Axial couplings of heavy hadrons

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work in collaboration with David Lin & Stefan Meinel
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Workshop on *"Beautiful Mesons and Baryons on the Lattice"*, ECT* Trento, April 5th, 2012

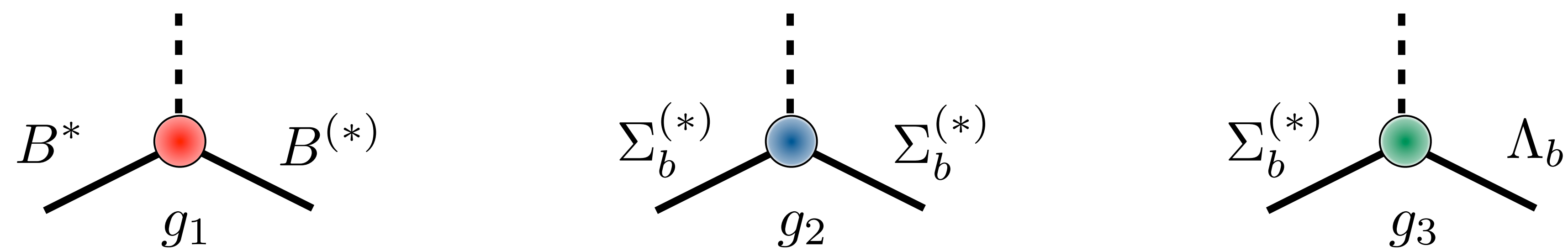
Dürer, "Castello di Trento" 1495

Outline

- Heavy-hadron axial couplings: $g_{1,2,3}$
  - Heavy hadron chiral perturbation theory
    [David Lin's talk on Tuesday]
- QCD calculation of axial couplings: details and results
  - Combine LQCD and HHχPT to control all systematic uncertainties
- Strong decay widths

Chiral dynamics of heavy hadrons

- Axial couplings *defined* in static limit



$\sim \hat{g} \sim g_\pi \sim g_{B^* B \pi}$

$$\langle P^{*d}(0,s)|\mathsf{A}_\mu^{-(\chi\mathrm{PT})}(0)|P^u(0)\rangle|_{\mathrm{LO}} = -2\, g_1\, \varepsilon_\mu^*(s).$$

B^* → P^{*d}, B → P^u

$$\langle S^{dd}(0,s)|\mathsf{A}^{\mu-(\chi\mathrm{PT})}(0)|S^{du}(0,s')\rangle|_{\mathrm{LO}} = -\frac{i}{\sqrt{2}}\, g_2\, v_\lambda\, \epsilon^{\lambda\mu\nu\rho}\, \overline{U}_\nu(s) U_\rho(s').$$

$$\langle S^{dd}(0,s)|\mathsf{A}^{\mu-(\chi\mathrm{PT})}(0)|T^{du}(0,s')\rangle|_{\mathrm{LO}} = -g_3\, \overline{U}^\mu(s)\, \mathcal{U}(s').$$

S: $\begin{pmatrix} \Sigma_b^+ & \frac{1}{\sqrt{2}}\Sigma_b^0 \\ \frac{1}{\sqrt{2}}\Sigma_b^0 & \Sigma_b^- \end{pmatrix}^{(*)}$ T: $\begin{pmatrix} 0 & \Lambda_b \\ -\Lambda_b & 0 \end{pmatrix}$

- Heavy-light mesons and baryons: dynamics amenable to HQ and chiral expansions [Wise; Burdman & Donoghue; Cheng et al.]

H-L hadrons in lattice QCD

- Light quark mass dependence of H-L(L) observables controlled by pion loops, coupled through $g_{1,2,3}$
- Very important for control of current lattice QCD calculations at unphysical quark masses
  Examples so far this week:
  - ETMC: chiral extrapolation of f_{Bs}/f_B is dominant systematic uncertainty
  - FNAL/MILC: B, D semi-leptonic FFs, g_π major systematic uncertainty
  - HPQCD: requires prior in B meson properties

Current knowledge of g_1

- Experimental extraction of g_1 from $D^* \to D\pi,\ D^* \to D\gamma$
  - g_1=0.5(?) [Arnesen et al.]
- Lattice calculations for g_1

Reference	n_f, action	$[m_\pi^{(\mathrm{vv})}]^2$ (GeV^2)	g_1
De Divitiis *et al.*, 1998 [14]	0, clover	0.58 - 0.81	$0.42 \pm 0.04 \pm 0.08$
Abada *et al.*, 2004 [15]	0, clover	0.30 - 0.71	$0.48 \pm 0.03 \pm 0.11$
Negishi *et al.*, 2007 [16]	0, clover	0.43 - 0.72	0.517 ± 0.016
Ohki *et al.*, 2008 [17]	2, clover	0.24 - 1.2	$0.516 \pm 0.005 \pm 0.033 \pm 0.028 \pm 0.028$
Bećirević *et al.*, 2009 [18]	2, clover	0.16 - 1.2	$0.44 \pm 0.03^{+0.07}_{-0.00}$
Bulava *et al.*, 2010 [19]	2, clover	0.063 - 0.49	0.51 ± 0.02

  - Need fully quantified uncertainties

Current knowledge of $g_{1,2,3}$

- Model estimates for $g_{1,2,3}$ [Cho normalisation]

Reference	Method	g_1	g_2	g_3
Yan *et al.*, 1992 [5]	Nonrelativistic quark model	1	2	$\sqrt{2}$
Colangelo *et al.*, 1994 [45]	Relativistic quark model	1/3	...	...
Bećirević, 1999 [46]	Quark model with Dirac eq.	0.6 ± 0.1	...	...
Guralnik *et al.*, 1992 [47]	Skyrme model	...	1.6	1.3
Colangelo *et al.*, 1994 [48]	Sum rules	0.15 - 0.55	...	...
Belyaev *et al.*, 1994 [49]	Sum rules	0.32 ± 0.02	...	...
Dosch and Narison, 1995 [50]	Sum rules	0.15 ± 0.03	...	...
Colangelo and Fazio, 1997 [51]	Sum rules	0.09 - 0.44	...	...
Pirjol and Yan, 1997 [52]	Sum rules	...	$< \sqrt{6 - g_3^2}$	$< \sqrt{2}$
Zhu and Dai, 1998 [53]	Sum rules	...	$1.56 \pm 0.30 \pm 0.30$	$0.94 \pm 0.06 \pm 0.20$
Cho and Georgi, 1992 [54]	$\mathcal{B}[D^* \to D\,\pi]$, $\mathcal{B}[D^* \to D\,\gamma]$	0.34 ± 0.48	...	...
Arnesen *et al.*, 2005 [57]	$\mathcal{B}[D^*_{(s)} \to D_{(s)}\pi]$, $\mathcal{B}[D^*_{(s)} \to D_{(s)}\gamma]$, $\Gamma[D^*]$	0.51	...	...
Li *et al.*, 2010 [58]	$\mathrm{d}\Gamma[B \to \pi \ell \nu]$	< 0.87	...	...

- All over the place!

- Precise calculation needed

Actions and ensembles

- Domain-wall light quarks
  [RBC/UKQCD]
  - Lattice chiral symmetry
- Static heavy quarks with n_{HYP}=0,1,2,3,5,10 levels of HYP smearing
- Two lattice spacings
  a = 0.085, 0.112 fm
- Six valence quark masses
  m_π = 0.23–0.35 GeV
- Single (2.5 fm)^3 volume

Ensemble	a (fm)	$L^3 \times T$	$am_{u,d}^{(\mathrm{sea})}$	$m_\pi^{(\mathrm{ss})}$ (MeV)
A	0.1119(17)	$24^3 \times 64$	0.005	336(5)
B	0.0849(12)	$32^3 \times 64$	0.004	295(4)
C	0.0848(17)	$32^3 \times 64$	0.006	352(7)

Ensemble	$am_{u,d}^{(\mathrm{val})}$	$m_\pi^{(\mathrm{vs})}$ (MeV)	$m_\pi^{(\mathrm{vv})}$ (MeV)	t/a
A	0.001	294(5)	245(4)	4, 5, ..., 10
A	0.002	304(5)	270(4)	4, 5, ..., 10
A	0.005	336(5)	336(5)	4, 5, ..., 10
B	0.002	263(4)	227(3)	6, 9, 12
B	0.004	295(4)	295(4)	6, 9, 12
C	0.006	352(7)	352(7)	13

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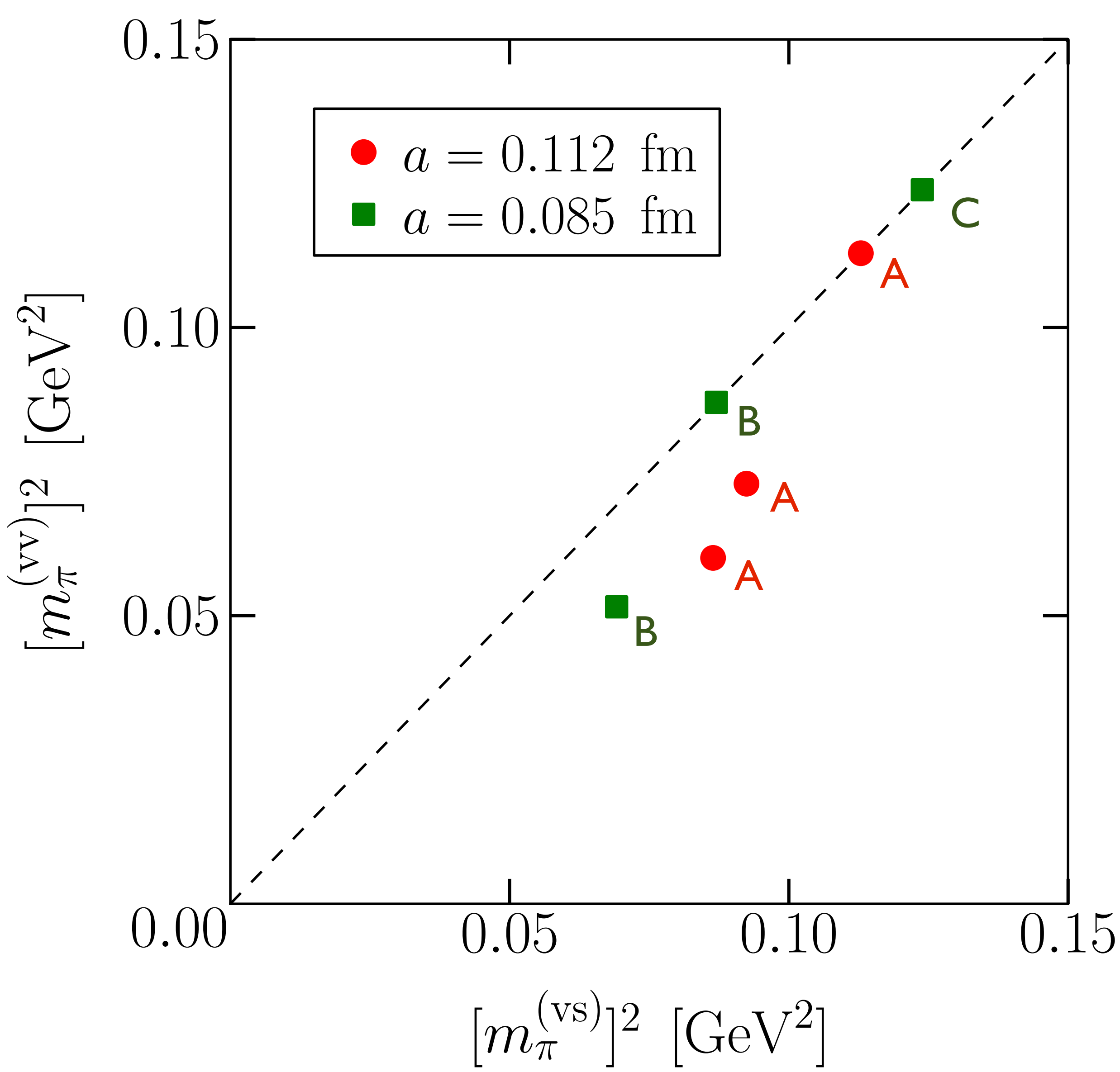

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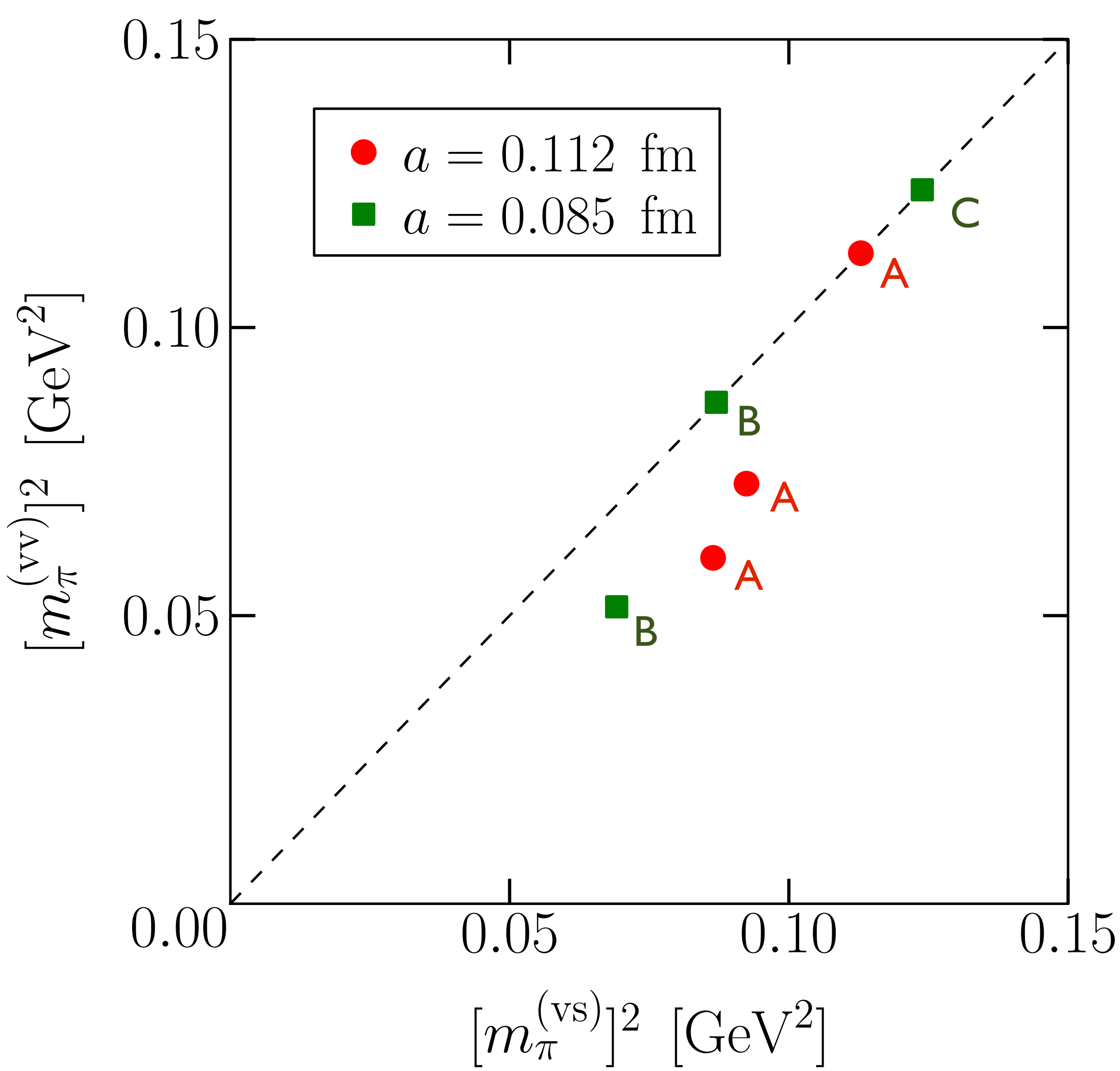


- O(a) improved* axial current:

$$Z_A = \begin{cases} 0.7019(26) & \text{for } a = 0.112 \text{ fm}, \\ 0.7396(17) & \text{for } a = 0.085 \text{ fm}. \end{cases}$$ [RBC]

Correlation functions

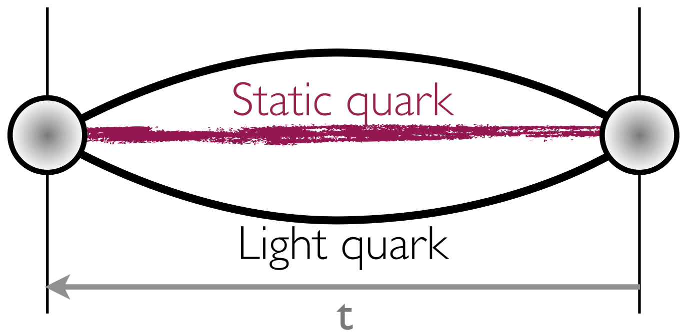
- Interpolating operators in static limit

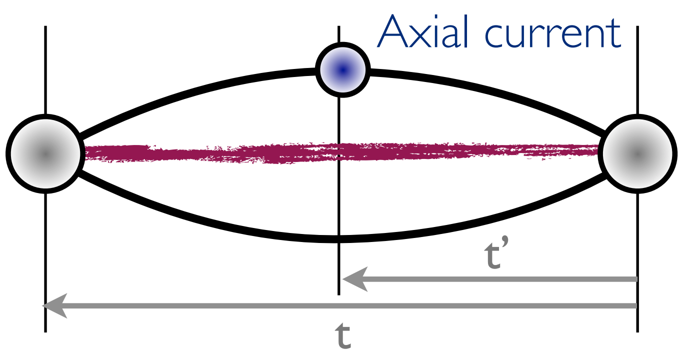
$$P^i = \overline{Q}_{a\alpha}\,(\gamma_5)_{\alpha\beta}\,\tilde{q}^i_{a\beta}, \qquad S^{ij}_{\mu\,\alpha} = \epsilon_{abc}\,(C\gamma_\mu)_{\beta\gamma}\,\tilde{q}^i_{a\beta}\,\tilde{q}^j_{b\gamma}\,Q_{c\alpha},$$
$$P^{*i}_\mu = \overline{Q}_{a\alpha}\,(\gamma_\mu)_{\alpha\beta}\,\tilde{q}^i_{a\beta}, \qquad T^{ij}_\alpha = \epsilon_{abc}\,(C\gamma_5)_{\beta\gamma}\,\tilde{q}^i_{a\beta}\,\tilde{q}^j_{b\gamma}\,Q_{c\alpha}.$$

- Two point and three point correlation functions

$$C[P^u\,P^\dagger_u](t) = \sum_{\mathbf{x}} \langle\, P^u(\mathbf{x},t)\,P^\dagger_u(0)\,\rangle,$$
$$C[P^{*d}\,P^{*\dagger}_d]^{\mu\nu}(t) = \sum_{\mathbf{x}} \langle\, P^{*d\,\mu}(\mathbf{x},t)\,P^{*\,\nu\dagger}_d(0)\,\rangle,$$
$$C[S^{dd}\,\overline{S}_{dd}]^{\mu\nu}_{\alpha\beta}(t) = \sum_{\mathbf{x}} \langle\, S^{dd\,\mu}_\alpha(\mathbf{x},t)\,\overline{S}^\nu_{dd\,\beta}(0)\,\rangle,$$
$$C[S^{du}\,\overline{S}_{du}]^{\mu\nu}_{\alpha\beta}(t) = \sum_{\mathbf{x}} \langle\, S^{du\,\nu}_\alpha(\mathbf{x},t)\,\overline{S}^\nu_{du\,\beta}(0)\,\rangle,$$
$$C[T^{du}\,\overline{T}_{du}]_{\alpha\beta}(t) = \sum_{\mathbf{x}} \langle\, T^{du}_\alpha(\mathbf{x},t)\,\overline{T}_{du\,\beta}(0)\,\rangle.$$

$$C[P^{*d}\,A\,P^\dagger_u]^{\mu\nu}(t,\,t') = \sum_{\mathbf{x}}\sum_{\mathbf{x}'} \langle\, P^{*d\,\mu}(\mathbf{x},t)\,A^\nu(\mathbf{x}',t')\,P^\dagger_u(0)\,\rangle,$$
$$C[S^{dd}A\,\overline{S}_{du}]^{\mu\nu\rho}_{\alpha\beta}(t,\,t') = \sum_{\mathbf{x}}\sum_{\mathbf{x}'} \langle\, S^{dd\,\mu}_\alpha(\mathbf{x},t)\,A^\nu(\mathbf{x}',t')\,\overline{S}^\rho_{du\,\beta}(0)\,\rangle,$$
$$C[S^{dd}A\,\overline{T}_{du}]^{\mu\nu}_{\alpha\beta}(t,\,t') = \sum_{\mathbf{x}}\sum_{\mathbf{x}'} \langle\, S^{dd\,\mu}_\alpha(\mathbf{x},t)\,A^\nu(\mathbf{x}',t')\,\overline{T}_{du\,\beta}(0)\,\rangle,$$
$$C[T^{du}A^\dagger\,\overline{S}_{dd}]^{\mu\nu}_{\alpha\beta}(t,\,t') = \sum_{\mathbf{x}}\sum_{\mathbf{x}'} \langle\, T^{du}_\alpha(\mathbf{x},t)\,A^{\mu\dagger}(\mathbf{x}',t')\,\overline{S}^\nu_{dd\,\beta}(0)\,\rangle.$$





- Calculate with forward propagators from 2 sources

Correlator ratios

- Ratios of 3pt to 2pt correlation functions give effective couplings

$$R_1(t,\, t') = -\frac{\frac{1}{3}\sum_{\mu=1}^{3} C[P^{*d}\, A\, P_u^\dagger]^{\mu\mu}(t,\, t')}{C[P^u\, P_u^\dagger](t)} \quad \xrightarrow{t,t'\to\infty} \quad (g_1)_{\rm eff}$$

$$R_2(t,\, t') = 2\,\frac{\frac{i}{6}\sum_{\mu,\nu,\rho=1}^{3} \epsilon_{0\mu\nu\rho}\, C[S^{dd} A\ \overline{S}_{du}]^{\mu\nu\rho}(t,\, t')}{\frac{1}{3}\sum_{\mu=1}^{3} C[S^{dd}\, \overline{S}_{dd}]^{\mu\mu}(t)} \quad \xrightarrow{t,t'\to\infty} \quad (g_2)_{\rm eff}$$

- For transition coupling, double ratio

$$R_3(t,\, t') = \sqrt{\frac{\left[\frac{1}{3}\sum_{\mu=1}^{3} C[S^{dd} A\ \overline{T}_{du}]^{\mu\mu}(t,\, t')\right]\left[\frac{1}{3}\sum_{\mu=1}^{3} C[T^{du} A^\dagger\ \overline{S}_{dd}]^{\mu\mu}(t,\, t')\right]}{\left[\frac{1}{3}\sum_{\mu=1}^{3} C[S^{dd}\, \overline{S}_{dd}]^{\mu\mu}(t)\right]\ \left[C[T^{du}\, \overline{T}_{du}](t)\right]}} \quad \xrightarrow{t,t'\to\infty} \quad (g_3)_{\rm eff}$$

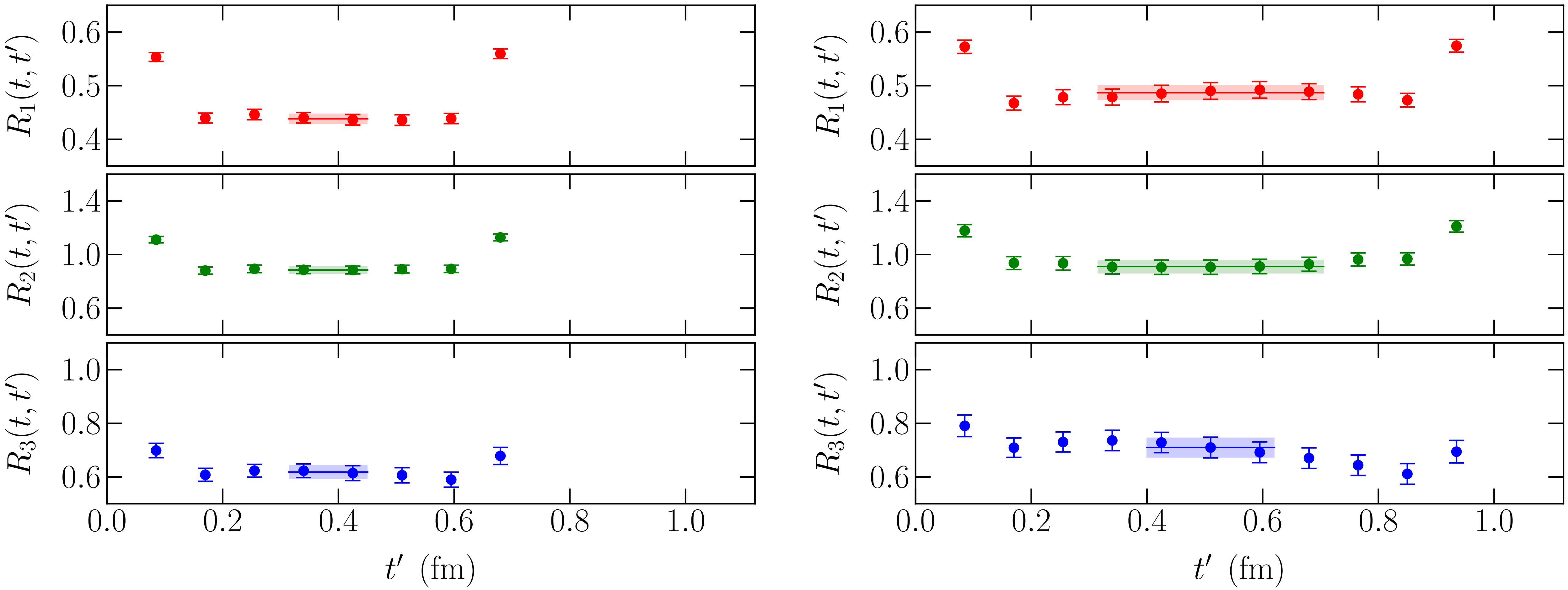
- Excited state contributions important for t,t'<∞
E.g.

$$R_2(t,\, t/2) = A_{11}^{(SS)} + \left|\frac{Z_{S,2}}{Z_{S,1}}\right|^2 (A_{22}^{(SS)} - A_{11}^{(SS)})\, e^{-\delta_S\, t} + 2\,\Re\left[\frac{Z_{S,1} Z_{S,2}^*}{|Z_{S,1}|^2}\, A_{12}^{(SS)}\right]\, e^{-\frac{1}{2}\delta_S\, t} + \ldots$$

with energy gap $\delta_S = E_{S,2} - E_{S,1}$

Correlator ratios

- Ratios for varying operator insertion time



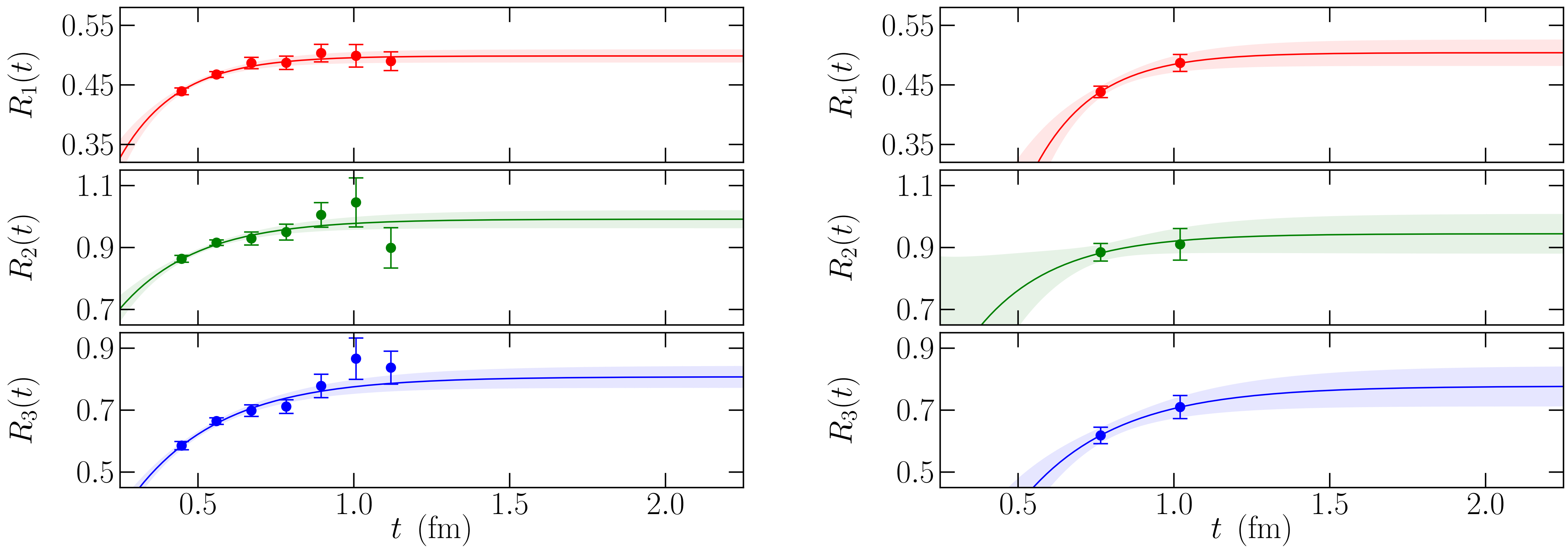
- Negligible t' dependence away from source/sink
  - No evidence for transition matrix elements

Source-sink separation

- Extract effective axial couplings $(g_i)_{\text{eff}}$ from t extrapolation

$$R_i(t, a, m_\pi, n_{\text{HYP}}) = (g_i)_{\text{eff}}(a, m_\pi, n_{\text{HYP}}) - A_i(a, m_\pi, n_{\text{HYP}})e^{-\delta_i(a,m_\pi,n_{\text{HYP}})t}$$

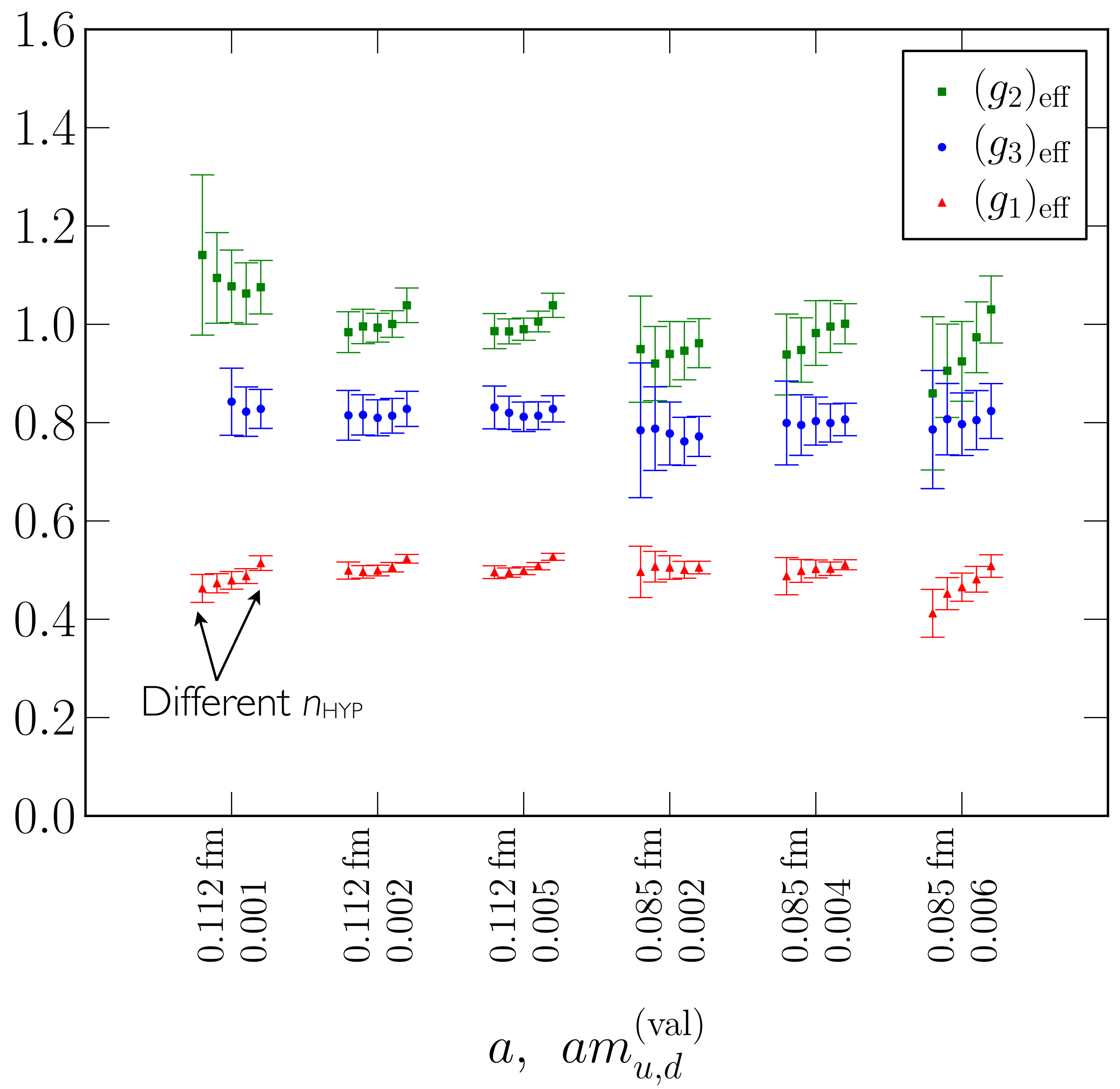
- Constrain δ_i for a=0.086 fm from δ_i at a=0.112 fm



- Fitted gaps: $\delta_i \sim 0.7$—1.0 GeV

Source-sink separation

- Extracted effective couplings $(g_i)_{\text{eff}}(a, m_\pi, n_{\text{HYP}})$
- Estimate systematic uncertainty in extrapolation
    - Remove 1 or 2 points
    - Add second exp with Gaussian priors
    - 2, 3, 5% for $g_{1,2,3}$



Chiral and continuum extrapolation

- Use NLO partially quenched SU(4|2) HHχPT at finite volume and include polynomial discretisation effects

$$(g_1)_{\rm eff}(a,m,n_{\rm HYP}) = g_1\Big[1-\frac{2}{f^2}\,\mathcal{I}(m_\pi^{(\rm vs)})+\frac{g_1^2}{f^2}\Big\{4\,\mathcal{H}(m_\pi^{(\rm vs)},\,0)-4\,\delta_{VS}^2\mathcal{H}_{\eta'}(m_\pi^{(\rm vv)},\,0)\Big\}$$
$$+\,c_1^{(\rm vv)}\,[m_\pi^{(\rm vv)}]^2+c_1^{(\rm vs)}\,[m_\pi^{(\rm vs)}]^2+d_{1,\,n_{\rm HYP}}\,a^2\Big].$$

$$(g_2)_{\rm eff}(a,m,n_{\rm HYP}) = g_2\Big[1-\frac{2}{f^2}\,\mathcal{I}(m_\pi^{(\rm vs)})+\frac{g_2^2}{f^2}\Big\{\frac{3}{2}\,\mathcal{H}(m_\pi^{(\rm vs)},\,0)-\delta_{VS}^2\mathcal{H}_{\eta'}(m_\pi^{(\rm vv)},\,0)\Big\}$$
$$+\frac{g_3^2}{f^2}\Big\{2\,\mathcal{H}(m_\pi^{(\rm vs)},\,-\Delta)-\mathcal{H}(m_\pi^{(\rm vv)},\,-\Delta)-2\,\mathcal{K}(m_\pi^{(\rm vs)},\,-\Delta,\,0)\Big\}$$
$$+\,c_2^{(\rm vv)}\,[m_\pi^{(\rm vv)}]^2+c_2^{(\rm vs)}\,[m_\pi^{(\rm vs)}]^2+d_{2,\,n_{\rm HYP}}\,a^2\Big],$$

$$(g_3)_{\rm eff}(a,m,n_{\rm HYP}) = g_3\Big[1-\frac{2}{f^2}\,\mathcal{I}(m_\pi^{(\rm vs)})+\frac{g_3^2}{f^2}\Big\{\mathcal{H}(m_\pi^{(\rm vs)},\,-\Delta)-\frac{1}{2}\mathcal{H}(m_\pi^{(\rm vv)},\,-\Delta)$$
$$+\frac{3}{2}\mathcal{H}(m_\pi^{(\rm vv)},\,\Delta)+3\,\mathcal{H}(m_\pi^{(\rm vs)},\,\Delta)-\mathcal{K}(m_\pi^{(\rm vs)},\,\Delta,\,0)\Big\}$$
$$+\frac{g_2^2}{f^2}\Big\{-\mathcal{H}(m_\pi^{(\rm vs)},\,\Delta)-\mathcal{H}(m_\pi^{(\rm vv)},\,\Delta)+\mathcal{H}(m_\pi^{(\rm vs)},\,0)-\delta_{VS}^2\mathcal{H}_{\eta'}(m_\pi^{(\rm vv)},\,0)\Big\}$$
$$+\,c_3^{(\rm vv)}\,[m_\pi^{(\rm vv)}]^2+c_3^{(\rm vs)}\,[m_\pi^{(\rm vs)}]^2+d_{3,\,n_{\rm HYP}}\,a^2\Big].$$

Partial quenching

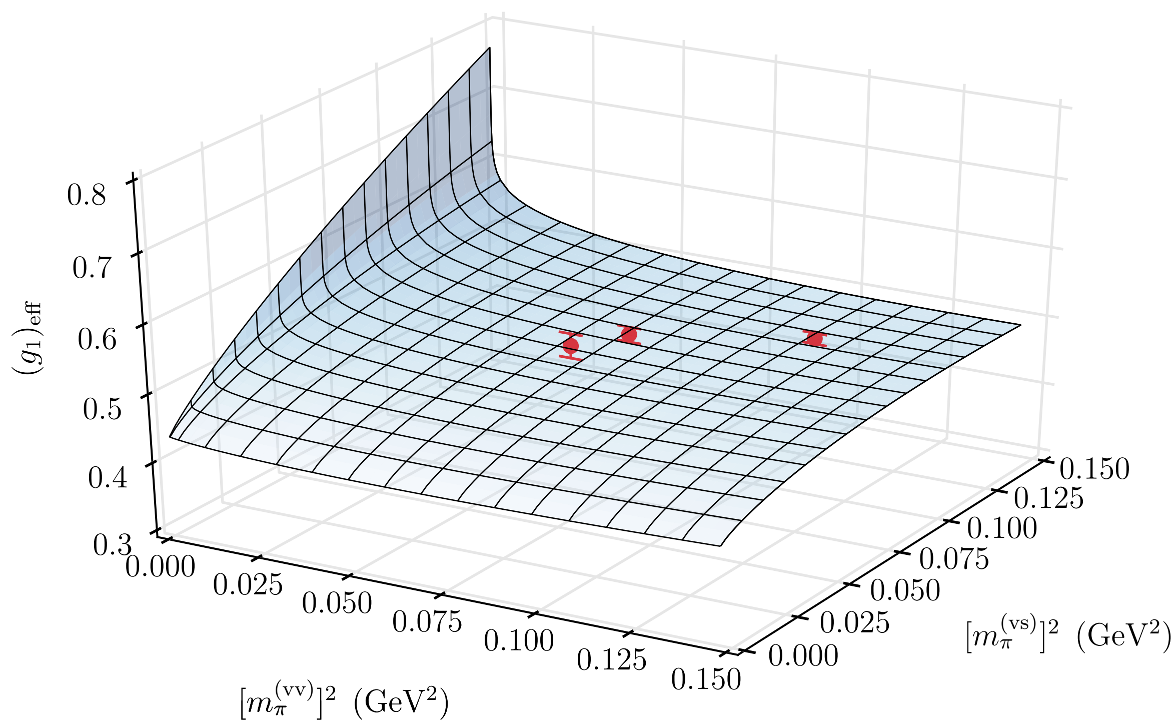
Loop functions

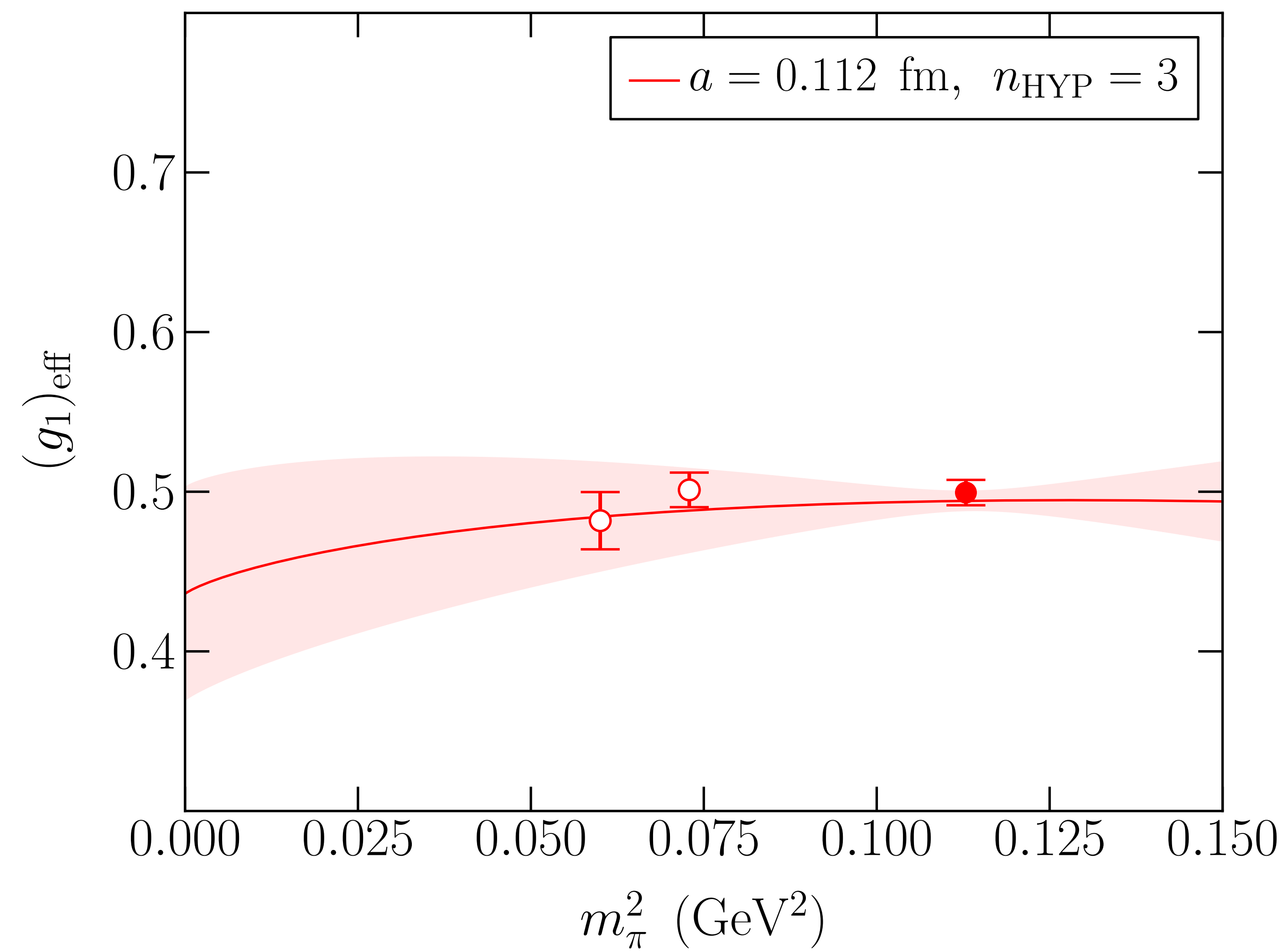
Lattice spacing effects depend on $n_{\rm HYP}$

$g_{2,3}$ extrapolation is coupled

Chiral and continuum extrapolation

g_1

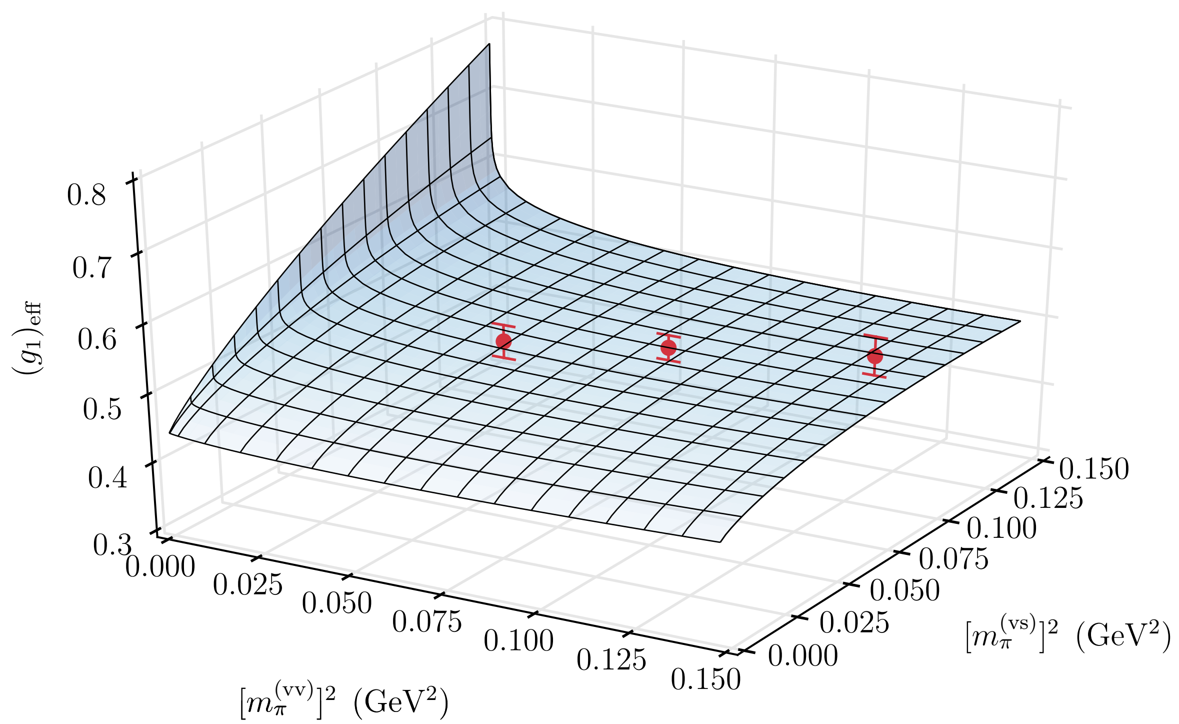


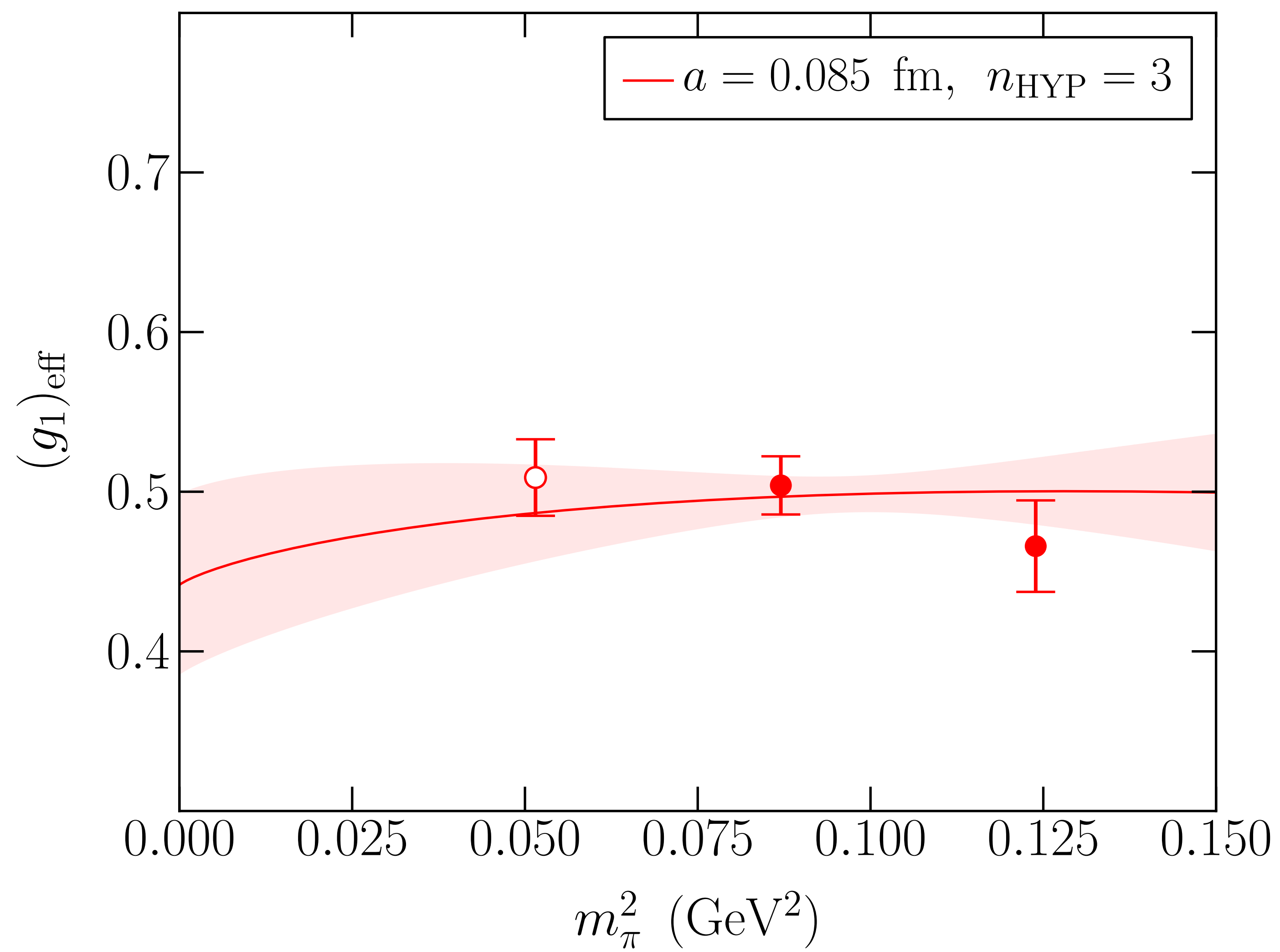


projection on unitary line

Chiral and continuum extrapolation

g1





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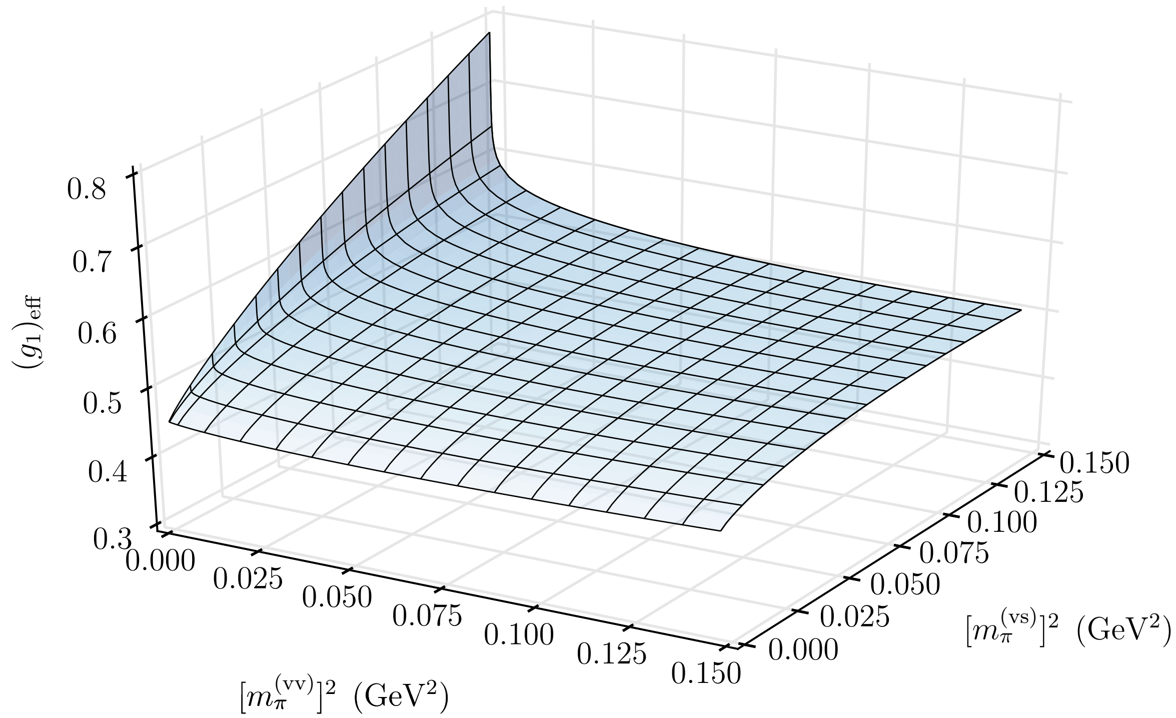
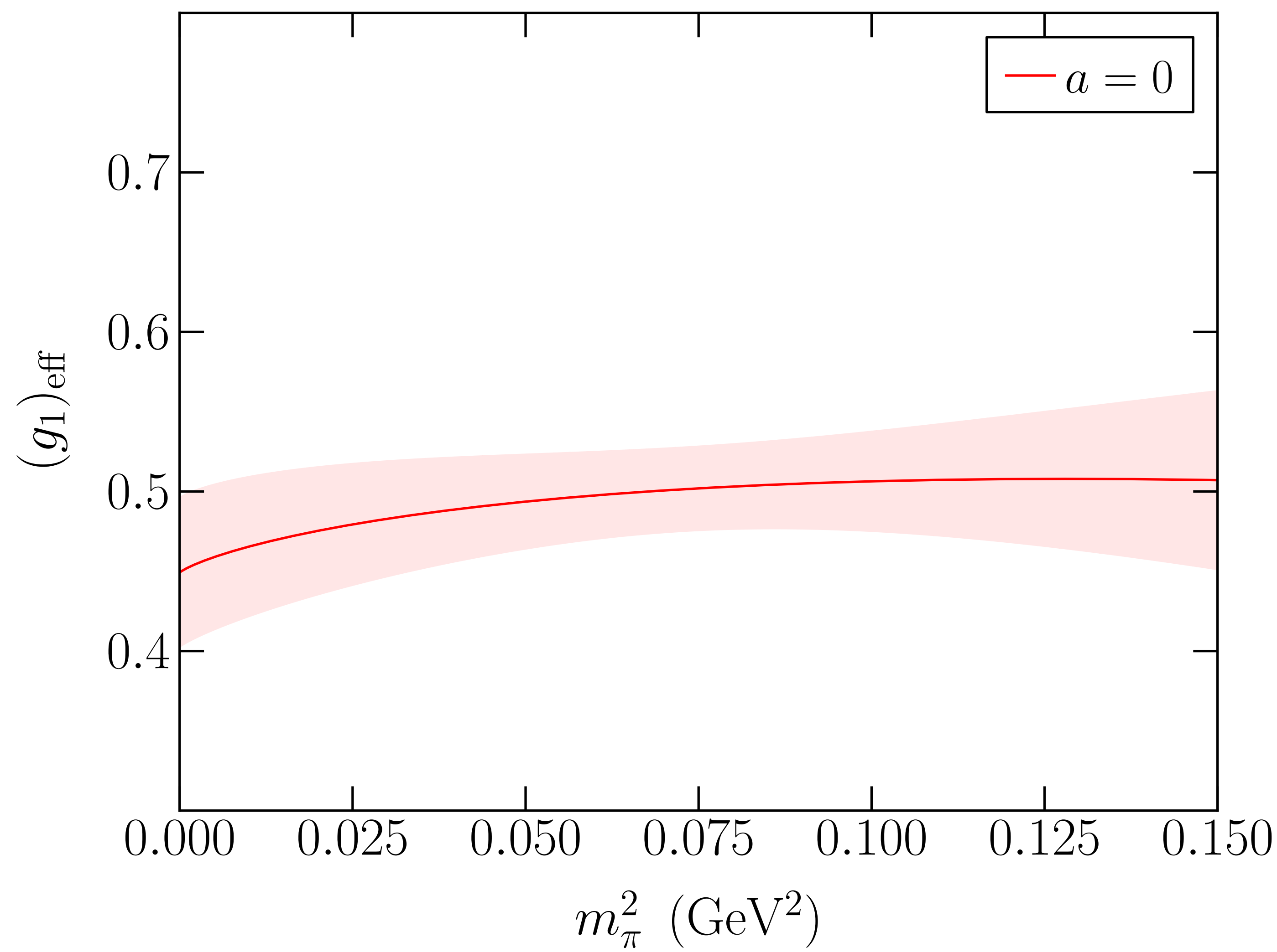
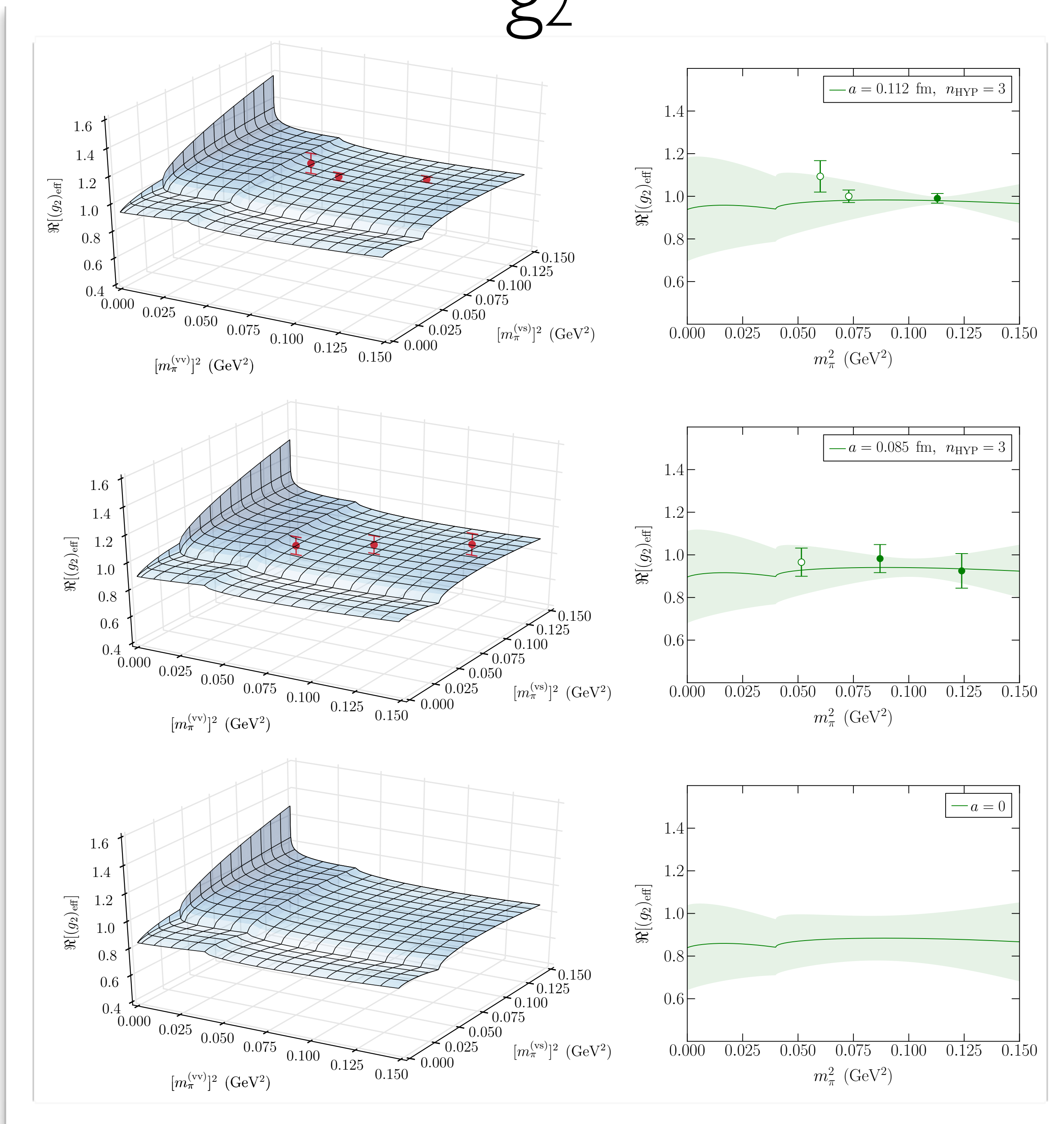




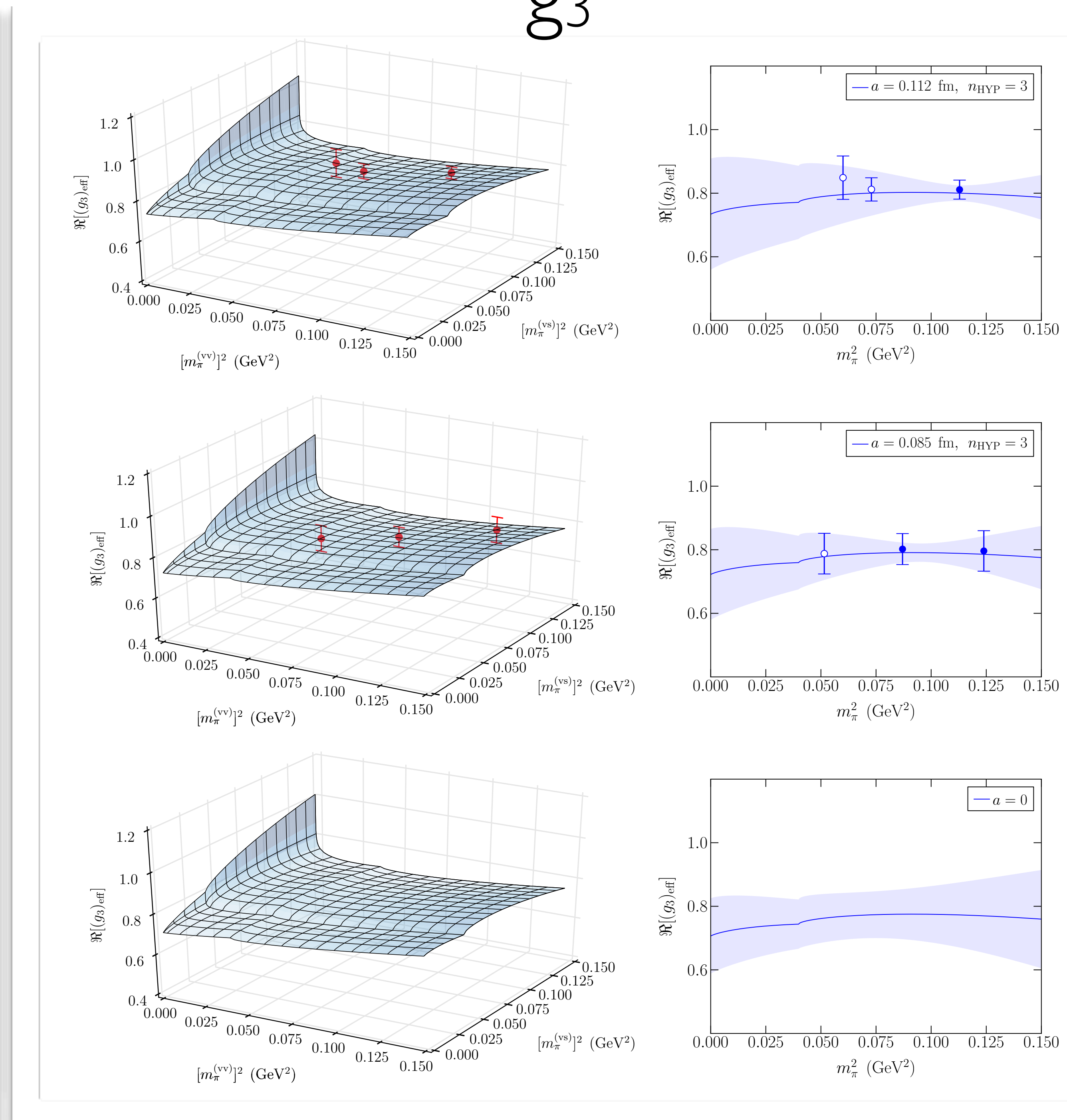
projection on unitary line

Chiral and continuum extrapolation

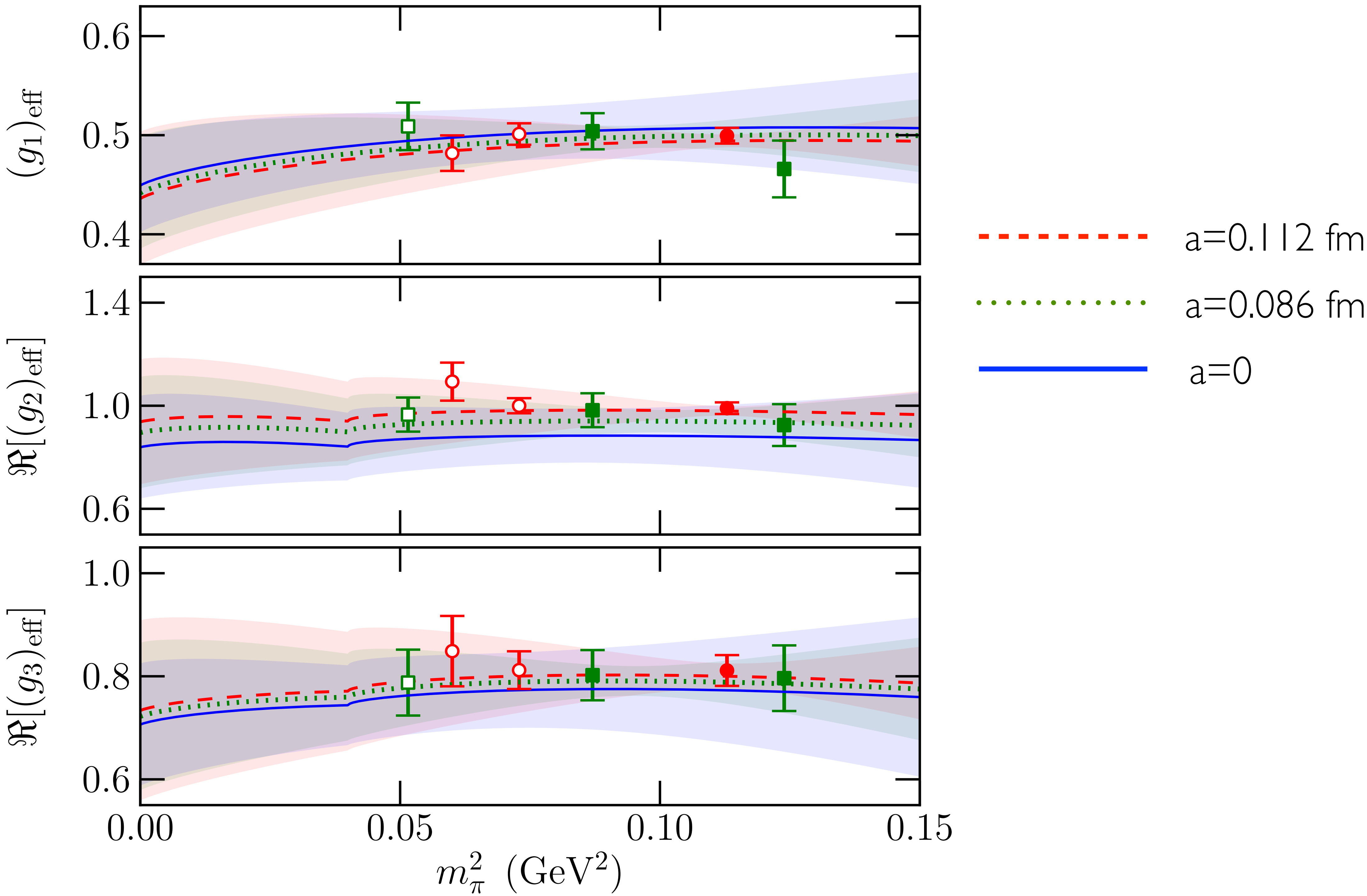
g_2



g_3



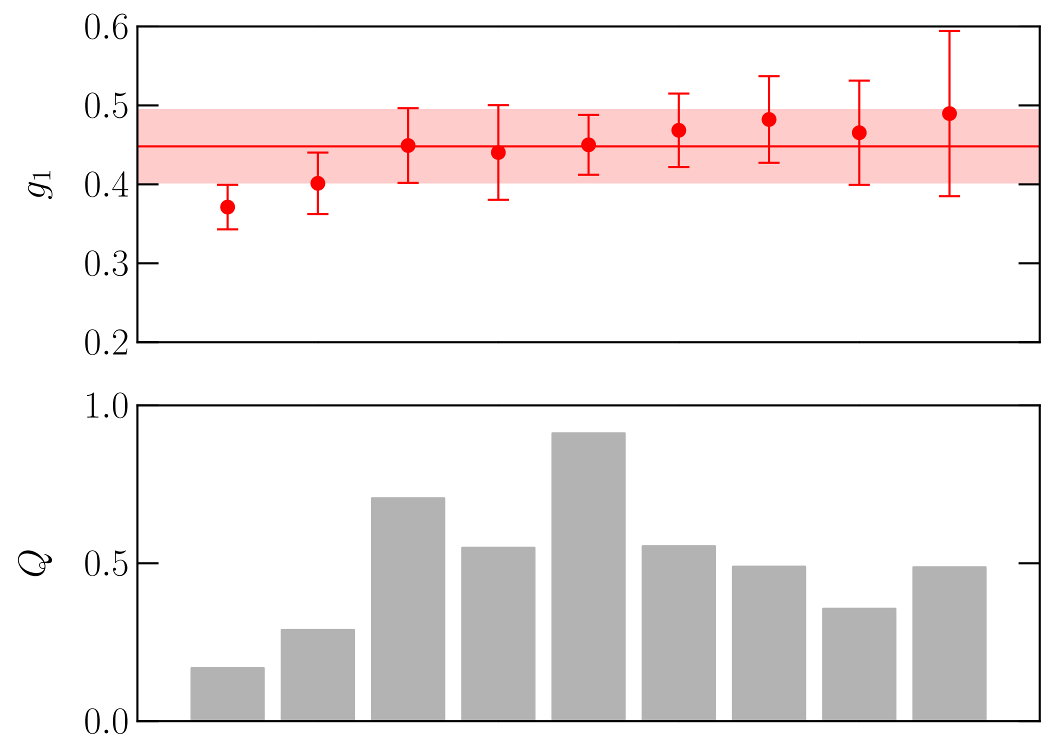
Chiral and continuum extrapolation



Chiral and continuum extrapolation

- Various choices of HQ actions to use in fits
- Heavy meson coupling g_1

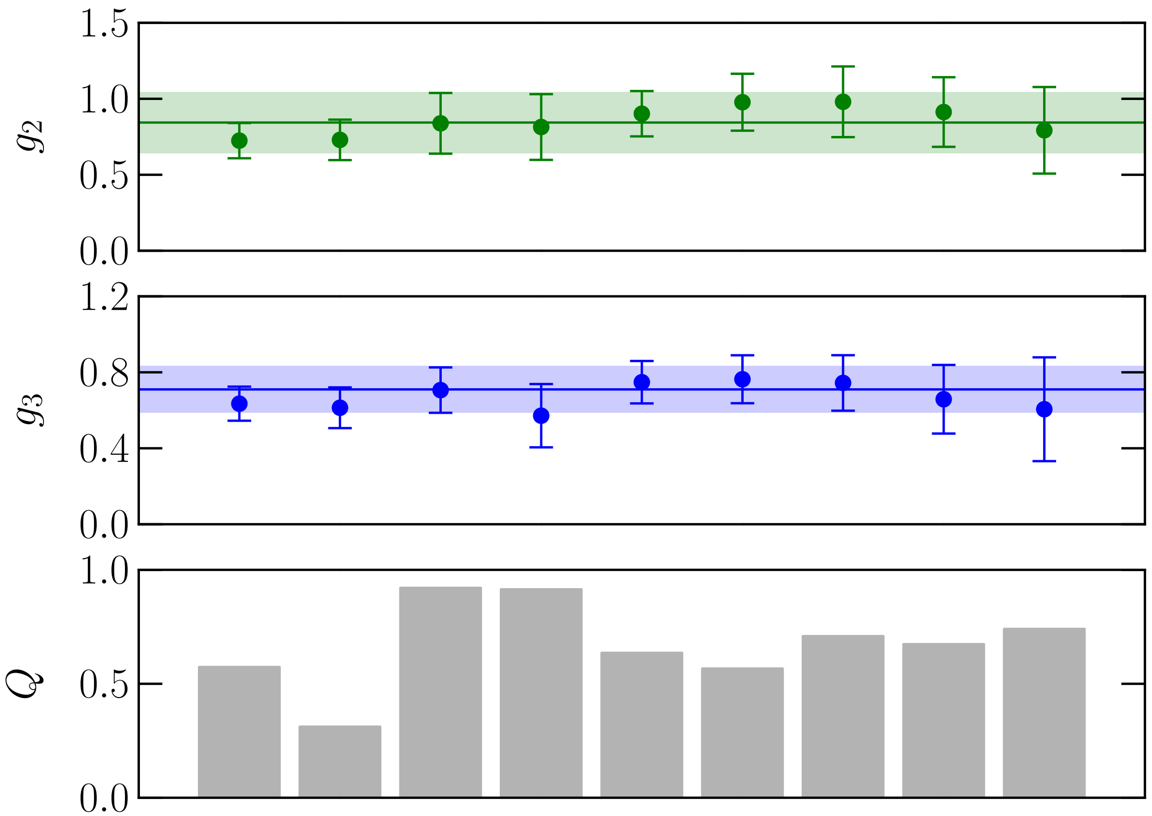
$n_{\rm HYP}$	g_1	d.o.f.	χ^2/d.o.f.	Q
1, 2, 3, 5, 10	0.371(28)	30 − 8	1.3	0.17
1, 2, 3, 5	0.401(39)	24 − 7	1.2	0.29
1, 2, 3	0.449(47)	18 − 6	0.75	0.70
1, 2	0.440(60)	12 − 5	0.85	0.54
10	0.450(38)	6 − 4	0.09	0.91
5	0.468(47)	6 − 4	0.61	0.55
3	0.482(55)	6 − 4	0.73	0.49
2	0.465(66)	6 − 4	1.0	0.36
1	0.49(10)	6 − 4	0.72	0.49



Chiral and continuum extrapolation

- Various choices of HQ actions to use in fits
- Heavy baryon couplings $g_{2,3}$

n_{HYP}	g_2	g_3	d.o.f.	χ^2/d.o.f.	Q
1, 2, 3, 5, 10	0.72(12)	0.635(90)	58 − 16	0.94	0.57
1, 2, 3, 5	0.73(13)	0.61(11)	46 − 14	1.1	0.31
1, 2, 3	0.84(20)	0.71(12)	34 − 12	0.61	0.92
1, 2	0.81(22)	0.57(17)	22 − 10	0.50	0.91
10	0.90(15)	0.75(11)	12 − 8	0.64	0.64
5	0.98(19)	0.76(13)	12 − 8	0.74	0.57
3	0.98(23)	0.74(15)	12 − 8	0.54	0.71
2	0.91(23)	0.66(18)	12 − 8	0.51	0.67
1	0.79(29)	0.61(27)	12 − 8	0.42	0.74



Higher order terms

- Add higher order analytic terms in quark masses and lattice spacings

$$(g_i)_{\rm eff}^{\rm (NLO+HO)}(a,m,n_{\rm HYP}) = (g_i)_{\rm eff}^{\rm (NLO)}(a,m,n_{\rm HYP}) + g_i\Big[c_i^{\rm (vv,vv)}\,[m_\pi^{\rm (vv)}]^4 + c_i^{\rm (vs,vs)}\,[m_\pi^{\rm (vs)}]^4 + c_i^{\rm (vv,vs)}\,[m_\pi^{\rm (vv)}]^2[m_\pi^{\rm (vs)}]^2 + d_{i,\,n_{\rm HYP}}^{\rm (vv)}\,a^2\,[m_\pi^{\rm (vv)}]^2 + d_{i,\,n_{\rm HYP}}^{\rm (vs)}\,a^2\,[m_\pi^{\rm (vs)}]^2 + h_{i,\,n_{\rm HYP}}\,a^4\Big].$$

- Refit with priors on c_i, d_i and h_i

$$\begin{aligned} c_i^{\rm (vv,vv)} &= 0 \pm w/\Lambda_\chi^4,\\ c_i^{\rm (vs,vs)} &= 0 \pm w/\Lambda_\chi^4,\\ c_i^{\rm (vv,vs)} &= 0 \pm w/\Lambda_\chi^4,\\ d_{i,\,n_{\rm HYP}}^{\rm (vv)} &= 0 \pm w\,\Lambda_{\rm QCD}^2/\Lambda_\chi^2,\\ d_{i,\,n_{\rm HYP}}^{\rm (vs)} &= 0 \pm w\,\Lambda_{\rm QCD}^2/\Lambda_\chi^2,\\ h_{i,\,n_{\rm HYP}} &= 0 \pm w\,\Lambda_{\rm QCD}^4. \end{aligned}$$

w	g_1	$\delta\sigma(g_1)$	g_2	$\delta\sigma(g_2)$	g_3	$\delta\sigma(g_3)$
0	0.449(47)	0	0.84(20)	0	0.71(12)	0
1	0.449(47)	0.0020	0.84(20)	0.0023	0.71(12)	0.0045
5	0.452(48)	0.0089	0.84(20)	0.014	0.70(12)	0.017
10	0.455(50)	0.016	0.84(20)	0.024	0.70(12)	0.026
50	0.464(72)	0.054	0.82(22)	0.099	0.68(15)	0.094
100	0.452(94)	0.082	0.78(26)	0.17	0.63(21)	0.17

$$\delta\sigma(g_i) = \sqrt{\sigma^2(g_i)^{\rm (NLO+HO)} - \sigma^2(g_i)^{\rm (NLO)}},$$

- w =10 gives systematic uncertainty (w=1 is NDA)

Finite volume effects

- Finite volume effects computed in HHχPT

$m_\pi^{(\mathrm{vs})}$ (MeV)	$m_\pi^{(\mathrm{vv})}$ (MeV)	$\frac{(g_1)_{\mathrm{eff}}^{(\infty)}-(g_1)_{\mathrm{eff}}^{(L)}}{(g_1)_{\mathrm{eff}}^{(\infty)}}$	$\frac{(g_2)_{\mathrm{eff}}^{(\infty)}-(g_2)_{\mathrm{eff}}^{(L)}}{(g_2)_{\mathrm{eff}}^{(\infty)}}$	$\frac{(g_3)_{\mathrm{eff}}^{(\infty)}-(g_3)_{\mathrm{eff}}^{(L)}}{(g_3)_{\mathrm{eff}}^{(\infty)}}$
294	245	0.0057	0.015	0.0074
304	270	0.0040	0.0070	0.0027
336	336	0.0016	0.00037	−0.00079
263	227	0.0072	0.028	0.013
295	295	0.0031	0.00027	−0.0012
352	352	0.0013	0.00033	−0.00071

- Very small, higher order FV negligible

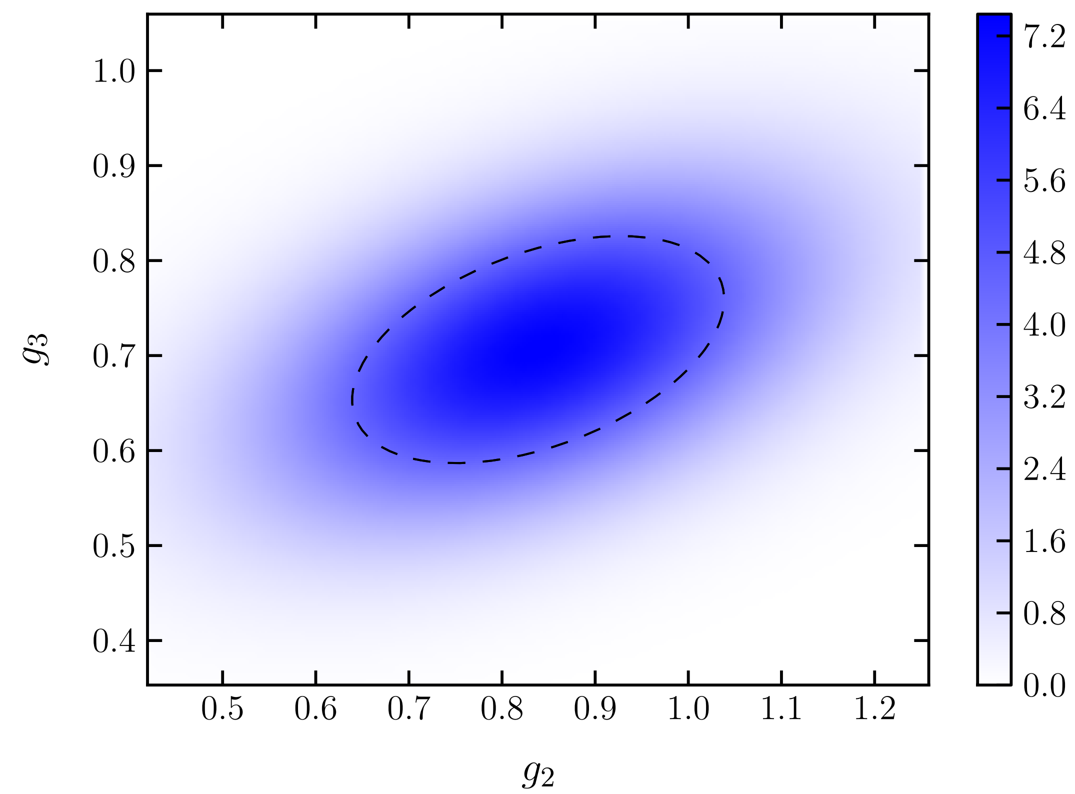
Axial couplings

- Final extracted values

$$
\begin{aligned}
g_1 &= 0.449 \pm 0.047_{\,\text{stat}} \pm 0.019_{\,\text{syst}} \\
g_2 &= 0.84 \pm 0.20_{\,\text{stat}} \pm 0.04_{\,\text{syst}} \\
g_3 &= 0.71 \pm 0.12_{\,\text{stat}} \pm 0.04_{\,\text{syst}}
\end{aligned}
$$

- Sources of systematic errors

Source	g_1	g_2	g_3
NNLO terms in fits of m_π- and a-dependence	3.6%	2.8%	3.7%
Higher excited states in fits to $R_i(t)$	1.7%	2.8%	4.9%
Unphysical value of $m_s^{(\text{sea})}$	1.5%	1.5%	1.5%
Total	4.2%	4.3%	6.3%



- Dominated by statistical errors

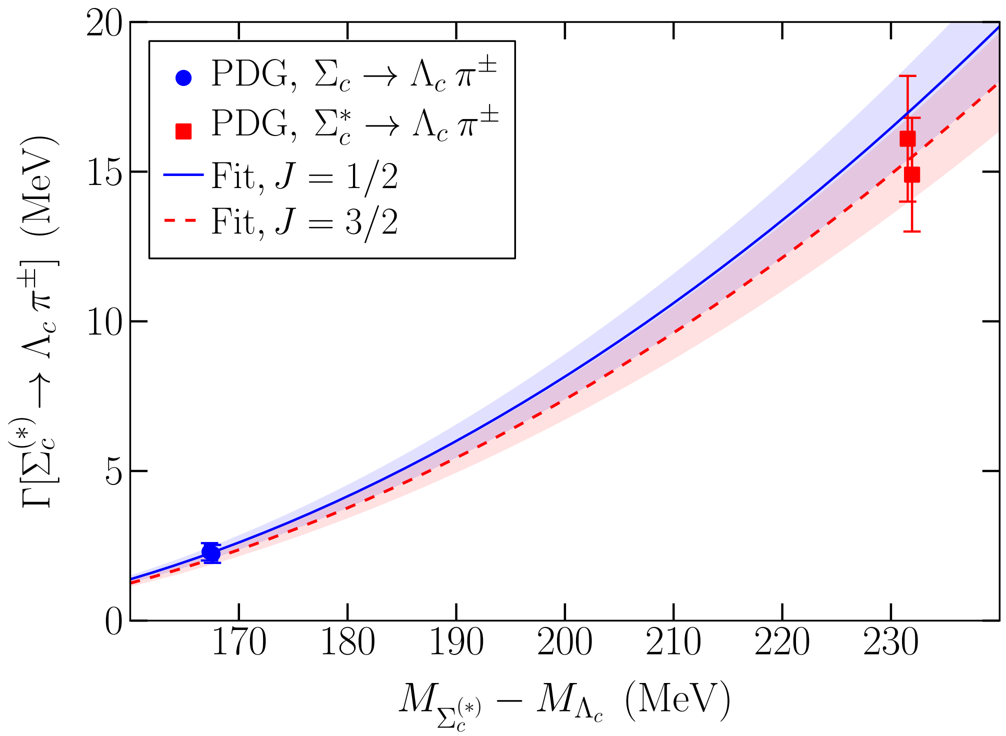
Decay widths

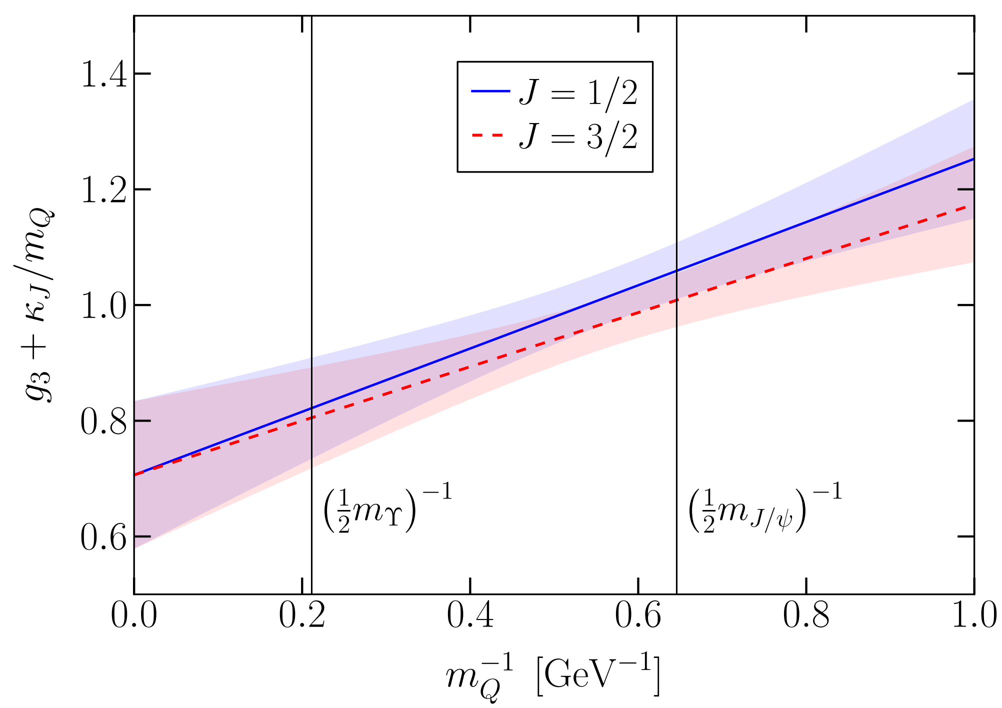
- Strong decays allowed for heavy baryons

$$\Gamma[S \to T\,\pi] = c_{\rm f}^2\,\frac{1}{6\pi f_\pi^2}\left(g_3 + \frac{\kappa_J}{m_Q}\right)^2 \frac{M_T}{M_S}\,|\mathbf{p}_\pi|^3$$

$$c_{\rm f} = \begin{cases} 1 & \text{for} \quad \Sigma_Q^{(*)} \to \Lambda_Q\,\pi^\pm, \\ 1 & \text{for} \quad \Sigma_Q^{(*)} \to \Lambda_Q\,\pi^0, \\ 1/\sqrt{2} & \text{for} \quad \Xi_Q^{\prime(*)} \to \Xi_Q\,\pi^\pm, \\ 1/2 & \text{for} \quad \Xi_Q^{\prime(*)} \to \Xi_Q\,\pi^0. \end{cases}$$

- $1/m_Q$ corrections important: determine from charm sector
- Effective coupling vs $1/m_Q$
- Valid only at LO in HHχPT

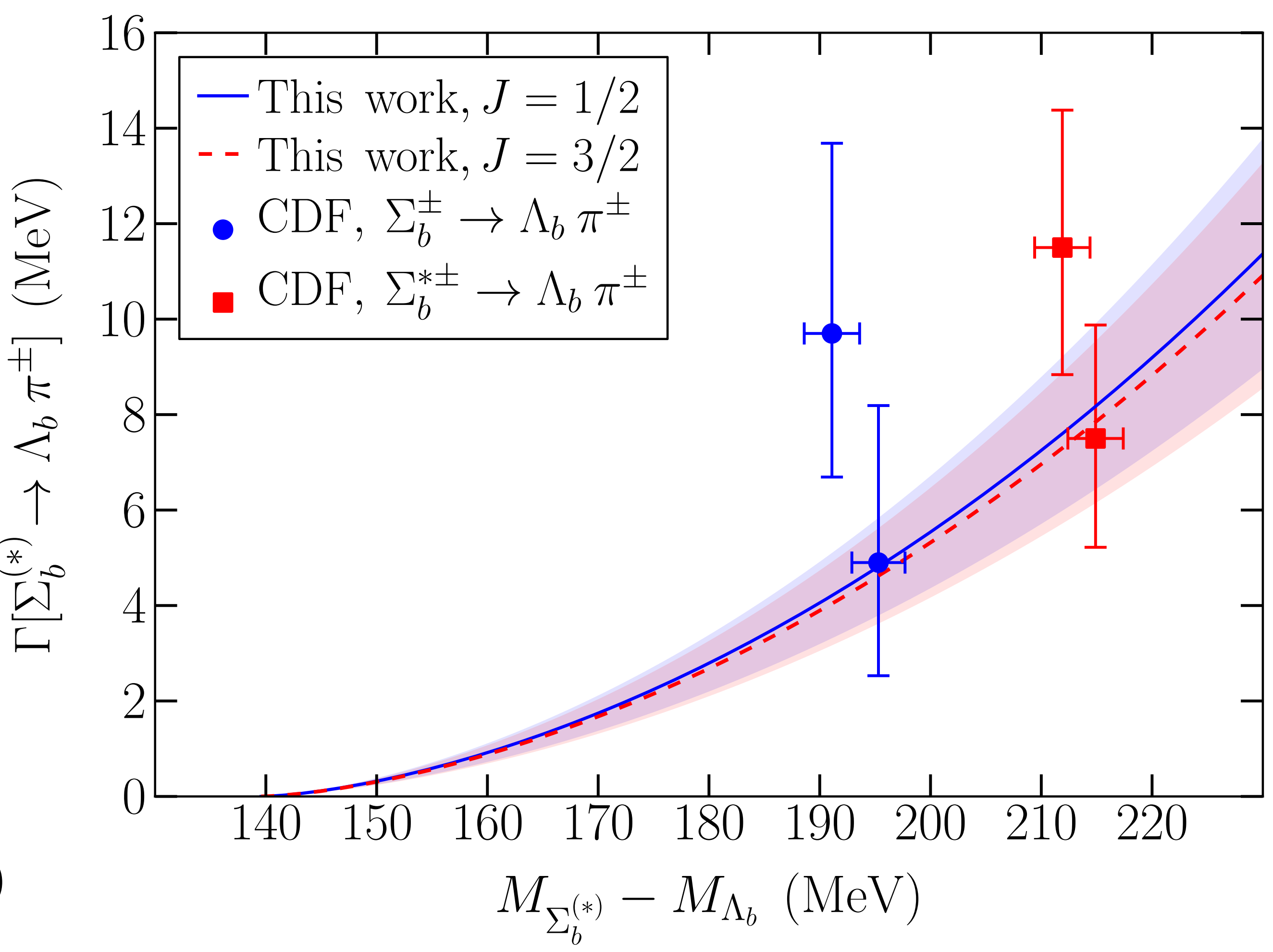




Decay widths

- Calculate (and predict) bottom and charm baryon decay widths

Hadron	This work	Experiment
Σ_b^+	4.2(1.0)	$9.7^{+3.8+1.2}_{-2.8-1.1}$ [13]
Σ_b^-	4.8(1.1)	$4.9^{+3.1}_{-2.1} \pm 1.1$ [13]
Σ_b^{*+}	7.3(1.6)	$11.5^{+2.7+1.0}_{-2.2-1.5}$ [13]
Σ_b^{*-}	7.8(1.8)	$7.5^{+2.2+0.9}_{-1.8-1.4}$ [13]
Ξ_b'	1.1 (CL=90%)	...
Ξ_b^*	2.8 (CL=90%)	...
Ξ_c^{*+}	2.44(26)	< 3.1 (CL=90%) [70]
Ξ_c^{*0}	2.78(29)	< 5.5 (CL=90%) [71]



- Uses determinations of Ξ_b', Ξ_b^* masses from LQCD [Lewis & Woloshyn 09]

Heavy hadron axial couplings

- First complete calculation of axial couplings controlling all systematics

$$\begin{aligned} g_1 &= 0.449 \pm 0.047_{\,\text{stat}} \pm 0.019_{\,\text{syst}} \\ g_2 &= 0.84 \pm 0.20_{\,\text{stat}} \pm 0.04_{\,\text{syst}} \\ g_3 &= 0.71 \pm 0.12_{\,\text{stat}} \pm 0.04_{\,\text{syst}} \end{aligned}$$

  - Considerably smaller than quark model estimates
  - Pleasant consequences for convergence of HHχPT

- Allows pre- (and post-) dictions of strong decay widths (also $\Gamma[\Xi_c^* \to \Xi_c \gamma]$)

[fin]

Actions and ensembles

- Further details

$L^3 \times T$	$am_s^{(\text{sea})}$	$am_{u,d}^{(\text{sea})}$	$am_{u,d}^{(\text{val})}$	a (fm)	$m_\pi^{(\text{ss})}$ (MeV)	$m_\pi^{(\text{vs})}$ (MeV)	$m_\pi^{(\text{vv})}$ (MeV)
$24^3 \times 64$	0.04	0.005	0.001	0.1119(17)	336(5)	294(5)	245(4)
$24^3 \times 64$	0.04	0.005	0.002	0.1119(17)	336(5)	304(5)	270(4)
$24^3 \times 64$	0.04	0.005	0.005	0.1119(17)	336(5)	336(5)	336(5)
$32^3 \times 64$	0.03	0.004	0.002	0.0849(12)	295(4)	263(4)	227(3)
$32^3 \times 64$	0.03	0.004	0.004	0.0849(12)	295(4)	295(4)	295(4)
$32^3 \times 64$	0.03	0.006	0.006	0.0848(17)	352(7)	352(7)	352(7)

- Numbers of measurements

$L^3 \times T$	$am_{u,d}^{(\text{val})}$	t/a	N_{meas} (approx.)
$24^3 \times 64$	0.001	10	550
$24^3 \times 64$	0.001	9, 8, 7, 6	240
$24^3 \times 64$	0.001	5	460
$24^3 \times 64$	0.001	4	120
$24^3 \times 64$	0.002	10	880
$24^3 \times 64$	0.002	9, 8, 7, 6, 4	240
$24^3 \times 64$	0.002	5	480
$24^3 \times 64$	0.005	10	960
$24^3 \times 64$	0.005	9, 8, 7, 6, 4	240
$24^3 \times 64$	0.005	5	480
$32^3 \times 64$	0.002	12	1200
$32^3 \times 64$	0.002	9, 6	480
$32^3 \times 64$	0.004	12	1200
$32^3 \times 64$	0.004	9, 6	480
$32^3 \times 64$	0.006	13	700