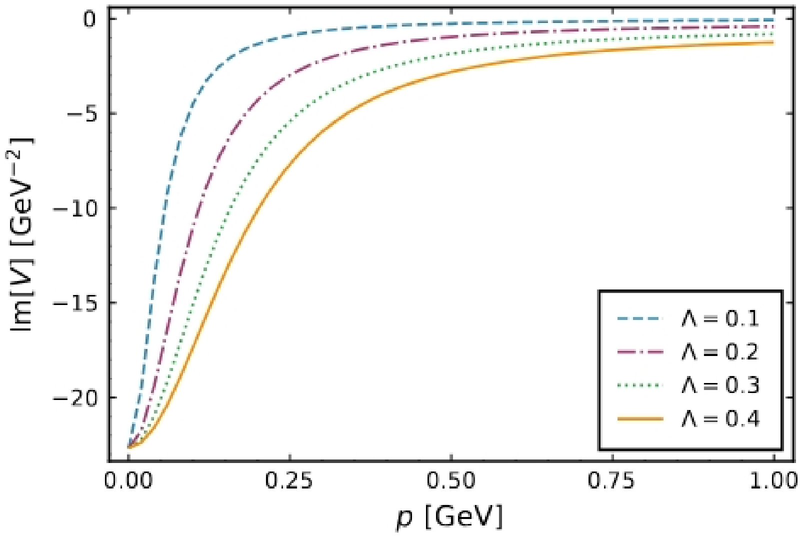


(b)

- Pomeron is required to satisfy the Regge condition $s \gg |t|$

$|t| \propto p^2$ in the two-body c.m. frame

→ The Pomeron exchange is expected to be suppressed at kinematics far from the threshold (long-distance attractive interaction)

→
- The suppression becomes stronger with decreasing Λ, in better agreement with the Regge condition approximation.

3. Results

The scattering length, effective range and compositeness

Non-relativistic scattering amplitude: $f_s = -\frac{\mu}{2\pi} T(E;k,k)$

Effective-Range-Expansion: $f_s(k)^{-1} = -\frac{1}{a} - ik + \frac{1}{2} r_{\text{eff}} k^2 + \mathcal{O}(k^4)$

Scattering length: $a_0 = -f_s(k=0)$

Effective range: $r_{\text{eff}} = [\frac{d^2 f_s^{-1}}{dk^2}]_{k=0}$

Compositeness: $\bar{X} = \frac{1}{\sqrt{1 + \left|\frac{2r_{\text{eff}}}{a_0}\right|}}$

$\bar{X} \to 1$ (predominantly molecular)

$\bar{X} \to 0$ (predominantly compact)

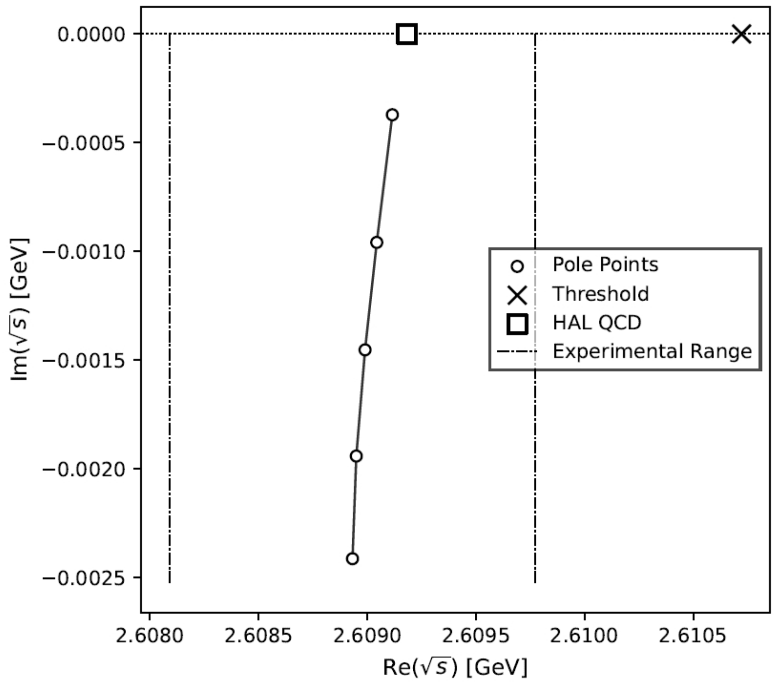
	Λ_p=0	Λ_p=0.1	Λ_p=0.15	Λ_p=0.2	Λ_p=0.25	Spin ave	Quintet	HAL QCD
$\boldsymbol{a_0}$(fm)	$6.99 - 1.06i$	$5.76 - 2.39i$	$4.87 - 2.49i$	$4.11 - 2.47i$	$3.52 - 2.40i$	$4.89^{+0.66}_{-0.54}$	$4.27^{+0.68}_{-0.43}$	$5.30^{+0.16}_{-0.01}$
$\boldsymbol{r}$(fm)	$0.99 + 0.22i$	$1.01 + 0.08i$	$1.18 + 0.25i$	$1.26 + 0.30i$	$1.28 + 0.29i$	$2.32^{+0.44}_{-0.52}$	$1.53^{+0.54}_{-0.66}$	$1.26^{+0.02}_{-0.01}$
$\bar{X}$	0.88	0.87	0.83	0.81	0.79	$0.72^{+0.06}_{-0.06}$	$0.76^{+0.1}_{-0.07}$	$0.82^{+0.01}_{-0.00}$

- $\boldsymbol{a_0}$ and $\boldsymbol{r}$ agree well with experimental and lattice data near $\Lambda_p = 0.15$ GeV.
- Pomeron exchange and coupled-channel absorption produce a large imaginary part.
- Considerable molecular-state component

I. Matuschek, V. Baru, F. K Guo and C. Hanhart, *Eur.Phys.J.A* 57 (2021) 3, 101

V. Baru, X. K. Dong, M. L. Du, A. Filin, F. K. Guo,C. Hanhart, A. Nefediev, J. Nieves and Q. Wang, *Phys. Lett. B* 833,137290

Poles trajectories on the complex energy plane



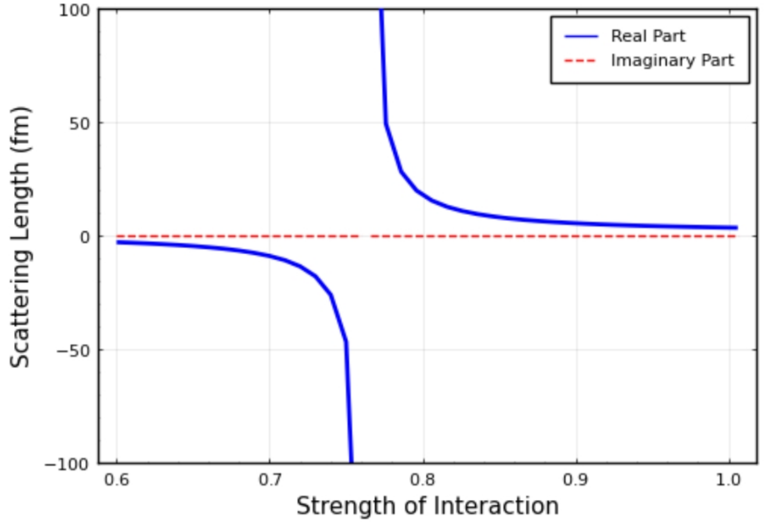
- Bound state: pole below threshold on real axis of the first Riemann sheet of complex energy plane
- The binding energy is also consistent with experimental and lattice results.
- Without the Pomeron, the BE, a_0 and r_{eff} fail to match experimental and lattice data simultaneously.

	Λ_p=0	Λ_p=0.1	Λ_p=0.15	Λ_p=0.2	Λ_p=0.25	Spin ave	Quintet	HAL QCD
Re(B)(MeV)	1.61	1.68	1.73	1.77	1.79	$1.51^{+1.12}_{-0.56}$	$1.55^{+1.44}_{-0.50}$	$1.54^{+0.04}_{-0.10}$

3. Results

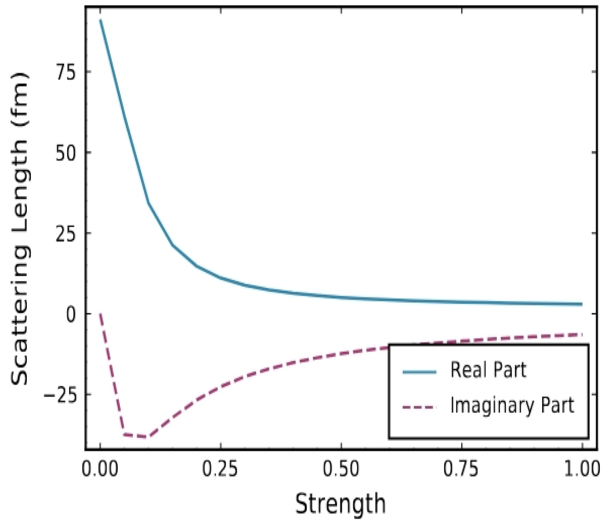
Impact of Pomeron strength on pole properties

Only consider scalar potential $V = V_s$:

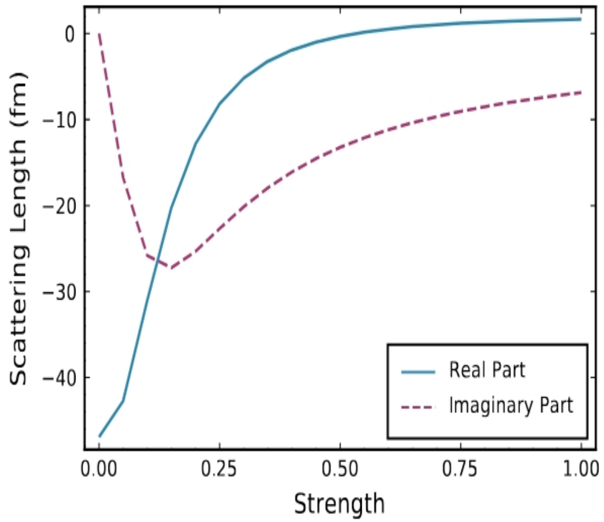


- a_0 (only V_s) is positive: Pomeron provides an extra attractive interaction that reduces the scattering length
- a_0 (only V_s) is negative: the scattering length crosses the x-axis and transitions from negative to positive values.
- The Pomeron makes the pole structure become more compact.

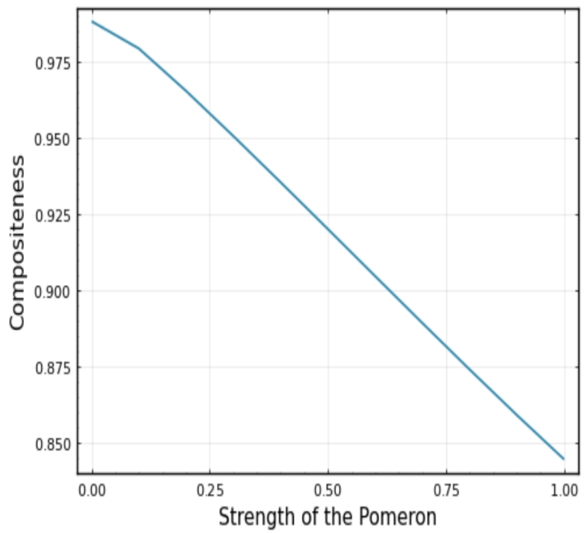
Scalar potential plus Pomeron potential $V = V_s + V_P$:

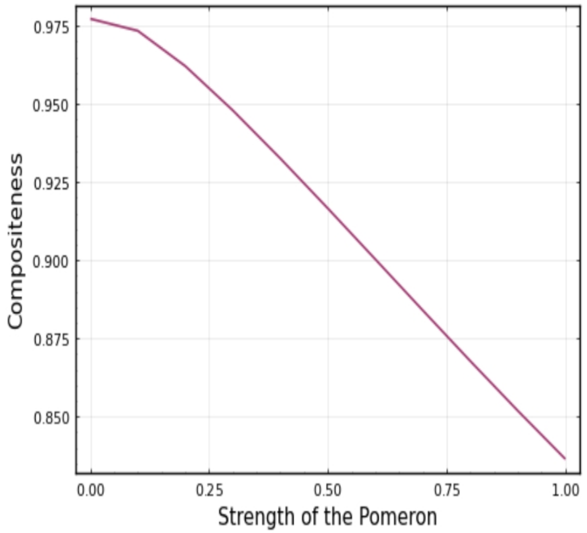


(a)



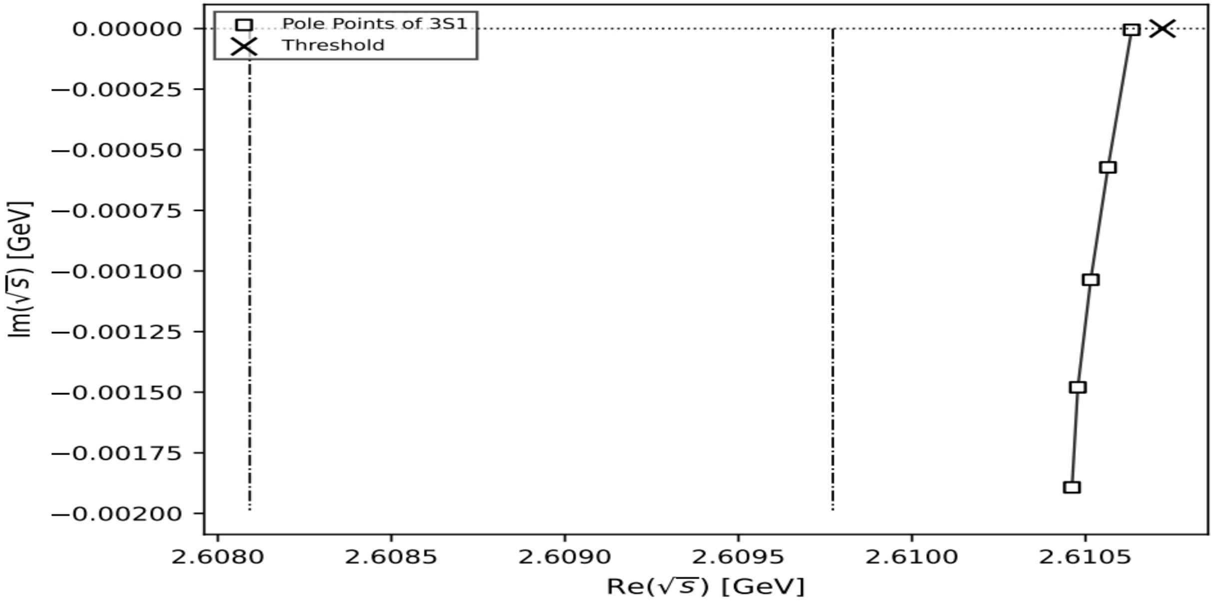
(b)

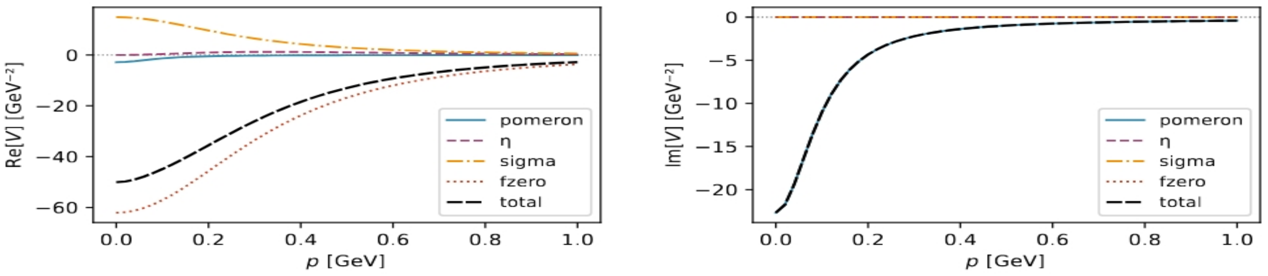




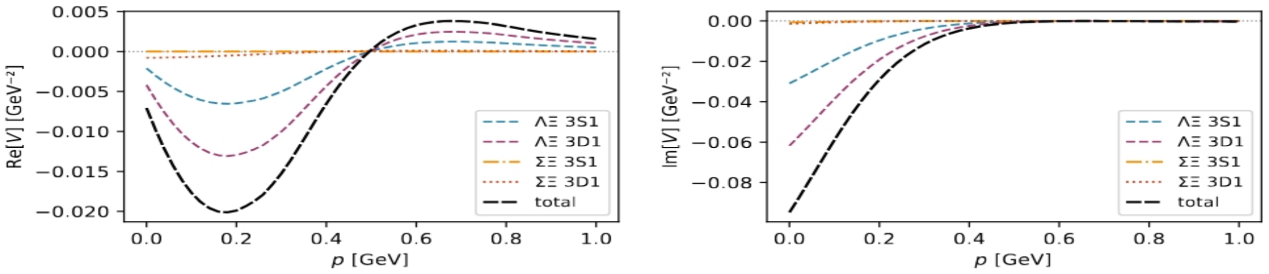
3. Results

Poles trajectories of $p\Omega^-(^3S_1)$ on the complex energy plane





(a)



(b)

- A weak quasi-bound state near the threshold in this channel due to weak absorption effect from open channels.
- This pole will move to the second Riemann sheet above the threshold as a resonance when Λ_m decreases.
- $p\Omega^-(^3S_1)$ could be a resonance or a bound state, depending on the valu of Λ_m.
- More experimental or lattice data are required to clarify the $p\Omega^-(^3S_1)$ state!

4. Summary

- By employing Pomeron exchange model and one boson exchange model, we extract pole information that is consistent with both experimental data and HALQCD results.

- Pomeron can offer an additional attractive potential, making the hadronic state more compact.

- For heavy-flavor hadrons with higher thresholds, the Pomeron exchange is expected to be significantly important.

Thanks for your attention!