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Prospects for rare decays and LFU measurements with the LHCb experiment

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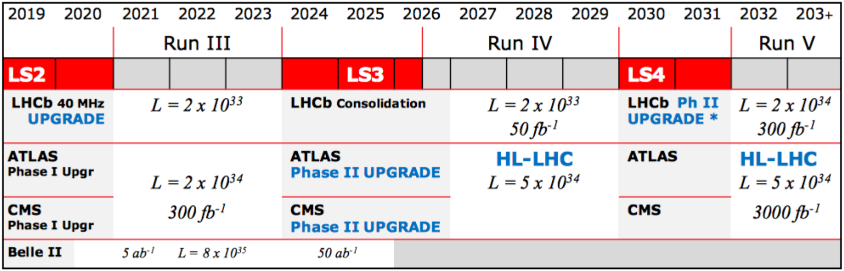
on behalf of the LHCb collaboration

Workshop on the physics of HL-LHC,
and perspectives at HE-LHC, CERN

October 30, 2017

LHC schedule



- LHCb expected to collect $\sim 300\ \text{fb}^{-1}$ after phase II upgrade

Prospects for rare decays

- Naively scaling Run 1 yields with $\sqrt{s}$ and integrated luminosity, and assuming a factor 2 in efficiency for electron channels after the removal of the hardware trigger, we expect large samples of these "rare" decays

Decay	Run I	$300\,\text{fb}^{-1}$
$B_s^0 \to \mu^+\mu^-$	15	2 700
$B_s^0 \to \mu^+\mu^-$ (tagged*)	-	80
$B^+ \to K^+\mu^+\mu^-$	4 700	858 000
$B^0 \to K^{*0}\mu^+\mu^-$	2 400	438 000
$B^+ \to \pi^+\mu^+\mu^-$	90	16 400
$B^0 \to \rho^0\mu^+\mu^-$	40	7 300
$B^+ \to K^+e^+e^-$ $(q^2 \in [1,6])$	250	91 300
$B^0 \to K^{*0}e^+e^-$ $(q^2 \in [1,6])$	110	40 200
$B_s^0 \to \phi\gamma$	4 000	743 000
$B_s^0 \to \phi\gamma$ (tagged*)	-	22 300

*Assumes 3% tagging power

- Improvement in detector performance could improve the situation in several areas

$B^0_{(s)} \to \mu^+\mu^-$ branching fractions

- Precisely predicted in the SM

$$\mathcal{B}_{SM}(B^0_s \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$$
$$\mathcal{B}_{SM}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

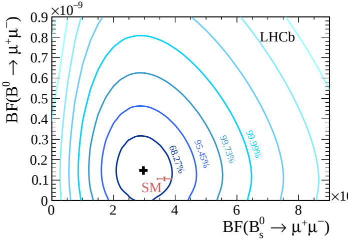
- Latest measurements from LHCb

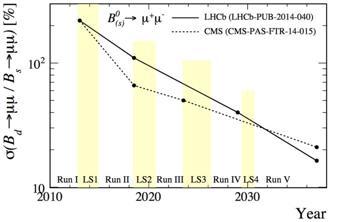
$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10} \,@\, 95\%\,\mathrm{CL}$$

- With 300 fb^{-1} the uncertainty on $\mathcal{B}(B^0_s \to \mu^+\mu^-) \sim 0.27 \times 10^{-9}$
  - Dominant syst. f_s/f_d will scale with luminosity

- For the ratio of $\mathcal{B}$'s of B^0 over B^0_s (r), LHCb could reach $\sigma(r) \sim 11 - 13\%$

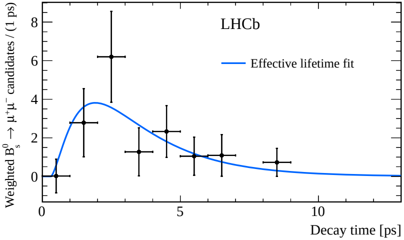
[PRL 118, 191801 (2017)]



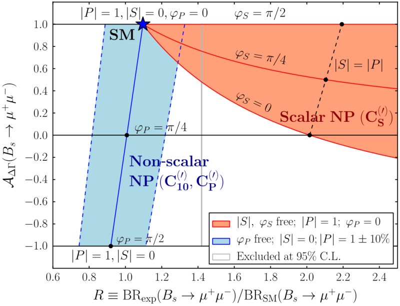


$B_s^0 \to \mu^+\mu^-$ effective lifetime

- Extremely clean theoretically and has complementary sensitivity to scalar operators
  - In the SM, only the heavy B_s^0 eigenstate couples to $\mu\mu$ ($\tau_{\mu\mu}^{SM} = \tau_H$)
- Recent LHCb measurement: $\tau_{\mu\mu} = 2.04 \pm 0.44 \pm 0.05\,\mathrm{ps}$
- Could reach $\sim$ 2% uncertainty with 300 fb^{-1}



[PRL 118, 191801 (2017)]



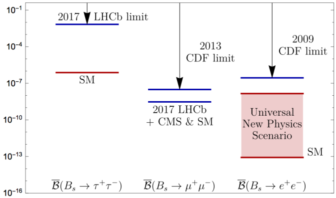
[PRL 109, 041801 (2012)]

Other very rare decays

- Other $B_{(s)} \to \ell^+\ell^-$ will still be far from the SM predictions
  - $B_s^0 \to e^+e^-$: $[4-11]\times 10^{-9}$ (exp. Run 1) $\to$ $[3-9]\times 10^{-10}$ (exp. Run 5)
  - $B_s^0 \to \tau^+\tau^-$: 6.8×10^{-3} (Run 1) $\to$ 3×10^{-4} (exp. Run 5)

- For lepton flavour violating modes such as $B_{(s)} \to e\mu$, $B^+ \to K^+ e\mu$ or $\tau \to \mu\mu\mu$ limit improvements $\sim$ one order of magnitude are expected

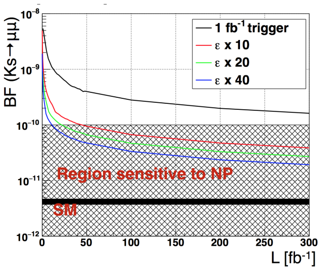
- Reconstruction of electrons and taus would benefit from the removal of the RF foil (see Greg Ciezarek's talk tomorrow) and the enhanced low momentum tracking [LHCb, EOI for phase II upgrade, CERN-LHCC-2017-003]



[Fleischer et al., 1703.10160]

Other very rare decays

- Large cross-section for strange and charm hadrons
- Strange decays
  - Principal show-stopper in Run1 was the hardware trigger $\rightarrow$ already improved in phase 1 upgrade with full software trigger
  - Proposed specialised processors for downstream track finding would increase efficiency for these decays
  - e.g. $K_S \rightarrow \mu\mu$: sensitive to $\mathcal{B} \sim 10^{-11}$
- Charm decays
  - Will be able to reach SM sensitivities for the SD contributions
  - More observables accesible: A_{FB}, A_{CP}



	BF(Short Distance)
$D^0 \to hh'\mu^+\mu^-$	10^{-9} - 10^{-8}
$D^0 \to \mu^+\mu^-$	10^{-11} - 10^{-10}
$D^+ \to h'\mu^+\mu^-$	10^{-10} - 10^{-9}
$D_s^+ \to h'\mu^+\mu^-$	10^{-9} - 10^{-8}
$L \to p\mu^+\mu^-$	10^{-9} - 10^{-8}
$D^0 \to e^+\mu^-$	10^{-10} - 10^{-9}

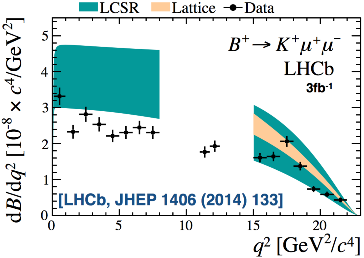
$b \to s\ell^+\ell^-$ transitions

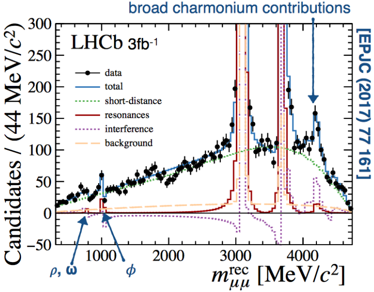
Run I has left us with an interesting set of results

- Branching fractions of $B \to K^{(*)}\mu^+\mu^-$, $B_s \to \phi\mu^+\mu^-$ and $\Lambda_b \to \Lambda\mu^+\mu^-$
  - Large theoretical uncertainties from hadronic form factors.
- Angular analyses of $B_s \to \phi\mu^+\mu^-$, $\Lambda_b \to \Lambda\mu^+\mu^-$ and $B^0 \to K^{*0}\mu^+\mu^-$
  - Access to observables with reduced dependence on theory uncertainties
- Lepton flavour universality in $B^+ \to K^+l^+l^-$ and $B^0 \to K^{*0}l^+l^-$
  - Cancellations of hadronic uncertainties in predictions

$b \to s\ell^+\ell^-$ transitions: branching fractions

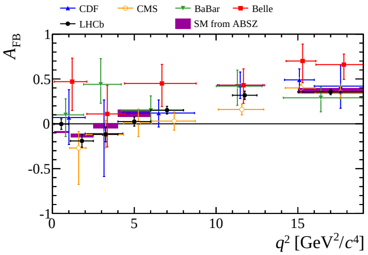
- Run 1 precision on $\mathcal{B}$'s is already at the level of the theory uncertainty for the SM predictions
- In terms of systematic uncertainty, the knowledge on $\mathcal{B}(B \to J/\psi X)$ modes used for normalisation is already a limiting factor. Encourage Belle 2 to update these measurements!
- Phase II will bring better control over the shape of $\mathrm{d}\mathcal{B}/\mathrm{d}q^2$ (feedback to theory)

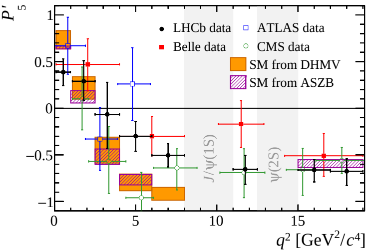




$b \to s\ell^+\ell^-$ transitions: angular analyses

- Give access to many different observables sensitive to NP
- The systematic experimental uncertainties are orthogonal to those affecting BR measurements
- These observables provide complementary constraints to the BRs in global fits
  - Possibility to construct observables with reduced form-factor dependence (e.g. P_5')

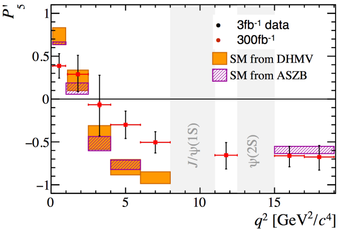


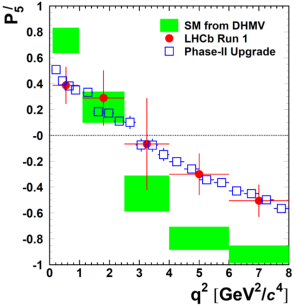


LHCb [JHEP 02 (2016) 104], CMS [PLB 753 (2016) 424], BaBar [PRD 93 (2016) 052015], CDF [PRL 108 (2012) 081807] and Belle [PRL 103 (2009) 171801]

Angular analyses prospects

- Systematic uncertainties will likely be ≤ 0.01 (many will scale as $\sqrt{N}$)
  - e.g. control angular distribution of the background with data, etc.
- Understanding the angular acceptance will need of large MC samples





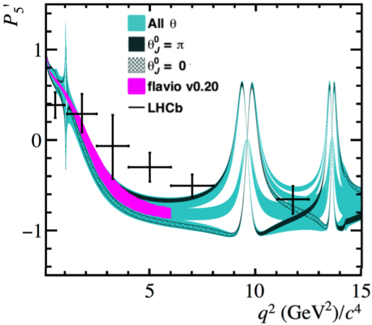
[LHCb, EOI for phase II upgrade CERN-LHCC-2017-003]

- Rescaling the existing measurement with the same binning to 300 fb^{-1} with a syst. of 0.01
- We could also reduce binning size to learn more about the shape of the distribution (input on $\mathrm{d}\Gamma/\mathrm{d}q^2$ to subdivide dataset within the existing bins)

Angular analyses prospects

- Perform a full angular analysis (e.g. of $K\pi\mu\mu$ final state) taking into account resonant contributions (J/ψ, $\psi(2S)$ and resonances above charm threshold)
    - Determine interference phases between rare decay and charm contributions $\rightarrow$ large effect on angular observables

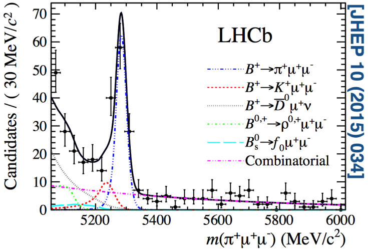
[Blake et al., arXiv:1709.03921]

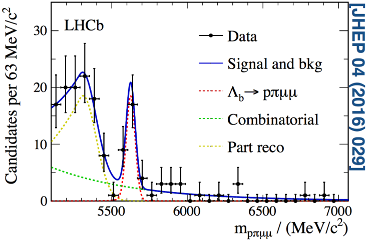


Variation of P_5' observable as a function of q^2 for different values of the phases of the resonant amplitudes.

$b \to d\ell^+\ell^-$ transitions

- With 300 fb^{-1}, we will achieve precise measurements of the $\mathcal{B}$'s of $b \to d\ell^+\ell^-$ penguins ($B^+ \to \pi^+\mu\mu$, $B_s^0 \to \overline{K}^{*0}\mu\mu$...)
- Will have access to angular observables too
  - For those decays where flavour tagging is needed, e.g. $B^0 \to \rho^0\mu\mu$, tagging efficiency still limiting factor in phase II (any improvement in FT will have direct impact here)

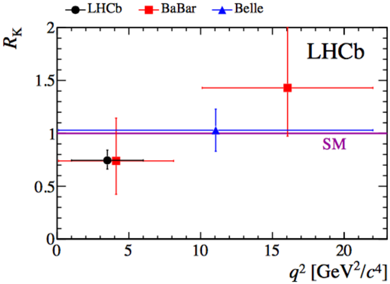


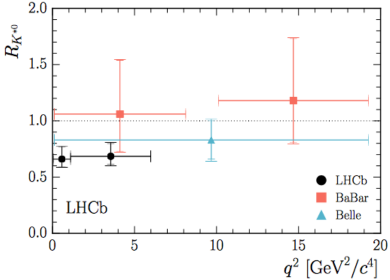


- In such a dataset $b \to de^+e^-$ processes will also be important (e.g. expect $O(1000)$ $B^+ \to \pi^+e^+e^-$), so will be able to perform LFU tests with $b \to d$ transitions

Lepton Flavour Universality

- With Run 1, we have found hints of lepton flavour non-universality in $b \to s\ell^+\ell^-$ transitions

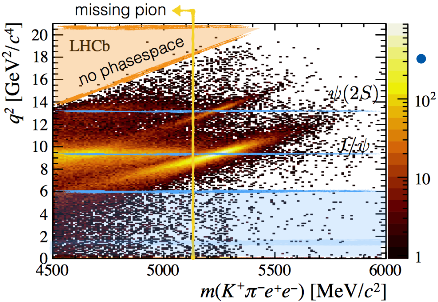




LHCb [PRL113 (2014) 151601], LHCb [JHEP 08 (2017) 055], BaBar [PRD 86 (2012) 032012], Belle [PRL 103 (2009) 171801]

Electron challenges

- Main experimental challenges related to large amount of bremsstrahlung emitted by the electrons in the detector (recovery of photon clusters in ECAL only for $E_T > 75\,\mathrm{MeV}$)
  - Degraded momentum, and mass/q^2 resolutions

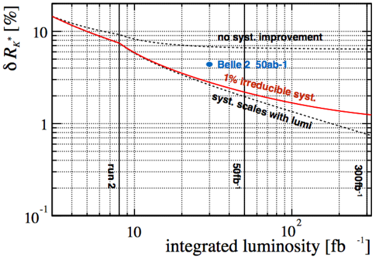


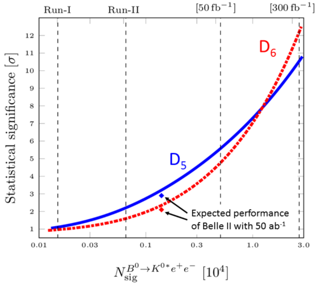
- Largest systematic uncertainties will still scale with luminosity, e.g. for $R_{K^{*0}}$:
  - modelling of $B \to K\pi\pi e^+e^-$ background
  - corrections to simulation (data-driven)

- But could do better with some detector improvements (see Preema Pais' talk tomorrow)
  - Reduce the amount of material in the detector
  - Improve ECAL energy granularity and resolution

LFU prospects

- For ratios of $\mathcal{B}$'s (e.g. R_K, $R_{K^{*0}}$) we could reach 1-2% precision
  - For comparison Belle 2 expects to reach a precision of 4-5% with a 50 ab^{-1} dataset [S. Sandilya at CKM 2016]



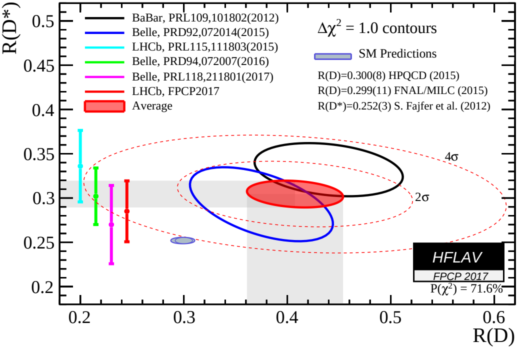


[LHCb, EOI for phase II upgrade CERN-LHCC-2017-003]

- Angular analyses with electrons have orthogonal systematics with respect to R_X's and these can also be kept under control
- Expect good sensitivity to differences in the angular distributions for electron/muon final states

LFU with $b \to c\ell\nu$ decays

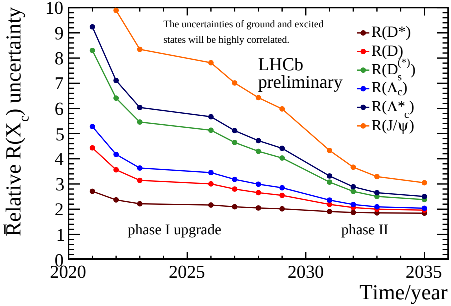
- We also have hints of $\mu - \tau$ non-universality in semileptonic $X_b \to X_c\ell\nu$
- Difficult measurement due to missing neutrinos, but Run 1 demonstrated LHCb's potential in this area



LFU with $b \to c\ell\nu$ decays - prospects

Phase-II will substantially benefit $R(X_c)$ measurements of B_s^0, Λ_b^0, B_c^+ hadrons

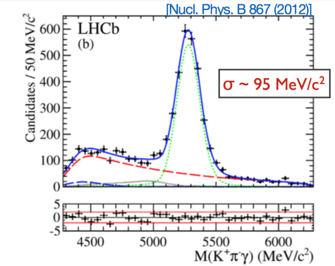
Complementary sensitivity to NP

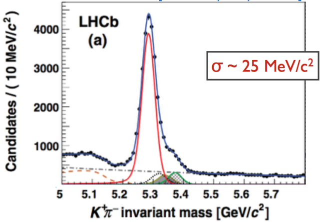


- What can we do better?
  - Reduction of background from additional charged tracks can be achieved with better vertex resolution
  - Neutral isolation to reject bacground with neutrals could benefit from an upgraded calorimeter

Radiative decays

- Will improve precision in $\mathcal{B}$'s, CP asymmetries and photon polarisation
- Large statistics will give access to $b \to d\gamma$ transitions, which have smaller $\mathcal{B}$'s but where CP asymmetries are expected to be larger
- Challenging analyses:
  - Invariant mass resolution dominated by photon reconstruction
    - control partially reconstructed backgrounds
  - Large photon backgrounds
    - $\pi^0 \to \gamma\gamma$ reconstructed as single cluster
    - Combinatorial, $O(10)$ reconstructed photons per event
- Performance improvements needed in many analyses to profit from statistics in phase II





Photon polarisation - $B_s^0 \to \phi\gamma$

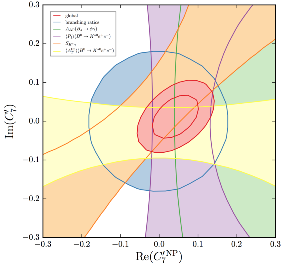
[Paul, Straub, 1608.02556]

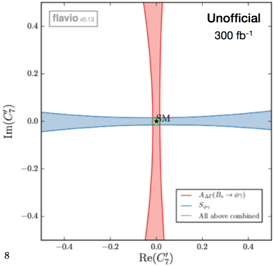
- Tagged time dependent analysis of $B_s^0 \to \phi\gamma$

$$\Gamma \sim e^{-\Gamma t}[\cosh(\frac{\Delta\Gamma t}{2}) - A^{\Delta}\sinh(\frac{\Delta\Gamma t}{2}) \pm C\cos(\Delta m t) \mp S\sin(\Delta m t)]$$

  - A^{Δ} and S sensitive to the photon polarisation
  - Expected sensitivity of Run 2 analysis ~ 0.3

- With 300 fb^{-1}:
  - $\sigma(A^{\Delta}) \sim 0.02$ (stat)
  - Need to work on reducing systematics from lifetime acceptance ($\sigma(A^{\Delta})$)
  - Uncertainties on C, S dominated by proper time resolution





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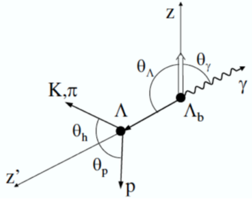
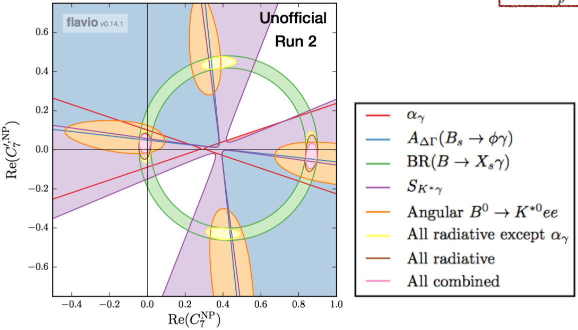
Photon polarisation - Baryonic decays

- Angular analysis of $\Lambda_b \to \Lambda\gamma$
  - Run 1 + Run 2: Expected sensitivity $\sigma(a_\gamma) < 0.2$
  - With 300 fb^{-1}:
    - Expected $\sigma(a_\gamma)(\text{stat}) \sim 0.01$
    - Acceptance modeling will be dominant uncertainty
    - Would benefit from improved downstream track reconstruction



$$\frac{d\Gamma}{d\cos\theta_\gamma} \propto 1 - \alpha_\gamma P_{\Lambda_b}\cos\theta_\gamma$$

$$\frac{d\Gamma}{d\cos\theta_p} \propto 1 - \alpha_\gamma \alpha_{p,1/2}\cos\theta_p$$



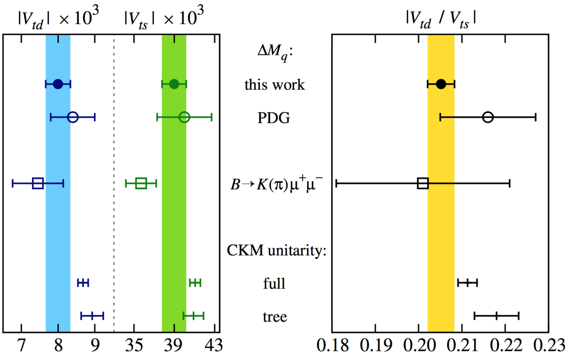
Summary

- The LHCb phase II upgrade will enable the study of highly suppressed decay modes
  - Will approach the SM predictions ($B_s^0 \to \mu\mu$) or be sensitive to possible NP effects in several channels (LFV)
- $b \to s\ell\ell$ transitions will not be "rare" any more
  - Branching fractions and angular observables might reach current SM precision by the end of Run 2
  - Still plenty of very clean observables to keep looking at (LFU)
  - Large samples will open new analysis posibilities that could help improve SM predictions
- Many radiative decays analyses will be systematics-limited by the end of phase I
  - The improved ECAL can greatly enhance our capabilities

Backup

$b \to d\ell^+\ell^-$ transitions

- As for $B_d \to \mu^+\mu^- / B_s \to \mu^+\mu^-$ and $\Delta m_d / \Delta m_s$, ratio of $b \to s$ and $b \to d$ decays is a test of MFV



FNAL/MILC PRD93,113016 (2016)

- EW penguins have additional uncertainty from ratio of form factors, will need improvements from Lattice too