Lattice QCD and V_{cb}

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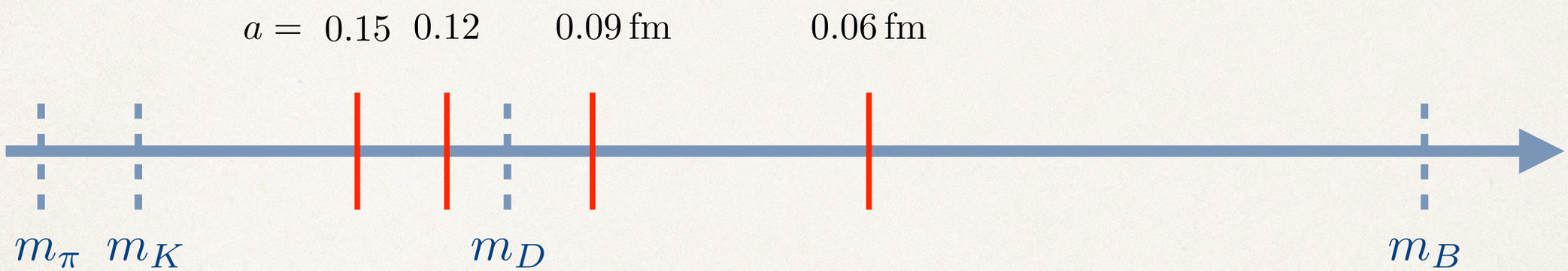
CKM Workshop, Mumbai, 29 November 2016

Outline

- Overview
- Semileptonic B to pseudoscalar D
- Semileptonic B to vector D*
- Look forward

What's the delay?



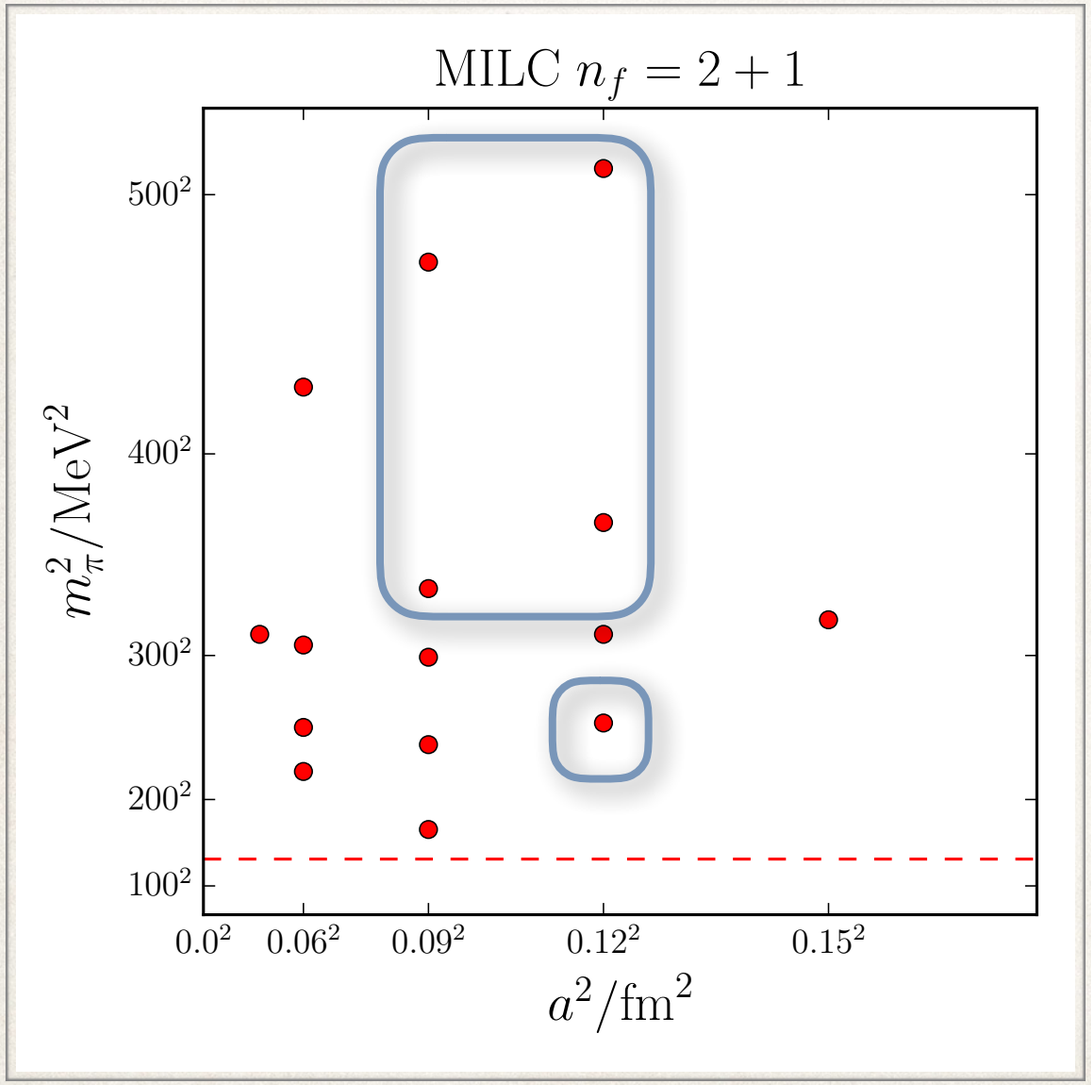
- Lattice spacing: cuts off short distance/high energy physics
- Cost of generating configurations ~ $(1/a)^5$ or worse
- Increased computing and improved actions now allow charm to be treated like *u, d, s*

Heavy quark methods

- Fermilab Lattice + MILC — Fermilab RHQ ***b*** & ***c***
- HPQCD — Nonrelativistic ***b***, staggered (HISQ) ***c***
- RBC-UKQCD — Columbia RHQ ***b*** & Möbius domain wall ***c***
- Paris group — ratio method, twisted-mass ***b*** & ***c***

Gauge field ensembles

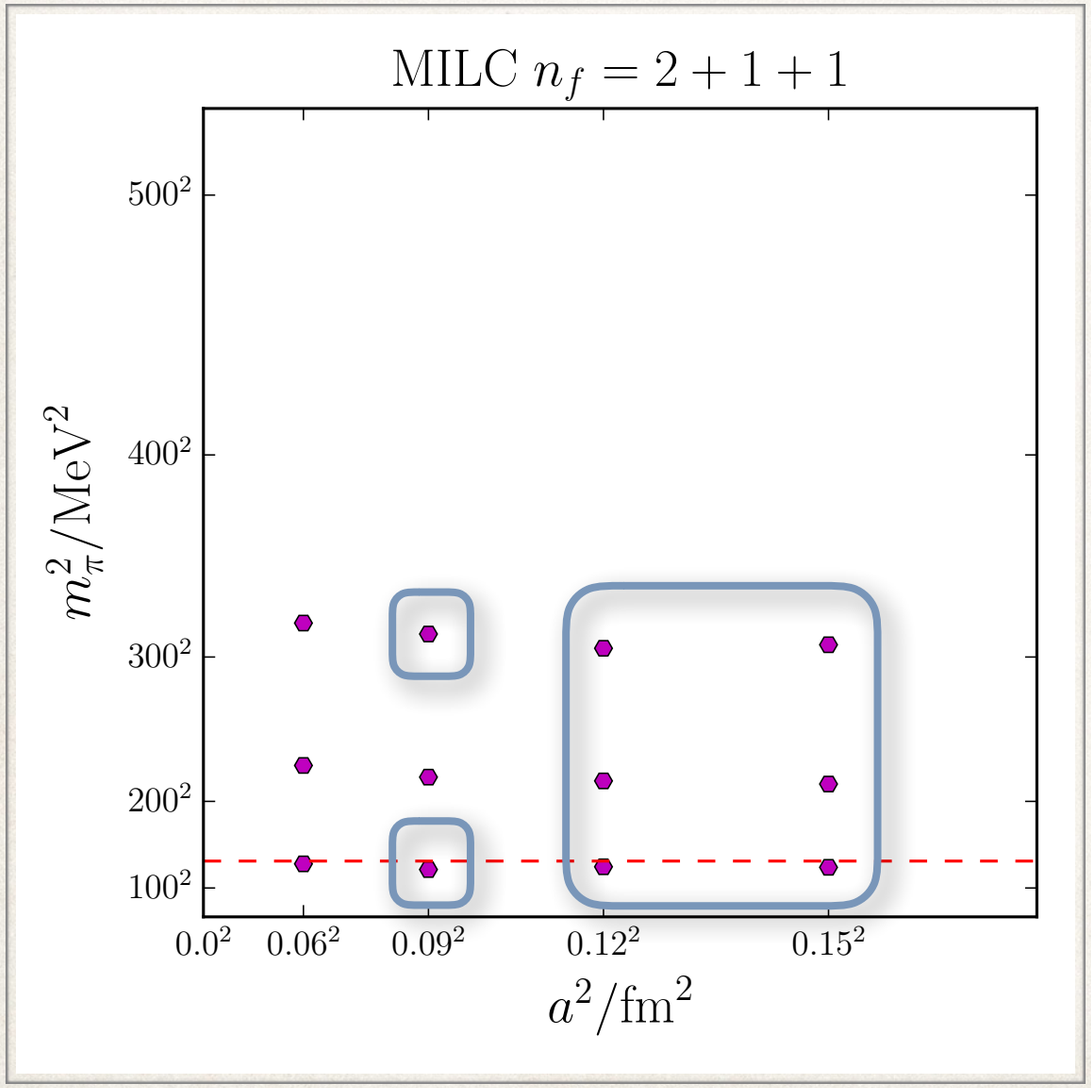
MILC asqtad, nf = 2+1



- FNAL/MILC use whole set
- HPQCD published $B \to D$ and Monahan (Lattice 2016) $B_s \to D_s$ use circled subset

Gauge field ensembles

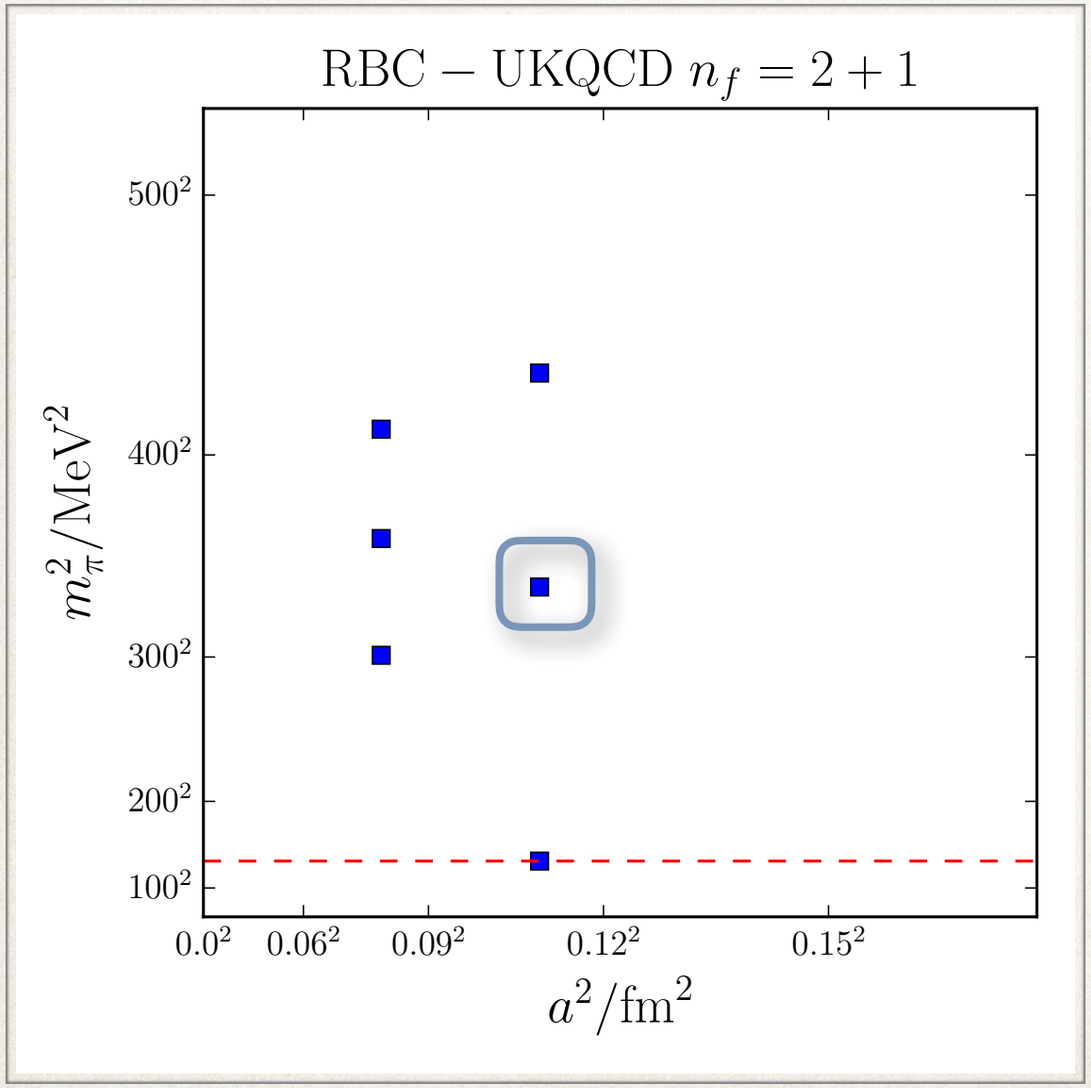
MILC HISQ, nf = 2+1+1



- At Lattice 2016, Harrison reported preliminary B → D* results on circled subset

Gauge field ensembles

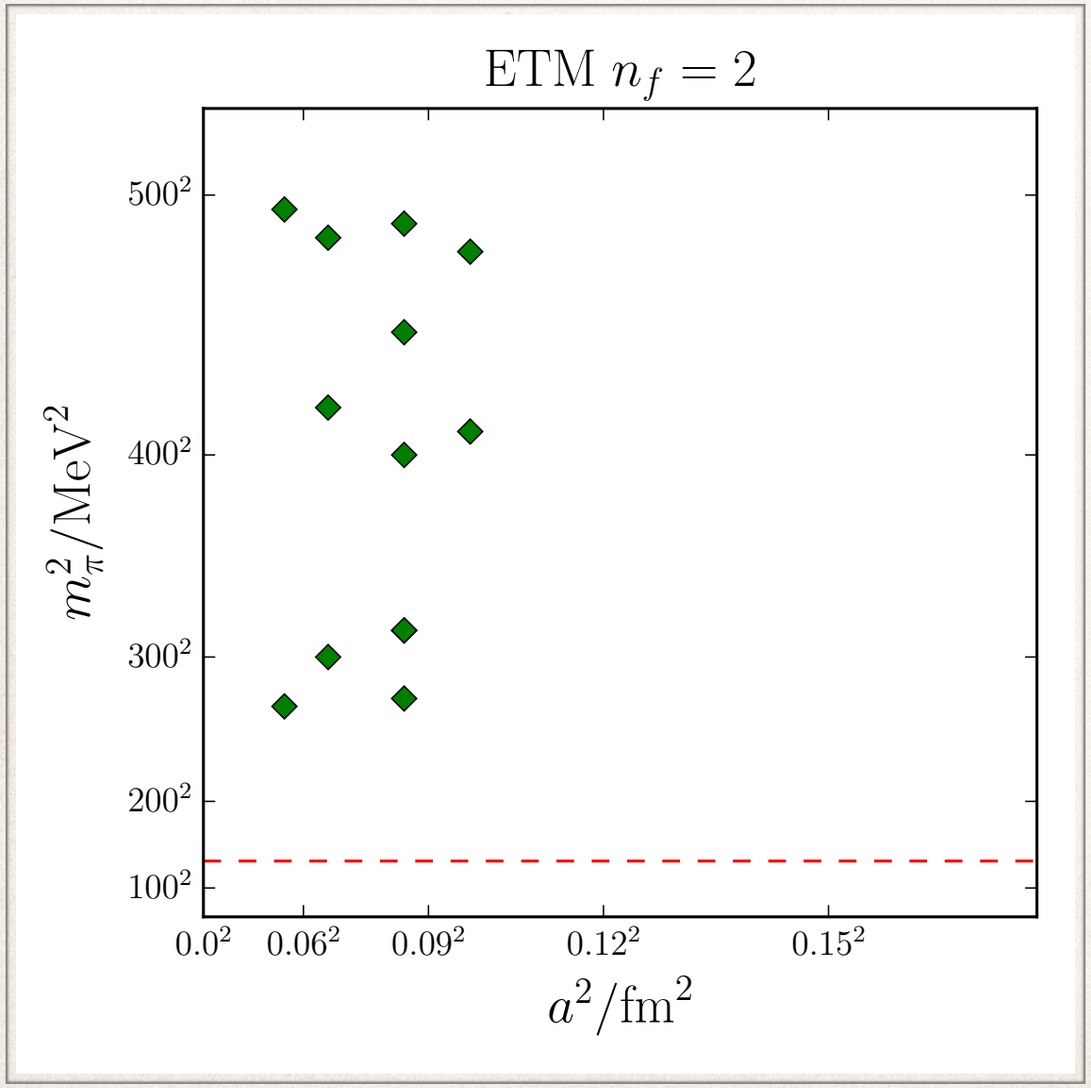
RBC-UKQCD, nf = 2+1



- At Lattice 2016 Witzel reported preliminary results on circled ensemble

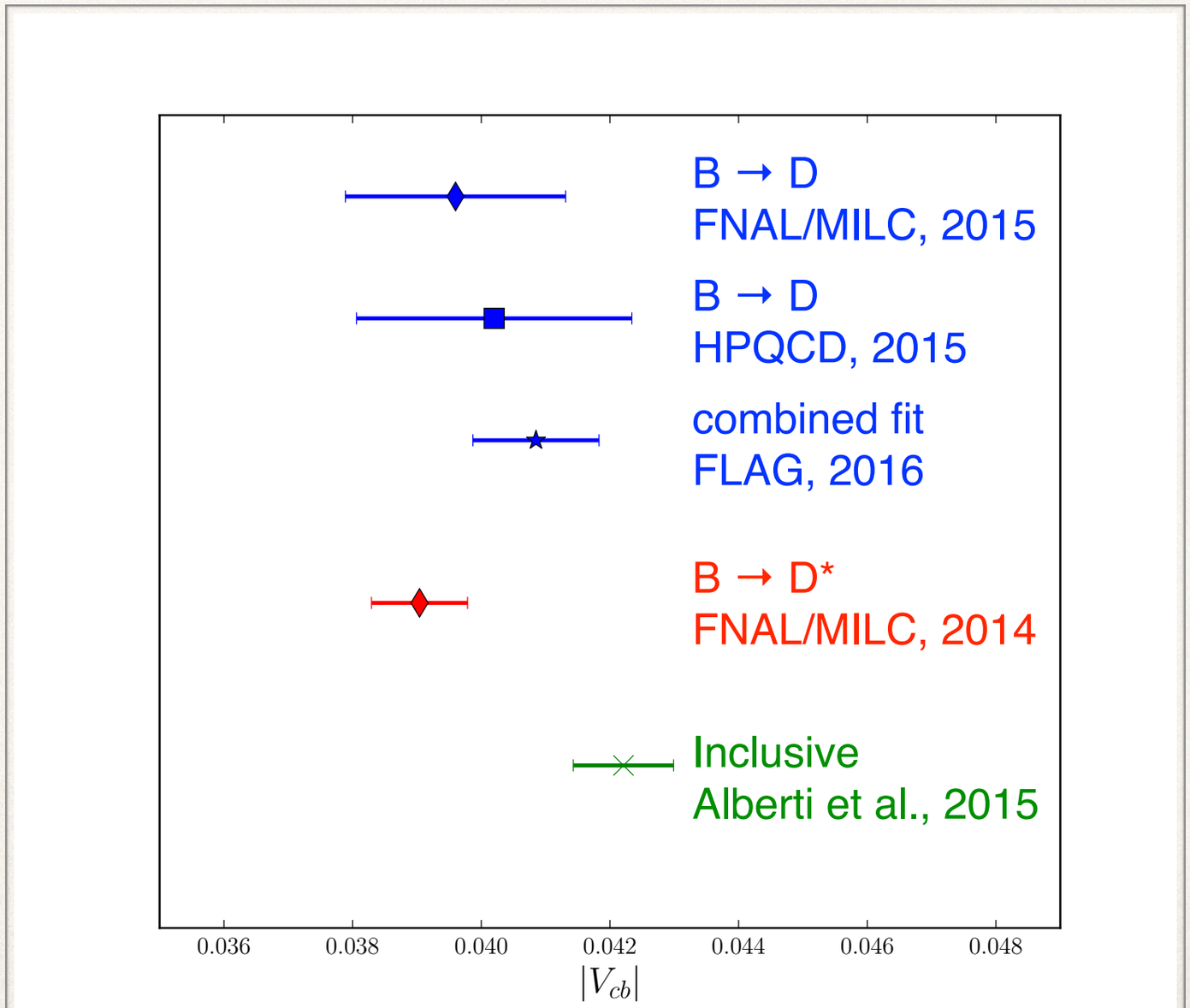
Gauge field ensembles

ETM, nf = 2



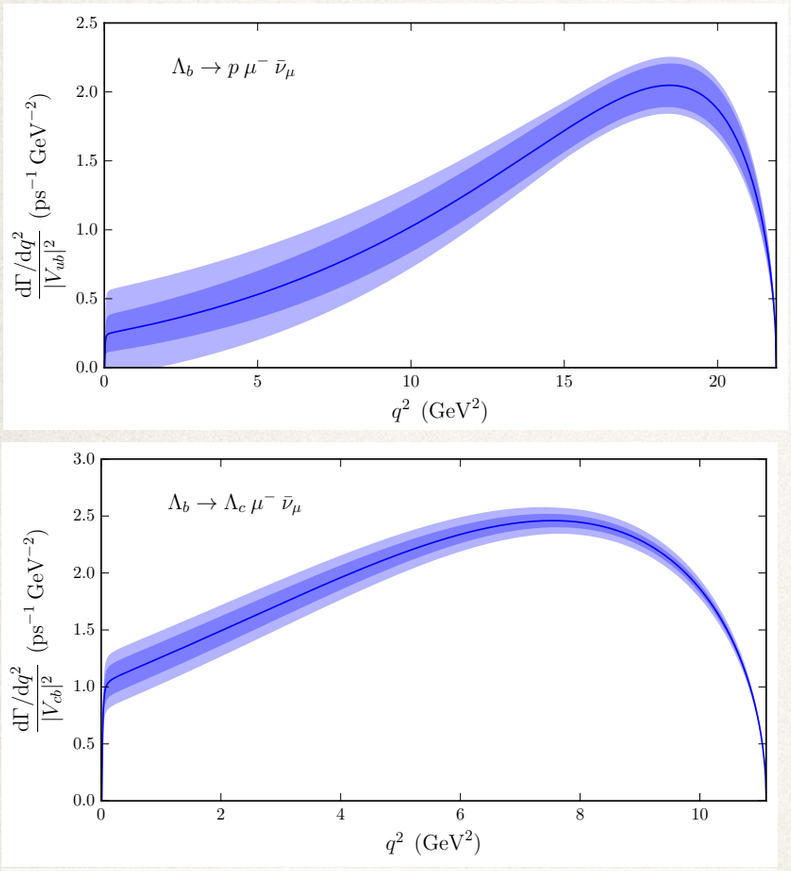
- Paris group (Atoui et al.) has published a study of Bs → Ds form factor near zero recoil using this set

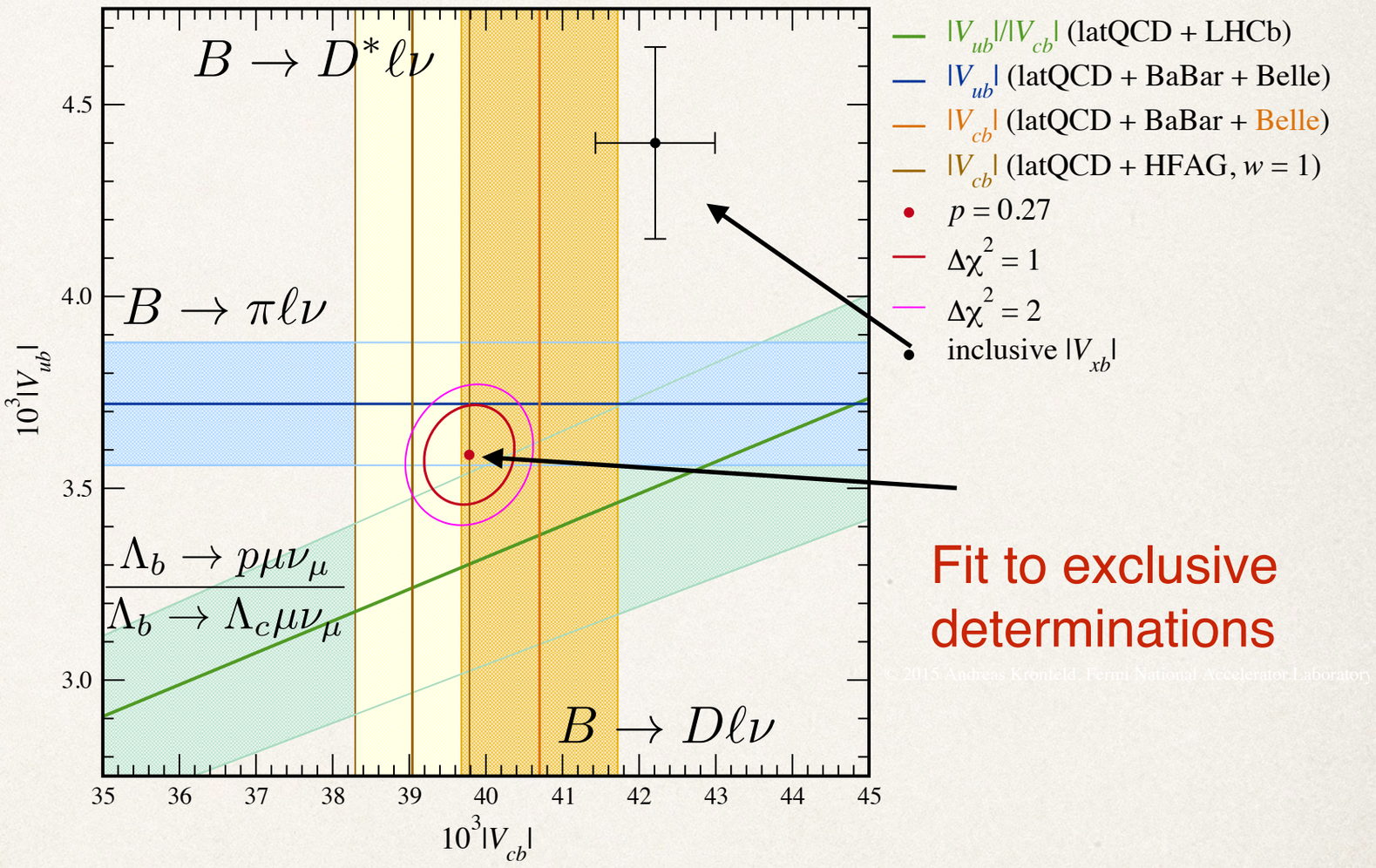
V_{cb} from exclusive decays



Baryonic decay

Detmold, Lehner, Meinel, 2015





Fit to exclusive determinations

Figure by A S Kronfeld, published in C DeTar (LP15), arXiv:1511.06884

$B \to D\, l\, \nu$

Differential decay rate ($l = e, \mu$)

$$\frac{d\Gamma}{dw}(B \to D\ell\nu) = |\eta_{EW}|^2 \frac{G_F^2 |V_{cb}|^2 m_B^5}{48\pi^3} (w^2-1)^{\frac{3}{2}} r^3 (1+r)^2 \mathcal{G}^2(w)$$

with $w = \dfrac{p \cdot k}{m_B m_D}$ and $r = \dfrac{m_D}{m_B}$

Form factor is one which parametrizes the matrix element

$$\langle D(k)|\bar{s}\gamma^\mu b|B(p)\rangle = \left[(p+k)^\mu - \frac{m_B^2 - m_D^2}{q^2} q^\mu\right] f_+(q^2) + \frac{m_B^2 - m_D^2}{q^2} q^\mu f_0(q^2)$$

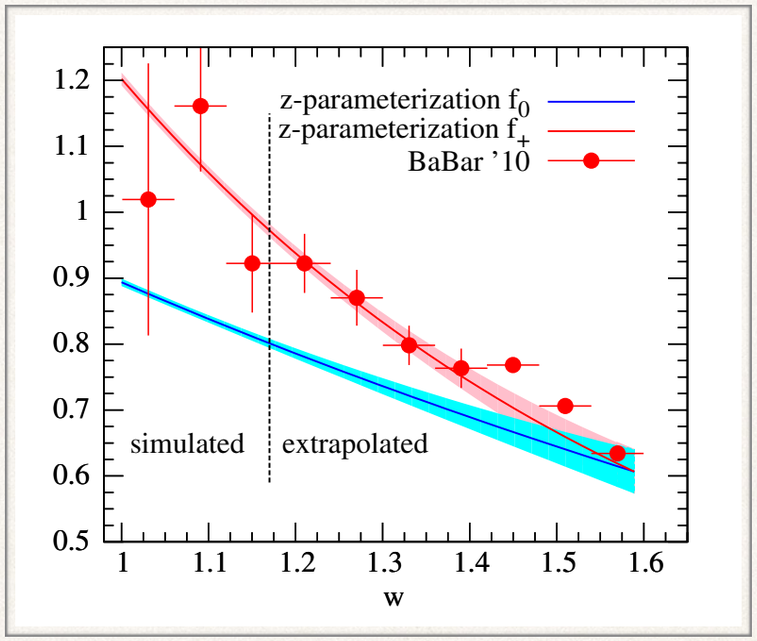
with

$$f_+^2(q^2) = \frac{(1+r)^2}{4r} \mathcal{G}^2(w)$$

The f_0 form factor is needed for $B \to D\, \tau\, \nu$.

Published B → D

Fermilab / MILC



Source	$f_+(\%)$	$f_0(\%)$
Statistics+matching+χPT cont. extrap.	1.2	1.1
(Statistics)	(0.7)	(0.7)
(Matching)	(0.7)	(0.7)
(χPT/cont. extrap.)	(0.6)	(0.5)
Heavy-quark discretization	0.4	0.4
Lattice scale r_1	0.2	0.2
Total error	1.2	1.1

HPQCD

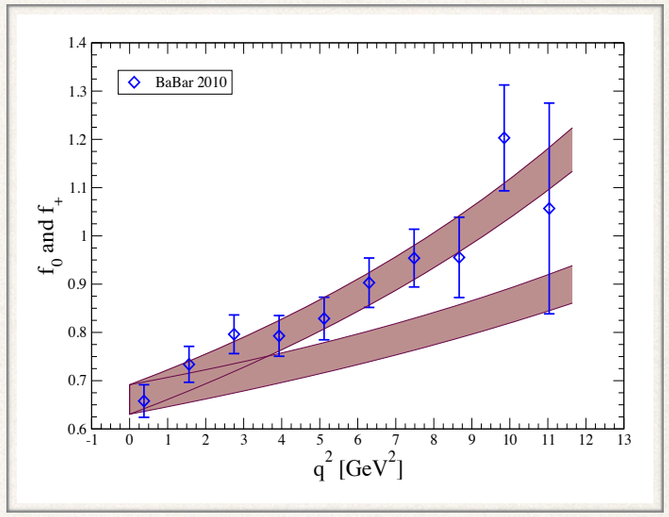
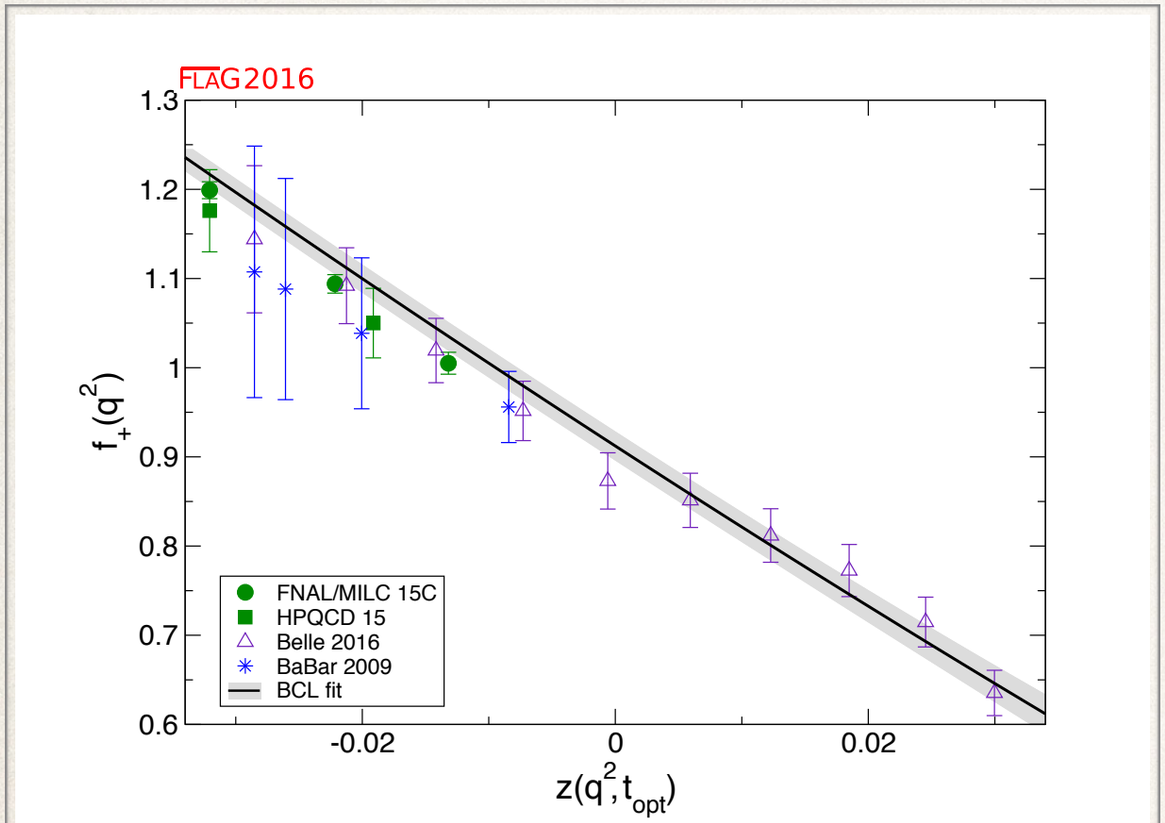
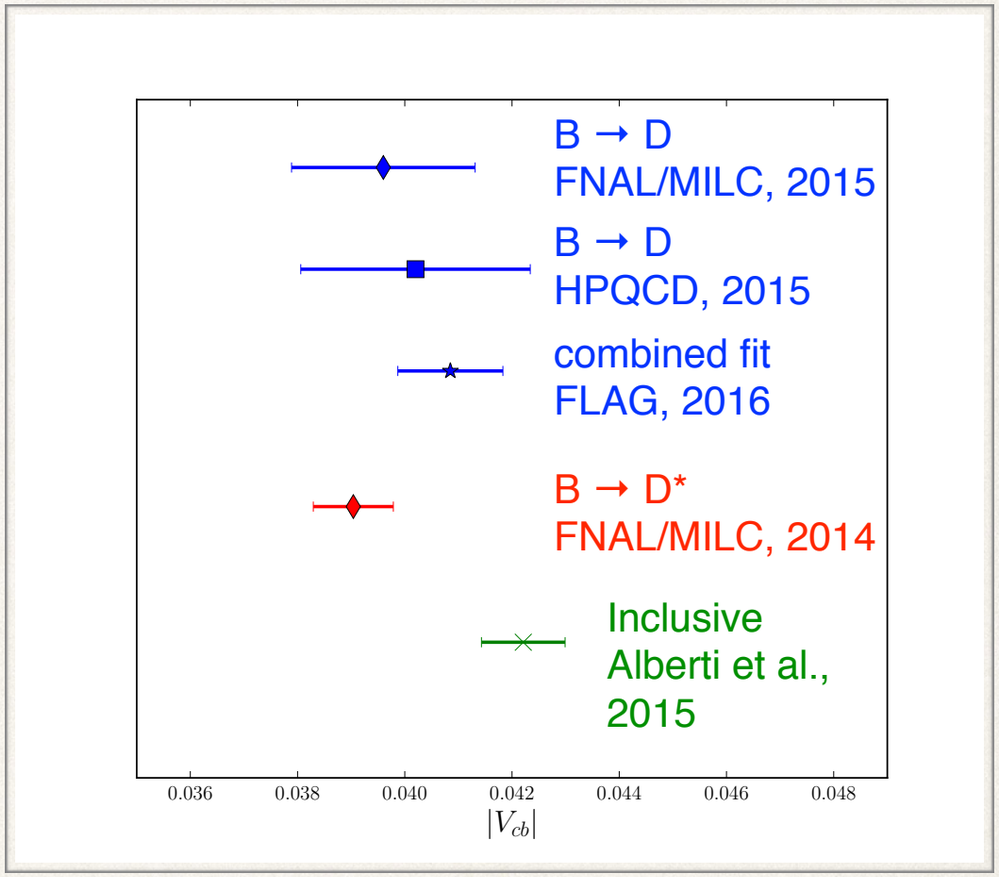


TABLE V. Error budget table for $|V_{cb}|$. The first three rows are from experiments, and the rest are from lattice simulations.

Type	Partial errors [%]
experimental statistics	1.55
experimental systematic	3.3
meson masses	0.01
lattice statistics	1.22
chiral extrapolation	1.14
discretization	2.59
kinematic	0.96
matching	2.11
electro-weak	0.48
finite size effect	0.1
total	5.34

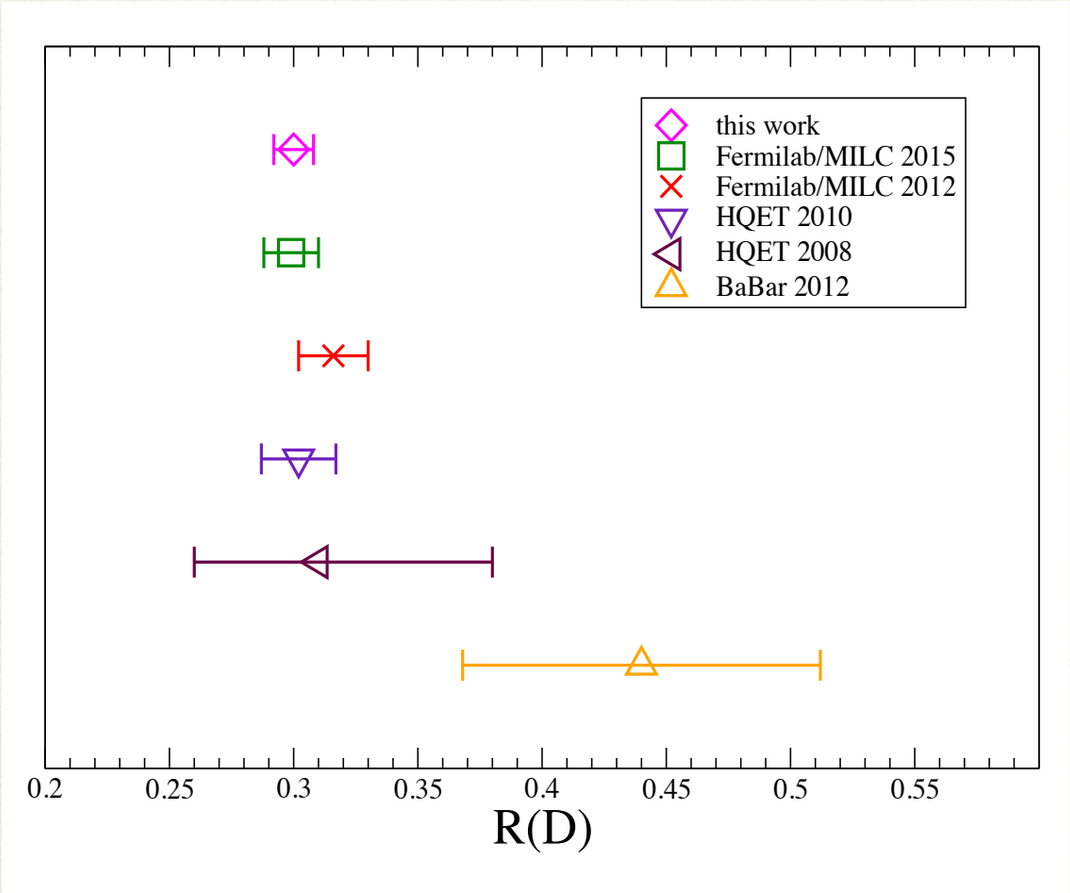
FLAG average





Flavour Lattice Averaging Group, arXiv:1607.00299

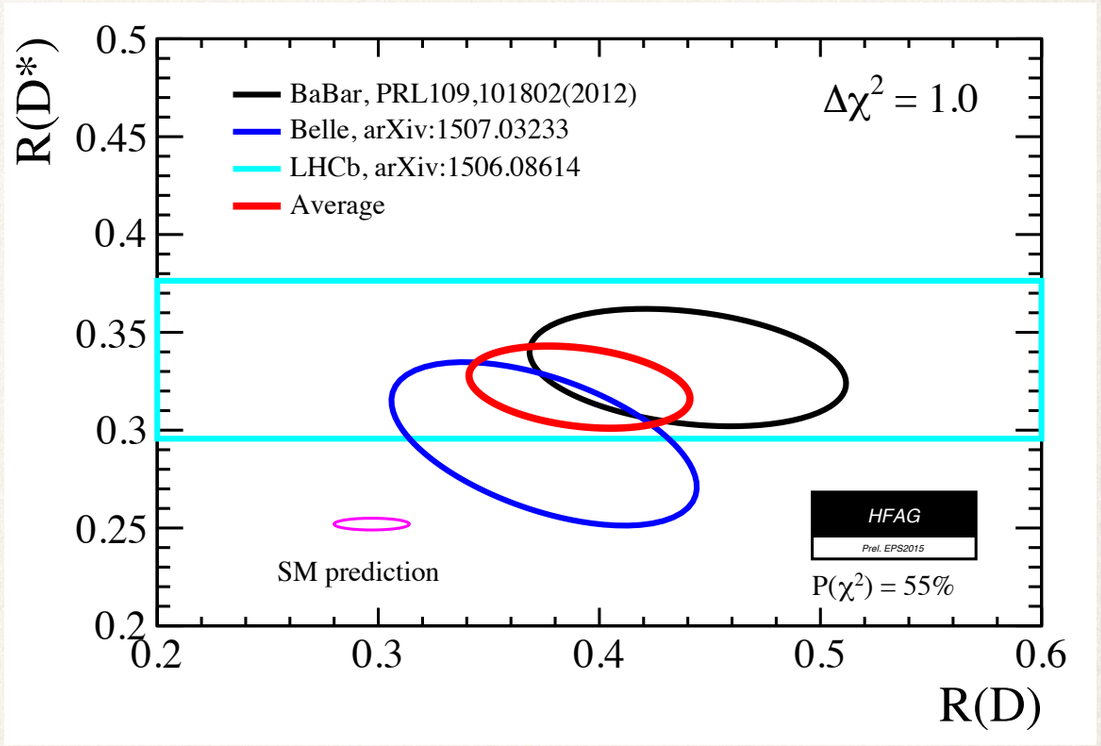
R(D)



Na *et al*. (HPQCD), arXiv:1505.03925

HQET 2010 = Tanaka, Watanabe
HQET 2008 = Nierste, Trine, Westhoff

$$R(D) = \frac{\mathcal{B}(B \to D\tau\nu_\tau)}{\mathcal{B}(B \to D\ell\nu_\ell)} \qquad \ell = e, \mu$$

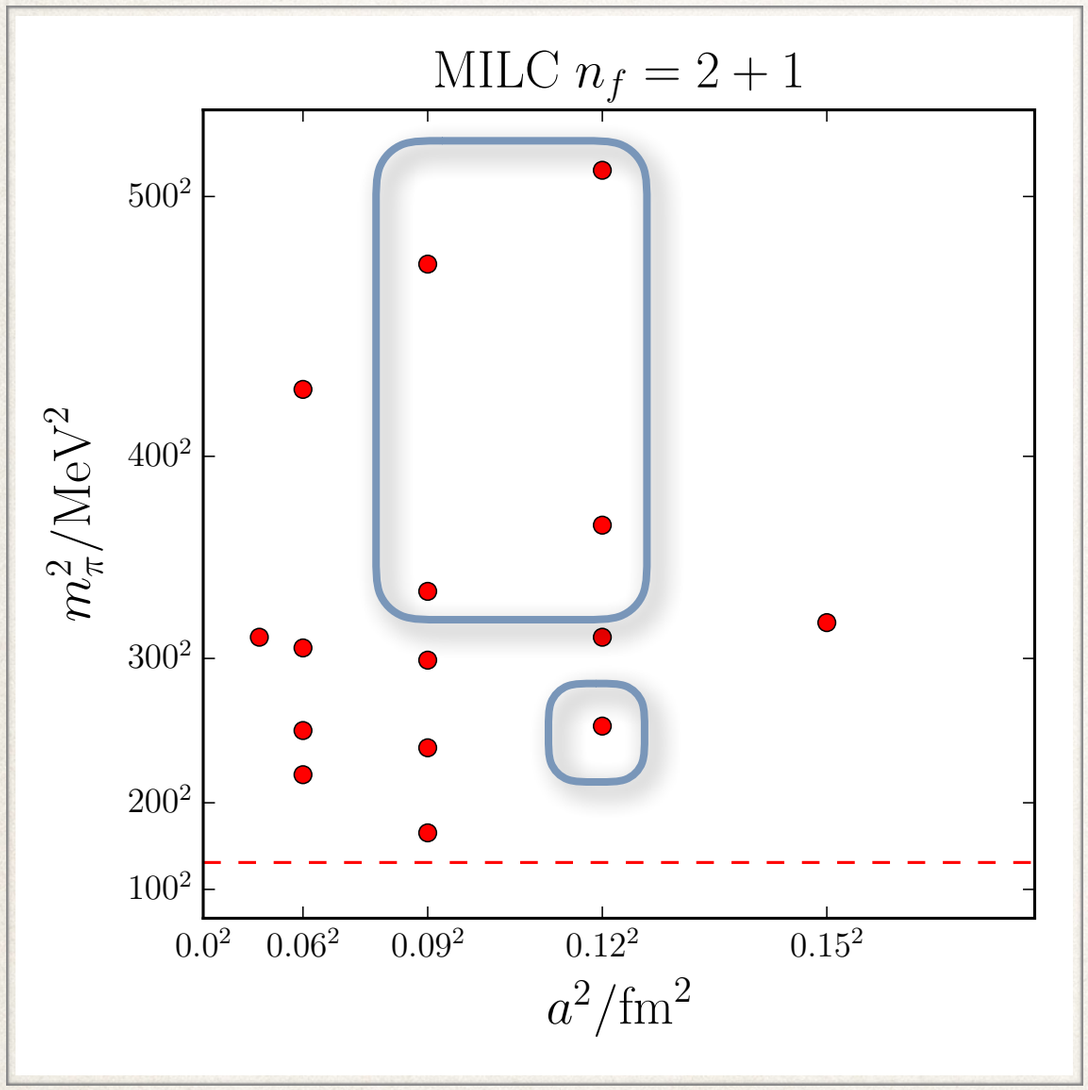


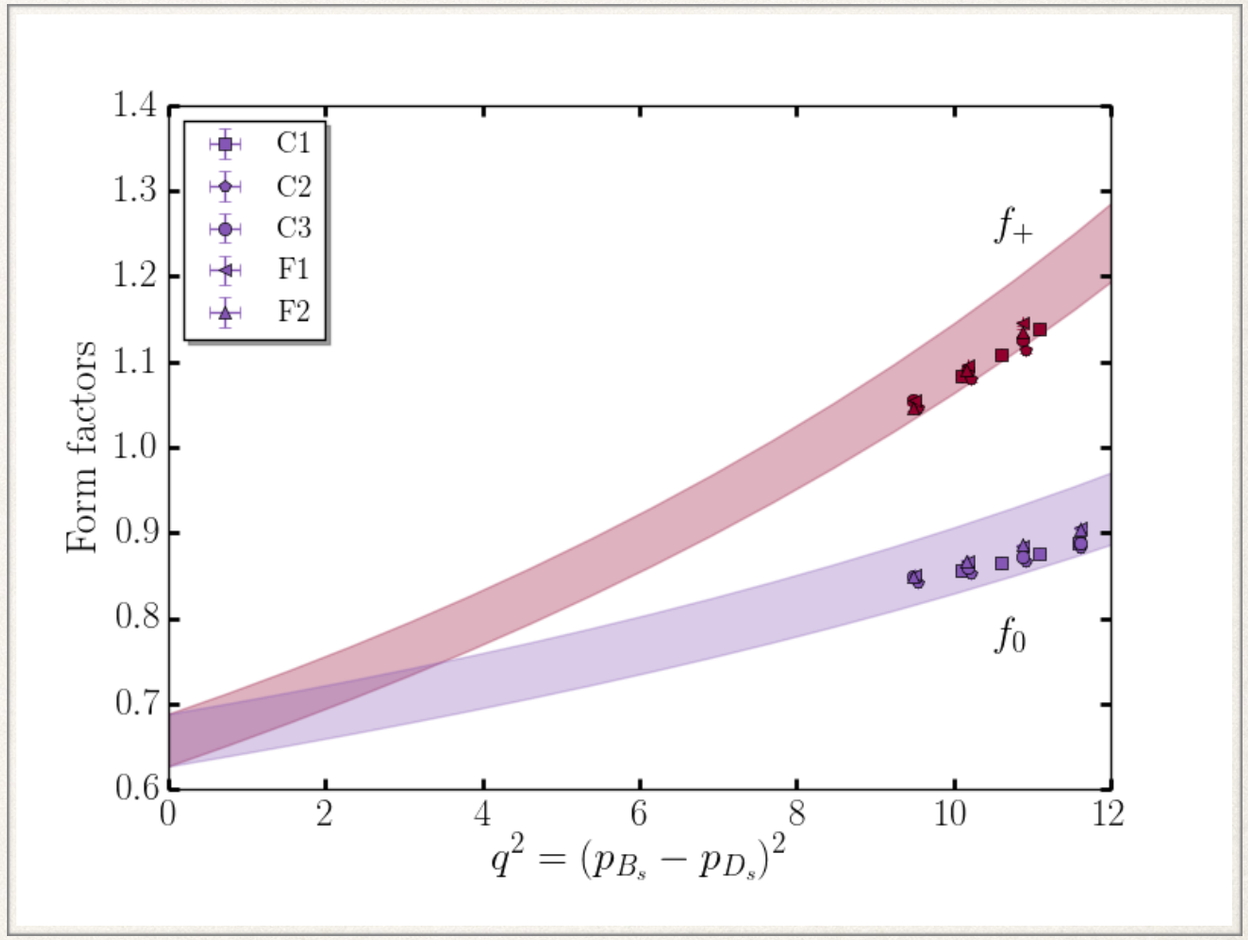
Plot from HFAG, for EPS-HEP 2015

Published $B_s \to D_s$

- Paris group (Atoui et al., 2014), $n_f = 2$ results $\mathcal{G}(1) = 1.052(46)$
- FNAL/MILC (Bailey, et al., 2015), ratio of form factors at large recoil useful for constraining ratio of fragmentation functions f_s/f_d, in turn useful for reducing uncertainties in $B_s \to \mu\,\mu$
- [f_q = probability that a b quark hadronizes into a B_q meson.]
- Opportunity to determine $|V_{cb}|$ with experimental data for $B_s \to D_s\, l\, \nu$

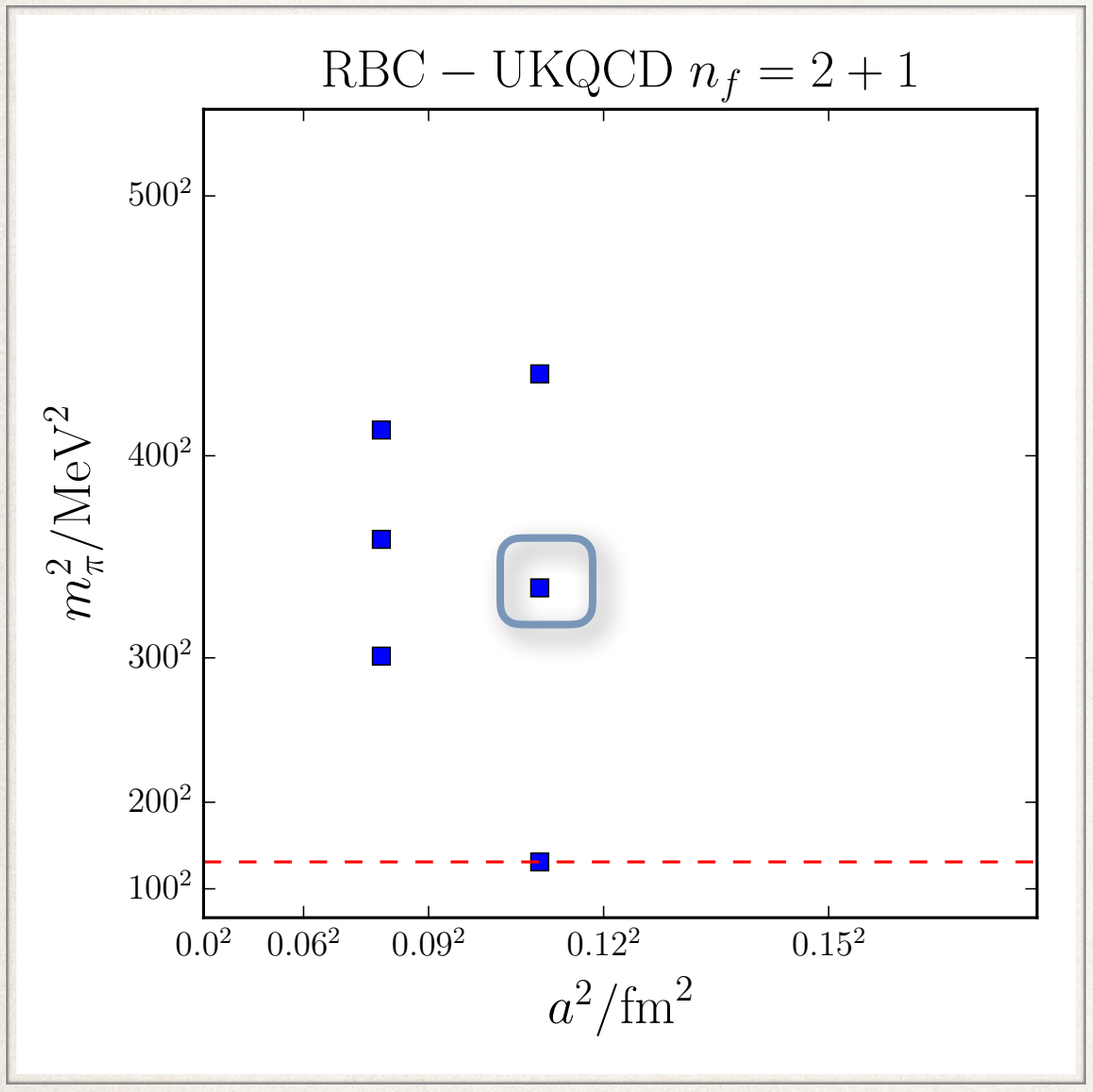
Preliminary $B_s \to D_s$ — HPQCD

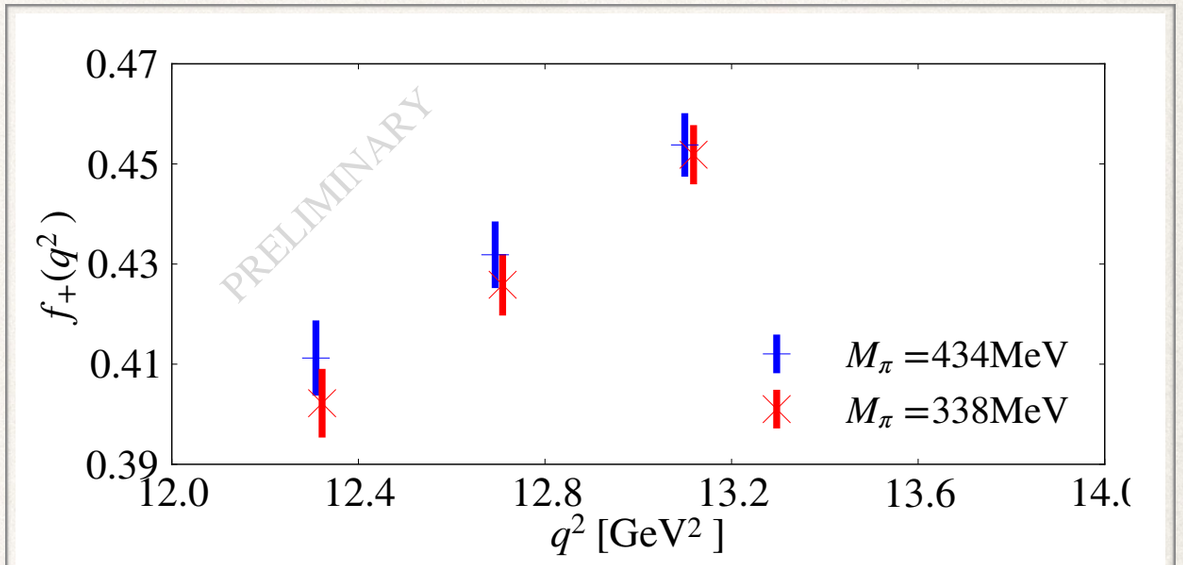


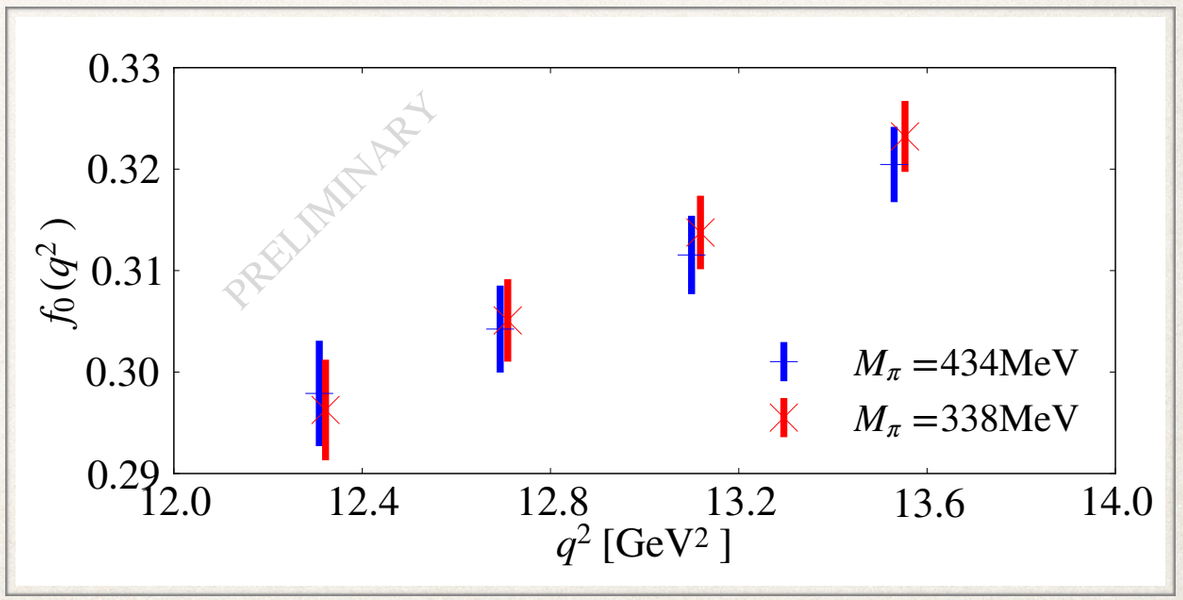


Monahan et al.,Lattice 2016

Preliminary $B_s \to D_s$ — RBC-UKQCD







Witzel @ Lattice 2016

$B \to D^* l \nu$

Differential decay rate ($l = e, \mu$)

$$\frac{d\Gamma}{dw} = |\eta_{EW}|^2 \frac{G_F^2 |V_{cb}|^2 m_{D^*}^2}{4\pi^3} (m_B - m_{D^*})^2 \sqrt{w^2 - 1} \chi(w) |\mathcal{F}(w)|^2$$

Where $F(w)$ is a linear combination of form factors

$$\frac{\langle D^*(p_{D^*}, \epsilon^{(\alpha)}) | \mathcal{A}^\mu | B(p_B) \rangle}{\sqrt{2M_{D^*}}\sqrt{2M_B}} = \frac{i}{2} \epsilon_\nu^{(\alpha)*} [g^{\mu\nu}(1+w) h_{A_1}(w) - v_B^\nu (v_B^\mu h_{A_2}(w) + v_{D^*}^\mu h_{A_3}(w))]$$

$$\frac{\langle D^*(p_{D^*}, \epsilon^{(\alpha)}) | \mathcal{V}^\mu | B(p_B) \rangle}{\sqrt{2M_{D^*}}\sqrt{2M_B}} = \frac{1}{2} \varepsilon^{\mu\nu}{}_{\rho\sigma} \epsilon_\nu^{(\alpha)*} v_B^\rho v_{D^*}^\sigma h_V(w),$$

At zero recoil, w=1 and $\mathcal{F}(1) = h_{A_1}(1)$

Published B → D*

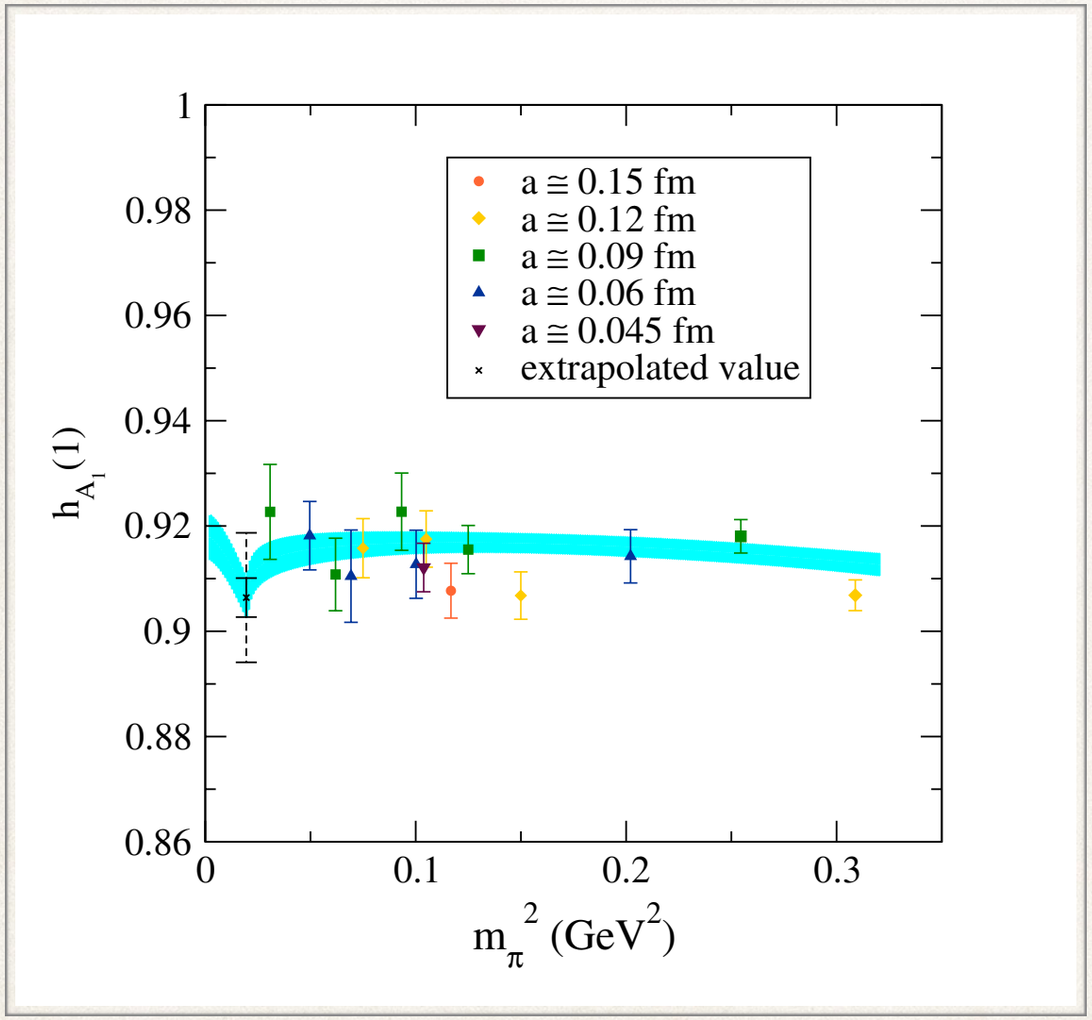
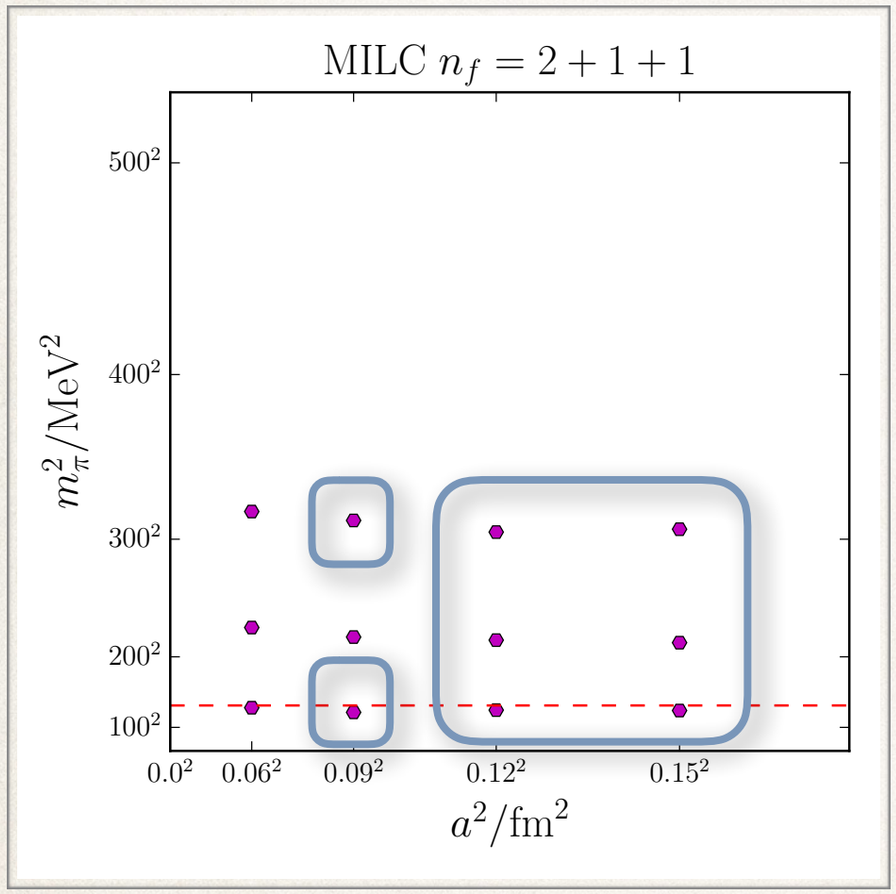


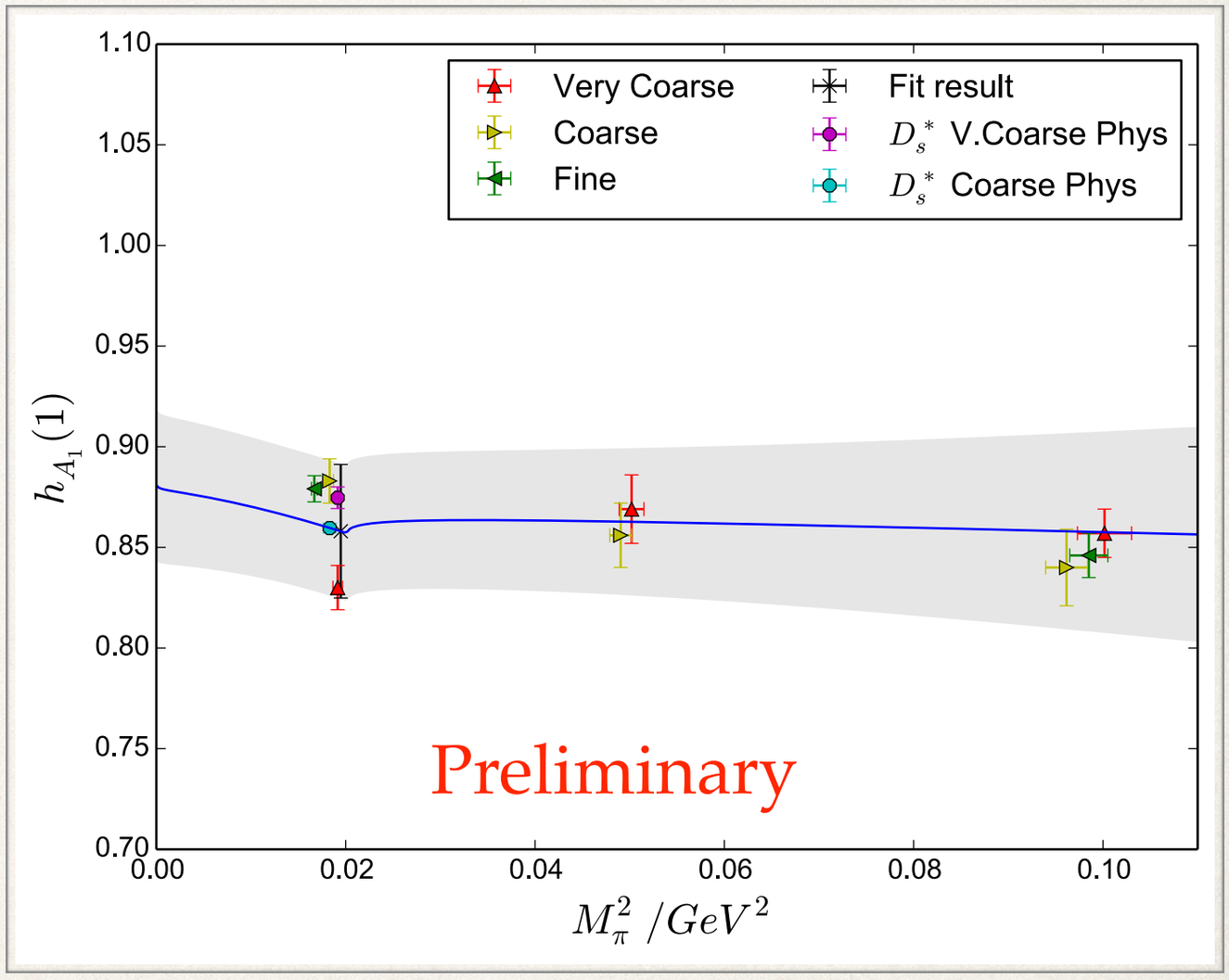
TABLE X. Final error budget for $h_{A_1}(1)$ where each error is discussed in the text. Systematic errors are added in quadrature and combined in quadrature with the statistical error to obtain the total error.

Uncertainty	$h_{A_1}(1)$
Statistics	0.4%
Scale (r_1) error	0.1%
χPT fits	0.5%
$g_{D^*D\pi}$	0.3%
Discretization errors	1.0%
Perturbation theory	0.4%
Isospin	0.1%
Total	1.4%

Zero recoil form factor

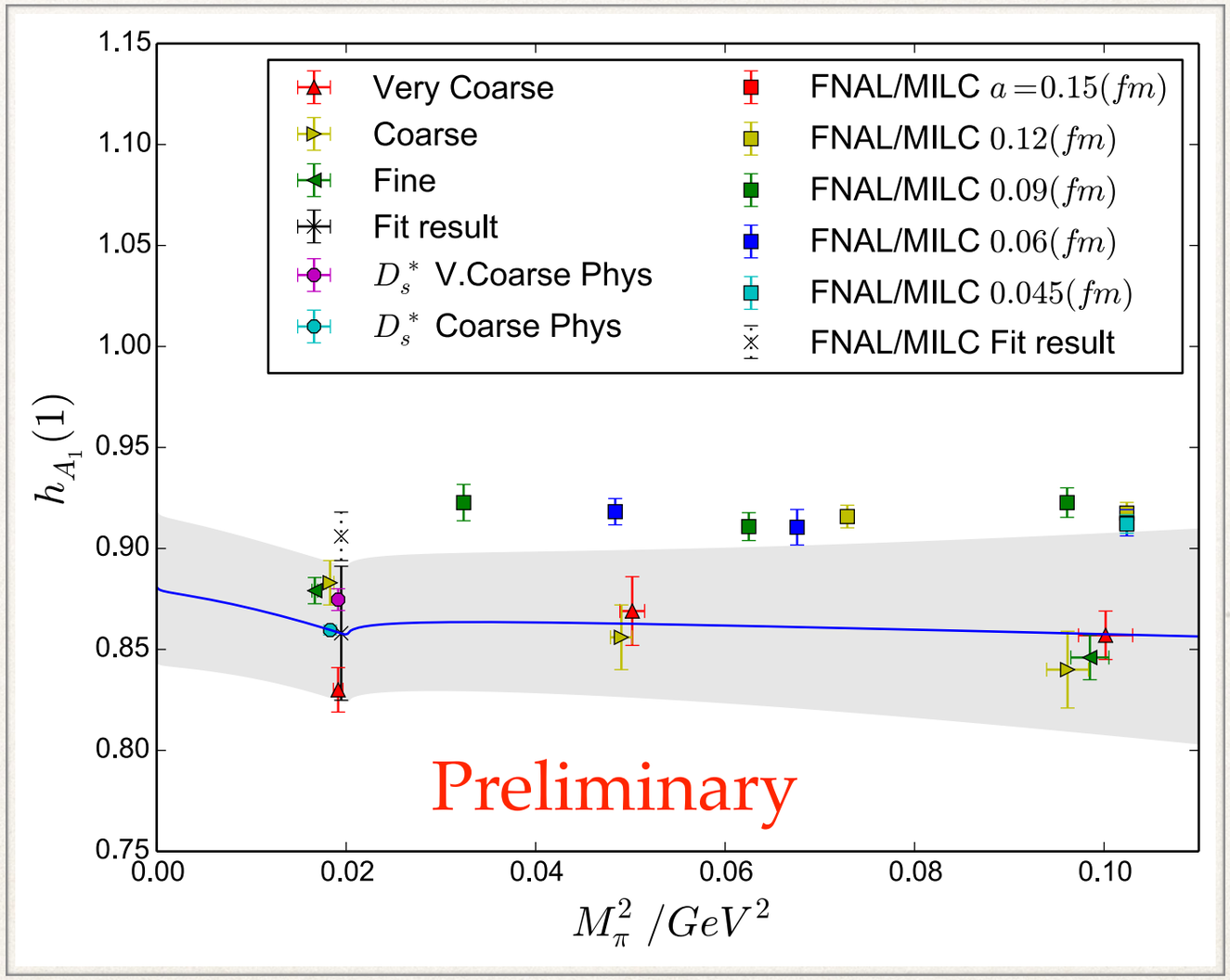


Statistically independent from published FNAL/ MILC calculation



Harrison et al. (HPQCD), Lattice 2016

Zero recoil form factor



Harrison et al., Lattice 2016

Looking forward

- Final results for HPQCD $B_s \rightarrow D_s$ (MILC asqtad) and HPQCD $B \rightarrow D^*$ (MILC HISQ) expected soon

- Underway: $B_{(s)} \rightarrow D^*_{(s)}$ at nonzero recoil by FNAL/MILC (asqtad) and HPQCD (HISQ)

- HPQCD also working on $B \rightarrow D$ (HISQ)

- HPQCD: compare NRQCD & relativistic HISQ to improve normalisation (see A. Lytle talk Wed 10:10, WG2)

Selected references

- Atoui et al., arXiv:1310.5238, Eur. Phys. J C74 (2014)
- Bailey et al. (FNAL/MILC), arXiv:1202.6246, Phys. Rev. D 85 (2012)
- Bailey et al. (FNAL/MILC), arXiv:1206.4992, Phys. Rev. Lett. 109 (2012)
- Bailey et al. (FNAL/MILC), arXiv:1403.0635, Phys. Rev. D 89 (2014)
- Bailey et al. (FNAL/MILC), arXiv:1503.07237, Phys. Rev. D 92 (2015)
- Detmold, Lehner, Meinel., arXiv:1503.01421, Phys. Rev. D 92 (2015)
- Harrison et al. (HPQCD), Lattice 2016 proceedings, to appear
- Monahan et al. (HPQCD), Lattice 2016 proceedings, to appear
- Na et al. (HPQCD), arXiv:1505.03925, Phys. Rev. D 92 (2015)
- Witzel et al. (RBC-UKQCD), Lattice 2016 proceedings, to appear