Lattice QCD Study of Doubly Heavy Tetraquarks

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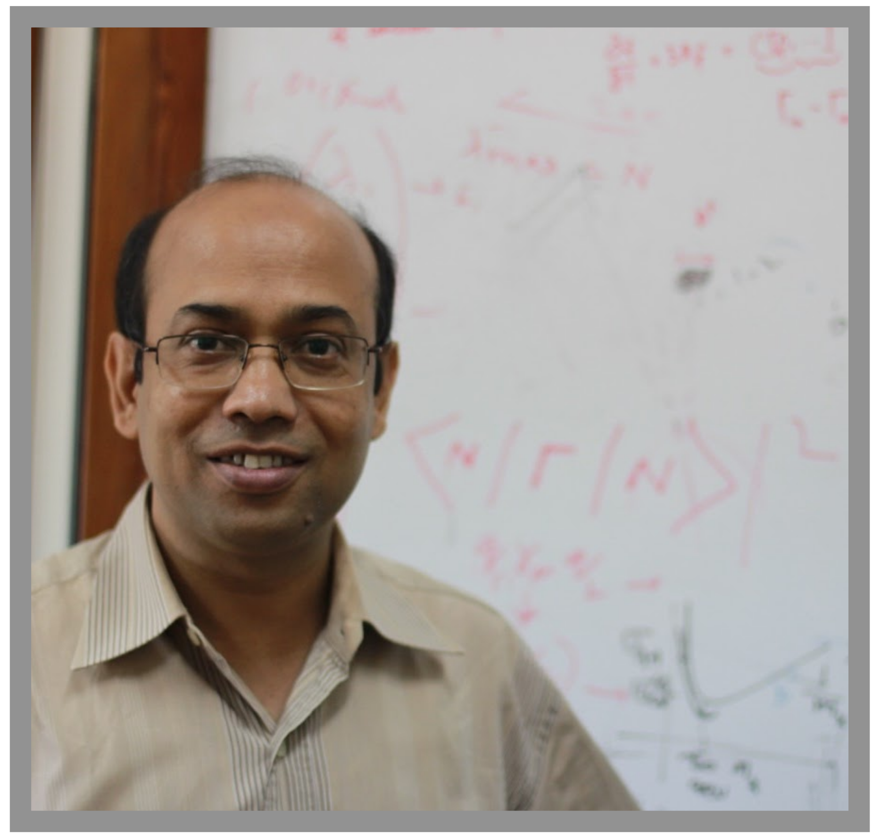
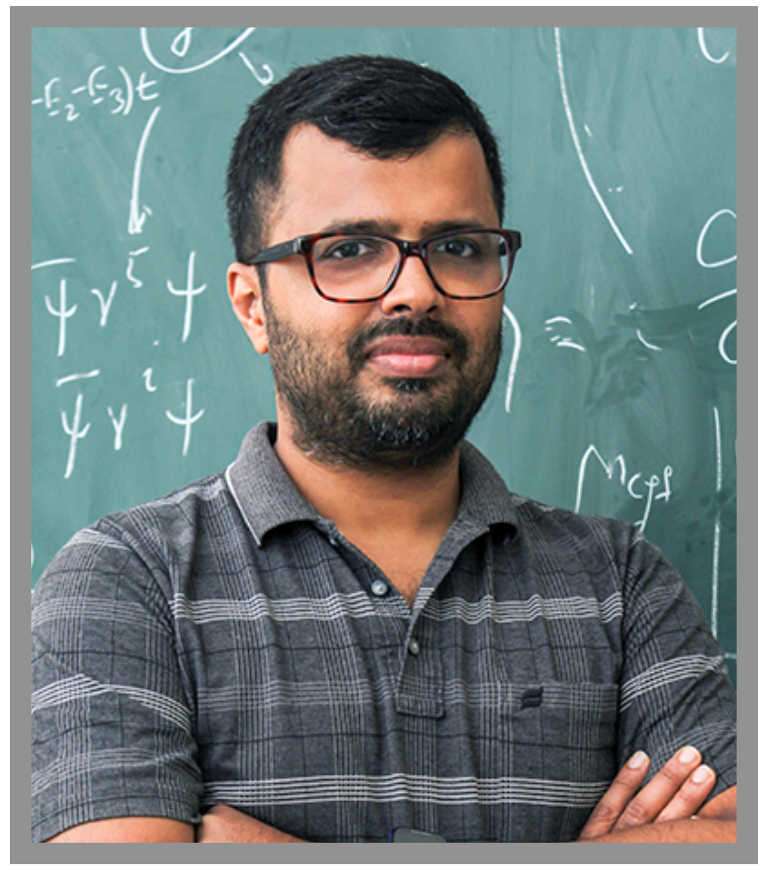


Nilmani Mathur(TIFR)

arxiv:2502.XXXX



M. Padmanath(IMSc)

Introduction and Motivation

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

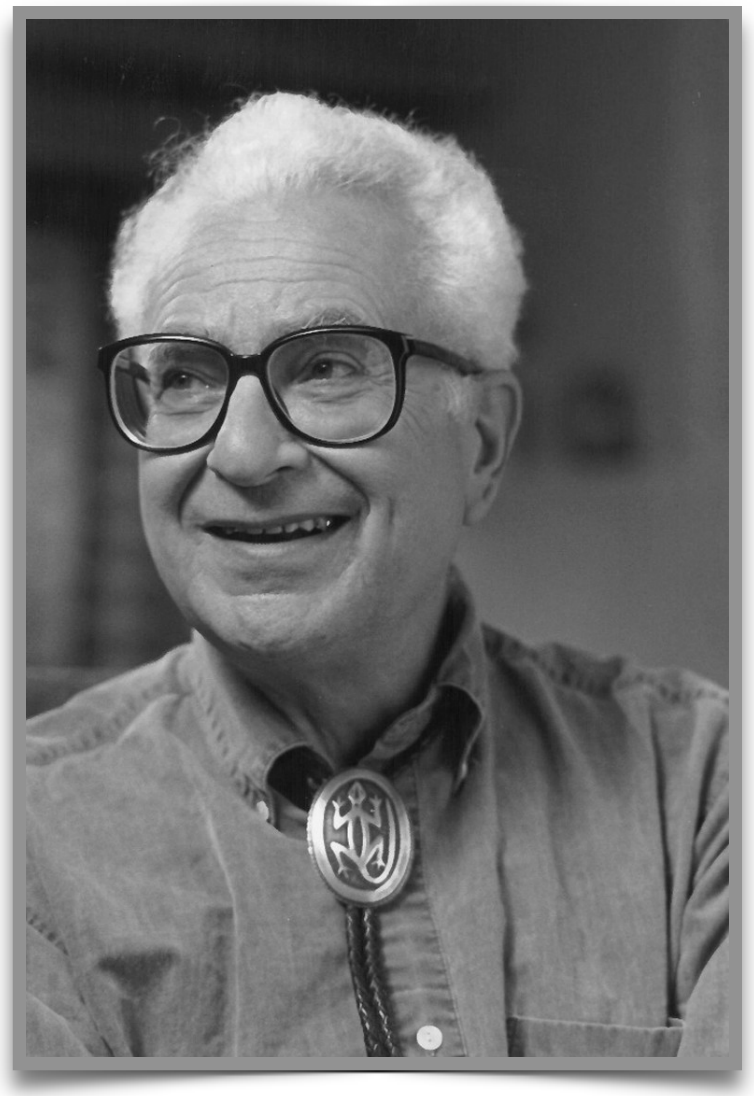
Received 4 January 1964

[illegible]. Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. [illegible]

PHYSICAL REVIEW D VOLUME 15, NUMBER 1 1 JANUARY 1977

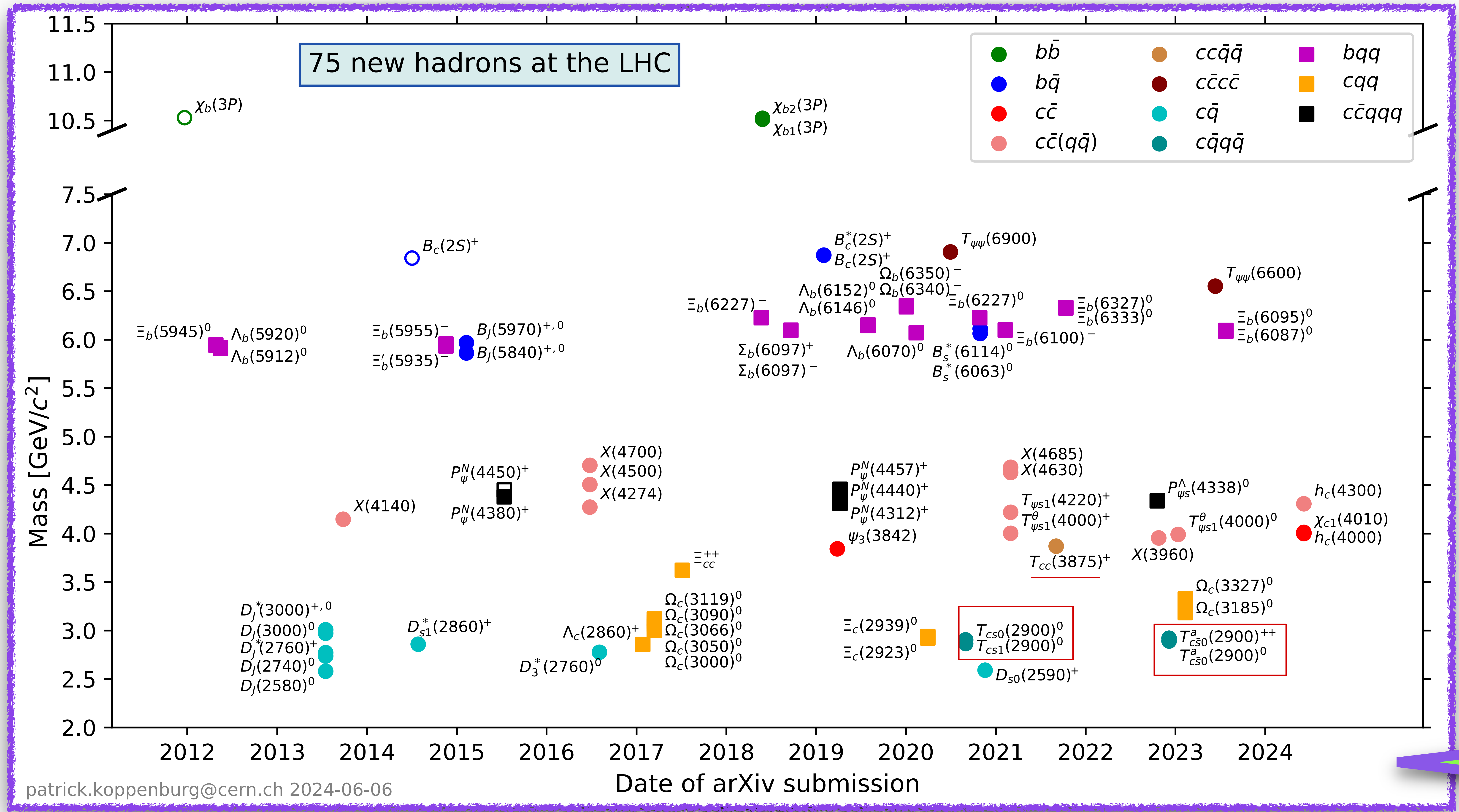
Multiquark hadrons. I. Phenomenology of $Q^2\bar{Q}^2$ mesons*

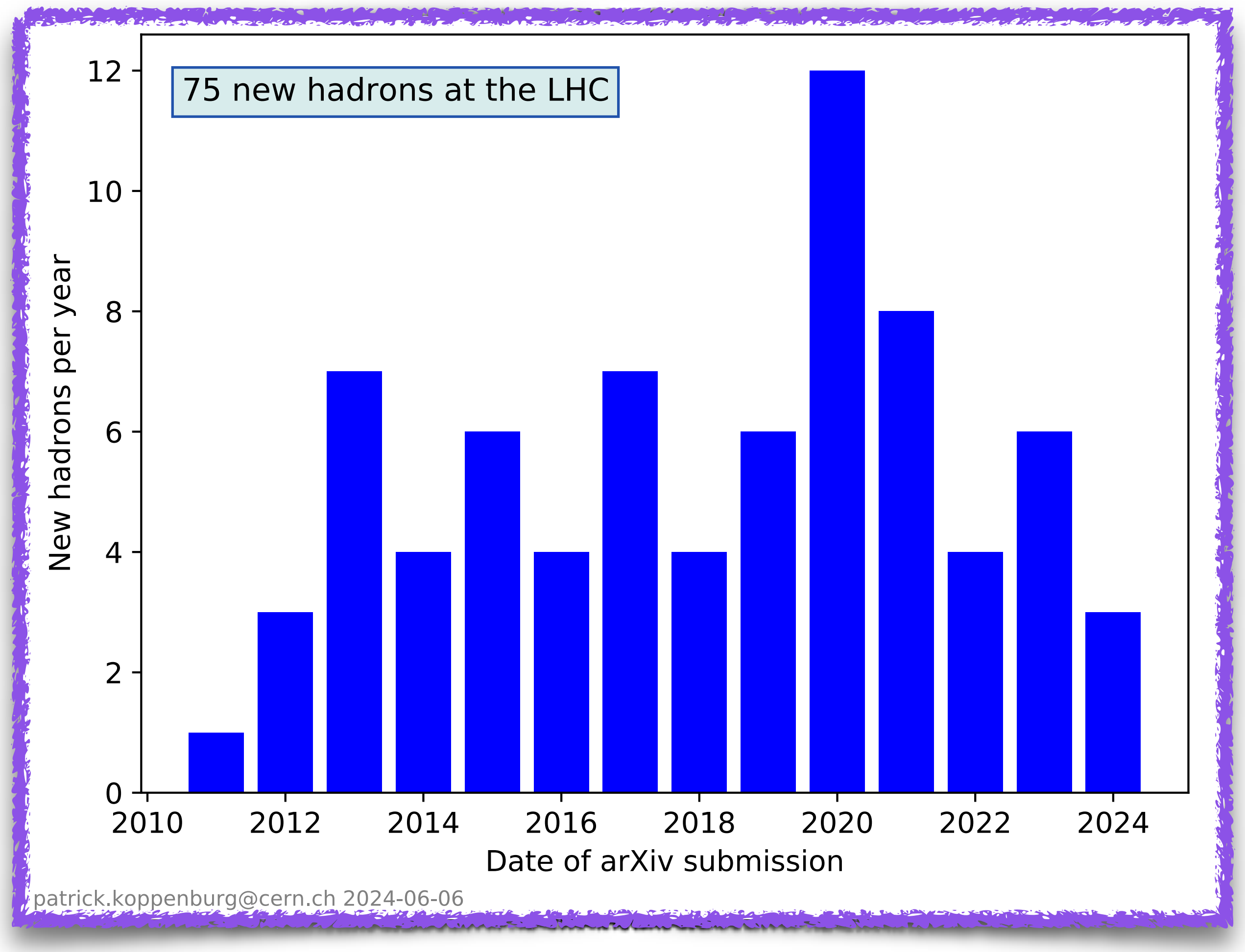
R. J. Jaffe†
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
and Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 15 July 1976)



- Murray Gellmann indicated the possibility of multiquark systems.
- Jaffe described it as color neutral states of diquark and antidiquark.
- Currently known as Tetraquarks and Pentaquarks.

Experimental Results in LHC





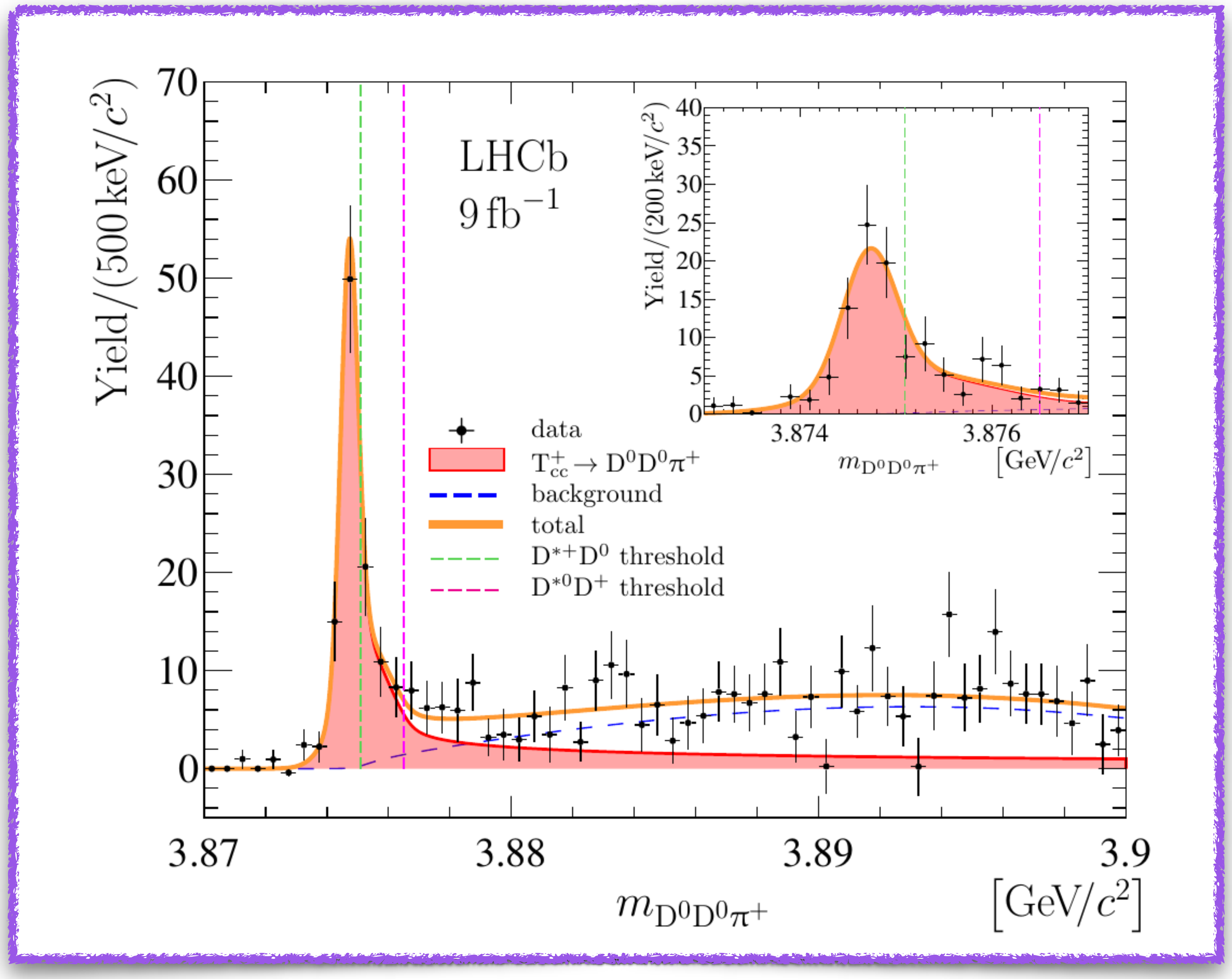
Patrick's Webpage:hhttps://www.nikhef.nl/pkoppenb/

Particles discovered in the last decade including conventional heavy hadrons, open flavor mesons, exotic particles

Other research facilities like Belle, BES-III etc. have active spectroscopy programs.

T_{cc} discovery at LHC

- In 2021, LHCb made headlines by discovering the longest-lived exotic state ever observed.
- Many more exotic tetraquark discovered recently e.g. T_{cs}, $T_{c\bar{s}}$, Z_c and so on. Scope for T_{bc}, T_{bs} in near future.



Nature phys: https://rdcu.be/dNMRV
Arxiv:2109.01038

$$\delta M = M_{T_{cc^+}} - (M_{D^{*+}} + M_{D^0})$$

$$\delta M_{pole} = -360 \pm 40(^{+4}_{-0}) keV/c^2$$

$$\Gamma_{pole} = 48 \pm 2(^{+00}_{-14}) KeV$$

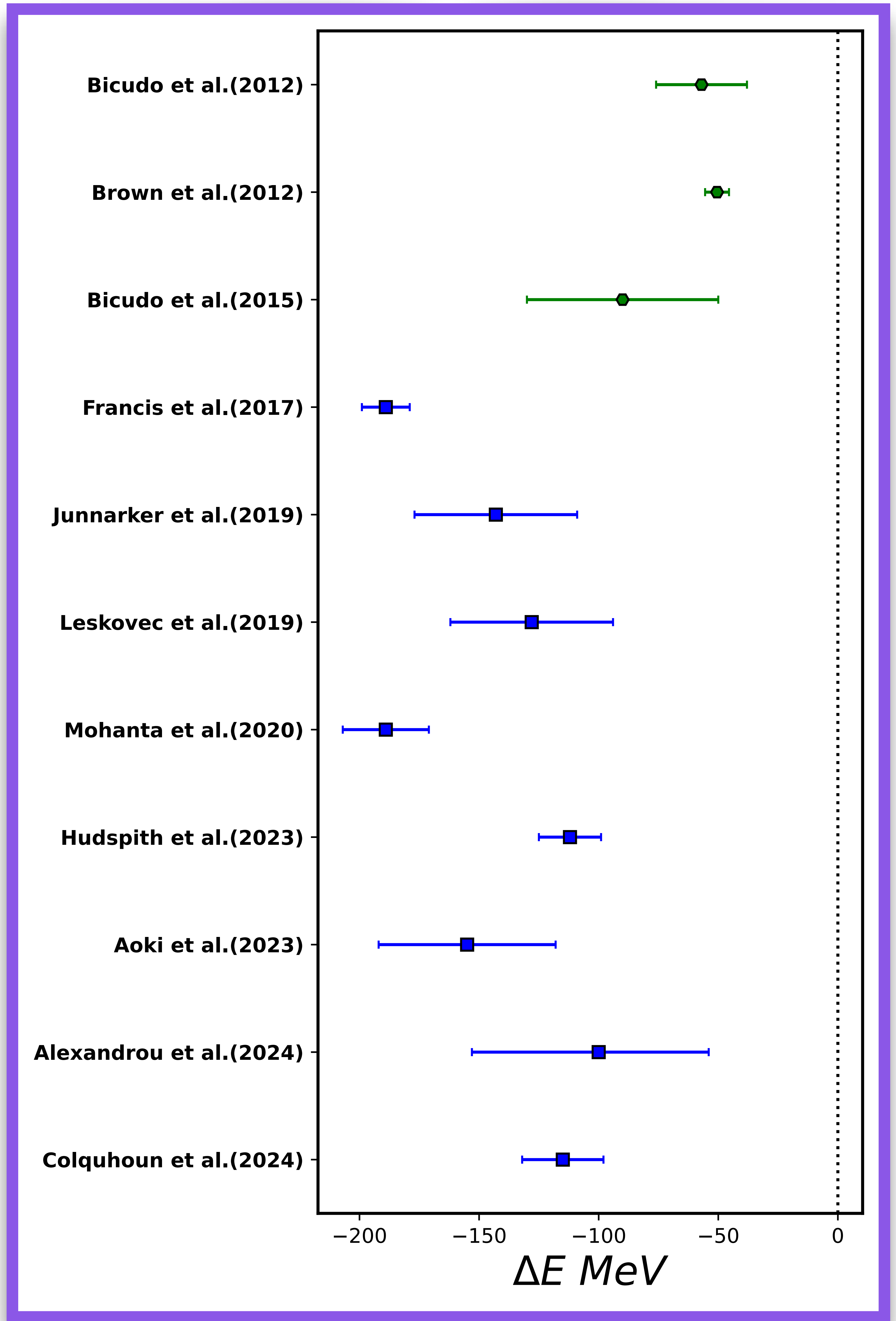
More on T_{cc} by Padmanath tomorrow

Long History of T_{bb}

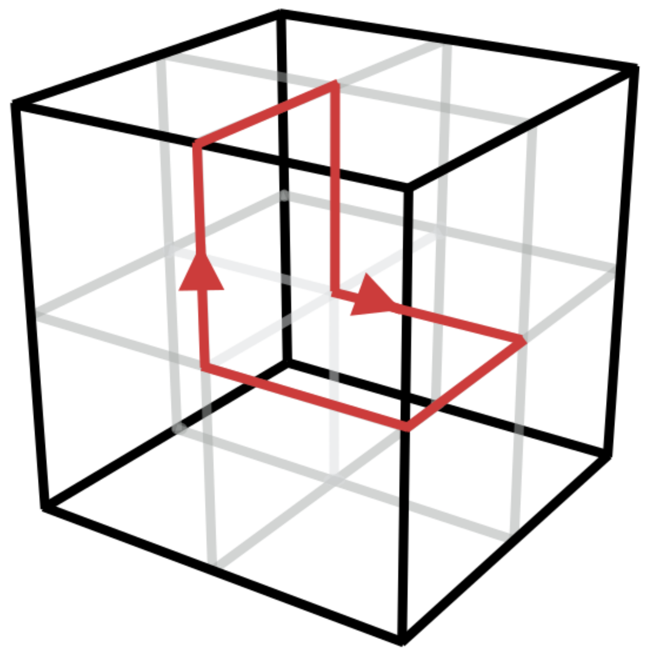
- Phenomenological calculation of T_{bb} can be trace back to the early 80's.
- Prediction of deeply bound state in the heavy quark limit.

Nucl.Phys.B 399 (1993)

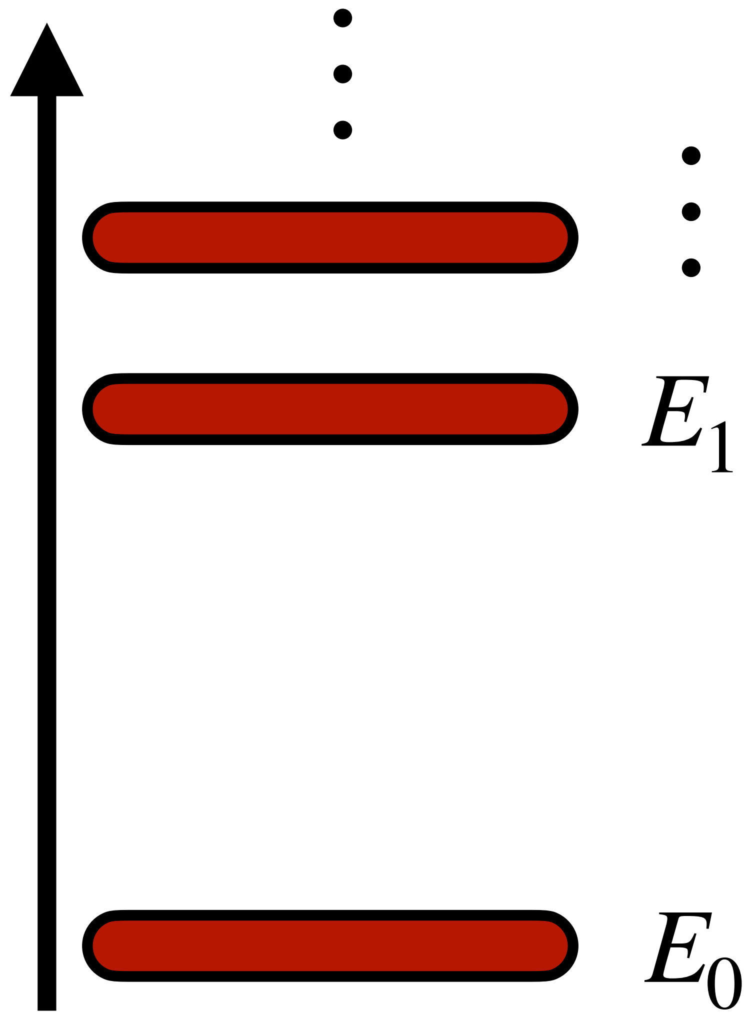
- Results from various phenomenological studies suggest possibility of deeply bound state.
- Previous lattice calculations on $bb\bar{u}\bar{d}\ I = 0$ shows deep bound state upto systematics.
- T_{cc} lattice results matches with that of the experimental results as pion mass decreases.



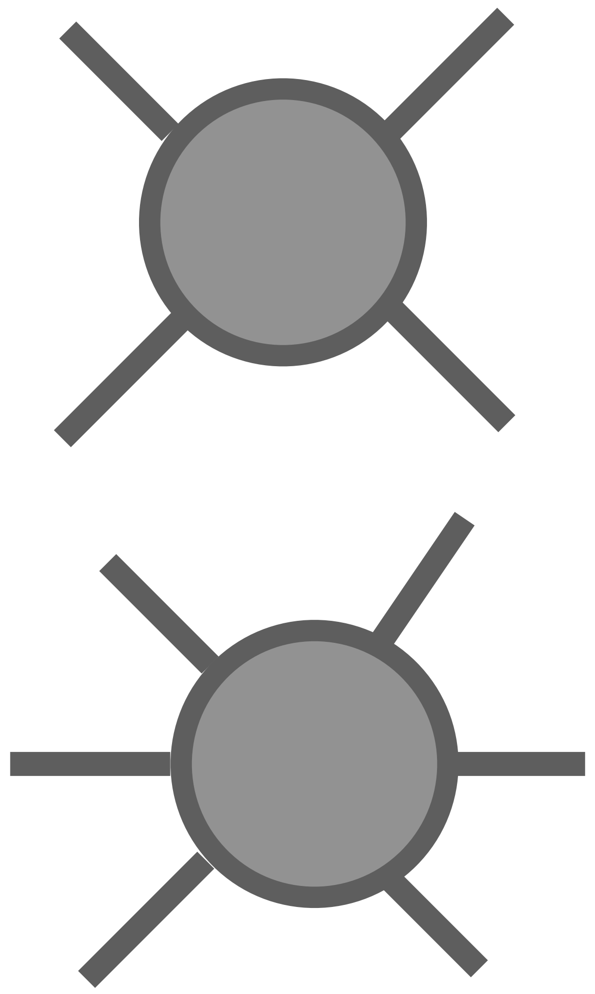
Hadron Spectroscopy in a Nutshell



Ensemble Generation



Finite Volume Spectra



Scattering Amplitude

$a \to 0$

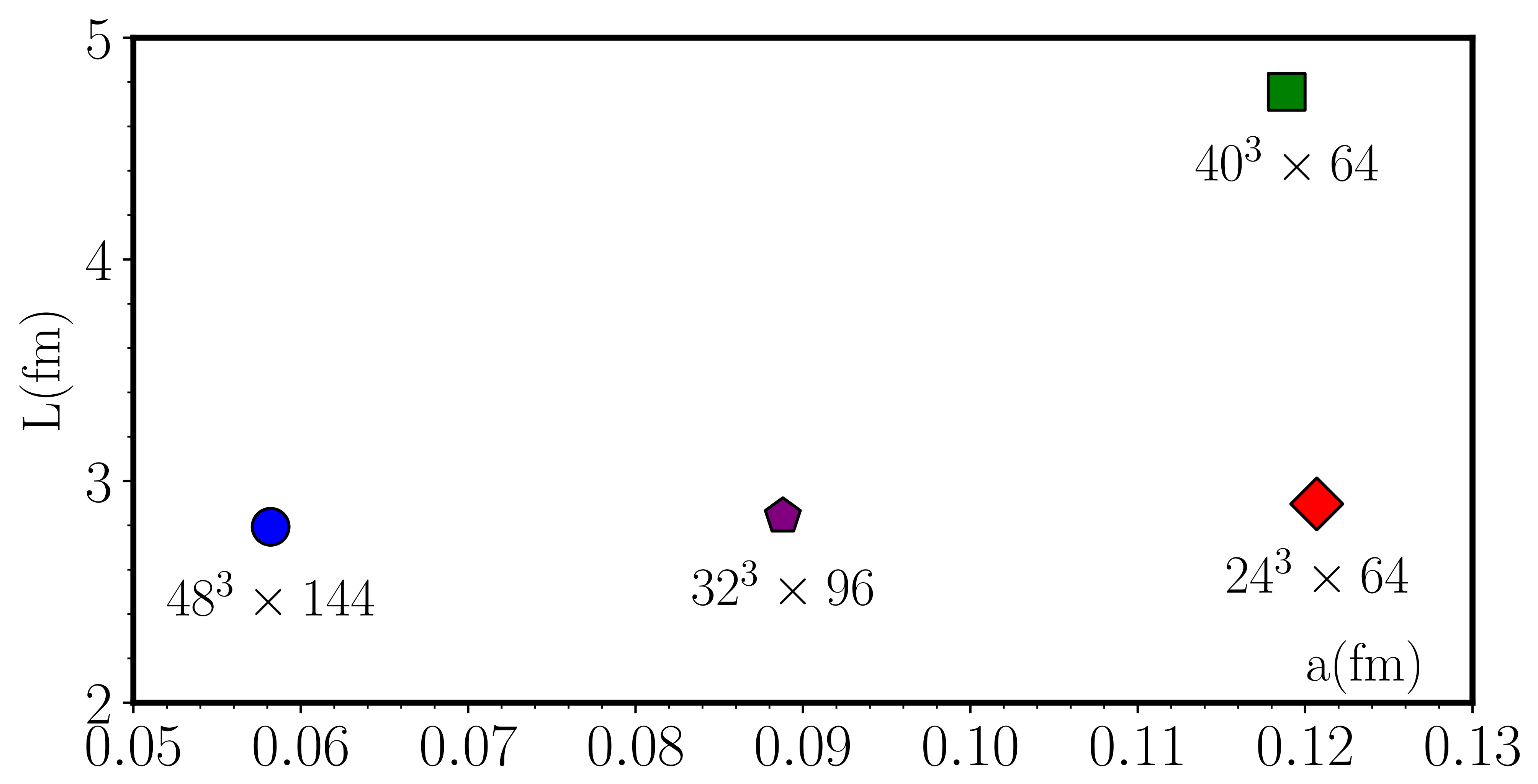
$L \to \infty$

$M_{ps} \to M_{\pi}^{phy}$

Continuum Extrapolation

Lattice Setup

- We are interested in doubly bottom tetra quarks $bb\bar{u}\bar{d}$ with $I(J^P) = 0(1^+)$.
- Worked with 4 MILC ensembles with $N_f = 2 + 1 + 1$ using HISQ action.
- Ensembles were generated at unphysical light quarks and physical charm and strange quarks.
- Light quark propagators were constructed using Overlap action. For heavy(bottom) quark, we used NRQCD action.
- Wall-source smearing setup.
- Used multiple volumes, box-sink correlators to reduce systematic effects.



Extracting Finite Volume Spectrum

- To extract spectrum we need good interpolating operators.
- Here we are using two types of operators.

Meson-Meson :

$$\Phi_{\mathscr{M}_{BB^*}}(x) = [\bar{u}(x)\gamma_i b(x)][\bar{d}(x)\gamma_5 b(x)] - [\bar{u}(x)\gamma_5 b(x)][\bar{d}(x)\gamma_i b(x)]$$

Diquark-antidiquark:

$$\Phi_{\mathscr{D}}(x) = [(\bar{u}(x)^T C\gamma_5 \bar{d}(x)) - (\bar{d}(x)^T C\gamma_5 \bar{u}(x)) \times (b^T(x) C\gamma_i b(x))]$$

- Finite volume spectrum can be calculated using Euclidean $\mathscr{C}_{ij}(t)$, between $\Phi's$

$$\mathscr{C}_{ij}(t) = \left\langle \Phi_i(\mathbf{x}, t)\tilde{\Phi}_j^\dagger(0) \right\rangle$$

Finite Volume Spectrum cont.

- We use GEVP to extract finite volume spectrum from correlation-matrix variationaly.

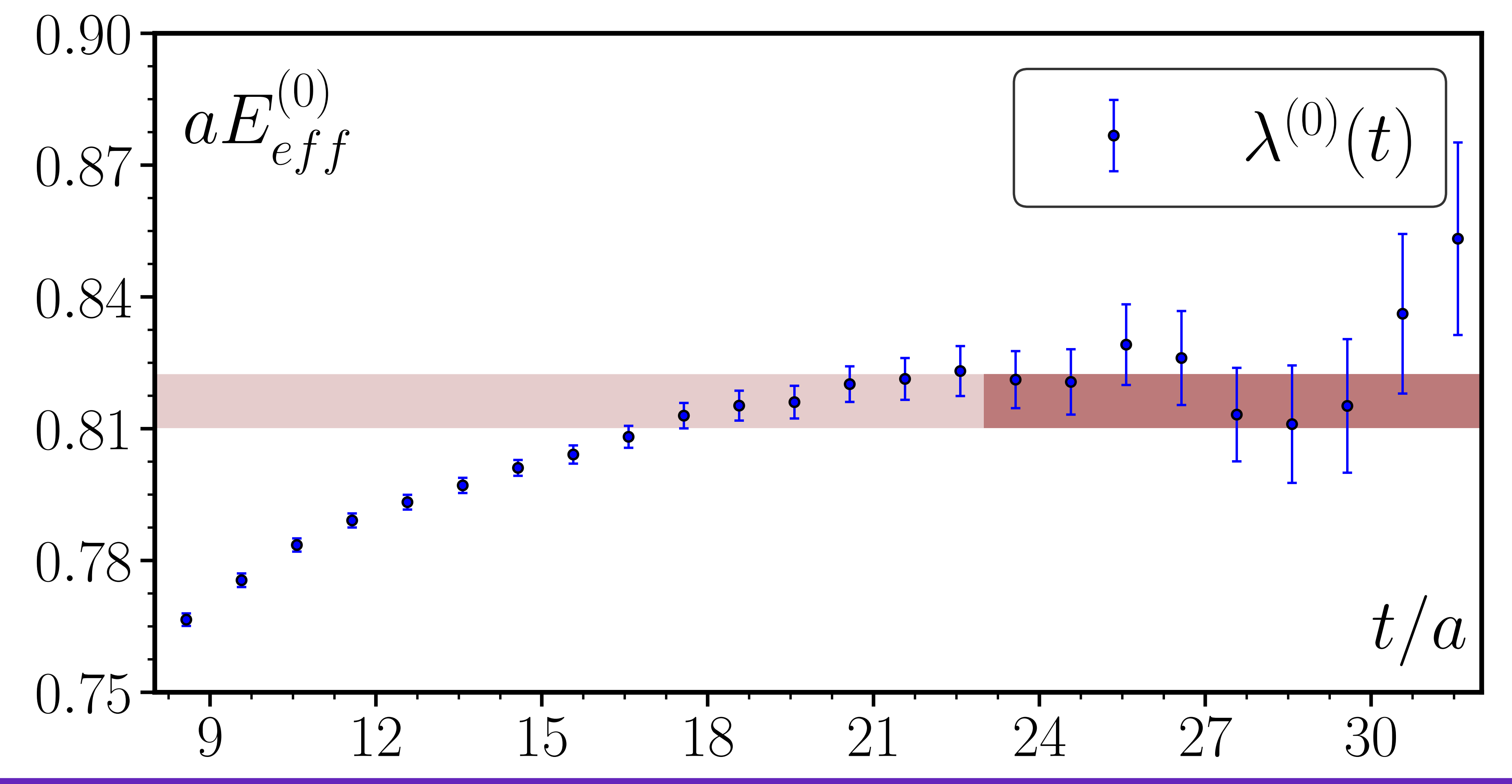
$$\mathscr{C}(t)v^{(n)}(t) = \lambda^{(n)}(t,t_0)\mathscr{C}(t_0)v^{(n)}(t)$$

- Fitting the leading exponential of $\lambda^n(t)$, yields the energy Eigen state E_n.

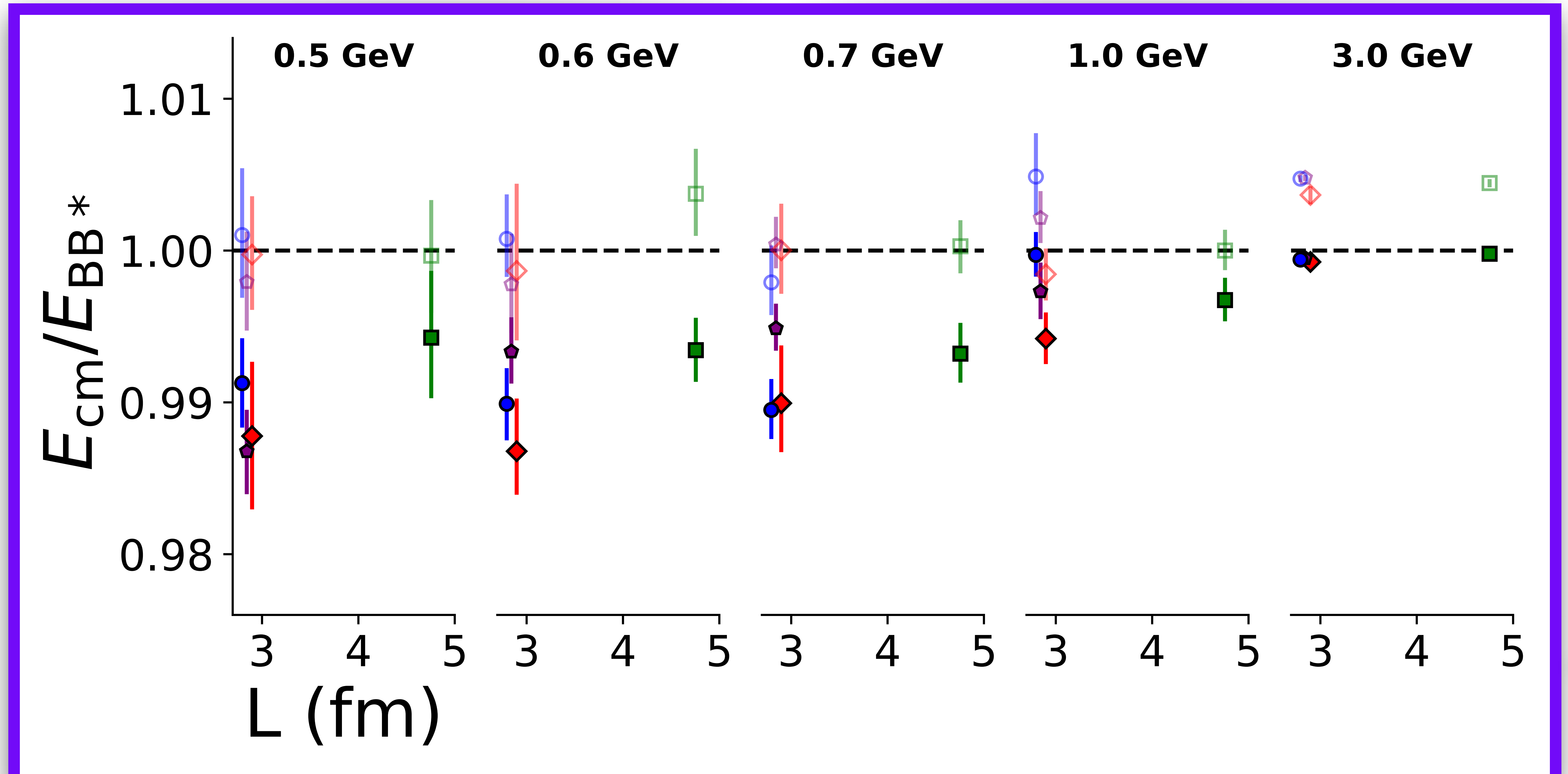
$$\lambda^n(t,t_0) = |A_n|^2 e^{-E_n(t-t_0)}[1 + \mathcal{O}(e^{-\Delta_n(t-t_0)})]$$

- Excited states can be determined with this method.

- Repeated for B and B^* mesons.



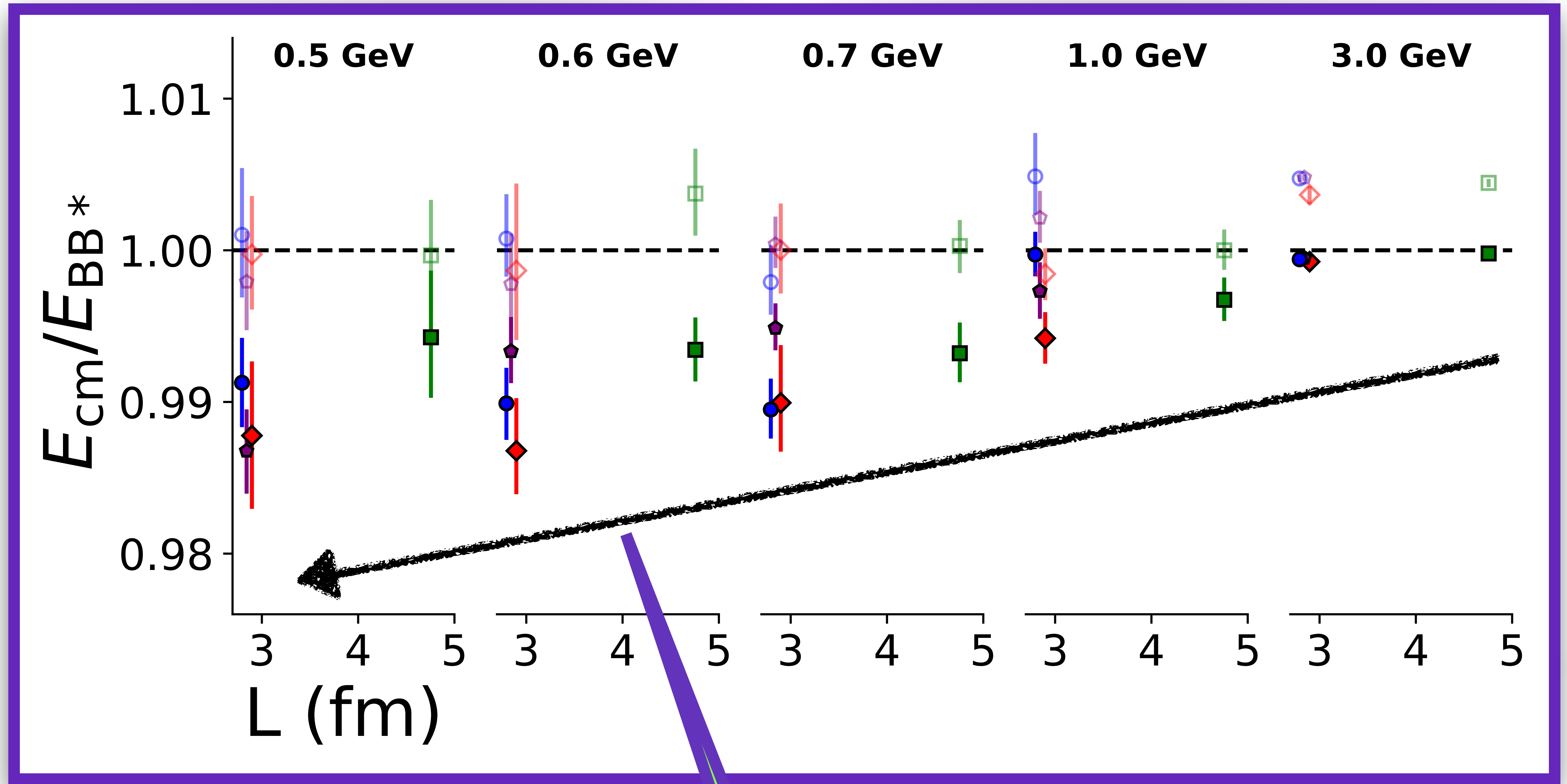
Finite Volume Spectrum cont.



- Spectrum extraction repeated for every M_{ps} and every ensemble.

Spectrum were calculated In terms of nearest Two body decay threshold BB^*.

Finite Volume Spectrum cont.



Spectrum extraction repeated for every M_{ps} and every ensemble.

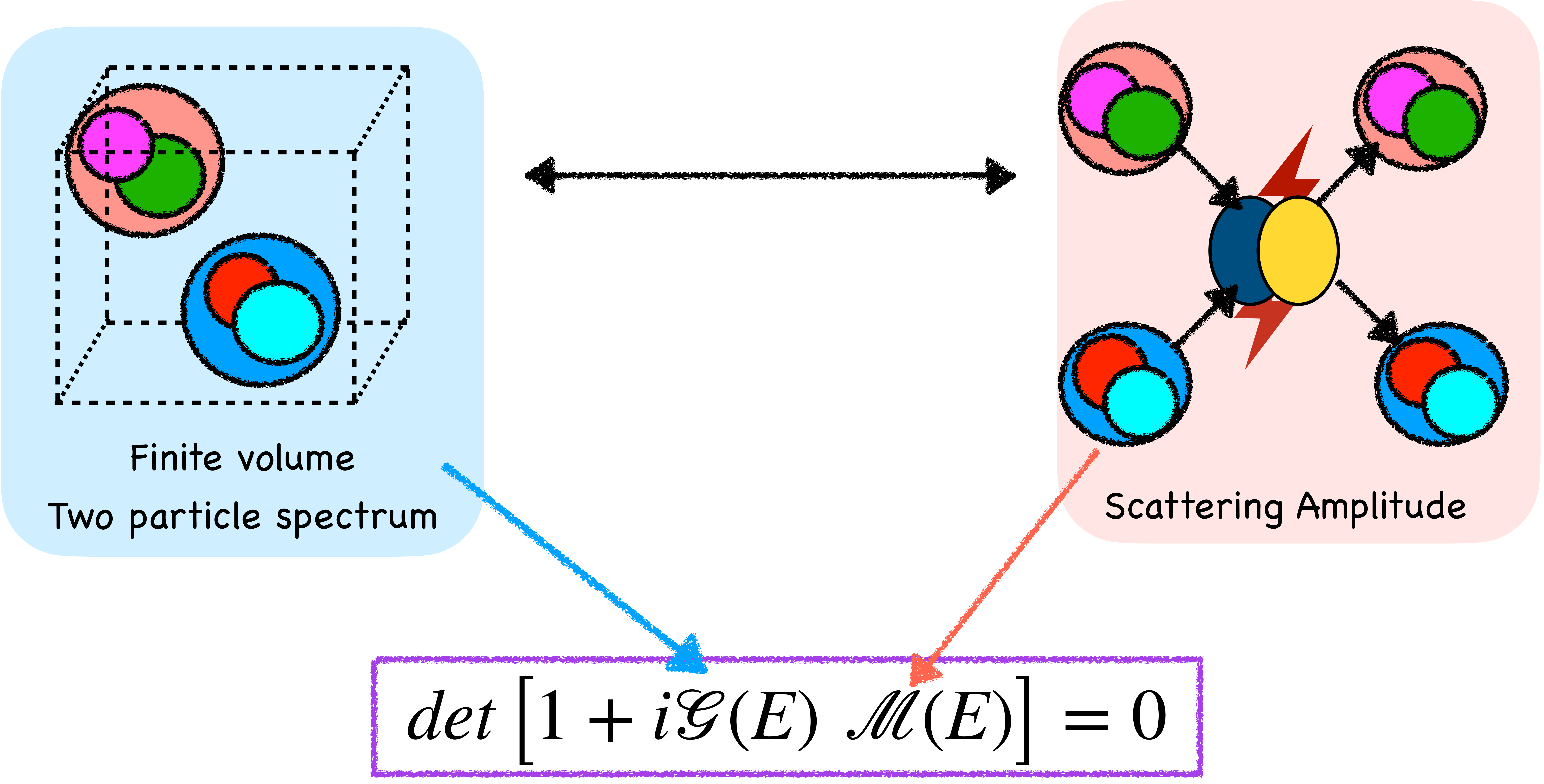
Spectrum were calculated In terms of nearest Two body decay threshold BB^*.

A decreasing trend can be observed

We need continuum extrapolation to have results in physical limit

Amplitude Analysis

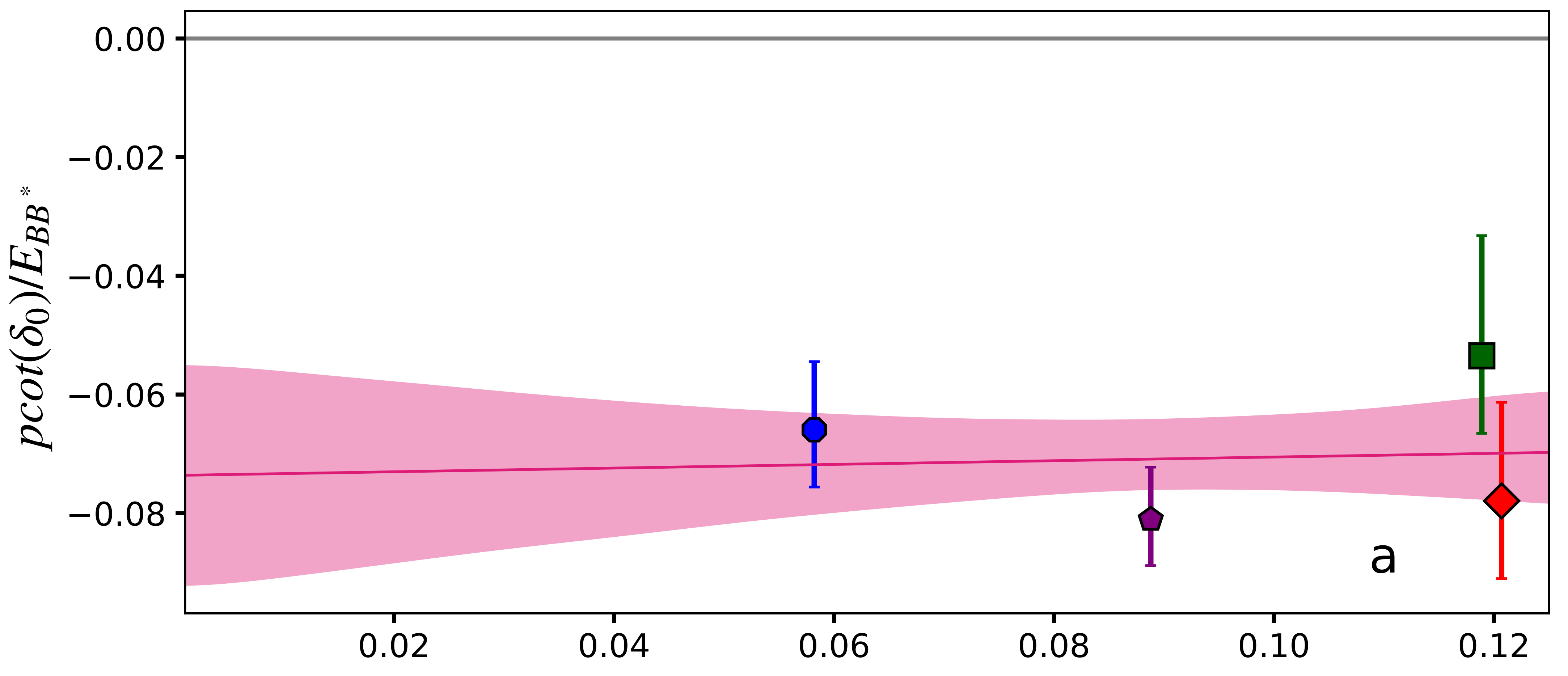
Lüscher based quantization condition(1991)



$$det\left[1+i\mathscr{G}(E)\ \mathscr{M}(E)\right]=0$$

Continuum Extrapolation

$M_{ps} = 0.5$ GeV



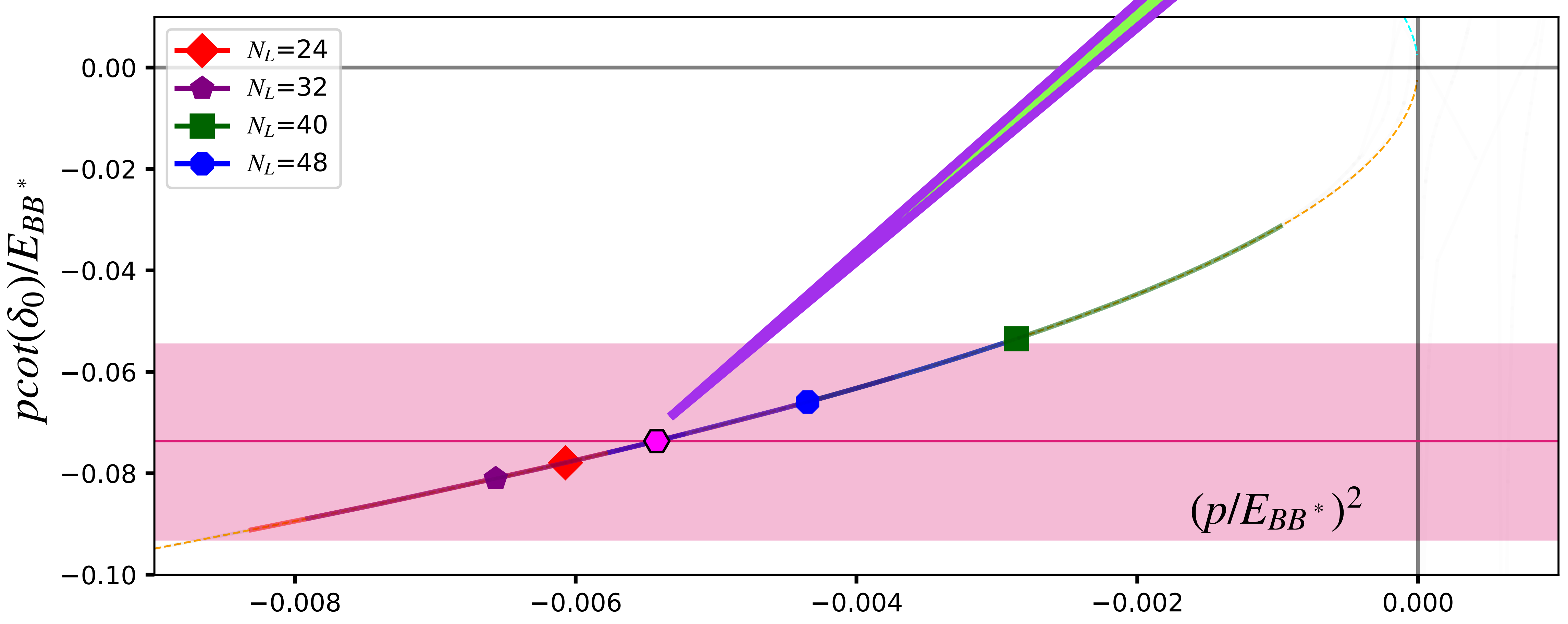
- **Scattering Amplitude is given as**

$$T \propto (pcot\ \delta - ip)^{-1}$$

- **It is parametrised as**

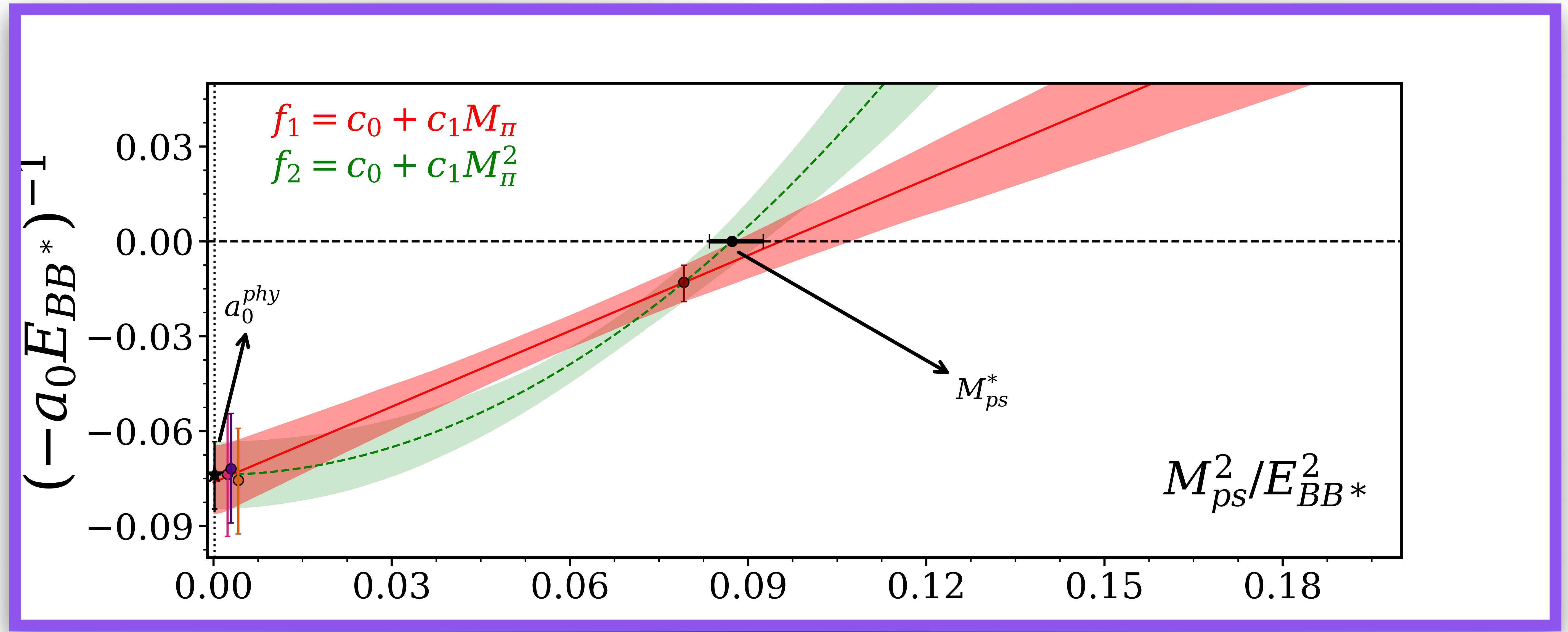
$$pcot\ \delta = -\frac{1}{a_0} + B \cdot a$$

Real Bound State



- **Same repeated for other M_{ps}.**
- **Consistent Negative values for other M_{ps} as well as real bound state.**

Chiral Extrapolation

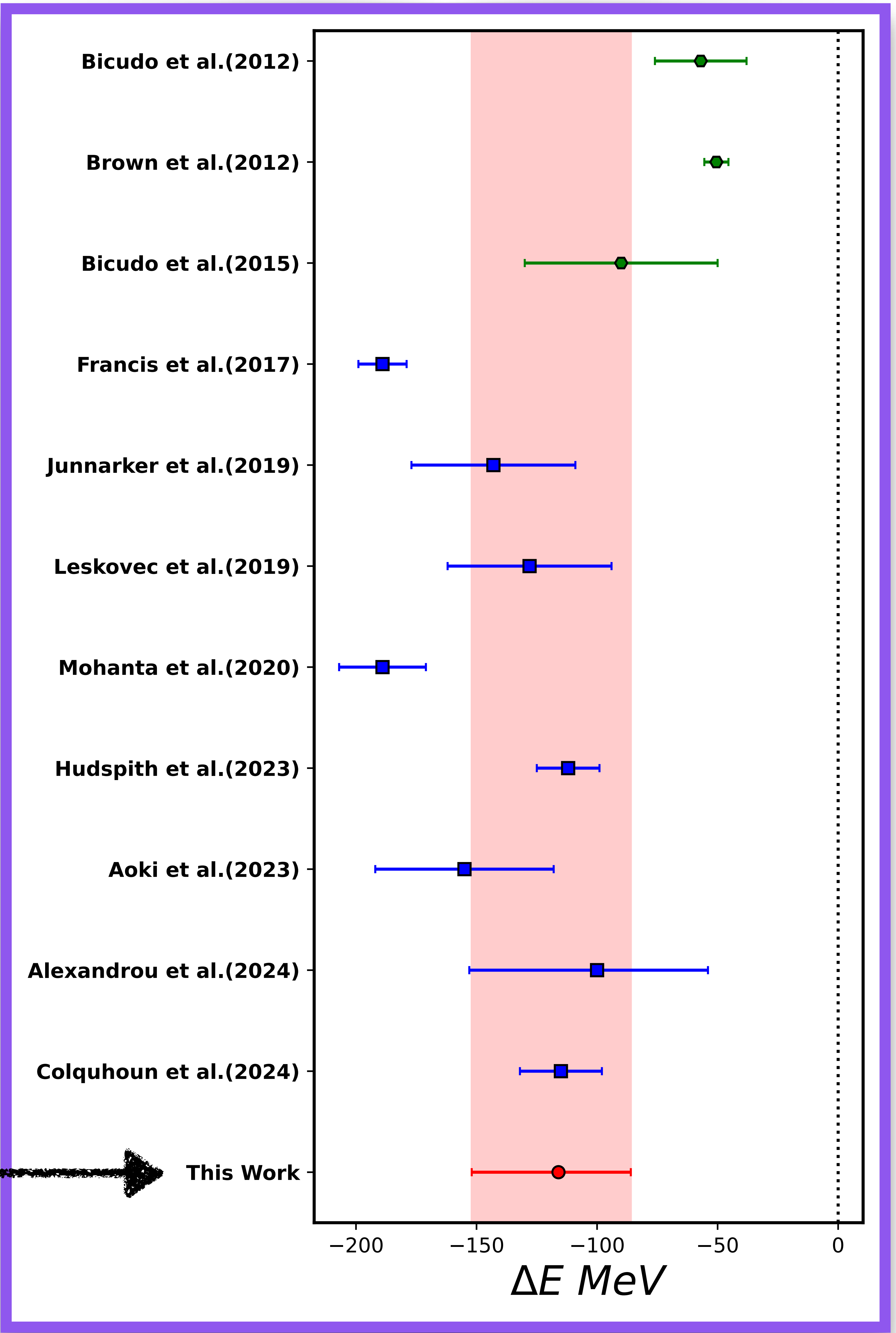


Result:

Scattering length at physical limit

$$a_0^{phy} = 0.25(^4_3)\ fm$$

Corresponds to binding energy $\Delta E = -116(^{+30}_{-36})$ **MeV.**



Summary and Outlook

- Various work widely predicted deep binding in isoscalar T_{bb}.
- Rigorous spectrum analysis were done for T_{bb} tetraquark with $I(J^P) = 0(1^+)$.
- We worked with multiple lattice spacing, two volumes to control systematics.
- Finite volume spectrum indicates negative energy shift with respect to BB^* threshold.
- Amplitude analysis were carried out with Lüscher Formalism.
- Found a possible deeply bound state.

THANK YOU

More Lattice Talks tomorrow

- Dr. Sanayantan Sharma
- Dr. M. Padmanath
- Dr. Indrakshi R.