B physics measurements at the HL-LHC

HL/HE-LHC Meeting

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on behalf of the LHCb colaboration

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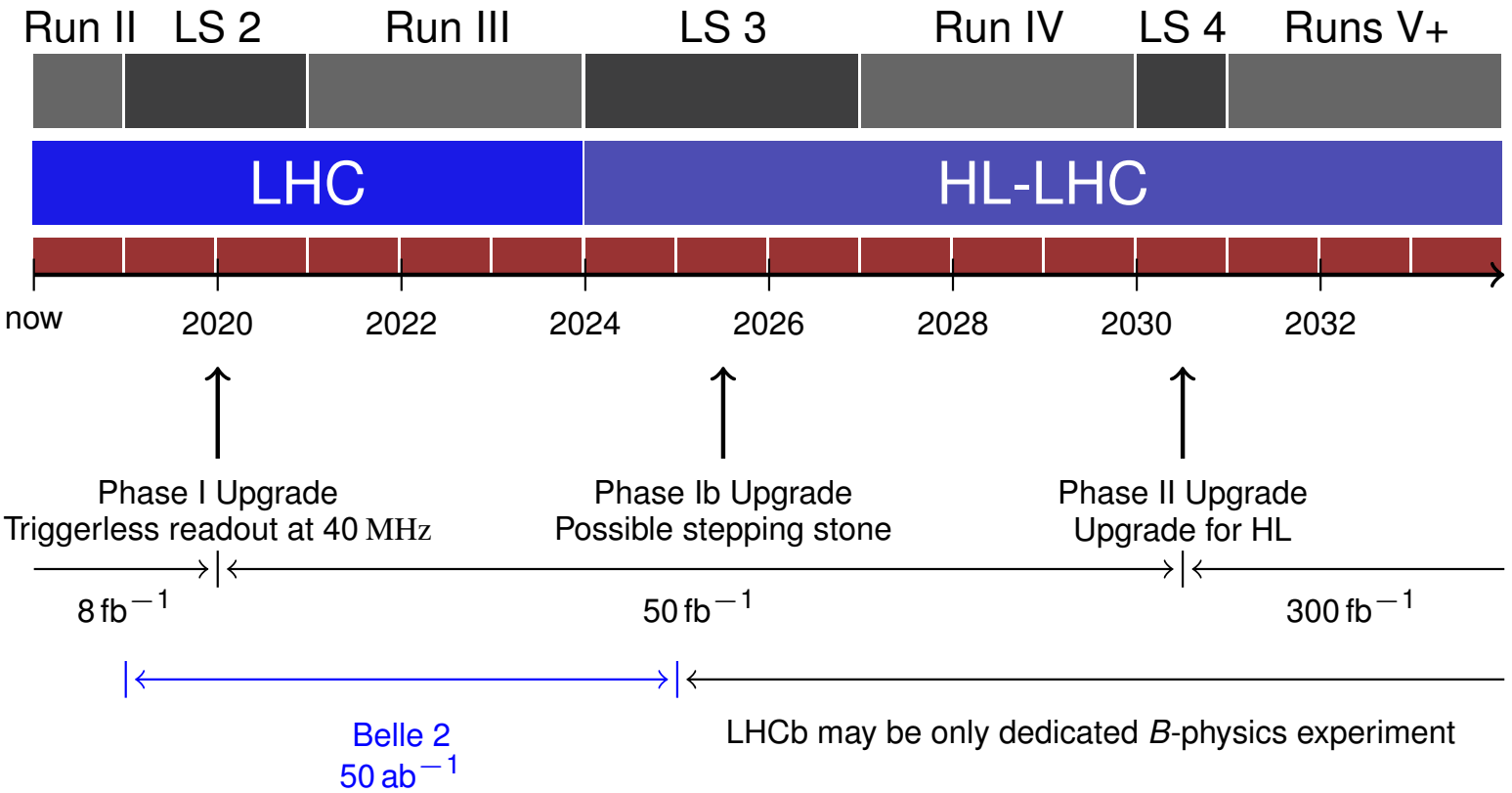
Overview

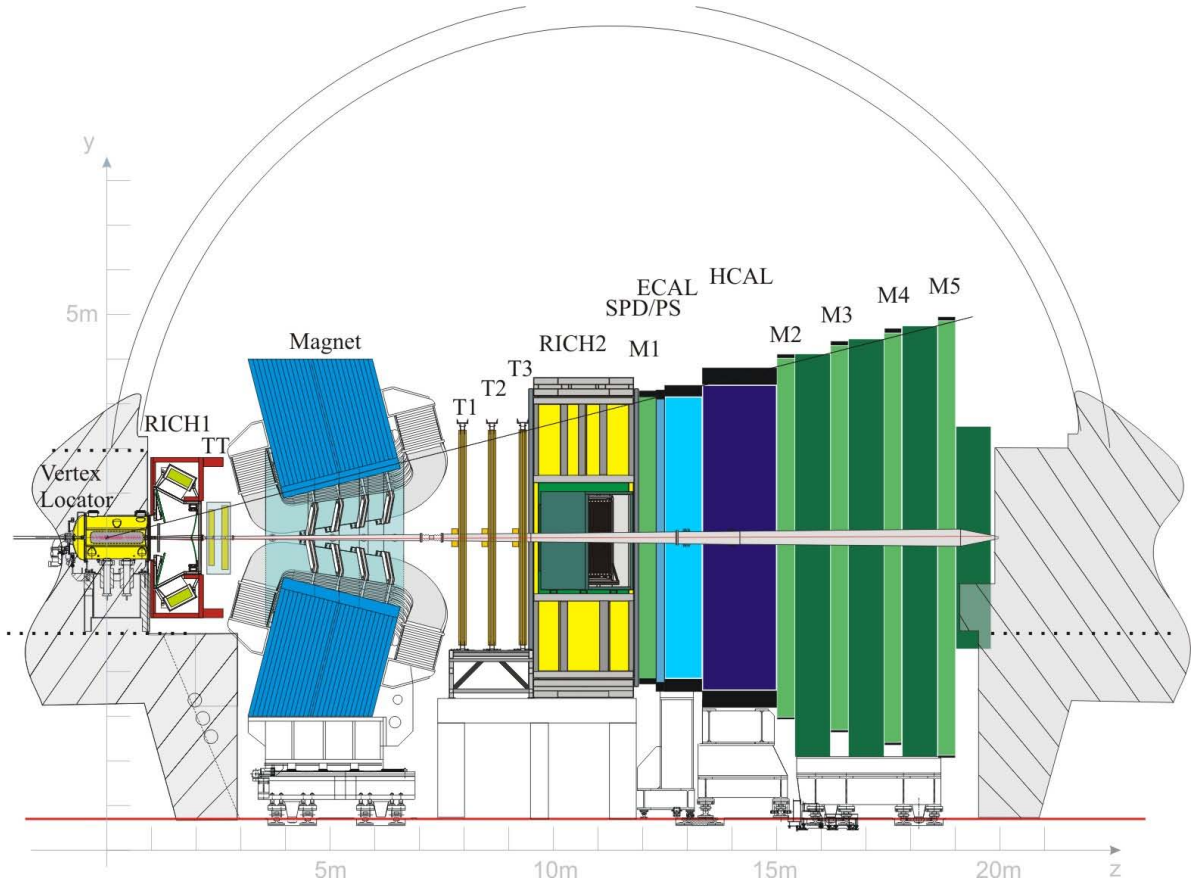
- *B* physics quite broad
- Will focus on areas most benefited by increased luminosity or LHCb detector changes
- As LHCb upgrade schedule is out of phase with HL-LHC, some parts also relevant to Run III (LHCb upgrade phase I)

Timeline


Run II
LS 2
Run III
LS 3
Run IV
LS 4
Runs V+
LHC
HL-LHC
now
2020
2022
2024
2026
2028
2030
2032
Phase I Upgrade
Triggerless readout at 40 MHz
Phase Ib Upgrade
Possible stepping stone
Phase II Upgrade
Upgrade for HL
8 fb^{-1}
50 fb^{-1}
300 fb^{-1}
Belle 2
50 ab^{-1}
LHCb may be only dedicated *B*-physics experiment

The LHCb Detector

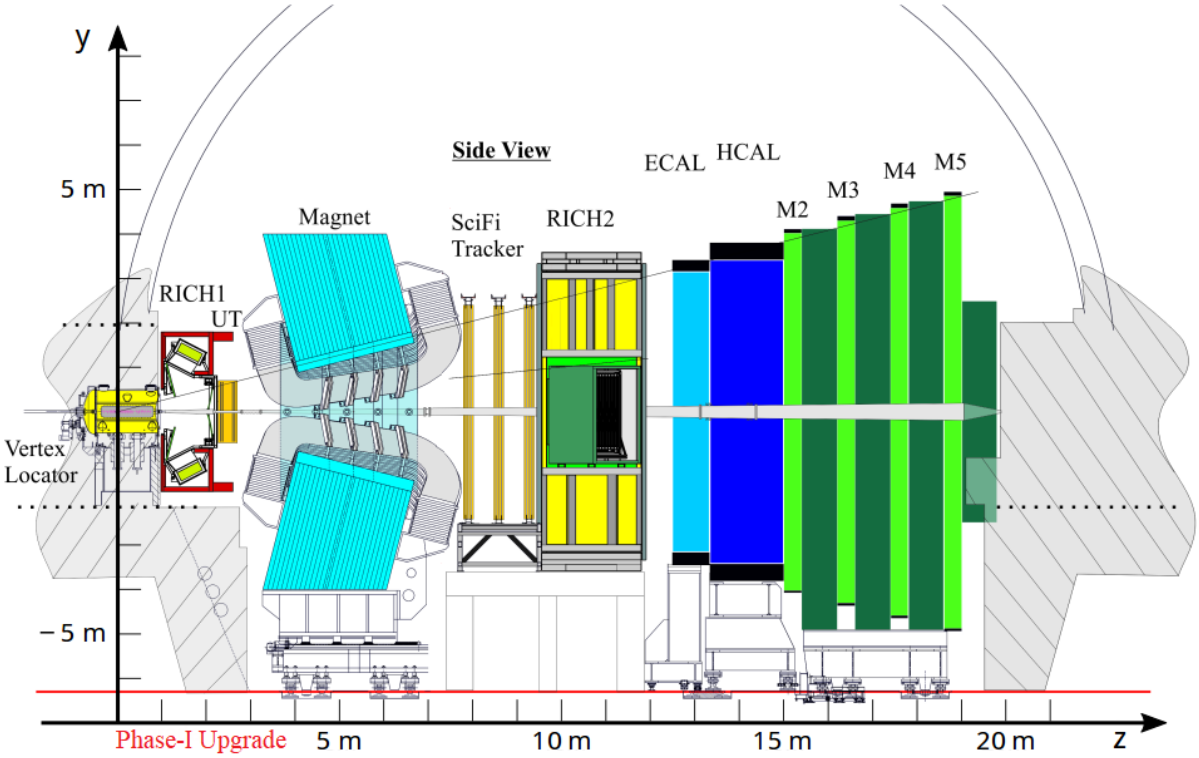
JINST **3** (2008) S08005



- Instrumentation in the forward region ($2 < \eta < 5$)
- Excellent secondary vertex reconstruction
- Precise tracking before and after magnet
- Good PID separation up to $\sim 100\,\mathrm{GeV}/c$

The LHCb detector: phase 1 upgrade

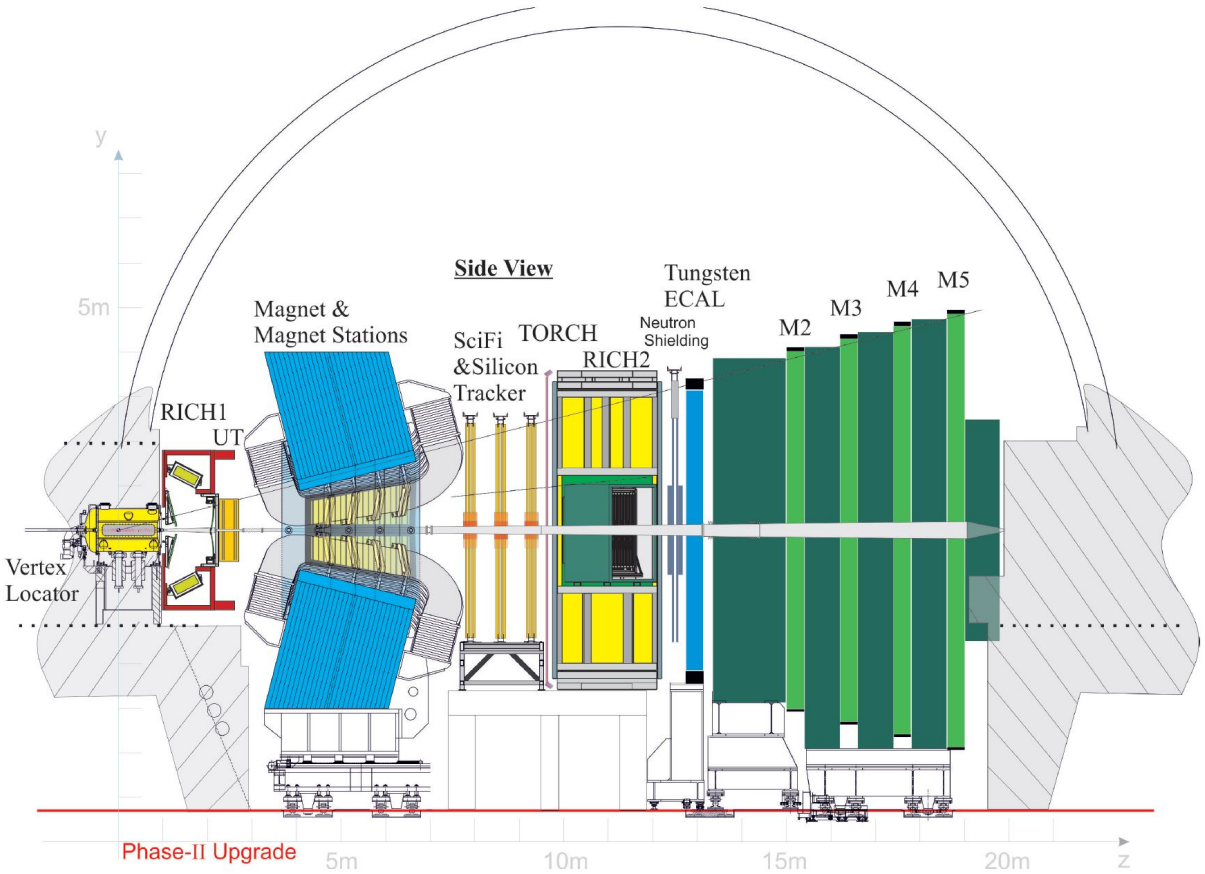
CERN-LHCC-2012-007



- Triggerless readout at 40 MHz
- New vertex locator
- New tracking (UT, SciFi)

The LHCb detector: phase 2 upgrade

CERN-LHCC-2017-003



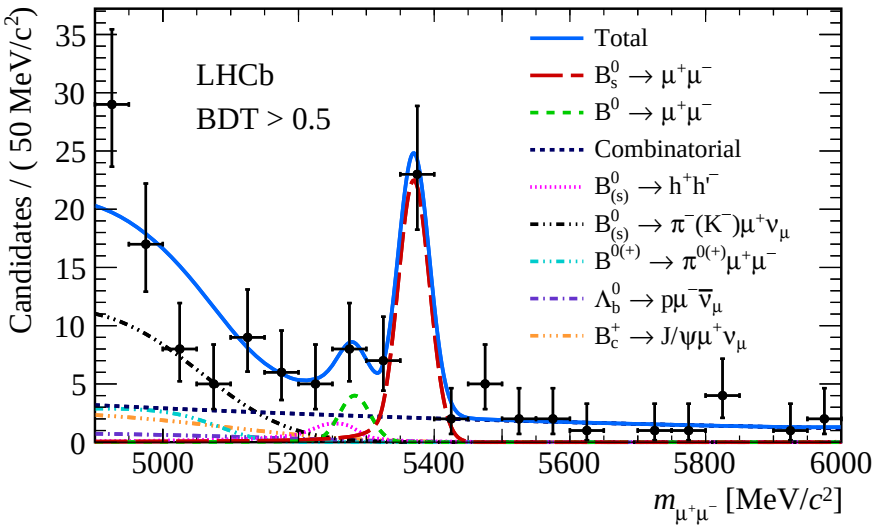
- Tracking in magnet
- ECAL upgrade
- TORCH for PID or ToF
- Replace HCAL with shielding
- Some changes could happen as part of phase Ib

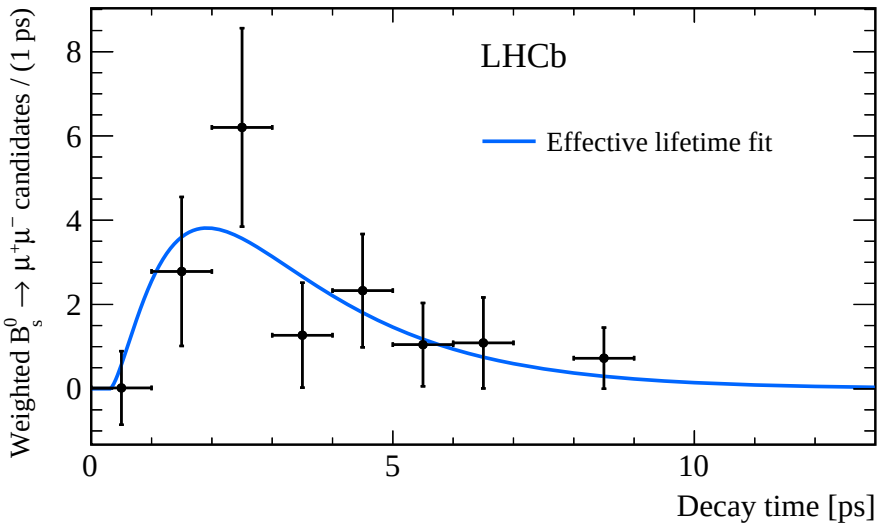
Rare decays

- Rare SM processes sensitive to new physics contributions
- Typically limited by statistics
- Clear physics case for increased luminosity

Rare decays: $B^0_{(s)} \to \mu^+\mu^-$

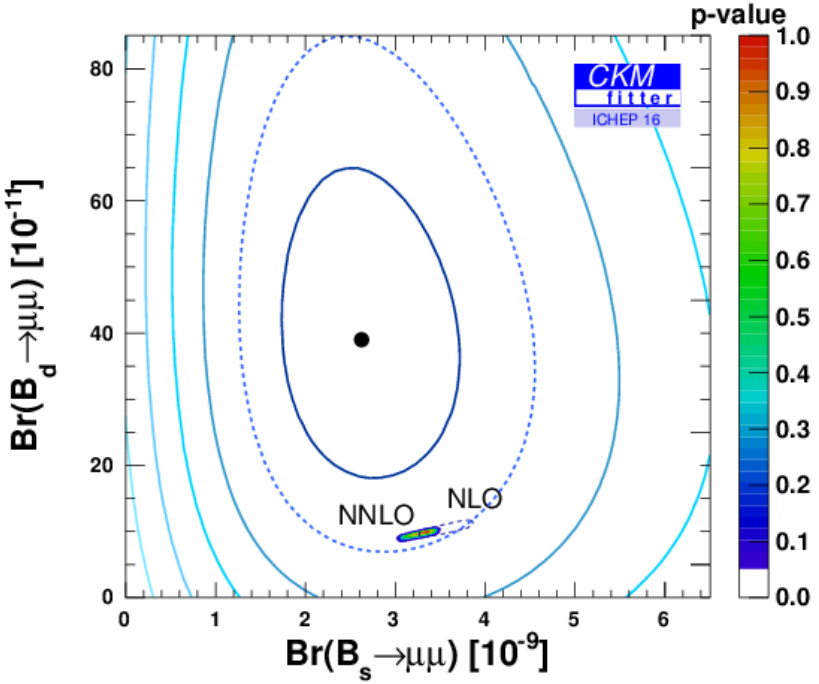
- Loop mediated and helicity suppressed
- Leptonic final state allows for precise SM predictions
- Sensitive probe for new physics *e.g.* extended Higgs sector
- B^0_s branching ratio observed to be consistent with SM with 23 % precision
- B^0 decay remains unobserved

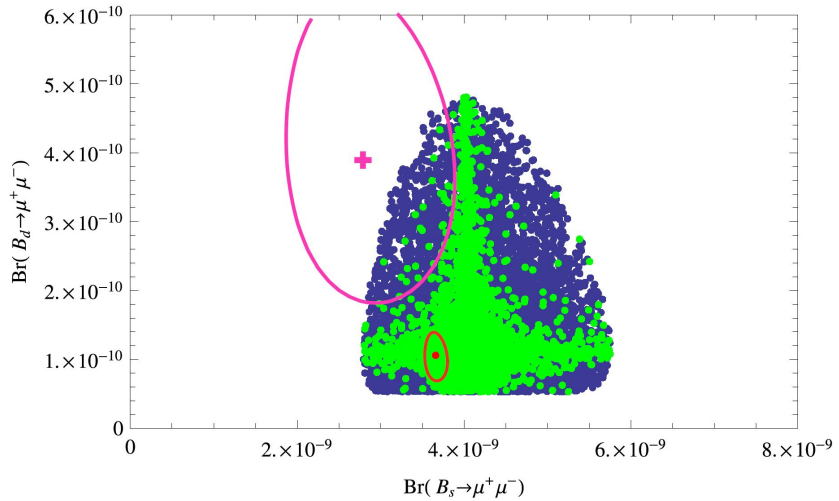




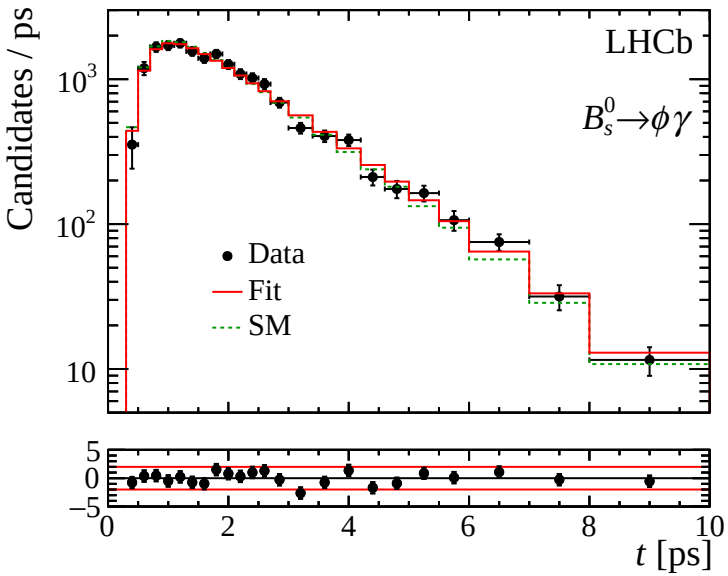
Rare decays: $B^0_{(s)} \to \mu^+\mu^-$

- By end of Run IV expect to see B^0 decay and (if SM) measure ratio B^0/B^0_s with precision of $\sim 40\,\%$
- From HL-LHC expect combined LHCb+CMS precision on ratio of $\sim 14\,\%$
- Will also be able to study other quantities such as *CP* asymmetry for the B^0_s decay
- Require a time-dependent flavour-tagged study
- Important for discriminating between BSM models





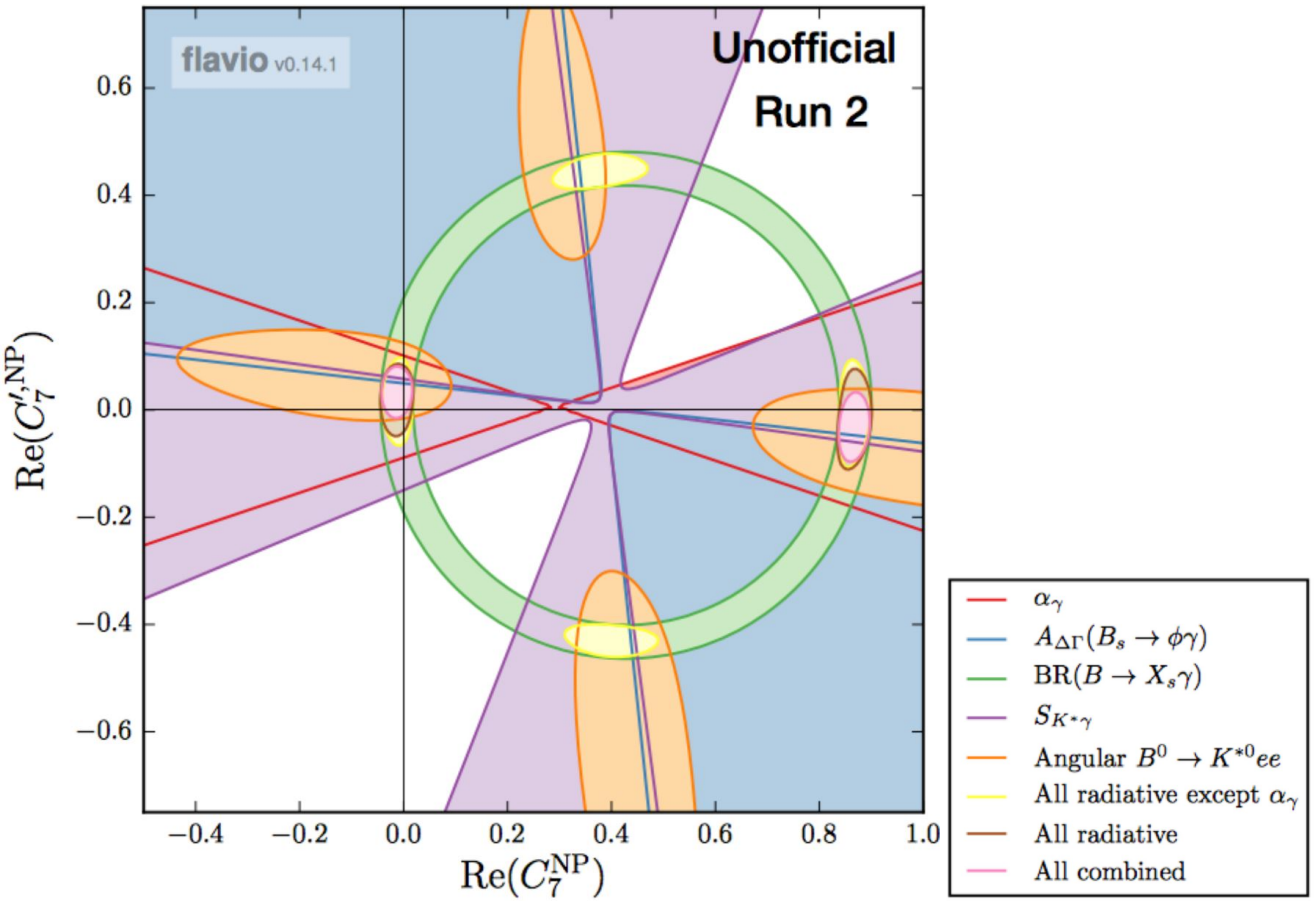
Rare decays: $B_s^0 \to \phi\gamma$ *et al.*



- SM predicts photon in $b \to s\gamma$ transitions to be predominantly left handed
- LHCb presented first study of photon polarisation in $B_s^0 \to \phi\gamma$ using Run I data...
- ECAL upgrade in phase 2 will offer significant improvement in sensitivity for $b \to s\gamma$ and $b \to d\gamma$ processes
- Uncertainties on photon polarisation in $B_s^0 \to \phi\gamma$ will be comparable to those on SM predictions for first time

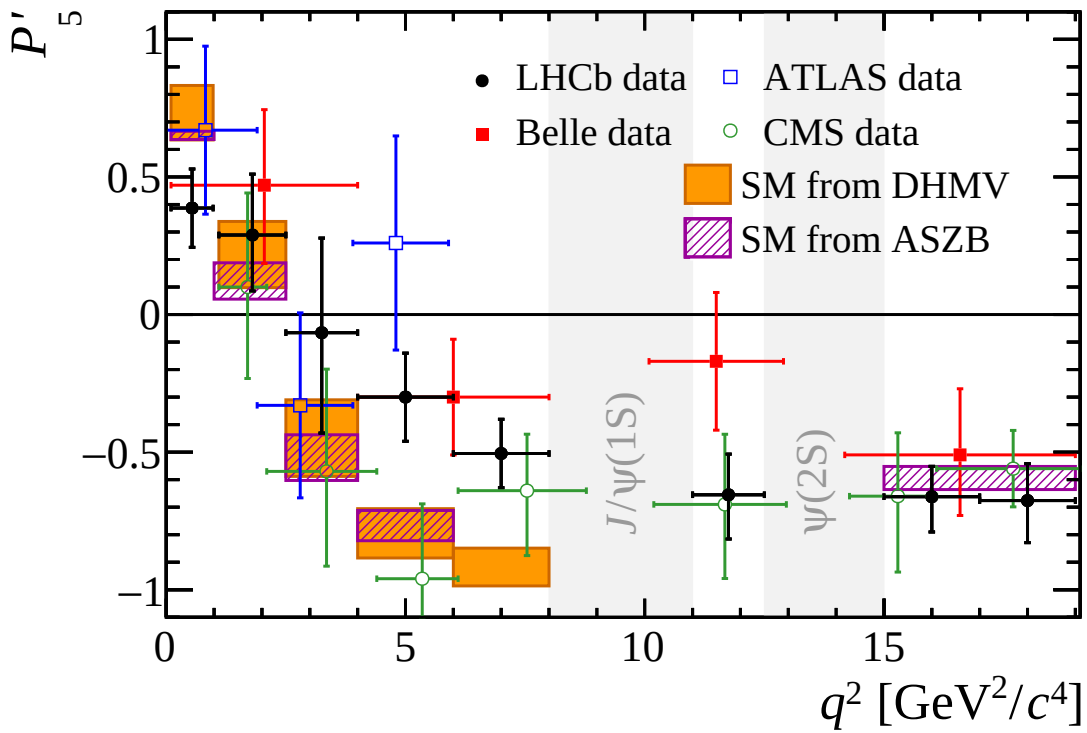
Rare decays: $B_s^0 \to \phi\gamma$ *et al.*

- Will also be possible to study radiative decays of *b*-baryons
- Additional measurements provide complimentary information



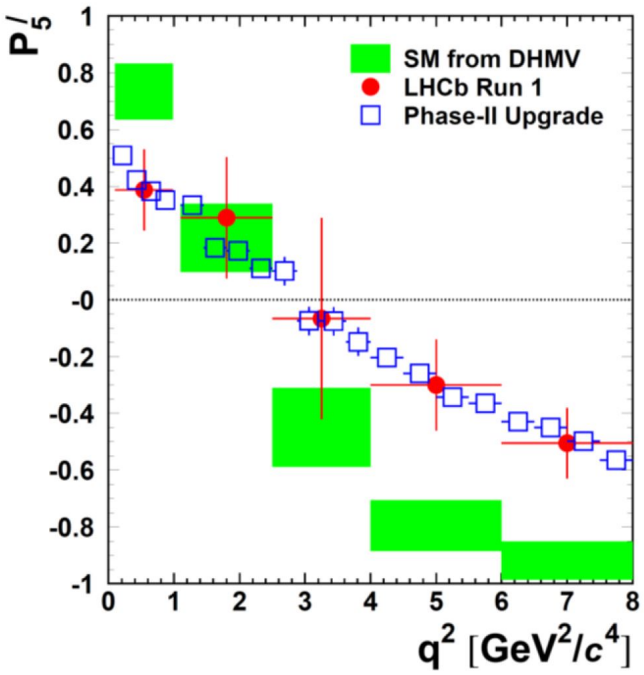
Rare decays: $b \to s\ell^+\ell^-$ and $b \to d\ell^+\ell^-$

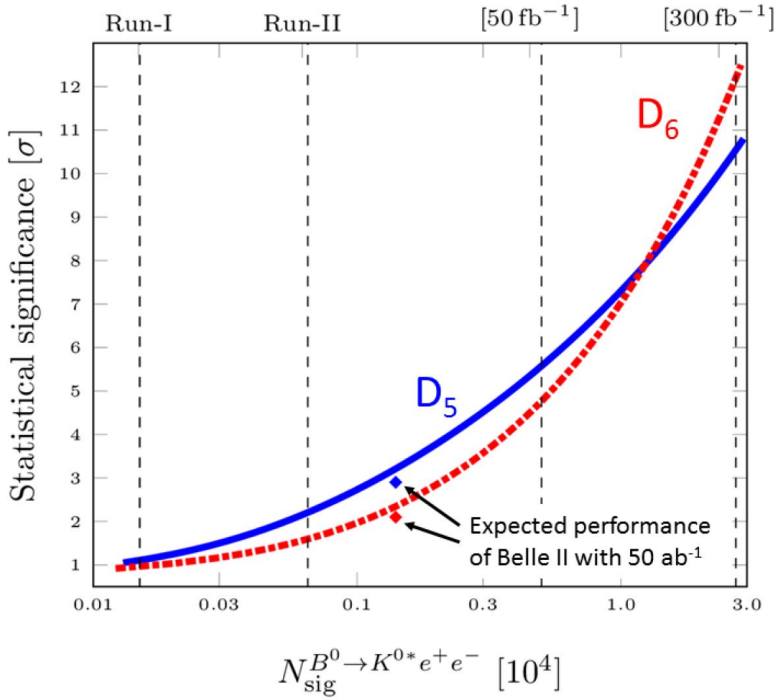
- FCNC processes promising for new physics
- Analyses of $B^+ \to K^+\ell^+\ell^-$ and $B^0 \to K^{*0}\ell^+\ell^-$ already hint at lepton non-universality
- $K^*\mu^+\mu^-$ Angular variables also show hints at new physics



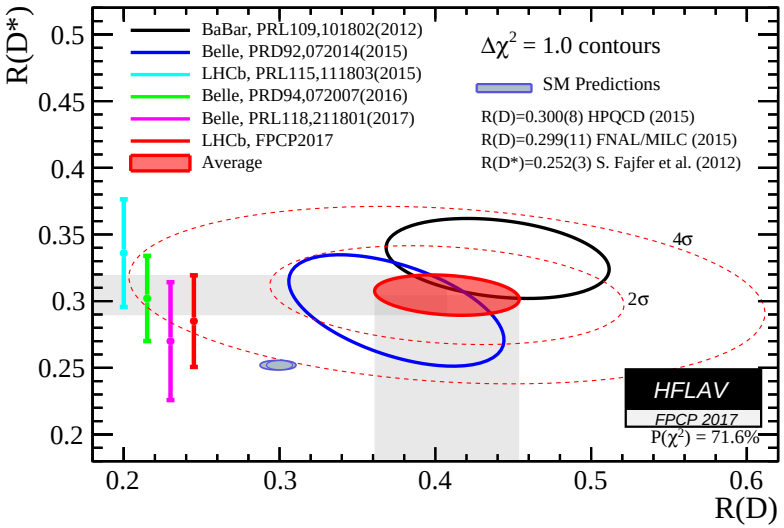
Rare decays: $b \to s\ell^+\ell^-$ and $b \to d\ell^+\ell^-$

- Significant improvements in precision for angular quantities and $\mu - e$ asymmetry ratios in HL-LHC era
- Angular studies of B_s^0 and b-baryon decays should also become possible
- Measuring additional quantities will lead to a robust global test of SM and discriminate between NP models





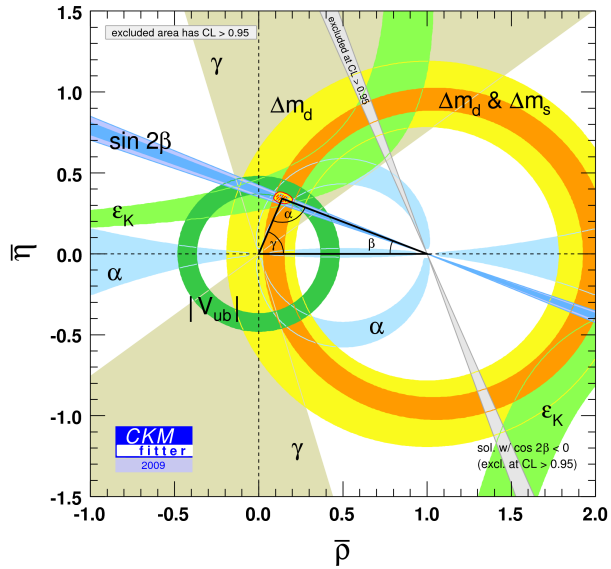
Lepton universality: $b \to c\ell^-\nu_\ell$

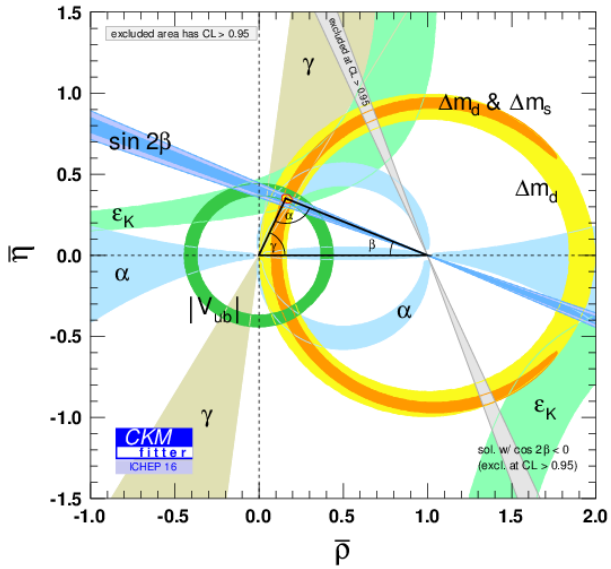


- Lepton universality also tested in semi-leptonic decays
- Measurements of $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ give one of the most significant hints of new physics to date
- During HL-LHC era, LHCb should be able to test both $\tau - \mu$ and $\mu - e$ universality in $b \to c\ell^-\nu_\ell$ decays to %-level precision
- Larger datasets will allow precise LFU tests with the full suite of b-hadrons
- Measure angular and kinematic observables, which are currently out of reach

CKM measurements

- LHC era has seen marked improvements in key measurements (top→bottom)
- But deviations from the CKM quark-mixing mechanism continue to elude detection
- Uncertainties on “tree” quantities still give room for new physics in loops
- Key goal to improve precision on γ and $|V_{ub}|$
- Continue to improve other key measurements such as ϕ_s, Δm_s and Δm_d

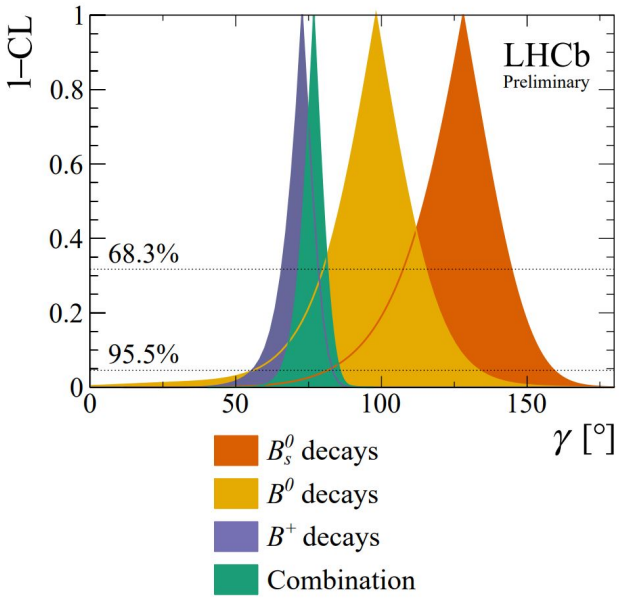


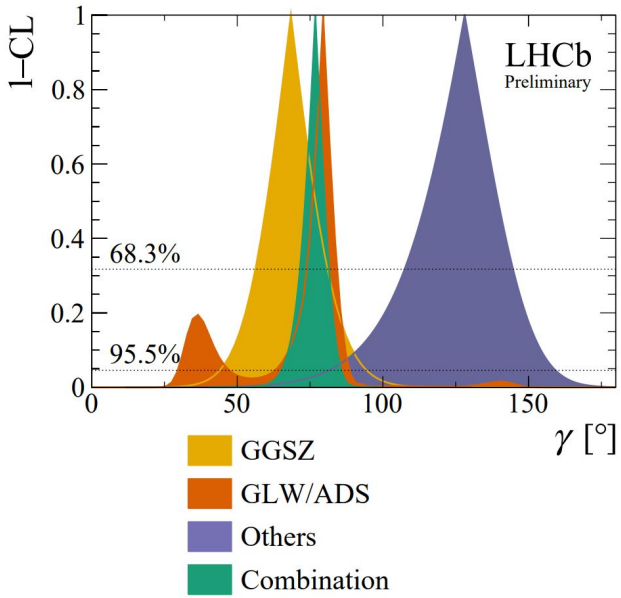


CKM measurements: γ

LHCb-CONF-2017-004

- Least well measured angle of the CKM Unitarity Triangle
- Can be determined at "tree"-level to reduce new physics "loop" contributions
- Current LHCb average has precision of $\sim 5\,\%$
- Results dominated by time-independent $B \to DX$ measurements
- Expect sub-degree uncertainty on LHCb combined result by the end of Run IV
- Larger datasets also allow new methods to be exploited...





CKM measurements: γ

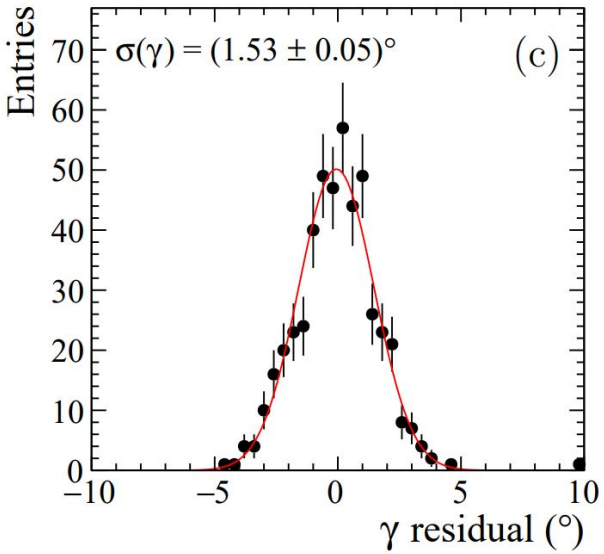
PRD **97** (2017) 056002

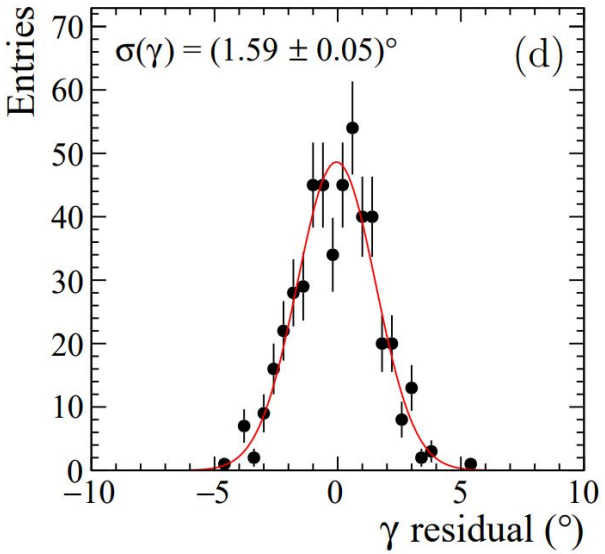
- One such method utilises subsequent three-body decays $B^0 \to DK^+\pi^-$, $D \to K^0_S\pi^+\pi^-$
- This "double-Dalitz" method benefits from a larger value of r_B relative to $B^+ \to DK^+$ without the need for hadronic parameters as in $B^0 \to DK^{*0}$
- Aided by interference of $b \to c$-only D^{*-} contributions
- Can be performed in bins of both Dalitz plots to avoid model uncertainties
- Coefficients of the D Dalitz plot may be taken from independent CLEO and BES results as with the GGSZ method

CKM measurements: γ

PRD **97** (2017) 056002

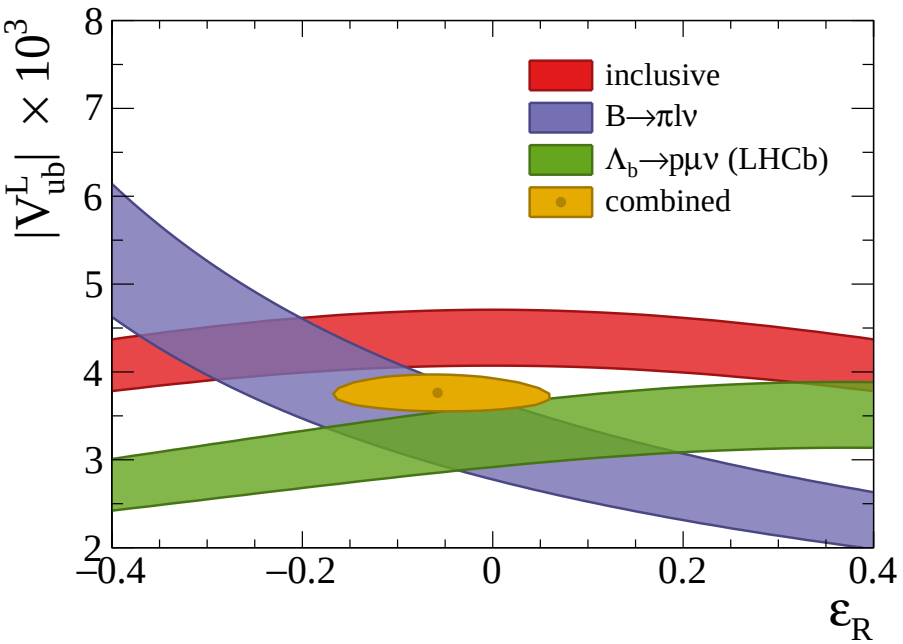
- Additional D decays may be included as additional bins in the D phasespace with appropriate choices of coefficients
- Expect degree-level precision on γ after Run IV
- Plots show precision after Run IV (left) from using $K^0_S\pi^+\pi^-$, $K^-\pi^+$, K^+K^-, $\pi^+\pi^-$ and $K^+\pi^-$ decays and (right) precision if partially reconstructed B^0_s backgrounds preclude the use of DCS $K^+\pi^-$



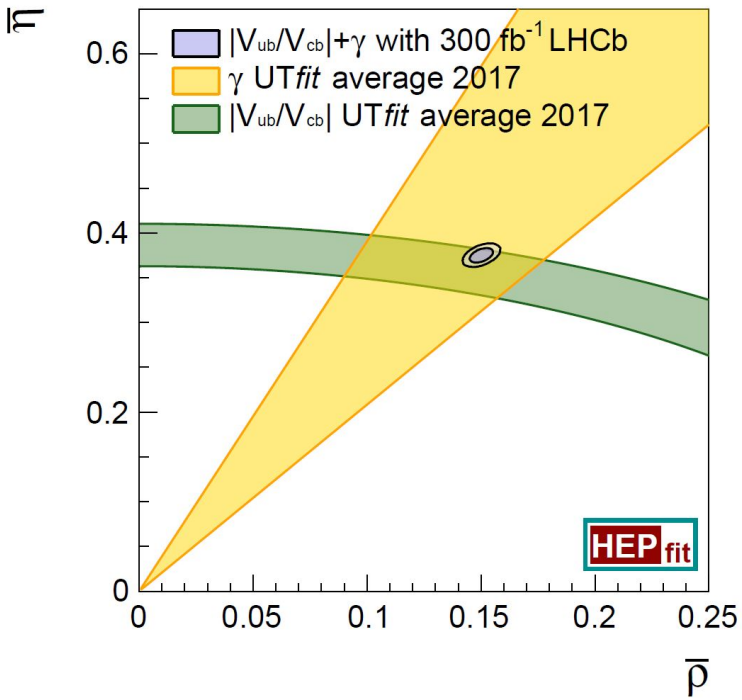


CKM measurements: $|V_{ub}|$

- LHCb uniquely able to measure $|V_{ub}|$ in exclusive B_s^0, B_c^+ and b-baryon decays
- Measurements from different decay modes have different hadronic uncertainties and produce differently shaped contours in the phasespace
- Λ_b^0 measurement has significantly reduced the required right-handed component in the combined result



CKM measurements: γ and $|V_{ub}|$

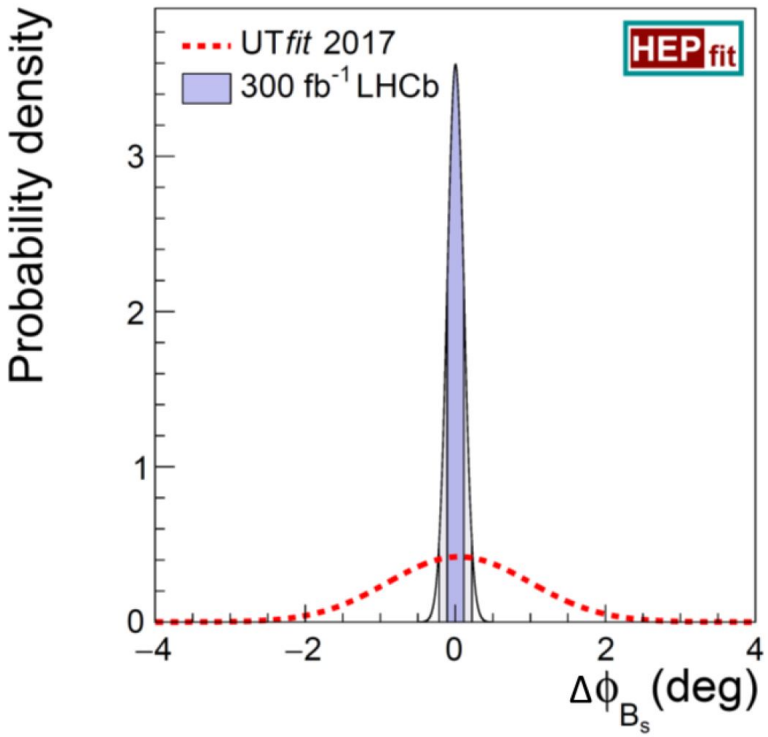


- Precision on γ expected to be improved to $\sim 0.4^\circ$ following phase 2 upgrade
- Multiple independent degree-level measurements
- Improved neutral reconstruction in modes such as $D^0 \to \pi^+\pi^-\pi^0$ may boost this further
- $|V_{ub}|$ decay-rate measurements should be more precise than lattice for all channels
- Measurements from a wider range of b-hadrons and decays
- HL-LHC era results for γ and $|V_{ub}|$ will significantly reduce uncertainty on the UT apex position at "tree" level

CKM measurements: ϕ_s

- Large $B_s^0 \to J/\psi\,\phi$ and $B_s^0 \to \phi\phi$ datasets would allow for ultra-precise measurements of ϕ_s
- PV association rate can be maintained at the percent level, despite the ~ 50 pileup interactions, by exploiting fast timing technologies

  See Matt Rudolph's talk on detector challenges tomorrow afternoon
- Precision expected to reach $9\,\mathrm{mrad}$ after Run IV and $\sim 2\,\mathrm{mrad}$ in HL-LHC era

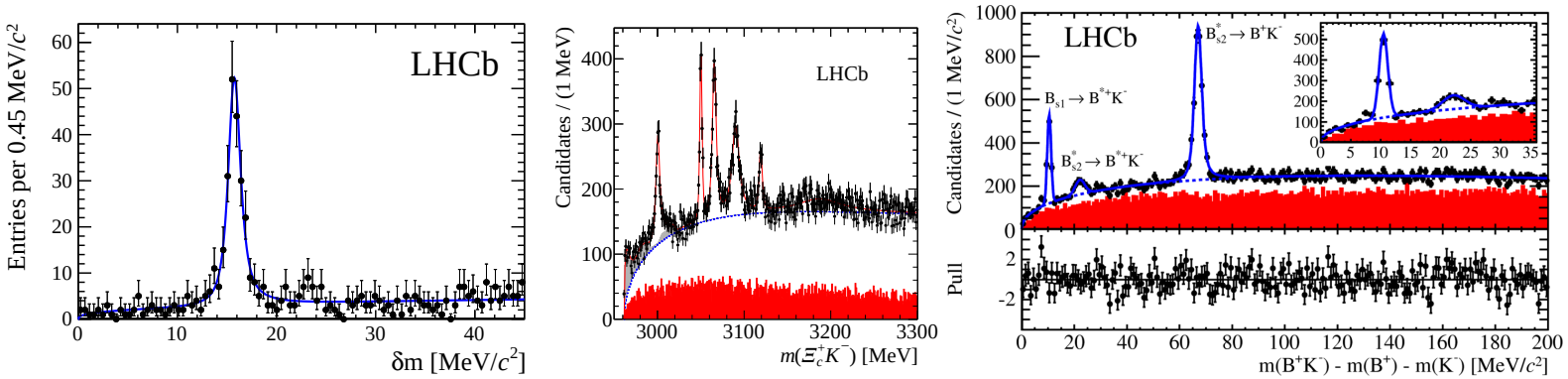


b-baryons

- LHC provides a unique environment to study *b*-baryons
- Many new states and decays observed
- First evidence of *CP* violation in Λ_b^0 decays
- Larger dataset will also open up new opportunities
- Extend studies to Ω_b and doubly-heavy baryons
- Short-lived doubly-heavy baryons will benefit from improved vertexing
- High multiplicity decays will benefit from low momentum tracking

B spectroscopy

- Spectroscopy of both conventional and exotic states has been an unexpected triumph of the LHCb physics programme
- Larger samples allow precision probes of the nature of exotic states such as $X(3872)$ and the hidden-charm pentaquarks
- New ECAL will help searches for photonic decays of exotic states
- Lower momentum PID will help to access corners of the phasespace
- Multibody decays of Ω_b and Ξ_b excellent environments to further study excited *c*- and *b*-baryon states and determine J^P assignments



Summary

- A rich *B*-physics programme awaits us in the HL-LHC era
- Many analyses will benefit from larger datasets and improvements to the LHCb sub-detectors
- Rare SM-processes will continue to offer probes of new physics
- Ultra-precision tests of CKM quantities
- Unique large *b*-baryon datasets will continue to provide new insights