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Prediction of positive parity Bs mesons and search for the X(5568)

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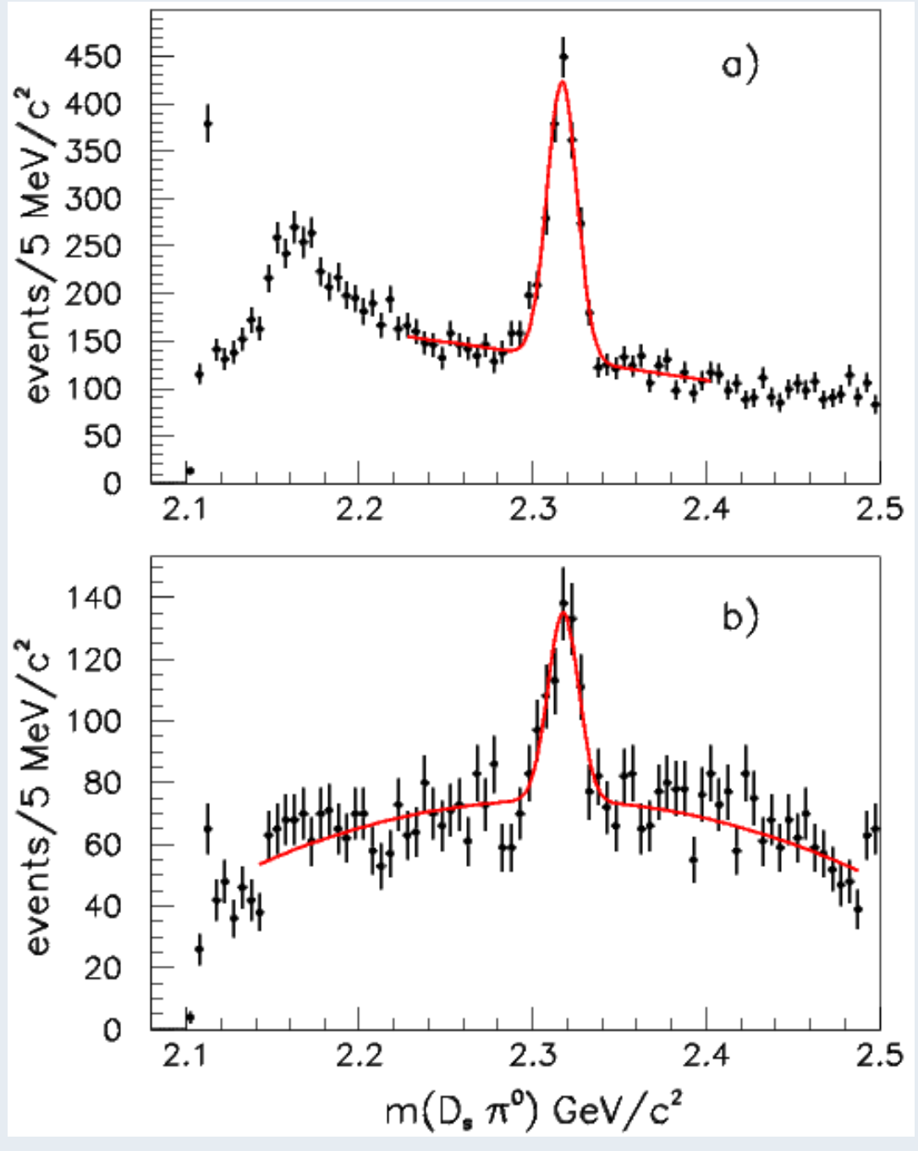
A look at the past: positive parity D_s mesons

Established D_s s and p-wave states:

$$D_s\ (J^P=0^-) \text{ and } D_s^*\ (1^-)$$
$$D_{s0}^*(2317)\ (0^+),\ D_{s1}(2460)\ (1^+),$$
$$D_{s1}(2536)\ (1^+),\ D_{s2}^*(2573)\ (2^+)$$

- Peculiarity: $M_{c\bar{s}} \approx M_{c\bar{d}} \quad \rightarrow \quad$ exotic structure? (tetraquark, molecule)
- Traditional lattice studies (using single hadron operators) tend get too large or badly determined masses
- Qualitative agreement of lattice data with experiment when using a combined basis of D_s and $D^{(*)}K$ interpolators [2, 3]
- For charm quarks discretization uncertainties are large

$D_{s0}^*(2317)$, BaBar [1]



Established B_s s and p-wave states:

$$B_s\ (J^P=0^-) \text{ and } B_s^*\ (1^-)$$
$$B_{s1}(5830)\ (1^+),\ B_{s2}^*(5840)\ (2^+)$$

- Observed B_s p-wave states from two body decays into K^-B^+ (CDF/D0 and LHCb)
- Remaining positive parity states (cousins of the exotic $D_{s0}^*(2317)$ and $D_{s1}(2460)$) not yet observed in experiment!

Gauge fields and lattice techniques

- We use a 2+1 flavors of Wilson-Clover quarks generated by the PACS-CS collaboration [4]

$N_L^3\times N_T$	N_f	a[fm]	L[fm]	#configs	m_π[MeV]	m_K[MeV]
$32^3\times 64$	2+1	0.0907(13)	2.90	196	156(7)(2)	504(1)(7)

- We use the stochastic distillation technique [5]
- For the heavy b-quarks in the Fermilab interpretation [6] we tune κ_b for the spin averaged kinetic mass $M_{\overline{B_s}}=(M_{B_s}+3M_{B_s^*})/4$ to assume its physical value
- Energy splittings are expected to be close to physical
- For MeV values of masses

$$M=\Delta M+M_{\overline{B_s}}$$

- We work with a partially quenched strange quark
  - Use ϕ meson and η_s to set strange quark mass
  - We obtain $\kappa_s=0.13666$

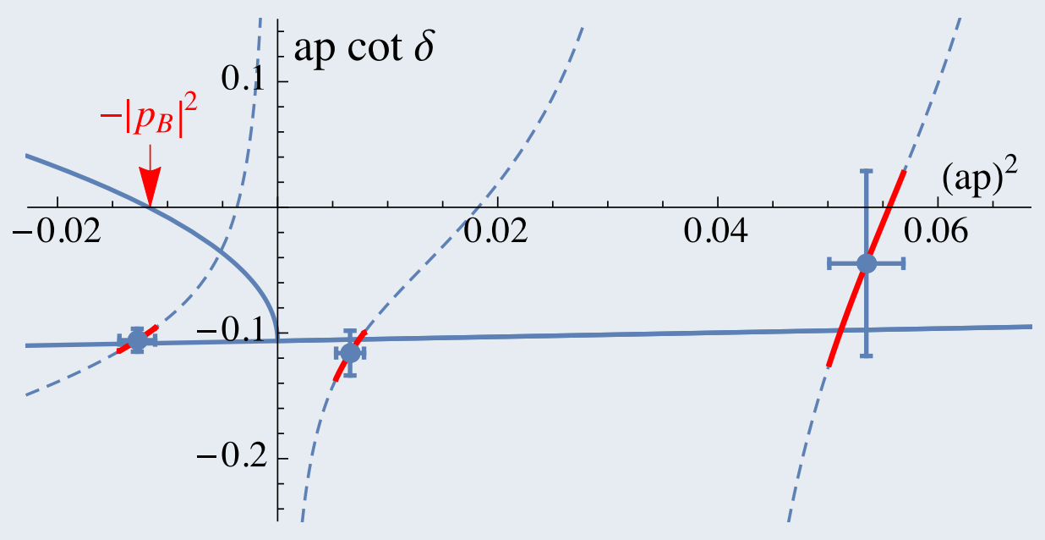
	Lattice [MeV]	Exp. [MeV]
$m_{B^*}-m_B$	46.8(7.0)(0.7)	45.78(35)
$m_{B_{s^*}}-m_{B_s}$	47.1(1.5)(0.7)	$48.7^{+2.3}_{-2.1}$
$m_{B_s}-m_B$	81.5(4.1)(1.2)	87.35(23)
$m_\Upsilon-m_{\eta_b}$	44.2(0.3)(0.6)	62.3(3.2)
$2m_{\overline{B}}-m_{\overline{bb}}$	1190(11)(17)	1182.7(1.0)
$2m_{\overline{B_s}}-m_{\overline{bb}}$	1353(2)(19)	1361.7(3.4)
$2m_{B_c}-m_{\eta_b}-m_{\eta_c}$	169.4(0.4)(2.4)	167.3(4.9)

Prediction of positive parity B_s mesons

- We have to take into account both quark-antiquark as well as B-K structures.
- Similar to the $D_{s0}^*(2317)$ and $D_{s1}(2460)$ [2, 3], the missing B_s states are extracted as a bound-state pole from the finite-volume simulation of B-meson – Kaon scattering
- Lüscher relation for the phase shift [7]

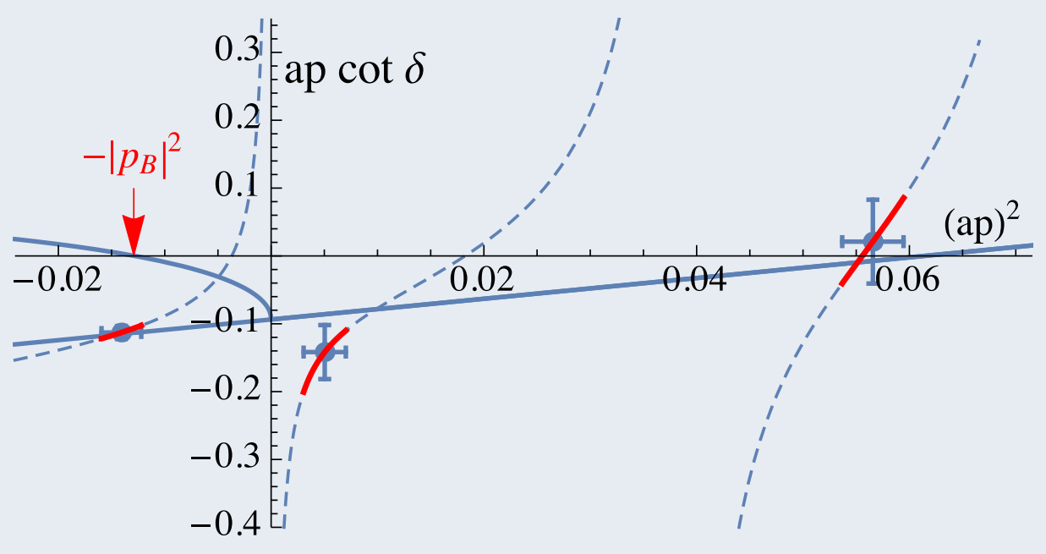
$$p\cot\delta(p)=\frac{2}{\sqrt{\pi}L}Z_{00}(1;q^2)\approx\frac{1}{a_0}+\frac{1}{2}r_0p^2$$

B_{s0}^*



$$a_0^{BK}=-0.85(10)\,\mathrm{fm}$$
$$r_0^{BK}=0.03(15)\,\mathrm{fm}$$
$$M_{B_{s0}^*}=5.711(13)\,\mathrm{GeV}$$

B_{s1}



$$a_0^{B^*K}=-0.97(16)\,\mathrm{fm}$$
$$r_0^{B^*K}=0.28(15)\,\mathrm{fm}$$
$$M_{B_{s1}}=5.750(17)\,\mathrm{GeV}$$

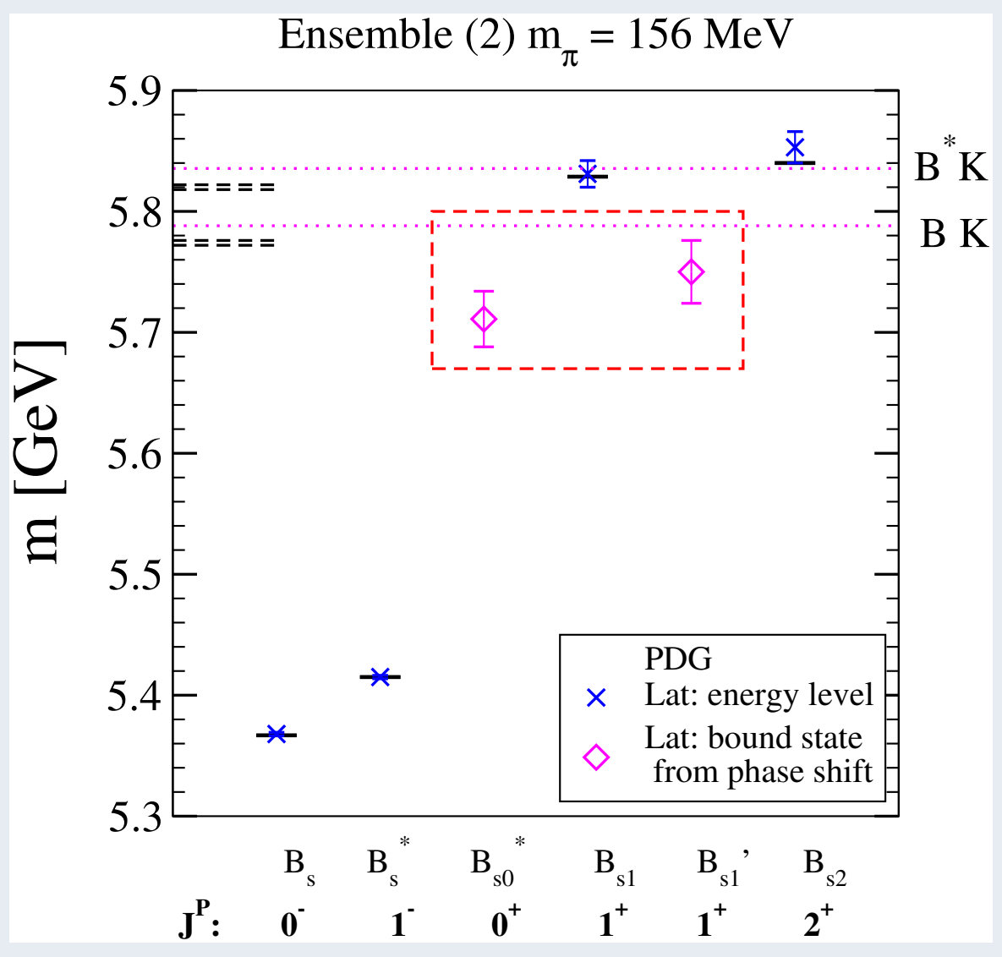
Uncertainty estimate

source of uncertainty	expected size [MeV]
heavy-quark discretization	12
finite volume effects	8
unphysical Kaon, isospin & EM	11
b-quark tuning	3
dispersion relation	2
spin-average (experiment)	2
scale uncertainty	1
3 pt vs. 2 pt linear fit	2
total (added in quadrature)	19

- discretization effects estimated from HQET power counting also considering mass mismatches [8]
- Finite volume estimate from difference between the energy level and the pole

Spectrum results

- States with blue symbols from naive energy levels (statistical uncertainty only)
- $j^{\frac{3}{2}}$ states agree well with experiment ($B_{s1}(5830)$ and $B_{s2}^*(5840)$)
- Full uncertainty estimate only for magenta B_s states
- We observe bound states below the $B^{(*)}K$ threshold
- Bound state energy determined from the difference to the threshold
- Prediction of exotic states from Lattice QCD!

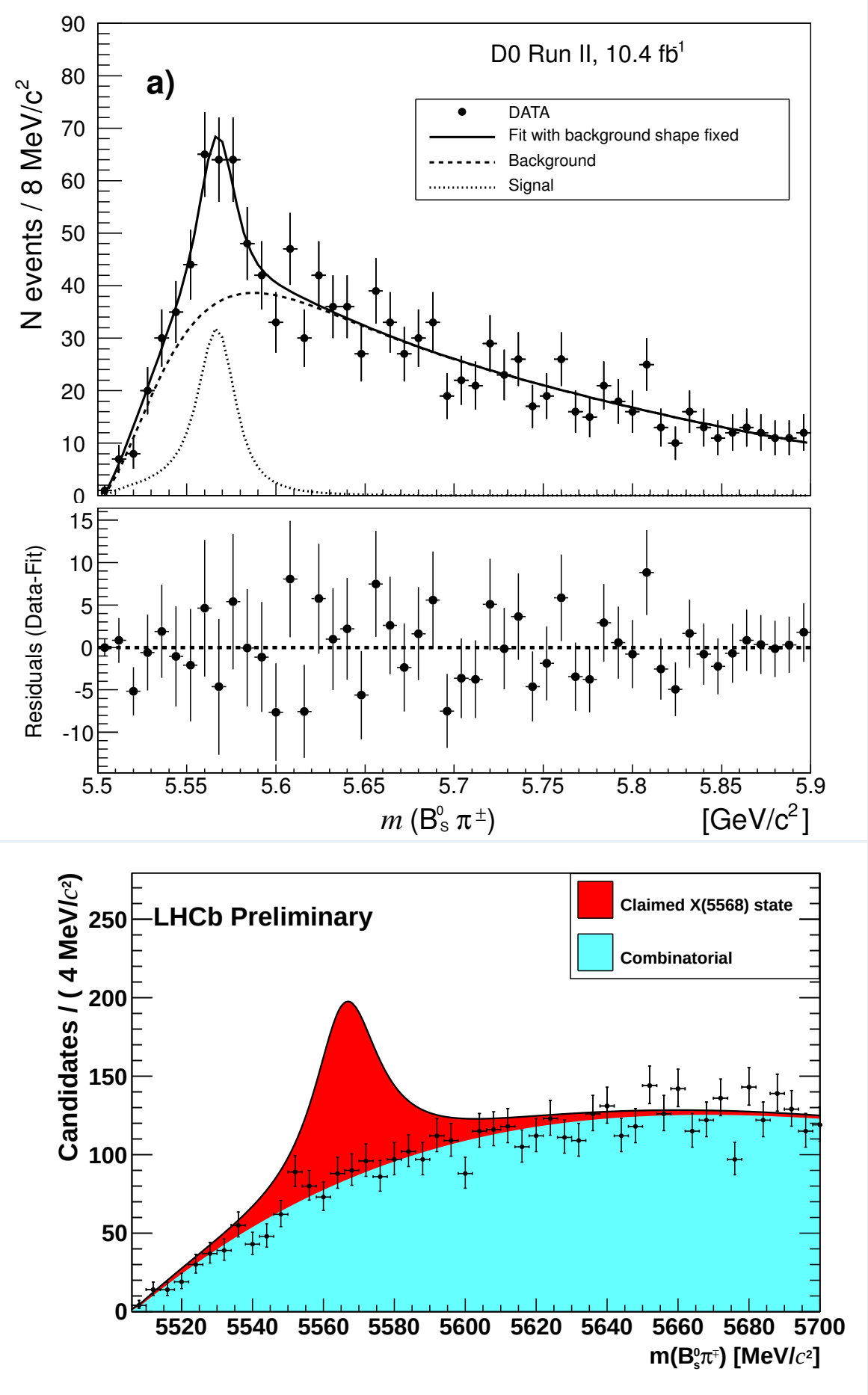


$B_s\pi^+$ scattering and search for the X(5568)

- The D0 collaboration is reporting evidence for a peak in the $B_s\pi^+$ invariant mass not far above threshold [9] (see upper pane in the rhs plot)
- D0 attributes this to a resonance dubbed X(5568)

$$m_X=5567.8\pm2.9^{+0.9}_{-1.9}\ \mathrm{MeV}$$
$$\Gamma_X=21.9\pm6.4^{+5.0}_{-2.5}\ \mathrm{MeV}$$

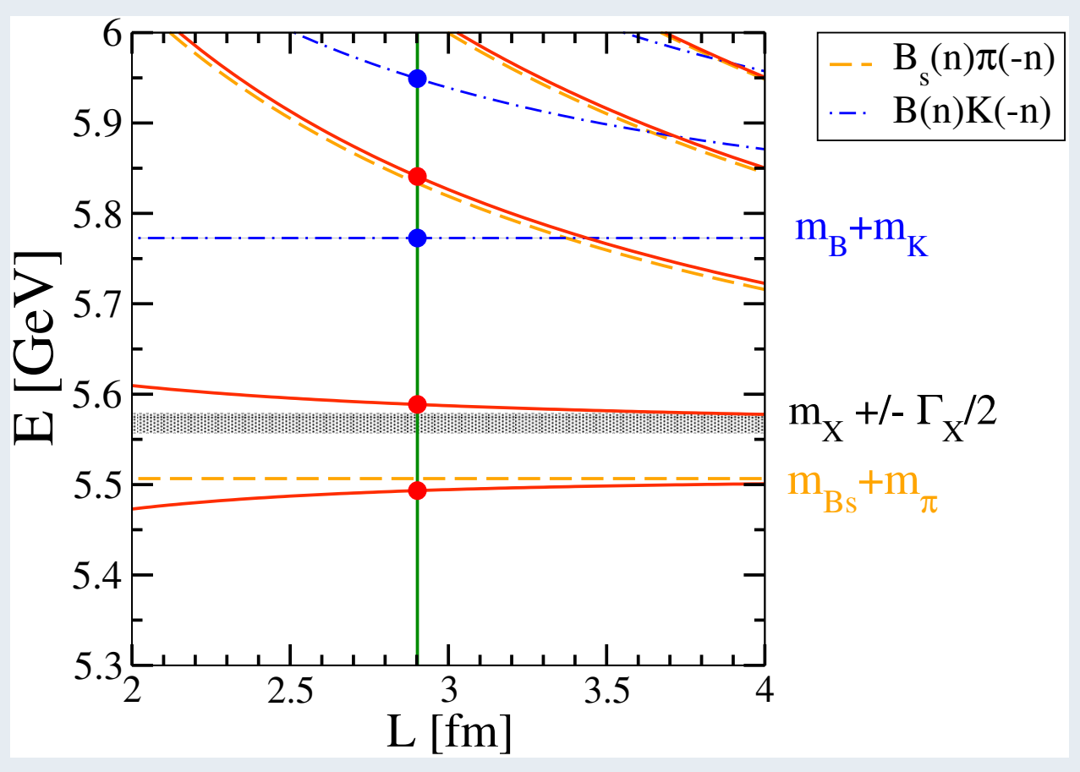
- Decay to $B_s\pi^+$ implies exotic flavor structure $\bar{b}s\bar{d}u$
- Most model studies which accommodate a X(5568) propose $J^P=0^+$
- The LHCb collaboration in the meantime investigated the cross-section as a function of the $B_s\pi^+$ invariant mass with increased statistics and did not find any peak in the same region [10] (see lower pane in the rhs plot)



Expected signatures of X(5568)

The figure shows analytic predictions for energies of eigenstates for an elastic resonance in $B_s\pi$ (with $J^P=0^+$) as a function of the lattice size L.

- The orange (blue) dashed lines show the $B_s\pi$ (BK) eigenstates when B_s and π (B and K) do not interact
- The red lines show the expectation for lattice energy levels in elastic $B_s\pi$ scattering (decoupled from BK) if a resonance with a mass and width of the X(5568) as observed by D0 were present. The resonance mass and width are indicated by the grey band.
- In the unlikely scenario of a deeply bound BK state, the simulation would result in an eigenstate with $E\approx m_X$ up to exponentially small corrections in L.

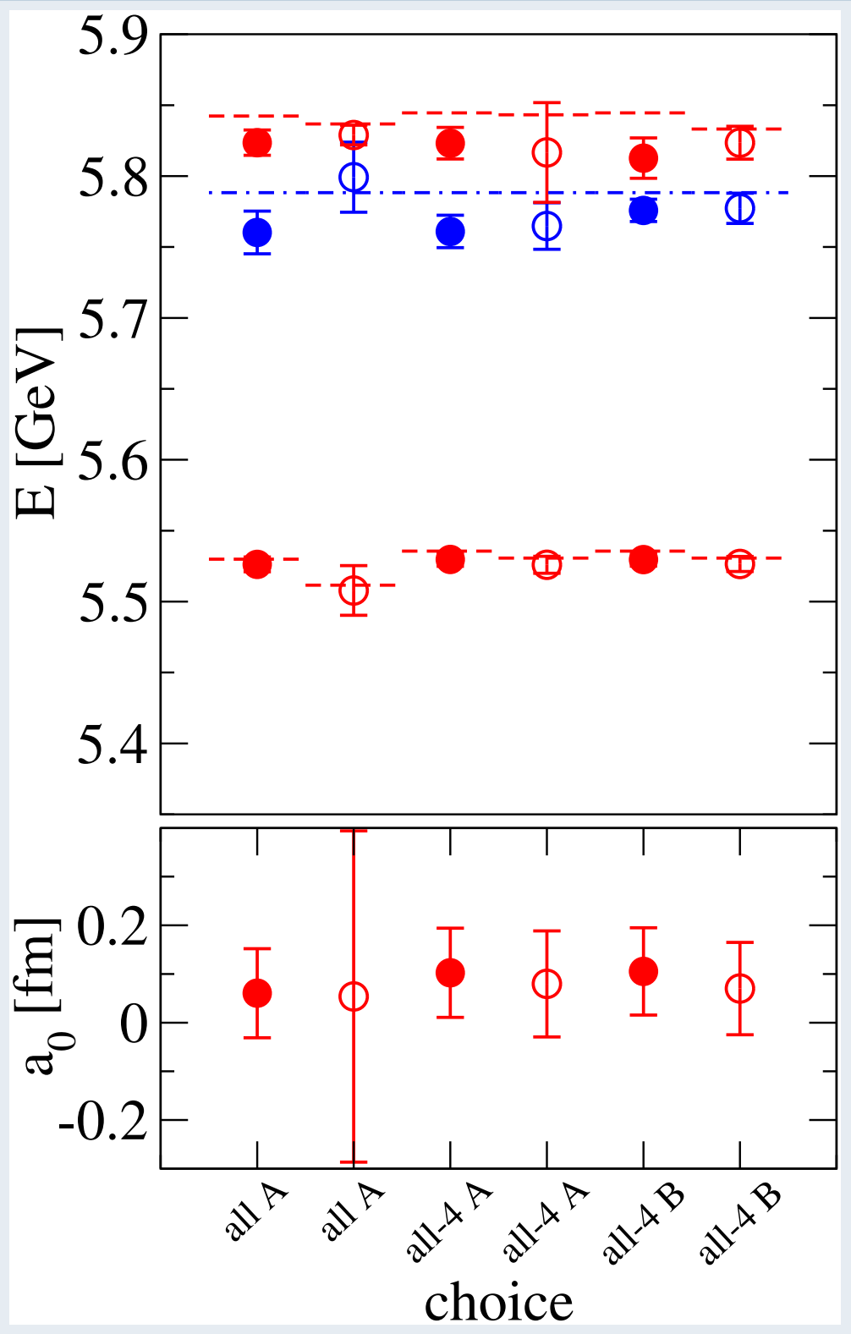


Lattice simulation

- Interpolator basis

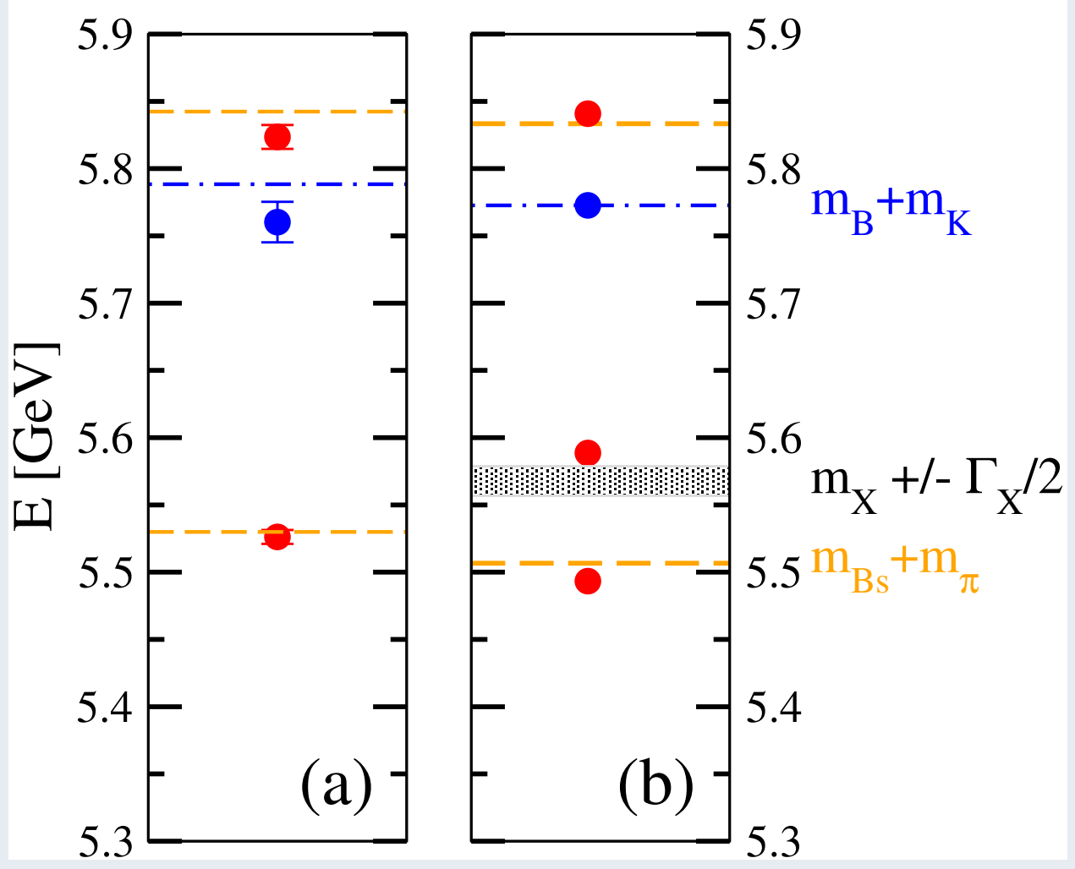
$$O_{1,2}^{B_s(0)\pi(0)}=\left[\bar{b}\Gamma_{1,2}s\right](\mathbf{p}=0)\left[\bar{d}\Gamma_{1,2}u\right](\mathbf{p}=0)$$
$$O_{1,2}^{B_s(1)\pi(-1)}=\sum_{\mathbf{p}=\pm\mathbf{e_{x,y,z}}\,2\pi/L}\left[\bar{b}\Gamma_{1,2}s\right](\mathbf{p})\left[\bar{d}\Gamma_{1,2}u\right](-\mathbf{p})$$
$$O_{1,2}^{B(0)K(0)}=\left[\bar{b}\Gamma_{1,2}u\right](\mathbf{p}=0)\left[\bar{d}\Gamma_{1,2}s\right](\mathbf{p}=0)$$

- The figure shows the eigenstates determined from our simulation for various choices. The sets with full symbols are from correlated fits while open symbols result from uncorrelated fits. Notation "all" refers to the full set of gauge configurations while "all-4" refers to the set with four (close to exceptional) gauge configurations removed. Set A is from interpolator basis $O_1^{B_s(0)\pi(0)}$, $O_1^{B_s(1)\pi(-1)}$, $O_1^{B(0)K(0)}$ while set B results from a larger basis $O_1^{B_s(0)\pi(0)}$, $O_{1,2}^{B_s(1)\pi(-1)}$, $O_{1,2}^{B(0)K(0)}$.



Spectrum results and conclusions

- The figure shows the eigenenergies of the $\bar{b}s\bar{d}u$ system with $J^P=0^+$ calculated on the lattice (left pane) compared to the analytic prediction based on the $X(5568)$ as observed by D0 (right pane).
- The lattice simulation at close-to-physical quark masses does not yield a second low-lying energy level which would be expected for the case of the X(5568)
- Our results do not support the existence of $X(5568)$ with $J^P=0^+$. Instead, the results appear closer to the limit where B_s and π do not interact significantly, leading to a $B_s\pi$ scattering length compatible with 0 within errors.



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