Shallow S-wave pion-baryon resonances

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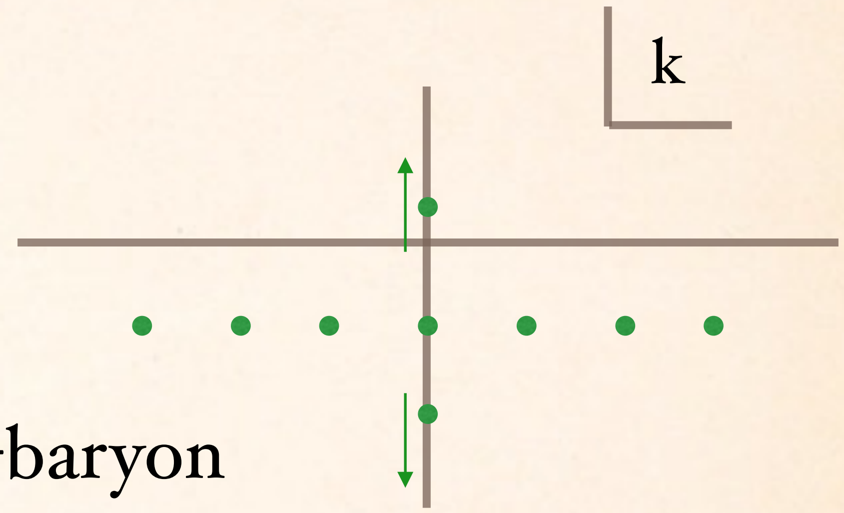
Resonances coupled to pion-baryon in S-wave



- With varying m_π, resonance poles move
- At $m_\pi^\star$ → a zero-energy bound state of pion-baryon
- What happens around $m_\pi^\star$? [Hyodo(2014), Hanhart et al.(2014)]

$$\Lambda_c^+(2595) \to \pi\Sigma_c(2455)$$

- What's the role of chiral symmetry?

On charmed baryons:
Lutz & Kolomeitsev ('04)
Jimenez-Tejero et al ('09)
Haidenbauer et al ('11)
Romanets et al ('13)
...

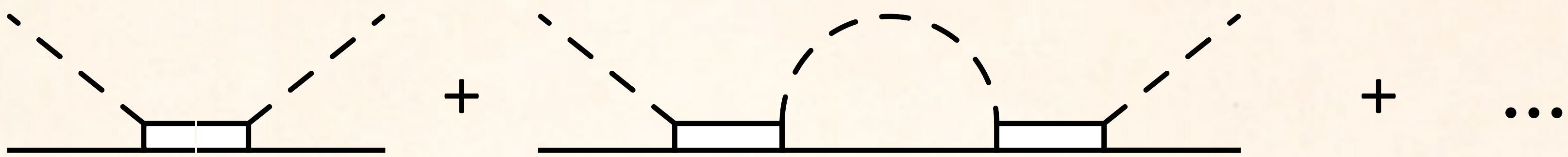
What's the role of chiral symmetry?

$$\mathcal{L}^{(0)} = \Sigma^{a\dagger}\left[i\partial_0\delta_{ab} + \frac{i}{f_\pi^2}\left(\pi^a\dot{\pi}^b - \pi^b\dot{\pi}^a\right)\right]\Sigma^b$$
$$+ \Psi^\dagger\left(i\partial_0 - \Delta\right)\Psi + i\frac{g_\Sigma}{f_\pi}\epsilon_{abc}\Sigma^{a\dagger}\vec{\sigma}\cdot\vec{\nabla}\pi^b\Sigma^c$$
$$+ \boxed{\frac{h}{\sqrt{3}f_\pi}\left(\Sigma^{a\dagger}\dot{\pi}^a\Psi + h.c.\right)} + \cdots$$

Ψ: excited baryon
Σ: ground state baryon
h: O(1)

- Ψ coupled to the S wave → time derivative on π
- Nonrelativistic pion → coupling ∝ m_π !
- Mass splitting Δ ~ m_π^*

The effective range can be large



Assuming h = O(1)

$$f^{(0)} = \frac{1}{-\frac{1}{a} + \frac{r}{2}k^2 - ik}$$

$$r = -\frac{4\pi f_\pi^2}{h^2 m_\pi^3} \sim \left(\frac{328\text{MeV}}{m_\pi^\star}\right)^2 \frac{1}{m_\pi^\star}$$

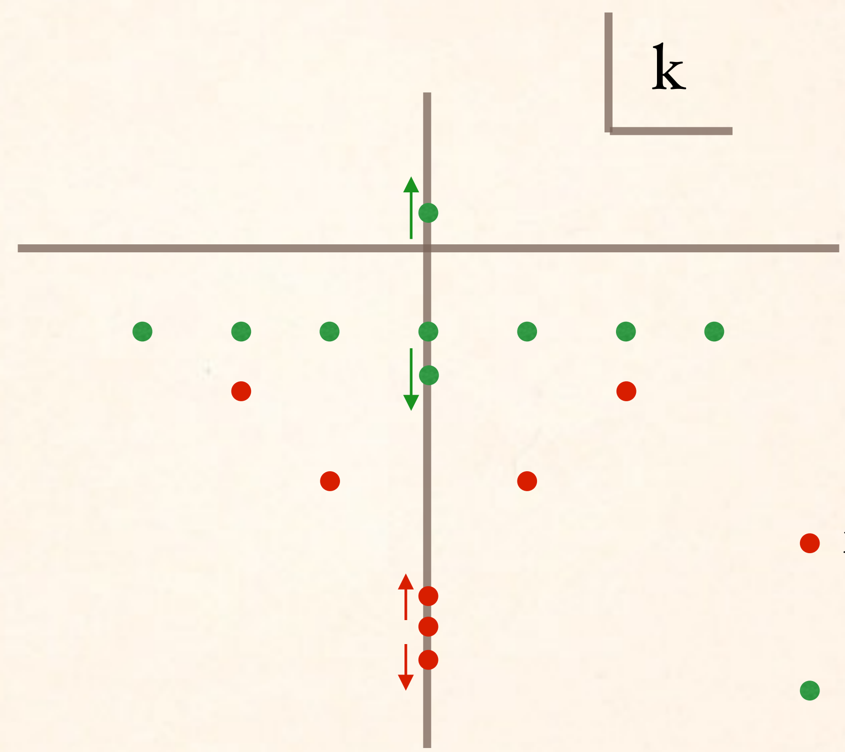
$$\frac{1}{a} = \frac{4\pi f_\pi^2}{h^2 m_\pi^2}\delta \sim \left(\frac{328\text{MeV}}{m_\pi^\star}\right)^2 (m_\pi - m_\pi^\star)$$

$\Lambda_c^+(2595)$:
h = 0.7
r = -19.5 fm
a = -10.5 fm

Values for a and r from Hyodo(2013)

- r can be quite large when $m_\pi^\star \ll \sqrt{4\pi} f_\pi = 328\text{MeV}$
- a single fine-tuning $m_\pi^\star - m_\pi \to 0$ makes both a and r large
- $\sqrt{4\pi}$ (rather than 4π) arises because the pion is nonrelativistic

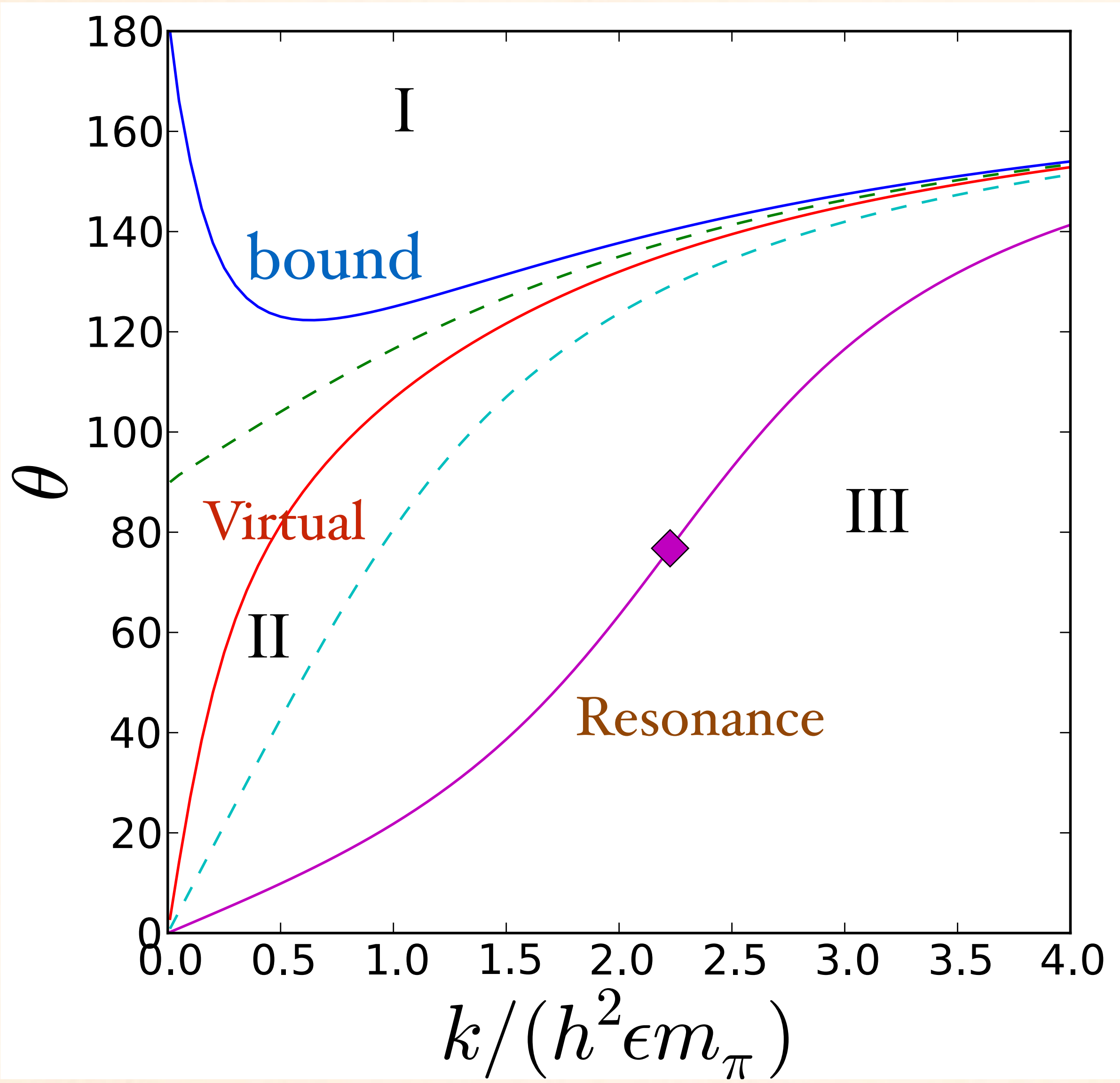
Consequences of large r
— shallow two-body resonance



- models w/ naturally sized $r < 1/m_\pi$ or smaller
- large $r >> 1/m_\pi$

- Res. poles close to real axis → weak coupling of excited baryon to two-body channel (among others) is possible
- Shallow p-wave resonance doesn’t need help from chiral symmetry and its spontaneous breaking

The phase shifts



$$\epsilon = \left(\frac{m_\pi}{\sqrt{4\pi} f_\pi} \right)^2$$

$$\tilde{\delta} \equiv \left(\frac{\sqrt{4\pi} f_\pi}{h m_\pi} \right)^4 (m_\pi^\star - m_\pi)$$

From top down

$$\tilde{\delta} = -0.2, \; 0.2, \; \text{and} \; 3$$

Consequences of large r
— breakdown of universality

- Universality : observables expected to scale w/ $m_\pi^\star - m_\pi \to 0$
- Additional small parameter $\epsilon = \left(\frac{m_\pi}{\sqrt{4\pi} f_\pi}\right)^2$ breaks universality down sooner than expected

E.g., binding energy when $m_\pi > m_\pi^\star$

$$B_0(\delta; m_\pi) = \frac{h^4}{2}\epsilon^2 m_\pi \left(\sqrt{1 - \frac{2\delta}{h^4\epsilon^2 m_\pi}} - 1\right)^2 \qquad \delta = m_\pi^\star - m_\pi$$

Universality recovered only in a tiny window

$$B = \frac{\delta^2}{h^4\epsilon^2 m_\pi}\left[1 + \mathcal{O}\left(\frac{\delta}{h^2\epsilon^2 m_\pi}\right)\right] \text{ for } \left|\frac{m_\pi - m_\pi^\star}{m_\pi}\right| \ll \left(\frac{m_\pi^\star}{328\text{MeV}}\right)^4$$

Summary and outlook

- Around m_π^*, chiral symmetry ensures, to a certain extent, the S-wave effective range of pion-baryon to be large:

$$m_\pi^\star \ll \sqrt{4\pi} f_\pi = 328\text{MeV}$$

- Large r helps S-wave resonance stay close to threshold and be narrow

- Coexistence of r and a breaks down universality quickly, e.g., as seen from binding energy

- 2 pions + baryon?