J/ψ-nucleon scattering in P_c^+ pentaquark channels

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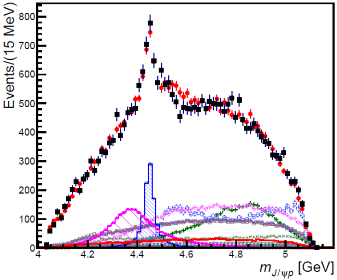
Motivation

- In 2015 charmed pentaquark state P_c^+, decaying into $N + J/\psi$ was discovered by LHCb (LHCb; *PRL*, 2015(115),072001).

$$N + J/\psi \to P_c^+ \to N + J/\psi$$

- Two states were observed:
  - lower state with $J = \frac{3}{2}$, mass $m_{P_c^+} = 4380 \pm 8$MeV and width $\Gamma = 205 \pm 18$MeV
  - upper state with $J = \frac{5}{2}$, mass $m_{P_c^+} = 4449{,}8 \pm 1{,}7$MeV and width $\Gamma = 39 \pm 5$MeV
  - states have opposite parity. It is not clear which state is positive and which negative under parity transformation.
  - States with $J^P = \frac{3}{2}^+, \frac{3}{2}^-, \frac{5}{2}^+, \frac{5}{2}^-$ should be seen in irreps $G_2^{\pm}$ and $H^{\pm}$



J	irrep, O_h , $\vec{P} = 0$
$\frac{1}{2}$	G_1
$\frac{3}{2}$	H
$\frac{5}{2}$	$H \oplus G_2$
$\frac{7}{2}$	$G_1 \oplus H \oplus G_2$

This channel was already studied by HALQCD method only for energies below Pc and no bound state was found

(T. Sugiura et. all Proccedings of Lattice 2017 conference, EPJ Web of Conferences 175, 05011 (2018))

Overview

Channels for strong decay of P_c^+

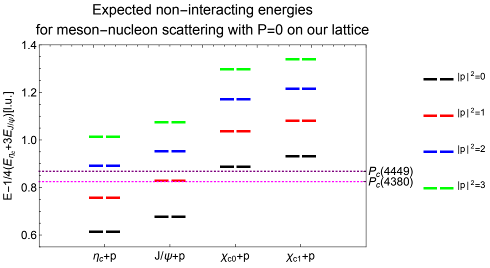
Results

- Lattice setup
- Single hadron results
- Operators for states with desired quantum numbers
- Results for scattering

Conclusion

Possible channels for strong decay of P_c^+

- $\vec{P} = \vec{p}_{H_1} + \vec{p}_{H_2} = 0$
- P_c^+ : $uudc\bar{c}$
- Simulation are made in approximation of 1 channel scattering for $J/\psi - p$
- It should be sufficient to study scattering up to $|p_{H_i}|^2 = 2$, we could be able to see both P_c^+ states
- other possible chanells: $(D^- - \Sigma_c^{++}, \bar{D}^0 - \Lambda_c^+, ...)$



Lattice setup

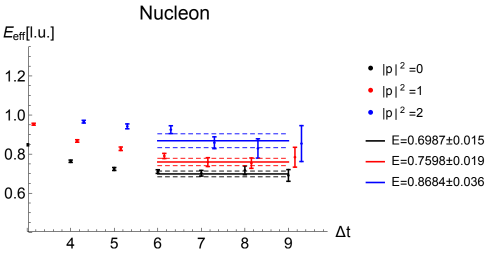
- Properties of used lattice

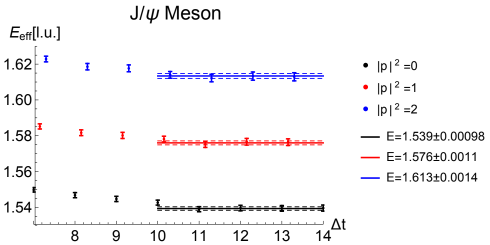
$N^3 \times N_T$	a[fm]	L[fm]	#config	m_π[MeV]
$16^3 \times 32$	0.1239(13)	1.98	280	266(3)

- Wilson-Clover action for light quarks
- Fermi lab approach for charm quarks
- Full distillation:
  - J/ψ : $N_v = 96$
  - N : $N_v = 48$

Single hadron results

- Both hadrons (nucleon and J/ψ meson) were simulated with momentum $|p|^2 = 0$, $|p|^2 = 1$ and $|p|^2 = 2$
- Nucleon: 3 operators for each value of momentum
- J/ψ: 2 operators for each value of momentum





Combining single hadron correlators

- $\vec{P} = \vec{p}_{H_1} + \vec{p}_{H_2} = 0,\ O \approx N(p)V(-p)$
- Operators in Partial wave method:

$$O^{|p|,J,m_J,L,S} = \sum_{m_L,m_S,m_{s1},m_{s2}} C^{Jm_J}_{Lm_L,Sm_S} C^{Sm_S}_{s_1 m_{s1},s_2 m_{s2}} \times \sum_{R\in O} Y^{*}_{Lm_L}(\widehat{Rp}) N_{m_{s1}}(Rp) V_{m_{s2}}(-Rp)$$

- Subduction to irrep: $O^{[J,L,S]}_{|p|,\Gamma,r} = \sum_{m_J} \mathcal{S}^{J,m_J}_{\Gamma,r} O^{|p|,J,m_J,L,S}$

J	irrep Γ
$\frac{1}{2}$	G_1
$\frac{3}{2}$	H
$\frac{5}{2}$	$H \oplus G_2$
$\frac{7}{2}$	$G_1 \oplus H \oplus G_2$

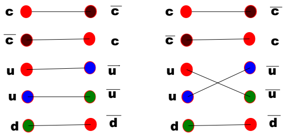
All explicit expressions for $H_1(p)H_2(-p)$ operators : (S. Prelovsek, U.S., C.B. Lang ; *JHEP* 2017(1), 129.).
Partial wave method for *NN* scattering was considered by CalLat: (Berkowitz, et. all *PLB* , 2016(12) 024.)

Subduction coefficients $\mathcal{S}^{J,m_J}_{\Gamma,r}$ are given in: (J. Dudek, et.all; *PRD* 2010(82), 034508.)

Example: Scattering in P_c^+ pentaquark candidate channel: for irrep H^- and $J=\frac{3}{2}, S=\frac{3}{2}, L=0$ and $|p|^2=0$

Anihilation operator for this example is:

$$O^{H^-,r=1}_{J=\frac{3}{2},S=\frac{3}{2},L=0}(0) = N_{\frac{1}{2}}(0)\left(V_x(0) - iV_y(0)\right)$$



Creation operator:

$$\bar{O}^{H^-,r=1}_{J=\frac{3}{2},S=\frac{3}{2},L=0}(0) = N_{\frac{1}{2}}(0)\left(V_x(0) + iV_y(0)\right)$$

Correlation function:

$$C^{VN;H^-}_{J=\frac{3}{2},S=\frac{3}{2},L=0}(|p|=0) = \langle\Omega|O^{H^-}_{J=\frac{3}{2},S=\frac{3}{2},L=0}\bar{O}^{H^-}_{J=\frac{3}{2},S=\frac{3}{2},L=0}|\Omega\rangle =$$

$$C^N_{\frac{1}{2}\to\frac{1}{2}}C^V_{x\to x} - iC^N_{\frac{1}{2}\to\frac{1}{2}}C^V_{x\to y} + iC^N_{\frac{1}{2}\to\frac{1}{2}}C^V_{y\to x} + C^N_{\frac{1}{2}\to\frac{1}{2}}C^V_{y\to y}$$

$$C^H_{pol_{src}\to pol_{snk}} = \langle\Omega|H_{pol_{snk}}\bar{H}_{pol_{src}}|\Omega\rangle$$

Anhilation operators for H^- and $|p|^2 = 1$

$J = \frac{3}{2}, S = \frac{3}{2}, L = 0$:

$$O^{H^-,r=1}_{J=\frac{3}{2},S=\frac{3}{2},L=0}(1) = N_{\frac{1}{2}}(e_z)\left(V_x(-e_z) - iV_y(-e_z)\right) + N_{\frac{1}{2}}(-e_z)\left(V_x(e_z) - iV_y(e_z)\right) + N_{\frac{1}{2}}(e_x)\left(V_x(-e_x) - iV_y(-e_x)\right) + N_{\frac{1}{2}}(-e_x)\left(V_x(e_x) - iV_y(e_x)\right) + N_{\frac{1}{2}}(e_y)\left(V_x(-e_y) - iV_y(-e_y)\right) + N_{\frac{1}{2}}(-e_y)\left(V_x(e_y) - iV_y(e_y)\right)$$

$J = \frac{3}{2}, S = \frac{1}{2}, L = 2$:

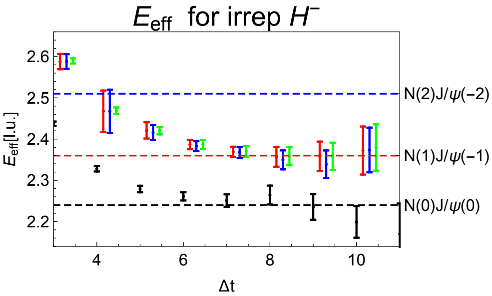
$$O^{H^-,r=1}_{J=\frac{3}{2},S=\frac{1}{2},L=2}(1) = N_{\frac{1}{2}}(e_x)\left(V_x(-e_x) + iV_y(-e_x)\right) + N_{\frac{1}{2}}(-e_x)\left(V_x(e_x) + iV_y(e_x)\right) - N_{\frac{1}{2}}(e_y)\left(V_x(-e_y) + iV_y(-e_y)\right) - N_{\frac{1}{2}}(-e_y)\left(V_x(e_y) + iV_y(e_y)\right) - N_{-\frac{1}{2}}(e_x)V_z(-e_x) - N_{-\frac{1}{2}}(-e_x)V_z(e_x) + N_{-\frac{1}{2}}(e_y)V_z(-e_y) + N_{-\frac{1}{2}}(-e_y)V_z(e_y)$$

$J = \frac{3}{2}, S = \frac{3}{2}, L = 2$:

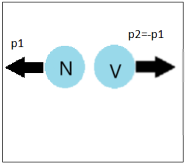
$$O^{H^-,r=1}_{J=\frac{3}{2},S=\frac{3}{2},L=2}(1) = N_{\frac{1}{2}}(e_z)\left(V_x(-e_z) - iV_y(-e_z)\right) + N_{\frac{1}{2}}(-e_z)\left(V_x(e_z) - iV_y(e_z)\right) - N_{-\frac{1}{2}}(e_x)V_z(-e_x) - N_{-\frac{1}{2}}(-e_x)V_z(e_x) - N_{\frac{1}{2}}(e_x)V_x(-e_x) - N_{\frac{1}{2}}(-e_x)V_x(e_x) + N_{-\frac{1}{2}}(e_y)V_z(-e_y) + N_{-\frac{1}{2}}(-e_y)V_z(e_y) + iN_{\frac{1}{2}}(e_y)V_y(-e_y) + iN_{\frac{1}{2}}(-e_y)V_y(e_y)$$

Results for irrep H^- with momentum $|p|^2 \leq 1$

- $4 \times 6 = 24$ interpolators
- GEVP: 8 operators



- One state for $|p|^2 = 0$ and 3 states at $|p|^2 = 1$
- state $|p|^2 = 0$: $(J = \frac{3}{2}, S = \frac{3}{2}, L = 0)$
- states with $|p|^2 = 1$:
  $(J = \frac{3}{2}, S = \frac{3}{2}, L = 0)$
  $(J = \frac{3}{2} S = \frac{1}{2}, L = 2)$
  $(J = \frac{3}{2}, S = \frac{3}{2}, L = 2)$



Dashed lines:
non-interacting
energy for scattering

Expected number of eigenstates for non-interacting scattering

- degeneracy of states origins from spin of scattered hadrons
- Candidate channels for P_c^+ - J^P: $\frac{3}{2}^-$, $\frac{3}{2}^+$, $\frac{5}{2}^-$, $\frac{5}{2}^+$ (irreps G_2^-, G_2^+, H^- ,H^+)

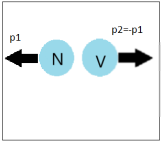
	G_1^-	G_1^+	G_2^-	G_2^+	H^-	H^+
$\lvert p\rvert^2 = 0$	1	0	0	0	1	0
$\lvert p\rvert^2 = 1$	2	2	1	1	3	3
$\lvert p\rvert^2 = 2$	3	3	3	3	6	6
total number of states	6	5	4	4	10	9
total number of operators	36	30	24	24	60	54

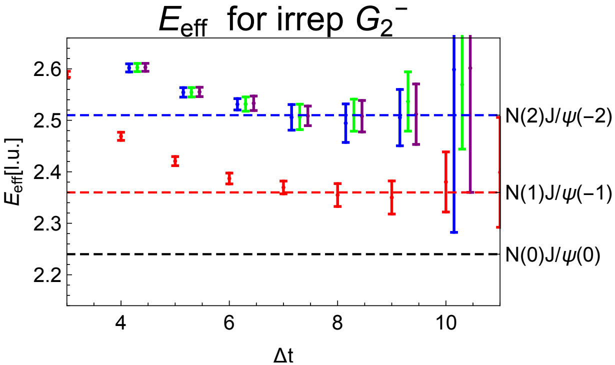
Results for scattering in irrep G_2^-

(P_c^+ candidate channel)

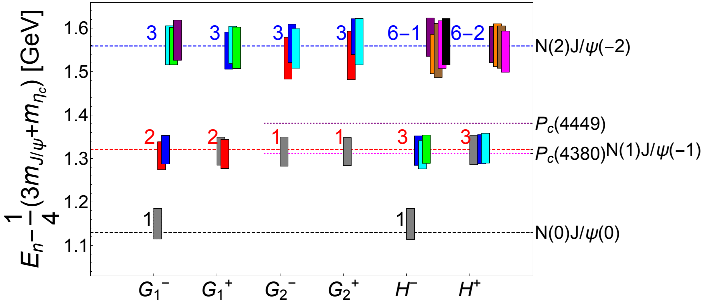
- $1 + 3$ states
- state with $|p|^2 = 1$: $(J = \frac{5}{2}, S = \frac{3}{2}, L = 2)$
- states with $|p|^2 = 2$: $(J = \frac{5}{2}, S = \frac{1}{2}, L = 2)$, $(J = \frac{5}{2} S = \frac{3}{2}, L = 2)$, $(J = \frac{5}{2}, S = \frac{3}{2}, L = 4)$

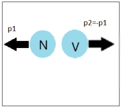
$\|p\|^2$	G_2^-
0	0
1	1
2	3
# states	4





All calculated energies





	G_1^-	G_1^+	G_2^-	G_2^+	H^-	H^+
$\lvert p\rvert^2 = 0$	1	0	0	0	1	0
$\lvert p\rvert^2 = 1$	2	2	1	1	3	3
$\lvert p\rvert^2 = 2$	3	3	3	3	6	6
# states	6	5	4	4	10	9

- We are able to see all expected states
- few interpolators are left out- huge errors:
  - $6-1$: one out of 6 interpolators is not used (to avoid large errors)
  - $6-1=5$: states observed
- No additional states
- No strong indication of P_c^+

Conclusion

- Results of one channel approximation for P_c^+ channels were presented.
- All states required by degeneration caused by spin are observed, but some are left out due to huge errors
- In our approximation there is no sign of extra eigenstate or significant energy shift, which would indicate to P_c^+ state
- P_c^+ could be a result of other neglected effects (coupled channels effect,...)
- Future plans:
  - Look at other scattering channels which may be related to P_c^+
  - Look at coupled channel effects

J^P	L	$m_m + m_b$ [MeV]	meson	m_{meson} [MeV]	J^{PC}_{meson}	barion	m_{barion} [MeV]	J^P_{barion}
$\frac{3}{2}^-$	2^+	3921	$\eta_c(1s)$	2983.4	0^{-+}	p	938,3	$\frac{1}{2}^+$
	0^+	4034	J/ψ	3096.900	1^{--}	p	938,3	$\frac{1}{2}^+$
	0^+	4293	$D^{*0}(\bar{2}007)$	2006.85	1^-	Λ_c^+	2286.46	$\frac{1}{2}^+$
	0^+	4387	D^-	1869.59	0^-	$\Sigma_c^{++}(2520)$	2518.41	$\frac{3}{2}^+$
	1^-	4352	χ_{c0}	3414.75	0^{++}	p	938,3	$\frac{1}{2}^+$
	1^-	4448	χ_{c1}	3510.66	1^{++}	p	938,3	$\frac{1}{2}^+$
$\frac{3}{2}^+$	1^-	3921	$\eta_c(1s)$	2983.4	0^{-+}	p	938,3	$\frac{1}{2}^+$
	1^-	4034	J/ψ	3096.900	1^{--}	p	938,3	$\frac{1}{2}^+$
	1^-	4151	$\bar{D}^0$	1864.83	0^-	Λ_c^+	2286.46	$\frac{1}{2}^+$
	1^-	4293	$D^{*0}(\bar{2}007)$	2006.85	1^-	Λ_c^+	2286.46	$\frac{1}{2}^+$
	1^-	4324	D^-	1869.59	0^-	$\Sigma_c^{++}(2455)$	2453.97	$\frac{1}{2}^+$
	1^-	4387	D^-	1869.59	0^-	$\Sigma_c^{++}(2520)$	2518.41	$\frac{3}{2}^+$
	0^+	4448	χ_{c1}	3510.66	1^{++}	p	938,3	$\frac{1}{2}^+$
$\frac{5}{2}^-$	2^+	3921	$\eta_c(1s)$	2983.4	0^{-+}	p	938,3	$\frac{1}{2}^+$
	2^+	4034	J/ψ	3096.900	1^{--}	p	938,3	$\frac{1}{2}^+$
	1^-	4448	χ_{c1}	3510.66	1^{++}	p	938,3	$\frac{1}{2}^+$
$\frac{5}{2}^+$	3^-	3921	$\eta_c(1s)$	2983.4	0^{-+}	p	938,3	$\frac{1}{2}^+$
	1^-	4034	J/ψ	3096.900	1^{--}	p	938,3	$\frac{1}{2}^+$
	1^-	4293	$D^{*0}(\bar{2}007)$	2006.85	1^-	Λ_c^+	2286.46	$\frac{1}{2}^+$
	1^-	4387	D^-	1869.59	0^-	$\Sigma_c^{++}(2520)$	2518.41	$\frac{3}{2}^+$