第七届强子谱和强子结构研讨会

格点QCD上的强子谱与强子结构

CLQCD

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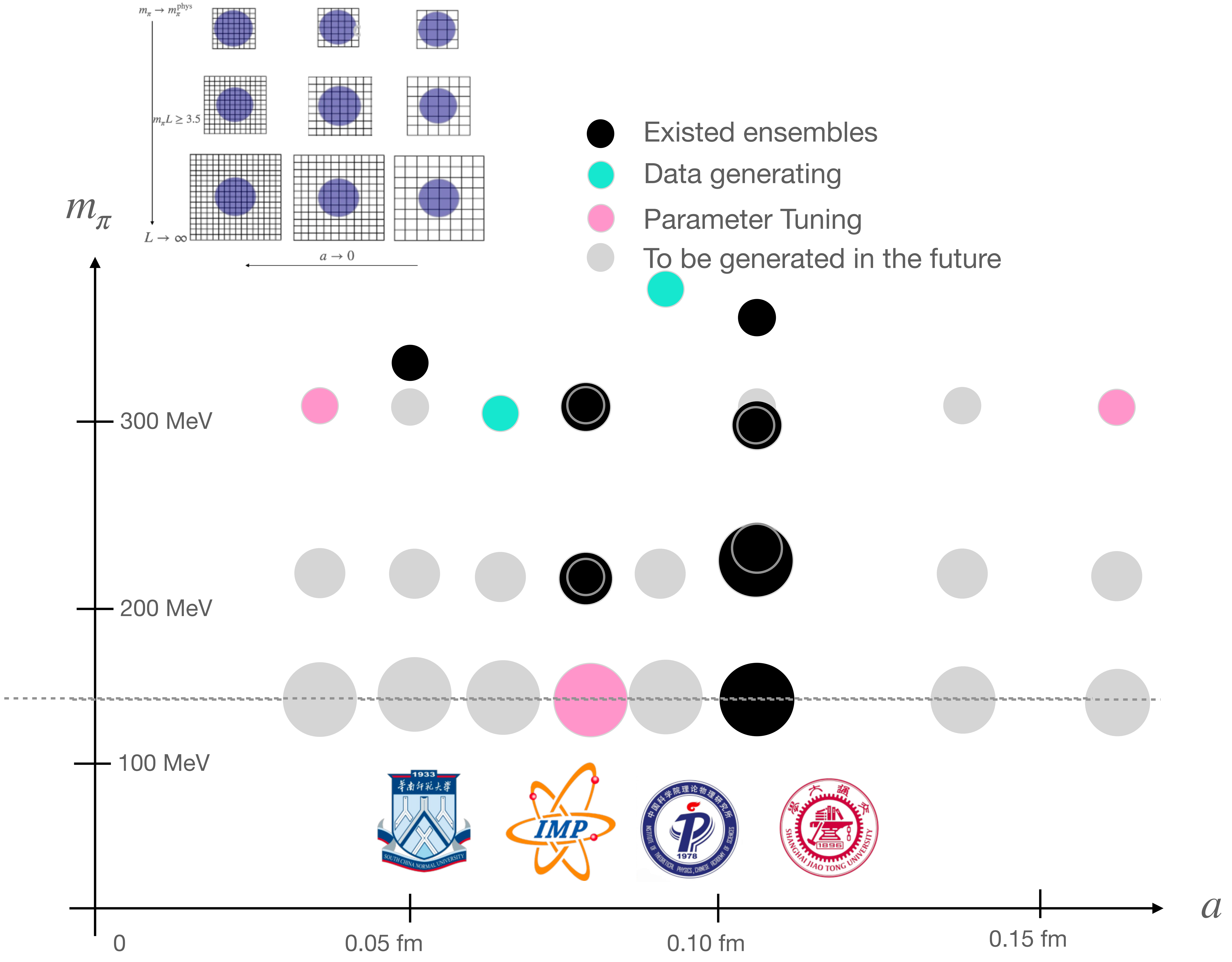
CLQCD ensembles



Current status

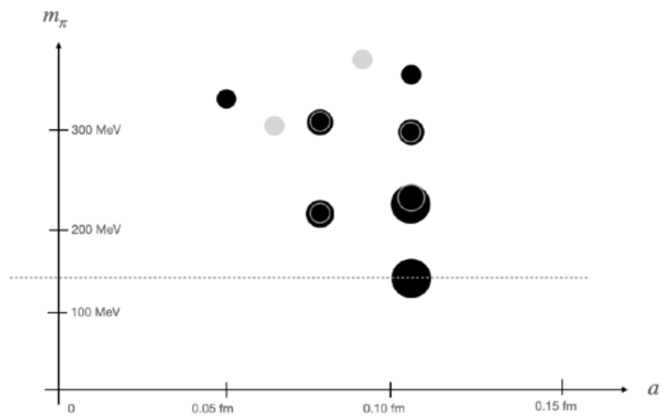
★In production：

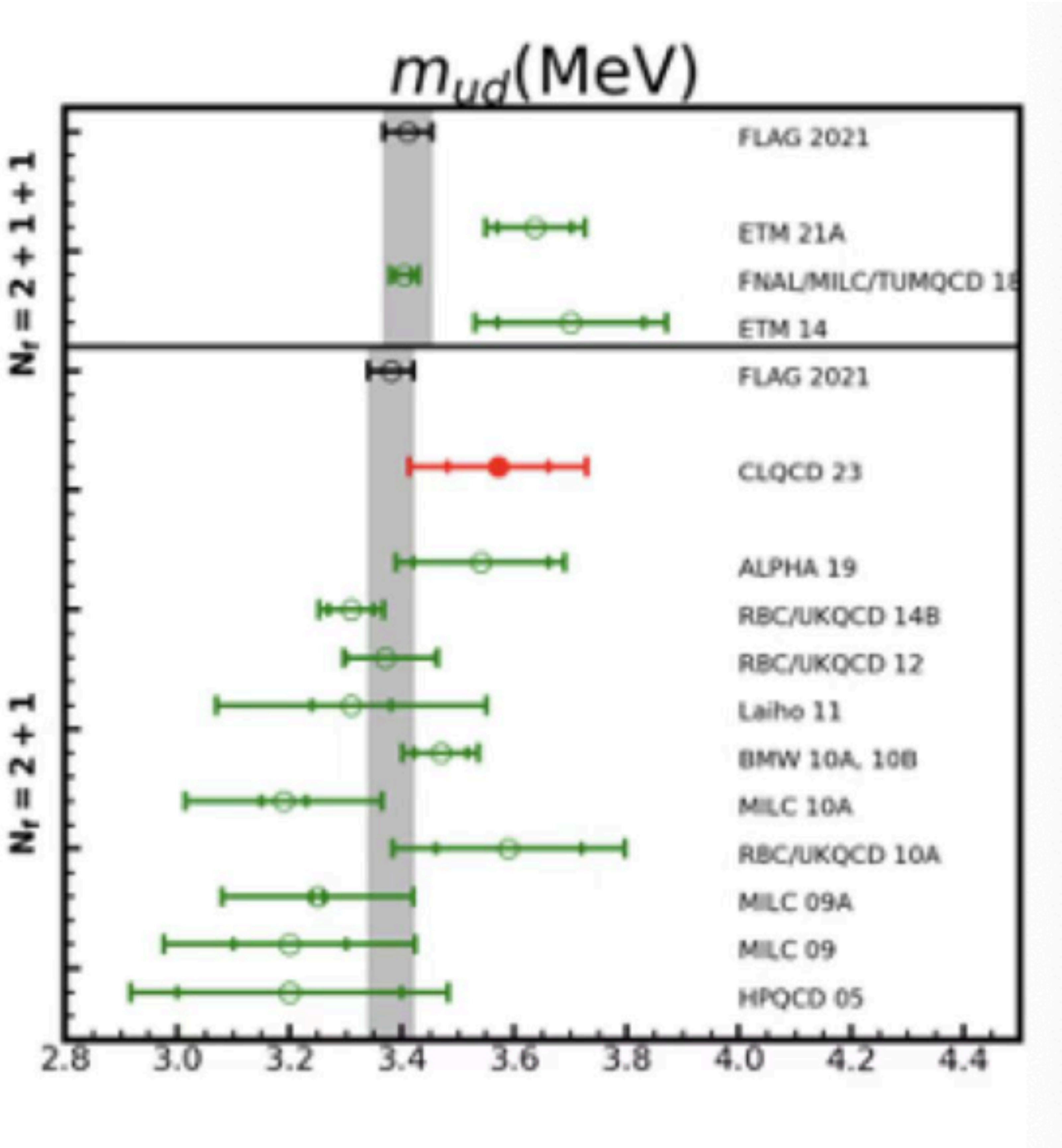
- a=0.0888(3) fm, mpi=349(2) MeV, L=2.49 fm;
- a~0.0683(3) fm, mpi=291(2) MeV, L=2.46 fm;
- Aboot 100 independent configurations each.

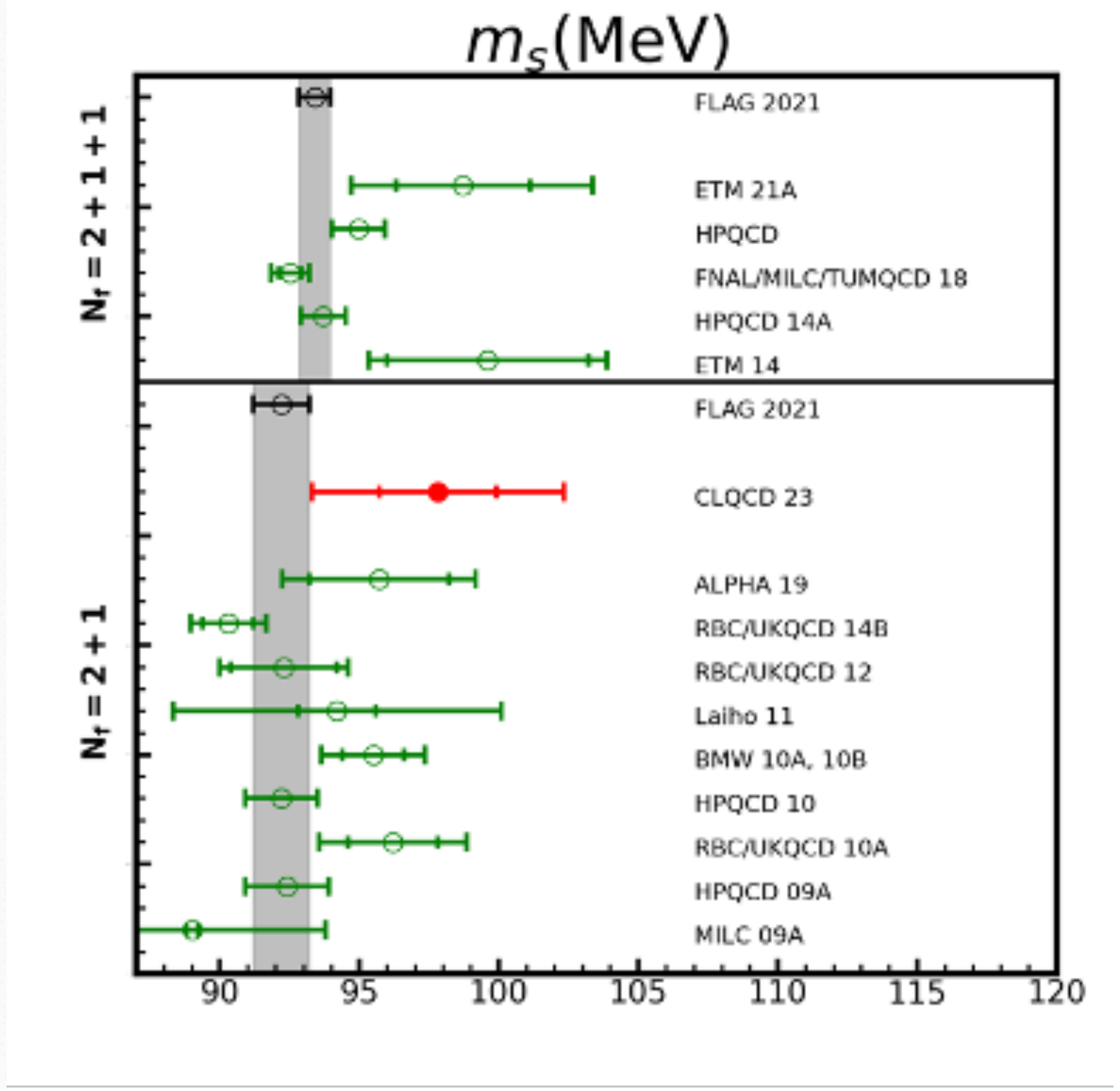
★Parameter tuning：

- a~0.04 fm, mpi~300 MeV;
- a~0.20 fm, mpi~300 MeV;
- a~0.08 fm, mpi~135 MeV.

Light quark mass determination



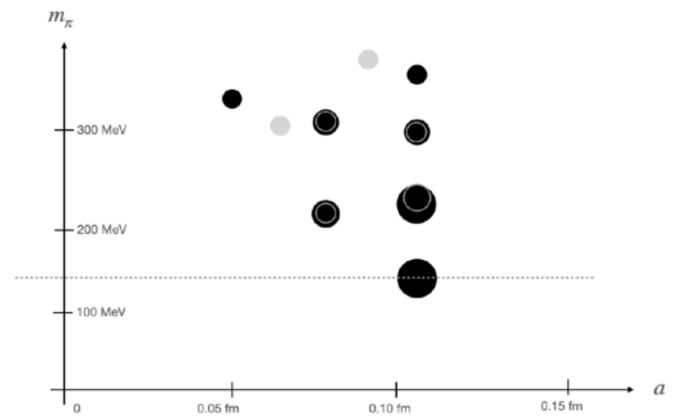


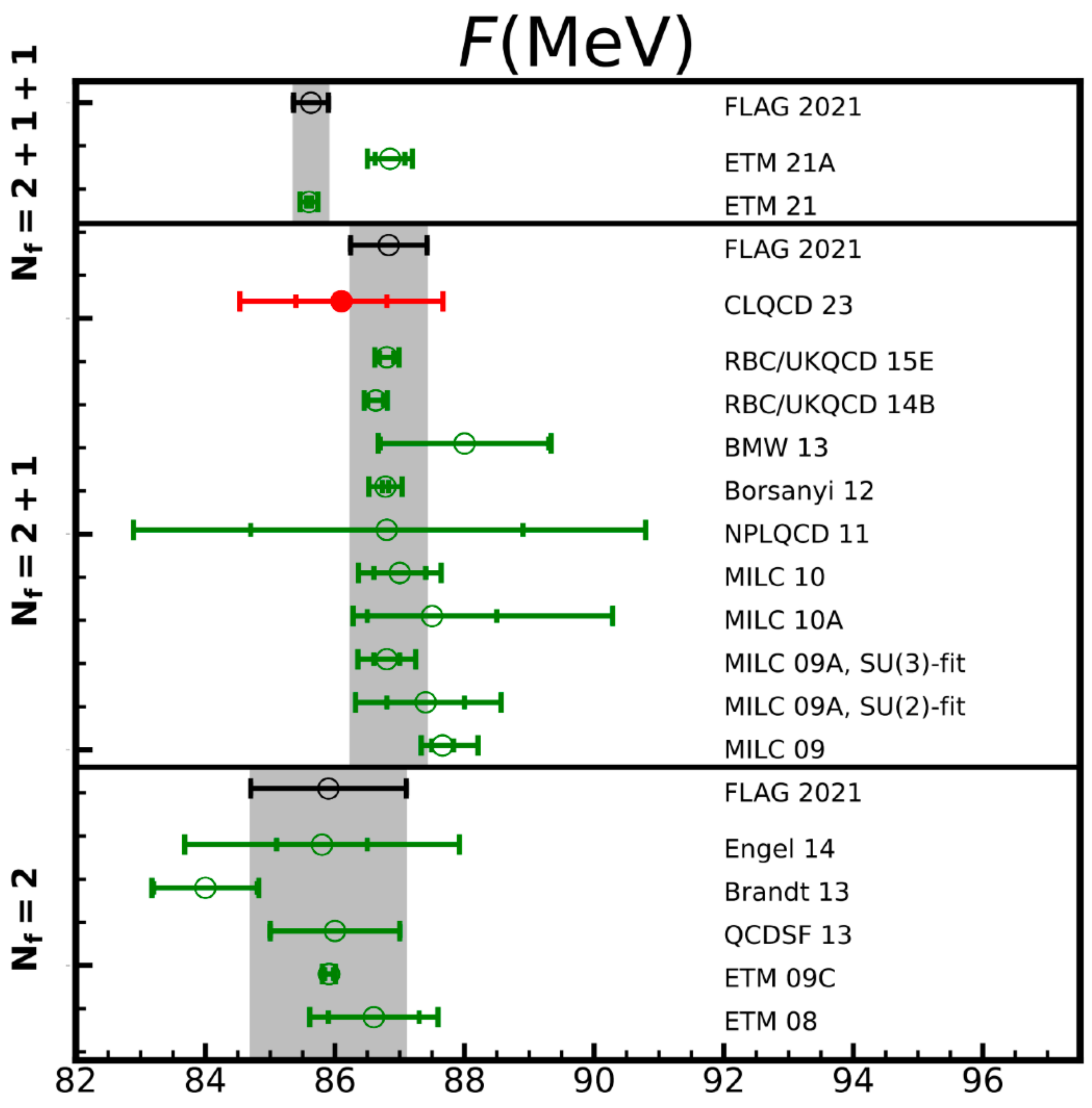


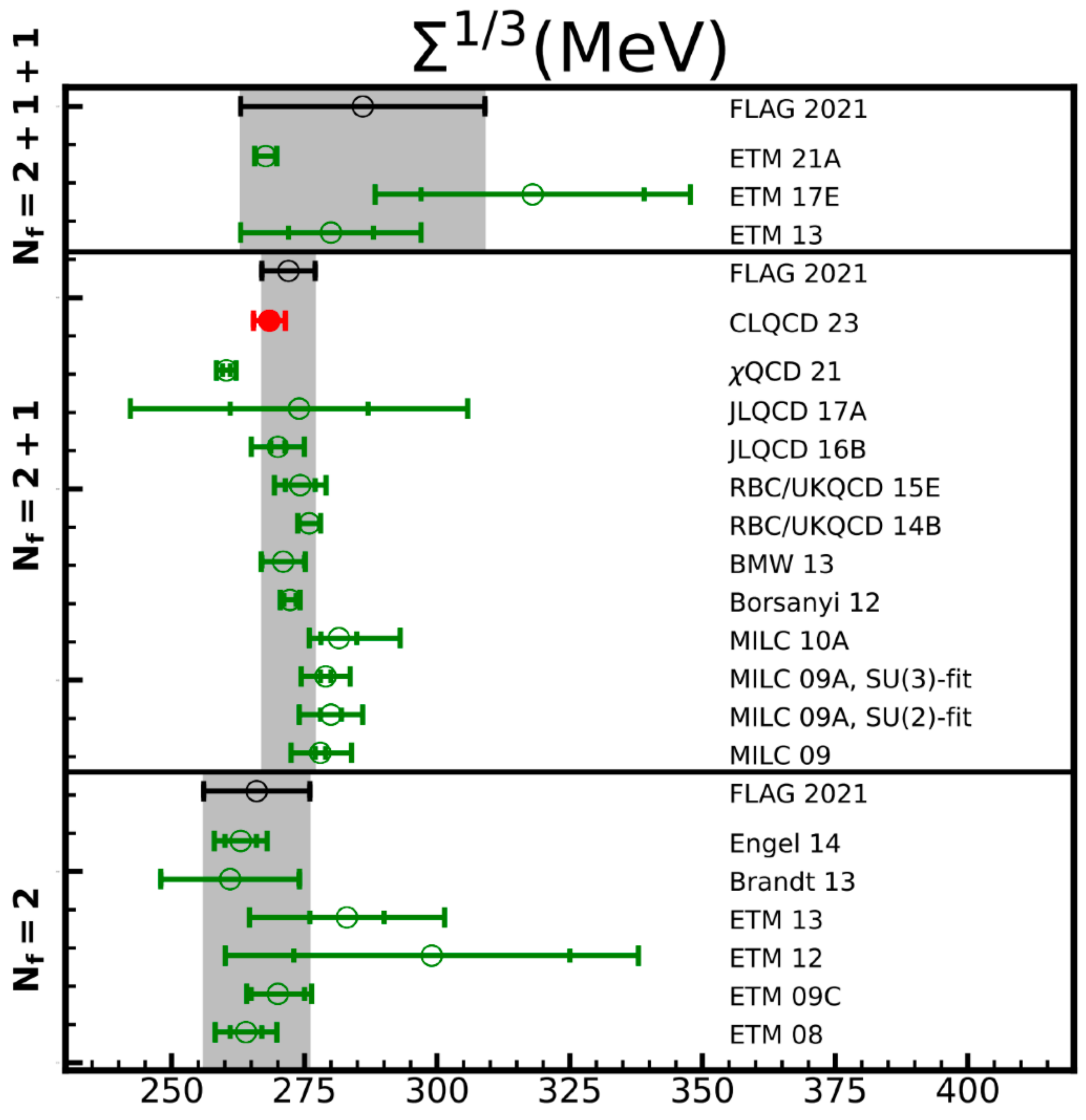
- Present CLQCD prediction of the u-d averaged light quark masses is consistent with the lattice averages within 5% uncertainty.
- Most of the uncertainties come from the non-perturbative renormalization and further improvements are in progress.
- All the finite volume, discretization and sea quark mass effects have been taken into account.

Z.C. Hu, B.L. Hu, J.H. Wang, et. al., CLQCD, Phys.Rev.D109 (2024) 054507

Low energy constants determination







- The CLQCD prediction on the low energy constants can be more precise.
- The precision of the NLO low energy constants are higher than the present lattice averages.

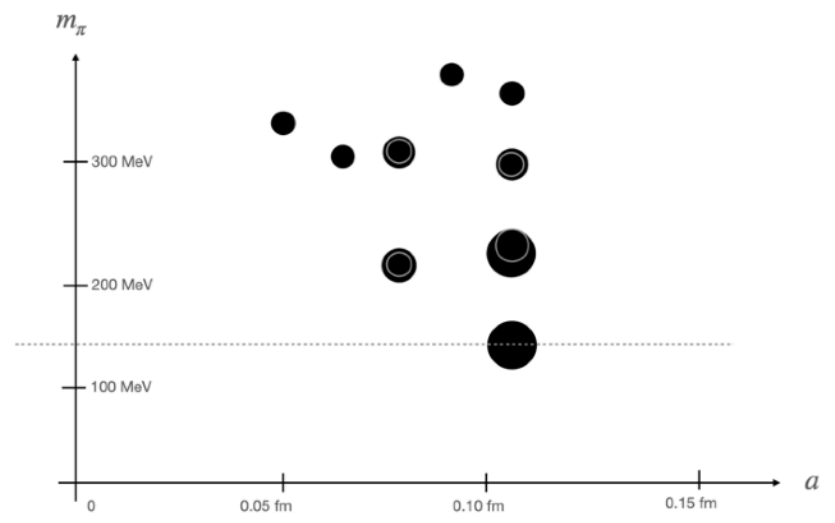
$$m_\pi^2 = \Lambda_\chi^2 2y \left[1 + y\left(\ln\frac{2y\Lambda_\chi^2}{m_{\pi,\mathrm{phys}}^2} - \ell_3\right) + \mathcal{O}(y^2)\right],$$

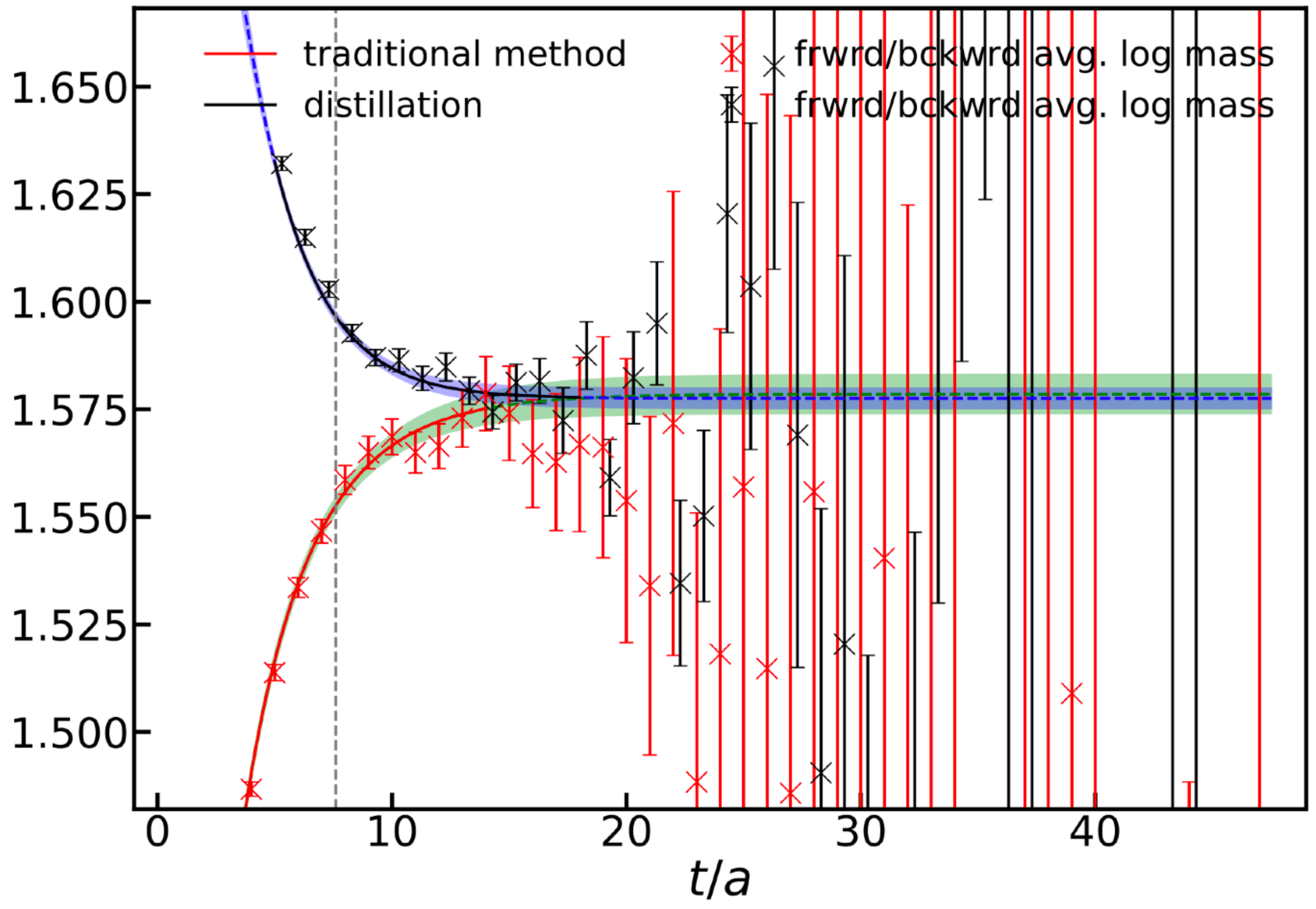
$$F_\pi = F\left[1 - 2y\left(\ln\frac{2y\Lambda_\chi^2}{m_{\pi,\mathrm{phys}}^2} - \ell_4\right) + \mathcal{O}(y^2)\right],$$

	l_3	l_4
CLQCD	2.43(54)	4.32(12)
FLAG	3.07(64)	4.02(45)

Z.C. Hu, B.L. Hu, J.H. Wang, et. al., CLQCD, Phys.Rev.D109 (2024) 054507

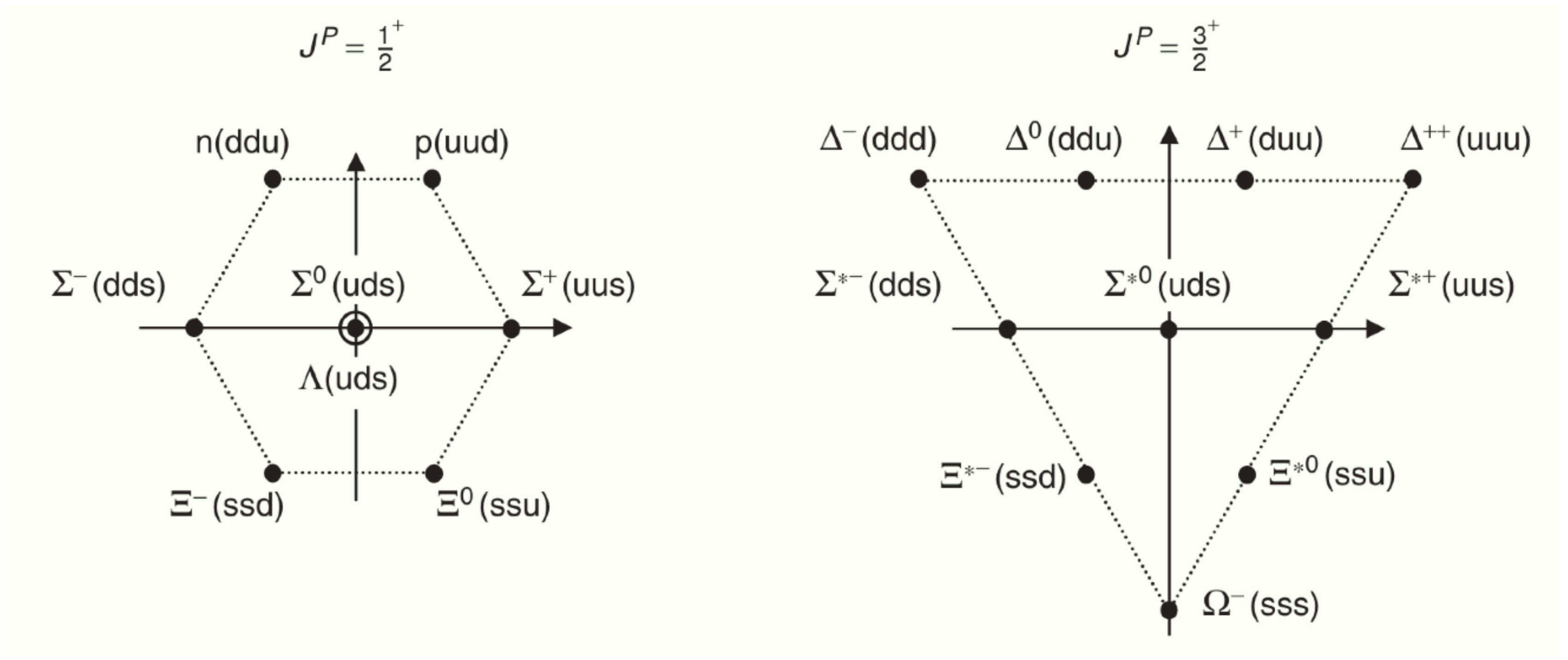
Baryon spectrum based CLQCD ensembles

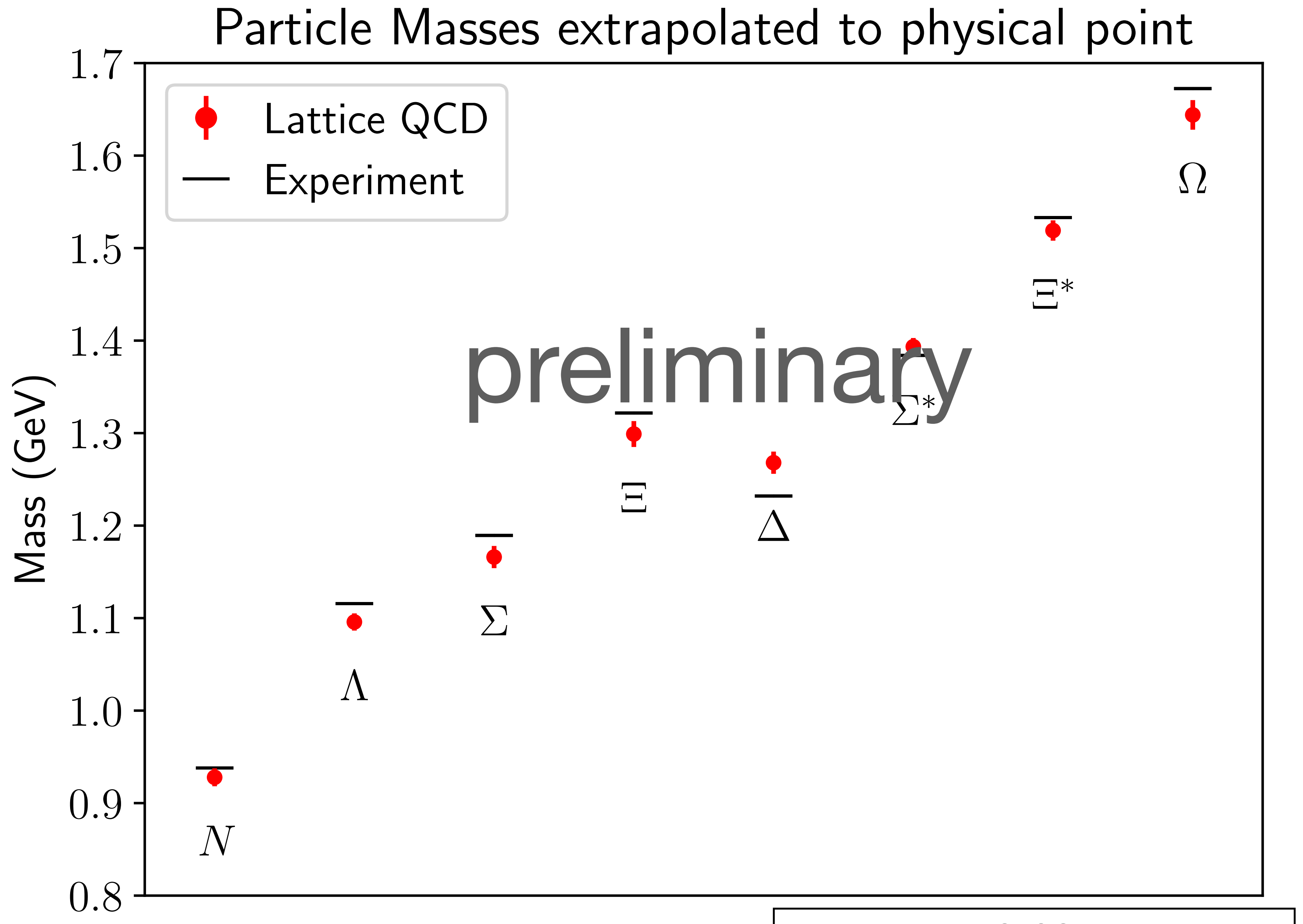




Extract the ground state mass using multiple interpolation fields:

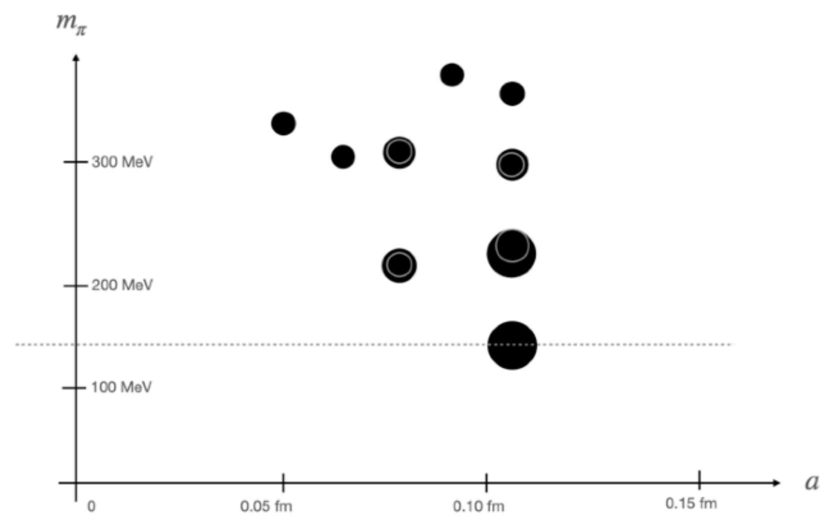
- The extracted mass is independent of the interpolation fields.
- Agree with the experimental value within a few percents;
- The mass difference between octet and decuplet baryon in the $N_f = 3$ chiral limit is 0.31(7) GeV.





B.-L. Hu, et. al., CLQCD, in preparation

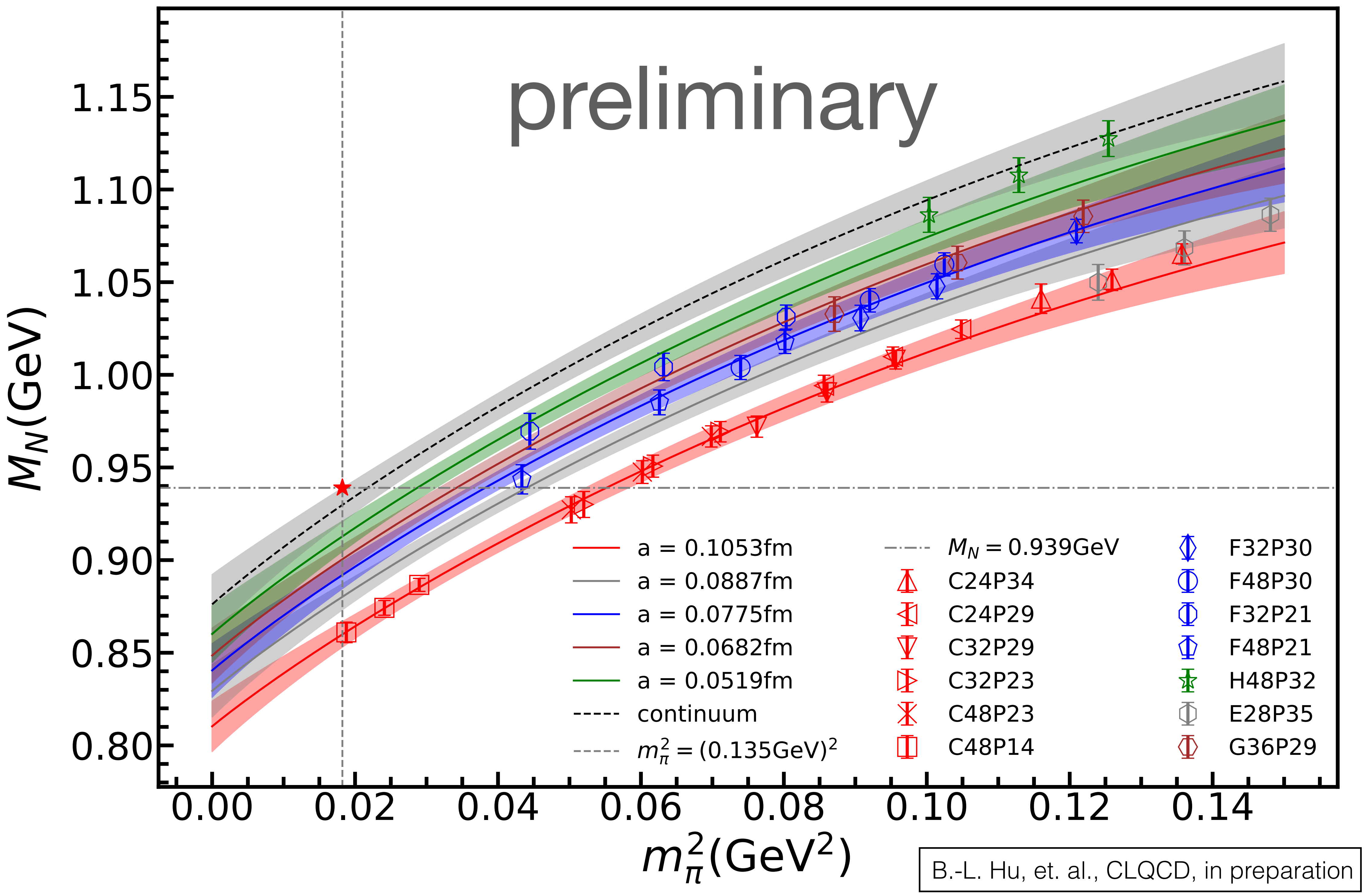
Nucleon mass based CLQCD ensembles



$$M\left(m_\pi^v, m_\pi^{\text{sea}}, m_s^{\text{sea}}, a, L\right) = \Bigg[M_0 + C_1\left(m_\pi^v\right)^2 + C_2\left(m_\pi^{\text{sea}}\right)^2 - \frac{\left(g_A^2 - 4g_Ag_1 - 5g_1^2\right)\pi}{3\left(4\pi f_\pi\right)^2}\left(m_\pi^v\right)^3$$
$$-\frac{\left(8g_A^2 + 4g_Ag_1 + 5g_1^2\right)\pi}{3\left(4\pi f_\pi\right)^2}\left(m_\pi^{pq}\right)^3 + C_4\frac{\left(m_\pi^v\right)^2}{L}e^{-m_\pi^v L} + C_5(m_s^{\text{sea}} - m_s^{\text{phys}})\Bigg](1 + C_3a^2),$$

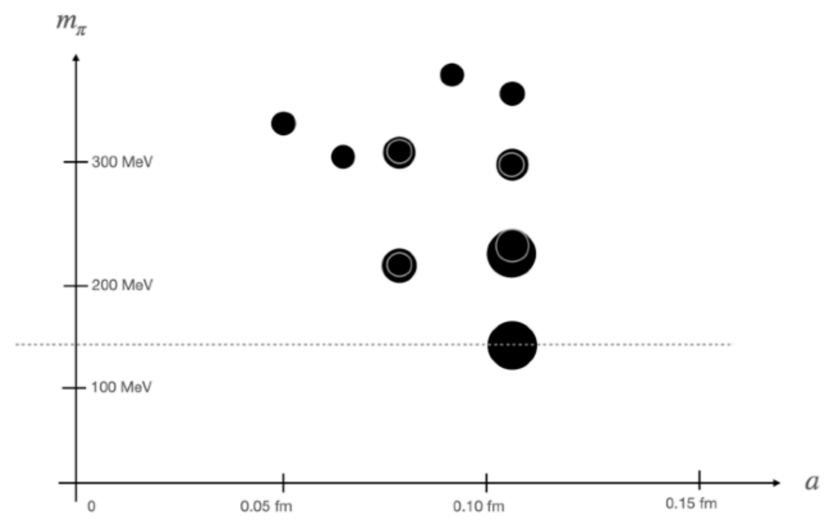
Parameter	Value
M_0	0.876(16)
C_1	2.13(39)
C_2	1.39(59)
C_3	−6.77(57)
C_4	1.85(49)
C_5	0.92(38)
g_A	0.99(27)
g_1	−0.03(51)
M_{phys}	0.9296(91)
χ^2	0.73
Q	0.86

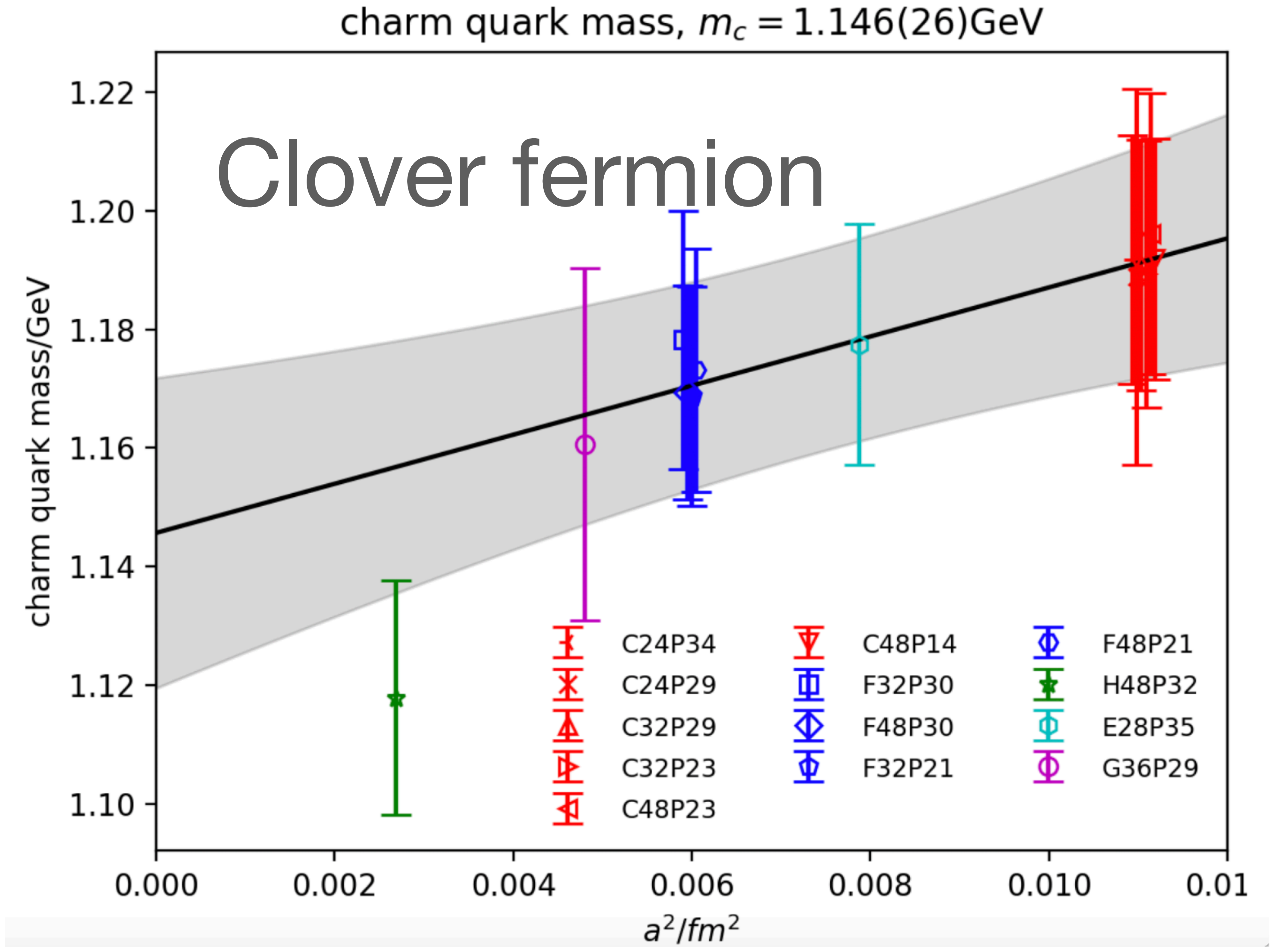
- Sigma term based on FH theorem:
  $\sigma_{\pi N} \equiv m_l\langle p\,|\,\bar{u}u + \bar{d}d\,|\,p\rangle = m_l\frac{\partial M_N}{\partial m_l}$
  =48.8(6.4) MeV;
- Previous Overlap result based on FH theorem:
  $\sigma_{\pi N}$ = 52(8) MeV;
- Previous Overlap result based on direct ME calculation:
  $\sigma_{\pi N}$ = 46(7) MeV.



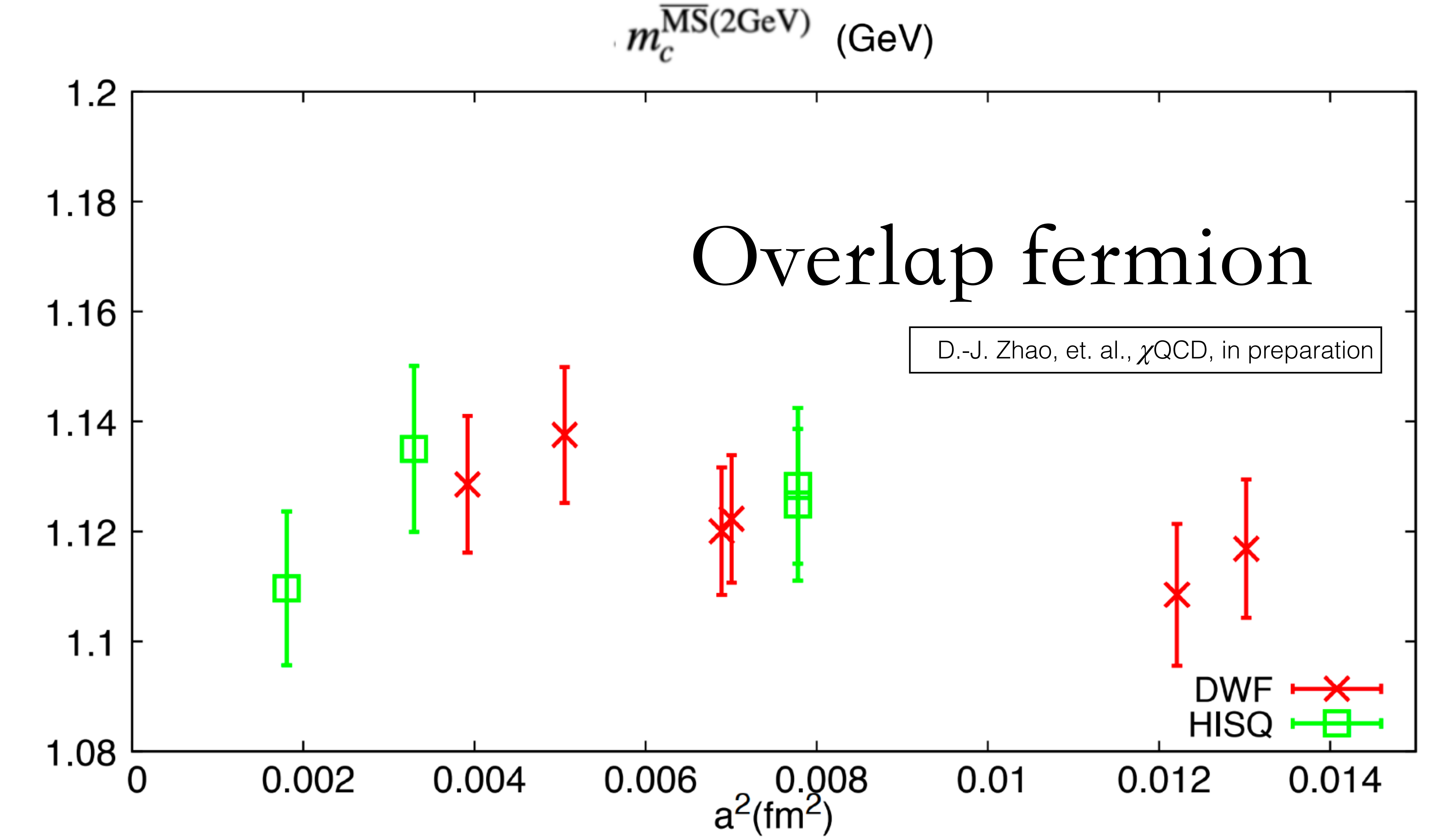
B.-L. Hu, et. al., CLQCD, in preparation

Charm quark mass determination



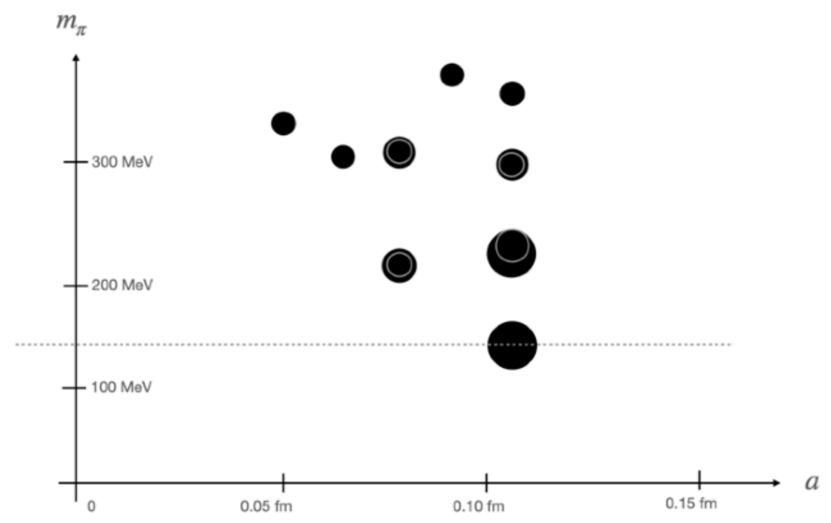


H.-Y. Du, et. al., CLQCD, in preparation



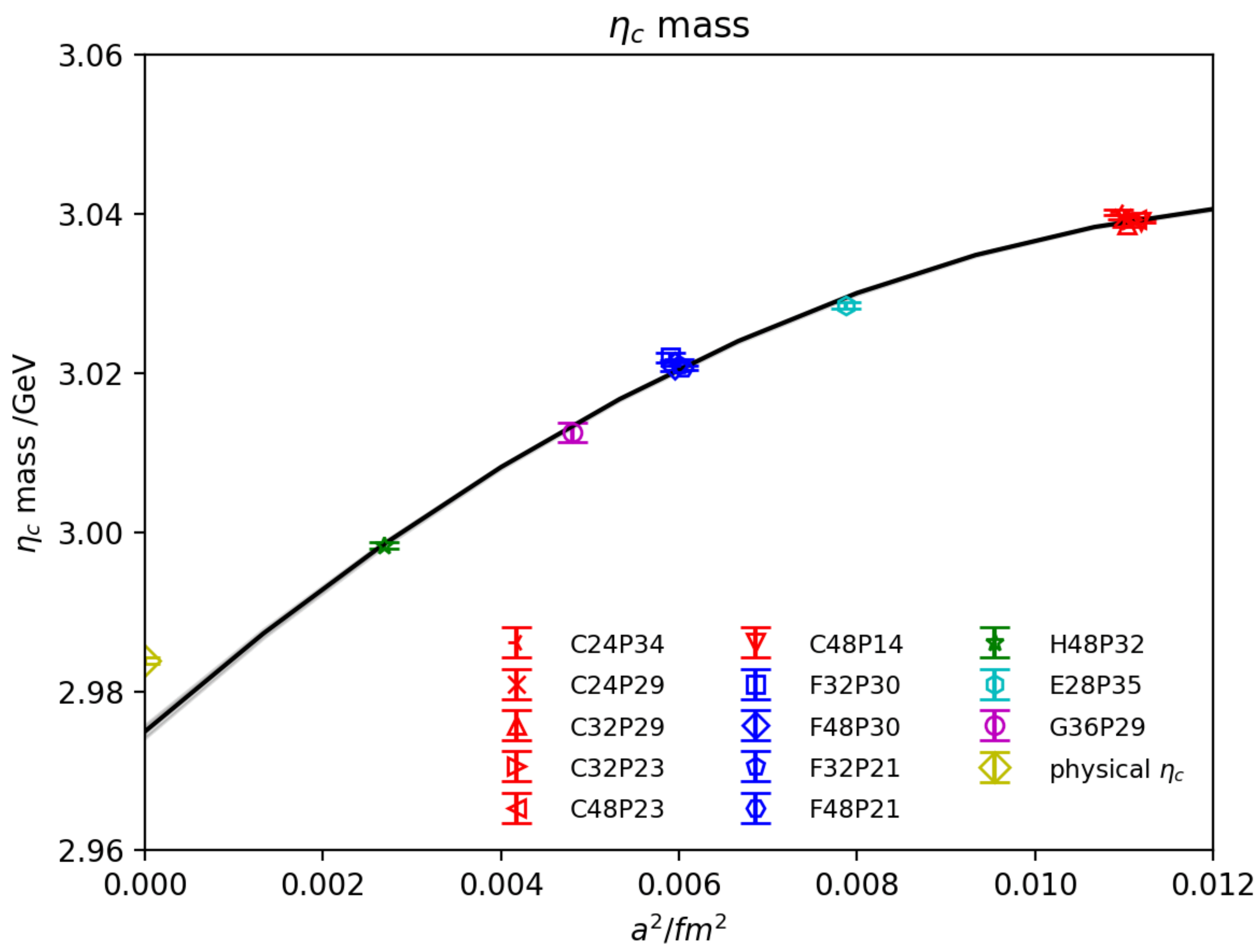
- The charm quark mass $m_c^{\overline{\rm MS}(2\rm GeV)}$ extracted using the physical J/ψ mass is 1.146(26) GeV.
- Consistent with the overlap fermion results while requiring further suppression on the systematic uncertainties.

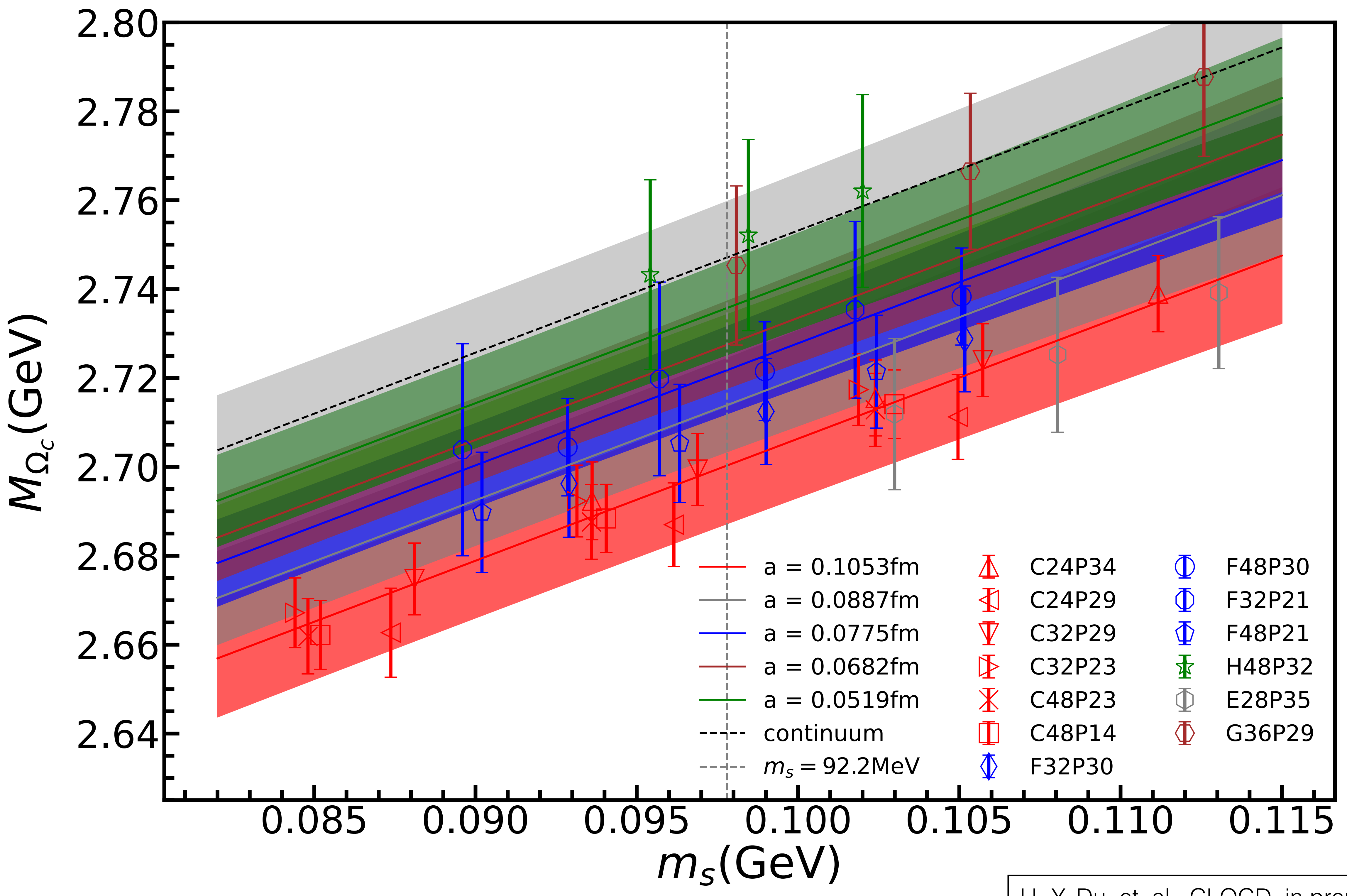
Stable hadron masses



- The η_c mass extrapolated to continuum is consistent with the previous HPQCD results while slightly lower than the experimental value due to the QED and disconnected charm sea effects.

- The Ω_c mass extrapolated to continuum is 2745(10)(20) MeV.

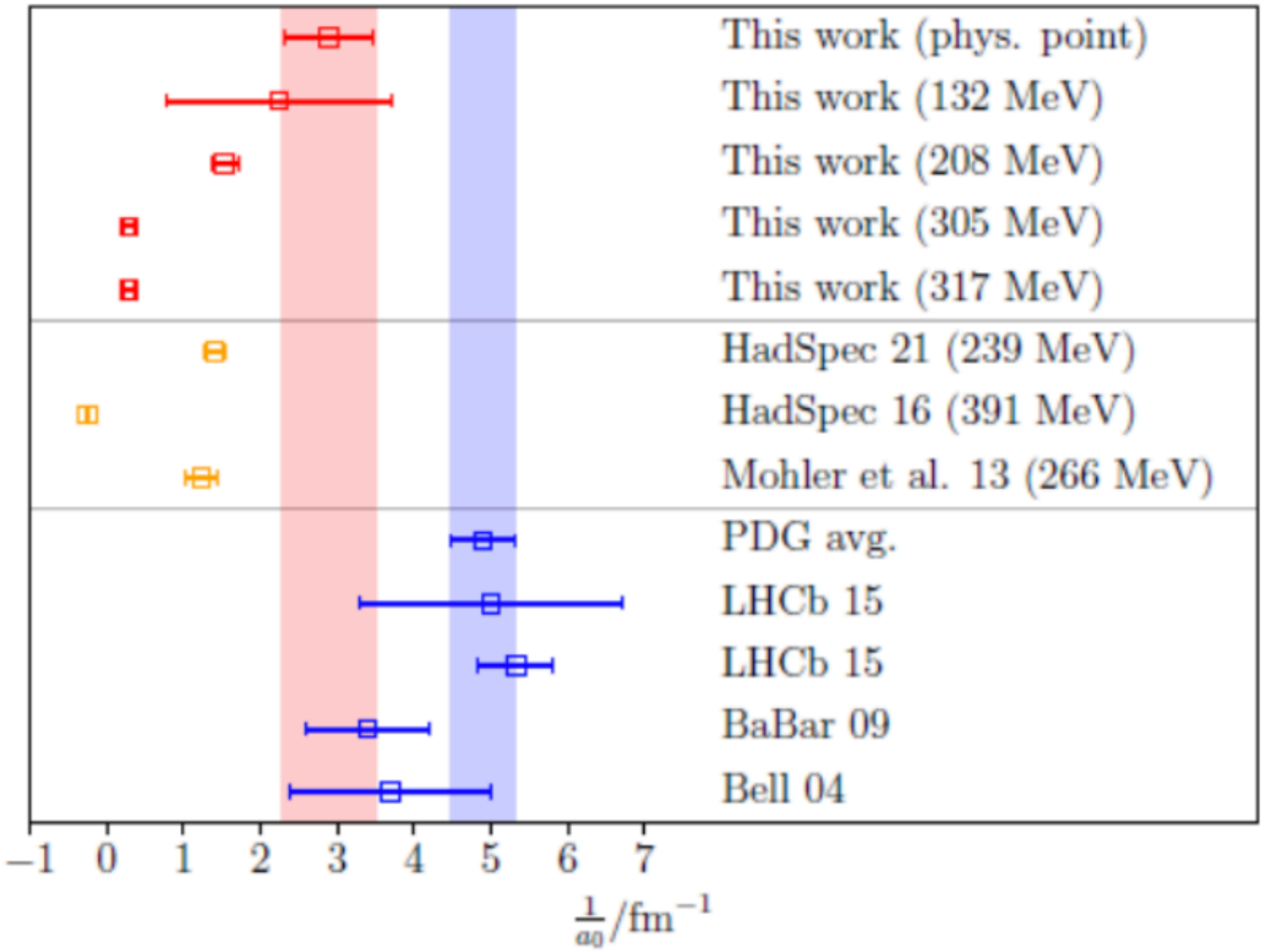


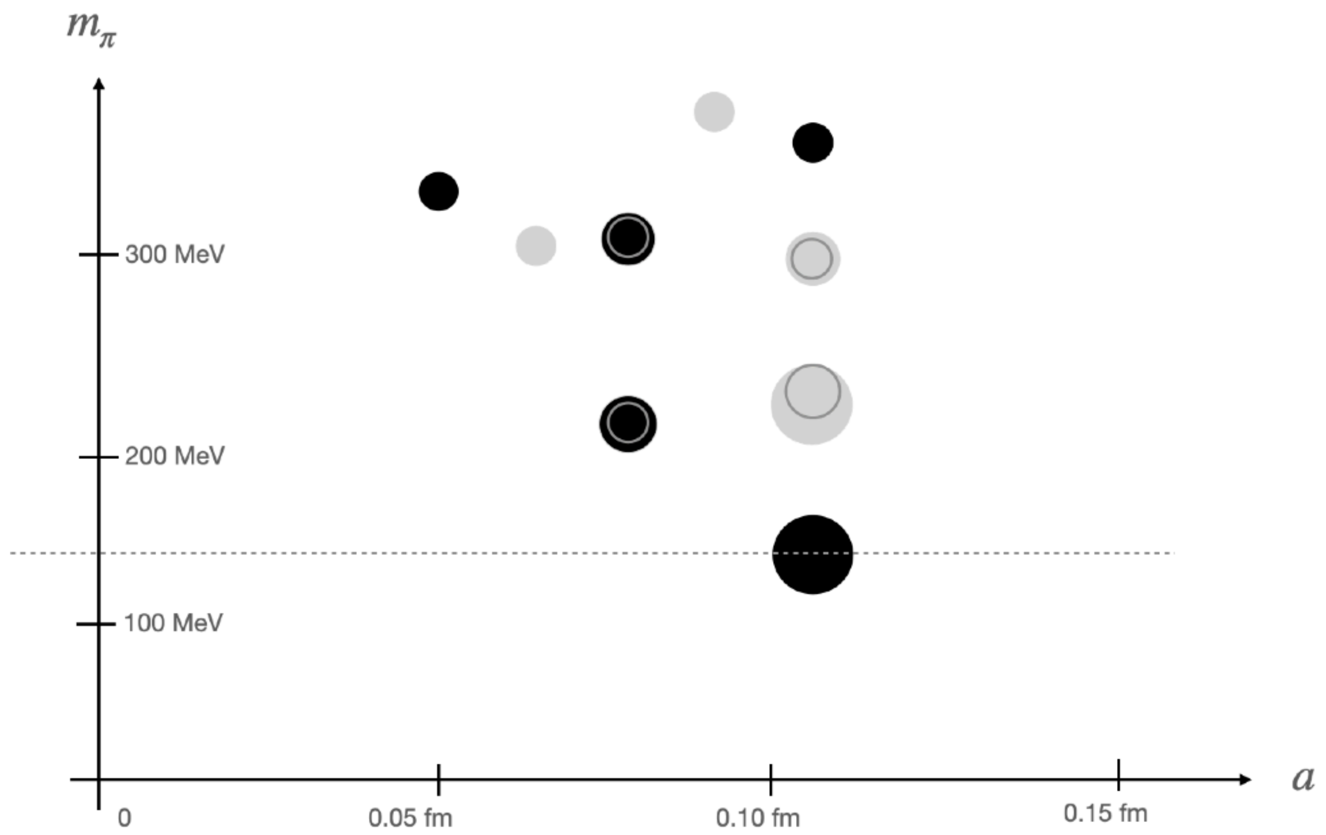


H.-Y. Du, et. al., CLQCD, in preparation

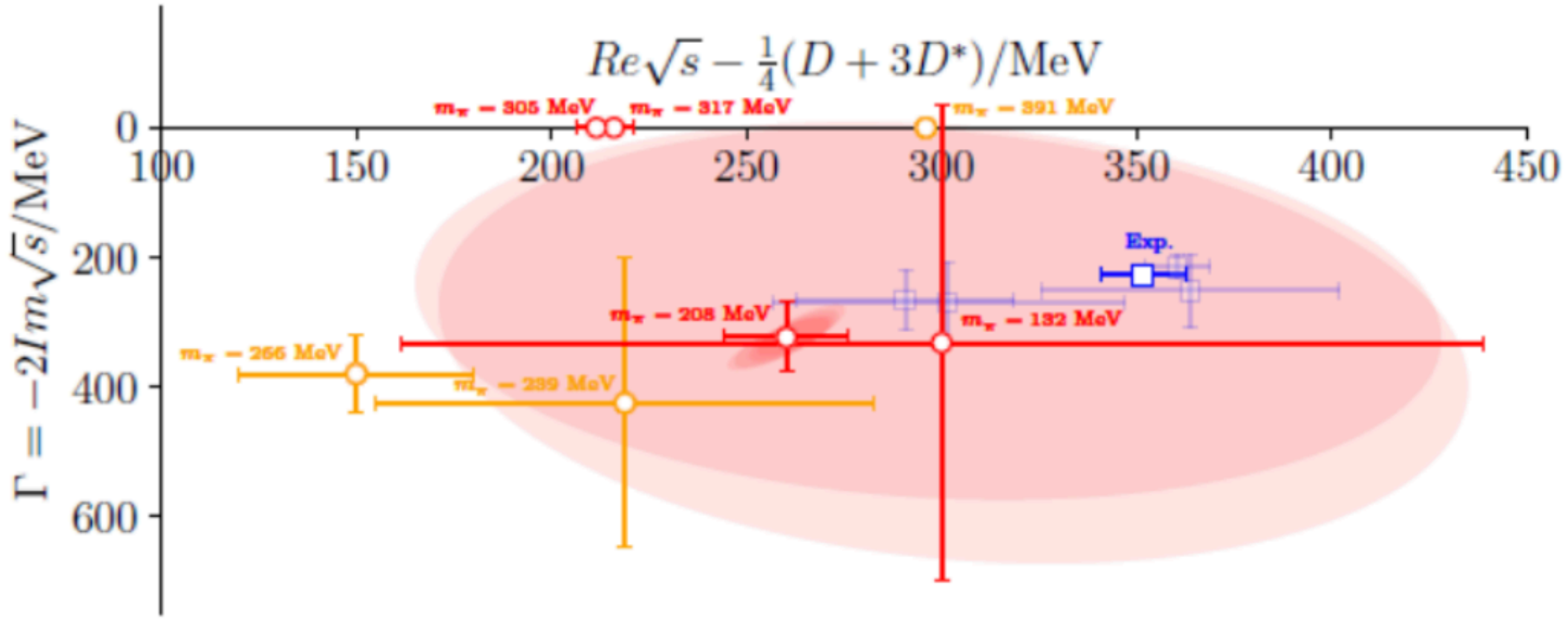
Study of $D_0^*(2300)$

Scattering length





Pole position

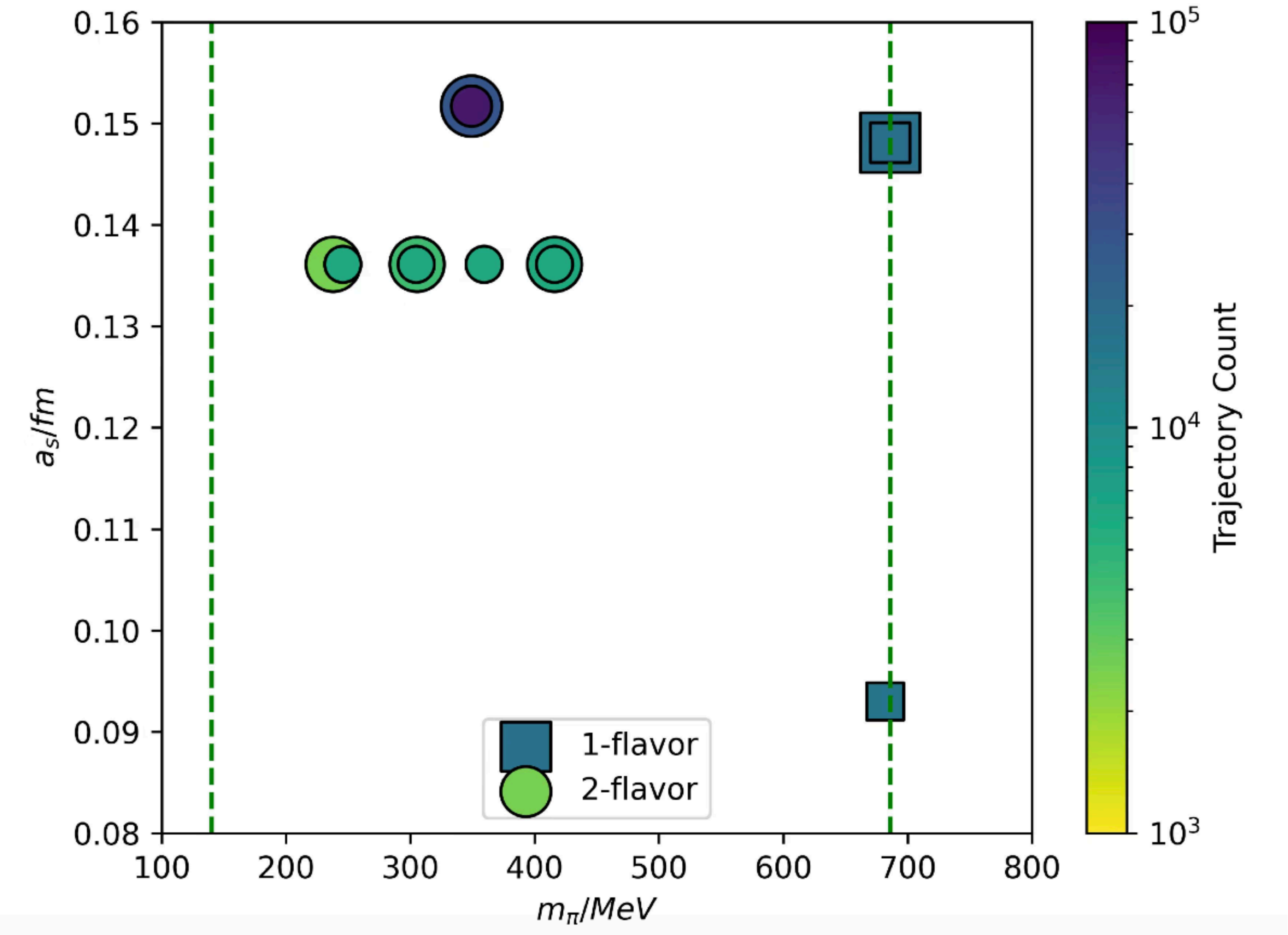


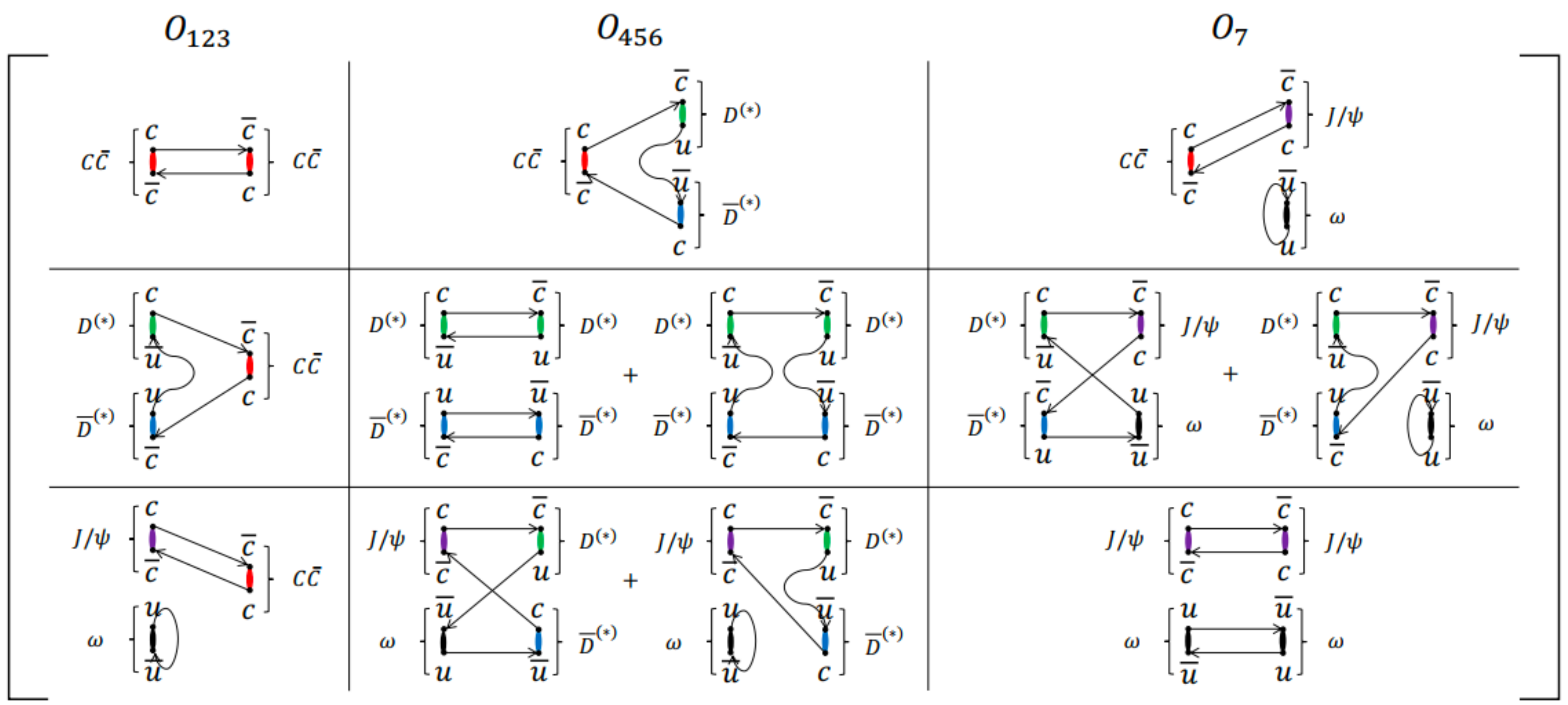
At $m_\pi \sim$ 300 MeV, there is a virtual state pole;

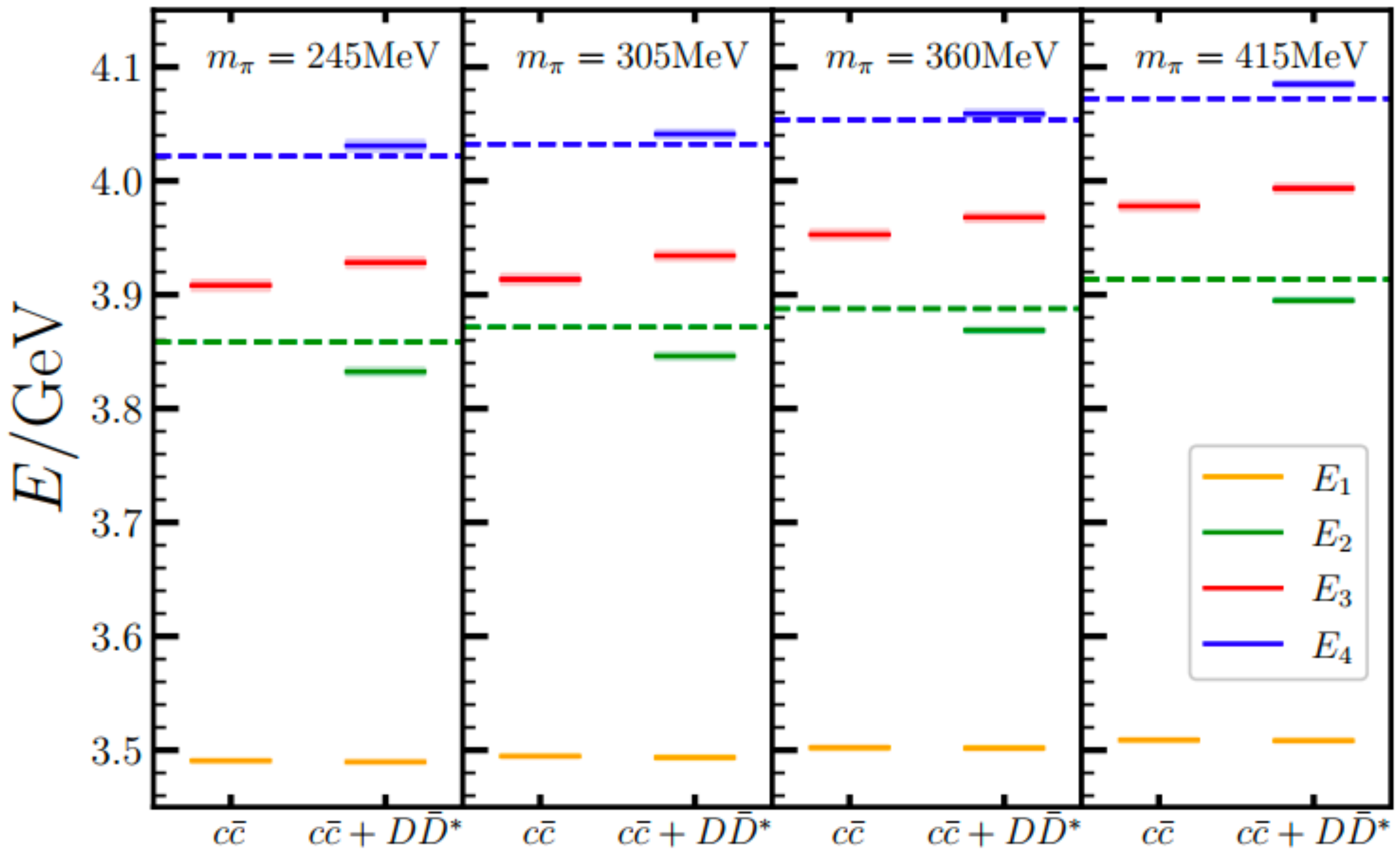
When pion mass decreases, it becomes a resonance and the pole position gets close to the experiment.

H.-B. Yan, et.al., 2404.13479

X(3872) study using anisotropic lattices



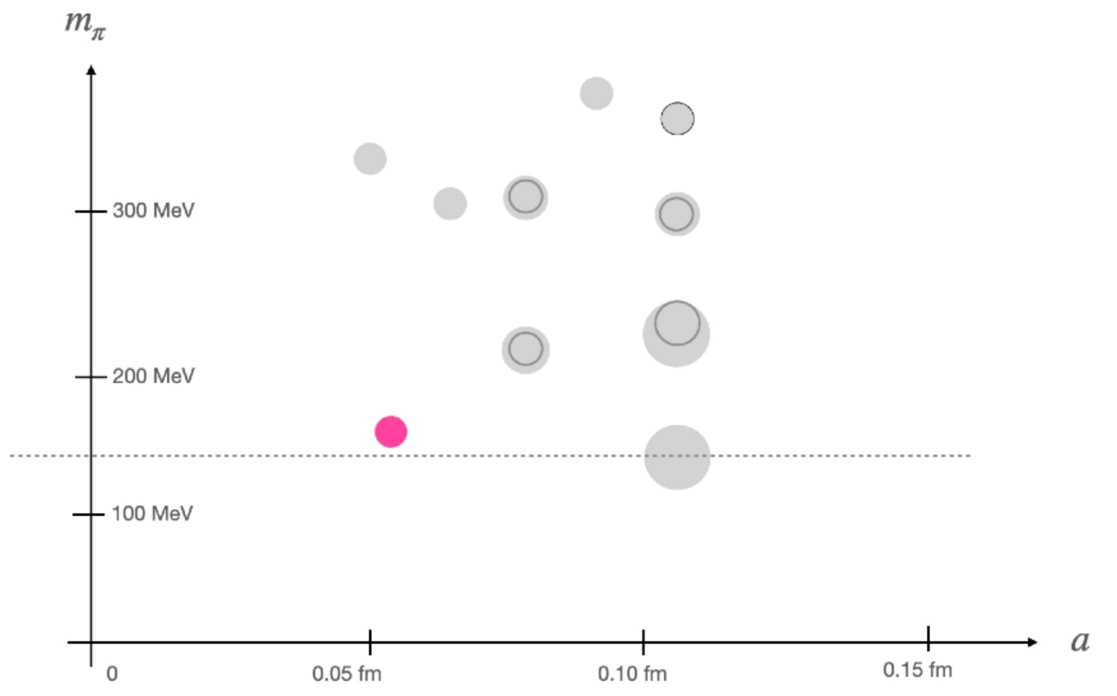




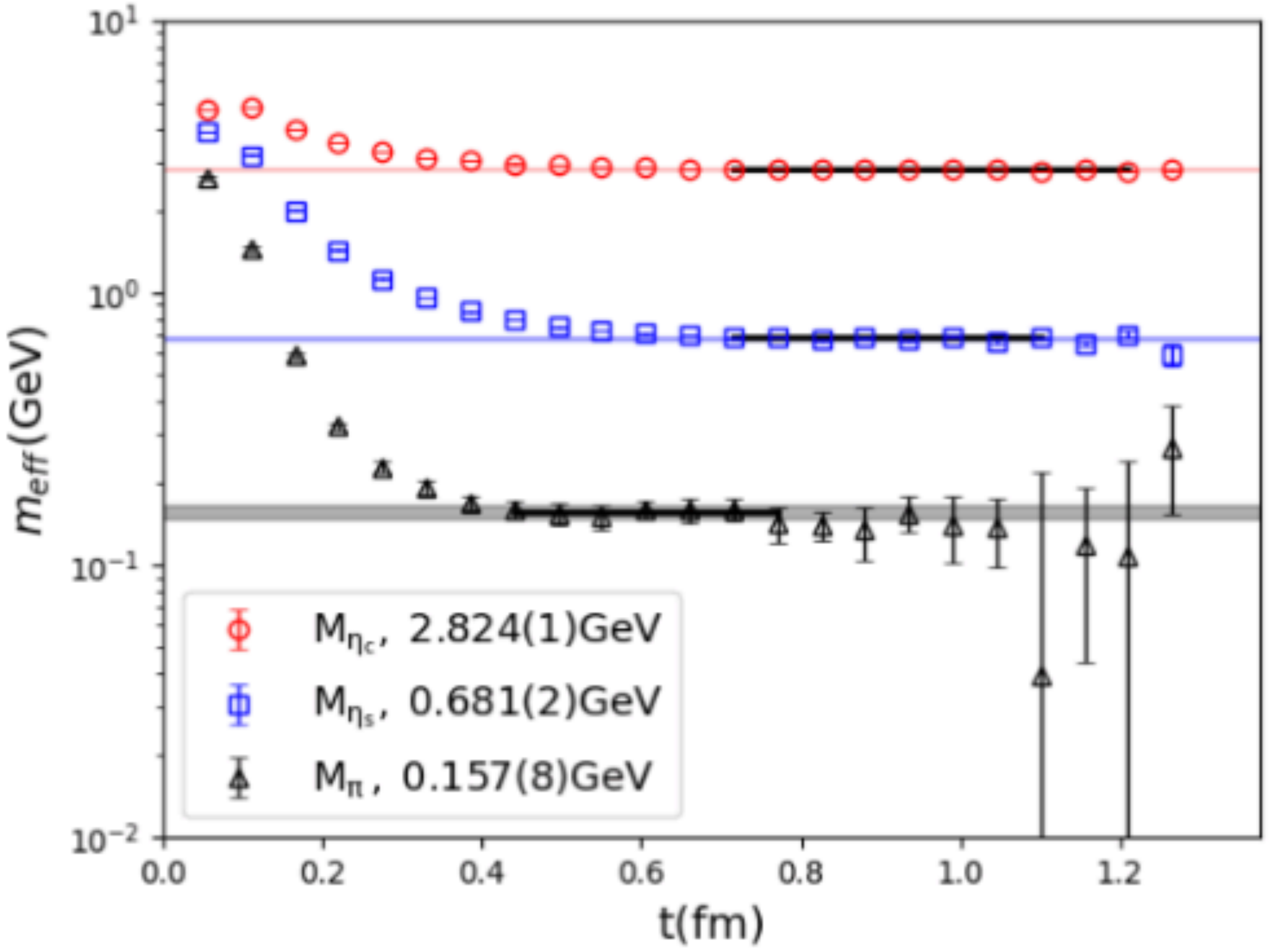
- Energy level changes after the $D\bar{D}^*$ operator is added while is insensitive to the $J/\psi\omega$ operator.
- **More details can be found in Chunjiang Shi's talk on Monday at 9:10 AM.**

H.-Z. Li, C.-J. Shi, et.al., 2402.14541

QCD in finite volume



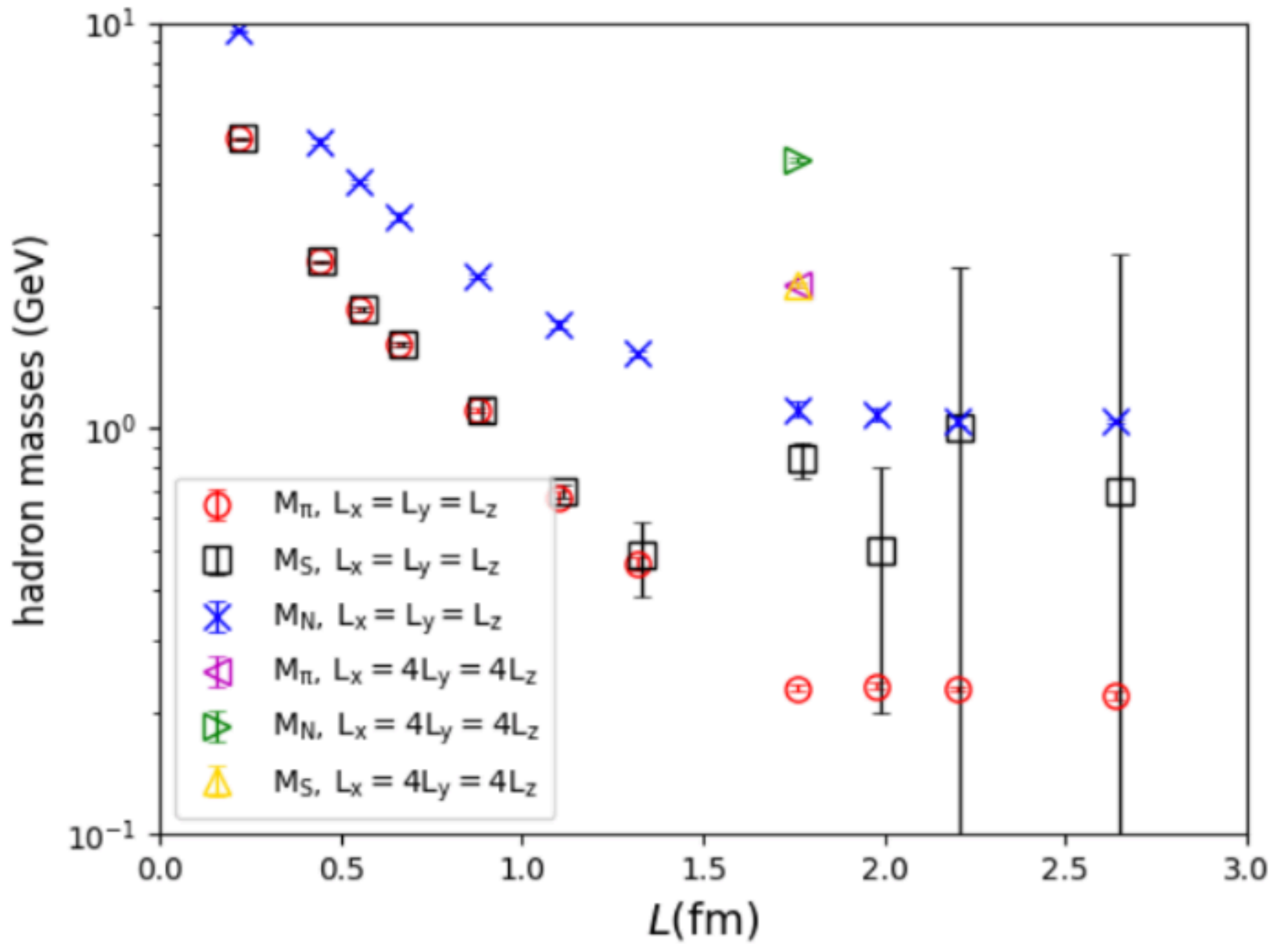
$10/g^2$	$m_l a$	$m_s a$	$m_c a$	V	$n_{\rm cfg}$
6.784	0.000731	0.01975	0.2293	$4^3 \times 96$	238
				$8^3 \times 96$	350
				$8^2 \times 32 \times 96$	100
				$10^3 \times 96$	148
				$12^3 \times 96$	150
				$16^3 \times 96$	146
				$20^3 \times 96$	148
				$24^3 \times 96$	151
				$32^3 \times 96$	98
				$40^3 \times 96$	72
				$40^3 \times 96$	80
				$48^3 \times 48$	100

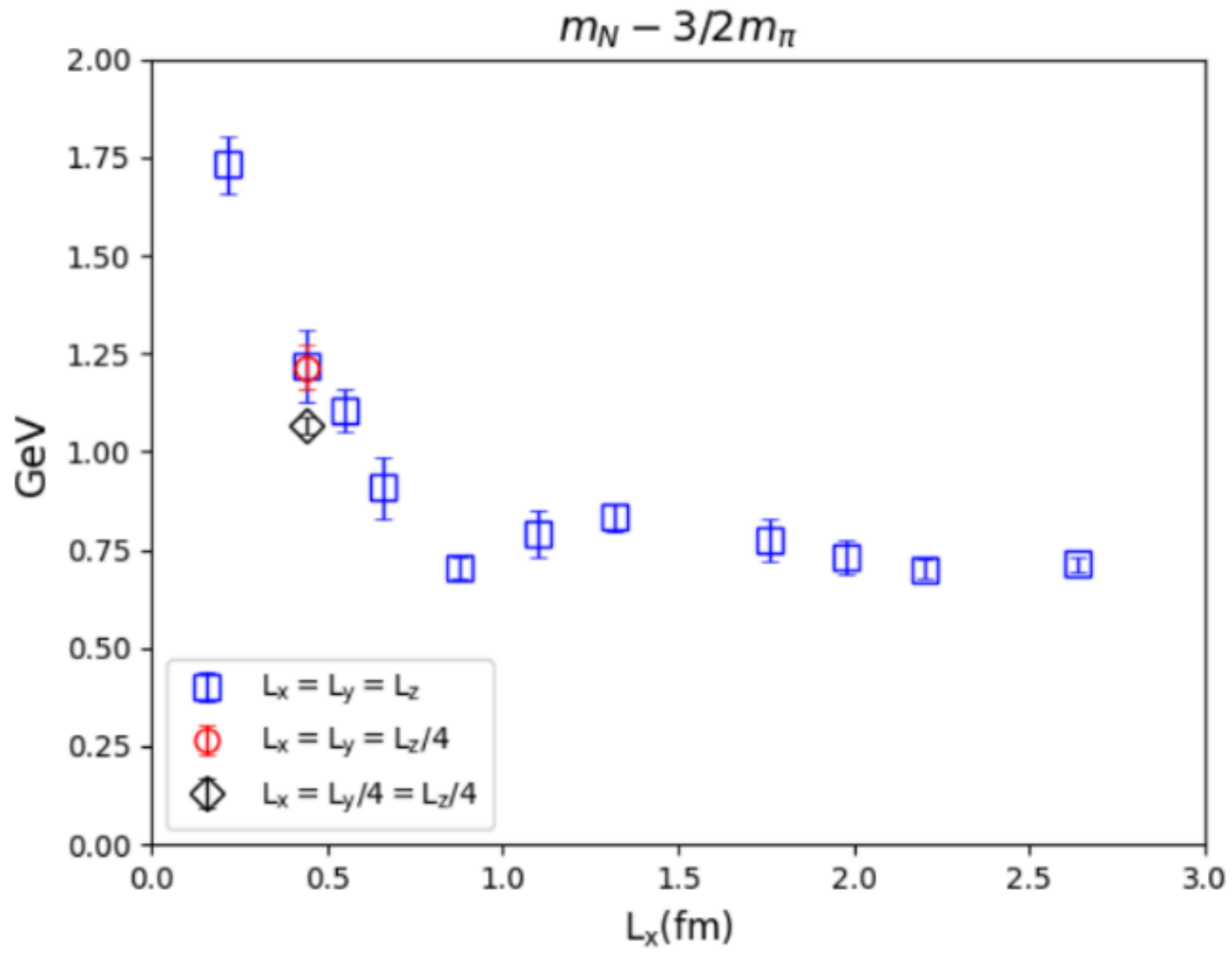


- Exploratory study of generating 2+1+1 flavor HISQ ensemble;
- Lattice spacing $a \sim 0.055$ fm is close to that of CLQCD ensemble H48P32 ($a = 0.052$ fm).

X.-L. Meng, et.al., 2403.01378, accepted by CTP

Hadron masses in finite volume

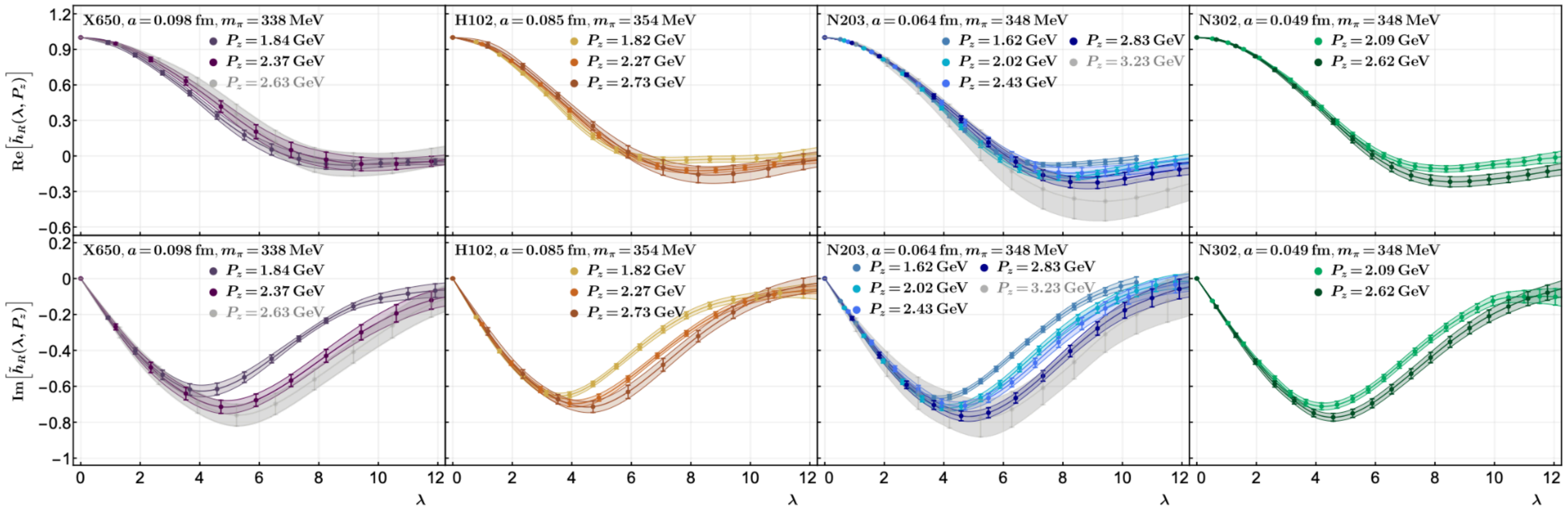




- All the hadron masses increas at small L and chiral symmetry restored at $L \sim 1$ fm (corresponds to $1/L \sim$ 200 MeV)
- The $m_N - 3/2m_\pi$ (or $m_N - 3/2m_{a_0}$ at small L) remains at small L.

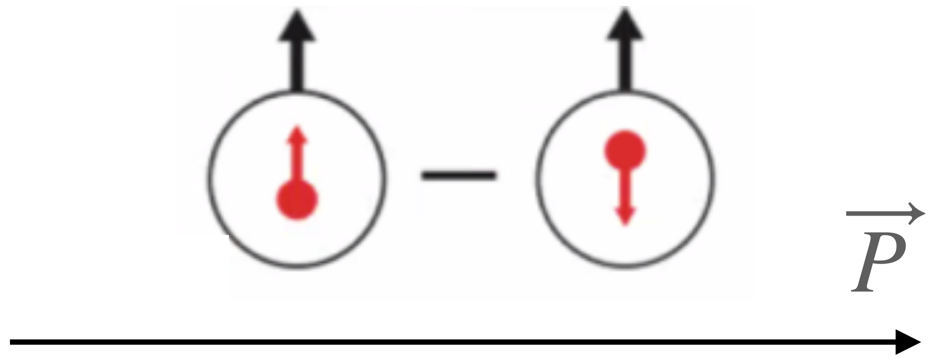
X.-L. Meng, et.al., 2403.01378, accepted by CTP

Transversity PDF of nucleon



Ensemble	a(fm)	$L^3 \times T$	m_π(MeV)	$m_\pi L$	$N_{\text{conf.}}$
X650	0.098	$48^3 \times 48$	338	8.1	1500
H102	0.085	$32^3 \times 96$	354	4.9	500
H105		$32^3 \times 96$	281	3.9	500
C101		$48^3 \times 96$	222	4.6	500
N203	0.064	$48^3 \times 128$	348	5.4	500
N302	0.049	$48^3 \times 128$	348	4.2	500

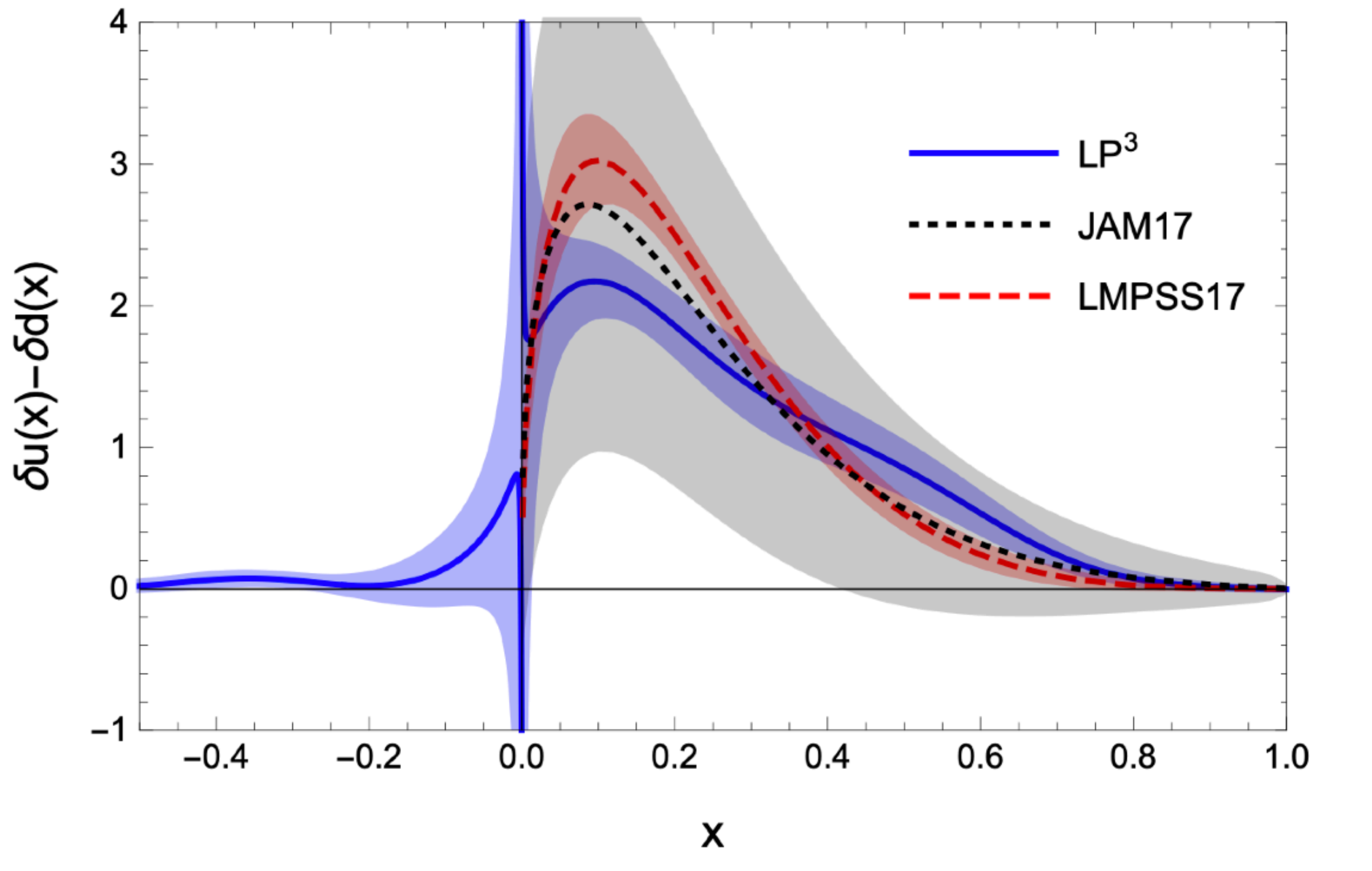
F. Yao, et. al., LPC, PRL131(2023) 261901



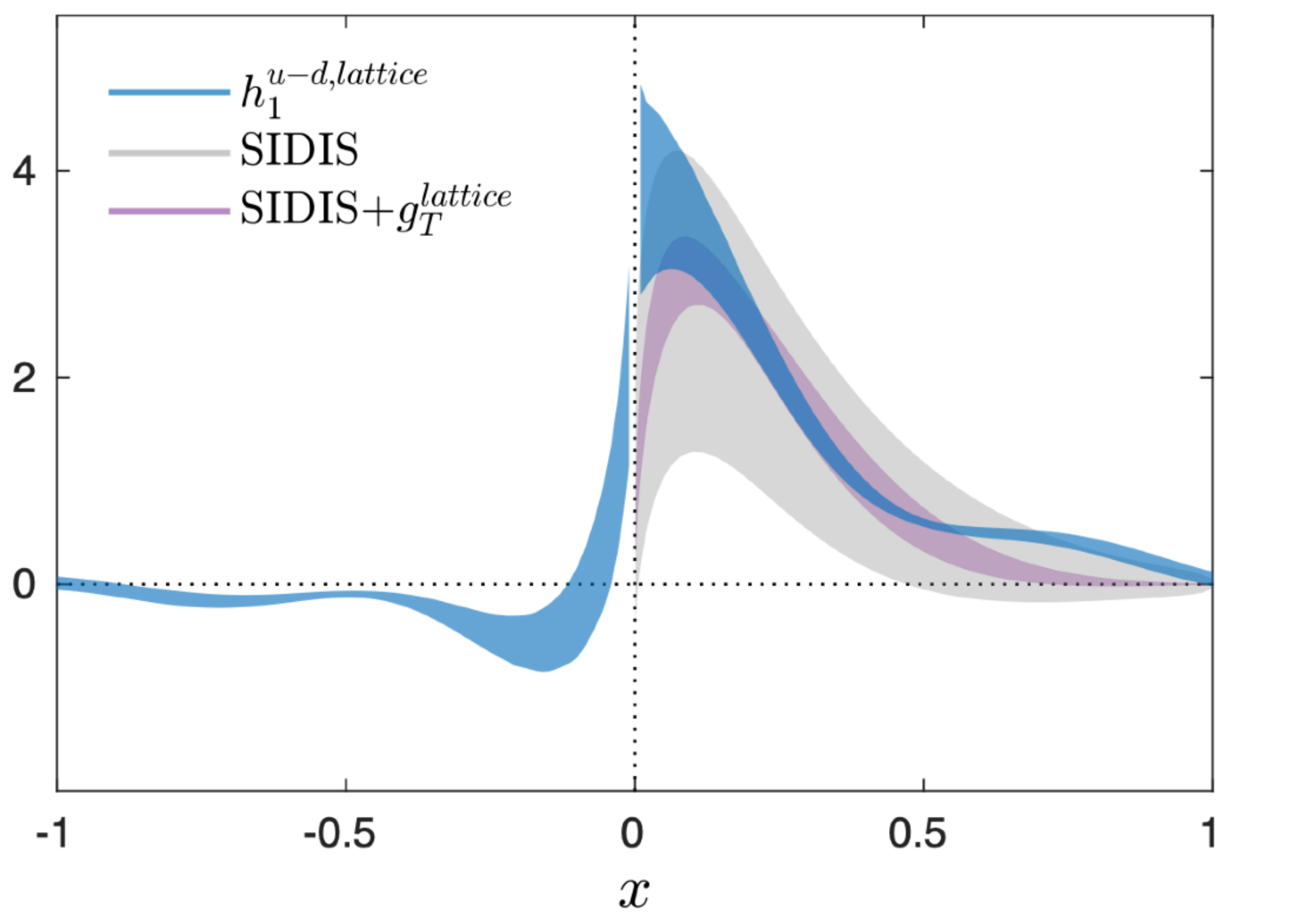
Correlation between transverse polarized nucleon and its component quarks:

- Iso vector quark contribution only (u-d);
- International collaboration including members from China, US and Germany;
- First PDF prediction extrapolated to the continuum, infinite momentum and physical quark mass limits.

Transversity PDF of nucleon



C. Alexandrou, et. al., PRD98(2018)091503

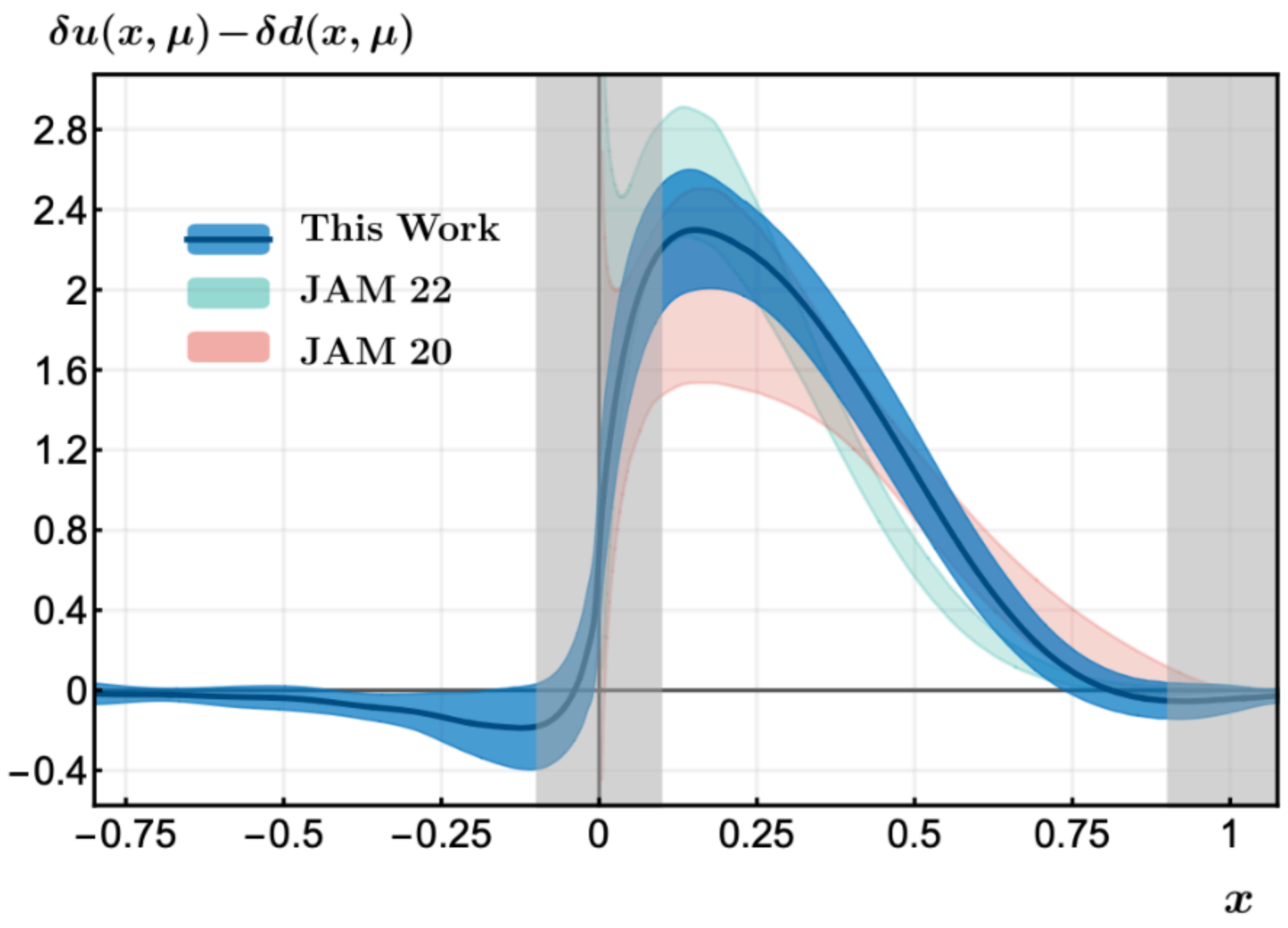


Y.-S. Liu, et. al., LP3, 1810.05043

Comparing to the previous Transversity calculation:

- Proper renormalization to remove all the power divergences;
- First attempt of using the joint fit to do the controllable extrapolations;
- Include the systematic uncertainties from renormalization scale and scheme, and also kinds of extrapolations.

$$\delta q\left(x, P_z, a, m_\pi\right)=\frac{1-g' m_\pi^2 \ln(m_\pi^2/\mu_0^2)+m_\pi^2 k(x)}{1-g' m_\pi^2 \ln(m_\pi^2/\mu_0^2)} \times\left[\delta q_0(x)+a^2 f(x)+a^2 P_z^2 h(x)+\frac{g(x,a)}{P_z^2}\right]$$



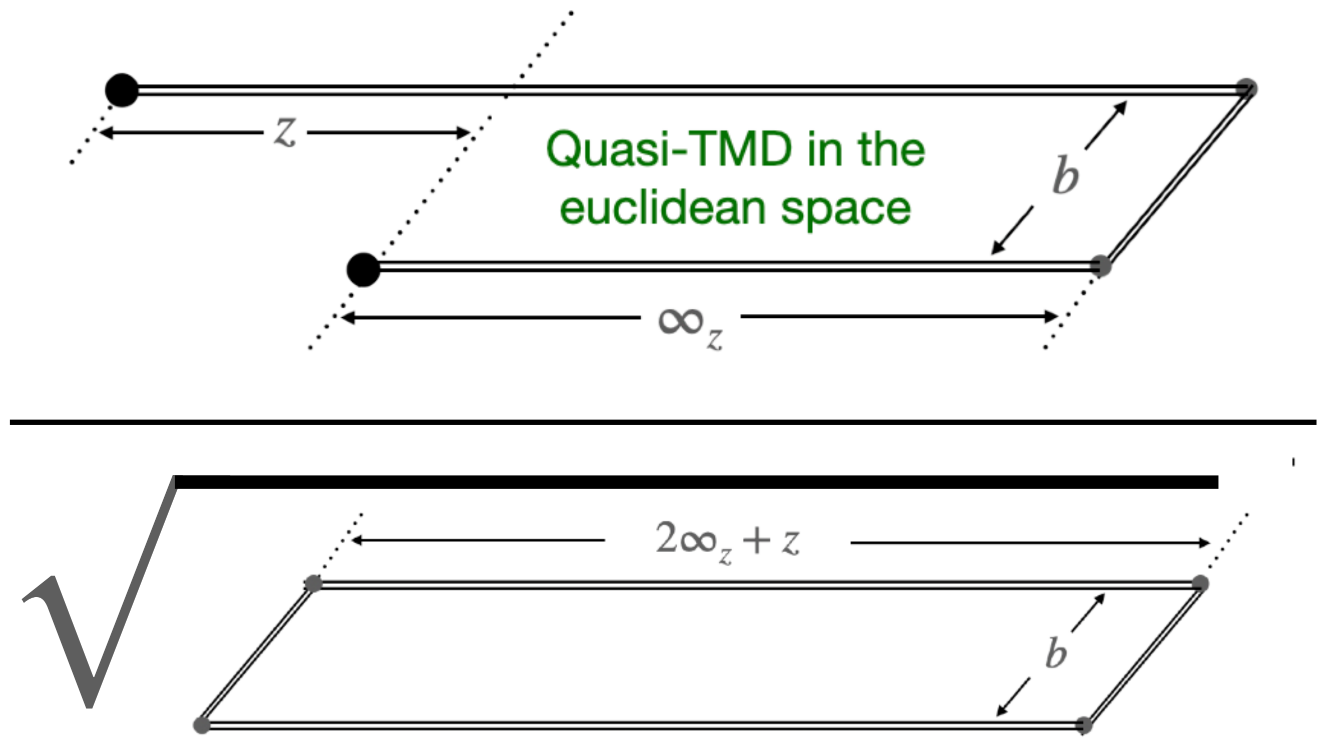
F. Yao, et. al., LPC, PRL131(2023) 261901

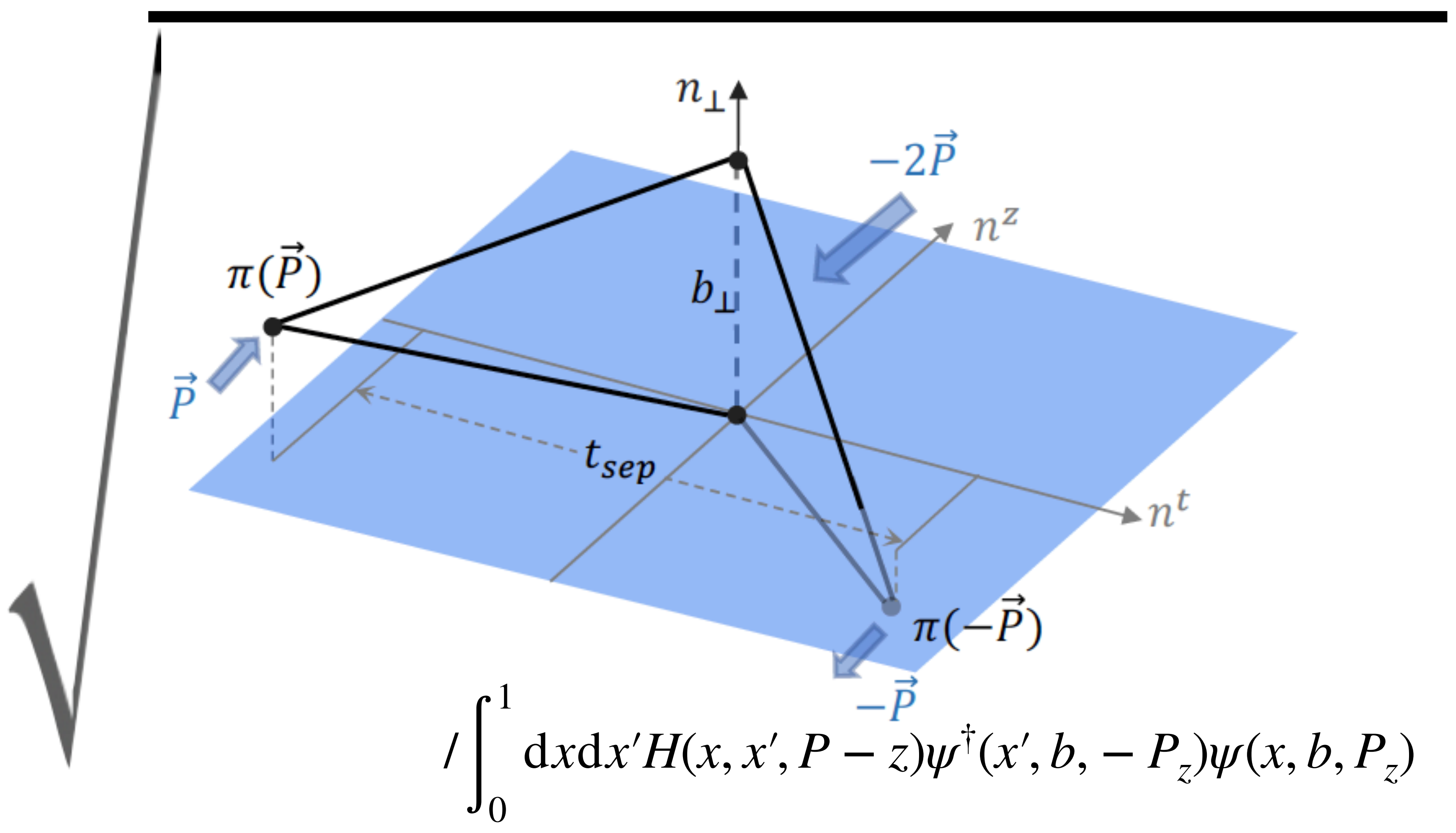
From quasi-TMD to TMD

Besides the quasi-TMD $\tilde{f}$ and perturbative calculable hard kernel H, one also need the following non-perturbative quantities to reach the physical TMD f:

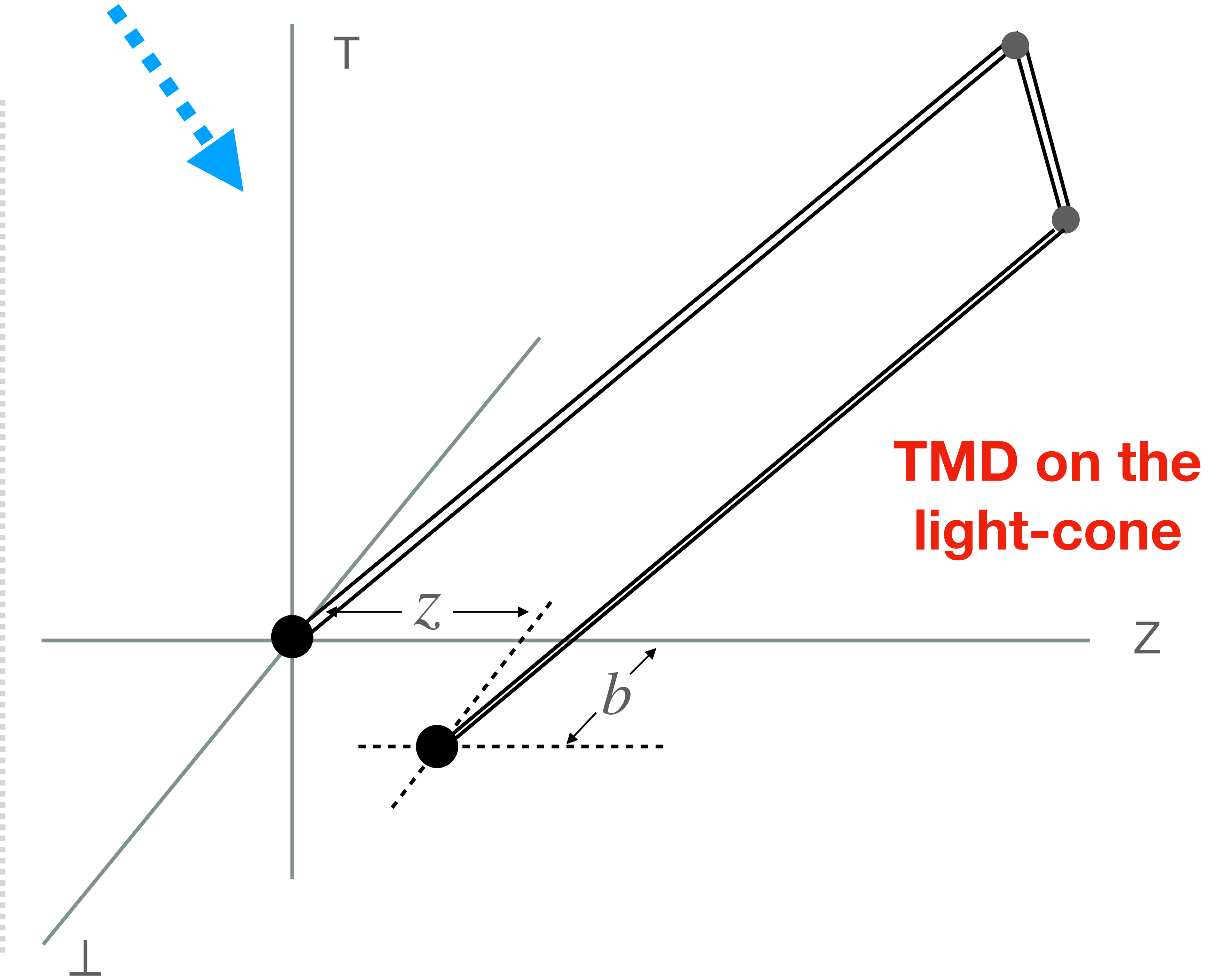
- Intrinsic soft function S_I;
- Rapidity evolution kernel (CS-kernel) K.

$$\tilde{f}\left(x, b_\perp, \zeta_z, \mu\right) \sqrt{S_I\left(b_\perp, \mu\right)} = H(r)\, e^{\frac{1}{2}\ln\left(\frac{\zeta_z}{\zeta}\right) K\left(b_\perp, \mu\right)} \times f\left(x, b_\perp, \mu, \zeta\right) + \mathcal{O}\left(\frac{\Lambda_{\mathrm{QCD}}^2}{\zeta_z}, \frac{M^2}{(P^z)^2}, \frac{1}{b_\perp^2 \zeta_z}\right),$$

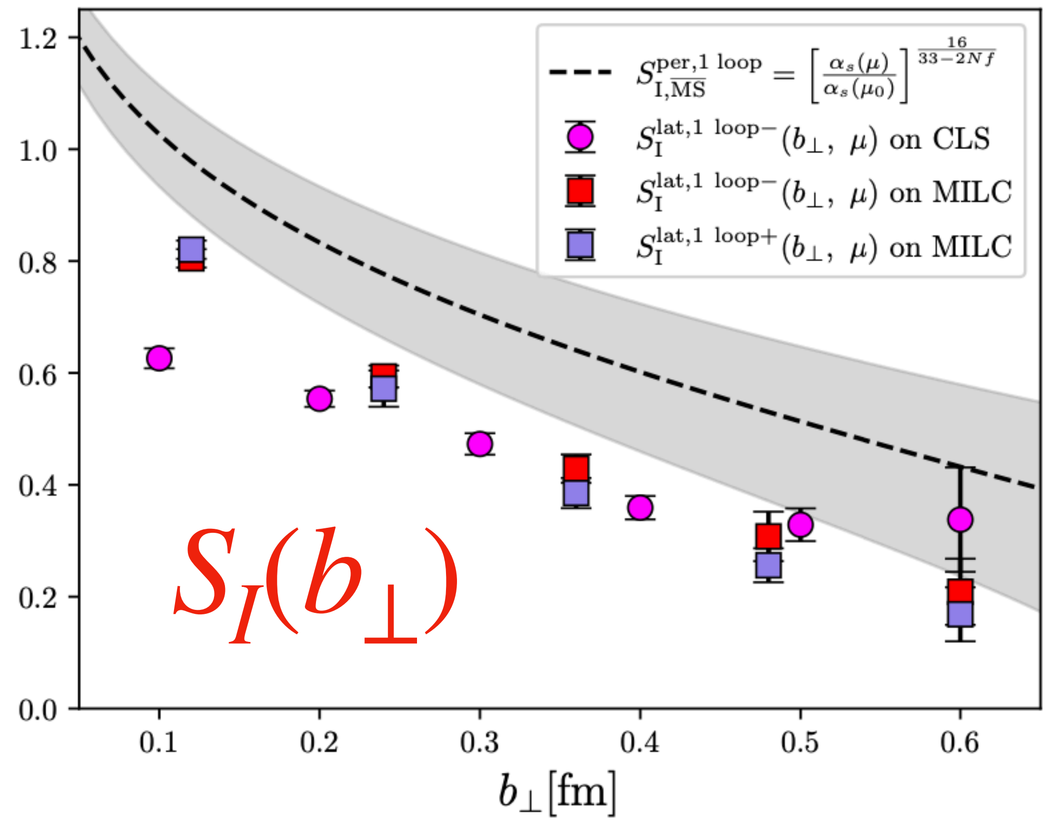


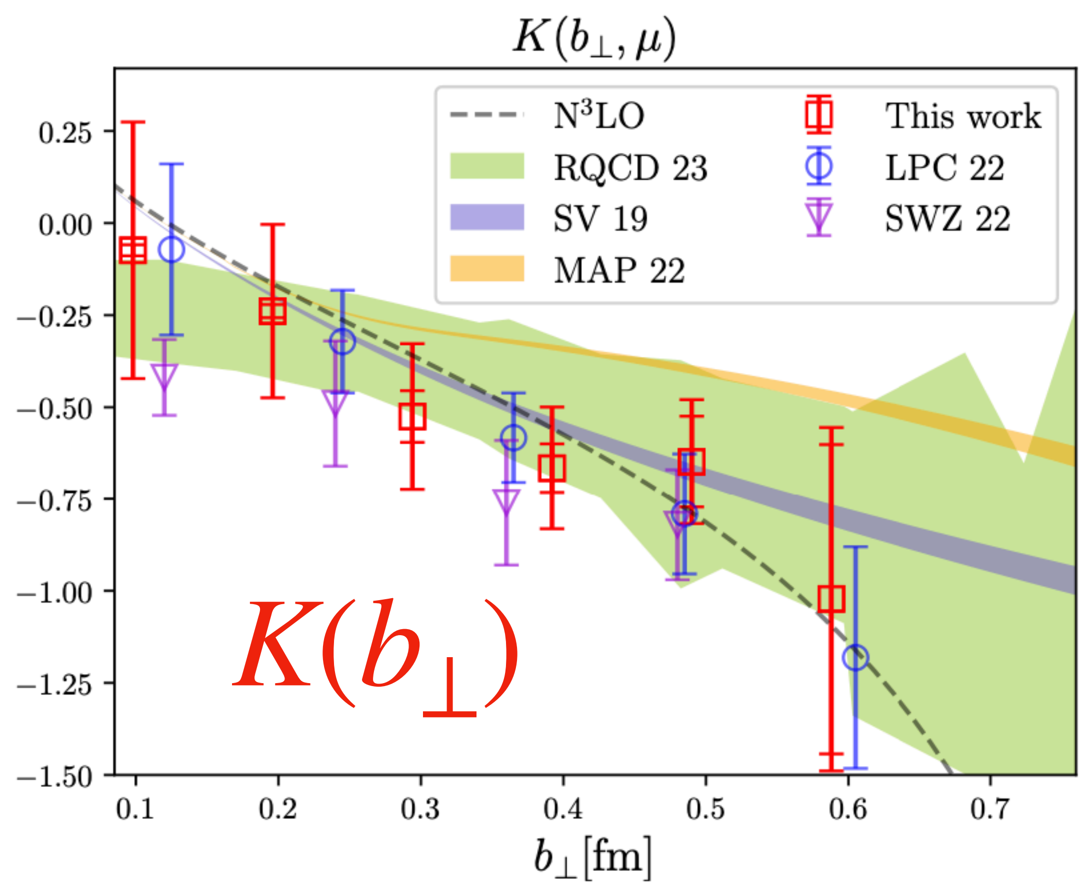


X.Ji. et.al., PLB(2020)135946

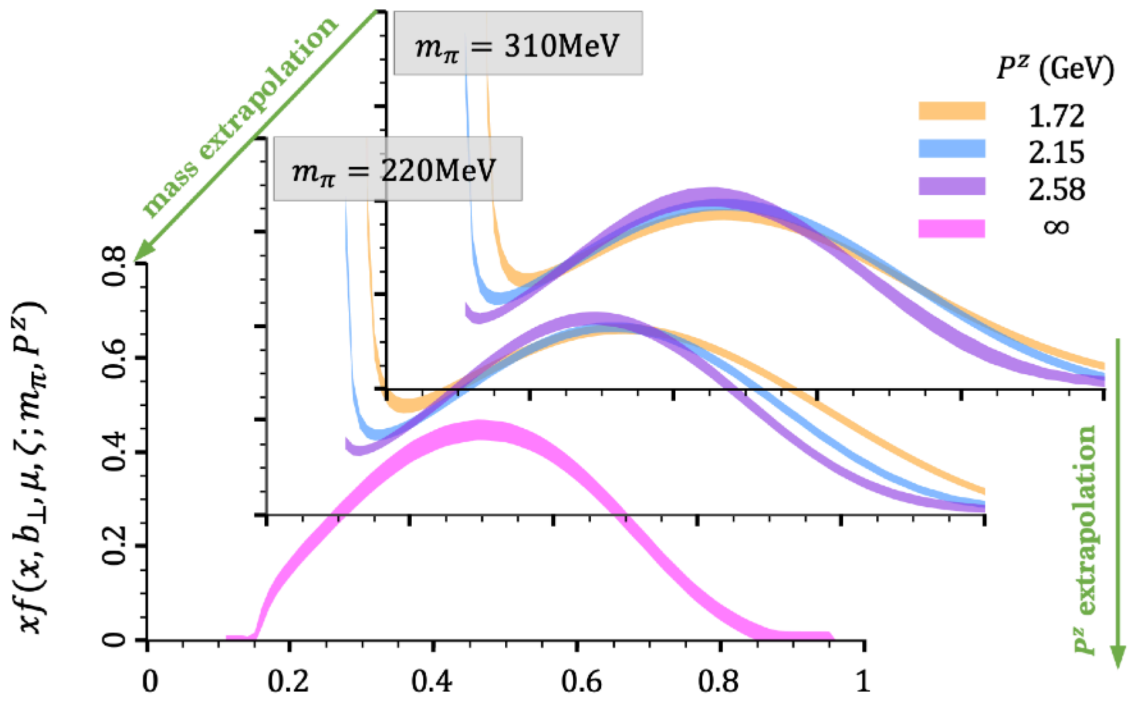


First prediction on physical TMD PDF and WF

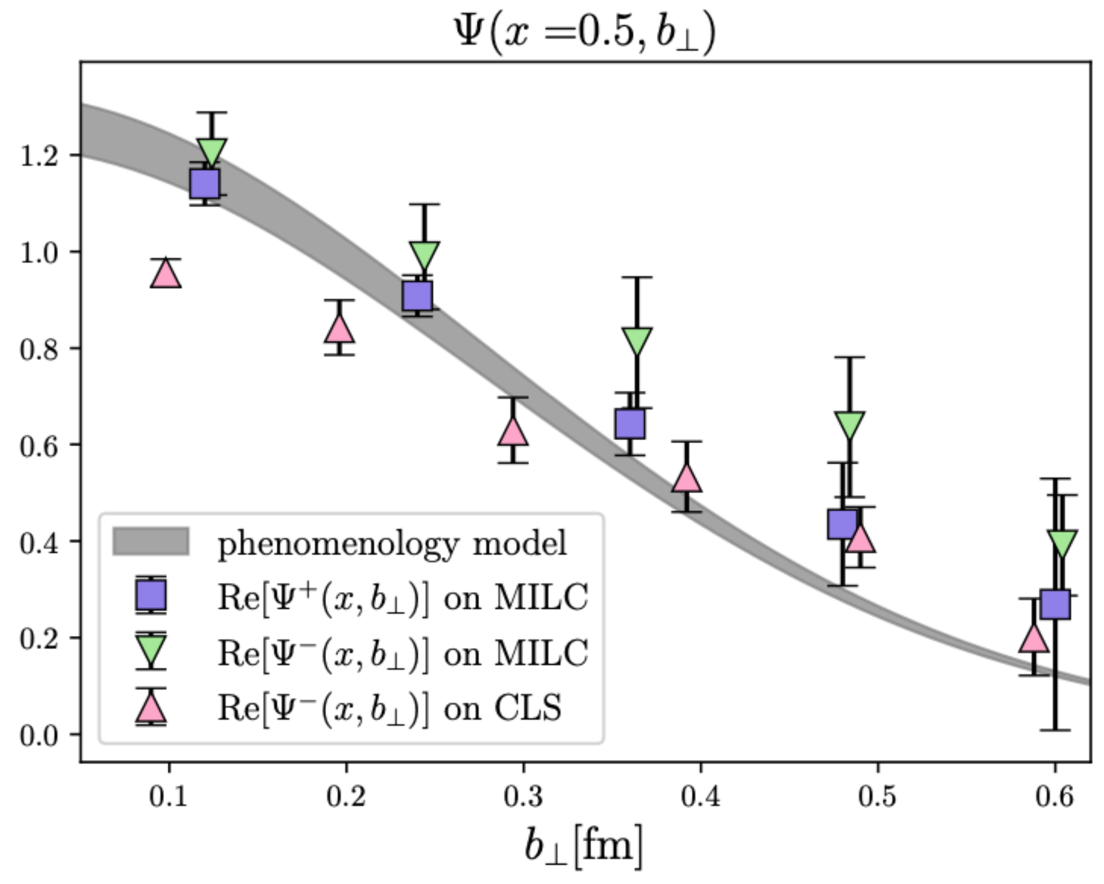




M.-H. Chu, et. al., LPC, JEHP(2023) 172



J.-C. He, et. al., LPC, 2211.042340

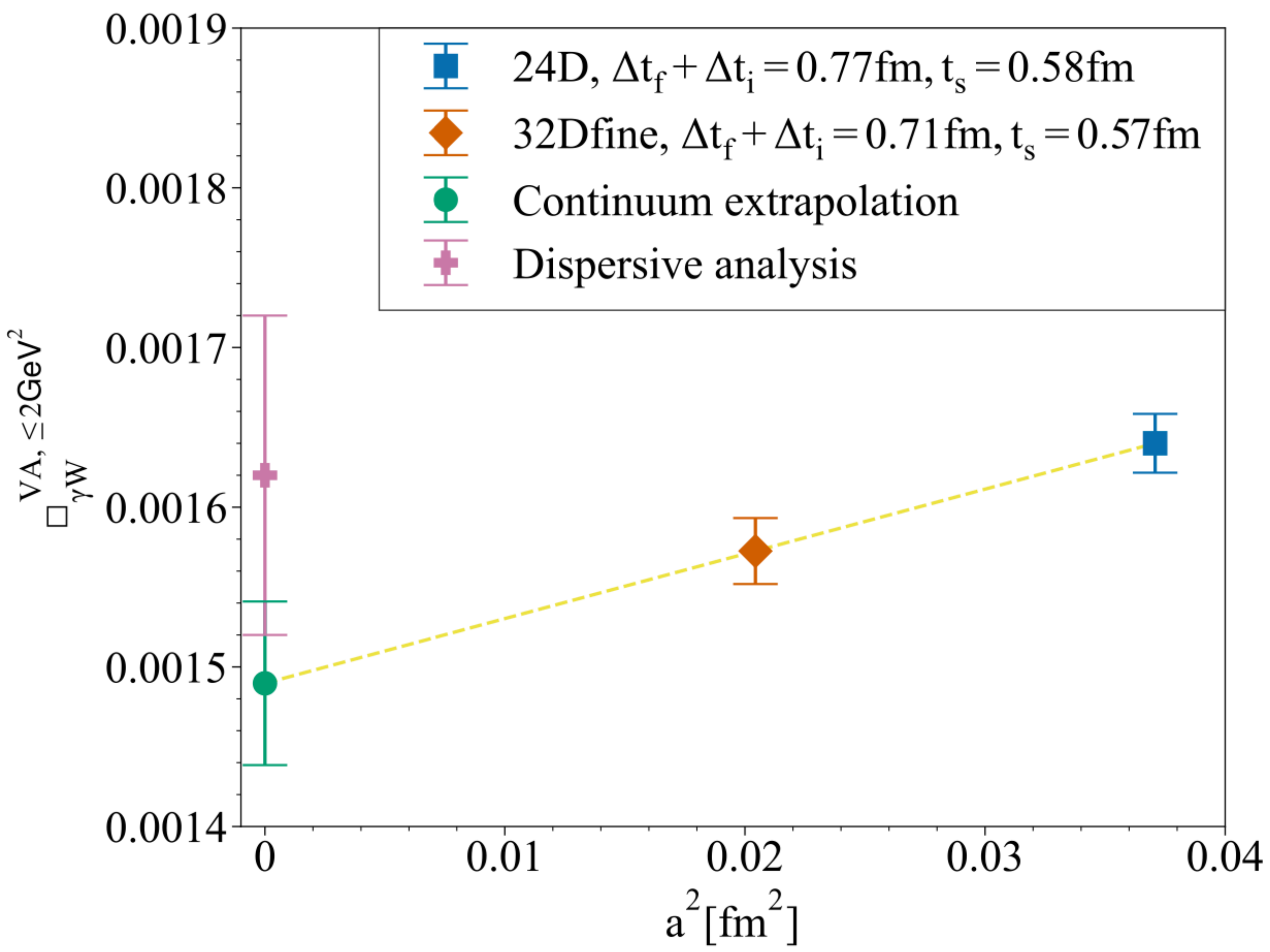


M.-H. Chu, et. al., LPC, 2302.09961

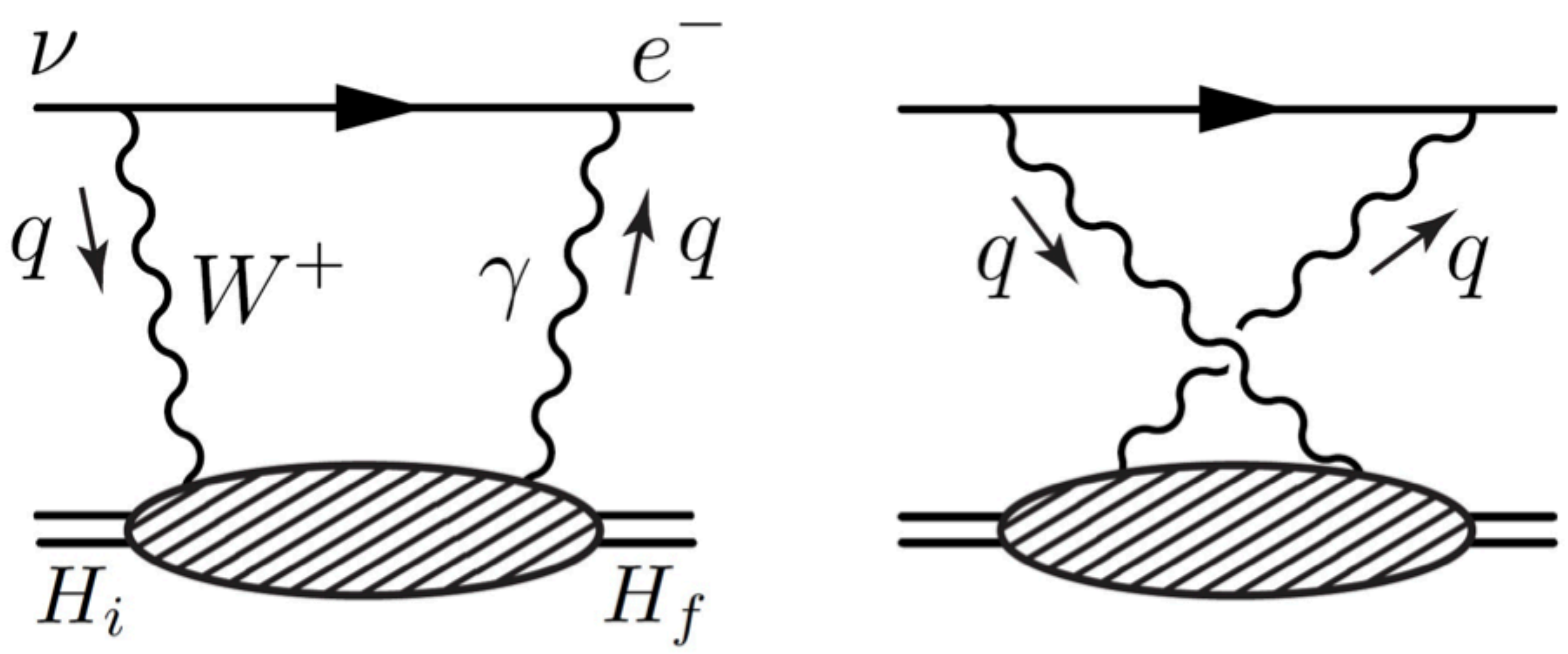
$$\tilde{f}\left(x, b_\perp, \zeta_z, \mu\right)\sqrt{S_I\left(b_\perp, \mu\right)} = H\left(r\right) e^{\frac{1}{2}\ln\left(\frac{\zeta_z}{\zeta}\right)K\left(b_\perp, \mu\right)}$$
$$\times f\left(x, b_\perp, \mu, \zeta\right) + \mathcal{O}\left(\frac{\Lambda^2_{\text{QCD}}}{\zeta_z}, \frac{M^2}{(P^z)^2}, \frac{1}{b^2_\perp \zeta_z}\right),$$

- Based on intrinsic soft function S_I and CS-kernel K, first predictions on physcial TMD PDF and TMD WF are provided;
- Control of the systematic uncertainties is in progress.

Electroweak box diagram and V_{ud}



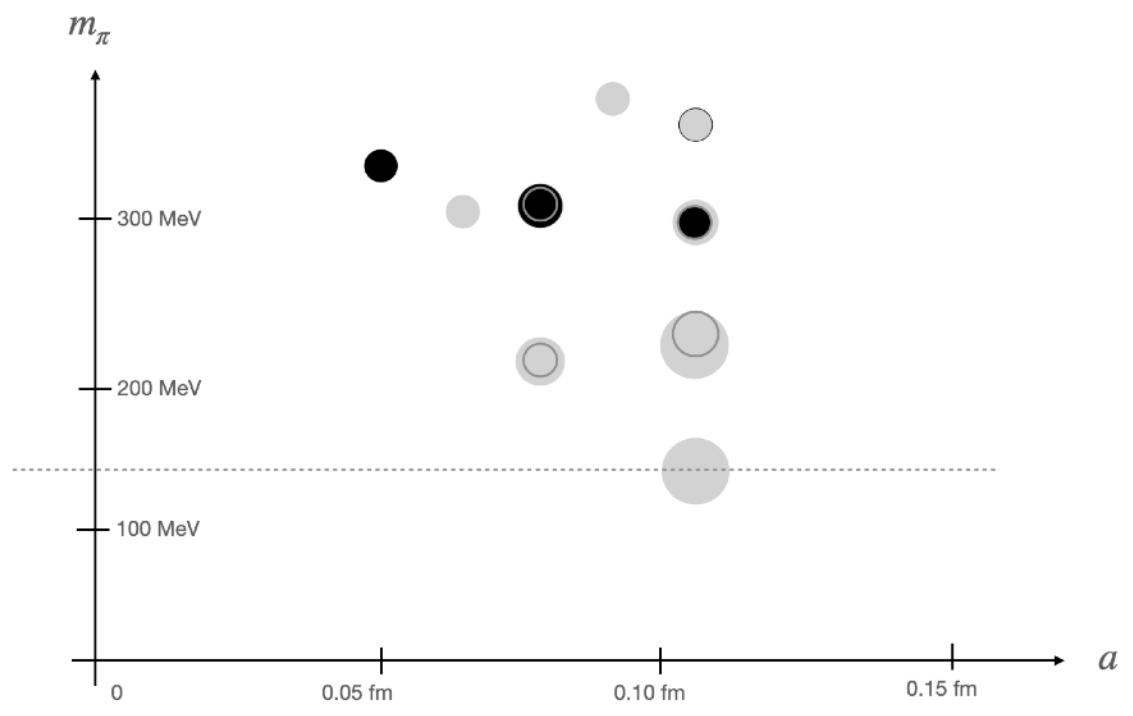
Ensemble	m_π [MeV]	L	T	a^{-1} [GeV]	N_{conf}
24D	142.6(3)	24	64	1.023(2)	207
32D-fine	143.6(9)	32	64	1.378(5)	69



- The first lattice QCD calculation the universal axial γW-box contribution to both superallowed nuclear and neutron beta decays;
- Results shows mild lattice spacing dependence using DW fermion, yields $|V_{ud}| = 0.97386(11)_{\text{exp}}(9)_{\text{RC}}(27)_{\text{NS}}$ and slightly reduces the tension with the CKM unitarity.

P.-X. Ma, et.al., 2308.16755, accepted by PRL

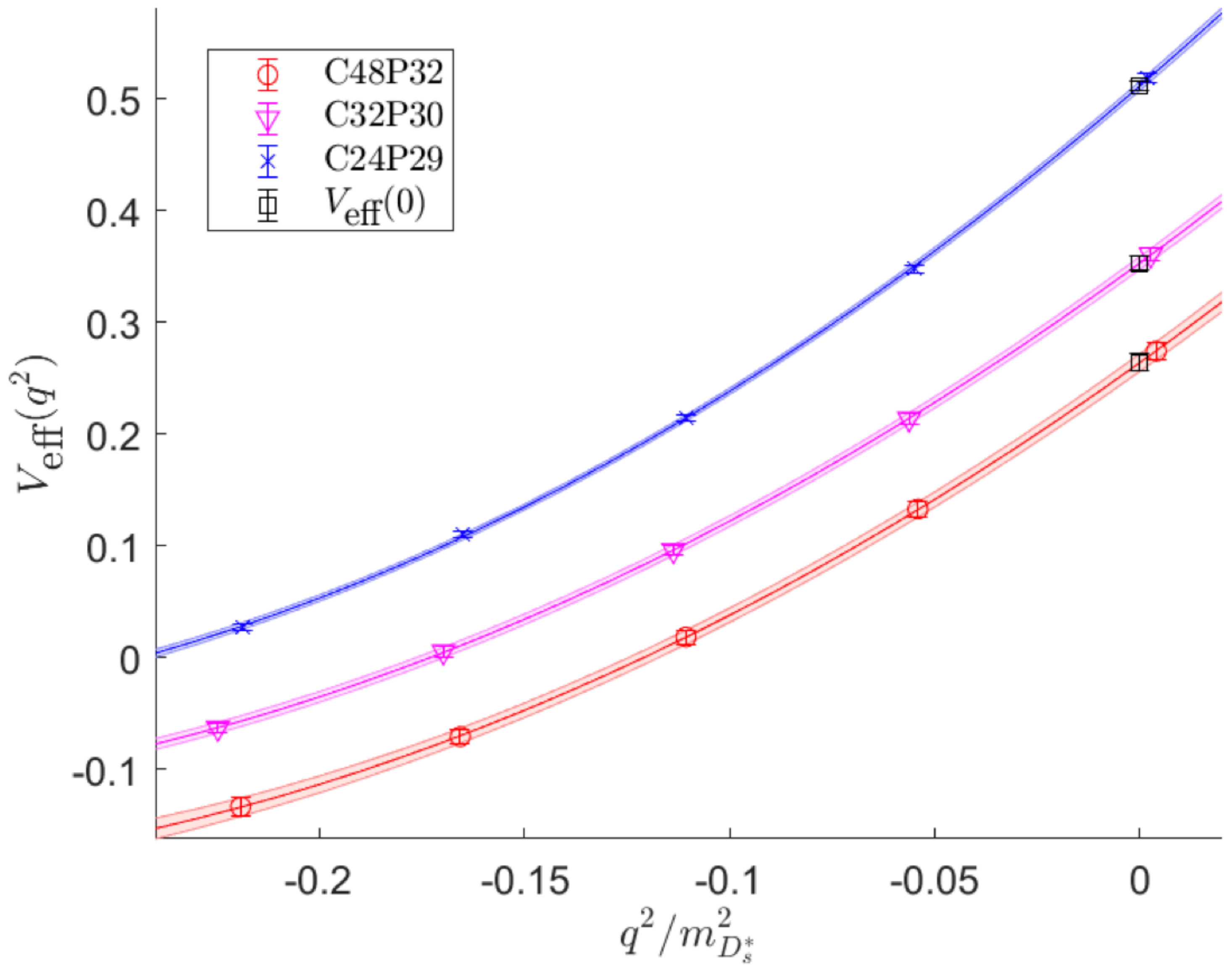
D_s^* radiative decay and V_{cs}



$$\langle 0|\mathcal{O}_{D_s}(0)|D_s(\vec{p})\rangle = Z_{D_s}$$

$$\langle D_s(p)|J_\nu^{\text{em}}(0)|D_{s,\mu}^*(p')\rangle = \frac{2V_{\text{eff}}(q^2)}{m_{D_s}+m_{D_s^*}}\epsilon_{\mu\nu\alpha\beta}p_\alpha p'_\beta$$

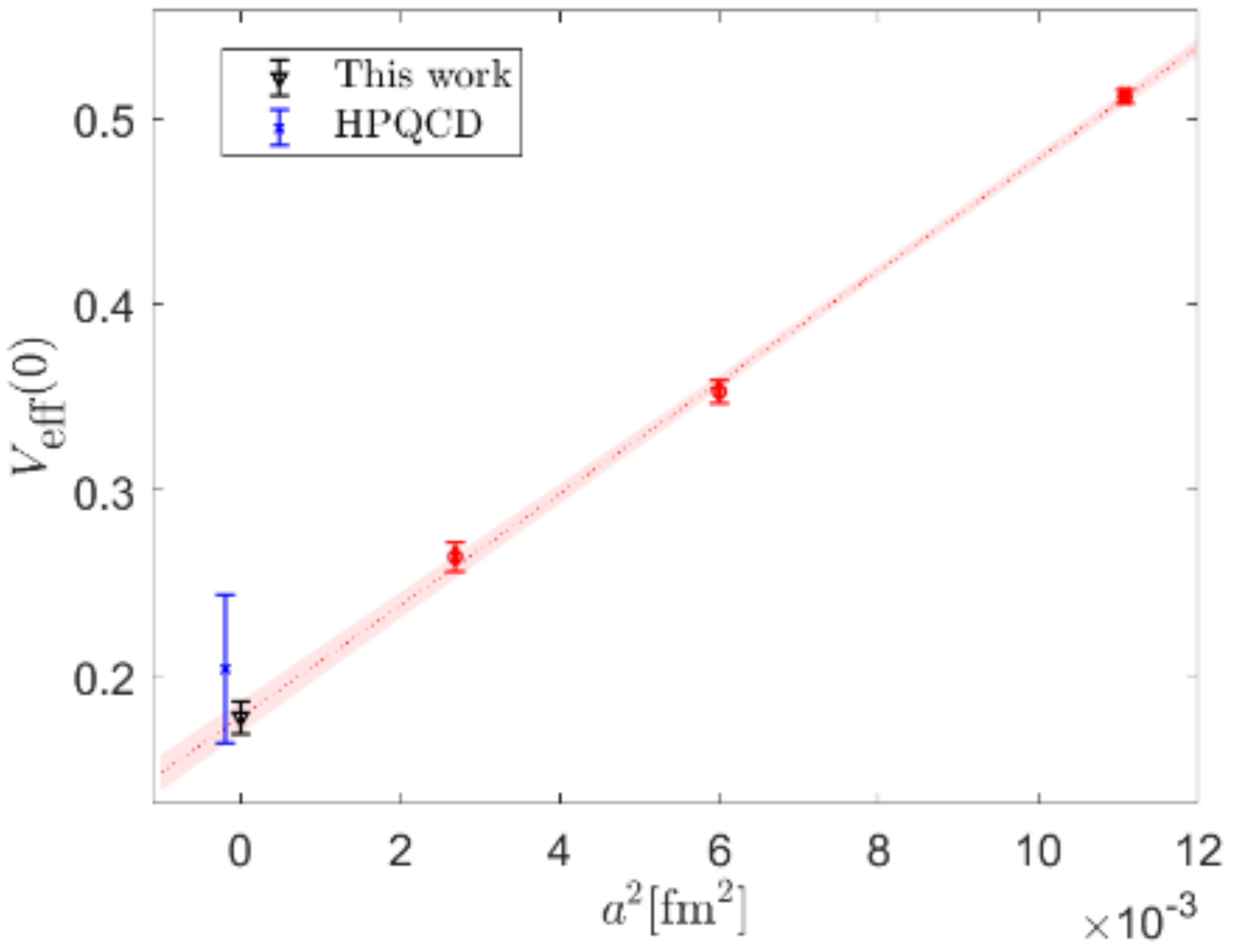
$$V_{\text{eff}}(q^2) = \frac{-(m_{D_s}+m_{D_s^*})E_{D_s}}{2Z_{D_s}m_{D_s^*}}e^{E_{D_s}t} \times \int d^3\vec{x}\frac{j_1(|\vec{p}||\vec{x}|)}{|\vec{p}||\vec{x}|}\epsilon_{\mu\nu\alpha 0}x_\alpha H_{\mu\nu}(\vec{x},t)$$



- Predict $\Gamma(D_s^* \to D_s\gamma)$ =0.0549(54) KeV and then suppress the uncertainty of the previous HPQCD calculation by a factor of 4;

- Combining the recent experiment, one can obtain $f_{D_s^*}|V_{cs}| = 190.5^{+55.1}_{-41.7} \pm 12.6$ MeV.

- **More details can be found in Yu Meng's talk on Monday at 9:50 AM.**



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Sumary

- Light quark mass and low energy constants have been properly extracted using the CLQCD ensembles, and study on the charm quark and also hadron spectrums are on going.
- Systematic hadron spectrum and structure studies can be carried out using the CLQCD ensembles.
- We expect more LQCD studies will use the CLQCD ensembles in the near future, based on the techniques we developed on the other ensembles.