Hadron Spectroscopy and Interactions from Lattice QCD

Liuming Liu

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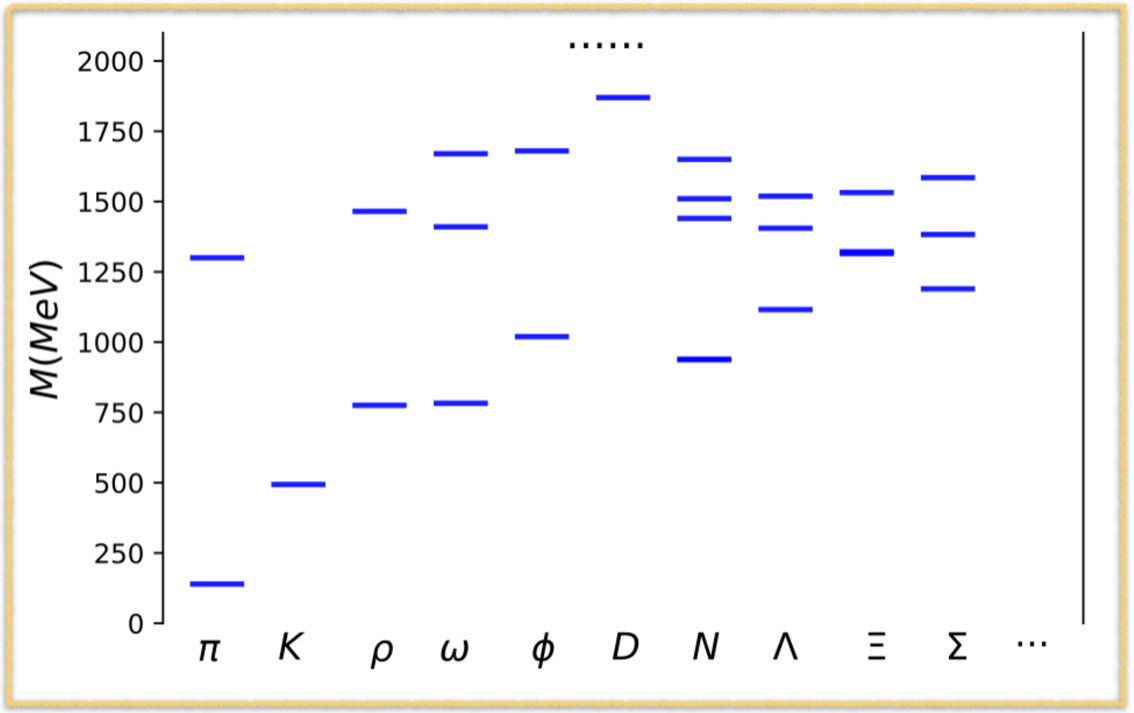
Lattice 2022, Bonn

Aug. 8- 13, 2022

First of all, I would like to thank...

- ★ The LOC for the kind invitation
- ★ Those who sent me materials for this talk:
  Sinya Aoki, Yan Lyv, M. Padamanath, Sasa Prelovsek,
  Michael L. Wagman, ……
- ★ My collaborators at CLQCD
  Y. Chen, J. Liang, C. Liu, Y. B. Liu, Peng Sun, Y. B. Yang, ……

Spectroscopy in experiments

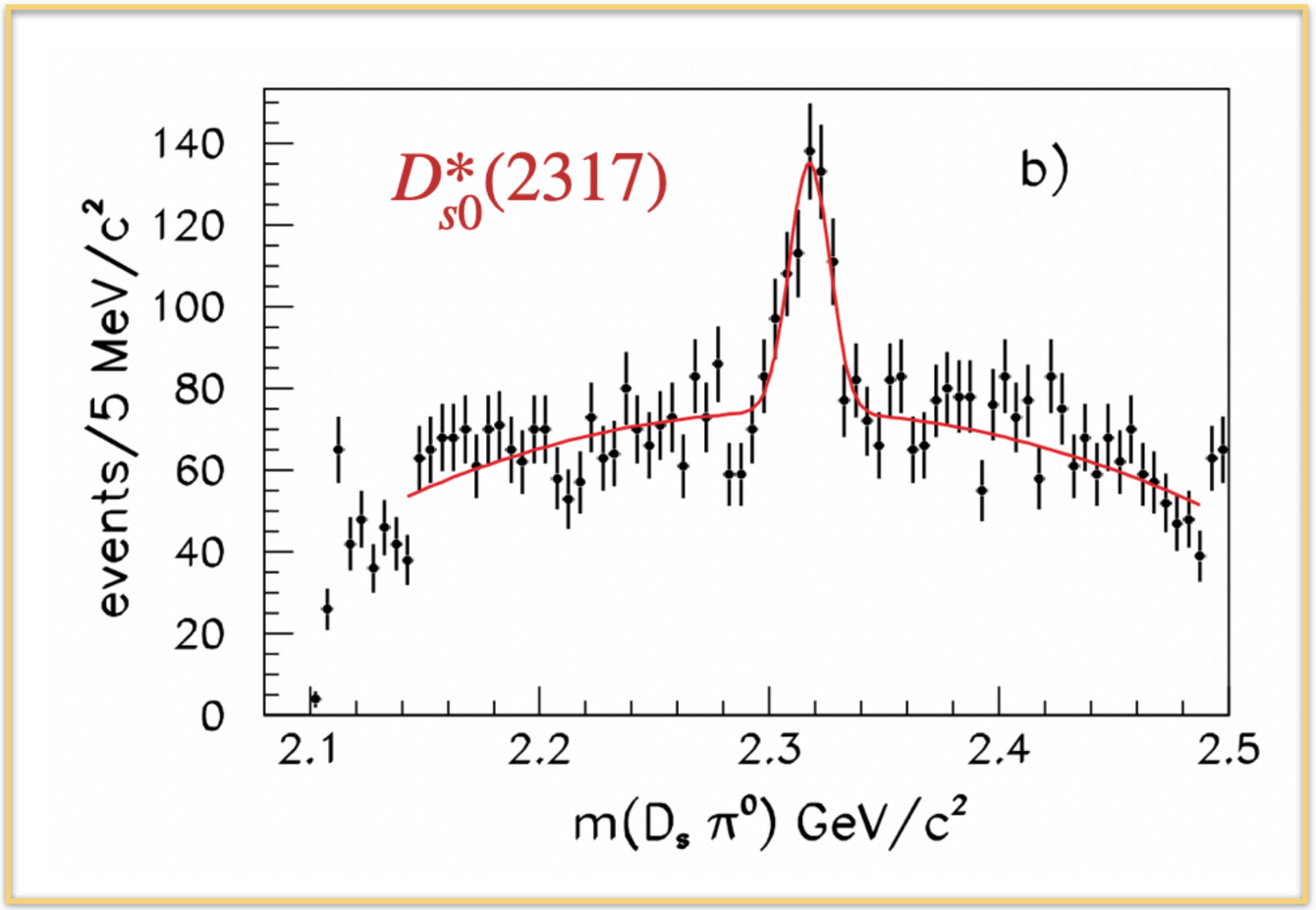


✦ Spectroscopy:

- Obtain hadron masses.
- Understand how hadrons are built from quarks and gluons.

✦ New experimental discoveries provide opportunities and challenges for lattice.

Spectroscopy in experiments



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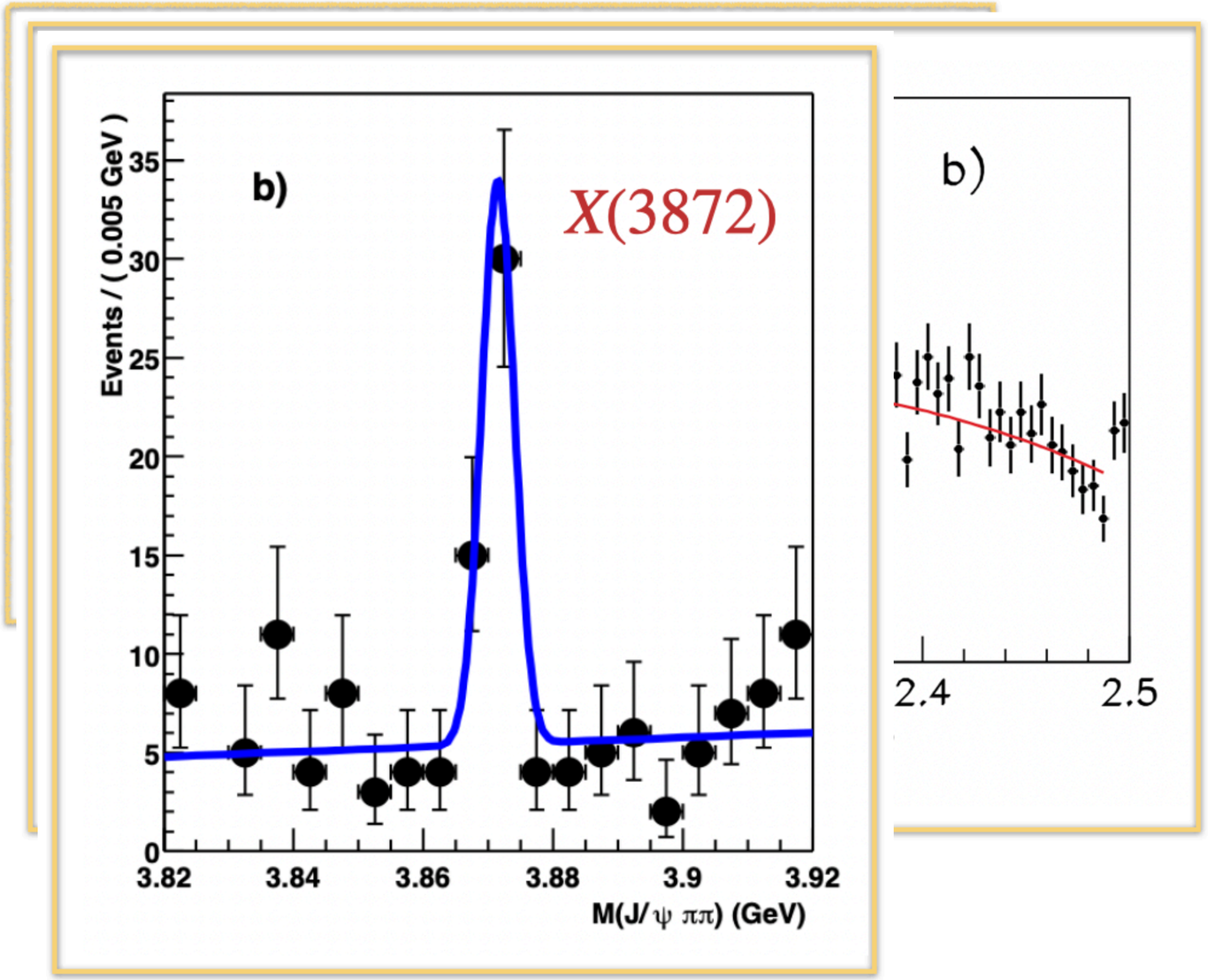

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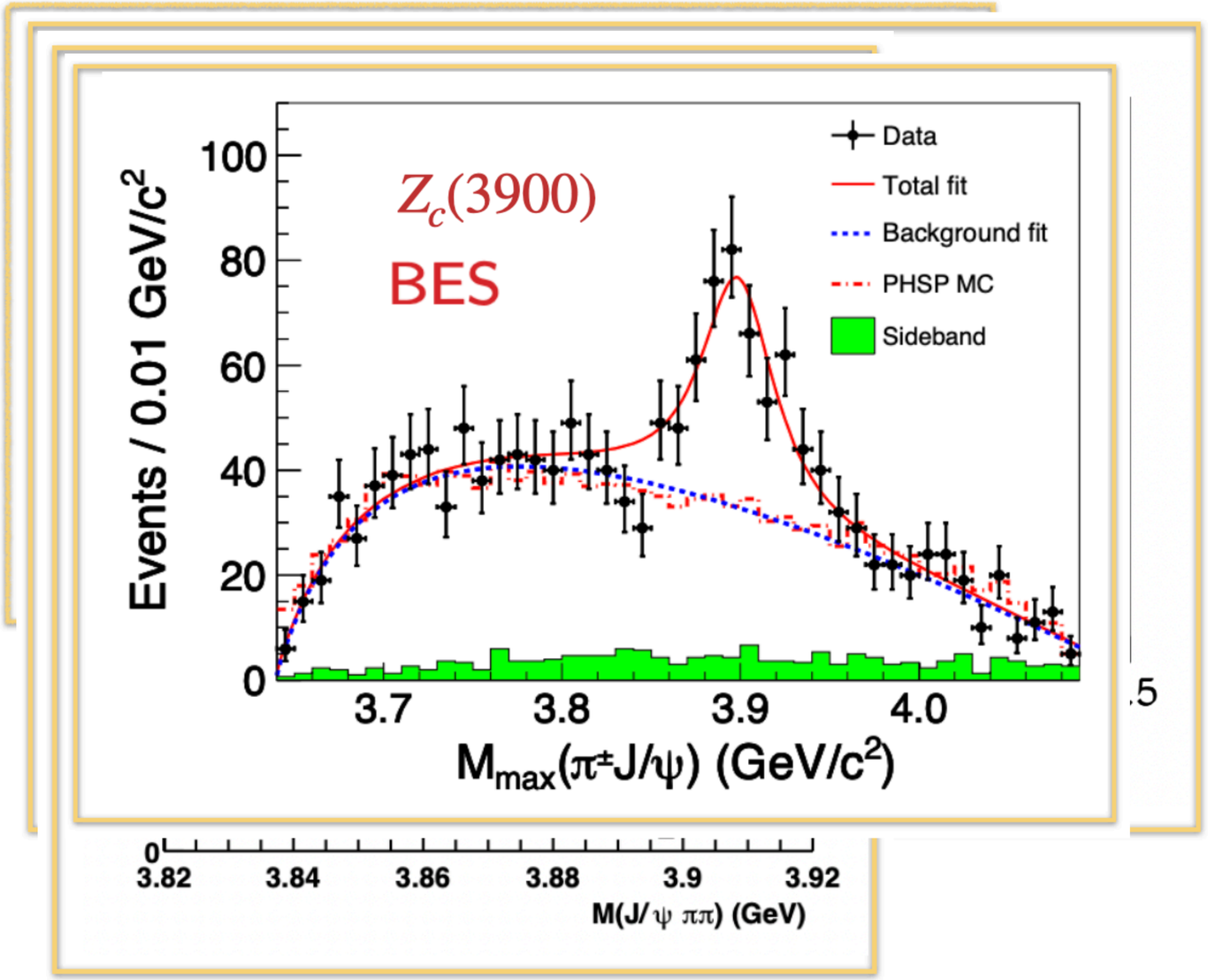

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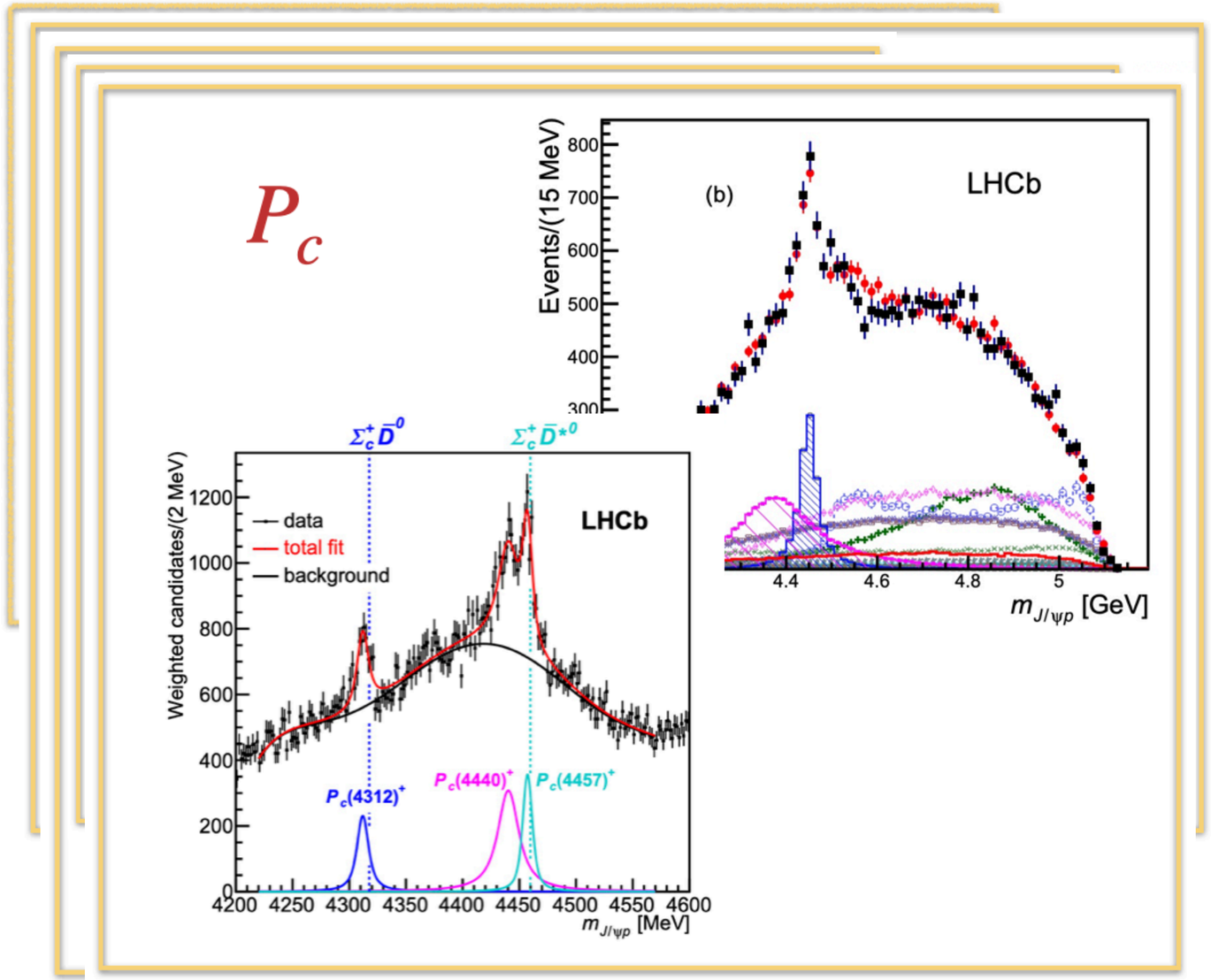

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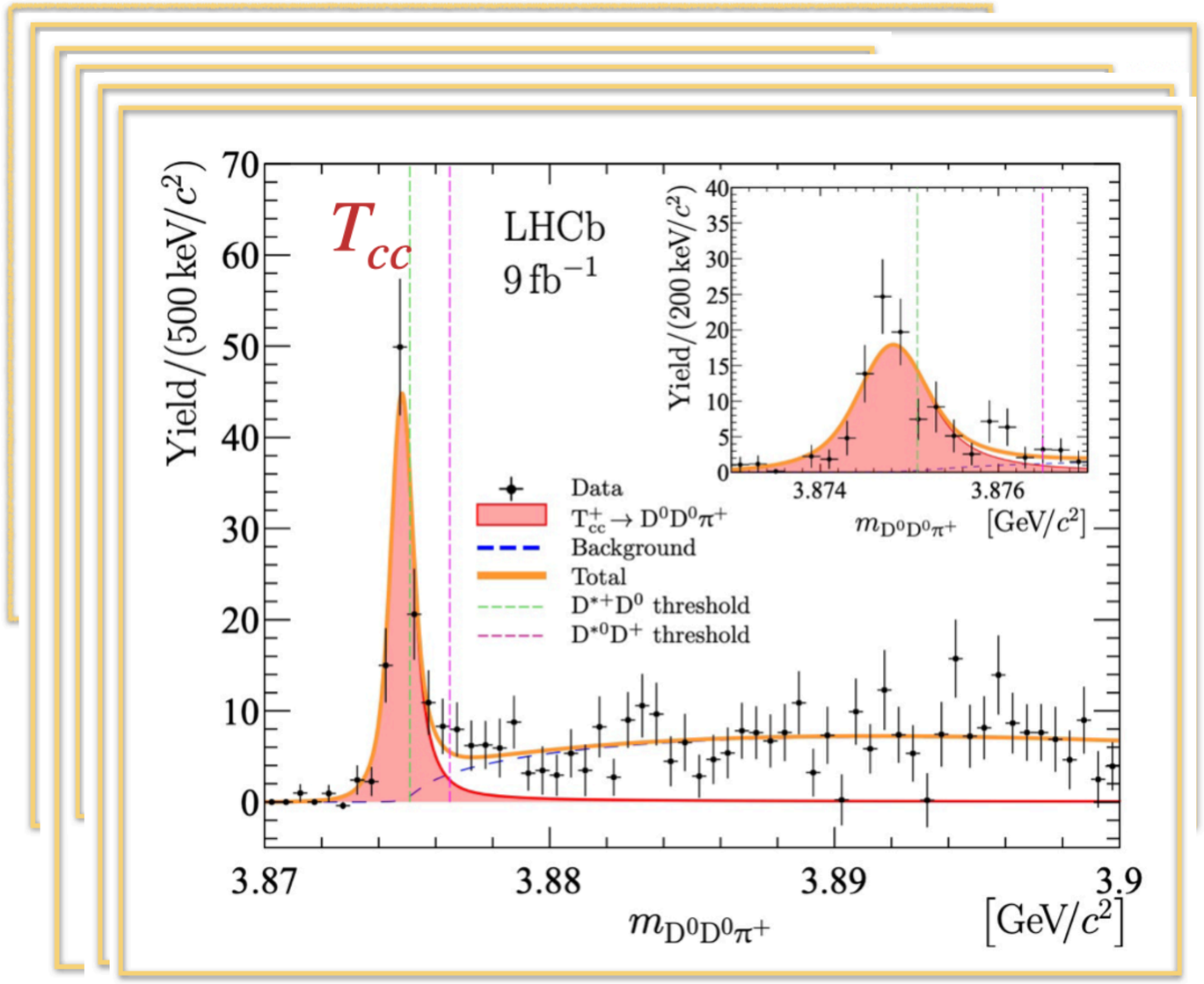

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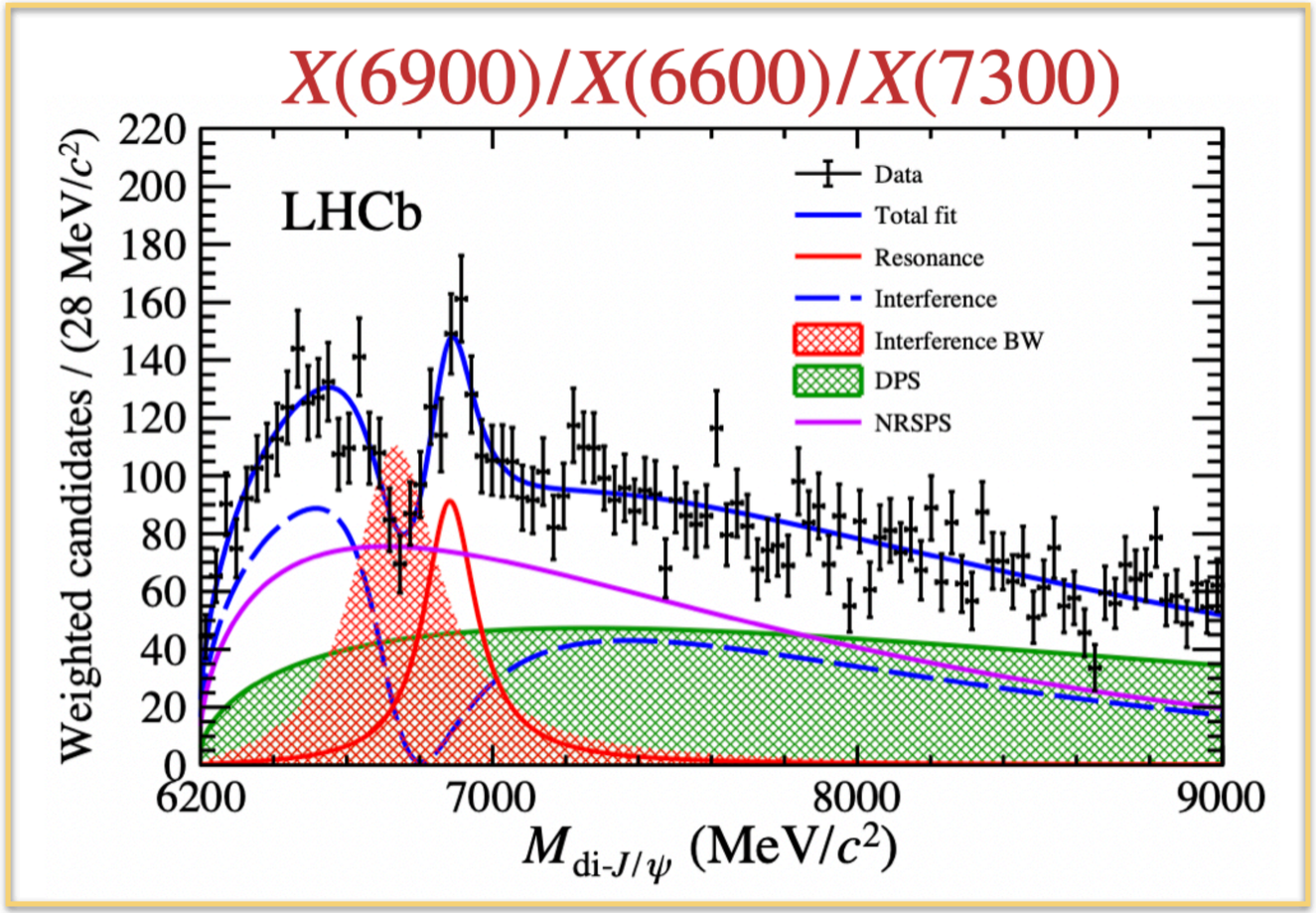

✦ Spectroscopy:

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Spectroscopy on lattice

Standard procedures:

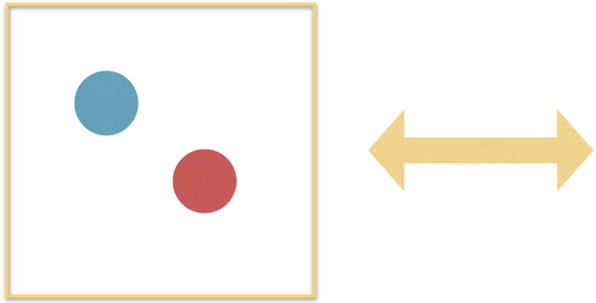
- Write down a set of interpolating operators with the right quantum numbers $\{\mathcal{O}_i\}$.
- Compute the correlation functions $C_{ij}(t) = \langle 0 | \mathcal{O}_i(t) \mathcal{O}_j^\dagger(0) | 0 \rangle$.
- A tower of energy levels can be extracted from $C_{ij}(t)$.
- Precise results have been obtained for **stable** hadrons, including isospin breaking effects and QED corrections.

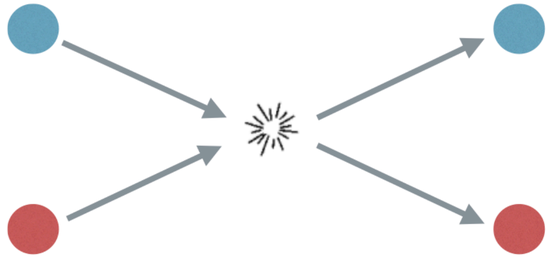
However……

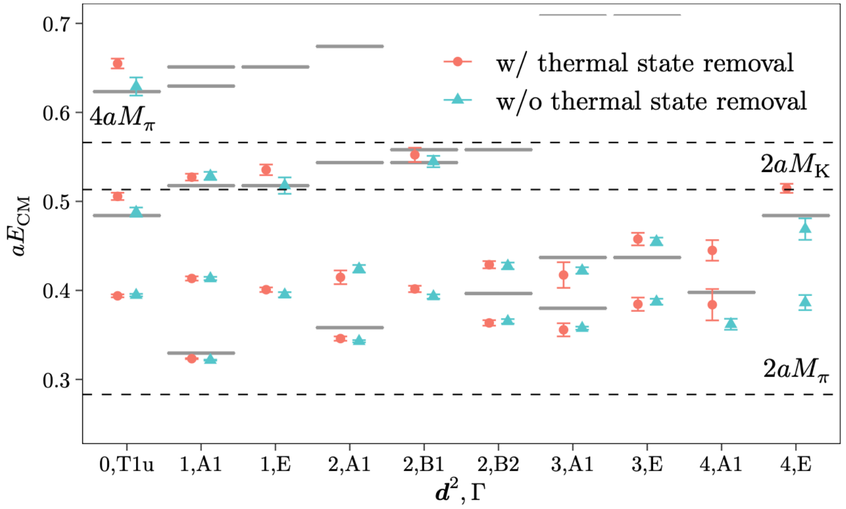
- Most of the hadrons are not stable.
- Scattering of two or more hadrons is needed.

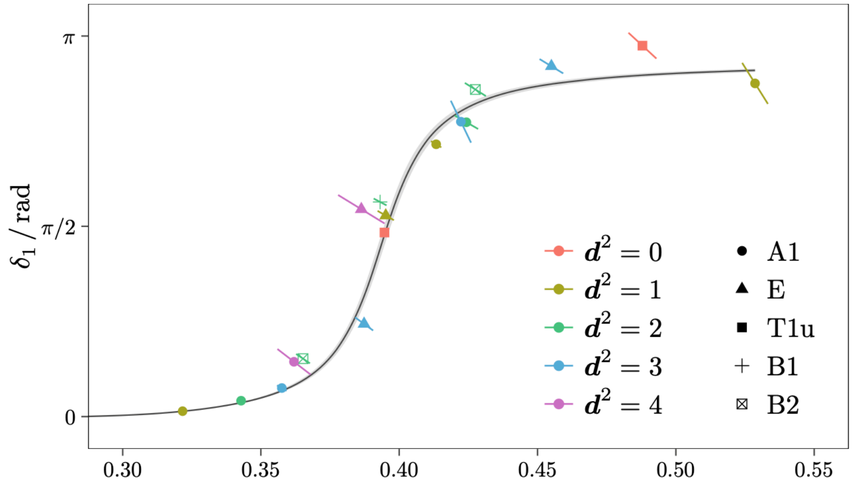
Spectroscopy on lattice

Lüscher's finite volume method (M. Lüscher, Nucl. Phys. B354, 531(1991))









Spectroscopy on lattice

Generalization of Lüscher's method: moving frames, particles with arbitrary spin, coupled channels, three-body interaction…

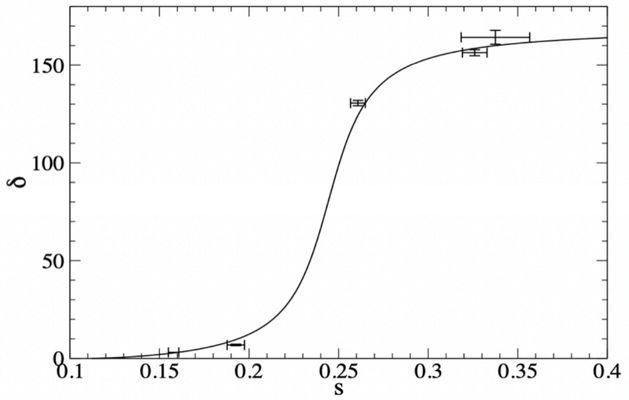
- K. Rummukainen and S. A. Gottlieb, Nucl. Phys. B 450, 397 (1995).
- C. h. Kim, C. T. Sachrajda and S. R. Sharpe, Nucl. Phys. B 727, 218 (2005)
- M. Gockeler et al., Phys. Rev. D 86, 094513 (2012)
- R. A. Briceno, Phys. Rev. D 89, 074507 (2014)
- K. Polejaeva and A. Rusetsky, Eur. Phys. J. A48, 67 (2012)
- M. T. Hansen and S. R. Sharpe, Phys. Rev. D 92, 114509 (2015)
- H. W. Hammer, J. Y. Pang and A. Rusetsky, JHEP 10, 115 (2017)
- M. Mai and M. D¨oring, Phys. Rev. Lett. 122, 062503 (2019)
- ……

HALQCD method: see talk by Sinya Aoki, Tue. 14:40-15:00

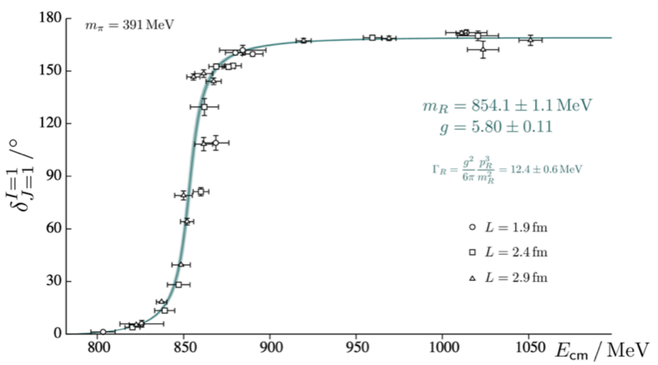
Application of Lüscher's method

ρ resonance

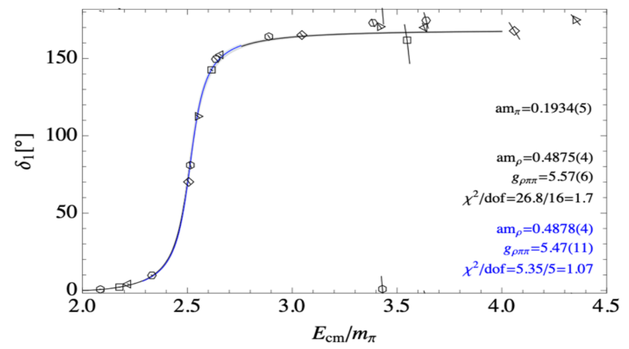
C. B. Lang et, al., Phys. Rev. D 84, 054503 (2011)



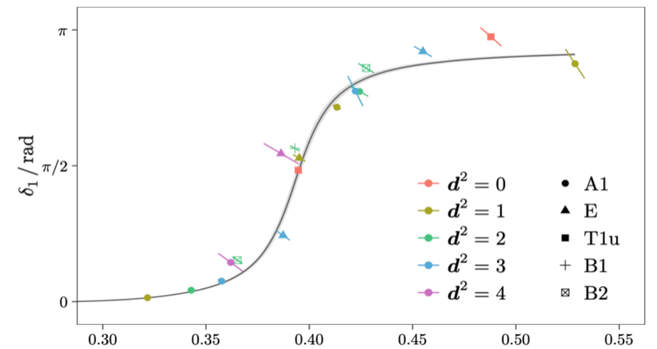
J. Dudek, el. al.,Phys. Rev. D 87, 034505 (2013)



D. Guo, el. al., Phys. Rev. D 94, 034501 (2016)



M. Werner, el.al., Eur. Phys. J. A (2020) 56:61



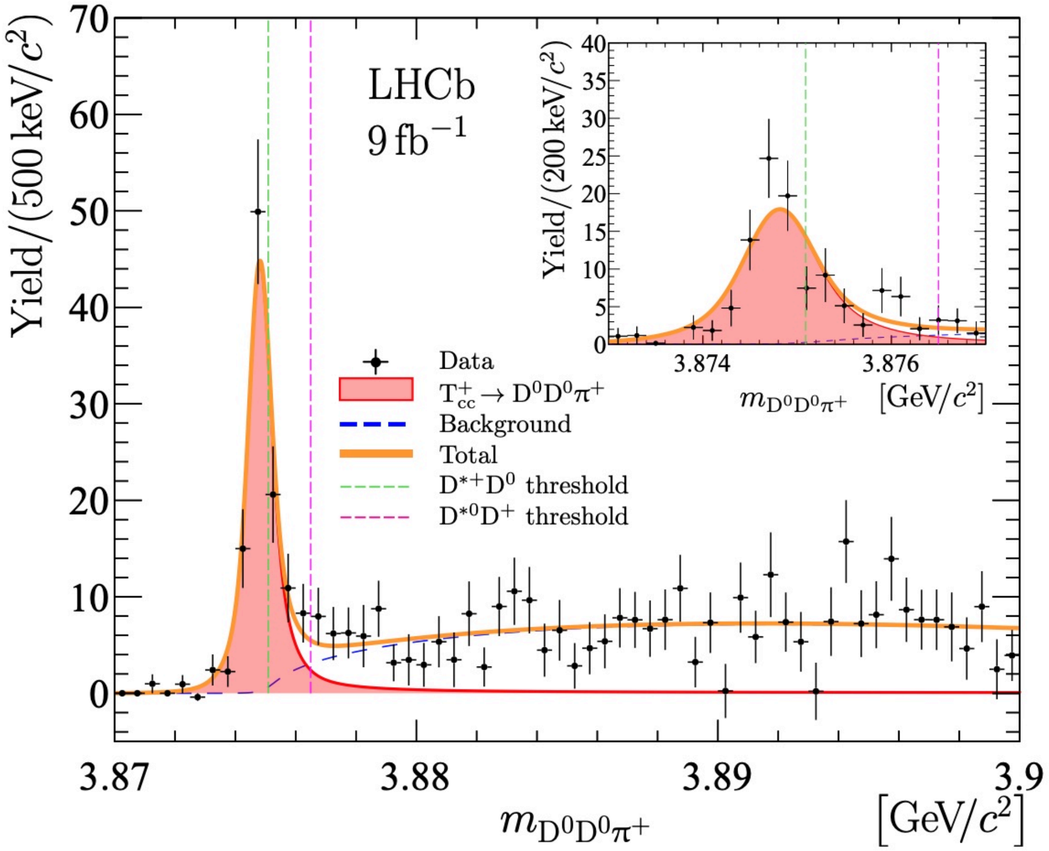
Plenary talks by

- Davide Vadacchino, “A review on Glueball hunting”, Tue. 11:45-13:30
- Fernando Romero-Lopez, “Topical plenary on multi-particle interactions from lattice QCD”, Wed. 11:00-11:30

Review of recent results

- ✦ Meson-meson scattering:
  - DD^* and the doubly charmed tetraquark T_{cc}
  - BB^* and the T_{bb}
  - $D\bar{D} - D_s\bar{D}_s$ charmonium(like) states
- ✦ Meson-baryon Scattering:
  - $\Sigma_c - \bar{D}(\bar{D}^*)$
  - $N - \phi$
- ★ Baryon-Baryon scattering:
  - NN
  - $\Lambda\Lambda$
  - $\Omega_{bbb}\Omega_{bbb}$

DD^* and T_{cc}



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

$$= -361 \pm 40(\text{keV})$$

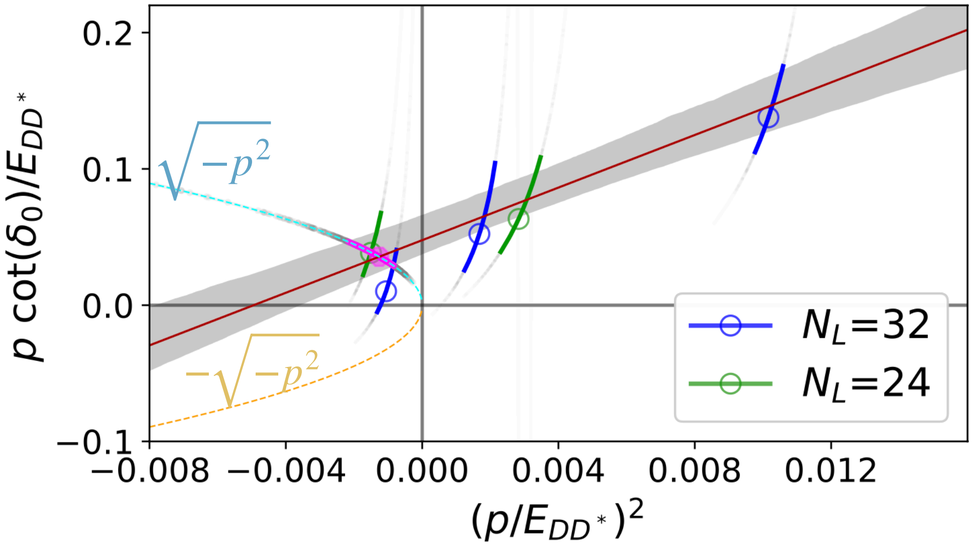
$$\Gamma = 47.8 \pm 1.9(\text{keV})$$

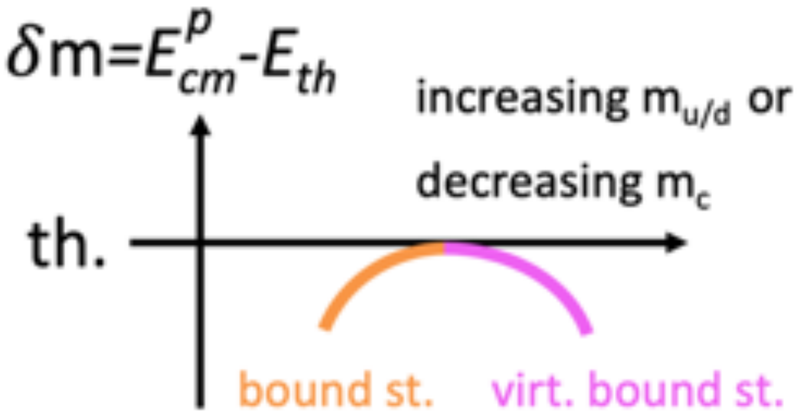
LHCb collaboration, R. Aaij et al., *Nature Phys*. 18 (2022) 7, 751-754.

LHCb collaboration, R. Aaij et al., Nature Communicatitions, 13, 3351 (2022)

DD^* and T_{cc}

M. Padmanath and S. Prelovsek, Phys.Rev.Lett. 129 (2022) 3, 032002





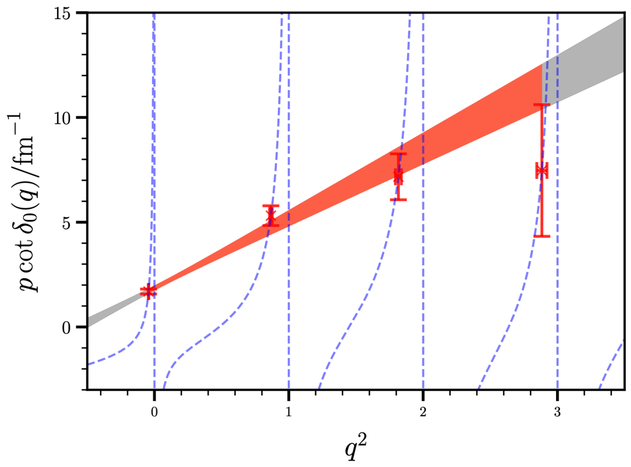
- Finite-volume energy eigenvalues are extracted using DD^* interpolating operatros in rest and moving frames.
- A virtual bound state pole is found in the scattering amplitude.
- Quark mass dependence of the binding energy and pole position.

Talk by M. Padmanath, Tue. 14:00-14:20

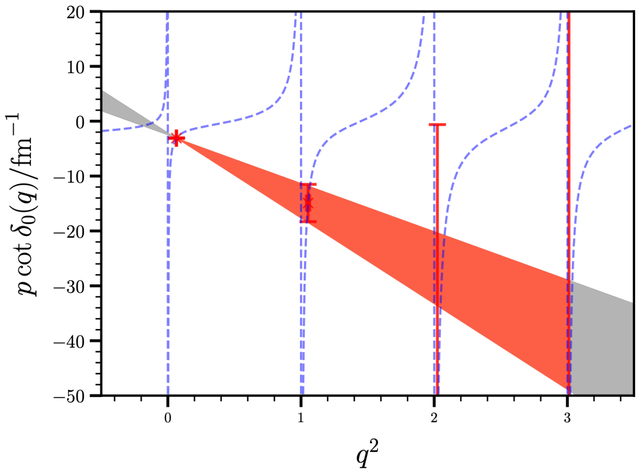
Talk by S. Prelovsek, Tue. 14:20-14:40

DD^* and T_{cc}

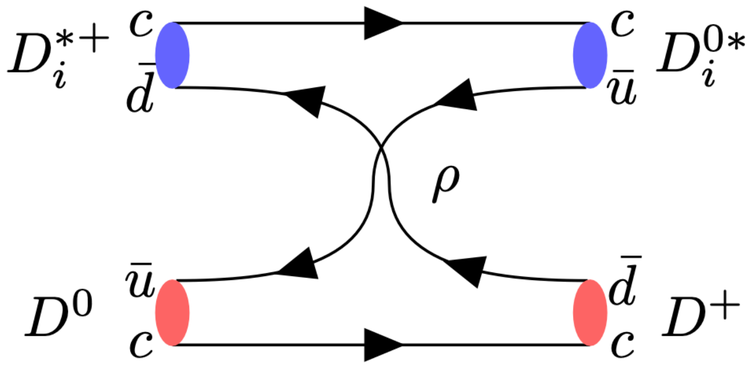
Siyang Chen, et.al (CLQCD), arXiv:2206.06185



I=0
Attractive

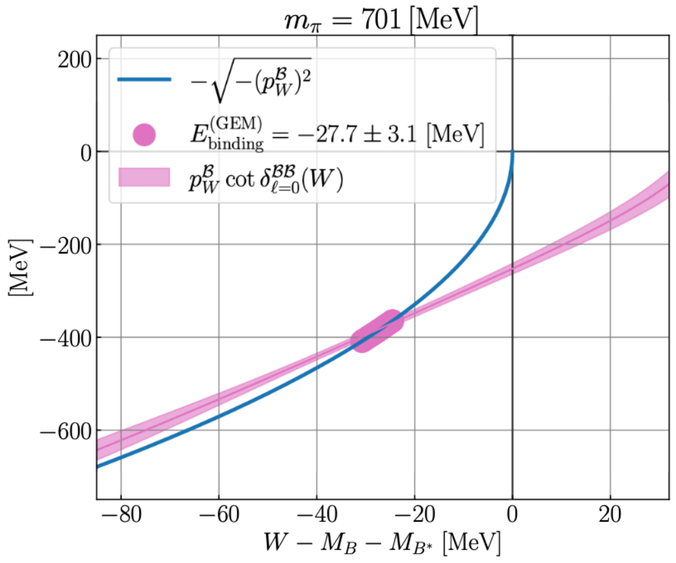


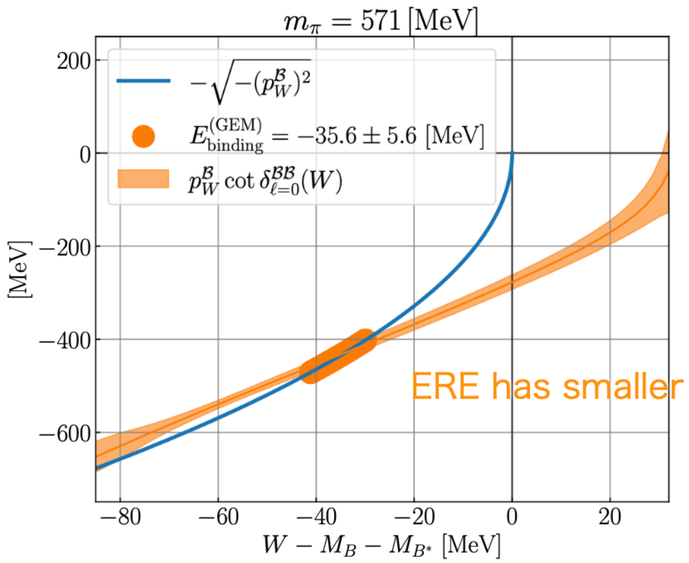
I=1
Repulsive



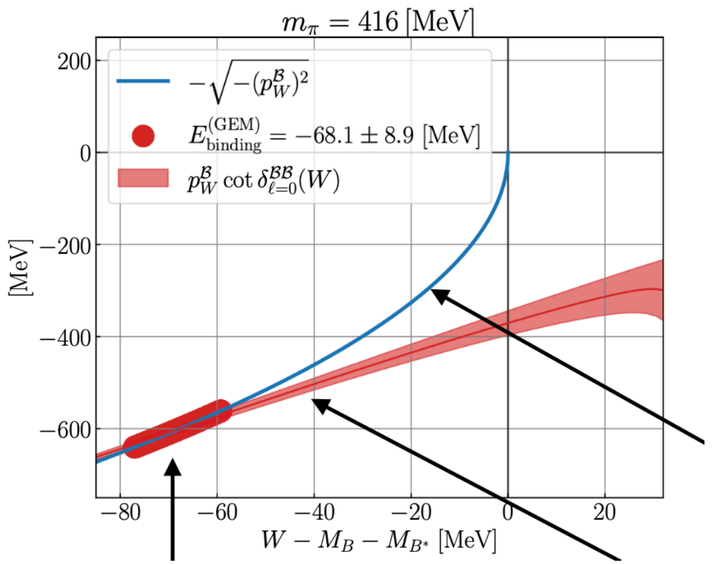
The attraction in I=0 channel mainly comes from the charged ρ exchange.

BB^* and T_{bb}





ERE has smaller errors



Bound state energy by the Gaussian Expansion Method

Analytic continuation of Effective Range Expansion

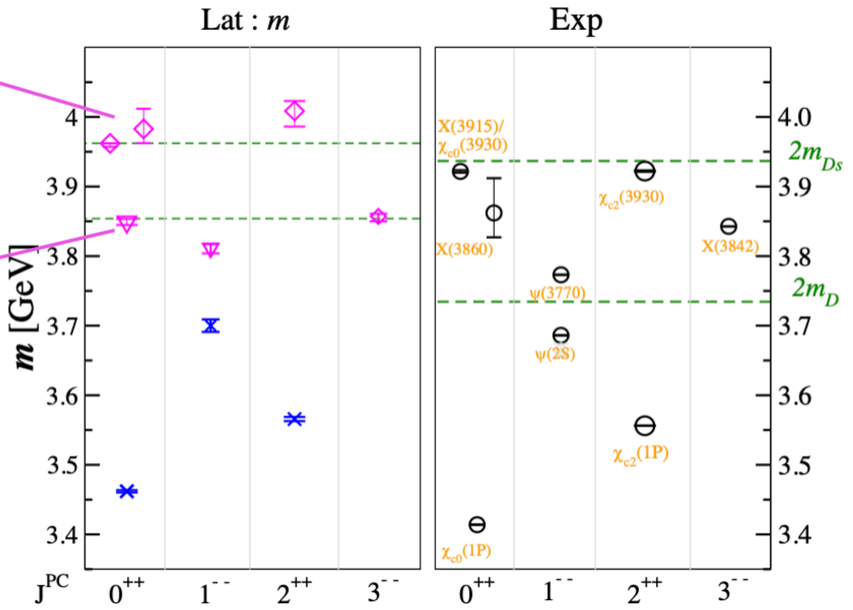
- $\bar{B}\bar{B}^*$, $\bar{B}^*\bar{B}^*$ coupled channel analysis. Coupled channel effects are important.
- Bound state pole is found for each of the three pion masses

Talk by Sinya Aoki, Tue. 14:40-15:00

Charmonium(like) states

$D_s\bar{D}_s$
$X(3915)/\chi_{c0}(3930)$

$D\bar{D}$
$\chi_{c0}(3860)$



- Couple channel $D\bar{D}$ and $D_s\bar{D}_s$ scattering .
- A Bound state poles just below $D\bar{D}$ is found in the 0^{++} channel.
- A narrow resonance just below $D_s\bar{D}_s$ thresholds is found, likely related to $X(3915)/\chi_{c0}(3930)$.

S. Prelovsek, et. al, JHEP 06 (2021) 035
S. Piemonte, Phys.Rev.D 100 (2019) 7, 074505

More meson-meson interaction talks in this conference:

Talk by Daniel Mohler, Tue. 15:00-15:20, on $D\pi$ scattering

Talk by Mitja Sadl, Tue. 15:20-15:40 on $D\bar{D}^*$ scattering

Talk by Martin Pflaumer, Tue. 17:50-18:10, on Antiheavy-antiheavy-light-light four-quark

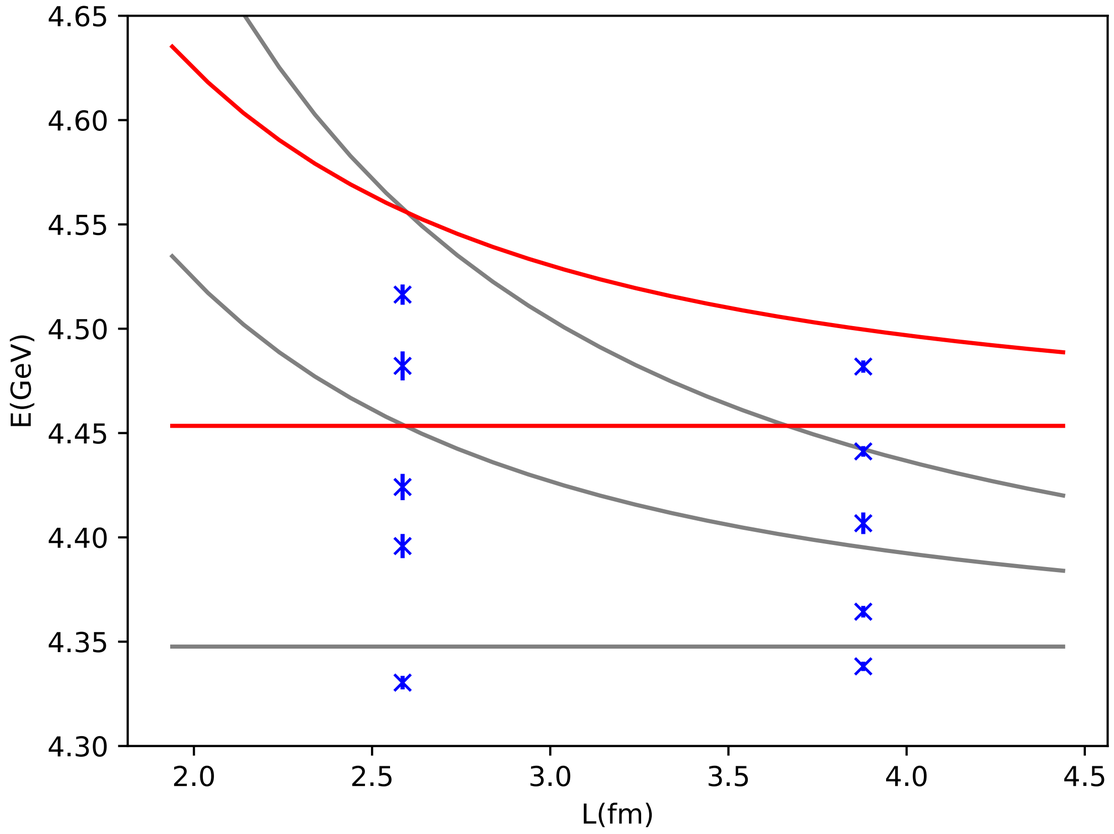
Talk by Arkaitz Rodas, Friday 17:00-17:20, on σ resonance

Talk by Rajnandini Mukherjee and Nelson Pitanga Lachini, Friday 17:20:18:00, on $K\pi$ scattering at physical point.

……

$\Sigma_c - \bar{D}(\bar{D}^*)$ scattering

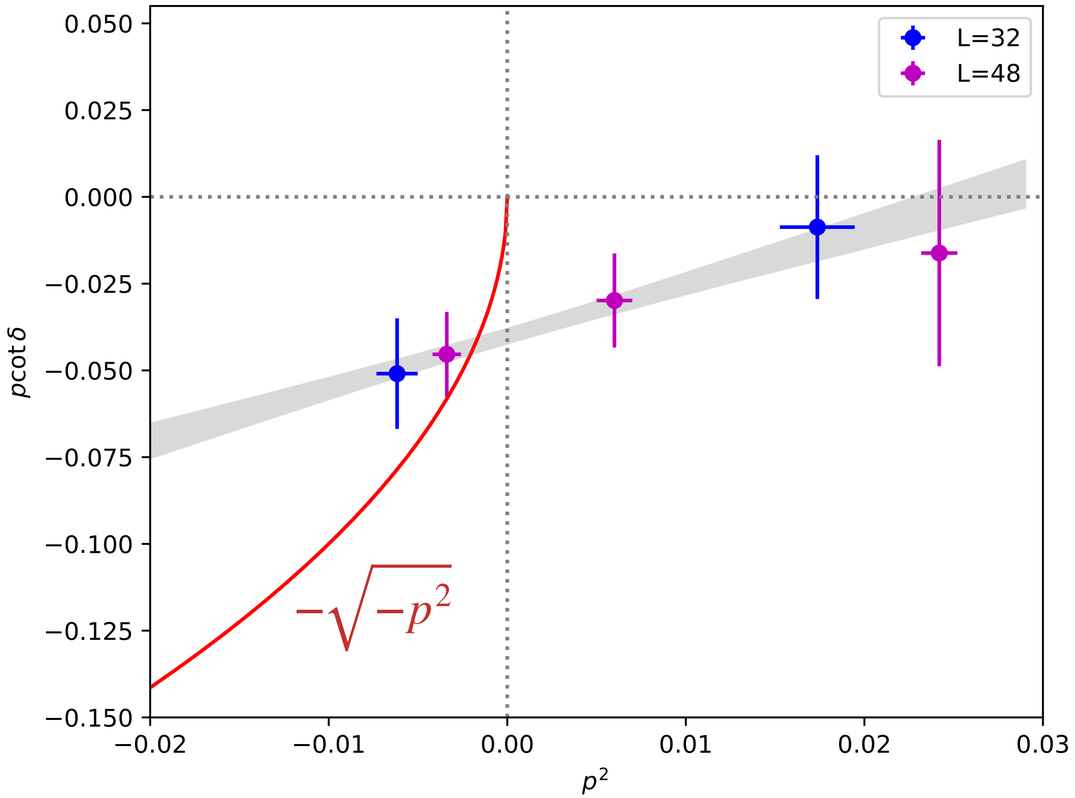
Hanyang Xing and Liuming Liu, in preparation



- $a = 0.08\,fm,\ m_\pi \sim 300$ MeV
- Two volumes: $L = 32,48$
- Five operators in the G_1^- irrep:
  - $\Sigma_c\bar{D}(|p| = 0)$
  - $\Sigma_c\bar{D}(|p| = 1)$
  - $\Sigma_c\bar{D}(|p| = \sqrt{2})$
  - $\Sigma_c\bar{D}^*(|p| = 0)$
  - $\Sigma_c\bar{D}^*(|p| = 1)$

$\Sigma_c - \bar{D}(\bar{D}^*)$ scattering

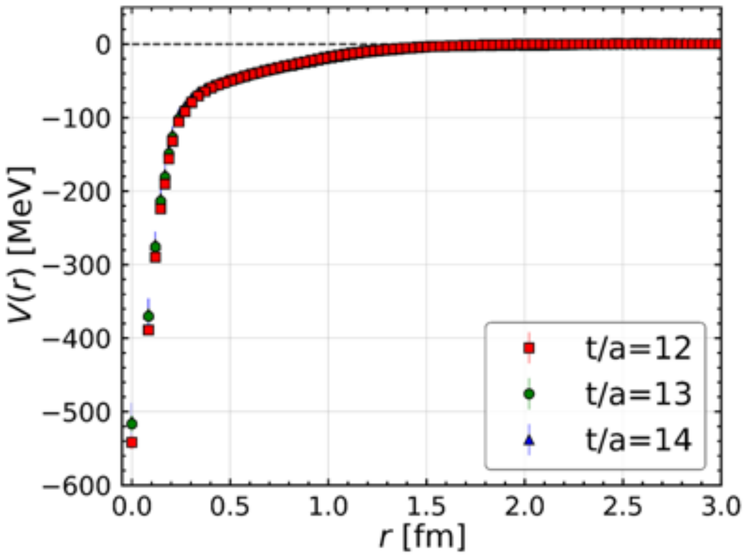
Hanyang Xing and Liuming Liu, in preparation

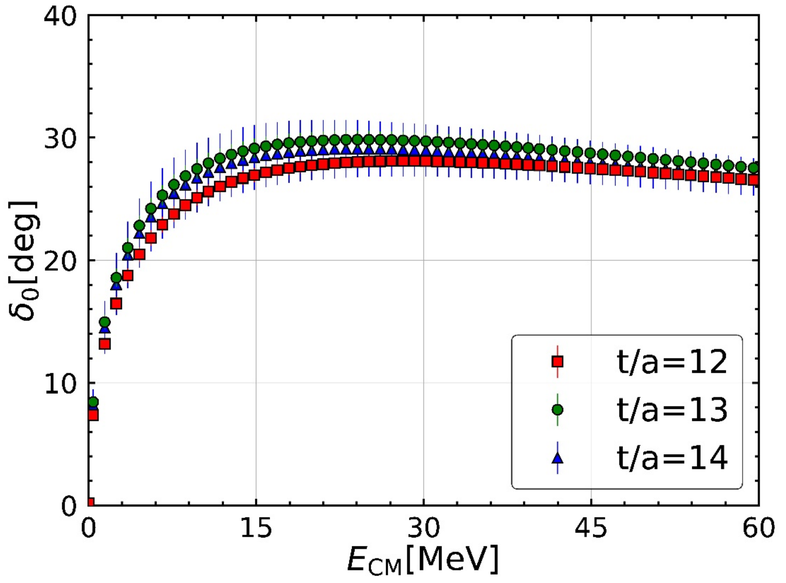


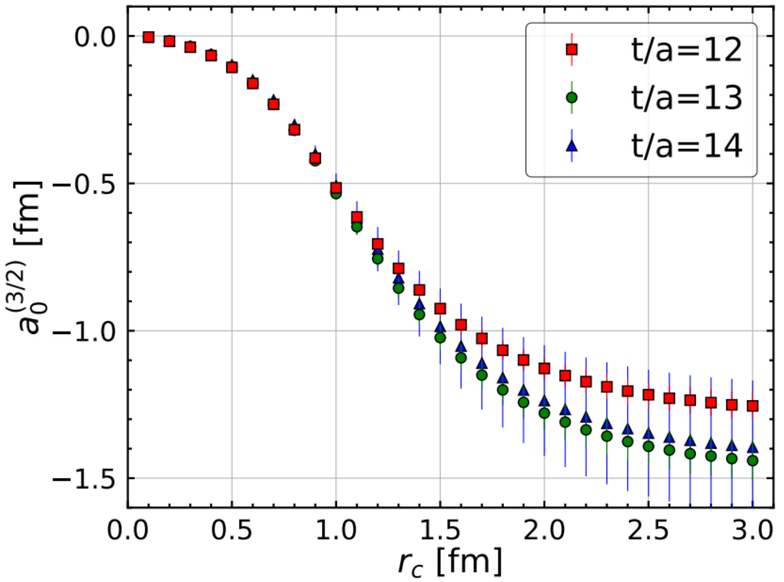
- Single channel scattering analysis using the lowest five energy levels.
- Bound state pole is found, likely related to the pentaquark $P_c(4312)$

$N - \phi$ scattering

Yan Lyu et. Al., (HALQCD), arXiv:2205.10544







- Attractive at all distance
- Long range tail

$$a_0^{(3/2)} = -1.43(23)_{\text{stat.}} \left(^{+36}_{-06}\right)_{\text{syst.}} \text{fm}$$

$$r_{\text{eff}}^{(3/2)} = 2.36(10)_{\text{stat.}} \left(^{+02}_{-48}\right)_{\text{syst.}} \text{fm}$$

$N - N$ scattering

S. Amarasinghe et. al.,(NPLQCD), arXiv:2108.10835

NN scattering has a long history of controversy ...

- NPLQCD, S. R. Beane *et al*., Phys. Rev. C88, 024003 (2013)
- NPLQCD, S. R. Beane *et al*., Phys. Rev. D87, 034506 (2013)
- NPLQCD, M. Wagman et al., Phys. Rev. D96, 114510(2017)
- CalLat, E. Berkowitz et al., PLB765,285(2017)

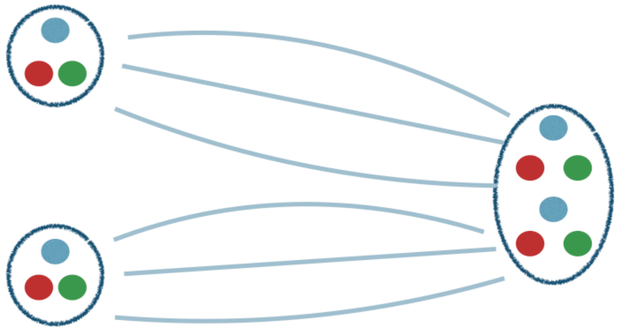
→ Deeply bound

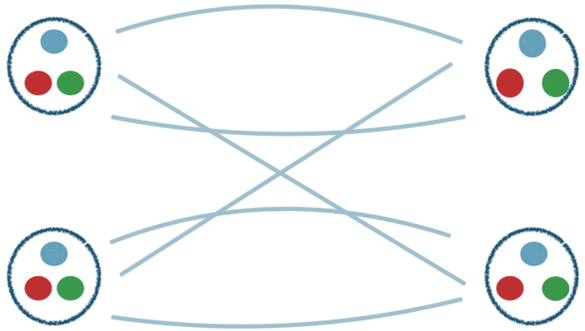
- J. R. Green, A. D. Hanlon, P. M. Junnarkar, and H. Wittig, (2021), 2103.01054.
- B. Hörz *et al*., Phys. Rev. C **103**, 014003 (2021), 2009.11825.
- A. Francis *et al*., Phys. Rev. D **99**, 074505 (2019), 1805.03966.
- S. Amarasinghe et. al.,(NPLQCD), arXiv:2108.10835

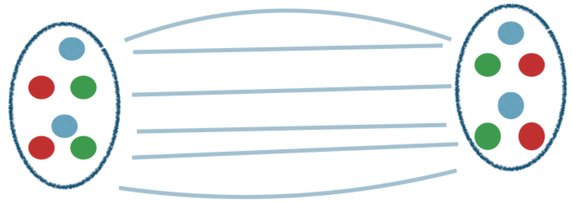
→ Do not support the existence of a bound state at the studied pion mass.

$N - N$ scattering

NN operators:

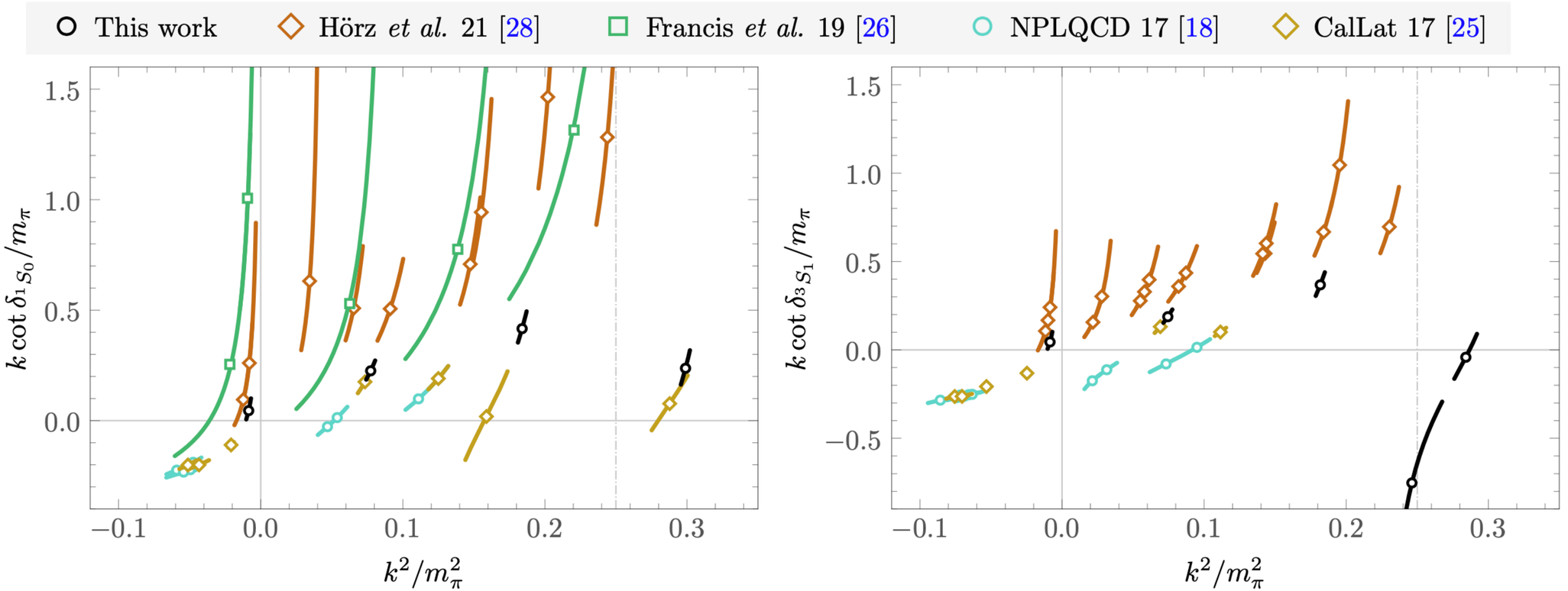






$N - N$ scattering

S. Amarasinghe et. al.,(NPLQCD), arXiv:2108.10835

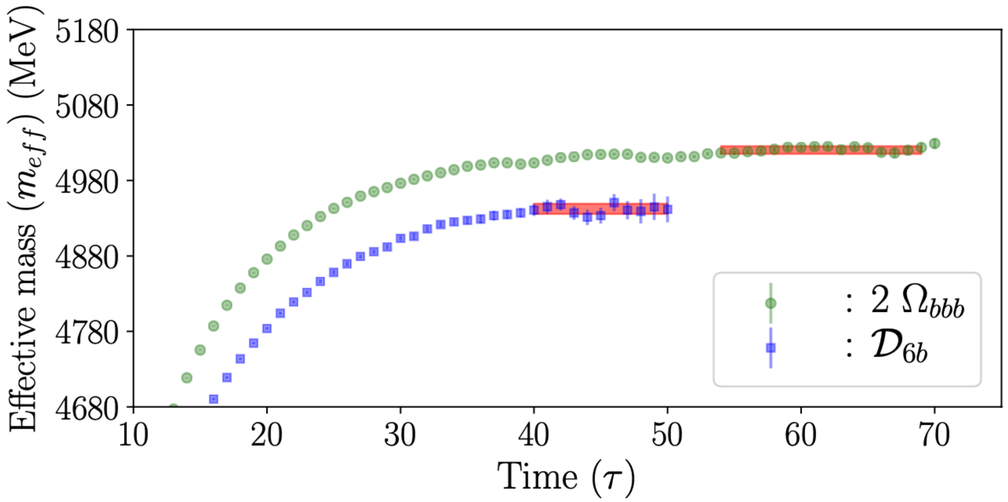


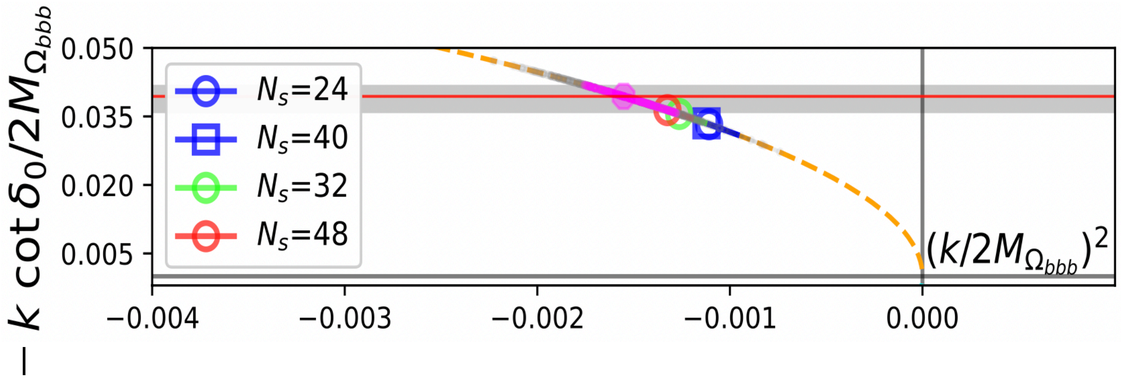
Talk by Michael Wagman, Thursday 11:30-11:50

Talk by Amy Nicholson, Friday 14:10-14:30

$\Omega_{bbb} - \Omega_{bbb}$ scattering

Nilmani Mathur et. al., arXiv:2205.02862



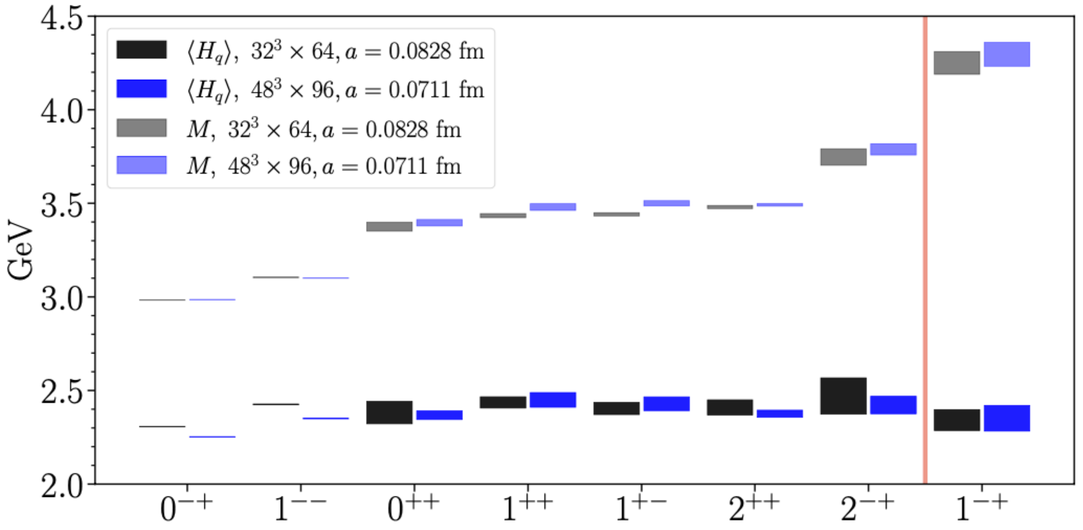


- Low lying Finite volume spectrum of s-wave $\Omega_{bbb}\Omega_{bbb}$ is calculated on 4 ensembles.
- Clear signal of a finite volume energy below the threshold.
- A Bound state pole is found. Binding energy -89^{+19}_{-12} MeV.

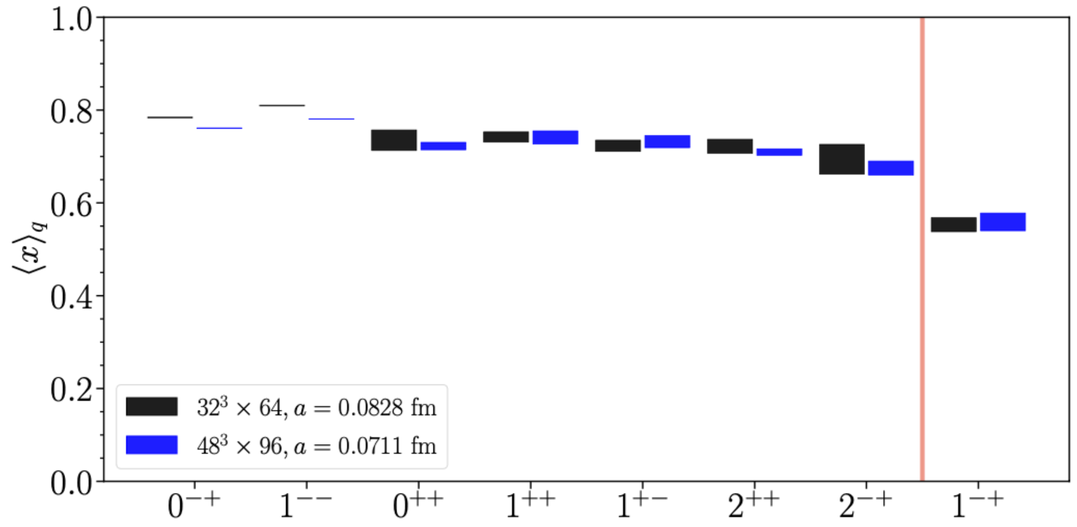
M. Padmanath, Poster session[208], Tue. 19:00-20:00

Gluons in Charmonium(like) states

Wei Sun et. al., Phys. Rev. D 103, 094503 (2021)



Charm quark mass contribution to the masses of chamonia



Charm quark momentum fraction

Structure calculation can help us understand exotic states.

Discussions

✦ Precision frontier:

- Control of the systematics: continuum extrapolation, physical pion mass, finite volume effects, iso-spin breaking effects, QED corrections etc.
- Depends on the available configurations.
  talk by Jens Lücke, Friday 16:40-17:00, QCD + QED configs.
  talk by Marco Cè, Thur. 11:50-12:10, master field simulation, $L \sim 18fm$
  Session devoted to configuration generation, Tue. 14:00-16:00

✦ Multi coupled channels :

- Light meson-meson coupled channel have been investigated. Coupled channel heavy meson scattering and baryon scattering is still rare.

Discussions

- ✦ Multi-hadron scattering:
  - Formalism is developing, simple system has been investigated.
- ✦ Nucleon and nuclei system with near physical pion mass:
  - Signal to noise ratio, more open multi-particle channels…
  - Probably will remain a challenge in the near future.
  - Revolutionary computation techniques may help? — quantum computing