Charm Physics

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Flavour physics

- Heavy flavour sector
  - Charm not so well served by HQET
  - CLEO-c and B-Factories → lots of data
  - f_{Ds} critical quantity
- Charmed hadrons accessible on lattice
  - $am_c < 1$
  - Simulate directly on lattice
  - Easy to control effective theory techniques

Outline

- Past calculations - Quenched
  - Ds spectrum – New states
    - A. Dougall, R.D. Kenway, C.M., C. McNeile Phys.Lett. B569 (2003) 41-44
  - Charm quark mass
    - A. Dougall, C.M., C. McNeile hep-lat/0409089
- Future calculation – dynamical fermions
  - f_{Ds} and Ds spectrum: Overlap on KS sea
  - Heavy quarks on a GW sea

New states in D_s spectrum

- B. Aubert *et al*. (BaBar) Phys.Rev.Lett 90 242001, 2003 Cited 162 times!
- Discovery of new narrow state
  - Mass ~ 2.32 GeV
  - Decays to $D^+_s \pi^0$ $J^P=0^+$(?)
  - Is it $c\bar{s}$ meson?
- Confirmed by Belle and CLEO
  - Other narrow states discovered

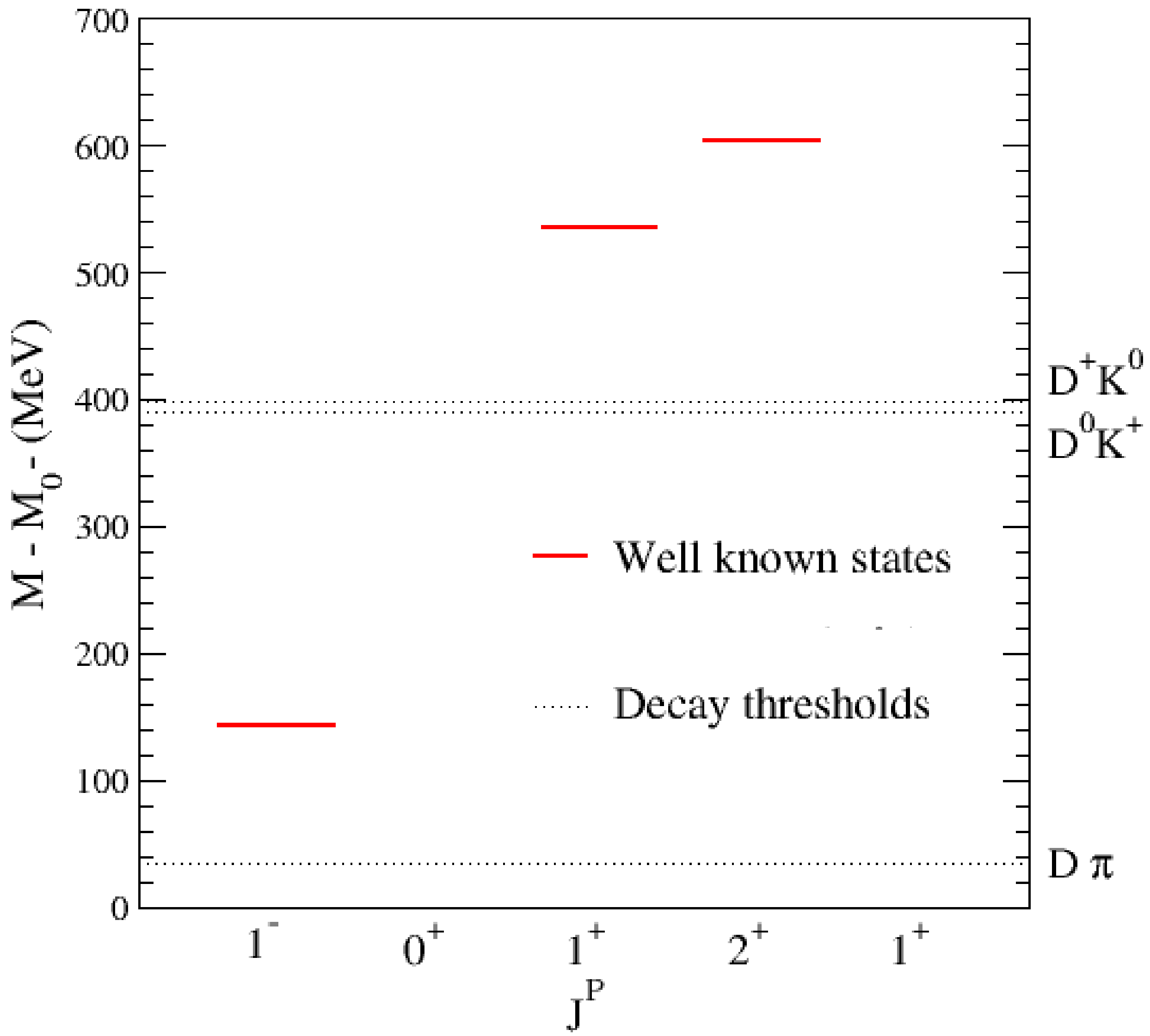
Ds Spectrum

Potential model mass is high, resonance is wide

BaBar: Narrow resonance in D+π channel $J^P=0^+$

speculation that new state is not a meson but 4 quark molecule

$0 \rightarrow M_{Ds}(Ps) = 1.9685$ GeV



Problems for theory?

- These states "*not predicted by theory*"
- Some melodramatic statements in popular press
- "*This sends theorists back to their drawing boards*"
  - SLAC director Jonathan Dorfan – BBC
- Predictions come from Quark Model not QCD

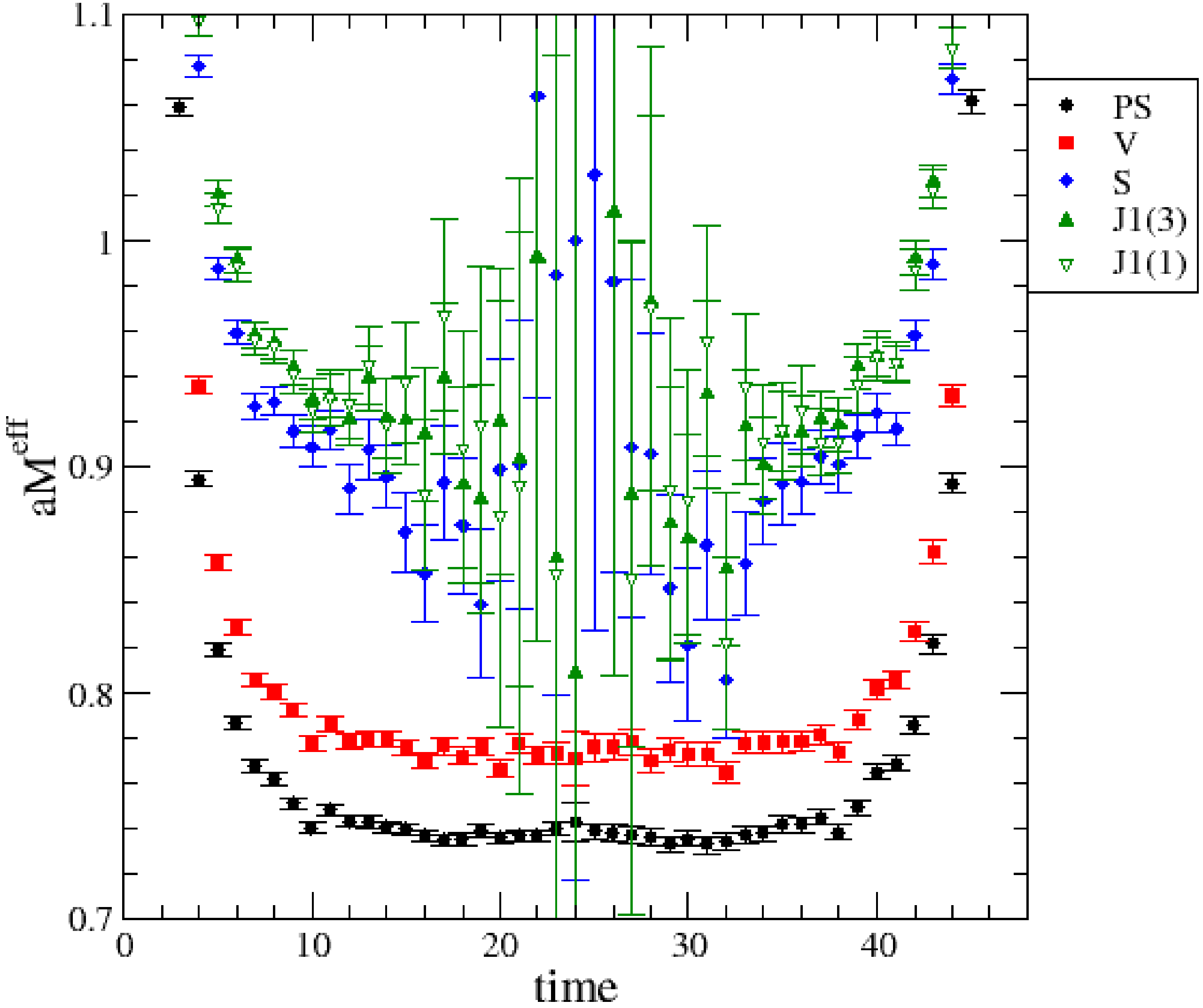
Correlation functions

$$C(\tilde{p},t) = \sum_{\tilde{x}} e^{i\tilde{p}\cdot\tilde{x}} \langle \Omega_X(\tilde{x},t)\Omega_X(\tilde{0},0)\rangle = \sum_n A e^{-m_n t}$$

Local correlation functions

$$\Omega_{ij}(x) = \psi_i(x)\Gamma\psi_j(x)$$

$$\Gamma = \{1, \gamma_\mu, \gamma_5, i\gamma_5\gamma_\mu, \sigma_{\mu\nu}\}$$



Quenched β=6.2
Valence quark masses roughly

$c\bar{s}$

2004/9/30

Data sets

Wilson Glue, Clover-Wilson quarks NP c_{SW}
Quenched and N_F=2

{ β , κ }	V	a^{-1} (GeV)	#cfgs	M_{PS}/M_V
6.2,0	24^3x48	2.91	216	N/A
6.0,0	16^3x48	2.12	496	N/A
5.93,0	16^3x32	1.90	623	N/A
5.2,0.1350	16^3x32	1.91	202	0.70(1)

Scale set by $r_0 = 0.5\ fm$

P wave states and symmetry

- States labelled by spin of light quark j

$$L = 1 \ \Rightarrow \ j \ = \{\tfrac{1}{2}, \tfrac{3}{2}\}$$

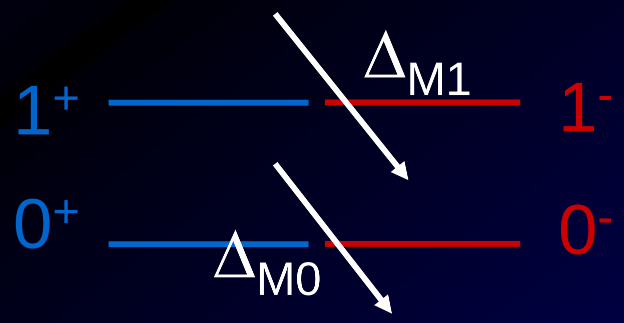
- Plus spin of heavy quark → 2 doublets

$$j = \tfrac{1}{2} \ni J = \{0, 1\} \qquad j = \tfrac{3}{2} \ni J = \{1, 2\}$$

- J=1 states no definite C
  - Mixing → see lowest state on lattice

Heavy and Chiral symmetry

- Double limit → parity doublets $\{0^-,1^-\}$ $\{0^+,1^+\}$ degenerate
- Spontaneous χ-sym breaking splits
  - $\Delta_{M1}(1^+ - 1^-) = \Delta_{M0}(0^+ - 0^-)$



- CLEO Δ_{M1}=351(2), Δ_{M0}=350(1) MeV

Mass splittings

$$\frac{C_i(t)}{C_j(t)} = \lim_{t\to\infty} A_{ij} e^{-(m_i - m_j)t}$$

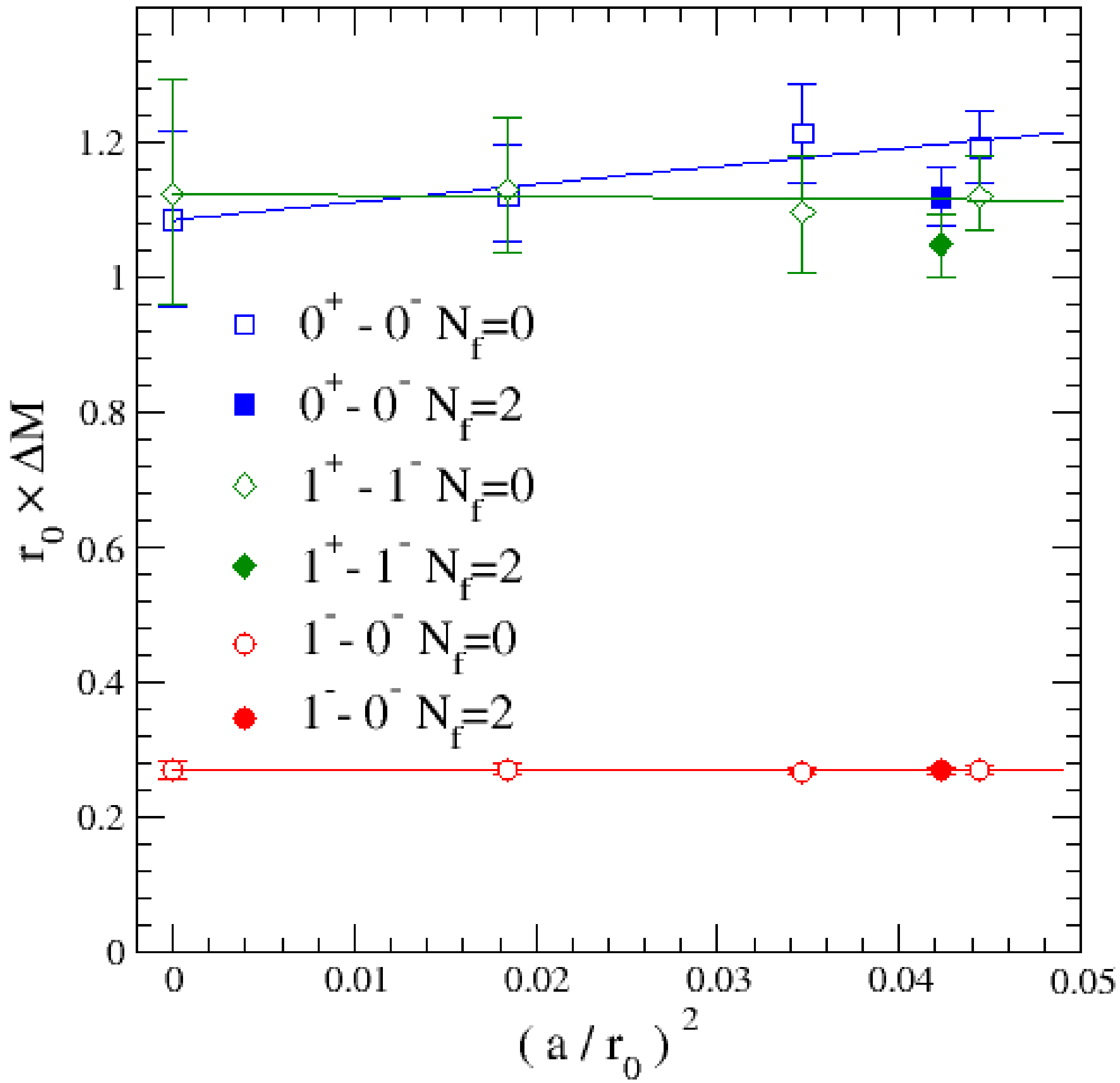
- Fitting Δm can help reduce stat errors
- Interpolate mass splittings
  - $\Delta_{M0}=0^+-0^-$, $\Delta_{M1}=1^+-1^-$, $\Delta_{MH}=1^--0^-$
  - $(m_{PS})^2$ for lights – kaon for strange
  - $1/m_{PS}$ for heavies – M_{Ds} for charm

Continuum extrapolation

Green and blue Symbols show Δ_{M1} and Δ_{M0}
Red is Δ_{MH}

$\Delta_{M0} = \Delta_{M1}$

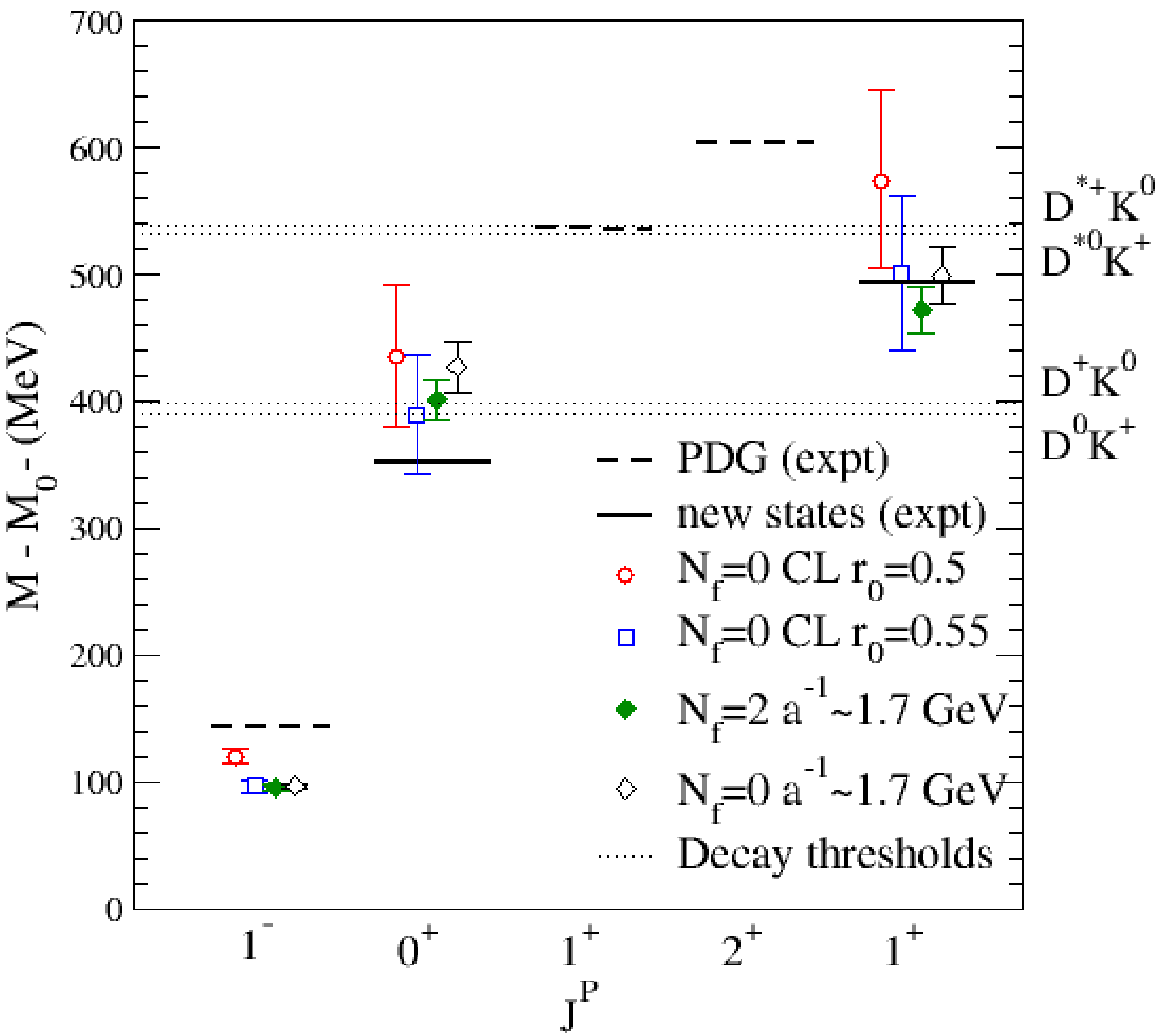
No statistically significant effect for DF



Ds Spectrum II

Results *consistent* with mesonic interpretation

Narrow width as state is below threshold and decay to pion channel is isospin suppressed



Charm quark mass

- $M_c \sim M(\eta_c)/2 - \Lambda_{QCD} \sim 1.3$ GeV
- M_c is both scale and scheme dependent
  – Not well known quantity

$$1.0 < \overline{m}^{\overline{MS}}_{\mathrm{charm}}(\overline{m}_{\mathrm{charm}}) < 1.4\ \mathrm{GeV}$$ PDG2002

- Many quenched calculations
  – Require dynamical fermions to do better

General strategy

- Coefficients $\{Z_J, b_J, c_J\}$ not known NP on coarse lattice
  - Use tadpole improved PT Bhattacharya *et al* `hep-lat/0009038` in $\overline{\text{MS}}$ scheme
  - Lattice artefacts $O(\alpha_s a)$ and $O(a^2)$
    - *coarsest lattice* → $am_q \sim 0.7$
  - Compare to FNAL method
- Interpolate quark masses to charm (Ds)
- Scale $m_c(\mu=a)$ to $m_c(\mu=m_c)$ with RunDec

Axial Ward Identity

$$m_{ij} = \frac{\partial_4 \langle A_4^I \mathcal{O} \rangle}{2\langle P \mathcal{O} \rangle} = \frac{m_i + m_j}{2}$$

$$A_4^I = A_4 + a c_A \partial_4 P$$

$$A_4(x) = \bar{\psi}_i(x) \gamma_4 \gamma_5 \psi_j(x)$$

$$P(x) = \bar{\psi}_i(x) \gamma_5 \psi_j(x)$$

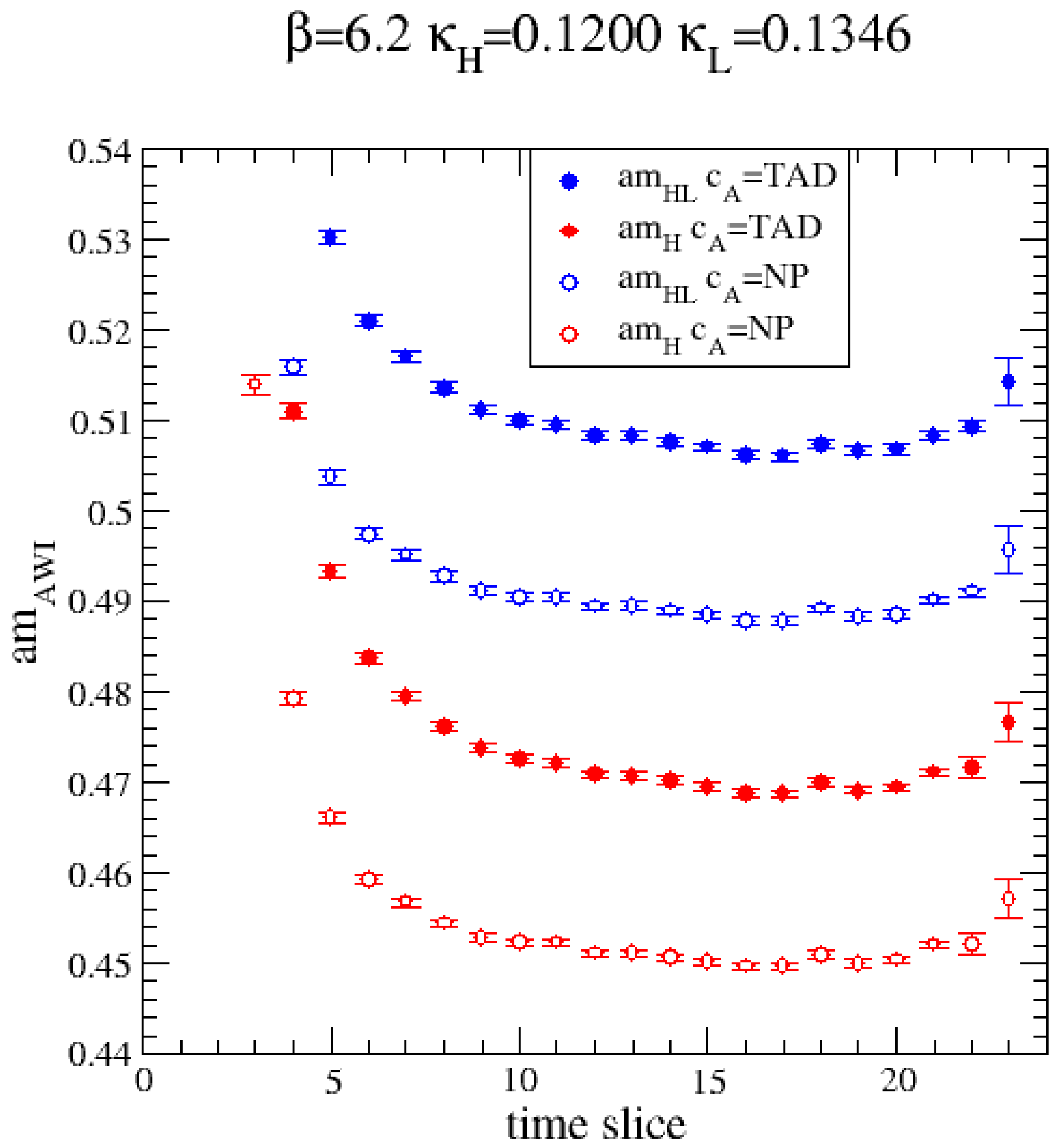
$$m_A = \frac{Z_A}{Z_P}(1 + [b_A - b_P] am) m$$

Bare axial mass

Effective mass plot for axial Ward identity mass

Open symbols show the effect of NP C_A

Effect of NP C_A half as big as am_L



Hopping parameter mass

$$m_q = \frac{1}{2}(\frac{1}{\kappa} - \frac{1}{\kappa_{\rm crit}})$$

$$m_V = Z_M(1 + b_m a m_q) m_q$$

$b_m = -1/2$ at tree-level

FNAL Method

Aim to include all $O(am)^n$ lattice artefacts

Tree level definitions …

$$m_2 = \frac{e^{m_1} \sinh m_1}{1 + \sinh(m_1)}$$

$$m_1 = \ln(1 + m_q) \sim m_q - \frac{1}{2} m_q^2 + \cdots \qquad (2)$$

m_1 same as m_V to $O(am)$

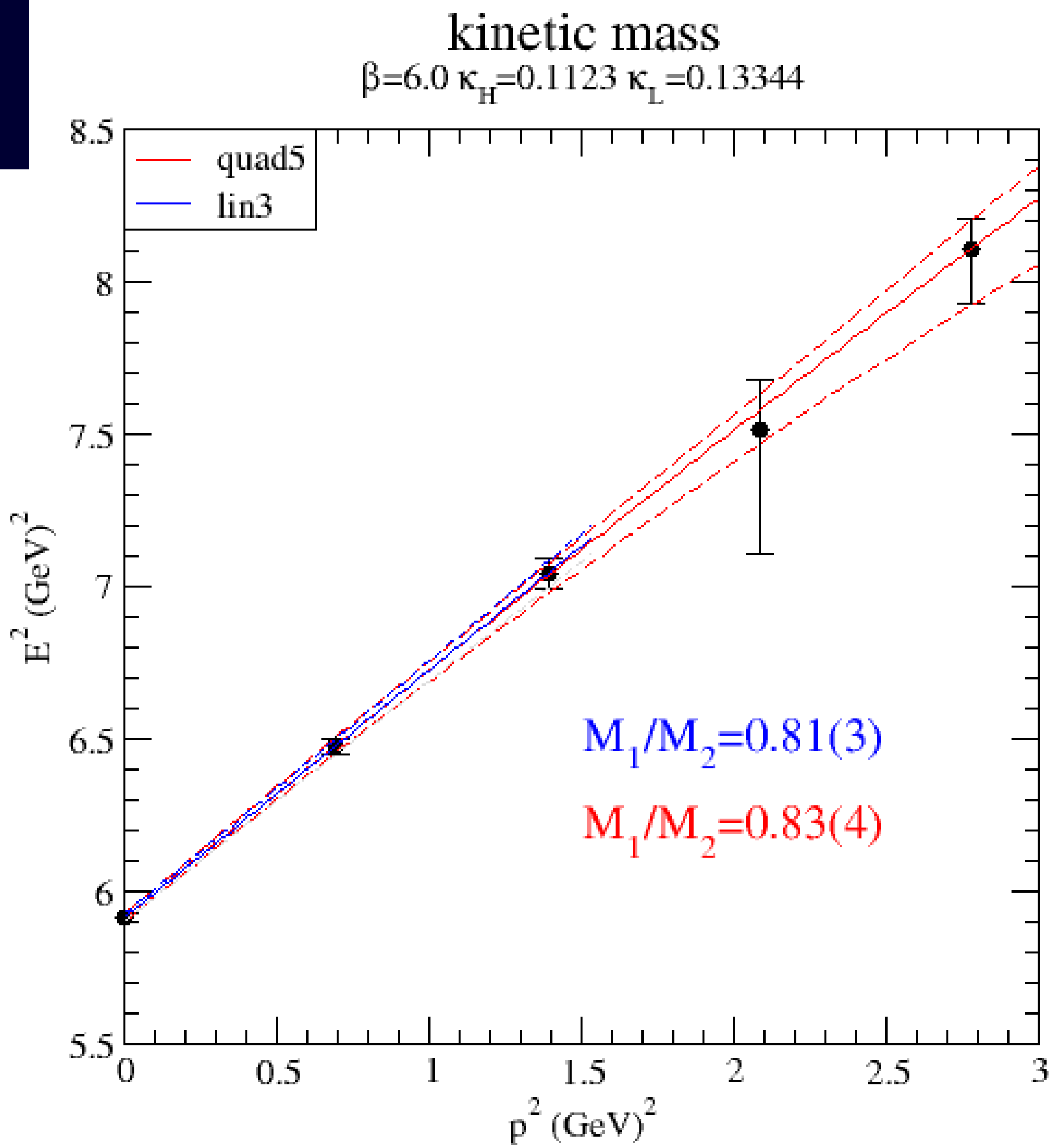
Use one-loop definitions in Mertens *et al*

hep-lat/9712024

Dispersion relation

$$E^2 = M_1^2 + \frac{M_1}{M_2}\vec{p}^2 + \mathcal{O}(\vec{p}^4)$$

$$\frac{1}{M_2} = \frac{\partial^2 E}{\partial p_k^2}$$



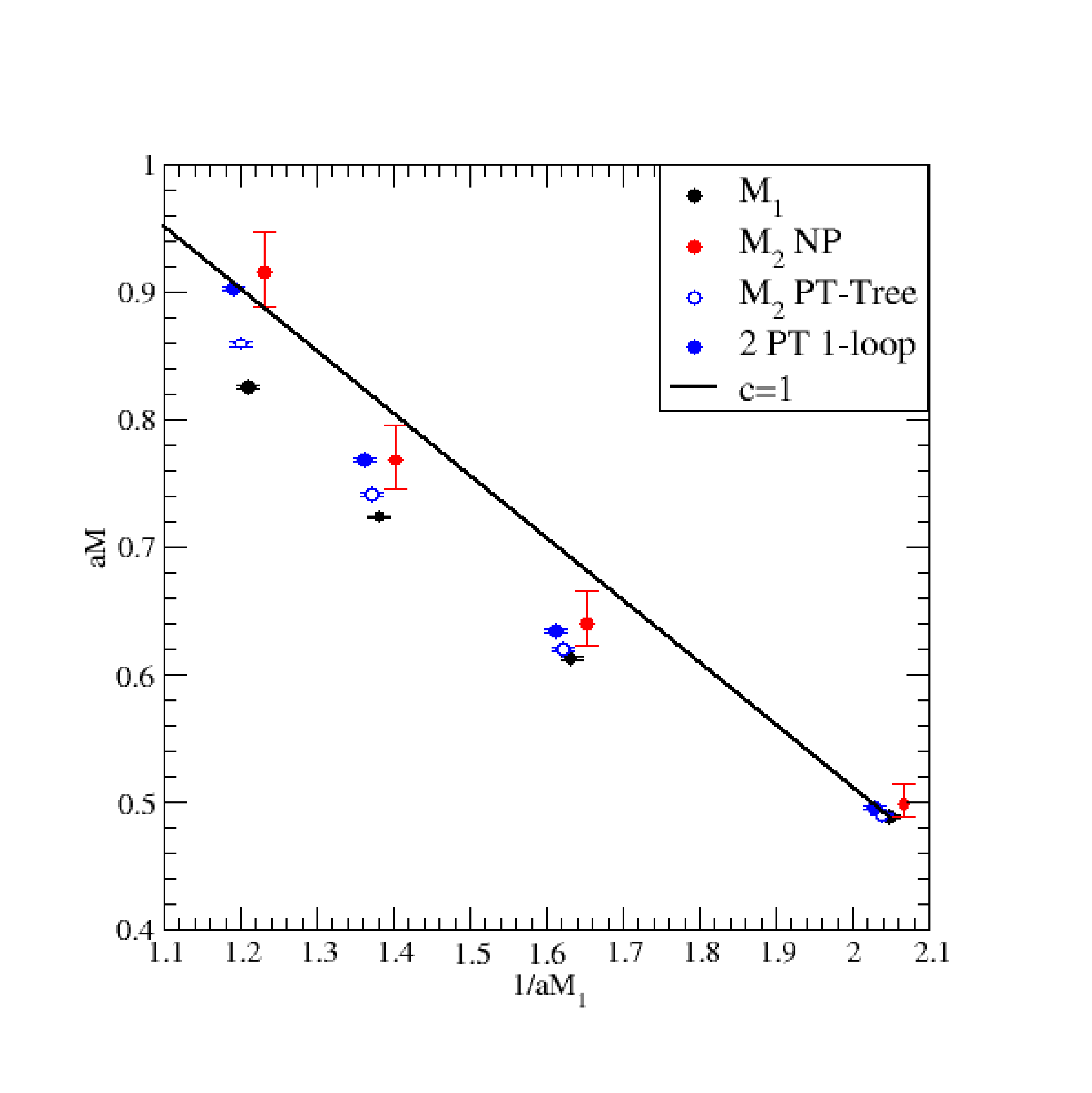
M_1 vs M_2 Hadron masses

$M_2 = M_1 + (m_2 - m_1)$

Tree-level M_2 is a poor estimate of NP M_2

1-loop M_2 track NP M_2

Use 1-loop M_2



Functional form of interpolation

HQS

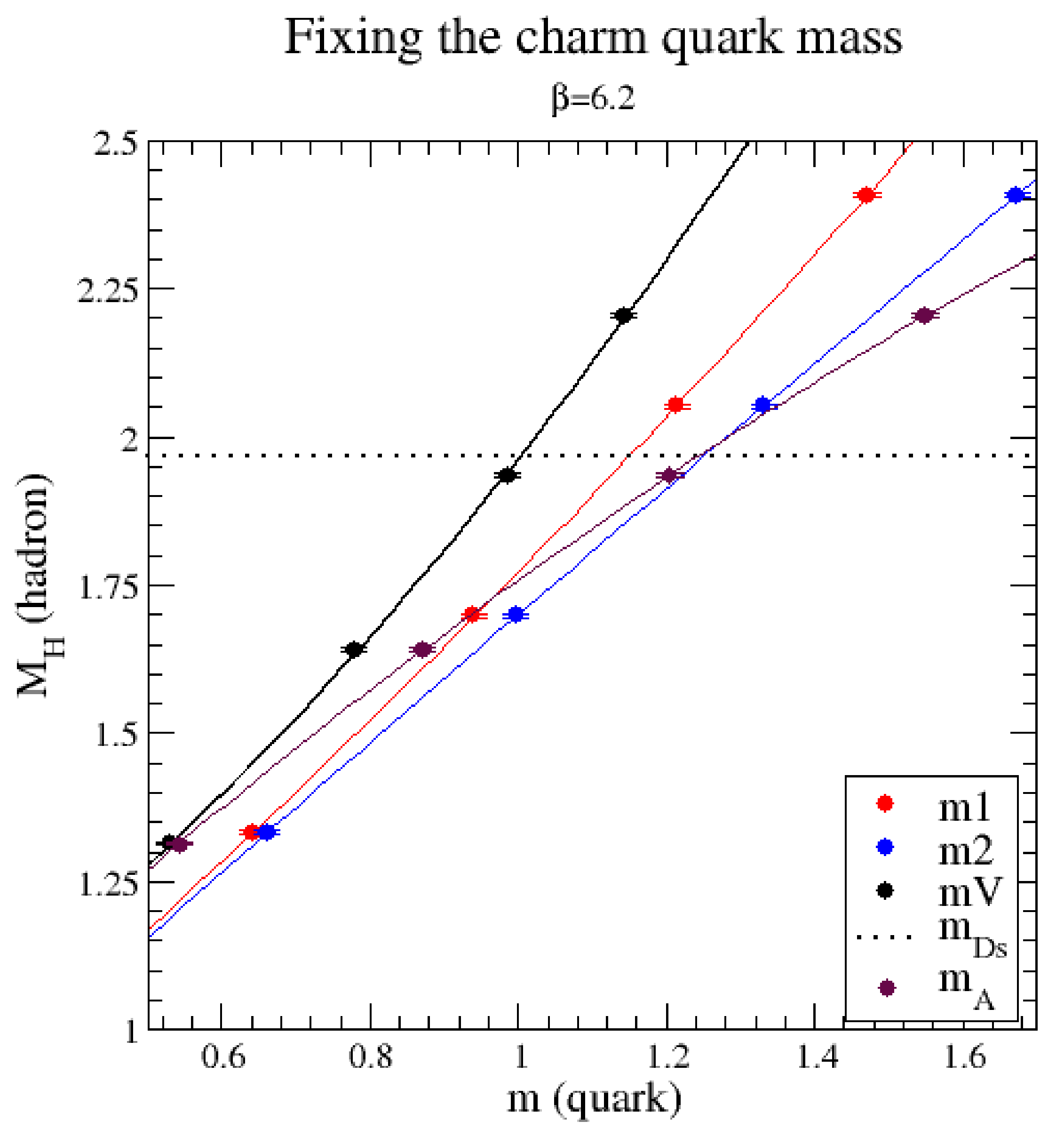
$$f(x) = b_0 + \frac{b_1}{x} + \cdots$$

But mass have *O(am)* corrections

$$f(x) = a_0 + a_1 x + \cdots$$

Same in fixed range

$$\frac{1}{4} < x < \frac{3}{4}$$



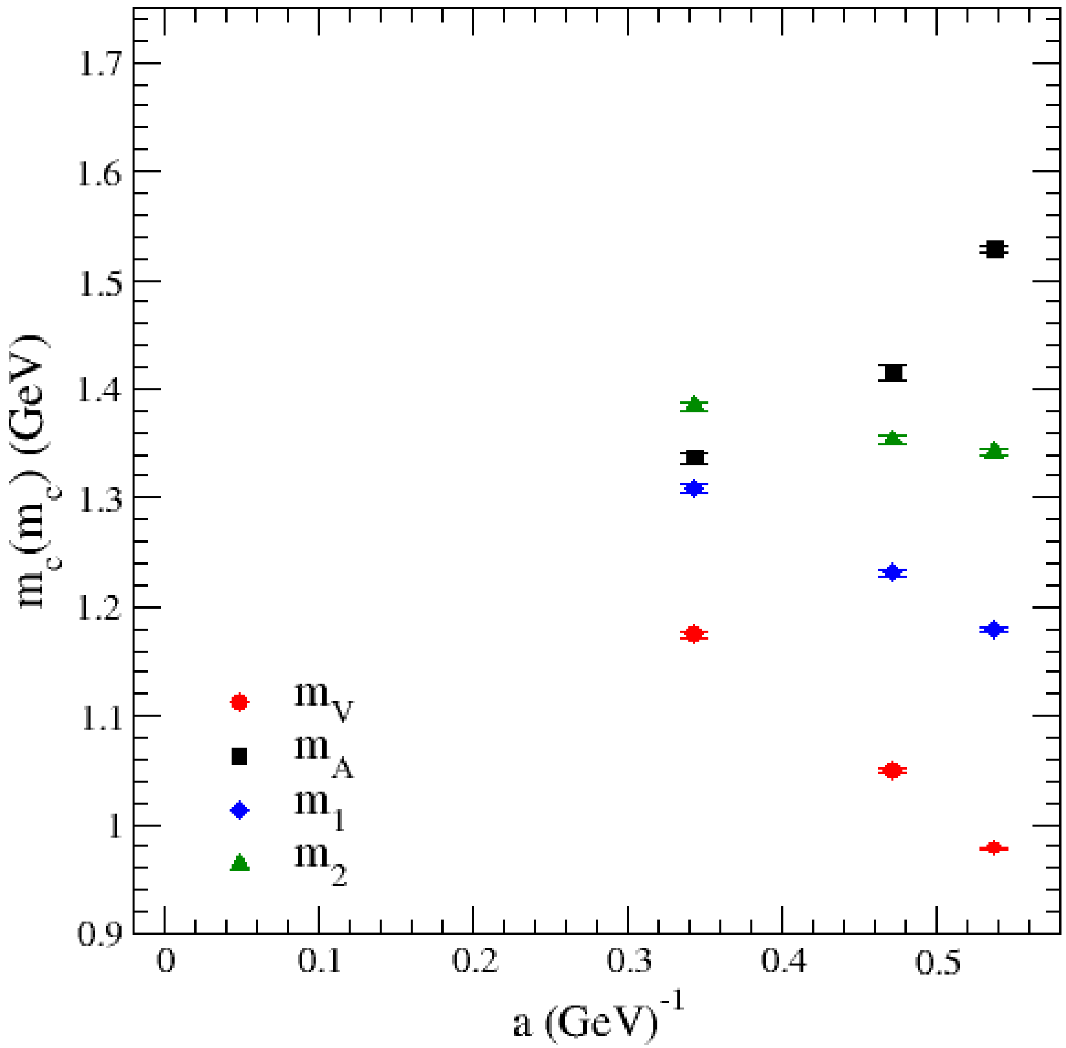
Quenched data

Lattice artefacts

O(a) and O(α_Sa)

But O(a^2) from data

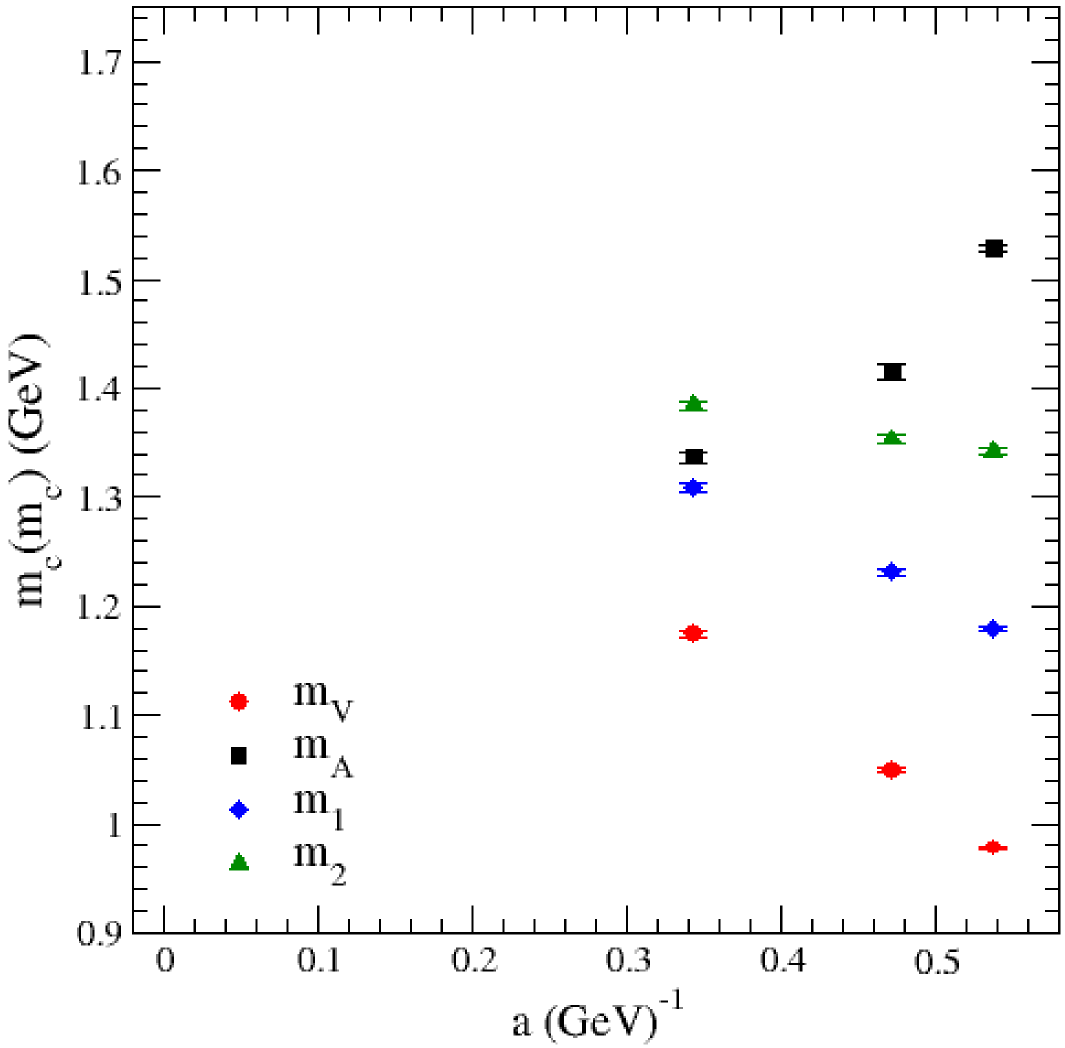
Not linear!



Continuum limit of "ALPHA" masses

Consistent def^{n} of quark masses should give same continuum limit (Rolf and Sint *JHEP 0212 (2002) 007*)

Simultaneous fit to m_A and m_V (quadratic)



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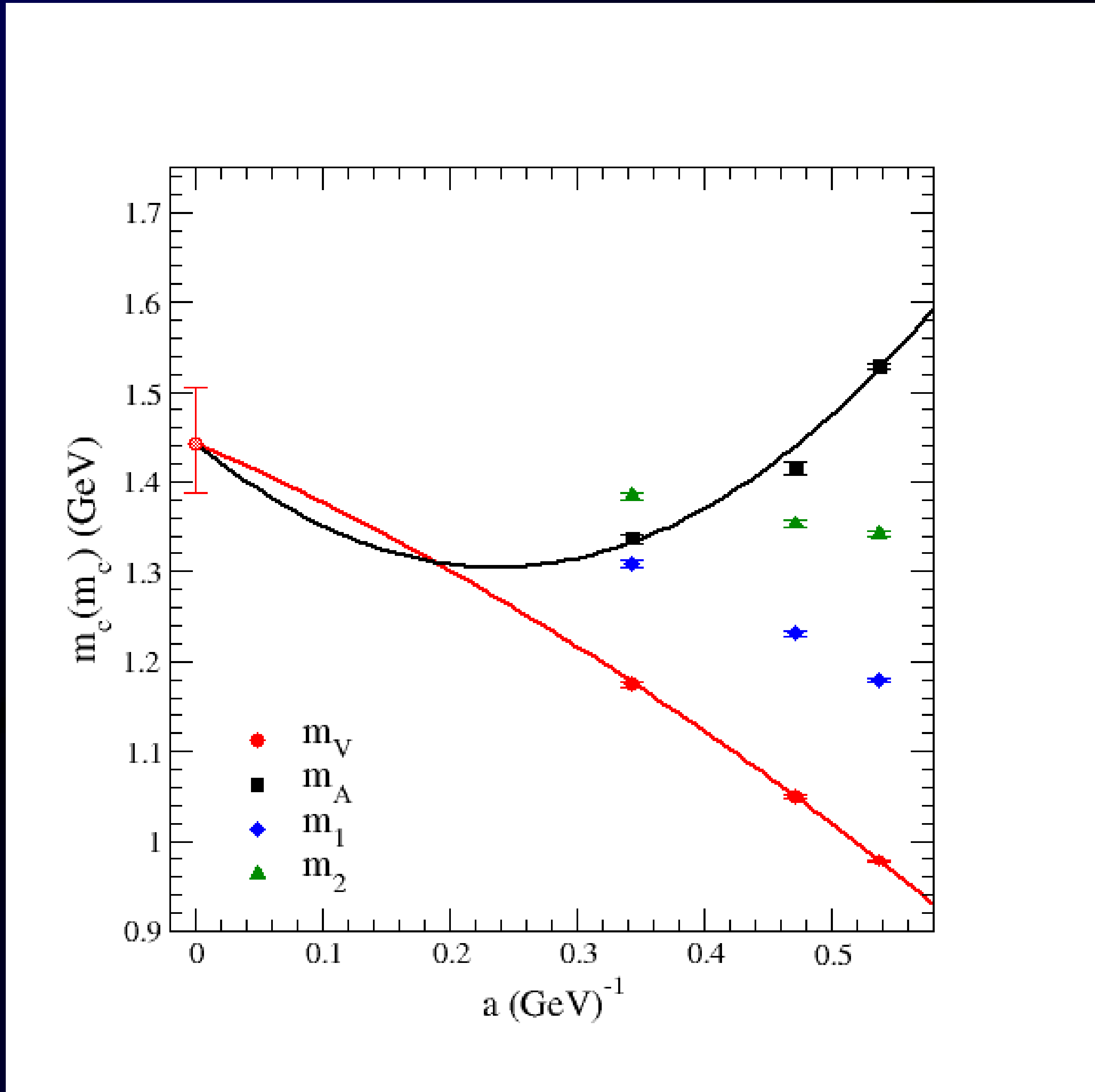
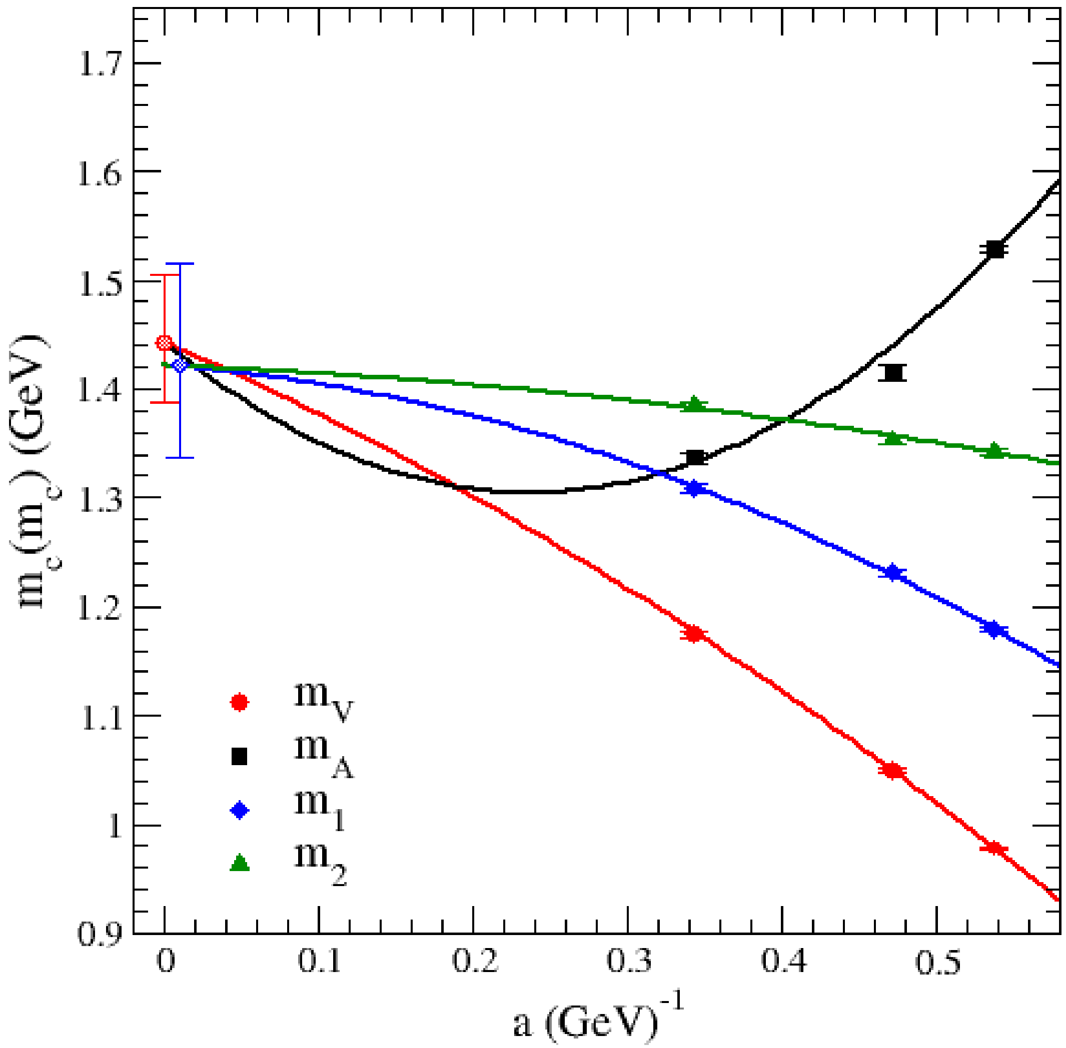


Continuum limit of FNAL masses

Simultaneous fit to fnal masses

Continuum limits agree!

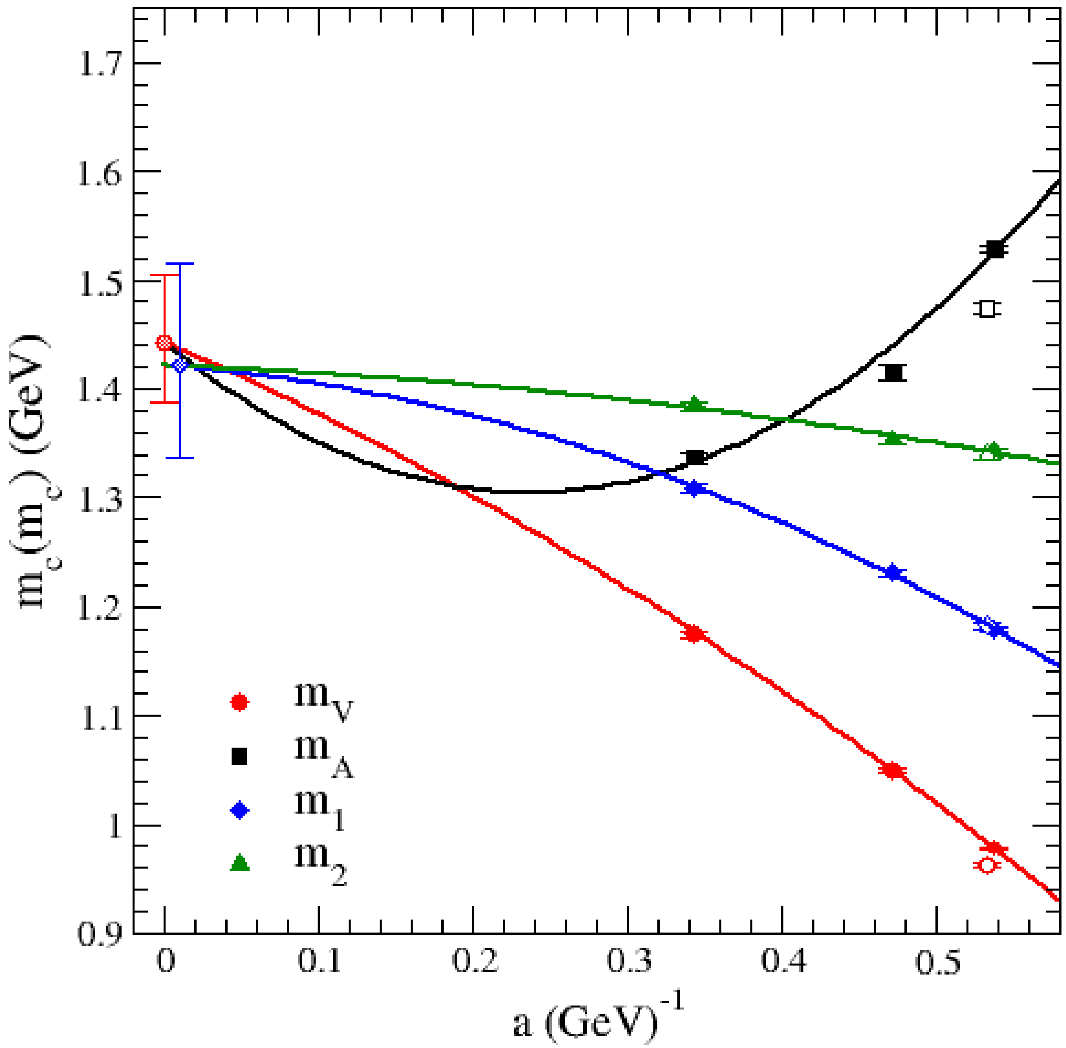


DF data at fixed lattice spacing

Open symbols show DF data

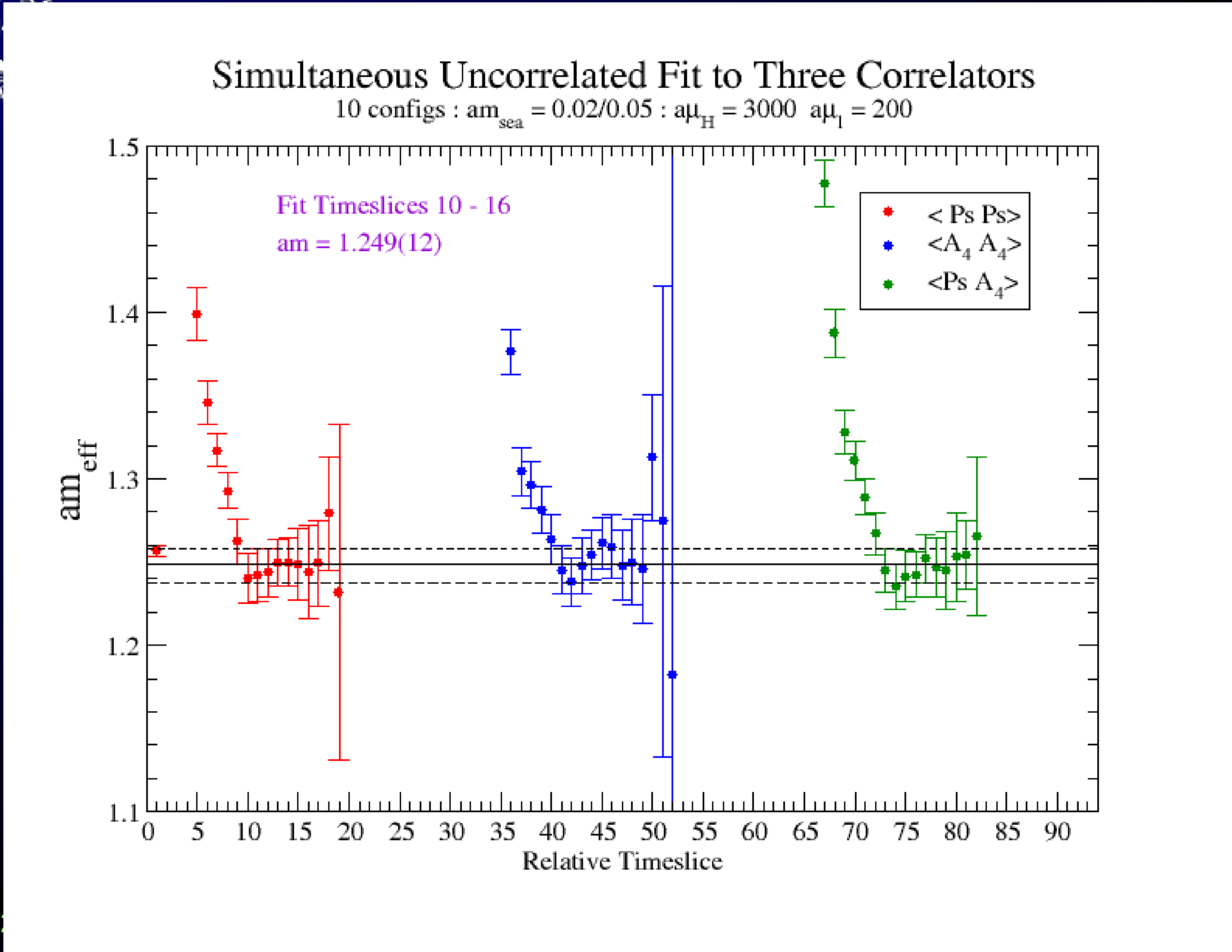
Alpha data quenched is too high at fixed lattice spacing. Lattice artefacts?

No effect for FNAL masses



fDs: Overlap on KS sea

- See talk by RDK for background
- a ~ 0.125fm → $am_c \sim 1$
  - Rather coarse lattice spacing
- Overlap lattice artefacts $O(am)^2$
  - → largest $(am)^2 \sim 3/4$
- Multi-mass solver
  - Charm quark propagator is free!



Simultaneous Uncorrelated Fit to Three Correlators
10 configs : am_{sea} = 0.02/0.05 : $a\mu_H$ = 3000 $a\mu_l$ = 200
Fit Timeslices 10 - 16
am = 1.249(12)
< Ps Ps>
<A_4 A_4>
<Ps A_4>
am_{eff}
1.1
1.2
1.3
1.4
1.5
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
Relative Timeslice

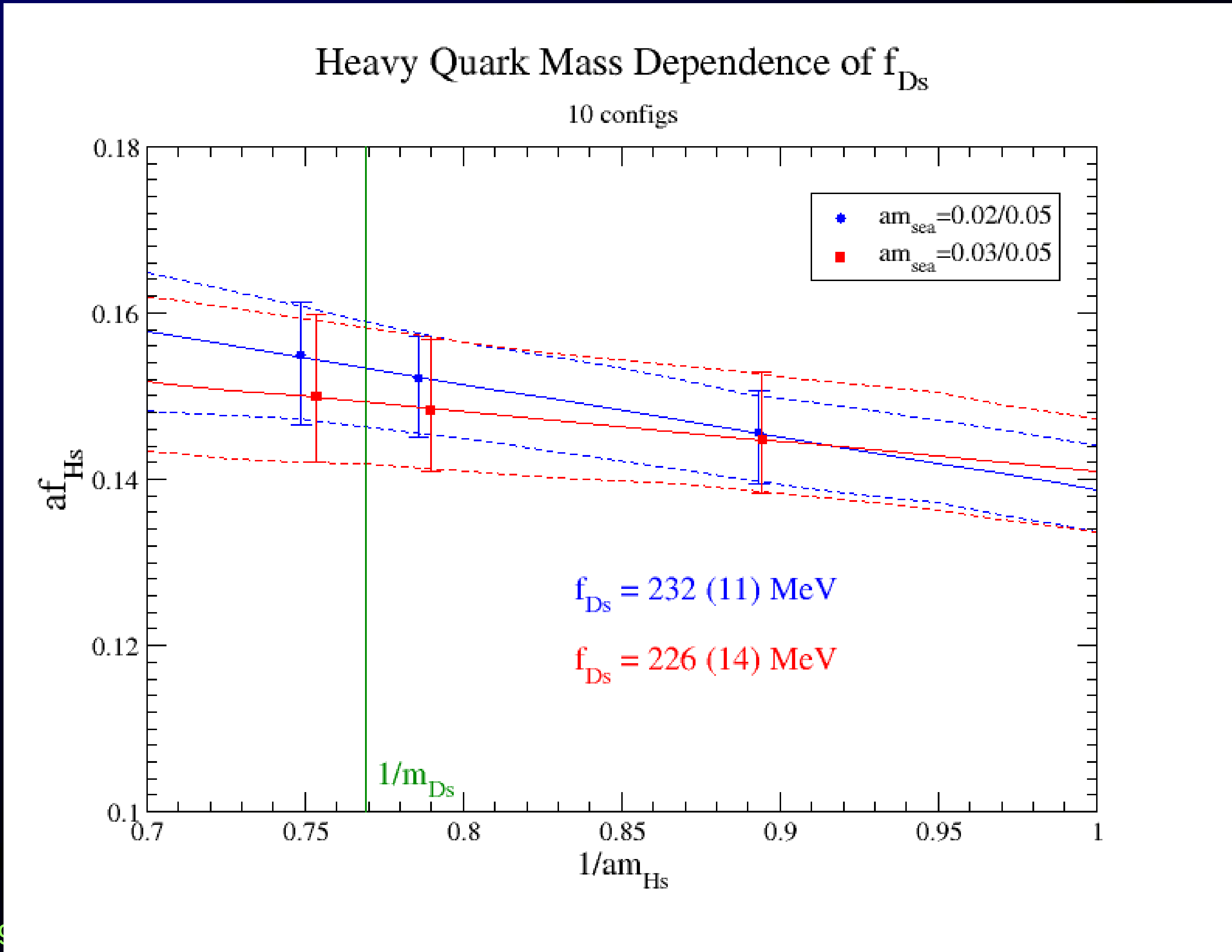
Extracting f_{Ds}

- From Axial Ward Identity
  - Chiral symmetry → only Z_A needed

$$Z_A \langle \partial_\mu A_\mu \mathcal{O} \rangle = 2 m_q \langle P \mathcal{O} \rangle$$

Can define Z_A in terms of C_{PP} and C_{A4P}
This cancels in the definition of f_{Ds}
Determine renormalised f_{Ds} from Ps correlator

Operating mixing is under control



Heavy Quark Mass Dependence of f_{Ds}
10 configs
am_{sea}=0.02/0.05
am_{sea}=0.03/0.05
f_{Ds} = 232 (11) MeV
f_{Ds} = 226 (14) MeV
$1/m_{Ds}$
af_{Hs}
$1/am_{Hs}$
0.18
0.16
0.14
0.12
0.1
0.7
0.75
0.8
0.85
0.9
0.95
1

Summary

- QCL: Ds mesons consistent with new charm states
- ALPHA and FNAL m_c same QCL
  - Stat and sys error large from coarse *a*
- Minimal evidence for sea quark effects
  - Heavy sea / fixed lattice spacing
- HQ from overlap very promising
- GW on GW all above, plus semileptonics