The search for new physics in neutral kaon mixing and $B \to D^{(*)}\ell\nu$ form factors from lattice QCD

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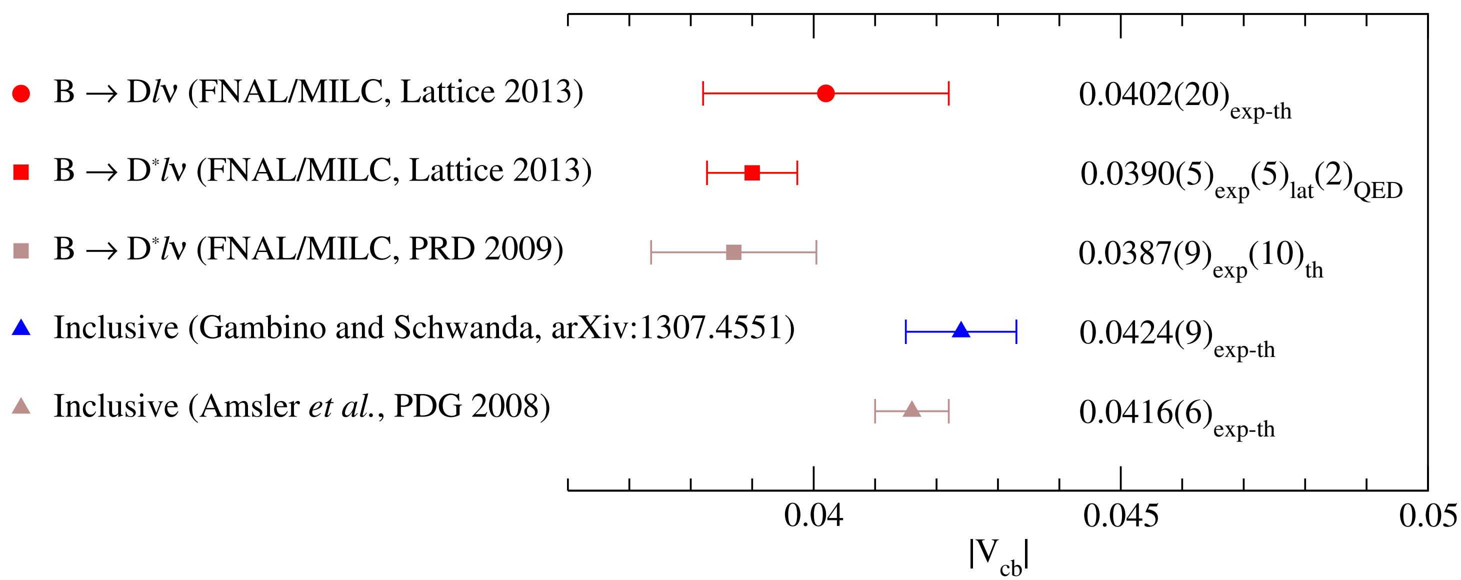
Goals

- Understanding physics of quark flavor, CP violation
- Searches for new physics ~ significant pressure on CKM description of quark flavor physics
  - 3σ differences: $|V_{ub}|_{excl.}$ and $|V_{ub}|_{incl.}$, BaBar excess in $R(D^{(*)})$
  - Error in SM $BR(K \to \pi\nu\overline{\nu})$ dominated by error in $|V_{cb}|$
  - Error in SM $|\varepsilon_K|$ dominated by error in $|V_{cb}|$
- Determinations of $|V_{cb}|$ and $|V_{ub}|$ with greater precision, essential
- Experiment ahead of theory
  - Errors in hadronic weak matrix elements (theory) often dominate, limit impact of high-luminosity experiments
  - Next generation B: Belle II, BESIII, LHCb
  - Kaon experiments: KLOE, ORKA, NA62, KOTO, TREK, Project X
- Need calculations with controlled, improvable errors ~ LQCD

Indirect CP violation and $|V_{cb}|$

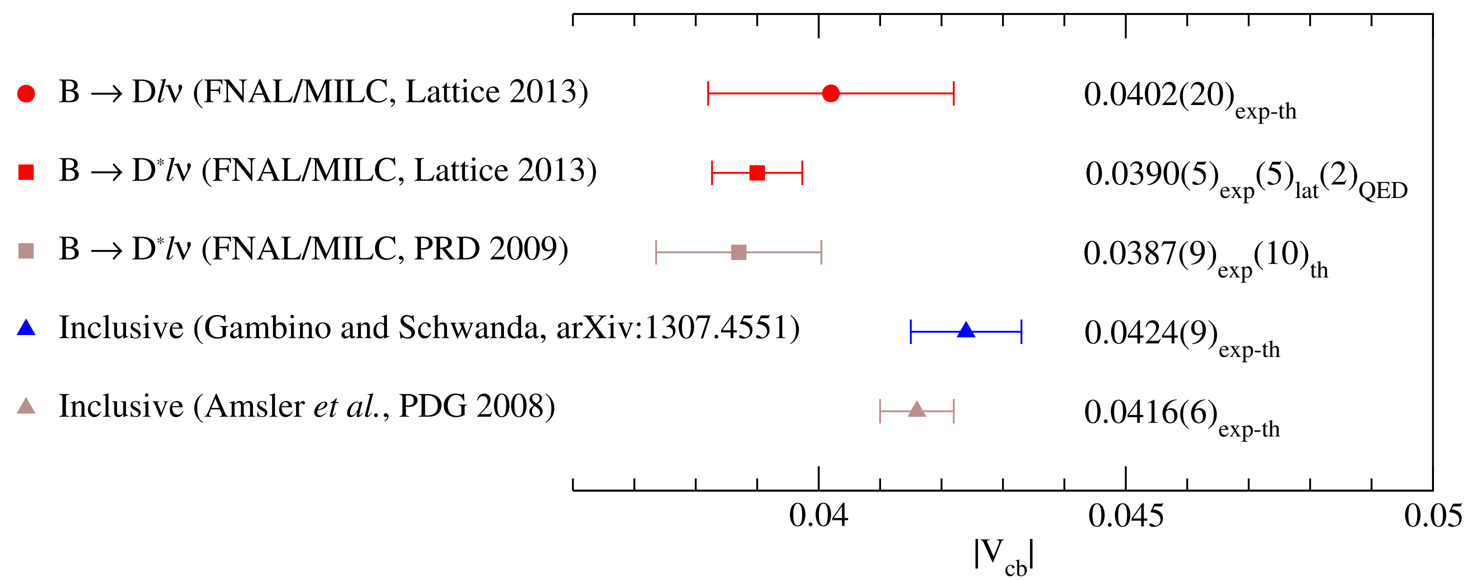
- $\sim 3\sigma$ difference between SM and experimental $|\varepsilon_K| \sim |V_{cb}|^4$ reported by SWME (Lattice 2012 proc.)
  - Exclusive $|V_{cb}|$ (from $B \to D^* l\nu$ at zero recoil), SWME or lattice average B_K
  - Vanishes with inclusive $|V_{cb}|$
- Updates of exclusive $|V_{cb}|$ from $B \to D^{(*)} l\nu$ (FNAL/MILC, Lattice 2013)



- New exclusive $|V_{cb}|$ increases difference between SM and experimental $|\varepsilon_K|$

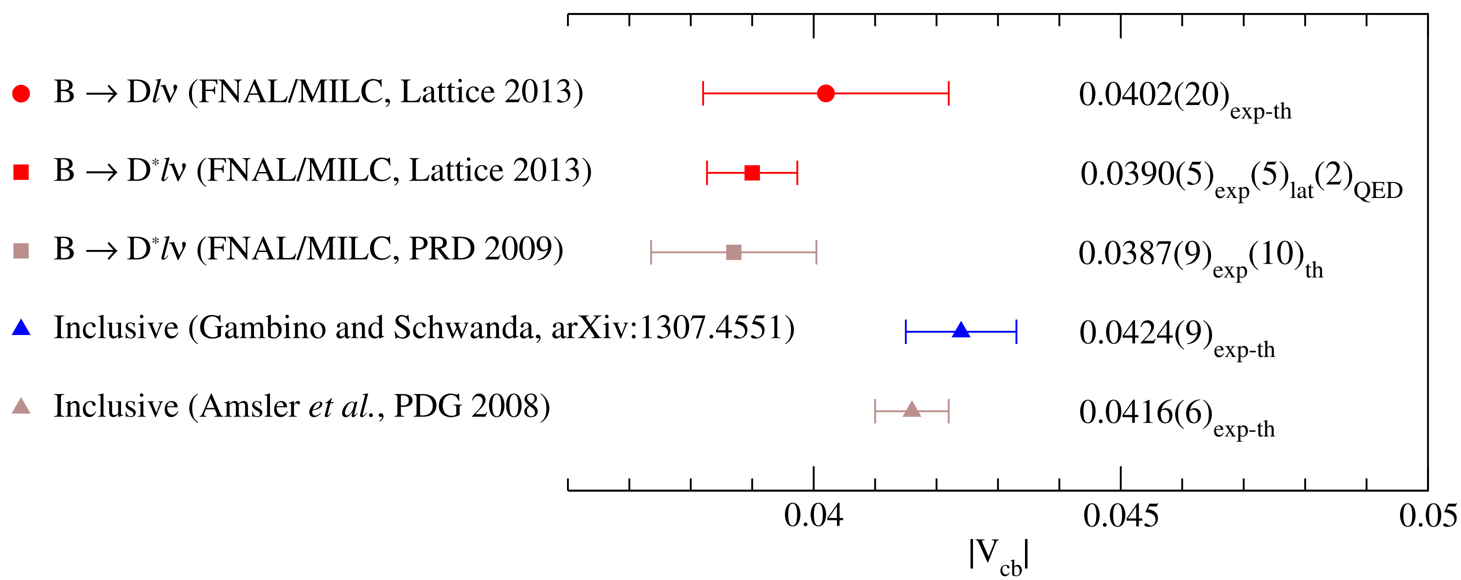
Exclusive and inclusive $|V_{cb}|$

- 3.0σ difference: exclusive $|V_{cb}|$ from $B \to D^* l\nu$ and inclusive $|V_{cb}|$
- New exclusive $|V_{cb}|$ from only lattice QCD calculations for $B \to D l\nu$ and $B \to D^* l\nu$ including vacuum polarization effects (update supersedes previous)
- Cross-checks of systematics ~ lattice QCD calculations with different discretizations of valence, sea quark actions



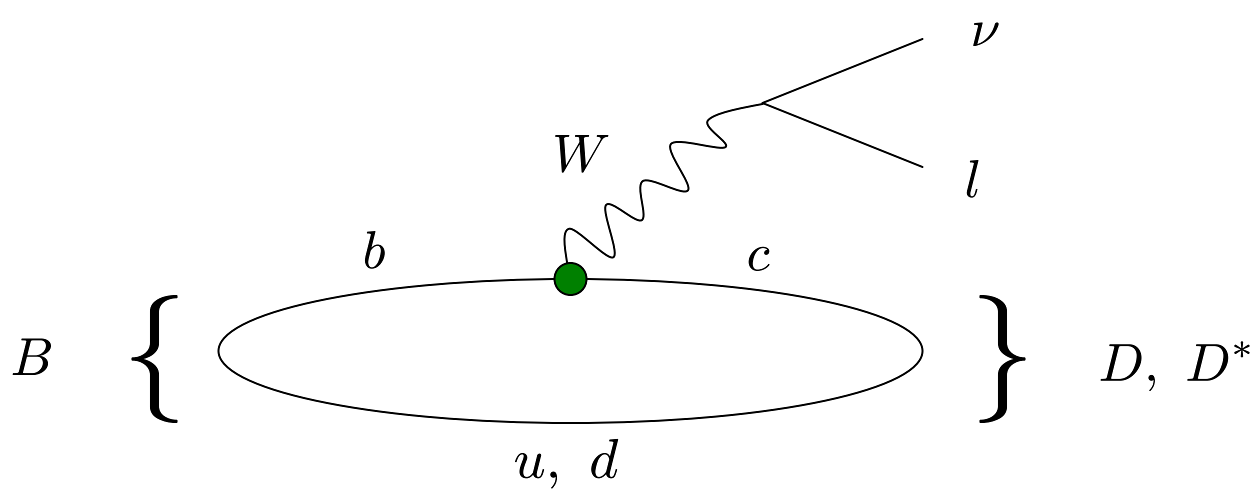
Exclusive $|V_{cb}|$ and new physics

- Next generation intensity-frontier experiments will push experimental errors in $B \to Dl\nu$ and $B \to D^*l\nu$ below ~ 1%
- $|V_{cb}|$ normalizes Unitarity Triangle ~ impact on flavor physics
- Lattice QCD calculations for $B \to D^*l\nu$ and $B \to Dl\nu$ with different systematics, greater precision, vital to search for new physics



- FNAL/MILC, RBC/UKQCD, HPQCD preparing next attack on $B \to D^{(*)}l\nu$

$|V_{cb}|$ from $B \to D^{(*)} l\nu$



- At tree-level in SM, $b \to c$ transition *via* vector, axial currents ~ $|V_{cb}|$
- Spectator *u* (*d*) quark for charged (neutral) B and neutral (charged) $D^{(*)}$
- Valence quarks immersed in sea of gluons, quark-antiquark vacuum polarization
- Stability under strong interactions ~ gold-plated for lattice QCD

$|V_{cb}|$ from $B \to D^{(*)} l\nu$

$$\frac{d\Gamma}{d\omega}(B \to D\ell\nu) = \frac{G_F^2 |V_{cb}|^2 M_B^5}{48\pi^3}(\omega^2 - 1)^{3/2} r^3 (1+r)^2 {F_D}^2(\omega)$$

$$\frac{d\Gamma}{d\omega}(B \to D^*\ell\nu) = \frac{G_F^2 |V_{cb}|^2 M_B^5}{4\pi^3}|\eta_{\mathrm{EW}}|^2 (1+\pi\alpha)(\omega^2 - 1)^{1/2} r^{*3} (1-r^*)^2 \chi(\omega) {F_{D^*}}^2(\omega)$$

- Partial decay rates, form factor shapes (*not* normalization), from experiment
- $D^{(*)}$ energy in B rest frame ~ $\omega = v_B \cdot v_{D^{(*)}}$
- Well-known quantities, kinematic factors, higher order electroweak corrections
  - Coulomb attraction in charged D^* final state (for neutral D^*, $\pi\alpha \to 0$)
  - Electroweak correction η_{EW} from NLO box diagrams, γ or Z exchanged with W
  - $r = M_D/M_B,\ r^* = M_{D^*}/M_B$
  - $\chi(\omega) = \dfrac{\omega+1}{12}\left(5\omega + 1 - \dfrac{8\omega(\omega-1)r^*}{(1-r^*)^2}\right)$
- Form factors from theory ~ hadronic matrix elements
- CKM matrix element

$B \to D^{(*)} l\nu$ form factors

$$F_D(\omega) = h_+(\omega) + \left(\frac{1-r}{1+r}\right) h_-(\omega)$$

$$\begin{aligned} 12(1-r^*)^2\chi(\omega){F_{D^*}}^2(\omega) = & \left[(\omega - r^*)(\omega+1)h_{A_1}(\omega) - (\omega^2-1)\left(r^* h_{A_2}(\omega) + h_{A_3}(\omega)\right)\right]^2 \\ & + \ 2(1-2\omega r^* + r^{*2})\left[(\omega+1)^2 {h_{A_1}}^2(\omega) + (\omega^2-1){h_V}^2(\omega)\right] \end{aligned}$$

- Heavy-quark spin-flavor symmetry

$$F_D(\omega) = F_{D^*}(\omega) = \xi(\omega), \ \ \xi(1) = 1$$

- $B \to D^* l\nu$ at zero recoil

$$F_{D^*}(1) = h_{A_1}(1)$$

- Theorists must calculate small deviation from 1

B → D$^{(*)}$$lv$ hadronic matrix elements

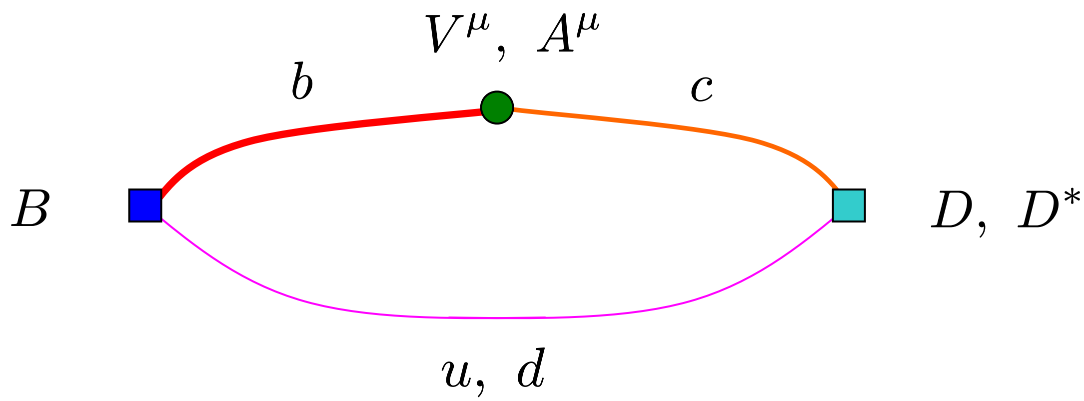
$$\frac{\langle D(p_D)|V^\mu|B(p_B)\rangle}{\sqrt{M_D M_B}} = (v_B + v_D)^\mu h_+(\omega) + (v_B - v_D)^\mu h_-(\omega),$$

$$\frac{\langle D^*(p_{D^*},\epsilon)|A^\mu|B(p_B)\rangle}{\sqrt{M_{D^*} M_B}} = i\left[\epsilon^{*\mu}(1+\omega)h_{A_1}(\omega) - (\epsilon^*\cdot v_B)(v_B^\mu h_{A_2}(\omega) + v_{D^*}^\mu h_{A_3}(\omega))\right],$$

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

- Hadronic matrix elements ← coefficients of exponential expansions of lattice QCD correlation functions
  - Lattice theory interpolating operators for B, D$^{(*)}$
  - Lattice theory axial, vector currents
- Optimal correlator ratios
  - Statistical errors from Monte Carlo integration cancel
  - Lattice current renormalization partially cancels
- For B → D*lv at zero recoil, $F_{D*}(1) = h_{A1}(1)$ ~ axial current matrix element at $p_{D*} = p_B$

B → D$^{(*)}l\nu$ correlators



- Hadronic matrix elements ← coefficients of exponential expansions of lattice QCD correlation functions
  - Lattice theory interpolating operators for B, D$^{(*)}$
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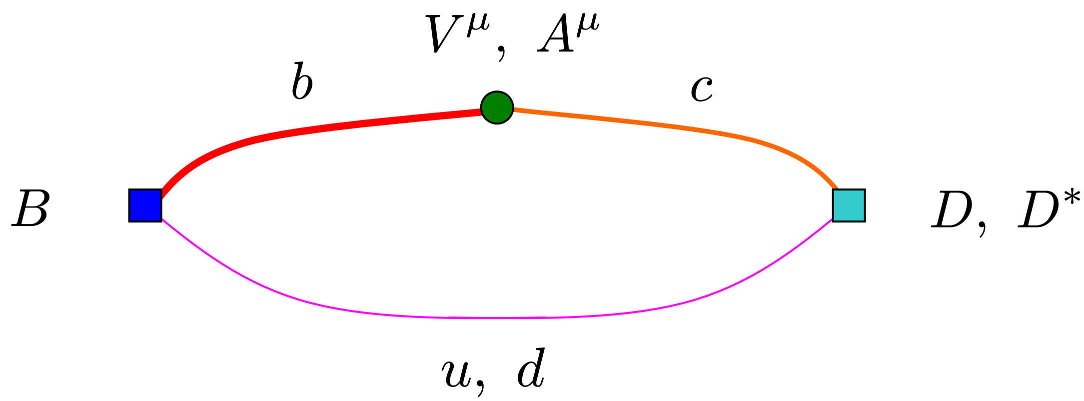
- For B → D$^*l\nu$ at zero recoil, $F_{D*}(1) = h_{A1}(1)$ ~ axial current matrix element at $p_{D*} = p_B$

B → D$^{(*)}$ program philosophy



- Maximize precision: Calculate all (six) form factors at non-zero recoil ~ maximize statistics, kinematic overlap with experiments
  - Multiple-year FNAL/MILC effort began with low statistics calculation of axial current matrix element at zero recoil (one form factor); high statistics update (Lattice 2013) is precision world leader
  - Non-zero recoil calculations require vector current matrix elements, suffer from larger statistical errors, need additional current renormalization factors
  - B → D* at non-zero recoil (four form factors) not done ~ FNAL/MILC effort another first [Laiho and Du]
- Maximize efficiency: Calculate *one* form factor h_{A1} (for B → D*) *at zero recoil* with target errors dictated by threshold for phenomenological impact ~ 1%

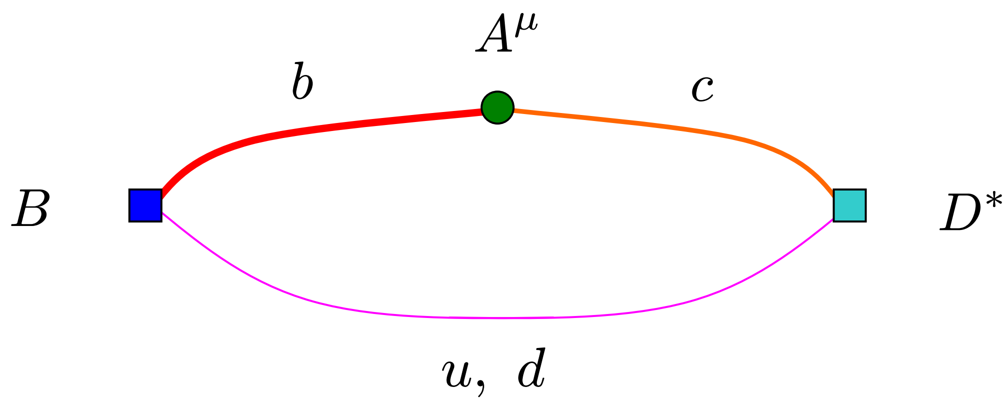
$B \to D^*$ at zero recoil

- Calculations of $h_{A1}(1)$ from PRD 2009, Lattice 2013 update [FNAL/MILC]
- Error budgets from PRD 2009 (left) and for Lattice 2013 PRELIMINARY (right)

Error	PRD 2009	Lattice 2013
Statistics	1.4%	0.4%
χPT	0.9%	0.6%
$g_{DD^*\pi}$	0.9%	0.3%
Kappa tuning	0.7%	0.2%
Discretization errors	1.5%	1.0%
Current matching	0.3%	0.5%
Tadpole tuning	0.4%	–
Isospin breaking	–	0.1%
Total	2.6%	1.4%

- "Discretization errors" are (mostly) heavy-quark discretization effects
- Dominant errors are heavy quark errors (1st) and chiral extrapolation (2nd)

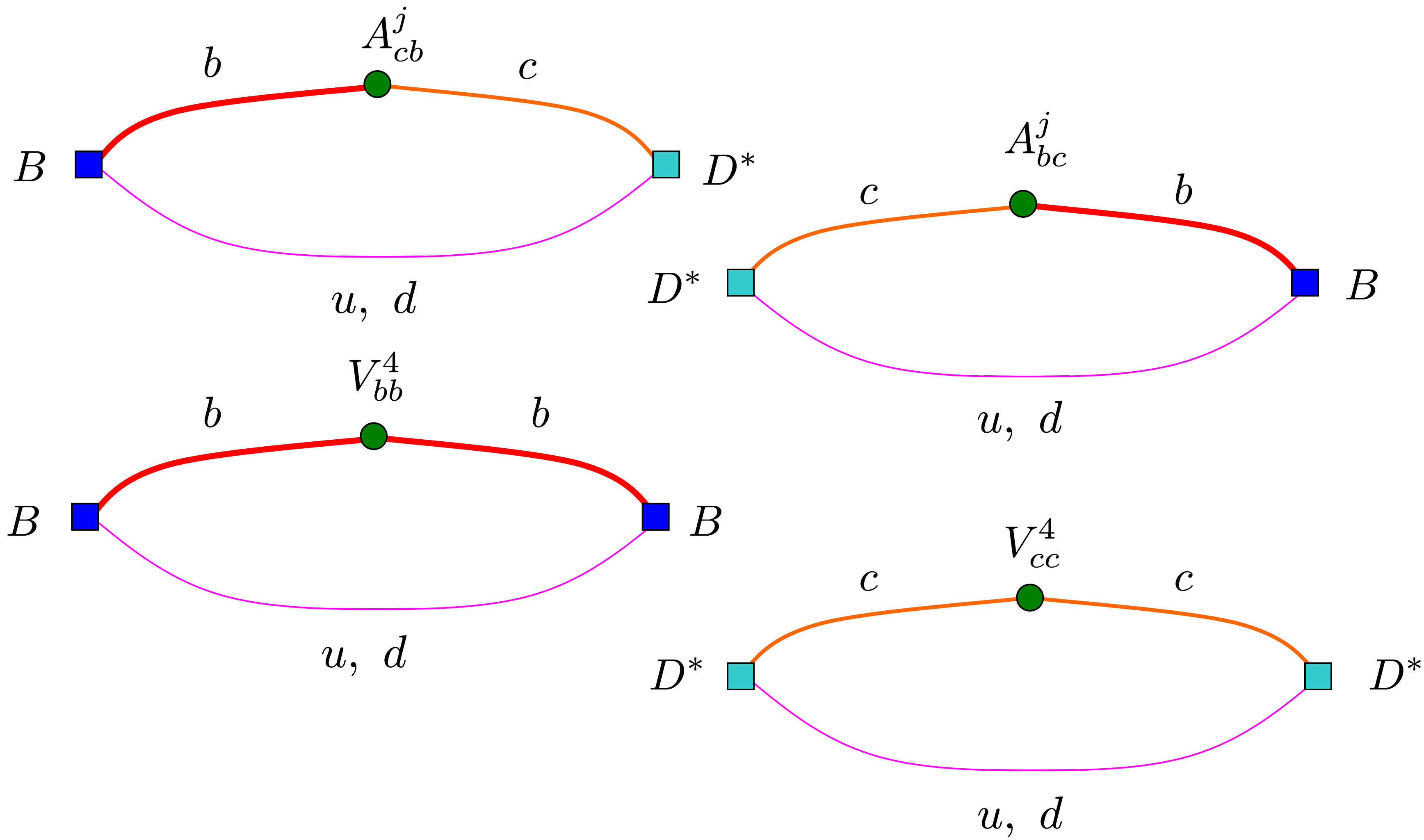
Approach



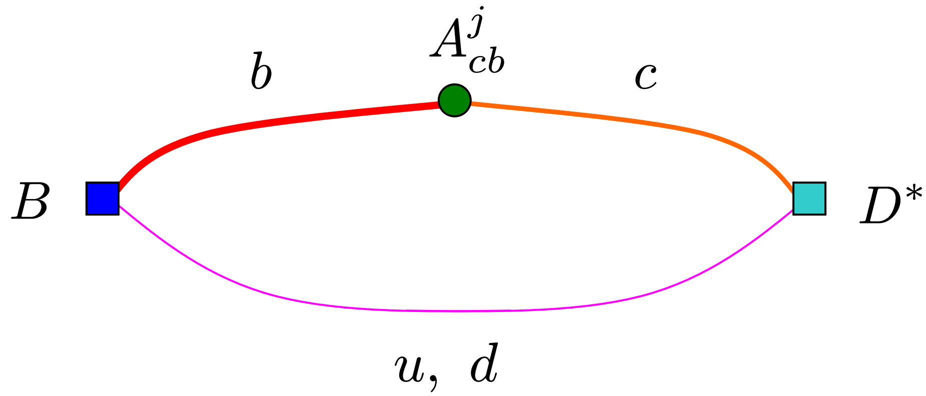
- Clover-improved Wilson bottom, charm with Fermilab interpretation *via* HQET [El-Khadra et al., PRD 1997; Kronfeld, PRD 2000]
- Asqtad-improved staggered light quarks (equal up and down quark masses, no electromagnetism) [MILC, PRD 1999; Lepage, PRD 1999]
- 2+1 flavor Asqtad staggered gauge ensembles [Weisz, NPB 1983; Curci et al., PLB 1983; Weisz and Wohlert, NPB 1984; Luscher and Weisz, PLB and CMP 1985; Alford et al., PLB 1995; Bernard et al., PRD 1998]
  - Five lattice spacings from 0.15 to 0.045 fm for continuum extrapolation
  - Up-down masses from 0.4 to 0.1 of strange mass for chiral extrapolation (to 0.037)

- Oktay-Kronfeld action (improved Fermilab action) designed to reduce heavy-quark discretization errors ~ competitive with HISQ charm, best for bottom [Oktay and Kronfeld, PRD 2008]
- 2+1+1 flavor HISQ gauge ensembles generated at physical up-down masses [MILC, PRD 2013]

Correlators



Correlator ratio



- For $t_{source} << t << t_{source} + T$, ratio plateau ~ form factor
  [FNAL/MILC, PRD 2009, and refs. therein]

$$\frac{C^{B\to D^*}(t,T)C^{D^*\to B}(t,T)}{C^{B\to B}(t,T)C^{D^*\to D^*}(t,T)} \to \frac{\langle D^*|A^j_{cb}|B\rangle\langle B|A^j_{bc}|D^*\rangle}{\langle B|V^4_{bb}|B\rangle\langle D^*|V^4_{cc}|D^*\rangle} = \left|\frac{h_{A_1}(1)}{\rho_{A^j}}\right|^2 + \ldots$$

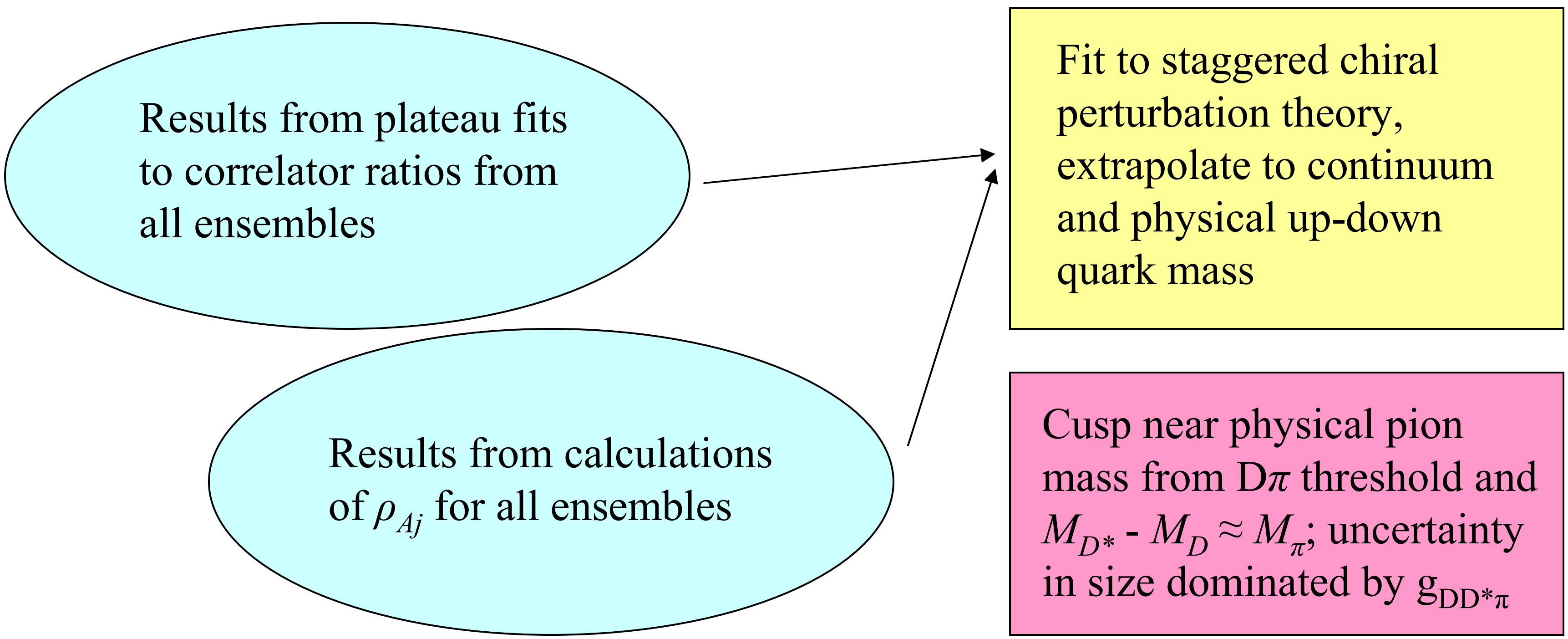
- ρ_{Aj}, ratio of lattice to continuum current renorm. factors [Harada et al., PRD 2002; FNAL/MILC, PRD 2009]
  - Very close to one by construction
  - Computing deviation separate from generation of correlators
  - Perturbation theory applies, numerical suppression of first order

$$\rho_{A^j} = 1 + O(\alpha_s)$$

Chiral-continuum extrapolation

[Laiho and Van de Water, PRD 2006]

- Staggered chiral perturbation theory through NLO, with NNLO analytic terms
  - Build chiral effective field theory for effective continuum action of lattice theory
    - Fermilab charm, bottom quarks
    - Staggered up, down, strange quarks in valence and sea
  - Light-quark and gluon discretization errors, (staggered) taste symmetry breaking
  - Light-quark mass dependence of form factor



Error budget projections

Error	Lattice 2013	1-loop OK	tree-level OK
Statistics	0.4%	0.3%	0.3%
χPT, $g_{DD^*\pi}$	0.7%	0.3%	0.3%
Kappa tuning	0.2%	0.2%	0.2%
Discretization errors	1.0%	0.2%	0.7%
Current matching	0.5%	0.5%	0.5%
Isospin breaking	0.1%	0.1%	0.1%
Total	1.4%	0.7%	1.0%

- Projected discretization errors from power-counting estimates of heavy-quark errors
- "1-loop OK" means mass-dimension five operators in the action, corresponding operators in the current, are improved at one-loop
- "tree-level OK" means tree-level improvement for action, current
- Assumptions:
  - 8 source times per ensemble, 1000 gauge configurations on existing HISQ ensembles, additional ensemble with lattice spacing 0.03 fm [MILC, planned for HISQ bottom]
  - Errors from statistics, kappa tuning, ChPT, $g_{DD^*\pi}$ scale with statistics
  - 50% of errors from ChPT, $g_{DD^*\pi}$ eliminated by inclusion of physical-point ensembles

Major tasks

- Design B and D^* interpolating operators ← presently used operators suffice
- Improve current, action ← FNAL/MILC colleagues ~ expert consultants
  - Enumerate operators through third-order in HQET
  - Match matrix elements at tree-level, one-loop
- Develop code
  - Inverter (quark propagator constructor) for OK action ← optimization in progress [SWME]
  - Application (correlator construction) code ← made available by FNAL/MILC
- Generate data
  - Kappa tuning runs ← production and analysis begun for tree-level OK action
  - Physical-mass ensembles ← HISQ ensembles made publicly available by MILC
- Calculate current renormalization factors ← independent of developing code, data production
- Analyze data
  - Correlator fits
  - Staggered chiral perturbation theory fits ← presently used formula applies for OK bottom and charm, HISQ light quarks on HISQ ensembles
  - Estimate systematics

Recent work

- Optimization of OK inverter ~ Lattice 2013 talk [Yong-Chull Jang *et al.*, SWME]
  - Precalculate gauge-link combinations ~ acceleration of bi-stabilized conjugate gradient inverter
  - Wrote and tested GPU code
  - Optimizations to reduce overheads in progress

- Masses of $B_s^{(*)}$ mesons and bottomonium ~ spectrum tests of tree-level improved OK action
  - Data for coarse (~ 0.12 fm) Asqtad staggered ensemble
  - Quantify improvement in hyperfine mass splittings, inconsistency parameter [DeTar et al., Lattice 2010]
  - Completed preliminary tests of dispersion relations, extractions of rest and kinetic masses
  - Correlator fits for cross checks with increased statistics in progress

Summary and outlook

- Flavor physics entering an exciting era
  - Increasing precision of SM and experimental results → very precise tests of CKM description, searches for new physics
  - $|V_{cb}|$ crucial in this era, precise determination essential
- Lattice QCD calculations of $B \to D^{(*)} l\nu$ form factors + experimental branching fractions will yield very precise values for $|V_{cb}|$
  - Great opportunities afforded by high impact, (comparatively) low effort approaches ~ improve state of art; $B \to D^*$ form factor at zero recoil
  - Powerful competition, but generous experts; FNAL/MILC generating 0.03 fm HISQ ensemble
- Oktay-Kronfeld improved Fermilab action for bottom and charm can be competitive with other approaches (*e.g.*, HISQ-HISQ, NRQCD-HISQ) in near future
- Taking advantage of opportunities ~ coding and analysis, formal efforts, investigating alternative approaches (*e.g.*, OK-HISQ bottom-charm, interp.)