Meson Baryon Scattering

Aaron Torok

Department of Physics, Indiana University

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Meson Baryon Scattering in Lattice QCD

Calculation of the $\pi^+\Sigma^+$, and $\pi^+\Xi^0$ scattering lengths

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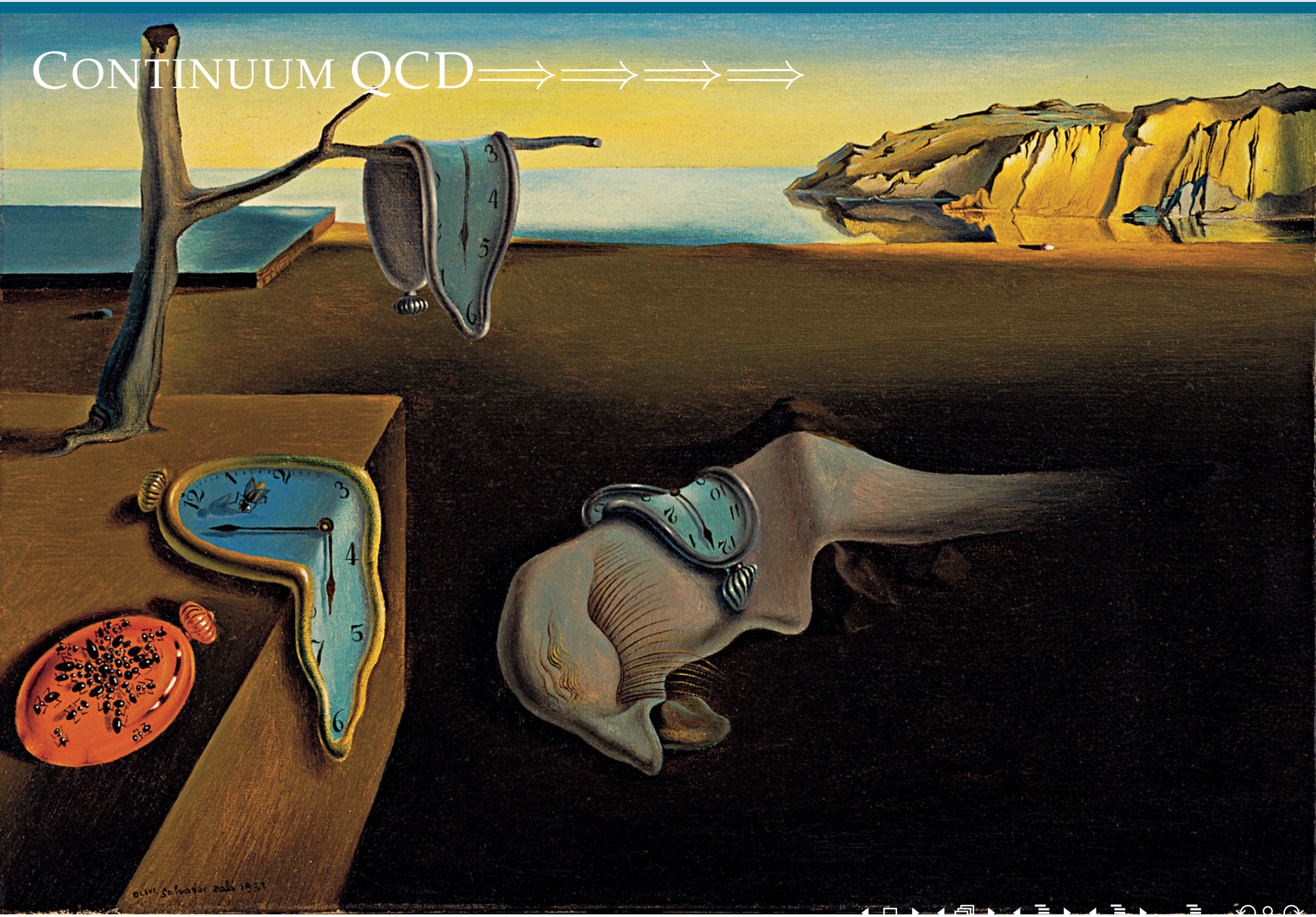
Outline

- Background and motivation
- Calculating scattering lengths using LQCD
- Signal to Noise Ratio
- Meson-Baryon Results
- Conclusion

Background and Motivation

- We need to calculate in the non-perturbative regime!
- Number of counterterms in χPT beyond leading order (LO) or next-to-leading order (NLO) in many calculations often exceeds the number of experimental measurements available $\rightarrow$ turn to the lattice
- Important to recover what is known experimentally to high precision, however, not the main objective $\rightarrow$ calculate what cannot be accessed experimentally, or which can be measured with only limited precision

Continuum QCD $\longrightarrow \longrightarrow \longrightarrow \longrightarrow$



$\Longrightarrow\Longrightarrow\Longrightarrow\Longrightarrow$ Lattice QCD

Lattice QCD: Some Challenges

- Calculational cost
- Calculations done at unphysical (larger) light quark masses; Chiral extrapolation convergence $m_\pi^{latt} > m_\pi^{phys} \rightarrow$ χPT extrapolation
- Signal to noise ratio (not a problem with pions)
- Discriminating the ground state from excited states
- Many interesting processes have annihilation diagrams $\rightarrow$ cost

Steps to calculate the scattering length

- Start with gauge fields, in this case MILC staggered
- Generate propagators
- Calculate contractions $\rightarrow$ correlators
- Fit the correlators to sum of exponentials $\rightarrow$ extract masses, energies
- Using jackknifed tables of masses and energies calculate the scattering length
- Using scattering lengths calculated at several quark masses, calculate χPT LECs
- With LECs that have been fit, extrapolate to physical pion mass

Gauge Ensembles

- MILC gauge ensembles, staggered, asqtad-improved, coarse ($b \sim 0.125$ fm), and fine ($b \sim 0.09$ fm).
- The Chroma software system

cfgs generated by	m_l/m_s	m_π(MeV)	L(fm)	cfgs $\times$ sources
MILC	0.14	291	2.5	1039×24
MILC	0.2	352	2.5	769×24
MILC	0.4	491	2.5	486×24
MILC	0.6	591	2.5	564×24
MILC	0.2	352	3.5	128×8
MILC	0.21	320	2.5	1001×8

Energy Eigenvalues in a Box

The exact energy eigenvalue equation for E_n:

$$\Delta E_n \equiv E_n - m_1 - m_2 = \sqrt{p_n^2 + m_1^2} + \sqrt{p_n^2 + m_2^2} - m_1 - m_2$$

Energy levels occur at momenta $\mathbf{p} = 2\pi\mathbf{j}/L$ (no interaction); The Lüscher formula:

$$p\cot\delta(p) = \frac{1}{\pi L}\mathbf{S}\left(\frac{pL}{2\pi}\right), \qquad \mathbf{S}\left(\frac{pL}{2\pi}\right) \equiv \sum_{\mathbf{j}}^{\Lambda_j} \frac{1}{|\mathbf{j}|^2 - \left(\frac{pL}{2\pi}\right)^2} - 4\pi\Lambda_j$$

the effective range expansion for $pcot\delta(p) \to 1/a$, as $p \to 0$.

Calculating ΔE, and Single Particle Masses

The correlation functions for the meson (ϕ) and baryon (B) systems are

$$C_\phi(t) = \sum_{\mathbf{x}} \langle \phi^\dagger(t,\mathbf{x})\, \phi(0,\mathbf{0})\rangle, \qquad C_B(t) = \sum_{\mathbf{x}} \langle \bar{B}(t,\mathbf{x})\, B(0,\mathbf{0})\rangle$$

$$C_\phi(t) \to \mathcal{B} e^{-m_\phi t}, \qquad C_B(t) \to \mathcal{D} e^{-m_B t}, \qquad \text{for } t, L \to \infty$$

$$C_{\phi B}(p,t) \;=\; \sum_{|\mathbf{p}|=p} \sum_{\mathbf{x},\mathbf{y}} e^{i\mathbf{p}\cdot(\mathbf{x}-\mathbf{y})} \langle \phi^\dagger(t,\mathbf{x})\, \bar{B}(t,\mathbf{y})\, \phi(0,\mathbf{0})\, B(0,\mathbf{0})\rangle$$

$$G_{\phi B}(p,t) \;\equiv\; \frac{C_{\phi B}(p,t)}{C_\phi(t) C_B(t)} \;\to\; \sum_{n=0}^{\infty} \mathcal{A}_n\, e^{-\Delta E_n t}$$

Calculating ΔE, and Single Particle Masses

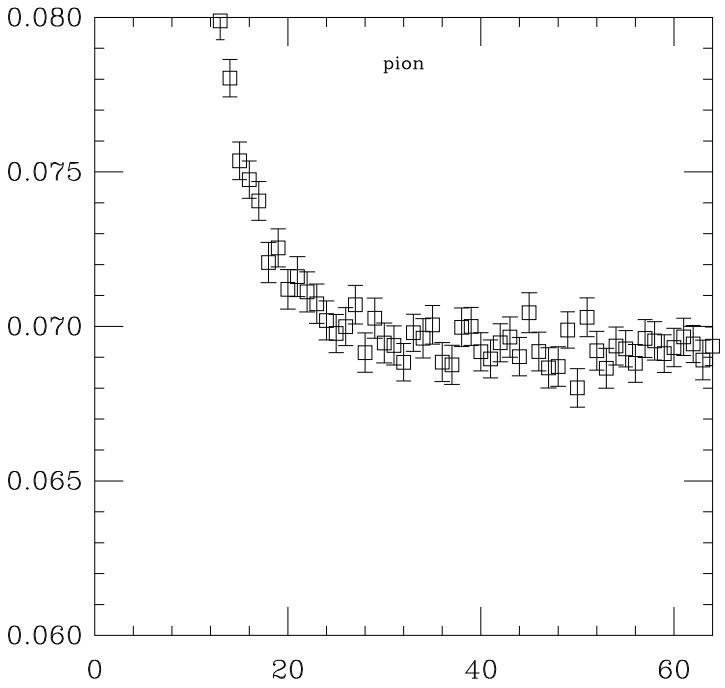
We extract, m_ϕ, m_B, and ΔE

$$C_\phi(t) \to \mathcal{B}e^{-m_\phi t}, \qquad C_B(t) \to \mathcal{D}e^{-m_B t}, \qquad \text{for } t, L \to \infty$$

$$G_{\phi B}(p,t) \equiv \frac{C_{\phi B}(p,t)}{C_\phi(t)C_B(t)} \to \sum_{n=0}^{\infty} \mathcal{A}_n \, e^{-\Delta E_n t}$$

Effective Plots

$$m^{\text{eff}}_{\phi,B} = \frac{1}{n_J}\log\left(\frac{C_{\phi,B}(t)}{C_{\phi,B}(t+n_J)}\right), \qquad \Delta E^{\text{eff}}_{\phi B} = \frac{1}{n_J}\log\left(\frac{G_{\phi B}(t)}{G_{\phi B}(t+n_J)}\right).$$



Linear Combination of Correlators

$$C^{SS}(t) = Ae^{-m_1 t} + Be^{-m_2 t} + \ldots, \qquad C^{SP}(t) = Ce^{-m_1 t} + De^{-m_2 t} + \ldots,$$

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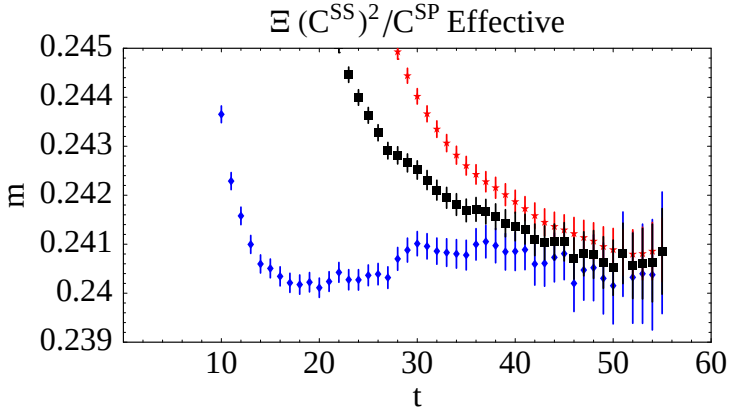
$$\frac{(C^{SS}(t))^2}{C^{SP}(t)} \approx \frac{A^2}{C} e^{-m_1 t} + \left(\frac{2ABC - A^2 D}{C^2} \right) e^{-m_2 t} + \ldots$$



LINEAR COMBINATION OF CORRELATORS

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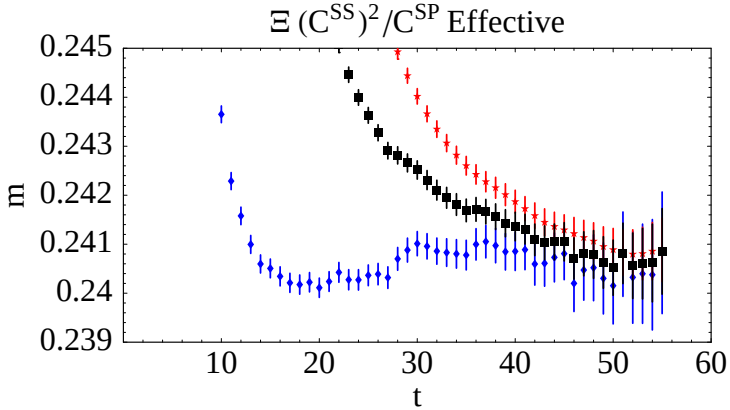
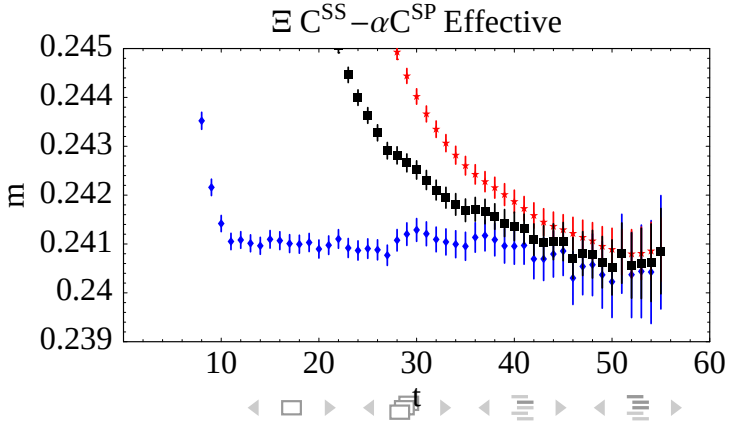
$$C^{SS}(t) - \alpha C^{SP}(t) = (A - \alpha C) e^{-m_1 t} + (B - \alpha D) e^{-m_2 t} + \ldots$$





Signal to Noise Ratio

- for the pion, signal $\rightarrow Ae^{-m_\pi t}$, $\sigma^2 \rightarrow Be^{-2m_\pi t}$
- for the proton, signal $\rightarrow Ce^{-m_p t}$, $\sigma^2 \rightarrow De^{-3m_\pi t}$
- s/n(t): pion $\rightarrow$ constant
- s/n(t): proton $\sim e^{-(m_p - \frac{3}{2}m_\pi)t}$

Meson Baryon

The are six elastic MB scattering processes without annihilation diagrams that we calculated on the Lattice

Particles	Isospin	Quark Content
$\pi^+\Sigma^+$	2	$uu\bar{u}ds$
$\pi^+\Xi^0$	3/2	$uu\bar{d}ss$
K^+p	1	$uuud\bar{s}$
K^+n	0 *and* 1	$uudd\bar{s}$
$\overline{K}^0\Sigma^+$	3/2	$uu\bar{d}ss$
$\overline{K}^0\Xi^0$	1	$u\bar{d}sss$

MESON BARYON

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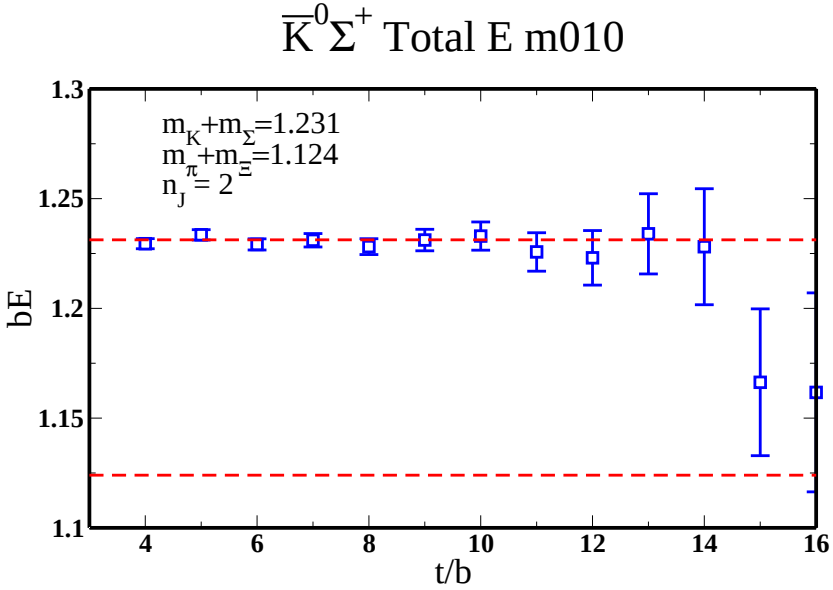
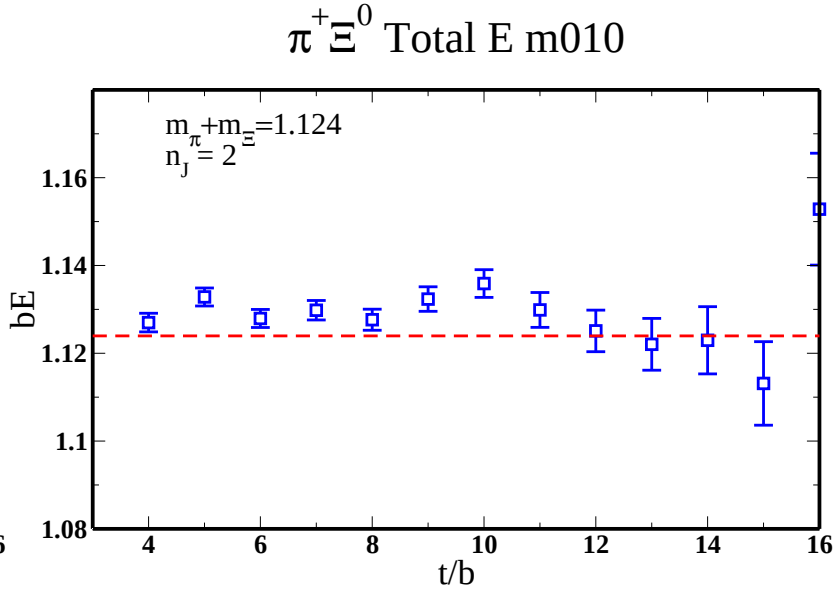
$\overline{K}^0\Sigma^+$	3/2	$uu\bar{d}ss$
$\overline{K}^0\Xi^0$	1	$u\bar{d}sss$

coupled channel, same valence quarks $\rightarrow uu\bar{d}ss$

Coupled Channel

The $\pi^+\Xi^0$ and $\overline{K}^0\Sigma^+$ have the same quark content, and constitute a coupled channel...





We extracted $a_{\pi^+\Xi^0}$, but not $a_{\overline{K}^0\Sigma^+}$

Calculated meson and baryon masses and ΔE

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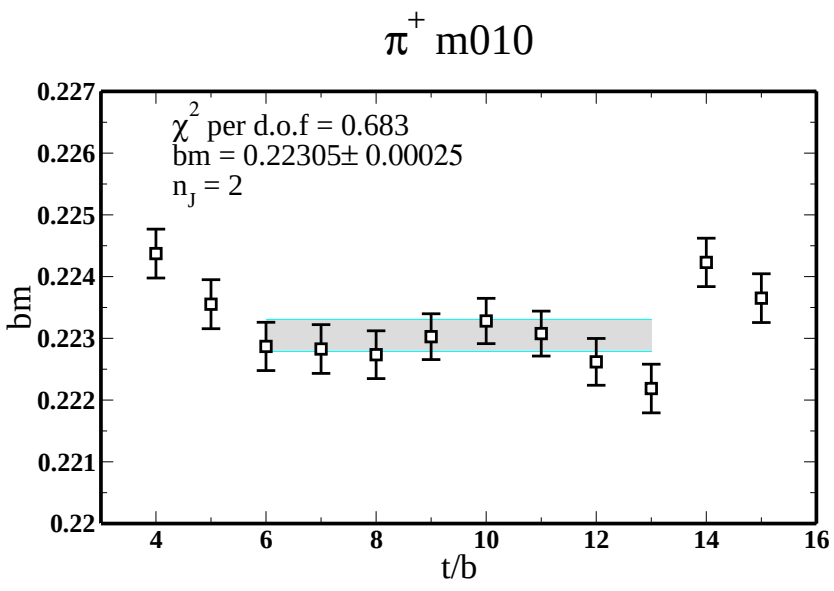
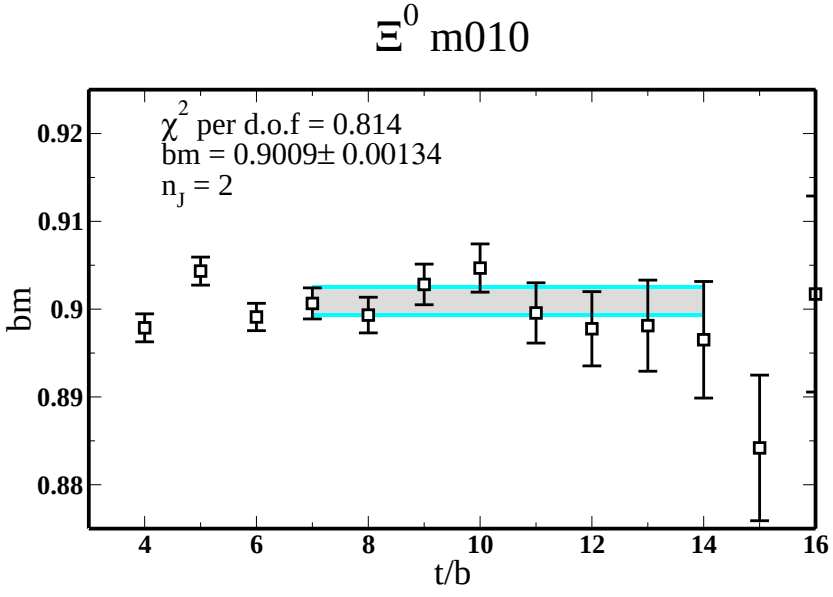
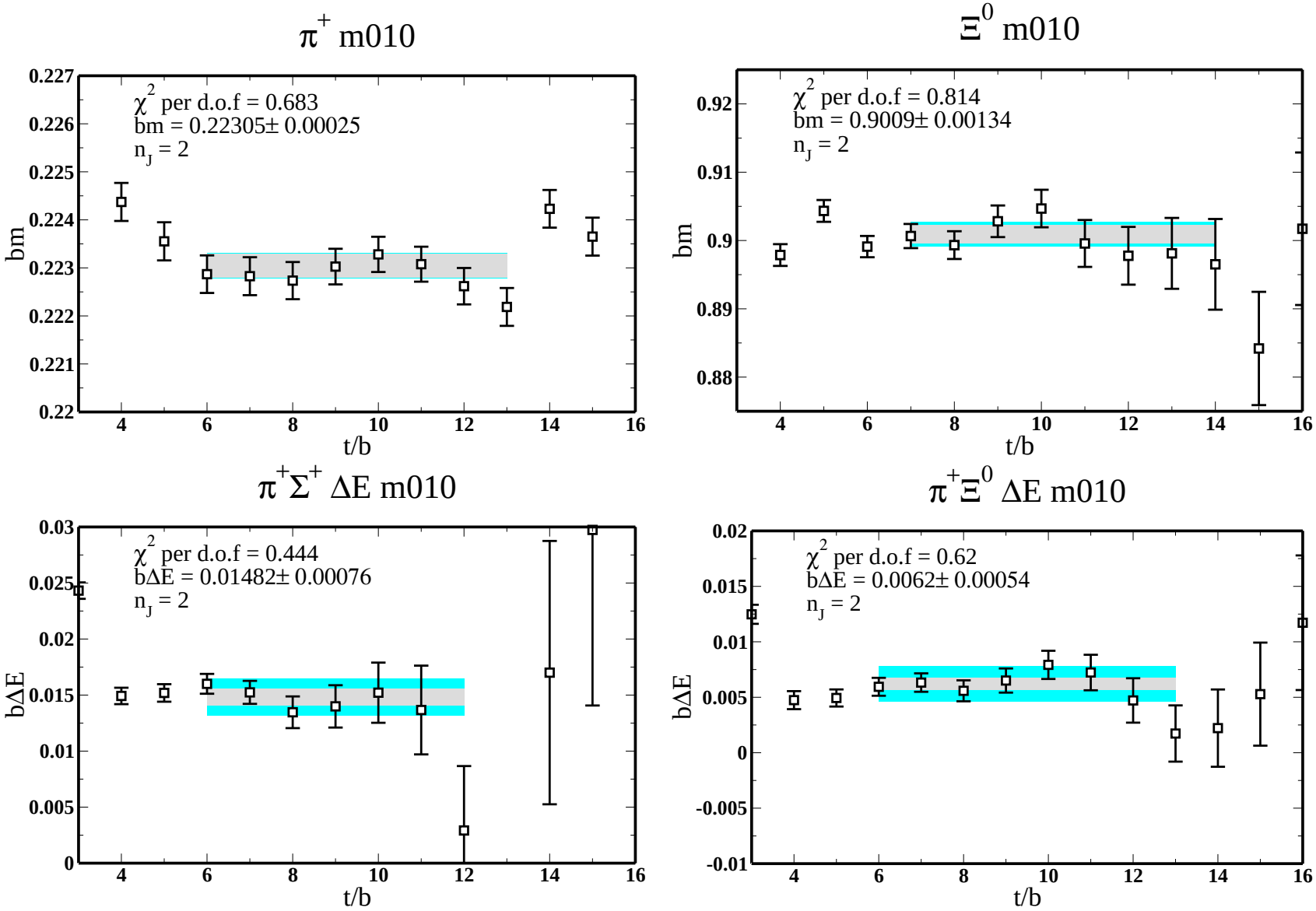


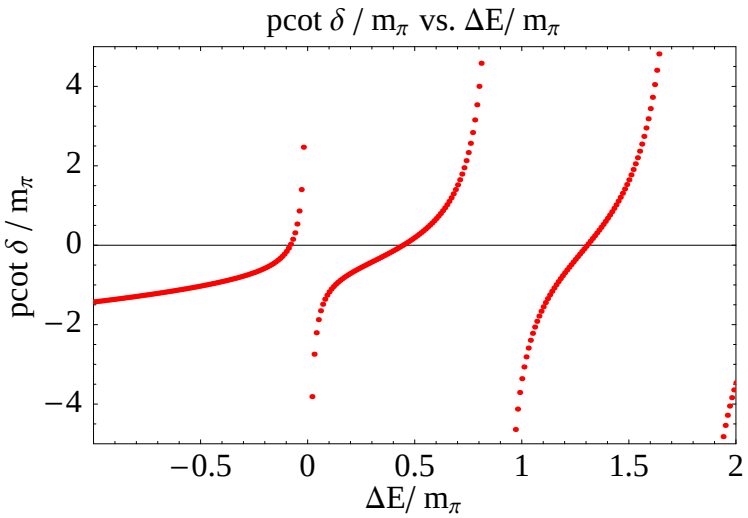


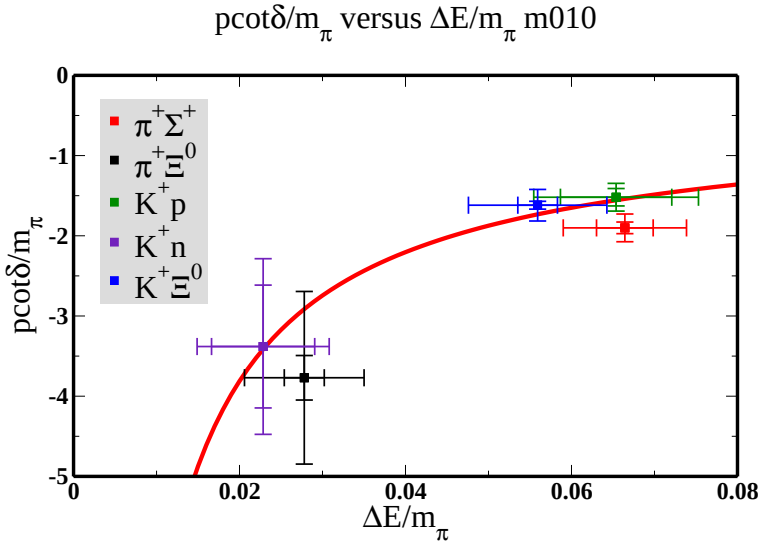
Calculated meson and baryon masses and ΔE



Lattice Calculation of $1/a$

$$p\cot\delta(p) = \frac{1}{\pi L}\,\mathbf{s}\left(\frac{pL}{2\pi}\right), \qquad \mathbf{s}\left(\frac{pL}{2\pi}\right) \equiv \sum_{\mathbf{j}}^{\Lambda_j} \frac{1}{|\mathbf{j}|^2 - \left(\frac{pL}{2\pi}\right)^2} - 4\pi\Lambda_j$$





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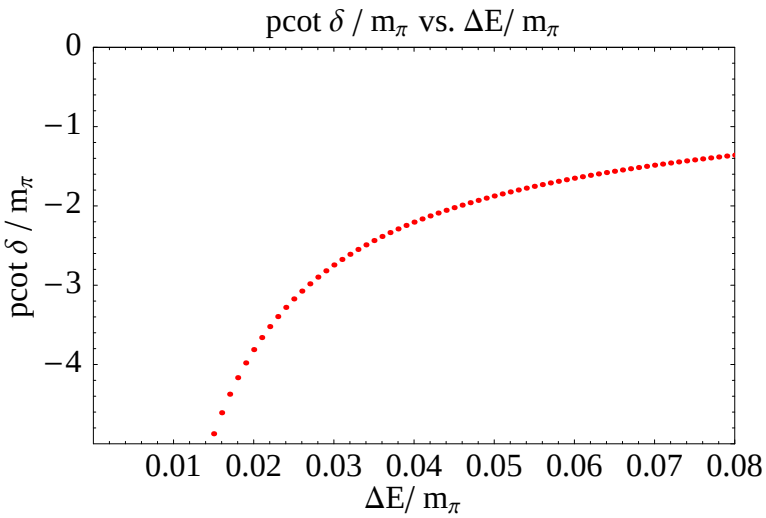
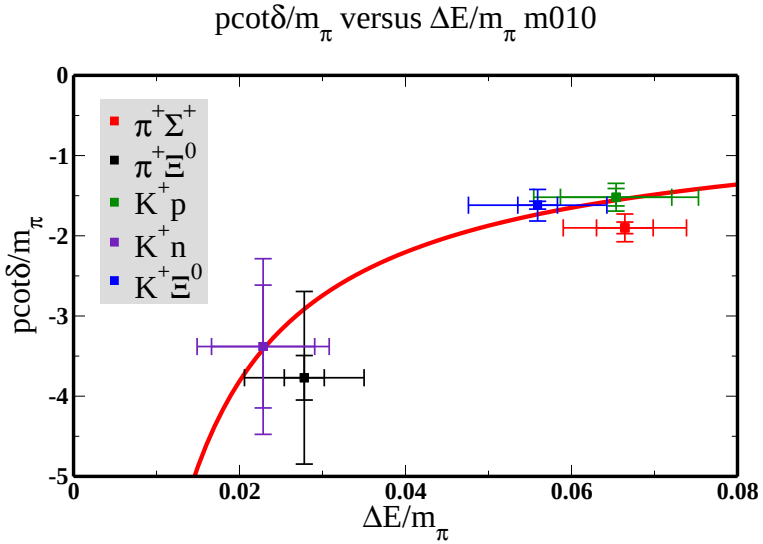
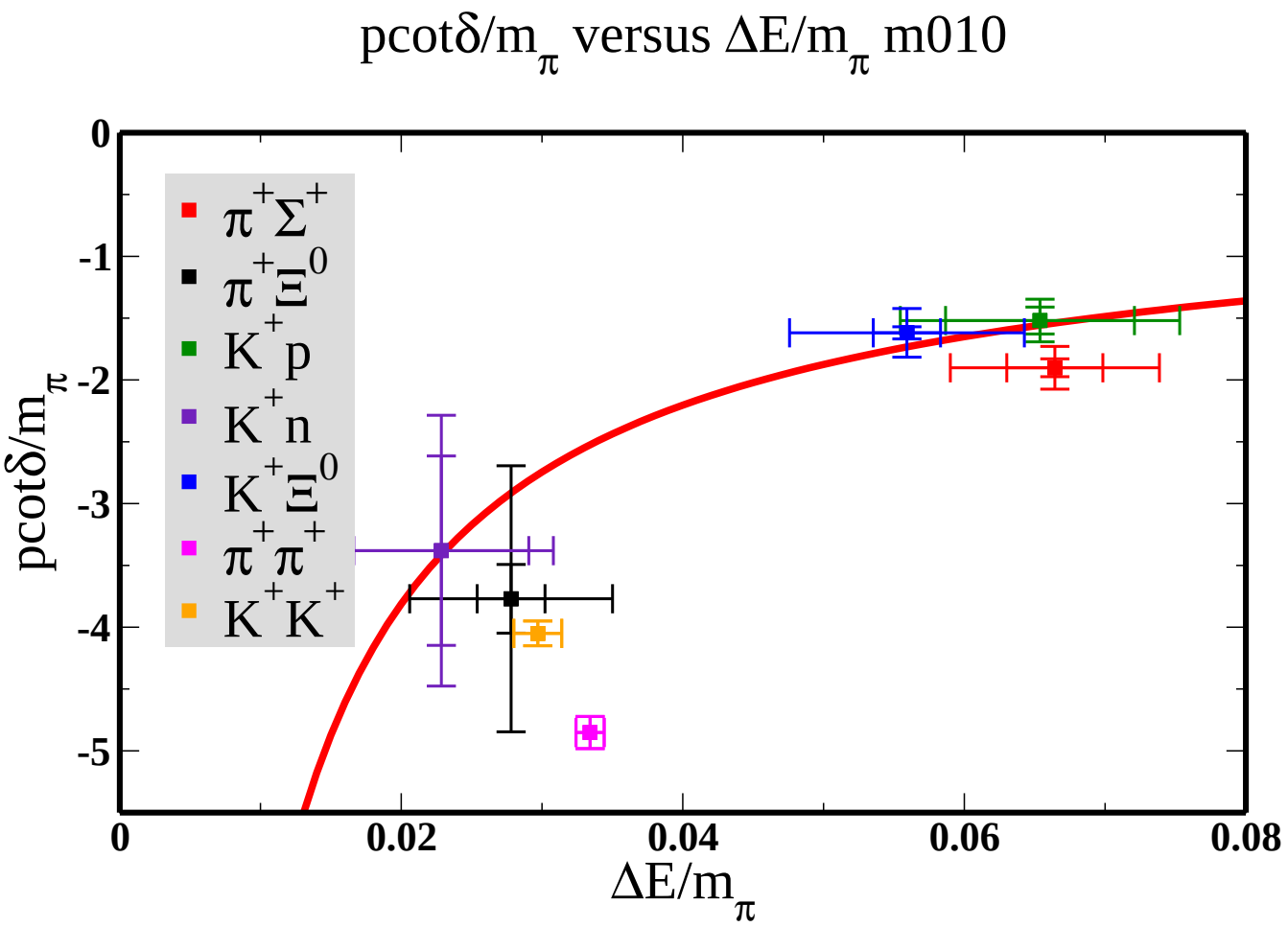




Lattice Calculation of $1/a$

For comparison, including $\pi^+\pi^+$ and K^+K^+ on the plot:



Chiral Extrapolation: SU(3) HBχPT to NNLO

$$
\begin{aligned}
a_{\pi^+\Sigma^+} &= \frac{1}{4\pi}\frac{m_\Sigma}{m_\pi+m_\Sigma}\left[-\frac{2m_\pi}{f_\pi^2}+\frac{2m_\pi^2}{f_\pi^2}C_1+\mathcal{Y}_{\pi^+\Sigma^+}(\mu)+8h_{123}(\mu)\frac{m_\pi^3}{f_\pi^2}\right]\\
a_{\pi^+\Xi^0} &= \frac{1}{4\pi}\frac{m_\Xi}{m_\pi+m_\Xi}\left[-\frac{m_\pi}{f_\pi^2}+\frac{m_\pi^2}{f_\pi^2}C_{01}+\mathcal{Y}_{\pi^+\Xi^0}(\mu)+8h_1(\mu)\frac{m_\pi^3}{f_\pi^2}\right]\\
a_{K^+p} &= \frac{1}{4\pi}\frac{m_N}{m_K+m_N}\left[-\frac{2m_K}{f_K^2}+\frac{2m_K^2}{f_K^2}C_1+\mathcal{Y}_{K^+p}(\mu)+8h_{123}(\mu)\frac{m_K^3}{f_K^2}\right]\\
a_{K^+n} &= \frac{1}{4\pi}\frac{m_N}{m_K+m_N}\left[-\frac{m_K}{f_K^2}+\frac{m_K^2}{f_K^2}C_{01}+\mathcal{Y}_{K^+n}(\mu)+8h_1(\mu)\frac{m_K^3}{f_K^2}\right]\\
a_{\overline{K}^0\Xi^0} &= \frac{1}{4\pi}\frac{m_\Xi}{m_K+m_\Xi}\left[-\frac{2m_K}{f_K^2}+\frac{2m_K^2}{f_K^2}C_1+\mathcal{Y}_{\overline{K}^0\Xi^0}(\mu)+8h_{123}(\mu)\frac{m_K^3}{f_K^2}\right]
\end{aligned}
$$

[1] Liu and Zhu, hep-ph/0607100, hep-ph/0702246

CHIRAL EXTRAPOLATION: SU(3) HBχPT TO NNLO

tree-level (Weinberg), and the LEC's at NLO and NNLO[1]

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a_{\pi^+\Sigma^+} &= \frac{1}{4\pi}\frac{m_\Sigma}{m_\pi+m_\Sigma}\left[-\frac{2m_\pi}{f_\pi^2}+\frac{2m_\pi^2}{f_\pi^2}C_1+\mathcal{Y}_{\pi^+\Sigma^+}(\mu)+8h_{123}(\mu)\frac{m_\pi^3}{f_\pi^2}\right]\\
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a_{\overline{K}^0\Xi^0} &= \frac{1}{4\pi}\frac{m_\Xi}{m_K+m_\Xi}\left[-\frac{2m_K}{f_K^2}+\frac{2m_K^2}{f_K^2}C_1+\mathcal{Y}_{\overline{K}^0\Xi^0}(\mu)+8h_{123}(\mu)\frac{m_K^3}{f_K^2}\right]
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Chiral Extrapolation: SU(3) HBχPT to NNLO

tree-level (Weinberg), and the LEC's at NLO and NNLO[1]

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a_{\pi^+\Sigma^+} &= \frac{1}{4\pi}\frac{m_\Sigma}{m_\pi+m_\Sigma}\left[-\frac{2m_\pi}{f_\pi^2}+\frac{2m_\pi^2}{f_\pi^2}C_1+\mathcal{Y}_{\pi^+\Sigma^+}(\mu)+8h_{123}(\mu)\frac{m_\pi^3}{f_\pi^2}\right]\\
a_{\pi^+\Xi^0} &= \frac{1}{4\pi}\frac{m_\Xi}{m_\pi+m_\Xi}\left[-\frac{m_\pi}{f_\pi^2}+\frac{m_\pi^2}{f_\pi^2}C_{01}+\mathcal{Y}_{\pi^+\Xi^0}(\mu)+8h_1(\mu)\frac{m_\pi^3}{f_\pi^2}\right]\\
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\end{aligned}
$$

$\mathcal{Y}_{\phi B}$ are the loop functions.

[1] Liu and Zhu, hep-ph/0607100, hep-ph/0702246

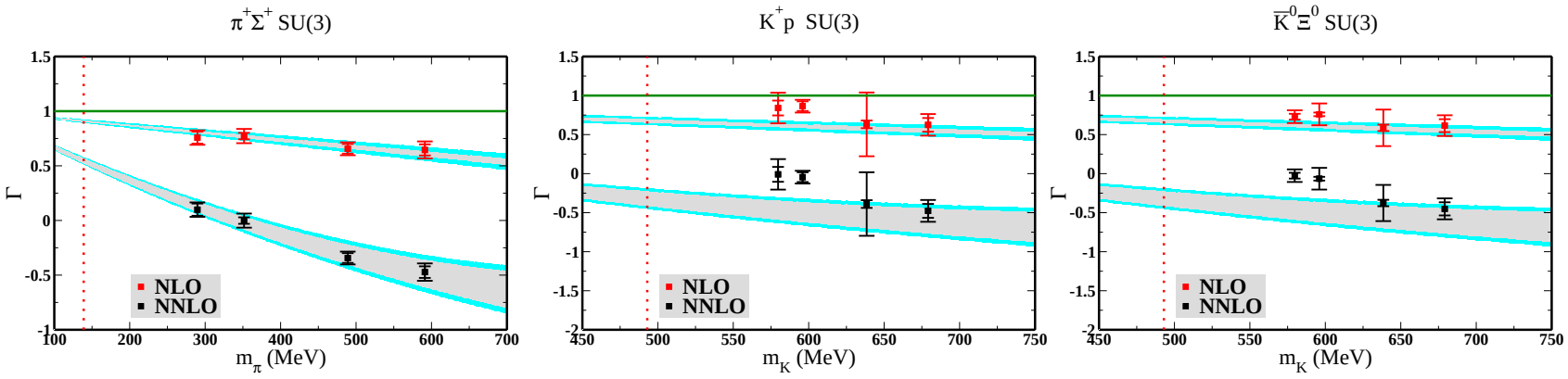
Chiral Extrapolation: SU(3) HBχPT to NNLO

$\pi^+\Sigma^+$, K^+p, and $\overline{K}^0\Xi^0$

$$\Gamma^{(1)}_{LO} \equiv -\frac{2\pi a f_\phi^2}{m_\phi}\left(1+\frac{m_\phi}{m_B}\right) = 1$$

$$\Gamma^{(1)}_{NLO} \equiv -\frac{2\pi a f_\phi^2}{m_\phi}\left(1+\frac{m_\phi}{m_B}\right) = 1 - C_1 m_\phi$$

$$\Gamma^{(1)}_{NNLO} \equiv -\frac{\mathbf{2\pi a f_\phi^2}}{\mathbf{m_\phi}}\left(\mathbf{1}+\frac{\mathbf{m_\phi}}{\mathbf{m_B}}\right) + \frac{\mathbf{f_\phi^2}}{\mathbf{2m_\phi}}\mathcal{Y}_{\phi\mathbf{B}}(\Lambda_\chi) = 1 - C_1 m_\phi - 4h_{123}(\Lambda_\chi)m_\phi^2$$



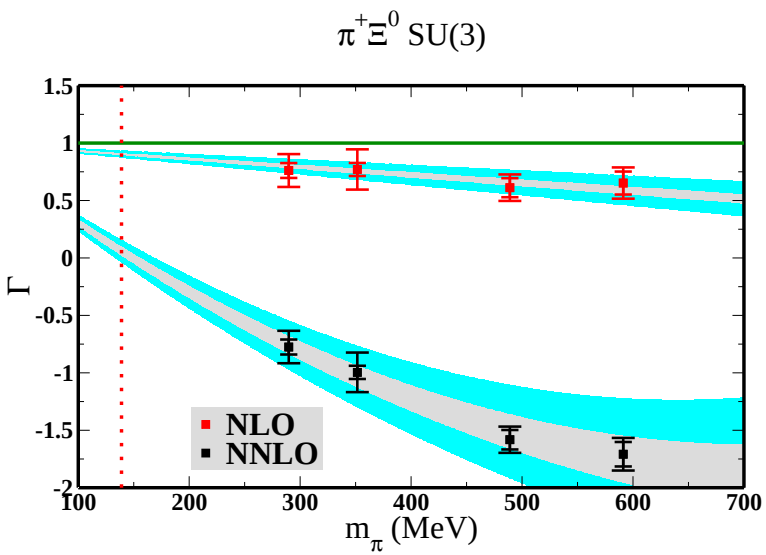
CHIRAL EXTRAPOLATION: SU(3) HBχPT TO NNLO

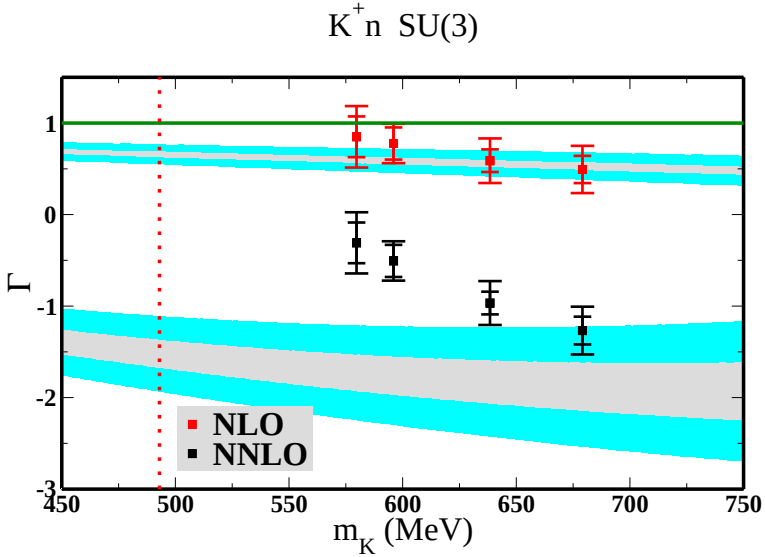
$\pi^+\Xi^0$, and K^+n

$$\Gamma^{(2)}_{LO} \equiv -\frac{4\pi a f_\phi^2}{m_\phi}\left(1+\frac{m_\phi}{m_B}\right) = 1$$

$$\Gamma^{(2)}_{NLO} \equiv -\frac{4\pi a f_\phi^2}{m_\phi}\left(1+\frac{m_\phi}{m_B}\right) = 1 - C_{01} m_\phi$$

$$\Gamma^{(2)}_{NNLO} \equiv -\frac{\mathbf{4\pi a f_\phi^2}}{\mathbf{m_\phi}}\left(\mathbf{1}+\frac{\mathbf{m_\phi}}{\mathbf{m_B}}\right) + \frac{\mathbf{f_\phi^2}}{\mathbf{m_\phi}}\mathcal{Y}_{\phi B}(\Lambda_\chi) = 1 - C_{01} m_\phi - 8h_1(\Lambda_\chi) m_\phi^2 \,.$$





Chiral Extrapolation: SU(2) χPT to NNLO

$a_{\pi^+\Sigma^+}$ and $a_{\pi^+\Xi^0}$ are given by [2]

$$a_{\pi^+\Sigma^+} = \frac{1}{4\pi}\frac{m_\Sigma}{m_\pi + m_\Sigma}\left[-\frac{2m_\pi}{f_\pi^2} + \frac{2m_\pi^2}{f_\pi^2}C_{\pi^+\Sigma^+} + \frac{m_\pi^3}{\pi^2 f_\pi^4}\log\frac{m_\pi}{\mu} + \frac{2m_\pi^3}{f_\pi^2}h_{\pi^+\Sigma^+}(\mu)\right]$$

$$a_{\pi^+\Xi^0} = \frac{1}{4\pi}\frac{m_\Xi}{m_\pi + m_\Xi}\left[-\frac{m_\pi}{f_\pi^2} + \frac{m_\pi^2}{f_\pi^2}C_{\pi^+\Xi^0} + \frac{m_\pi^3}{2\pi^2 f_\pi^4}\log\frac{m_\pi}{\mu} + \frac{m_\pi^3}{f_\pi^2}h_{\pi^+\Xi^0}(\mu)\right]$$

[2] Mai, et. al., arXiv:0905.2810v1[hep-ph]

CHIRAL EXTRAPOLATION: SU(2) χPT TO NNLO

$a_{\pi^+\Sigma^+}$ and $a_{\pi^+\Xi^0}$ are given by [2]
tree-level (Weinberg), and the LEC's at NLO and NNLO

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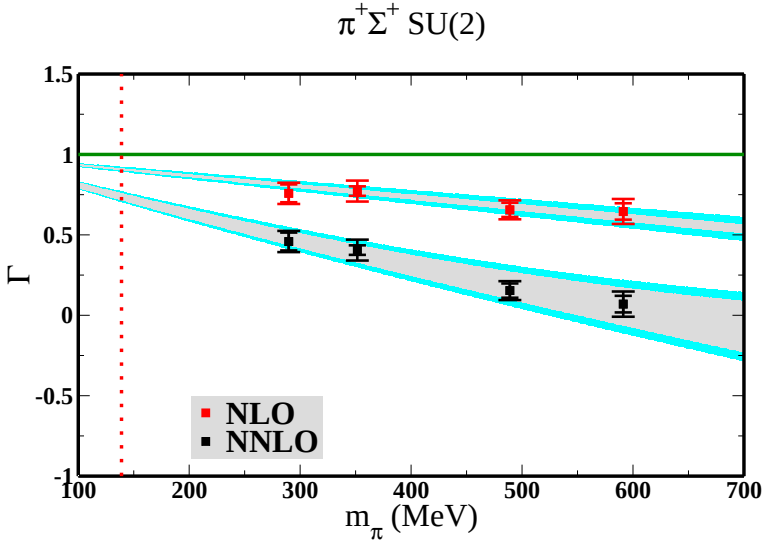
$$a_{\pi^+\Xi^0} = \frac{1}{4\pi}\frac{m_\Xi}{m_\pi + m_\Xi}\left[-\frac{m_\pi}{f_\pi^2} + \frac{m_\pi^2}{f_\pi^2}C_{\pi^+\Xi^0} + \frac{m_\pi^3}{2\pi^2 f_\pi^4}\log\frac{m_\pi}{\mu} + \frac{m_\pi^3}{f_\pi^2}h_{\pi^+\Xi^0}(\mu)\right]$$

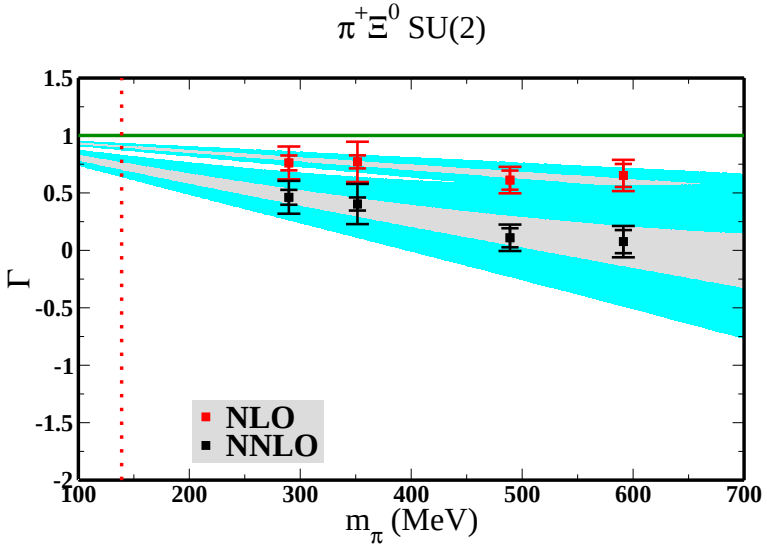
[2] Mai, et. al., arXiv:0905.2810v1[hep-ph]

Chiral Extrapolation: SU(2) χPT to NNLO

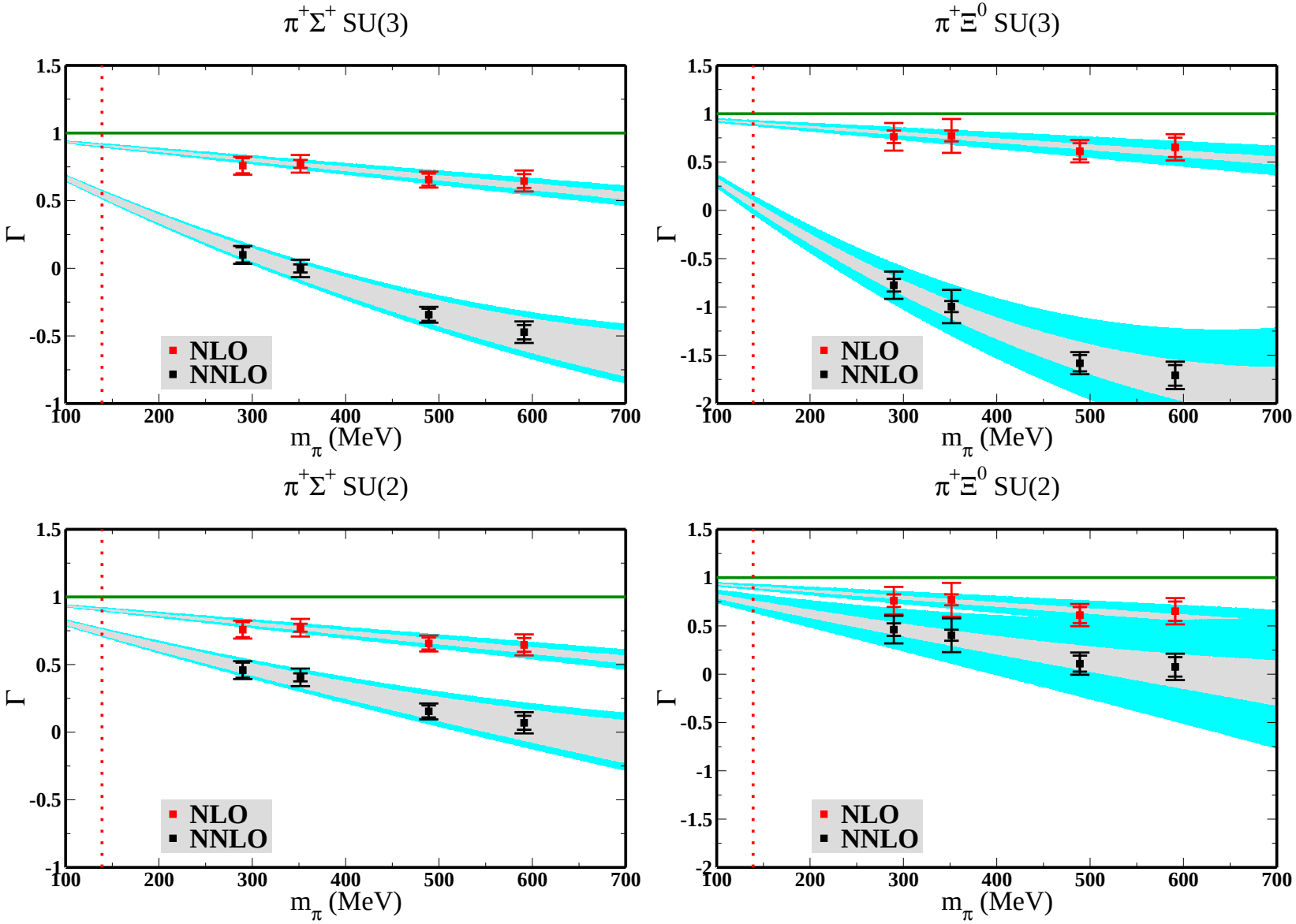
$$
\begin{aligned}
\Gamma_{LO} &\equiv 1 \\
\Gamma_{NLO} &\equiv 1 - C_{\pi+B} m_\pi \\
\Gamma_{NNLO} &\equiv 1 - C_{\pi+B} m_\pi - h_{\pi+B}(\Lambda_\chi) m_\pi^2
\end{aligned}
$$

where B is either Σ^+ or Ξ^0





Chiral Extrapolation:



RESULTS

extrapolating using SU(2) χPT , the scattering lengths are

$$
\begin{aligned}
a_{\pi^+\Sigma^+} &= -0.197 \pm 0.017 \text{ fm} \quad (-0.2294 \text{ fm}) \\
a_{\pi^+\Xi^0} &= -0.098 \pm 0.017 \text{ fm} \quad (-0.1158 \text{ fm})
\end{aligned}
$$

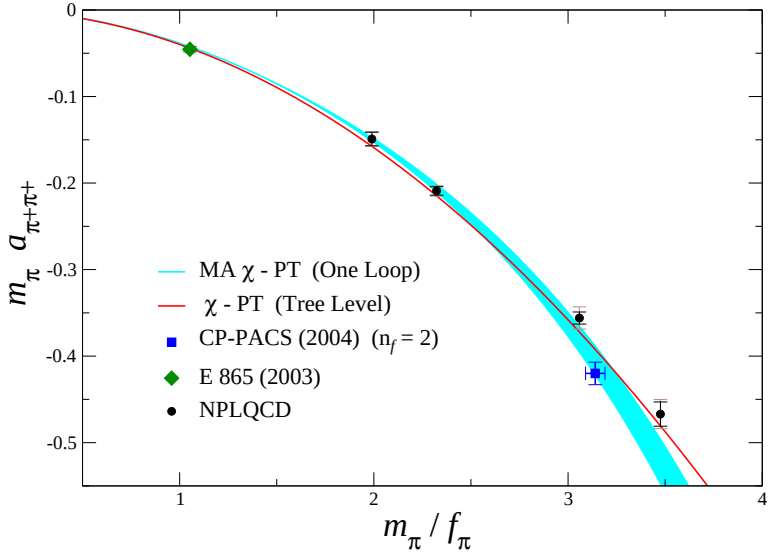
where the error encompasses statistical and systematic uncertainties

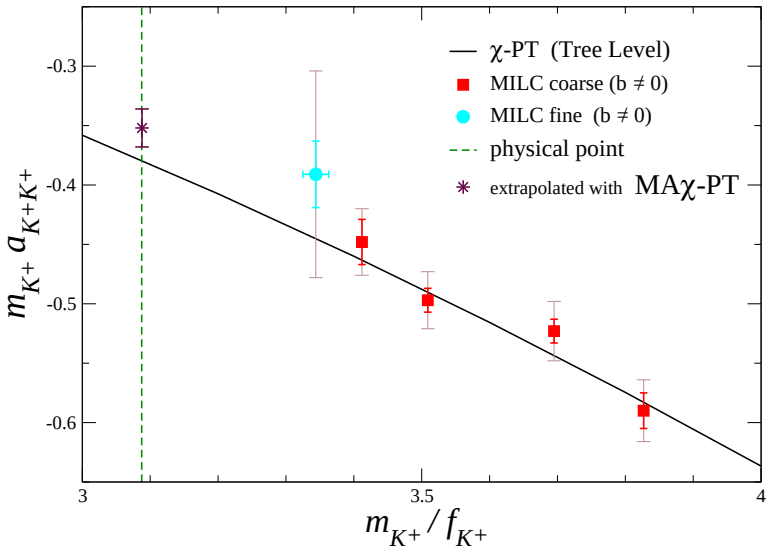
RESULTS

As pointed out by Mai, et. al., if $f_\pi \to f$, where f is the decay constant in the chiral limit, chiral log is removed.

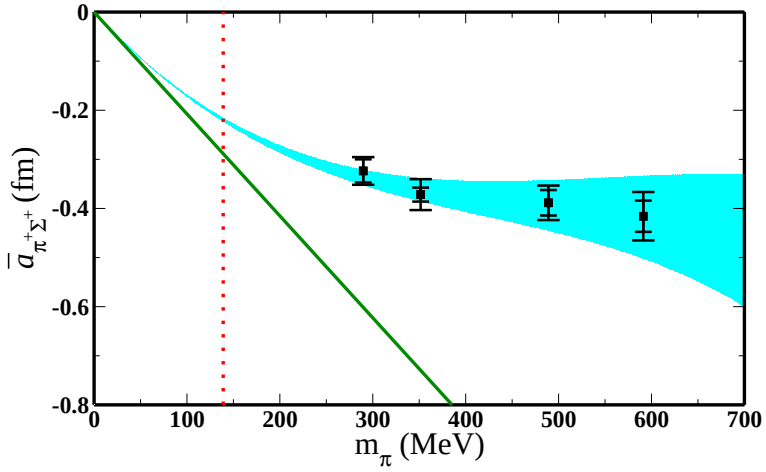
$$a_{\pi^+\Sigma^+} = \frac{1}{2\pi}\frac{m_\Sigma}{m_\pi + m_\Sigma}\left[-\frac{m_\pi}{f^2} + \frac{m_\pi^2}{f^2}C_{\pi^+\Sigma^+} + \frac{m_\pi^3}{f^2}h'_{\pi^+\Sigma^+}\right],\ h'_{\pi^+\Sigma^+} = \frac{4}{f^2}\ell_4^r + h_{\pi^+\Sigma^+}$$

$$a_{\pi^+\Xi^0} = \frac{1}{4\pi}\frac{m_\Xi}{m_\pi + m_\Xi}\left[-\frac{m_\pi}{f^2} + \frac{m_\pi^2}{f^2}C_{\pi^+\Xi^0} + \frac{m_\pi^3}{f^2}h'_{\pi^+\Xi^0}\right],\ h'_{\pi^+\Xi^0} = \frac{4}{f^2}\ell_4^r + h_{\pi^+\Xi^0}$$

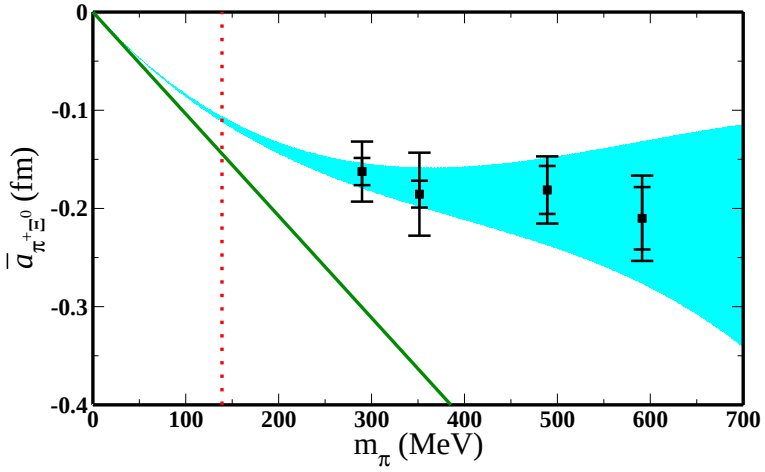




$\bar{a}_{\pi^+\Sigma^+}$ SU(2)



$\bar{a}_{\pi^+\Xi^0}$ SU(2)



The Future → Higher Statistics

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and the lesser known second part:

The Future → Higher Statistics

"Speak softly and carry a big stick..." –*Theodore Roosevelt*

and the lesser known second part:

"then use it to beat down the exponentially-increasing noise!"

HIGH STATISTICS CALCULATIONS:

Recent studies of single baryon, two-baryon, and 3-baryons at one quark mass and one volume [3]

stats increased by factor of $\sim$10

[3] see recent papers "High Statistics Anisotropic...NPLQCD collaboration"

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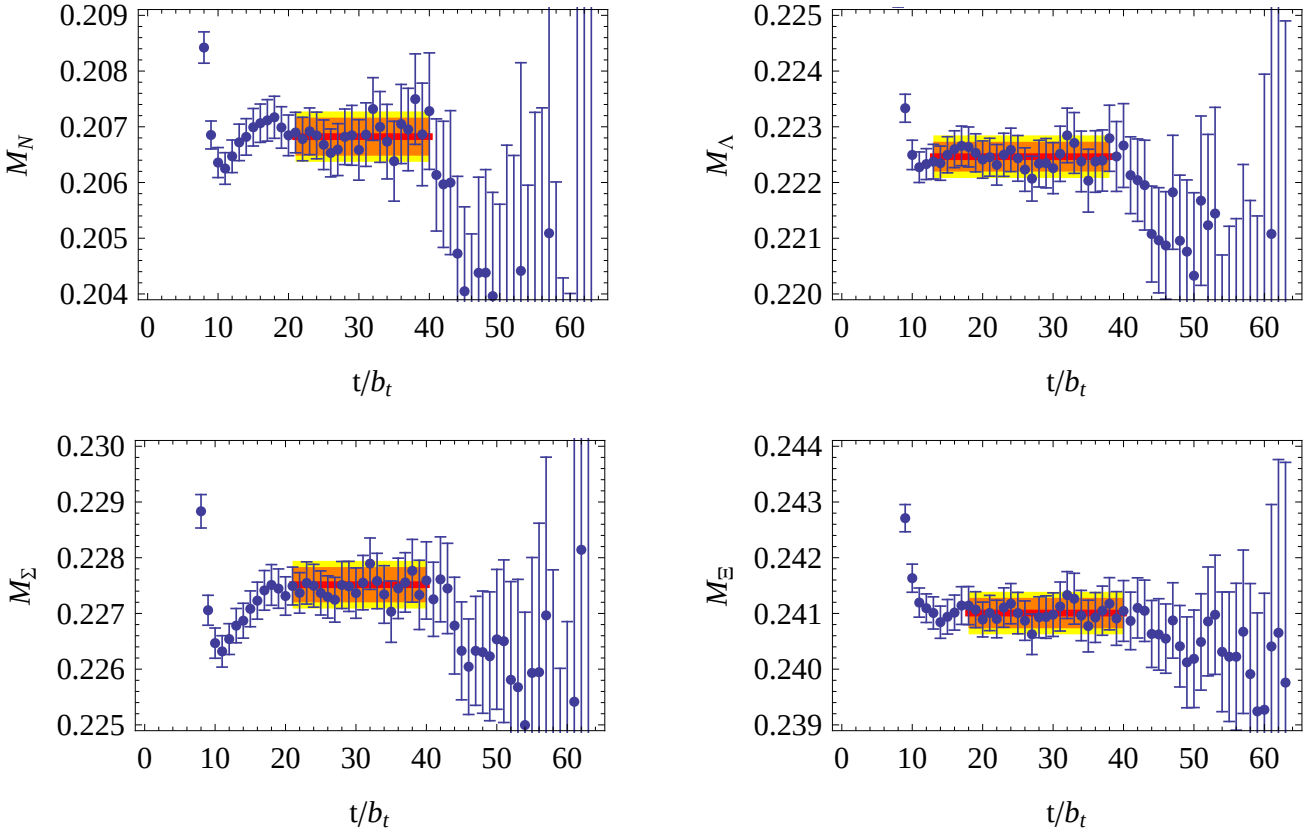

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CONCLUSION

- first dynamical LQCD calculation of meson-baryon scattering
- prediction of the $\pi^+\Sigma^+$ and $\pi^+\Xi^0$ scattering lengths using SU(2) χPT
- No convergence for kaon-baryon processes using SU(3) χPT

Acknowledgements

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