Proton-J/Ψ scattering in pentaquark Pc channel

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U. Skerbis and S.P. , PRD 99 094595 (2019), 1811.02285

Outline

- experiment: LHCb discovery of pentaquarks Pc

- First lattice study of charmed pentaquark P_c channel reaching energies where Pc reside

$$p \;\; J/\psi \rightarrow P_c \rightarrow p \;\; J/\psi$$

More general lessons

- scattering / interactions of particles with spin, beyond s-wave
- construction of two-hadron operators
- why several nearly-degenerate eigen-states appear (even in continuum)

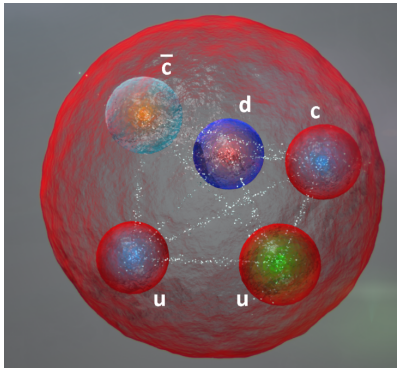
What do we learn from our simulation on Pc

Future challenges

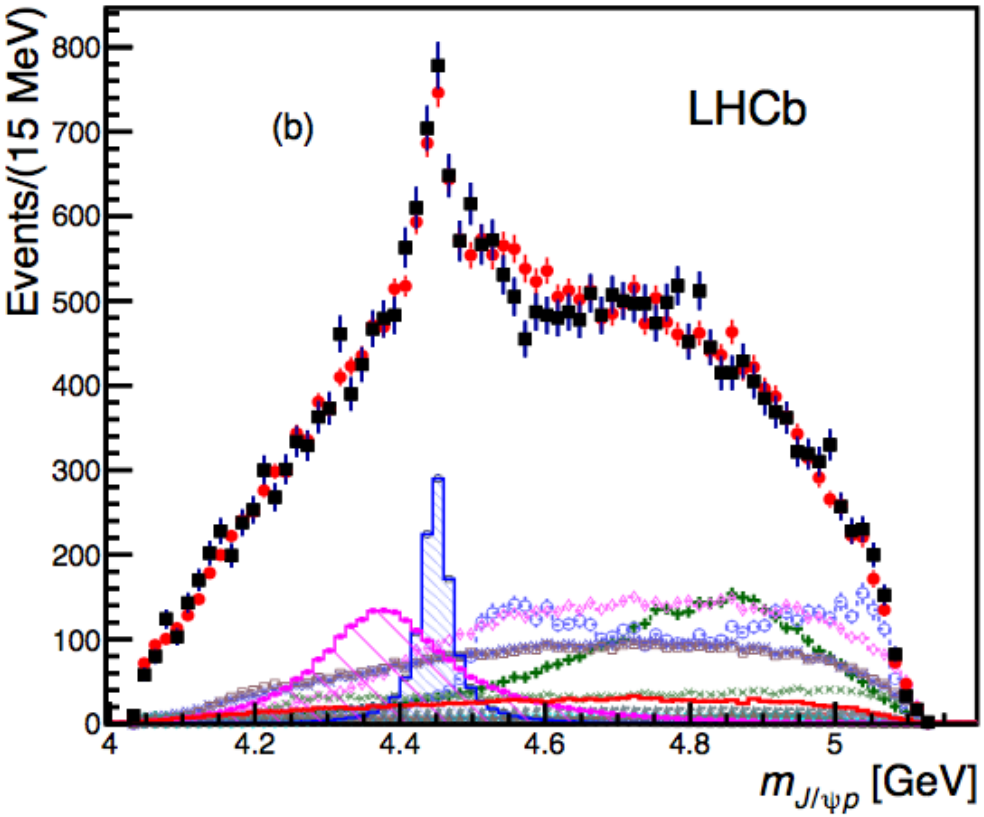
Pc pentaquark discovery: LHCb 2015

LHCb PRL
1507.03414

$$P_c \rightarrow p \;\; J/\psi$$



uud $\bar{c}c$



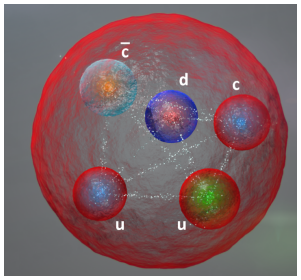
knowledge of J^P from exp:

- they have opposite parities
- J= 3/2 or 5/2
- favoured J^P in Table

(full amplitude analysis has not been done)

LHCb 2015	m (MeV)	Γ (MeV)	favoured J^{PC}
Pc(4380)	4380 ± 40	205 ± 100	$3/2^-$ (L=0)
Pc(4449)	4450 ± 5	40 ± 25	$5/2^+$ (L=1)

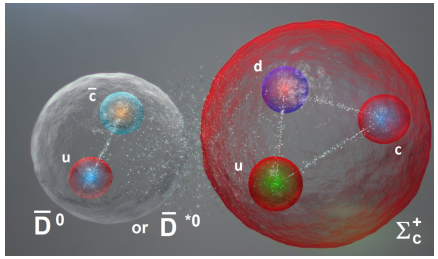
More pentaqarks
LHCb 2019

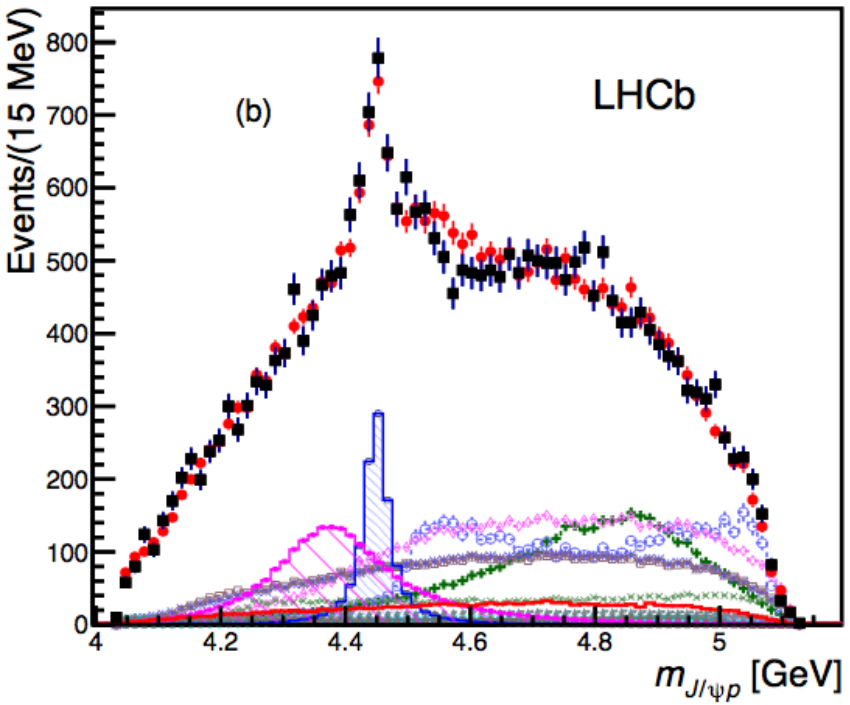


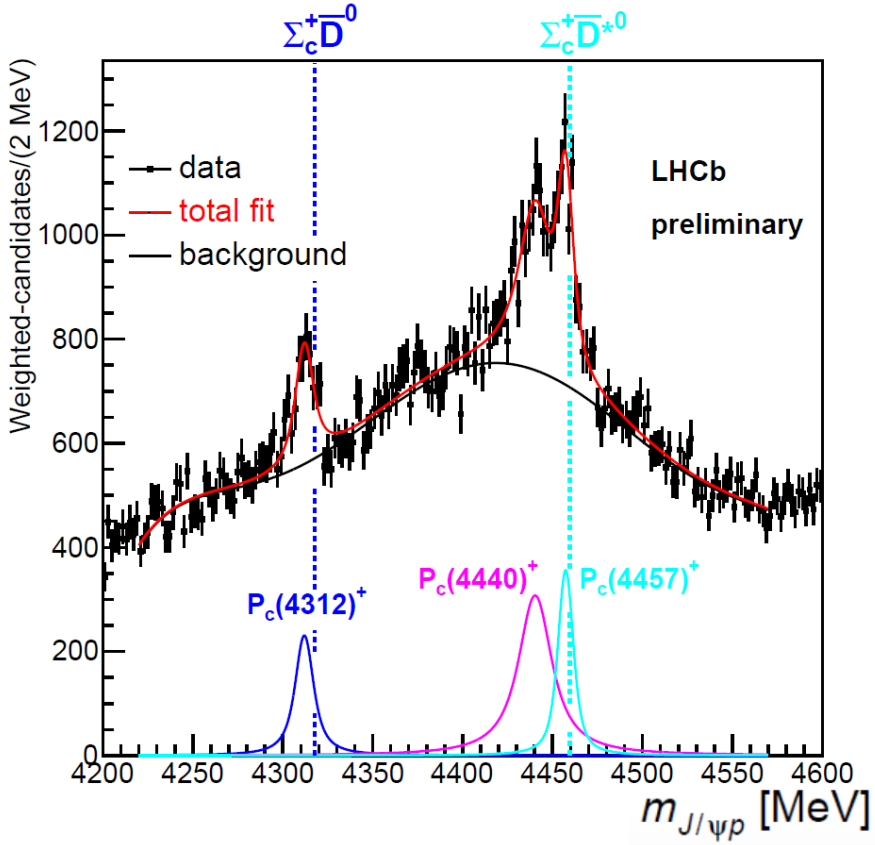
LHCb 2015

LHCb 2019

1904.03947







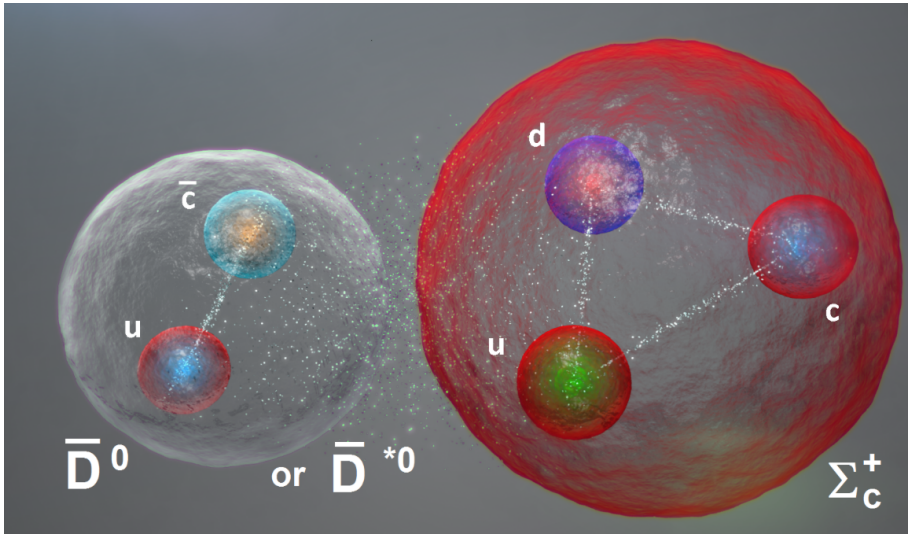
LHCb 2015	m (MeV)	Γ (MeV)
Pc(4380)	4380 ± 40	205 ± 100
Pc(4449)	4450 ± 5	40 ± 25

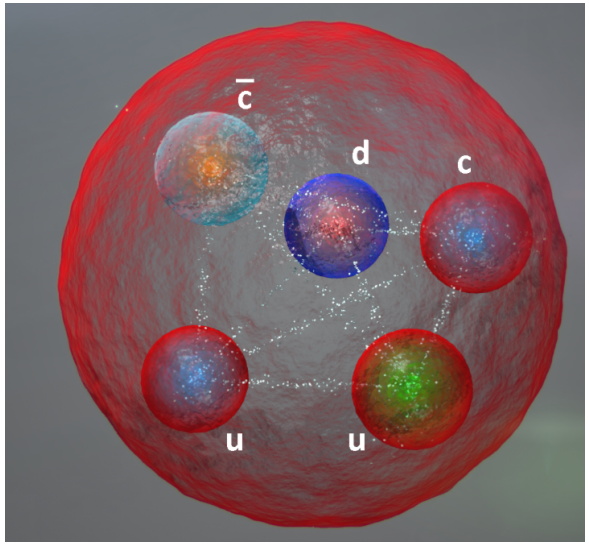
LHCb 2019	m (MeV)	Γ (MeV)
Pc(4312)	4311 ± 8	9.8 ± 2.7 + 3.7/-4.5
Pc(4440)	4440 ± 5	20.6 ± 4.9 + 8.7/-10.1
Pc(4457)	4457 ± 5	6.4 ± 2 + 5.7/-1.9

All pentaquarks observed in p J/ψ decay

$$P_c \rightarrow p \;\; J/\psi$$

$$\mathrm{uud} \;\; \bar{\mathrm{c}}\mathrm{c}$$





Status of Pc channel from previous lattice simulations

No previous lattice QCD simulation reaching energies of Pc (which are far above p J/Ψ threshold)

Previous lattice simulations: study of p J/Ψ interactions near threshold

- HALQCD method (Nf=2+1, PACS-CS)

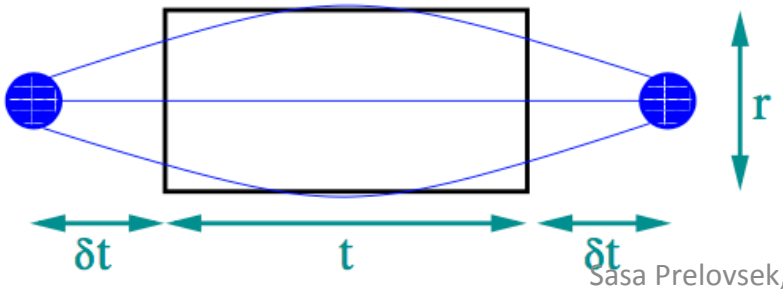
  Sugiura, Ikeda, Ishii, Proceedings of Lattice 2017, EPJ Web of Conferences 175, 05011 (2018) ; 1905.03934

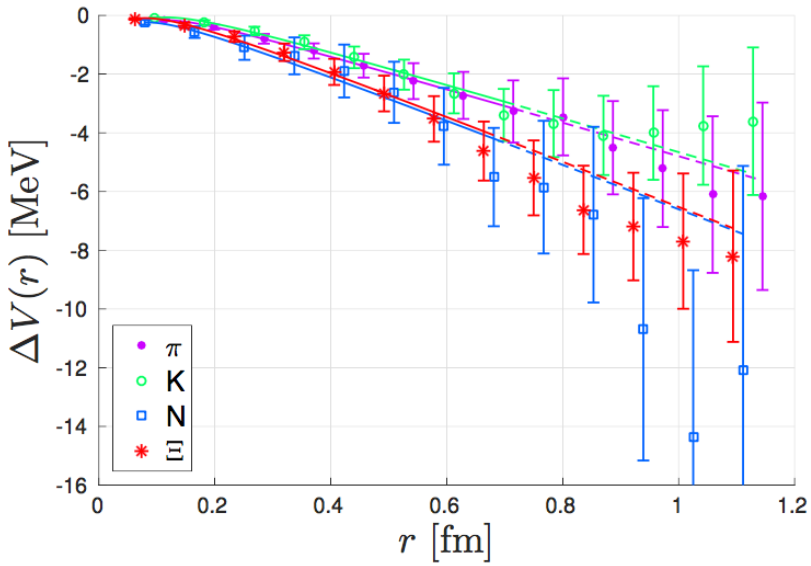
  Small interaction found, which does not support bound states or resonances

- Hadro-quarkonium with static heavy quark

  Alberti, Bali, Collins, Knechtli, Moir, Soldner, PRD 2017

  1608.06537





this talk focuses on this

↓

Nucleon-J/Ψ and nucleon-η_c scattering in Pc pentaquark channel from LQCD

U. Skerbis and S.P. , PRD 99 094595 (2019), 1811.02285

this work was completed before LHCb 2019 discovery ...

Decay channels related to Pc

Pc(4380)

Pc(4449)

Threshold locations

J^P	L	$m_m + m_b$ [MeV]	meson	barion
$\frac{3}{2}^-$	2^+	3921	$\eta_c(1s)$	p
	0^+	4034	J/ψ	p
	0^+	4293	$D^{*0}(\bar{2}007)$	Λ_c^+
	0^+	4387	D^-	$\Sigma_c^{++}(2520)$
	1^-	4352	χ_{c0}	p
	1^-	4448	χ_{c1}	p
$\frac{3}{2}^+$	1^-	3921	$\eta_c(1s)$	p
	1^-	4034	J/ψ	p
	1^-	4151	$\bar{D}^0$	Λ_c^+
	1^-	4293	$D^{*0}(\bar{2}007)$	Λ_c^+
	1^-	4324	D^-	$\Sigma_c^{++}(2455)$
	1^-	4387	D^-	$\Sigma_c^{++}(2520)$
	0^+	4448	χ_{c1}	p
$\frac{5}{2}^-$	2^+	3921	$\eta_c(1s)$	p
	2^+	4034	J/ψ	p
	1^-	4448	χ_{c1}	p
$\frac{5}{2}^+$	3^-	3921	$\eta_c(1s)$	p
	1^-	4034	J/ψ	p
	1^-	4293	$D^{*0}(\bar{2}007)$	Λ_c^+
	1^-	4387	D^-	$\Sigma_c^{++}(2520)$

$$P_c = \mathrm{uud}\bar{\mathrm{c}}\mathrm{c} \rightarrow (\mathrm{uud})\,(\bar{\mathrm{c}}\mathrm{c})$$

light-baryon charmonium

$$\rightarrow (\mathrm{uuc})\,(\bar{\mathrm{c}}\mathrm{d})$$

charmed-baryon charmed-meson

We address simplified question :

Do Pc resonances appear in one-channel p J/ψ scattering on the lattice (in approximation where this channel is decoupled from other channels)

$$p\ \ J/\psi \rightarrow P_c \rightarrow p\ \ J/\psi$$

or equivalently

$$N\ \ J/\psi \rightarrow P_c \rightarrow N\ \ J/\psi$$

Note: we make only a first step towards Pc ;

Lattice setup

In order to not to get to many N(p) J/Ψ(-p) states below Pc :
small L is welcome for exploratory simulations

$16^3 \times 32$, a=0.124 fm, L≈2 fm

N_f=2, m_π=266 MeV

Wilson clover, charm quarks: Fermilab approach: **E-E_{ref}**

$$E_{ref} = \frac{1}{4}(3m_{J/\psi} + m_{\eta_c})$$

Full distillation: N_v=96 for charm quarks
N_v=48 for light quarks

Partial waves L for N J/Ψ

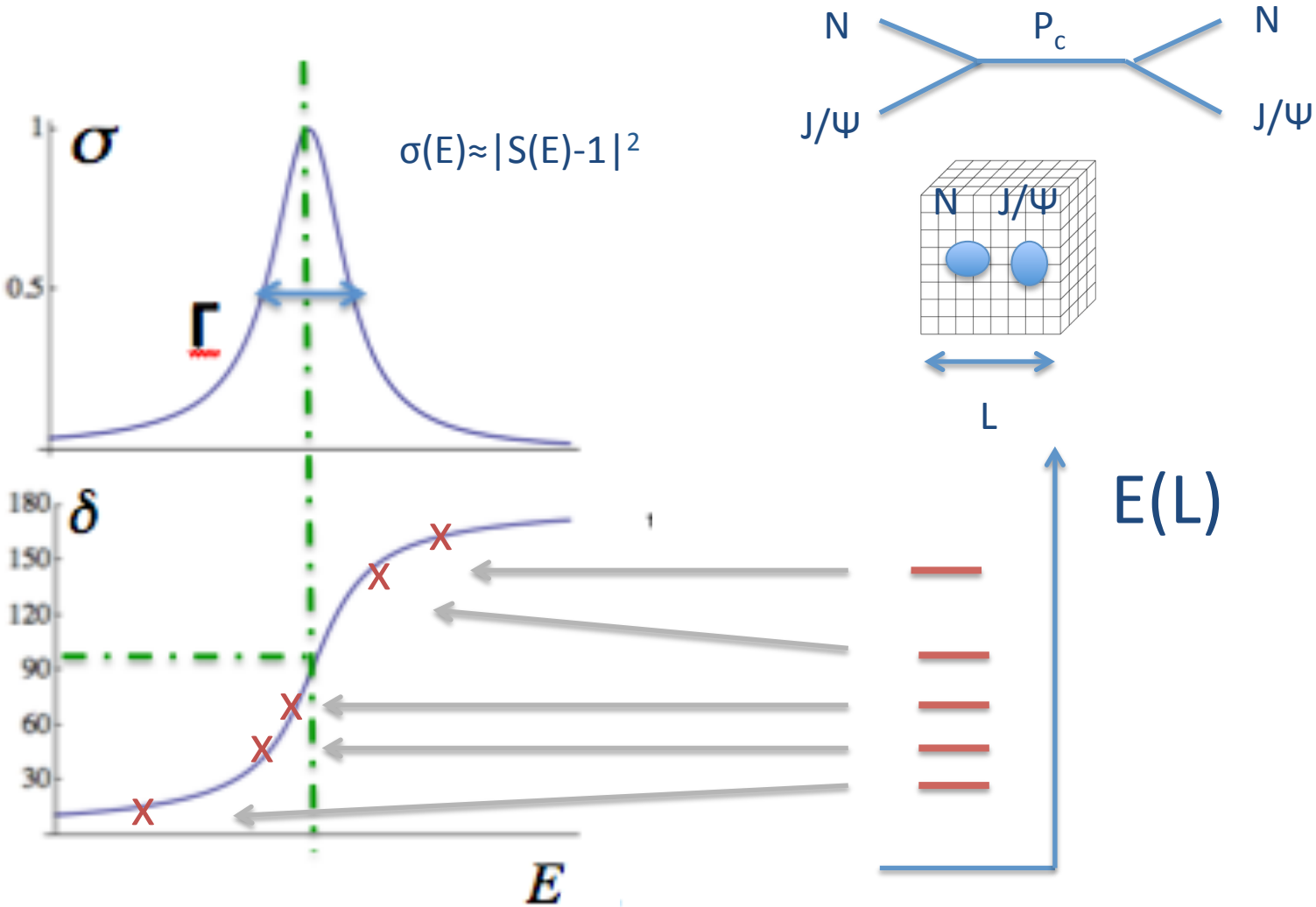
$$N \quad J/\psi \rightarrow P_c \rightarrow N \quad J/\psi$$

favoured by LHCb 2015

$J^P(N)$	$J^P(J/\Psi)$	$J^P(Pc)$	lowest L
$1/2^+$	1^-	$3/2^-$	0
		$3/2^+$	1
		$5/2^-$	2
		$5/2^+$	1

L > 0 : non-trivial operators

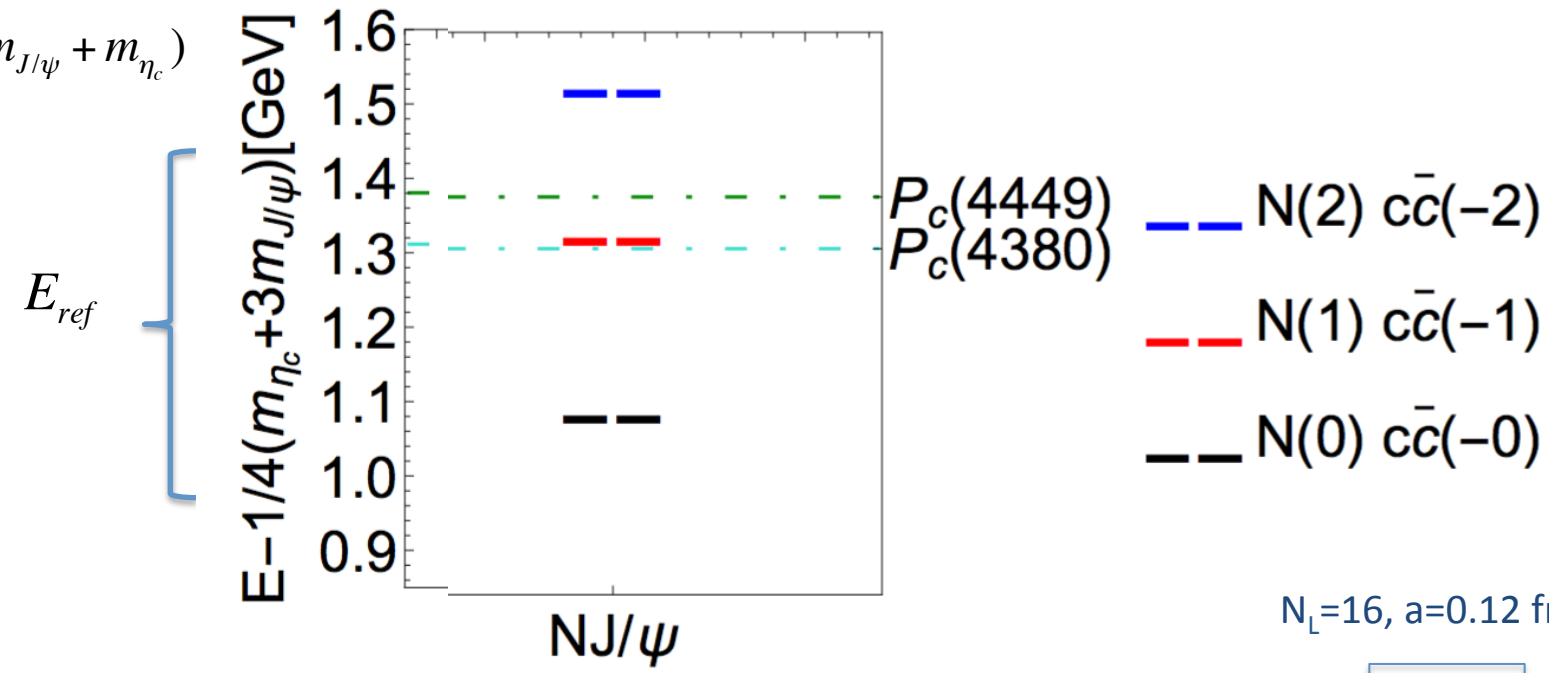
Scattering amplitude and eigen-energies E_n



scattering amplitude	$S(E)=e^{2i\,\delta(E)}$	generalized Luscher's relation ←	$E(L)$	energies from lattice with spatial extent L

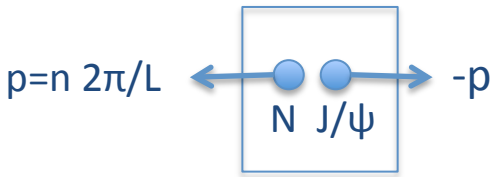
Expected E_n of N J/Ψ in non-interacting limit

$$E_{ref} = \tfrac{1}{4}(3m_{J/\psi} + m_{\eta_c})$$



$$N \quad J/\psi \rightarrow P_c \rightarrow N \quad J/\psi$$

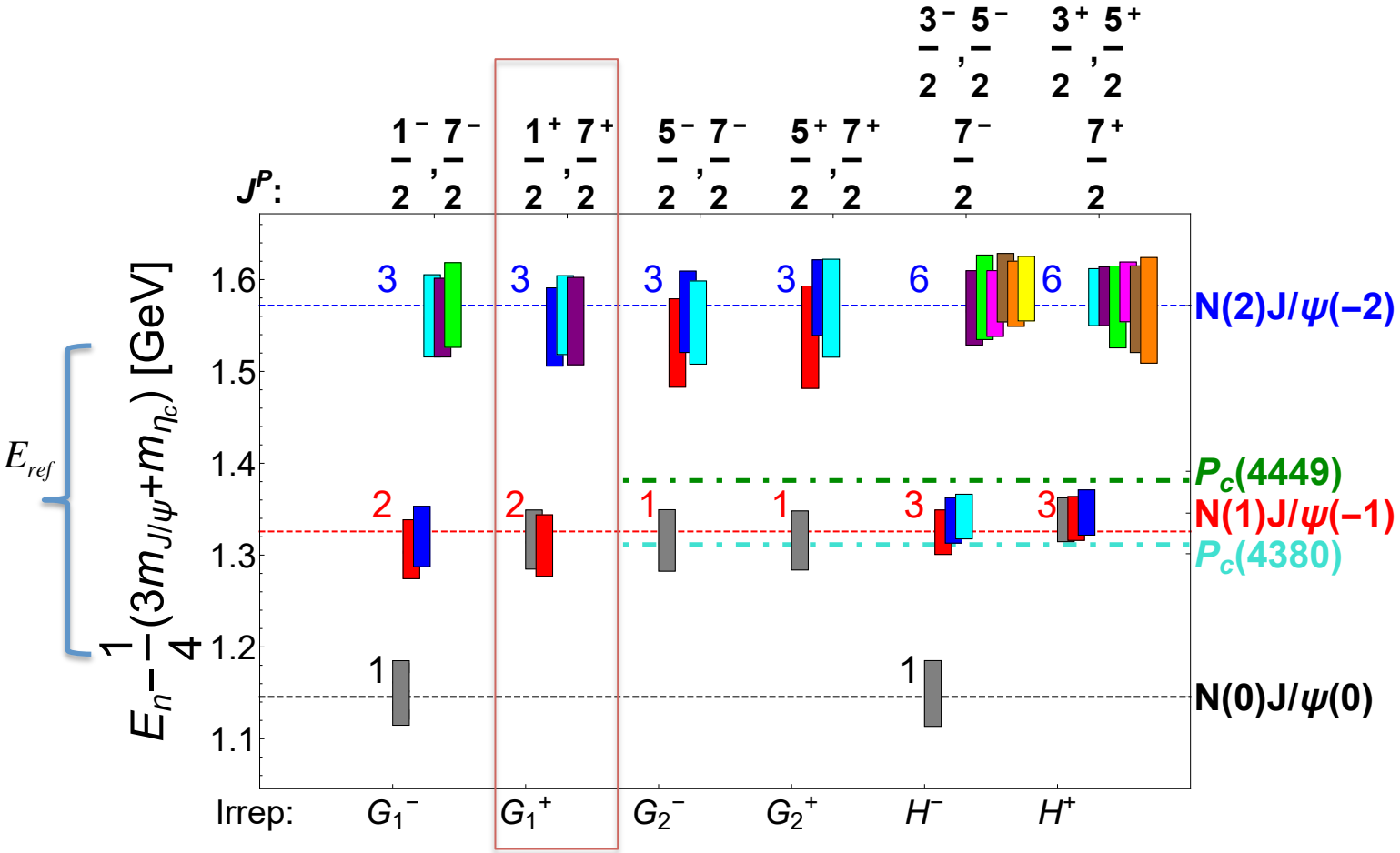
N_L=16, a=0.12 fm



We consider **P_{tot}=0** since parity is good quantum number in this case

Aim: extract all eigen-energies up to **N(p) J/ψ(-p)** for p<=2 for all J^P with J ≤ 5/2

Glimpse at results: N J/Ψ eigen-energies
Why there are so many almost-degenerate states?



linearly independent N J/Ψ (non-interacting)

N(1/2⁺) J/ψ(1⁻) S=1/2 L=1 / S=3/2 L=1 } $J^P=1/2^+$

two degenerate eigenstates expected even in continum since N and J/Ψ carry spin

Irreducible representations for Pc channel with half-integer spin

O_h

SO(3)

irrep Γ^P	J^P
$G_1^\pm$	$\frac{1}{2}^\pm, \frac{7}{2}^\pm$
$G_2^\pm$	$\frac{5}{2}^\pm, \frac{7}{2}^\pm$
$H^\pm$	$\frac{3}{2}^\pm, \frac{5}{2}^\pm, \frac{7}{2}^\pm$

- Simulating system with total momentum zero.
- We consider all six irreps since J^P is not completely known from exp
- Particular focus on J favoured by LHCb 2015: J=3/2 or J=5/2

  H irrep H, G_2 irreps

operators for N J/Ψ scattering

O="N_{ms} (p) V_i(-p)"

used at source and sink

$$V_i(p) = \sum_x \bar{q}\, \Gamma\, \gamma_i\, q\, e^{ipx} \qquad i = x, y, z \qquad \Gamma : (I, \gamma_4)$$

$$N_{\pm 1/2}(p) = \sum_x \epsilon_{abc}\, P_+ \Gamma q_{\frac{1}{2}}\, [q^{bT} \tilde{\Gamma} q^c]\, e^{ipx}$$

$$(\Gamma, \tilde{\Gamma}) : (\mathbb{1}, C\gamma_5),\ (\gamma_5, C),\ (\mathbb{1}, \imath\gamma_4 C\gamma_5)$$

How to combine them (i,ms) to make correct quantum numbers (transform under irreps) ?

irrep Γ^P	J^P
$G_1^\pm$	$\frac{1}{2}^\pm, \frac{7}{2}^\pm$
$G_2^\pm$	$\frac{5}{2}^\pm, \frac{7}{2}^\pm$
$H^\pm$	$\frac{3}{2}^\pm, \frac{5}{2}^\pm, \frac{7}{2}^\pm$

Operators with partial-wave method

O="N_{ms} (p) V_i(-p)"

$$O^{|p|,J,m_J,L,S} = \sum_{m_L,m_S,m_{s1},m_{s2}} C^{Jm_J}_{Lm_L,Sm_S} C^{Sm_S}_{s_1m_{s1},s_2m_{s2}} \sum_{R\in O} Y^*_{Lm_L}(\widehat{Rp}) N_{m_{s1}}(Rp) V_{m_{s2}}(-Rp)$$

CalLat: Berkowitz, et. all PLB , 2016(12) 024;
proof of transform. properties S. P., U.S., C.B. Lang ; JHEP 2017

$$R_a O^{J,m_J,S,L} R_a^{-1} = \sum_{m'_J} D^J_{m_J m'_J}(R_a^{-1}) O^{J,m'_J,S,L}$$

subduction to irrep

S : HSC; PRD 2010(82), 034508

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

one example for |p|=1

$$O^{[J=\frac{5}{2},L=1,S=\frac{3}{2}]}_{G_2^+,r=1} =$$

$$= N_{\frac{1}{2}}(e_x)V_y(-e_x) - N_{\frac{1}{2}}(-e_x)V_y(e_x) - iN_{-\frac{1}{2}}(e_x)V_z(-e_x) + iN_{-\frac{1}{2}}(-e_x)V_z(e_x)$$
$$+N_{\frac{1}{2}}(e_y)V_x(-e_y) - N_{\frac{1}{2}}(-e_y)V_x(e_y) + N_{-\frac{1}{2}}(e_y)V_z(-e_y) - N_{-\frac{1}{2}}(-e_y)V_z(e_y)$$
$$-iN_{-\frac{1}{2}}(e_z)V_x(-e_z) + iN_{-\frac{1}{2}}(-e_z)V_x(e_z) + N_{-\frac{1}{2}}(e_z)V_y(-e_z) - N_{-\frac{1}{2}}(-e_z)V_y(e_z)$$

Number of degenerate N J/Ψ eigen-states in non-interacting limit
=
Number of linearly independent N J/Ψ operators

explicit expressions for all p=0,1 operators

S. P., U.S., C.B. Lang ; JHEP 2017

irrep	$N(p)J/\psi(-p)$		
	$p^2=0$	$p^2=1$	$p^2=2$
G_1^+	0	2	3
G_1^-	1	2	3
G_2^+	0	1	3
G_2^-	0	1	3
H^+	0	3	6
H^-	1	3	6

for each of
this operator-type
we use two vector
and three nucleon choices:
6 =2*3 times more operators
than number of states expected
in non-interacting limit

General remark on two-hadron operators

Explicit expressions all for $H^{(1)}(p)H^{(2)}(-p)$

- PV, PN, VN, NN

- in three methods (projection, partial-wave, helicity)

- including proofs for all methods

- all irreps, $|p|=0,1$

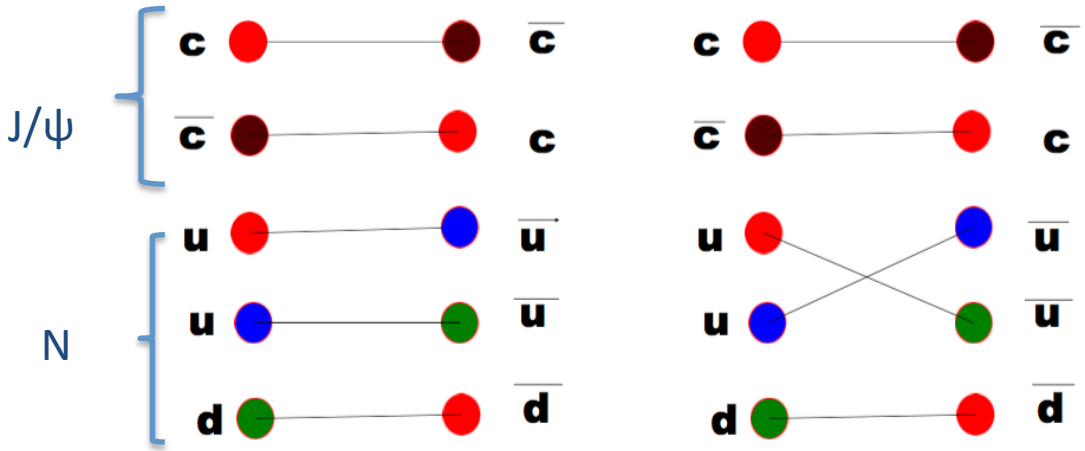
given in [S. P., U. Skerbis, C.B. Lang, arXiv:1607:06738, JHEP 2016]

operators from three methods are consistent (not equal) with each other

Correlation matrices for N J/ψ system

$O = \Sigma\ N_{ms}(p)\, V_i(-p)$

$$C_{ij}(t) = \langle 0|O_i(t)\bar{O}_j(0)|0\rangle$$



Wick contractions:

no quark line connects N and J/ψ

charm annihilation omitted

$$C = \sum \langle\langle 0|N_{m_s'}(p')\bar{N}_{m_s}(p)|0\rangle\langle 0|V_{i'}(p')V_i^\dagger(p)|0\rangle\rangle$$

separately pre-calculated for all momenta and polarizations

Correlation matrices and eigenstates

$$C_{ij}(t) = \langle 0|O_i(t)\bar{O}_j(0)|0\rangle =$$

$$= \sum_{n=1}^{\mathtt{N}} e^{-E_n t}\langle 0|O_i|n\rangle\langle n|\bar{O}_j|0\rangle, \;\; i,j = 1,...,\mathtt{N}$$

Number of operatros in each irrep

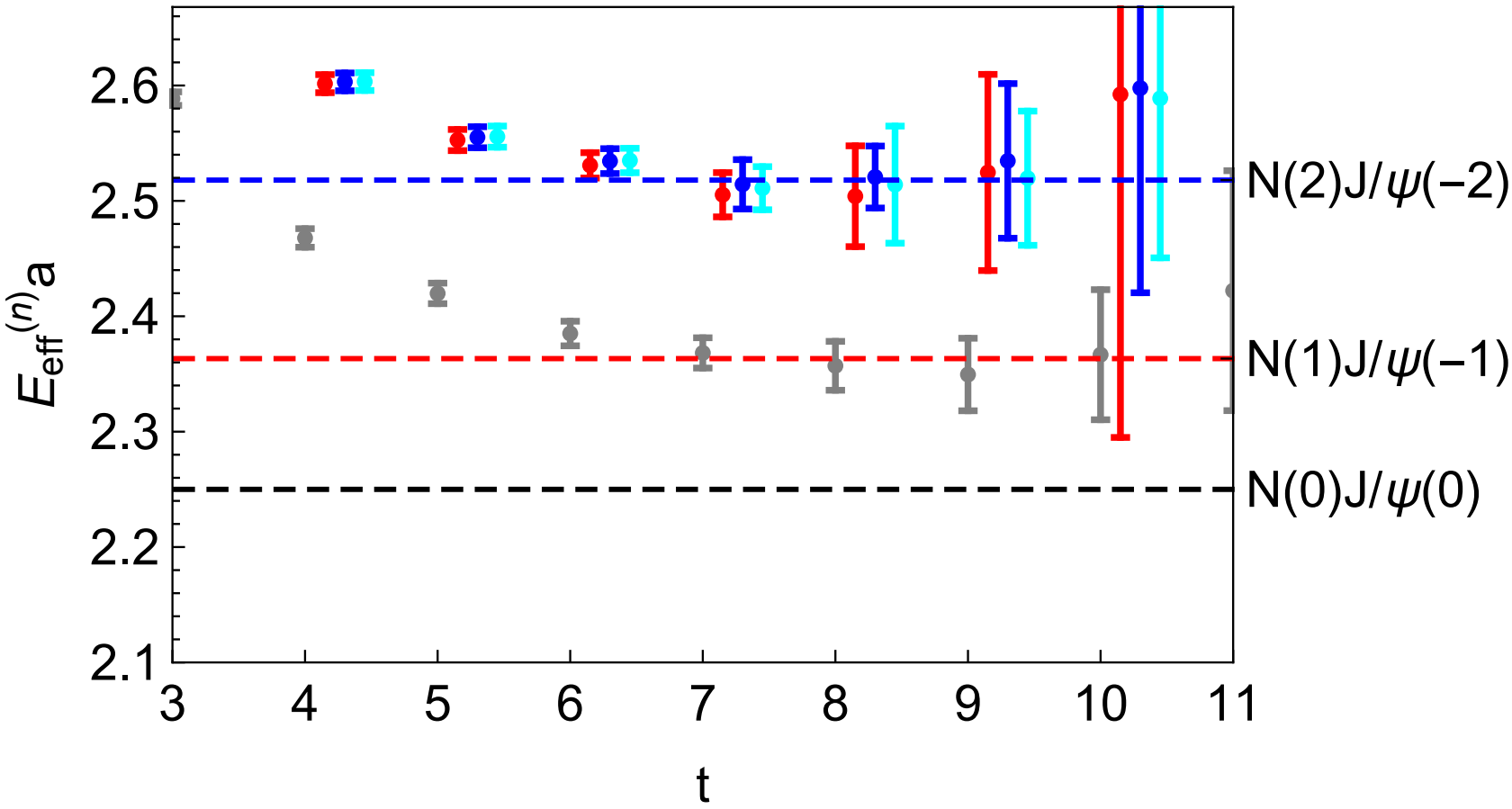
irrep	G_1^-	G_1^+	G_2^-	G_2^+	H^-	H^+
NJ/ψ	6×6	5×6	4×6	4×6	10×6	9×6

extracting eigen-energies using GEVP

$$C(t)u^{(n)}(t) = \lambda^{(n)}(t)C(t_0)u^{(n)}(t)$$

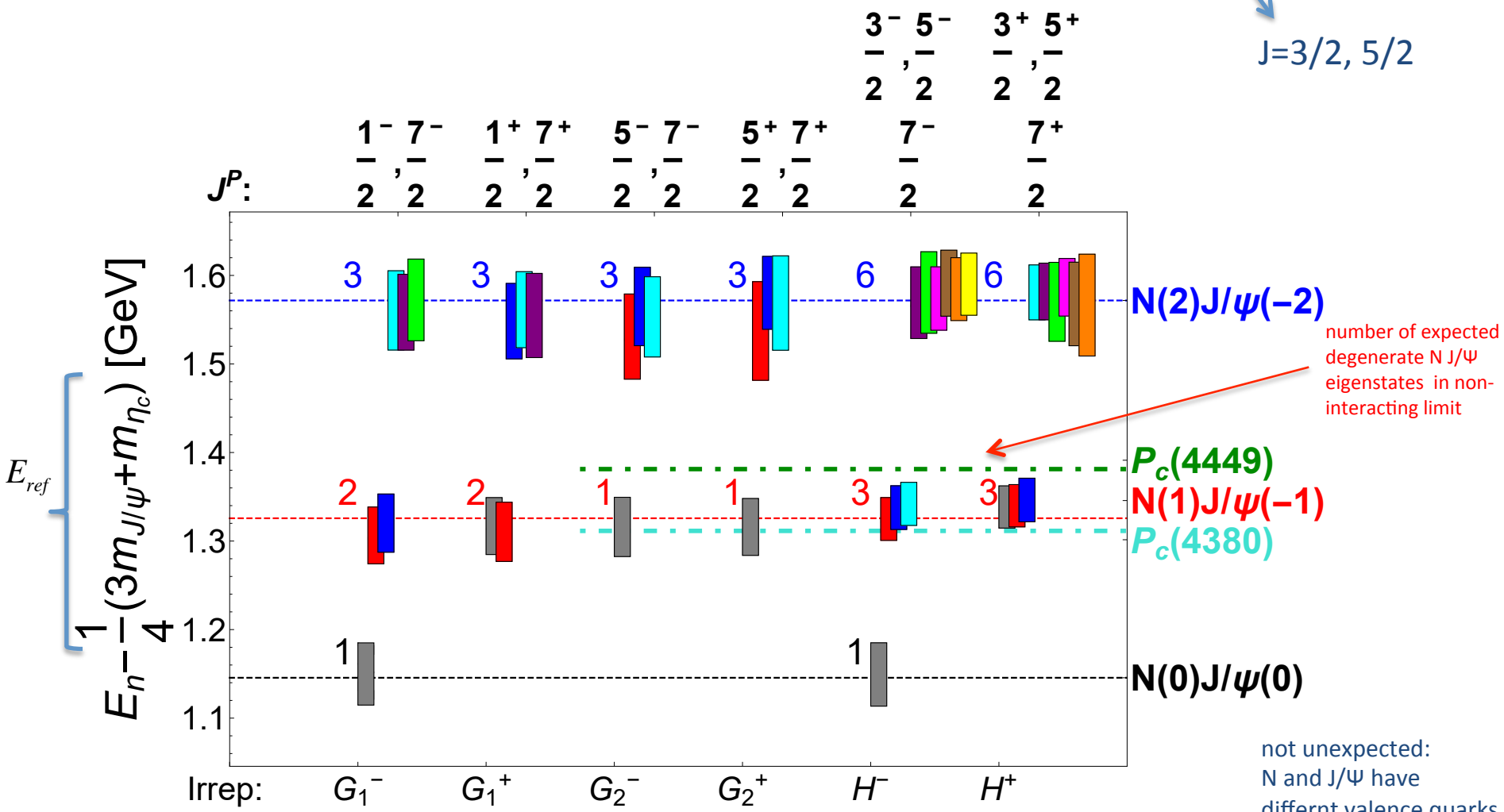
$$\lambda^{(n)}(t)_{\text{large t}} = A_n e^{-E_n t}$$

Example of effective masses: G_2^+



Result: N J/Ψ eigen-energies for all irreps (including Pc channels)

J=3/2, 5/2



number of expected degenerate N J/Ψ eigenstates in non-interacting limit

not unexpected: N and J/Ψ have differnt valence quarks

- E consistent with non-interacting energies (dashed lines); no significant energy shifts; no significant interaction
- number of states consistent with non-interacting case: carefully constructed operators crucial for this
- no additional eigenstate (related to Pc) observed

$\delta(E) \approx 0$

$S(E) \approx 1$

within large errors

Analytic prediciton of E_n based on experimental P_c assuming coupling only to N J/Ψ

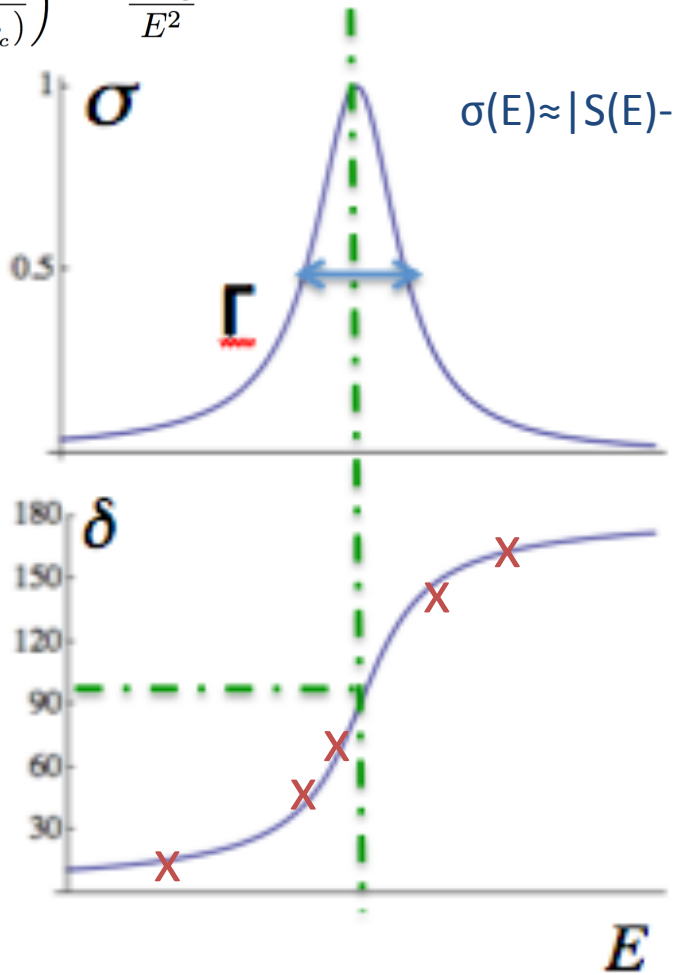
$$\cot\delta_{(L,S)} = \frac{M_{P_c} - E^2}{E\,\Gamma(E)}$$

$$\Gamma(E) = \Gamma_{P_c}\left(\frac{p(E)}{p(M_{P_c})}\right)^{2L+1}\frac{M_{P_c}^2}{E^2}$$

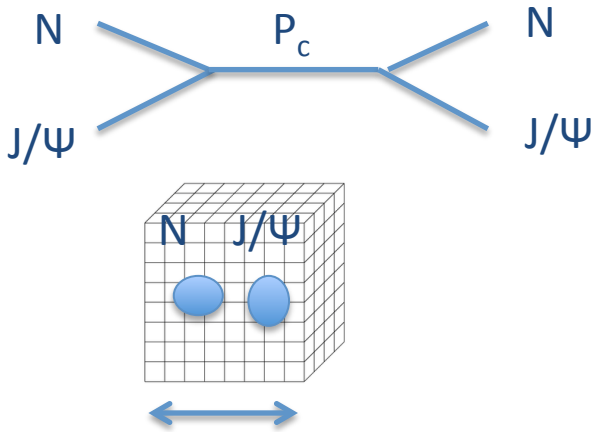
taking Pc from LHCb 2015

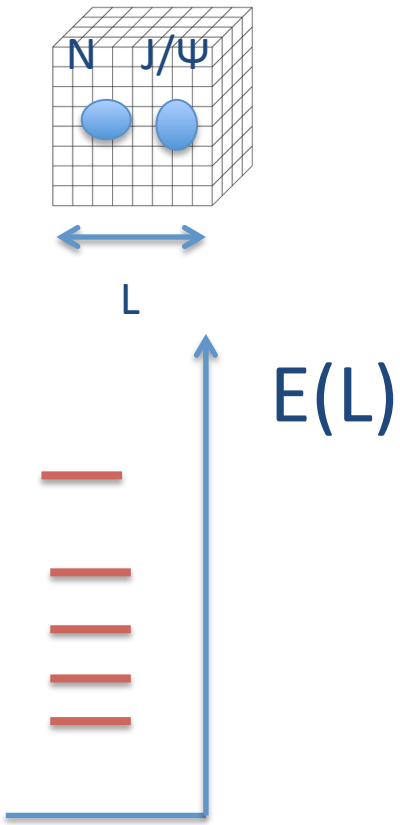
Pc(4380)

Pc(4449)



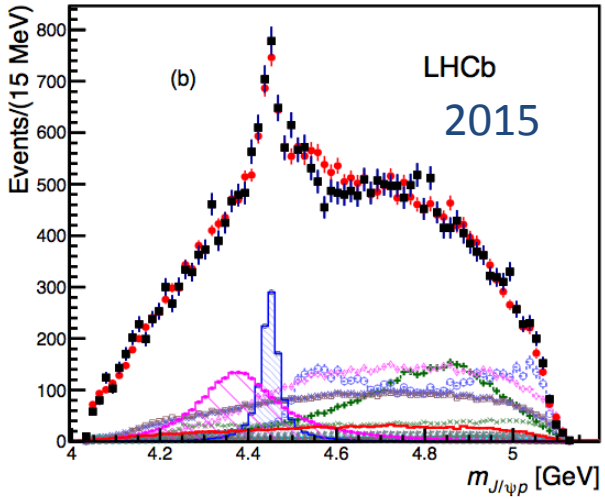
σ(E)≈|S(E)-1|²

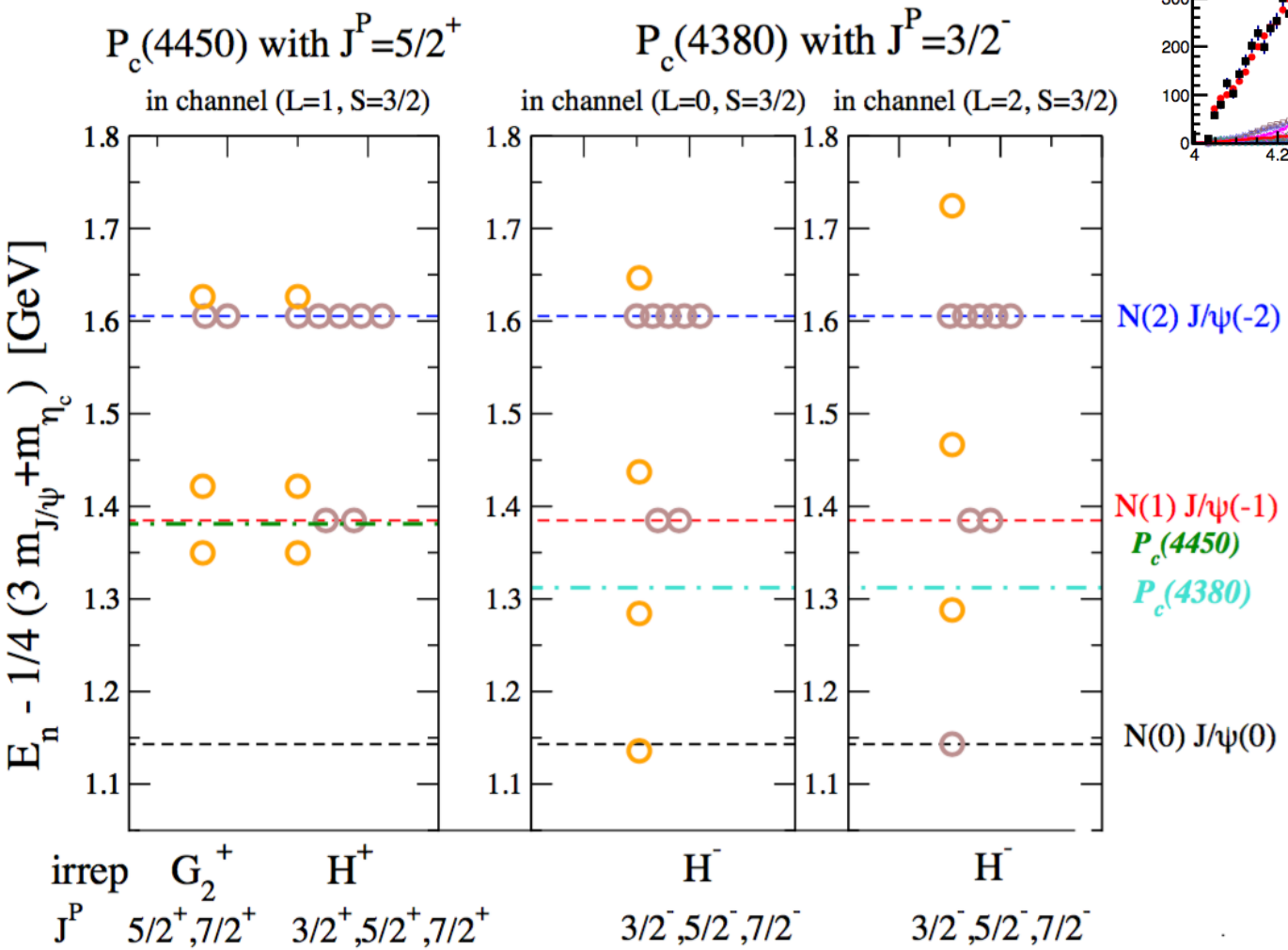




scattering amplitude	$S(E)=e^{2i\,\delta(E)}$	generalized Luscher's relation →	E(L)	energies from lattice with spatial extent L

Analytic prediciton based on $P_c(4449)$ or $P_c(4380)$ assuming coupling only to N J/Ψ





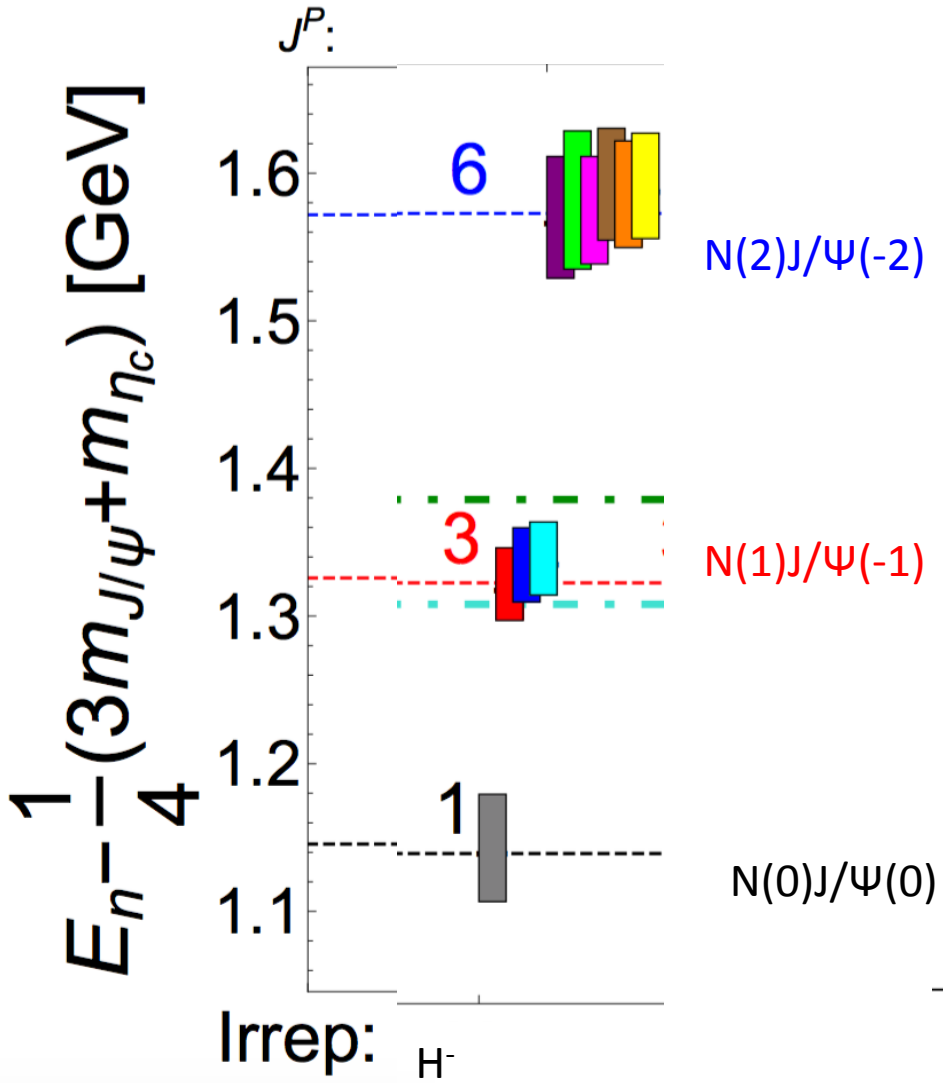
Predicts one extra level with respect to interacting case

assuming that P_c resides only in a single partial wave (L, S) and that there is no interaction in the other channels.

Comparing lattice data and analytic prediction for one-channel Pc(4380) with $J^P = 3/2^-$

10=1+3+6 states expected in non-interacting limit

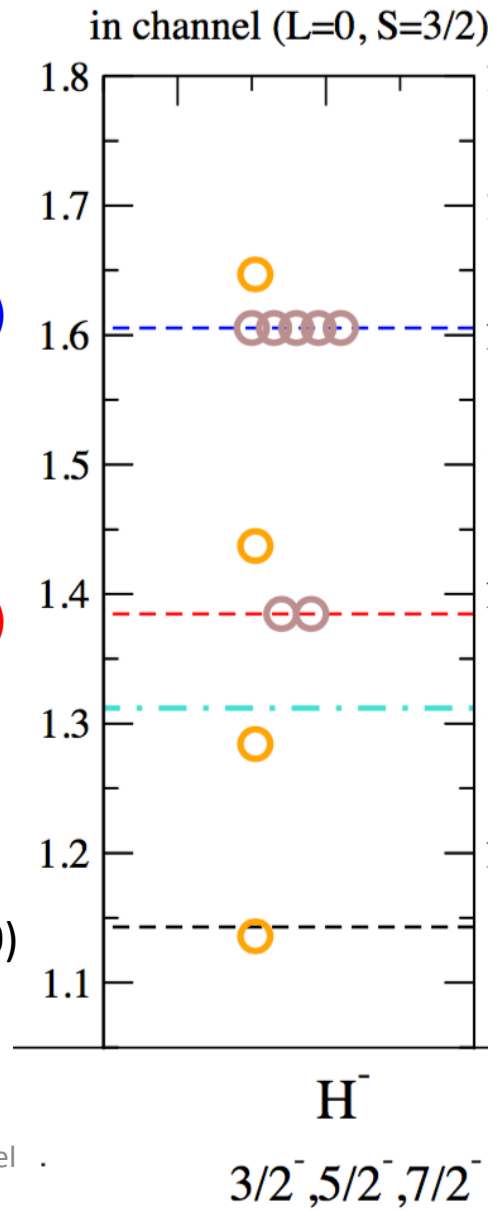
10 states found

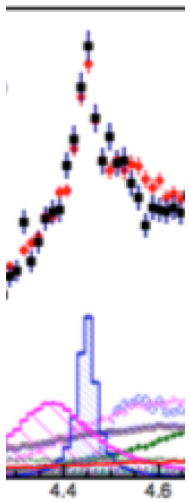


N(2)J/Ψ(-2)

N(1)J/Ψ(-1)

N(0)J/Ψ(0)

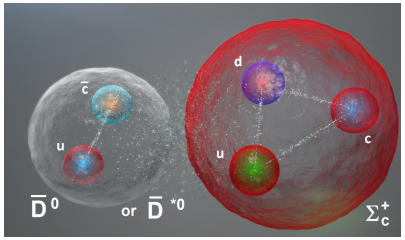




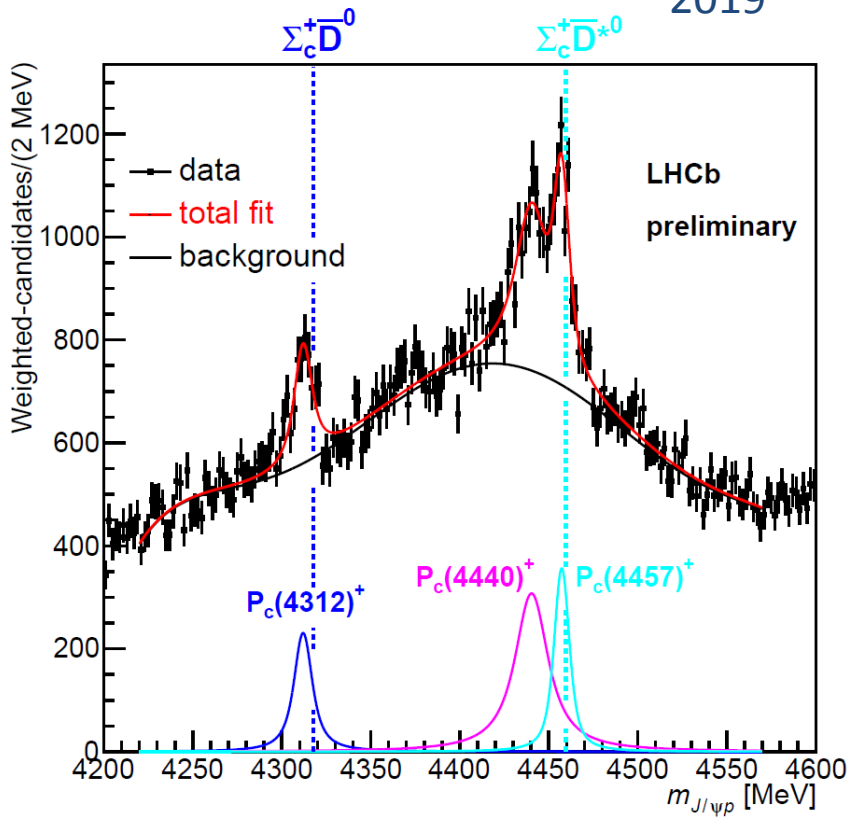
11 states expected in case of Pc

$P_c(4380)$

Answer to the question posed



2019



Question we addressed: Do Pc resonances appear in one-channel p J/ψ scattering on the lattice (in approximation where this channel is decoupled from other channels)

$$p \;\; J/\psi \rightarrow P_c \rightarrow p \;\; J/\psi$$

The answer from our lattice simulation : No.

The Pc resonances do NOT appear in one-channel p J/ψ scattering on the lattice

This indicates that the coupling of p J/ψ channel with other two-hadron channels is likely responsible for Pc resonances in experiment.

This is in line with LHCb 2019 results, where Pc's are found near other thresholds. This by itself indicates that other channels are important.

Conclusions concerning P_c (so far)

- Interaction between N and J/Ψ found to be small:
  consistent with previous lattice studies of this system near threshold

- Lattice spectra do not support the scenario where a P_c resonance couples only to N J/Ψ decay channel and is decoupled from other channels.

- Lattice results indicate that **the existence of Pc resonance within one-channel N J/Ψ scattering is not favored in QCD**.

- This might **suggest that the strong coupling between the N J/Ψ with other channels might be responsible for the existence of the Pc resonances in experiment.**

- Future lattice simulations of the coupled-channel scattering will be needed to confirm or refute this.

- Future challenge: incorporate also charmed-meson charmed-baryon channel.

Backup

Energies of single hadrons

particle	p^2	$E_H(p)a$	$\sigma_E a$
N	0	0.701	0.019
	1	0.769	0.028
	2	0.849	0.054
J/ψ	0	1.539	0.001
	1	1.576	0.001
	2	1.613	0.001

Analytic prediciton of E_n based on P_c assuming coupling only to N J/Ψ

Relation between E_n and δ for arbitrary spin [Briceno, PRD89, 074507 (2014)

$S = I + i\,M = e^{2i\delta}$

$$\det_{oc}\left[\det_{lSJm_J}\left[\mathcal{M}^{-1} + \delta\mathcal{G}^V\right]\right] = 0 \qquad c \propto Z_{00}$$

$$[\delta\mathcal{G}_j^V]_{Jm_J,lS;J'm_{J'},l'S'} = \frac{ik_j^*\delta_{SS'}}{8\pi E^*} n_j \left[\delta_{JJ'}\delta_{m_Jm_{J'}}\delta_{ll'} + i\sum_{l'',m''}\frac{(4\pi)^{3/2}}{k_j^{*l''+1}} c^{\mathbf{d}}_{l''m''}(k_j^{*2};L)\right.$$

$$\left.\times \sum_{m_l,m_{l'},m_S}\langle lS, Jm_J|lm_l, Sm_S\rangle\langle l'm_{l'}, Sm_S|l'S, J'm_{J'}\rangle \int d\Omega\, Y^*_{l,m_l}Y^*_{l'',m''}Y_{l',m_{l'}}\right]$$

assume that P_c resides only in a single partial wave (L, S) and that there is no interaction in the other channels.

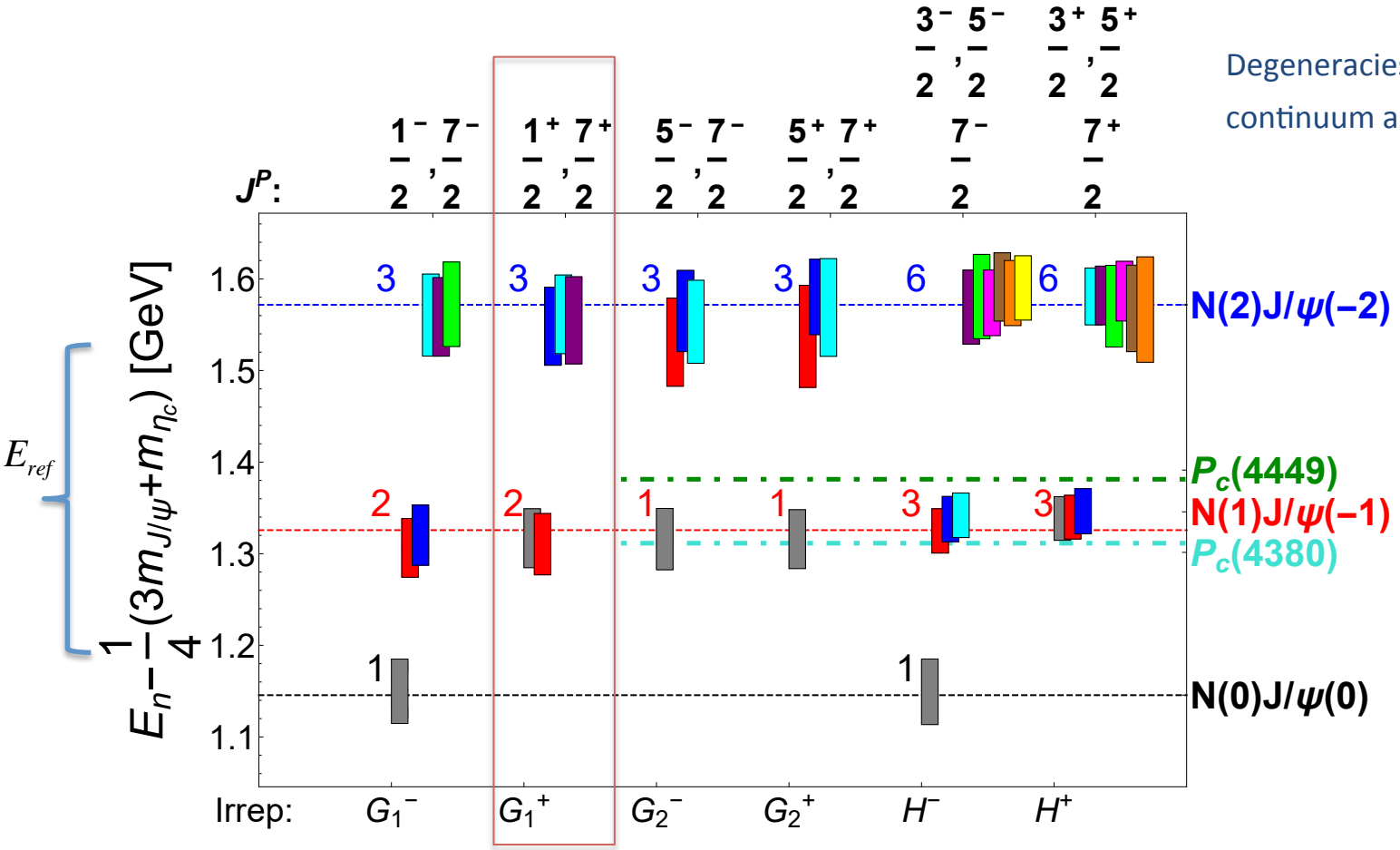
$$\cot\delta_{(L,S)} = \frac{2Z_{00}(1;\ p^2(\frac{2\pi}{\mathrm{L}})^2)}{\sqrt{\pi}\ \mathrm{L}\ p}$$

Luscher's relation between E_n and δ

BW form for P_c assumed, M_{Pc} and Γ_{Pc} taken from exp , E_n predicted

$$\cot\delta_{(L,S)} = \frac{M_{P_c} - E^2}{E\ \Gamma(E)} \qquad \Gamma(E) = \Gamma_{P_c}\left(\frac{p(E)}{p(M_{P_c})}\right)^{2L+1}\frac{M_{P_c}^2}{E^2}$$

Glimpse at results: N J/Ψ eigen-energies for all irreps
Why there are so many almost-degenerate states?



Degeneracies expected also in continuum as N and J/Ψ carry spin

linearly independent N J/Ψ (non-interacting)

favourite for narrow Pc

example G_1^+ : N(1/2⁺) J/ψ(1⁻) S=1/2 L=1

S=3/2 L=3

J^P=1/2⁺ two degenerate eigenstates expected even in continuum

S=3/2 L=3 J^P=7/2⁺

three degenerate eigenstates expected in G2-

G_1^+

Nucleon-η_c scattering