



Discretization effects in baryon-baryon scattering

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Lattice 2026

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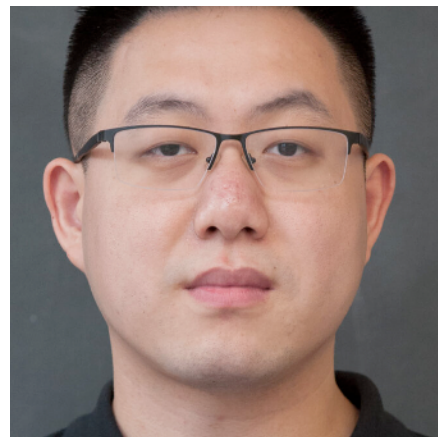
Thanks to my collaborators



Davoudi



Detmold



Fu



Grebe



Hackett



Illa



Parreño



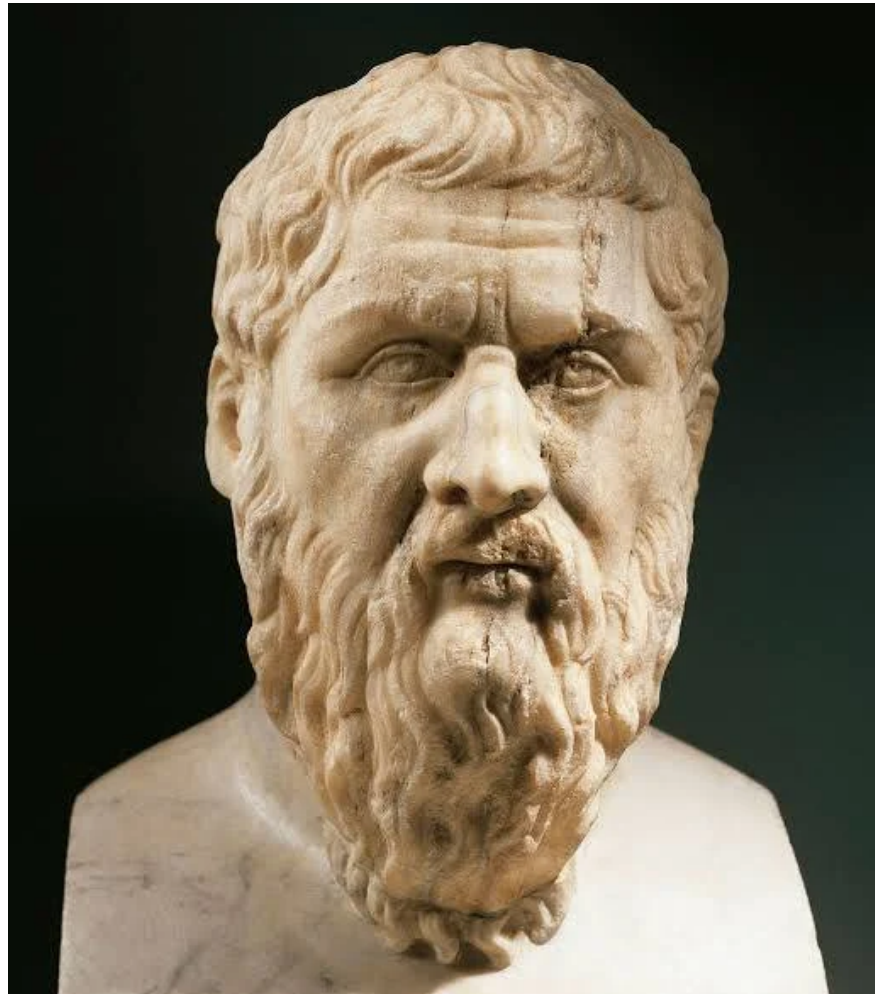
Perry



Shanahan



Plato vs data



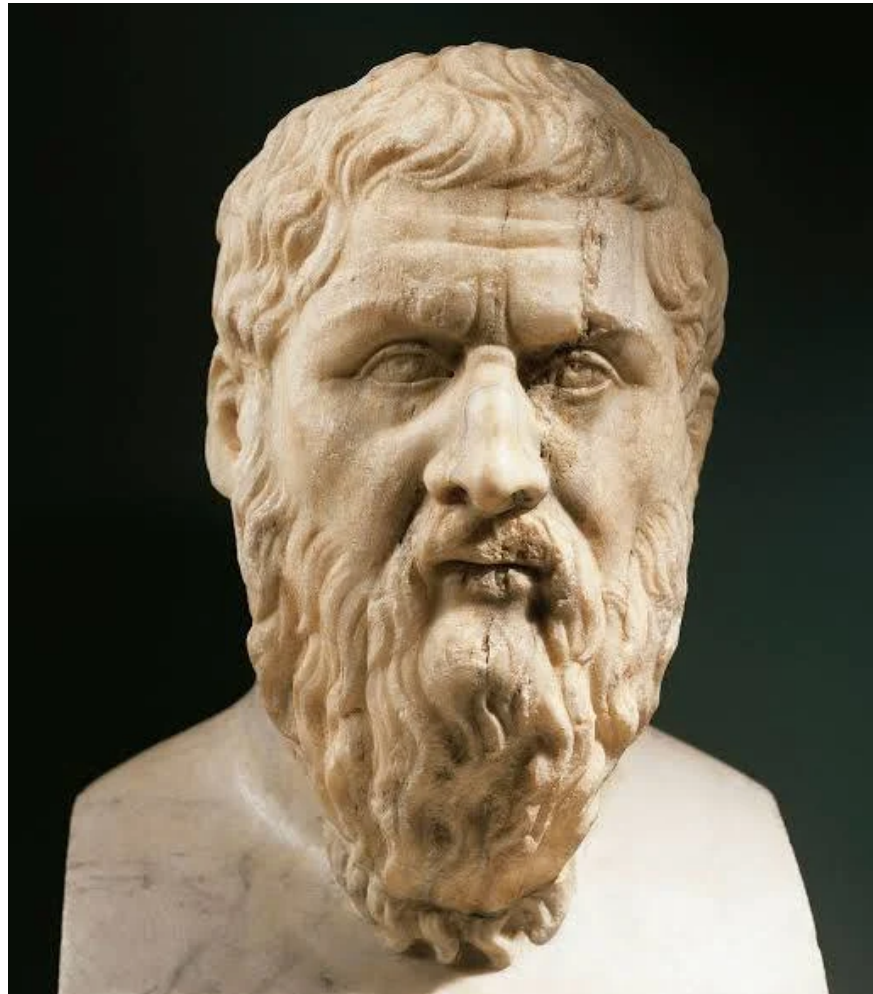
Lüscher's quantization condition and generalizations apply to continuum limit spectrum at fixed volume

$$E_n(L) = \lim_{a \rightarrow 0} E_n(L\Lambda_{\text{QCD}}, a\Lambda_{\text{QCD}})$$

Platonic ideal: constrain S-matrix from QC using continuum extrapolated FV energies

$$0 = \det [\mathbf{1} + \mathbf{S}(E)\mathbf{V}(E, L)|_{E_n(L)}$$

Plato vs data



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Numerical simulations are performed using integer L/a with action parameters tuned to **approximately** match $L\Lambda_{\text{QCD}}$ for different values of a

$$\{E_n^{(i)} a^{(i)}, L^{(i)} / a^{(i)}, a^{(i)} / w_0^{(i)}\} \quad i \in \{1, \dots, N_{\text{ensembles}}\}$$

State labels n assumed consistent across ensembles (“no missing states”)

Discretizing Lüscher's formalism

How can we model discretization effects on multi-particle energy spectra?

- $O(a^2)$ effects in single-hadron mass can be propagated through QC

[Hansen and Peterken, arXiv:2408.07062](#)

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Further discretization effects should arise in multi-hadron interactions

- Taylor expand effective range parameters?

$$k \cot \delta(k) = \sum_{i=0}^{N-1} c_i k^{2i}, \quad c_i = c_{i0} + c_{i1} a^2$$

[Green et al, PRL 127 \(2021\)](#)

[Liu et al, arXiv:2603.05854](#)

UV cutoff / IR cutoff mix together in energies in complicated non-analytic ways...

Is this expressive enough to capture generic lattice real-time amplitudes?

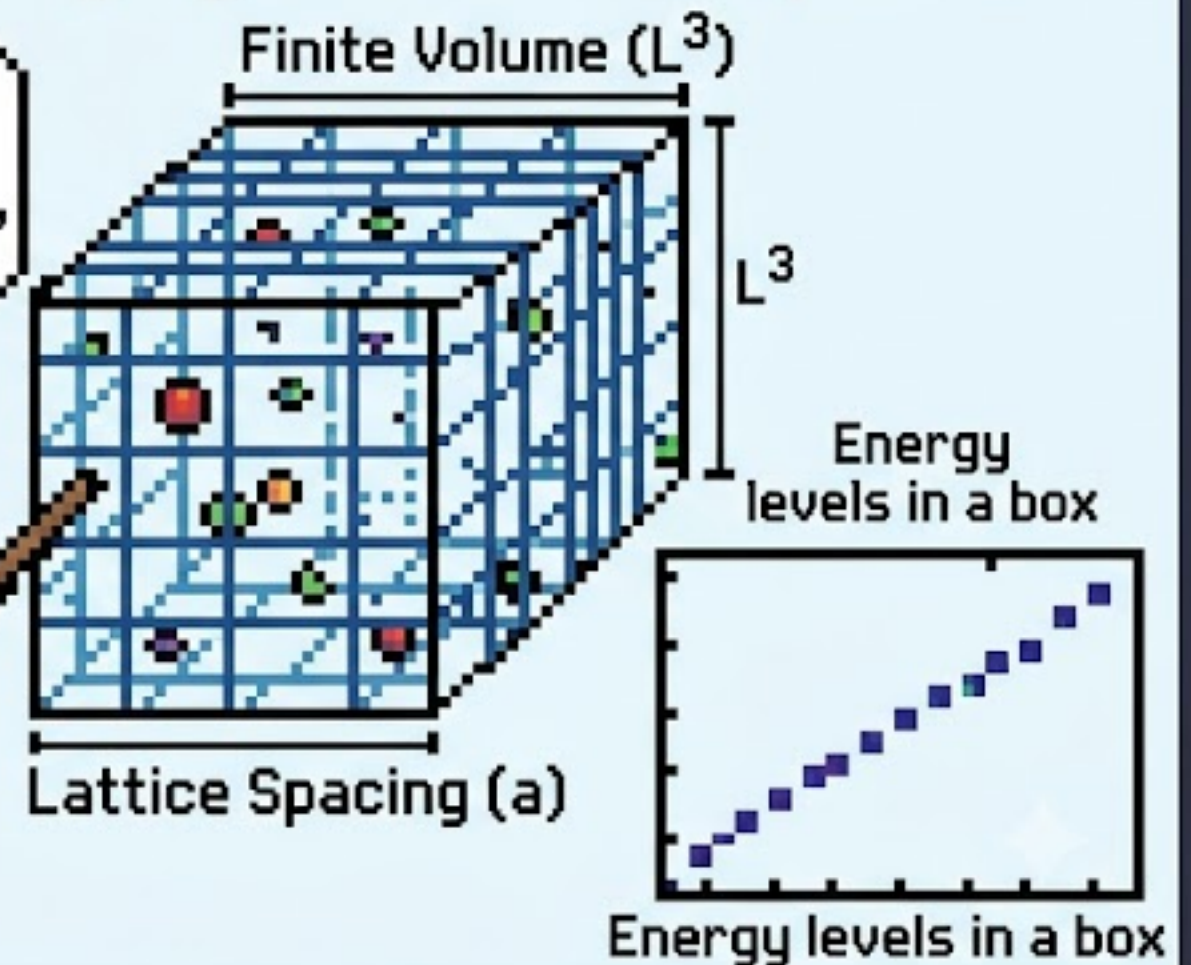
Discretizing Lüscher's formalism

DISCRETIZING LÜSCHER'S FORMALISM: FINITE VOLUME, PIXELATED RESULTS

(Or: How I learned to stop worrying and love the pixel.)



"It's all about the boundaries...
and the pixel size!"



Discretizing Lüscher's formalism

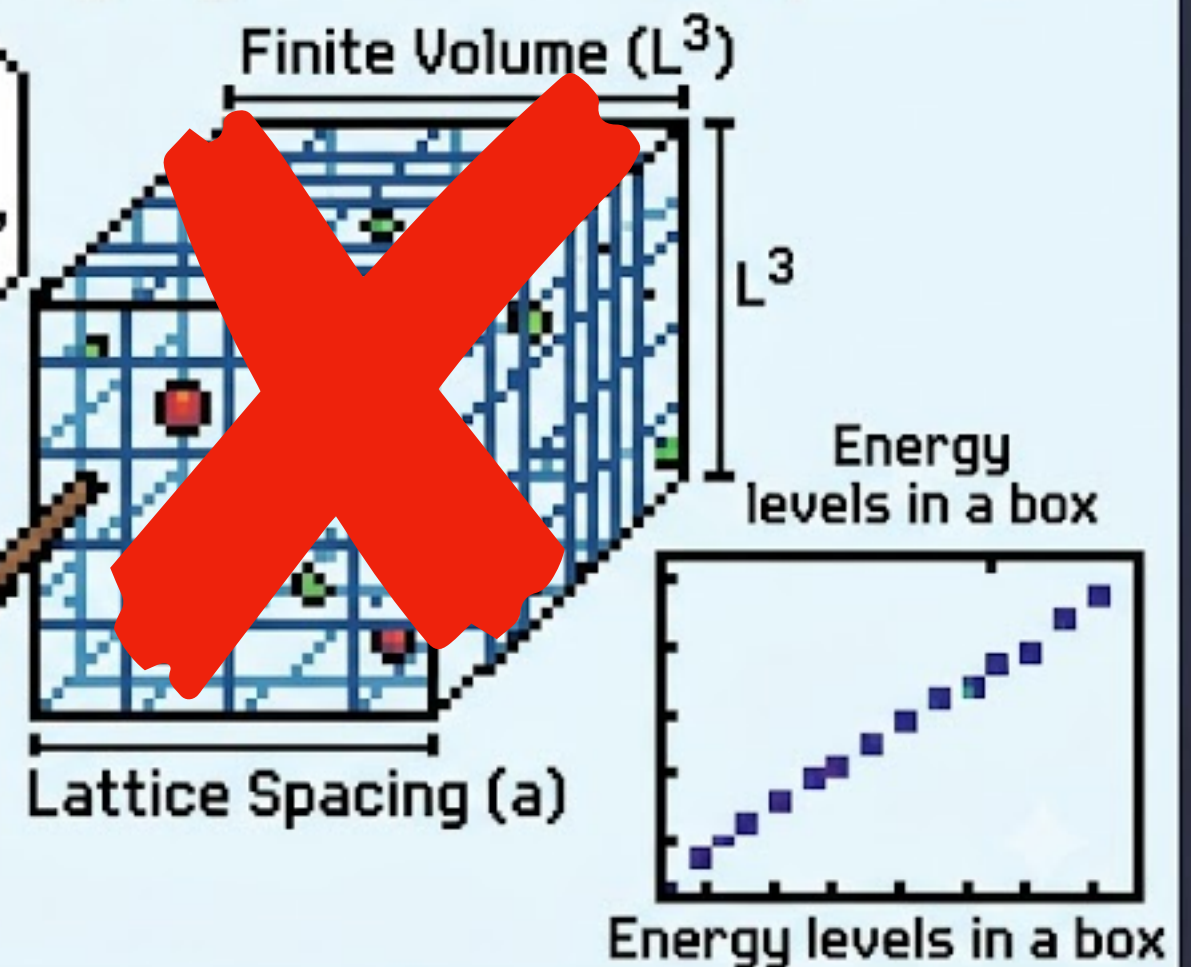
It's not that easy!!

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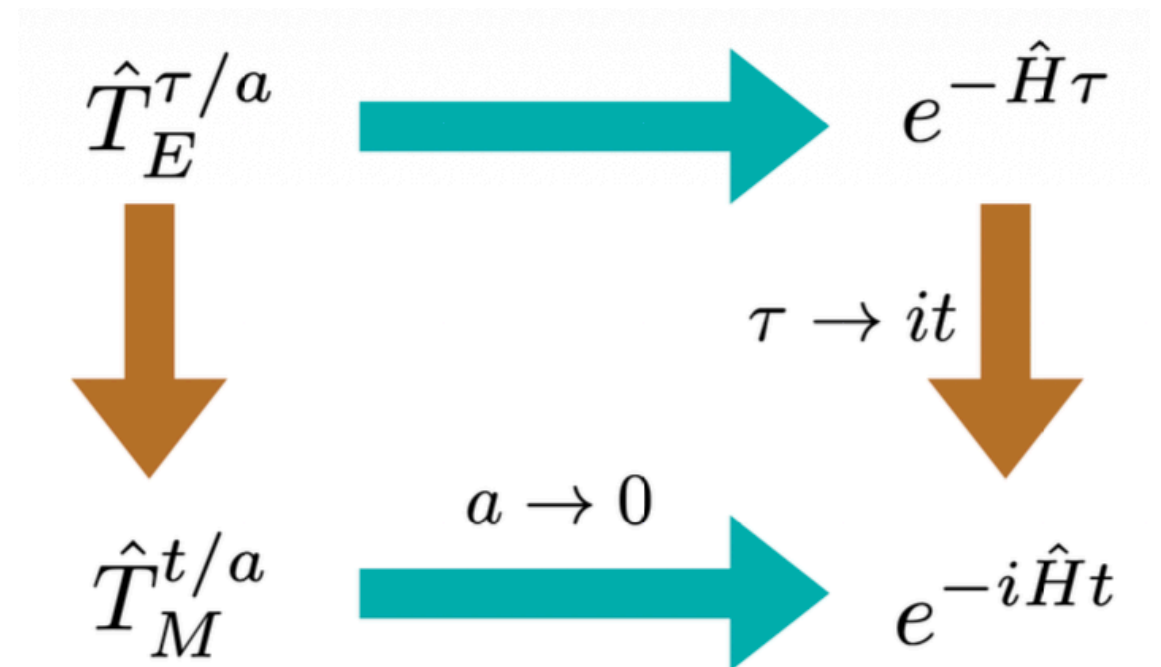


Real-time lattice is hard

To compute a discretized real-time scattering amplitude, need to start with a discretized Minkowski theory

This is really hard.

Kanwar and MW, PRD 104 (2021)



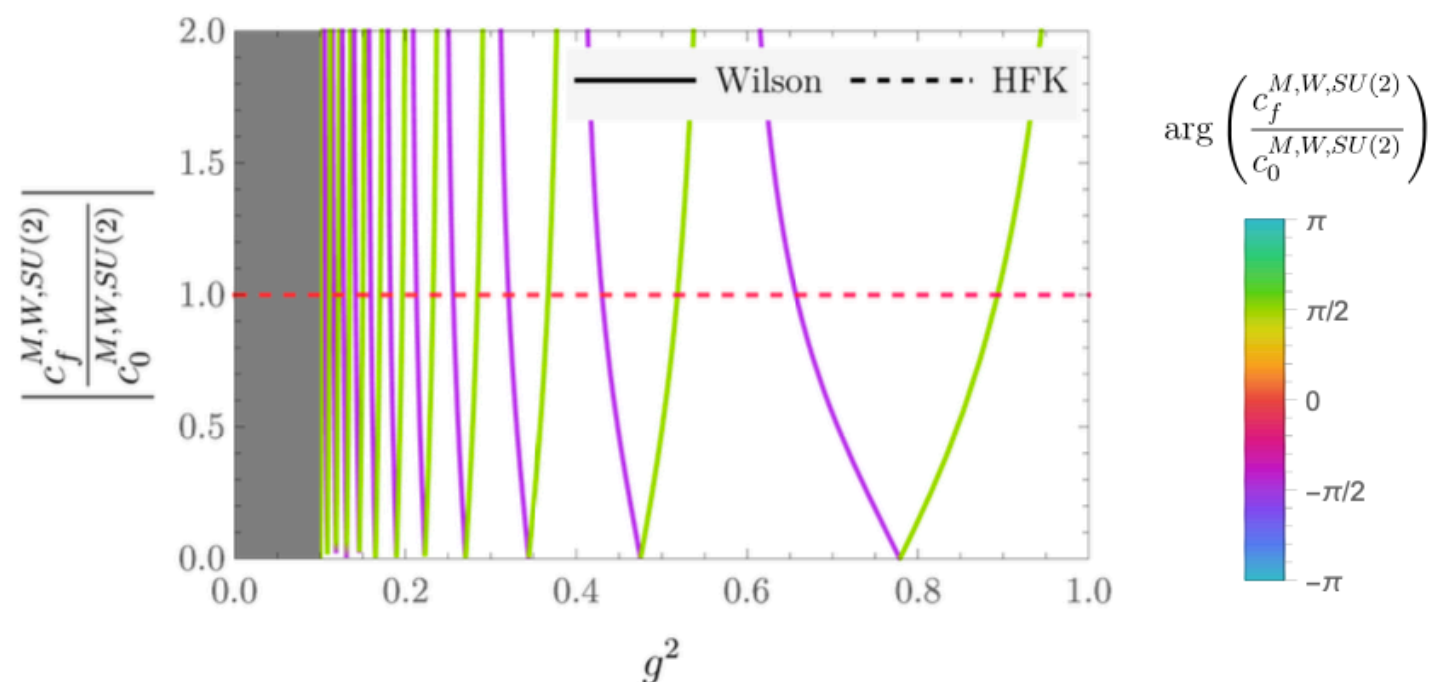
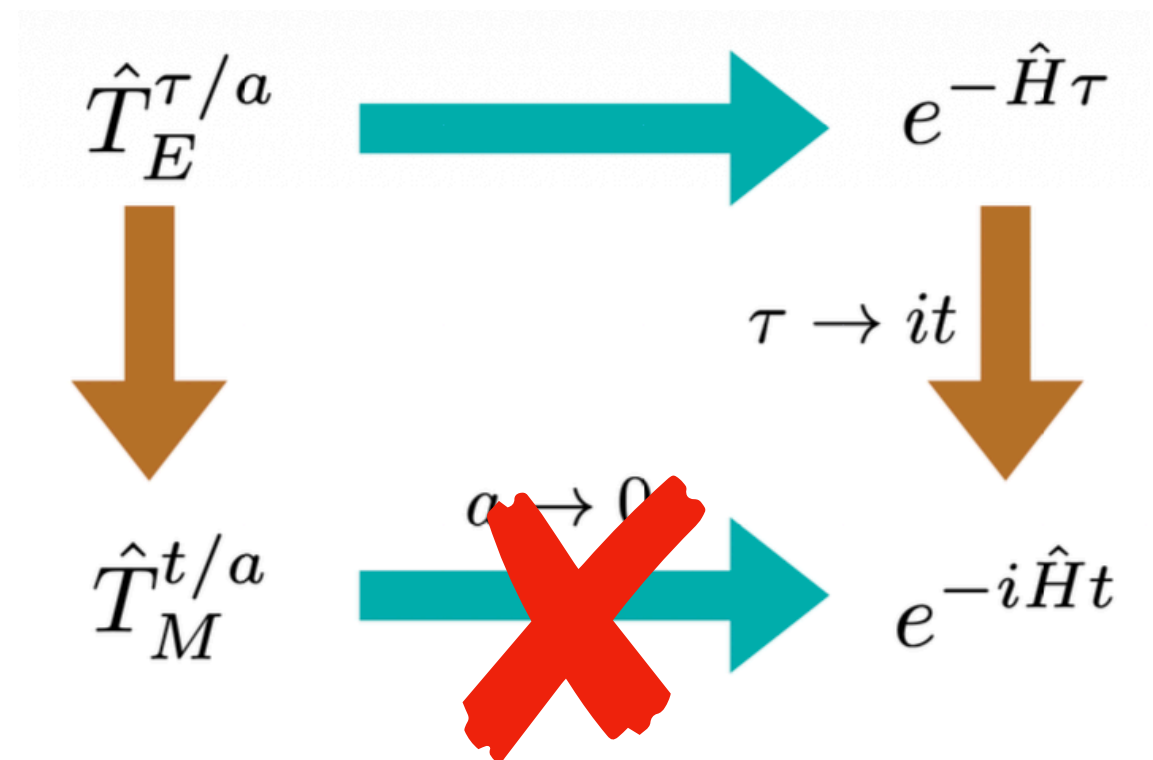
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- Wick rotation does not commute with the continuum limit
- Wick rotate the Wilson action, then take the continuum limit leads to **no limit** for $SU(2)$ and a **wrong, non-unitary** limit for $SU(3)$ pure gauge
- Unitary real-time lattice gauge theory action can be constructed. Repeating Lüscher derivation with $\overline{\text{HK}}$ action is “possible”



Discretize FV spectra, not amplitudes

Standard assumption: single-hadron energies in LQCD can be Taylor expanded about their continuum limits (up to logarithmic corrections)

$$E_n(L, a) = E_n(L) + c_n^{(2)} a^2 + c_n^{(3)} a^3 + \dots$$

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Standard assumption: single-hadron energies in LQCD can be Taylor expanded about their continuum limits (up to logarithmic corrections)

$$E_n(L, a) = E_n(L) + c_n^{(2)} a^2 + c_n^{(3)} a^3 + \dots$$

Same logic should apply to energies of multi-hadron states

$$\chi^2 \sim \sum_{n,i} \left(E_n^{(i)} - E_n(L, a^{-1}, r, \rho, \dots) - c_n^{(2)} [a^{(i)}]^2 - c_n^{(3)} [a^{(i)}]^3 - \dots \right)^2$$

Correlations important
in practice

Discretization effects on FV
energies

Continuum QC solution with parameterized S-matrix

$$0 = \det \left[\mathbf{1} + S(E, a^{-1}, r, \rho, \dots) V(E, L) \right]_{E_n(L, a^{-1}, r, \rho, \dots)}$$

Symanzik EFT

Hadron-level EFTs (e.g. pionless EFT for baryons at heavy quark masses) represent scattering length / effective range / ... with 0 / 2 / ... derivative interactions

$$\mathcal{L}^{\text{EFT}(\#)} = B^\dagger \left(i\partial_t + \frac{\nabla^2}{2M_B} \right) B + \frac{4\pi}{M_B(-a^{-1} + \mu)} (BB)(BB)^\dagger \\ + \frac{\pi r}{4M_B(-a^{-1} + \mu)^2} [(B\nabla^2 B)(BB)^\dagger + \text{h.c.}] + \dots$$

Physically motivated scheme used extensively for single-hadron energies: hadron-level **Symanzik EFT** with low-energy constants proportional to powers of lattice spacing

Sharpe and Singleton, PRD 58 (1998)

Symanzik EFT

Hadron-level EFTs (e.g. pionless EFT for baryons at heavy quark masses) represent scattering length / effective range / ... with 0 / 2 / ... derivative interactions

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Analogous strategy for multi-hadron interactions (also applicable to $\pi\pi$, DD^* , ...)

$$\mathcal{L}_{\text{Symanzik}(\not{\pi})}^{\text{EFT}} = \mathcal{L}^{\text{EFT}(\not{\pi})} + l_0^{(2)} a^2 [(BB)(BB)^\dagger + \text{h.c.}] + l_0^{(3)} a^3 [(BB)(BB)^\dagger + \text{h.c.}] + \dots + l_2^{(2)} a^2 [(B\nabla^2 B)(BB)^\dagger + \text{h.c.}] + \dots$$

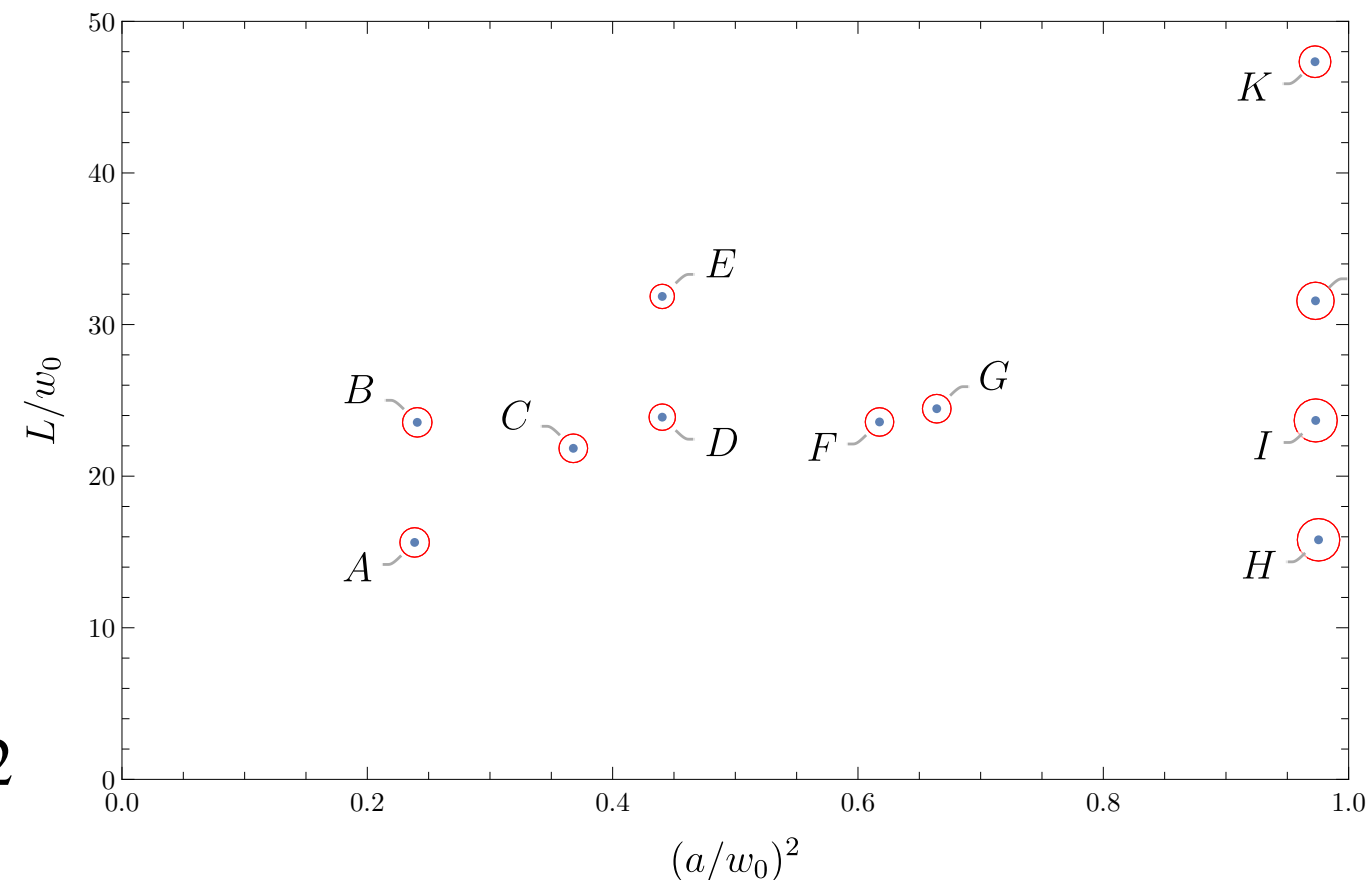
Leads to $O(a^2 \Lambda_{\text{QCD}}^2)$, $O(a^2 [k^\star]^2)$, and higher-order corrections to **FV energies**

Same EFT could be applied to scattering amplitudes. Slightly different from adding $O(a^2)$ to scattering length/effective range; not obviously physically meaningful either way.

Multi-ensemble *BB* scattering

New NPLQCD campaign: **11 ensembles**, $m_u = m_d = m_s$ with $m_\pi \sim 800$ MeV

- Large $m_\pi L \gtrsim 10$ (Lüscher works), spans **factor of 3 in spatial extent L**
- Four values of gauge coupling, spans **factor of 2 in lattice spacing**
- 5-10% spread in $m_\pi/M_B \approx 1/2$, enables “not chiral” extrapolation* $m_\pi/M_B \rightarrow 1/2$



Boost	$N_{\text{Operators}}$	Little group	Irreps
$\frac{2\pi}{L} (0, 0, 0)$	5	O_h	A_1^+, E^+, T_2^+
$\frac{2\pi}{L} (0, 0, 1)$	11	C_{4v}	A_1
$\frac{2\pi}{L} (0, 1, 1)$	20	C_{2v}	A_1
$\frac{2\pi}{L} (1, 1, 1)$	12	C_{3v}	A_1

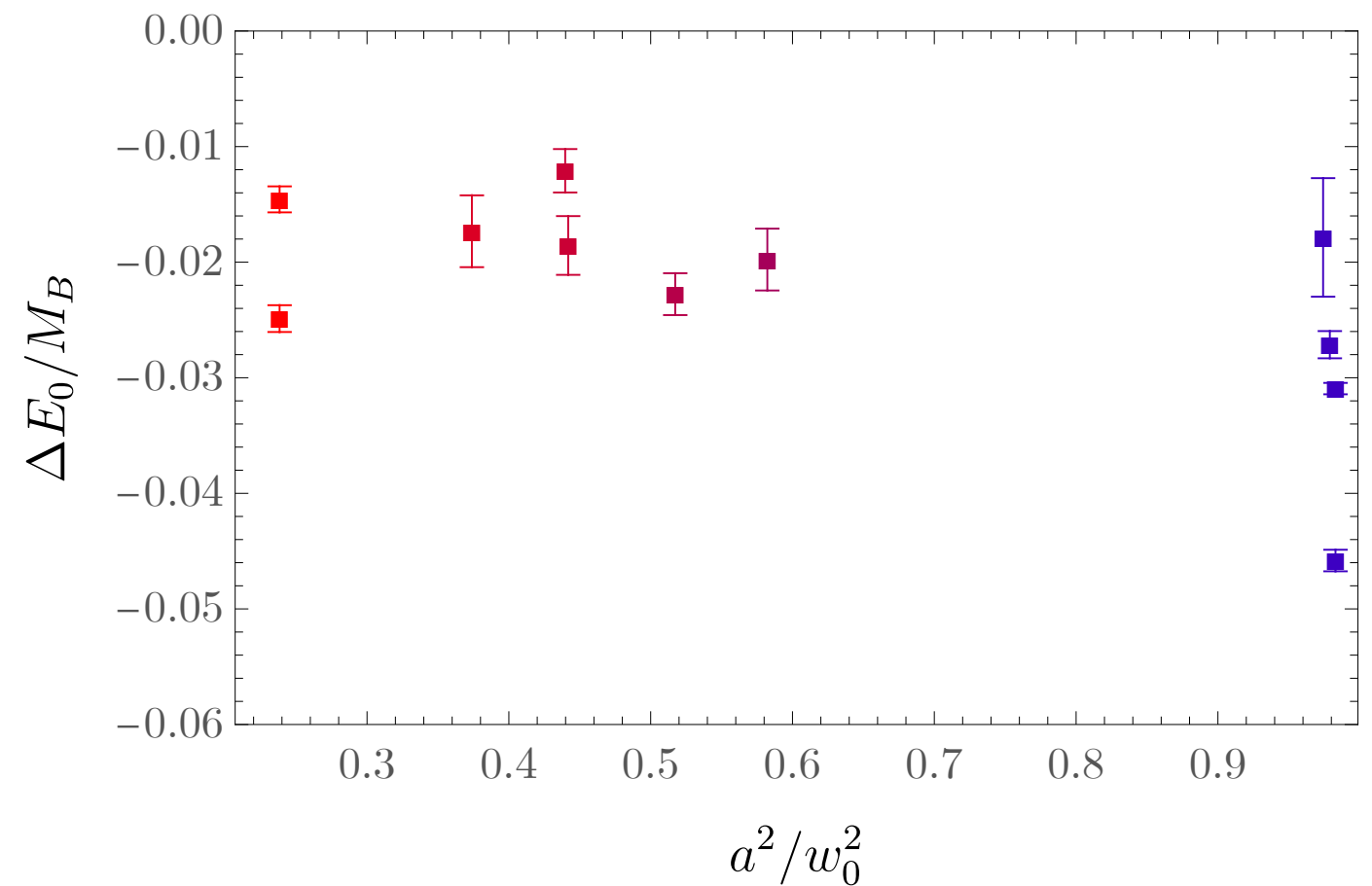
*continuum-limit LQCD,

$$m_q \gg m_q^{\text{PDG}}$$

Data-driven discretization modeling

Can data help us understand the physics of lattice artifacts?

- No clear evidence in LQCD data for $O(a\Lambda_{\text{QCD}})$: formally present but small



*Note points also have different L ,
1D projection of multi-D problem*

Data-driven discretization modeling

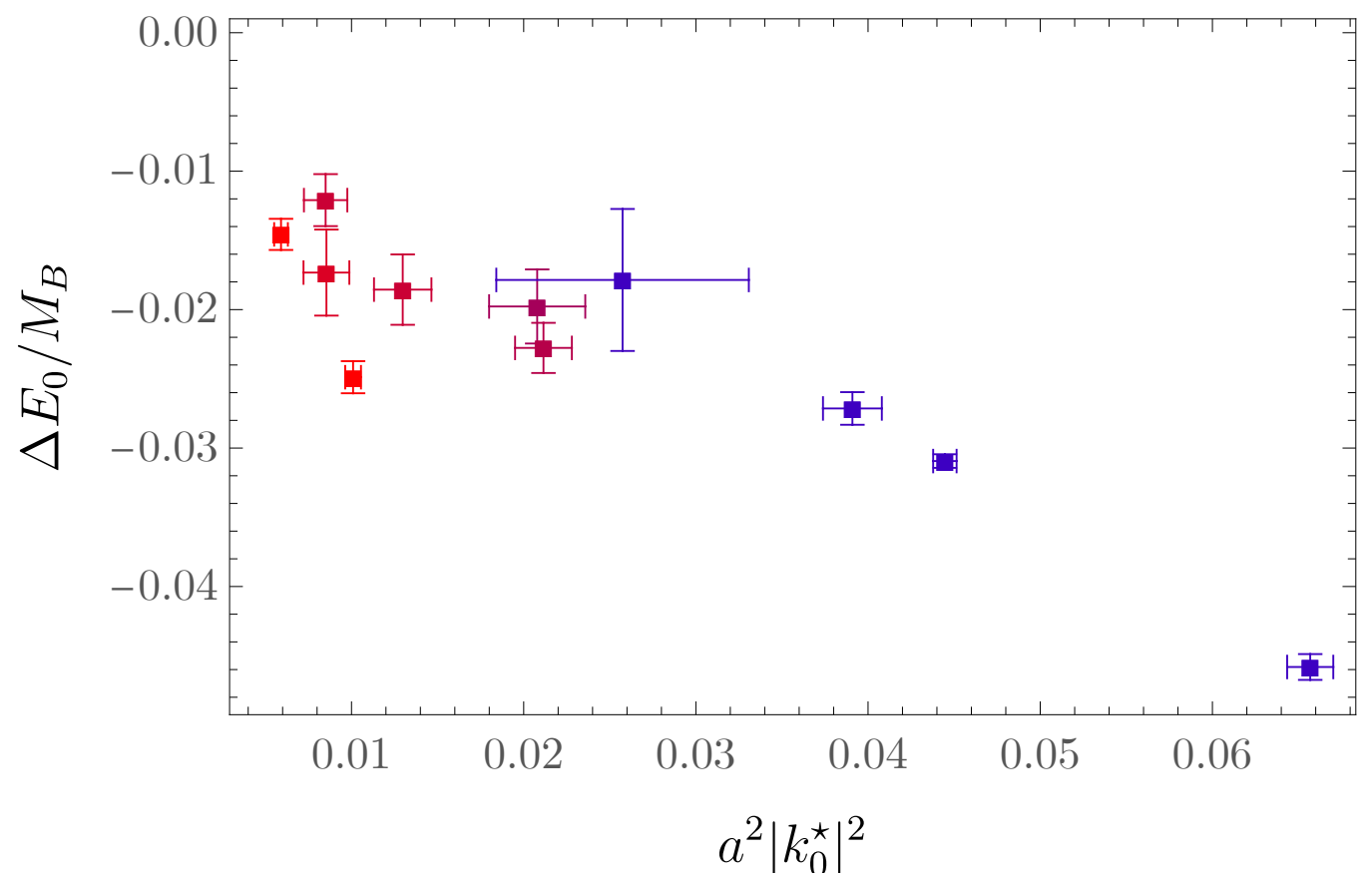
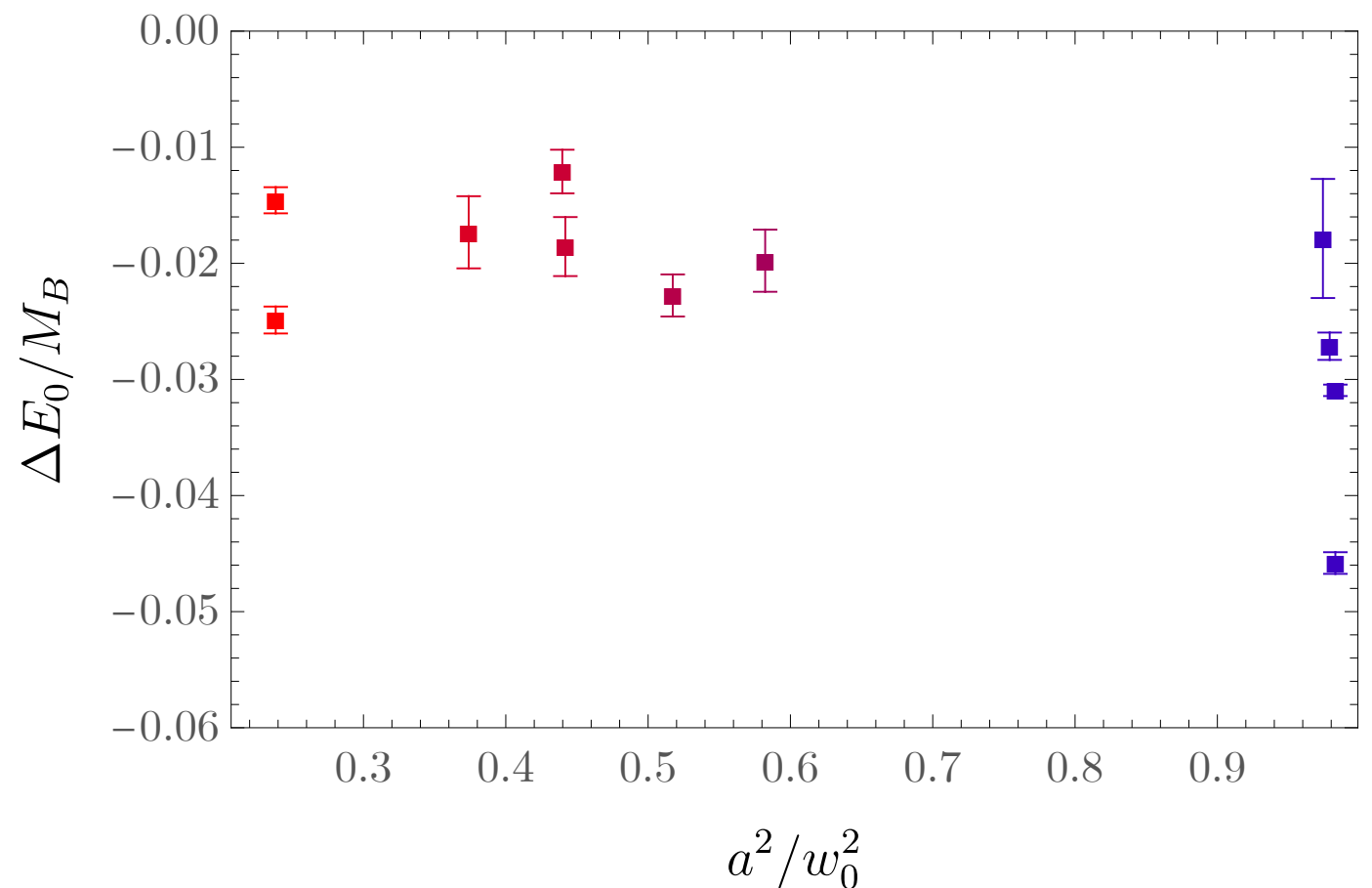
Can data help us understand the physics of lattice artifacts?

- No clear evidence in LQCD data for $O(a\Lambda_{\text{QCD}})$: formally present but small

- Clear evidence in LQCD data for $O(ak^\star)$ lattice artifacts

$$k^\star = \frac{1}{2} \sqrt{s - 4M_B^2}$$

*Note points also have different L ,
1D projection of multi-D problem*



Rest-frame fits

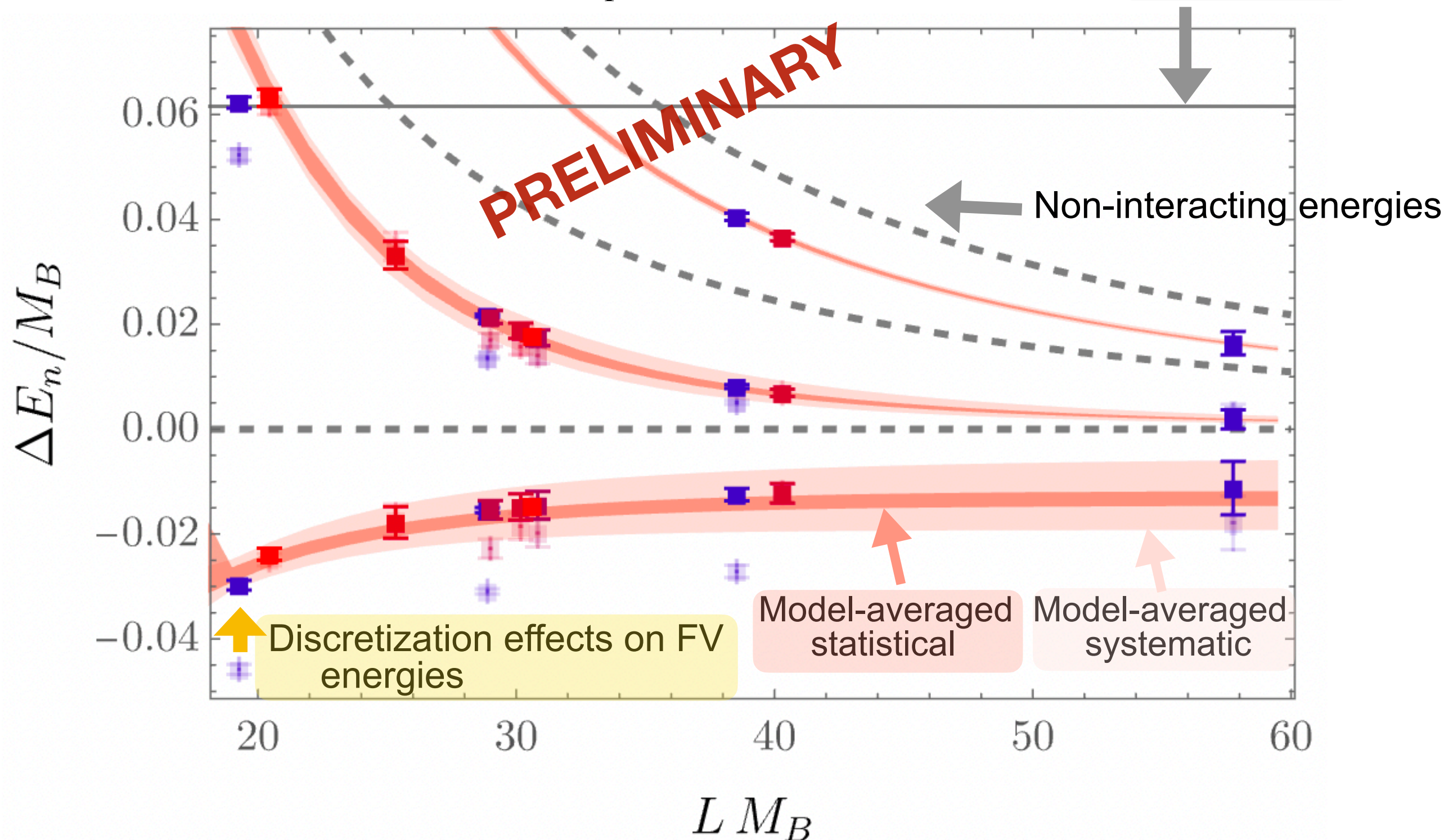
ERE params	Nuisance	χ^2	N_{dof}	χ^2_{gap}	AIC	$1/(m_\pi a_1^S)$	$m_\pi r_1^S$	$m_\pi^3 \rho_1^S$
a_1^S, r_1^S	-	138.2	23	6.48	142.	0.194	2.37	-
a_1^S, r_1^S, ρ_1^S	-	137.3	22	16.13	143.	0.196	2.38	0.13
a_1^S, r_1^S	m_π/M_N	102.1	20	33.68	112.	0.191	2.41	-
a_1^S, r_1^S	$e^{-m_\pi L}$	122.2	20	20.74	132.	0.187	2.53	-
a_1^S, r_1^S	ERE + a^2/w_0^2	11.5	21	0.08	20.	0.112	3.19	-
a_1^S, r_1^S, ρ_1^S	ERE + a^2/w_0^2	8.4	19	0.05	20.	0.131	3.06	1.21
a_1^S, r_1^S	$a^2 p^2$	53.4	20	3.69	63.	0.160	2.58	-
a_1^S, r_1^S, ρ_1^S	$a^2 p^2$	7.3	19	0.06	19.	0.154	2.92	3.32
a_1^S, r_1^S	$a^2 p_{\text{cntm}}^2$	63.8	20	3.42	74.	0.168	2.41	-
a_1^S, r_1^S, ρ_1^S	$a^2 p_{\text{cntm}}^2$	16.4	19	0.06	28.	0.170	2.37	2.85
a_1^S, r_1^S	ap	38.6	20	0.98	49.	0.091	3.29	-
a_1^S, r_1^S, ρ_1^S	ap	19.4	19	0.98	21.	0.057	3.60	2.34
a_1^S, r_1^S	ap_{cntm}	6	19	0.98	21.	0.057	2.44	-
a_1^S, r_1^S, ρ_1^S	ap_{cntm}	5	18	0.98	21.	0.057	1.74	1.65
a_1^S, r_1^S	a^2/w_0^2	6	19	0.98	21.	0.057	2.44	-
a_1^S, r_1^S, ρ_1^S	a^2/w_0^2	5	19	0.98	21.	0.057	2.54	-0.55
a_1^S, r_1^S	$a^2 p^2, m_\pi/M_N$	46	17	0.09	21.	0.178	2.40	-
a_1^S, r_1^S, ρ_1^S	$a^2 p^2, m_\pi/M_N$	2.7	16	0.09	21.	0.178	2.65	2.41
a_1^S, r_1^S	$a^2 p^2, e^{-m_\pi L}$	34.3	17	0.14	50.	0.162	2.93	-
a_1^S, r_1^S, ρ_1^S	$a^2 p^2, e^{-m_\pi L}$	3.7	16	0.02	22.	0.156	2.98	2.73
a_1^S, r_1^S	$a^2 p_{\text{cntm}}^2, m_\pi/M_N$	41.8	17	3.36	58.	0.188	2.41	-
a_1^S, r_1^S	$a^2 p_{\text{cntm}}^2, e^{-m_\pi L}$	16.0	17	0.02	32.	0.160	2.69	-
a_1^S, r_1^S	$ap, a^2 p^2$	38.4	17	0.76	54.	0.089	3.31	-
a_1^S, r_1^S, ρ_1^S	$ap, a^2 p^2$	3	16	0.02	21.	0.157	2.54	3.67
a_1^S, r_1^S	$ap_{\text{cntm}}, a^2 p_{\text{cntm}}^2$	61.2	17	3.68	77.	0.154	2.46	-
a_1^S, r_1^S, ρ_1^S	$ap_{\text{cntm}}, a^2 p_{\text{cntm}}^2$	3.2	16	0.00	21.	0.192	2.92	2.61
a_1^S, r_1^S	$a^2 p^2, a^2/w_0^2$	27.2	17	0.27	43.	0.117	3.07	-
a_1^S, r_1^S, ρ_1^S	$a^2 p^2, a^2/w_0^2$	3.1	16	0.02	21.	0.156	2.77	3.57
a_1^S, r_1^S	$a^2 p^2, a^3 p^3$	23.8	17	1.16	40.	0.019	4.52	-
a_1^S, r_1^S, ρ_1^S	$a^2 p^2, a^3 p^3$	3.1	16	0.02	21.	0.167	2.49	3.28
a_1^S, r_1^S	$a^2 p^2, a^4 p^4$	30.9	17	1.47	47.	0.071	3.88	-
a_1^S, r_1^S, ρ_1^S	$a^2 p^2, a^4 p^4$	3.0	16	0.02	21.	0.171	2.43	3.13

Models without discretization effects cannot fit the data

PRELIMINARY

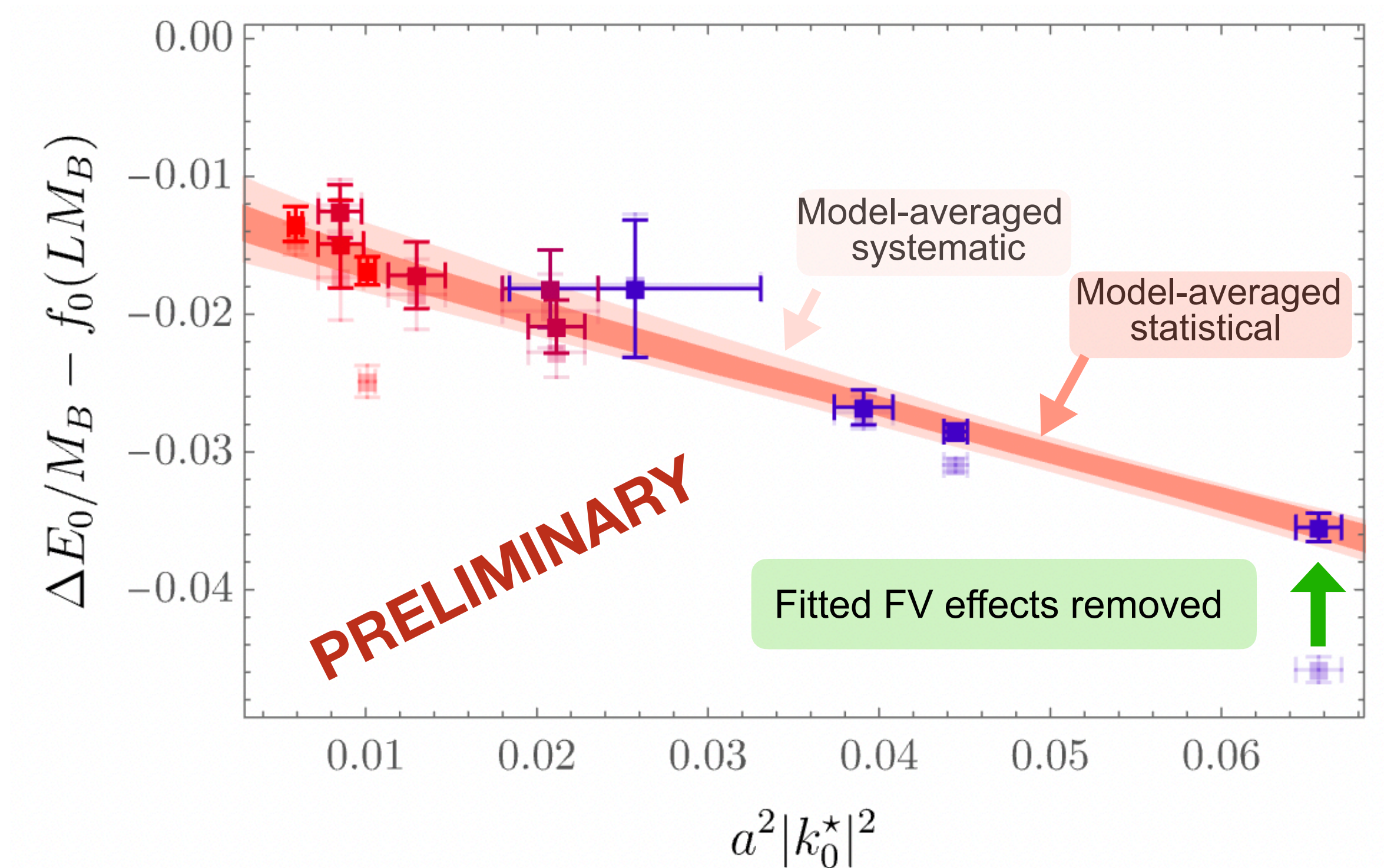
Rest-frame fits

$\Delta E_n = E_n - 2M_B$ analyzed for 25 A_1^+ energies ~below (right-hand) t -channel cut



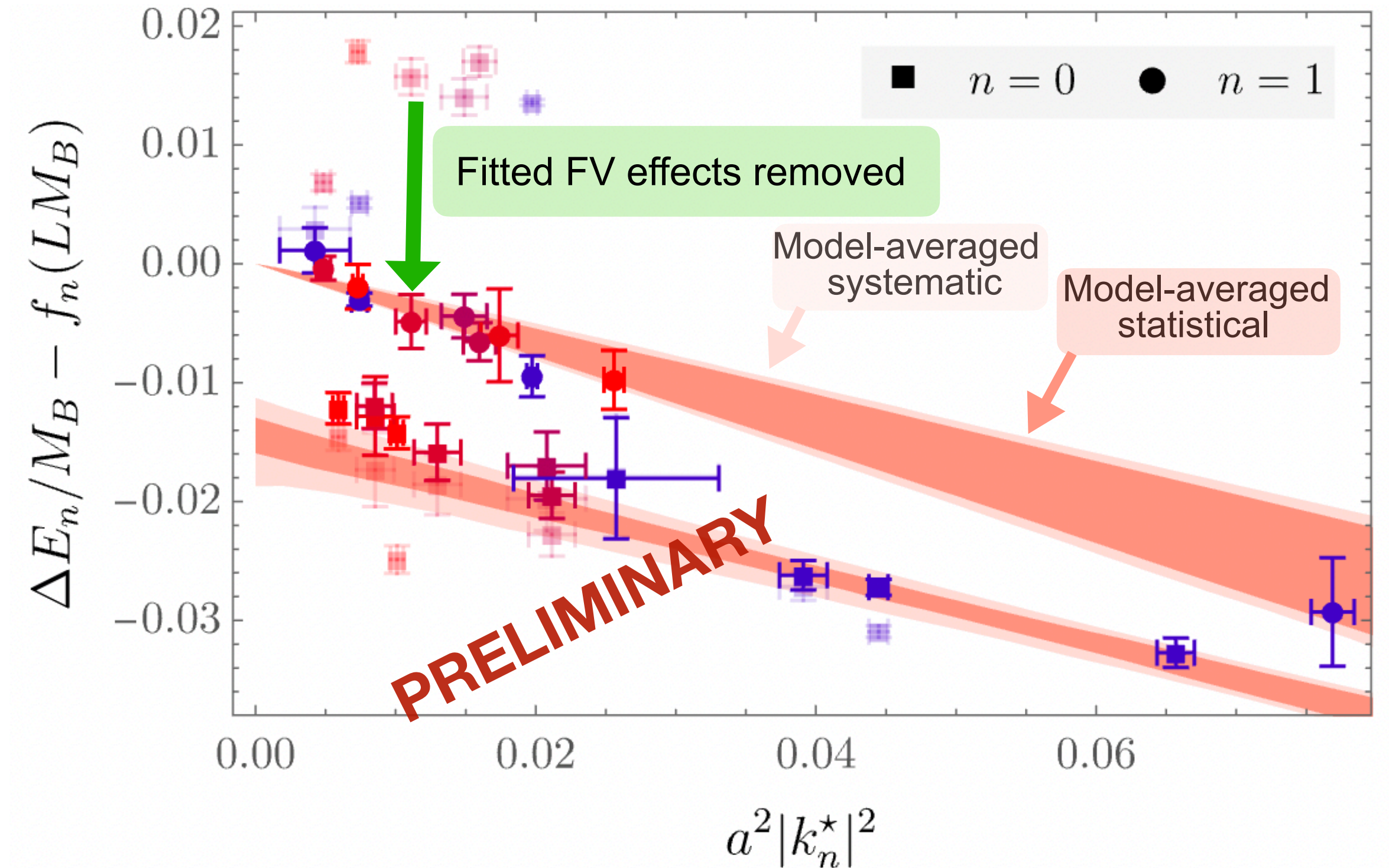
Red = finer lattice spacing, *blue* = coarser lattice spacing

Rest-frame fits



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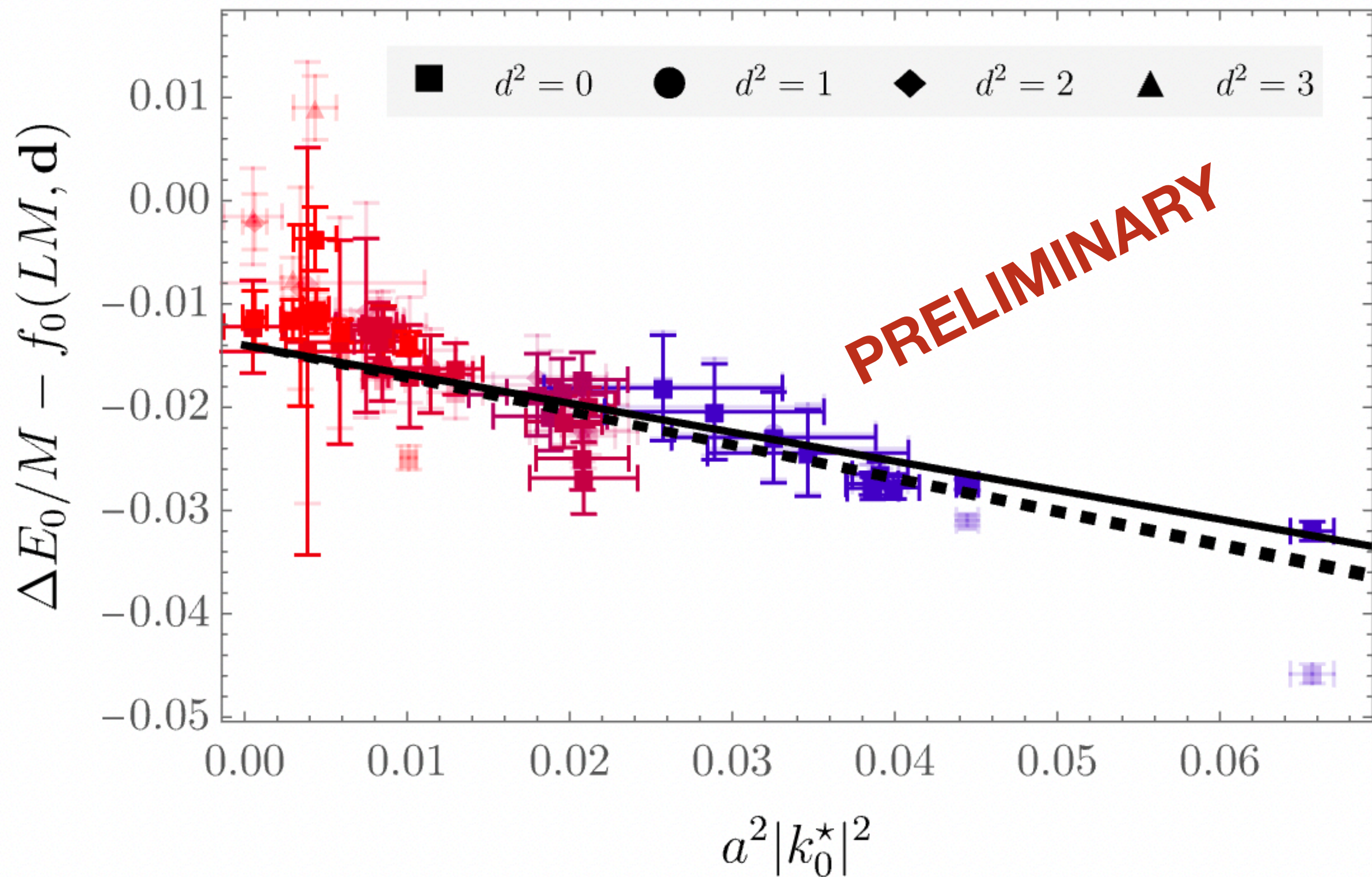
Boosted fits

ERE params	Nuisance	χ^2	N_{dof}	χ^2_{gap}	AIC	$1/(m_\pi a_1^S)$	$m_\pi r_1^S$	$m_\pi^3 \rho_1^S$	$m_\pi^3 a_1^D$	r_1^D/m_π
a_1^S, r_1^S	ERE + a^2/w_0^2	314.7	63	82.5	322.	0.108	3.31	-	-	-
a_1^S, r_1^S, a_1^D	ERE + a^2/w_0^2	154.9	61	72.1	167.	0.128	2.98	-	-1.70	-
a_1^S, r_1^S, ρ_1^S	ERE + a^2/w_0^2	311.4	61	74.3	323.	0.142	2.91	0.85	-	-
$a_1^S, r_1^S, \rho_1^S, a_1^D$	ERE + a^2/w_0^2	152.1	59	69.4	168.	0.157	2.77	1.23	-2.45	-
$a_1^S, r_1^S, \rho_1^S, a_1^D, r_1^D$	ERE + a^2/w_0^2	151.1	57	69.2	171.	0.161	2.74	1.38	-5.89	2.2
a_1^S, r_1^S	$a^2 p^2$	65.2	56	13.6	87.	0.161	2.54	-	-	-
a_1^S, r_1^S, a_1^D	$a^2 p^2$	64.3	55	13.6	88.	0.162	2.54	-	-1.31	-
a_1^S, r_1^S, ρ_1^S	$a^2 p^2$	29.6	55	2.3	54.	0.164	2.82	2.04	-	-
$a_1^S, r_1^S, \rho_1^S, a_1^D$	$a^2 p^2$	29.4	54	2.3	55.	0.164	2.80	1.90	-0.51	-
$a_1^S, r_1^S, \rho_1^S, a_1^D, r_1^D$	$a^2 p^2$	29.3	53	2.2	57.	0.165	2.78	1.93	-0.84	4.5
a_1^S, r_1^S	$ap, a^2 p^2$	54.4	47	3.0	94.	0.089	3.31	-	-	-
a_1^S, r_1^S, a_1^D	$ap, a^2 p^2$	53.9	46	2.8	96.	0.089	3.31	-	-1.00	-
a_1^S, r_1^S, ρ_1^S	$ap, a^2 p^2$	27.9	46	3.3	70.	0.156	2.82	2.04	-	-
$a_1^S, r_1^S, \rho_1^S, a_1^D$	$ap, a^2 p^2$	27.4	45	3.1	71.	0.156	2.78	2.27	-0.60	-
$a_1^S, r_1^S, \rho_1^S, a_1^D, r_1^D$	$ap, a^2 p^2$	22.9	44	2.9	72.	0.161	2.74	2.02	-1.50	4.0
a_1^S, r_1^S	$a^2 p^2, m_\pi/M_N$	76.	47	6.2	98.	0.144	2.76	-	-	-
a_1^S, r_1^S, a_1^D	$a^2 p^2, m_\pi/M_N$	61.	46	5.9	99.	0.145	2.74	-	-1.15	-
a_1^S, r_1^S, ρ_1^S	$a^2 p^2, m_\pi/M_N$	22.	46	1.2	70.	0.156	2.82	2.04	-	-
$a_1^S, r_1^S, \rho_1^S, a_1^D$	$a^2 p^2, m_\pi/M_N$	20.	45	1.1	68.	0.166	2.70	1.97	-0.60	-
$a_1^S, r_1^S, \rho_1^S, a_1^D, r_1^D$	$a^2 p^2, m_\pi/M_N$	21.	44	1.1	70.	0.167	2.71	2.02	-1.00	4.0
a_1^S, r_1^S	$a^2 p^2, a^2/w_0^2$	46.3	47	4.3	86.	0.139	2.83	-	-	-
a_1^S, r_1^S, a_1^D	$a^2 p^2, a^2/w_0^2$	46.1	46	4.3	88.	0.140	2.81	-	-0.60	-
a_1^S, r_1^S, ρ_1^S	$a^2 p^2, a^2/w_0^2$	23.8	46	1.6	66.	0.164	2.82	2.04	-	-
$a_1^S, r_1^S, \rho_1^S, a_1^D$	$a^2 p^2, a^2/w_0^2$	23.4	45	1.5	67.	0.165	2.82	2.22	0.00	-
$a_1^S, r_1^S, \rho_1^S, a_1^D, r_1^D$	$a^2 p^2, a^2/w_0^2$	23.4	44	1.5	69.	0.165	2.82	2.22	0.00	0.0
a_1^S, r_1^S	$a^2 p^2, a^3 p^3$	57.	47	6.2	98.	0.144	2.76	-	-	-
a_1^S, r_1^S, a_1^D	$a^2 p^2, a^3 p^3$	57.1	46	5.9	99.	0.145	2.74	-	-1.15	-
a_1^S, r_1^S, ρ_1^S	$a^2 p^2, a^3 p^3$	27.7	46	1.2	70.	0.156	2.82	2.04	-	-
$a_1^S, r_1^S, \rho_1^S, a_1^D$	$a^2 p^2, a^3 p^3$	24.2	45	1.1	68.	0.166	2.70	1.97	-0.60	-
$a_1^S, r_1^S, \rho_1^S, a_1^D, r_1^D$	$a^2 p^2, a^3 p^3$	24.0	44	1.1	70.	0.167	2.71	2.02	-1.00	4.0
a_1^S, r_1^S	$a^2 p^2, a^4 p^4$	57.8	47	5.9	98.	0.144	2.74	-	-	-
a_1^S, r_1^S, a_1^D	$a^2 p^2, a^4 p^4$	45.5	46	4.9	87.	0.075	3.82	-	-1.50	-
a_1^S, r_1^S, ρ_1^S	$a^2 p^2, a^4 p^4$	25.5	46	0.9	67.	0.166	2.81	2.04	-	-
$a_1^S, r_1^S, \rho_1^S, a_1^D$	$a^2 p^2, a^4 p^4$	25.4	45	0.9	69.	0.166	2.81	2.04	-0.35	-
$a_1^S, r_1^S, \rho_1^S, a_1^D, r_1^D$	$a^2 p^2, a^4 p^4$	25.3	44	0.9	71.	0.166	2.80	2.04	-0.60	8.0

Models with scattering parameters modified by discretization effects cannot fit the data

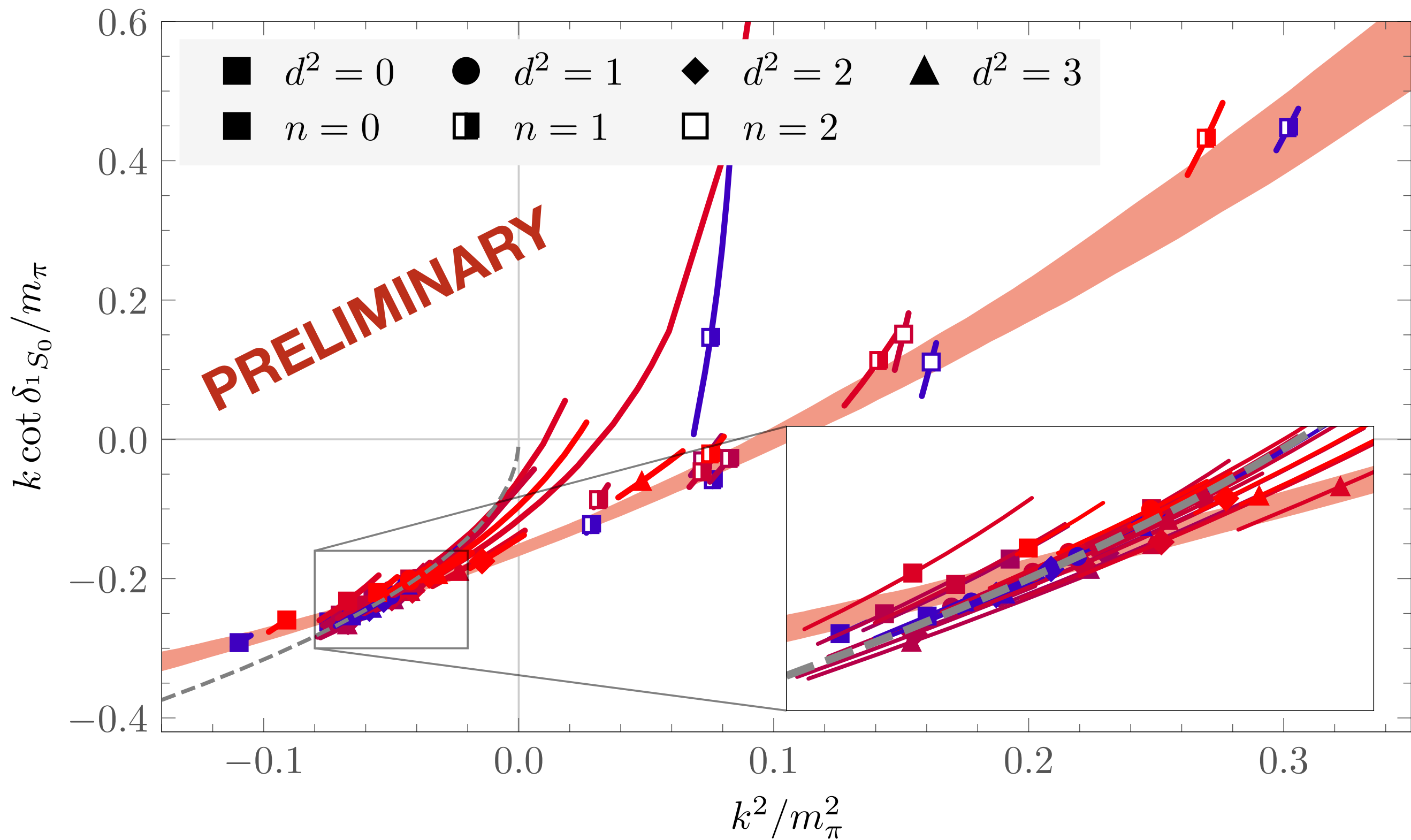
PRELIMINARY

Boosted fits



Red = finer lattice spacing, *blue* = coarser lattice spacing

BB phase shifts

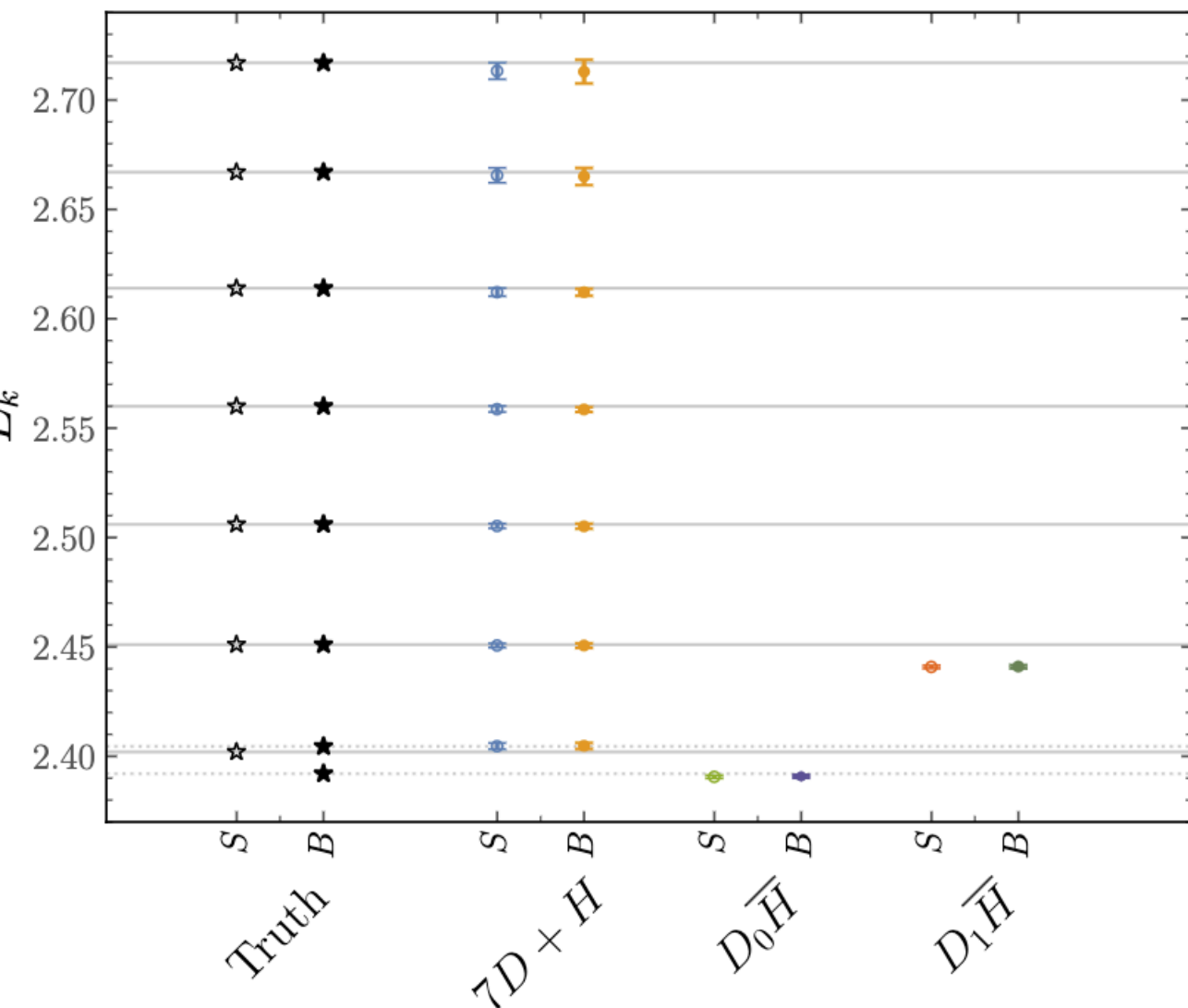


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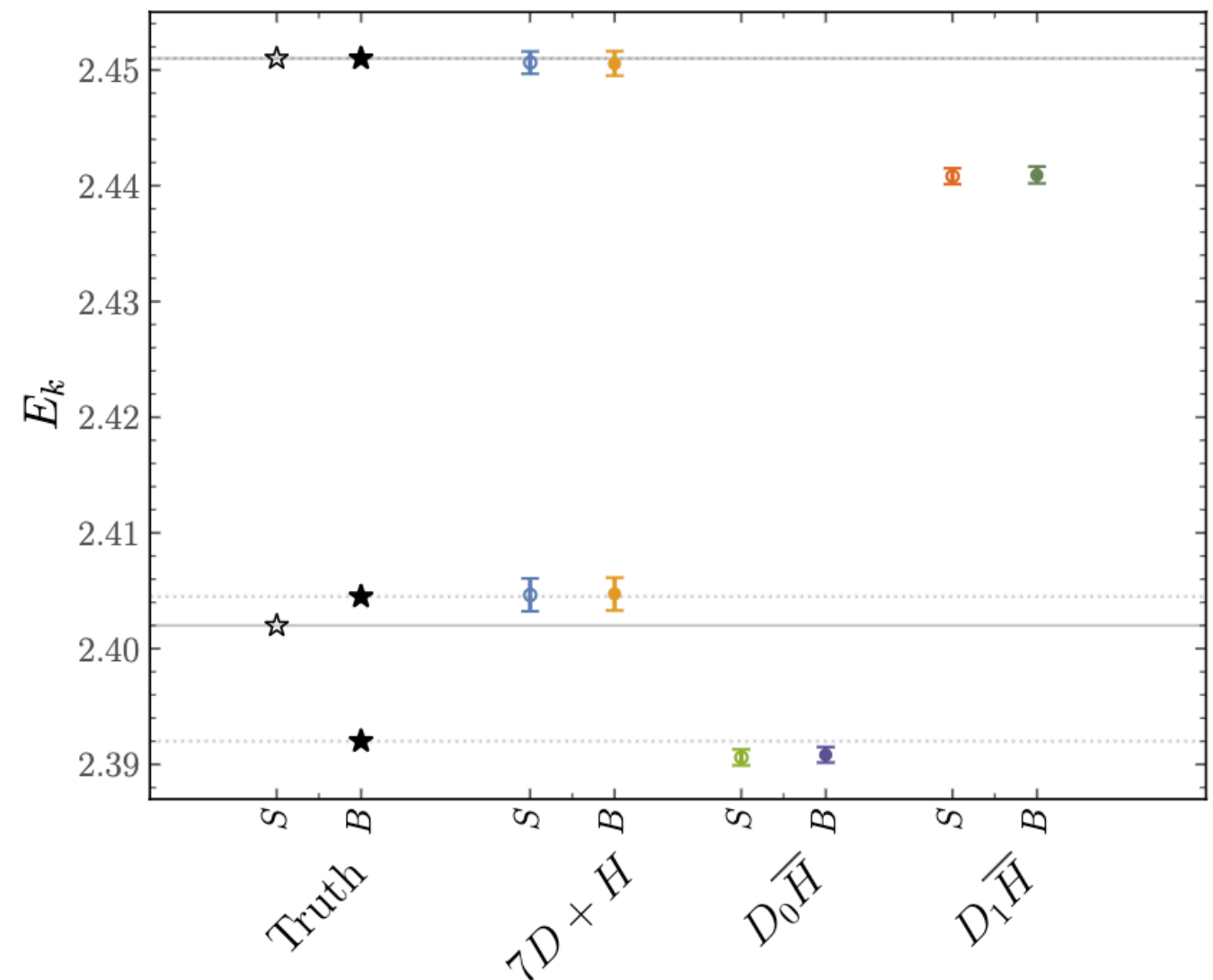
Spectral bounds

Spectroscopy is formally an ill-posed inverse problem

- *Spectroscopy = spectral reconstruction for specific energy ranges*
- *Multiple underlying spectra can give rise to identical energy estimators*



Detmold, MW, et al [NPLQCD], arXiv:2601.22272



See talk by Will Detmold 20 minutes ago

Assumptions for spectroscopy

Assume nothing

- **Lanczos residual bounds**

MW, PRL 134 (2025)

$$O(\sqrt{B})$$

New directly calculable small parameter for quantifying systematic errors

More conservative

More precise

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$O(B)$ calculable error bounds

[Detmold, MW, et al \[NPLQCD\], arXiv:2601.22272](#)

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Assume energy estimators have saturated their asymptotic values

- **Statistical uncertainties on fits / energy estimators**

$O(e^{-\delta_1 t})$ systematics, no calculable error bounds

Requires strong assumptions about energy spectrum and operator overlaps for multi-hadron systems where $e^{-\delta_1 t}$ is not a small parameter

More conservative

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Assumptions for spectroscopy

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MW, PRL 134 (2025)

$$O(\sqrt{B})$$

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More conservative

Assume no missing levels in some energy range

- **Lanczos gap bounds**

$O(B)$ calculable error bounds

Detm

Detm

**Already required for multi-ensemble FV analysis:
quantization conditions predict E_n for specific n**

More precise

Assume energy estimators have saturated their asymptotic values

- **Statistical uncertainties on fits / energy estimators**

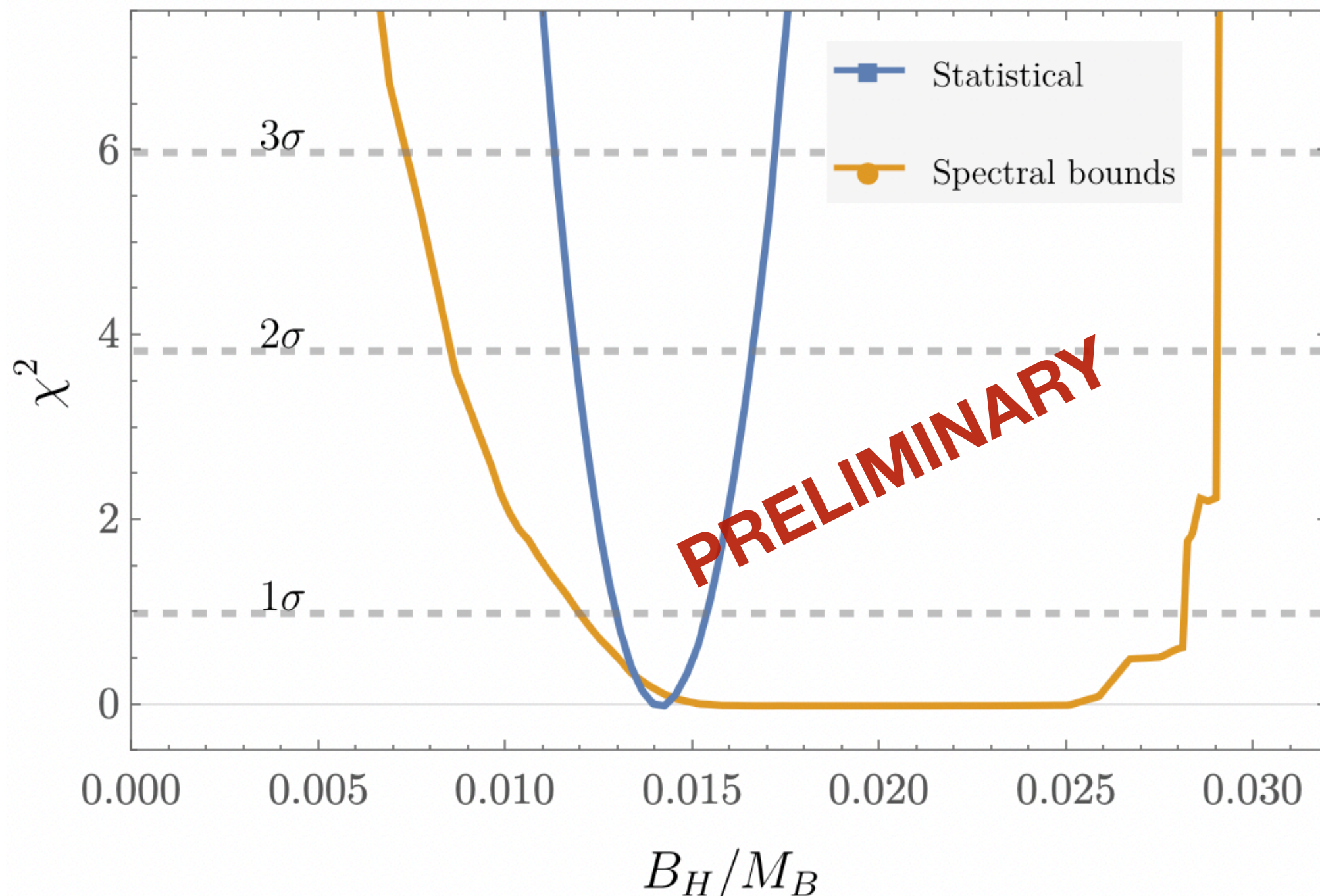
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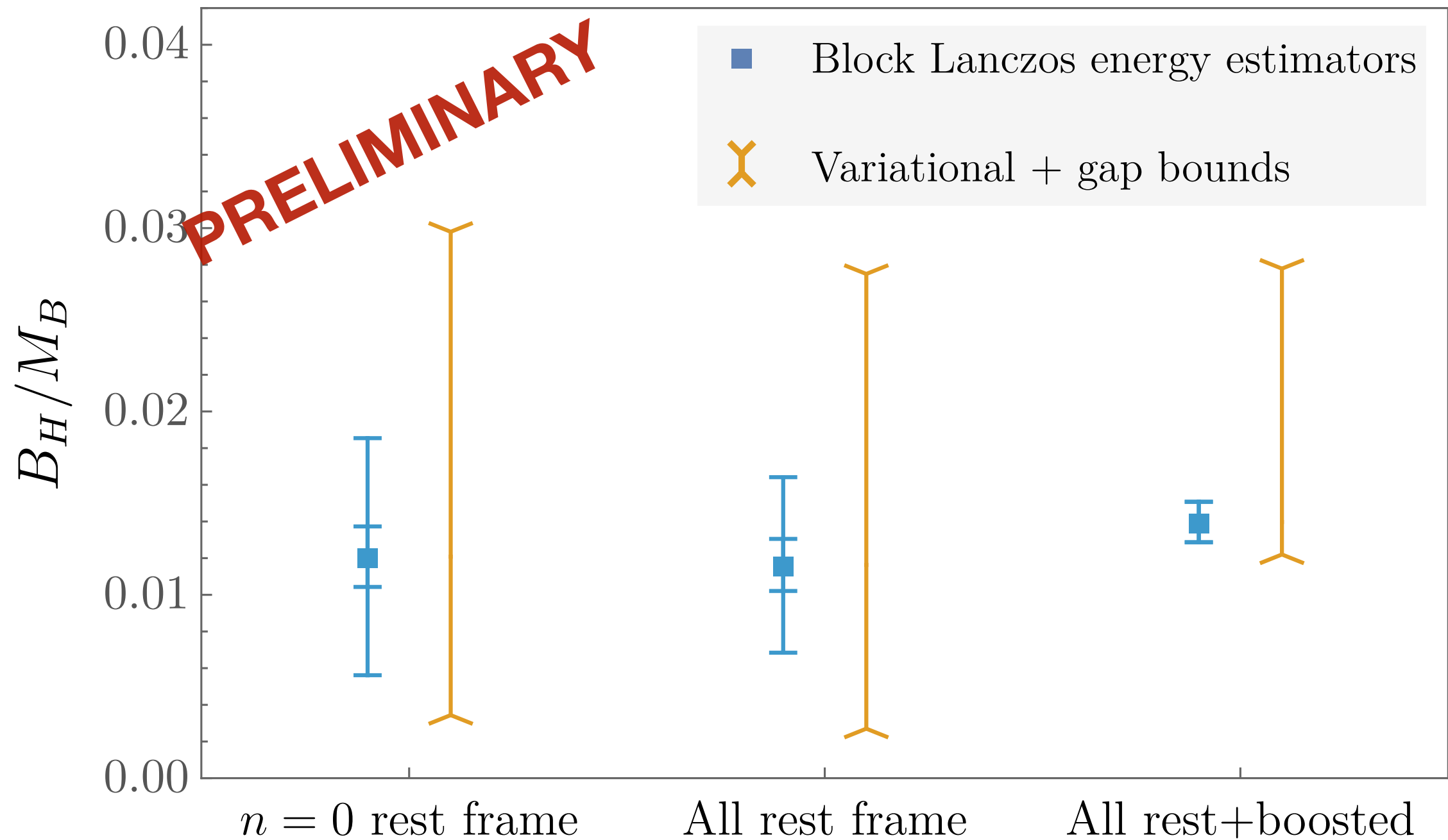
Spectral bounds

The H-dibaryon is bound in QCD at the $SU(3)$ point with $m_\pi/M_N = 1/2$, at $> 99\%$ confidence assuming no missing states

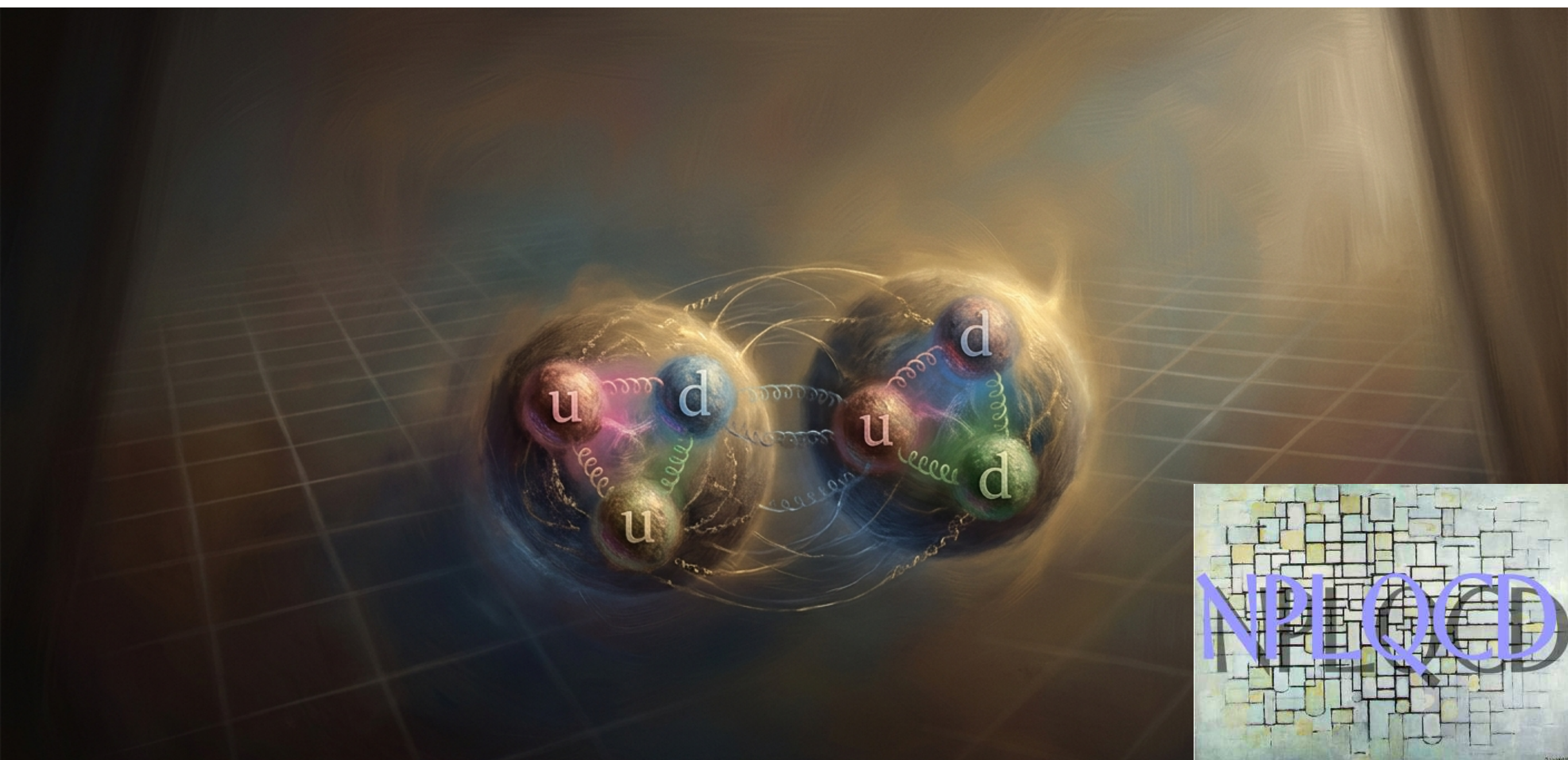
- ***Spectral bounds require no further assumptions that excited-state effects are “small” or interpolator overlaps are “large”***



Spectral bounds



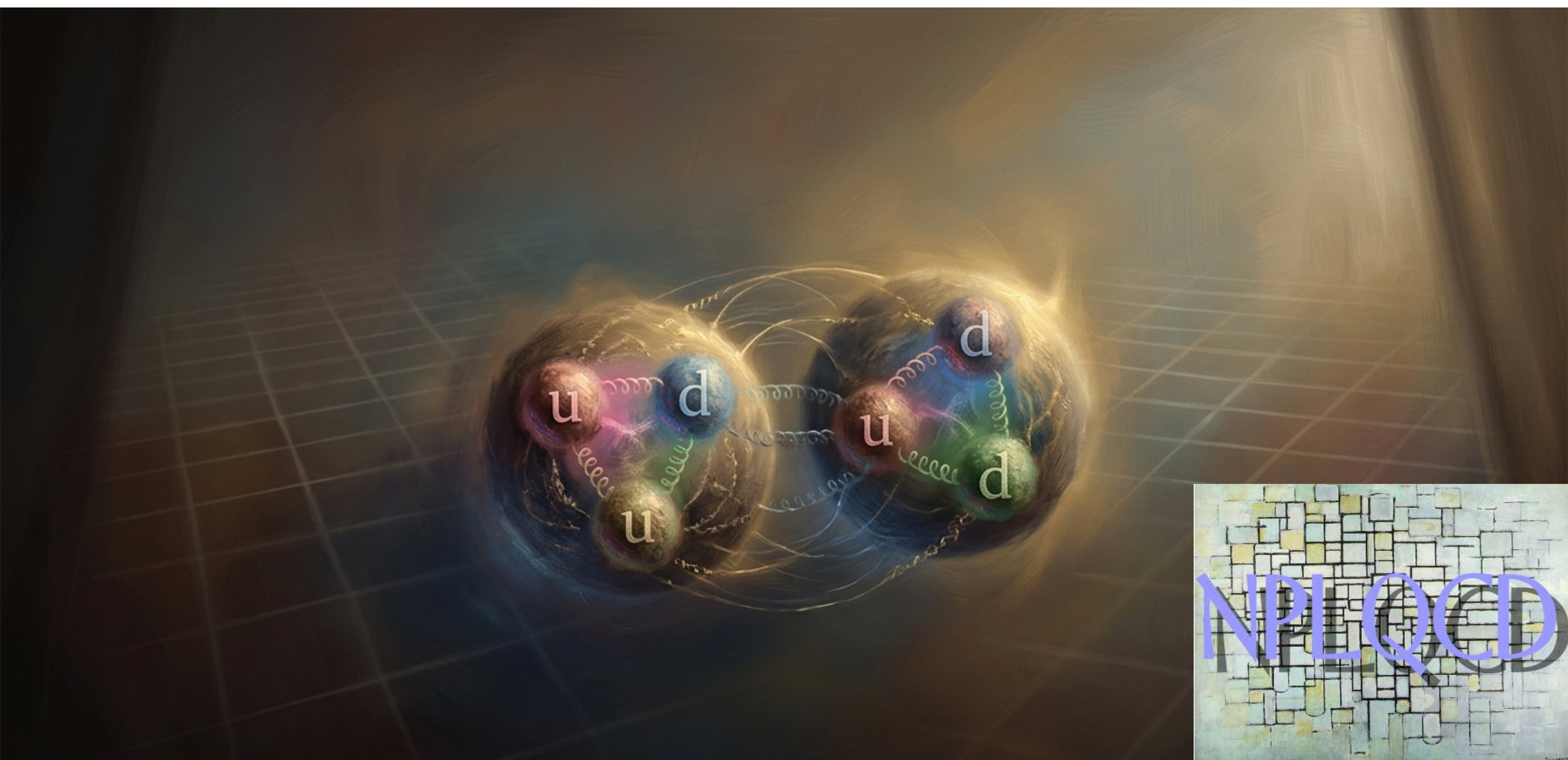
... so what's the *BB* spectrum for $m_\pi \sim 135$ MeV?



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Stay tuned

We have the technology!



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We have the technology!

- Excited-state effects
- Discretization effects

- Physical quark masses

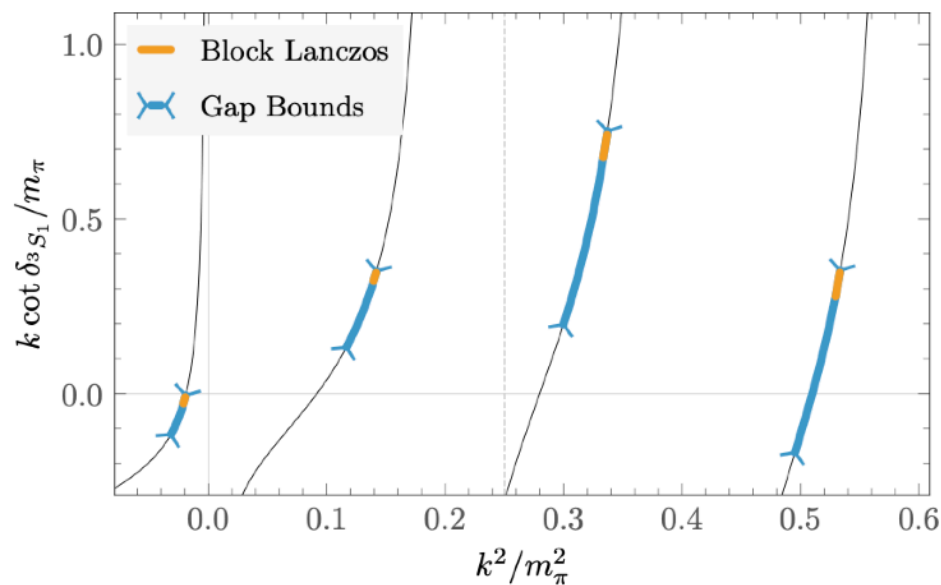


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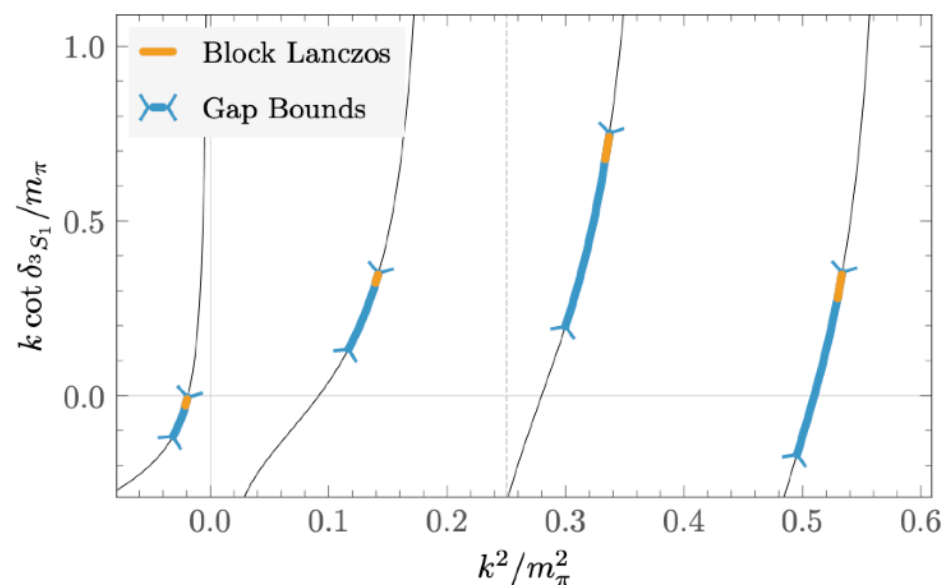


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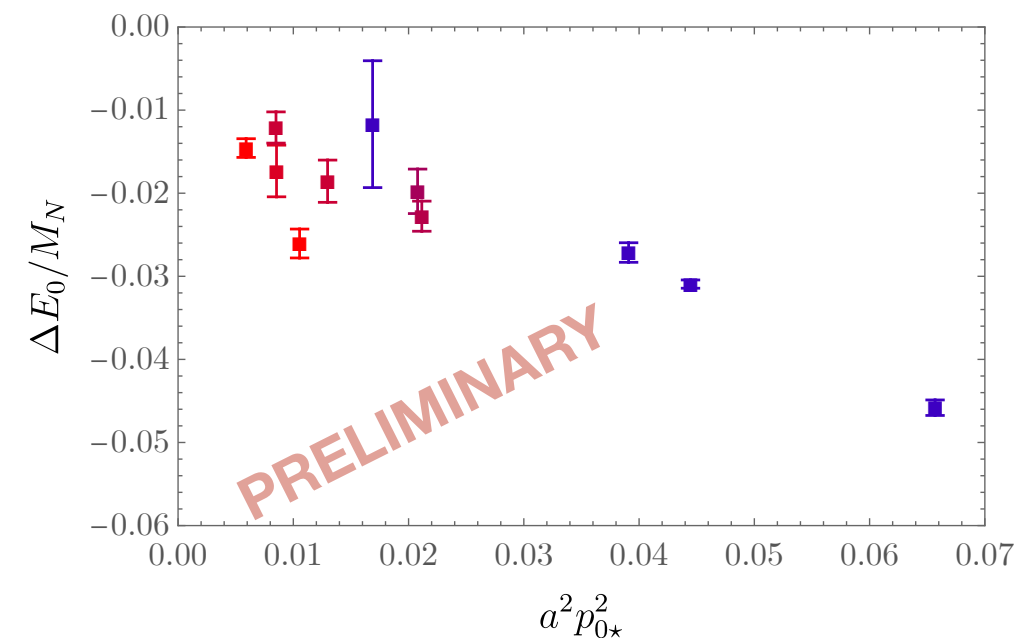
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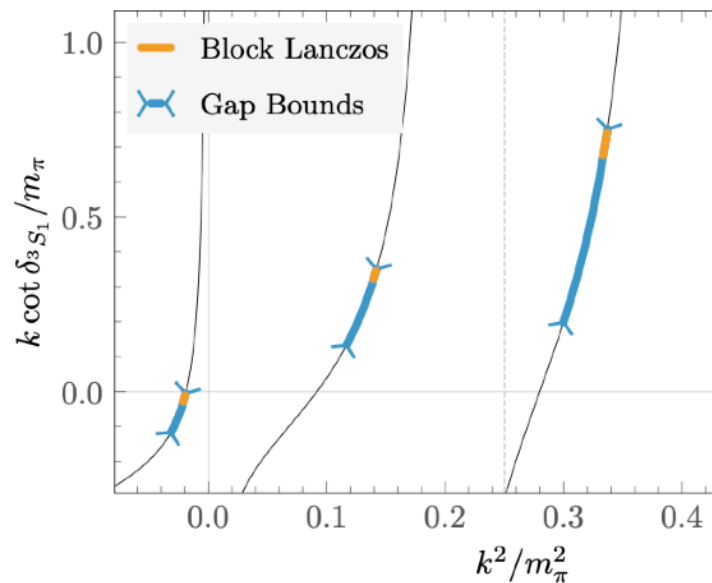


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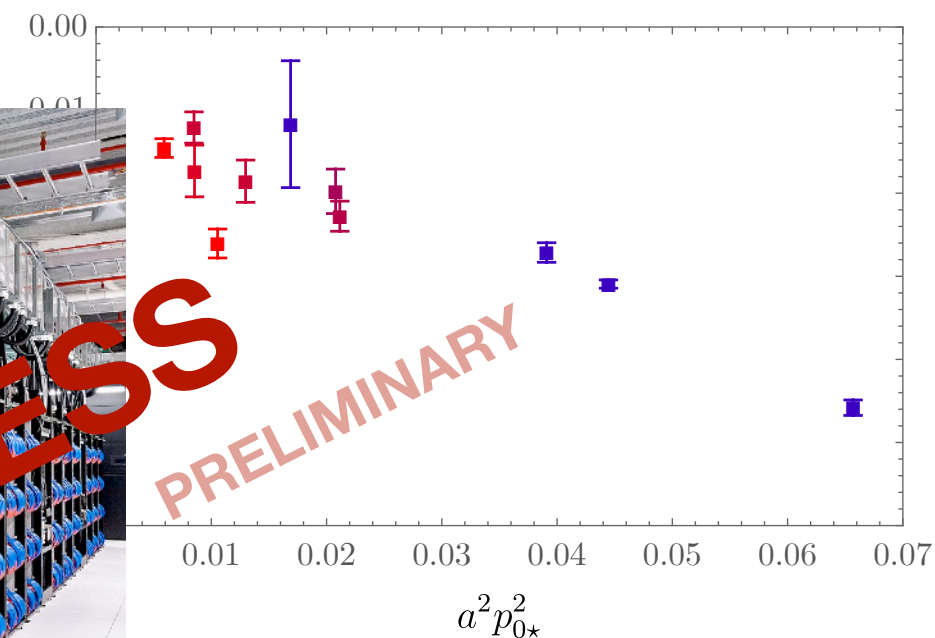
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WORK IN PROGRESS

- Physical quark masses

