Z_b tetraquark channel and $B\bar{B}^*$ interaction

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Outline

- Discovery of Z_b in experiment

$$Z_b^+ \approx \bar{b}\, b\, \bar{d}\, u$$

- Why it is (to) difficult to study scattering in Z_b channel with Luscher's method
- Study of Z_b system with static b quarks
- possible indication for existence of Z_b tetraquarks under employed approximations

Zb in experiment

discovered by Belle in 2011 [PRL 108 (2012) 122001]

$Z_b^+(10610)$, $Z_b^+(10650)$

I=1, $J^{PC}=1^{+-}$

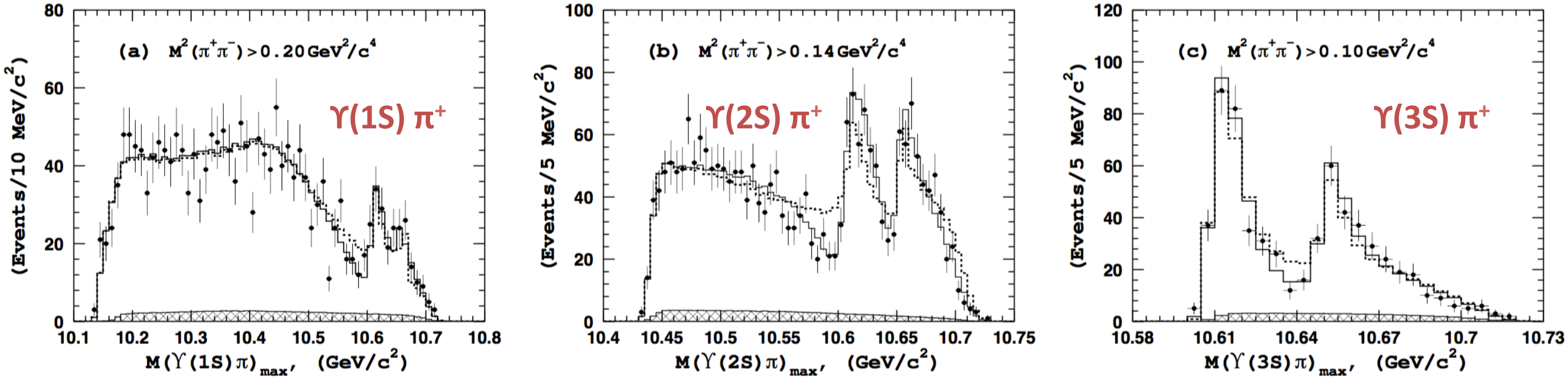
$$Z_b^+ \rightarrow \Upsilon \ \pi^+$$

$$\bar{b}b \ \bar{d}u$$

$\bar{b}$ u
b $\bar{d}$

Z_b observed in decays Υ(1S,2S,3S) π
h_b(1S,2S) π
B $\underline{B}$* , B* $\underline{B}$*

Belle PRD 91 (2015) 072003



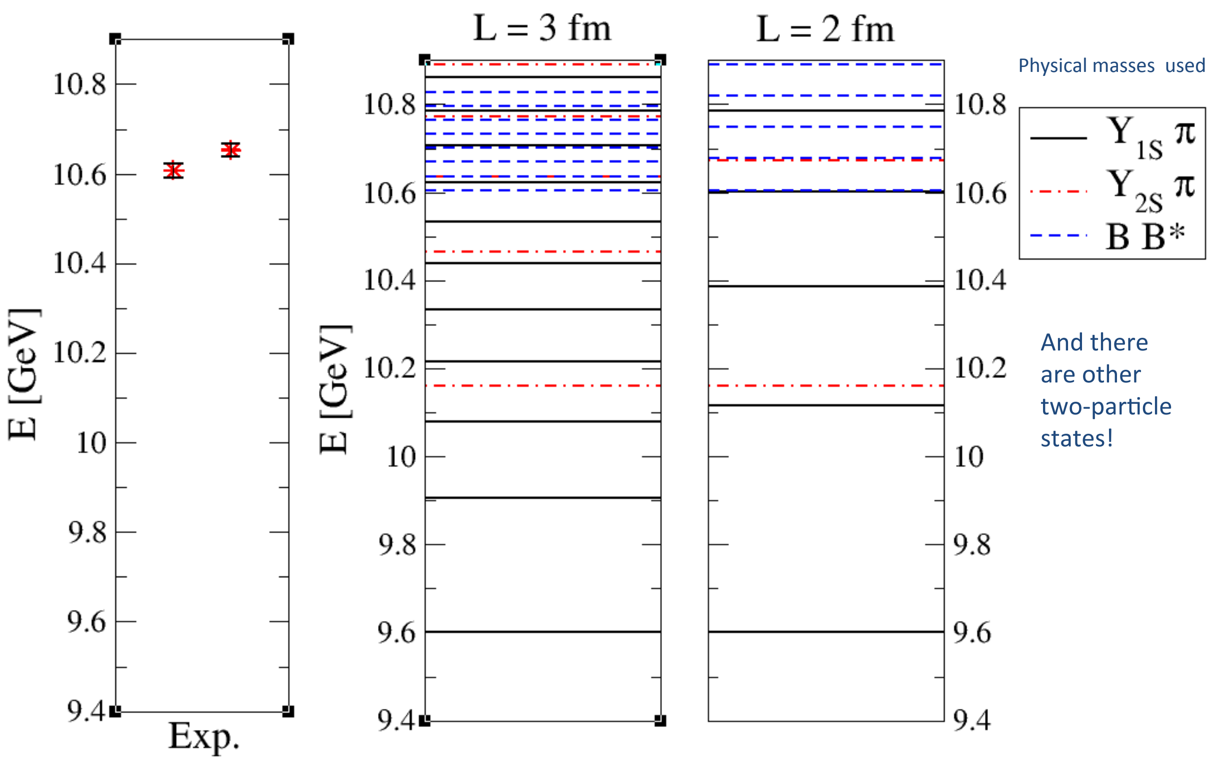
↑ m_B+m_{B*}

Z_b^+ with non-static b and Luscher's approach: (to) challenging

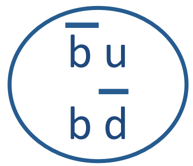
Eigen-energies in non-interacting limit

$$E^{n.i.}(L) = \sqrt{m_1^2 + \vec{p}^2} + \sqrt{m_2^2 + (-\vec{p})^2}$$

$$\vec{p} = \frac{2\pi}{L}\vec{n}$$



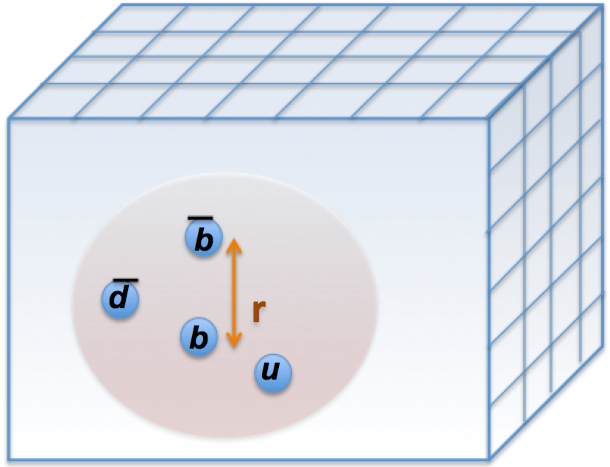
And there are other two-particle states!



Rigorous treatment very challenging:

- at least 7 two-particle channels coupled
- very dense B$\underline{B}$* and B*$\underline{B}$* energy levels

Z_b with static b and $\bar{b}$

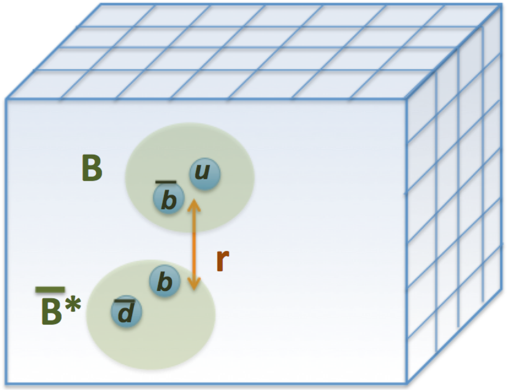


Only previous lat study

Bicudo, Cichy, Peters, Wagner [proceedings Lat16: 1602.07621
proceedings Lat17: 1709.03306]

Born-Oppenheimer approach

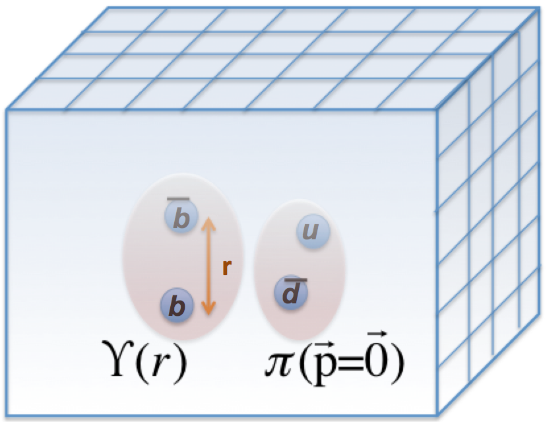
Fock components incorporated

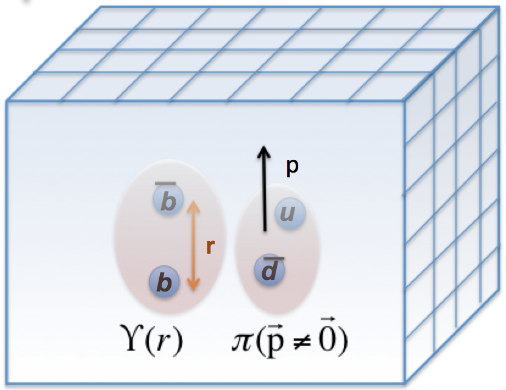


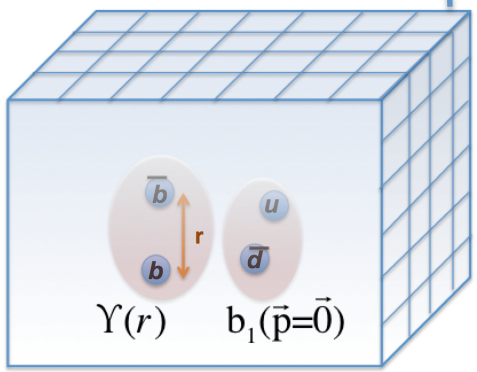
- main aim: extract static potential V(r) between B and $\bar{B}$*
- momentum of light degrees of freedom not conserved

in presence of static quarks

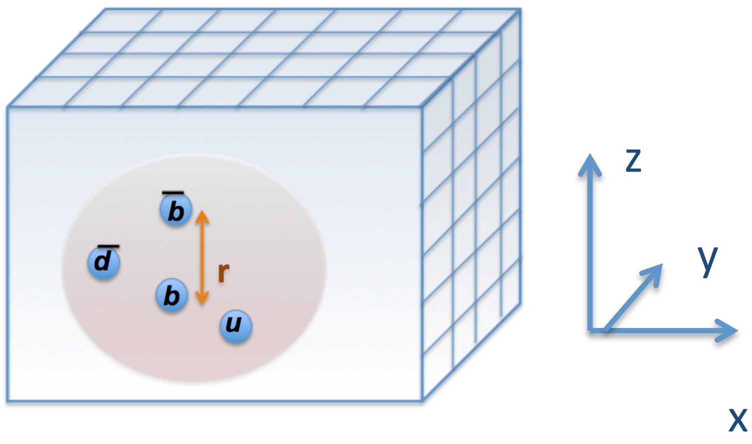
not incorporated before







Zb with static b $\underline{b}$



Good symmetries and quantum numbers:

$I=1 \quad I_3=0$ (consider neutral Z_b)

$S_{heavy}=1 \quad (Sz)_{heavy}=0 \qquad \bar{b}(\uparrow)b(\downarrow)-\bar{b}(\downarrow)b(\uparrow)$ heavy quark can not flip spin via gluon exchange

note: transition is not possible to final states with

$S_{heavy}=0$ (η_b, h_b) $\quad \bar{b}(\uparrow)b(\downarrow)+\bar{b}(\downarrow)b(\uparrow)$

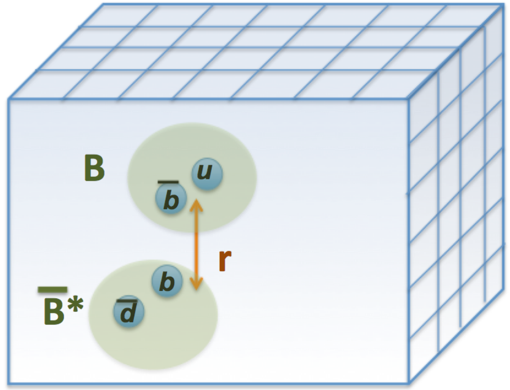
$(Jz)_{light}=0$ [Jx and Jy not conserved]

C•P= -1 (P= inversion over midpoint between b and $\underline{b}$)

R_{light}= reflection over yz plane = P_{light} * $R_{light}(y,\pi)$: ε=-1

momentum of light degrees of freedom: not conserved

Operators $O_{1\text{-}6}$ with given quantum numbers



in this way $(Jz)_{light}$, S_{heavy} and $(Sz)_{heavy}$
are indeed separately good quantum num.

inspired by Wagner et al.

$$O_1 = O^{B\bar{B}*} = \sum_{a,b} \sum_{A,B,C,D} \Gamma_{BA}\tilde{\Gamma}_{CD}\ \bar{b}^a_C(0) q^a_A(0)\ \bar{q}^b_B(r) b^b_D(r)\ , \quad \Gamma = P_-\gamma_5\ \tilde{\Gamma} = \gamma_z P_+,$$

$$= \sum_{a,b} \sum_{A,B,C,D} \bar{q}^b_B(r)\Gamma_{BA} q^a_A(0)\ \bar{b}^a_C(0)\tilde{\Gamma}_{CD} b^b_D(r)$$

$$\propto [\bar{b}(0)P_-\gamma_5 q(0)]\ [\bar{q}(r)\gamma_z P_+ b(r)] + [\bar{b}(0)P_-\gamma_z q(0)]\ [\bar{q}(r)\gamma_5 P_+ b(r)]$$

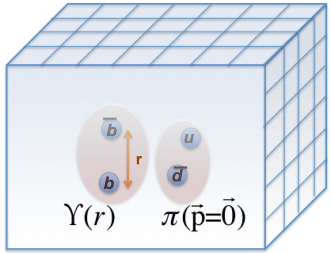
$$- [\bar{b}(0)P_-\gamma_x q(0)]\ [\bar{q}(r)\gamma_y P_+ b(r)] + [\bar{b}(0)P_-\gamma_y q(0)]\ [\bar{q}(r)\gamma_x P_+ b(r)]$$

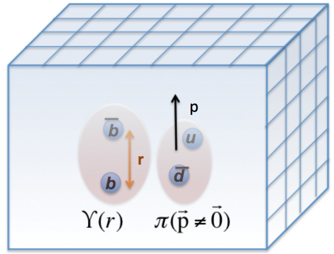
$$O_5 = O^{B\bar{B}*} = \sum_{a,b} \sum_{A,B,C,D} \Gamma_{BA}\tilde{\Gamma}_{CD}\ \bar{b}^a_C(0)\nabla^2 q^a_A(0)\ \bar{q}^b_B(r)\nabla^2 b^b_D(r)\ , \quad \Gamma = P_-\gamma_5\ \tilde{\Gamma} = \gamma_z P_+,$$

$I=1$ $I_3=0$: $\quad \bar{q}q \to \bar{u}u - \bar{d}d$

Operators $O_{1\text{-}6}$

[..] indicate color singlets





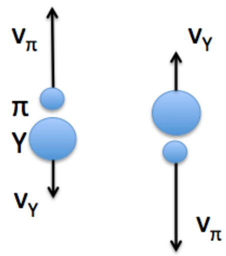


illustration of O_3,4
for non-static case

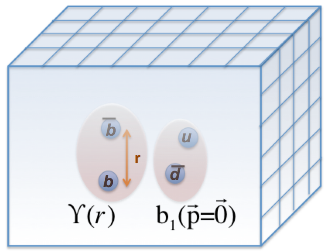
$$O_2 = O^{\Upsilon\pi(0)} = \Upsilon_z\ \pi_{p=000} = [\bar{b}(0)\gamma_z P_+ b(r)]\ [\bar{q}\gamma_5 q]_{p=000}$$

$$O_3 = O^{\Upsilon\pi(1)} = \Upsilon_z\ (\pi_{p=001} + \pi_{p=00-1}) = [\bar{b}(0)\gamma_z P_+ b(r)]\ \left([\bar{q}\gamma_5 q]_{p=001} + [\bar{q}\gamma_5 q]_{p=00-1}\right)$$

$$O_4 = O^{\Upsilon\pi(2)} = \Upsilon_z\ (\pi_{p=002} + \pi_{p=00-2}) = [\bar{b}(0)\gamma_z P_+ b(r)]\ \left([\bar{q}\gamma_5 q]_{p=002} + [\bar{q}\gamma_5 q]_{p=00-2}\right)$$

- momentum in z direction ensures that $(J_z)_{light}=0$
- the sum ensures that CP is good q.n.

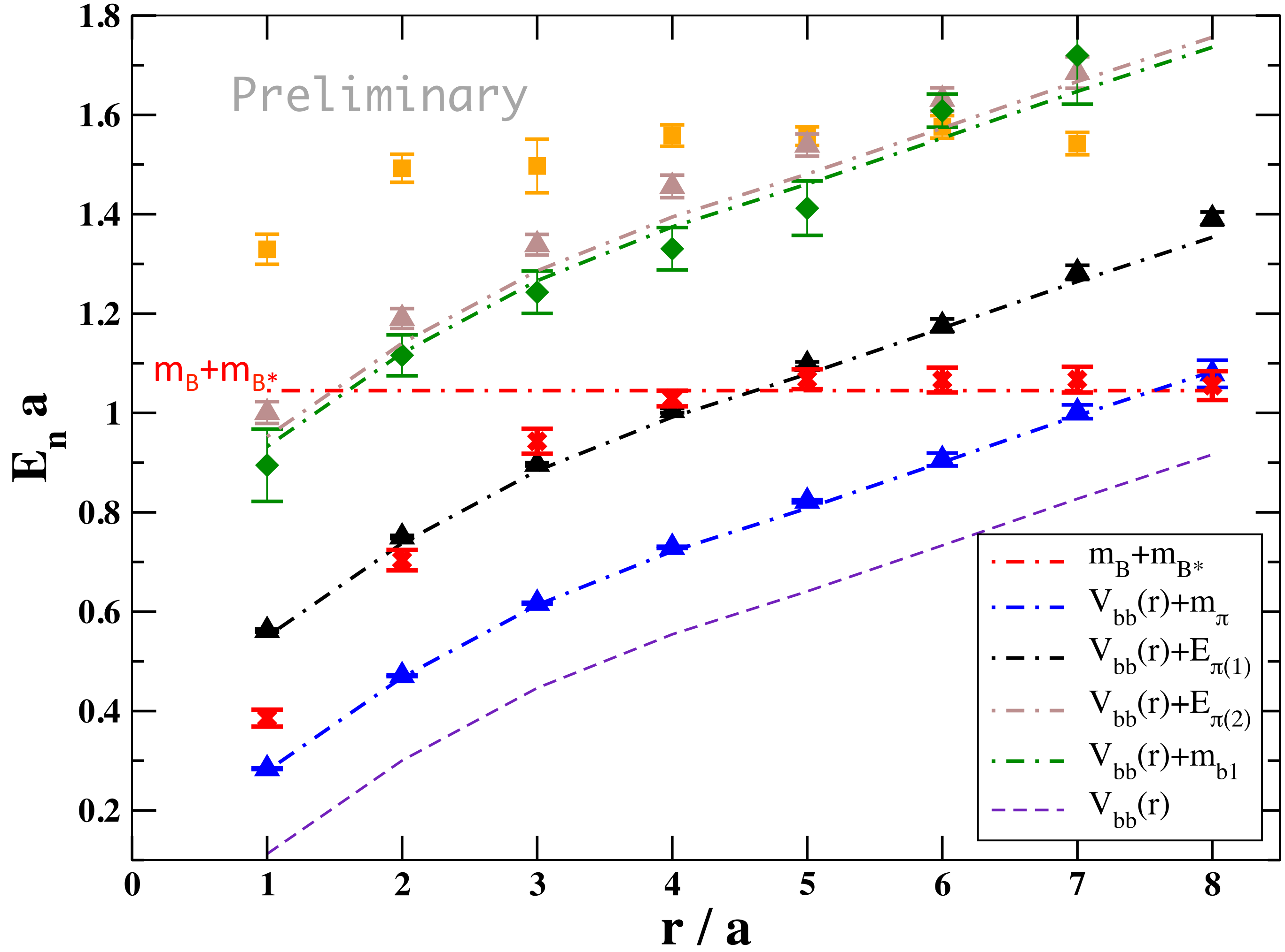
$$O_6 = O^{\Upsilon\ b1(0)} = \Upsilon_z\ (b1_z)_{p=000} = [\bar{b}(0)\gamma_z P_+ b(r)]\ [\bar{q}\gamma_x\gamma_y q]_{p=000}$$

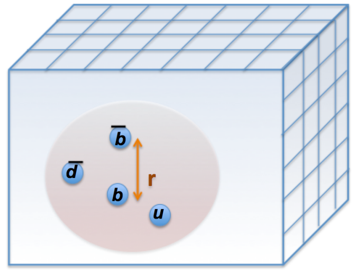


Nf=2, $m_\pi \approx 266$ MeV, a≈0.124 fm, L≈2 fm [larger L would require Υπ(p=003) ...]

full distillation method to compute Wick contractions

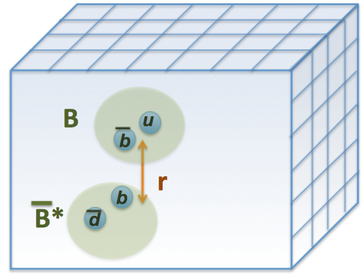
Eigen-energies $E_n(r)$ of 6x6 correlation matrix from GeVP

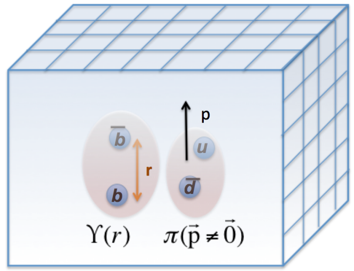


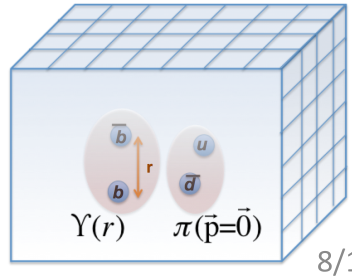


dot-dashed-lines:

$E_n^{\text{non-int}}$







dominant operator in each |n> according to $\langle O_i|n\rangle$

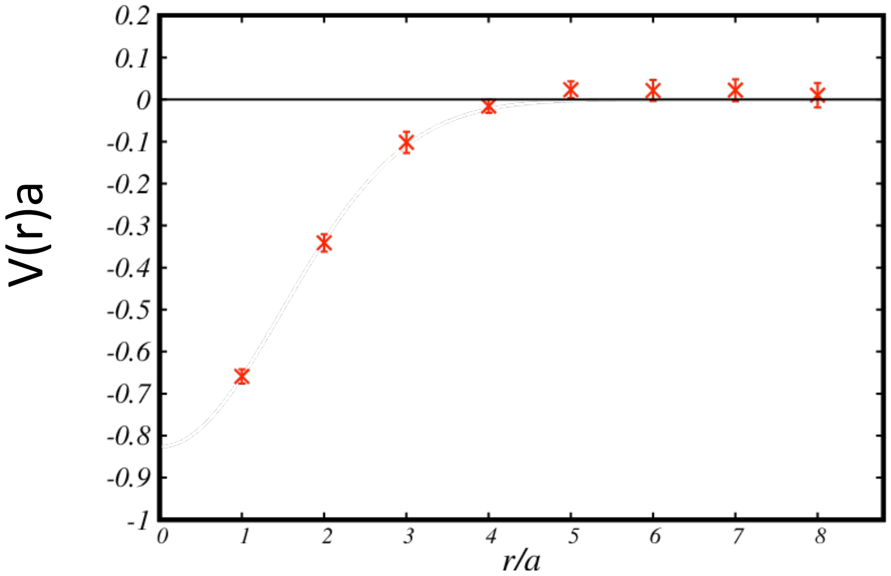
■ (orange)	O=B barB*
▲ (blue)	O=Y π(0)
▲ (black)	O=Y π(1)
▲ (pink)	O=Y π(2)
◆ (green)	O=Y b_1(0)
✖ (red)	O=B barB*

$\Delta E_n = E_n - E_n^{\text{non-int}} \neq 0$ claimed only for level BB* at r<=4

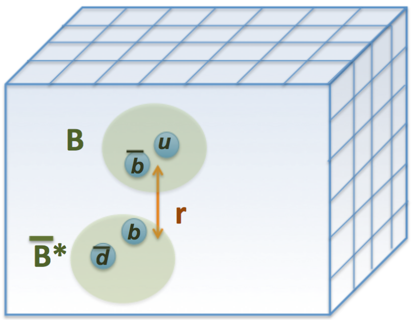
significance of other ΔE_n not yet systematically explored

- we verified there is no other Υ M (M=ρ, a_1, a_0) same the with same quantum num.
- η_b M and and h_b M have S_{heavy}=0, so they also have different quantum num.

Static potential V(r) for interaction between B and B*



V(r<1) = ?



We assume that B B* eigenstate is docupled from Υπ and Υb_1 channels (overlaps support that).

Born-Oppenheimer approach: B and B* move in

$V(r)= E_n(r) - m_B - m_{B*}$ $(m_{B*}=m_B)$

$$\left[-\frac{\hbar^2}{2\mu}\frac{d^2}{dr^2}+\frac{\hbar^2 L(L+1)}{2\mu r^2}+V(r)\right]u(r)=Eu(r)$$

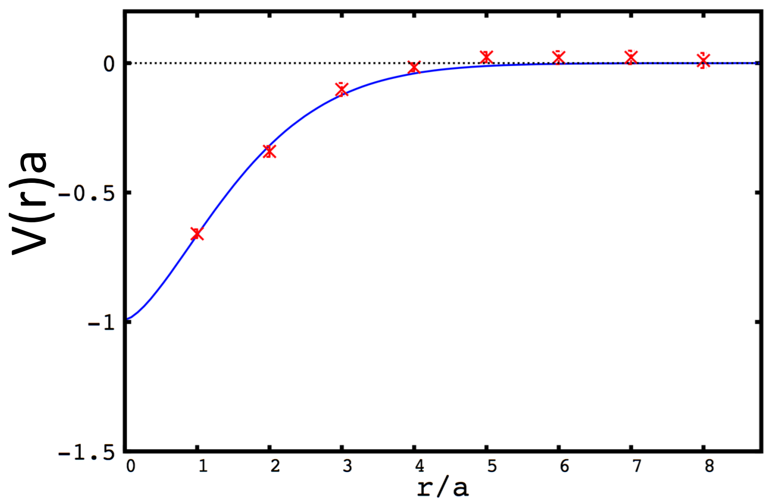
$$\mu=\tfrac{1}{2}m_B^{exp}, \quad \psi\propto\frac{u}{r}Y_{LM}$$

We focus on most relevant : s-wave (L=0)

BB* (virtual) bound states in s-wave

fits with V(r) with V(0)=finite

$$V(r) = -\alpha \exp[-(r/d)^p]$$



example: p=1.5, r=1-4

fit results: α = 0.99(5) , d=1.8(1)

(1) virtual bound st. : E_B = 34 ± 24 MeV

(2) deep bound st.: E_B = 403 ± 70 MeV

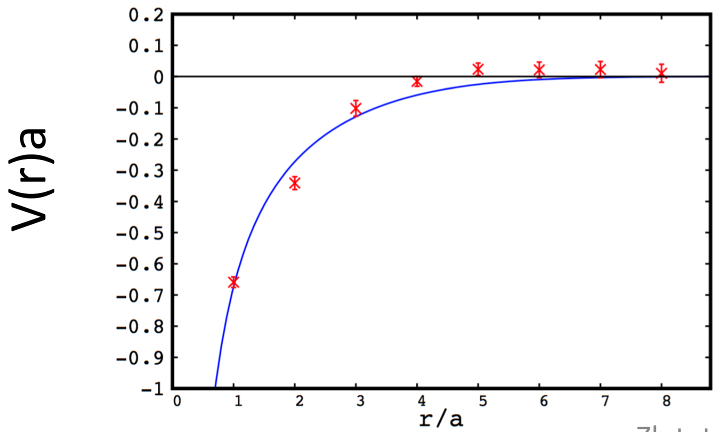
Various fit choices for p and range in r (taking or omitting r=1)

(1) virtual bound st.: state with small E_B present or not

(2) deep bound st: E_B =250 MeV – 500 MeV

fits with V(r) with V(0)=-∞

$$V(r) = -\frac{\alpha}{r} \exp[-(r/d)^p]$$



Various fit choices for p and range in r (taking or omitting r=1)

(1) bound state: E_B = 2 – 10 MeV

(2) deep bound st.: E_B = 400 MeV – 600 MeV

Relating lattice results to Belle experiment

lattice

deep bound st. found on the lattice: prediction of a new exotic state?

It could be perhaps visible only in $\Upsilon(1S)\,\pi$, since it is located below all other thresholds.

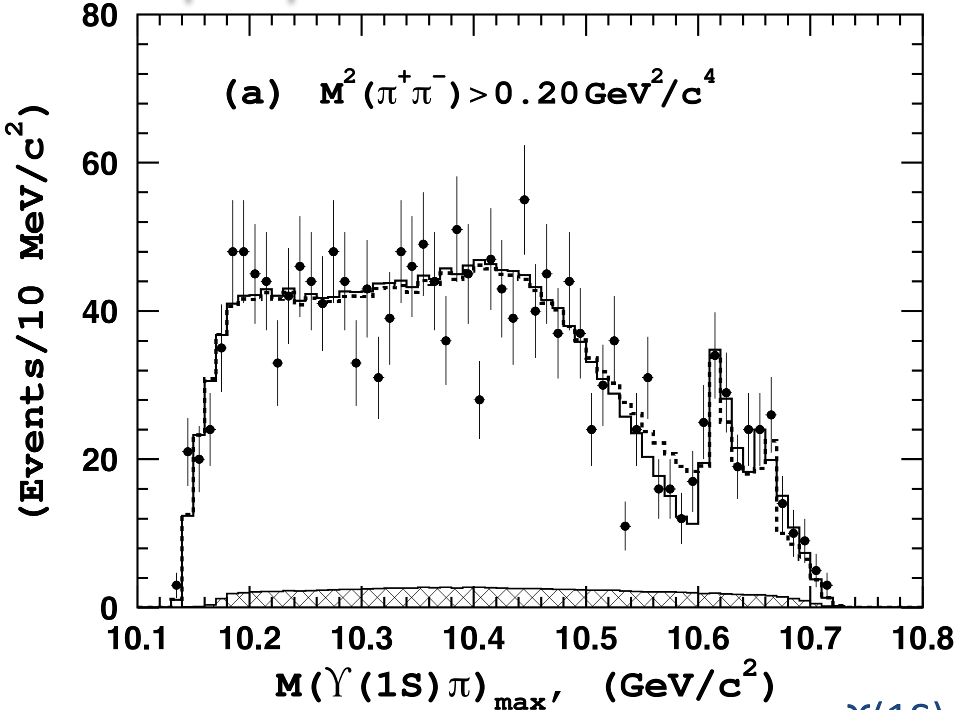
bound st. or virtual bound st. just below threshold is perhaps related to Zb

experiment

Belle PRD 91 (2015) 072003

nothing claimed by Belle; significant "bump" could perhaps emerge at higher statistics

exp Z_b res

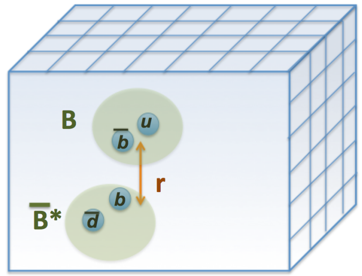


$\Upsilon(1S)\,\pi$

m_B+m_{B*}- 400 MeV

m_B+m_{B*}

Conclusions



- Exploratory study of Zb channel

- Simplifications:

✧ $m_b = \infty$

✧ B $\underline{B}^*$ channel treated as decoupled from other channels in Schrodinger eq.

- Conclusions based on these simplifications:

✧ Sizable attraction between B and $\underline{B}^*$ at small distances

✧ Bound state found far below B$\underline{B}^*$ threshold : yet undiscovered exotic state ??

✧ Bound state or virtual bound state found slightly below B$\underline{B}^*$ threshold:
this state might be related to Zb from Belle experiment

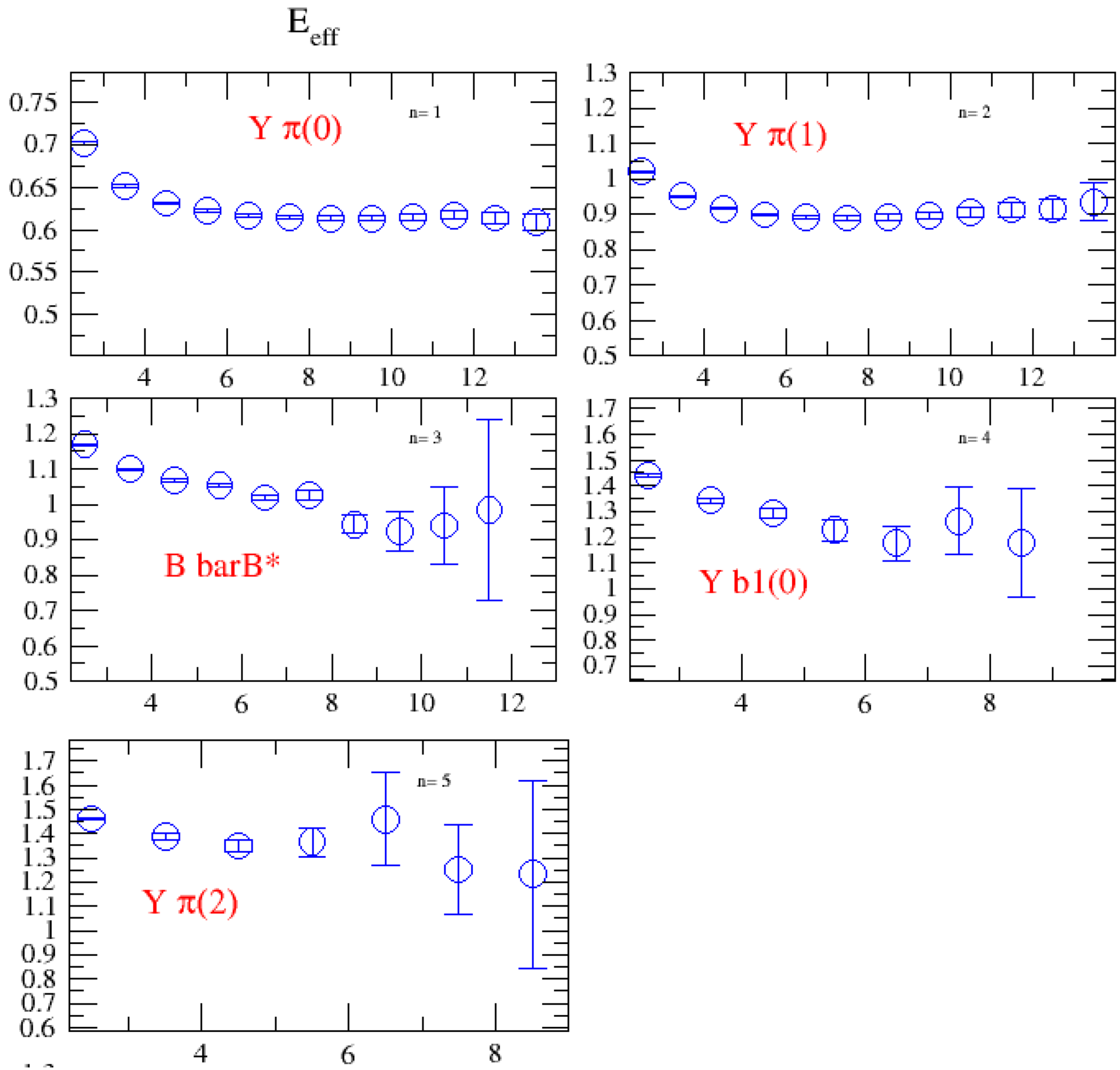
- Future plans:

✧ coupled-channel analogue of Schrodinger equation

✧ .....

Backup

Effective energies for r=3

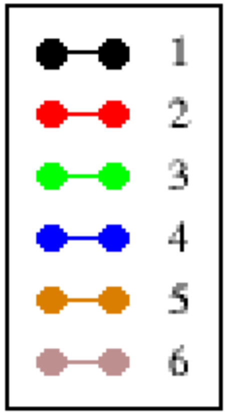


red labels denote

dominant operators

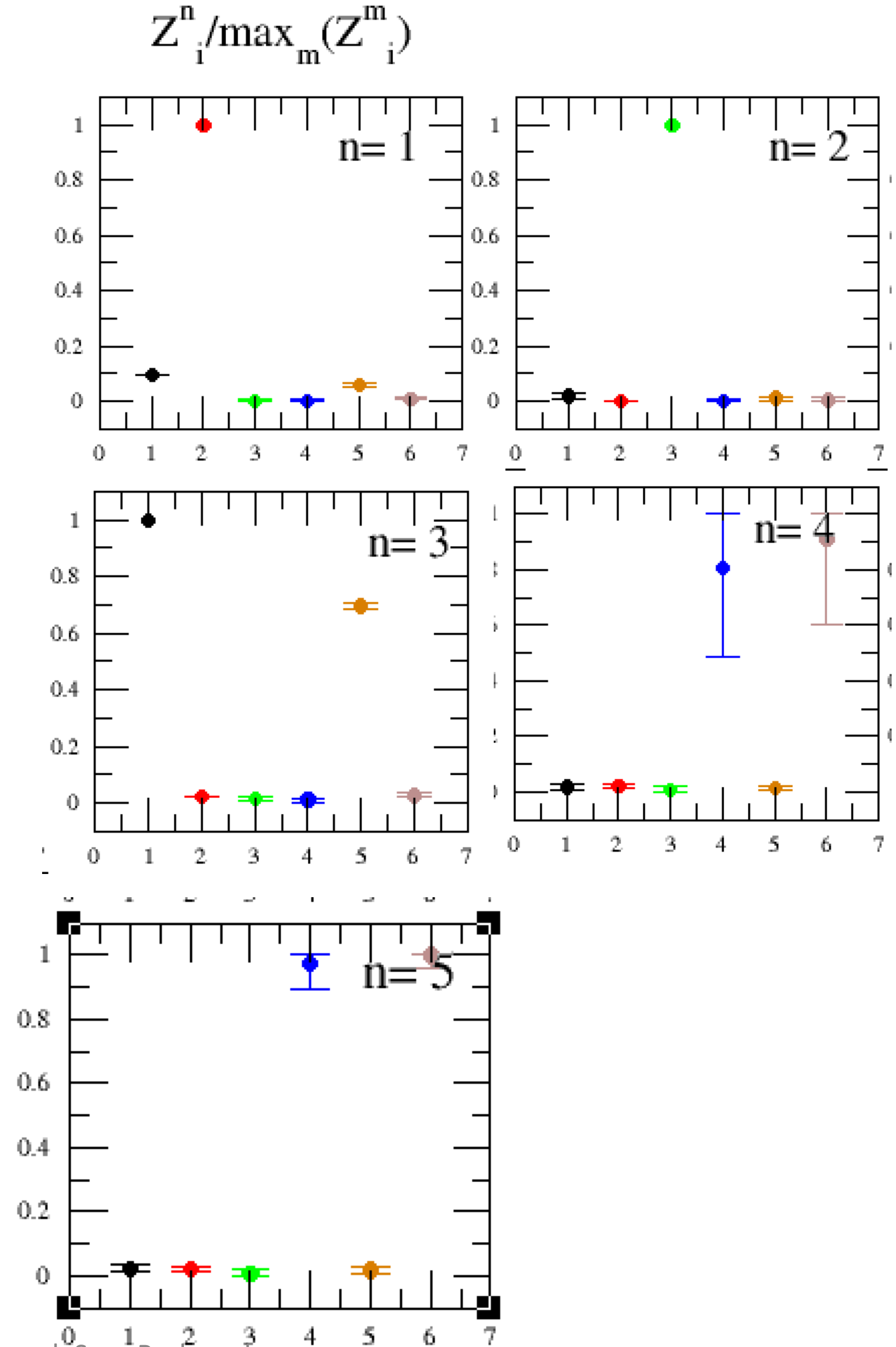
in each eigenstate

Overlaps of eigenstates |n> for r=3



O=B barB*
O=Y π(0)
O=Y π(1)
O=Y π(2)
O=Y $b_1(0)$
O=B barB*

$Z_i^n = \langle O_i | n \rangle$



Consideration of symmetries in the static case

In the static limit: heavy (S_{heavy} and Sz_{heavy}) and light (J_{light}) angular mom. are separately conserved, because heavy quark can not flip direction of spin under interaction with gluon.

The operator below does not transform irreducibly separately under heavy spin and separately under light spin transformations.

$$\bar{b}P_-\gamma_5 q \;\; \bar{q}\gamma_z P_+ b + \bar{b}P_-\gamma_z q \;\; \bar{q}\gamma_5 P_+ b$$

$$= (S_{heavy} = 1)(S_{light} = 0) + (S_{heavy} = 0)(S_{light} = 1)$$