Letter of interest for

Hadron Spectroscopy with Lattice QCD

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SNOWMASS21-RF7_RF0-TF5_TF4-052

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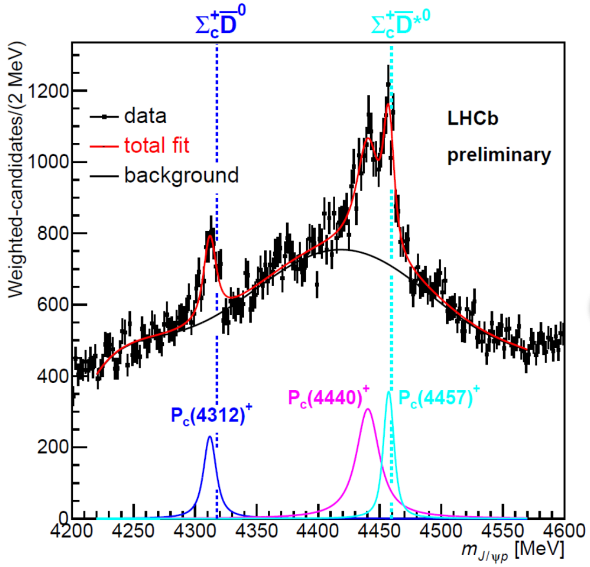
townhall meeting

Snowmass, RF7

Experimentally discovered exotic hadrons decay strongly

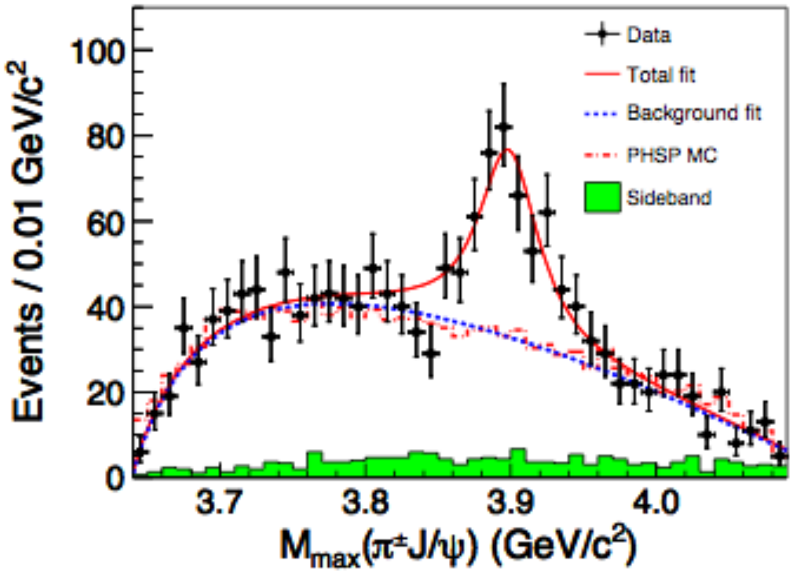
LHCb 2019: Pc



$E(J/\psi\ p)\ [GeV]$

ccuud

Bess III, Belle 2013 Zc



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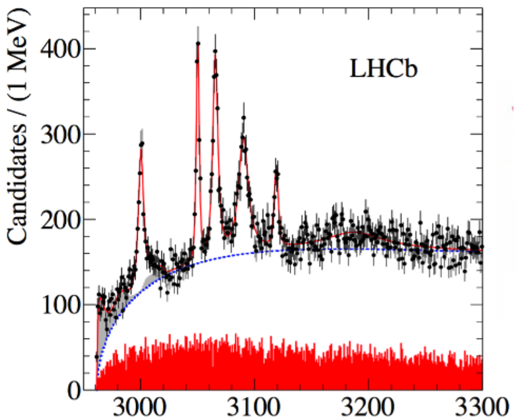
Most of conventional hadrons decay strongly

LHCb 2017



$E(\Xi_c^+\ K^-)\ [GeV]$

css

many many more

Non-perturbative theory approach: QCD on lattice

x,t (Minkovsky) → x, i t (Euclidean)

$$L_{QCD} = -\tfrac{1}{4} G^{a}_{\mu\nu} G^{\mu\nu}_{a} + \sum_{q=u,d,s,c,b,t} \bar{q} i \gamma_\mu (\partial^\mu + i g_s G^\mu_a T^a) q - m_q \bar{q} q$$

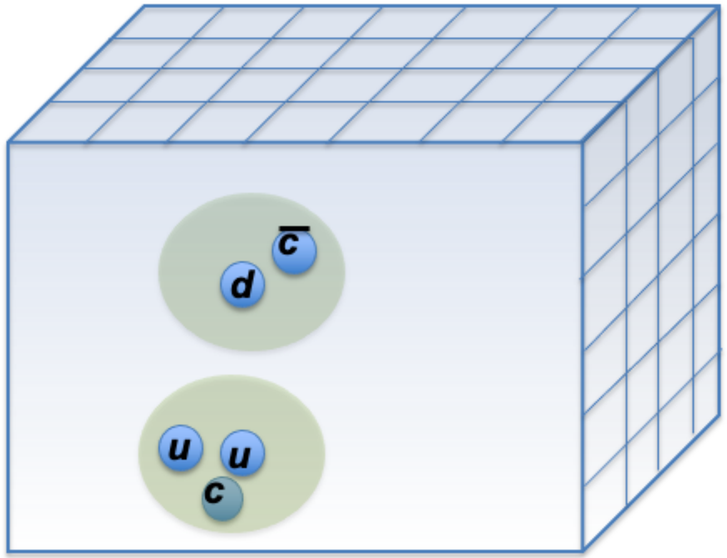
input: g_s , m_q

output: hadron properties

hadron interactions

Evaluation of Feynman path integrals
in discretized space-time

$$\int DG\, Dq\, D\bar{q}\, e^{-S_{QCD}/\hbar}$$



resonances:

- not QCD eigenstates
- inferred from decay products (like in exp)

$H_1 H_2 \to R \to H_1 H_2$

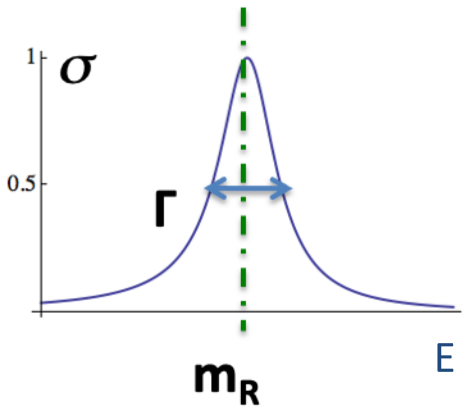
scattering amplitudes T

↓

cross sections, poles of T

↓

masses and widths of R



LoI:

- solved problems
- challenges to address

"Solved problems" in lattice QCD

more difficult ↑

Resonances that have only one strong decay channel

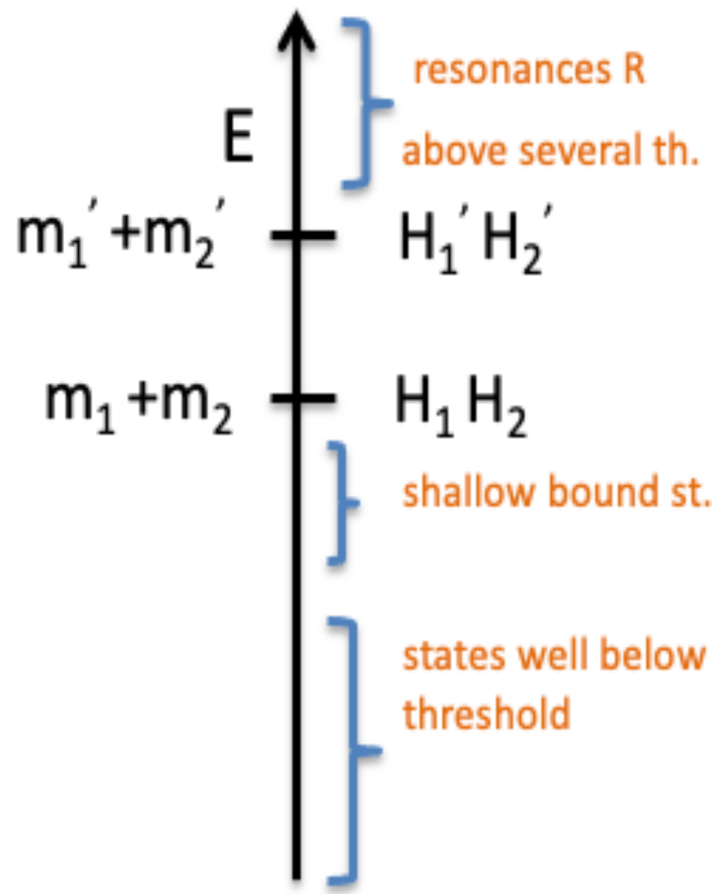
- masses
- widths $R \rightarrow H_1 H_2$

Hadrons that are slightly below threshold:

- masses

Hadrons that can not decay strongly (well below threshold):

- masses
- transition matrix elements $\langle H_f | J | H_i \rangle$



Status

$R \to H_1 H_2, H_1' H_2'$

"difficult": - decay via two or three channels:

T for coupled-channel scattering

[Hadron Spectrum collaboration

extracted coupled-channel T for several channels]

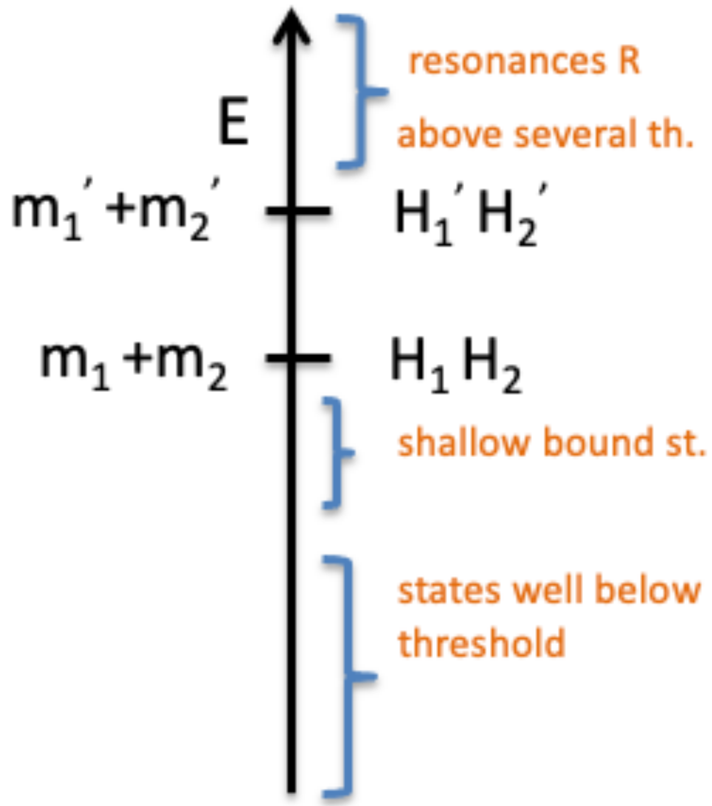
"too chalenging" (for now):

- decay to more than three channels

  (if none of them can be "neglected")

- if $H_1 H_2 H_3$ decays are important

  in addition to two-hadron decays



LoI: challenges to focus on

- Identify certain exotic hadrons that could be studied reliably on lattice and in exp

exp. discovered exotic hadrons ⟷ difficult for lattice QCD

P_c , Z_c , X(6900), ... (several strong decay channels)

some exotic hadrons identified on lattice ⟷ (too) difficult for experiment

$b\,b\,\underline{u}\,\underline{d}$, $b\,b\,\underline{u}\,\underline{s}$ those two not discovered yet

- hadrons that can decay via two or three channels, including those with heavy quarks

$$R \rightarrow H_1 H_2 \, , \, H_1' H_2'$$

- hadrons that can decay via more than three channels
  - try to find simplifications
  - determine which channels could be treated as decoupled

- hadrons that have two-particle and three-particle decay channels:
  - try to simulate
  - look for simplifications

$$R \rightarrow H_1 H_2 \, , \, H_1' H_2' H_3'$$

LoI: challenges to focus on (continued)

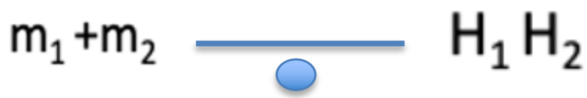
- identify reliable criterion on the importance of molecular and diquark configurations
- can overlaps $\langle O_i | n \rangle$ give rigorous info on structure of hadrons

currently qualitative

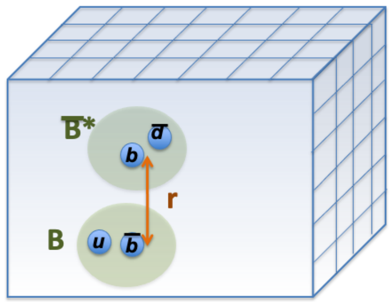
- vary masses of quarks u/d, s, c, b

  explore position of the resonances with respect to thresholds

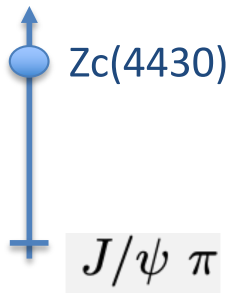
  (one can not do it in experiment)



- QQ... or QQ... systems: determine Born Oppenheimer potentials
  - V(r) on the lattice, r>a
  - V(r) analytically at small r<a



- Lattice study of a high-lying resonance R: all energy region below it has to be extracted
  - find some approach that could address just a certain higher-lying energy region
  - this does not seem viable with currently used lattice methods



LoI: challenges to focus on (continued) & relation to other efforts

- determine relevant $\langle R_f | J | H_i \rangle$ and $\langle H_f | J | R_i \rangle$ J=EM or weak current

  only $\langle \rho | J^{EM} | \pi \rangle$ determined [first by Had. spec. coll]

  relation to other Snowmass efforts

  $\mathrm{B} \to K^* l^+ l^-$ (new physics search) , $\mathrm{B} \to D^* l^+ l^-$ (lepton fl. universality) , $\mathrm{D} \to \rho\, l\, \upsilon$ (semileptonic decays)

  $\langle K^* | J | B \rangle$ $\langle D^* | J | B \rangle$ $\langle \rho | J | D \rangle$

- Improve analytical methods to extract poles of scattering amplitudes

  relation to scattering amplitudes Snowmass efforts

- Relation to Theory Snowmass efforts

- Relation to Computational Snowmass efforts

Schedule

- march 2021: contact LoI authors and inquire who will actively contribute
- april 2021: discuss physics of white paper
- may, june 2021: write white-paper

What would I like to come out of the Snowmass process ?

- contribute to a (partial) solution of at least few of the given challenges

- it would be very welcome if scientists seriously think about some suggested simplifications

  otherwise community will not be able to provide lattice QCD results for most interesting states soon

- identify some exotic hadrons that can be reliably studied in lattice and exp

Conclusions

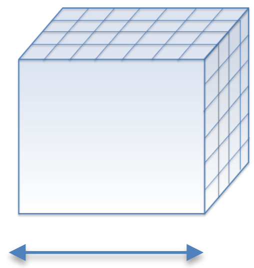
- lots of very interesting results on exotic and conventional hadrons from experiment

- many urgent challenges to resolve in ab-initio theoretical studies of these states

Backup

lattice QCD extracts energies E_n of eigenstates

$R \rightarrow H_1 H_2$

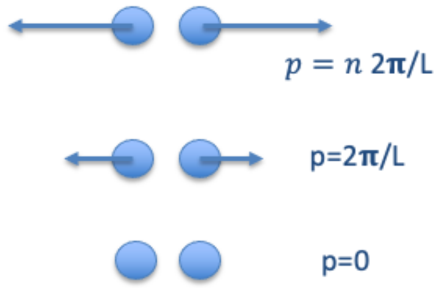


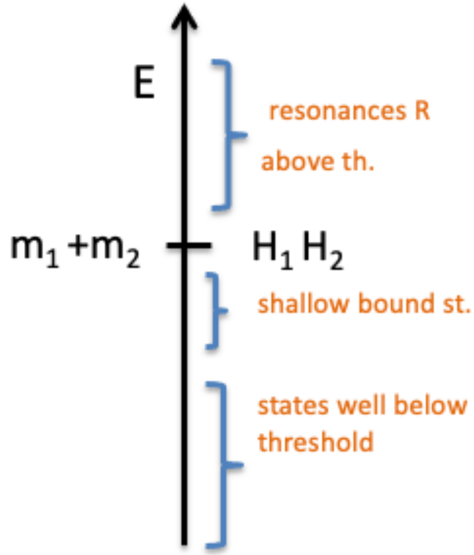
$E^{n.i.}$ (in non-interaction limit)

$$E^{n.i.} = \sqrt{m_1^2 + p^2} + \sqrt{m_2^2 + p^2}$$

$E = m_1 + m_2$

$H_1 H_2$ (cm frame)



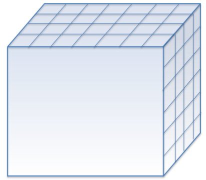


one has to extract ALL eigen-energies below the energy of interest

(can not focus on just particular higher-lying energy window like in exp)

exp (L=inf): continous spectrum above th., lat (L=finite): discrete spectrum

Example: channel Z_c , $J^P=1^+$

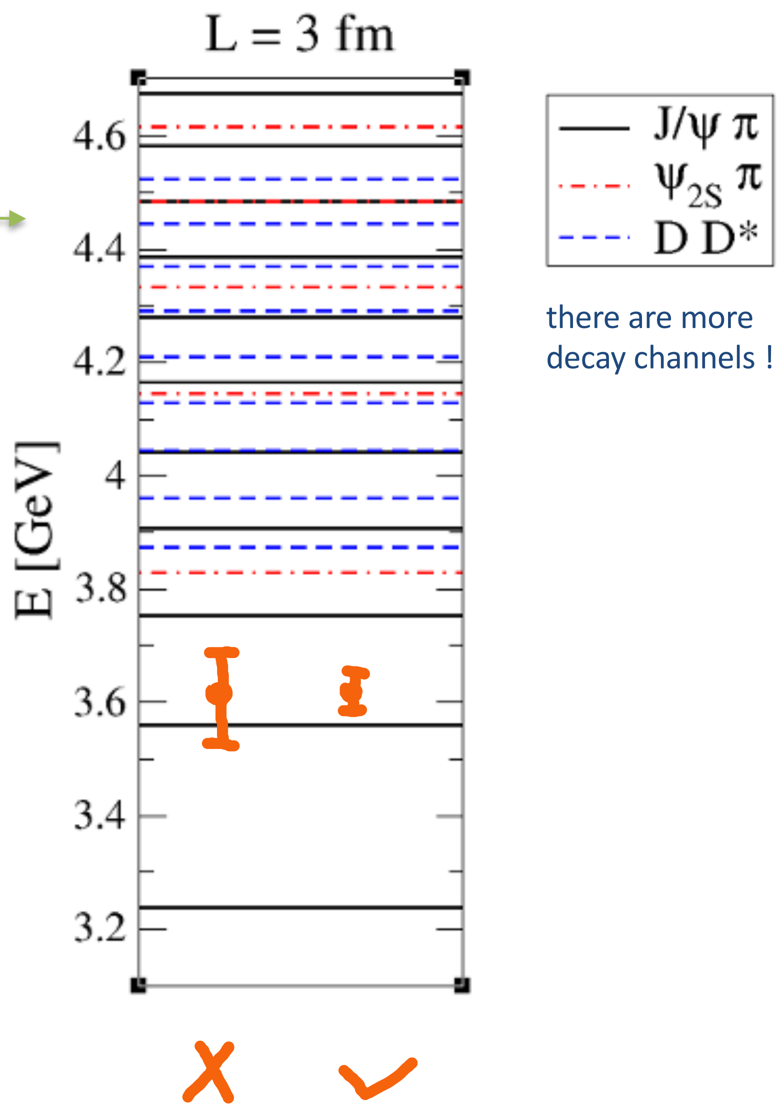


plot of non-interacting energies

$$E^{n.i.} = \sqrt{m_1^2 + p^2} + \sqrt{m_2^2 + p^2} \quad , \; p = n\, 2\boldsymbol{\pi}/L$$

$Z_c^+(4430)$

$Z_c^+(3900)$



there are more decay channels !

challenge:

very accurate determination of E is needed

higher E have larger statistical noise

One needs to resolve

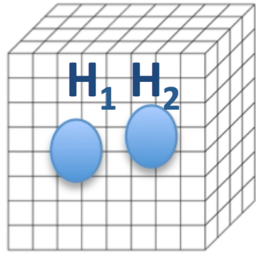
$$\Delta E = \mathrm{E} - E^{n.i.}$$

Scattering matrix T can be determined

only when ΔE are resolved

Resonance above one threshold

$$R \rightarrow H_1 H_2 \qquad T(E) \quad \underset{\text{Luscher's method}}{\leftarrow} E_n$$



Lattice simulation of one-channel scattering via Luscher's method: doable

Resonance above two or more thresholds

most of exotic hadrons are above more than one threshold:
for example Zc(4430), X(6900), Zb

$$R \rightarrow H_1 H_2,\ H_1' H_2'$$

channel a: $H_1 H_2$
channel b: $H_1' H_2'$

$$T(E) = \begin{bmatrix} T_{aa}(E) & T_{ab}(E) \\ T_{ab}(E) & T_{bb}(E) \end{bmatrix} \quad \underset{\text{Luscher's method}}{\leftarrow} E_n$$

(a -> a, a -> b, b->a, b -> b)

det[T(E) – f(E)] =0 : at given E: one equation, three unknowns

↓ known f