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Charm physics with physical light and strange quarks using domain wall fermions

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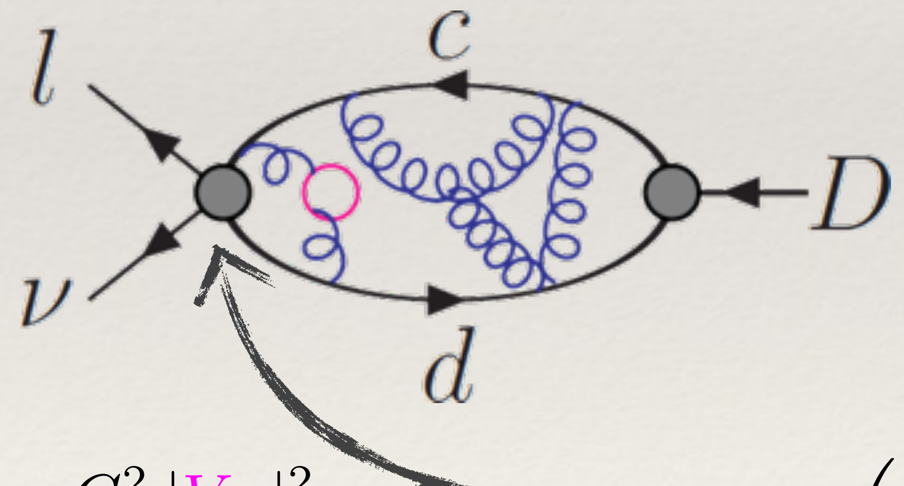
Charm phenomenology

test the Standard Model:

- SM provides correlation between processes
- experiment + theory → over constrain SM

$$\Gamma_{\text{exp.}} \stackrel{???}{=} V_{\text{CKM}}(\text{WEAK})(\text{EM})(\text{STRONG})$$

e.g tree level leptonic D decay



$$\mathcal{B}(D_{(s)} \to l\nu_l) = \frac{G_F^2 |V_{cq}|^2 \tau_{D_{(s)}}}{8\pi} f_{D_{(s)}}^2 m_l^2 m_{D_{(s)}} \left(1 - \frac{m_l^2}{m_{D_{(s)}}^2}\right)^2$$

Experimental measurement + theory prediction allows for extraction of CKM MEs

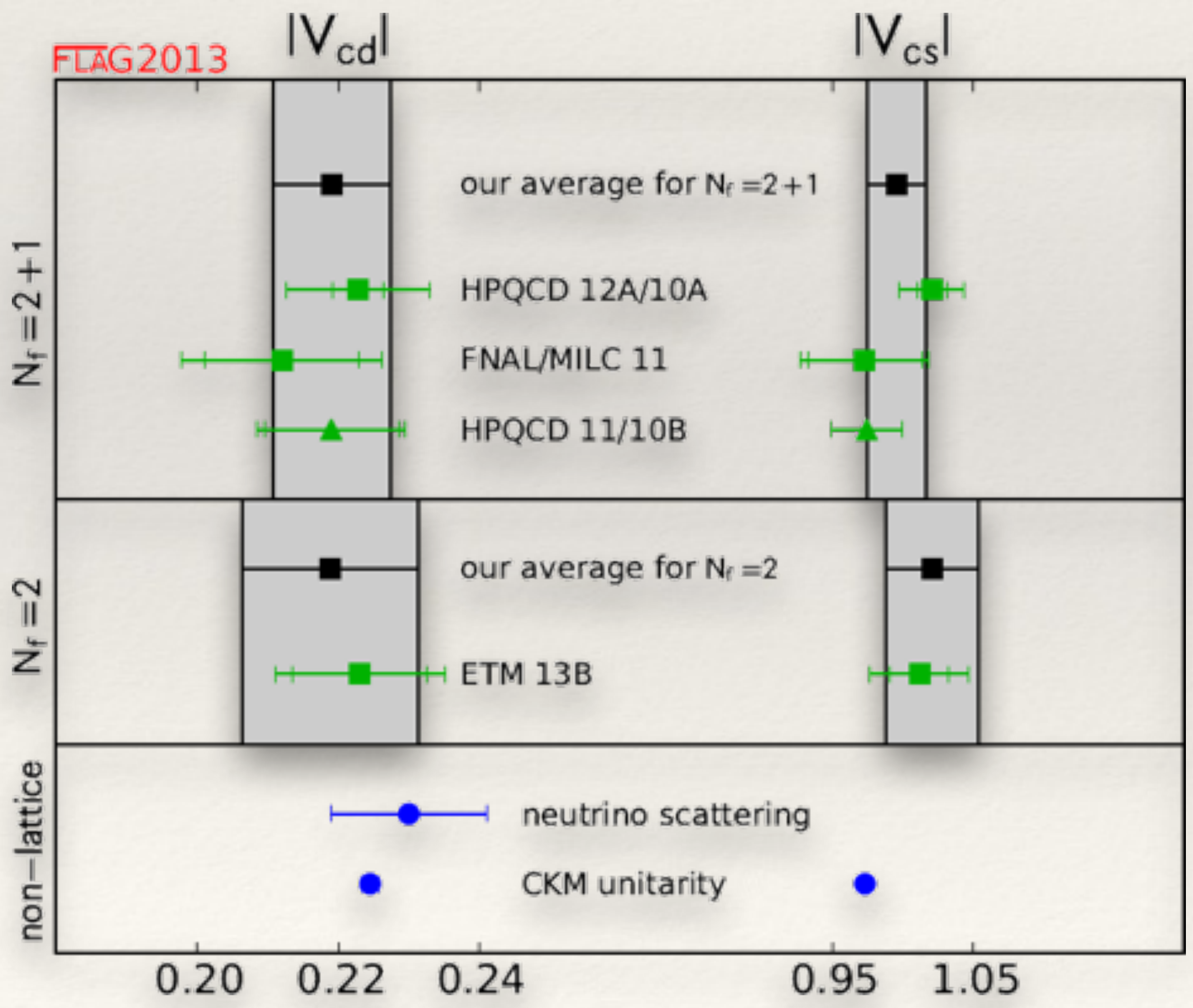
Motivation for (more) charm on the lattice

Lattice + experiment → CKM matrix elements: e.g. leptonic D and D_s decay

$$f_D|V_{cd}| = 46.40(1.98)\text{MeV}, \; f_{D_s}|V_{cs}| = 253.1(5.3)\text{MeV}$$ (Stone, Rosner in PDG)

similar for semi-leptonic decay…

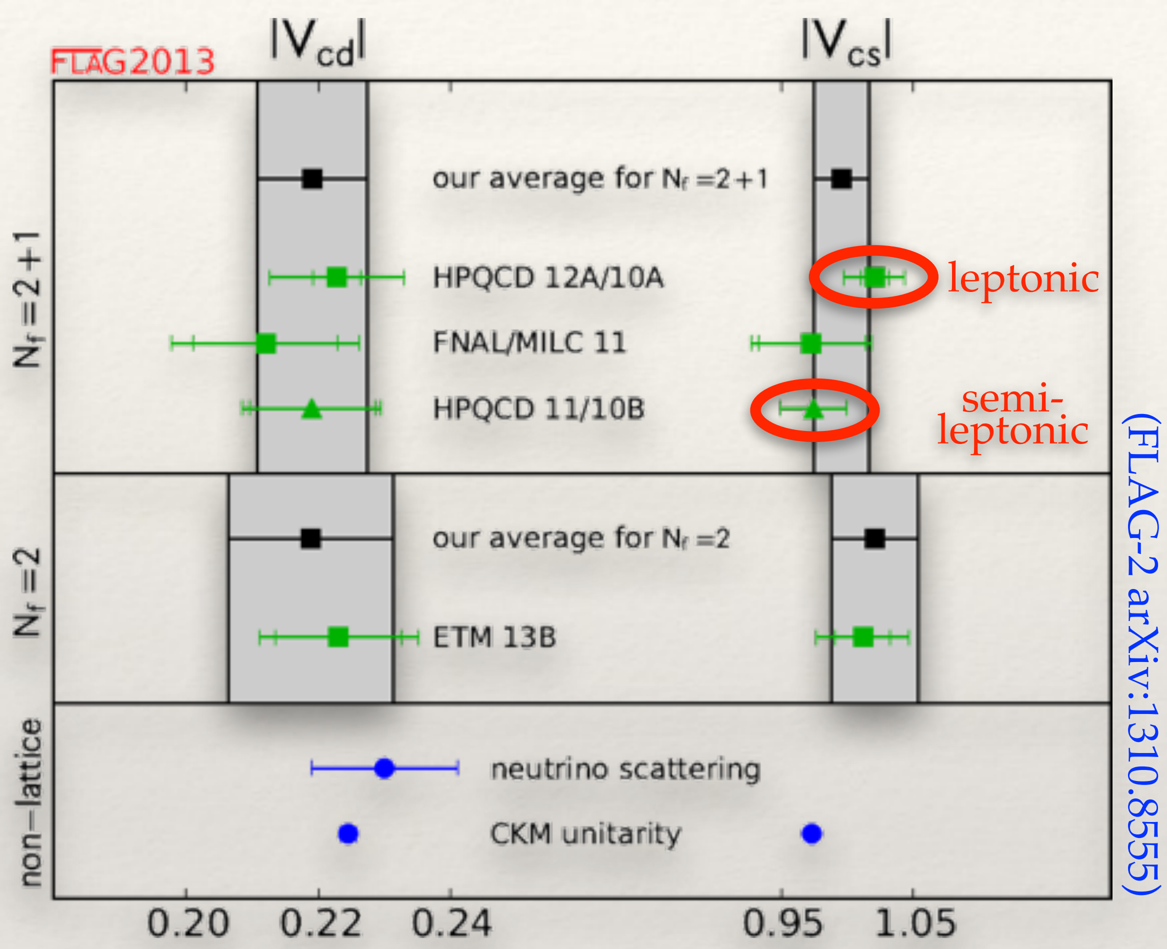
Status:



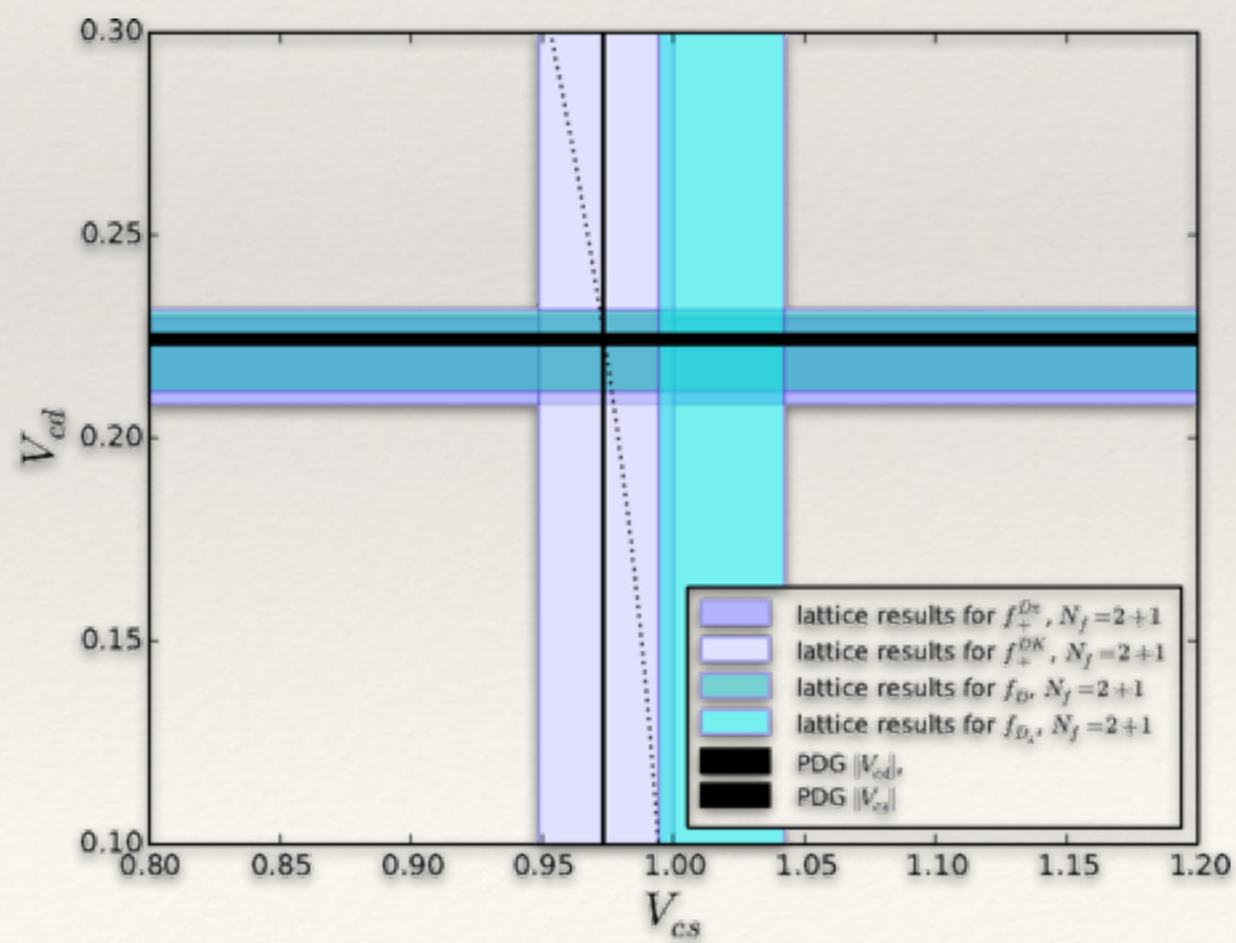
(FLAG-2 arXiv:1310.8555)

- "state-of-the-art results":
  - very few
  - staggered, twisted mass
- phenomenologically important
- tensions?

Motivation for (more) charm on the lattice



- $|V_{cs}|$ from leptonic decays is slightly larger than from semileptonic decays
- $|V_{cs}|$ from leptonic decays is at tension with CKM-unitarity by 1.9σ (→HPQCD)



Our strategy - setup

- Domain wall fermions as light **and** charm quark discretisation
  - automatically $O(a)$-improved
  - good chiral properties

- use RBC/UKQCD $N_f = 2+1$ DWF ensembles
  - a^{-1}=1.7, 2.3 GeV readily available
  - m_π physical ensembles in large volumes

- complementary to ongoing RBC/UKQCD B-physics program

see talks by Witzel and Ishikawa in session 5G, Wednesday 9:20 ff

Our strategy

Edinburgh-Soton-KEK:
talks by T. Tsang and Y.-G. Cho

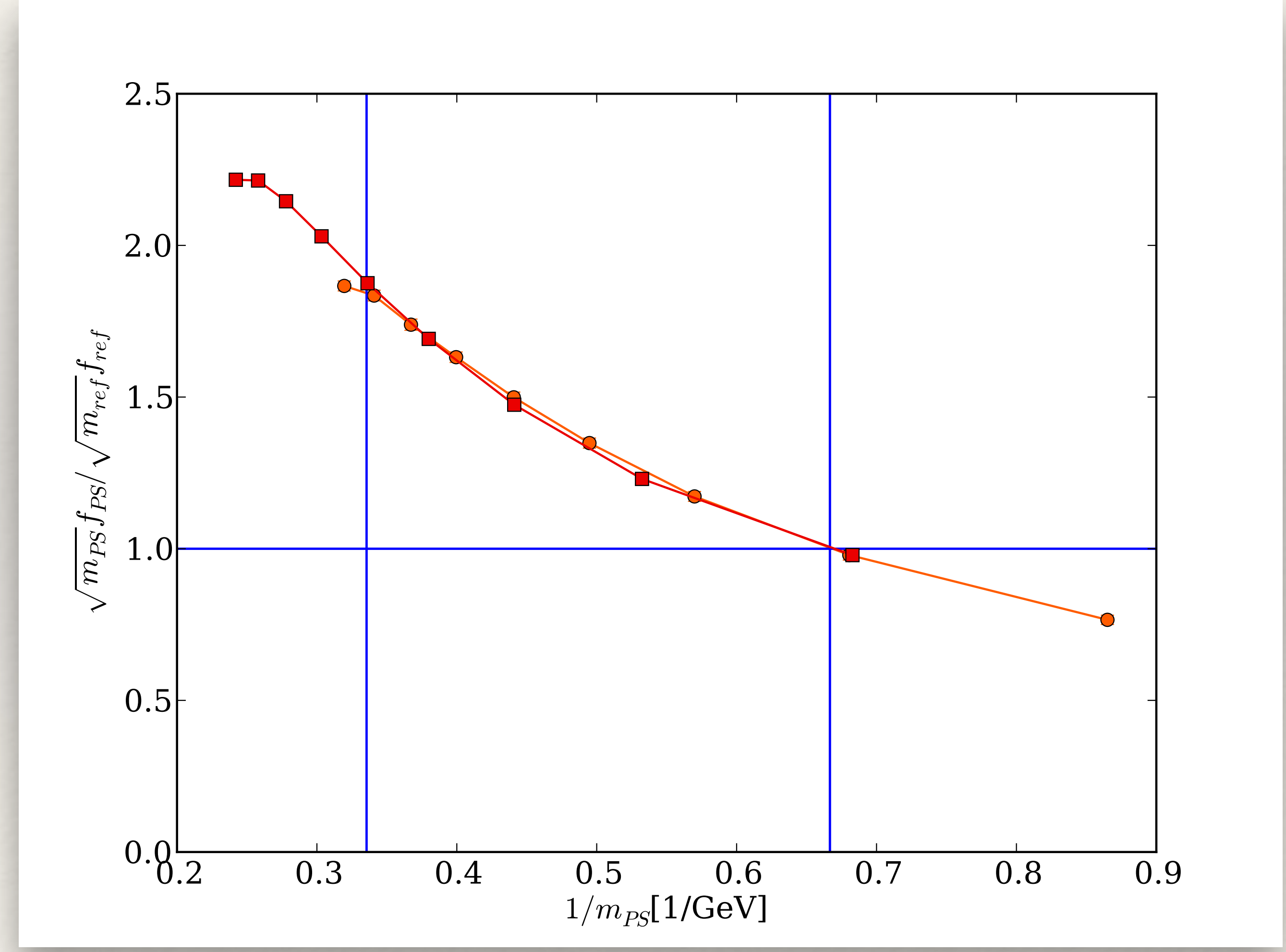
- **Quenched pilot study**
  - $a^{-1} \sim 2, 3, 4, 6$ GeV → scaling study
  - small volume L=1.6fm
  - parameter tuning
  - map out range of applicability
  - qualitative picture should apply also to dynamical case

- **$N_f = 2+1$ DWF charm project (RBC/UKQCD)**
  - strategy: simulate several '*charm*' masses
  - inter/extrapolate to charm (and beyond?)
  - heavy-light, heavy-strange, heavy-heavy
  - leptonic/semileptonic decays, mixing (BSM), *g*-2, …

Quenched DWF pilot study

Edinburgh-Soton-KEK:
talks by T. Tsang and Y.-G. Cho

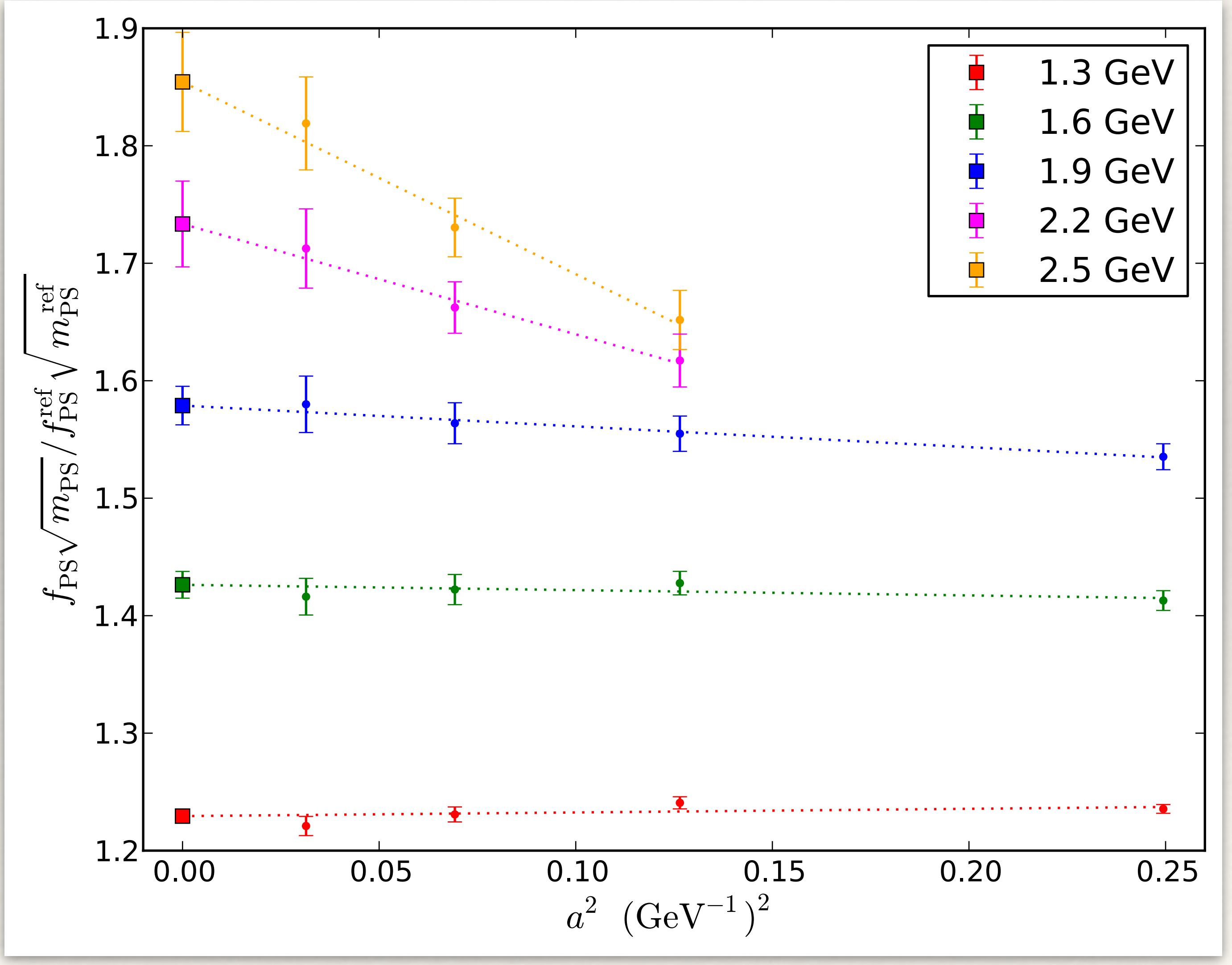
- small volume L=1.6fm
- $a^{-1} \sim 2, 3, 4, 6$ GeV
- DWF maintain its properties up to $am_q \lesssim 0.45$
- parameter tuning (M_5, L_s, largest am_h,…)



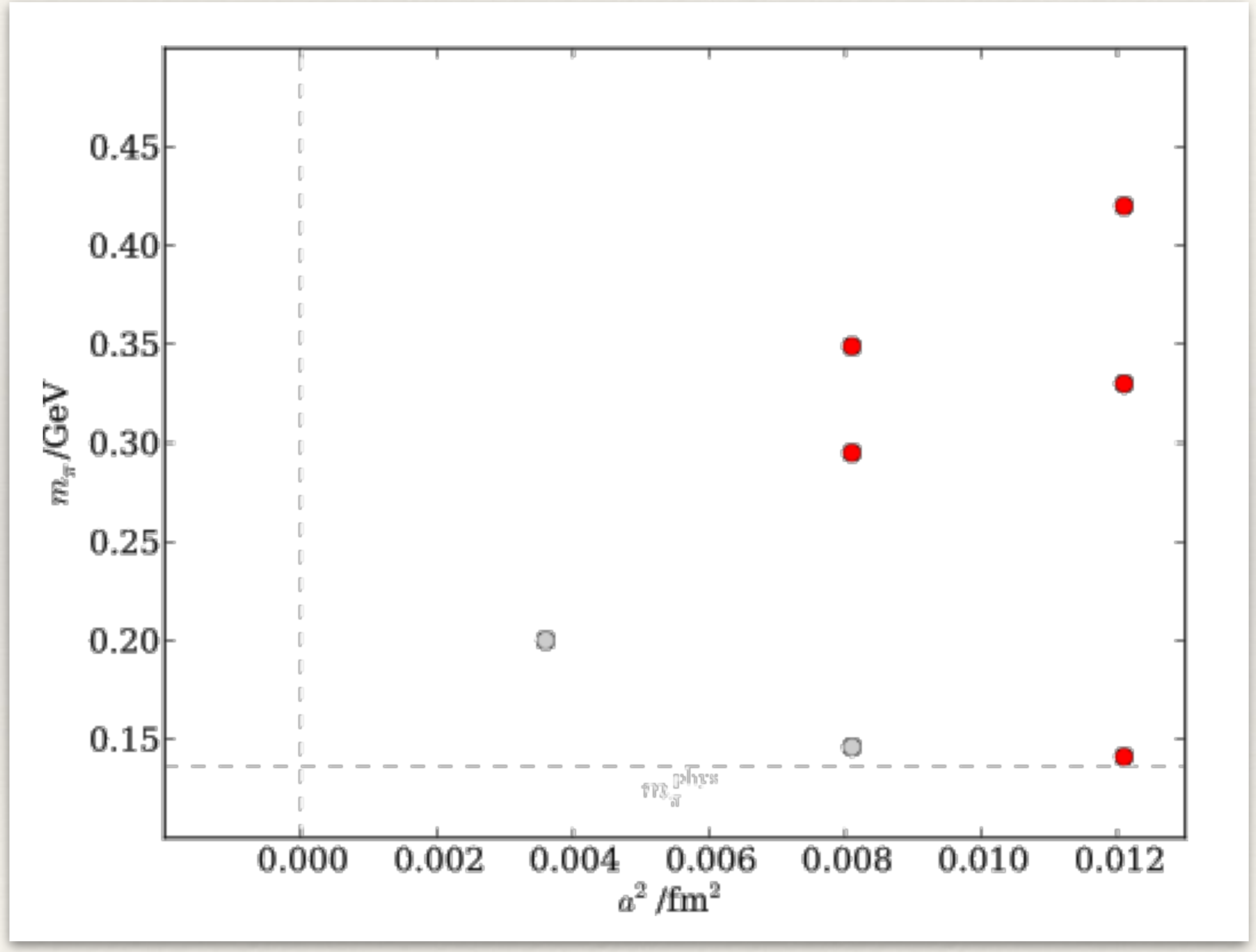
Quenched DWF pilot study

- small volume L=1.6fm
- $a^{-1} \sim 2, 3, 4, 6$ GeV
- DWF maintain its properties up to $am_q \lesssim 0.45$
- parameter tuning (M_5, L_s, largest am_h,…)
- beautiful a^2-scaling
- properties expected to carry over to dynamical case

Edinburgh-Soton-KEK:
talks by T. Tsang and Y.-G. Cho



Dynamical case: simulation parameters



RBC/UKQCD DWF $N_{f=2+1}$ ensembles:
(Shamir/Moebius + Iwasaki)

L	a	m
48	1.7	physical
24	1.7	330
24	1.7	420
32	2.3	295
32	2.3	350
64	2.3	physical
	3.0	

Dynamical case: simulation parameters

- add Moebius `*charm quarks*` with am_h in the range 0.2-0.45
  (Brower, Neff, Orginos, arXiv:1206.5214, P. Boyle's talk on Monday)
- limited to below charm on 1.7GeV lattices → extrapolation in m_h
- optimal domain wall height from quenched run: M_5=1.6
- 48 random Z_2 noise wall sources per config (one-end trick)
- monitor heavy quark CG-convergence via time-slice residual

$$r(t) = \frac{|A\psi - \eta|_t}{|\psi|_t}$$

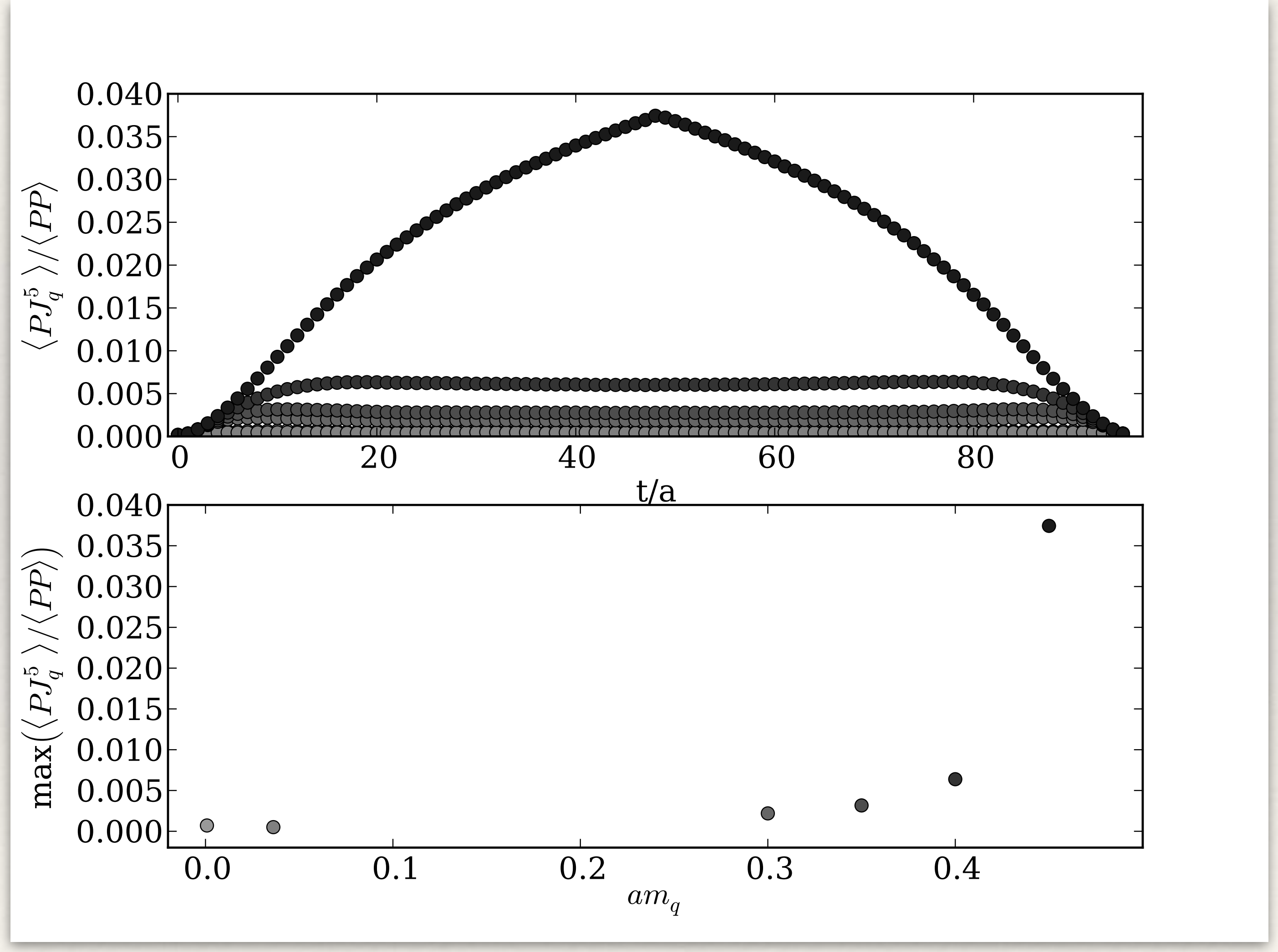
Does DWF mechanism work for charm?

Observation in quenched study:
nice properties of DWF break down for too heavy quark masses ($am_q \approx 0.4$-0.5)
(Jansen, Schmaltz Phys.Lett. B296 (1992) 374-378, T. Tsang's talk)

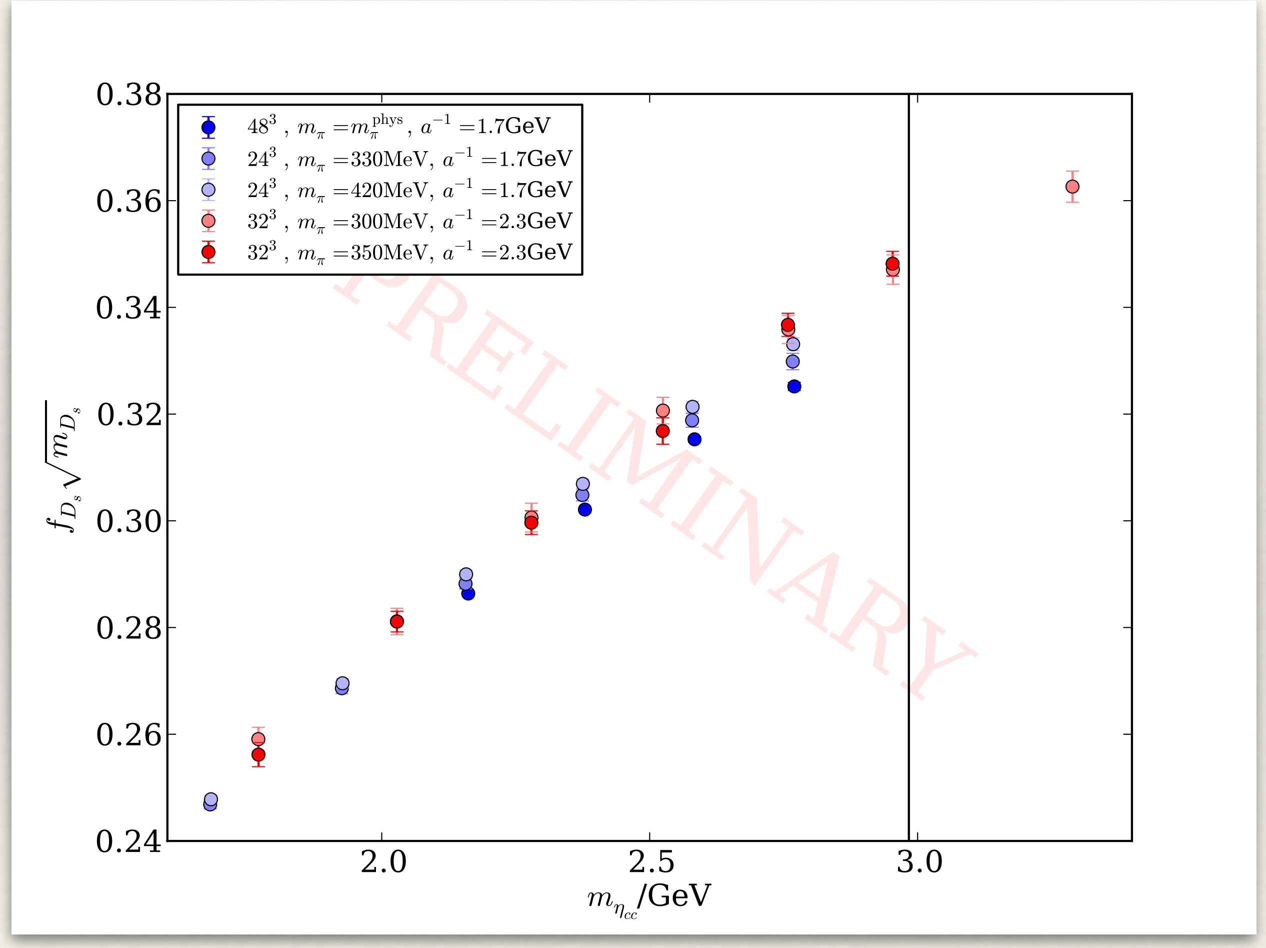
monitor Axial Ward Identity:

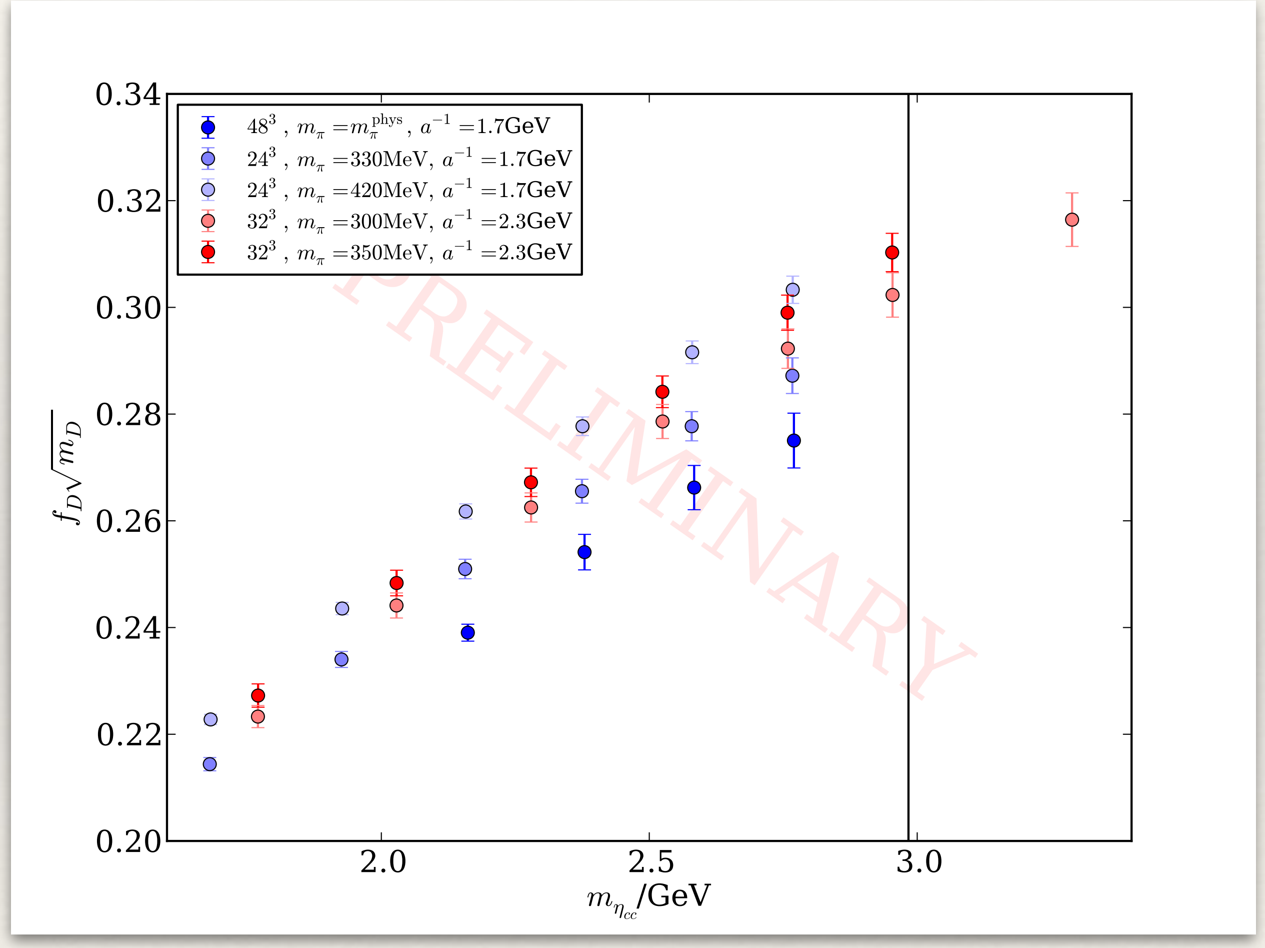
$$\begin{aligned} \langle \partial_\mu \mathcal{A}_\mu(x) P(0) \rangle &= 2m \langle P(x) P(0) \rangle \\ &+ 2 \langle J_{5q}(x) P(0) \rangle \end{aligned}$$

$$m_{\rm res} \equiv \frac{\left\langle \sum_x J_{5q}(x) P(0) \right\rangle}{\left\langle \sum_x P(x) P(0) \right\rangle}$$



data so far


0.38
0.36
0.34
0.32
0.30
0.28
0.26
0.24
2.0
2.5
3.0
48^3 , $m_\pi = m_\pi^{\text{phys}}$, a^{-1} =1.7GeV
24^3 , m_π =330MeV, a^{-1} =1.7GeV
24^3 , m_π =420MeV, a^{-1} =1.7GeV
32^3 , m_π =300MeV, a^{-1} =2.3GeV
32^3 , m_π =350MeV, a^{-1} =2.3GeV
PRELIMINARY
$f_{D_s}\sqrt{m_{D_s}}$
$m_{\eta_{cc}}$/GeV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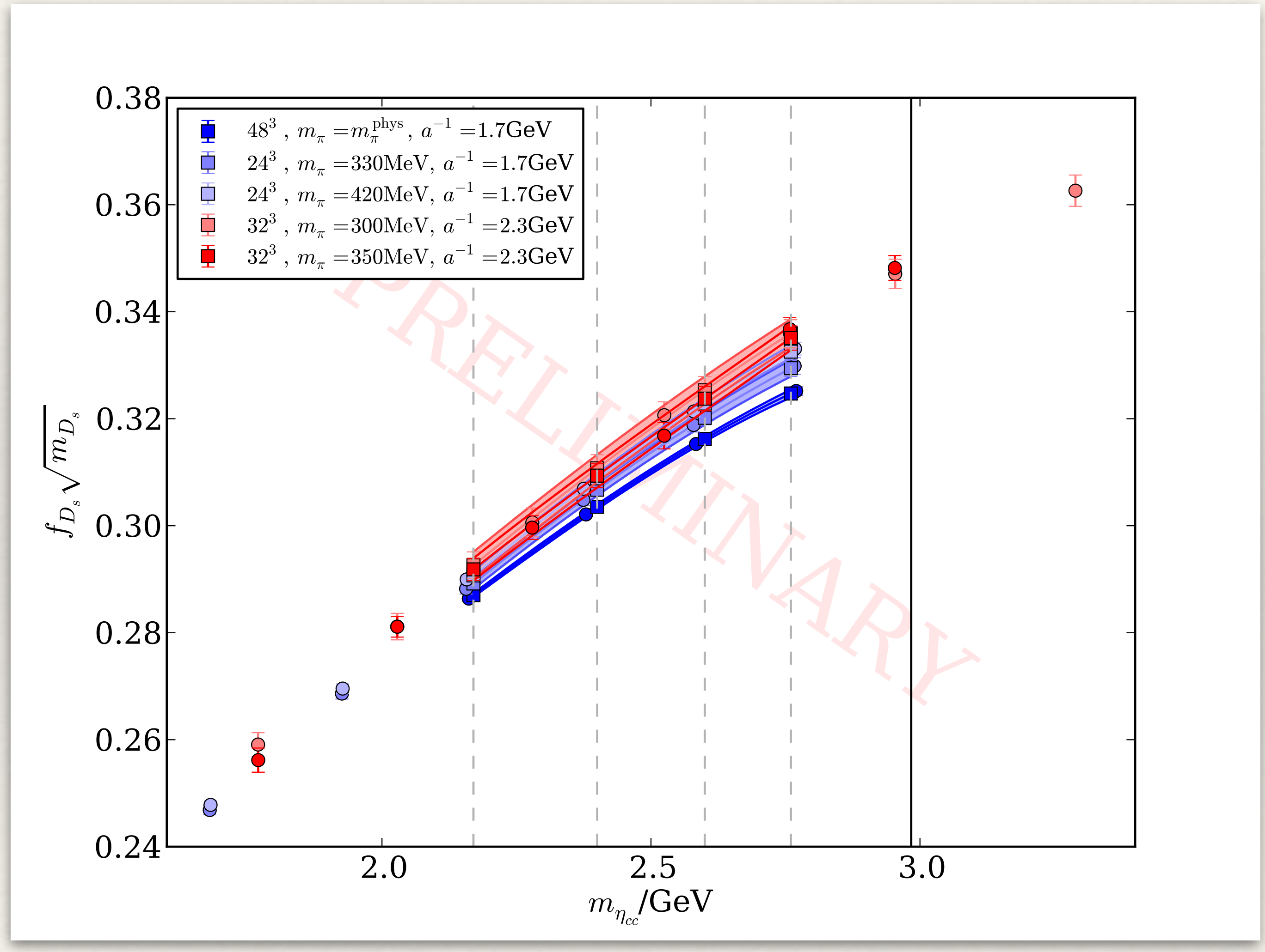
32^3 , m_π =350MeV, a^{-1} =2.3GeV
PRELIMINARY
$f_D\sqrt{m_D}$
$m_{\eta_{cc}}$/GeV

Analysis

1. interpolate observables on all ensembles to reference heavy quark masses
2. interpolate to the physical light quark mass
3. extrapolate to the continuum limit
4. extrapolate results in the continuum limit to the physical charm quark point

Results interpolated to common η_{cc}-masses

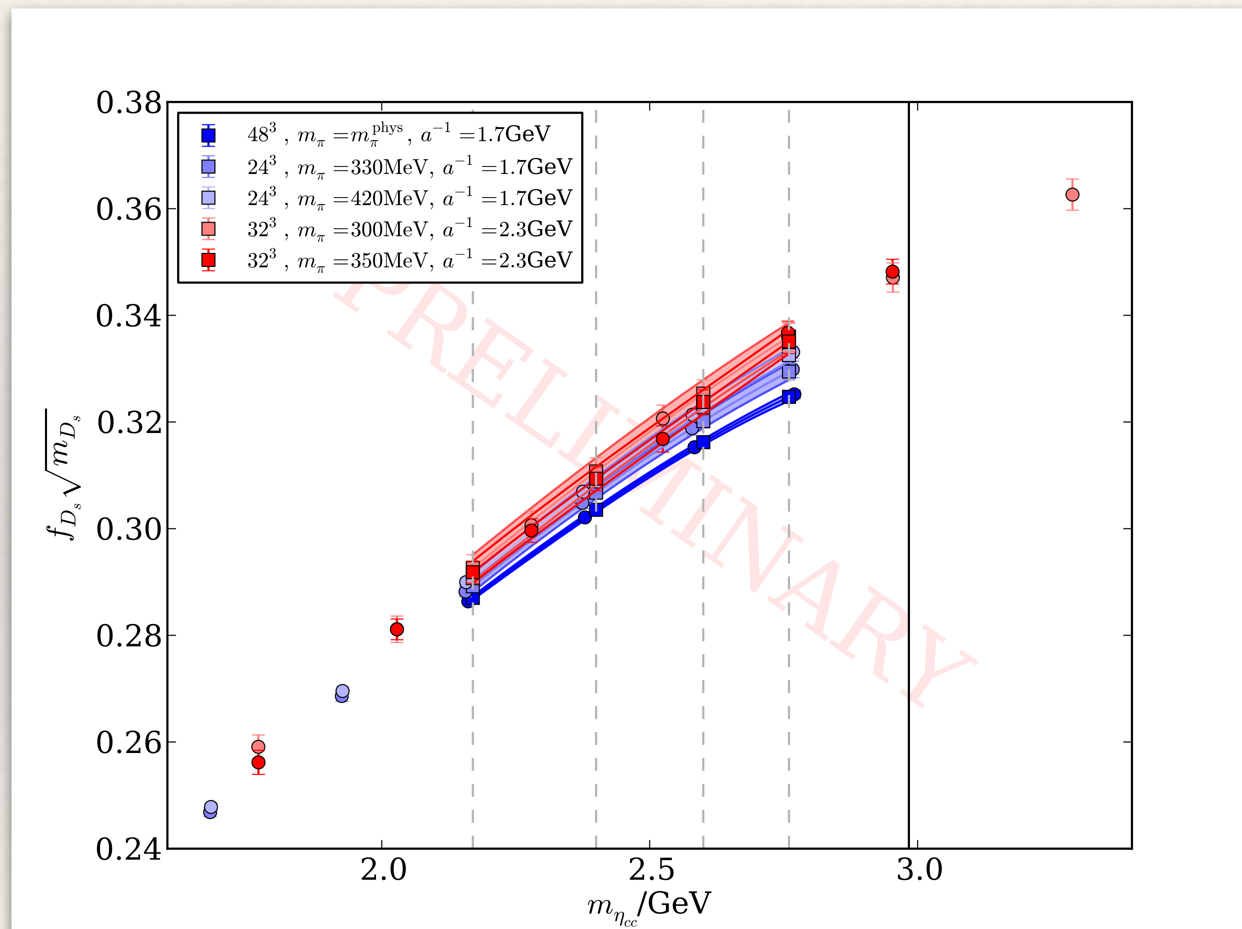


1st STEP:
interpolation to common η_{cc}-masses

- $m_{\eta cc} \approx 2.2, 2.4, 2.6, 2.8$GeV
- polynomial ansatz, data benign
- interpolation points mostly close to data points
- solid vertical line: charm

Results interpolated to common heavy quark masses

D_s



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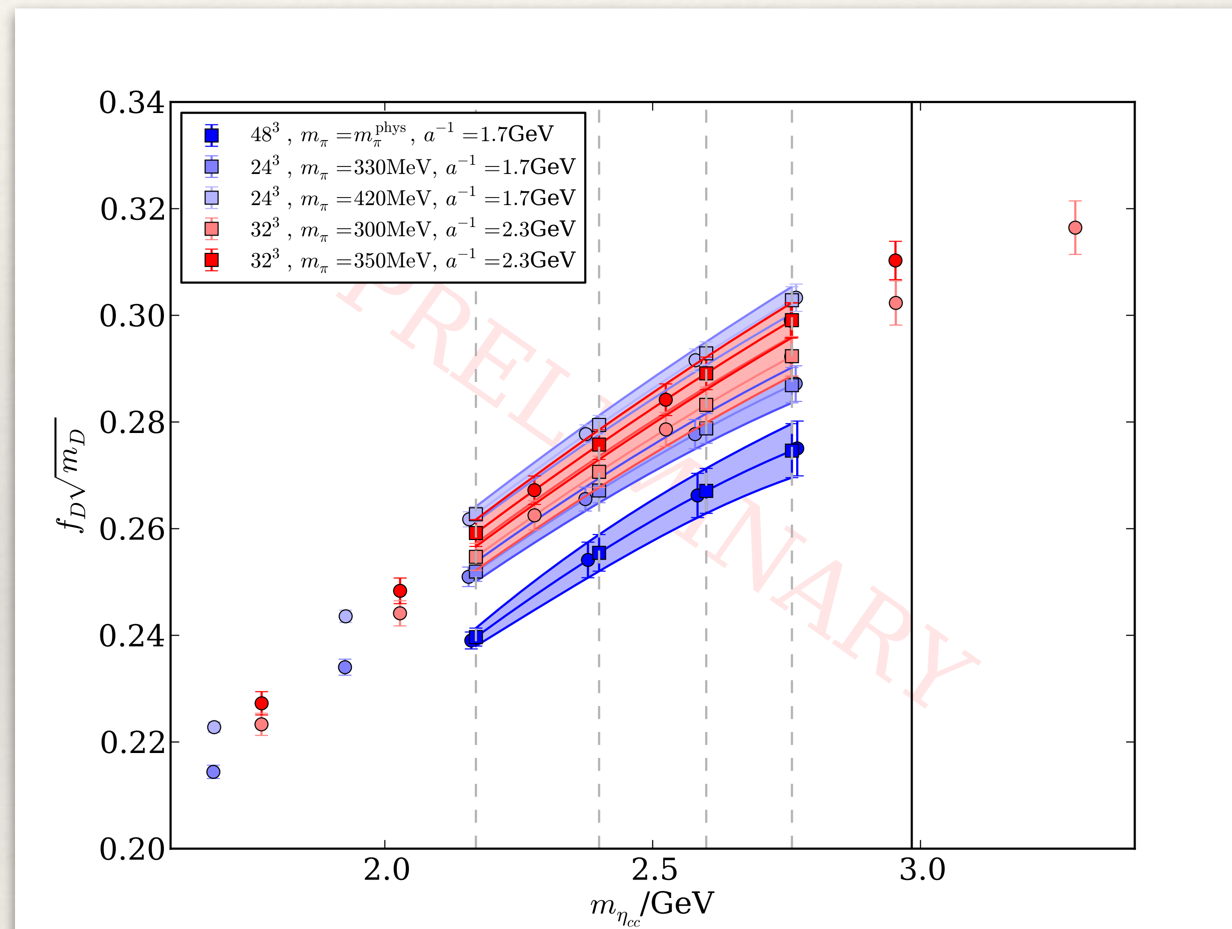
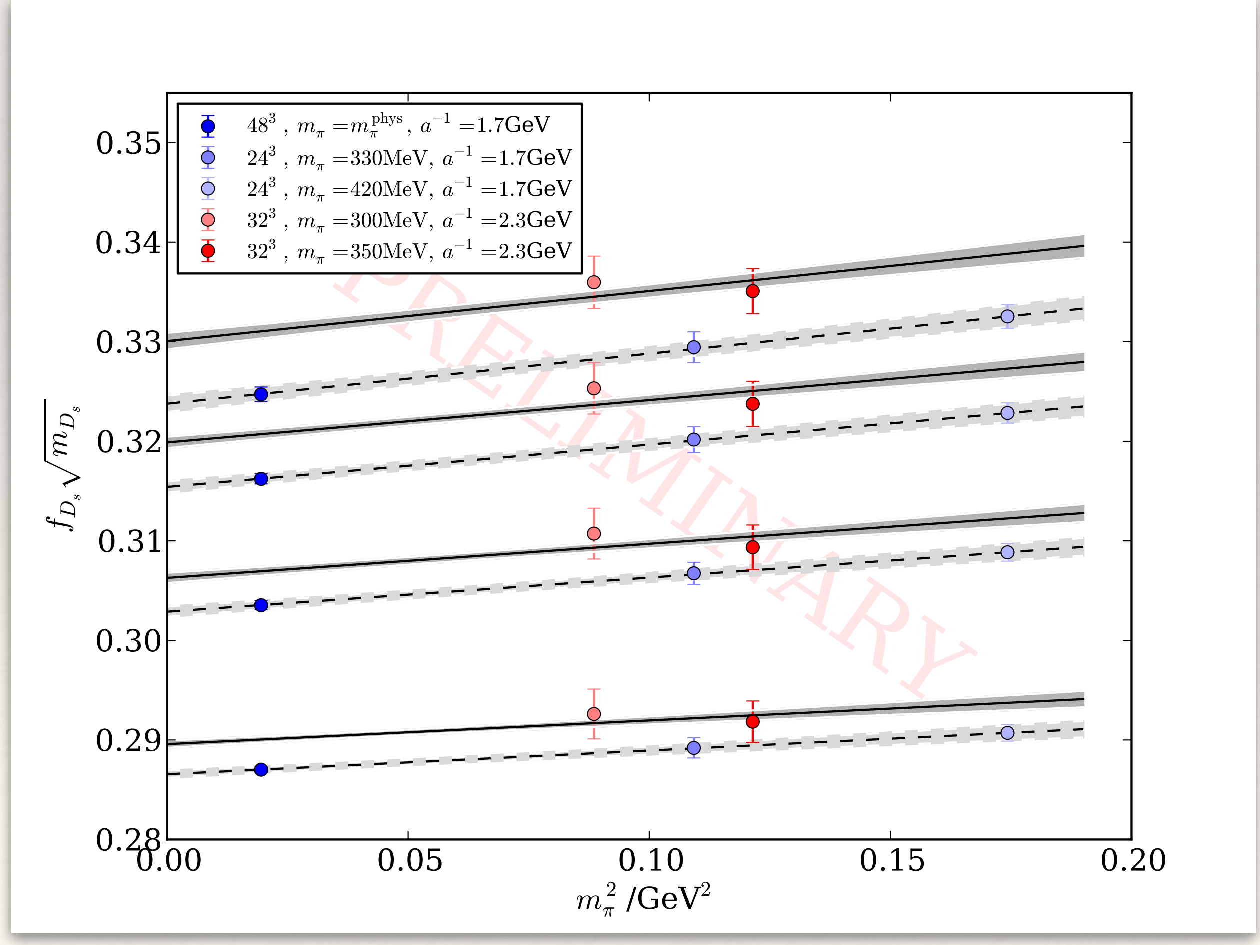


Light quark mass dependence

2nd STEP: light quark mass *interpolation*

- Data on 1.7GeV covers m_π down to physical point - **NO curvature seen!!**
  → linear interpolation to physical point
- outlook: physical point on 2.3GeV lattice coming soon

D_s



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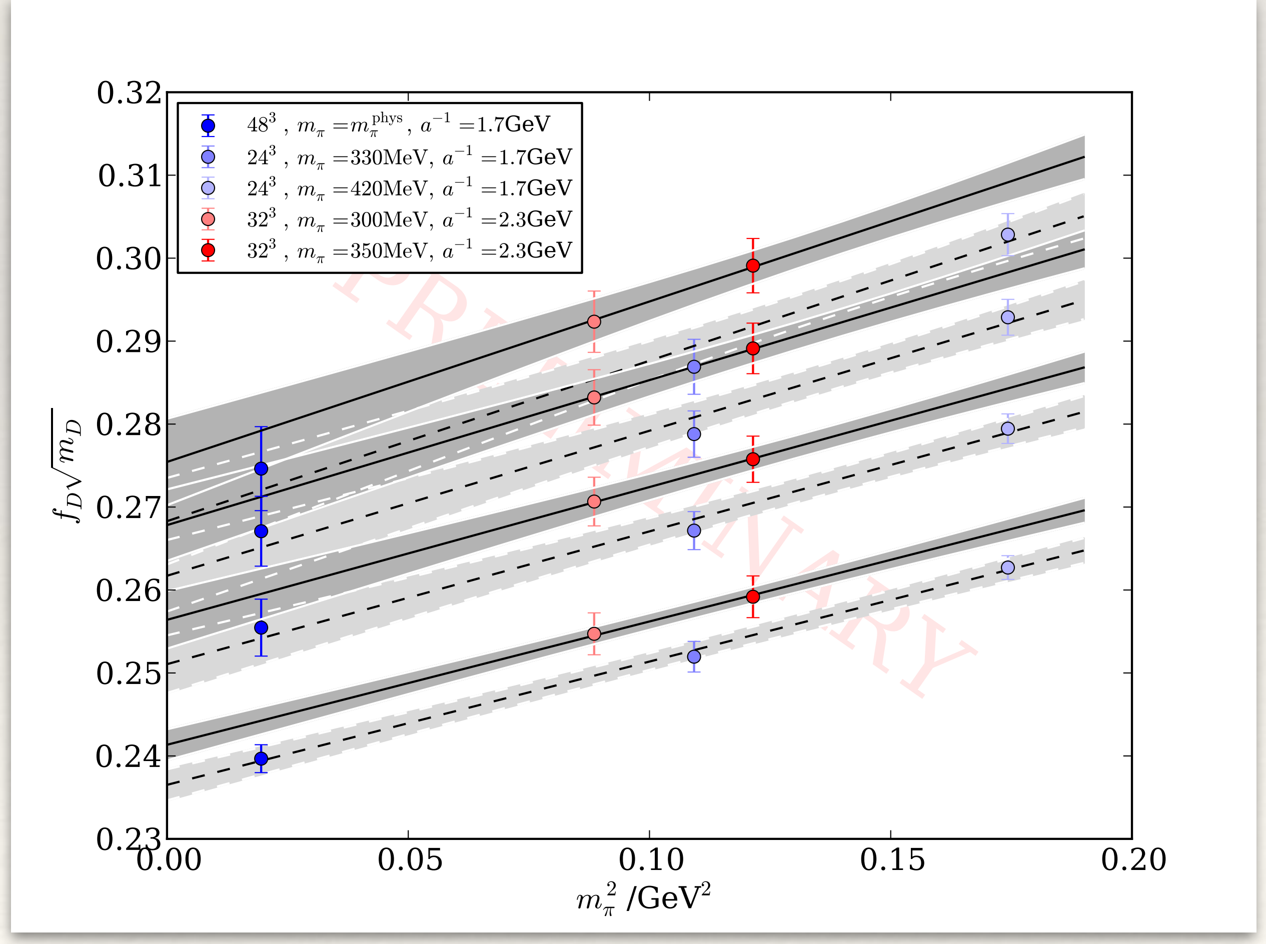
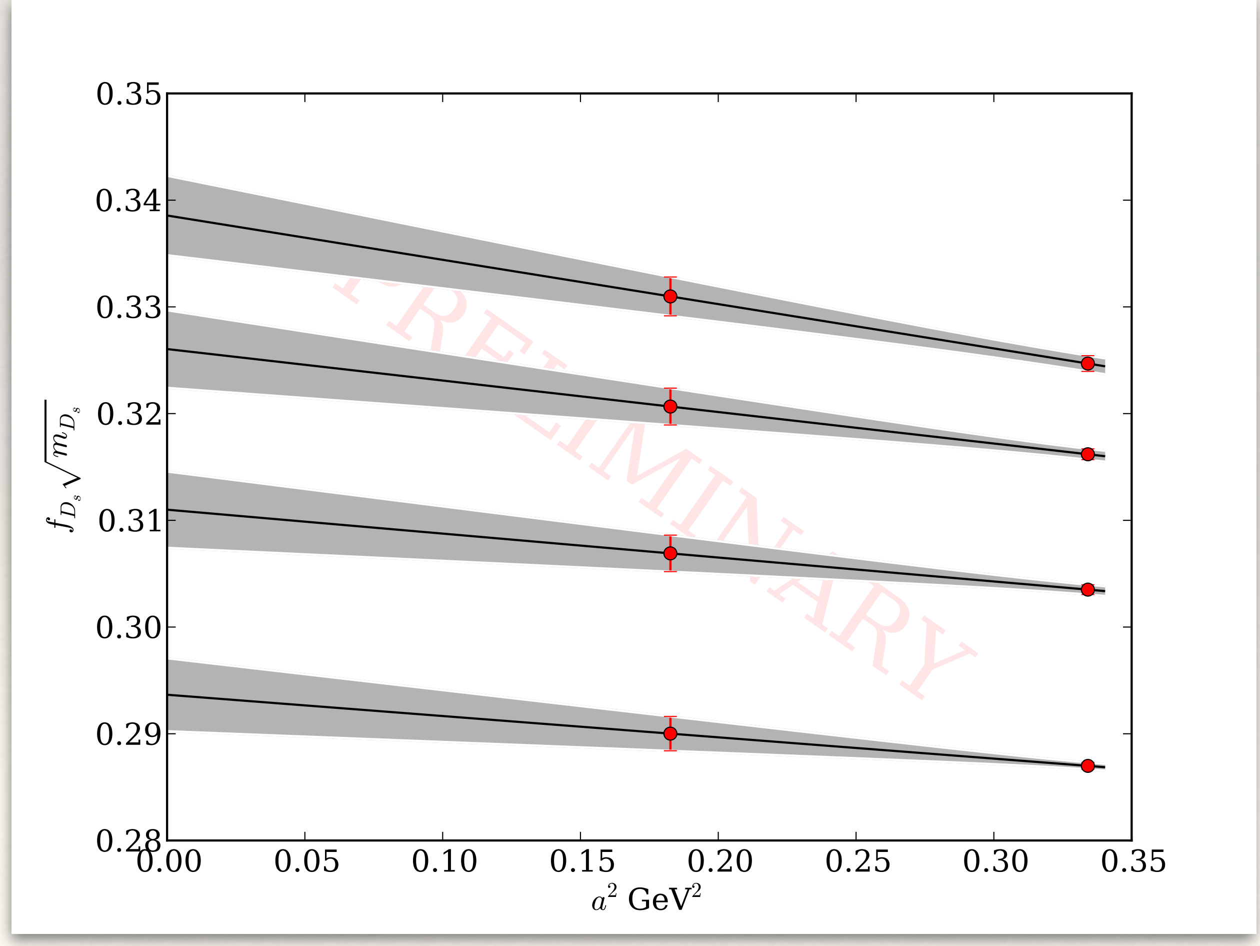


Continuum limit

3rd STEP: continuum limit:

- so far only 1.7 and 2.3GeV and therefore very preliminary
- quenched study suggests linear dependence on a^2
- but clearly **need 3rd lattice spacing for reliable predictions**
  → we are working on it

D_s



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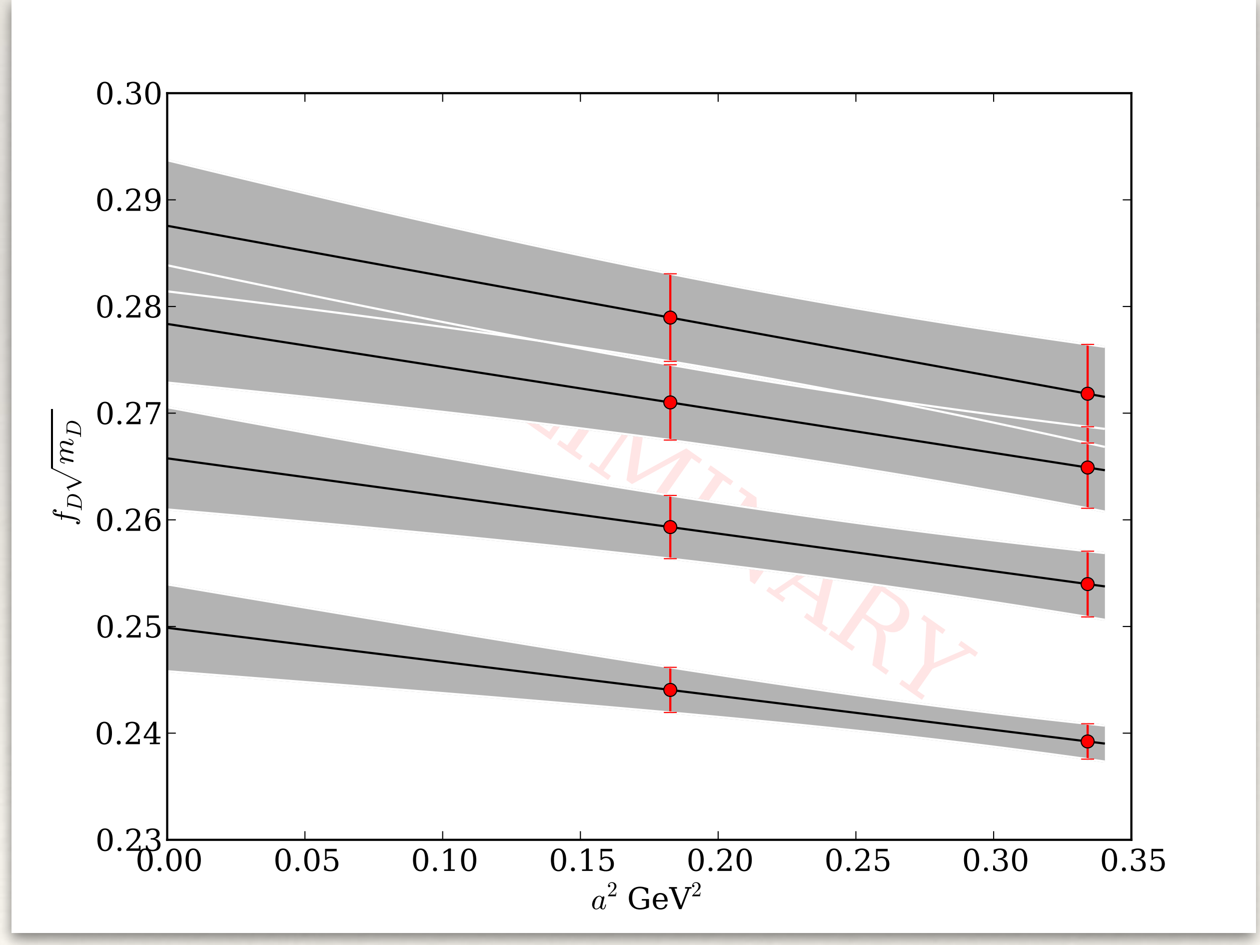
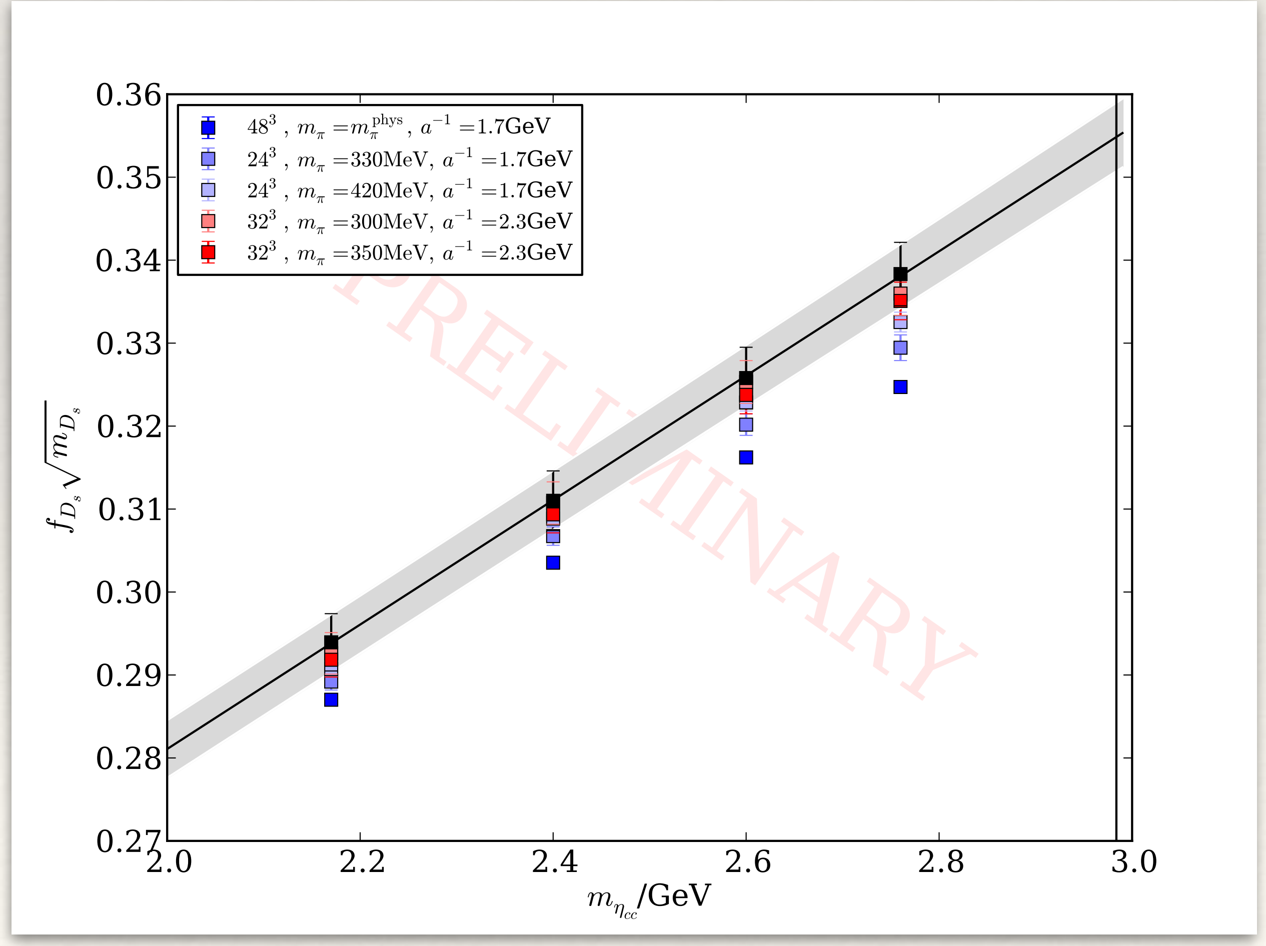


Extrapolation to charm

3rd STEP: extrapolation to charm

- looks quite linear but will study systematics
- already at this early stage astonishingly good statistical precision

D_s



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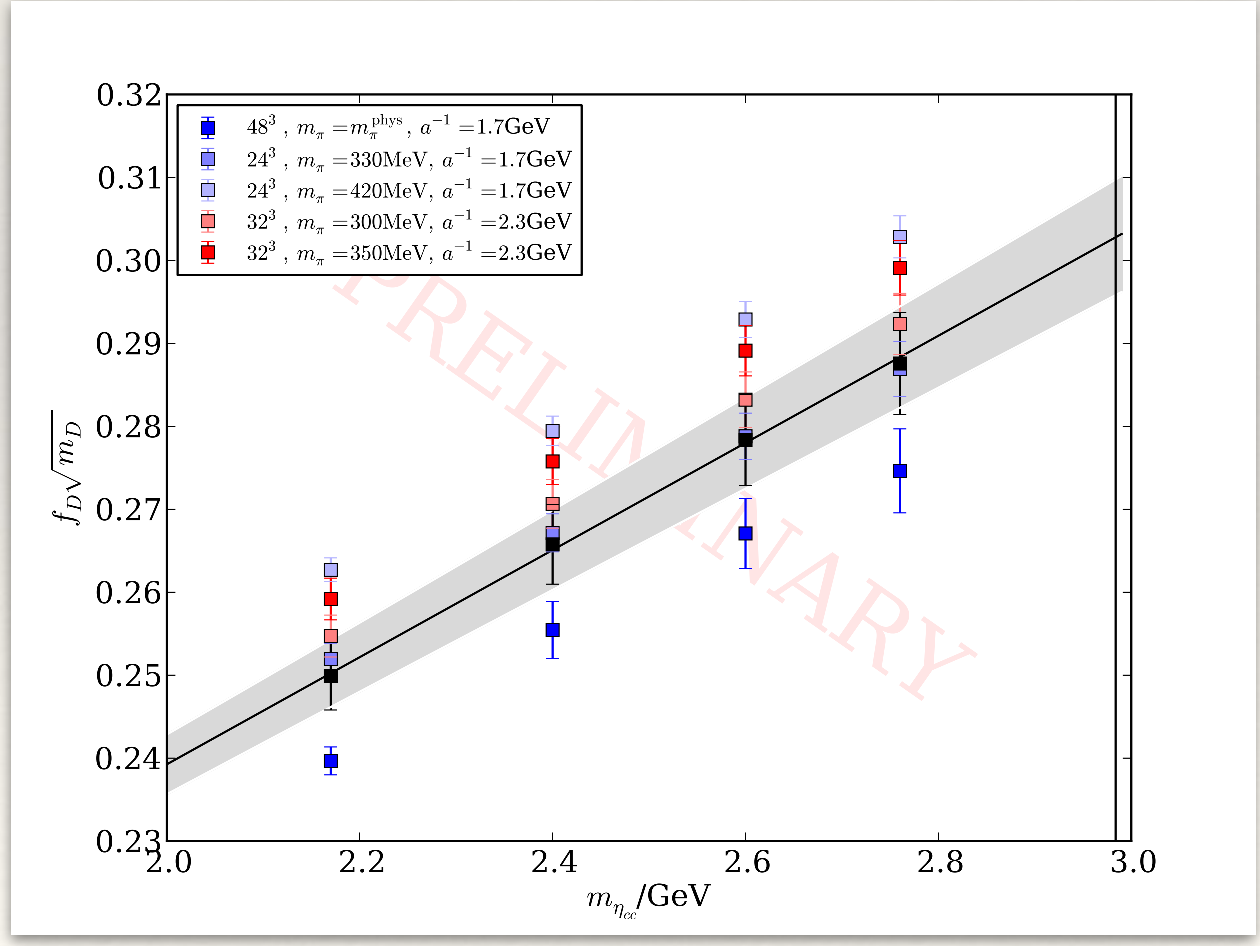

Comments/Conclusion

This was the first shot at it:

- additional data coming in (48cube stats, 2.3GeV physical pt., ~3GeV ensemble, …)
- need to check impact of alternative fit-ansaetze (interpolation in m_h at finite lattice spacing, extrapolation to m_c in the continuum $\rightarrow$systematics)

Results so far:

- no curvature in m_π seen down to the physical point
- benign mass-dependence, polynomial parameterisations should work well
- charm not far away $\rightarrow$ short extrapolation to charm, good statistical properties
- all results very preliminary, too early to provide numbers
- DWF excellent for charm!

Outlook:

- look into ratio method, interpolate to static, …
- other observables: quark masses, mixing, HVP, semi-leptonics

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