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

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Based on: Skerbis and Prelovsek, Phys. Rev. D 99, 094505 (2019)

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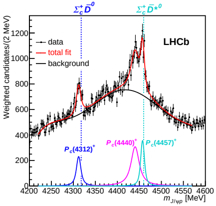
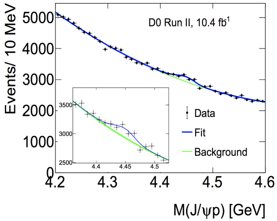
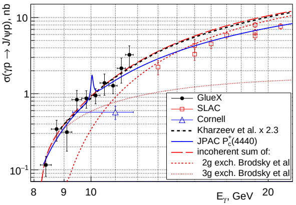
Overview

Motivation

- In 2015 charmed pentaquark state P_c^+ in the spectrum $N + J/\psi$
- In 2019 additional anaysis showed one additional peak
- upper $P_c(4450)$ peak are in fact two peaks
- no additional info about $P_c(4380)$
- 2019 results confirmed by D0 collaboration (old Fermilab data)
- P_c was not seen by GlueX experiment $\gamma p \to J/\psi p$
- most belived interpretation at the moment P_c is bound state of $D^{\bar{0}(*)}\Sigma_c^{(*)}$

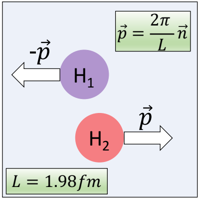


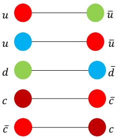


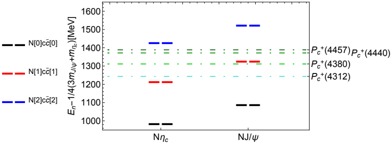


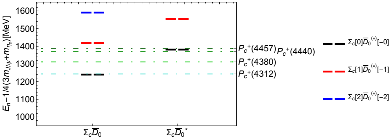
Strong decay of P_c^+

- $\vec{P} = \vec{p}_{H_1} + \vec{p}_{H_2} = 0$
- 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 until $|p_{H_i}|^2 = 2$, we could be able to see both P_c^+ states
- other possible channels: $(\bar{D}^0 - \Sigma_c^+, \bar{D}^{*0} - \Sigma_c^+, \ldots)$





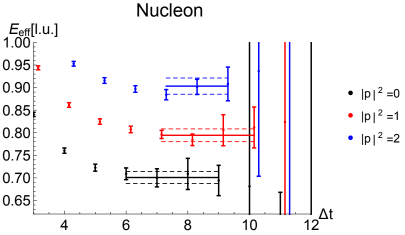


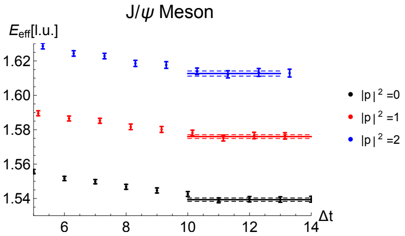


Single hadron results

$N^3 \times N_T$	N_f	a[fm]	L[fm]	#config	m_π[MeV]
$16^3 \times 32$	2	0.1239(13)	1.98	280	266(3)

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

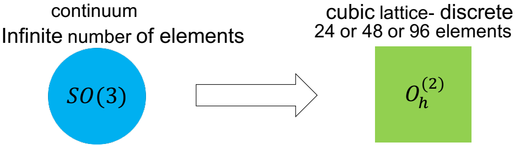


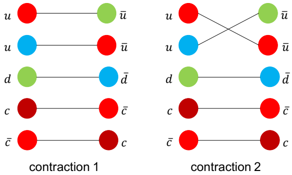


Example: Scattering in P_c^+ pentaquark candidate channel: for irrep H^- and $J=\frac{3}{2}, S=\frac{3}{2}, L=0$ and $|p|^2=0$

An. Op: $O^{|p|,J,m_J,L,S} = \sum_{\substack{m_L,m_S \\ m_{s1},m_{s2}}} C^{Jm_J}_{Lm_L,Sm_S} C^{Sm_S}_{s_1 m_{s1},s_2 m_{s2}} \sum_{R\in O} Y^*_{Lm_L}(\widehat{Rp}) H^{(1)}_{m_{s1}}(Rp) H^{(2)}_{m_{s2}}(-Rp)$

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





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 for this example is:

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

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

$$C^{VN;H^-}_{J=\frac{3}{2},S=\frac{3}{2},L=0}(|p|=0) = C^N_{\frac{1}{2}\to\frac{1}{2}} C^V_{x\to x} - iC^N_{\frac{1}{2}\to\frac{1}{2}} C^V_{x\to y} + iC^N_{\frac{1}{2}\to\frac{1}{2}} C^V_{y\to x} + C^N_{\frac{1}{2}\to\frac{1}{2}} C^V_{y\to y},$$

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

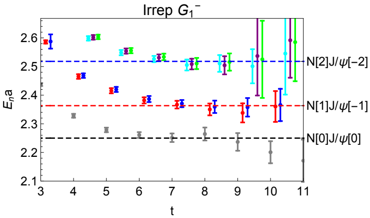
Results for scattering in irrep G_1^- (pentaquark candidate channel)

degeneration due to the spin of the particles
# of states in the non-interacting limit

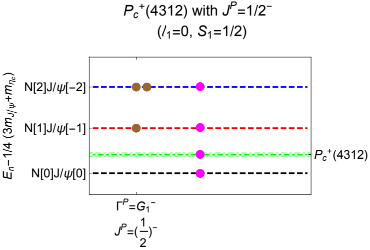
- state with $|p|^2 = 0$: $(J = \frac{1}{2}, S = \frac{1}{2}, L = 0)$
- state with $|p|^2 = 1$: $(J = \frac{1}{2}, S = \frac{1}{2}, L = 0)$, $(J = \frac{1}{2} S = \frac{3}{2}, L = 2)$
- states with $|p|^2 = 2$: $(J = \frac{1}{2}, S = \frac{1}{2}, L = 0)$, $(J = \frac{1}{2} S = \frac{3}{2}, L = 2)$, $(J = \frac{7}{2}, S = \frac{3}{2}, L = 2)$

$\|p\|^2$	G_1^-
0	1
1	2
2	3
# states	6

Result



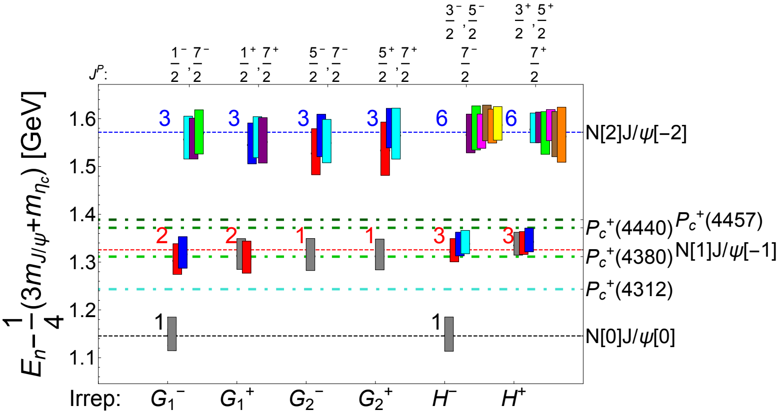
Prediction



Phase shift:

Th: $\cot\delta = \dfrac{2Z_{0,0}\left(1;\left(|\vec{p}|\frac{L}{2\pi}\right)^2\right)}{\sqrt{\pi}L|\vec{p}|}$ Exp: $\cot\delta_l(E) = \dfrac{M^2 - E^2}{E\ \Gamma(E)}$

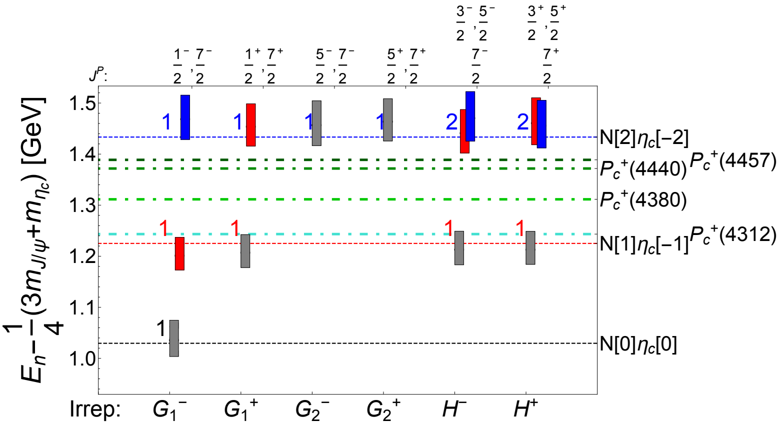
All calculated energies $J/\psi N$



	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 see all states expected by the non-interacting limit
- No additional states
- No strong indication of P_c^+

All calculated energies $\eta_c N$

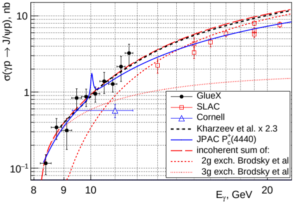


	G_1^-	G_1^+	G_2^-	G_2^+	H^-	H^+
$\lvert p\rvert^2 = 0$	1	0	0	0	0	0
$\lvert p\rvert^2 = 1$	1	1	0	0	1	1
$\lvert p\rvert^2 = 2$	1	1	1	1	2	2
# states	2	2	1	1	3	3

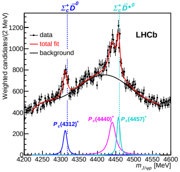
- We see all states expected by the non-interacting limit
- No additional states

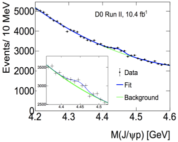
Comparation between lattice and exp results

GlueX experiment



LHCb and D0 experiment





- $\gamma p \to P_c \to J/\psi p$
- P_c coupled only to the $J/\psi - N$ channel
- P_c **is not** observed

- P_c is not coupled only to $J/\psi - N$ channel
- P_c **is** observed

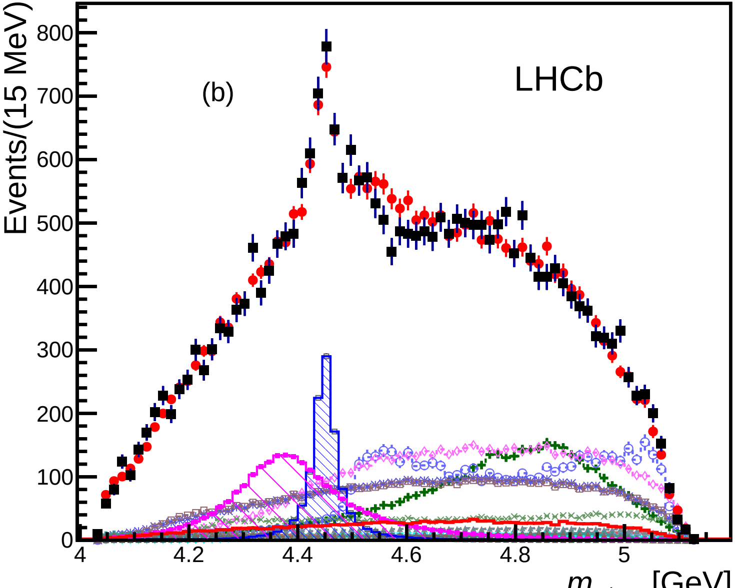
Comment:

- the P_c is probably not coupled only to the $J/\psi - N$ channel
- experimental results and our lattice results agree
- Lattice study of coupled channels ($\bar{D}^0\Sigma_c$,$\bar{D}^{*0}\Sigma_c$, $J/\psi N$,...) is needed

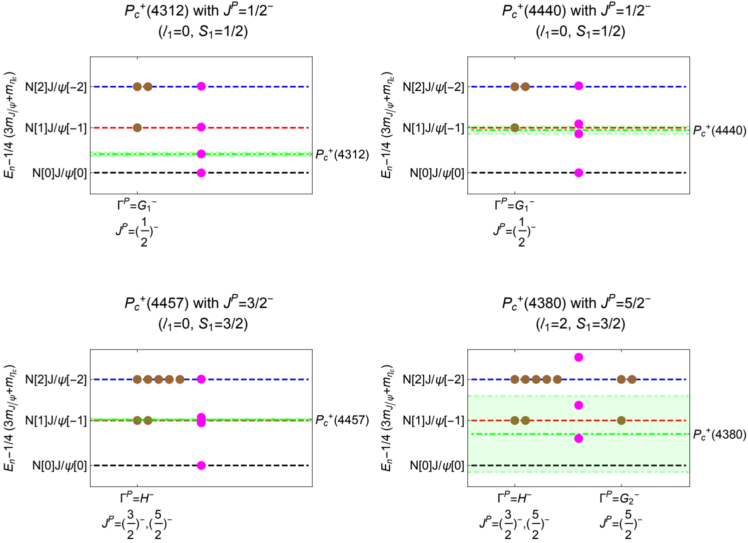
Conclusion

- Results of one channel approximation for $J/\psi - N$ scattering including the P_c^+ channels
- Degeneration of states is caused by spin of particles, all these states are observed
- In our approximation there is no sign of extra eigenstate or significant energy shift, which would indicate to P_c^+ state
- P_c^+ is probably a result of other neglected effects (coupled channels effect,...)

Old LHCb results for P_c



Prediction of spectrum for P_c coupled only to $J/\psi - N$ channel



J^P	I	$m_M + m_B$ [MeV]	M	B
$\frac{1}{2}^-$	0	3921	η_c	p
		4034	J/ψ	p
		4319	$\bar{D}^0$	Σ_c^+
		4461	$\bar{D}^{*0}$	Σ_c^+
	1	4352	χ_{c0}	p
		4448	χ_{c1}	p
	2	4034	J/ψ	p
		4461	$\bar{D}^{*0}$	Σ_c^+
$\frac{1}{2}^+$	0	4352	χ_{c0}	p
		4448	χ_{c1}	p
	1	3921	η_c	p
		4034	J/ψ	p
		4319	$\bar{D}^0$	Σ_c^+
		4461	$\bar{D}^{*0}$	Σ_c^+
	2	4352	χ_{c0}	p
		4448	χ_{c1}	p
$\frac{3}{2}^-$	0	4034	J/ψ	p
		4461	$\bar{D}^{*0}$	Σ_c^+
	1	4352	χ_{c0}	p
		4448	χ_{c1}	p
	2	3921	η_c	p
		4034	J/ψ	p
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$\frac{3}{2}^+$	0	4448	χ_{c1}	p
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		4461	$\bar{D}^{*0}$	Σ_c^+
$\frac{5}{2}^+$	1	4034	J/ψ	p
		4461	$\bar{D}^{*0}$	Σ_c^+
	2	4352	χ_{c0}	p
		4448	χ_{c1}	p

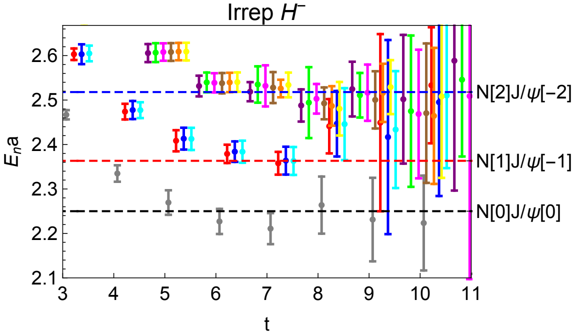
Combining single hadron correlators

- $\vec{P} = \vec{p_{H_1}} + \vec{p_{H_2}} = 0$
- Operators in Partial wave method:
  $O^{|p|,J,m_J,L,S} = \sum_{m_L,m_S,m_{s1},m_{s2}} C^{Jm_J}_{Lm_L,Sm_S} C^{Sm_S}_{s_1 m_{s1},s_2 m_{s2}} \sum_{R\in O} Y^*_{Lm_L}(\widehat{Rp}) H^{(1)}_{m_{s1}}(Rp) H^{(2)}_{m_{s2}}(-Rp)$
- 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
$\frac{1}{2}$	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.).
- Subduction coefficients $\mathcal{S}^{J,m_J}_{\Gamma,r}$ are given in:
  (J. Dudek, et.all; *PRD* 2010(82), 034508)

Results for the H^- irrep



	1	2	3	4	5	6	7	8	9	10
$\lvert p\rvert^2$	0	1	1	1	2	2	2	2	2	2
J	$\frac{3}{2}$	$\frac{3}{2}$	$\frac{3}{2}$	$\frac{3}{2}$	$\frac{3}{2}$	$\frac{3}{2}$	$\frac{5}{2}$	$\frac{5}{2}$	$\frac{5}{2}$	$\frac{7}{2}$
l	0	2	0	2	0	2	2	2	4	2
S	$\frac{3}{2}$	$\frac{1}{2}$	$\frac{3}{2}$	$\frac{3}{2}$	$\frac{3}{2}$	$\frac{3}{2}$	$\frac{1}{2}$	$\frac{3}{2}$	$\frac{3}{2}$	$\frac{3}{2}$

Quantum number basis for $J/\psi - N$-part 1

irrep	type-number	p^2	J	l	S
G_1^-	1	0	$\frac{1}{2}$	0	$\frac{1}{2}$
	2	1	$\frac{1}{2}$	0	$\frac{1}{2}$
	3	1	$\frac{1}{2}$	2	$\frac{3}{2}$
	4	2	$\frac{1}{2}$	0	$\frac{1}{2}$
	5	2	$\frac{1}{2}$	2	$\frac{3}{2}$
	6	2	$\frac{7}{2}$	2	$\frac{3}{2}$
G_1^+	1	1	$\frac{1}{2}$	1	$\frac{1}{2}$
	2	1	$\frac{1}{2}$	1	$\frac{3}{2}$
	3	2	$\frac{1}{2}$	1	$\frac{1}{2}$
	4	2	$\frac{1}{2}$	1	$\frac{3}{2}$
	5	2	$\frac{7}{2}$	3	$\frac{3}{2}$
G_2^-	1	1	$\frac{5}{2}$	2	$\frac{3}{2}$
	2	2	$\frac{5}{2}$	2	$\frac{1}{2}$
	3	2	$\frac{5}{2}$	2	$\frac{3}{2}$
	4	2	$\frac{5}{2}$	4	$\frac{3}{2}$
G_2^+	1	1	$\frac{5}{2}$	1	$\frac{3}{2}$
	2	2	$\frac{5}{2}$	3	$\frac{1}{2}$
	3	2	$\frac{5}{2}$	1	$\frac{3}{2}$
	4	2	$\frac{5}{2}$	3	$\frac{3}{2}$

Quantum number basis for $J/\psi - N$-part 2

irrep	type-number	p^2	J	$\mathcal{L}$	S
H^-	1	0	$\frac{3}{2}$	0	$\frac{3}{2}$
	2	1	$\frac{3}{2}$	2	$\frac{1}{2}$
	3	1	$\frac{3}{2}$	0	$\frac{3}{2}$
	4	1	$\frac{3}{2}$	2	$\frac{3}{2}$
	5	2	$\frac{3}{2}$	0	$\frac{3}{2}$
	6	2	$\frac{3}{2}$	2	$\frac{3}{2}$
	7	2	$\frac{5}{2}$	2	$\frac{1}{2}$
	8	2	$\frac{5}{2}$	2	$\frac{3}{2}$
	9	2	$\frac{5}{2}$	4	$\frac{3}{2}$
	10	2	$\frac{7}{2}$	2	$\frac{3}{2}$
H^+	1	1	$\frac{3}{2}$	1	$\frac{1}{2}$
	2	1	$\frac{3}{2}$	1	$\frac{3}{2}$
	3	1	$\frac{3}{2}$	3	$\frac{3}{2}$
	4	2	$\frac{3}{2}$	1	$\frac{1}{2}$
	5	2	$\frac{3}{2}$	3	$\frac{3}{2}$
	6	2	$\frac{5}{2}$	3	$\frac{1}{2}$
	7	2	$\frac{5}{2}$	1	$\frac{3}{2}$
	8	2	$\frac{5}{2}$	3	$\frac{3}{2}$
	9	2	$\frac{7}{2}$	3	$\frac{1}{2}$

Quantum number basis for $\eta_c - N$

irrep	type-number	$\lvert p\rvert^2$	J	$\mathcal{L}$	S
G_1^-	1	0	$\frac{1}{2}$	0	$\frac{1}{2}$
	2	1	$\frac{1}{2}$	0	$\frac{1}{2}$
	3	2	$\frac{1}{2}$	0	$\frac{1}{2}$
G_1^+	1	1	$\frac{1}{2}$	1	$\frac{1}{2}$
	2	2	$\frac{1}{2}$	1	$\frac{1}{2}$
G_2^-	1	2	$\frac{5}{2}$	2	$\frac{1}{2}$
G_2^+	1	2	$\frac{5}{2}$	3	$\frac{1}{2}$
H^-	1	1	$\frac{3}{2}$	2	$\frac{1}{2}$
	2	2	$\frac{3}{2}$	2	$\frac{1}{2}$
	3	2	$\frac{5}{2}$	2	$\frac{1}{2}$
H^+	1	1	$\frac{3}{2}$	1	$\frac{1}{2}$
	2	2	$\frac{3}{2}$	1	$\frac{1}{2}$
	3	2	$\frac{3}{2}$	3	$\frac{1}{2}$