Testing the Standard Model under the weight of Heavy Flavors

Chris Bouchard

Ohio State

23 June 2014

Experimental results/activity

- Heavy Flavor Averaging Group (HFAG): www.slac.stanford.edu/xorg/hfag

Many consistency checks

- UTfit: www.utfit.org/UTfit
- CKMfitter: ckmfitter.in2p3.fr
- Flavor Lattice Averaging Group (FLAG): itpwiki.unibe.ch/flag

Recent interest in rare decays

- experimental, phenomenological, and on the lattice

c Experiment

BESIII

- running since 2011
- threshold charm: $c\bar{c}$ production at $\psi(3770)$, $\psi(4040)$, ...

LHCb

- D^0 mixing, PRL 110, 101802 (2013)
- rare decays (i.e. $D \to \pi\mu\mu$, PLB 724 (2013) 203-212))

ATLAS

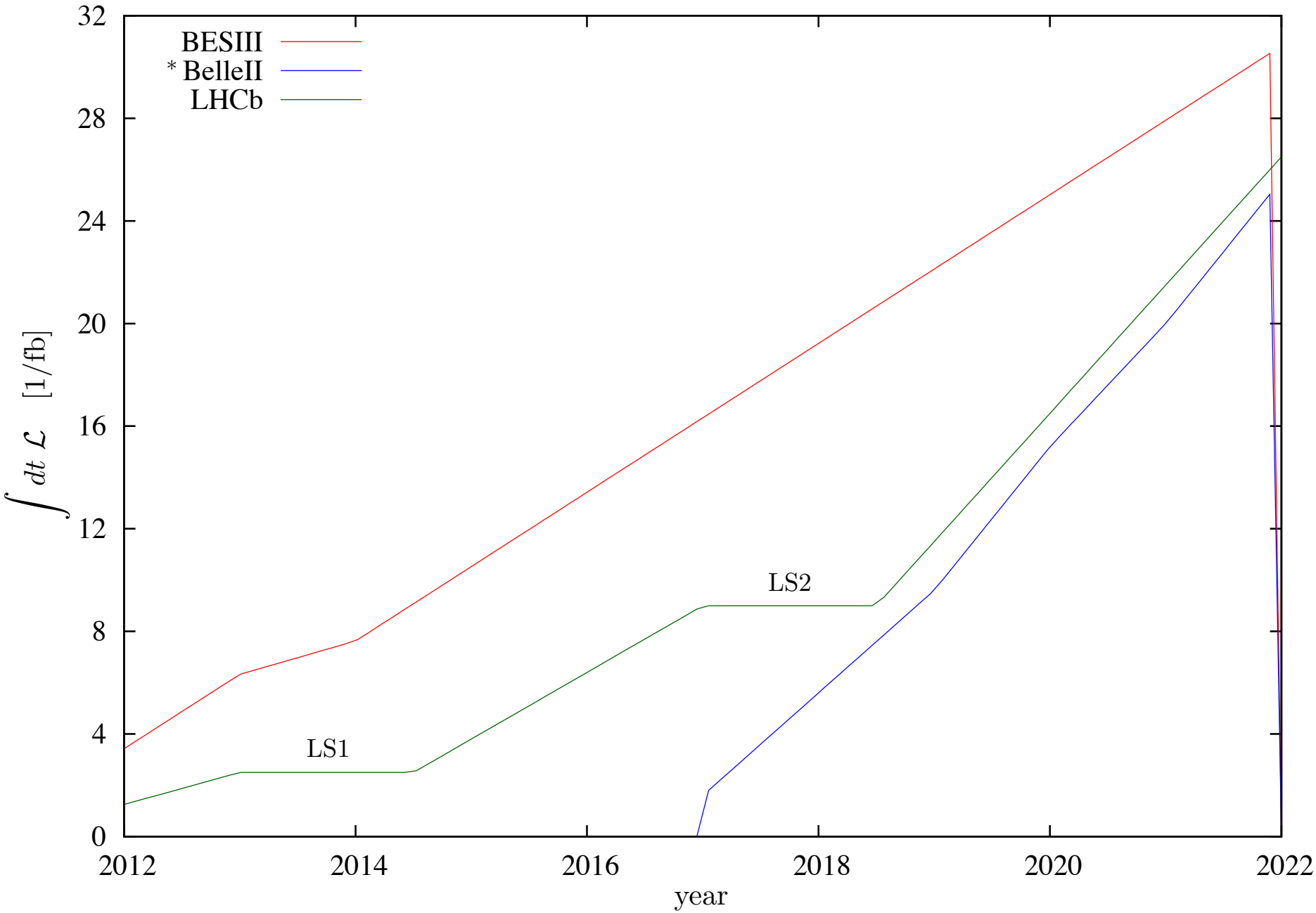
- continue until 2017 (spectroscopy - not much overlap with this talk)

BelleII

- start 2017
- $\sigma(e^+e^- \to B\bar{B}) \sim \sigma(e^+e^- \to c\bar{c})$

PANDA (FAIR in Darmstadt): would commission 2018, spectroscopy

Possible future threshold charm at Cabibbo lab near Rome, Novosibirsk



* normalized to LHCb-equivalent via # of reconstructed benchmark decays ($D^{+*} \to D^0\pi^+$, $D^0 \to K^-\pi^+$)

b Experiment

LHCb

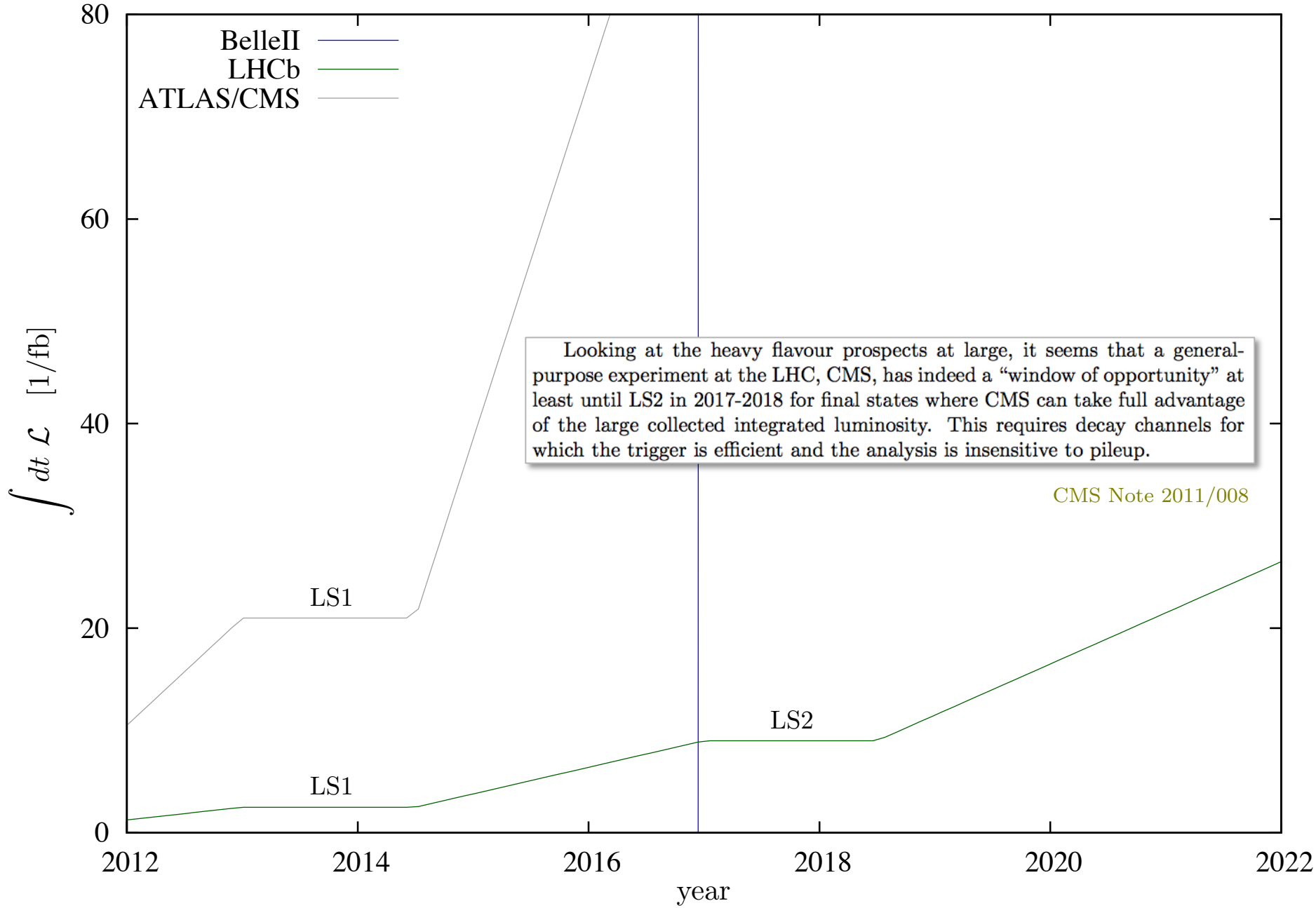
- precision vertex reconstruction for B physics
- semileptonic decays difficult due to backgrounds
- $B \to K^{(*)}\mu\mu$, $B \to \pi\mu\mu$, $B_s \to \mu\mu$, $B_s \to J/\Psi\phi$, ...

CMS/ATLAS

- more integrated luminosity than LHCb, before BelleII
- angular coverage complementary to LHCb ($B \to K^*\mu\mu$)
- limited to final state dimuons (trigger)
- poor (*vs.* LHCb) mass/time resolution $\Rightarrow$ limited $B^0_{(s)}$ mixing

BelleII

- start 2017
- e^+e^- threshold machine to run at $\Upsilon(4S)$ for B, $\Upsilon(5S)$ for B_s


80
60
40
20
0
2012
2014
2016
2018
2020
2022
year
$\int dt\ \mathcal{L}$ [1/fb]
BelleII
LHCb
ATLAS/CMS
LS1
LS1
LS2
Looking at the heavy flavour prospects at large, it seems that a general-purpose experiment at the LHC, CMS, has indeed a "window of opportunity" at least until LS2 in 2017-2018 for final states where CMS can take full advantage of the large collected integrated luminosity. This requires decay channels for which the trigger is efficient and the analysis is insensitive to pileup.
CMS Note 2011/008

Precision CKM

- focus on SM tree-level
- determine V_{CKM} multiple ways

Rare Processes

- require loops in SM
- new physics may be discernible

Leptonic Decays

- $D_{(s)} \to \ell\nu$
- $B \to \ell\nu$

Semileptonic Decays

- $D \to \pi\ell\nu$, $D \to K\ell\nu$, $D_s \to \phi\ell\nu$, $D_s \to \eta^{(\prime)}\ell\nu$
- $B \to \pi\ell\nu$, $B_s \to K\ell\nu$, $B_{(s)} \to D_{(s)}\ell\nu$, $B \to D^*\ell\nu$

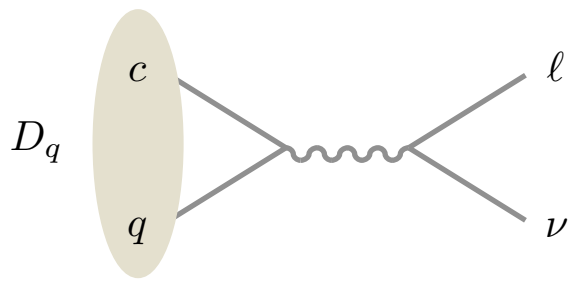
Rare Decays

- $B \to K^{(*)}\ell\ell$, $B_s \to \phi\ell\ell$, $B \to \pi\ell\ell$

Mixing

- D^0–$\bar{D}^0$
- $B^0_{(s)}$–$\bar{B}^0_{(s)}$

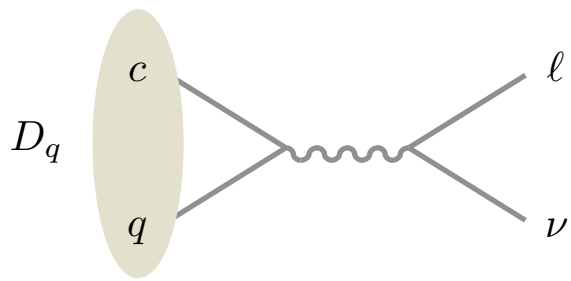
$D_{(s)} \to \ell\nu$



$$\underbrace{\mathcal{B}(D_q \to \ell\nu) = \tau_{D_q} \frac{G_F^2}{8\pi} m_\ell^2 M_{D_q} \left(1 - \frac{m_\ell^2}{M_{D_q}^2}\right)^2}_{\text{measure}} \underbrace{f_{D_q}^2}_{\text{calculate}} |V_{cq}|^2 + \underbrace{\mathcal{O}\left(\frac{M_{D_q}}{M_W}\right)^2}_{\text{small}}$$

extract

$D_{(s)} \to \ell\nu$



$$\mathcal{B}(D_q \to \ell\nu) = \tau_{D_q} \frac{G_F^2}{8\pi} m_\ell^2 M_{D_q} \left(1 - \frac{m_\ell^2}{M_{D_q}^2}\right)^2 f_{D_q}^2 \, |V_{cq}|^2 + \mathcal{O}\left(\frac{M_{D_q}}{M_W}\right)^2$$

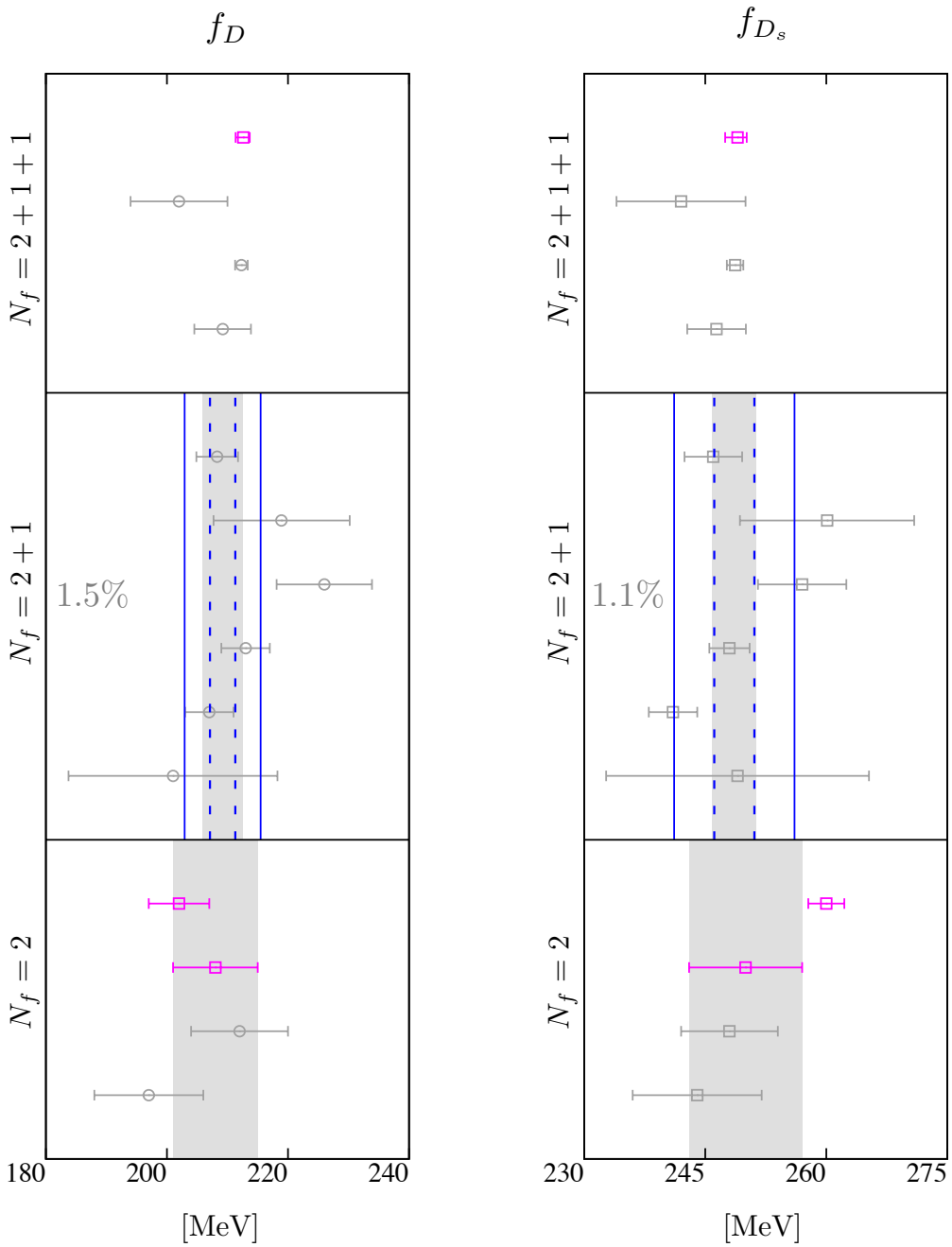
Now: $\sim 5.5\%(\mathcal{B}),\ < 1.5\%(\tau_D)$ $\quad < 0.4\%(M_D)$ $\quad < 0.06\%$ $\quad f_{D_{(s)}} \sim 3\%$

new BESIII result (PRD 89, 051104 (2014)): $\mathcal{B}(D \to \mu\nu)$ is 5.2%

2020: $\sim 2\%(\mathcal{B}),\ < 1\%(\tau_D)$ $\quad f_{D_{(s)}} \sim 1\%$

BelleII, 1002.5012

BESIII, 0809.1869



pre LAT'13:

Aoki et al. (FLAG), 1310.8555

new (since LAT'13):

Bazavov et al. (FNAL/MILC), *preliminary*

Chen et al. (TWQCD), 1404.3648

Carrasco et al. (ETM), JHEP **03** (2014) 016

experiment (now):

Amhis et al. (HFAG), 1207.1158

Eisenstein et al. (CLEO), PRD **78**, 052003 (2008)

Ablikim et al. (BESIII), PRD **89**, 051104 (2014)

experiment (∼2020):

Asner et al. (BESIII), 0809.1869

Akeroyd et al. (BelleII), 1002.5012

$|V_{cd}|$ and $|V_{cs}|$ from leptonic $D_{(s)}$ decays

$$\mathcal{B}(D \to \mu\nu), f_D(\text{FLAG } 2+1) \Longrightarrow |V_{cd}| = 0.2202(35)_{\text{QCD}}(57)_{\text{expt}}$$

$$\left.\begin{array}{r} \mathcal{B}(D_s \to \tau\nu), f_{D_s}(\text{FLAG } 2+1) \Longrightarrow |V_{cs}| = 0.988(29) \\ {}^{*}\mathcal{B}(D_s \to \mu\nu), f_{D_s}(\text{FLAG } 2+1) \Longrightarrow |V_{cs}| = 1.026(32) \end{array}\right\} \; |V_{cs}|_{\text{avg}} = 1.007(11)_{\text{QCD}}(21)_{\text{expt}}$$

Check 2nd row unitarity: $|V_{cd}|^2 + |V_{cs}|^2_{\text{avg}} + |V_{cb}|^2_{\text{PDG}} = 1.064(22)_{\text{QCD}}(42)_{\text{expt}}$

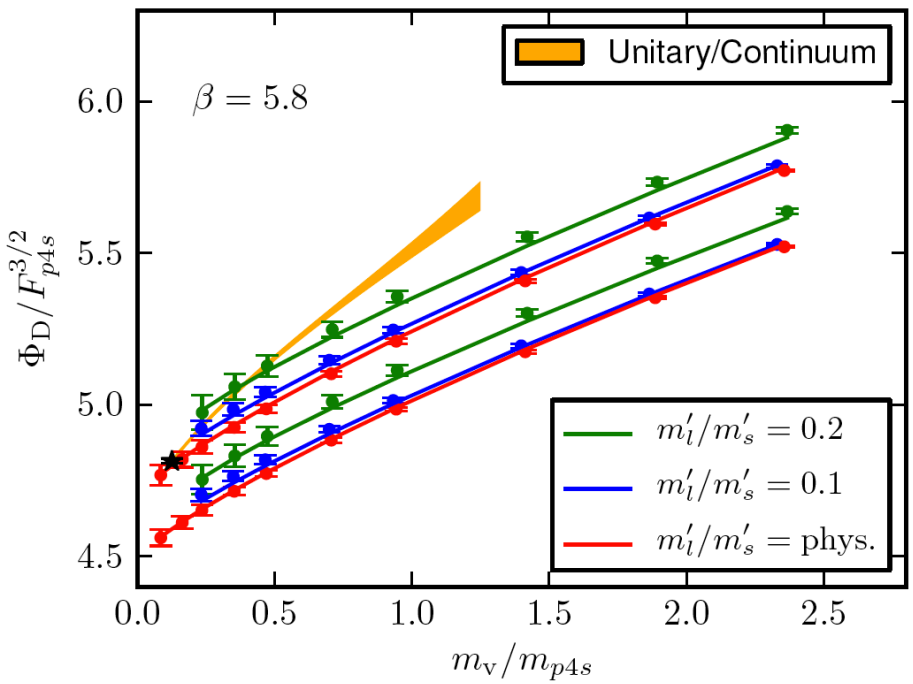
* HFAG's $\mathcal{B}(D_s \to \mu\nu)$ reduced by 1% to account for radiative corrections (Dobrescu & Kronfeld, PRL 100, 241802 (2008)). BESIII and CLEO account for this correction in reported $\mathcal{B}$s.

$$D_{(s)} \to \ell\nu$$

FNAL/MILC Bazavov et al. (FNAL/MILC), *preliminary*

Javad Komijani; 25th @ 12:10; sess. 6

MILC 2+1+1 HISQ
HISQ valence quarks
a: 0.06, 0.09, 0.12, 0.15 fm
Mpi: 130 – 349 MeV
2 analyses:
- physical masses only (no ChPT)
- partially quenched masses (stagg ChPT)



$$f_{D^+} = 212.6(0.4)(^{+1.0}_{-1.2})\ \text{MeV}$$

$$f_{D_s} = 249.0(0.3)(^{+1.1}_{-1.5})\ \text{MeV}$$

$$f_{D_s}/f_{D^+} = 1.1712(10)(^{+29}_{-32})$$

FNAL/MILC
MILC 2+1 asqtad sea
FNAL charm/bottom and asqtad light/strange
a: 0.045, 0.06, 0.09, 0.12, 0.15 fm
light-quark sea masses down to 1/20 of the strange-quark mass

Ethan Neil; 25th @ 12:30; sess. 6

Analysis includes c and b decay constants.

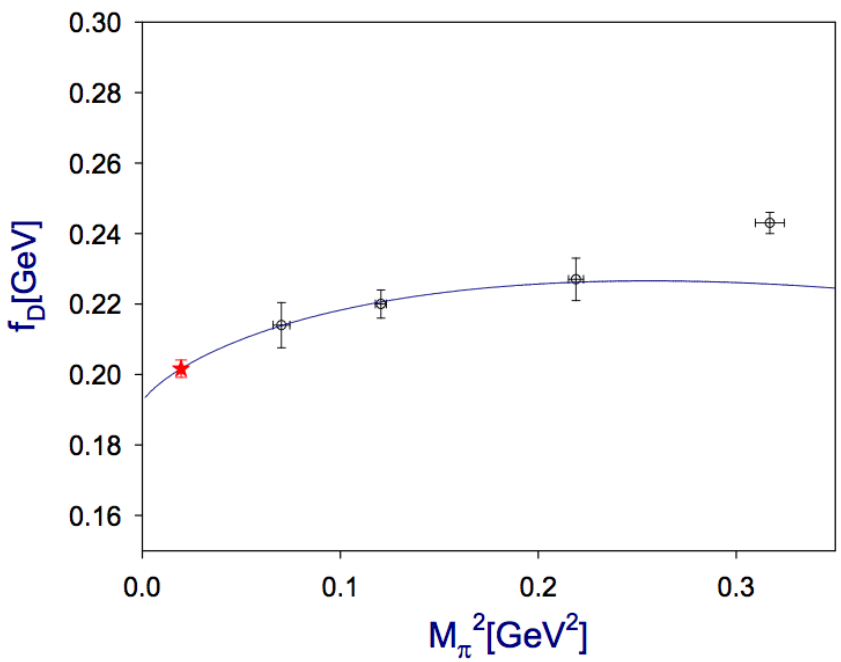
$$D_{(s)} \to \ell\nu$$

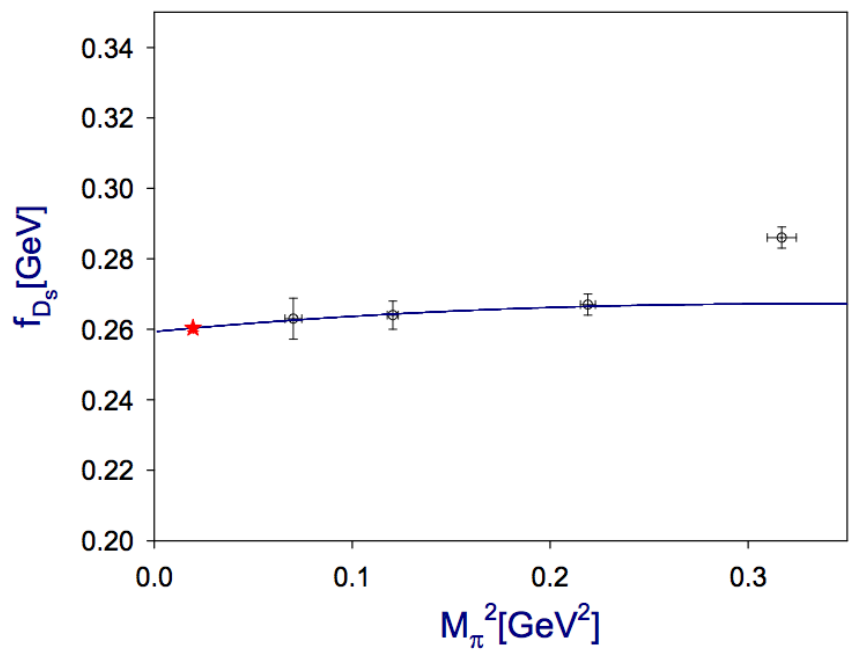
TWQCD Chen et al. (TWQCD), 1404.3648

Nf = 2 optimal DW, plaquette gauge action
DW valence quarks
a ~ 0.062 fm, 24^3x48, expected errors O(a^2)
Mpi: 265 – 560 MeV

Ting-Wai; 23rd @ 16:30; sess. 2

$$f_D = 202(3)_{\rm stat}(4)_{\rm syst}\ \text{MeV} \qquad f_{D_s} = 260(2)_{\rm stat}(1)_{\rm syst}\ \text{MeV} \qquad \frac{f_{D_s}}{f_D} = 1.287(34)$$





$$D_{(s)} \to \ell\nu$$

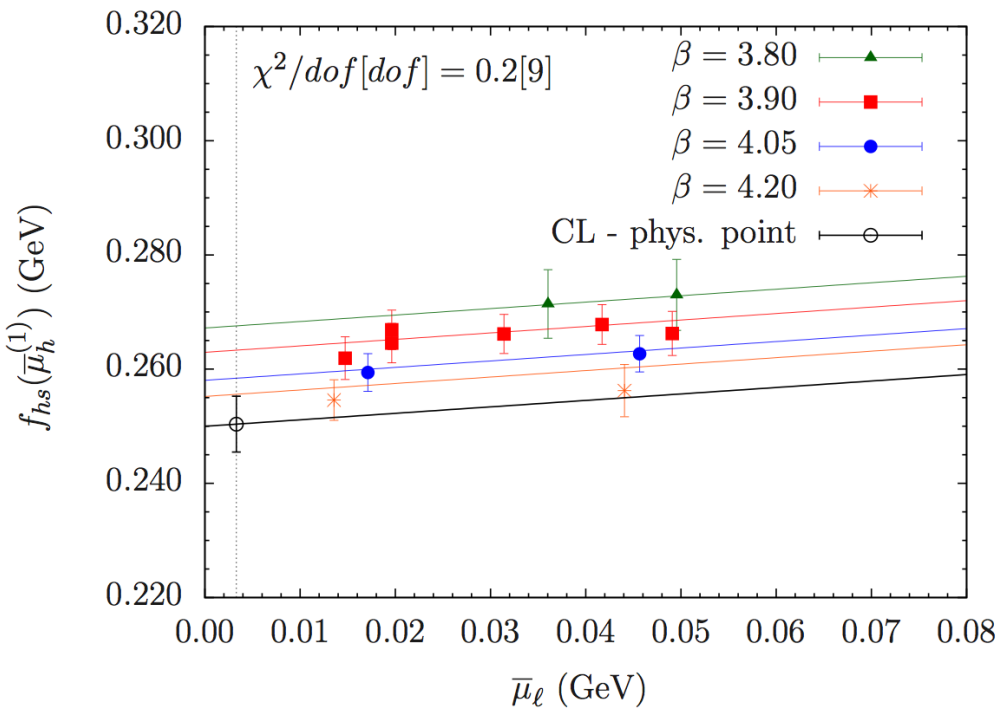
ETM Carrasco et al. (ETM), JHEP **03** (2014) 016

Nf=2 max. twisted mass, tree-level improved Symanzik gauge action (automatic O(a) improvement)
twisted mass valence light and strange
charm is triggering (starting) point in iterative process to interpolate to mb
4 lattice spacings ranging from 0.05 – 0.1 fm
Mpi: 280 – 500 MeV

$$f_D = 208(4)_{\rm stat}(6)_{\rm syst}\ \text{MeV}$$

$$f_{D_s} = 250(5)_{\rm stat}(5)_{\rm syst}\ \text{MeV}$$

$$\frac{f_{D_s}}{f_D} = 1.201(7)_{\rm stat}(20)_{\rm syst}$$



… and updated results at the physical point

Bartosz Kostrzewa; 27$^{\rm th}$ @ 15:35; sess. 2

$$D_{(s)} \to \ell\nu$$

Southampton-Edinburgh-KEK Collaboration: pilot study of DW charm

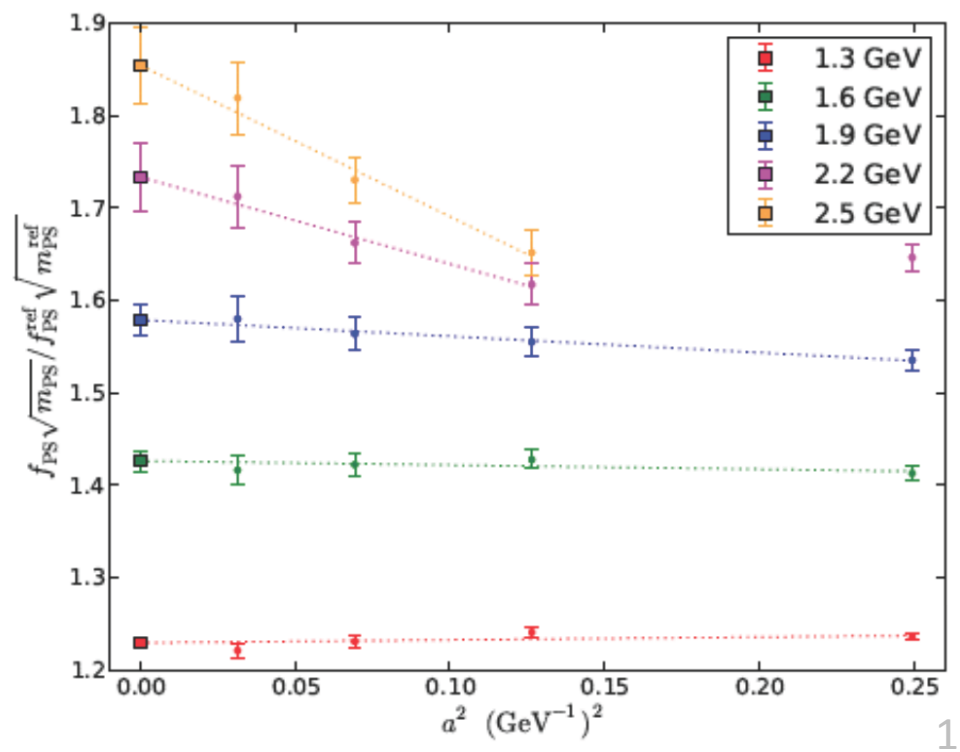
Quenched: up to 1/a ~ 6 GeV, hvy-q properties should be similar in dynamical simulations
Study spectrum and decay constants for several masses up to charm
Plan to use RBC/UKQCD and KEK 2+1 and 2+1+1 DW cfgs with DW light, strange, and charm valence

found:

- can tune distance in 5th dimension to minimize discretization effects
- flat a^2 scaling over range of a
- retain DW perks (chirality -> simple mixing under renormalization)

Tobias Tsang; 25th @ 11:10; sess. 6

L/a	a(fm)	a^{-1}(GeV)	L(fm)	β
16	0.0987(34)	2.00(07)	1.579(55)	4.41
24	0.0702(22)	2.81(09)	1.686(52)	4.66
32	0.0520(16)	3.80(12)	1.664(51)	4.89
48	0.0350(13)	5.64(22)	1.682(63)	4.94



$$D_{(s)} \to \ell\nu$$

RBC/UKQCD (based on findings of quenched study)
Nf=2+1 DW ensembles
1/a: 1.7, 2.3 GeV
Mpi: physical – 420 MeV
valence m_h <~ m_c

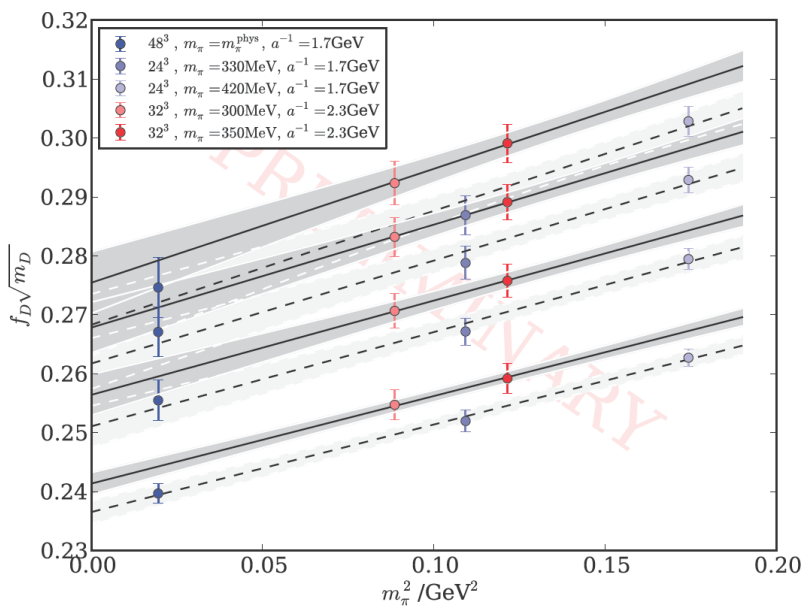
Andreas Jüttner; 25th @ 11:30; sess. 6

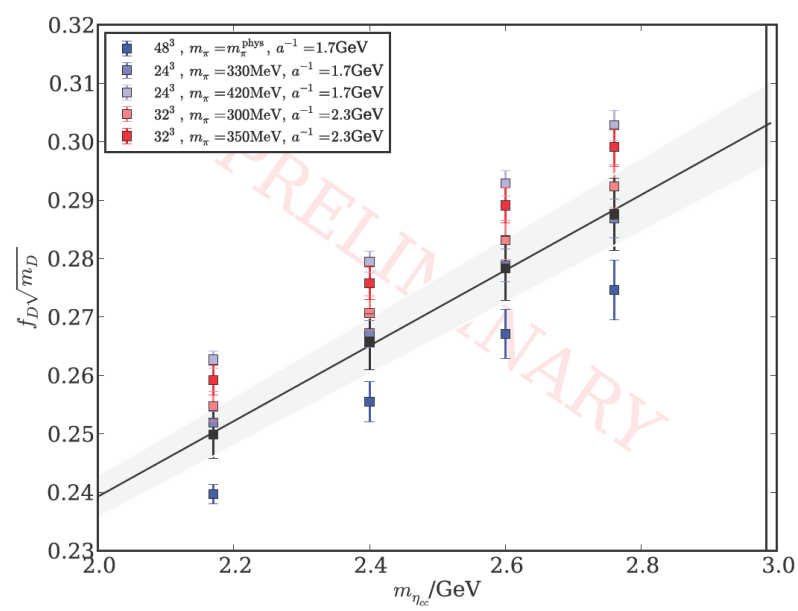
results:

- a^2 scaling similar to quenched study (2 lattice spacings – work in progress)
- no evidence of chiral logs

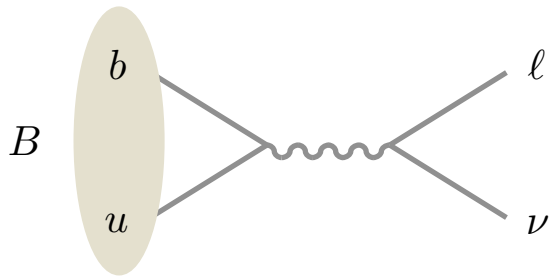
plans:

- add 1/a = 3 GeV and increase statistics
- spectrum, decay constants, mixing, vacuum polarization for muon g-2, semileptonic decays
- extrapolate/interpolate to mb





$$B \to \ell\nu$$



$$\underbrace{\mathcal{B}(B \to \ell\nu)}_{} = \underbrace{\tau_B \frac{G_F^2}{8\pi} m_\ell^2 M_B \left(1 - \frac{m_\ell^2}{M_B^2}\right)^2}_{} \; f_B^2 \; |V_{ub}|^2$$

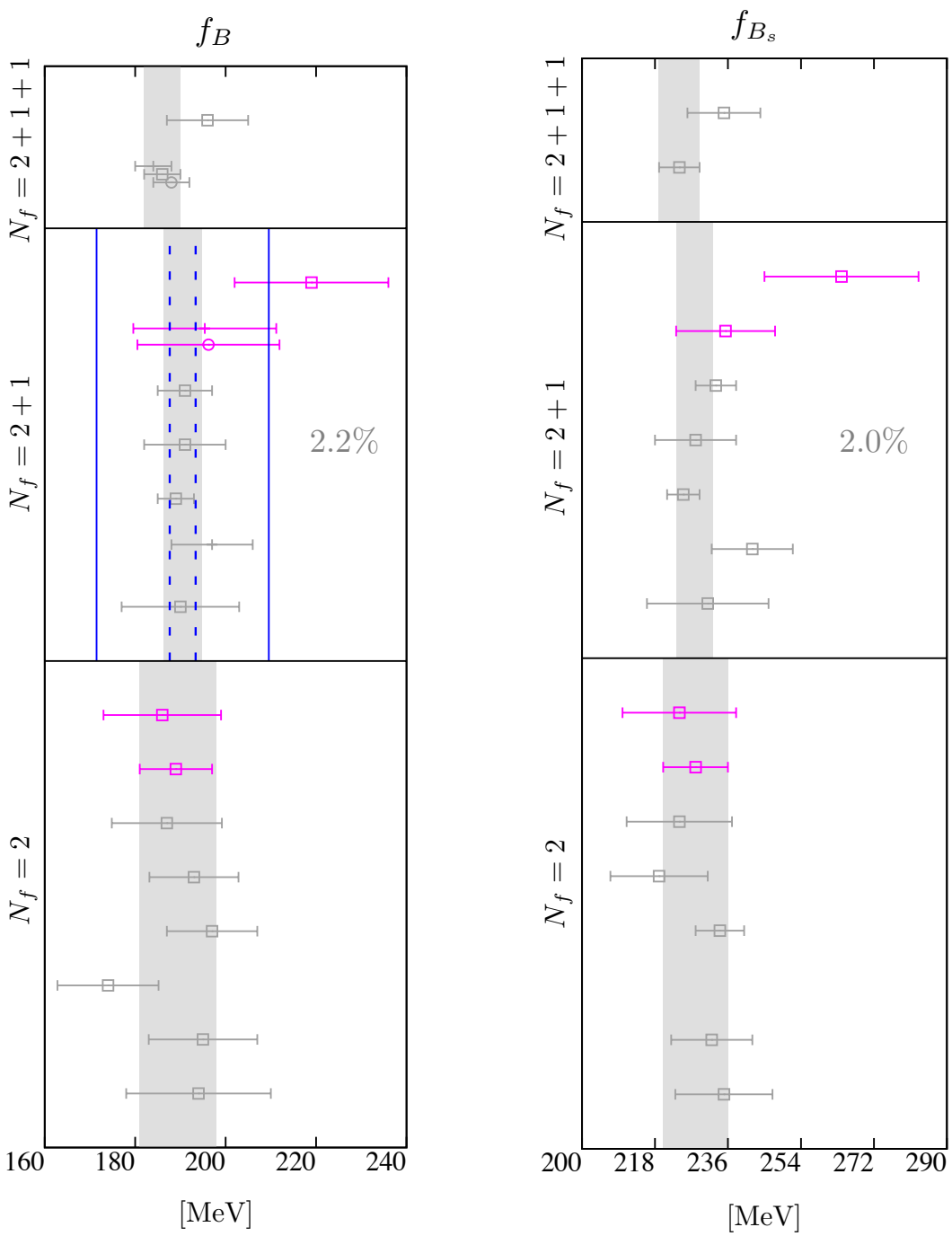
Now: 20-25% $< 0.5\%(\tau_B)$ $f_B \sim 10\%$

BaBar 2010: $10^6 \mathcal{B}(B \to \tau\nu) = 179 \pm 48$

Belle 2013: $10^6 \mathcal{B}(B \to \tau\nu) = 96 \pm 26$

2020: $\sim 3\%$ $f_B \sim 1.5\%$

BelleII, 1002.5012



f_{B^+}

f_{B^0}

f_B

pre LAT'13:

Aoki et al. (FLAG), 1310.8555

new (since LAT'13):

Ishikawa et al.

Christ et al. (RBC/UKQCD), 1404.4670

Bernardoni et al. (ALPHA), 1404.3590

Carrasco et al. (ETM), JHEP **03** (2014) 016

experiment (now):

Amhis et al. (HFAG), 1207.1158

experiment (∼2020):

Akeroyd et al. (BelleII), 1002.5012

$|V_{ub}|$ from leptonic B decay

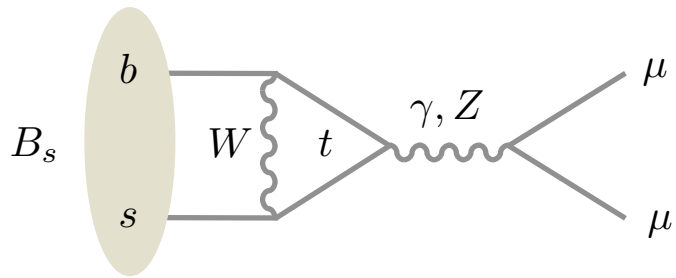
Using FLAG averages for $f_B(N_f = 2+1)$ and $\mathcal{B}(B \to \tau\nu)$

$$10^3|V_{ub}| = 4.18(9)_{\rm QCD}(52)_{\rm expt}$$

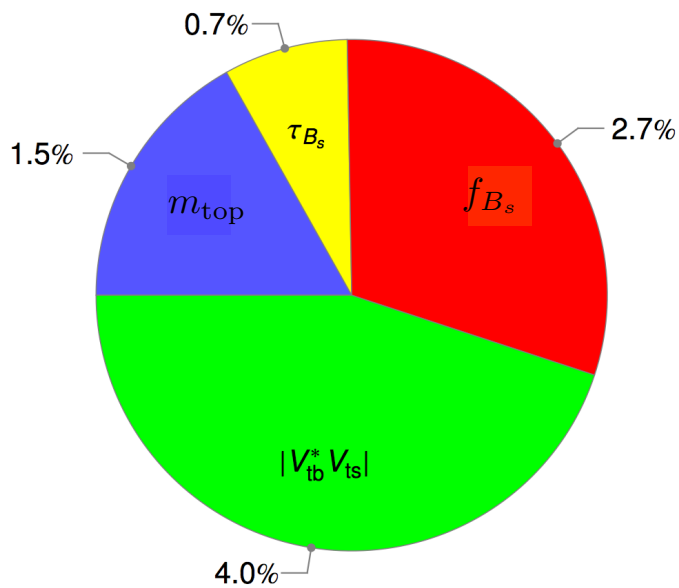
Not the most precise way of getting at $|V_{ub}|$,

but there is reason to continue pushing lattice calculations...

$f_{B_{(s)}}$ also useful input for other processes, e.g. $B_s \to \mu\mu$



$$\mathcal{B}(B_s \to \mu^+\mu^-)_{\rm SM} = 3.25 \times 10^{-9} \left(\frac{m_{\rm top}}{173.2\,{\rm GeV}}\right)^{3.07} \left(\frac{f_{B_s}}{225\,{\rm MeV}}\right)^2 \left(\frac{\tau_{B_s}}{1.500\,{\rm ps}}\right) \left|\frac{V_{tb}^* V_{ts}}{0.0405}\right|^2$$



Buras et al., JHEP **07** (2013) 077

$B \to \ell\nu$

RBC/UKQCD Christ et al. (RBC/UKQCD), 1404.4670

Nf=2+1 DW, Iwasaki gauge action
DW light and strange; non-pert tuned RHQ action b quarks

Oliver Witzel; 25th @ 9:40; sess. 6

a: 0.08 – 0.11 fm
Mpi: 289 – 422 MeV

fB, fBs/fB: NLO SU(2) HMChPT combined chiral-continuum extrapolation
fBs: linear interpolation to ms, followed by continuum extrapolation linear in a^2

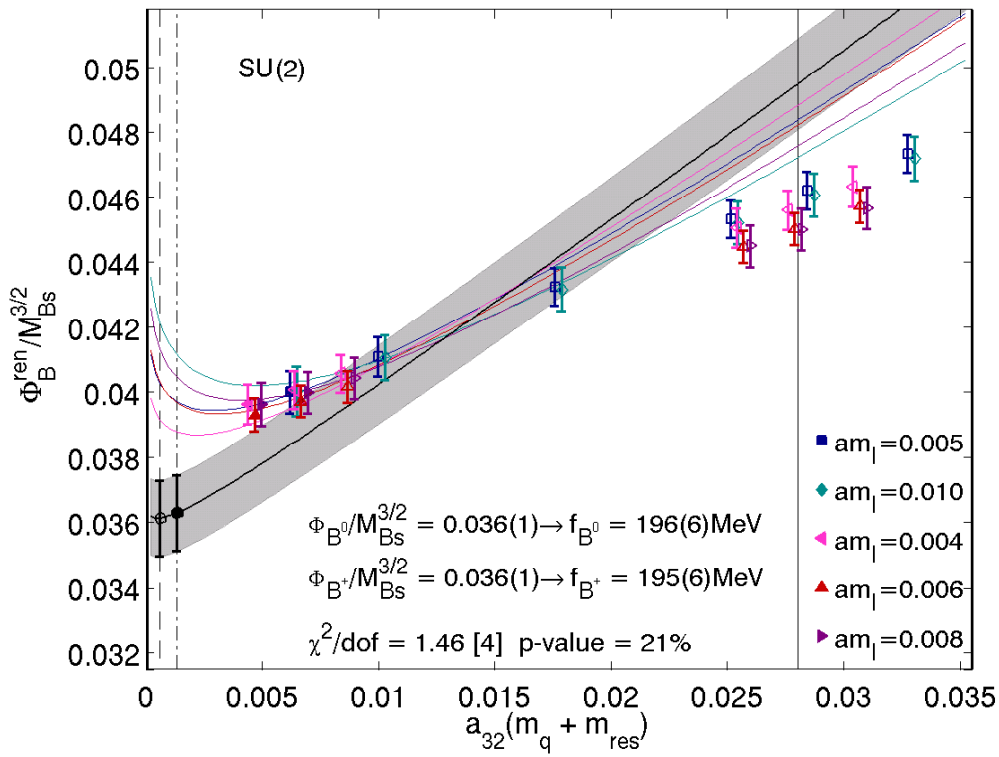
$$f_{B^+} = 195.4(15.8)\ \text{MeV}$$

$$f_{B^0} = 196.2(15.7)\ \text{MeV}$$

$$f_{B_s} = 235.4(12.2)\ \text{MeV}$$

$$\frac{f_{B_s}}{f_{B^+}} = 1.220(82)$$

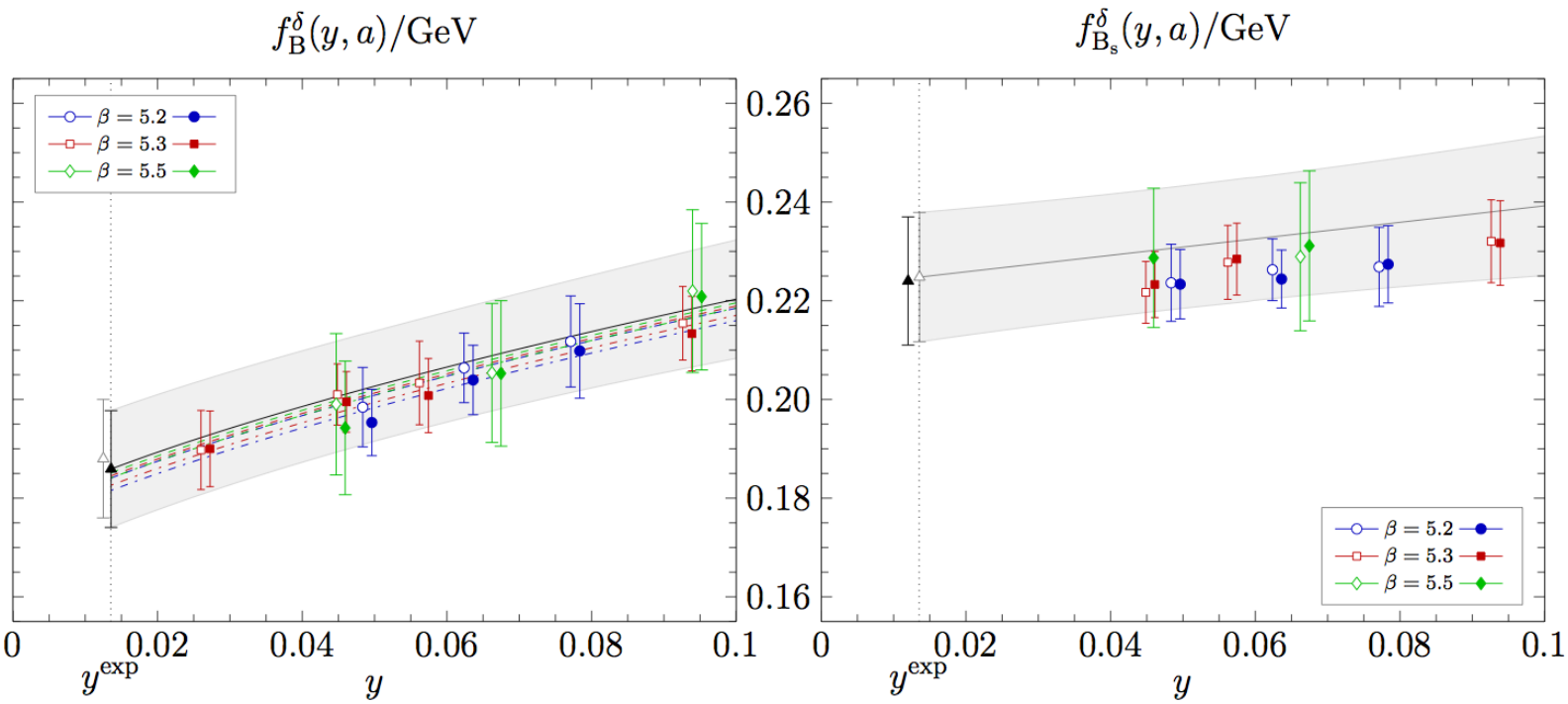
$$\frac{f_{B_s}}{f_{B^0}} = 1.193(59)$$



$$B \to \ell\nu$$

ALPHA Bernardoni et al. (ALPHA), 1404.3590

Nf=2 cfgs with non-pert O(a) improved Wilson sea, Wilson gauge action
HQET b, non-pert NLO improvement
O(a) improved Wilson valence quarks
a: 0.05 – 0.08 fm
Mpi: 190 – 440 MeV



$$f_B = 186(13)\ \mathrm{MeV} \qquad f_{B_s} = 224(14)\ \mathrm{MeV} \qquad \frac{f_{B_s}}{f_B} = 1.203(65)$$

$B \to \ell\nu$

ETM Carrasco et al. (ETM), JHEP **03** (2014) 016

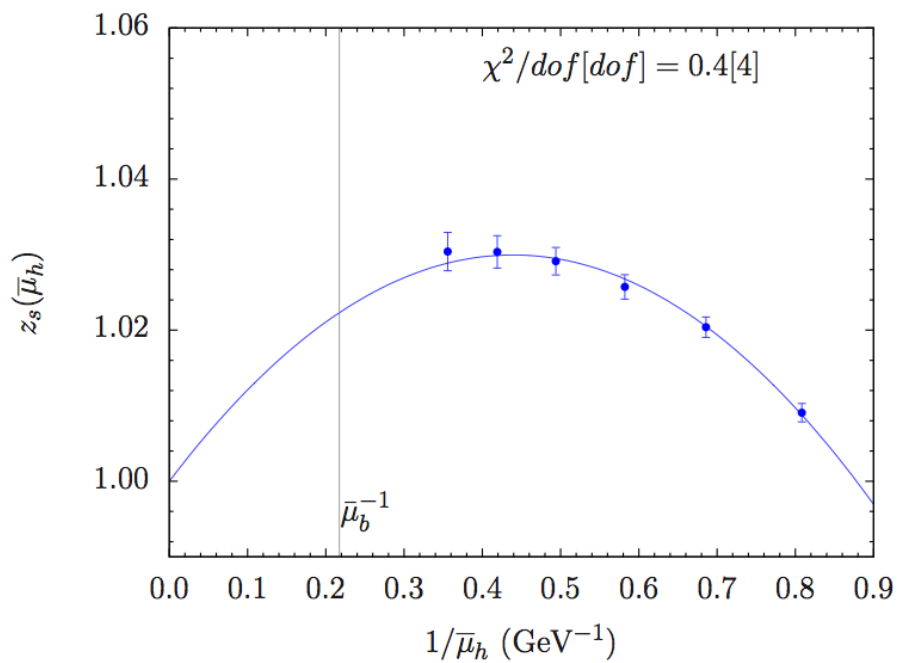
Nf=2 maximally twisted mass, tree-level improved Symanzik gauge action
maximally twisted mass valence with ratio method b JHEP **04** (2010) 049, JHEP **01** (2012) 046
a: 0.05 – 0.1 fm
Mpi: 280 – 500 MeV

- linear chiral-continuum extrapolation: double ratio (fBs/fB)/(fK/fPi) vs. fBs/fB
- directly calculate fB and fBs/fB

$$f_B = 189(8)\ \text{MeV}$$

$$f_{B_s} = 228(8)\ \text{MeV}$$

$$\frac{f_{B_s}}{f_B} = 1.206(24)$$



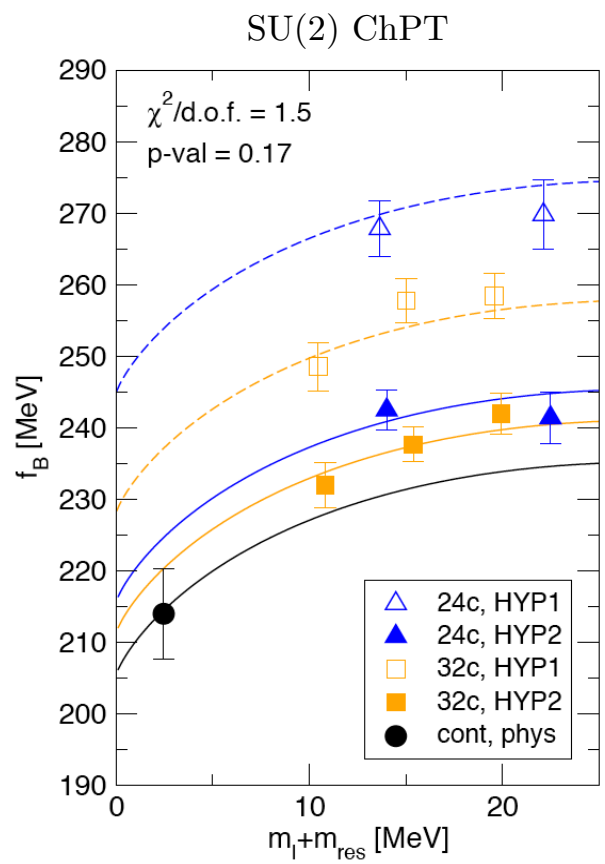
$B \to \ell\nu$

Ishikawa, Aoki, Izubuchi, Lehner, and Soni (to appear on arXiv tonight)

Idea
— anchor a HQ expansion with results in static limit
— relativistic heavy quark action for mQ ~ mc
— iterate between mc and anchor point ala ETM ratio method

Simulation
— Nf=2+1 DW, Iwasaki gauge
— static b with DW light valence
— a ~ 0.09, 0.11 fm
— Mpi: 289 – 418 MeV
— 1-loop matching (ok in static limit) including O(a) effects

Plans
— also have B-mixing results
— All-mode-averaging
— physical light quarks
— non-perturbative renormalization via RI-MOM

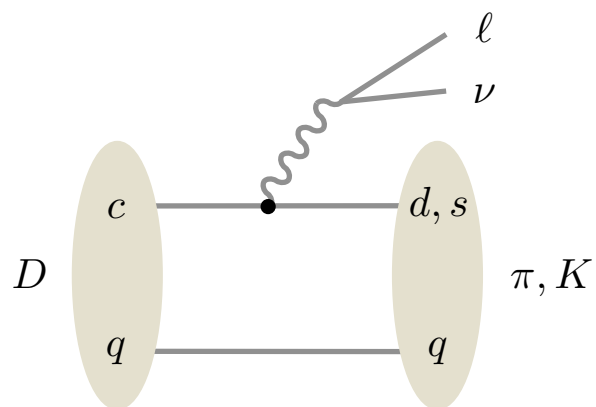


$$f_B = 218.8(6.5)_{\rm stat}(16.1)_{\rm sys}\ \text{MeV}$$
$$f_{B_s} = 263.5(4.8)_{\rm stat}(18.7)_{\rm sys}\ \text{MeV}$$
$$f_{B_s}/f_B = 1.193(20)_{\rm stat}(35)_{\rm sys}\ \text{MeV}$$

* No $\mathcal{O}(1/m_b)$ error included

Tomomi Ishikawa; 25th @ 9:20; sess. 6

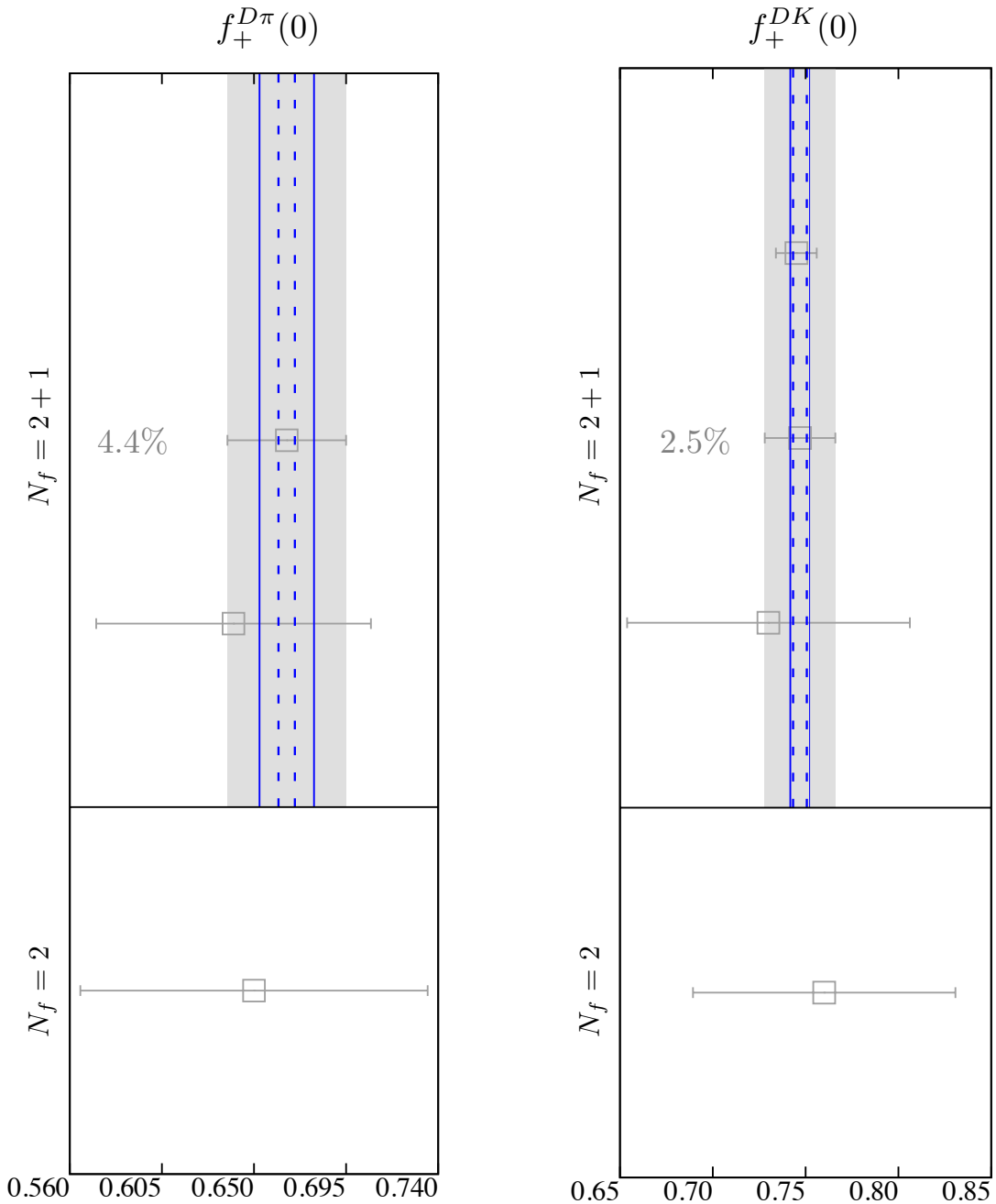
$$D \to \pi \ell \nu, \;\; D \to K \ell \nu$$



$$\underbrace{\frac{d\mathcal{B}(D \to P\ell\nu)}{dq^2} = \tau_D \frac{G_F^2 |\mathbf{p}_P|^3}{24\pi^3}}\; |V_{cx}|^2 \; |f_+|^2 \; + \mathcal{O}\left(\frac{m_\ell^2}{q^2}\right)$$

$< 10^{-9}\,\%$

Now:	$\mathcal{B}(D \to \pi e \nu)$: 4.0%	$f_+^{D\pi}$: 2.0%
	$\mathcal{B}(D \to K e \nu)$: 1.4%	f_+^{DK} : 0.7%
2020:	$\mathcal{B}(D \to \pi e \nu)$: 1.2%	$f_+^{D\pi}$: 0.6%
	$\mathcal{B}(D \to K e \nu)$: 1.0%	f_+^{DK} : 0.5%



pre LAT'13:

Aoki et al. (FLAG), 1310.8555

Koponen et al. (HPQCD), 1305.1462

experiment (now):

Amhis et al. (HFAG), 1207.1158

experiment (∼2020):

Asner et al. (BESIII), 0809.1869

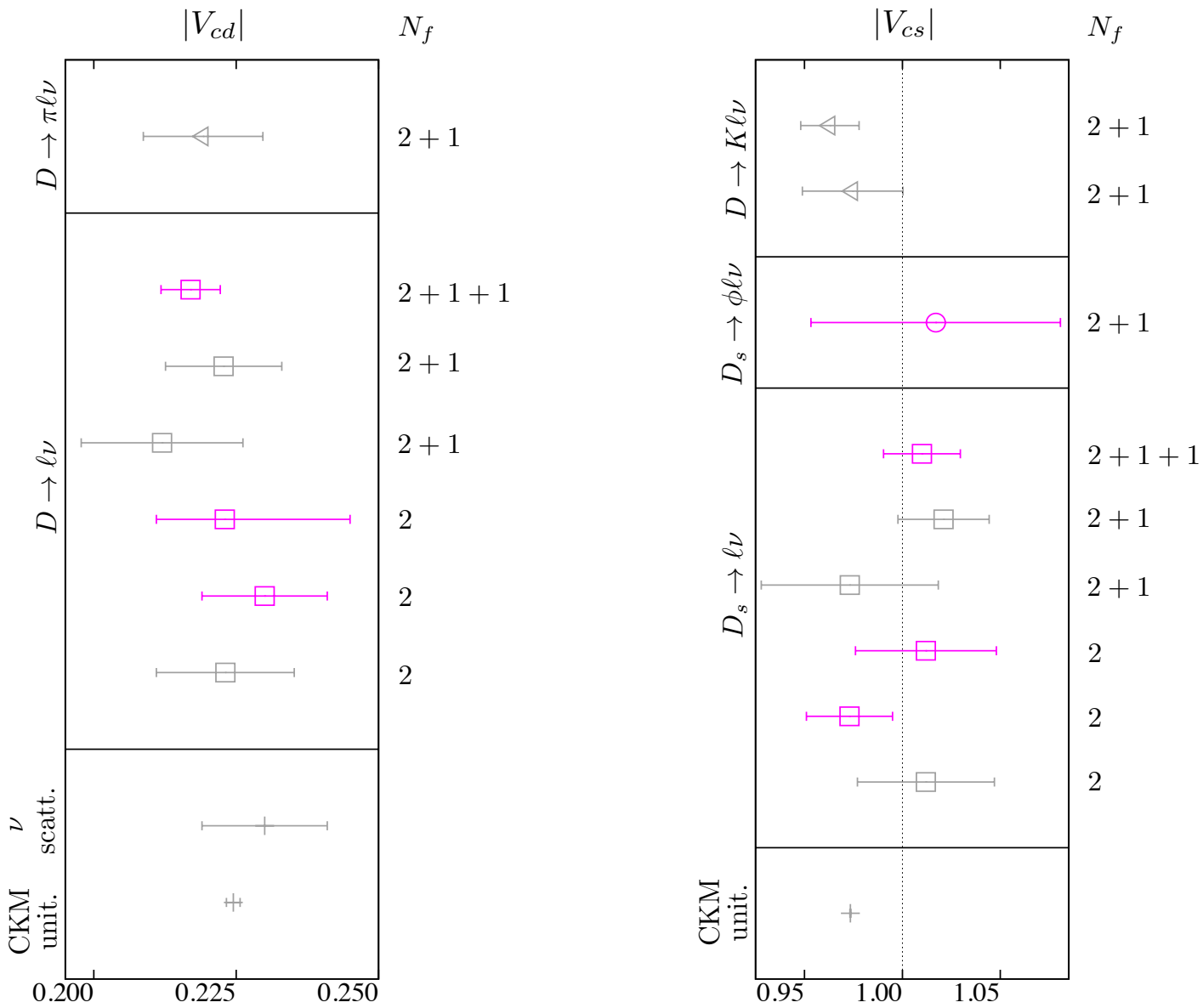
Akeroyd et al. (BelleII), 1002.5012

Semileptonic $|V_{cd}|$ and $|V_{cs}|$ (FLAG):

$$|V_{cd}| = 0.2192(95)_{\mathrm{QCD}}(45)_{\mathrm{expt+theory}}$$

$$|V_{cs}| = 0.9746(248)_{\mathrm{QCD}}(67)_{\mathrm{expt+theory}}$$

$|V_{cd}|$ and $|V_{cs}|$ from different processes



$$D \to \pi \ell \nu, \; D \to K \ell \nu$$

FNAL/MILC

MILC Nf=2+1+1 HISQ ensembles with HISQ valence
a: 0.06, 0.09, 0.12 fm
physical quark mass

Thomas Primer; poster

Calculating scalar form factors at q^2=0 (twisted bcs)

- f+(0) = f0(0)
- scalar matrix element absolutely normalized (no matching)
- twisted bc's
- plan to study form factors at q^2 > 0

FNAL/MILC

MILC Nf=2+1 astad sea/valence with FNAL charm
a: 0.045, 0.06, 0.09, 0.12 fm
Mpi: 200 - 500 MeV

looking at q^2 > 0

Plan to form ratios of form factors with D(s) decay constants.

- cancellation of charm quark discretization effects
- combine with FNAL/MILC Nf=2+1+1 HISQ decay constants

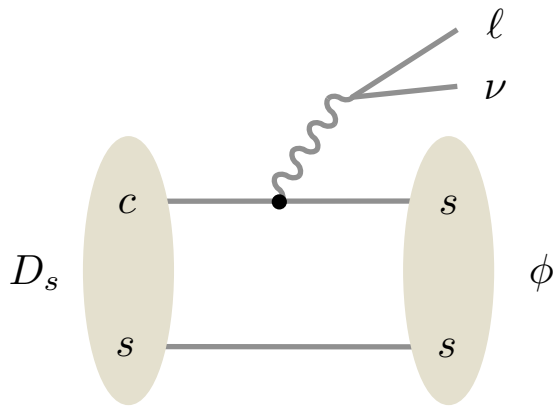
ETM

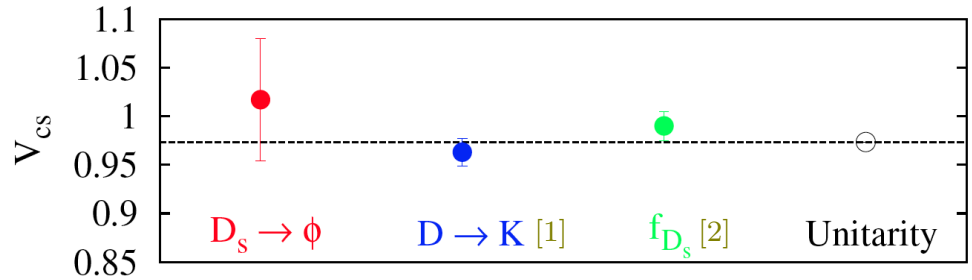
ETM Nf=2+1+1 twisted mass gauge fields
three lattice spacings
Mpi as light as 210 MeV

Lorenzo Riggio; 27th @ 17:10; sess. 6

$D_s \to \phi \ell \nu$

Donald et al. (HPQCD), 1311.6669





[1] Koponen et al. (HPQCD), 1305.1462

[2] Davies et al. (HPQCD), PRD **82**, 114504 (2010)

MILC Nf=2+1 asqtad sea, HISQ valence
a: 0.09, 0.12 fm
Mpi: 240 – 350 MeV

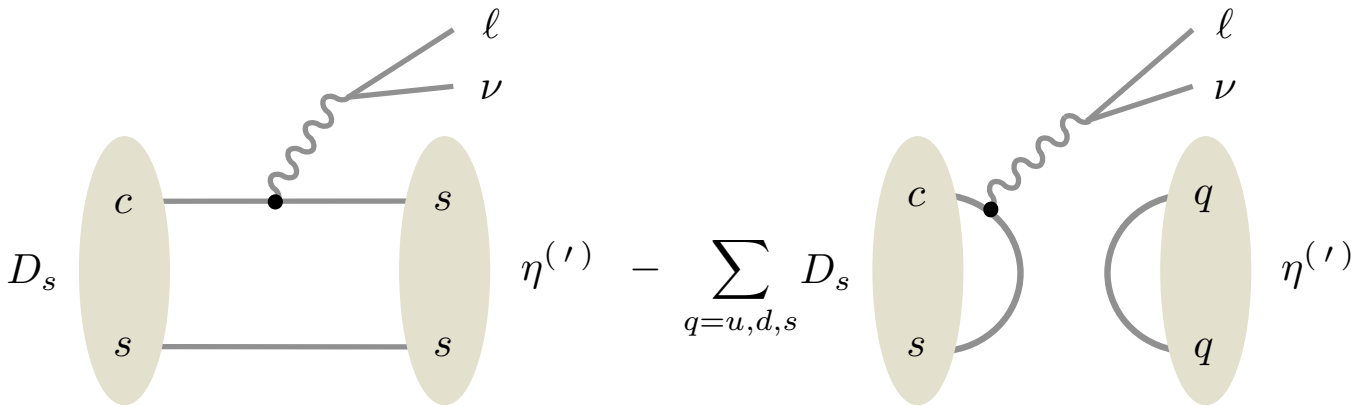
- alternative (to D->K) exclusive determination of Vcs
- first unquenched calculation of axial and vector form factors
- phi
    - strong decay to K\barK
    - neglect disconnected contributions
    - estimate 3% error on matrix element

Vcs = 1.017 (44)latt (35)expt (30)K\barK

expt error expected to be reduced by a factor of ~4 at BESIII (with 20/fb)

$D_s \to \eta^{(\prime)} \ell \nu$

Kanamori, Bali, Collins, and Durr (SFB-TR55)

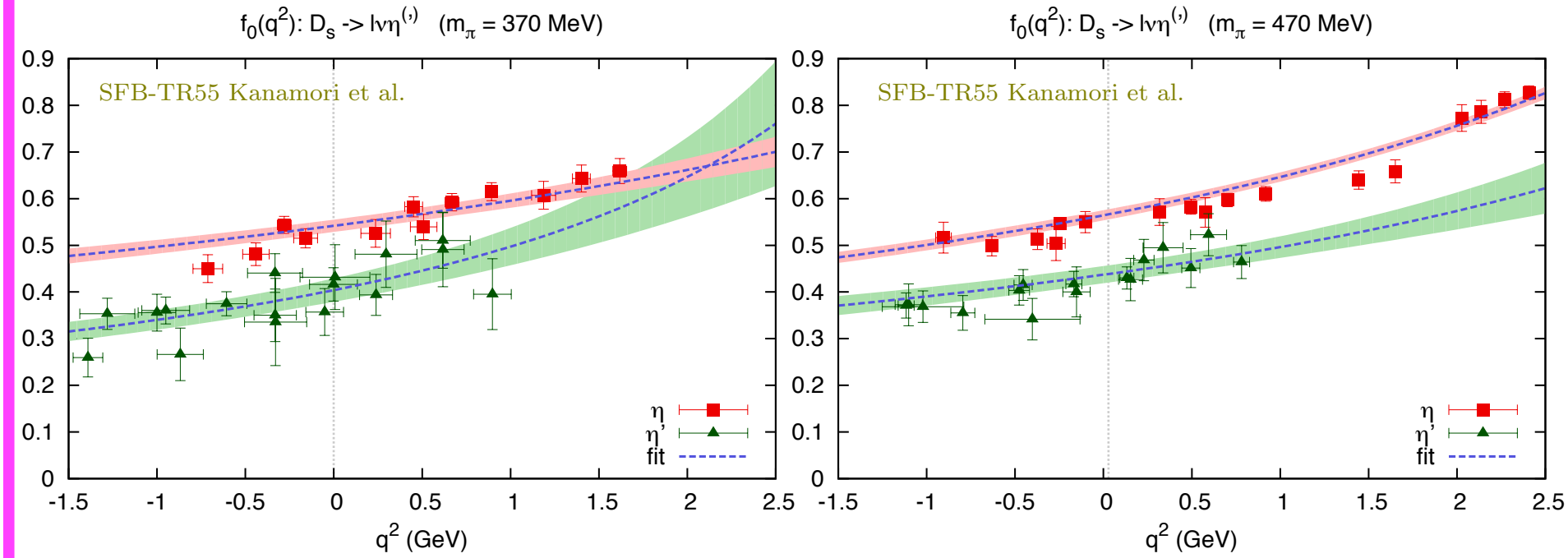


Exploratory calculation:

- focus on scalar form factor, $f_0(q^2)$
- include disconnected contributions, important for $D_s \to \eta'$
- QCDSF $N_f = 2 + 1$ stout link, nonperturbatively improved clover
- M_π: 370, 470 MeV ($m_u = m_d = m_s \Longrightarrow M_\eta = M_\pi$)
- $a = 0.075$ fm ($24^3 \times 48$)

$D_s \to \eta^{(\prime)}\ell\nu$

Kanamori, Bali, Collins, and Durr (SFB-TR55)



Single-pole ansatz: $f_0(q^2) = \dfrac{f_0(0)}{1 - bq^2}$

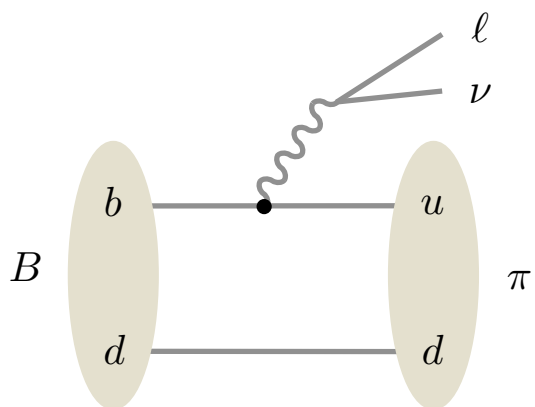
$$f_0^{D_s\eta}(0) = 0.542(13)_{\text{stat}}$$
$$f_0^{D_s\eta'}(0) = 0.404(25)_{\text{stat}}$$

$$f_0^{D_s\eta}(0) = 0.564(11)_{\text{stat}}$$
$$f_0^{D_s\eta'}(0) = 0.437(18)_{\text{stat}}$$

Plans:

- also extracting $\eta - \eta'$ mixing angles
- switching to CLS $N_f = 2 + 1$ configurations

$B \to \pi \ell \nu$



$$\frac{d\mathcal{B}(B \to \pi \ell \nu)}{dq^2} = \tau_B \frac{G_F^2 |\mathbf{p}_\pi|^3}{24\pi^3} \, |V_{ub}|^2 \, |f_+|^2 \; + \mathcal{O}\left(\frac{m_\ell^2}{q^2}\right)$$

q^2 varies from m_ℓ^2 to $(M_B - M_\pi)^2$: $\sim 0 - 26$ GeV^2

- simulation momenta $0 - 2\pi(1,1,1)/L$ covers: $\sim 26 - 18$GeV^2
- experiment most precise at small q^2
- to combine lattice and experiment, z expansion
  - based on general arguments (unitarity and analyticity)
  - maps $q^2 \to z$: $-1 < z < 1$
  - form factors are then expanded in z

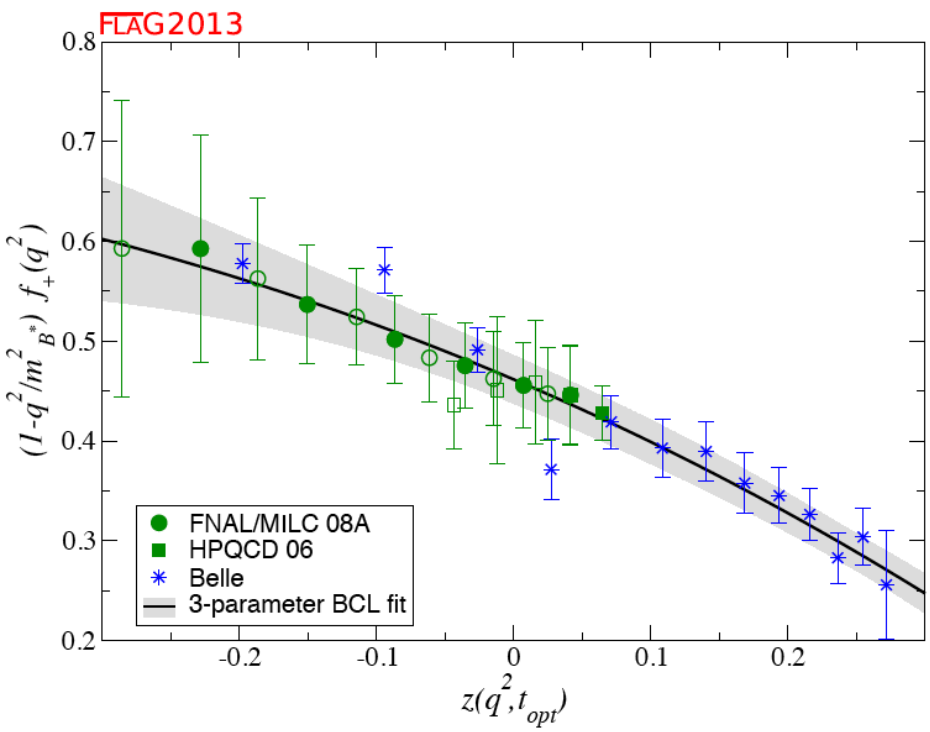
$$B \to \pi \ell \nu$$

$$\underbrace{\left(1 - \frac{q^2}{M_{B^*}^2}\right) \sqrt{\frac{d\mathcal{B}}{dq^2} \frac{24\pi^3}{\tau_B G_F^2 |\mathbf{p}_\pi|^3}}}_{} \frac{1}{|V_{ub}|} = \left(1 - \frac{q^2}{M_{B^*}^2}\right) |f_+|$$

Now: $3.9\%(d\mathcal{B}/dq^2)$

2017: 2.3%(BelleII with 5/ab)

2020: 1.9%(BelleII with 50/ab)

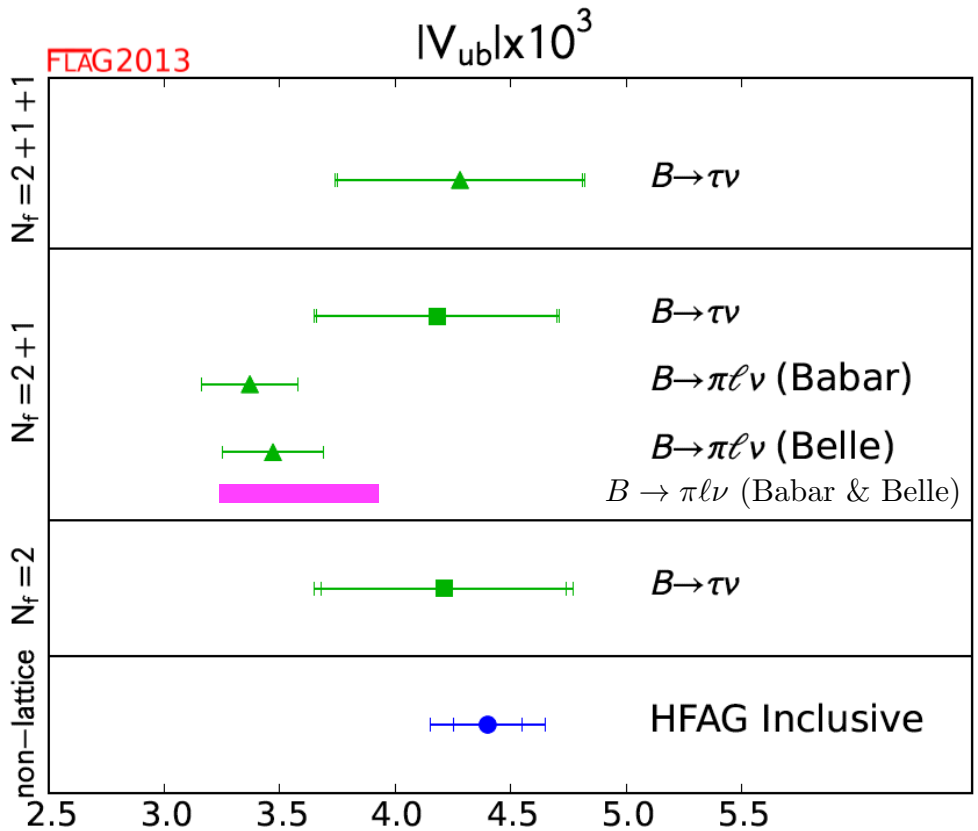


$10^3|V_{ub}| = 3.47(20)_{\rm QCD}(10)_{\rm expt}$

Error breakdown follows

BaBar, PRD 86, 092004 (2012).

$|V_{ub}|$ from different processes



RBC/UKQCD, *preliminary*

$\sim 3\sigma$ discrepancy between $B \to \pi\ell\nu$ and $B \to X_u\ell\nu$

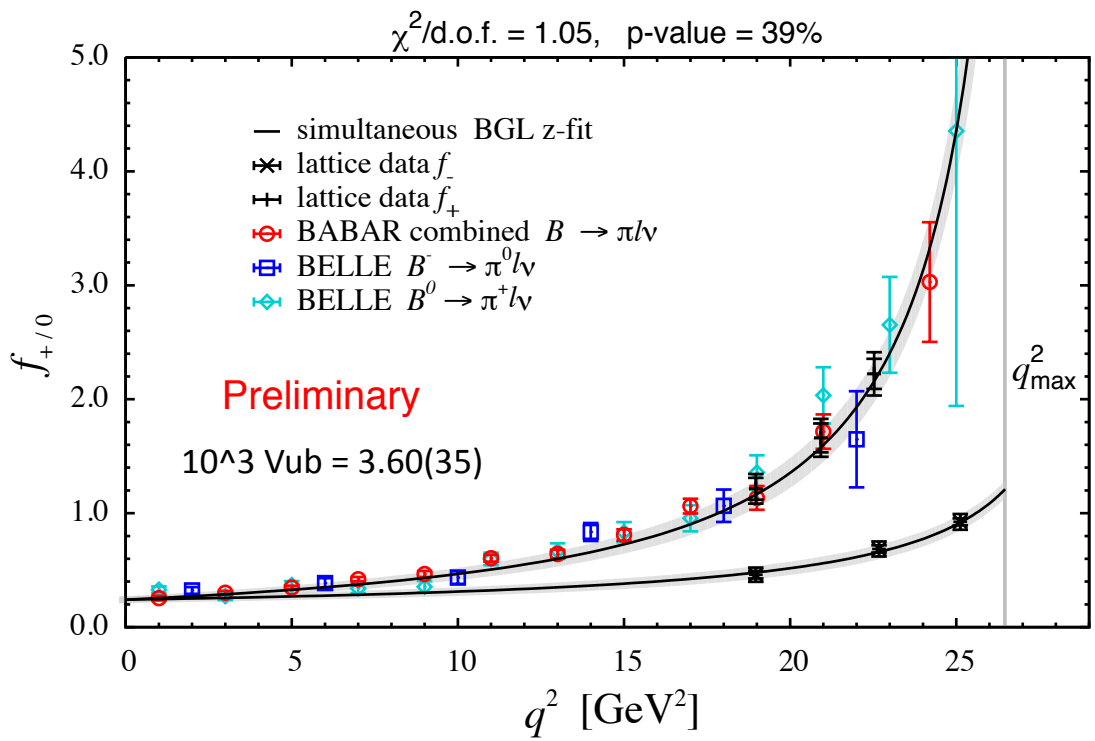
$$B \to \pi \ell \nu$$

RBC-UKQCD

2+1 flavor DW + Iwasaki gauge fields
DW light and non-pert tuned RHQ b valence
a: 0.08, 0.11 fm
Mpi: 289 – 422 MeV

Taichi Kawanai; 27th @ 16:50; sess. 6

combined chiral/continuum extrapolation with SU(2) Hard Pion ChPT
kinematic extrapolation via z-expansion



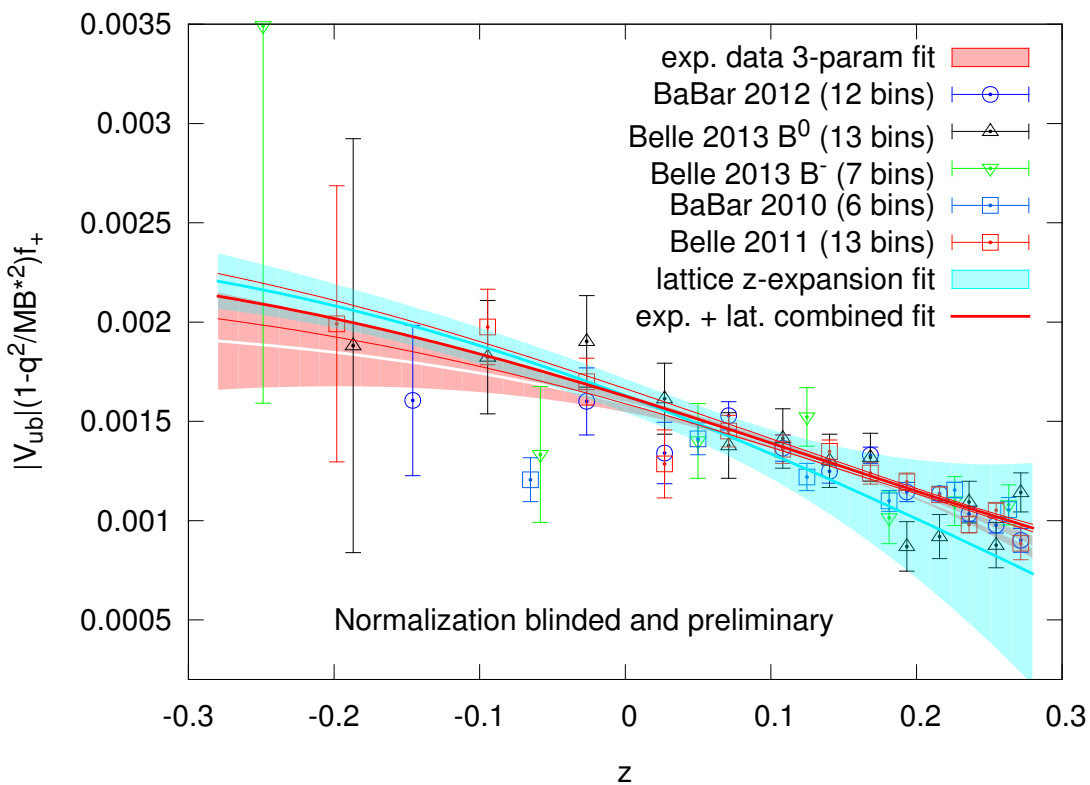
$$B \to \pi \ell \nu$$

FNAL

MILC 2+1 asqtad gauge cfgs
FNAL b with asqtad light valence
a: 0.045, 0.06, 0.09, 0.12 fm
Mpi: 177 – 450 MeV

- SU(2), hard pion, full-QCD, staggered HM ChPT
- functional z-expansion for kinematic extrapolation

Daping Du; 27th @ 16:30; sess. 6



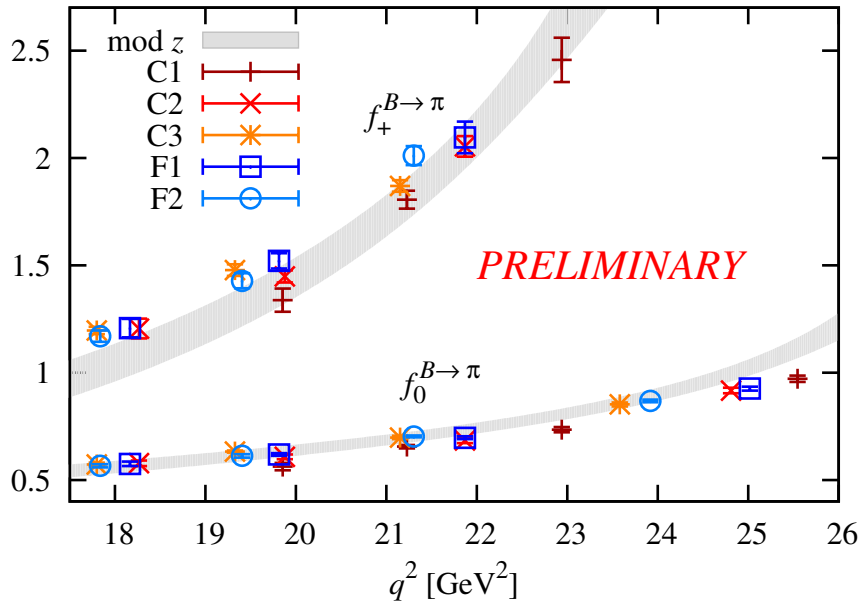
expected $|V_{ub}|$ error:

$(4.1 - 4.5)\%$

$B \to \pi \ell \nu$

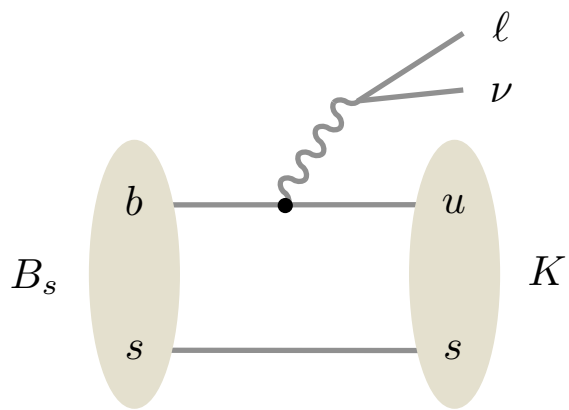
HPQCD

MILC 2+1 asqtad sea with NRQCD b and HISQ light valence
a: 0.09, 0.12 fm
Mpi: 190 – 400 MeV



- adding statistics
- exploring possibility of using Hard Pion ChPT + modified z-expansion to extend range of q^2 and improve overlap with experiment
  - p = 2pi/L (000, 001, 011, 111, 002, 003, 004)
  - would give q2 range: ~6 – 26 GeV^2

$$B_s \to K\ell\nu$$



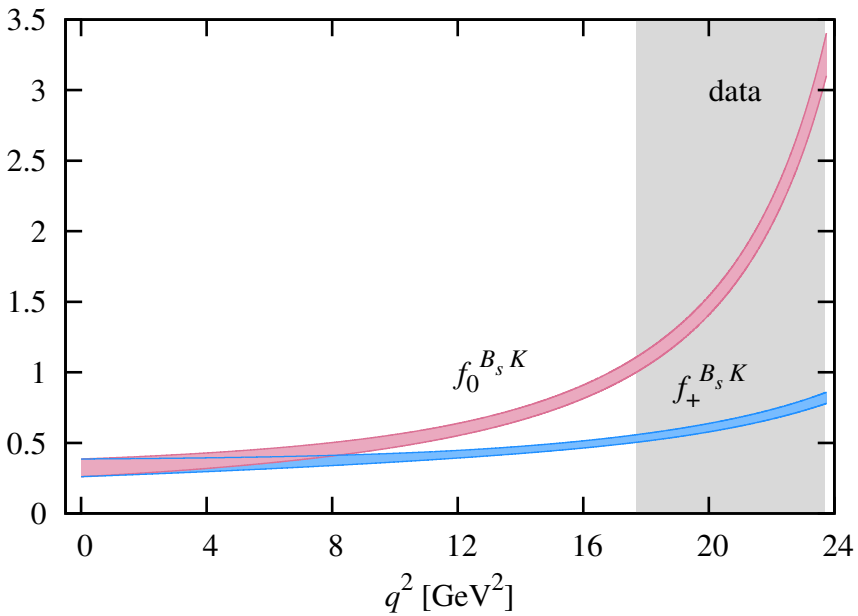
$$\frac{d\mathcal{B}(B_s \to K\ell\nu)}{dq^2} = \tau_{B_s} \frac{G_F^2 |\mathbf{p}_K|^3}{24\pi^3} \, |V_{ub}|^2 \, |f_+|^2 \; + \mathcal{O}\left(\frac{m_\ell^2}{q^2}\right)$$

- alternative exclusive $|V_{ub}|$
- not yet measured
  - prediction opportunity
  - LHCb is working on it and prospects at BelleII

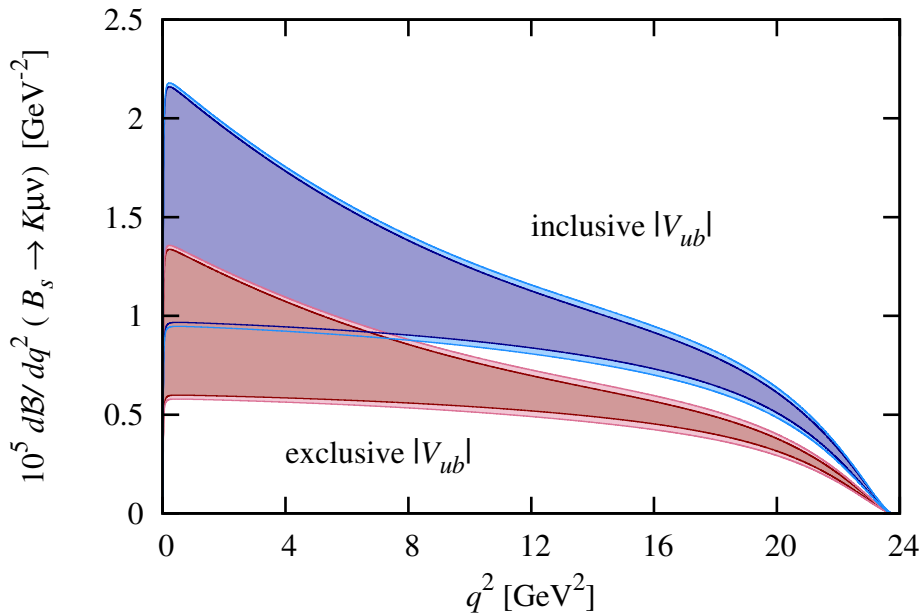
$B_s \to K\ell\nu$

HPQCD Bouchard et al. (HPQCD), 1406.2279
MILC Nf=2+1 asqtad ensembles
NRQCD b with HISQ light/strange
Mpi: 260 – 500 MeV

Heechang Na; 27th @ 17:30; sess. 6



simultaneous chiral, continuum, and kinematic extrapolation via "HPChPT z-expansion"



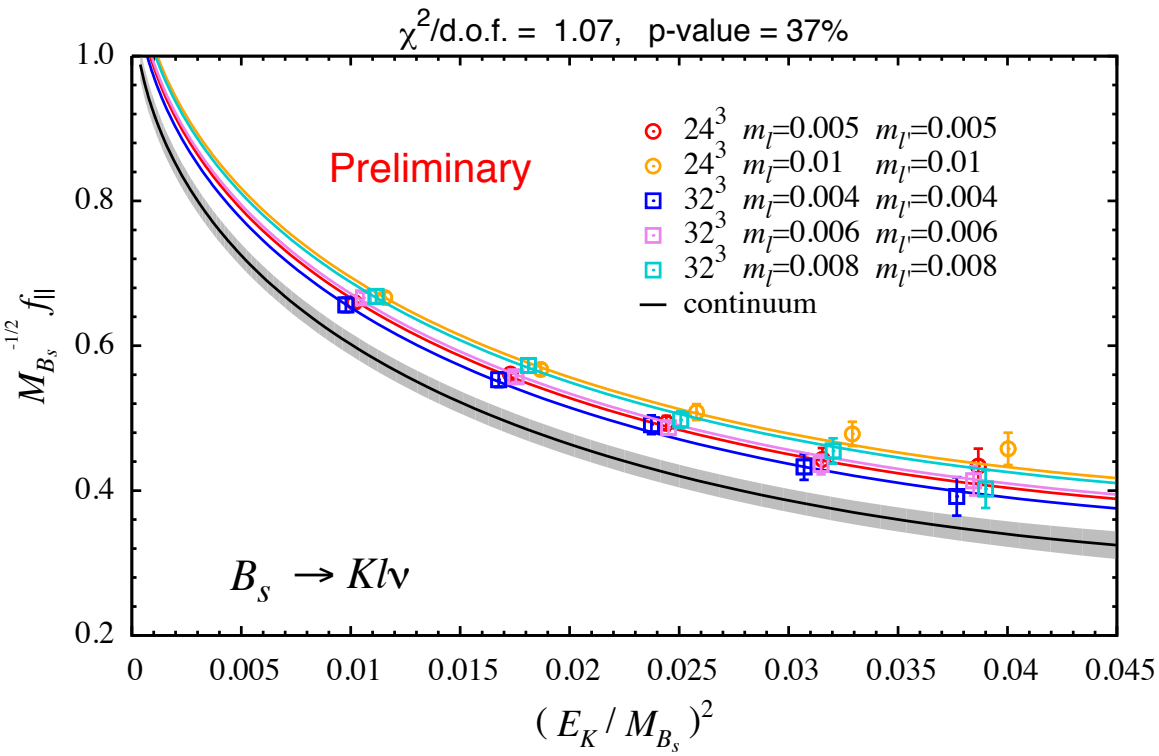
measurement at large q^2 with comparable error could distinguish between inclusive and exclusive Vub

$B_s \to K\ell\nu$

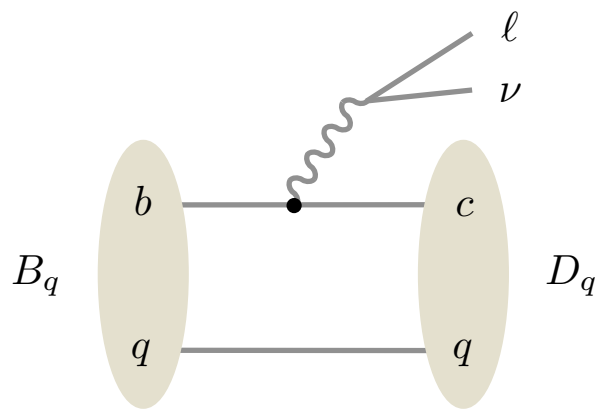
RBC-UKQCD

Taichi Kawanai; 27th @ 16:50; sess. 6

2+1 flavor DW + Iwasaki gauge fields
DW light/strange and non-pert tuned RHQ b valence
a: 0.08, 0.11 fm
Mpi: 289 – 422 MeV



$$B_{(s)} \to D_{(s)} \ell \nu$$



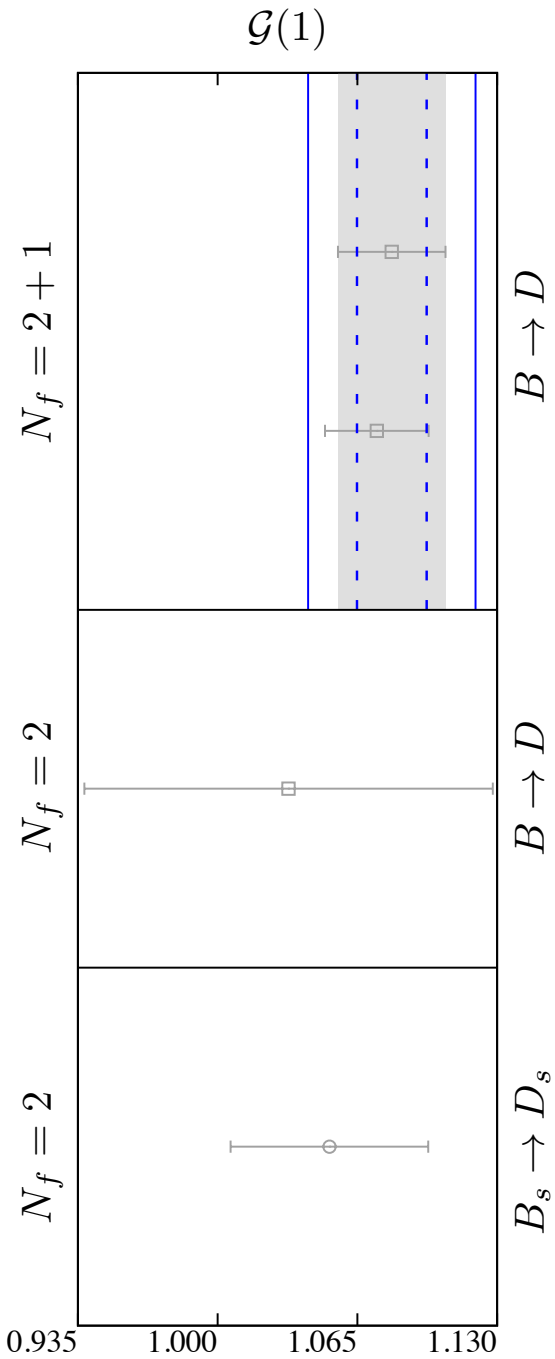
$$w = \frac{p_B}{M_B} \cdot \frac{p_D}{M_D}$$

$$\underbrace{\frac{d\Gamma(B^- \to D^0 \ell^- \bar{\nu})}{dw} = \frac{G_F^2 M_D^3}{48\pi^3}(M_B + M_D)^2 (w^2-1)^{3/2} |\eta_{EW}|^2}\ |V_{cb}|^2 |\mathcal{G}(w)|^2 \ + \ \mathcal{O}\left(\frac{m_\ell^2}{q^2}\right)$$

Now: 7.2% (Belle $B \to D\ell\nu$ coming soon) $\mathcal{G}(w)$: 3.6%

2020: $\sim 3\%$ for $B \to D\tau\nu$ at BelleII $\mathcal{G}(w)$: $\sim 1.5\%$

- most work done at zero recoil (D at rest, $w = 1$) using double ratio
  - current normalization cancels
  - heavy quark disc effects suppressed by $\Lambda_{\rm QCD}/m_b$
- simultaneous fit over w uses more information, beneficial in Qiu et al. (FNAL/MILC), 1312.0155



pre LAT'13:

Qiu et al. (FNAL/MILC), 1312.0155

Okamoto et al. (FNAL/MILC), hep-lat/0409116

Atoui et al., 1310.5238

experiment (now):

Amhis et al. (HFAG), 1207.1158

experiment (∼2020):

Akeroyd et al. (BelleII), 1002.5012

$$B_{(s)} \to D_{(s)} \ell \nu$$

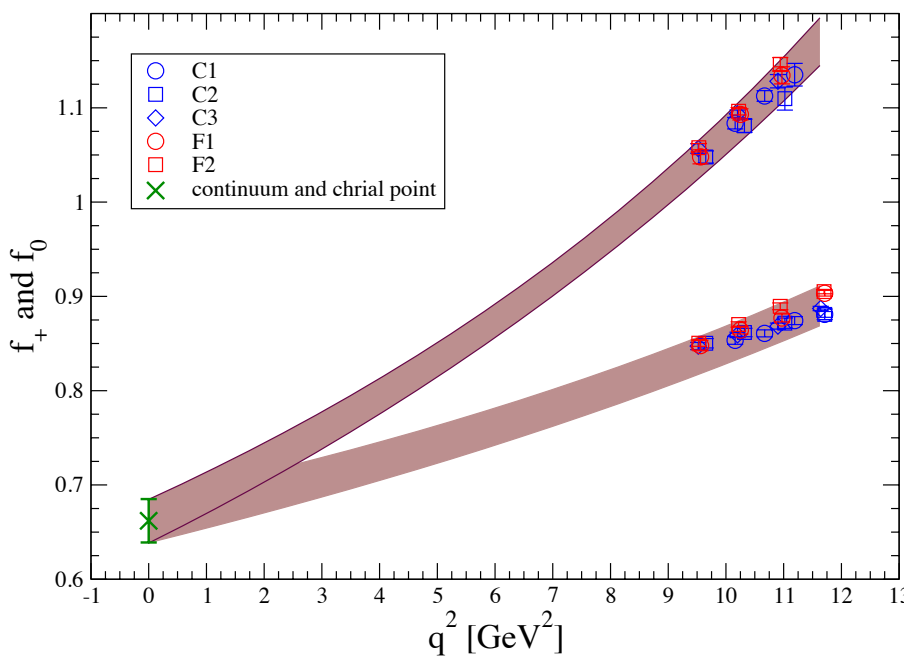
HPQCD

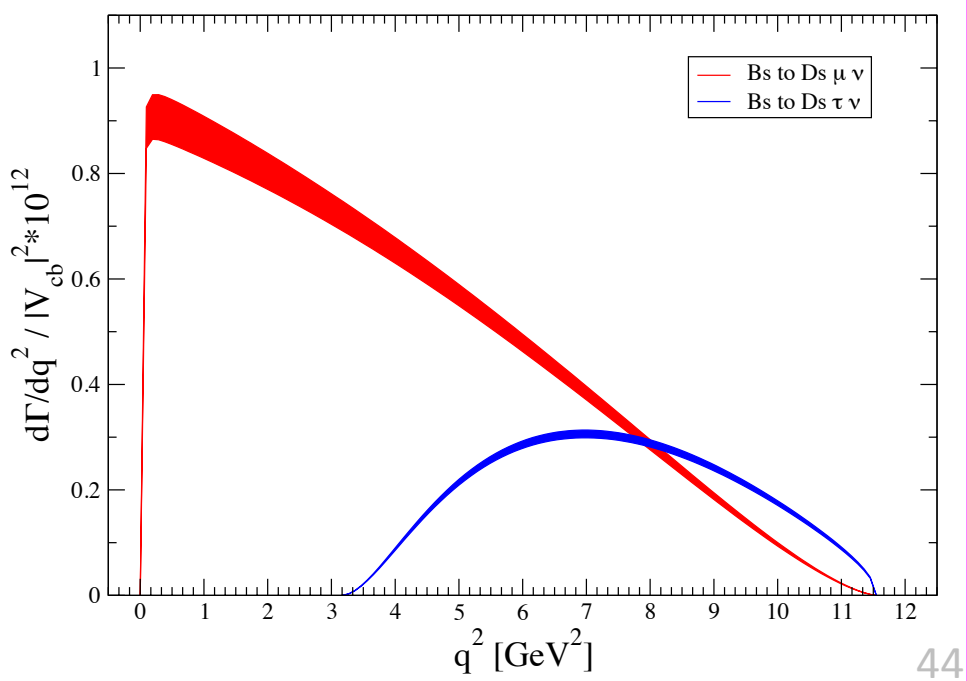
Heechang Na; 27th @ 17:30; sess. 6

MILC 2+1 asqtad gauge cfgs
NRQCD b with HISQ light valence
a: 0.09, 0.12 fm
Mpi: 260 – 500 MeV

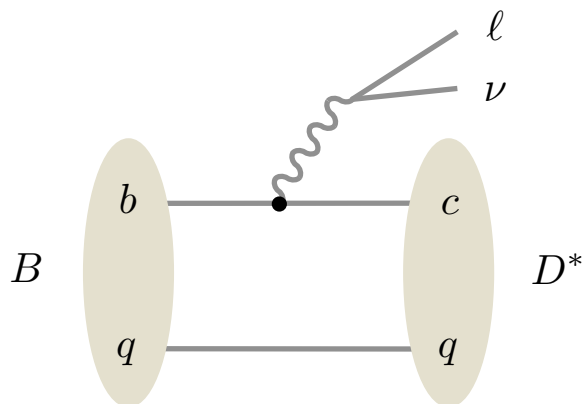
calculating:

- shape of form factors for all q^2
- ratio of branching fractions: R(D), R(Ds)





$$B \to D^{(*)} \ell \nu$$

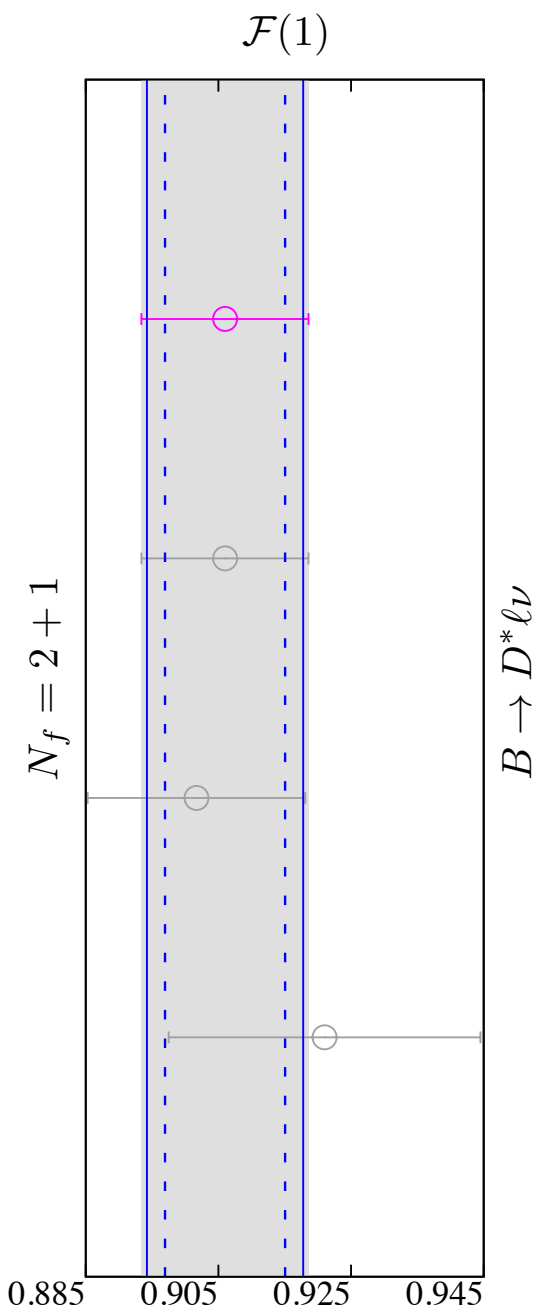


$$\underbrace{\frac{d\Gamma(B^- \to D^{0*}\ell^-\bar{\nu})}{dw} = \frac{G_F^2 M_D^3}{4\pi^3}(M_B - M_D)^2\sqrt{w^2-1}}\ |\eta_{EW}|^2|V_{cb}|^2\chi(w)|\mathcal{F}(w)|^2 \ + \ \mathcal{O}\left(\frac{m_\ell^2}{q^2}\right)$$

Now: 2.5% (zero recoil, $w = 1$) $\mathcal{F}(1)$: 1.3%

2020: $\sim 2\%$ for $B \to D^*\tau\nu$ at BelleII $\mathcal{F}(1)$: $\sim 1\%$

- zero recoil has advantages (only 1 form factor, Luke's theorem, ...)
- but, it would be nice to have shape for, e.g. $\mathcal{R}(D^*)$



pre LAT'13:

Aoki et al. (FLAG), 1310.8555

new (since LAT'13):

Bailey et al. (FNAL/MILC), 1403.0635

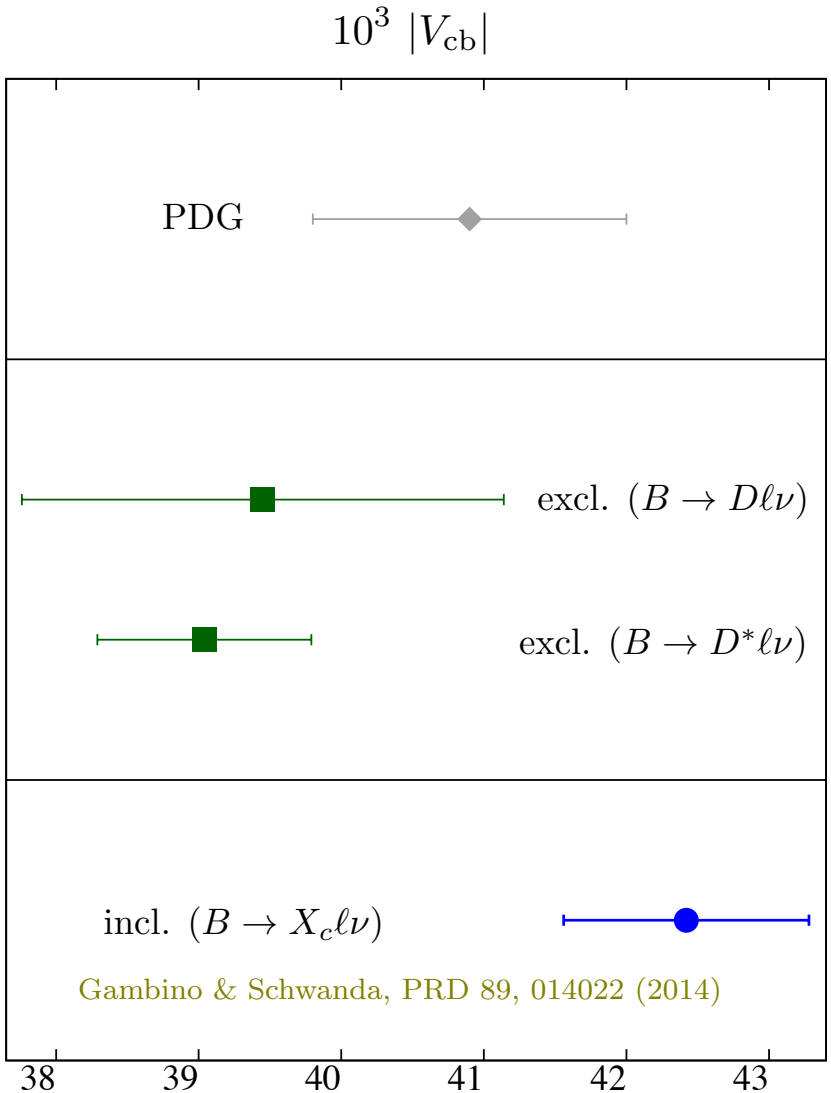
experiment (now):

Amhis et al. (HFAG), 1207.1158

experiment (∼2020):

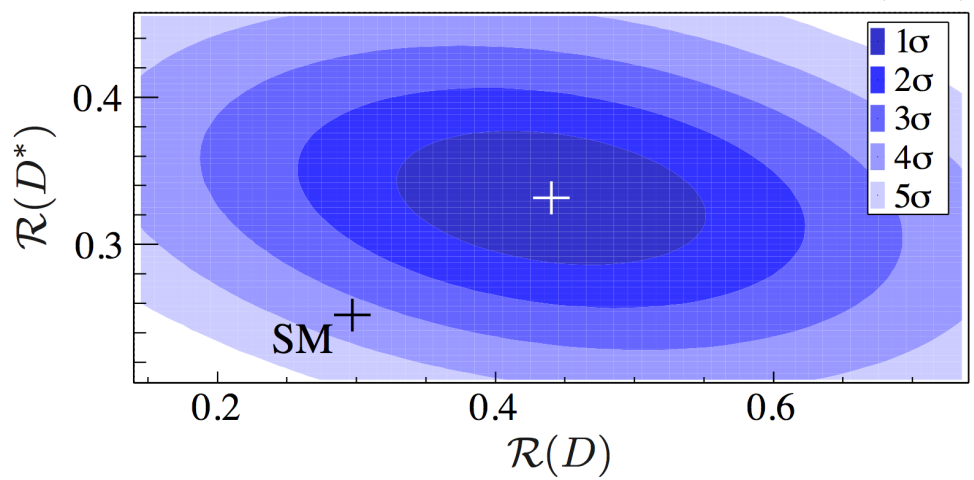
Akeroyd et al. (BelleII), 1002.5012

Phenomenology from $B_{(s)} \to D_{(s)}\ell\nu$ and $B \to D^*\ell\nu$



$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\mu\nu)}$$

BaBar, PRD 88, 072012 (2013)



$\mathcal{R}(D)_{\rm SM}$ from lattice FNAL/MILC, PRL 109, 071802 (2012)

$\mathcal{R}(D^*)_{\rm SM}$ needs lattice Fajfer et al., PRD 85, 094025 (2012)

excl. $(B \to D^*\ell\nu)$ *vs.* incl. $(B \to X_c\ell\nu)$: $\sim 3\,\sigma$

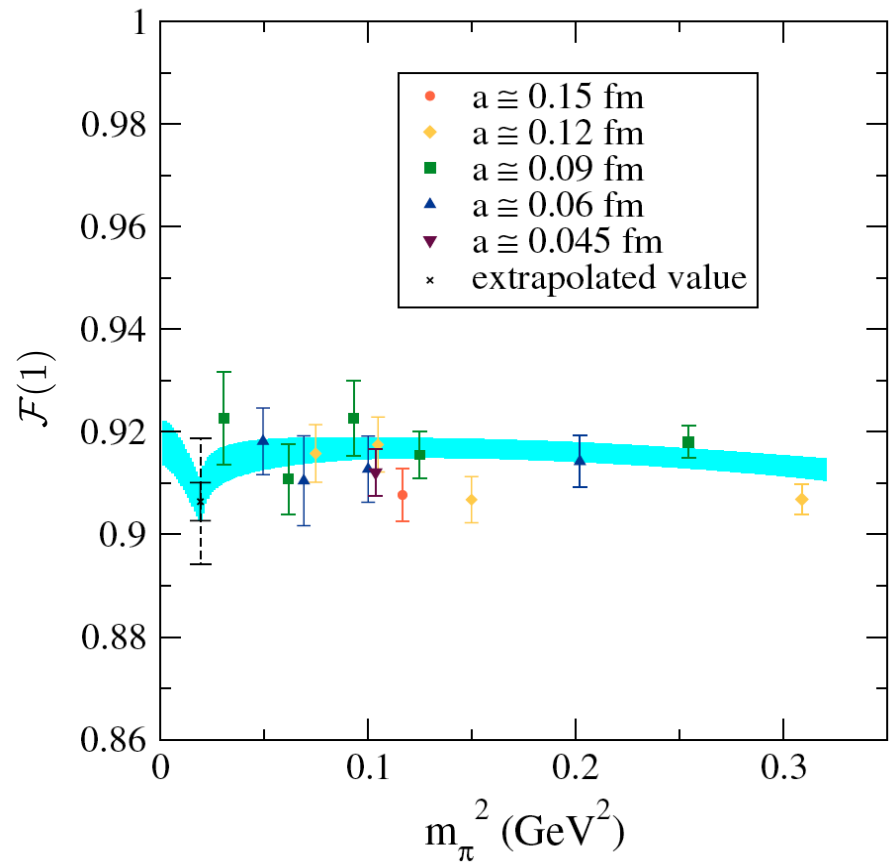
$$B \to D^{(*)}\ell\nu$$

FNAL/MILC Bailey et al. (FNAL/MILC), 1403.0635

MILC Nf=2+1 asqtad
FNAL b and c with asqtad light valence
a: 0.045 – 0.15 fm
Mpi: 174 – 520 MeV

work at zero recoil, calc F(1)

leading source of error is hvy q disc effects



* Lattice error now equal to experimental error.

$$B \to D^{(*)} \ell \nu$$

Jang, Oktay, Bailey, DeTar, Kronfeld, Lee

Attacking hvy quark errors with Oktay-Kronfeld action

- improved version of FNAL action
- includes additional O(a^2, a^3) improvement terms

verified improvement in B meson spectrum

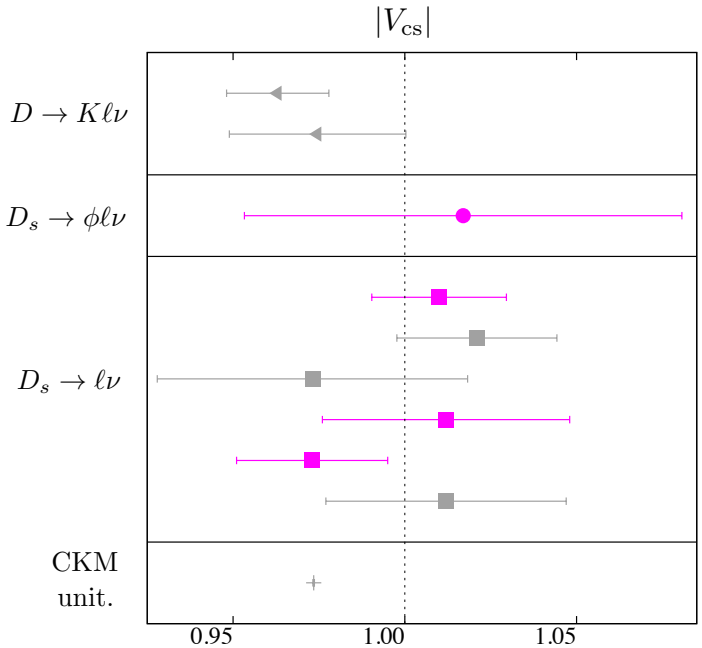
- dispersion relation
- hyperfine splitting

Yong-Chull Jang; 24th @ 17:50; sess. 2

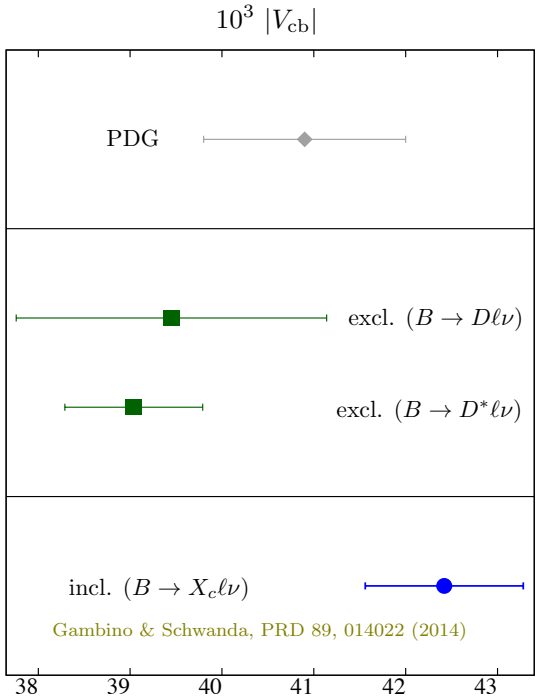
Improved calculation planned for B->D* at zero recoil

- Nf=2+1+1 HISQ gauge ensembles
- physical lt quark mass
- HISQ light/charm and OK b valence quarks
- Heavy-Light current, on-shell improvement through O(p^3)

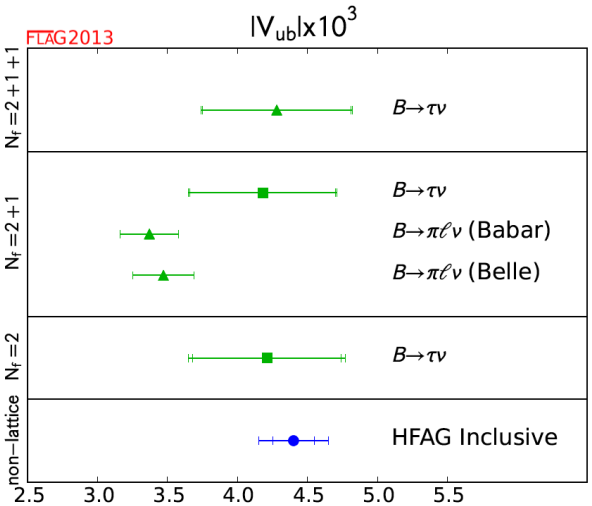
Jon Bailey; 27th @ 17:50; sess. 6

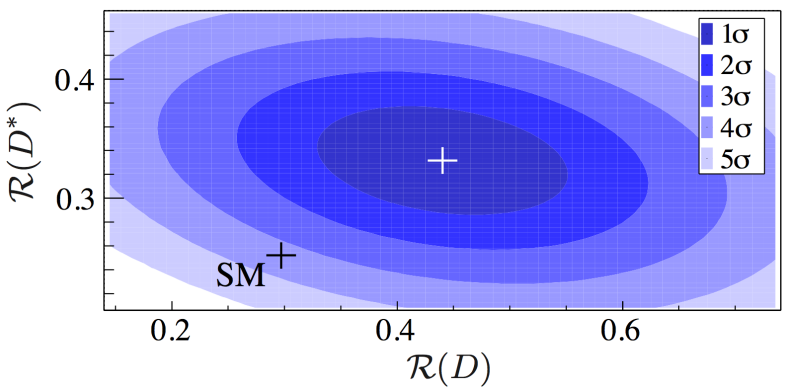


leptonic *vs.* semiletponic, leptonic $|V_{cs}| > 1$?



3σ incl. *vs.* excl.





need $\mathcal{R}(D^*)$ from lattice $\Rightarrow$ non-zero recoil

- $B \to \pi\ell\nu$: RBC/UKQCD, FNAL/MILC, HPQCD
- alt. excl. determinations: $B_s \to K\ell\nu$, $\Lambda_b \to p\ell\nu$

Leptonic Decays

- $D_{(s)} \to \ell\nu$
- $B \to \ell\nu$

Semileptonic Decays

- $D \to \pi\ell\nu$, $D \to K\ell\nu$, $D_s \to \phi\ell\nu$, $D_s \to \eta^{(\prime)}\ell\nu$
- $B \to \pi\ell\nu$, $B_s \to K\ell\nu$, $B_{(s)} \to D_{(s)}\ell\nu$, $B \to D^*\ell\nu$

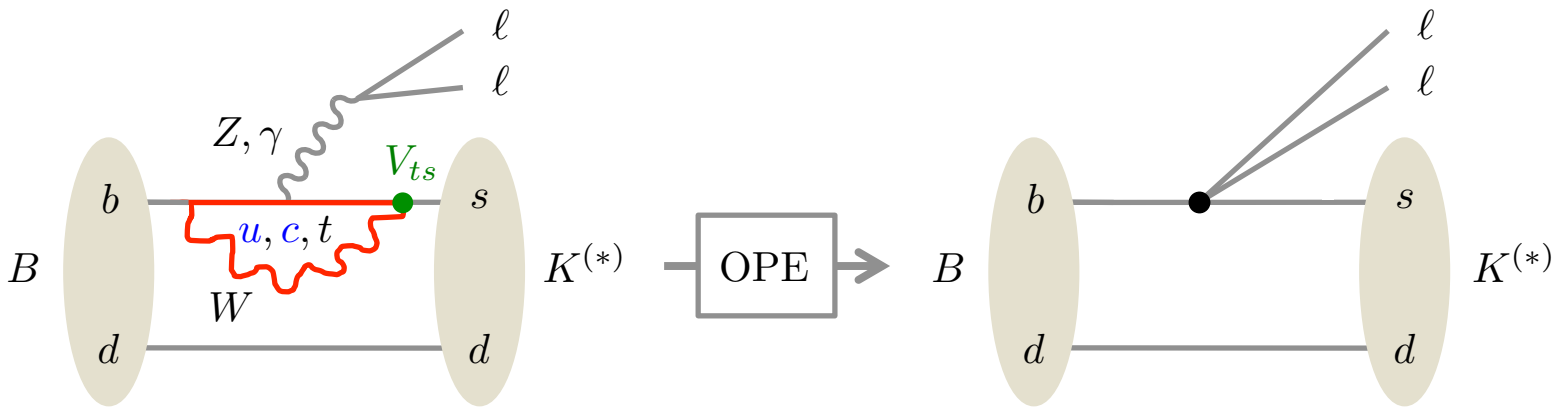
Rare Decays

- $B \to K^{(*)}\ell\ell$, $B_s \to \phi\ell\ell$, $B \to \pi\ell\ell$

Mixing

- D^0–$\bar{D}^0$
- $B^0_{(s)}$–$\bar{B}^0_{(s)}$

$$B \to K^{(*)}\ell\ell,\ B_s \to \phi\ell\ell \quad (b \to s\gamma,\ b \to s\ell\ell \text{ FCNCs})$$



$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \left(C_i O_i + C_i' O_i' \right)$$

- SM GIM, loop, and Cabibbo suppressed
- $O_i^{(\prime)}$ are local operators
- $C_i^{(\prime)}$ are Wilson coefficients (model specific)
- hadronic matrix elements $\langle K^{(*)} | O_i^{(\prime)} | B \rangle$
- observed rate constrains $C_i^{(\prime)}$

e.g.

$$O_7^{(\prime)} = \frac{e\, m_b}{16\pi^2}\ \bar{s}\sigma_{\mu\nu} P_{R(L)} b\ F^{\mu\nu}$$

$$O_9^{(\prime)} = \frac{e^2}{16\pi^2}\ \bar{s}\gamma_\mu P_{L(R)} b\ \bar{\ell}\gamma^\mu \ell$$

$$O_{10}^{(\prime)} = \frac{e^2}{16\pi^2}\ \bar{s}\gamma_\mu P_{L(R)} b\ \bar{\ell}\gamma^\mu \gamma_5 \ell$$

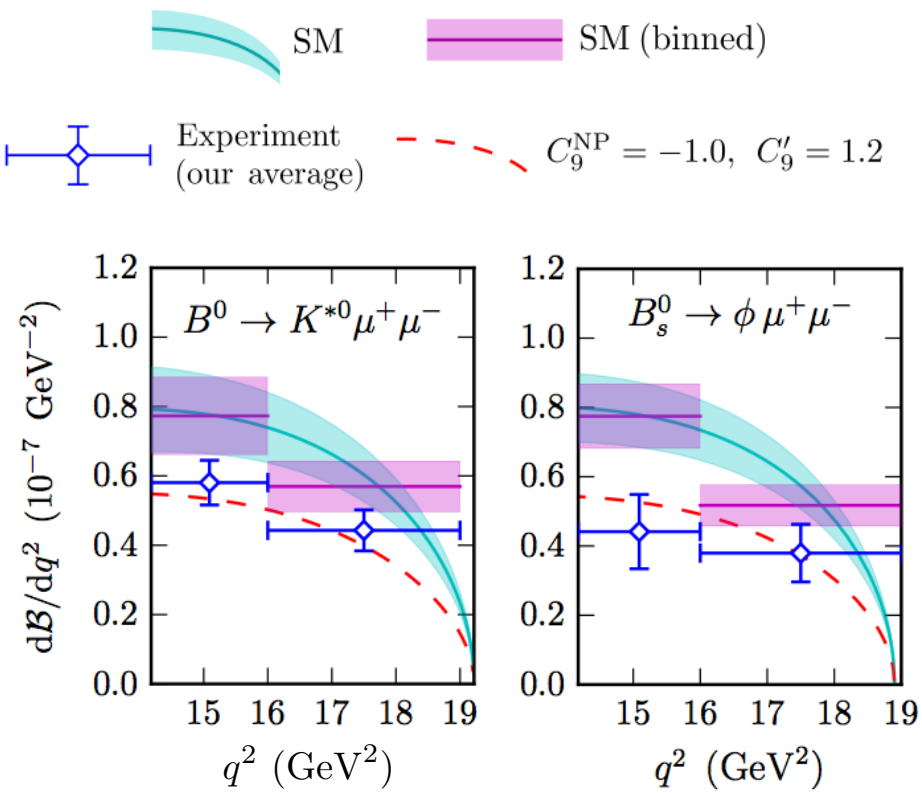
$\vdots$

$$B \to K^{(*)}\ell\ell,\ B_s \to \phi\ell\ell$$

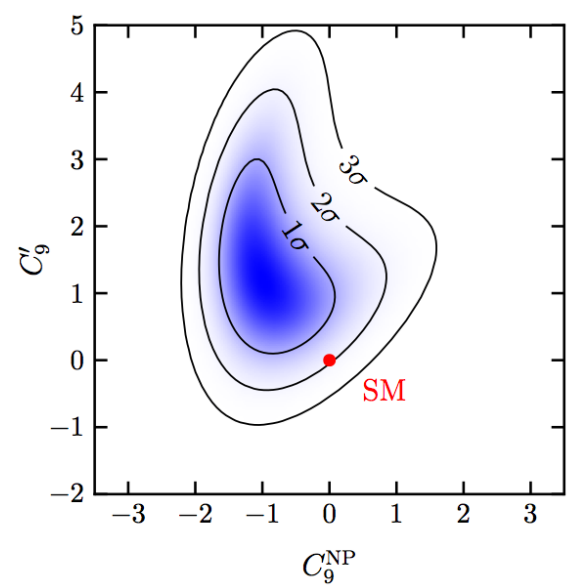
Horgan et al., PRL 112, 212003 (2014); PRD 89, 094501 (2014)

MILC 2+1 asqtad gauge fields
NRQCD b with asqtad light/strange valence
a: 0.09, 0.12 fm
Mpi: 313 – 519 MeV

Matt Wingate; poster



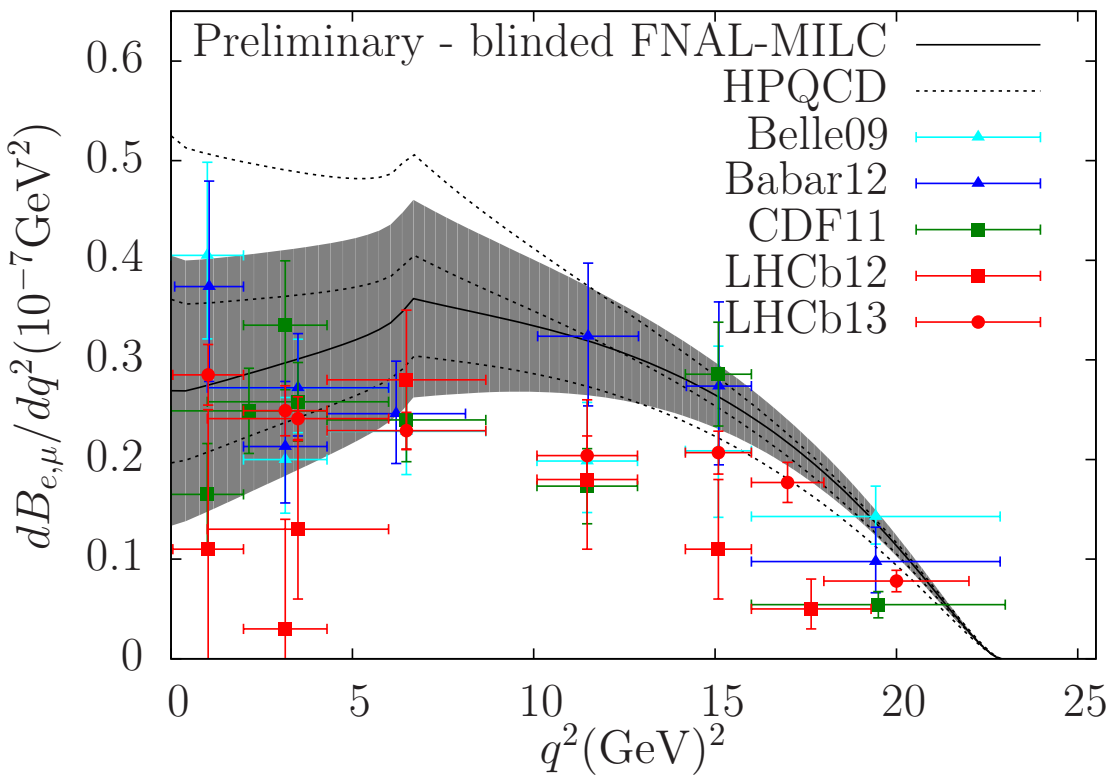
Combined fit to $B \to K^*\mu\mu$ and $B_s \to \phi\mu\mu$ data.



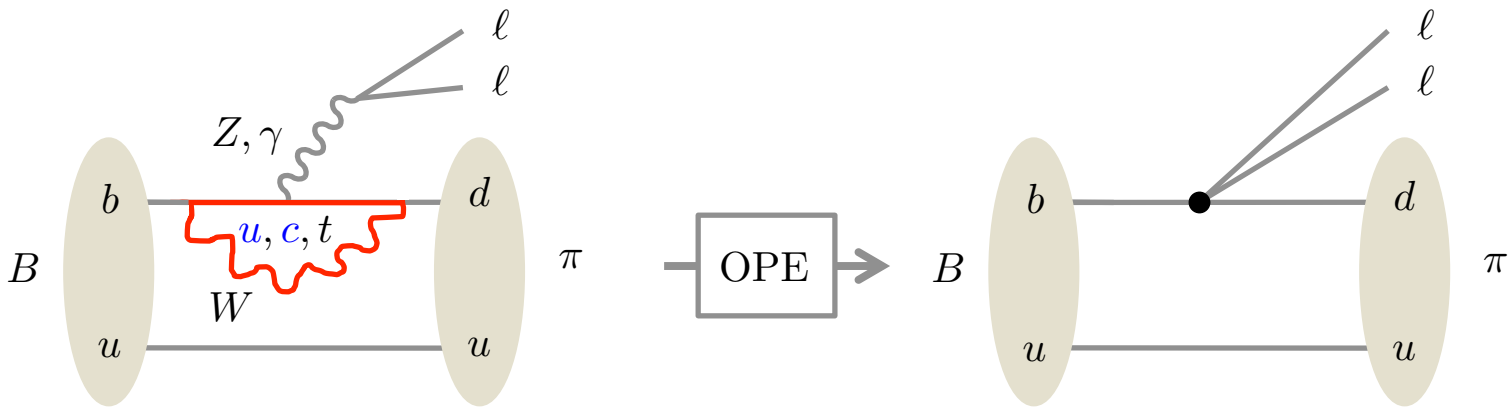
$B \to K\ell\ell$

FNAL/MILC

MILC 2+1 asqtad ensembles
FNAL b, asqtad light/strange valence
a: 0.045 – 0.12 fm
Mpi: 174 – 520 MeV



$B \to \pi \ell \ell$



$10^8 \mathcal{B}(B \to \pi\mu\mu) = 2.3(6)_{\text{stat}}(1)_{\text{sys}}$ LHCb, JHEP 12 (2012) 125

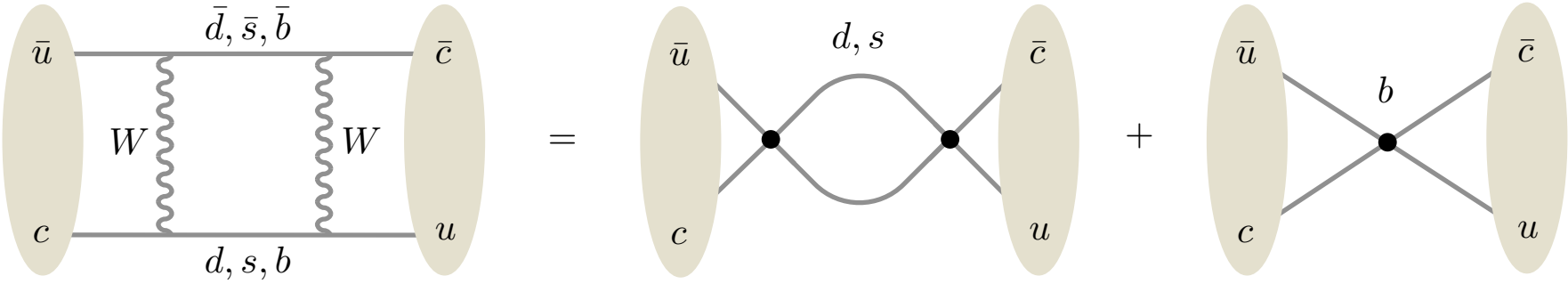
FNAL/MILC

MILC 2+1 asqtad ensembles
FNAL b, asqtad light/strange valence
a: 0.045 – 0.12 fm
Mpi: 174 – 520 MeV

HPQCD

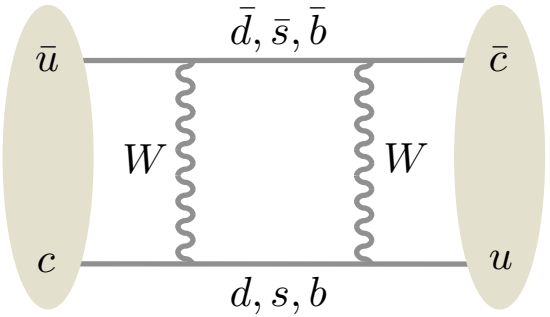
MILC 2+1 asqtad ensembles
NRQCD b, HISQ light/strange valence
a: 0.09, 0.12 fm
Mpi: 174 – 520 MeV

SM D^0 Mixing ($c \to u$ FCNCs)

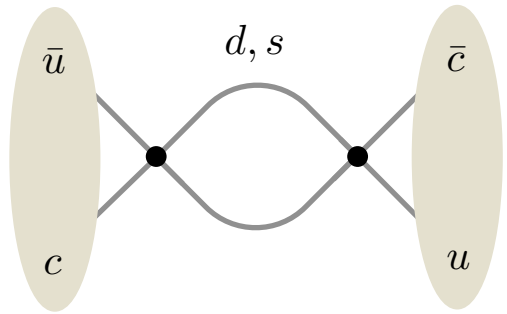


$$M_{12} - \frac{i}{2}\Gamma_{12} = \sum_{X;jk} \frac{C_j^{\Delta_c=1} C_k^{\Delta_c=1} \langle \bar{D}^0 | \mathcal{O}_k^{\Delta_c=1} | X \rangle \langle X | \mathcal{O}_k^{\Delta_c=1} | D^0 \rangle}{E_X - M_{D^0}} + \sum_i C_i^{\Delta_c=2} \langle \bar{D}^0 | \mathcal{O}_i^{\Delta_c=2} | D^0 \rangle$$

SM D^0 Mixing ($c \to u$ FCNCs)



$=$



$+$

$$M_{12} - \frac{i}{2}\Gamma_{12} = \sum_{X;jk} \frac{C_j^{\Delta_c=1} C_k^{\Delta_c=1} \langle \bar{D}^0 | \mathcal{O}_k^{\Delta_c=1} | X \rangle \langle X | \mathcal{O}_k^{\Delta_c=1} | D^0 \rangle}{E_X - M_{D^0}}$$

$$+ \sum_i C_i^{\Delta_c=2} \langle \bar{D}^0 | \mathcal{O}_i^{\Delta_c=2} | D^0 \rangle$$

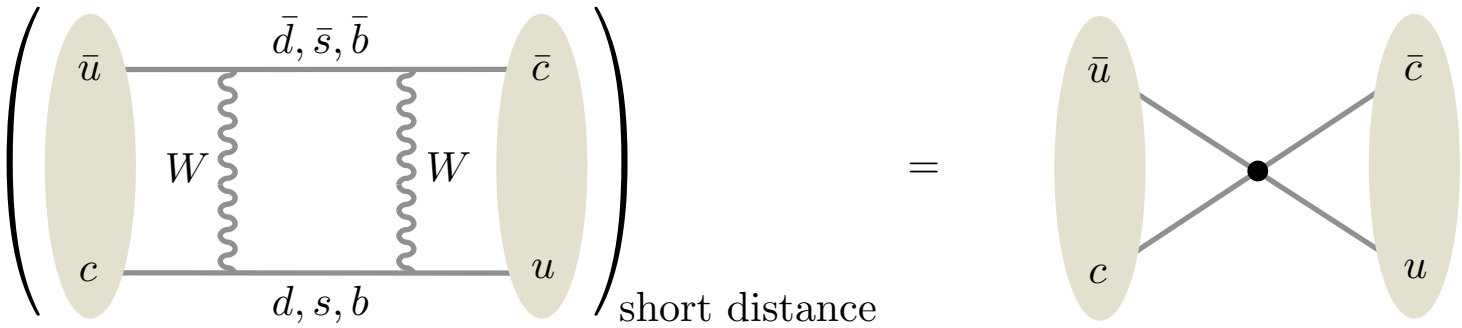
doubly Cabibbo suppressed
$\times \mathcal{O}(10^{-4})$

long distance: Chris Sachradja; 28th @ 10:30; plenary

disconnected: Alejandro Vaquero; 24th @ 16:50; sess. 4

1st 2 generations dominate $\Rightarrow$ SM CPV $[\text{Im}(M_{12}), \text{Im}(\Gamma_{12})] \sim \mathcal{O}(10^{-4})$

Short Distance D^0 Mixing ($c \to u$ FCNCs)



$$\left(M_{12} - \frac{i}{2}\Gamma_{12}\right)_{\text{short distance}} = \sum_i C_i^{\Delta_c=2} \langle \bar{D}^0 | \mathcal{O}_i^{\Delta_c=2} | D^0 \rangle$$

- BSM dominated by short distance
- hadronic matrix elements of local operators
- parameterized by *bag parameters*, B_i

$$\langle \bar{D}^0 | \mathcal{O}_i | D^0 \rangle = a_i B_i M_D^2 f_D^2$$

$$\mathcal{O}_1 = \left(\bar{c}^\alpha \gamma_\mu P_L u^\alpha\right) \left(\bar{c}^\beta \gamma_\mu P_L u^\beta\right)$$

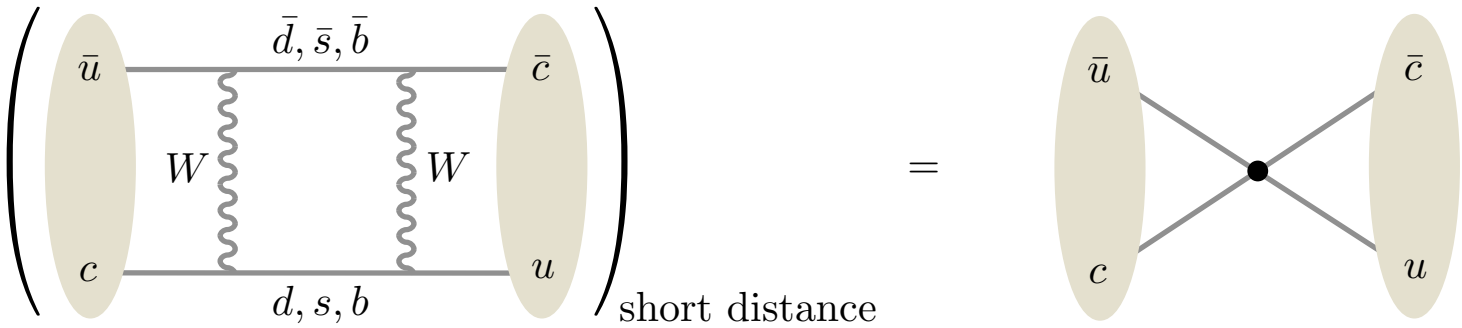
$$\mathcal{O}_2 = \left(\bar{c}^\alpha P_L u^\alpha\right) \left(\bar{c}^\beta P_L u^\beta\right)$$

$$\mathcal{O}_3 = \left(\bar{c}^\alpha P_L u^\beta\right) \left(\bar{c}^\beta P_L u^\alpha\right)$$

$$\mathcal{O}_4 = \left(\bar{c}^\alpha P_L u^\alpha\right) \left(\bar{c}^\beta P_R u^\beta\right)$$

$$\mathcal{O}_5 = \left(\bar{c}^\alpha P_L u^\beta\right) \left(\bar{c}^\beta P_R u^\alpha\right)$$

Short Distance D^0 Mixing ($c \to u$ FCNCs)



$$\left(M_{12} - \frac{i}{2}\Gamma_{12}\right)_{\text{short distance}} = \sum_i C_i^{\Delta_c=2} \langle \bar{D}^0 | \mathcal{O}_i^{\Delta_c=2} | D^0 \rangle$$

Now: UTfit, 1402.1664
LHCb, PRL 111, 251801 (2013)

$$|M_{12}| = (4.4 \pm 2.0) \times 10^{-3}\ \text{ps}^{-1}$$

$$|\Gamma_{12}| = (14.9 \pm 1.6) \times 10^{-3}\ \text{ps}^{-1}$$

$$\arg\left(\frac{\Gamma_{12}}{M_{12}}\right) = (2.0 \pm 2.7)^{\circ}$$

2020: Briere, ANL Intensity Frontier (2013)

$\sim 5\times$ current precision

Short Distance D^0 Mixing

ETM Carrasco et al. (ETM), 1403.7302

ETM Nf=2 cfgs

- tree-level improved Symanzik, APE smeared gauge links
- max. twisted Wilson quarks: automatic O(a) improvement

Osterwalder-Seiler valence: O(a) improvement with no wrong chirality mixing

a: 0.05 – 0.1 fm

Mpi: 280 – 500 MeV

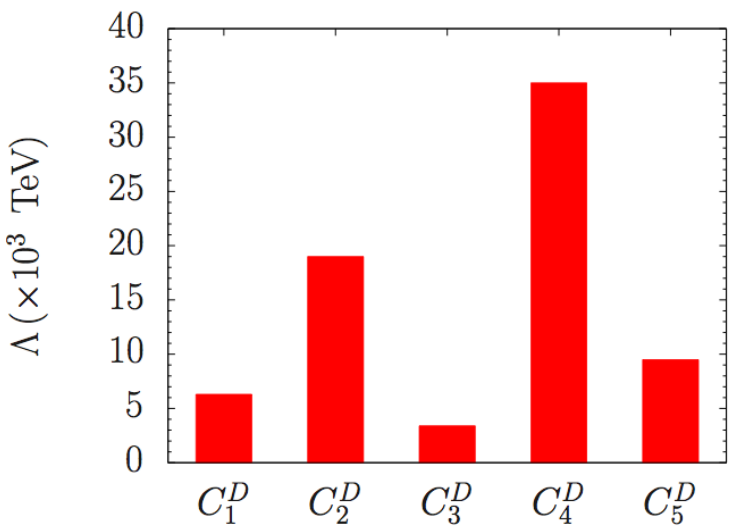
first unquenched calculation of all 5 bag parameters

	B_1	B_2	B_3	B_4	B_5
$\overline{\text{MS}}$ (3GeV)	0.75(02)	0.66(02)	0.96(05)	0.91(04)	1.10(05)
RI-MOM (3GeV)	0.74(02)	0.82(03)	1.21(06)	1.09(05)	1.35(06)

3-5% precision

- much better than current expt
- on par with 2020 exptl expectations

constraining the scale of new physics from CPV observables



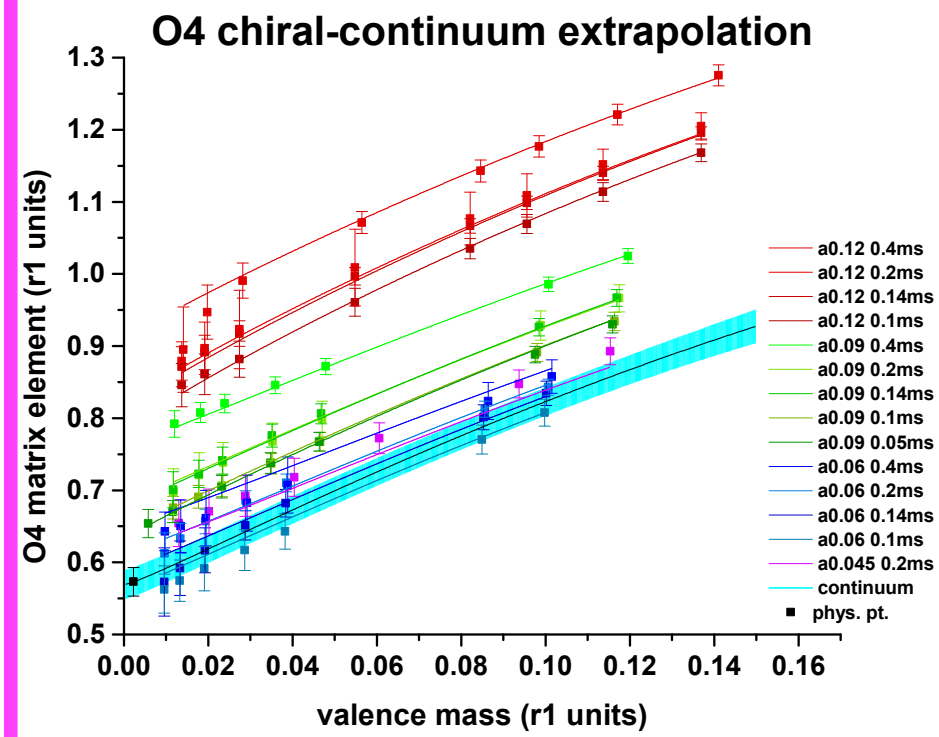
where $C_i^D \sim 1/\Lambda^2$

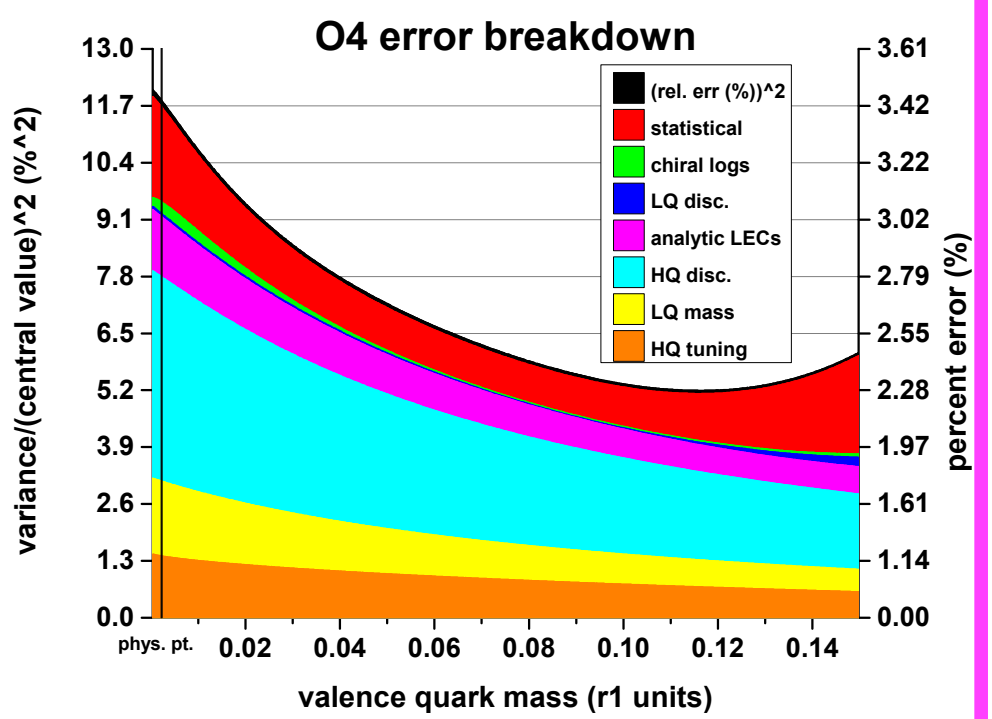
Short Distance D^0 Mixing

FNAL/MILC

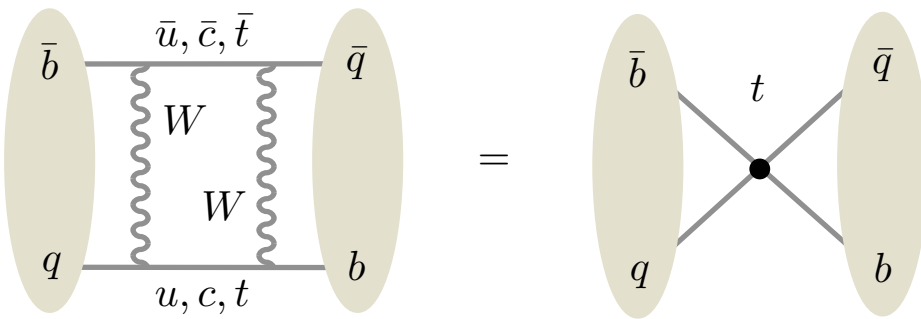
MILC Nf=2+1 asqtad configurations
FNAL charm and asqtad light valence
a: 0.045 - 0.125 fm
Mpi: 177 – 559 MeV

Chia Cheng Chang; 25th @ 12:50; sess. 6





$B^0_{(s)}$ Mixing ($b \to s, d$ FCNCs)



$$\Delta M_{(s)} = \sum_i C_i^{\Delta_b=2} \langle \bar{B}^0_{(s)} | \mathcal{O}_1^{\Delta_b=2} | B^0_{(s)} \rangle$$

- SM and BSM dominated by short distance
- hadronic matrix elements of local operators
- parameterized by *bag parameters*, B_i

$$\langle \bar{B}^0_{(s)} | \mathcal{O}_i | B^0_{(s)} \rangle = a_i B_i^{(s)} M^2_{B_{(s)}} f^2_{B_{(s)}}$$

- SU(3) breaking ratio (related to $|V_{td}/V_{ts}|$)

$$\xi = f_{B_s} \sqrt{B_1^{(s)}} \ / \ f_{B_d} \sqrt{B_1^{(d)}}$$

$$\mathcal{O}_1 = \left(\bar{b}^\alpha \gamma_\mu P_L q^\alpha\right) \left(\bar{b}^\beta \gamma_\mu P_L q^\beta\right)$$

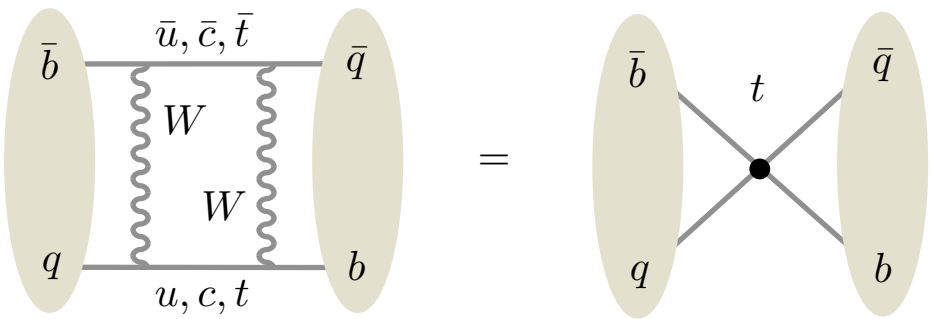
$$\mathcal{O}_2 = \left(\bar{b}^\alpha P_L q^\alpha\right) \left(\bar{b}^\beta P_L q^\beta\right)$$

$$\mathcal{O}_3 = \left(\bar{b}^\alpha P_L q^\beta\right) \left(\bar{b}^\beta P_L q^\alpha\right)$$

$$\mathcal{O}_4 = \left(\bar{b}^\alpha P_L a^\alpha\right) \left(\bar{b}^\beta P_R q^\beta\right)$$

$$\mathcal{O}_5 = \left(\bar{b}^\alpha P_L q^\beta\right) \left(\bar{b}^\beta P_R q^\alpha\right)$$

$B^0_{(s)}$ Mixing ($b \to s, d$ FCNCs)

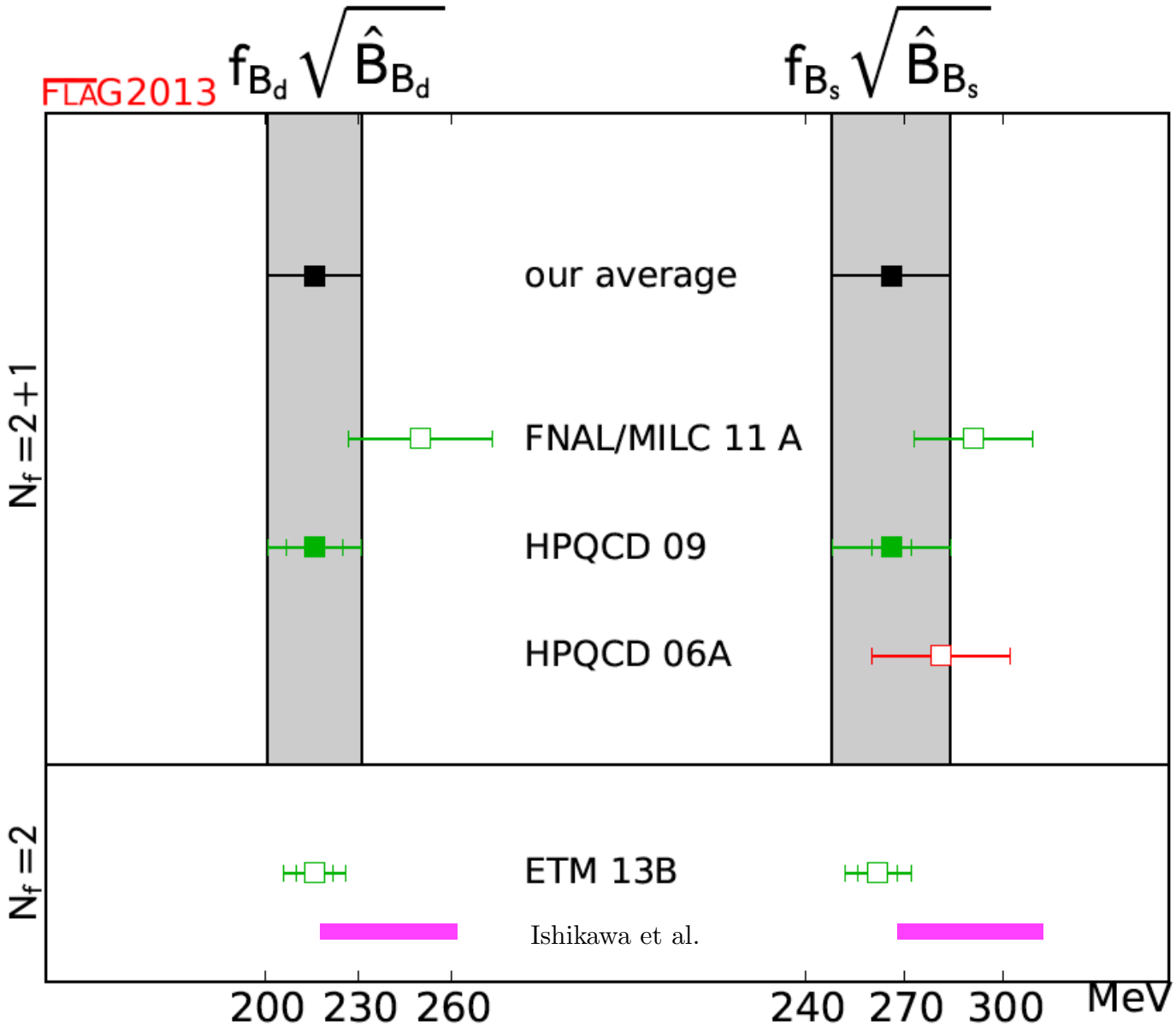


$$\Delta M_{(s)} = \sum_i C_i^{\Delta_b=2} \langle \bar{B}^0_{(s)} | \mathcal{O}_1^{\Delta_b=2} | B^0_{(s)} \rangle$$

status of experiment:

$$\Delta M = 0.510(3)\ \text{ps}^{-1} \qquad \sim 0.6\%$$

$$\Delta M_s = 17.761(22)\ \text{ps}^{-1} \qquad \sim 0.1\%$$


FLAG2013
$f_{B_d}\sqrt{\hat{B}_{B_d}}$
$f_{B_s}\sqrt{\hat{B}_{B_s}}$
our average
FNAL/MILC 11 A
HPQCD 09
HPQCD 06A
$N_f = 2+1$
$N_f = 2$
ETM 13B
Ishikawa et al.
200 230 260
240 270 300
MeV

SM and BSM $B^0_{(s)}$ Mixing

Ishikawa, Aoki, Izubuchi, Lehner, and Soni (to appear on arXiv tonight)

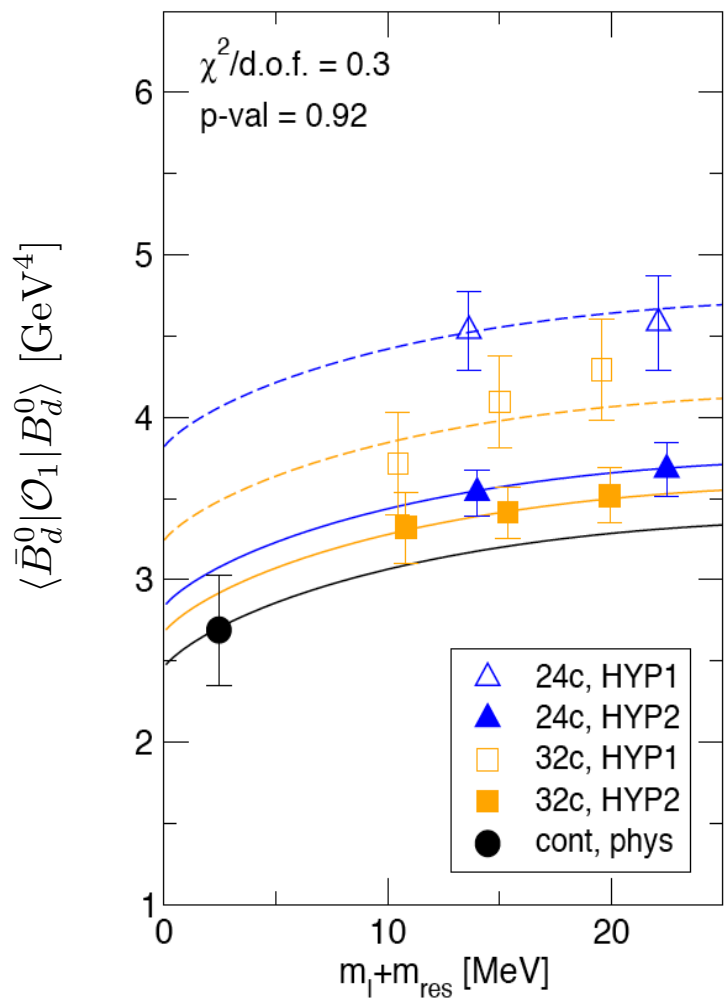
Tomomi Ishikawa; 25th @ 9:20; sess. 6

Idea
— anchor a HQ expansion with results in static limit
— relativistic heavy quark action for mQ ~ mc
— iterate between mc and anchor point ala ETM ratio method

Simulation
— Nf=2+1 DW, Iwasaki gauge
— static b with DW light valence
— a ~ 0.09, 0.11 fm
— Mpi: 289 – 418 MeV
— 1-loop matching (ok in static limit) including O(a) effects

$$
\begin{aligned}
f_B\sqrt{\hat{B}_B} &= 240(15)_{\text{stat}}(17)_{\text{sys}}\ \text{MeV} \\
f_{B_s}\sqrt{\hat{B}_{B_s}} &= 290(9)_{\text{stat}}(20)_{\text{sys}}\ \text{MeV} \\
\xi &= 1.208(41)_{\text{stat}}(44)_{\text{sys}} \\
\hat{B}_B &= 1.17(11)_{\text{stat}}(19)_{\text{sys}} \\
\hat{B}_{B_s} &= 1.22(6)_{\text{stat}}(12)_{\text{sys}} \\
B_{B_s}/B_B &= 1.028(60)_{\text{stat}}(43)_{\text{sys}}\ \text{MeV}
\end{aligned}
$$

* No $\mathcal{O}(1/m_b)$ error included



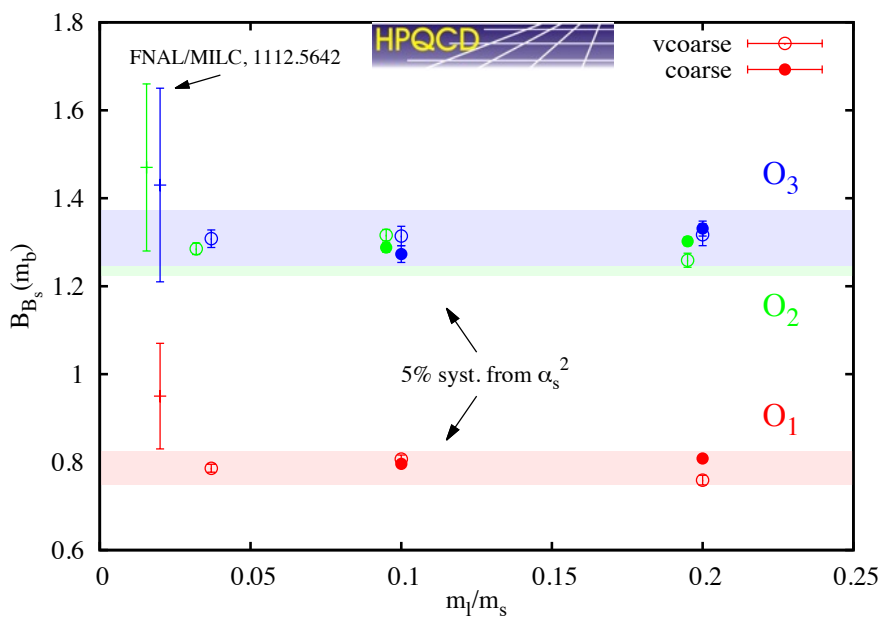
SM and BSM $B^0_{(s)}$ Mixing

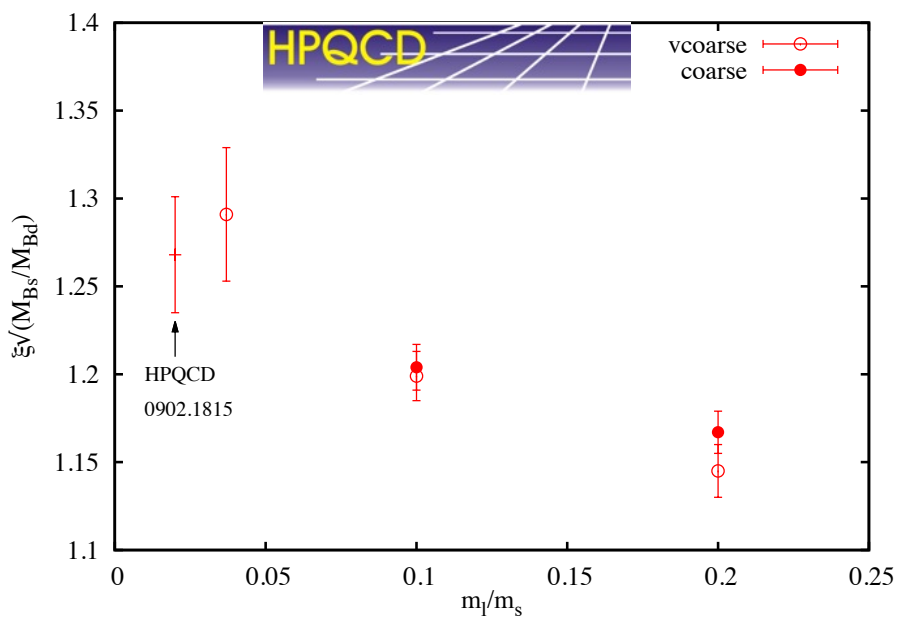
HPQCD

Christine Davies; poster

MILC 2+1+1 HISQ cfgs
radiatively-improved NRQCD b with HISQ light/strange
a: 0.09, 0.12, 0.15 fm
physical light masses (a first for B-mixing)

- extension of B-physics program on these ensembles (spectra, decay constants, etc.)
- still generating data
- impressive early results





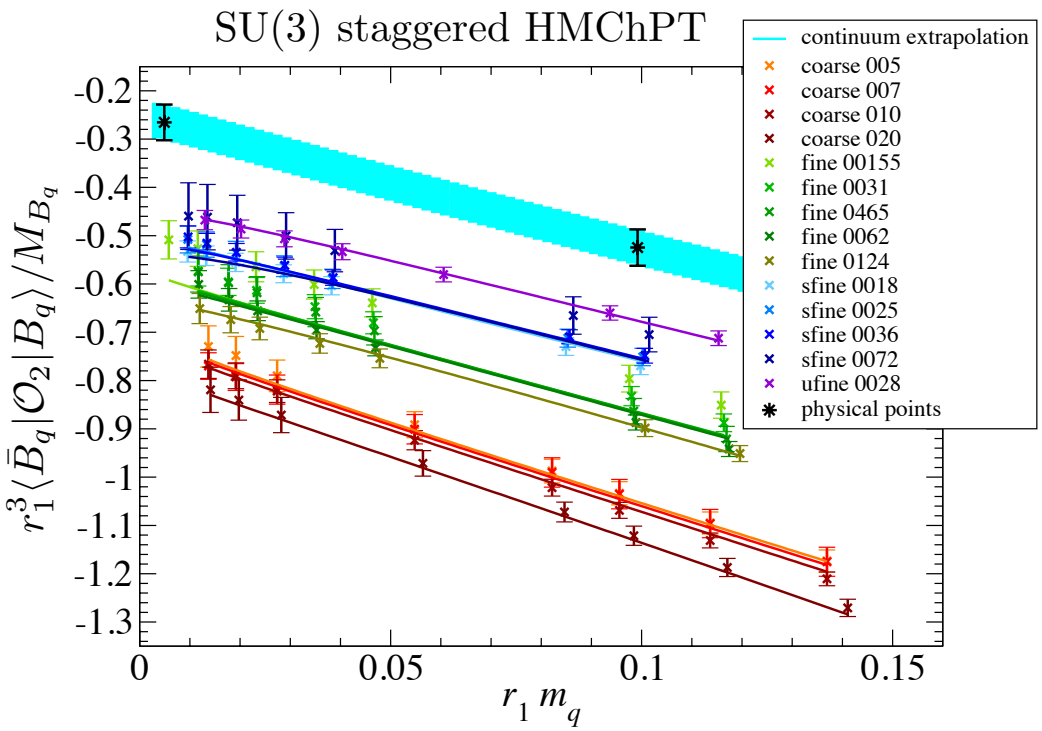
SM and BSM $B^0_{(s)}$ Mixing

FNAL/MILC

Update of ongoing B-mixing project.
Calculating matrix elements for all five mixing operators.

MILC Nf=2+1 asqtad gauge cfgs
asqtad light/strange with FNAL b quarks
a: 0.045, 0.06, 0.09, 0.12 fm
Mpi: 174 - 520 MeV

Aida El-Khadra; 25th @ 10:00; sess. 6



expected errors:

- $\langle \bar{B} | \mathcal{O}_1 | B \rangle$: $\sim 9\%$
- $\langle \bar{B} | \mathcal{O}_{2,3,4,5} | B \rangle$: $10 - 15\%$
- ξ: $< 2\%$
- $\langle \bar{B} | \mathcal{O}_3 | B \rangle / \langle \bar{B} | \mathcal{O}_1 | B \rangle$: $\sim 10\%$

Summary

- A lot of activity
  - 35 recent or ongoing calculations
  - 20 talks or posters
- How we're doing relative to experiment
  - leptonic $|V_{cs}| > 1$
  - inclusive *vs.* exclusive $|V_{ub}|$, $|V_{cb}|$
  - $\mathcal{R}(D)$, $\mathcal{R}(D^*)$
- Interest in rare decays
  - coordinate with phenomenologists & experimentalists

Thank you!

Thanks to the organizers for the invitation

...and thanks to those who sent me information:

Yasumichi Aoki, Jon Bailey, Claude Bernard, Jason Chang, Norman Christ, Christine Davies, Carleton DeTar, Daping Du, Jonathan Flynn, Elizabeth Freeland, Tomomi Ishikawa, Taku Izubuchi, Yong-Chull Jang, Andreas Jüttner, Issaku Kanamori, Taichi Kawanai, Weonjong Lee, Christoph Lehner, Thom Primer, Amarjit Soni, Cecilia Tarantino, Doug Toussaint, Ruth Van de Water, Oliver Witzel, Ran Zhou, and anyone I've missed.

Topics I didn't touch on but could have:

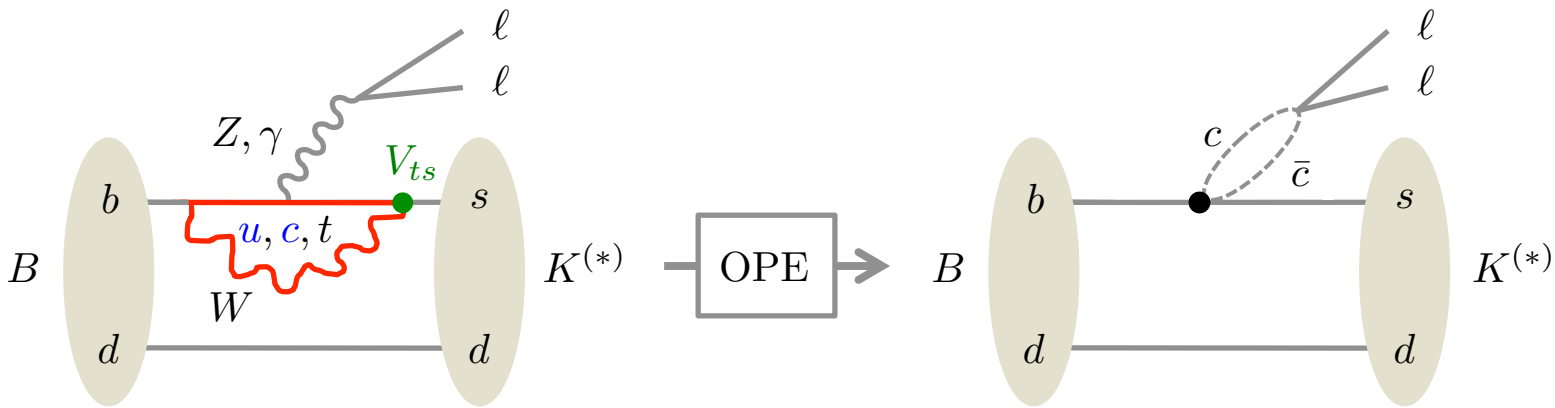
radiative decays

* talk by Ciaran Hughes, 26th @ 14:15; sess. 2
* Donald et al. (HPQCD), PRL 112, 212002 (2014)
* …

nonleptonic decays (D->K\barK, …)

* important for studying CPV
* perhaps possible with 3 particle generalization of Lellouch-Luescher
    - talk by Steve Sharpe, 24th @ 14:15, sess. 2
    - talk by Andre Walker-Loud, 24th @ 17:10, sess. 2

$$B \to K^{(*)}\ell\ell,\ B_s \to \phi\ell\ell \quad (b \to s\gamma,\ b \to s\ell\ell \text{ FCNCs})$$



$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \left(C_i O_i + C_i' O_i' \right)$$

- SM GIM, loop, and Cabibbo suppressed
- $O_i^{(\prime)}$ are local operators
- $C_i^{(\prime)}$ are Wilson coefficients (model specific)
- hadronic matrix elements $\langle K^{(*)} | O_i^{(\prime)} | B \rangle$
- observed rate constrains $C_i^{(\prime)}$

resonant $c\bar{c}$ states

- nonlocal, long distance interactions
- no first principles understanding
- limit use of data *vs.* q^2
- increasing interest

Lyon and Zwicky, 1406.0566