Heavy Flavor Physics

Ran Zhou

Fermilab

(Lattice 2016, Southampton, UK)

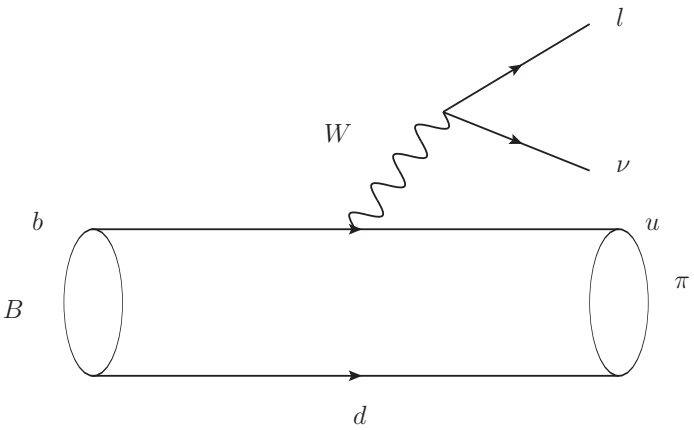
07/28/2016

Outline

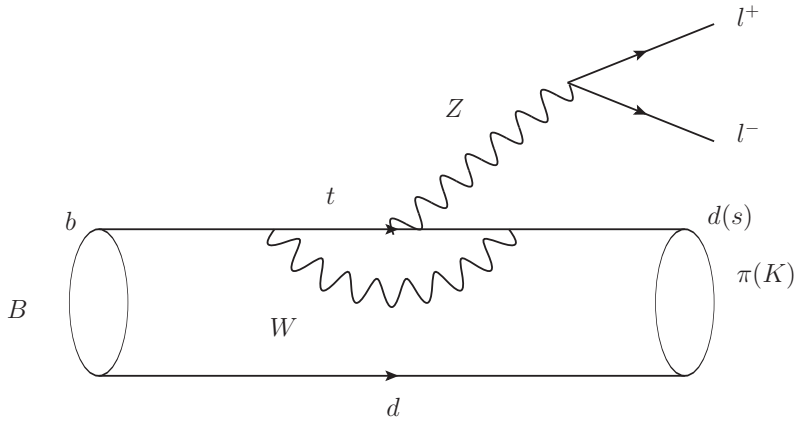
I will focus on published results after Lattice 2015 and their impact on Standard-Model phenomenology.

- Heavy to light semileptonic decays ($B \to \pi l \nu$, $B_s \to K l \nu$, $B \to K l l$, *etc..*)
- B-$\bar{B}$ mixing
- Heavy flavor physics talks on Lattice 2016.

Heavy to light semileptonic decays



Tree-level diagram



Loop-level diagram

- B-meson semileptonic decays through tree-level diagram ($b \to u l \nu$). For example, $B \to \pi l \nu$, $B_s \to K l \nu$, $\Lambda_b \to p l \nu$
- B-meson semileptonic decays through loop-level diagram ($b \to s(d) l l$) For example, $B \to K(\pi) l^+ l^-$, $B \to K(\pi) \nu \bar{\nu}$, $\Lambda_b \to \Lambda l l$

Standard Model prediction

The Standard Model prediction can be written in a generic form:

$$\text{Theo. pred.} \quad = \quad (\text{prefactors}) \times (\text{CKMfactor}) \times \langle f|\hat{O}|i\rangle$$

- Prefactors contain the Wilson coefficients (short distance physics).
- CKM factor depends on the processes.
- Lattice QCD calculates $\langle f|\hat{O}|i\rangle$ non-perturbatively from first principle. (long distance physics)

Hadronic matrix elements and form factors

Matrix elements in tree-level processes:

$$\langle B(p)|\bar{b}\gamma^\mu s|P(k)\rangle = f_+(p^\mu + k^\mu - \frac{m_B^2 - m_K^2}{q^2}q^\mu) + f_0\frac{m_B^2 - m_K^2}{q^2}q^\mu$$
$$= \sqrt{2m_B}\left[f_\parallel \frac{p^\mu}{m_B} + f_\perp k_\perp^\mu\right]$$

For the rare (loop-level) decays, there is an extra form factor via tensor current

$$q_\nu\langle P(k)|\bar{s}\sigma^{\mu\nu}b|B(p)\rangle = \frac{if_T}{m_B + m_K}\left[q^2(p^\mu + k^\mu) - (m_B^2 - m_K^2)q^\mu\right]$$

There are more form factors in the Λ_b semileptonic decays.

Heavy to light semileptonic decays (Tree level)

Lattice-QCD $B \to \pi l \nu$ form factors summarized by Carlos Pena at Lattice 2015:

new results for $B \to \pi l \nu$

	FNAL/MILC	RBC/UKQCD	HPQCD
ensembles	MILC	RBC/UKQCD	MILC
N_f	2+1	2+1	2+1
a (fm)	4/0.045 – 0.12	2/0.086, 0.11	2/0.09, 0.12
$M_\pi^{\min}$ [MeV]	220	289	260
$M_\pi^{\min} L$	3.8	4.0	3.8
l quarks	asqtad	DW	asqtad
b quark	RHQ (Fermilab)	RHQ (Columbia)	NRQCD
reference	[1503.07839]	[1501.05373]	[1310.3207]

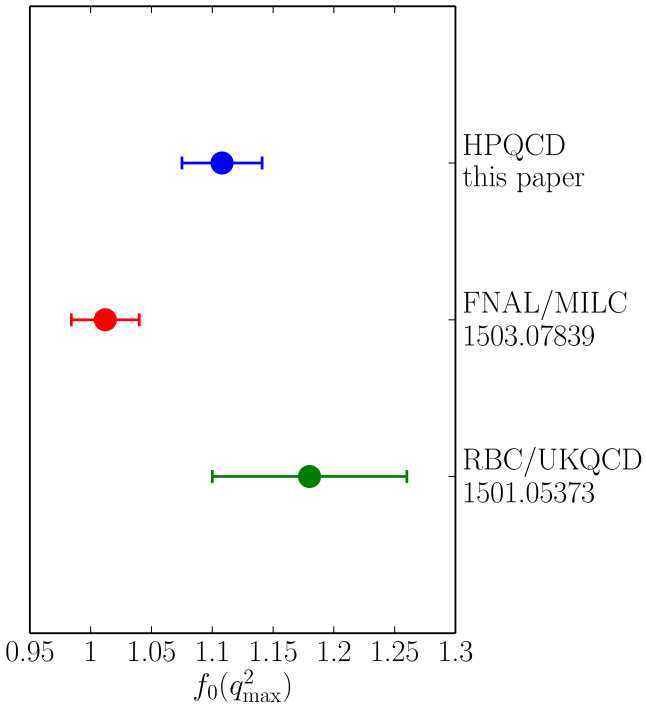
Other works: PRD.92.034503($\Lambda_b \to p l \nu$) PRD.91.074510, PRD.90.054506 ($B_s \to K l \nu$)

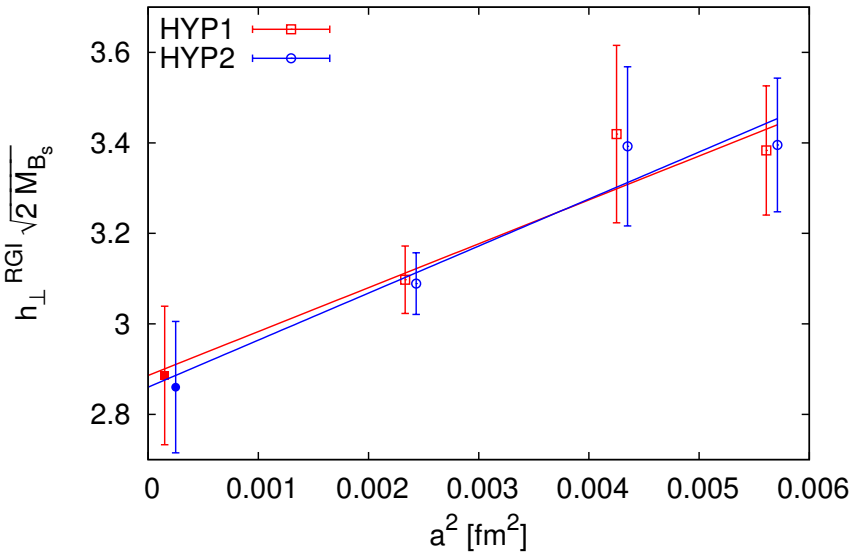
Heavy to light semileptonic decays (Tree level)

New published results after Lattice 2015:

	HPQCD	ALPHA
process	$B \to \pi$, $B_s \to \eta_s$, $B_s \to K$	$B_s \to K$
kinematics	$q^2 = q^2_{\rm max}$	$q^2 = 21.22 {\rm GeV}^2$
ensembles	MILC HISQ	CLS
N_f	2+1+1	2
a	3/0.15–0.09	0.048–0.075
$M_\pi^{\rm min}$	physical	310
light quark	HISQ	Improved Wilson
b quark	NRQCD	npHQET
Ref.	PRD.93.034502	PLB.2016.03.088

Heavy to light semileptonic decays (Tree level)





- (Left) First lattice-QCD result on $B \to \pi l \nu$ $f_0(q^2_{\rm max})$ at zero recoil from physical u/d quark mass. (HPQCD PRD.93.034502).
- (Right) Continuum extrapolation of $h_\perp$. (ALPHA, PLB.2016.03.088)

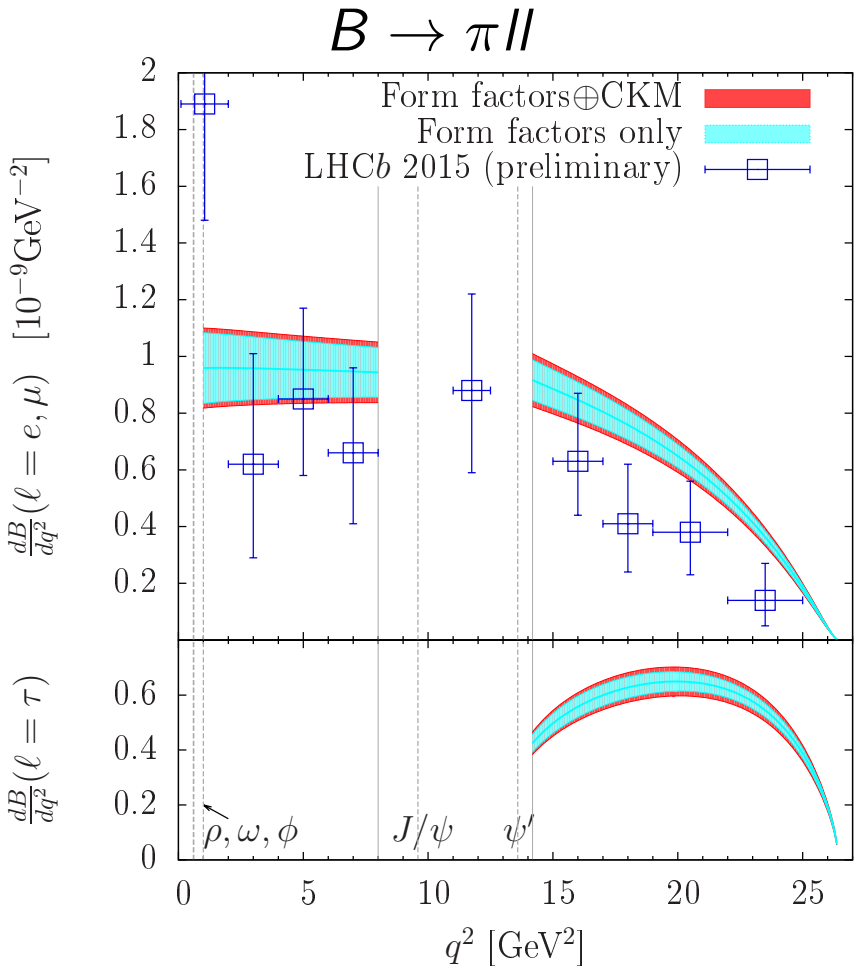
Heavy to light semileptonic rare decays (Loop level)

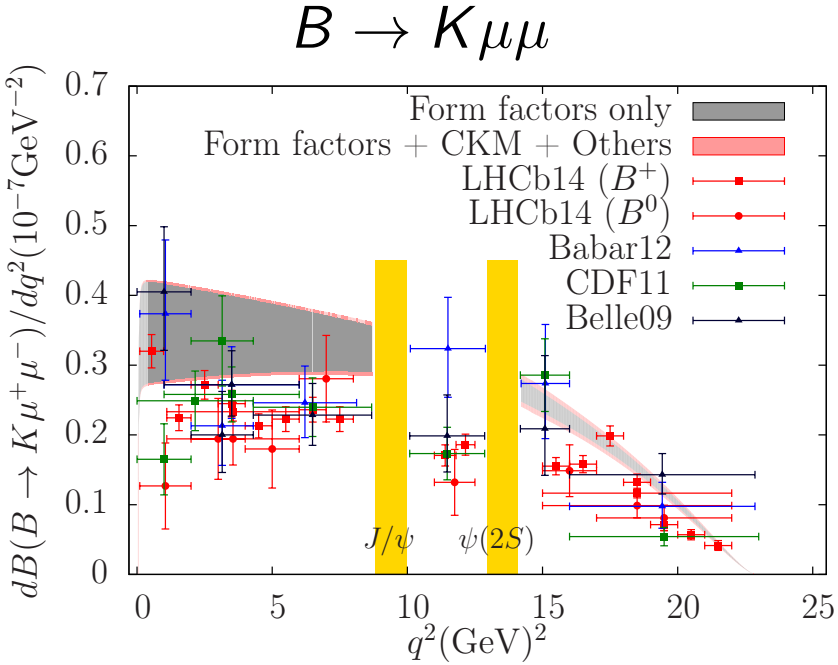
New results after Lattice 2015:

	Fermilab/MILC	Fermilab/MILC	Detmold and Meinel
process	$B \to Kll$,	$B \to \pi ll$	$\Lambda_b \to \Lambda$
kinematics	full q^2	full q^2	full q^2
ensembles	MILC asqtad	MILC asqtad	RBC/UKQCD DWF
N_f	2+1	2+1	2+1
a	4/0.045-0.12	4/0.045-0.12	2/0.09-0.12
$M_\pi^{\min}$	260	260	227
light quark	asqtad	asqtad	DWF
b quark	Fermilab	Fermilab	RHQ
Ref.	PRD.93.025026	PRL.115.152002	PRD.93.074501

- PRD.93.034005 (Fermilab/MILC, B rare decay pheno)
- PRD.94.013007 (Meinel and van Dyk, Λ_b rare decay pheno)
- PRD.88.054509, PRL.111.162002 (HPQCD, $B \to Kll$ ff and pheno), PRD.89.094501, PRL.112.212003 ($B \to K^* ll$ ff and pheno)

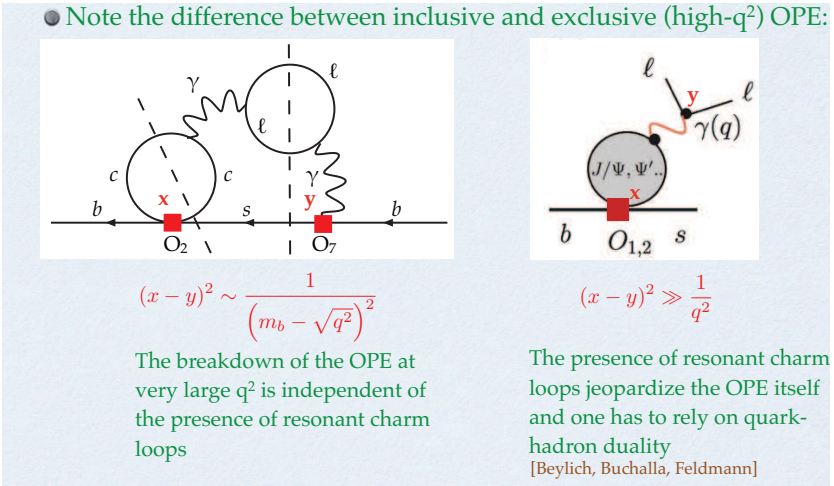
Standard Model predictions of B rare decays



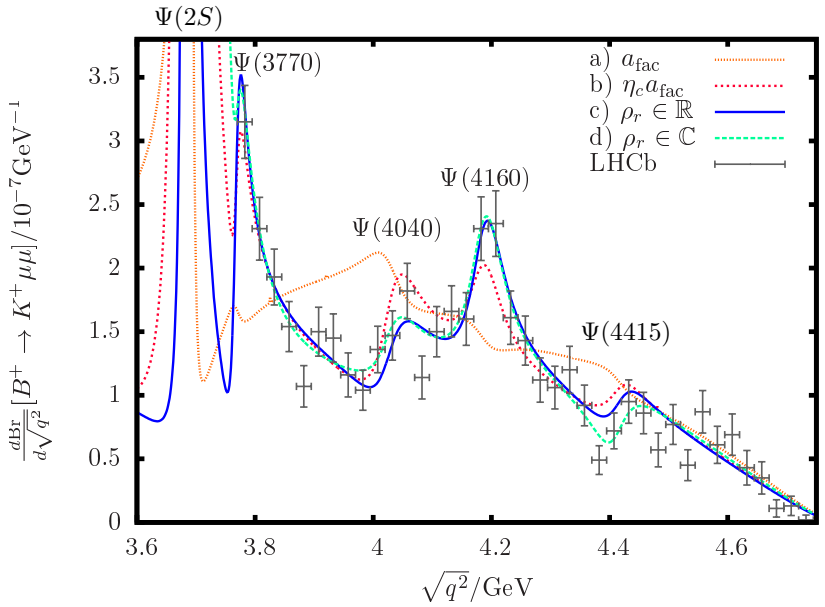


- Standard-Model predictions of the differential decay rate in $B \to \pi ll$ and $B \to Kll$ process (PRL.115.152002, PRD.93.034005).

Resonance states and non-lattice errors



E. Lunghi at KITP 2015

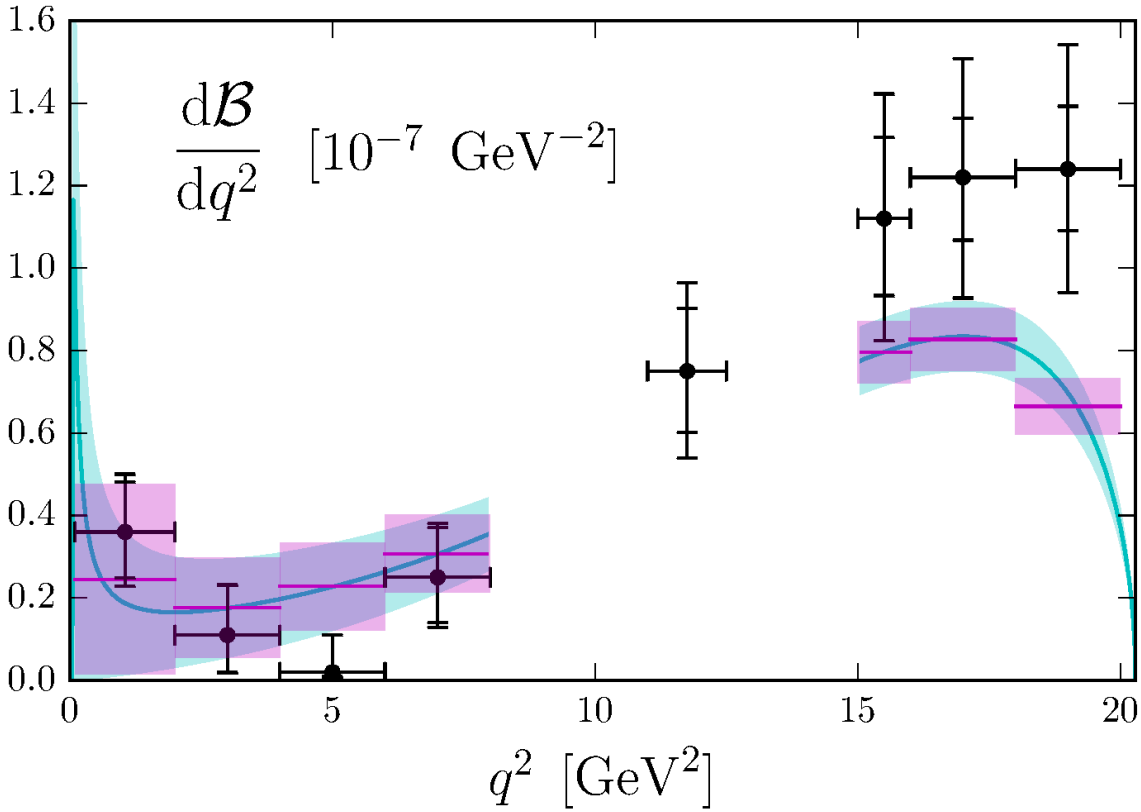


1406.0566

- As the form factor errors become smaller, cautious is needed to treat the non-lattice errors in the Standard-Model predictions.
- The resonance states could introduce the violation of quark-hadron duality in the high q^2 range (1406.0566, PRD.70.114005, EPJC.71.1625).
- For all non-lattice errors, please refer to E. Lunghi's talk at KITP Program "Lattice Gauge Theory for the LHC and Beyond"

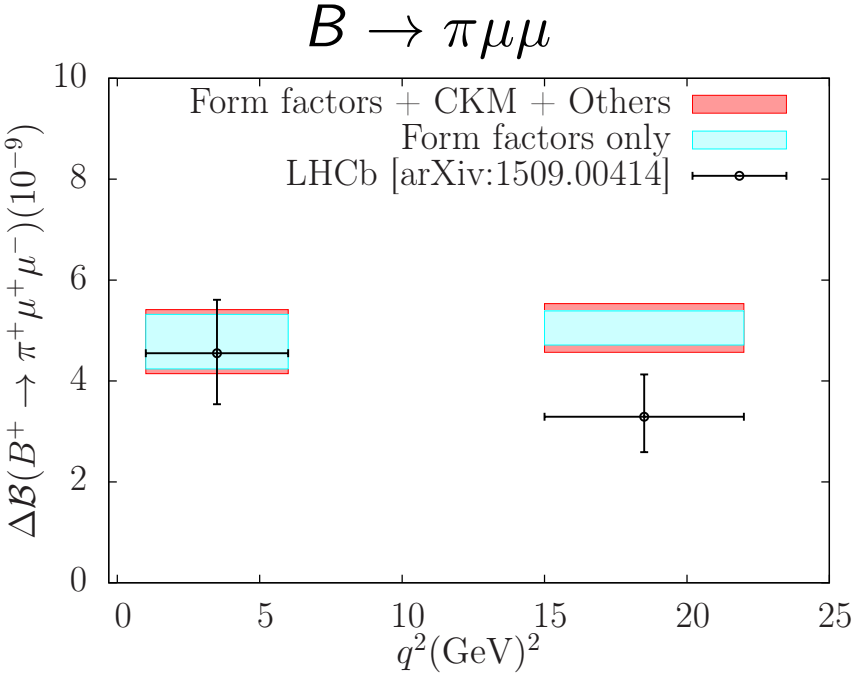
Standard Model predictions of B rare decays

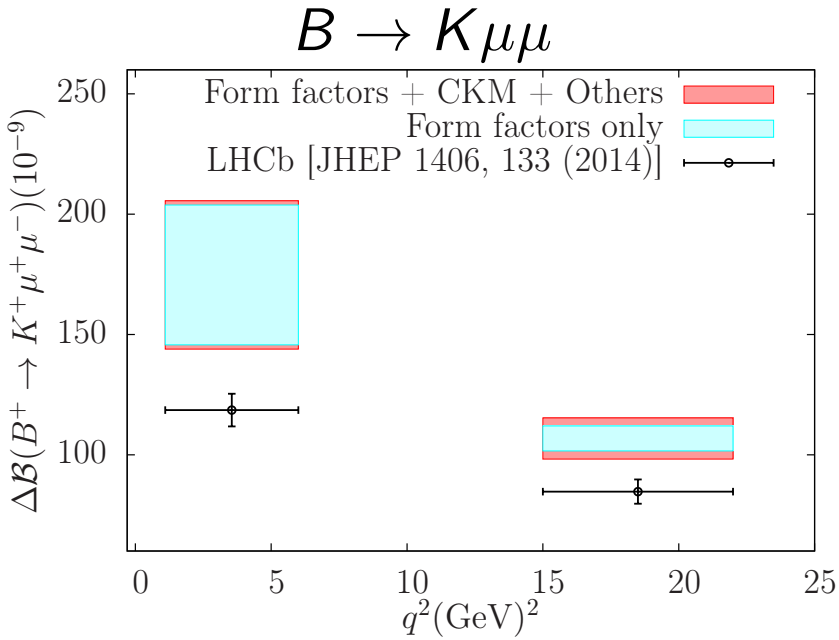
$\Lambda_b \to \Lambda ll$



- Standard-Model predictions of the differential decay rate in $\Lambda_b \to \Lambda ll$ processes. (PRD.93.074501)

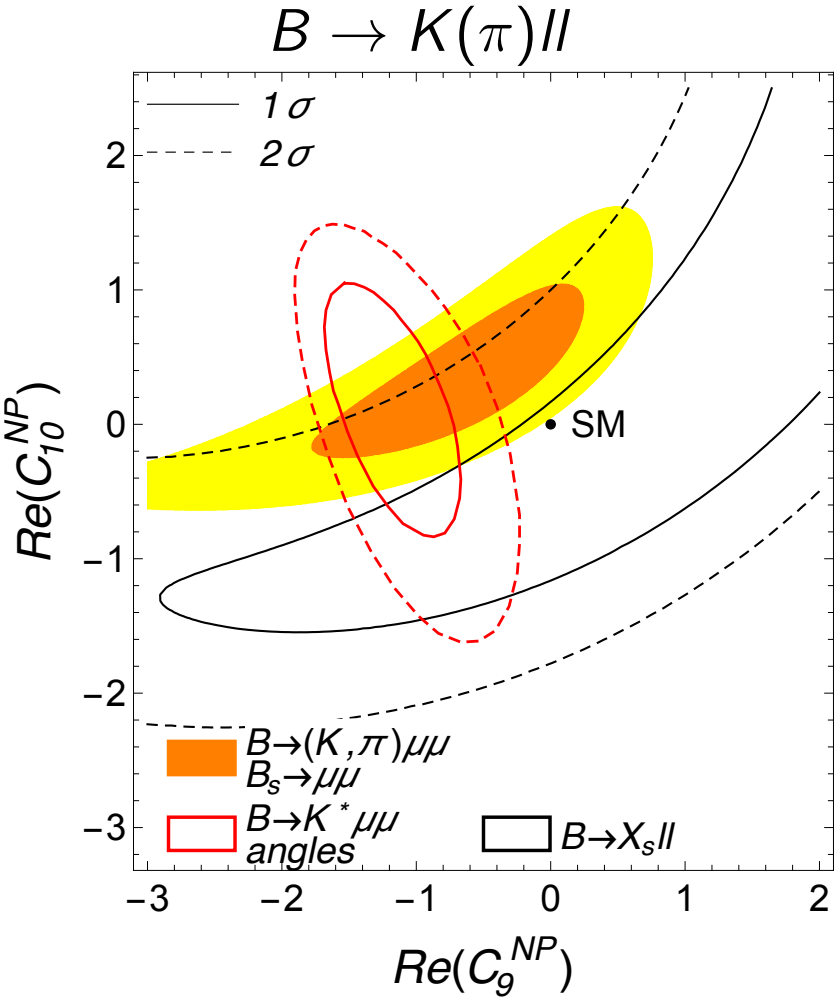
Standard Model predictions of B rare decays





- Four measurements combined disfavor the Standard-Model hypothesis at the 1.7σ level (PRD.93.034005).

Constraints on New Physics.



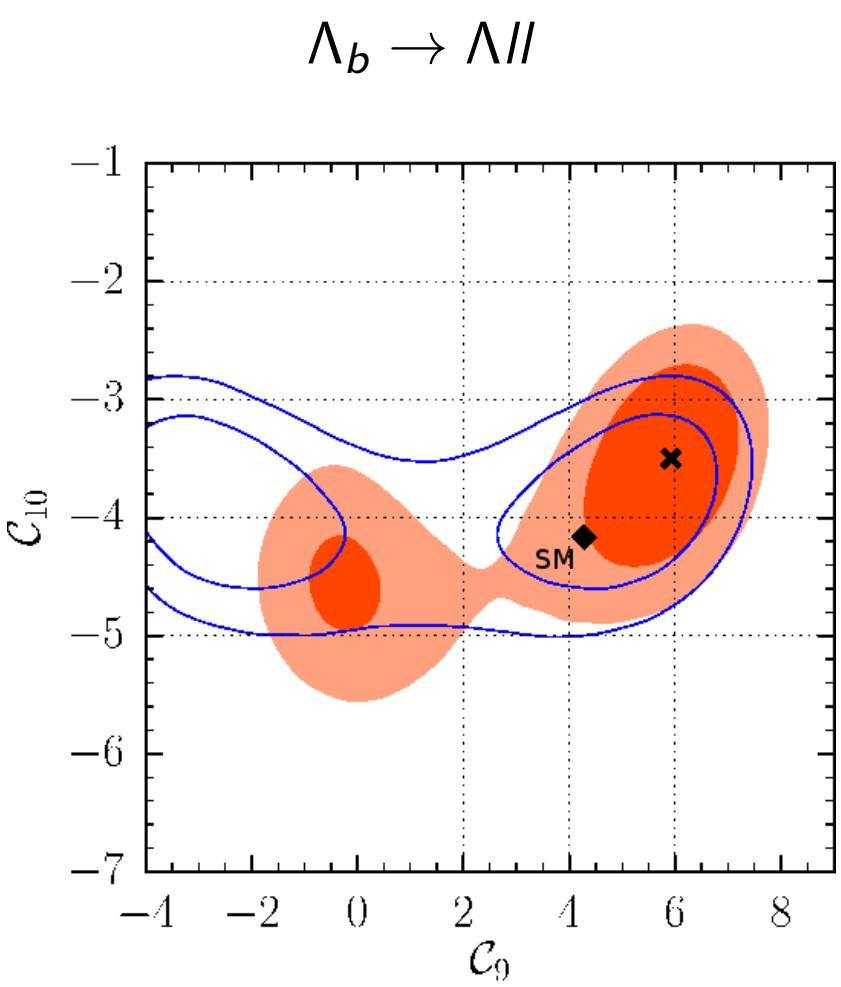


Figure : Constraints to new physics from $B \to K(\pi)ll$ plus $B_s \to \mu\mu$ decays (PRD.93.034005) and $\Lambda_b \to \Lambda ll$ decay (PRD.94.013007).

Related talks on Lattice 2016

Heavy to light meson semileptonic decay and $|V_{ub}|$, $|V_{cs}|$ determination.

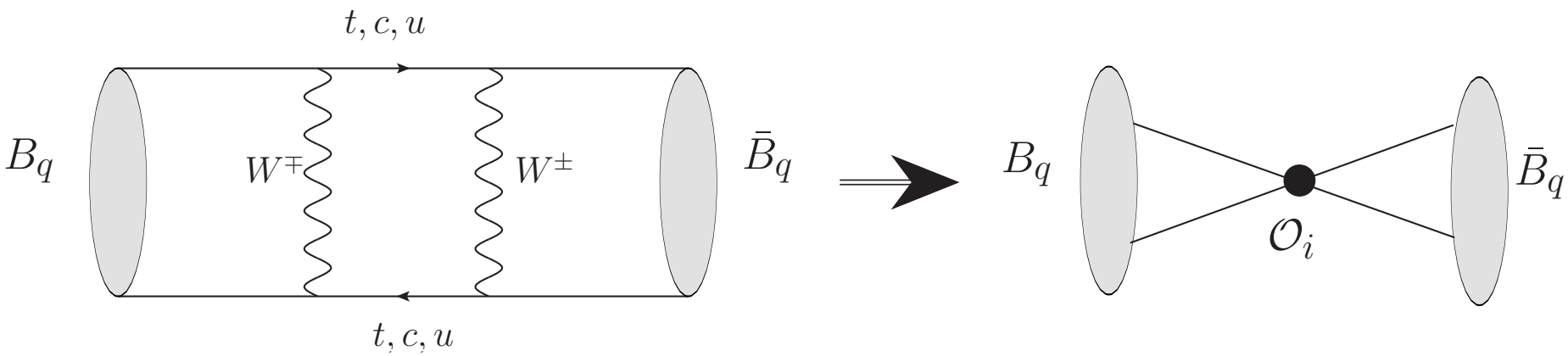
- Semi-leptonic form factors for rare B decays (Edwin Lizarazo Fri. 17:10)
- $B \to \pi$ semileptonic decay form factors with NRQCD/HISQ quarks (Chris Bouchard Fri. 17:30)
- Form factors in the $B_s \to Kl\nu$ decays using HQET and the lattice (Debasish Banerjee (Fri. 17:50)
- Extraction of the bare form factors for the semi-leptonic B_s decays (Mateusz Koren Fri. 18:10)
- Lattice QCD calculation of form factors for $\Lambda_b \to \Lambda(1520)l^+l^-$ decays (Stefan Meinel Fri. 15:50)
- D meson semileptonic decays in lattice QCD with Moebius domain-wall quarks (Takashi Kaneko Fri. 14:20)
- Hypercubic effects in semileptonic $D \to \pi$ decays on the lattice (Giorgio Salerno, Fri. 14:40)
- D meson semileptonic form factors with HISQ valence and sea quarks (Steven Gottlieb Fri. 15:20)

Related talks on Lattice 2016

Heavy to heavy semileptonic decay and $|V_{cb}|$ determination.

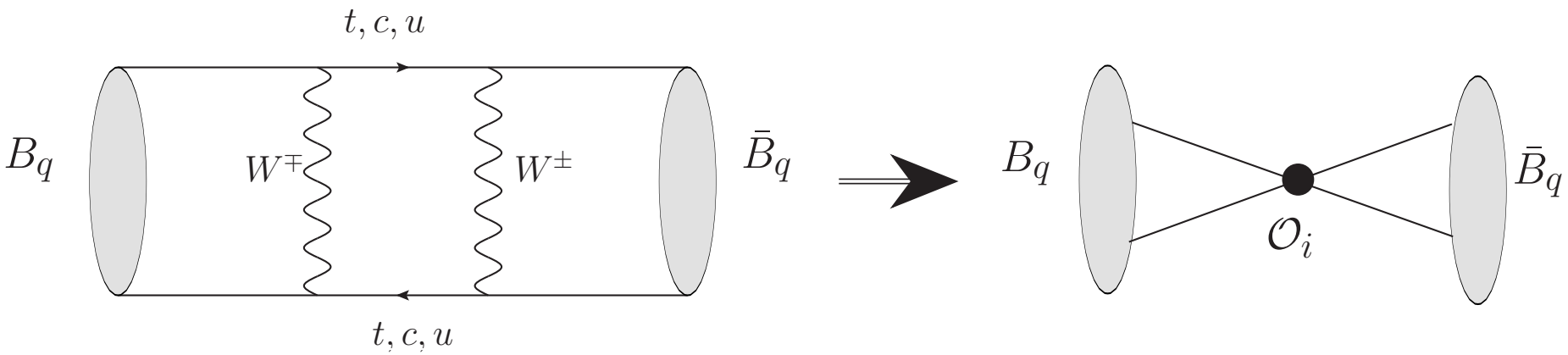
- Heavy-heavy current improvement for calculation of $B \to D^{(*)} l\nu$ semi-leptonic form factors using the Oktay-Kronfeld action (Jon Bailey on Wed. 9:00 and Jaehoon Leem in Poster session)
- V_{cb} from $\bar{B}^0 \to D^{*-} l^- \nu$ zero-recoil form factor using 2+1+1 flavour HISQ and NRQCD (Judd Harrison on Wed. 9:20)
- B_c decays from highly improved staggered quarks and NRQCD (Andrew Lytle on Wed. 9:40)
- $B_{(s)} \to D_{(s)}$ semileptonic decays with NRQCD-HISQ valence quarks (Chris Monahan on Wed. 10:00)
- Semi-leptonic B decays with charming final state (Oliver Witzel on Wed. 10:20)

B-mixing



- Mixing occurs via box diagrams and is dominated by short distance contributions.
- The mixing process is GIM suppressed in Standard-Model.

B-mixing



$$\mathcal{H}_{\text{eff}} = \sum_{i=1}^{5} C_i \mathcal{O}_i$$

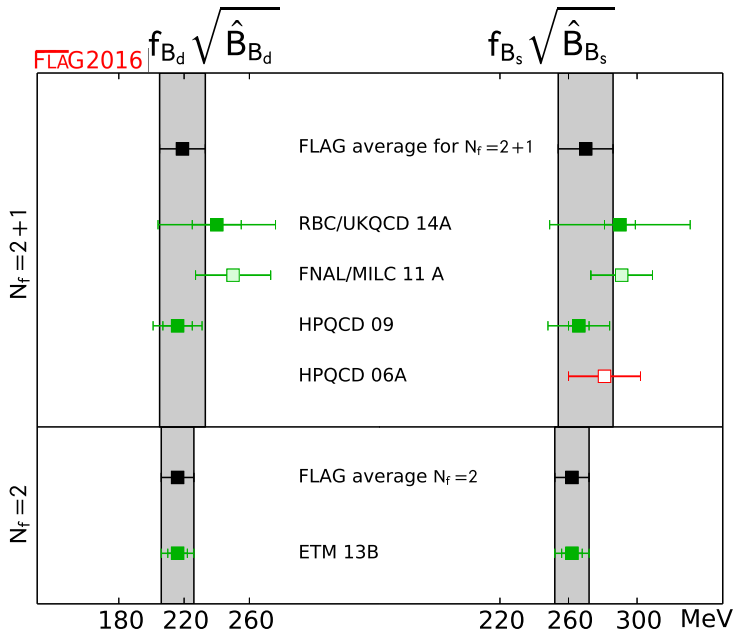
$$\mathcal{O}_1^q = \bar{b}^\alpha \gamma_\mu L q^\alpha \, \bar{b}^\beta \gamma_\mu L q^\beta$$
$$\mathcal{O}_2^q = \bar{b}^\alpha L q^\alpha \, \bar{b}^\beta L q^\beta$$
$$\mathcal{O}_3^q = \bar{b}^\alpha L q^\beta \, \bar{b}^\beta L q^\alpha$$
$$\mathcal{O}_4^q = \bar{b}^\alpha L q^\alpha \, \bar{b}^\beta R q^\beta$$
$$\mathcal{O}_5^q = \bar{b}^\alpha L q^\beta \, \bar{b}^\beta R q^\alpha$$

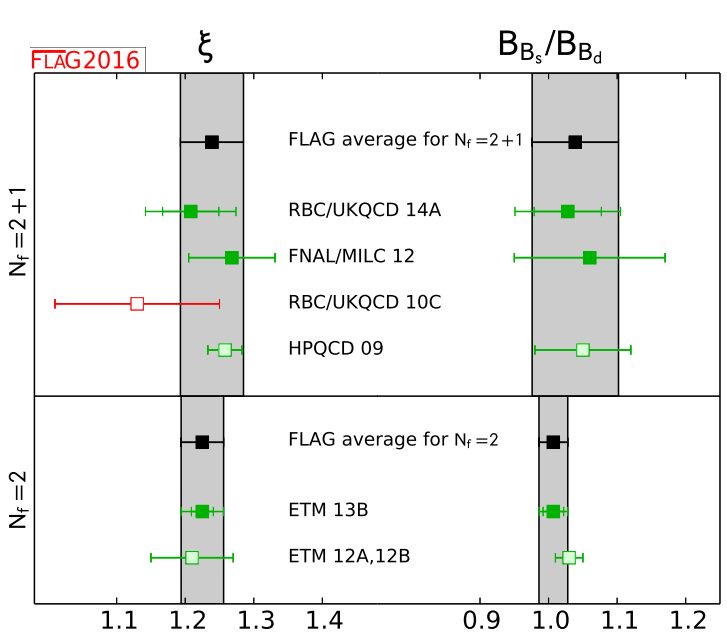
Bag parameters:

$$\langle \bar{B}_q^0 | \mathcal{O}_i(\mu) | B_q^0 \rangle = f_{B_q}^2 B_i(\mu)$$

$$\xi = \sqrt{\frac{f_{B_s}^2 \hat{B}_{B_s}^{(1)}}{f_{B_d}^2 \hat{B}_{B_d}^{(1)}}}$$

B-mixing in Lattice QCD





- FLAG-3 (1607.00299) summarizes results until November 30, 2015

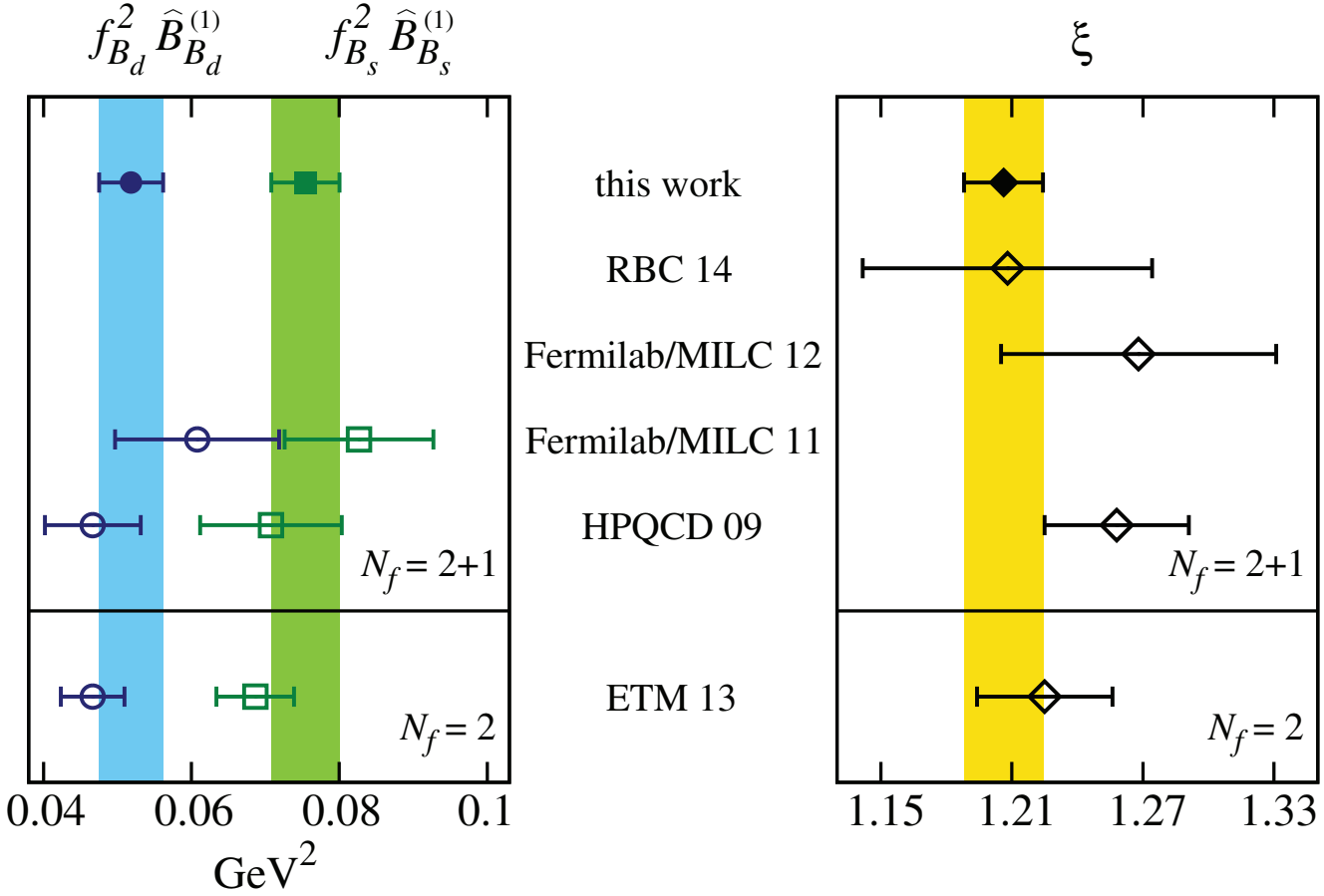
B-mixing in Lattice QCD

New published results after Lattice 2015:

	Fermilab/MILC
process	B-mixing, B_s-mixing
ensembles	MILC asqtad
N_f	2+1
a	4/0.12-0.045
$M_\pi^{\min}$	260
light quark	asqtad
b quark	Fermilab
Ref.	PRD.93.113016

- Fermilab/MILC PRD.93.113016 satisfies FLAG criteria for "green square"

Impact on B-mixing average



- Error on matrix elements and ξ is 1.5-2 times and 2.4 times smaller than FLAG-3 averages, respectively.

B-mixing observables

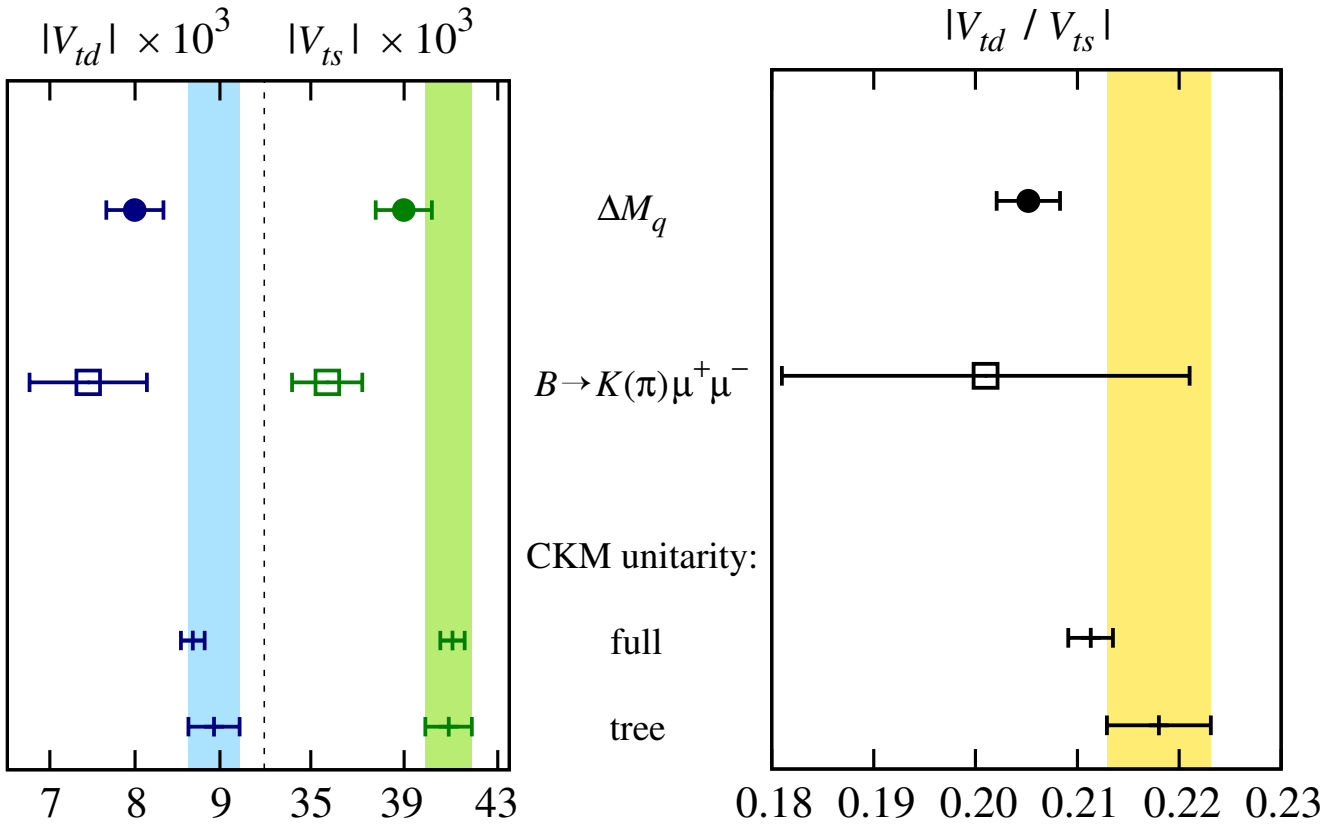
Mass difference and CKM matrix element determinations

$$\Delta M_d = \left(\frac{G_F^2 M_W^2 S_0}{4\pi^2}\right) \eta_B(\mu) \times |V_{tb} V_{td}^*|^2 \times \langle \bar{B}_d^0 | \mathcal{O}_1(\mu) | B_d^0 \rangle$$

$$\Delta M_s = \left(\frac{G_F^2 M_W^2 S_0}{4\pi^2}\right) \eta_B(\mu) \times |V_{tb} V_{ts}^*|^2 \times \langle \bar{B}_s^0 | \mathcal{O}_1(\mu) | B_s^0 \rangle$$

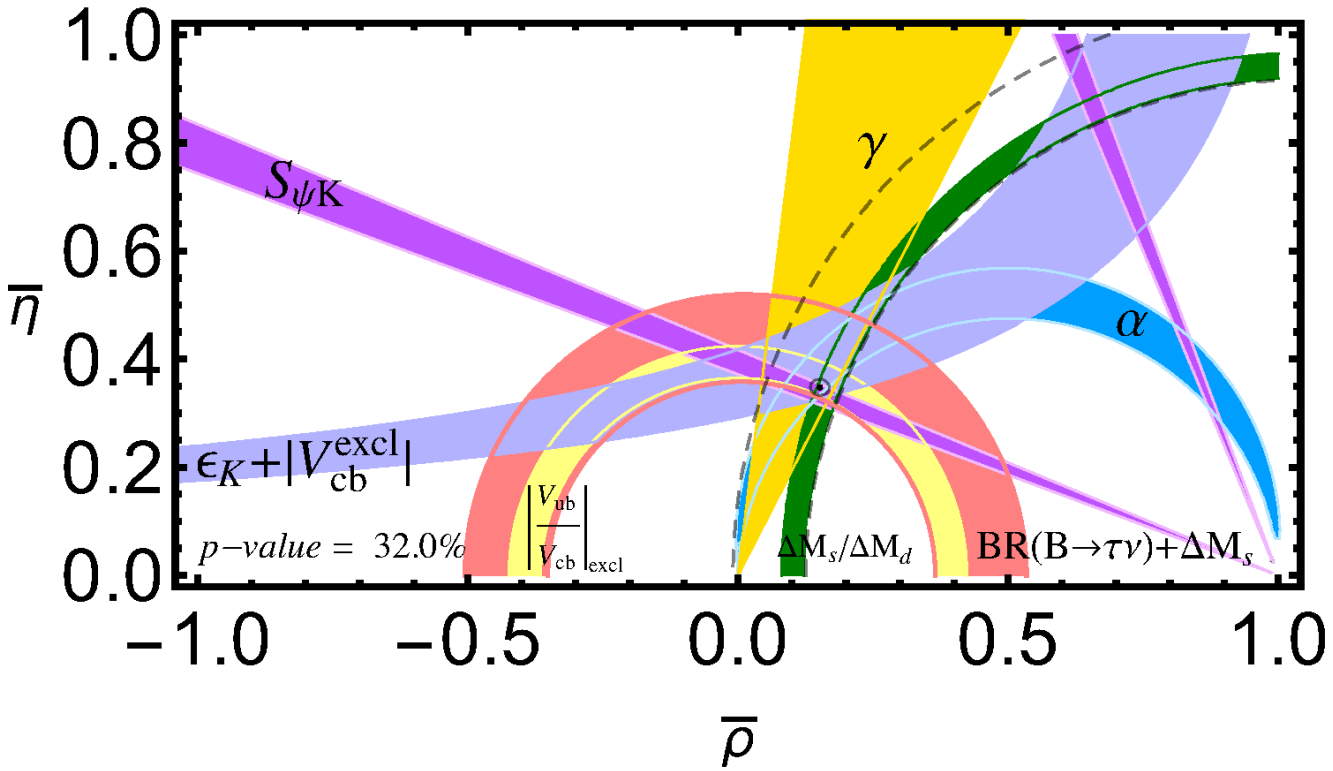
$$\frac{\Delta M_s}{\Delta M_d} = \left|\frac{V_{\rm ts}}{V_{\rm td}}\right|^2 \frac{\langle \bar{B}_s^0 | \mathcal{O}_1(\mu) | B_s^0 \rangle}{\langle \bar{B}_d^0 | \mathcal{O}_1(\mu) | B_d^0 \rangle} = \left|\frac{V_{\rm ts}}{V_{\rm td}}\right|^2 \frac{M_{B_s}}{M_{B_d}} \xi^2$$

Impact from new B-mixing results



- Determinations of $|V_{td}|$ and $|V_{ts}|$, and their ratio from B-mixing and rare $B \to K(\pi)\mu\mu$ decays (PRD.93.113016, PRD.93.034005).
- Tension between FCNC and tree processes: results from B-mixing (rare B decays) lie below the determinations from CKMfitters full global unitarity triangle fit using only tree-level inputs by 1.2–2.1σ.

Impact from new B-mixing results



- Global CKM-unitarity-triangle fit using the new determination of ξ as well as new $|V_{ub}|$ (PRD.92.014024) and $|V_{cb}|$ (PRD.92.034506).
- The constraint from B-meson mixing (solid green band) is approximately 3 times smaller than that obtained using the previous result for ξ from PRD.86.034503 at 2012 (dashed gray lines).

Related talks on Lattice 2016

B-mixing and D-mixing:

- Calculation of hadronic matrix elements contributing to the $B_s - \bar{B}_s$ width difference (Matthew Wingate on Wed. 10:40)
- D-Meson Mixing in 2+1 Lattice QCD and Related Topics (Andreas Kronfeld, Fri. 15:40)

Other topics which are not covered in this talk:

- Heavy to heavy semileptonic decays pheno (1605.07191).
- Heavy meson decay constants (ETMC 1603.04306)
  - Charm Physics with Domain Wall fermions (Justus Tobias Tsang Fri. 14:00)
  - Decay constants f_B and f_{B_s} and quark masses m_b and m_c from HISQ simulations (Javad KOMIJANI Fri. 16:30)

Summary

- There are many progresses in the heavy flavor physics from lattice calculations since Lattice 2015.
- Many new 2σ hints of NP have been revealed by the improvements of lattice calculations.
- Belle II and LHCb will improve measurements and observe new decays.
- We will continue to sharpen tests of SM and may reveal presence of NP.