Talk slides will be available at

https://navdeep-dhindsa.github.io/

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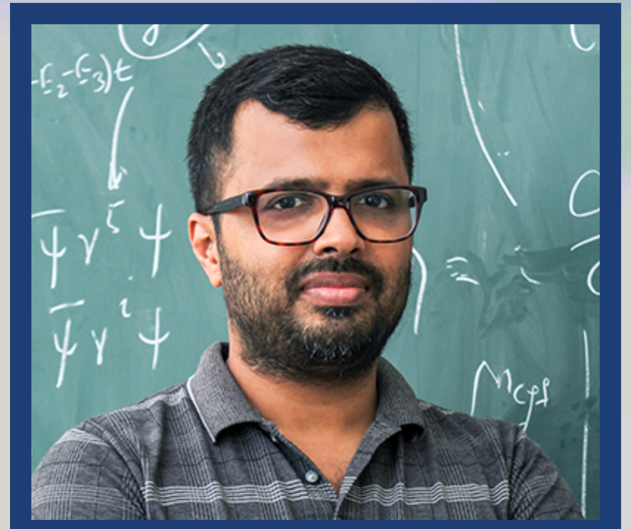
Navdeep Singh Dhindsa **15/07/2024**

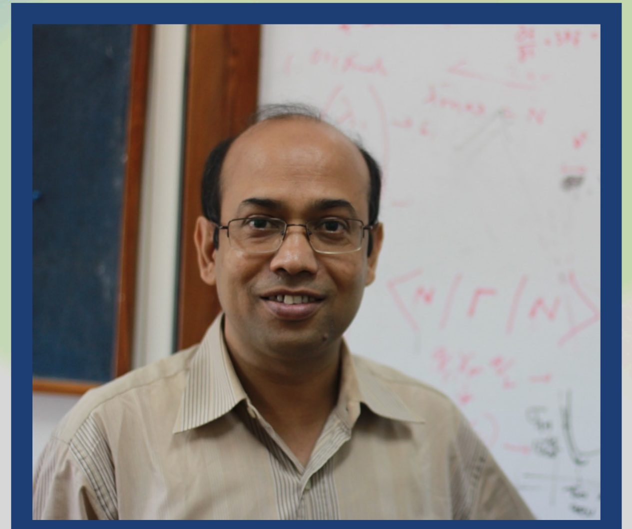
Insights into Dibaryon Interactions in the Heavy Quark Sector

Funding resources

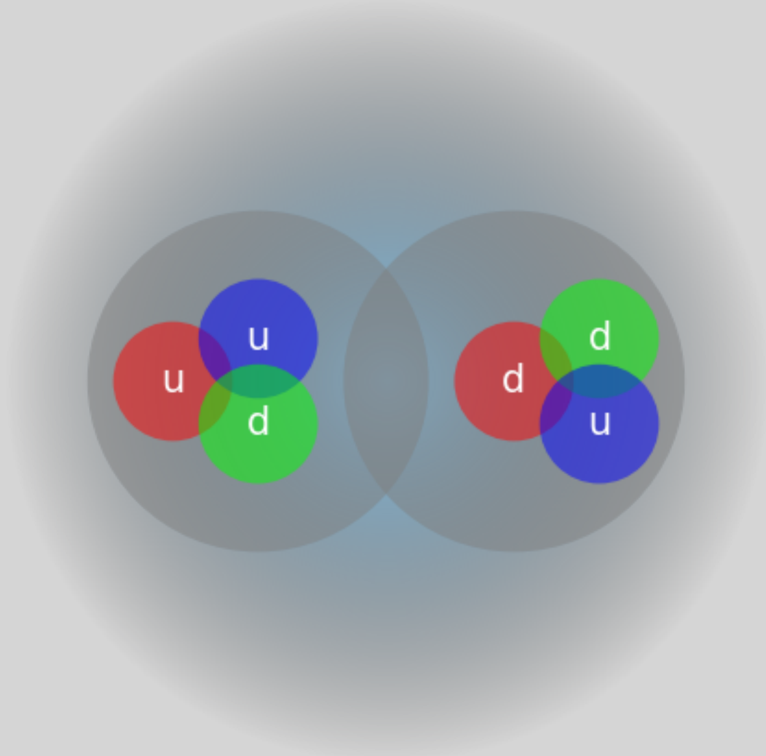
Work in collaboration with

M. Padmanath (IMSc Chennai) and Nilmani Mathur (TIFR Mumbai)





Deuteron



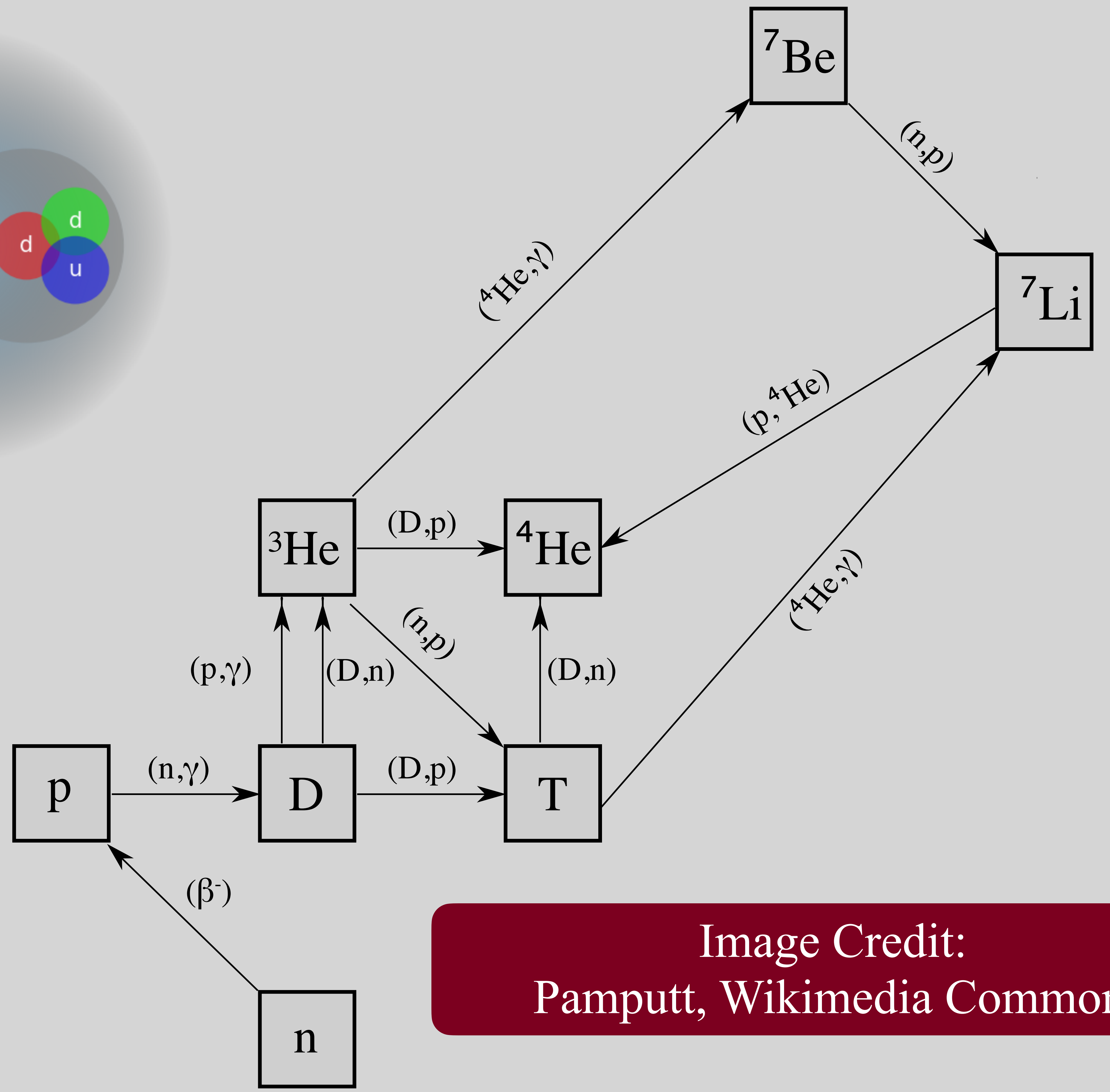


Image Credit:
Pamputt, Wikimedia Commons

- Deuterium destroyed in interior of stars faster than it is produced.
- All deuterium found in nature has origin from Big Bang nucleosynthesis. (Temperature hot enough to produce it but not hot enough to produce byproduct or get destroyed)
- Deuterium bottleneck after big bang and then only 20 minutes for nucleosynthesis.

Based on theory of strong interactions, we cannot rule out more dibaryons in nature.

Dineutron? Diproton?

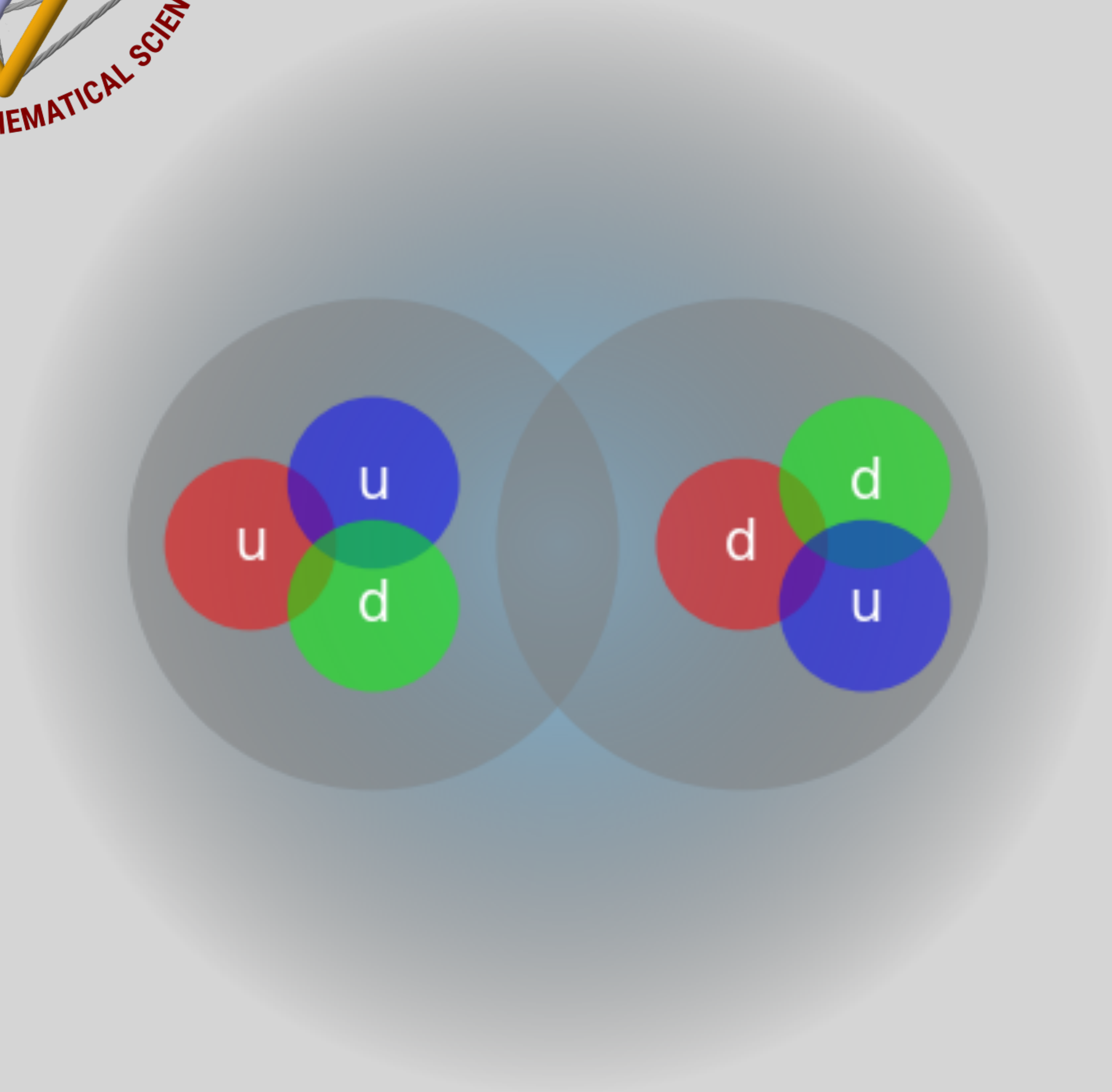
NN scattering experiments indicates absence of bound state

Deuteron Dibaryon

Any object with Baryon number 2

Composed of six valence quarks

Can be molecular or compact



1932

- Discovered around a century back
- Proton (uud) - Neutron (udd) bound state
- Binding Energy = 2.2 MeV

1950's

- Many predictions of various dibaryon states but failed experimental checks

2010's

- Recent renewal in interest due to discoveries of complex quark systems (not just baryons/mesons)
- Experimental evidence of existence of d*

Clement
PPNP (2016)

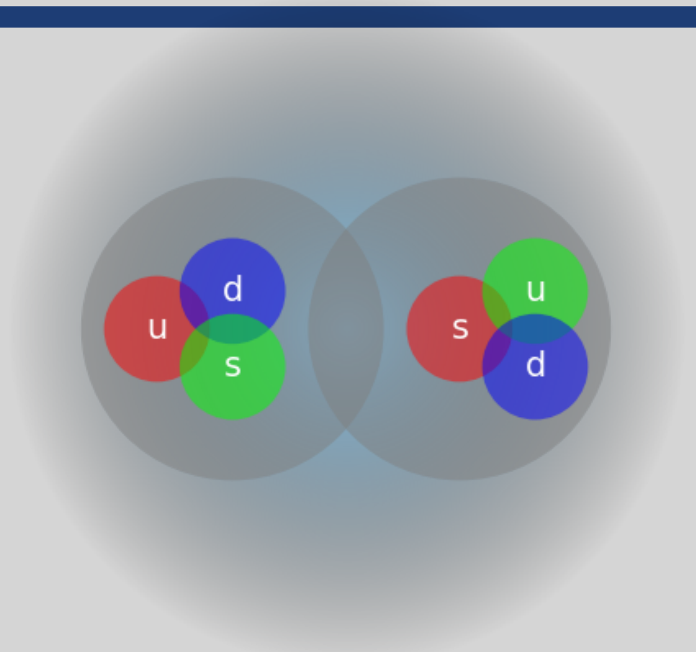
Hyperon-Nucleon

Clement
PPNP (2016)

Experimental results indicate:

- ΛN interaction is attractive, though less than NN, there is no strange deuteron.
- ΣN interaction even weaker than ΛN.
- $\Lambda\Lambda$ does not rule out bound system.

* NAGARA event - constraint on binding energy
* Dedicated experiments for H dibaryon indicates existence unlikely but its existence not ruled out yet.



* Jaffe prediction of dihyperons

Jaffe
PRL 138 (1977) 195

* Theoretical calculations vary from very deep bound (even more than Jaffe's prediction) to unbound.
* Lattice QCD - gives bound result (8 MeV) - Large pion mass used (discussed later).

Beane et al.
PRL 106(2011) 162001

* Chiral effective field theory calculation - smaller binding energy.

Talk by Green
Santa Fe Workshop 2023

Inoue et al.
PRL 106(2011) 162002

Haidenbauer and Meissner
PLB 206(2011) 100

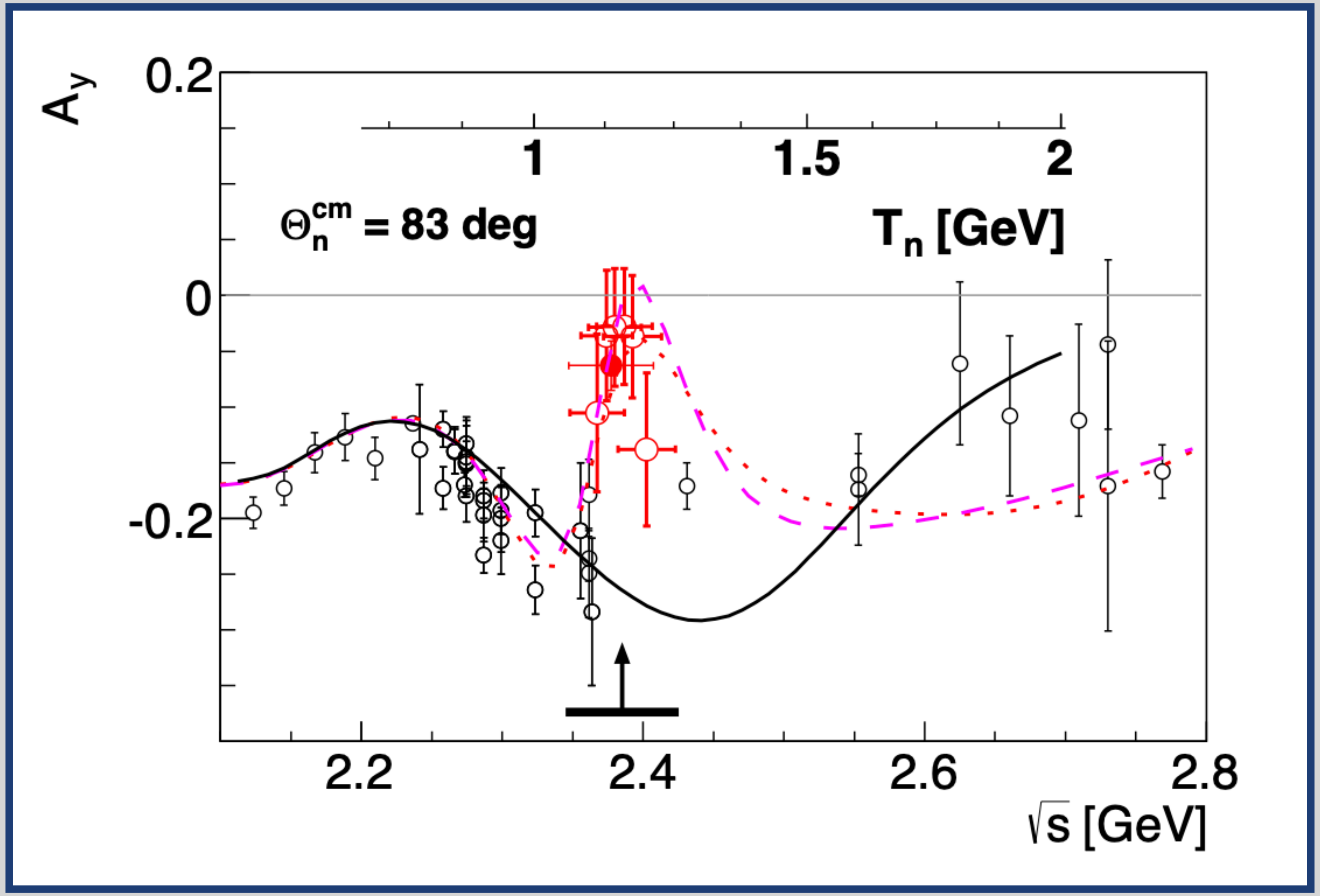
d*(2380)

Dyson and Xuong
PRL 13 (1964) 815

WASA @ COSY collaboration
SAID Data Analysis Center
PRL 112 (2014) 202301

1964 - Prediction of possible bound states

They predicted mass of D_{03} (close to d* which was found later)



Bremsstrahlung measurements

Kamae and Fujita
PRL 38 (1977) 471

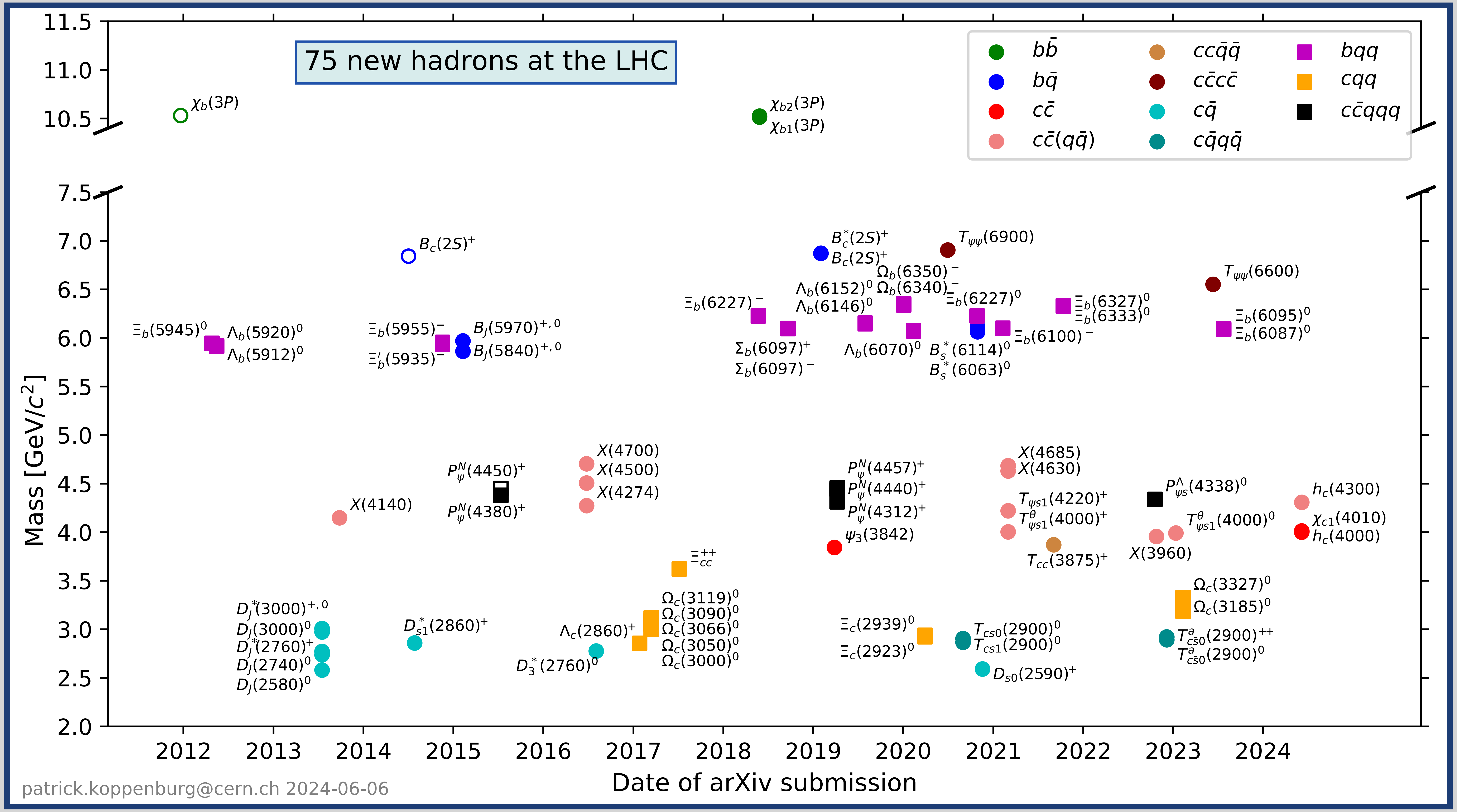
"An inevitable non-strange dibaryon"

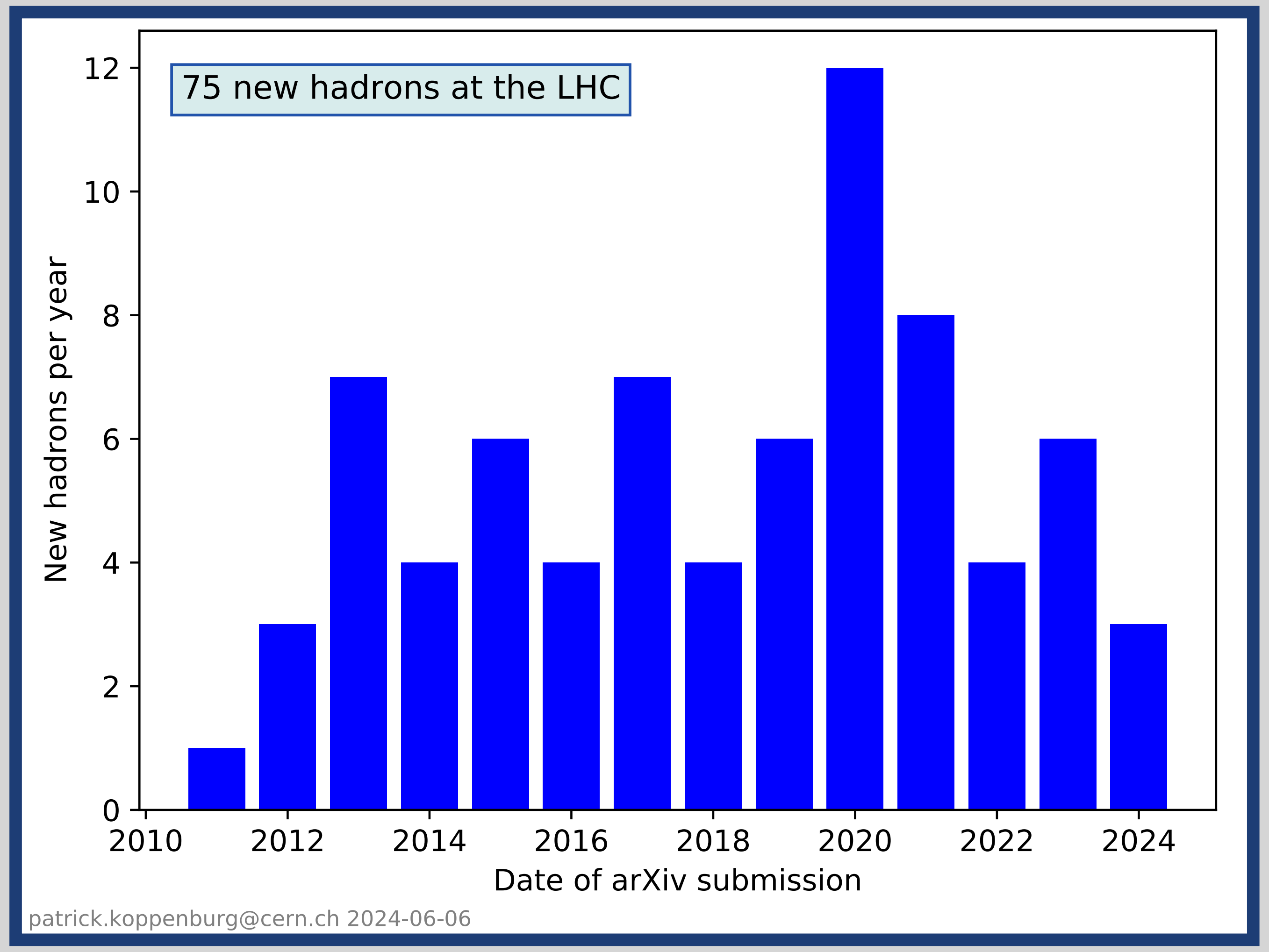
Goldman et al.
PRC 39 (1989) 1889

s-channel resonance

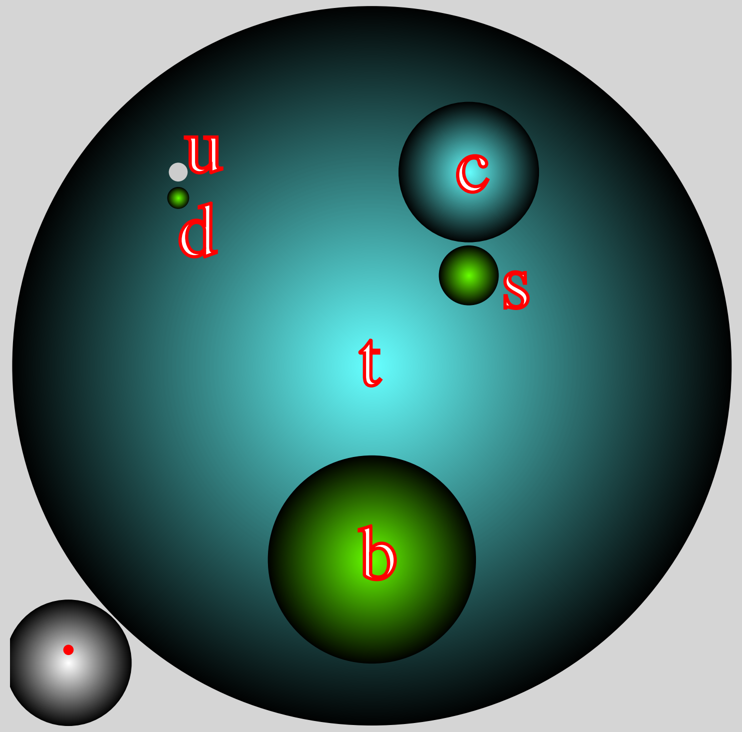
Pole in $^3D_3 - {^3G_3}$

What's up at LHC??





- More interest around heavier hadrons

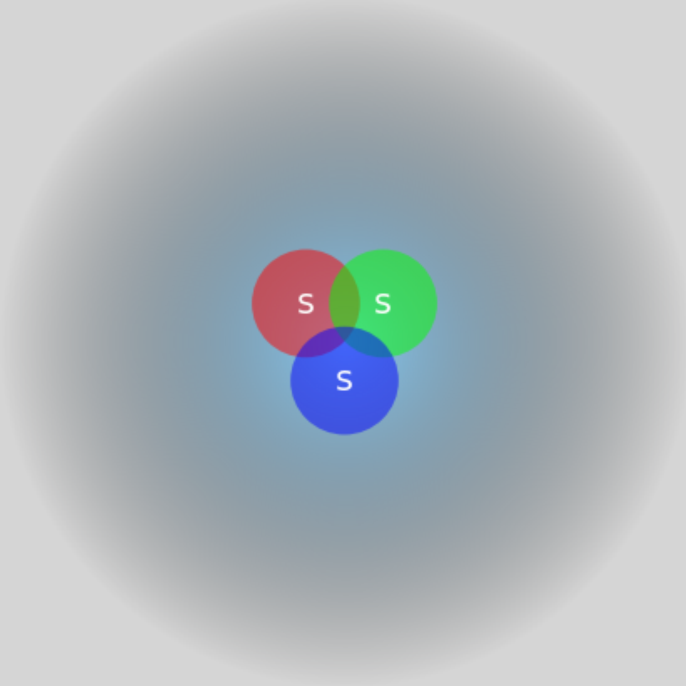


Picture from wiki

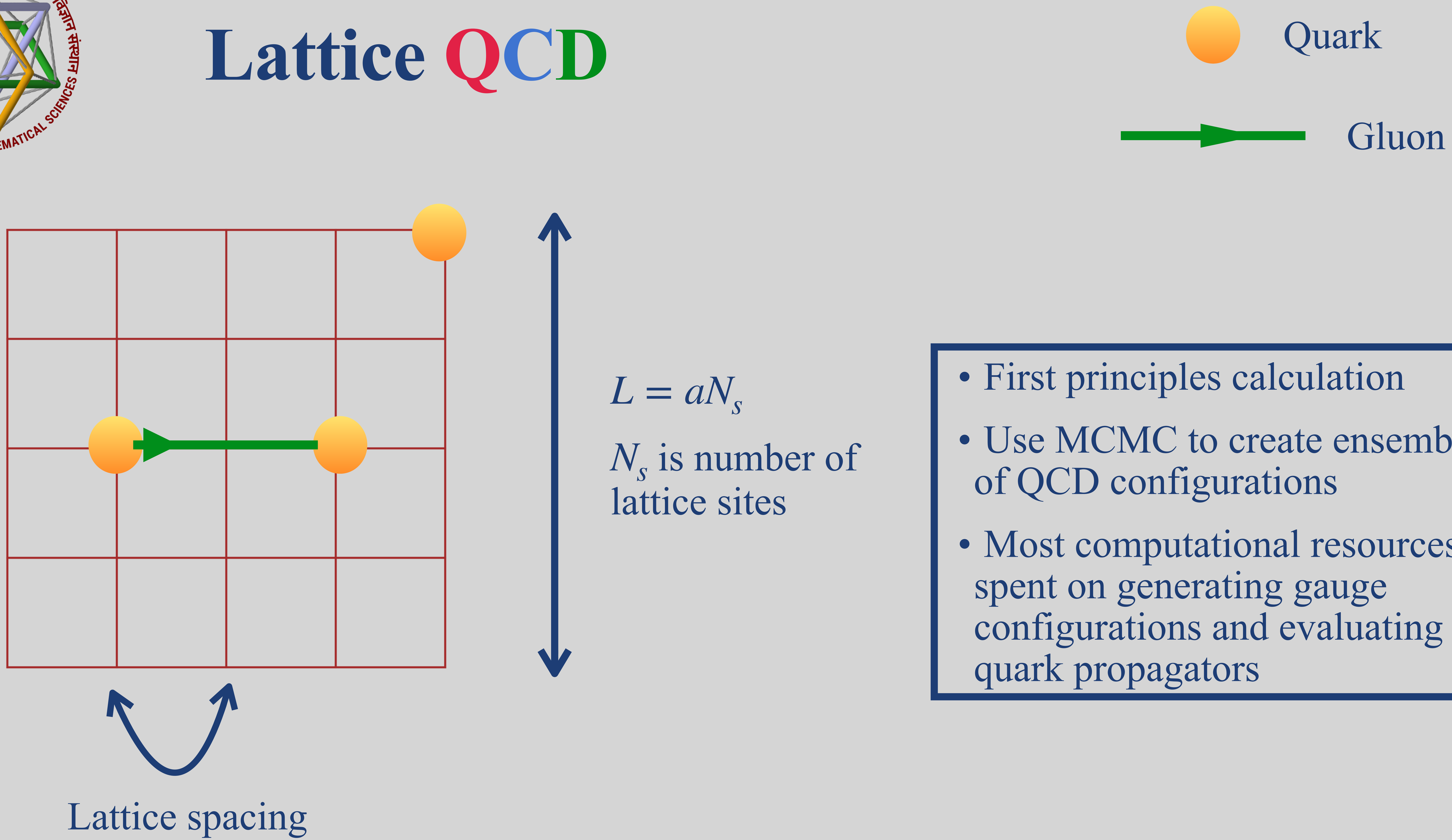
Navdeep Singh Dhindsa 15/07/2024

Today’s discussion

- Baryons consisting of either strange or charm
- Dibaryons consisting of either strange or charm



Lattice QCD



$L = aN_s$

N_s is number of lattice sites

- First principles calculation
- Use MCMC to create ensembles of QCD configurations
- Most computational resources spent on generating gauge configurations and evaluating quark propagators

Hadrons

Announcement
Talk Series
August
By Sasa and Feng-Kun

- Desire to understand nature through fundamental forces and interactions.
- Baryons and Mesons — Wide range of energy scale
- Recent experiments reveal missing baryon states, exotic tetraquark, and pentaquark hadrons.
- Lattice hadron spectroscopy predicted numerous bound states, including exotic hadrons.
- More progress for bound states stable under strong decay i.e. below threshold or for states closer to threshold

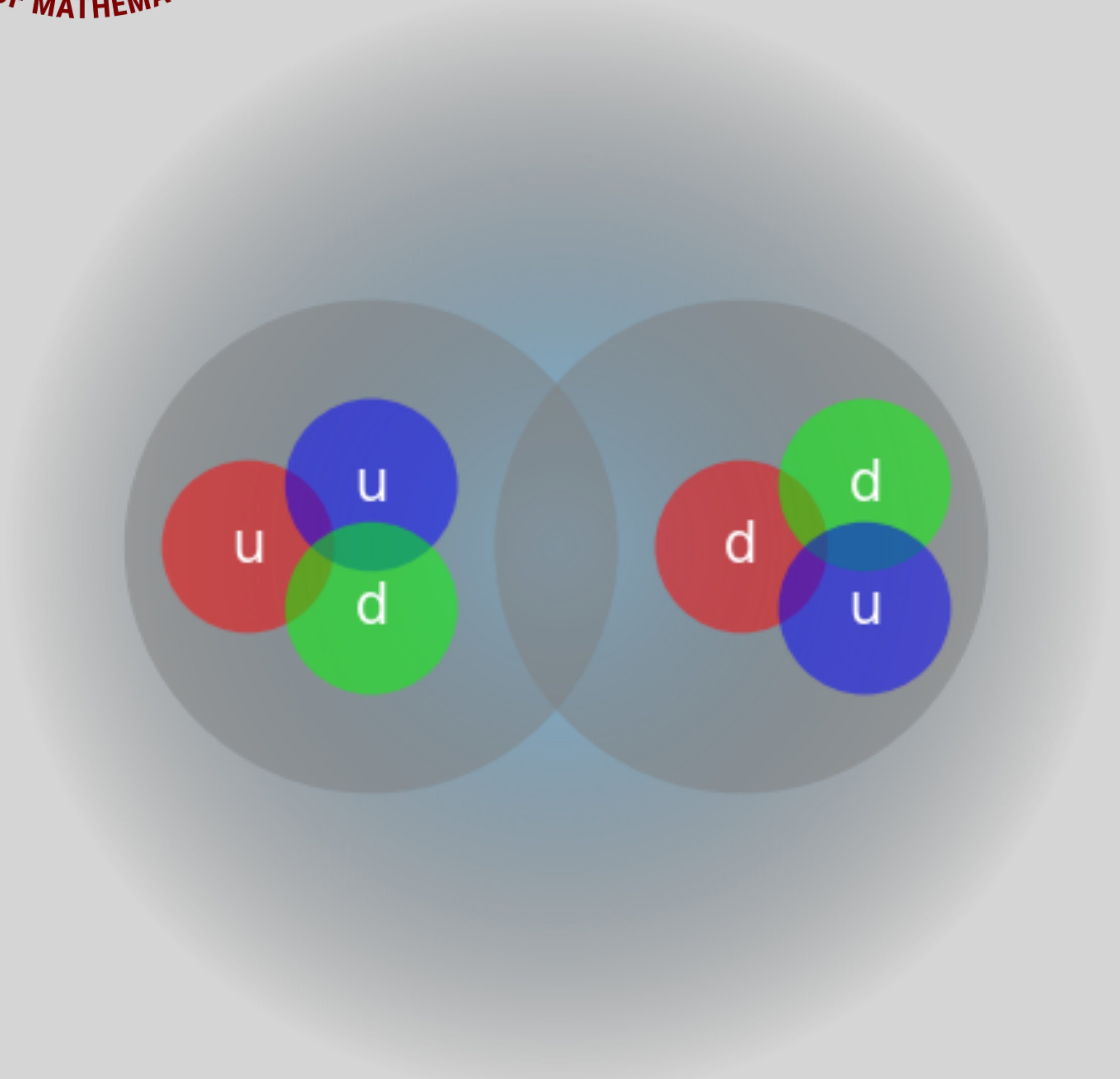
Deuteron

- Lattice calculations use $M_\pi \geq 300\ MeV$

HAL QCD, JHEP 1903 (2019) - Unbound Deuteron, Dineutron

NPLQCD, PRD 107 (2023) - Bound Deuteron, Dineutron

$M_\pi \approx 800\ MeV$



- Discovered around a century back
- Proton (uud) - Neutron (udd) bound state
- Binding Energy = 2.2 MeV

Why different observations from different Lattice studies?

Will this discrepancy be the case for heavier quarks?

Why heavier masses ?

$m_u, m_d << m_\pi$

Light quarks are expensive

$$\text{cost} \propto \left(\frac{1}{m}\right)^{1-2} \left(\frac{1}{a}\right)^{4-6} (L)^{4-5}$$

Lepage, TASI (1989)

Signal (m_N hadron)

$\propto e^{-m_N t}$

Noise

$\propto e^{-\frac{3}{2}m_\pi t}$

Error in propagator correlation function dominated by pions because of virtue of lower energy states

Signal to Noise ratio exponentially degrades for $m_q \to 0$

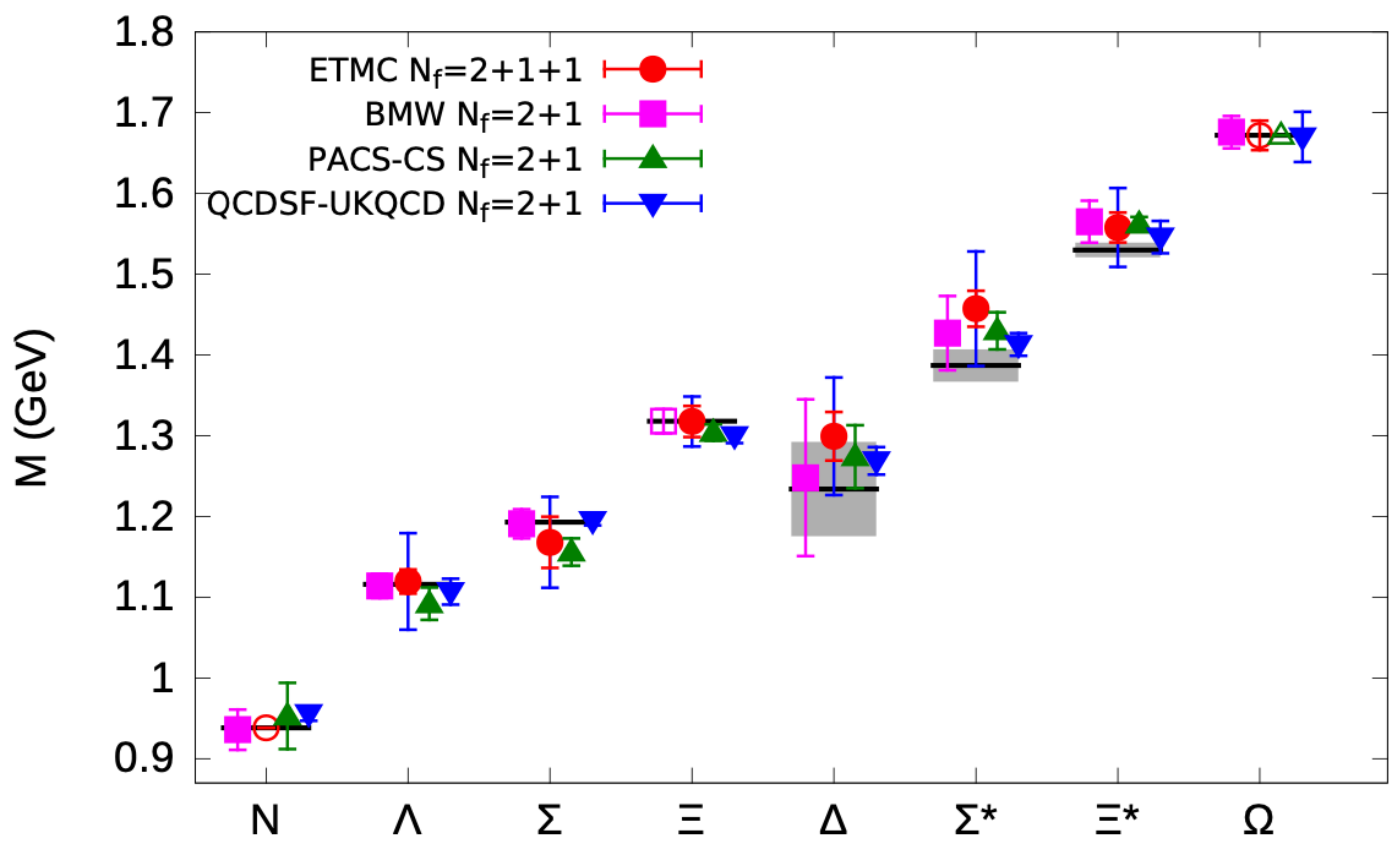
Lattice - More Requirements

Apart from unphysical heavy light quark masses we need:

* Multiple ensembles for continuum limit.
* Even more computing power in contractions for exotic hadrons.
* $m_\pi L \geq 4$, to constraint finite volume effects.
* Finer lattices for lesser discretisation errors.

Interplay between choice of a, L, m_π to have better results

Baryons from Lattice



Alexandrou, Drach, Jansen, Kallidonis, Koutsou
PRD 90, 074501 (2014)

- Masses of low lying baryons using LQCD.
- Results consistent with experiments.
- Predictions for hadrons not experimentally measured at that time.
- This calculation with $N_f = 2+1+1$

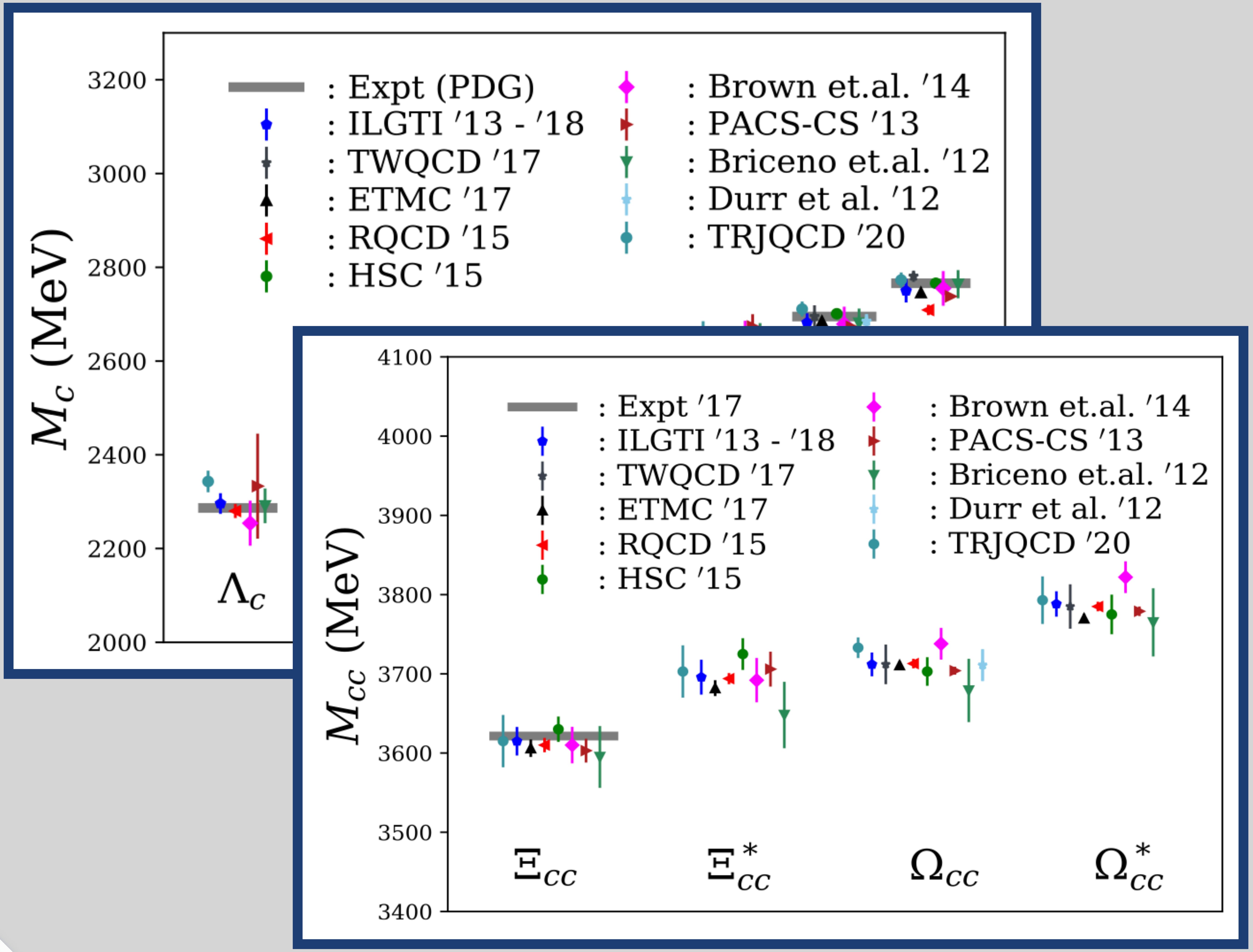
Heavier Baryons from Lattice

Observations of heavier baryons improved in Lattice calculations over the years (and experimentally):

- Bigger (and finer) lattice calculations. In our current calculations we have used $64^3 \times 192$ lattice with lattice spacing $a \approx 0.044\ fm$
- Improved algorithms
  $N_f = 0$ (quenched) $\rightarrow 2\ (u,d) \rightarrow 2+1\ (u,d,s) \rightarrow 2+1+1\ (u,d,s,c)$
- Growth of machine power from certain GFLOPS to $\mathcal{O}(10)$ PFLOPS

Heavier Baryons from Lattice

M. Padmanath, CHARM 2020 Talk



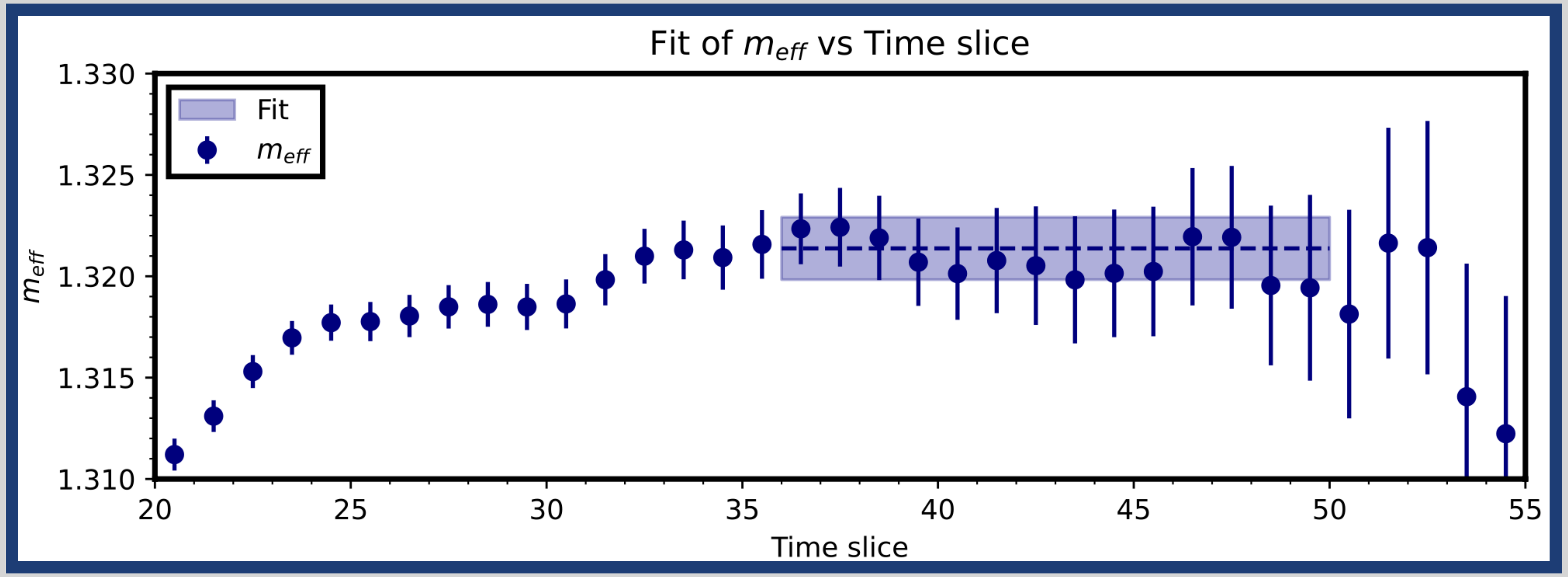
- ✱ Hadrons in charm sector.
- ✱ Benchmarks for lattice calculations.
- ✱ Xi double-charm baryon lattice calculation before experimental prediction.
- ✱ ILGTI calculations matches precisely with other calculations.

Masses from Lattice

* Euclidean two point correlator as: $C_{ji}(t_f - t_i) = \langle 0 | O_j(t_f)\bar{O}_i(t_i) | 0 \rangle = \sum_n \frac{Z_i^{n*} Z_j^n}{2m_n} e^{-m_n(t_f - t_i)}$

* $O_j(t_f)$ and $\bar{O}_i(t_i)$ are the desired interpolating operators and $Z_j^n = \langle 0 | O_j | n \rangle$

* Effective mass $= \log \left[\frac{C(t)}{C(t+1)} \right]$



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Operators

Operator for baryon: $\mathcal{O} = \epsilon_{abc} q^{a,f_1}_{1,\mu_1} q^{b,f_2}_{2,\mu_2} q^{c,f_3}_{3,\mu_3}$

In this work we focus on single flavored baryons

- Total wave function for baryon (fermion) anti symmetric
- Single (symmetric) flavor, color anti symmetric
- Spin must be symmetric - 3/2 - H^+ irrep

H^+ irrep has two embeddings corresponding to non-relativistic and relativistic operators

Operators Contraction

$$\mathcal{O} = \epsilon_{abc} q^a_{\mu_1} q^b_{\mu_2} q^c_{\mu_3}$$

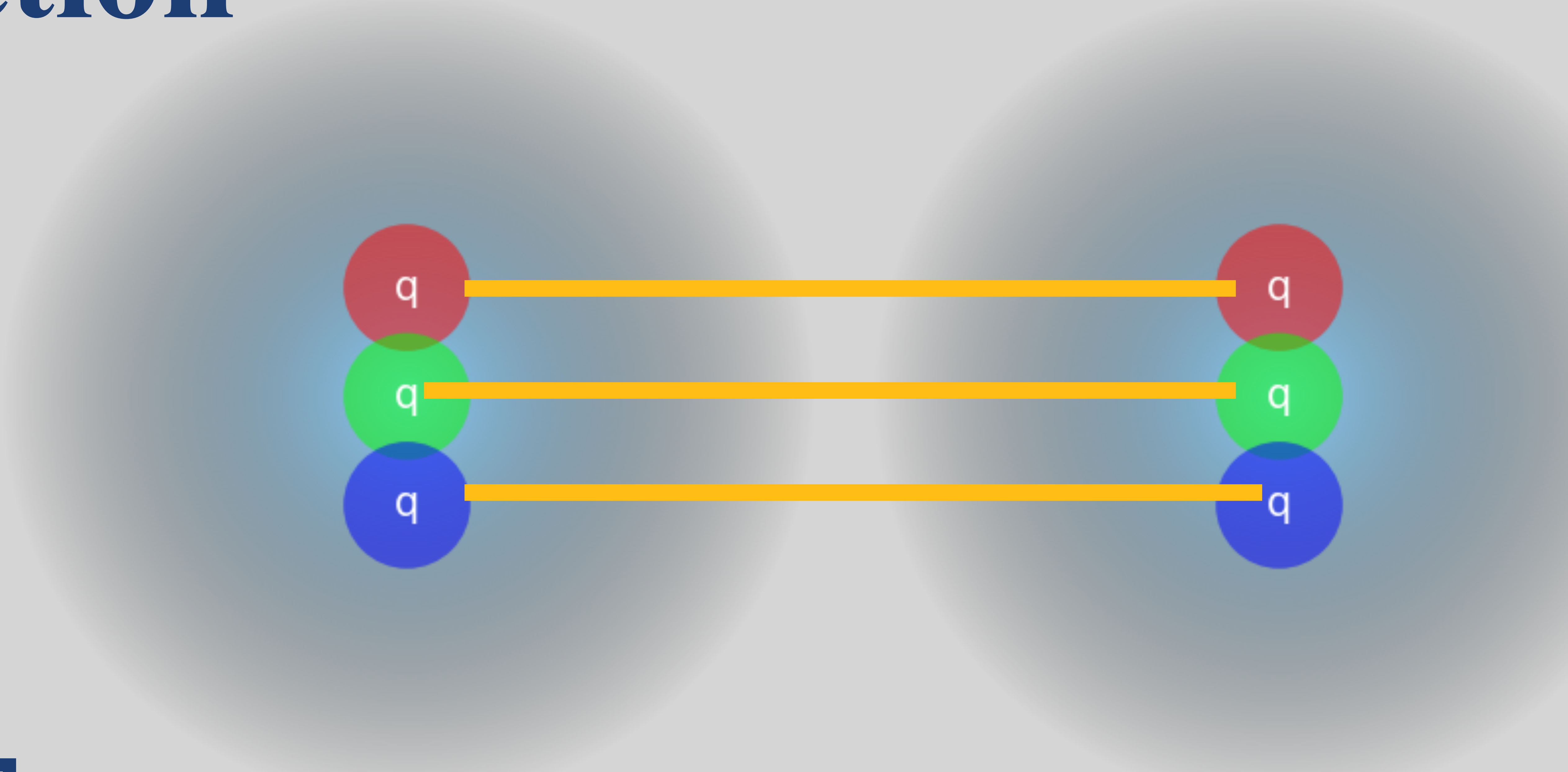
S_z	Operator	State
3/2	$^1H_{3/2}$	111
1/2	$^1H_{1/2}$	112+121+211
-1/2	$^1H_{-1/2}$	122+212+221
-3/2	$^1H_{-3/2}$	222

Non Relativistic Embedding [N]

S_z	Operator	State
3/2	$^2H_{3/2}$	133+313+331
1/2	$^2H_{1/2}$	233+323+332+134+341+413+143+431+314
-1/2	$^2H_{-1/2}$	144+414+441+234+342+423+243+432+324
-3/2	$^2H_{-3/2}$	244+424+442

Relativistic Embedding [R]

Basak et al., PRD 72, 074501 (2005)



Source slice

Sink slice

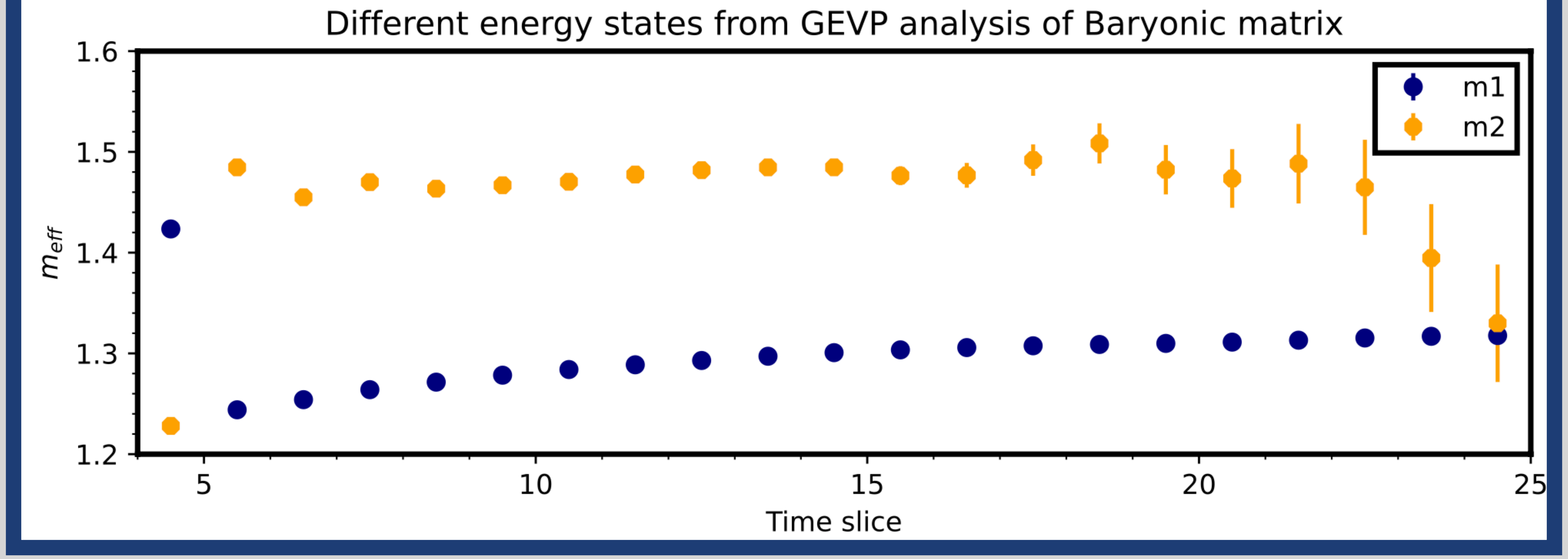
- We can choose different embedding for different operators
- Effectively single contraction

Operators Contraction

N-N	N-R
R-N	R-R

Baryonic matrix constructed out of both non-relativistic and relativistic operators on which we apply GEVP

- Larger overlap if we use just N-N operator combination
- We use full matrix to show that there is no excited state contamination



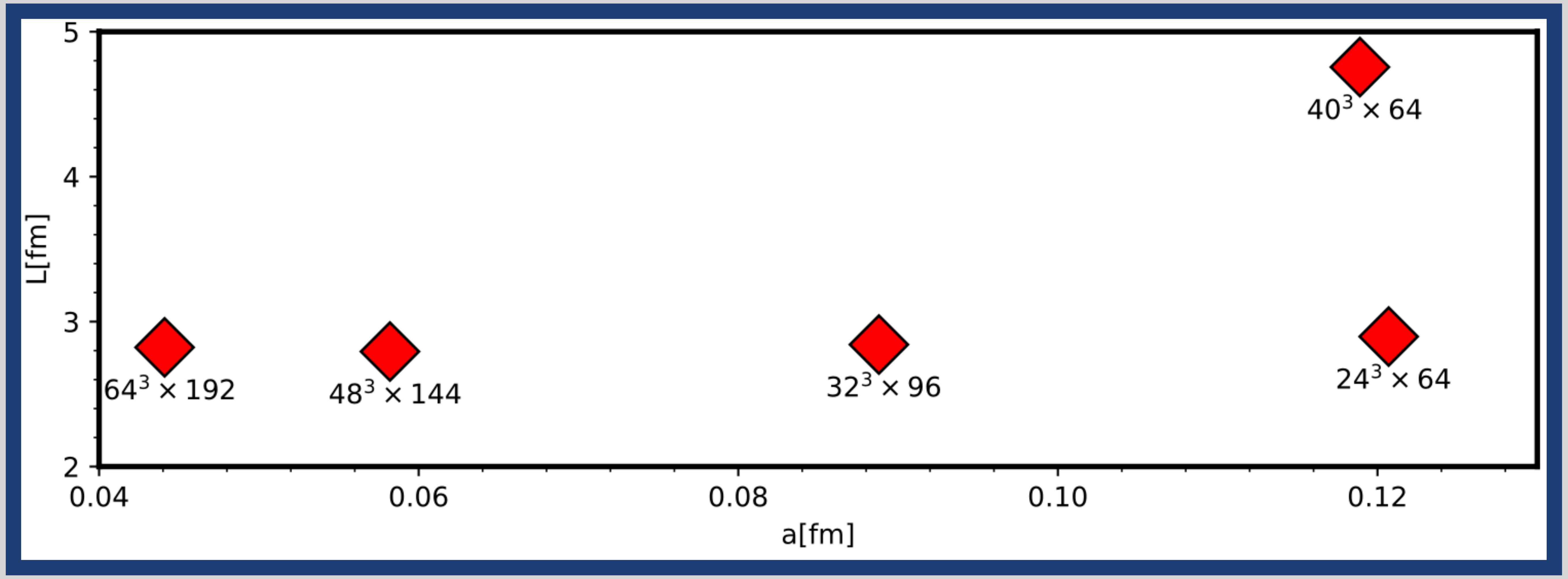
- Time reversed backward propagator used to double data
- Negative parity calculation also done

Lattice Setup

Bazavov et al., PRD 87 (2013) 5, 054505

- Overlap action on background of Highly Improved Staggered Quark (HISQ) gauge configurations.
- Strange and charm masses set at physical values.
- Up and down set as degenerate masses heavier than physical values.
- Finest lattice used $a \approx 0.044\ fm$ with Volume as $64^3 \times 192$

Ensembles

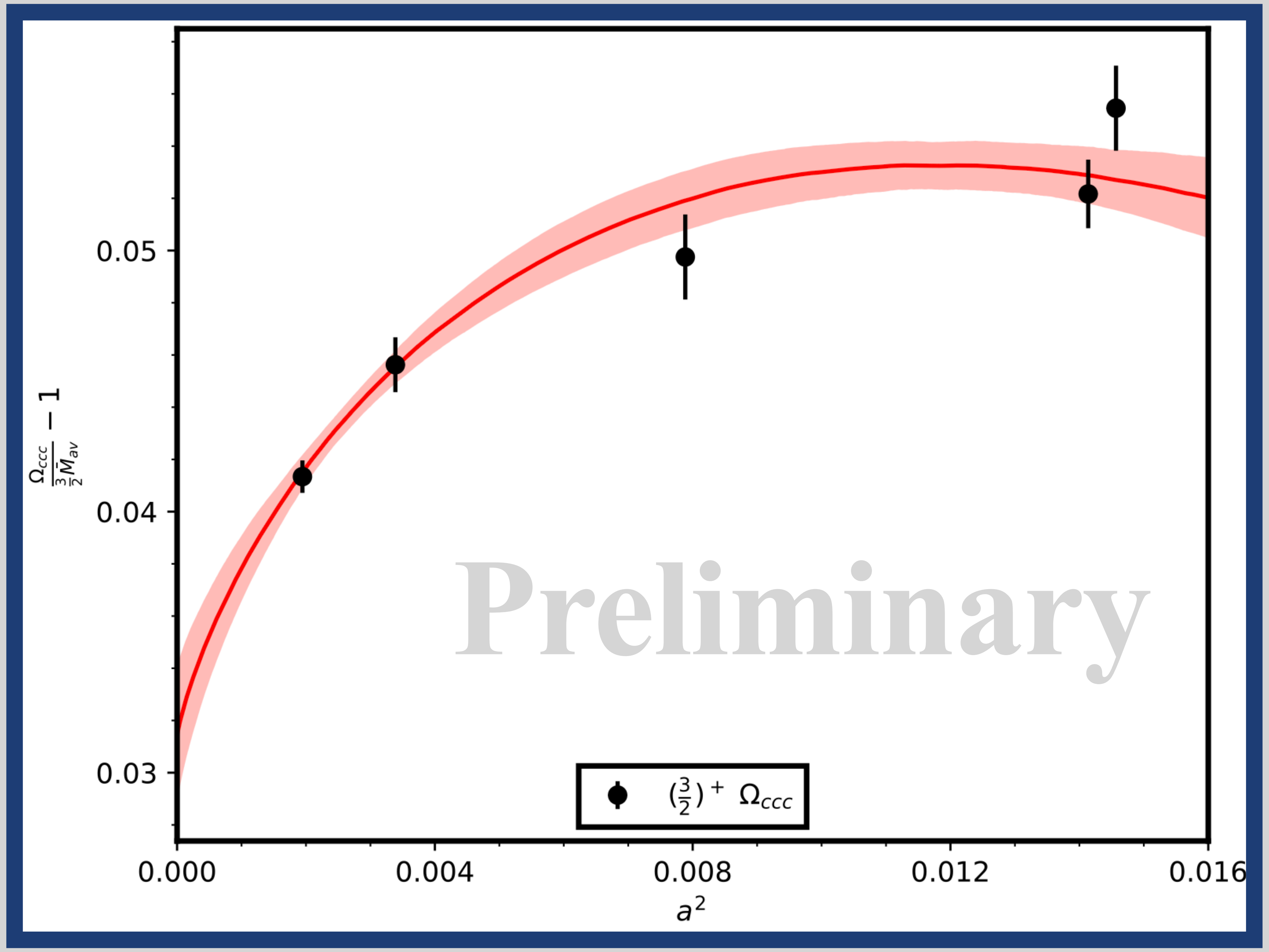


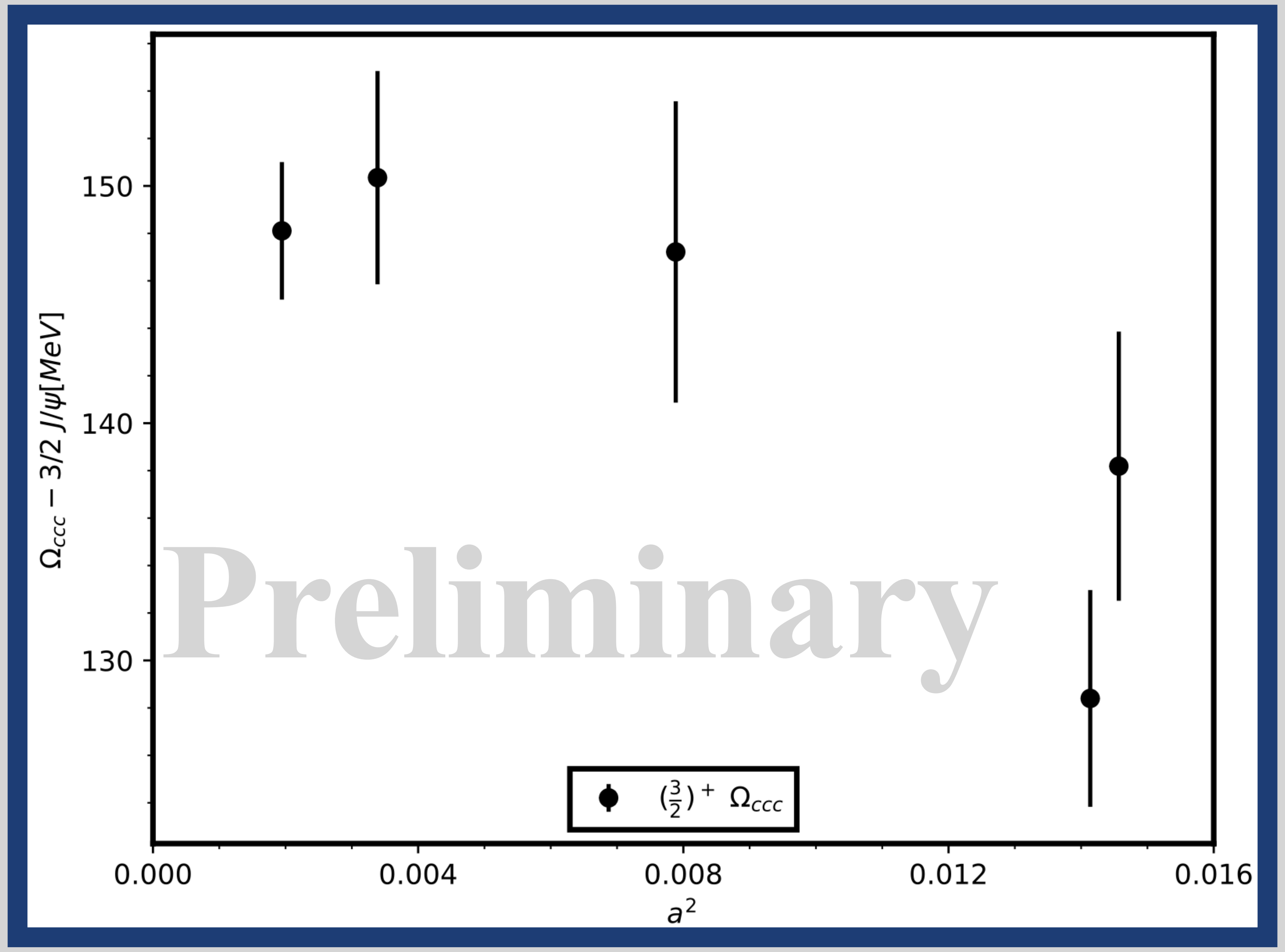
$$\bar{M}_{av} = \frac{1}{4}\left(M_{\eta_c} + 3M_{J/\psi}\right)$$

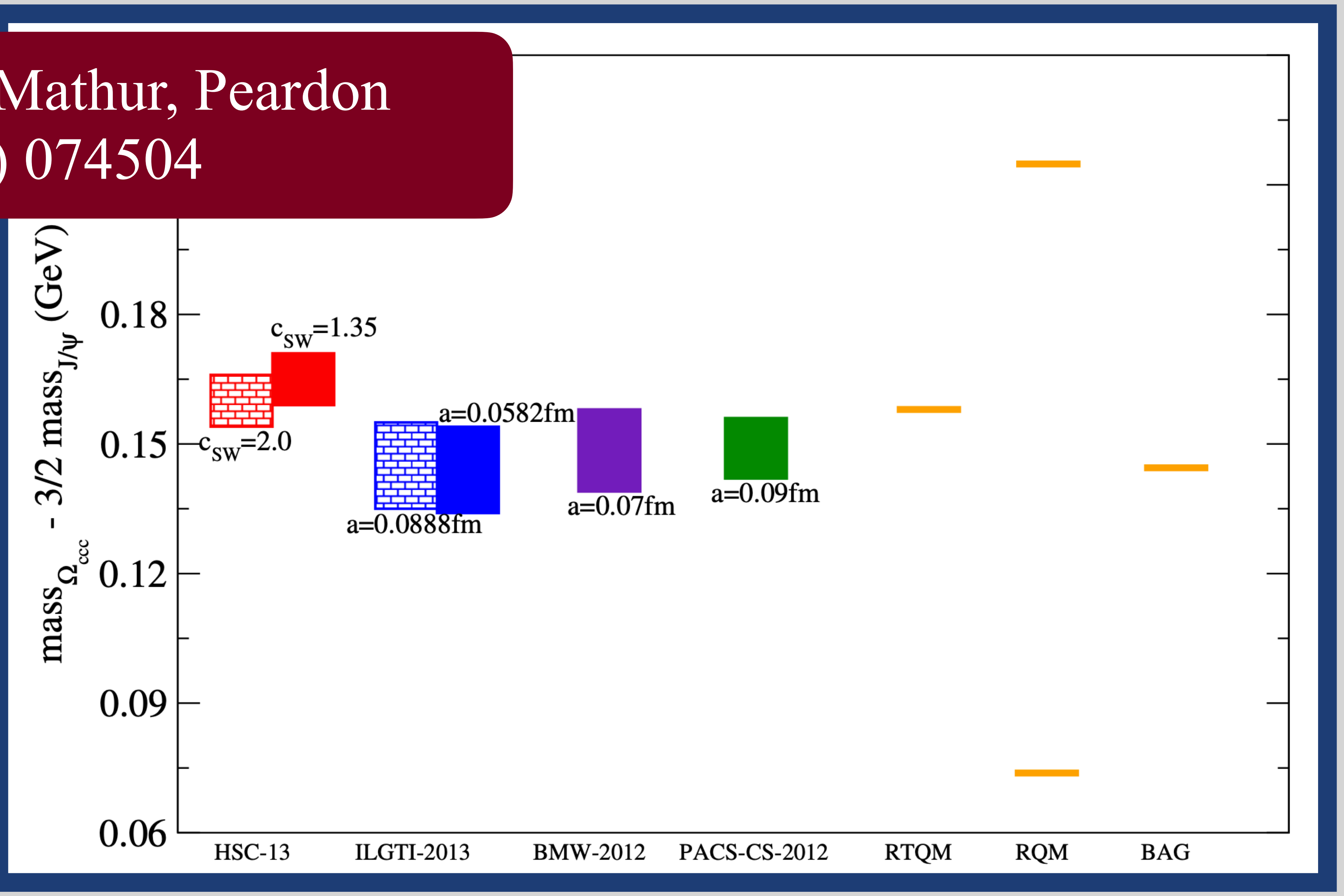
$$M_h - \frac{3}{2}\bar{M}_{av}$$

- Configurations generated by MILC.
- Discretisation effects highest in triply charmed baryons.
- Instead of effective mass in charmed baryons, we will plot effective splittings.

Ω_{ccc} Baryon







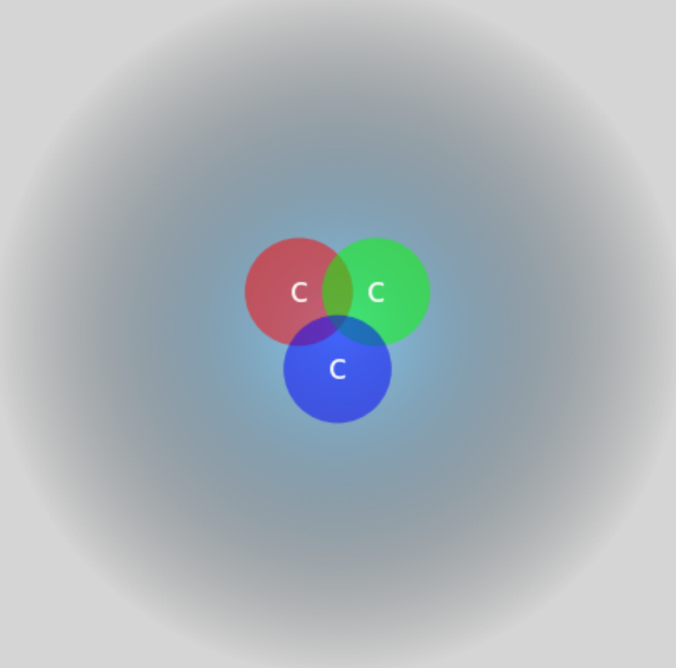
Padmanath, Edwards, Mathur, Peardon
PRD 90 (2014) 074504

$A + Ba^2 + Ca^2\ ln(a)$ fit

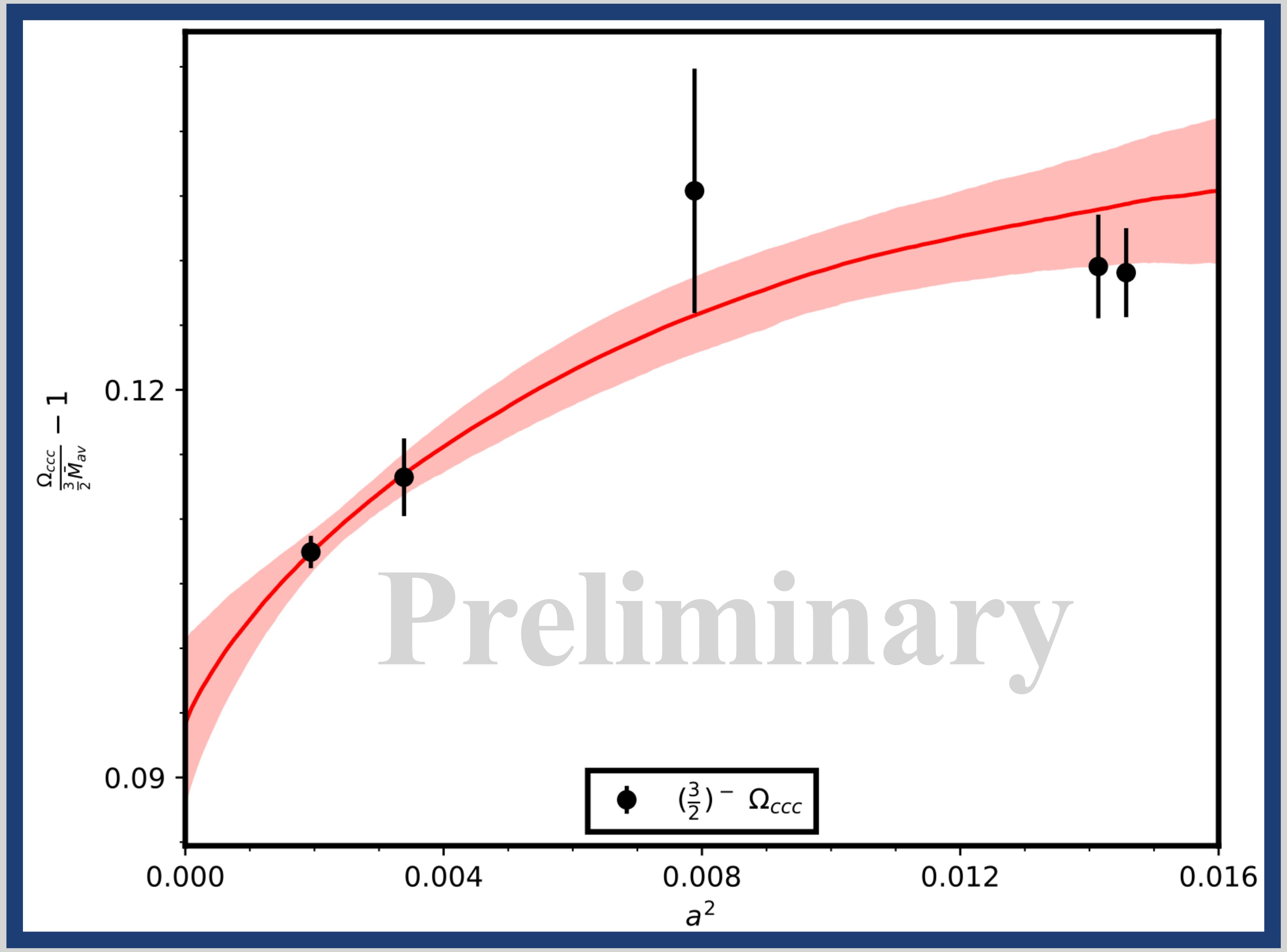
$$\bar{M}_{av} = \frac{1}{4}\left(M_{\eta_c} + 3M_{J/\psi}\right)$$

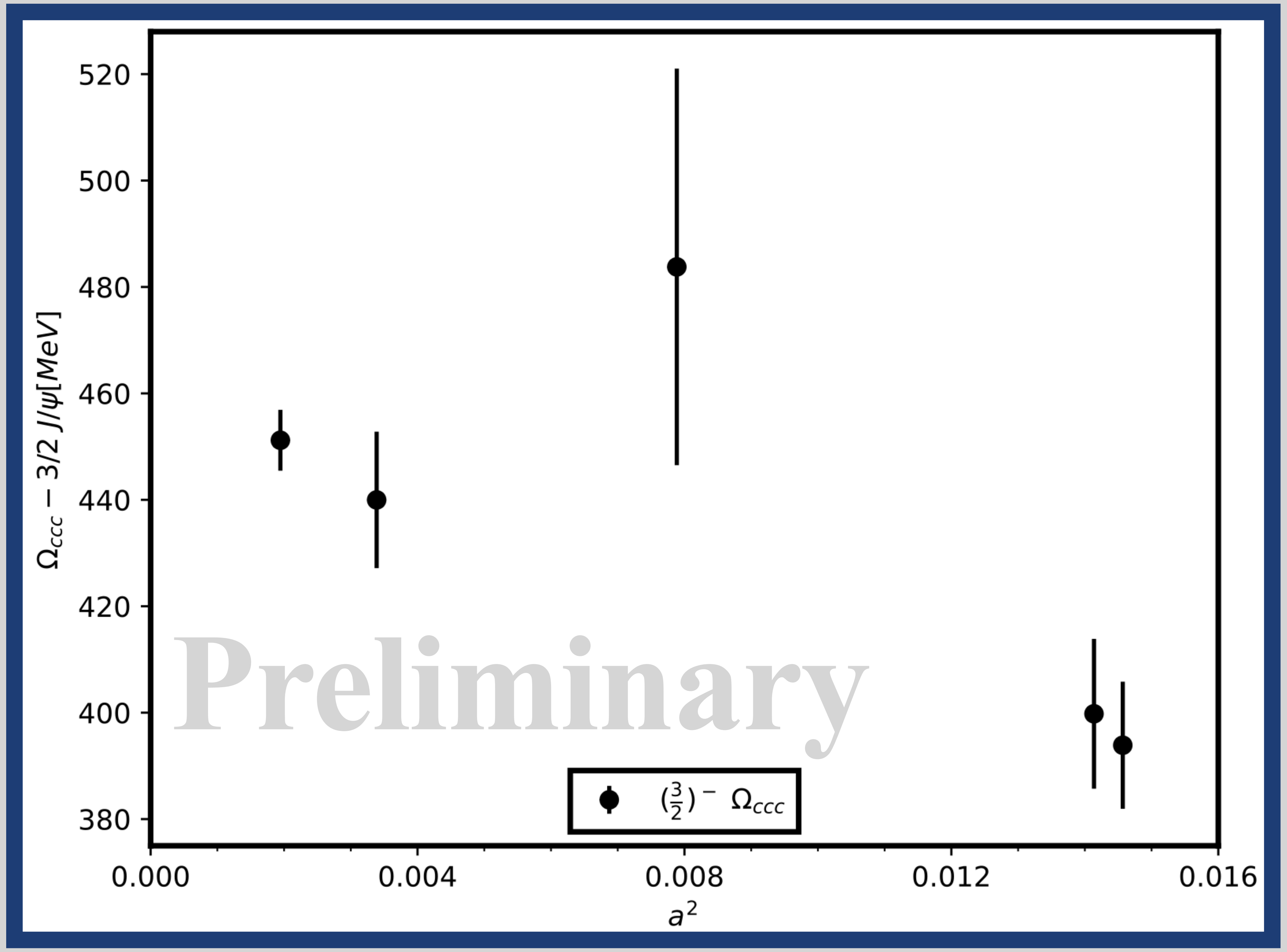
In Progress: NSD, Padmanath, Mathur

Ω_{ccc} Baryon



Will we see experimental observation of Ω_{cc} and Ω_{ccc} soon?

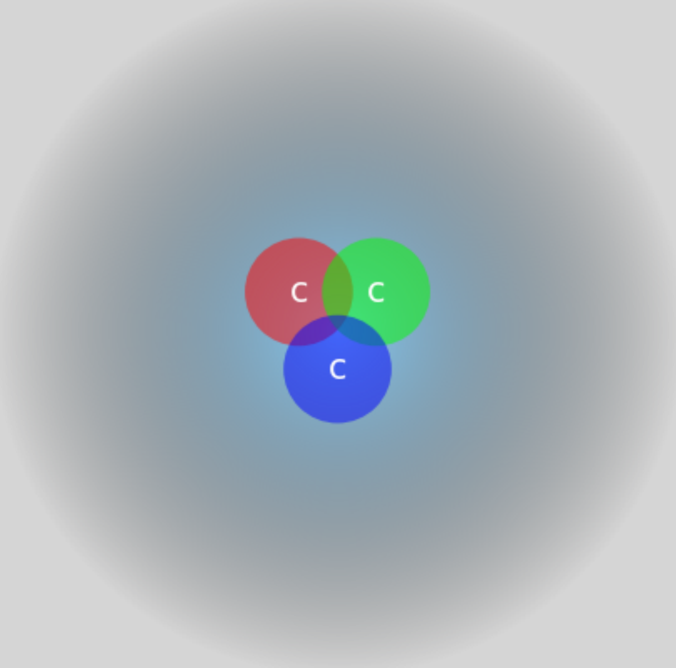


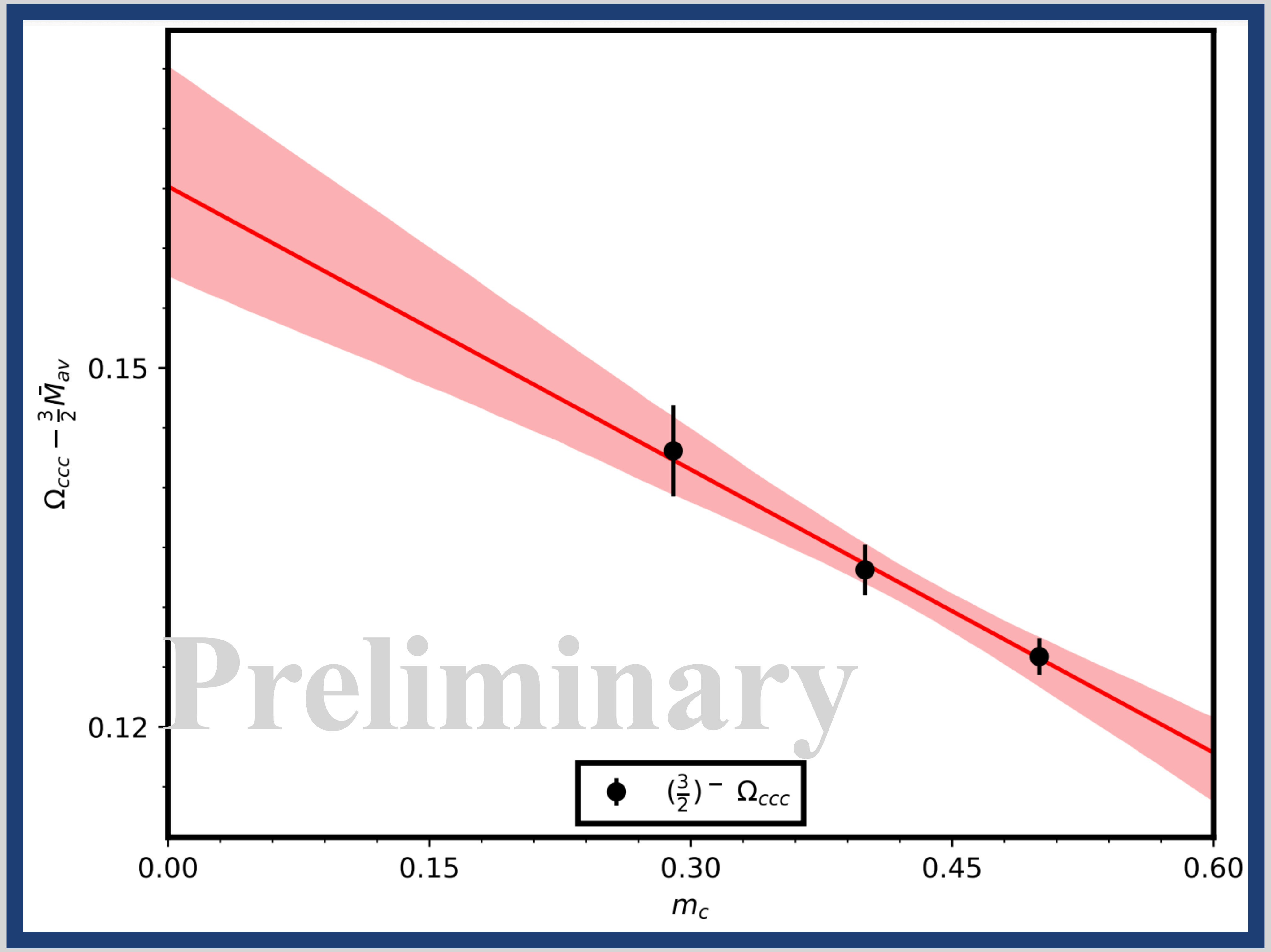


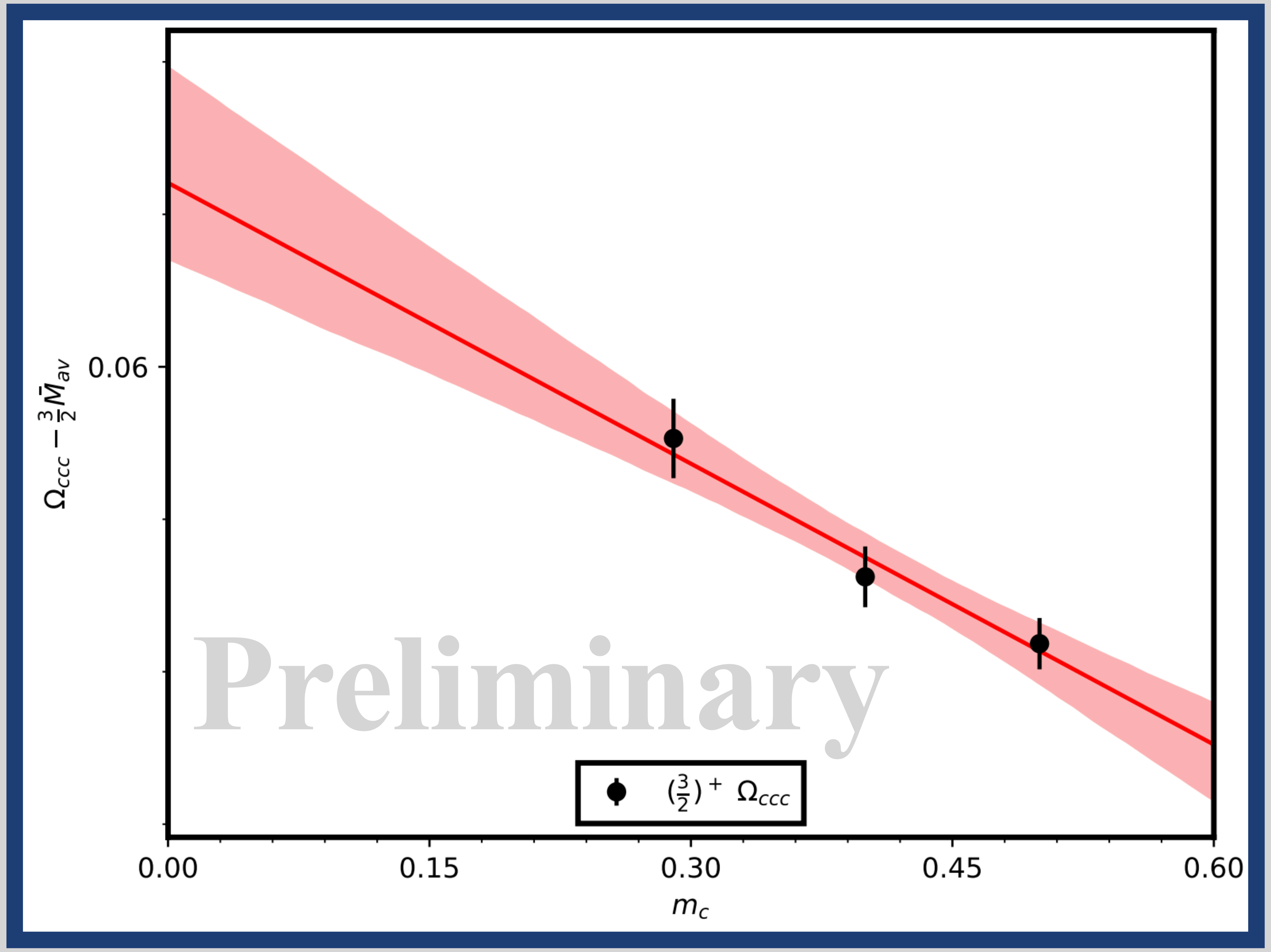
Negative Parity

In Progress: NSD, Padmanath, Mathur

Ω_{ccc} Baryon



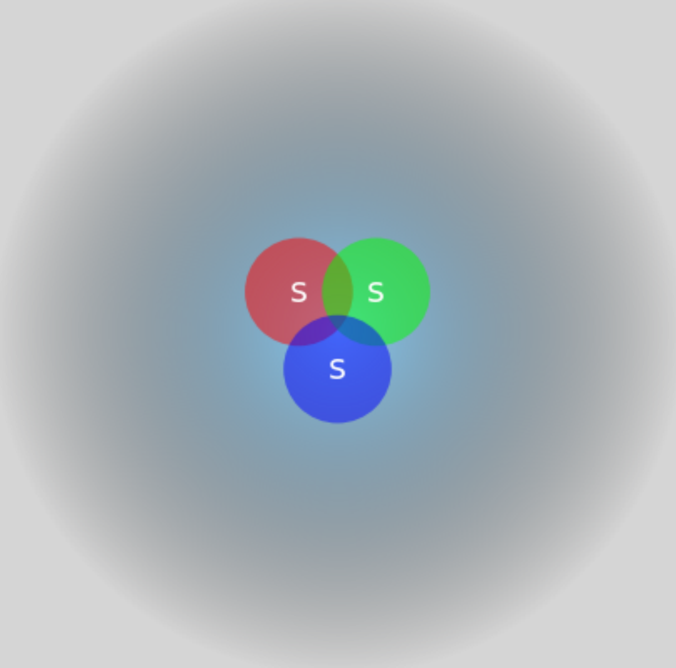


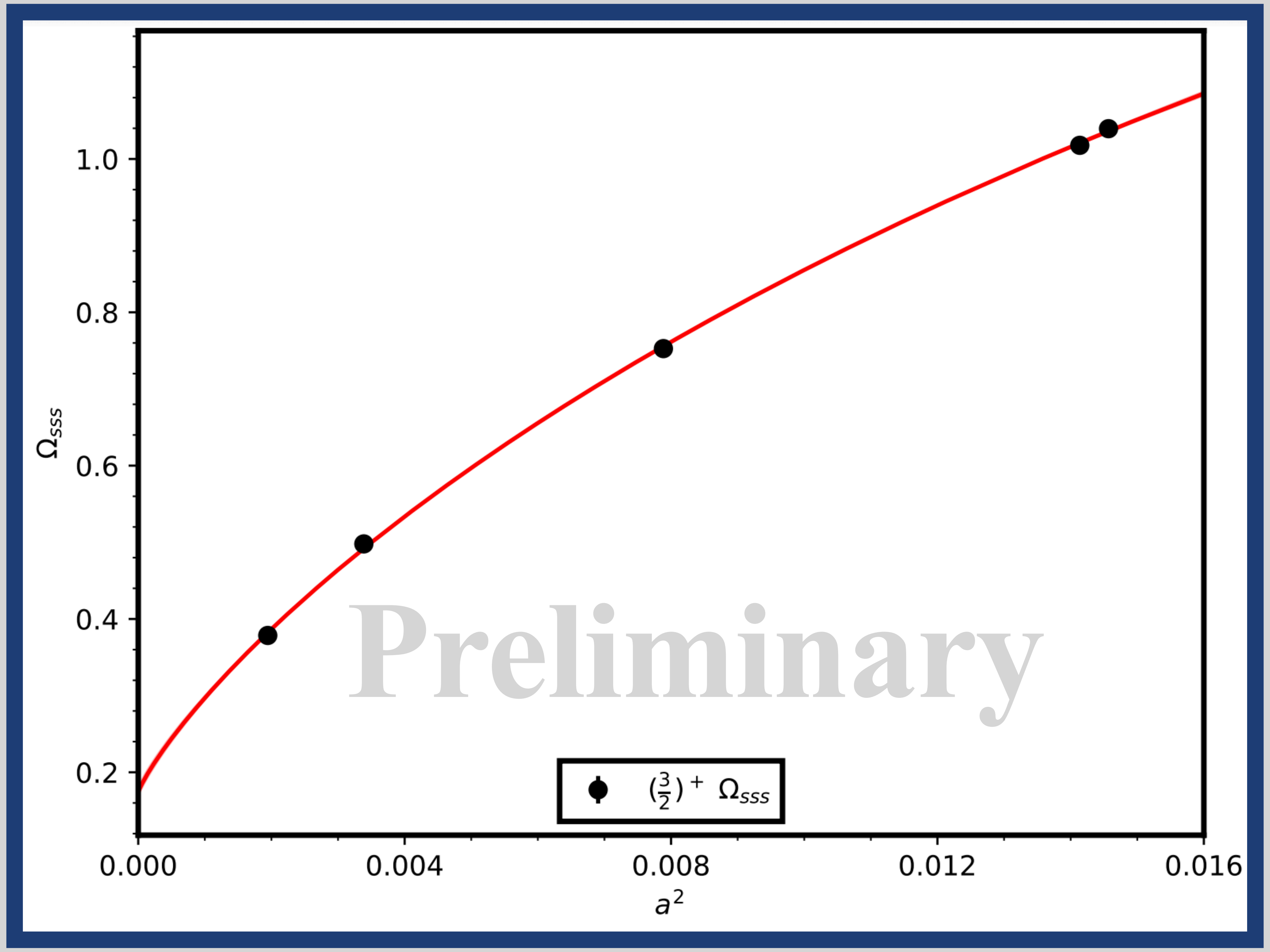


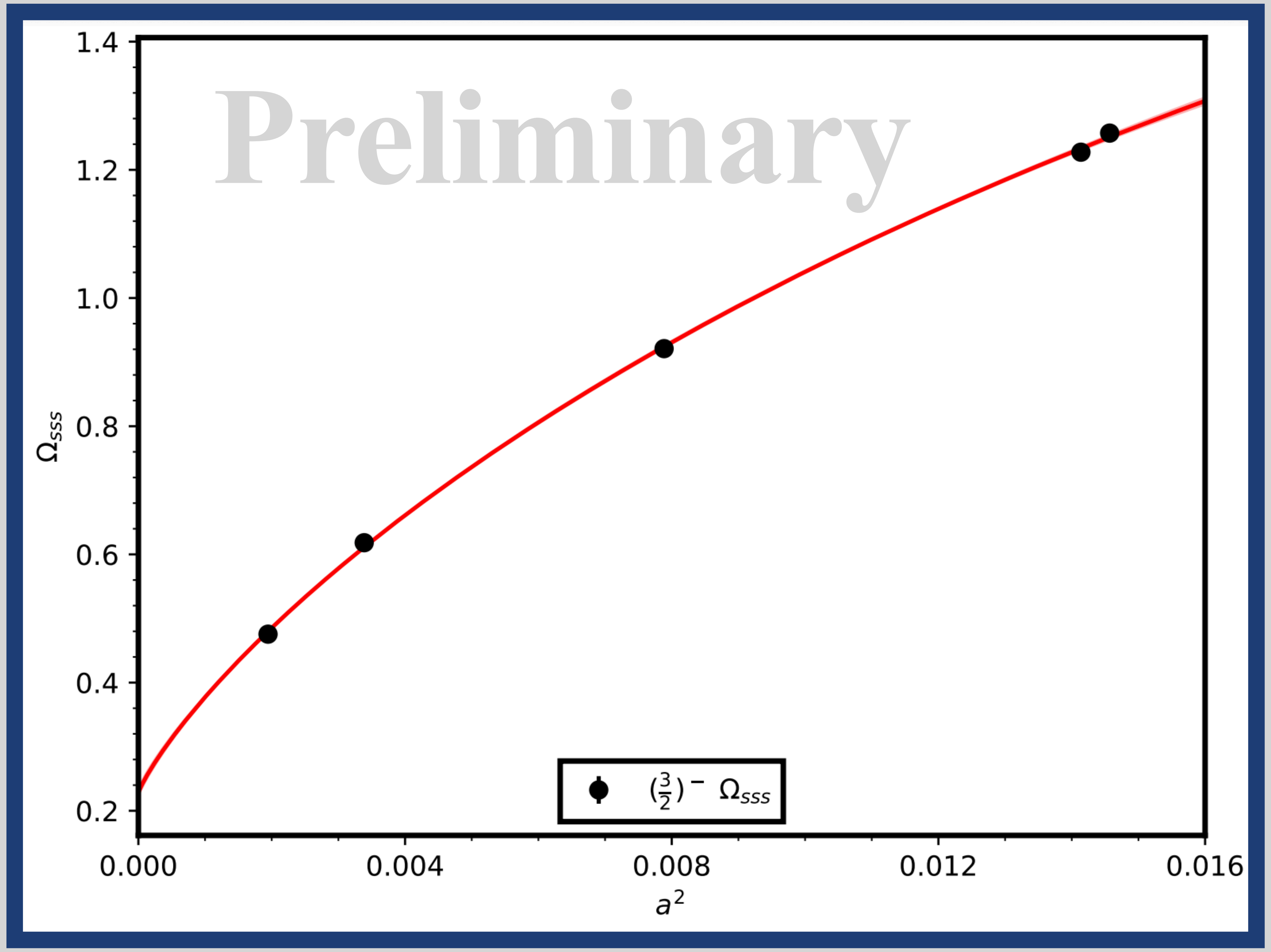
Tuning charm mass

In Progress: NSD, Padmanath, Mathur

Ω Baryon







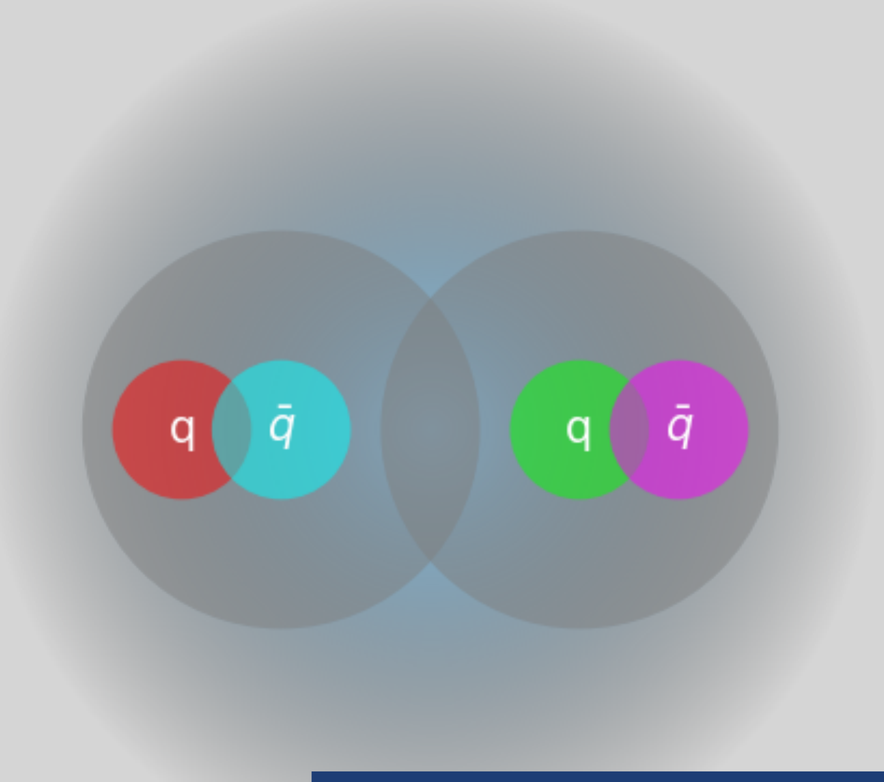
In Progress: NSD, Padmanath, Mathur

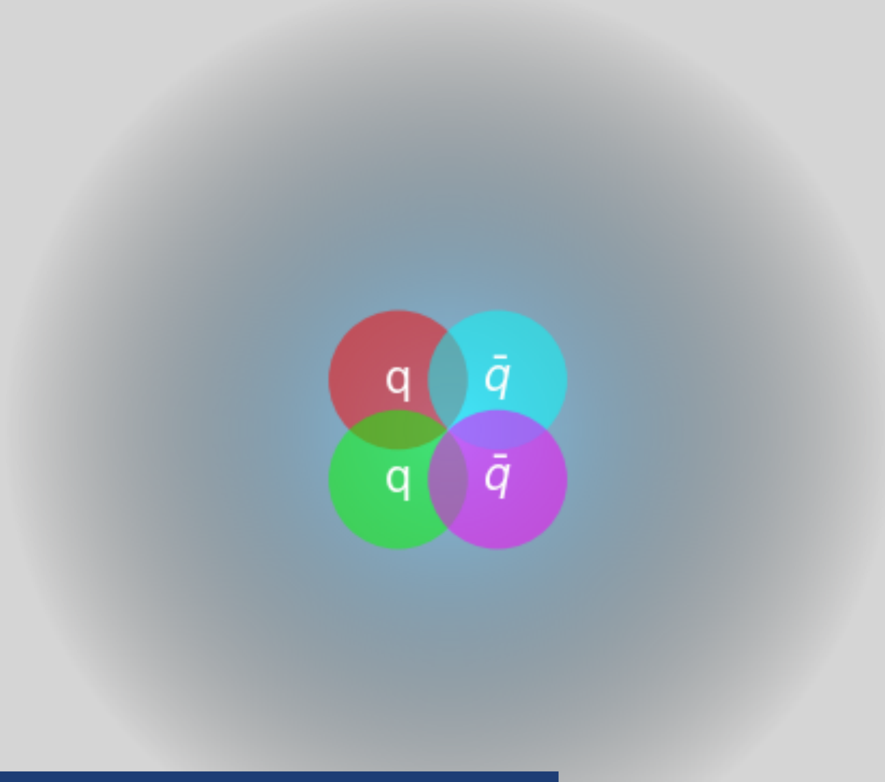
Exotic states

Instead of baryons and mesons we can have more exotic hadrons

Predicted in quark model

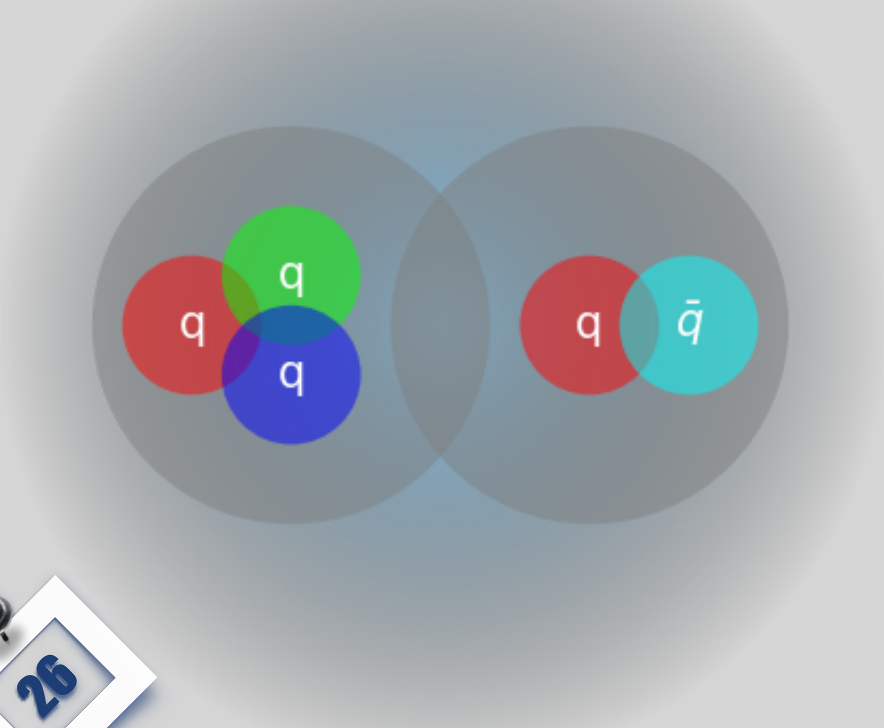
Recent experimental results show their existence

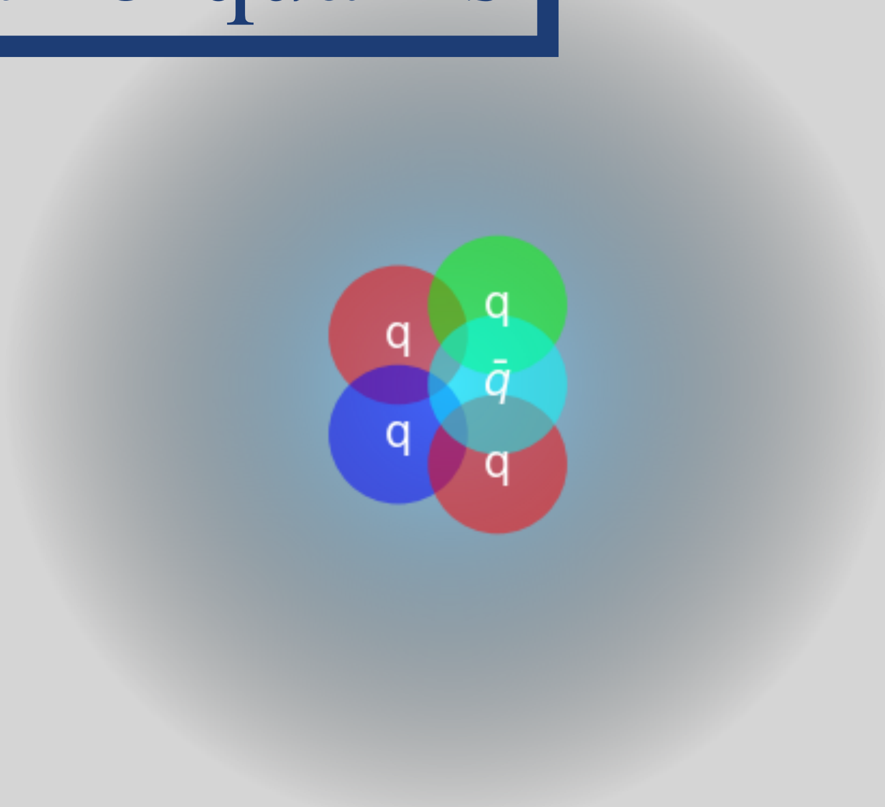


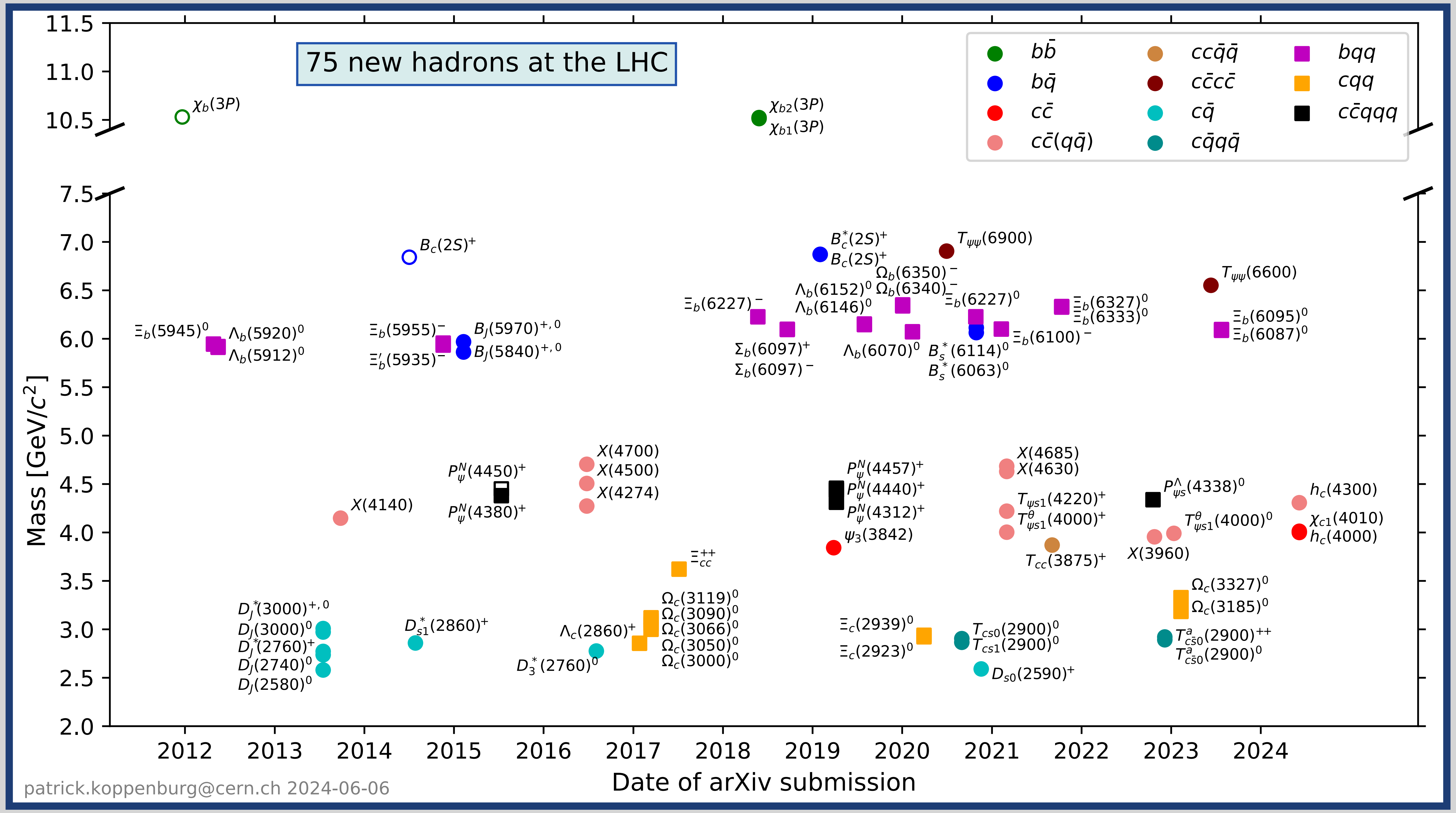


Hadron with 4 quarks

Hadron with 5 quarks

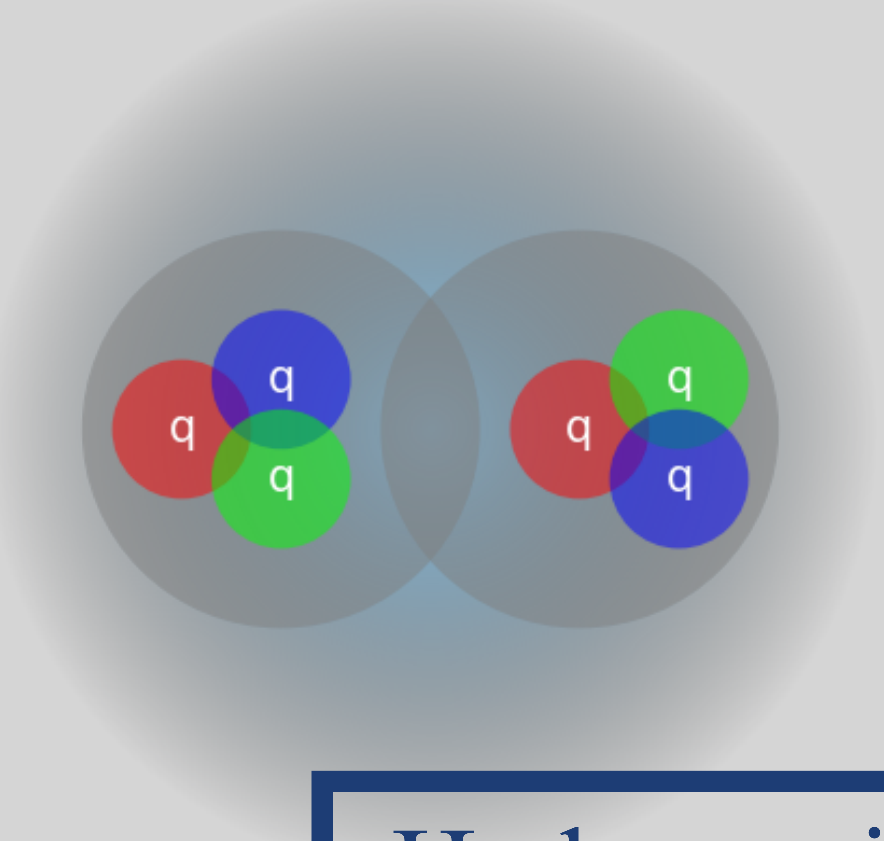


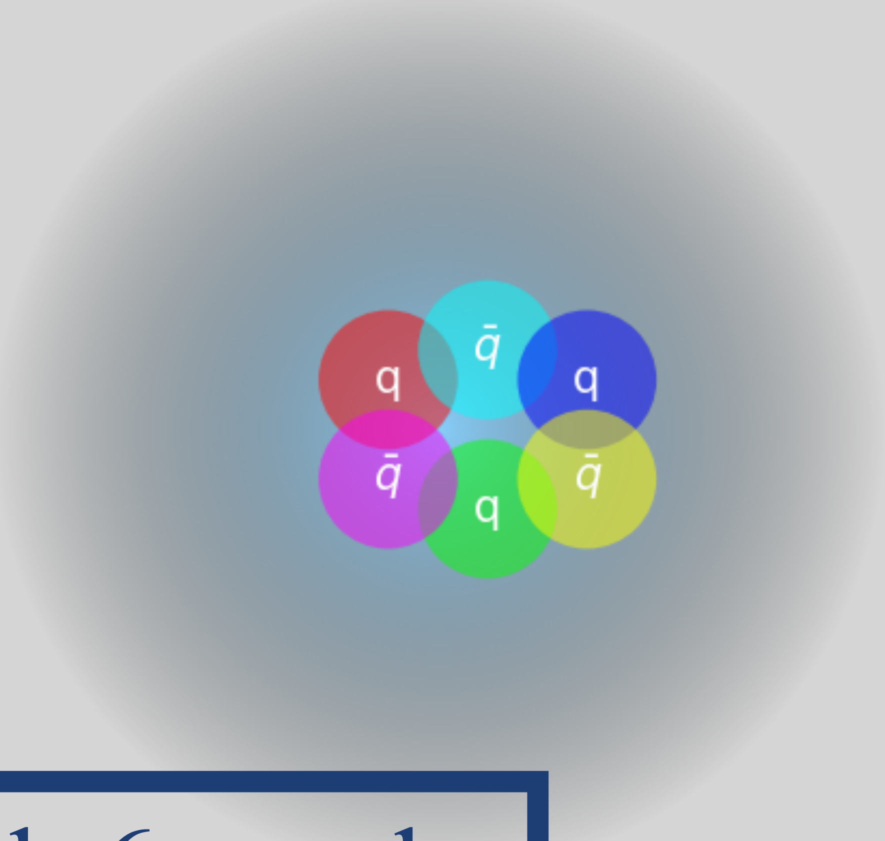




Hexaquark - Dibaryon

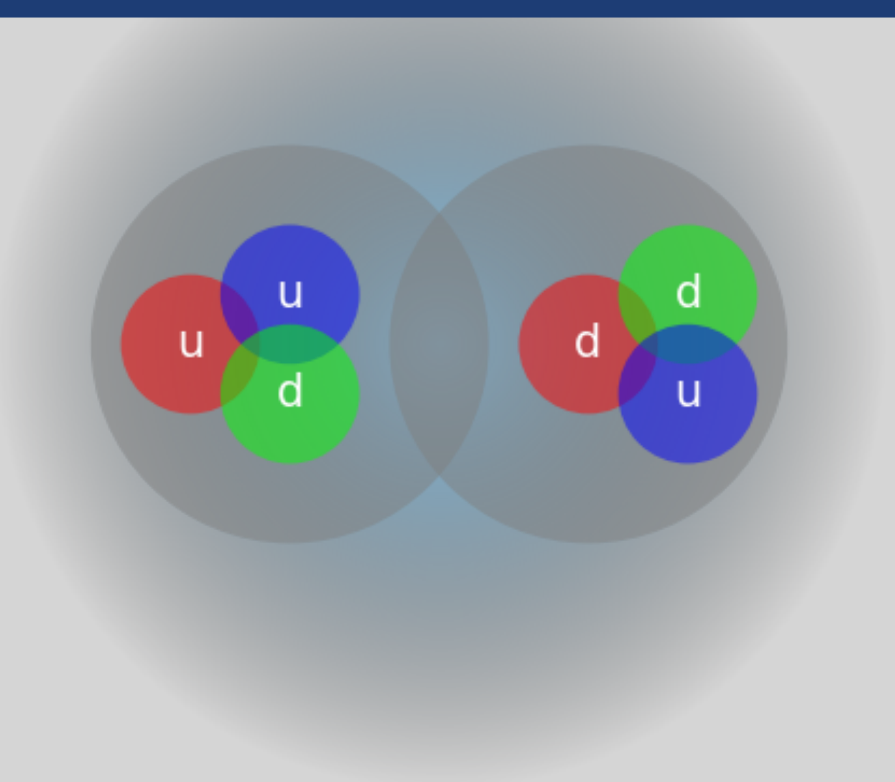
Extensive studies of deuteron like heavy dibaryons using Lattice QCD

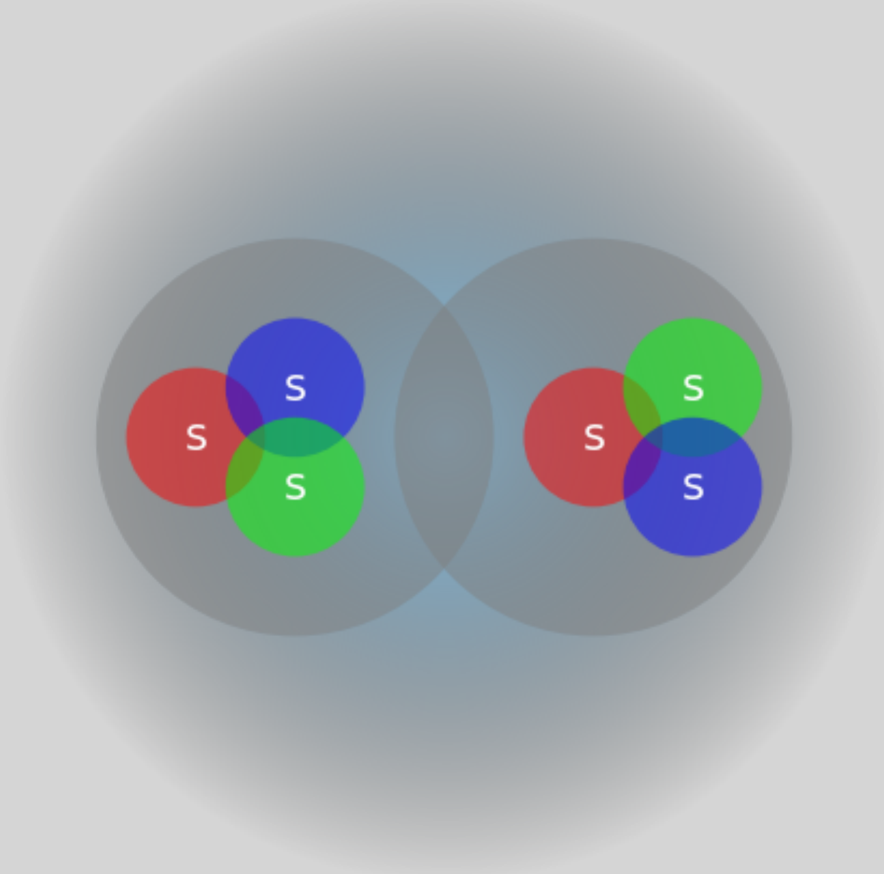


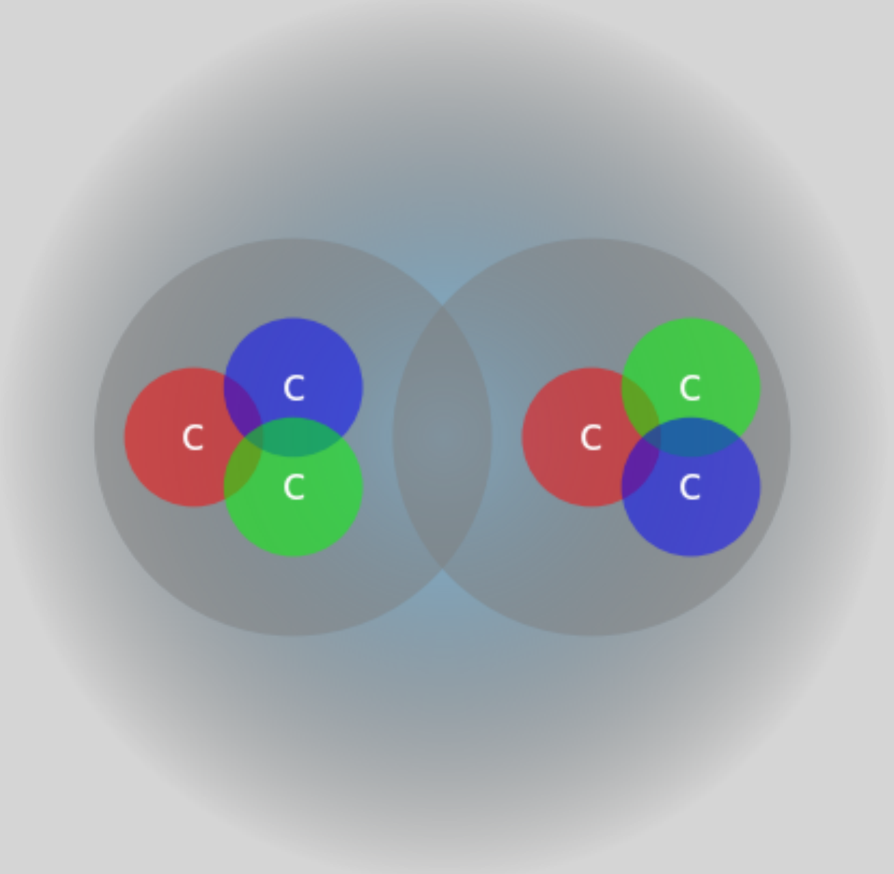


Hadron with 6 quarks

Deuteron

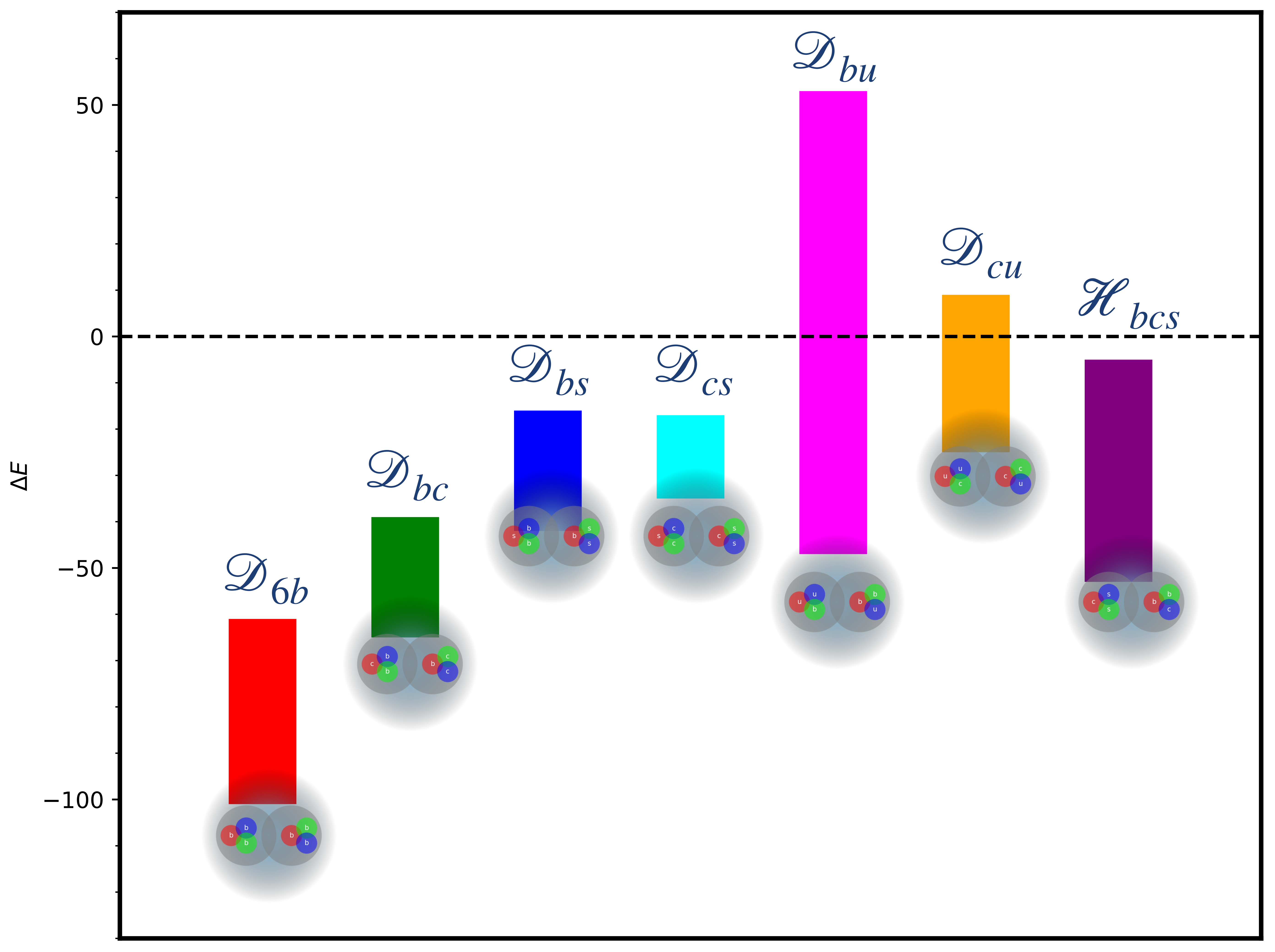






We work with single flavored dibaryons composed of strange and charm quarks named as $\mathscr{D}_{6s}$ and $\mathscr{D}_{6c}$ respectively

Dibaryons results from Lattice



$\mathscr{D}_{6b}$, $S = 0$

Mathur, Padmanath, Chakraborty
PRL, 130, 111901 (2023)

$\mathscr{D}_{bc}$, $\mathscr{D}_{bs}$, $\mathscr{D}_{cs}$, $\mathscr{D}_{bu}$, $\mathscr{D}_{cu}$

$S = 1$

Junnarkar, Mathur PRL, 123, 162003 (2019)

$\mathscr{H}_{bcs}$, $S = 0$

Junnarkar, Mathur PRD, 106, 054511 (2022)

Where does $\mathscr{D}_{6c}$, $\mathscr{D}_{6s}$ stand ??

$$\Delta E = E_{\text{dibaryon}} - E_{\text{1st baryon}} - E_{\text{2nd baryon}}$$

Dibaryon Operators

$$\mathcal{O} = \epsilon_{abc} q^a_{\mu_1} q^b_{\mu_2} q^c_{\mu_3}$$

$$\mathcal{O}_d = \mathcal{O}_1 \,.\, CG \,.\, \mathcal{O}_2$$

- Total wave function anti-symmetric under exchange of baryons.
- Single flavor baryons (symmetric).
- Assume only s wave interactions (symmetric) in dibaryon system.
- Color singlet baryons (symmetric)
- Hence Spin must be anti-symmetric which is in case of even spin (Spin 0 and 2)

- Use reduction coefficients to project continuum based operators to suitable octahedral group.
- $S = 0$ continuum spin subduces to one dimensional A_1^+ irrep.
- $S = 2$ continuum spin subduces to two dimensional E^+ and three dimensional T_2^+ irrep.

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Dibaryon Operators

a,b - different embeddings

$$\mathcal{O}^{[0]}_{d,A_1,1} = \frac{1}{2}\left({}^aH_{3/2}\ {}^bH_{-3/2} - {}^aH_{1/2}\ {}^bH_{-1/2} + {}^aH_{-1/2}\ {}^bH_{1/2} - {}^aH_{-3/2}\ {}^bH_{3/2}\right)$$

For Spin 0, dibaryon operator corresponding to one dimensional A_1^+ irrep.

For Spin 2, 5 such operators corresponding to E^+ and T_2^+ irrep.

S_z	Operator	State
3/2	${}^1H_{3/2}$	111
1/2	${}^1H_{1/2}$	112+121+211
-1/2	${}^1H_{-1/2}$	122+212+221
-3/2	${}^1H_{-3/2}$	222

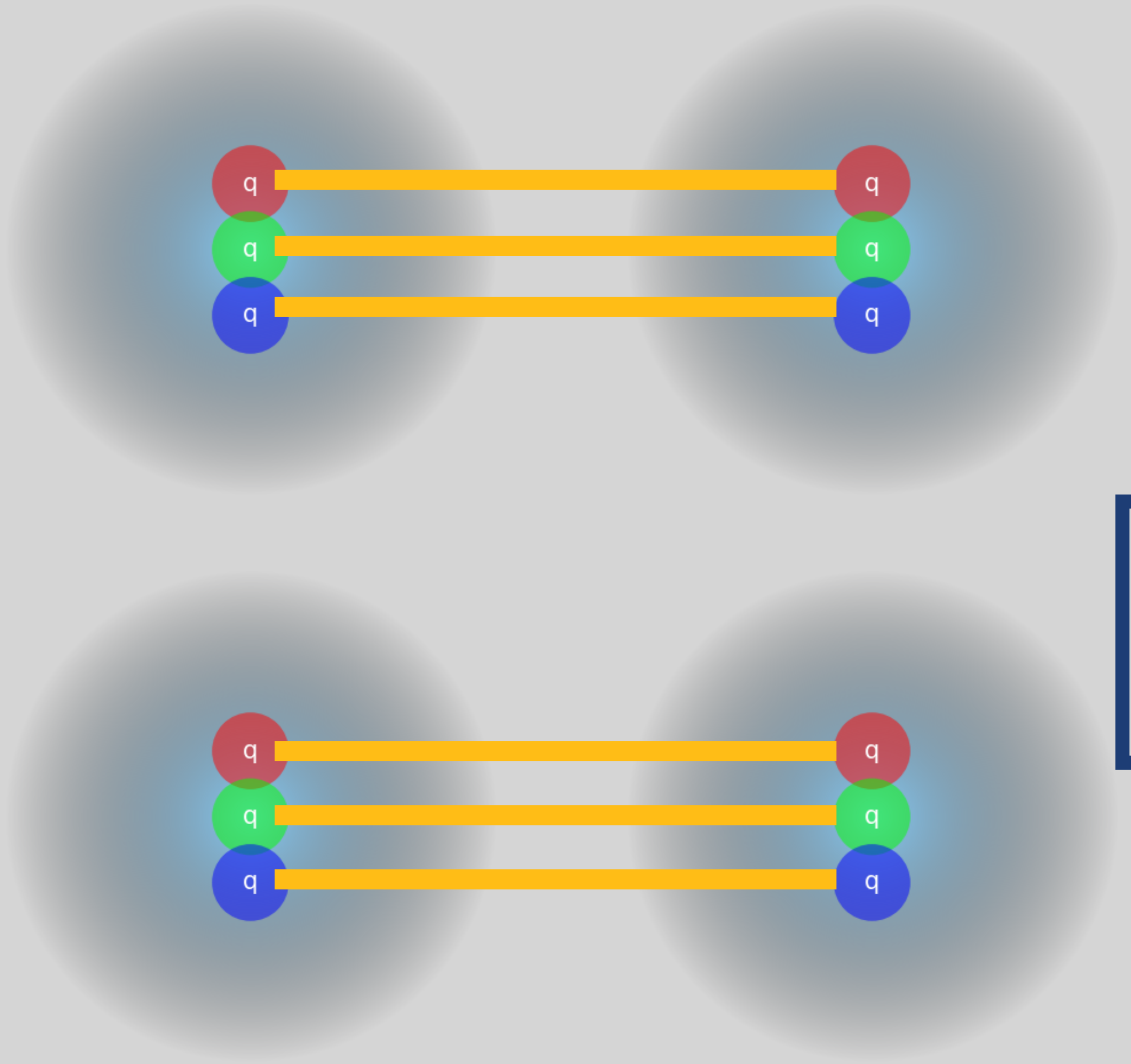
Non Relativistic Embedding

S_z	Operator	State
3/2	${}^2H_{3/2}$	133+313+331
1/2	${}^2H_{1/2}$	233+323+332+134+341+413+143+431+314
-1/2	${}^2H_{-1/2}$	144+414+441+234+342+423+243+432+324
-3/2	${}^2H_{-3/2}$	244+424+442

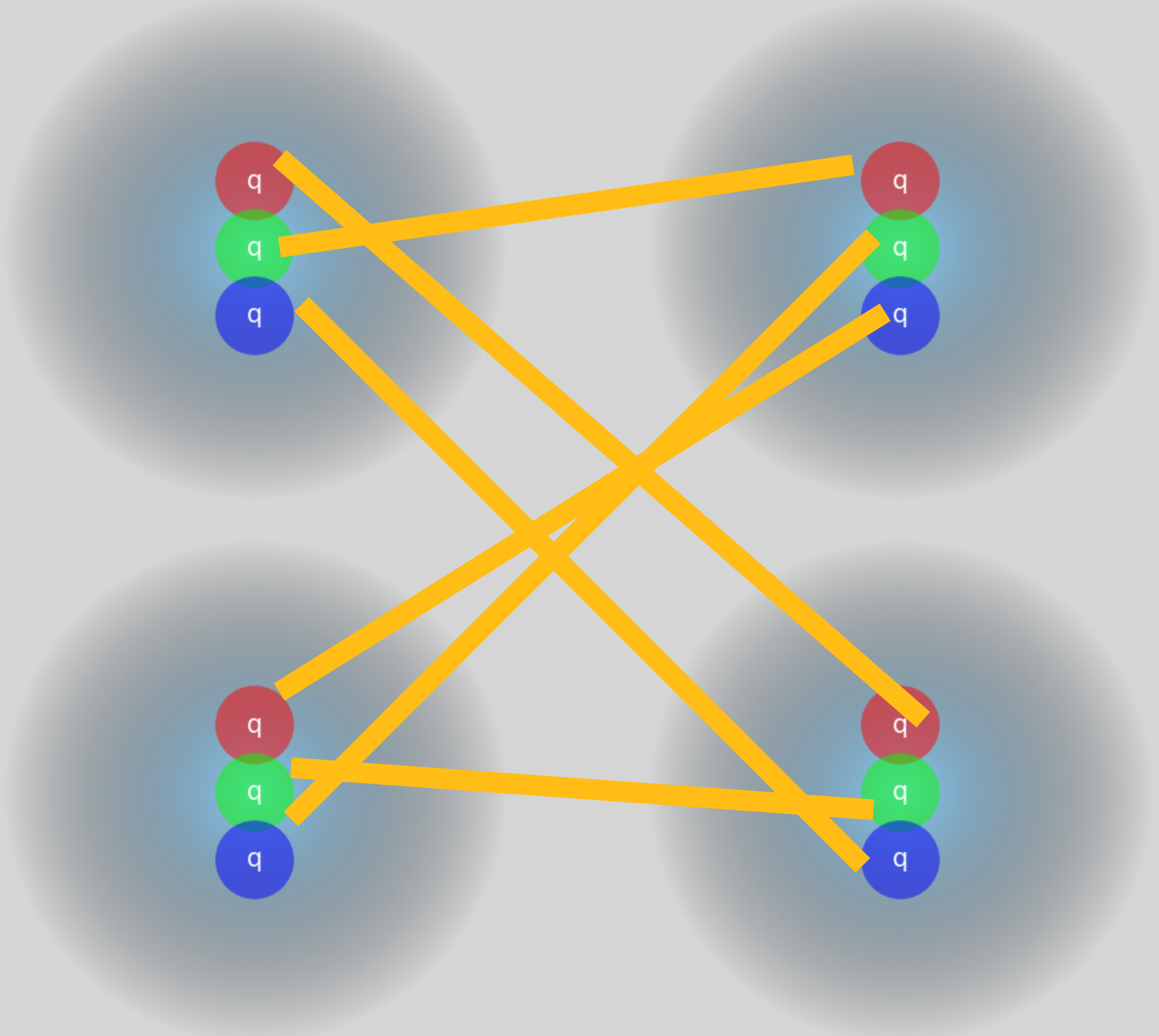
Relativistic Embedding

Operator Contraction

Now we have two baryons at source and two at sink



6! = 720 contraction possibilities

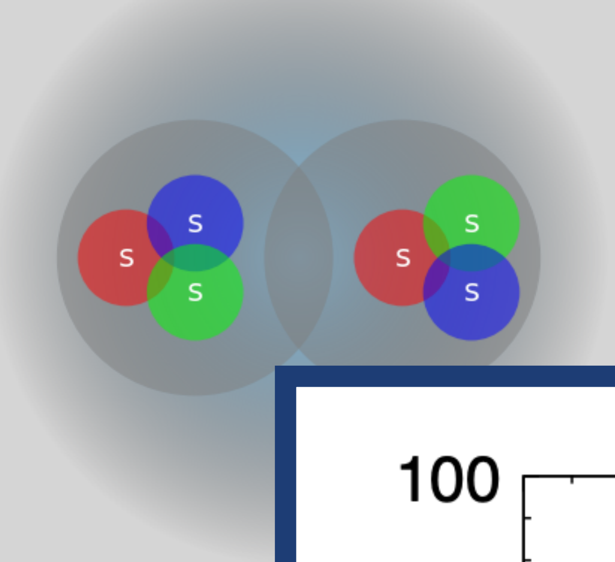


720 contractions can happen in 16 different ways depending on different embeddings

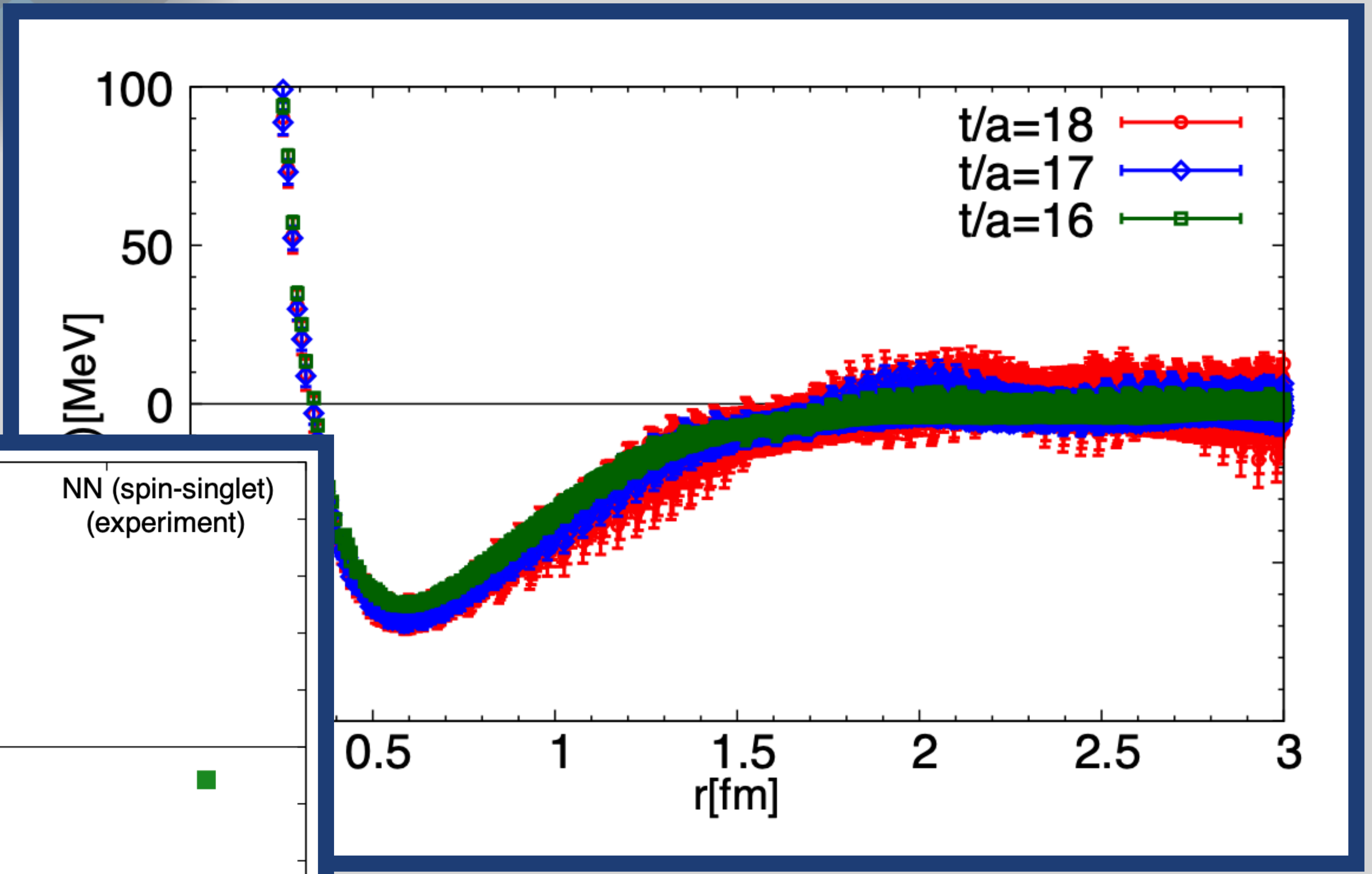
N-N-N-N	N-N-N-R	N-N-R-N	N-N-R-R
N-R-N-N	N-R-N-R	N-R-R-N	N-R-R-R
R-N-N-N	R-N-N-R	R-N-R-N	R-N-R-R
R-R-N-N	R-R-N-R	R-R-R-N	R-R-R-R

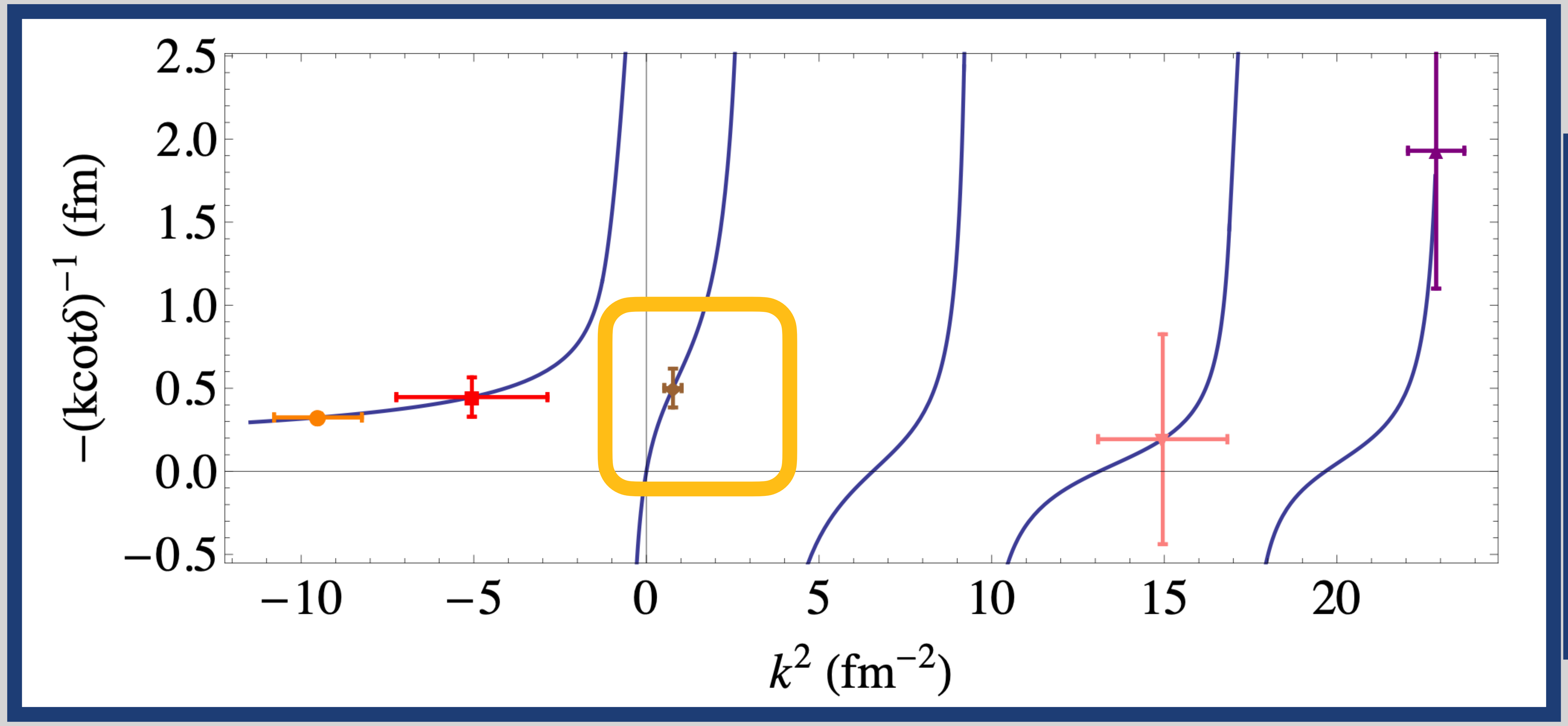
Some of these are degenerate and some of these do not contribute at all for different Spin cases

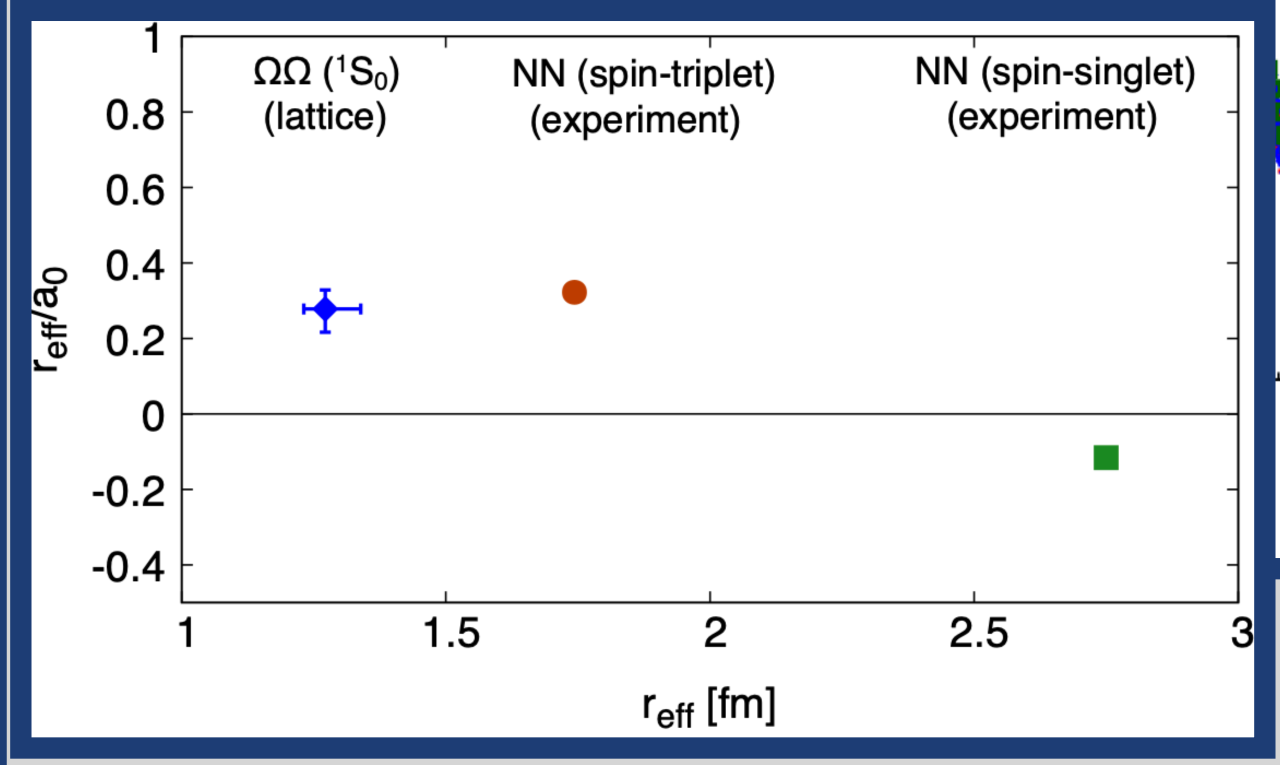
$\mathscr{D}_{6s}$ Existing Results



HALQCD
PRL 120, 212001 (2018)





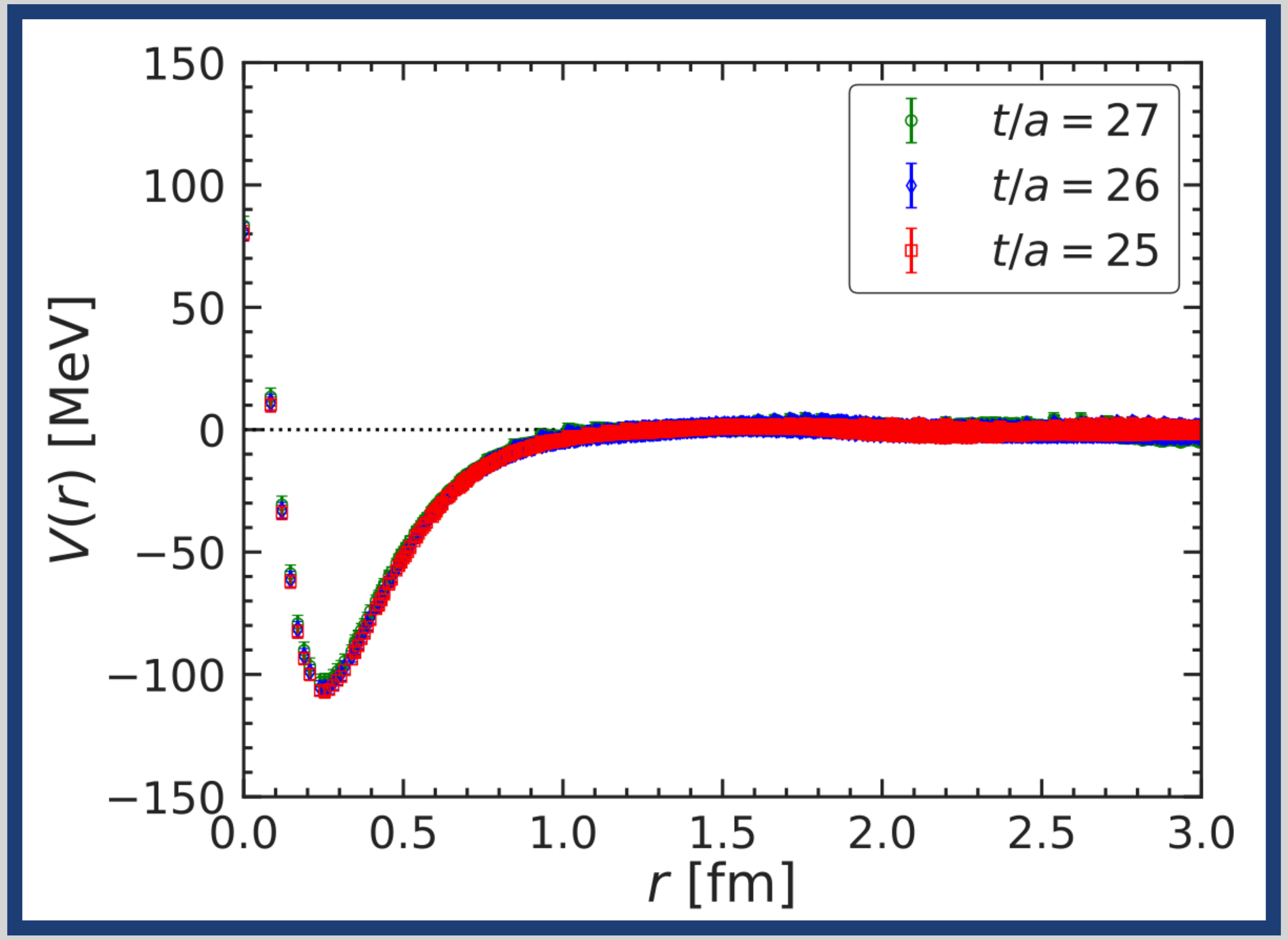


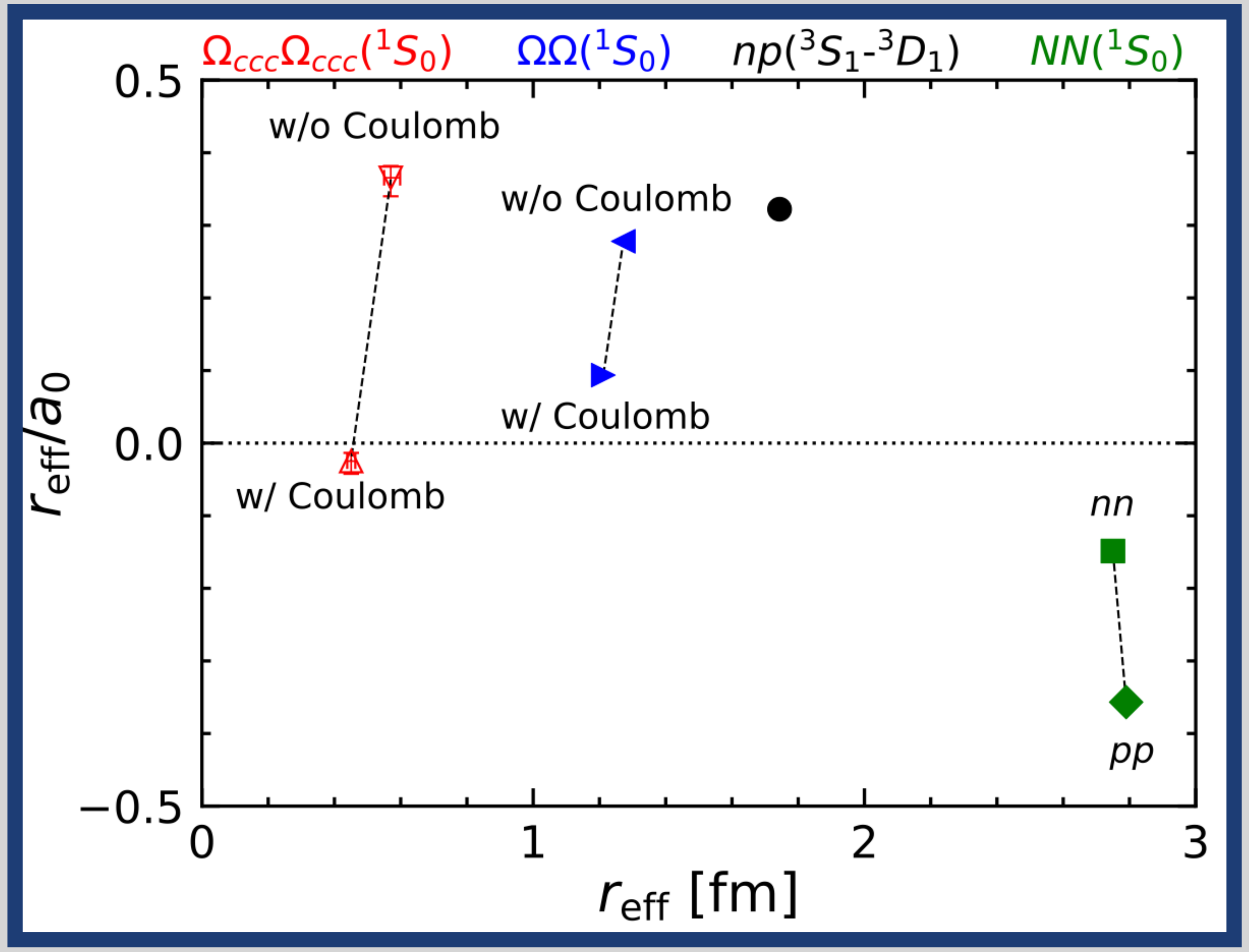
- Weakly attractive in Spin 0, hence bound state
- "Such a system can be best searched experimentally by the pair-momentum correlation in relativistic heavy-ion collisions."

Buchoff, Luu, Wasem
PRD 85, 094511 (2012)

- Weakly repulsive in Spin 0 H^+H^+ irrep, No bound state
- Attractive in Spin 1,2 $G_1^+H^+$ but only single volume used.

$\mathcal{D}_{6c}$ Existing Results





- Simulation with physical charm mass and near physical light quark mass.
- Dibaryon existence without Coulomb interaction.
- Near unitary region with Coulomb interaction (scattering length less than corresponding strange dibaryon calculation).

Is this a bound state?

★ Quoting bound state and binding energies directly from energy splittings of product hadron and its constituents.

In this talk

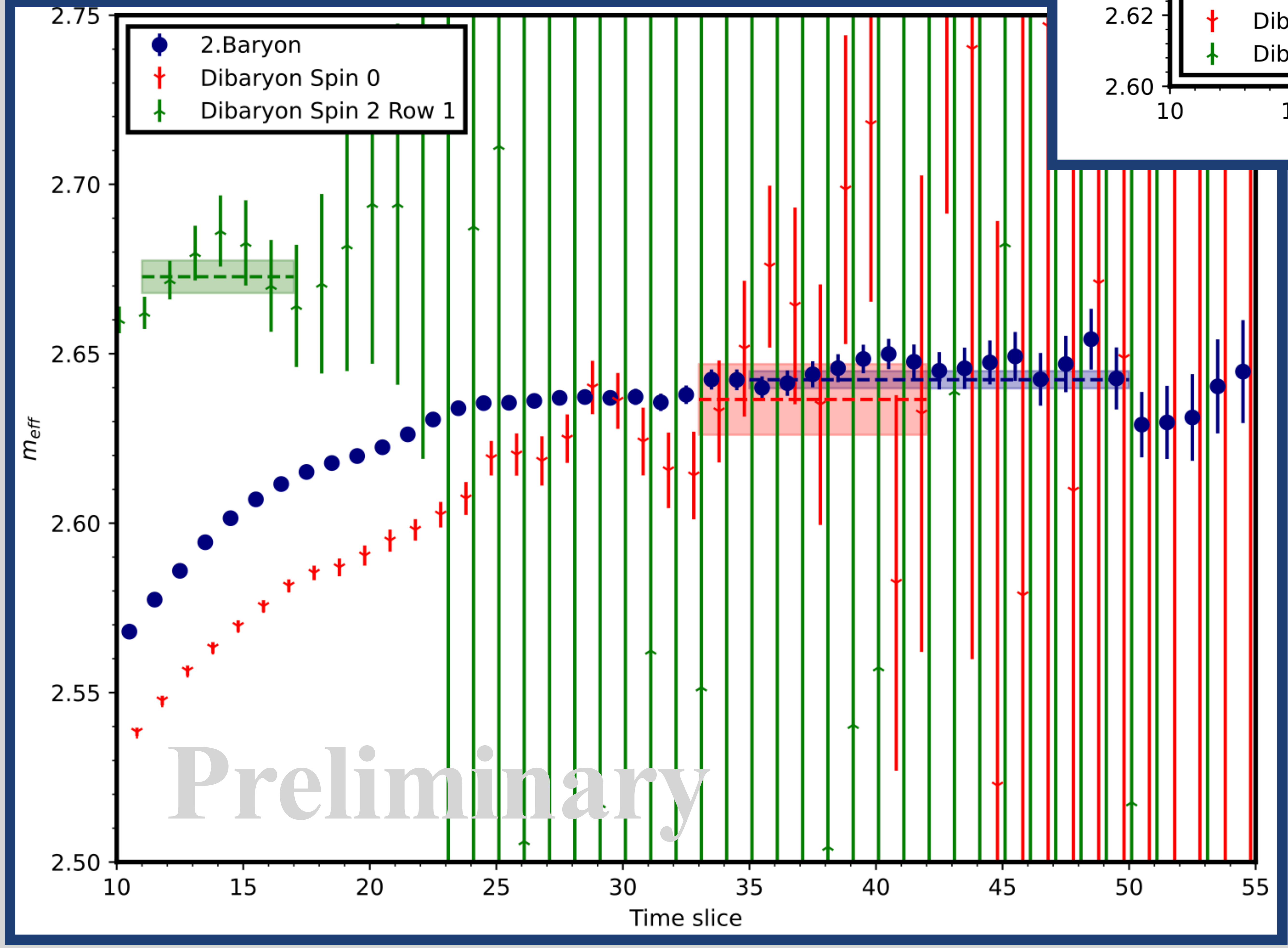
★ Extract hadron-hadron interactions by solving QM potentials from Nambu-Bethe-Salpeter wave function.

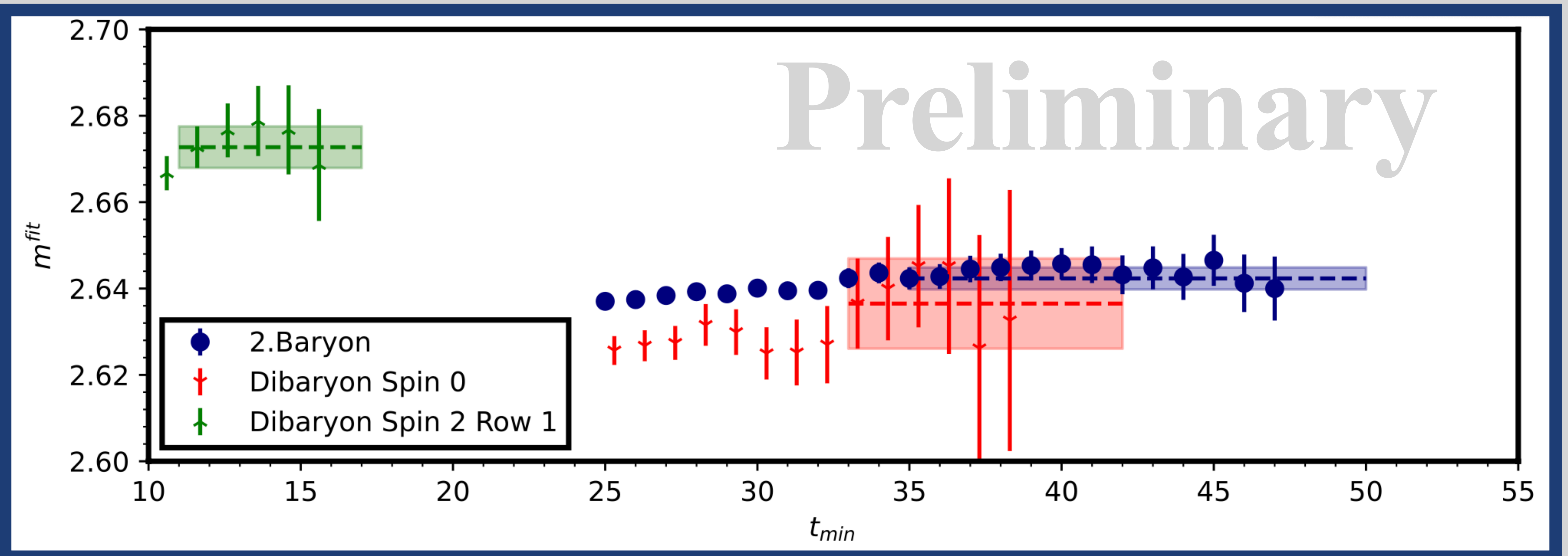
Previous slide HALQCD

★ Luscher's formalism - relating discrete finite-volume energy spectrum to few-body scattering amplitudes in the infinite limit.

Near future

Energy spectrum



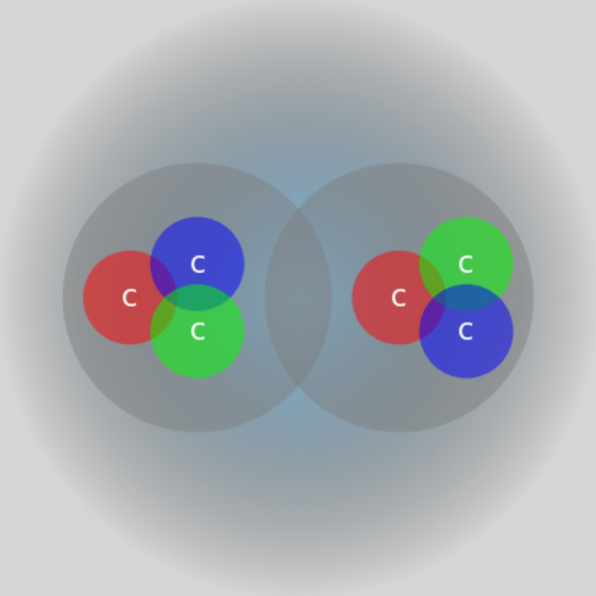


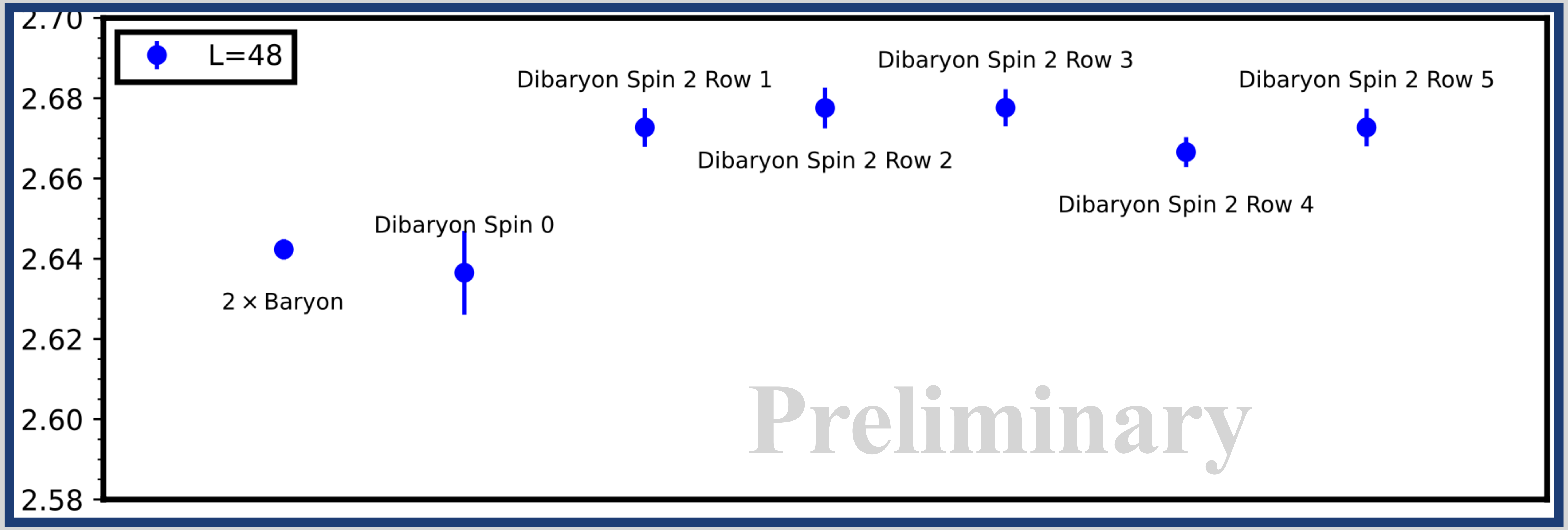
- Dependence of minimum time slice for fitting.

- Effective masses from lattice by using Dibaryon Spin 0 operator, one operator of Spin 2 for Dibaryon.
- Comparison with twice the effective mass from Baryon operator.

In Progress: NSD, Padmanath, Mathur

$\mathcal{D}_{6c}$ Results

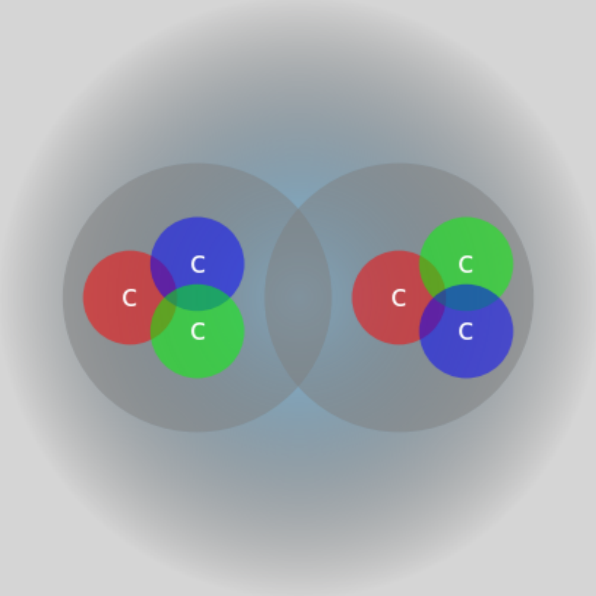


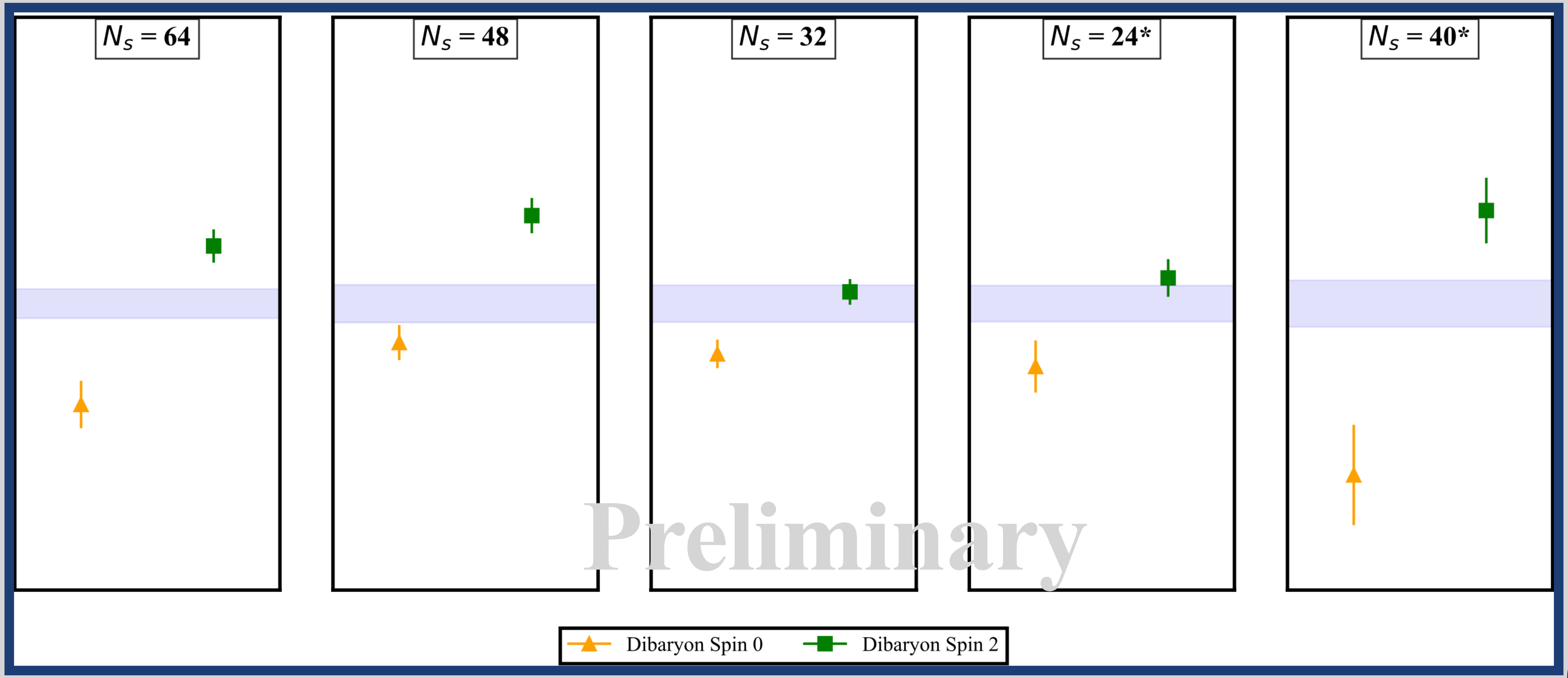


- Bound state, if exist, is shallow
- More probe using Luscher's formalism

- Two lattice volumes, 4 lattice spacings, this plot with L = 48
- Spin 2 - repulsive interactions, Spin 0 dibaryon energy same as twice of baryon

$\mathscr{D}_{6c}$ Results





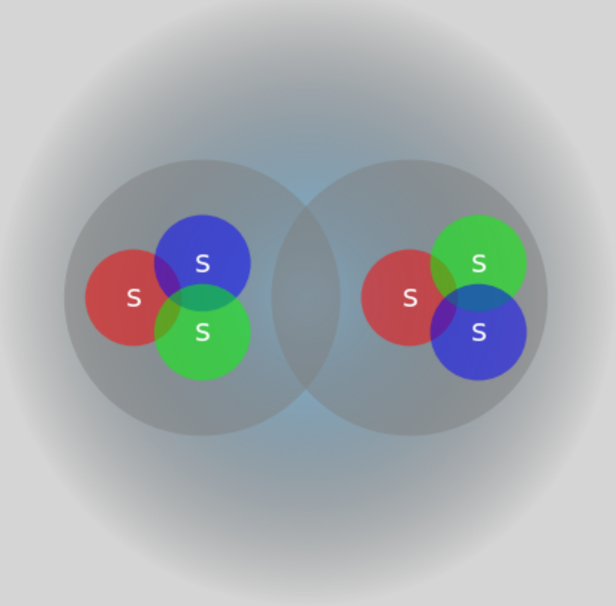
- Bound state, if exist, is shallow
- More probe using Luscher's formalism

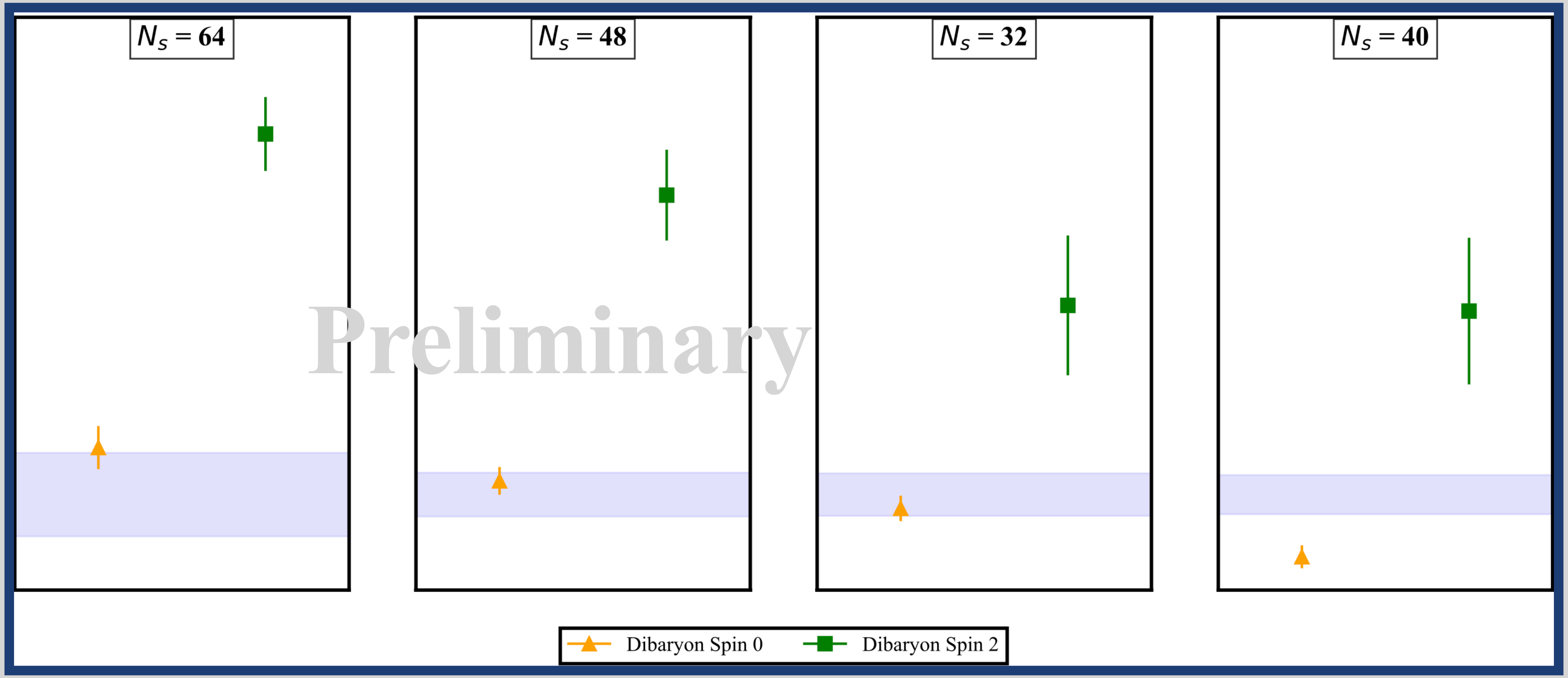
HALQCD
PRL 127, 072003 (2021)

Bound state without Coulomb interaction

In Progress: NSD, Padmanath, Mathur

$\mathcal{D}_{6s}$ Results





- No bound state
- More probe using Luscher's formalism

Buchoff, Luu, Wasem
PRD 85, 094511 (2012)

No bound state

HALQCD
PRL 120, 212001 (2018)

Bound state exists

In Progress: NSD, Padmanath, Mathur

Conclusions

- ★ Simulations with finer and big enough lattices.
- ★ Ω and Ω_{ccc} calculations with more ensembles in the continuum limit.
- ★ Dibaryon investigation in $\Omega - \Omega$ and $\Omega_{ccc} - \Omega_{ccc}$ systems.
- ★ Prediction: Absence of bound state (or very weakly bound state if any)

Future Directions

★ Luscher's formalism for dibaryon investigations.

★ Initial calculations indicate similar behaviour of E^+ and T_2^+ irrep, more detailed analysis to follow.

★ Do the heavier baryons composed of charm and bottom quarks and their corresponding dibaryons (if exist as a bound state) survive with temperature ?

★ Lattice estimation of d*(2380)…

THANK YOU

Navdeep Singh Dhindsa   15/07/2024