# Semileptonic Hyperon Decays in Full QCD

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# Outline

- Motivation/Background
- Quick Review of Lattice Calculations
- Lattice Techniques/Parameters
- Numerical Results
- Summary and Outlook

# Semileptonic Decays and CKM Matrix

- 1963: Cabibbo proposes current theory $J^i_\alpha = V^i_\alpha + A^i_\alpha$

$$J_\alpha = \cos\theta_C(J^1_\alpha + iJ^2_\alpha) + \sin\theta_C(J^4_\alpha + iJ^5_\alpha)$$

  to explain semileptonic decays.
- 1973: Kobayashi and Maskawa add mixing of three generations of quarks:

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

  before the discovery of the *b* quark.
- Cabibbo angle in CKM matrix: $\tan\theta_C = \frac{V_{us}}{V_{ud}}$

# $|V_{us}|$ in CKM Matrix

- Unitarity constraint: $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1.$
- PDG 2006 gives
  - Well determined $|V_{ud}| = 0.97377(27)$
  - Very small $|V_{ub}| = 4.31(30) \times 10^{-3}$
  - Less known $|V_{us}| = 0.2257(21)(2006)$

$$|V_{us}| = 0.2196(23)(2003)$$

- Experimentally,
  - $K \to \pi l \nu$
  - Hyperon decay $0.2250(27)$

$$\Lambda \to p e^- \overline{\nu},\ \Sigma^- \to n e^- \overline{\nu},$$
$$\Xi^- \to \Lambda e^- \overline{\nu},\ \Xi^0 \to \Lambda^+ e^- \overline{\nu}$$

  - Leptonic decay ratios: $0.2234(^{+12}_{-31})$
  - Hadronic $\tau$ decays: $0.2208(34)$

# Lattice Calculation of $|V_{us}|$ — Meson

- Calculate $K \rightarrow \pi$ matrix element
- Lorentz invariance

$$\langle \pi(p') | V_\mu | K(p) \rangle = (p_\mu + p'_\mu) f_+(q^2) + (p_\mu - p'_\mu) f_-(q^2)$$

with $V_\mu = \bar{s}\gamma_\mu u$

- Calculate the scalar form factor

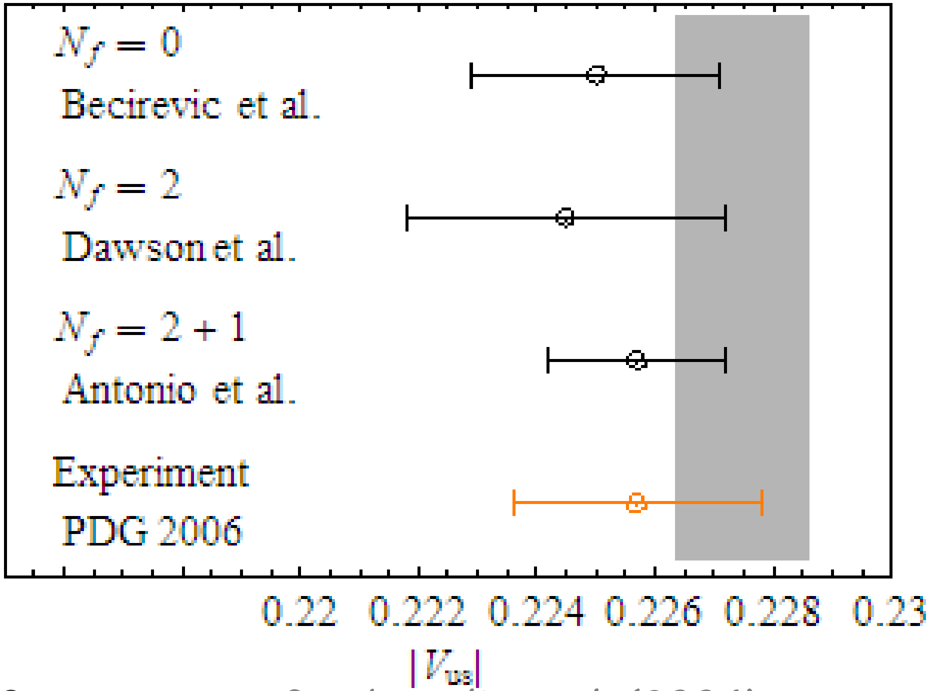
$$f_0(q^2) = f_+(q^2) + \frac{q^2}{m_K^2 - m_\pi^2} f_-(q^2)$$

- Extrapolate to $q = 0$ point in dipole
- Obtain $|V_{us}|$ from

$$\Gamma(K_{\ell 3}) = \frac{G_F^2 M_K^5}{128\pi^3} |V_{us}|^2 S_{\text{ew}} |f_+^{K^0\pi^-}(0)|^2 C_K^2 I_K^\ell(\lambda_i) \left[1 + \delta^K_{SU(2)} + \delta^{K\ell}_{\text{em}}\right]^2$$

# Lattice Calculation of $|V_{us}|$ — Meson

Multiple $K_{l3}$ decay calculations:




*Guadagnoli et. al. (2004)*

- Twisted-BC approach

$$\widetilde{\psi}(x + \hat{e}_j L) = e^{2\pi i \theta_j} \widetilde{\psi}(x)$$

momentum changes by $\widetilde{p}_j = \theta_j \frac{2\pi}{L} + n_j \frac{2\pi}{L}$

Tune $\theta_j$ to cancel out the mass difference.

No extrapolation in momentum is needed!

# Baryon Matrix Elements

- Matrix element of hyperon $\beta$ decay $B_1 \to B_2 e^- \overline{\nu}$

$$\mathcal{M} = \frac{G_s}{\sqrt{2}} \overline{u}_{B_2} (O_\alpha^{\mathrm{V}} + O_\alpha^{\mathrm{A}}) u_{B_1} \overline{u}_e \gamma^\alpha (1+\gamma_5) v_\nu$$

with

$$O_\alpha^{\mathrm{V}} = f_1(q^2)\gamma^\alpha + \frac{f_2(q^2)}{M_{B_1}} \sigma_{\alpha\beta} q^\beta + \frac{f_3(q^2)}{M_{B_2}} q_\alpha$$

$$O_\alpha^{\mathrm{A}} = \left( g_1(q^2)\gamma^\alpha + \frac{g_2(q^2)}{M_{B_1}} \sigma_{\alpha\beta} q^\beta + \frac{g_3(q^2)}{M_{B_2}} q_\alpha \right) \gamma_5$$

- The decay rate is

$$\Gamma = G_F^2 |V_{us}|^2 \frac{\Delta m^5}{60\pi^3} (1 + \delta_{\mathrm{rad}}) \times \left[ \left(1 - \frac{3}{2}\beta\right) (|f_1|^2 + |g_1|^2) + \frac{6}{7}\beta^2 \left( |f_1|^2 + 2|g_1|^2 + \mathrm{Re}(f_1 f_2^*) + \frac{2}{3}|f_2^2| \right) + \delta_{q^2} \right]$$

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- The vector form factor $f_1(0)$ links to $|V_{us}|$

More than just an alternative way to get $|V_{us}|$!

- $g_1(0)/f_1(0)$ gives information about strangeness content.
- $g_2(0)$ and $f_3(0)$ vanish in the SU(3) limit → Symmetry-breaking measure

# Hyperon Experiments

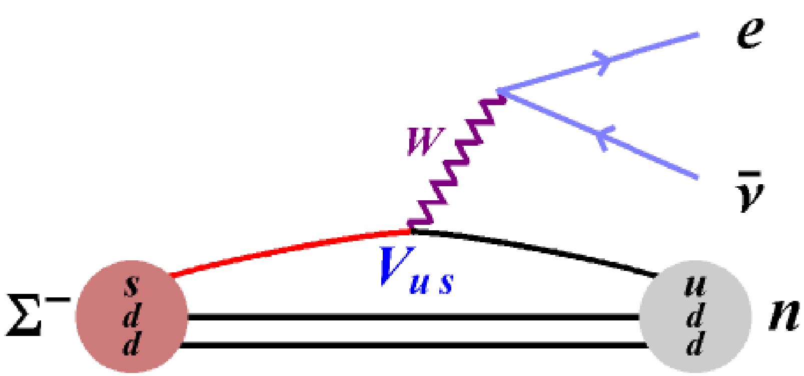
- Experiments: CERN WA2, Fermilab E715, BNL AGS, Fermilab KTeV, CERN NA48
- Summary

| Channel | $f_1^{SU(3)}$ | $\lvert f_1 V_{us}\rvert$ | $(g_1/f_1)^{SU(3)}$ | $(g_1/f_1)^{\exp}$ |
|---|---|---|---|---|
| $n \to p$ | $1$ | $n/a$ | $F+D$ | $1.2670(30)$ |
| $\Lambda \to p$ | $-\sqrt{3/2}$ | $0.2221(33)$ | $F+D/3$ | $0.718(15)$ |
| $\Sigma^- \to n$ | $-1$ | $0.2274(49)$ | $F-D$ | $-0.340(17)$ |
| $\Xi^- \to \Lambda$ | $\sqrt{3/2}$ | $0.2367(97)$ | $F-D/3$ | $0.25(5)$ |
| $\Xi^- \to \Sigma^0$ | $\sqrt{1/2}$ | $n/a$ | $F+D$ | $n/a$ |
| $\Xi^0 \to \Sigma^+$ | $1$ | $0.216(33)$ | $F+D$ | $1.32(22)$ |

- $\Xi$ measurements are still active!

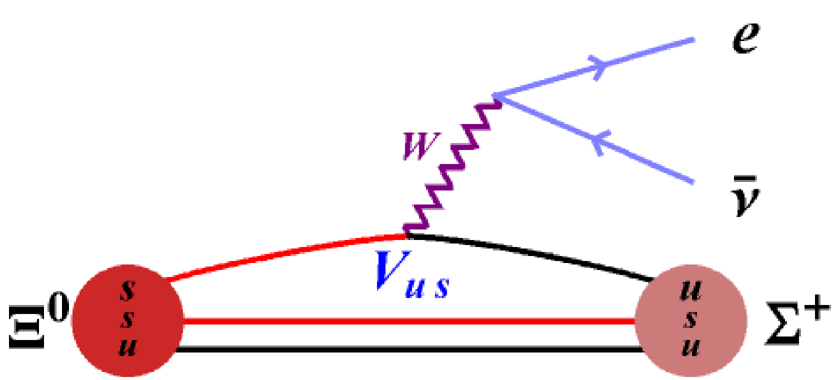
# Lattice Calculation of $|V_{us}|$ — Baryon

Two quenched calculations, different channels




* Pion mass > 700 MeV
* $f_1(0) = -0.988(29)_{\text{stat.}}$
* $|V_{us}| = 0.230(8)$

*Guadagnoli et al.*




* Pion mass ≈ 530–650 MeV
* $f_1(0) = -0.953(24)_{\text{stat}}$
* $|V_{us}| = 0.219(27)$

*Sasaki et al.*

# Lattice Actions

- (Improved) Staggered fermions (asqtad):
  - Relatively cheap for dynamical fermions (good)
  - Mixing among parities and flavors or *tastes*
  - Baryonic operators a nightmare — not suitable
- Chiral fermions (e.g., Domain-Wall/Overlap):
  - Automatically O(a) improved, suitable for spin physics and weak matrix elements
  - Expensive

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- Chiral fermions (e.g., Domain-Wall/Overlap):
  - Automatically O(a) improved, suitable for spin physics and weak matrix elements
  - Expensive
- Mixed actions:
  - Match the sea Goldstone pion mass to the DWF pion
  - Pion masses as low as 260 MeV
  - Volume: 2.6–3.5 fm

  - Free light quark propagators

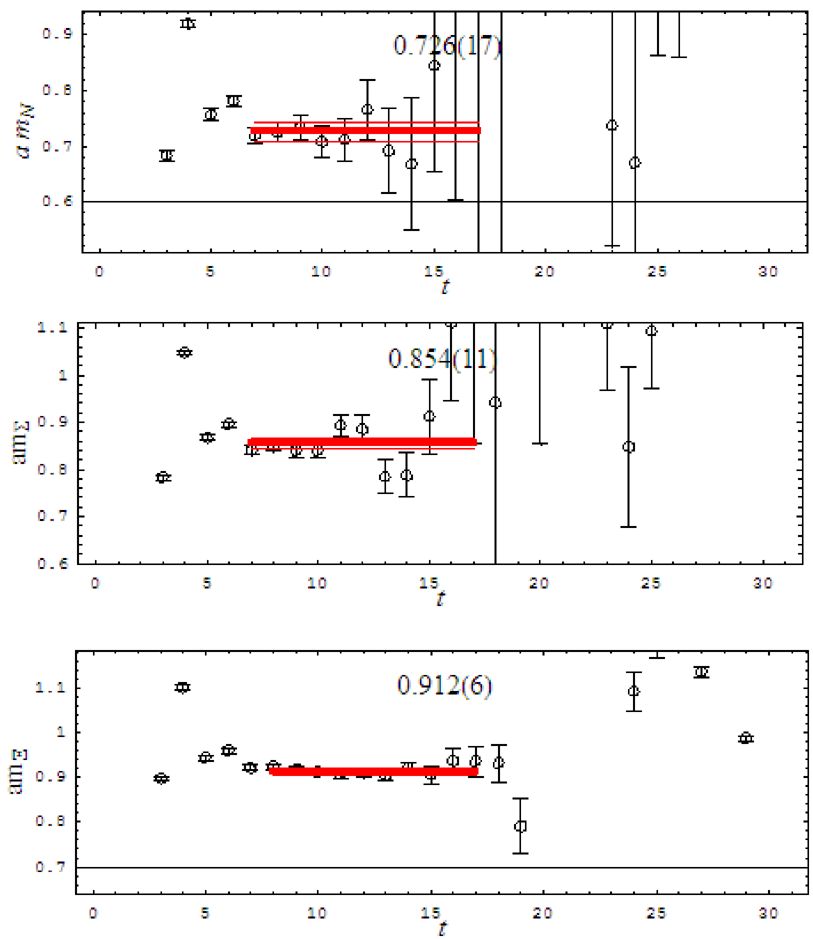
# Parameters

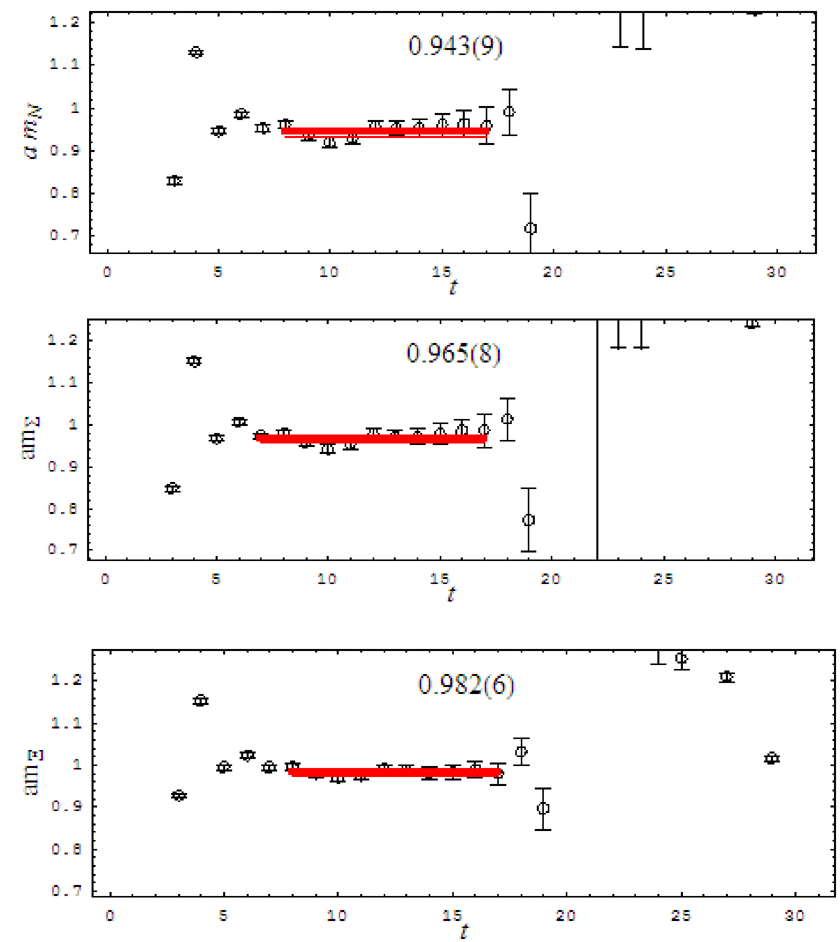
- This calculation:
  - Pion mass range: 360–700 MeV
  - Strange-strange Goldstone fixed at 763(2) MeV
  - Volume fixed at 2.6 fm
  - $a \approx 0.125$ fm, $L_s = 16$, $M_5 = 1.7$
  - HYP-smeared gauge, box size of $20^3 \times 32$

| Label | $m_\pi$ (MeV) | $m_K$ (MeV) | $\Sigma^- \to n$ conf. |
|---|---|---|---|
| m010 | 358(2) | 605(2) | 600 |
| m020 | 503(2) | 653(2) | 420 |
| m030 | 599(1) | 688(2) | 561 |
| m040 | 689(2) | 730(2) | 306 |

# Effective Mass Plots

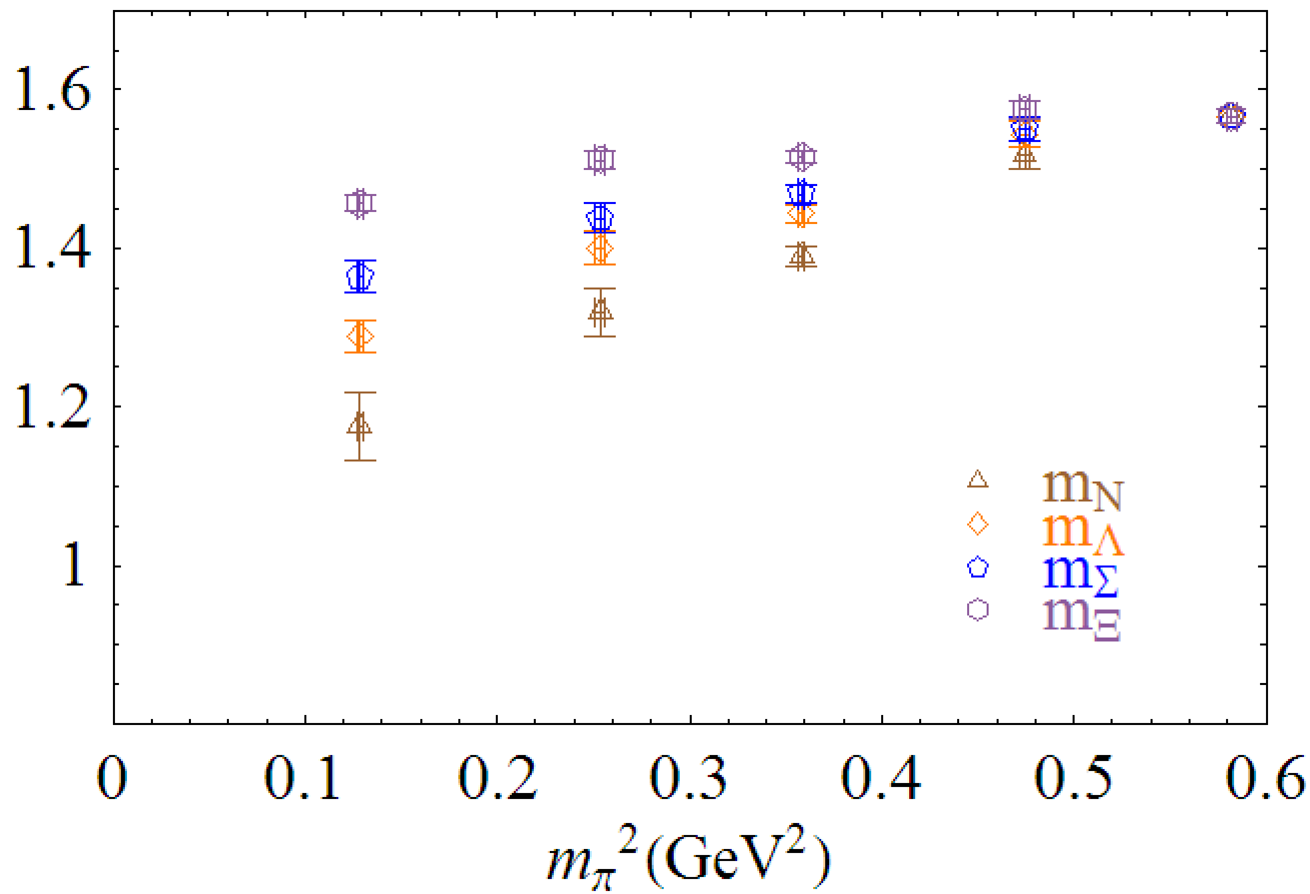
- The worst set
- The best set



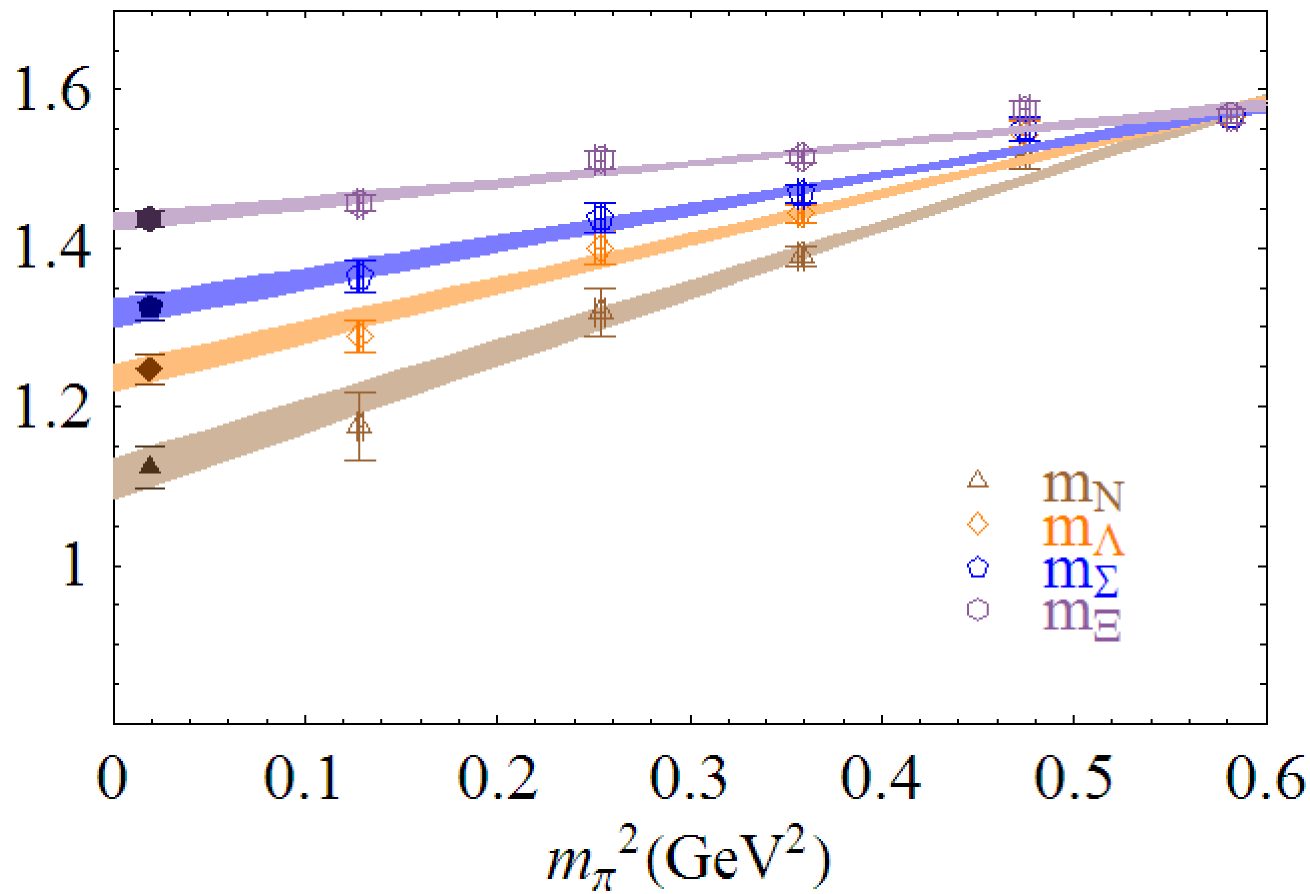
# Octet Spectrum

- Summary



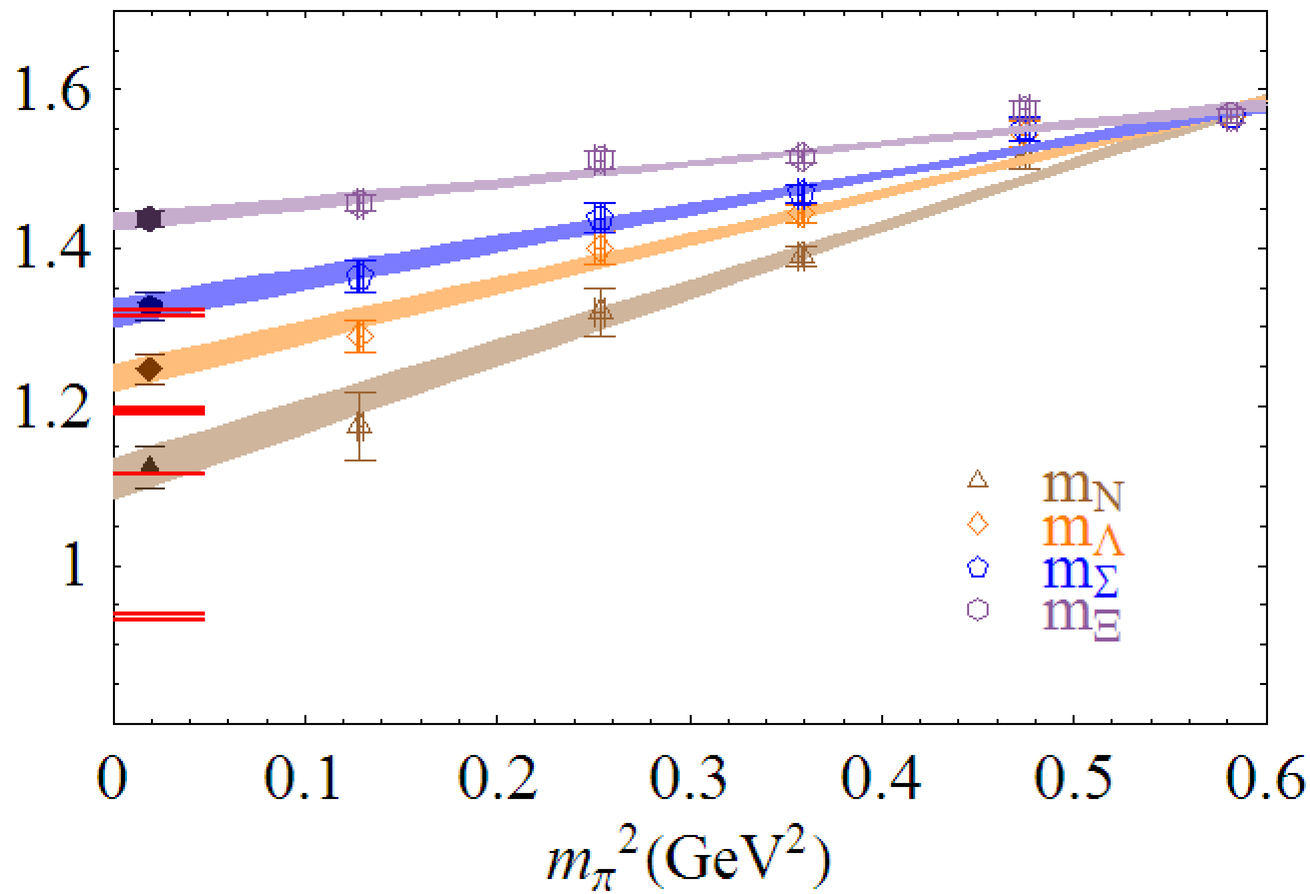
# Octet Spectrum

- Summary and extrapolation



# Octet Spectrum

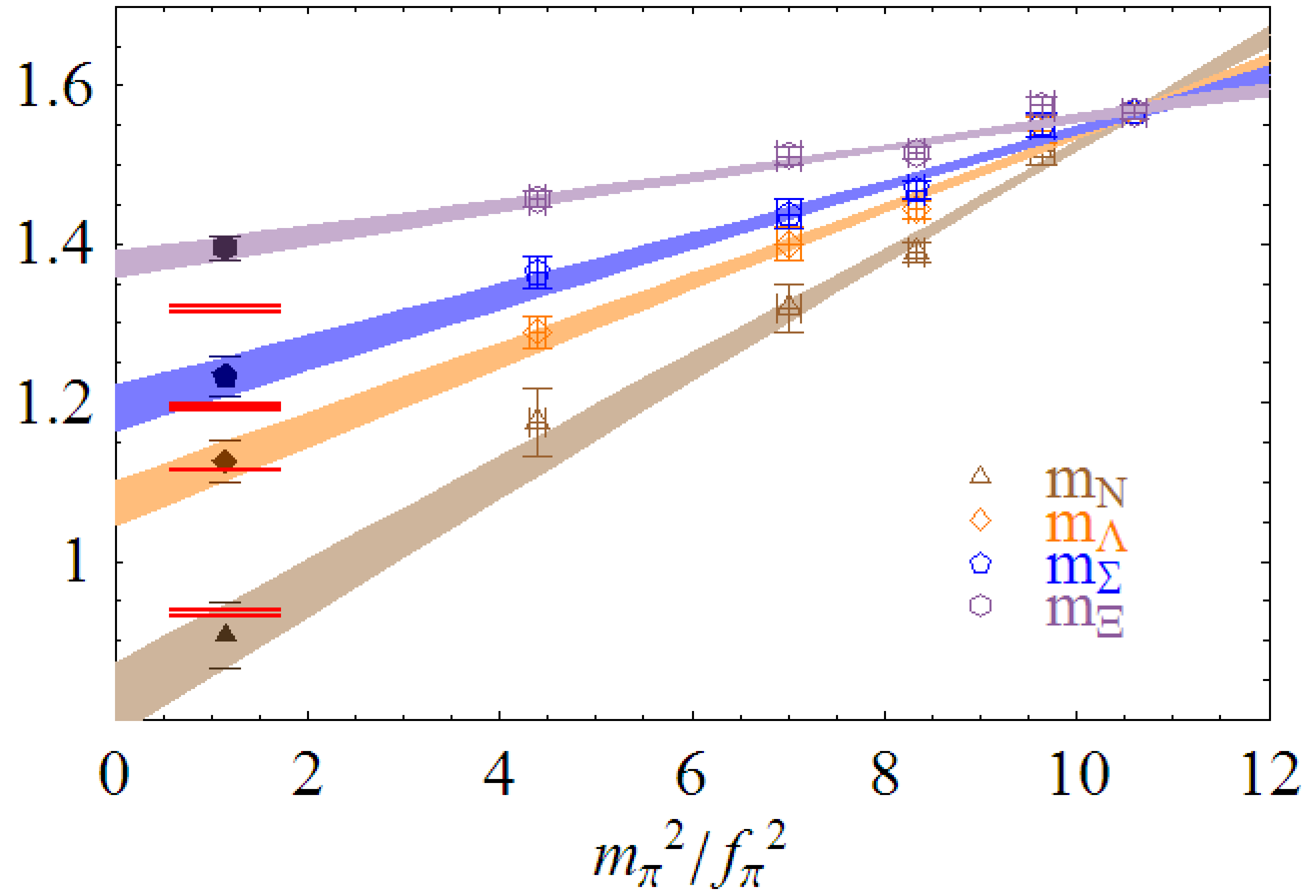
- Summary and extrapolation




- Disappointed ☹

# Octet Spectrum

- Alternative extrapolations




- Better agreement with experiments

# Constructions

## Two-point function

$$\Gamma_{AB}^{NN}(t_i, t_f, \vec{p}\,; T) \to$$
$$a^6 Z_B^N(p) Z_A^N(p) \sum_s T_{\alpha\beta} \bar{u}_\alpha(\vec{p}, s) u_\beta(\vec{p}, s)$$
$$\times \frac{m_N}{E_N(\vec{p})} e^{-(t_f - t_i) E_N(\vec{p})}$$
$$= \left( \frac{E_N(\vec{p}) + m_N}{2 E_N(\vec{p})} \right) e^{-(t_f - t_i) E_N(\vec{p})}$$

## Three-point function

$$\Gamma_{\mu,AB}^{NN}(t_i, t, t_f, \vec{p}_i, \vec{p}_f; T) \to$$
$$= \frac{m_N^2}{E_N(\vec{p}_f) E_N(\vec{p}_i)} e^{-(t_f - t) E_N(\vec{p}_f)} e^{-(t - t_i) E_N(\vec{p}_i)}$$
$$\sum_{s,s'} T_{\alpha\beta} Z_B(p_f) u_\beta(\vec{p}_f, s')$$
$$\langle N(\vec{p}_f, s') | j_\mu(0) | N(\vec{p}_i, s) \rangle \bar{u}_\alpha(\vec{p}_i, s) Z_A(p_i)$$

# Constructions

## Two-point function

$$\Gamma^{NN}_{AB}(t_i,t_f,\vec{p}\,;\,T) \to$$
$$a^6 Z^N_B(p) Z^N_A(p) \sum_s T_{\alpha\beta}\bar{u}_\alpha(\vec{p},s)u_\beta(\vec{p},s)$$
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$$\sum_{s,s'} T_{\alpha\beta} Z_B(p_f) u_\beta(\vec{p}_f,s')$$
$$\langle N(\vec{p}_f,s')\,|j_\mu(0)|\,N(\vec{p}_i,s)\rangle\,\bar{u}_\alpha(\vec{p}_i,s) Z_A(p_i)$$

## Ratio cancels out *t* and *Z* dependence

$$R_{j_\mu} = \frac{Z_V \Gamma^{\Sigma N}_{\mu,AB}(t_i,t,t_f,\vec{p}_i,\vec{p}_f\,;\,T)}{\Gamma^{NN}_{BC}(t_i,t_f,\vec{p}_f\,;\,T)} \sqrt{\frac{\Gamma^{\Sigma\Sigma}_{DE}(t_i,t_f,\vec{p}_i\,;\,T)}{\Gamma^{NN}_{FH}(t_i,t_f,\vec{p}_f\,;\,T)}}$$
$$\times \sqrt{\frac{\Gamma^{NN}_{CC}(t_i,t,\vec{p}_f\,;\,T)}{\Gamma^{\Sigma\Sigma}_{AA}(t_i,t,\vec{p}_i\,;\,T)}} \sqrt{\frac{\Gamma^{NN}_{FH}(t_i,t_f,\vec{p}_f\,;\,T)}{\Gamma^{\Sigma\Sigma}_{DE}(t_i,t_f,\vec{p}_i\,;\,T)}},$$

# Constructions

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$$\times \frac{m_N}{E_N(\vec{p})} e^{-(t_f - t_i)E_N(\vec{p})}$$
$$= \left( \frac{E_N(\vec{p}) + m_N}{2E_N(\vec{p})} \right) e^{-(t_f - t_i)E_N(\vec{p})}$$

## Three-point function

$$\Gamma^{NN}_{\mu,AB}(t_i, t, t_f, \vec{p}_i, \vec{p}_f;\, T) \to$$
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$$\sum_{s,s'} T_{\alpha\beta} Z_B(p_f) u_\beta(\vec{p}_f, s')$$
$$\langle N(\vec{p}_f, s') \,|j_\mu(0)|\, N(\vec{p}_i, s)\rangle \, \bar{u}_\alpha(\vec{p}_i, s) Z_A(p_i)$$

Ratio cancels out *t* and *Z* dependence

$$R_{j_\mu} = \frac{Z_V \Gamma^{\Sigma N}_{\mu,GG}(t_i, t, t_f, \vec{p}_i, \vec{p}_f\,;\, T)}{\Gamma^{NN}_{GG}(t_i, t_f, \vec{p}_f\,;\, T)} \sqrt{\frac{\Gamma^{\Sigma\Sigma}_{PG}(t, t_f, \vec{p}_i\,;\, T)}{\Gamma^{NN}_{PG}(t, t_f, \vec{p}_f\,;\, T)}}$$
$$\times \sqrt{\frac{\Gamma^{NN}_{GG}(t_i, t, \vec{p}_f\,;\, T)}{\Gamma^{\Sigma\Sigma}_{GG}(t_i, t, \vec{p}_i\,;\, T)}} \sqrt{\frac{\Gamma^{NN}_{PG}(t_i, t_f, \vec{p}_f\,;\, T)}{\Gamma^{\Sigma\Sigma}_{PG}(t_i, t_f, \vec{p}_i\,;\, T)}},$$

# Solve for From factors

- Redefine matrix element as

$$\langle B_2 \,|V_\mu|\, B_1\rangle(q) \;=\; \overline{u}_{B_2}(p')\left[\gamma_\mu F_1(q^2) + \sigma_{\mu\nu}q_\nu \frac{F_2(q^2)}{M_{B_1}+M_{B_2}} - iq_\mu \frac{F_3(q^2)}{M_{B_1}+M_{B_2}}\right] u_{B_1}(p)e^{-iq\cdot x}$$

$$\langle B_2 \,|A_\mu[\, B_1\rangle_\mu(q) \;=\; \overline{u}_{B_2}(p')\left[\gamma_\mu G_1(q^2) + \sigma_{\mu\nu}q_\nu \frac{G_2(q^2)}{M_{B_1}+M_{B_2}} - iq_\mu \frac{G_3(q^2)}{M_{B_1}+B_{B_2}}\right] \gamma_5 u_{B_1}(p)e^{-iq\cdot x}$$

- Use "mixed" projection operator

$$T = \tfrac{1}{8}(1+\gamma_4)(1+i\gamma_5\gamma_3)(1+\gamma_4)$$

- Solve the following:

$$\frac{1}{\sqrt{2E_{m_\Sigma}\left(m_\Sigma + E_{m_\Sigma}\right)}\left(m_N + m_\Sigma\right)} \times$$
$$\Big\{F_1\left(m_N + m_\Sigma\right)\left(p_y - ip_x\right) + F_2\left(-im_N p_x + iE_{m_\Sigma}p_x + m_N p_y + m_\Sigma p_y\right) + F_3\left(-2m_\Sigma p_x - 2E_{m_\Sigma}p_x\;\right),$$
$$F_1\left(-m_N - m_\Sigma\right)\left(p_x + ip_y\right) + F_2\left(-m_N p_x - m_\Sigma p_x - im_N p_y + ip_y E_{m_\Sigma}\right) + F_3\left(-2m_\Sigma p_y - 2E_{m_\Sigma}p_y\right),$$
$$-iF_1\left(m_N + m_\Sigma\right)p_z - iF_2\left(m_N - E_{m_\Sigma}\right)p_z - iF_3\left(-2im_\Sigma - 2iE_{m_\Sigma}\right)p_z,$$
$$F_1\left(m_\Sigma\left(m_N + m_\Sigma\right) + E_{m_\Sigma}\left(m_N + m_\Sigma\right)\right) - F_2\vec{p}^{\,2} + F_3\left(2i\vec{p}^{\,2} + 2im_\Sigma^2 - 2im_N m_\Sigma - 2i\left(m_N - m_\Sigma\right)E_{m_\Sigma}\right)\Big\}$$

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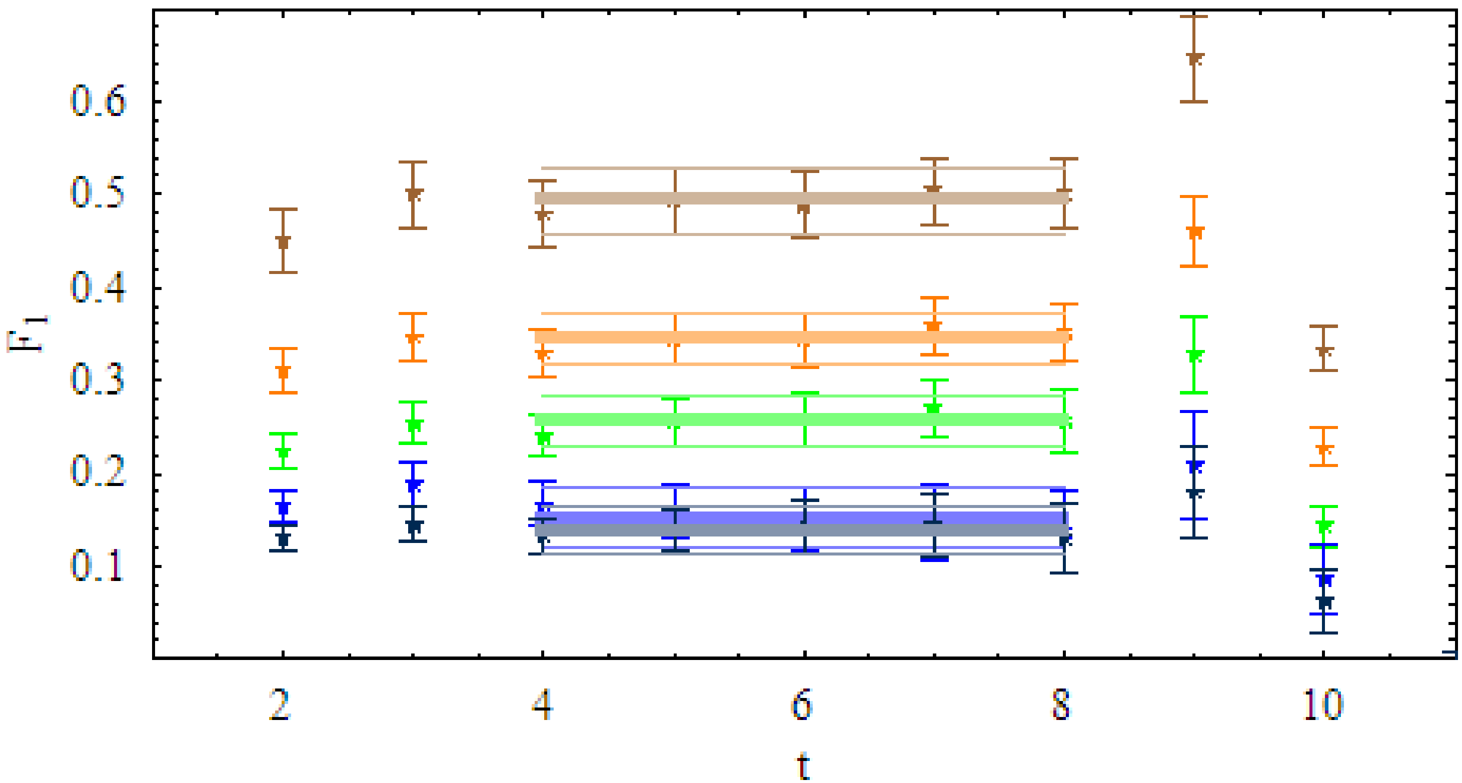
$$F_1\left(m_\Sigma\left(m_N+m_\Sigma\right) + E_{m_\Sigma}\left(m_N+m_\Sigma\right)\right) - F_2\vec{p}^{\,2} + F_3\left(2i\vec{p}^{\,2} + 2im_\Sigma^2 - 2im_Nm_\Sigma - 2i\left(m_N - m_\Sigma\right)E_{m_\Sigma}\right)\Big\}$$

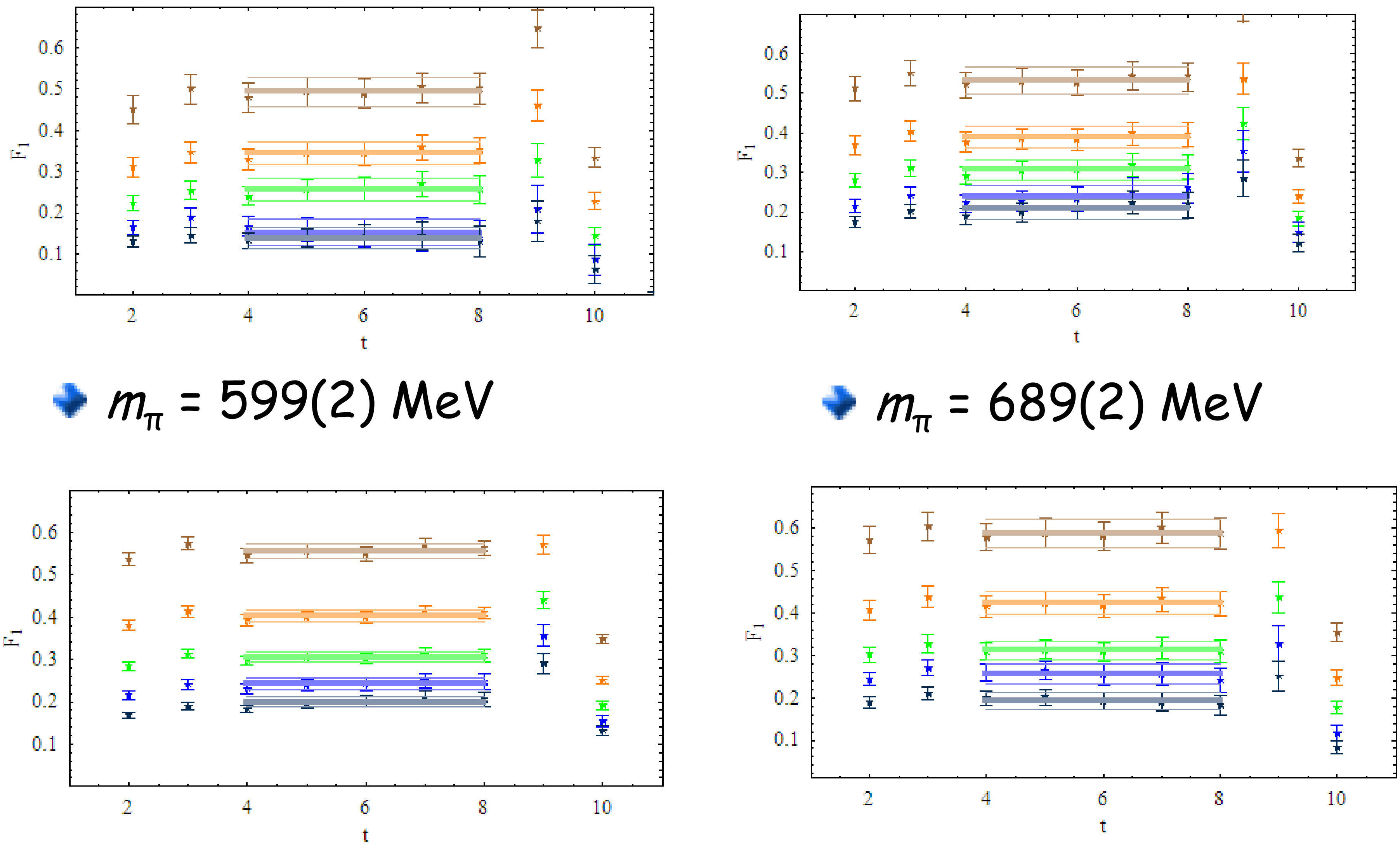
# Three-Point Plateau

- $m_\pi$ = 358(2) MeV



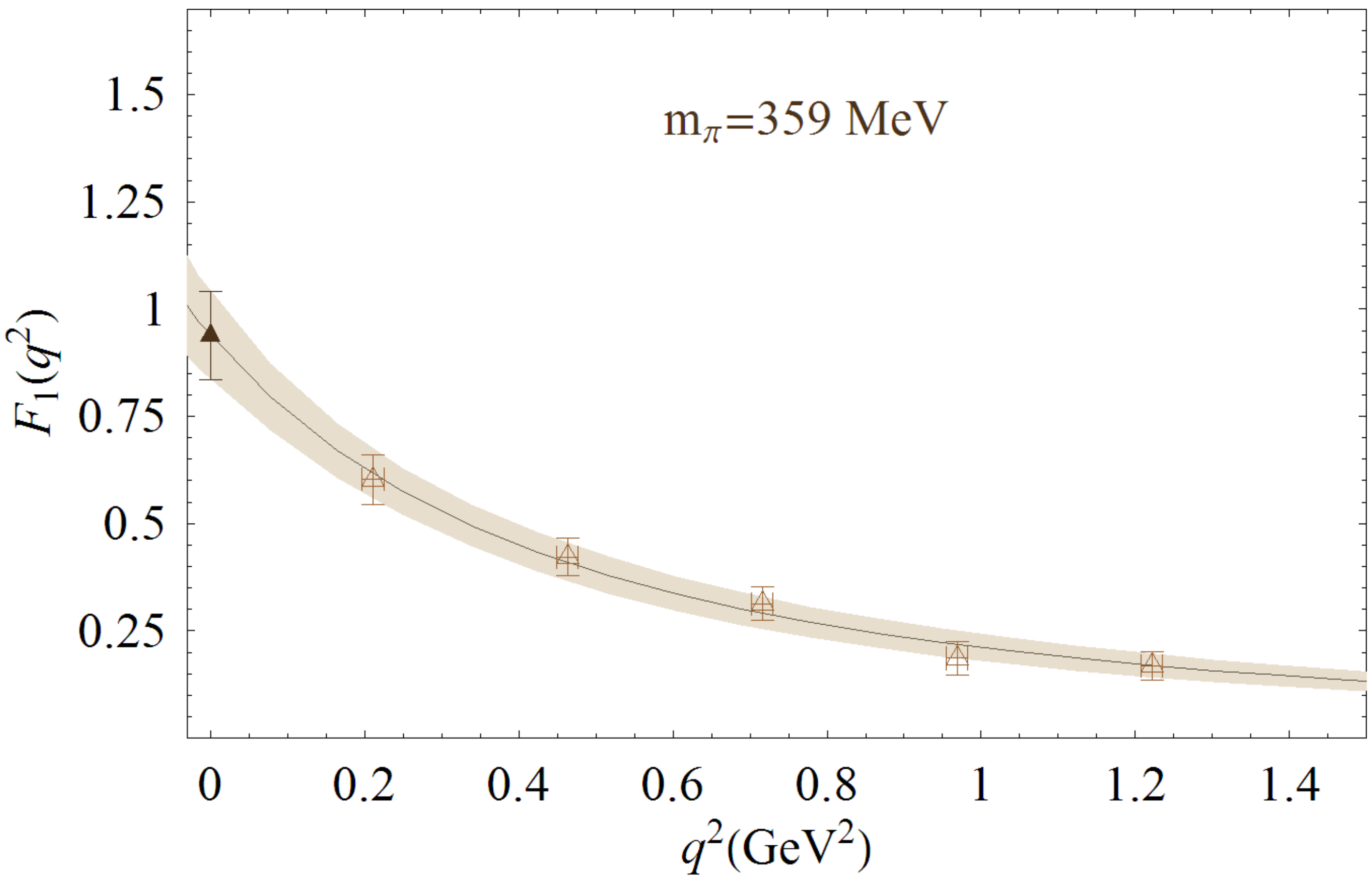
# Three-Point Plateau

- $m_\pi$ = 358(2) MeV
- $m_\pi$ = 503(2) MeV
- $m_\pi$ = 599(2) MeV
- $m_\pi$ = 689(2) MeV



# Momentum Extrapolation

- Fit to the dipole form



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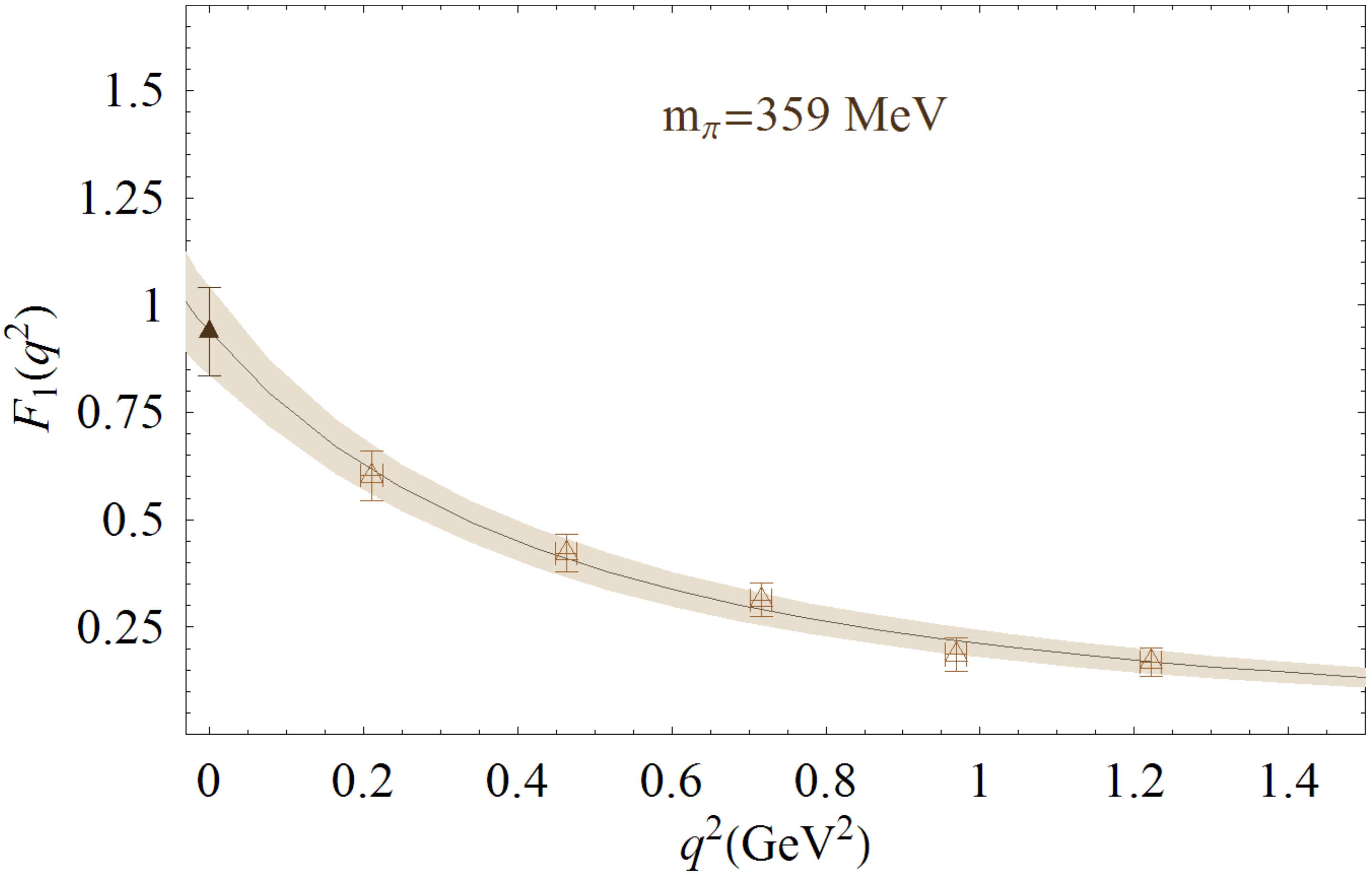


# Ademollo-Gatto Theorem

- Symmetry-breaking Hamiltonian

$$H' = \frac{1}{\sqrt{3}}\left(m_s - \frac{m_d + m_u}{2}\right)\bar{q}\lambda^8 q$$

- Long story short,

  There is no first order correction $O(H')$ to $f_1(0)$; thus

$$f_1(0) = f_1^{SU(3)}(0) + O(H'^2)$$

# Ademollo-Gatto Theorem

- Symmetry-breaking Hamiltonian

$$H' = \frac{1}{\sqrt{3}}\left(m_s - \frac{m_d + m_u}{2}\right)\bar{q}\lambda^8 q$$

- The theorem tells us that

  There is no first order correction $O(H')$ to $f_1(0)$; thus

$$f_1(0) = f_1^{SU(3)}(0) + O(H'^2)$$

- Choices of observable for $H'$:
  - $m_K{}^2 - m_\pi{}^2$
  - $(m_\Sigma - m_N)/\, m_\Sigma$
  - Others...

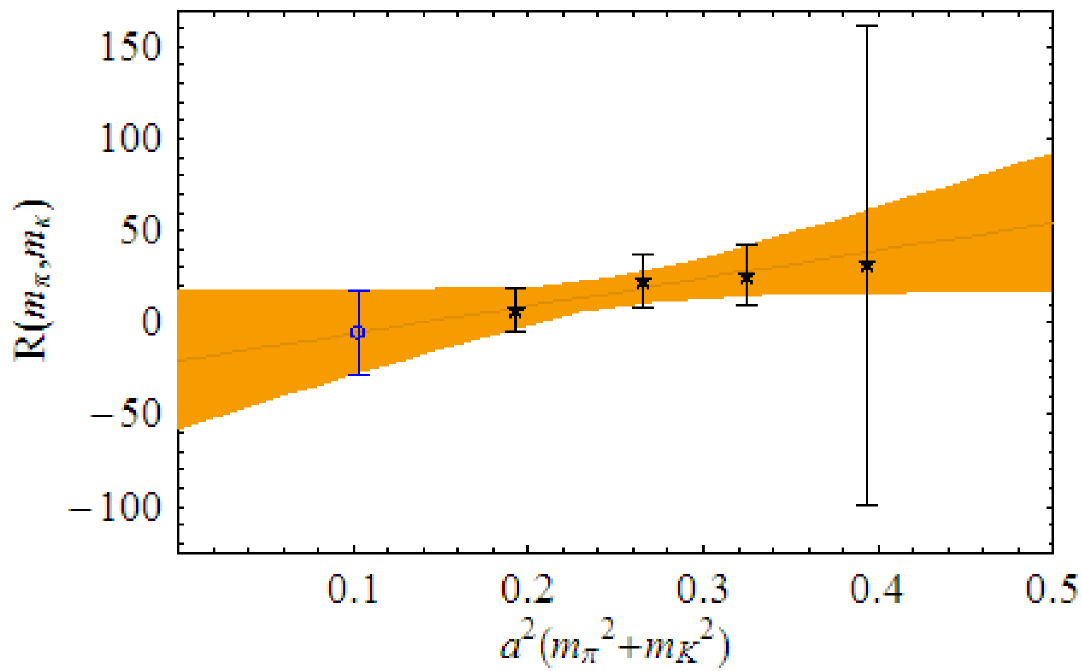
# Mass Dependence — I

## What has been done in the past…

- *Guadagnoli et al.* $\Sigma^- \to n$
  construct an AG ratio $$R(M_K, M_\pi) = \frac{1 - f_1(0)}{a^4(M_K^2 - M_\pi^2)^2}$$

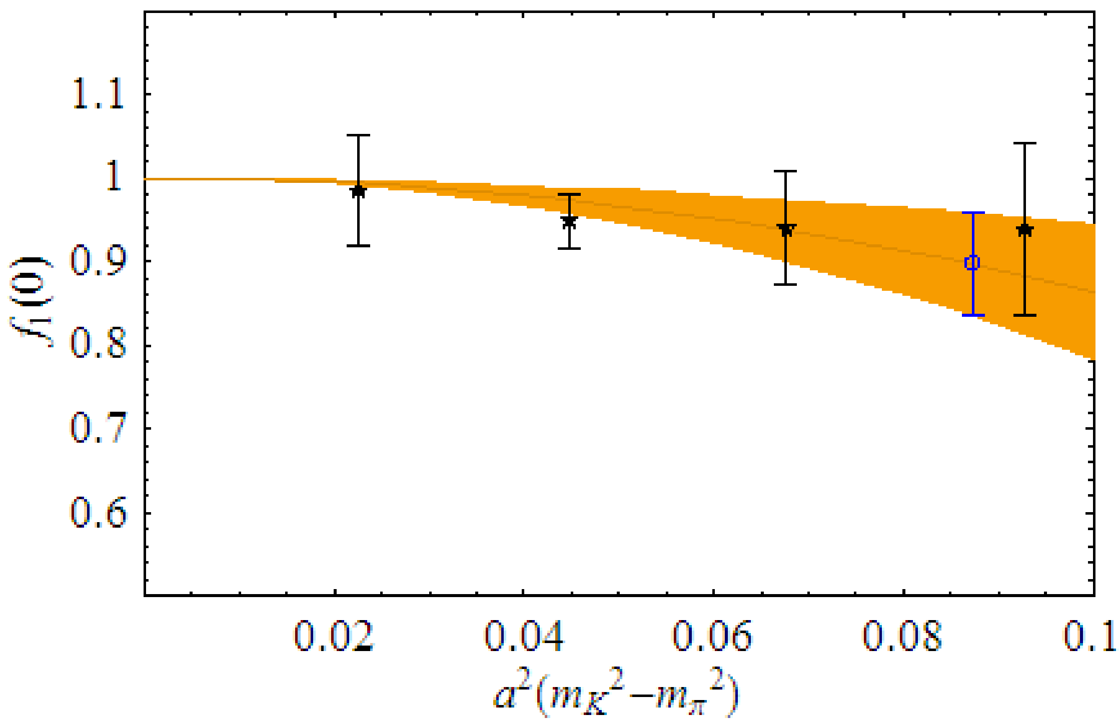
  and extrapolate mass dependence as

$$R(M_K, M_\pi) = b + ca^2(M_K^2 + M_\pi^2)$$



# Mass Dependence — II

- Use $\delta = a^2(M_K^2 - M_\pi^2)$ to describe the SU(3) symmetry breaking




$f_1(0) = 0.90(7)$ (Preliminary)

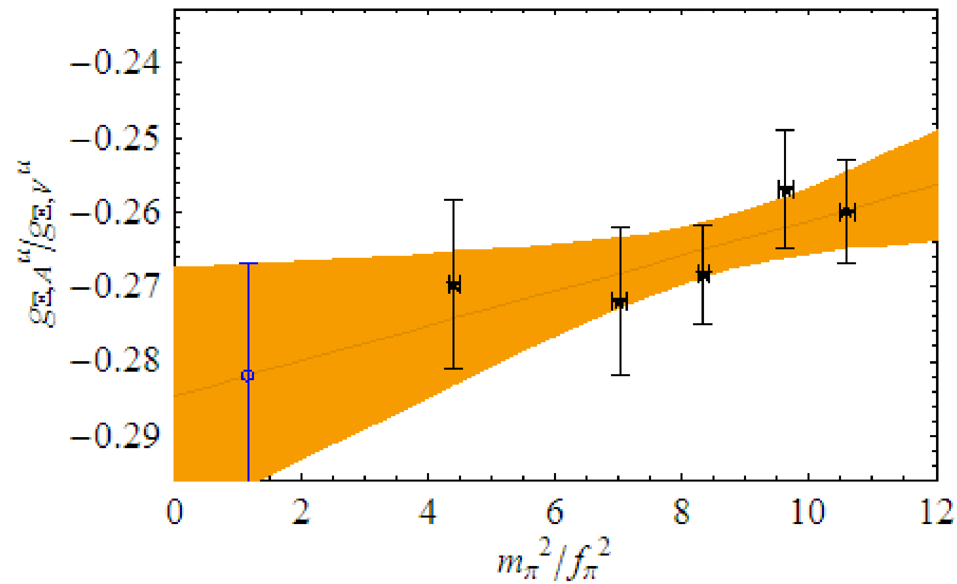
# Axial Coupling Constants: $g_{\Xi\Xi}$ and $g_{\Sigma\Sigma}$

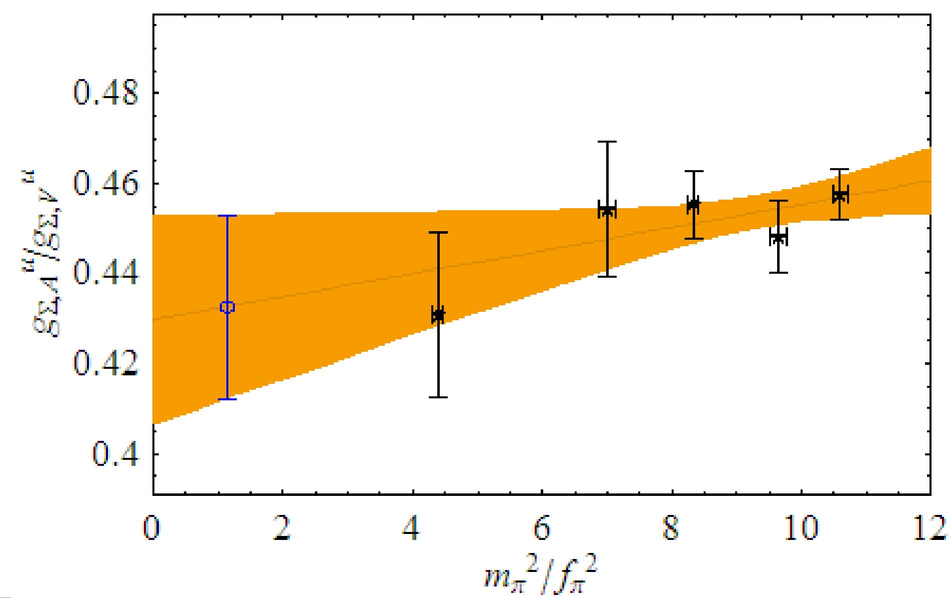
- Cannot be determined by exp.
- Existing predictions from χPT and large $N_c$ calculations

$$0.18 < -g_{\Xi\Xi} < 0.36$$

$$0.30 < g_{\Sigma\Sigma} < 0.55$$

- Applications such as hyperon scattering, non-leptonic decays, etc.




Jefferson Lab
Exploring the Nature of Matter

# Summary/Outlook

- First non-quenched calculation of hyperon semileptonic decays
- Lighter pion masses as low as 350 MeV
- Preliminary results show $|V_{us}|$ (from $\Sigma \to n$)
  - * Consistent with the previous lattice measurement
  - * Larger error due to lighter pion mass
  - * More statistics needed for lightest point!

In the near future:

- Finish the semileptonic form factor analysis, including $\Xi \to \Sigma$ channel
- $\Sigma$ and $\Xi$ structure-function form factors
- Possibly take $\Lambda \to p$ data, if time allows