Constraining beyond the Standard Model nucleon isovector charges

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QCDSF Collaboration

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- Ian van Schalkwyk (Adelaide, PhD)
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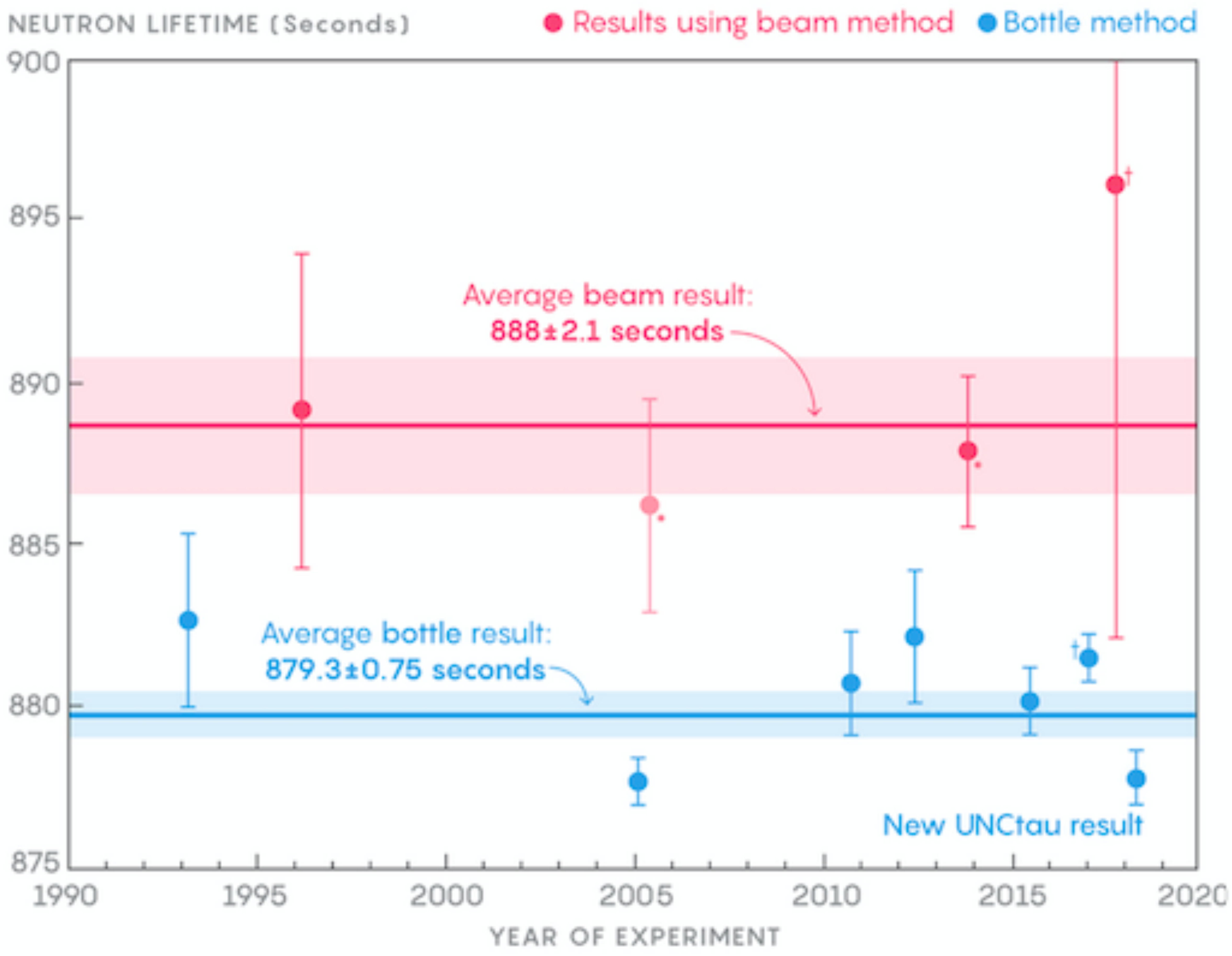
- R. Young (Adelaide)

Motivation

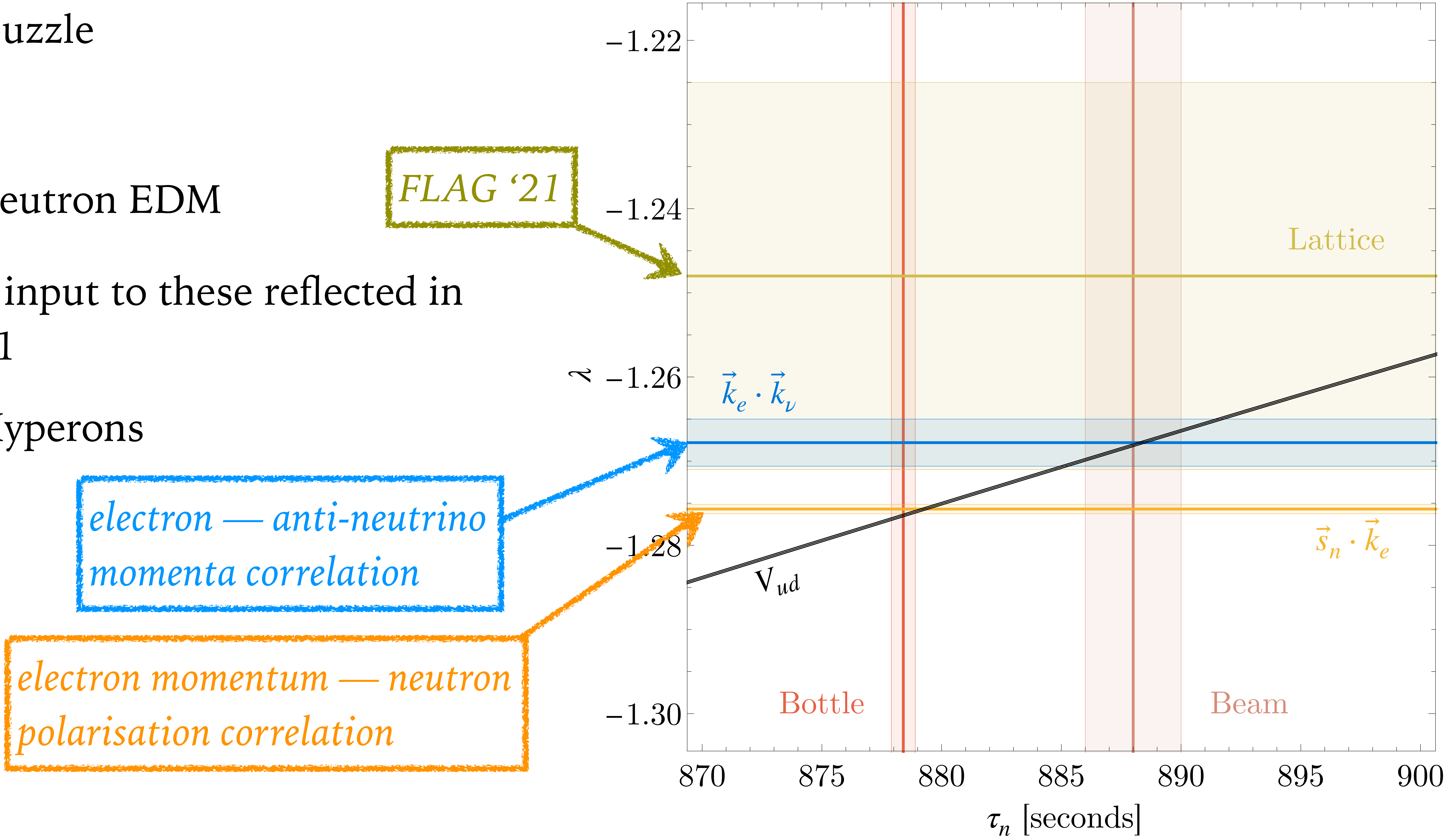
- Current $\tau^n_{\text{bottle}} - \tau^n_{\text{beam}} \sim 4\sigma$
- Unconsidered systematic error in the experiments? or evidence of new physics?
- Bottle counts how many neutrons left
- Beam counts final state protons only
- *Evidence of some unknown decay in bottle?*



Motivation

[QCDSF, PRD108 (2023)]

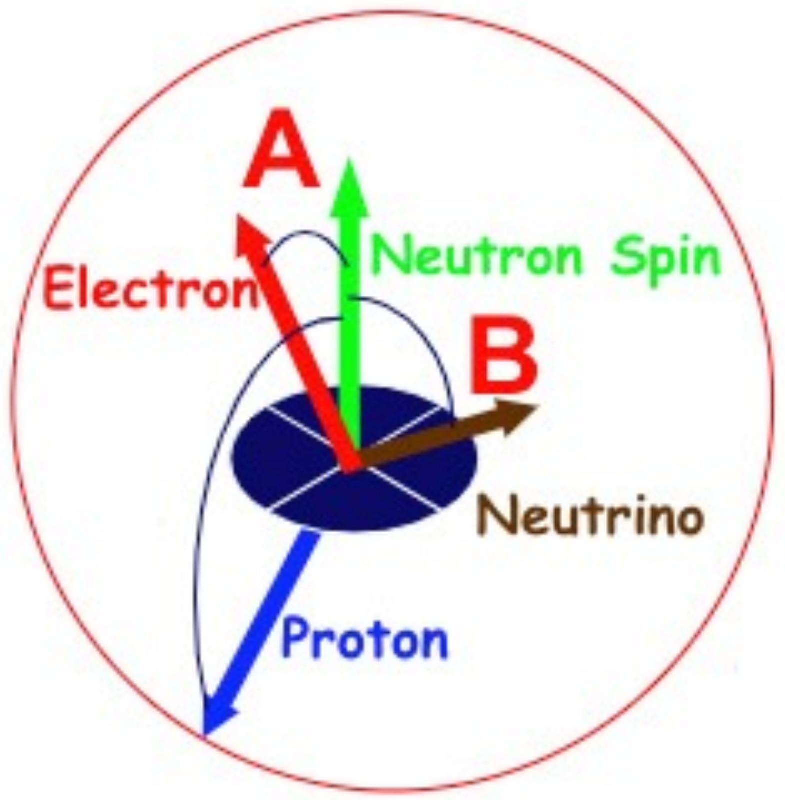
- Nucleon isovector charges ($g_A^{u-d}, g_T^{u-d}, g_S^{u-d}$) can have an impact on searches for New Physics
  - Neutron lifetime puzzle
  - Neutron β-decay
  - CP-violation and neutron EDM
- Importance of lattice input to these reflected in appearing in FLAG 21
- Not much work on Hyperons



Motivation

➤ For a beam of polarised neutrons the differential decay rate is described by:

$$dW \propto \frac{1}{\tau_n} F(E_n) \left[1 + a \frac{\vec{k}_e \cdot \vec{k}_\nu}{E_e E_\nu} + b \frac{m_e}{E_e} + A \frac{\vec{s}_n \cdot \vec{k}_e}{E_e} + B \frac{\vec{s}_n \cdot \vec{k}_\nu}{E_\nu} \right]$$



Fierz interference term

➤ SM: $b = 0$

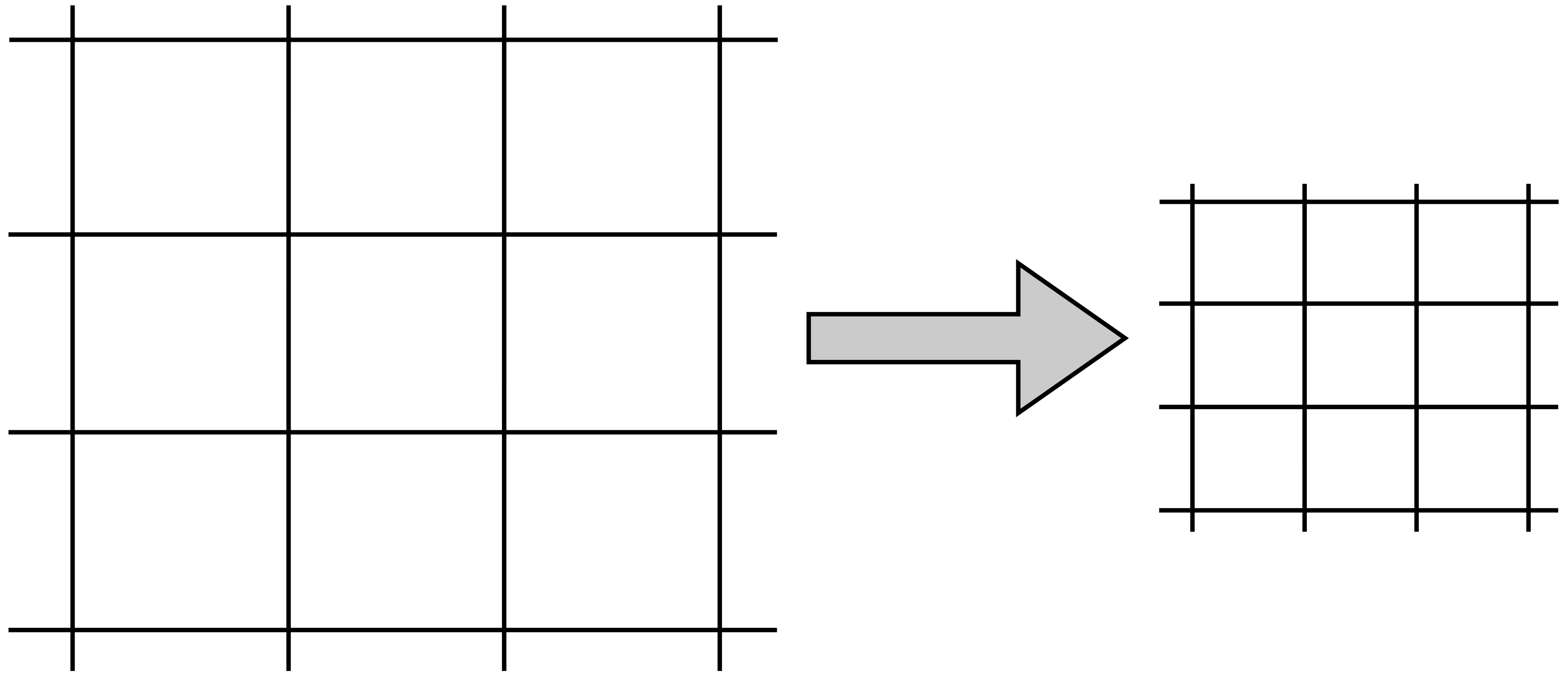
➤ Added to account for the possible BSM *scalar* and *tensor* interactions

SM	BSM
$\langle p \mid V/A \mid n \rangle$	$\langle p \mid T/S \mid n \rangle$
$g_V \approx 1, g_A = 1.2756(13)$	$g_S \approx ?, g_T \approx ?$

Lattice QCD

Extrapolations:

- Continuum
  - Unavoidable
  - Improved actions (errors O(a2))
  - Finer lattice spacings

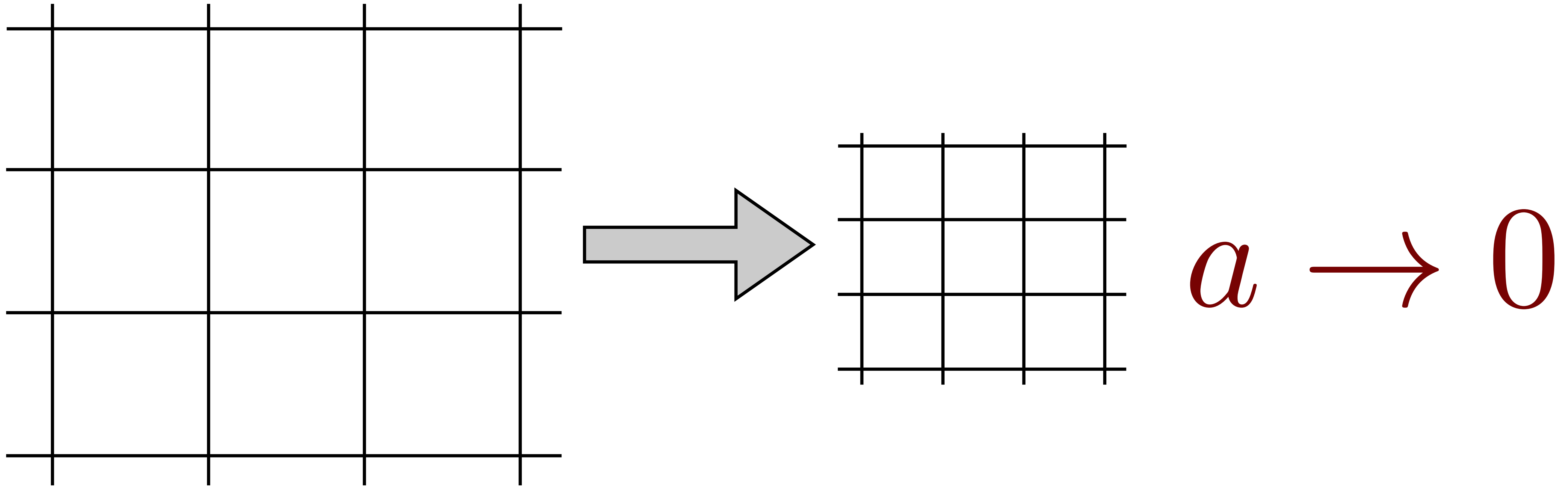


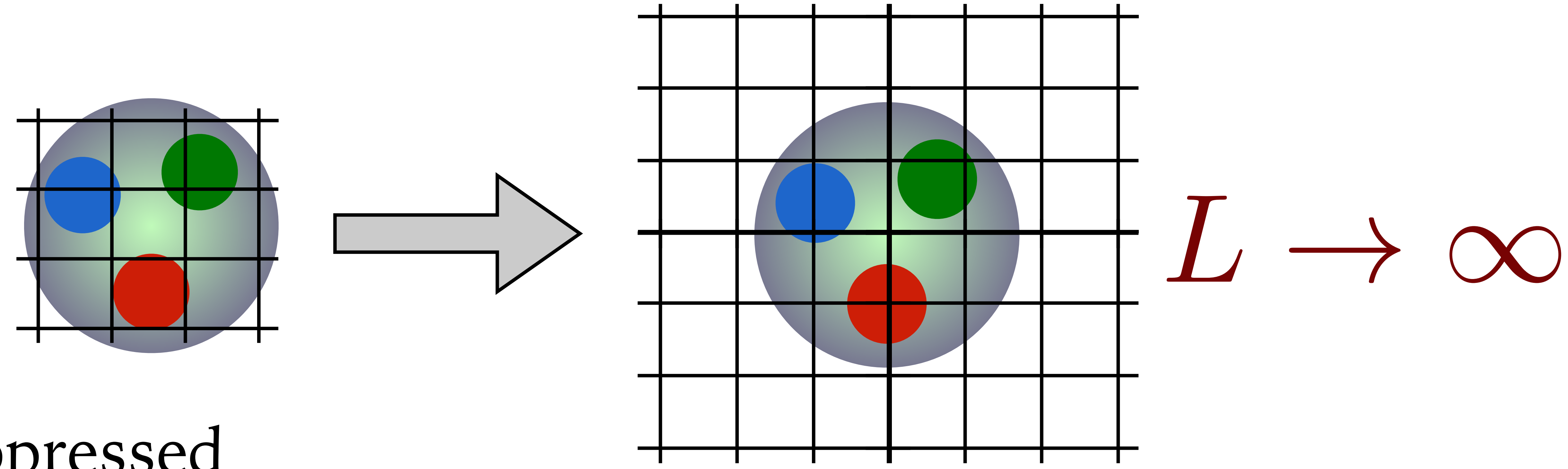
$a \to 0$

Lattice QCD

Extrapolations:

- Continuum
  - Unavoidable
  - Improved actions (errors O(a2))
  - Finer lattice spacings
- Finite volume
  - Large volumes so effects are exponentially suppressed

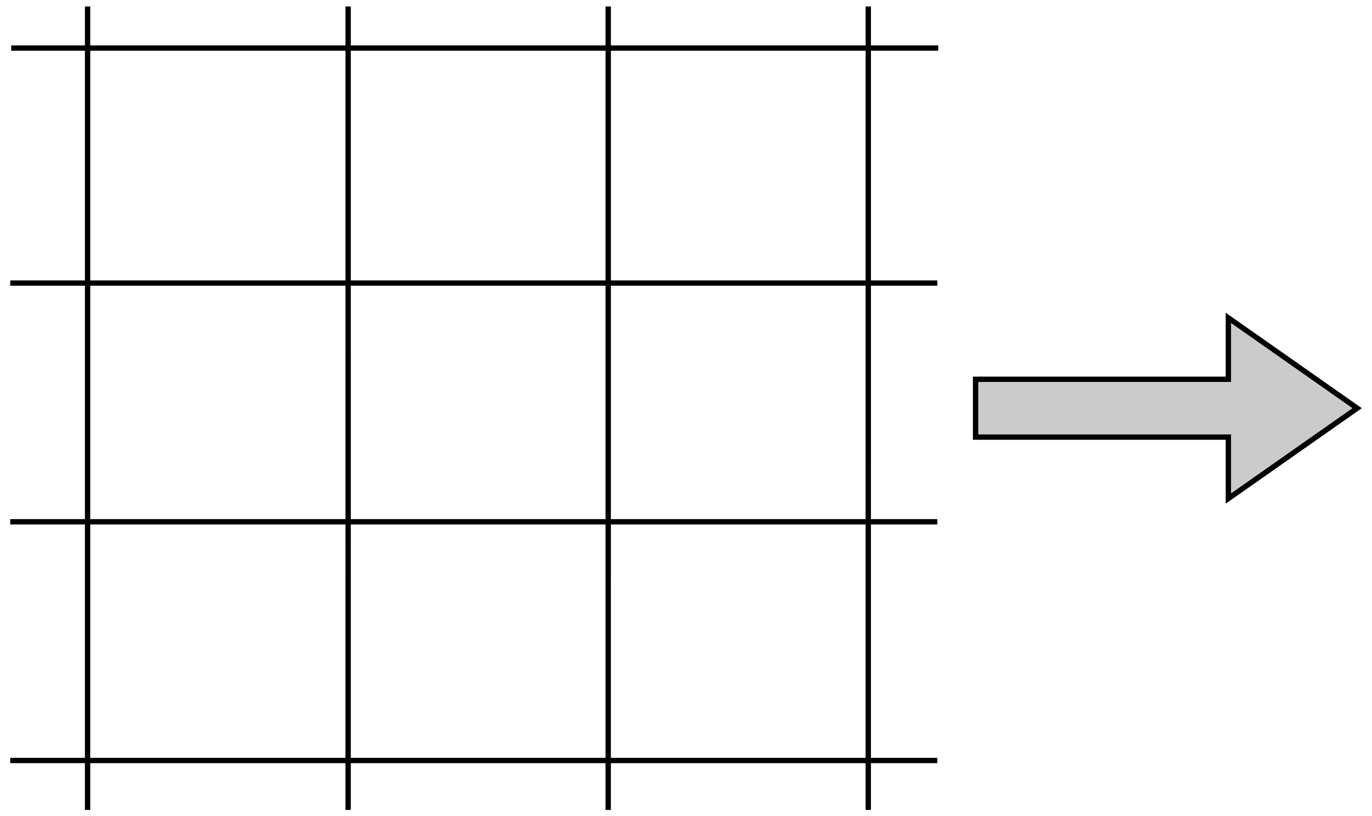




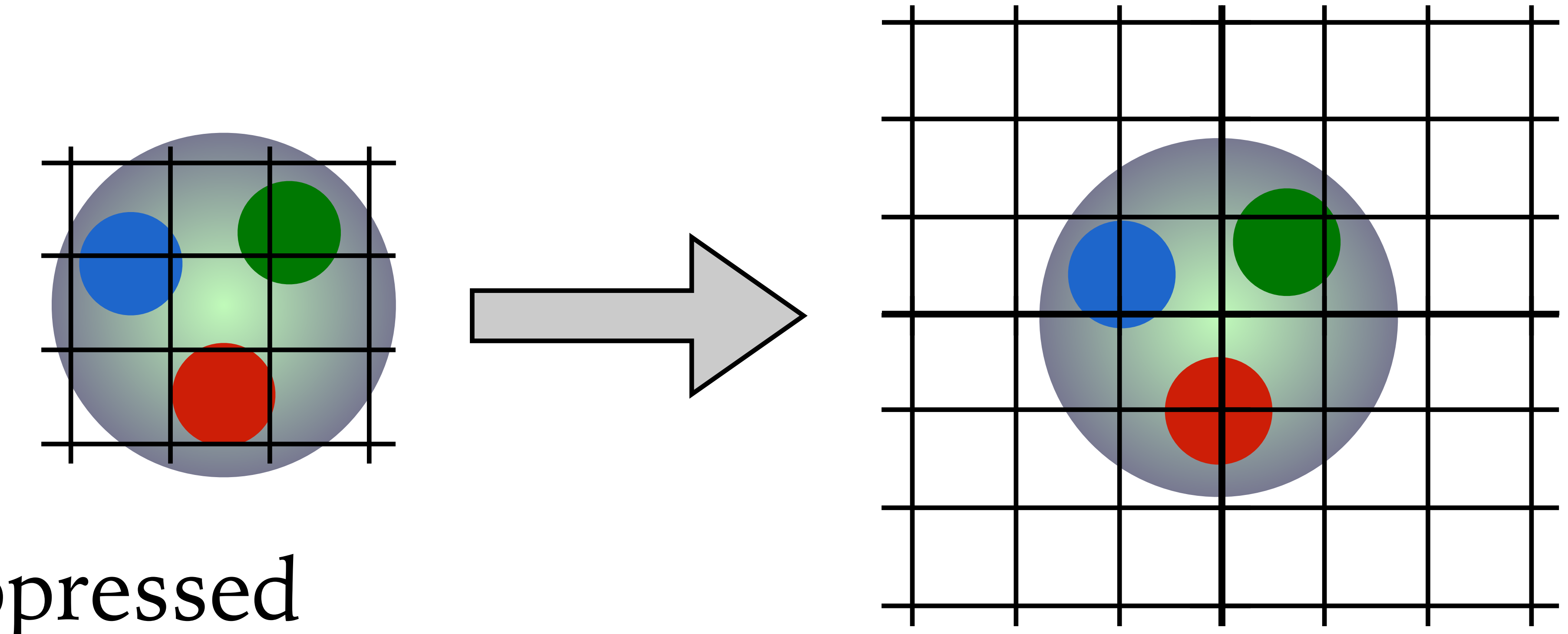
Lattice QCD

Extrapolations:

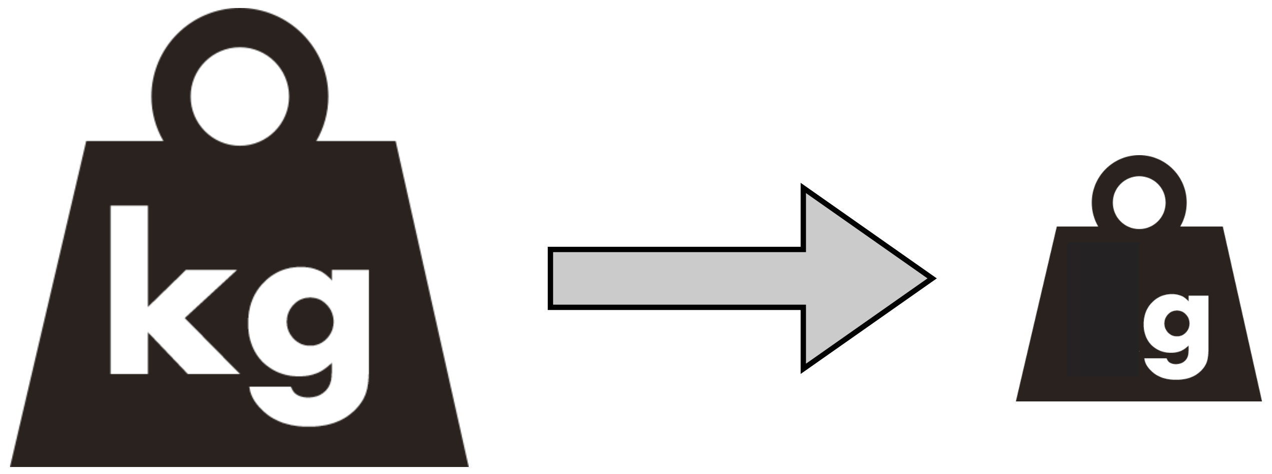
- Continuum
  - Unavoidable
  - Improved actions (errors O(a2))
  - Finer lattice spacings
- Finite volume
  - Large volumes so effects are exponentially suppressed
- Chiral
  - Simulate at physical quark masses
  - Chiral perturbation theory
  - Flavour-breaking expansion



$$a \to 0$$



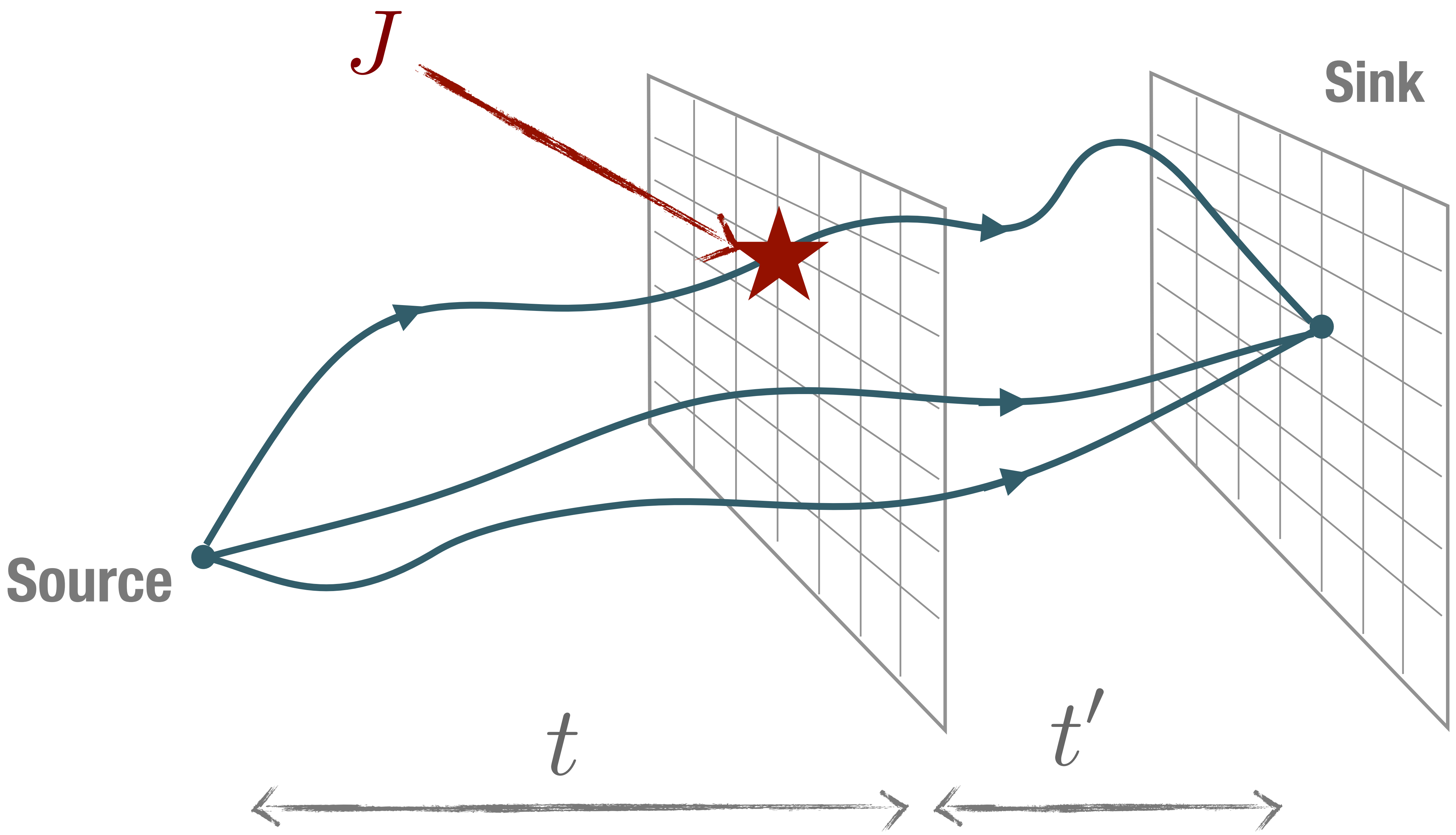
$$L \to \infty$$

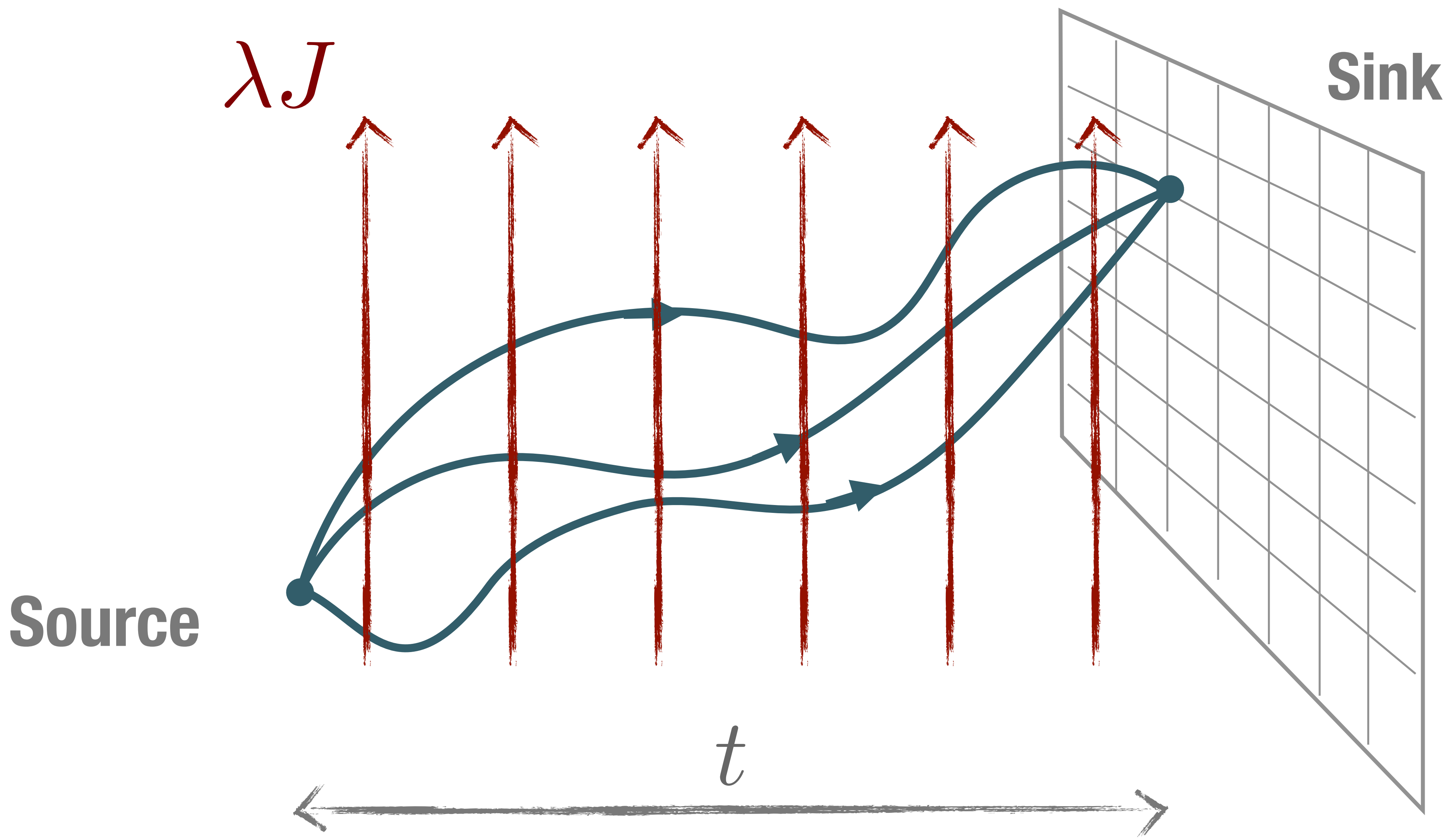


$$m_\pi \to 140 MeV$$

$$\text{GOR} \implies m_\pi^2 \propto m_q$$

Matrix elements on the lattice





3-pt functions

$$t, t' \gg \frac{1}{\Delta E}$$ ← energy gap to lowest excitation

$$\frac{\langle C_3(t,t')\rangle}{\langle C_2(t)\rangle\langle C_2(t')\rangle} \propto \langle N'|J|N\rangle$$

Feynman–Hellmann

$$t \gg \frac{1}{\Delta E}$$

$$\left.\frac{\partial E}{\partial \lambda}\right|_{\lambda\to 0} \propto \langle N|J|N\rangle$$

Feynman-Hellmann Theorem

Suppose we want: $\langle H | \mathcal{O} | H \rangle$

real parameter

Modify action with external field:

$$S \to S + \lambda \int d^4x\, \mathcal{O}(x)$$

local operator, e.g. $\bar{q}(x)\gamma_3 q(x)$

Measure hadron energy while changing λ

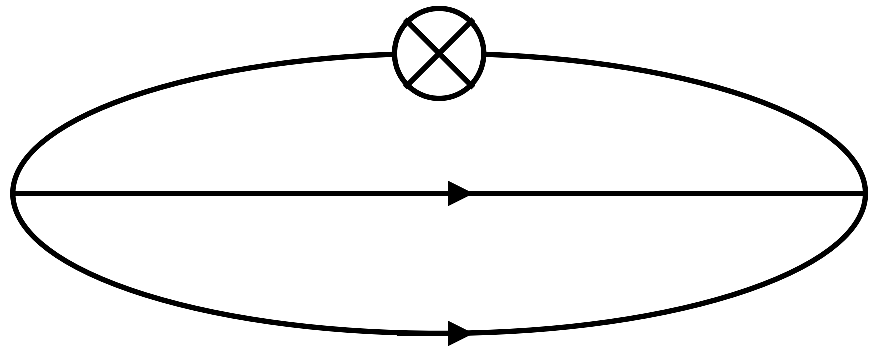
$$G(\lambda; \vec{p}; t) = \int dx\, e^{-i\vec{p}\cdot\vec{x}} \langle \chi'(x)\chi(0)\rangle \overset{\text{large t}}{\propto} e^{-E_H(\lambda,\vec{p})t}$$

Calculation of matrix elements ≡ hadron spectroscopy $\left.\frac{\partial E_H(\lambda,\vec{p})}{\partial \lambda}\right|_{\lambda=0} = \frac{1}{2E_H(\vec{p})} \langle H(\vec{p}) | \mathcal{O}(0) | H(\vec{p}) \rangle$

Feynman-Hellmann Theorem

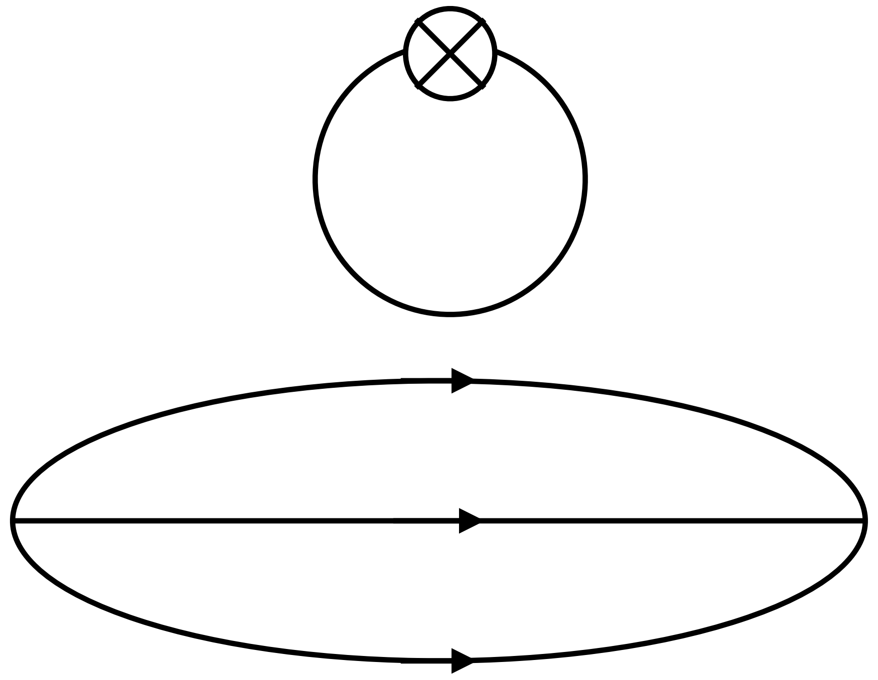
- Can modify fermion action in 2 places:

  - quark propagators



Connected

  - fermion determinant



Disconnected

(Requires new gauge configurations)

g_A, $\Delta\Sigma$ [PRD90 (2014)]

NPR [PLB740 (2015)]

G_E,G_M [PRD96 (2017)]

$F_{1,2}(\omega, Q^2)$ [PRL118 (2017), PRD102 (2020), PRD107 (2023)]

GPDs [PRD104 (2022), PRD110 (2024)]

$\Sigma \to n$ [PRD108 (2023)]

g_A, g_T, g_S [PRD108 (2023)]

$\langle x \rangle_g$ [PLB714 (2012)]

NPR [PLB740 (2015)]

Δs [PRD92 (2015)]

Feynman-Hellmann Theorem @ QCHSC24

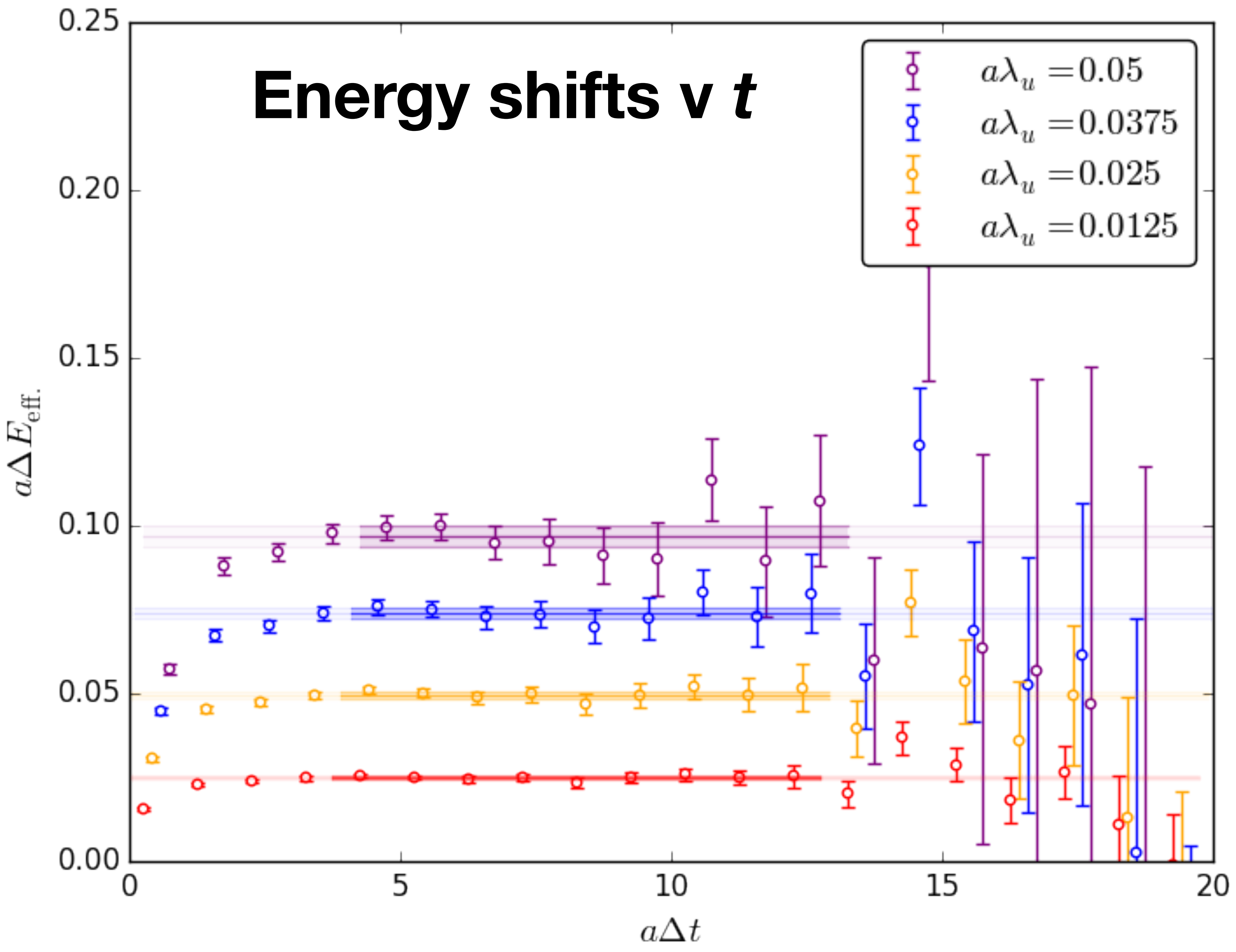
- K. Utku **Can**, Thur 15:00, Session B — *“The parity-odd structure function of the nucleon from the Compton amplitude in lattice QCD”*
- Jordan **McKee**, Wed 18:10, Session B — *”Compton Amplitude of the Pion using Feynman-Hellmann”*
- Thomas **Schar**, Thur 16:50, Session F — *“Reduction of discretisation artifacts in the lattice subtraction function calculation”*
- Ian **van Schalkwyk**, Poster — *“Calculation of the Compton Amplitude at High Momentum using Momentum Smearing”*
- Nabil **Humphrey**, Thur 11:00, Session B — *“Multi-nucleon matrix elements on the lattice with e-graph optimised Wick contractions and the Feynman-Hellmann theorem”*

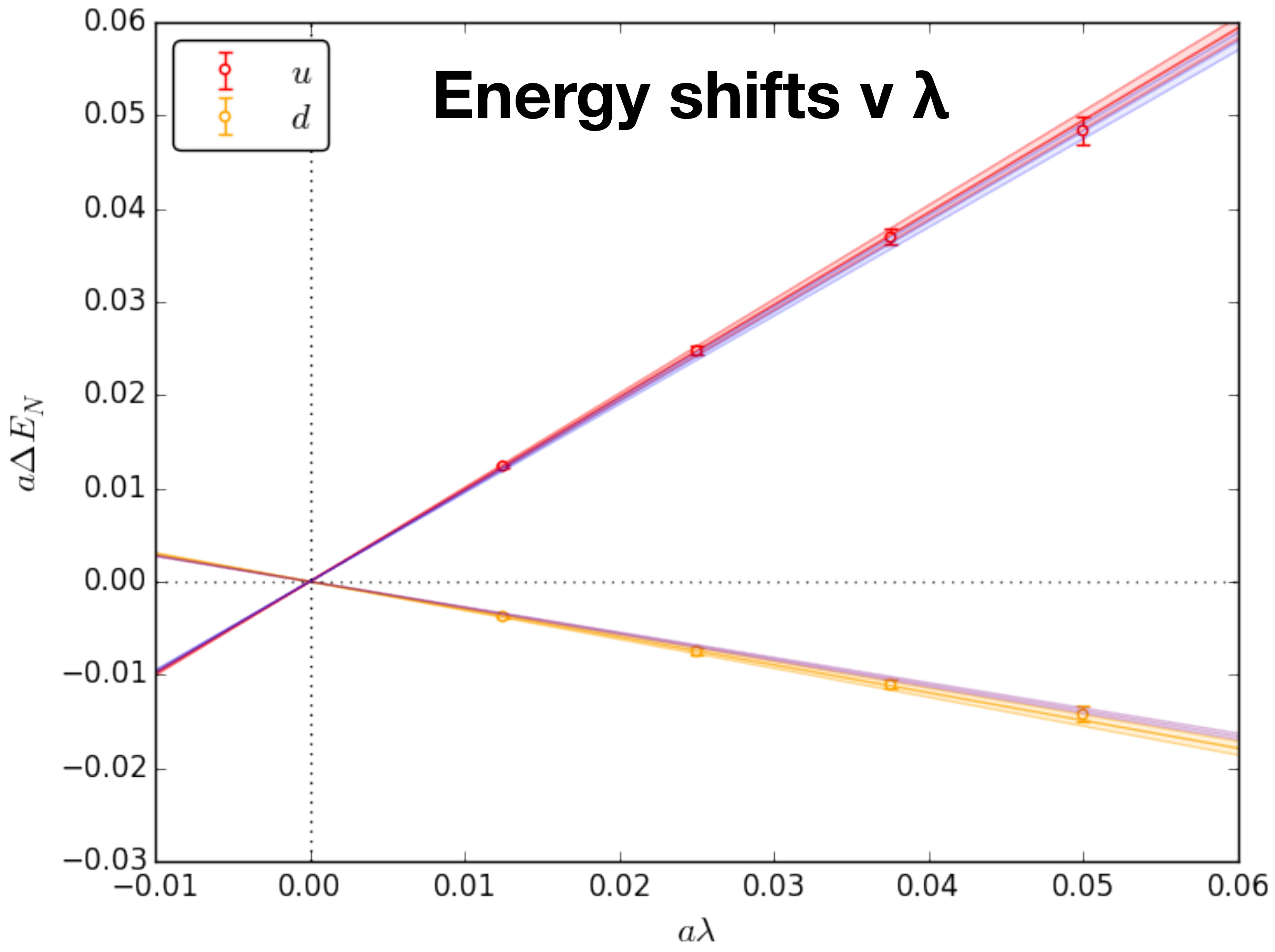
Demonstration: Axial charges

(Connected only, [PRD90 (2014)])

- Want $\langle N_s(\vec{p})|\bar{q}(0)\gamma_\mu\gamma_5 q(0)|N_s(\vec{p})\rangle = 2is_\mu \Delta q \qquad q \in (u,d)$

- Employ $\mathcal{L} \to \mathcal{L} + \lambda\bar{q}(-i\gamma_3\gamma_5)q \implies \left.\frac{\partial E_N(\lambda)}{\partial\lambda}\right|_{\lambda=0}^{\Gamma\pm} = \pm\Delta q_{\mathrm{conn.}}$

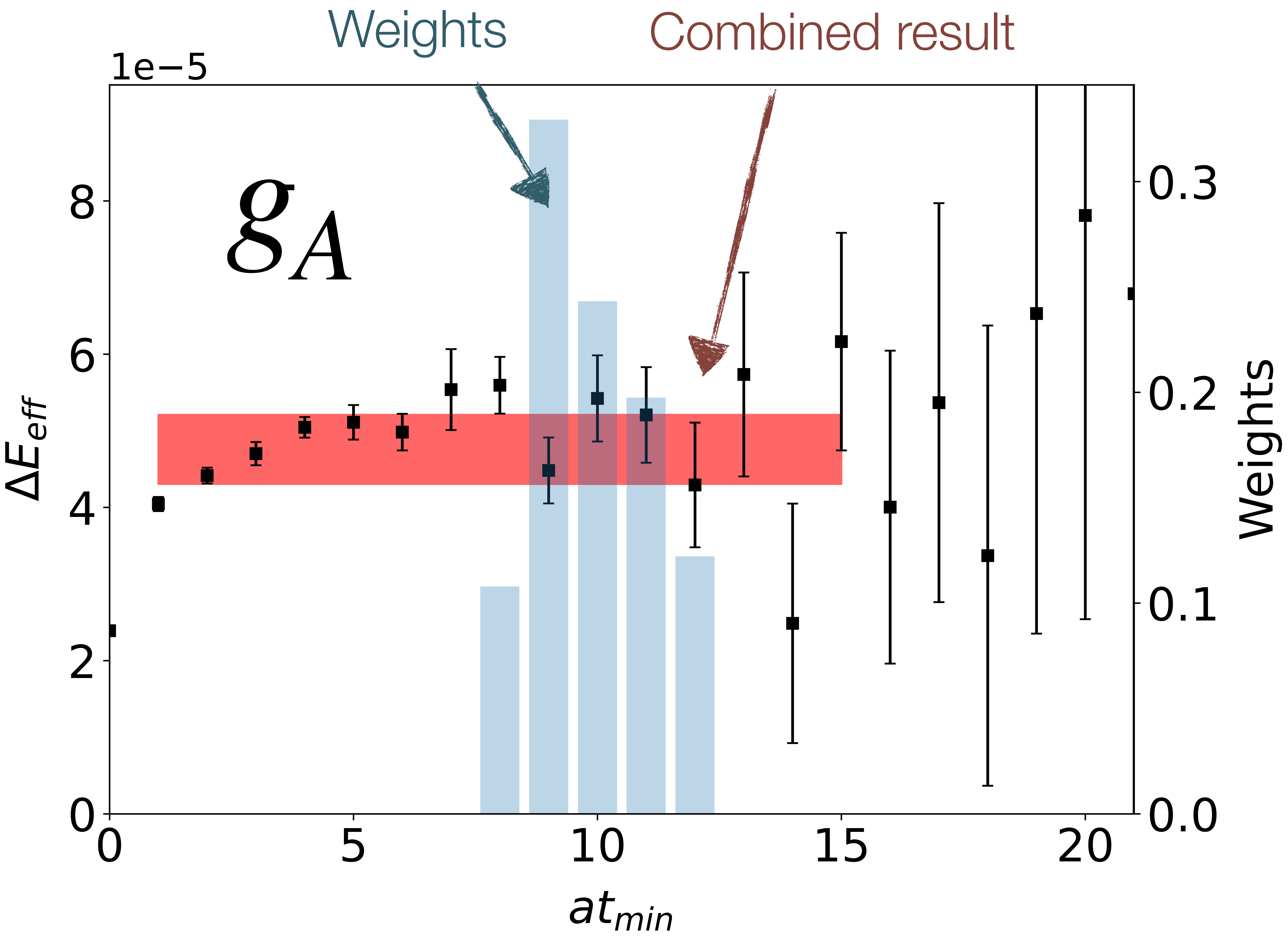




$m_\pi \approx 470$ MeV   350 configurations $32^3 \times 64$

Energy shifts: weighted average

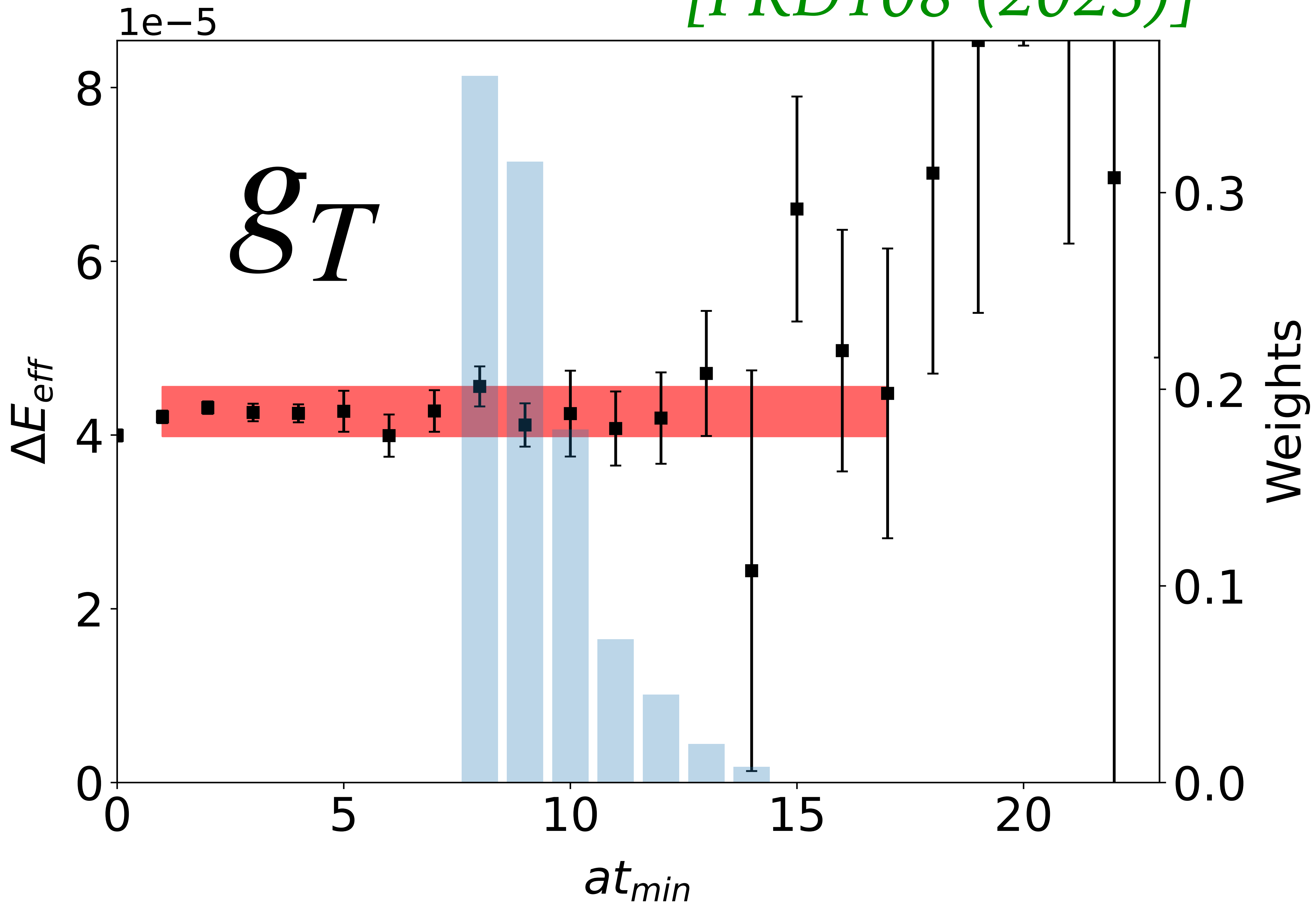
[PRD108 (2023)]



Minimum time used in fit~0.5-0.55fm

$t = 10, 9, 8, 7, 6$ for $a = 0.052,\ 0.058, 0.068, 0.074, 0.082$ fm

$m_\pi \approx 265\,\mathrm{MeV},\ \mathrm{a} = 0.068\,\mathrm{fm},\ \mathrm{V} = 48^3 \times 96,\ \lambda = 5 \times 10^{-4}$



see also: Beane *et al*. NPLQCD/QCDSF, PRD(2021), Rinaldi *et al*., PRD(2019)

(Non-normalised) weights:

$$\tilde{w}_f = \frac{p_f}{\sigma_f^2}$$

fit *p*-value

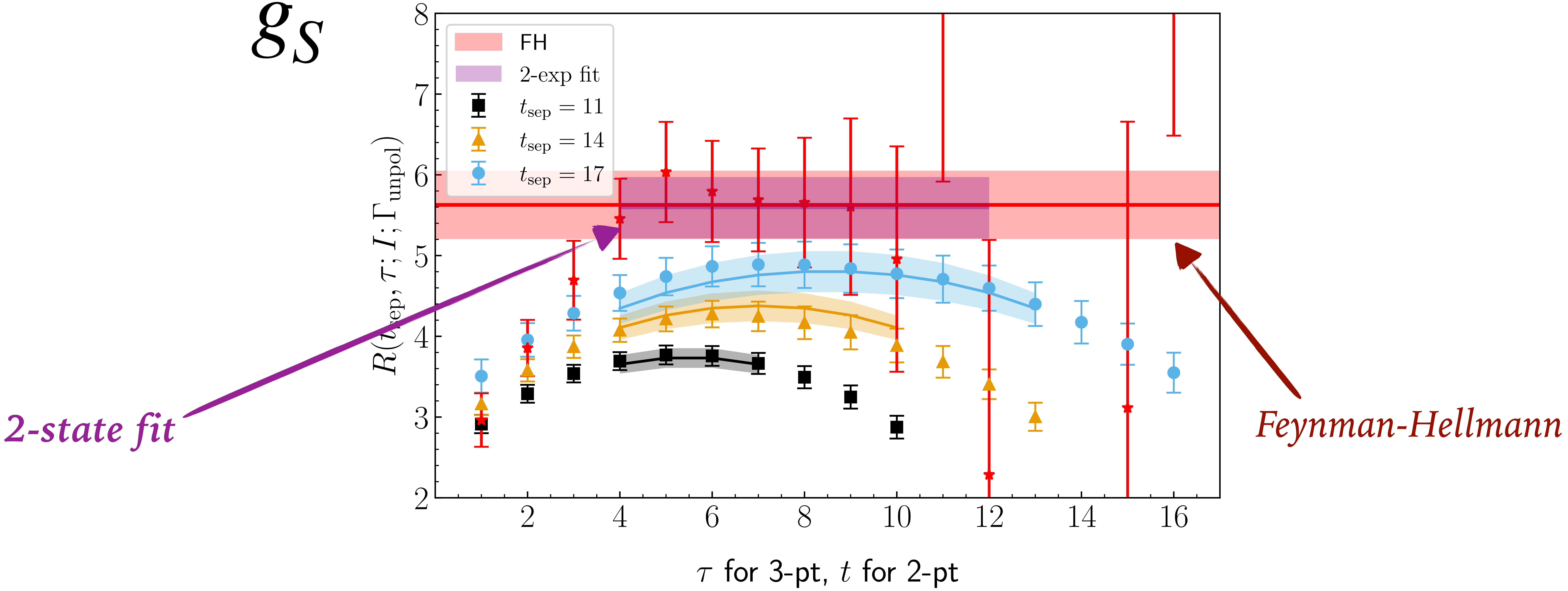
result uncertainty

Comparison to 3-point functions

$m_\pi \approx 265\,\mathrm{MeV}$

a=0.068fm, V=48³x96 , #measurements= 534x2sources

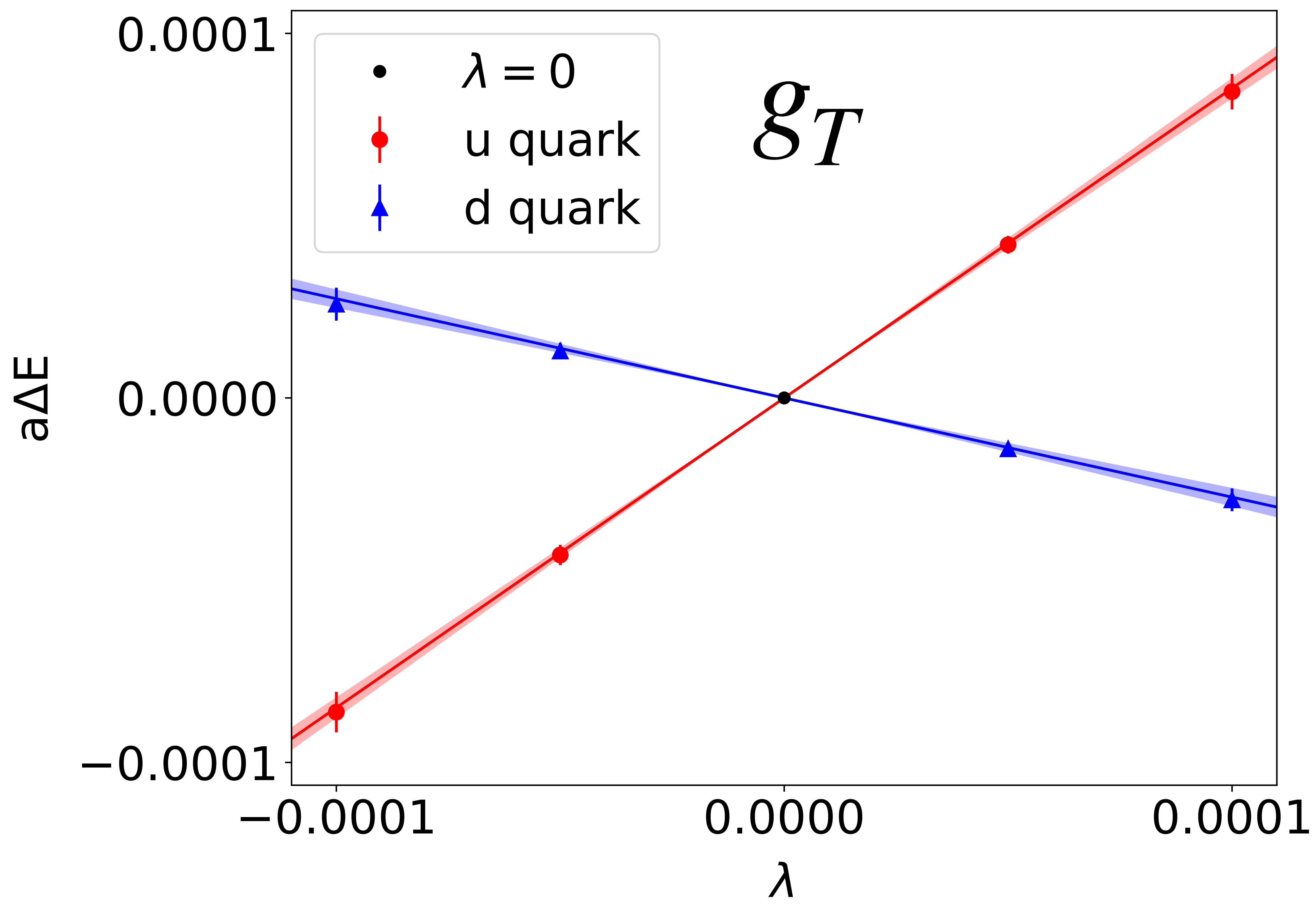
g_S

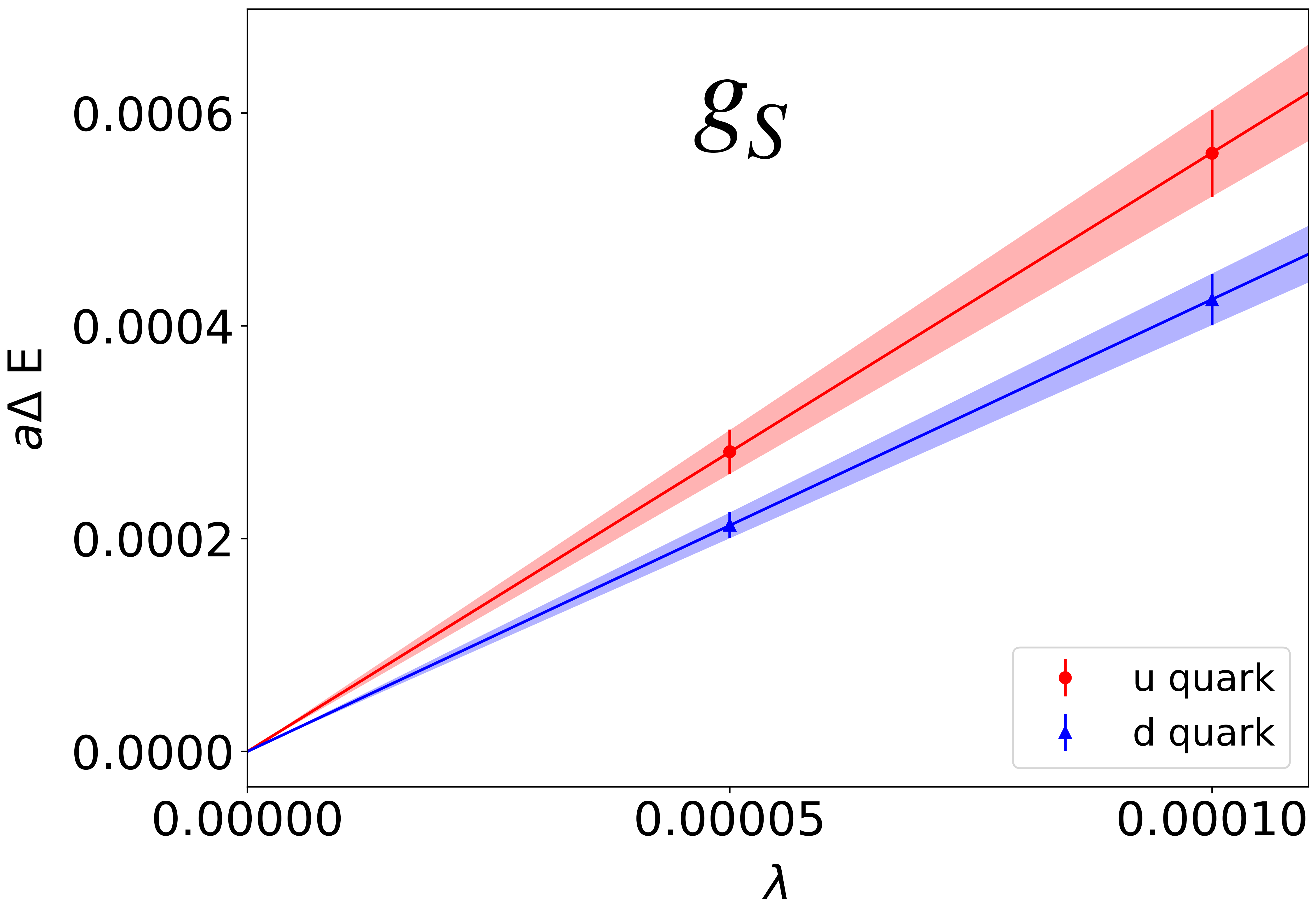


Excellent agreement between Feynman-Hellmann and standard 3-point function methods

Lambda dependence

$m_\pi \approx 265\,\mathrm{MeV},\ \mathrm{a} = 0.068\,\mathrm{fm},\ \mathrm{V} = 48^3 \times 96$





Spin-dependent:

$$\left.\frac{\partial E^{\uparrow}(\lambda)}{\partial \lambda}\right|_{\lambda=0} = + g_T^q \qquad \left.\frac{\partial E^{\downarrow}(\lambda)}{\partial \lambda}\right|_{\lambda=0} = - g_T^q$$

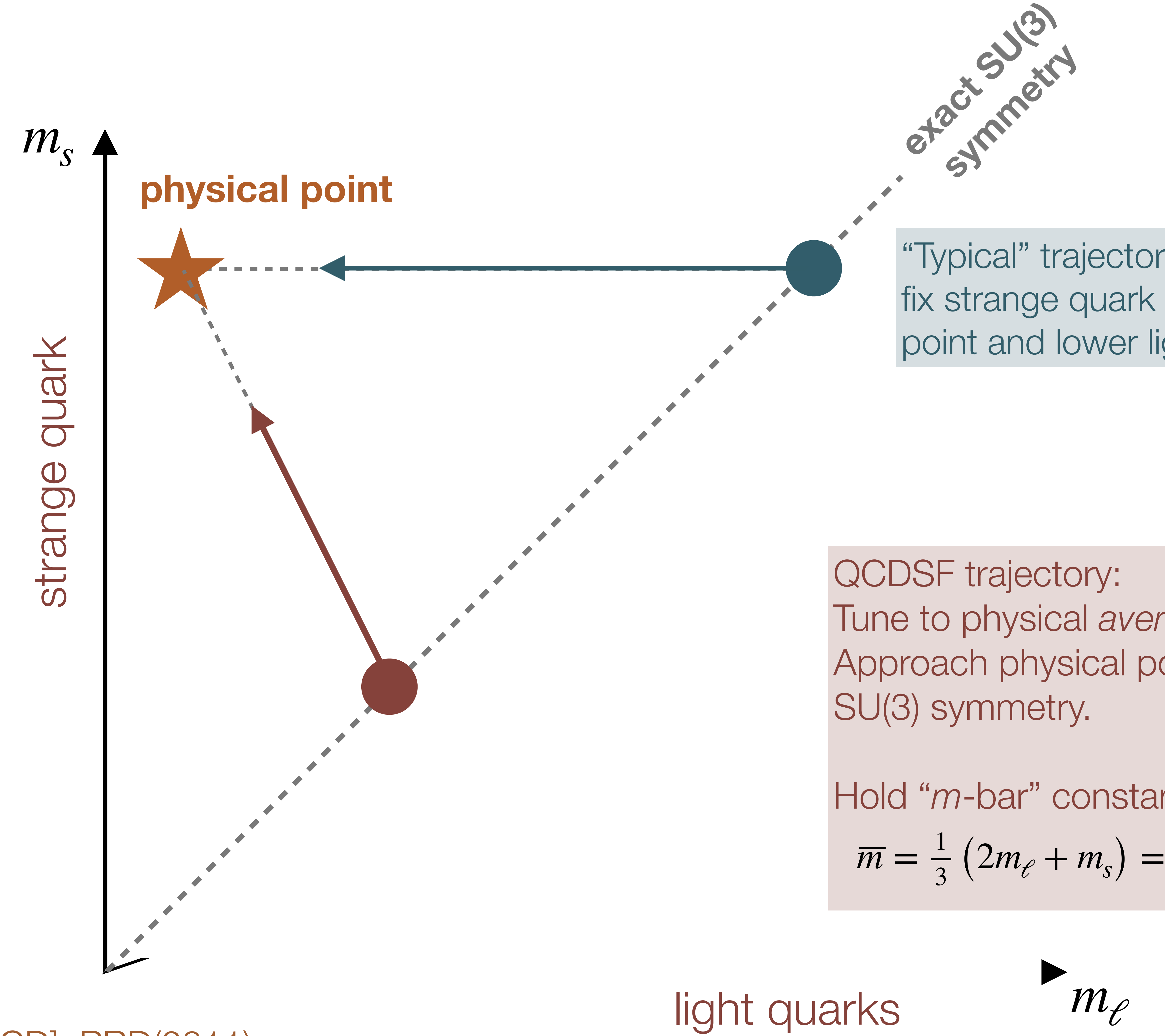
$$E(\lambda) = E(0) \pm \lambda g_T^q + \mathcal{O}(\lambda^2)$$

Spin-independent:

$$\left.\frac{\partial E(\lambda)}{\partial \lambda}\right|_{\lambda=0} = + g_S^q$$

$$E(\lambda) = E(0) + \lambda g_S^q + \mathcal{O}(\lambda^2)$$

Quark mass trajectory



“Typical” trajectory:
fix strange quark mass to physical point and lower light quark mass

QCDSF trajectory:
Tune to physical *average* quark mass.
Approach physical point by breaking SU(3) symmetry.

Hold “*m*-bar” constant:

$$\overline{m} = \frac{1}{3}\left(2m_\ell + m_s\right) = \frac{1}{3}\left(2m_\ell^{\text{phys}} + m_s^{\text{phys}}\right)$$

Bietenholz *et al*. [QCDSF-UKQCD], PRD(2011)

Flavour-breaking expansion

Bickerton, Horsley *et al.* [QCDSF], PRD(2019)

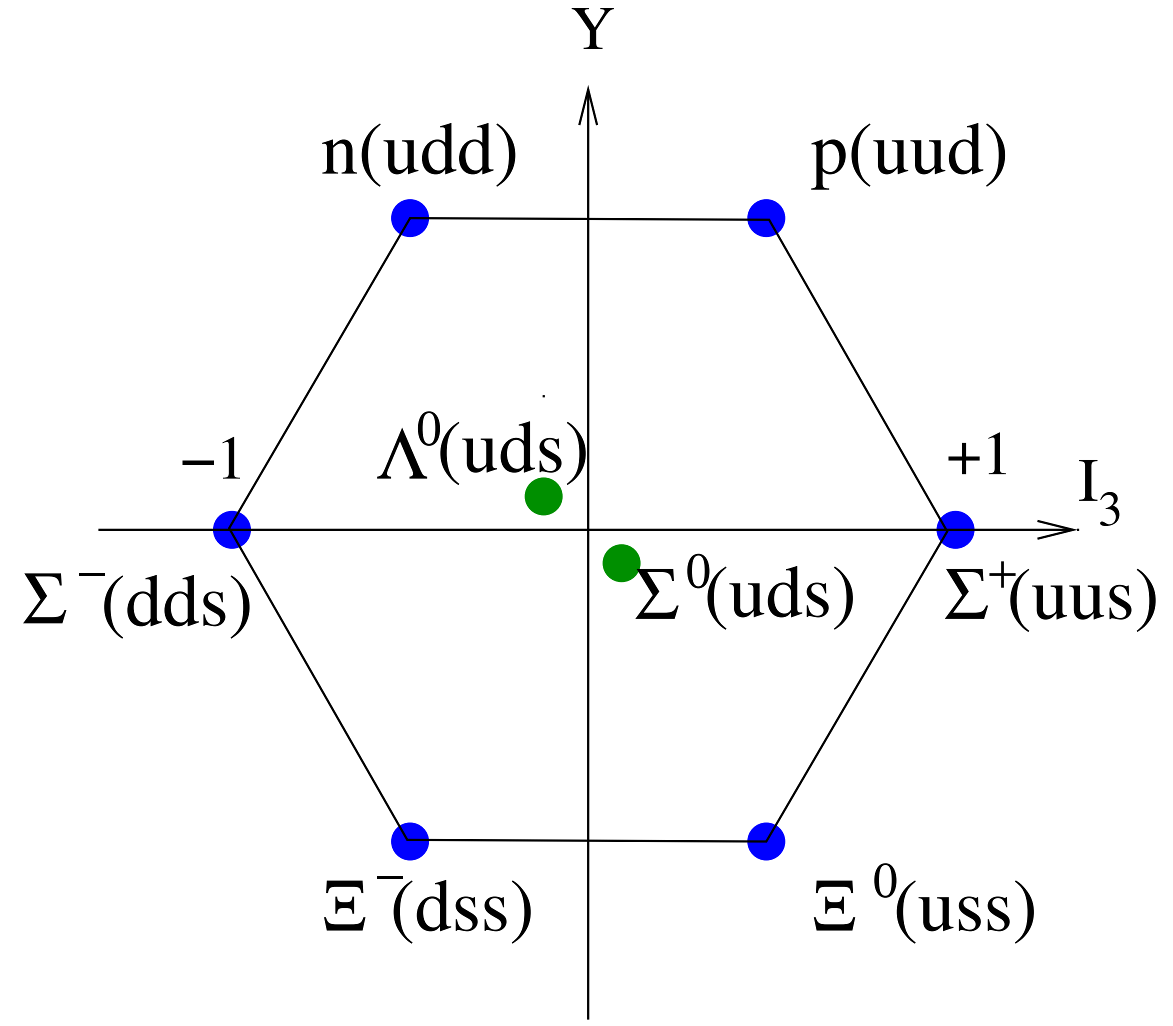
Consider general flavour matrix elements of octet baryons:

$$\langle B'|J^F|B\rangle = A_{B'FB}$$

In exact SU(3) limit, just 2 independent constants:

- *F*- and *D*-type couplings

At linear order in SU(3) breaking: 5 slope parameters (3 D's & 2 F's)



- # of parameters (polynomials/operators) reduced by restricting to $\bar{m}$ = constant line

$$F_1 \equiv \frac{1}{\sqrt{3}}(A_{\bar{N}\eta N} - A_{\bar{\Xi}\eta\Xi}) = 2f - \frac{2}{\sqrt{3}}s_2\delta m_l,$$

$$F_2 \equiv (A_{\bar{N}\pi N} + A_{\bar{\Xi}\pi\Xi}) = 2f + 4s_1\delta m_l,$$

$$F_3 \equiv A_{\bar{\Sigma}\pi\Sigma} = 2f + (-2s_1 + \sqrt{3}s_2)\delta m_l,$$

$$F_4 \equiv \frac{1}{\sqrt{2}}(A_{\bar{\Sigma}K\Xi} - A_{\bar{N}K\Sigma}) = 2f - 2s_1\delta m_l,$$

$$F_5 \equiv \frac{1}{\sqrt{3}}(A_{\bar{\Lambda}K\Xi} - A_{\bar{N}K\Lambda}) = 2f + \frac{2}{\sqrt{3}}(\sqrt{3}s_1 - s_2)\delta m_l.$$

All matrix elements identical in the SU(3) symmetric limit

Index	Baryon (B)	Meson (F)	Current (J^F)
1	n	K^0	$\bar{d}\gamma s$
2	p	K^+	$\bar{u}\gamma s$
3	Σ^-	π^-	$\bar{d}\gamma u$
4	Σ^0	π^0	$\frac{1}{\sqrt{2}}(\bar{u}\gamma u - \bar{d}\gamma d)$
5	Λ^0	η	$\frac{1}{\sqrt{6}}(\bar{u}\gamma u + \bar{d}\gamma d - 2\bar{s}\gamma s)$
6	Σ^+	π^+	$\bar{u}\gamma d$
7	Ξ^-	K^-	$\bar{s}\gamma u$
8	Ξ^0	$\bar{K}^0$	$\bar{s}\gamma d$
0		η'	$\frac{1}{\sqrt{6}}(\bar{u}\gamma u + \bar{d}\gamma d + \bar{s}\gamma s)$

Fan plots

a=0.068fm

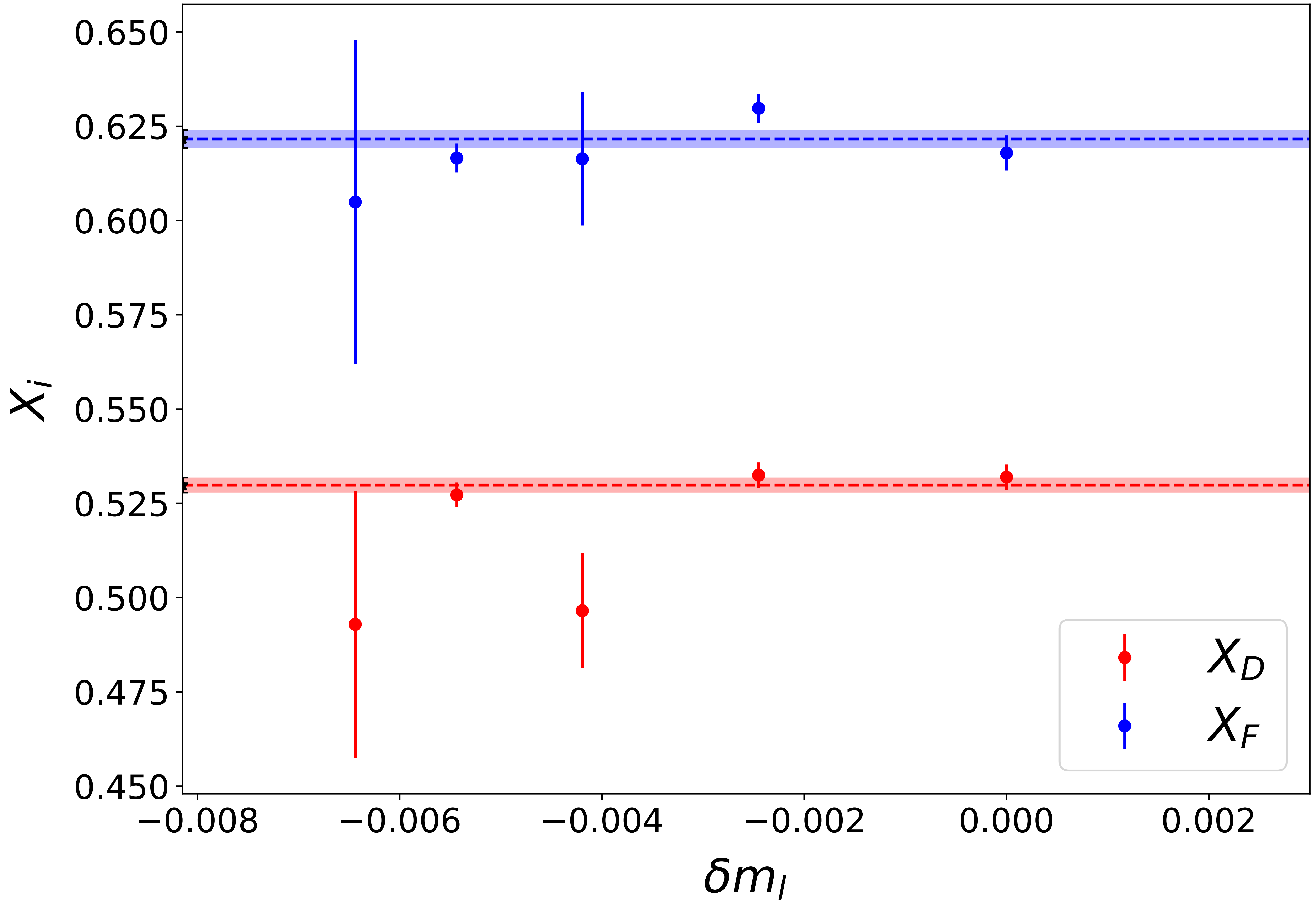
Can form a "singlet" combination

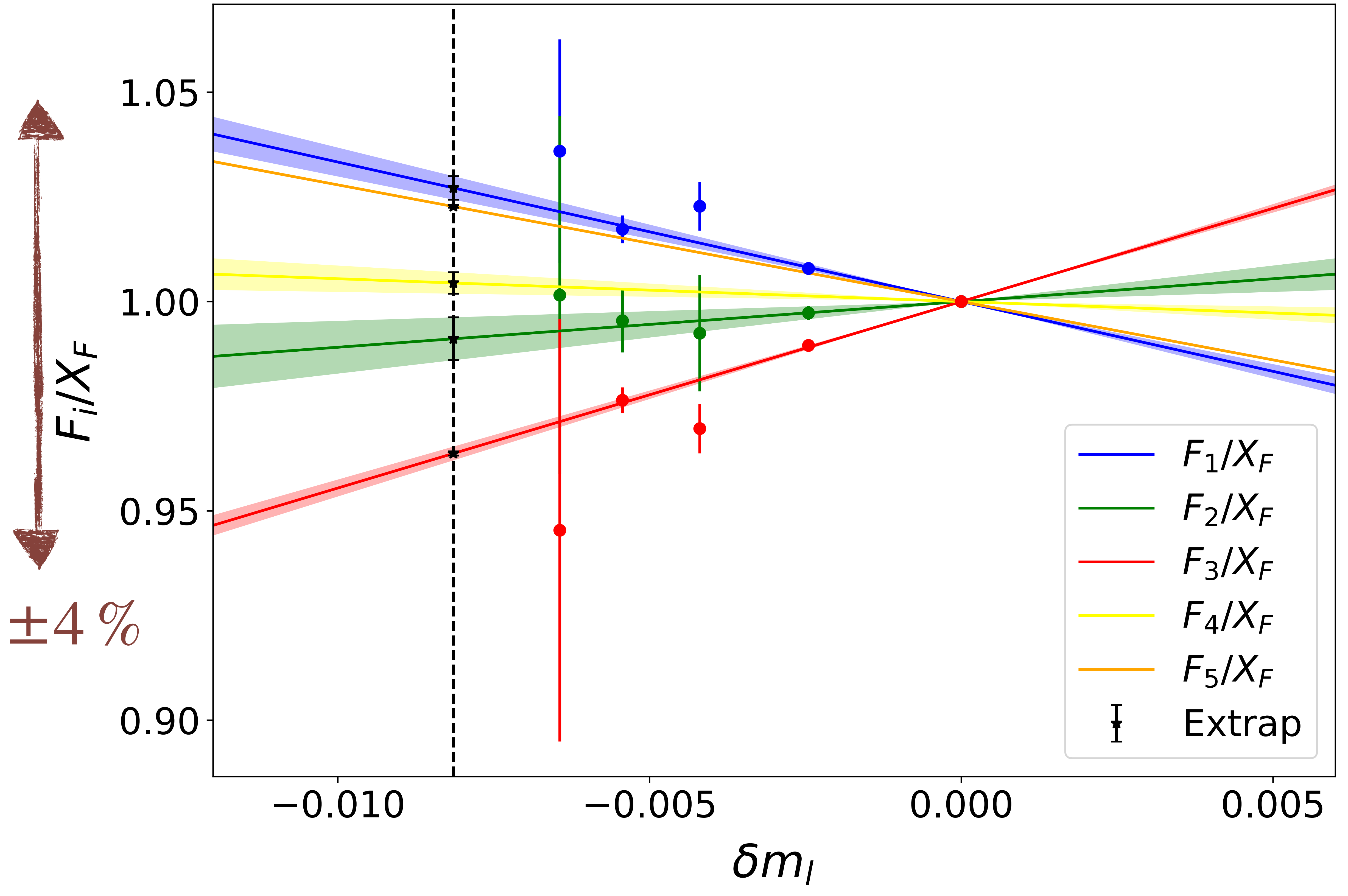
$$X_F = \frac{1}{6}(3F_1 + F_2 + 2F_3) = 2f + \mathcal{O}(\delta m_\ell^2)$$

General result: Singlet quantities only vary at 2nd-order in SU(3) breaking.

$$\begin{aligned}
F_1 \equiv \frac{1}{\sqrt{3}}(A_{\bar{N}\eta N} - A_{\bar{\Xi}\eta\Xi}) &= 2f - \frac{2}{\sqrt{3}} s_2 \delta m_l, \\
F_2 \equiv (A_{\bar{N}\pi N} + A_{\bar{\Xi}\pi\Xi}) &= 2f + 4 s_1 \delta m_l, \\
F_3 \equiv A_{\bar{\Sigma}\pi\Sigma} &= 2f + (-2s_1 + \sqrt{3} s_2)\delta m_l, \\
F_4 \equiv \frac{1}{\sqrt{2}}(A_{\bar{\Sigma}K\Xi} - A_{\bar{N}K\Sigma}) &= 2f - 2 s_1 \delta m_l, \\
F_5 \equiv \frac{1}{\sqrt{3}}(A_{\bar{\Lambda}K\Xi} - A_{\bar{N}K\Lambda}) &= 2f + \frac{2}{\sqrt{3}}(\sqrt{3} s_1 - s_2)\delta m_l.
\end{aligned}$$

F fan

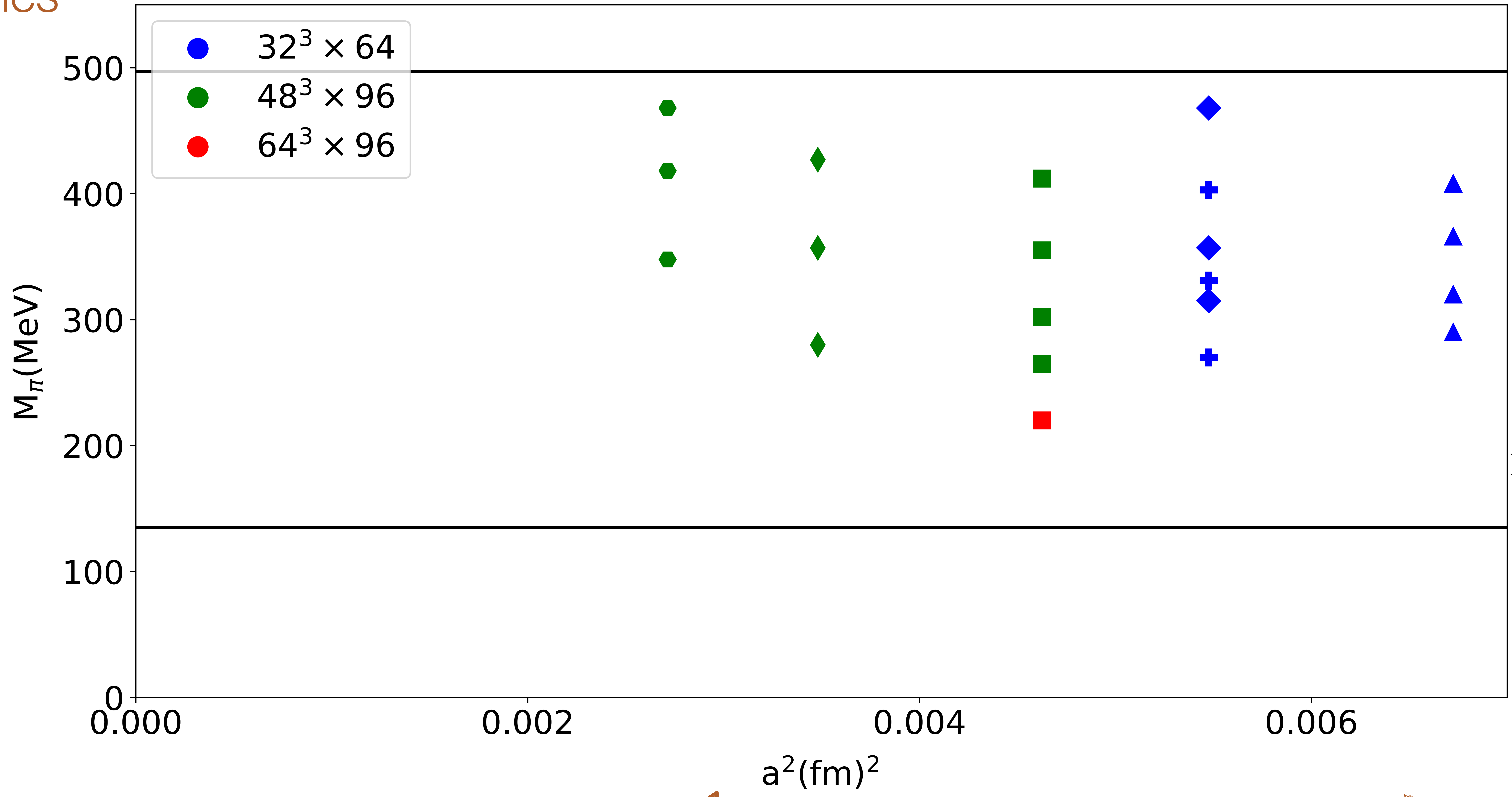




Simulation details

2+1 flavour, NP-improved Wilson fermions

3 volumes



pion masses

$220 \leftrightarrow 500\,\mathrm{MeV}$

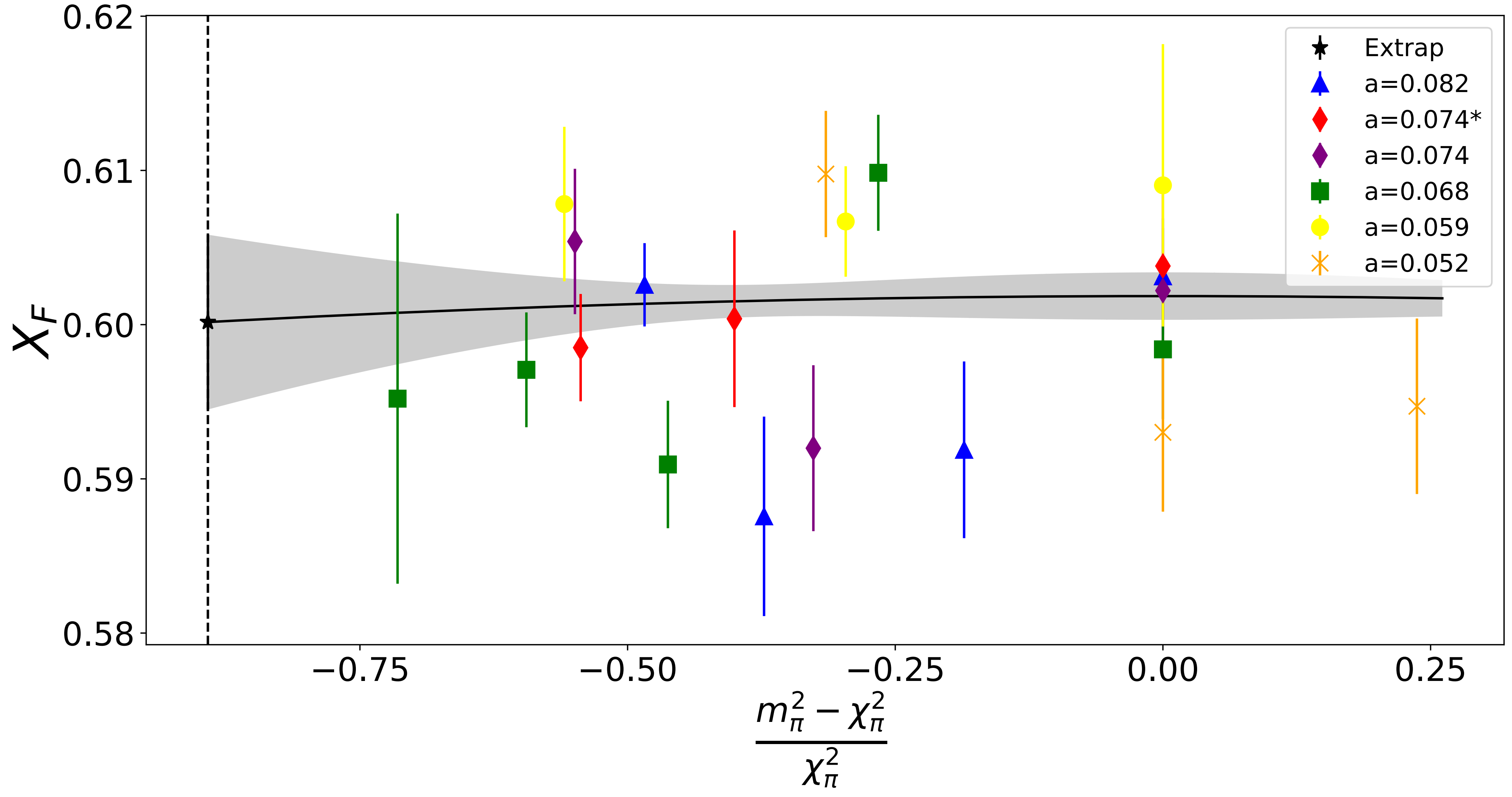
5 lattice spacings $0.052 \leftrightarrow 0.082\,\mathrm{fm}$

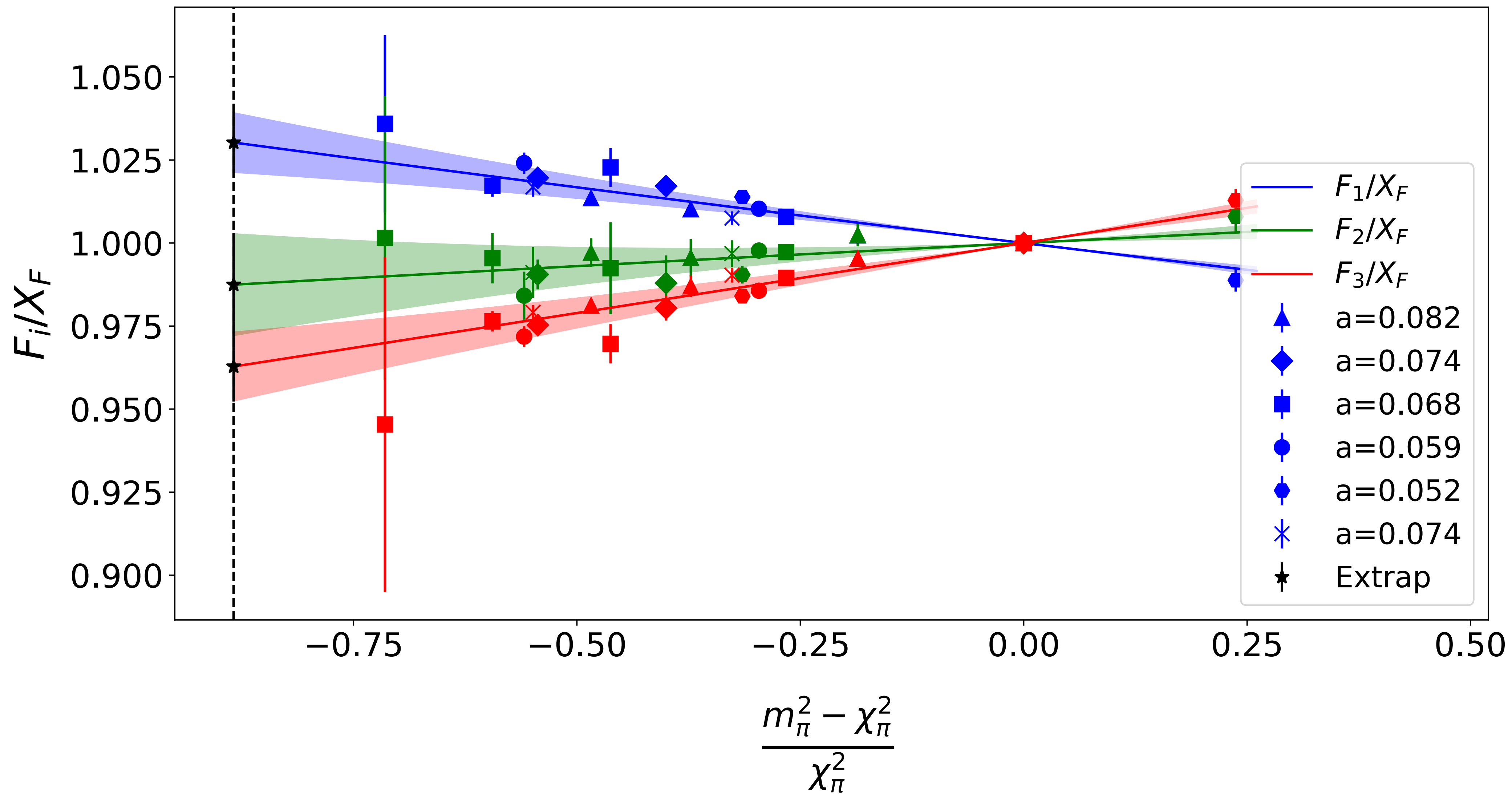
Global fits

Singlet X_F

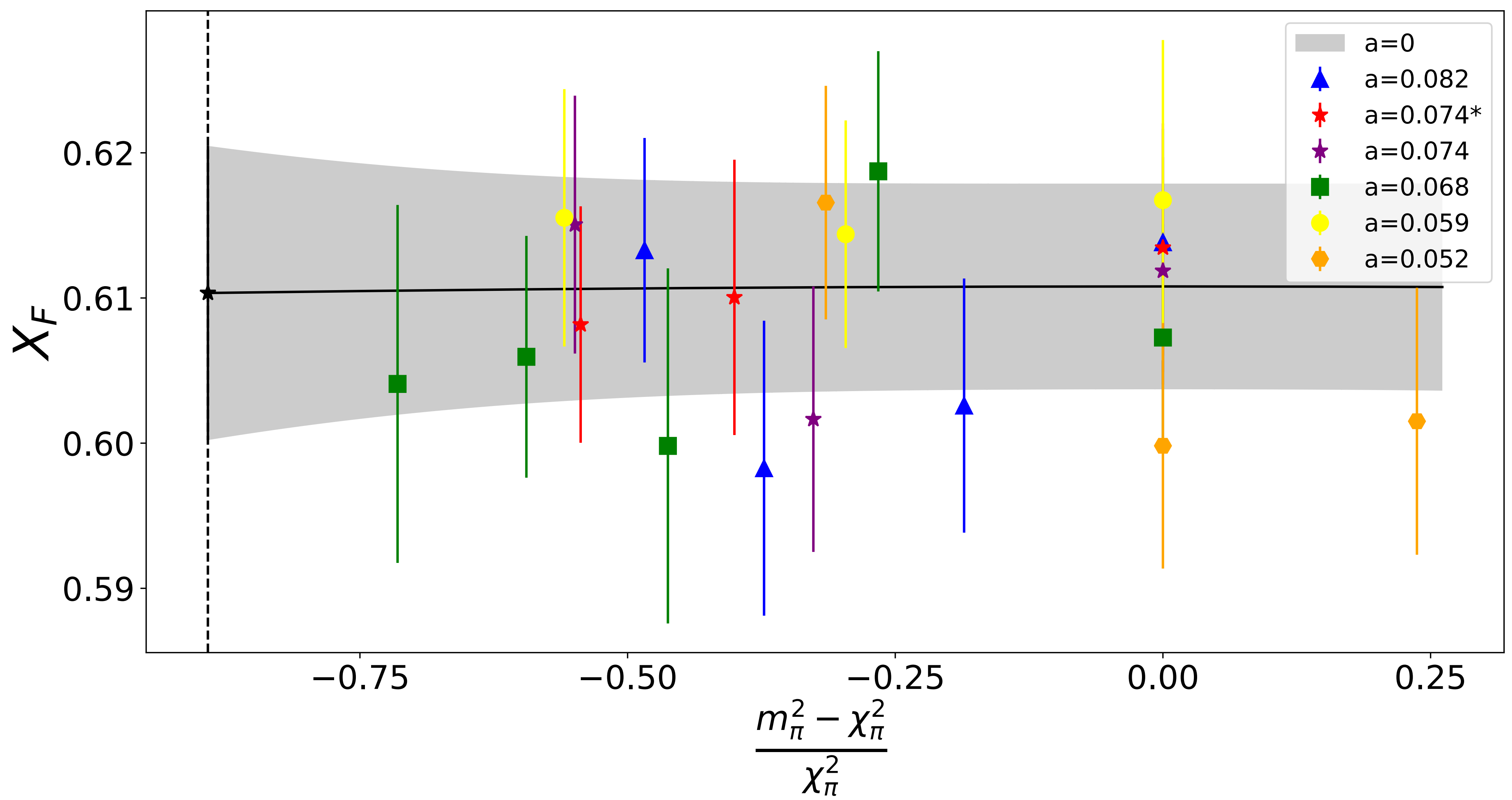
F slope parameters

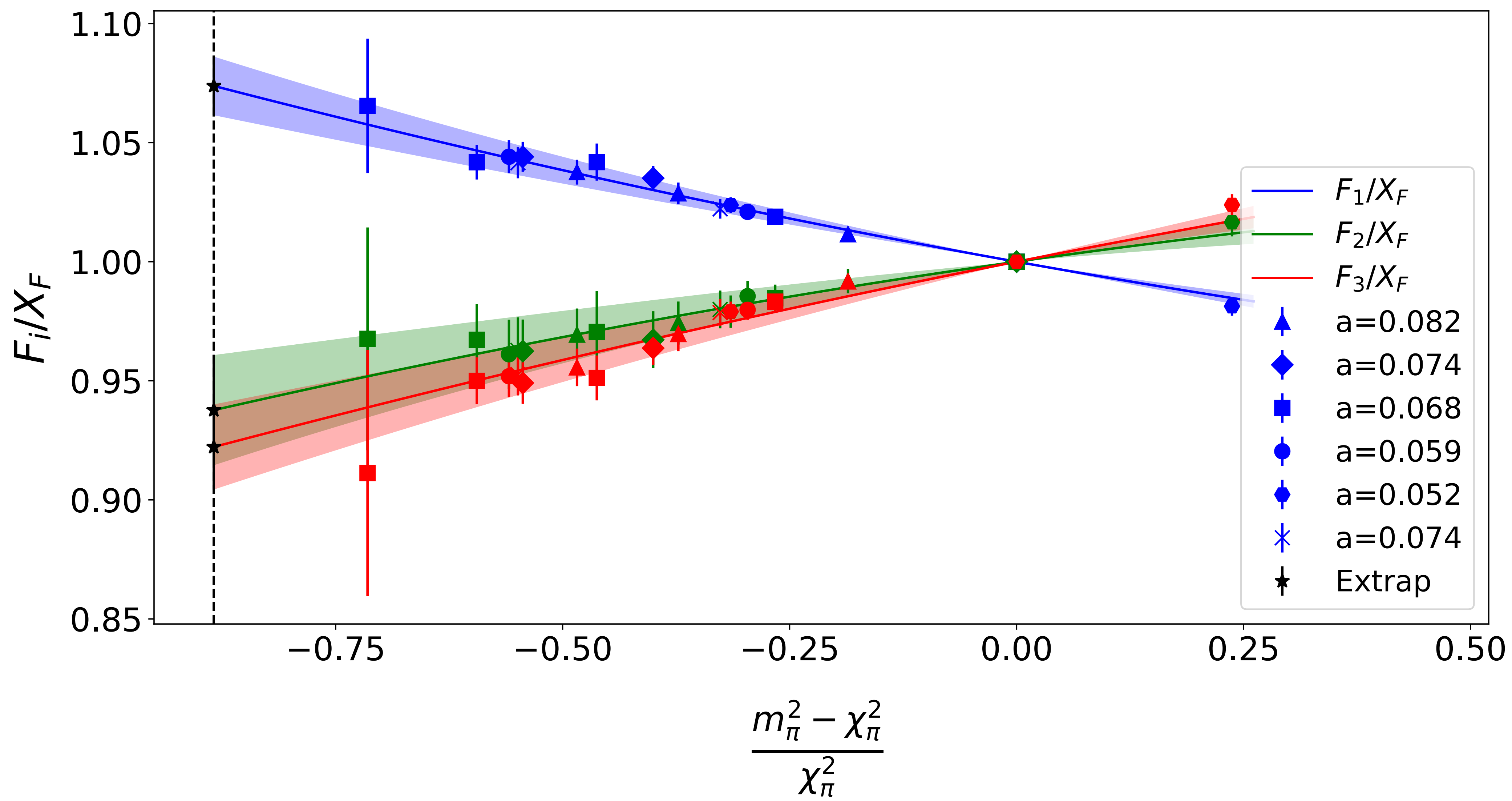
Quark mass only





With O(a) and FV

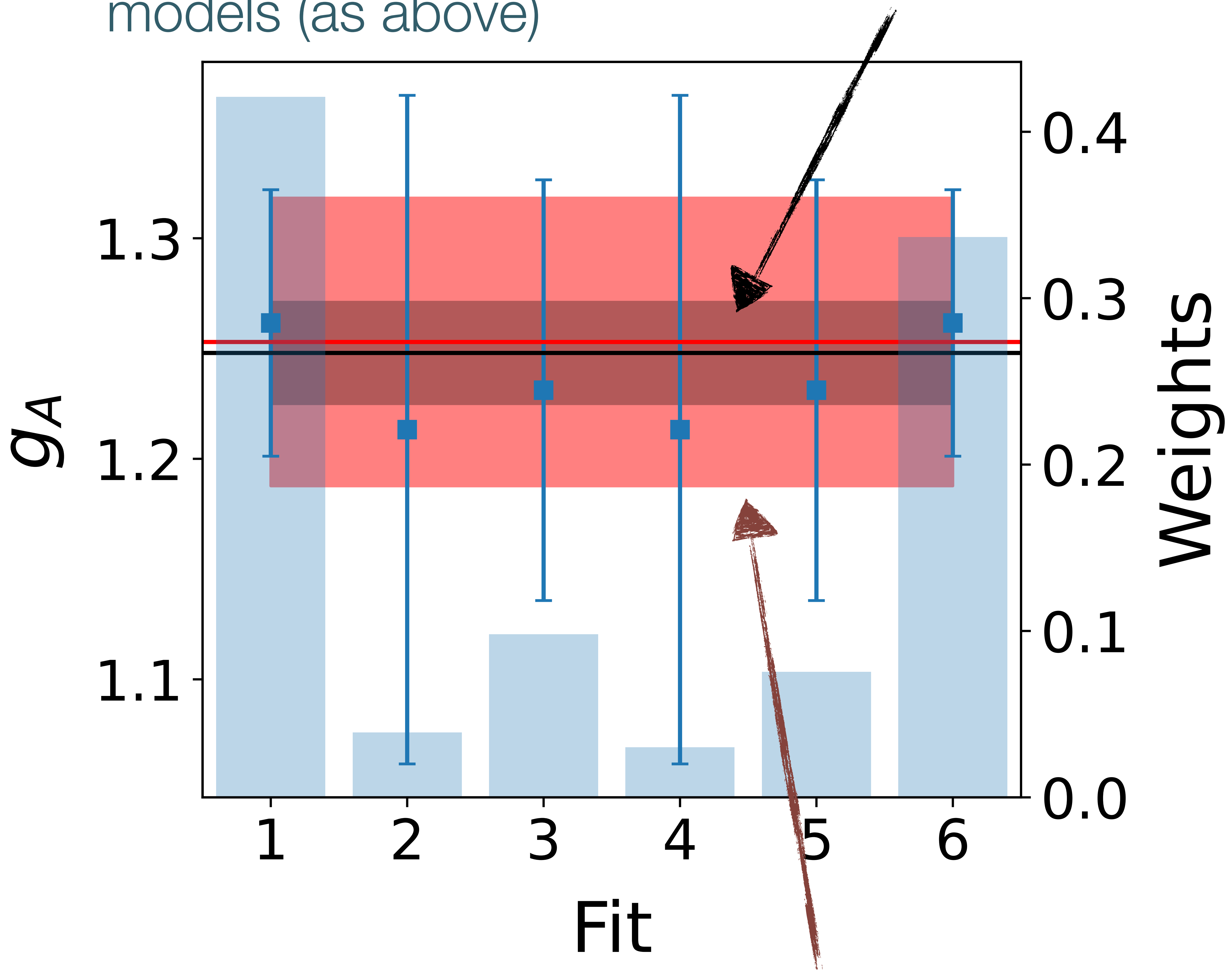




Results - g_A (isovector)

weighted average among models (as above)

FLAG result, ~2.2%

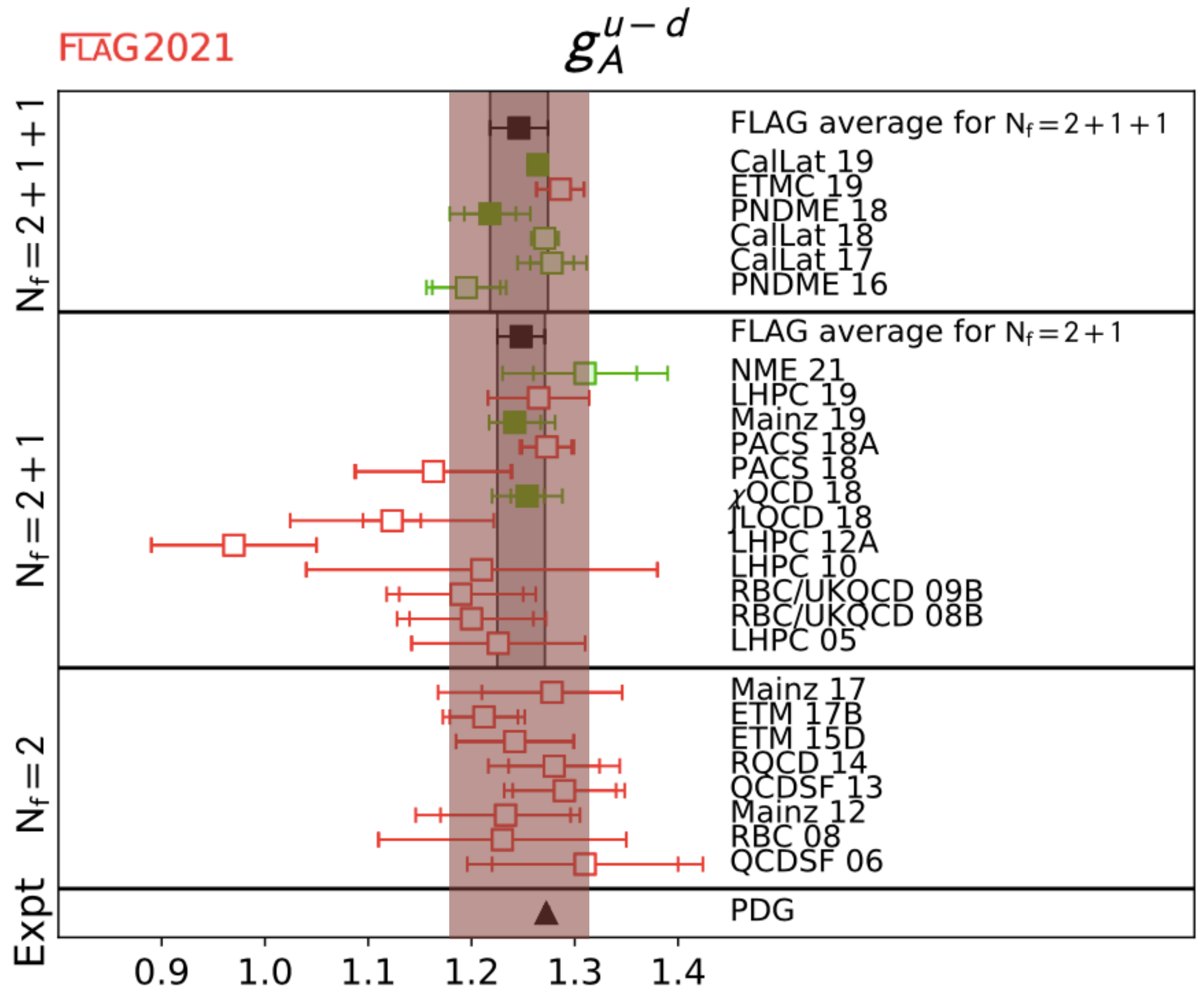


Our result, (stat+sys)~5.5%

$$g_A^{u-d} = 1.253(63)_{\text{stat}}(41)_a(03)_{\text{FV}}$$

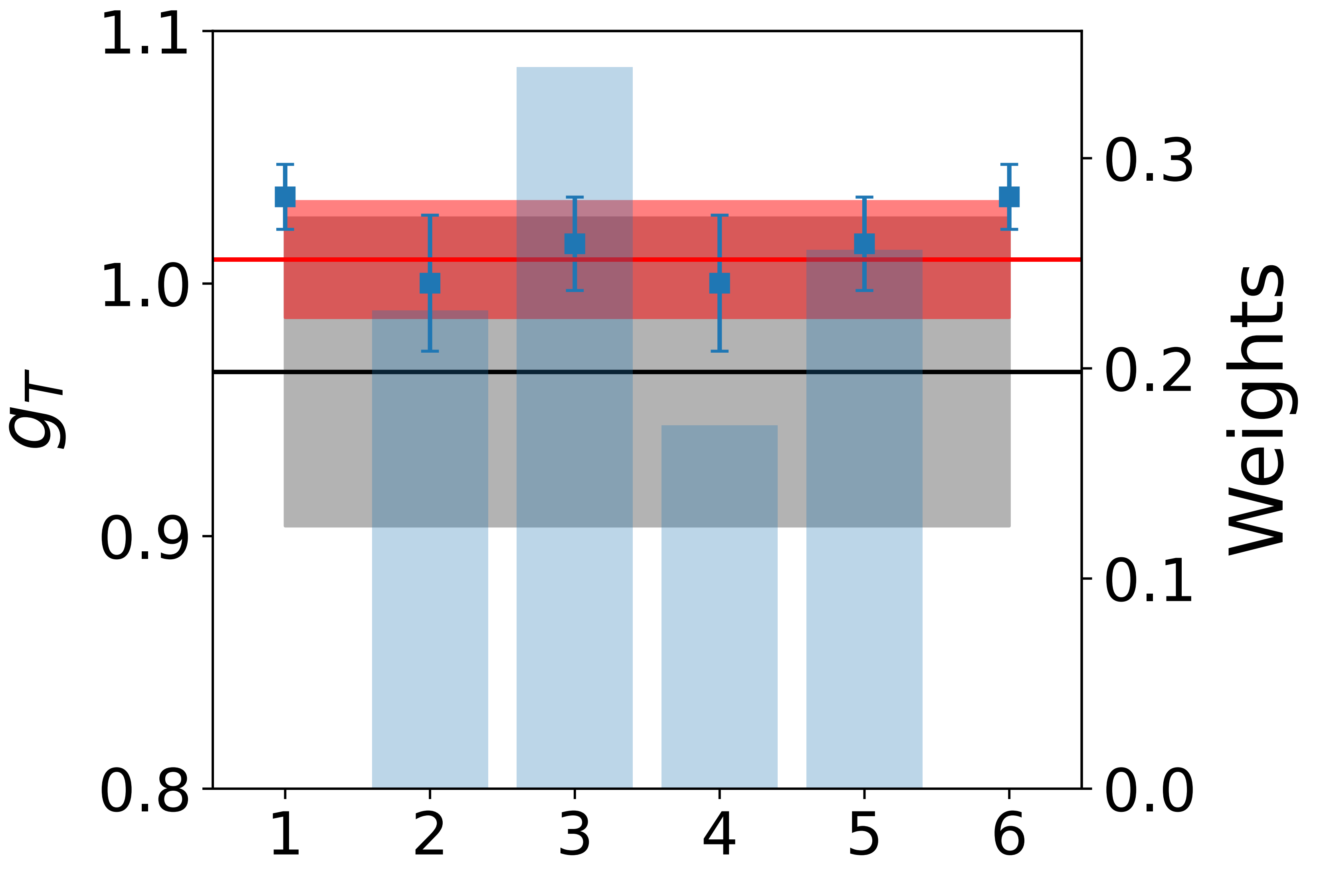
Different model parameterisations

1. δm_l^2
2. $a,\ \delta m_l^2$
3. $a^2,\ \delta m_l^2$
4. $a,\ \delta m_l^2,\ m_\pi L$
5. $a^2,\ \delta m_l^2,\ m_\pi L$
6. $\delta m_l^2,\ m_\pi L$



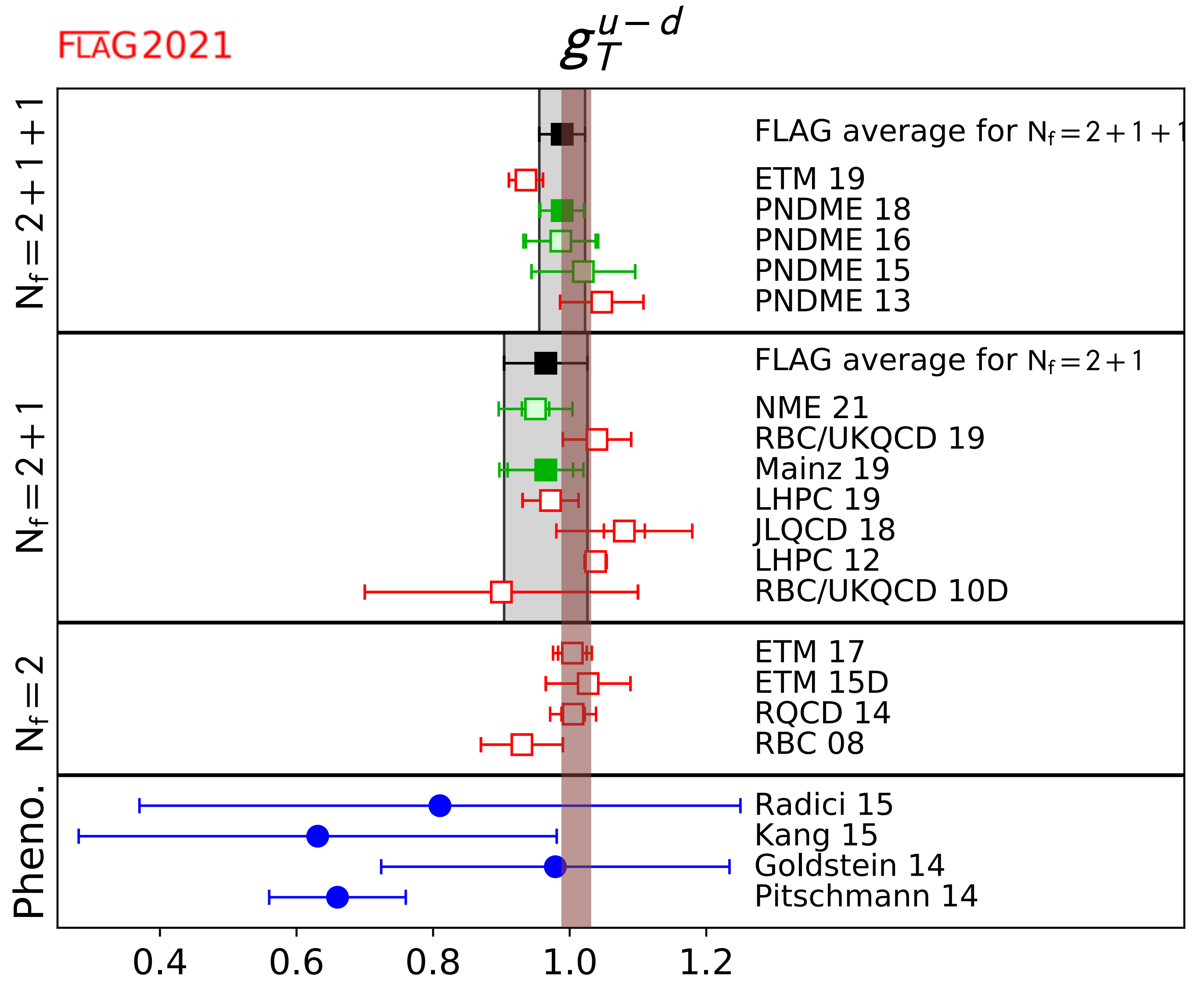
Results - isovector charges $N_f = 2 + 1$

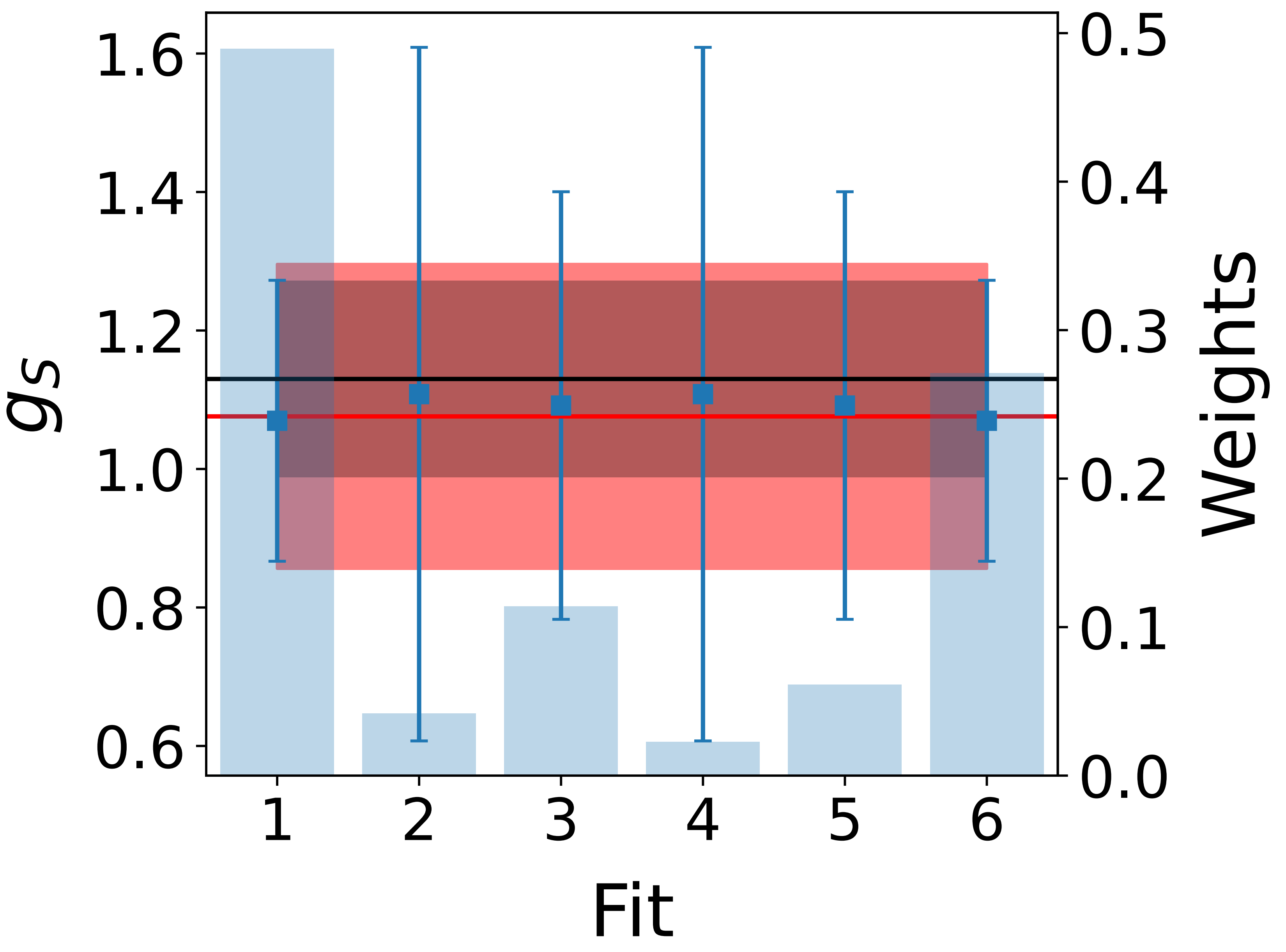
$\overline{\text{MS}}, \mu = 2\,\text{GeV}$



$$g_T^{u-d} = 1.010(21)_{\text{stat}}(12)_a(01)_{\text{FV}}$$

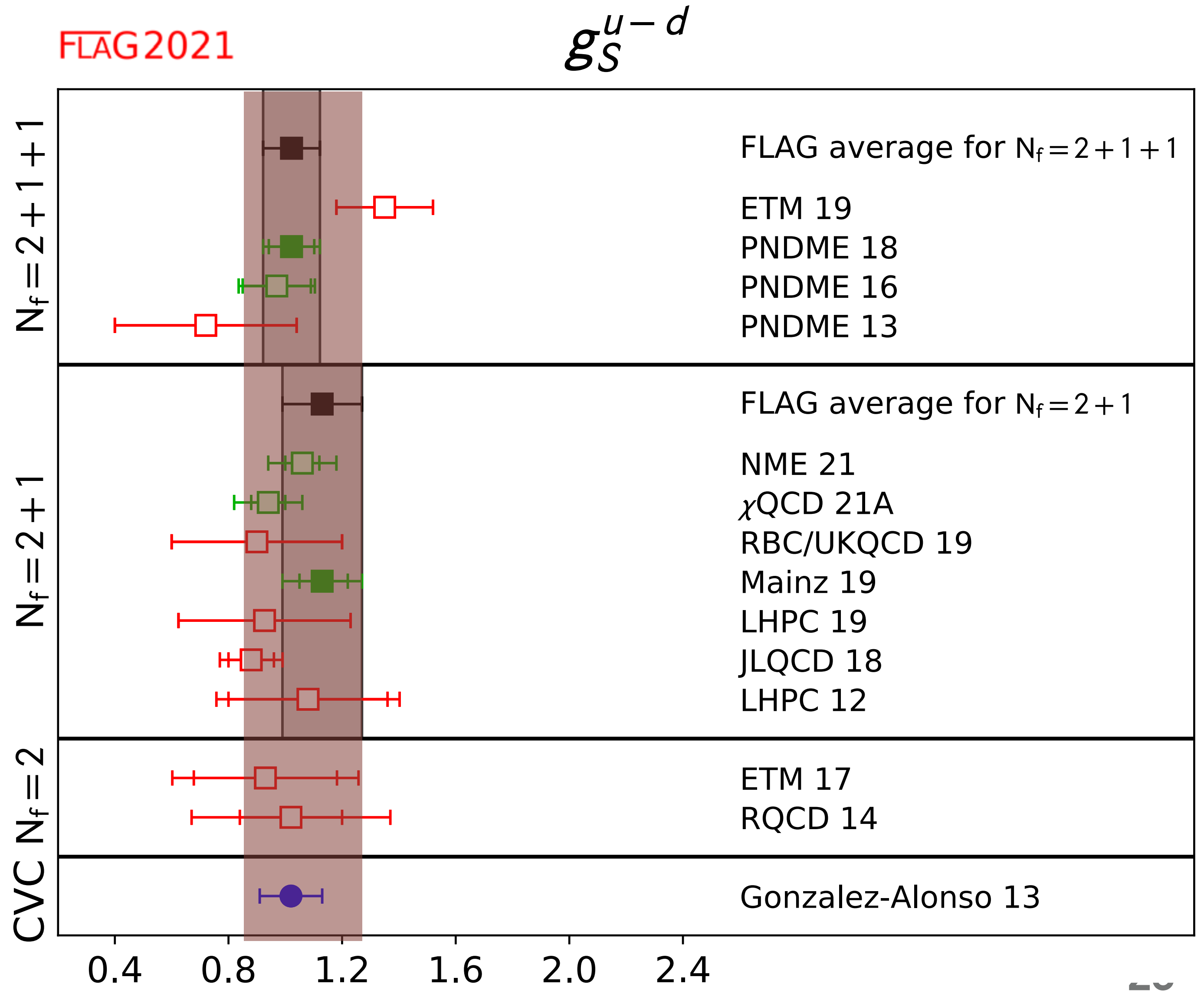
FLAG 2+1: ~6%
FLAG 2+1+1: ~3%
Our result: ~2%





$$g_S^{u-d} = 1.08(21)_{\text{stat}}(03)_a(01)_{\text{FV}}$$

FLAG 2+1: ~12%
Our result: ~19%



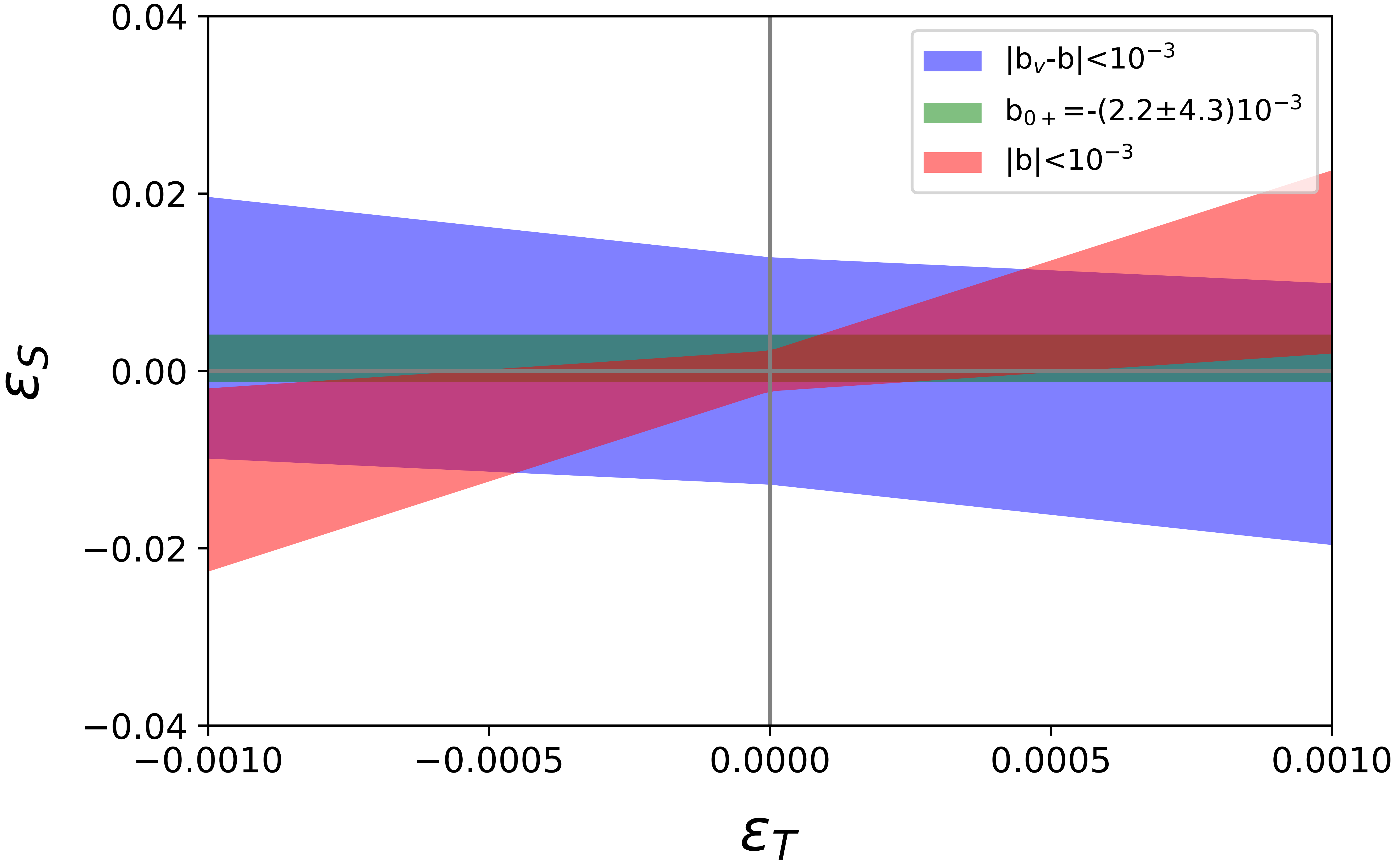
Impact on phenomenology

Following Bhattacharya et al., PRD, 2012

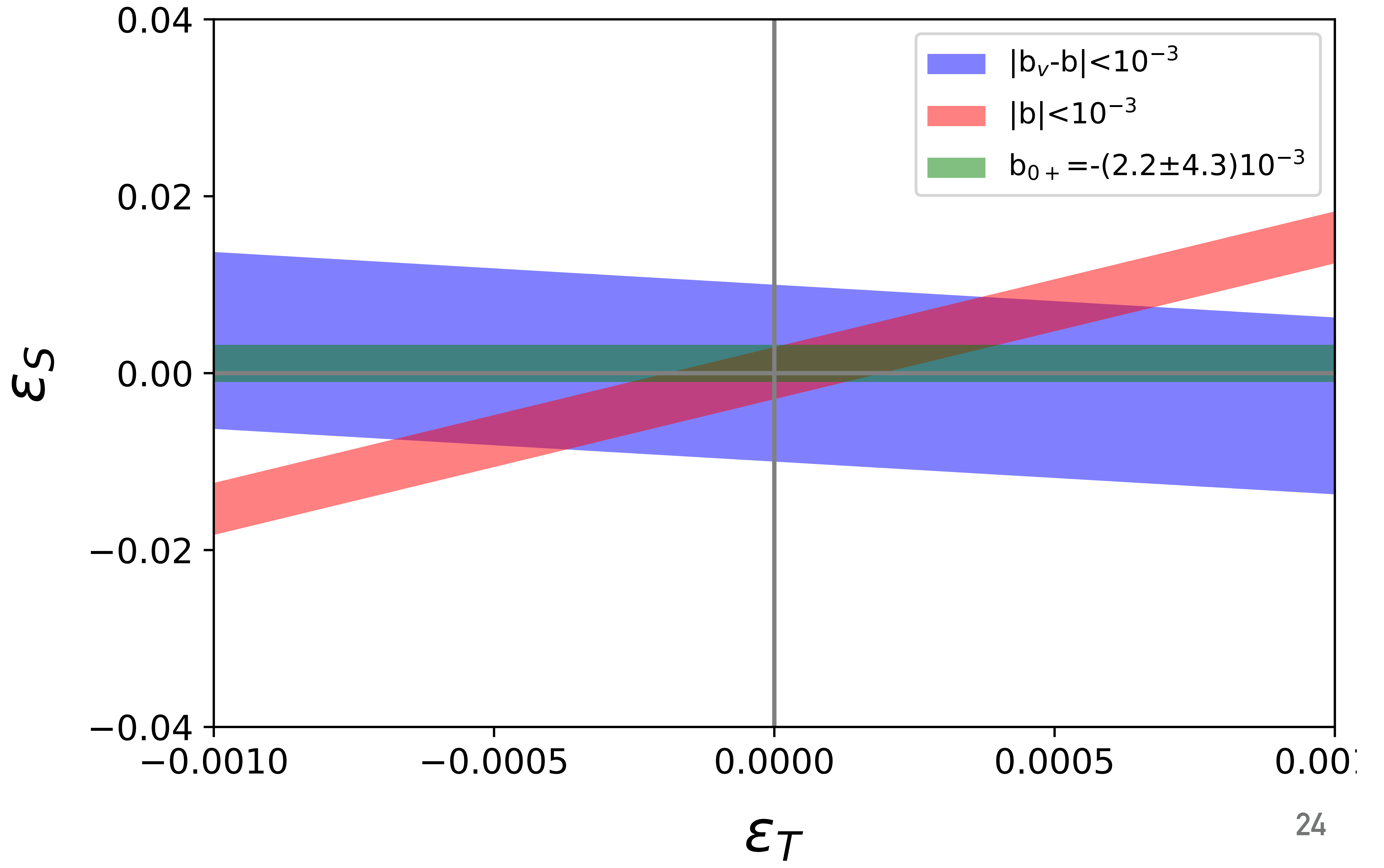
Experimental rates sensitive to product of

(Tensor and scalar charges: g_T/g_S) X (new-physics effective couplings: ϵ_T/ϵ_S)

Current and projected experimental limits with g_T/g_S (this work)

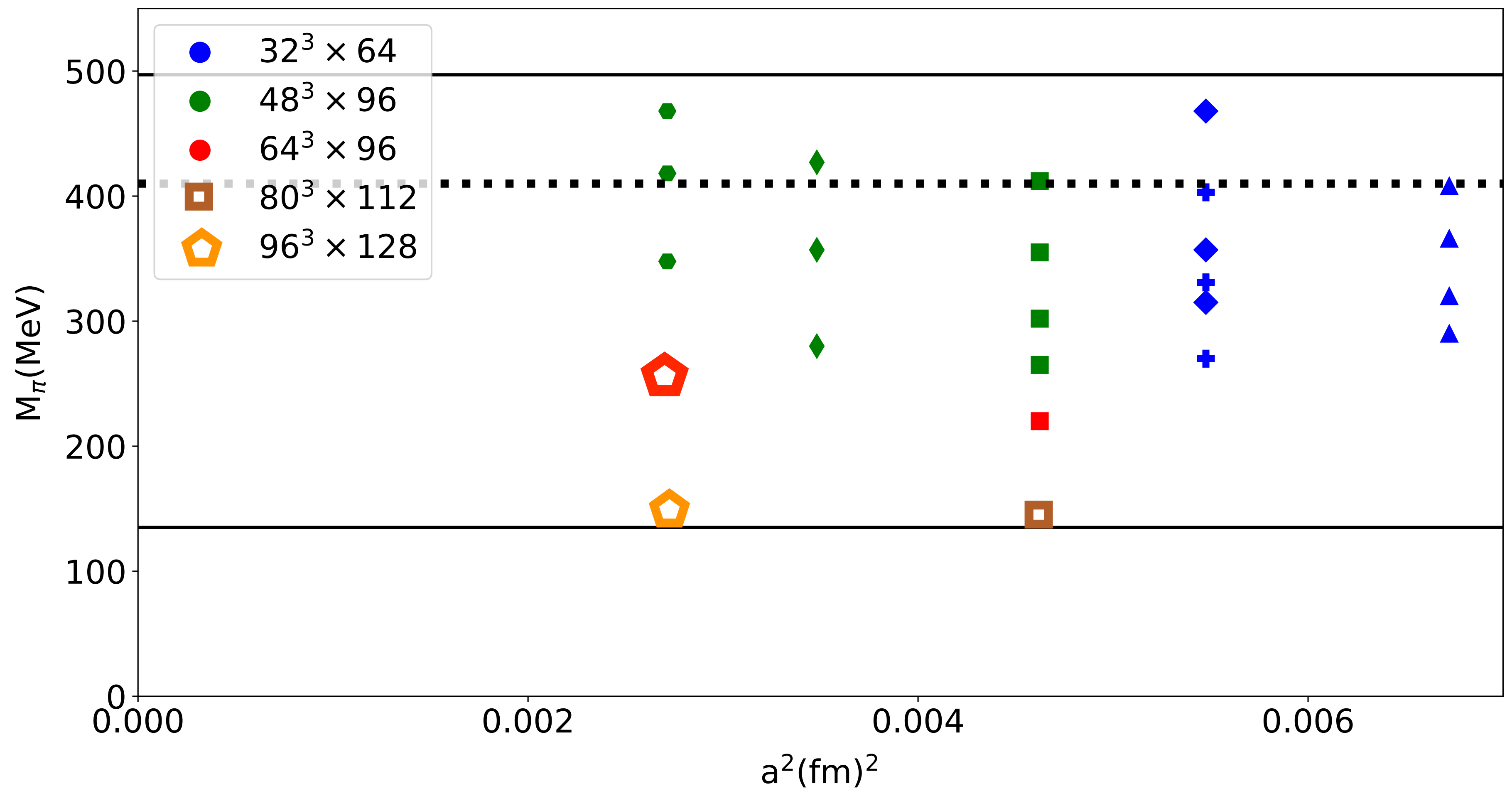


With $g_T = g_S = 1$ (no error)



Summary and outlook

- Feynman Hellman theorem
  - provides a viable alternative to 3-pt function methods for computing hadronic matrix elements
- Flavour-breaking expansion along the $\bar{m} = \text{constant}$ line
  - allows for a controlled extrapolation from the SU(3)-symmetric point
- Future improvements
  - ensembles with near-physical quark masses and $4 \lesssim m_\pi L$
  - strong isospin breaking effects [c.f. QCDSF PLB(2012)]
  - gamma-W box (dispersion integral over moments of $F_3^{\gamma W}$)



$$\Box^b_{\gamma W}(E_e) = \frac{3\alpha}{2\pi}\int_0^\infty \frac{dQ^2}{Q^2}\frac{M_W^2}{M_W^2+Q^2}\left[M_{3,-}(1,Q^2) + \frac{8E_eM}{9Q^2}M_{3,+}(2,Q^2)\right] + \mathcal{O}(E_e^2)$$

For progress on moments of $F_3^{\gamma Z}$ via the Compton Amplitude, see K.U. Can, Thu, 15:00 (Session B)

Global fits

Want result

- in continuum and infinite volume limits
- at physical quark masses

Global fit

$$\delta m_l \to \delta m_l = \frac{m_\pi^2 - X_\pi^2}{X_\pi^2}$$

- Include $O(a)$ or $O(a^2)$ terms in X (singlet) and slope parameters

$$X_{D,F} = X^*_{D,F}(1 + c_1 \frac{1}{3}[f_L(m_\pi) + 2f_L(m_\pi)]) + c_2 a + c_3 \delta m_l^2$$

e.g. $\tilde{D}_1 = 1 - 2(\tilde{r}_1 + \tilde{b}_1 a)\delta m_l + \tilde{d}_1 \delta m_l^2$

- Free parameter to encode leading finite-volume correction on singlet:

$$f_L(m) = \left(\frac{m}{X_\pi}\right)^2 \frac{e^{-mL}}{\sqrt{mL}}$$

[functional form from chiral EFT, see Beane & Savage PRD(2004)]

- Work to $O(\delta m_l^2)$ in flavour expansion

Results - Hyperon charges

Not in FLAG, but recent results by RQCD [PRD108(2023)]

This work	*RQCD*
$g_T^{\Sigma} = 0.805(15)$	$g_T^{\Sigma} = 0.798(26)$
$g_T^{\Xi} = -0.1952(75)$	$g_T^{\Xi} = -0.1872(72)$
$g_A^{\Sigma} = 0.876(28)$	$g_A^{\Sigma} = 0.875(49)$
$g_A^{\Xi} = -0.206(21)$	$g_A^{\Xi} = -0.267(18)$
$g_S^{\Sigma} = 2.80(25)$	$g_S^{\Sigma} = 3.98(33)$
$g_S^{\Xi} = 1.59(12)$	$g_S^{\Xi} = 2.57(16)$

some tension