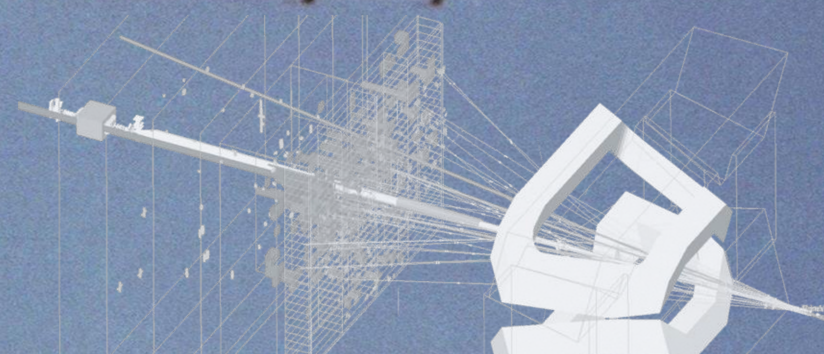
# Pushing the Envelope at LHCb (& MoEDAL)

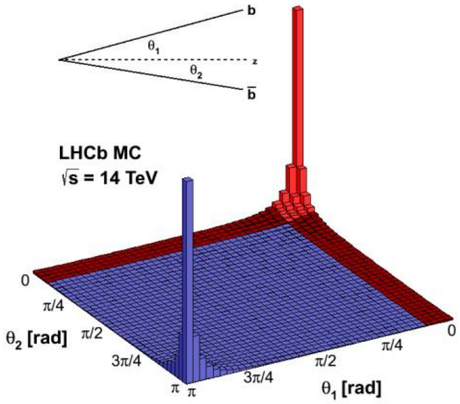
201st CERN Council Meeting
LHC Physics Jamboree
December 11, 2020


Phoebe Hamilton
(University of Maryland)

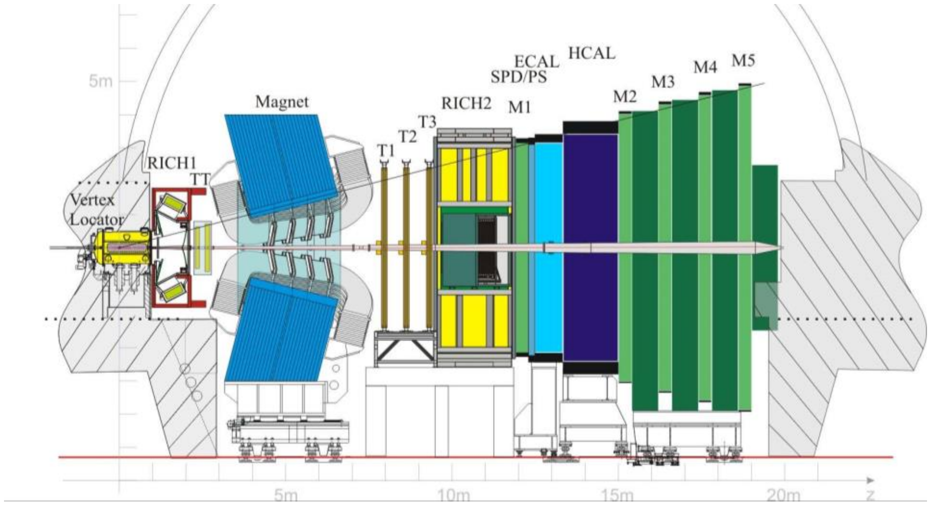

On behalf of the LHCb Collaboration

# LHCb *Classic*

- Forward detector to exploit kinematics of $b$ quark production in multi-TeV collisions: cover 27% (25%) of $b$-hadron (pair) production while instrumenting < 3% of the solid angle (value!)
- Heavy flavour cross-sections very large at LHC
  - Heavy-flavour events happen very rapidly, challenge is to quickly select them and throw away uninteresting events


$b\bar{b}$ quark mass much smaller than collision energy, leads to rapidly-moving b-hadrons



# LHCb’s Big Questions

- Does the standard model adequately explain all matter-antimatter asymmetry (“CP violation”, “CPV”) in hadrons?
  - CP Violation studies in bottom and charm hadrons
  - Search for CPT violation
  - T-violating asymmetries

- What are the dynamics that bind the hadrons like?
  - Excited hadron spectroscopy
  - Pentaquarks? Tetraquarks?
  - Molecular hadron states?

- Are there additional forces that distinguish the three generations of matter beyond the Higgs?
  - Lepton Flavour Universality Tests
  - Lepton Flavour Violation Searches

- What is the nature of the ‘dark’ gravitating matter?
  - Dark Photon Searches
  - Hidden Sector/LLP searches

# Farewell to a Superb Detector

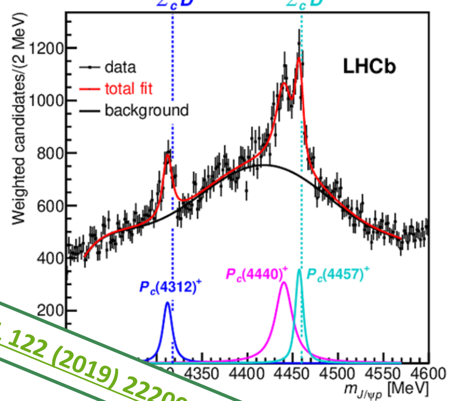
- LHCb remains diverse and vibrant experimental collaboration during long shutdown:
  - ~1400(!!!) members across 85 institutions in 18 countries working on Run1&2 data, upgrade construction, upgrade software, planning for further future, etc.


- LHCb as we knew it has been disassembled to make room for the Phase-I upgrade detector
  - Fast readout for real-time software decision-making
  - More granular subdetectors to cope with ‘busier’ events

- Photos: LHCbExperiment on Instagram

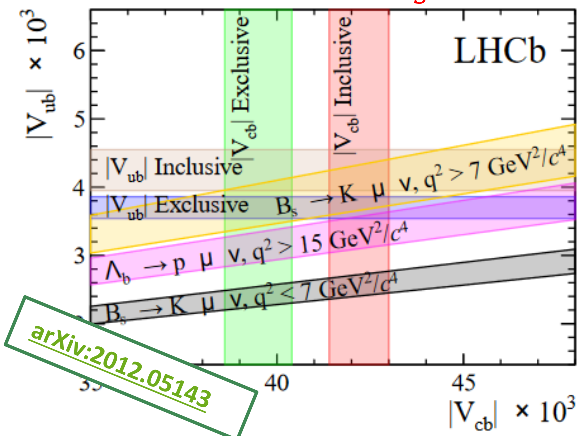

# LHCb Physics Programme Continues Full-Steam!

Pentaquark discovery



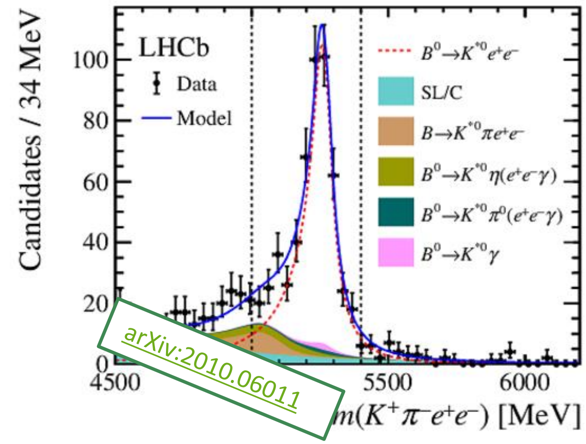

PRL 122 (2019) 222001

Vub with $B_s^0$



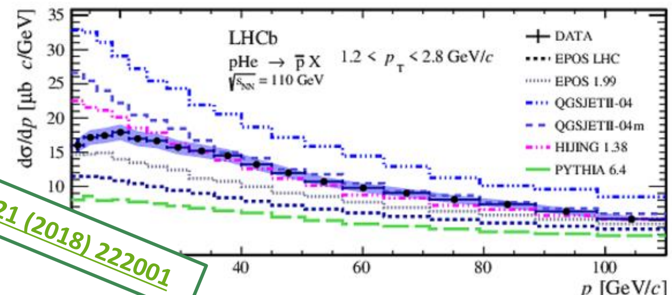

arXiv:2012.05143

$b \to s\gamma^*$ FCNC decays



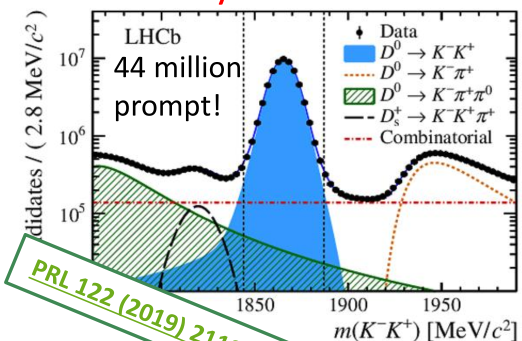

arXiv:2010.06011

Antiprotons in p-on-He collisions



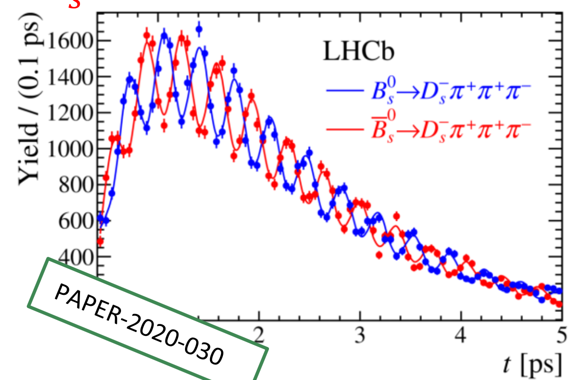

PRL 121 (2018) 222001

Discovery of Charm CPV



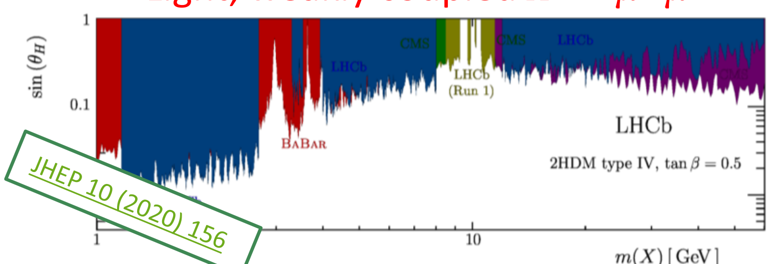

PRL 122 (2019) 211803

$B_s^0$ matter-antimatter oscillation




PAPER-2020-030

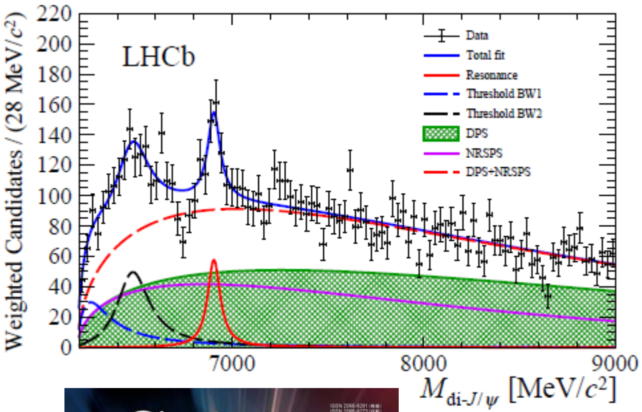
Light, weakly coupled $X \to \mu^+\mu^-$




JHEP 10 (2020) 156

- Many of these completed/submitted despite COVID-19 pandemic

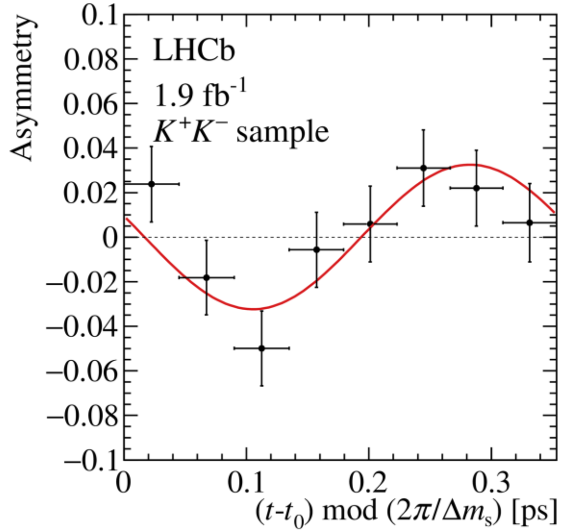
# Notable Recent Breakthroughs





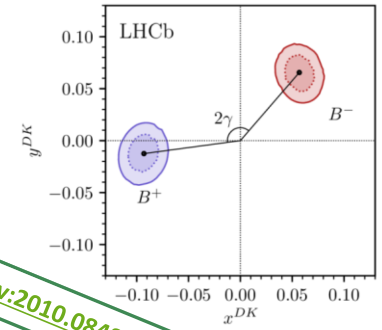
Observation of tetraquark $T_{cc\bar{c}\bar{c}}$ enhancement

Science Bulletin 2020 65(23)1983-1993

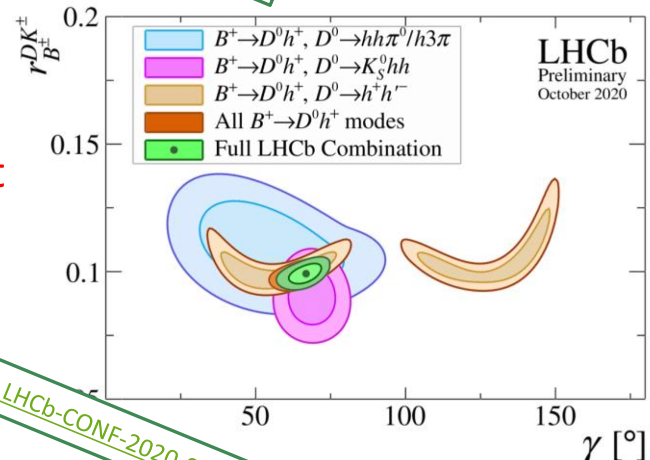



Discovery of time-dependent matter-antimatter asymmetries in Bs mesons

LHCb-PAPER-2020-029




arXiv:2010.08483



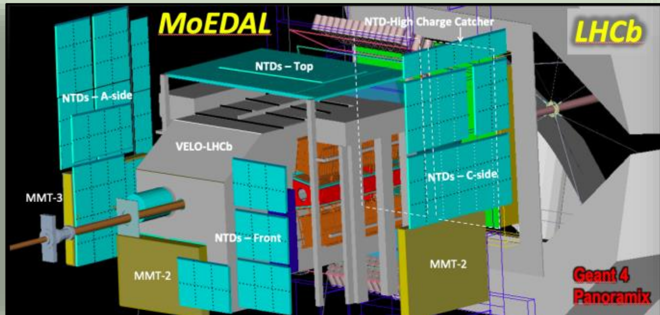

LHCb-CONF-2020-003

Best determination of matter-antimatter asymmetry parameter γ

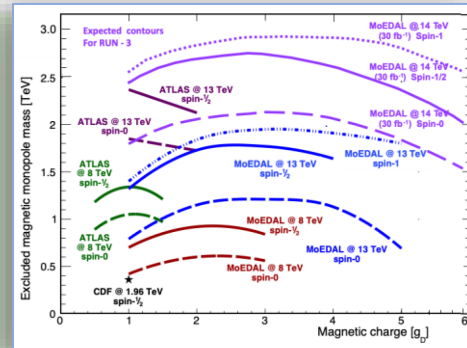
# The MoEDAL- MAPP Experiment at the LHC

## *The LHC's 1st Dedicated Search Experiment*

## *MoEDAL (Run-2)*

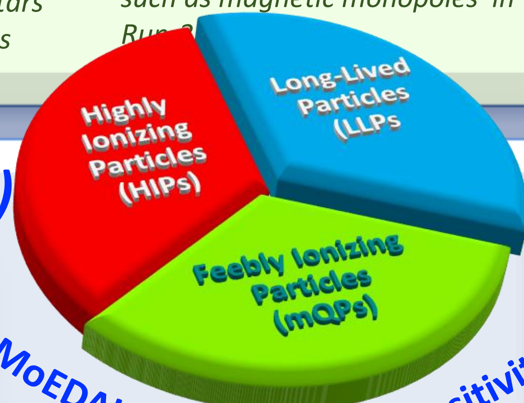



*MoEDAL is a passive detector that can track {NTDs & Capture (MMTs) Highly Ionizing Particle avatars of new physics with no SM physics backgrounds*




*MoEDAL will continue to provide the best collider limits on HIPs such as magnetic monopoles in Ru*

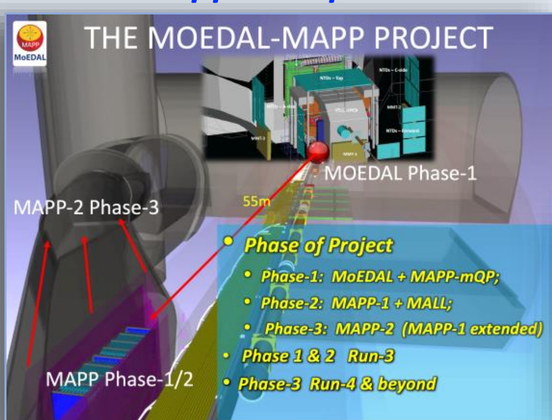

*MoEDAL papers currently in progress*

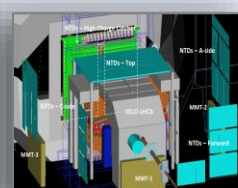


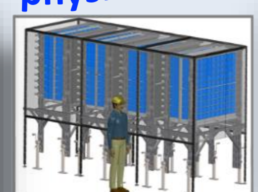

MoEDAL-MAPP physics Sensitivity

## *MoEDAL-MAPP (Run-3 +)*

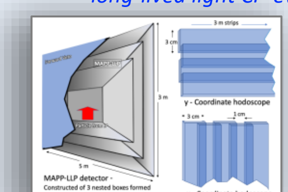
### *In approval process*



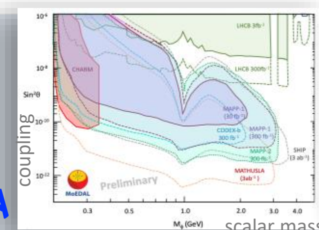





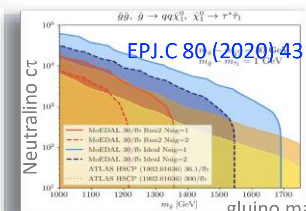
*PHASE-1 instal MoEDAL/install MAPP-mQP*



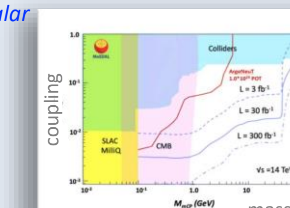

*PHASE-2 instal MAPP-LLP*




*B → $X_s\phi$ decays, where φ is a long-lived light CP-even scalar*

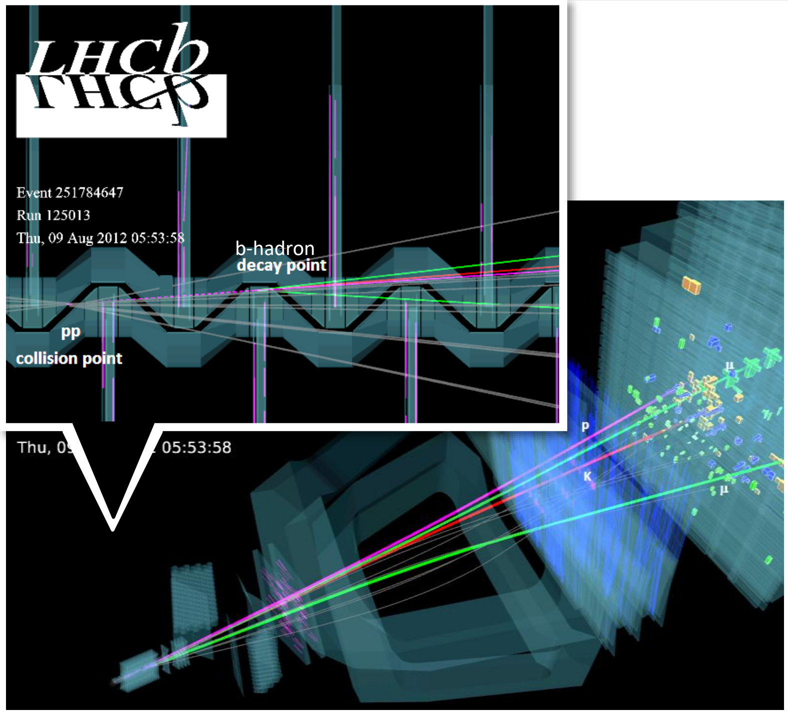


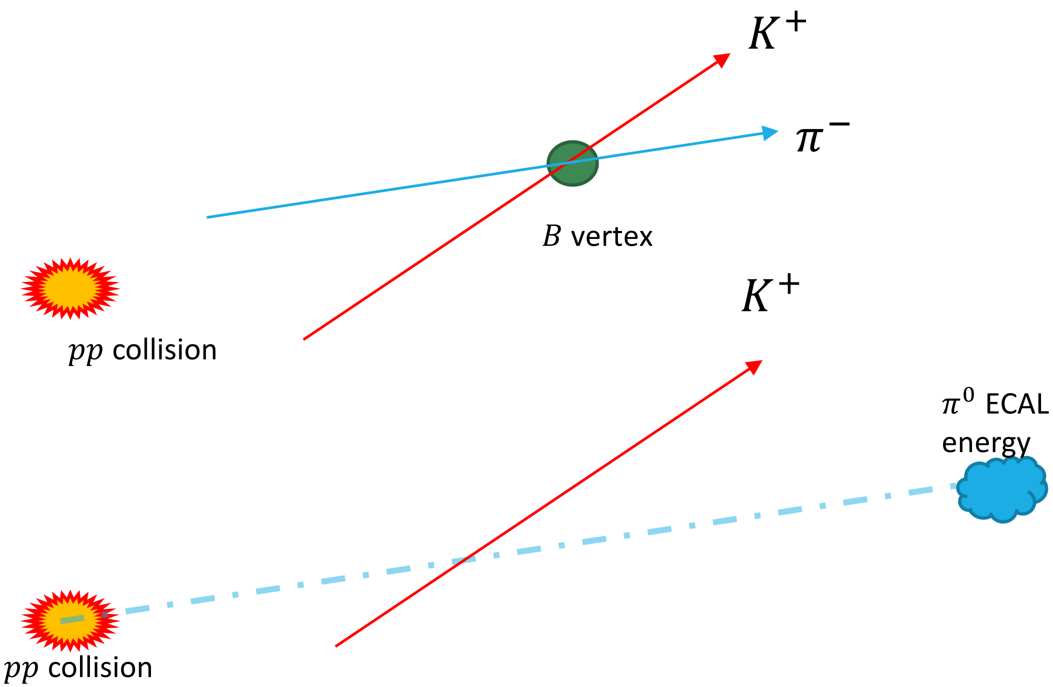

*GMSB SUSY gluino → a along lived neutralino → slow slepton*




*Search for a DY produced dark milli-charged fermion*

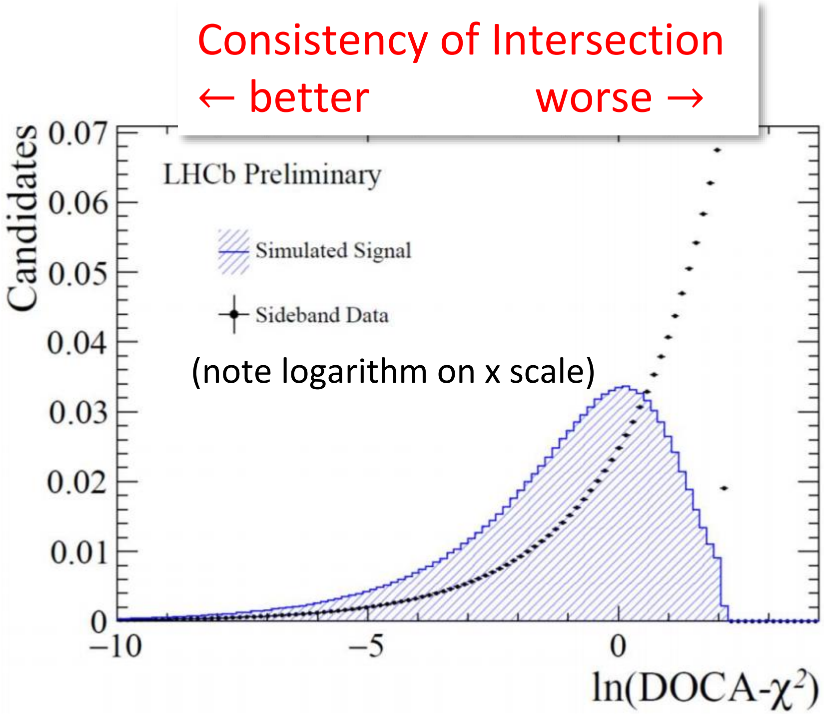
# LHCb Events & $B \rightarrow K^{+}\pi^{-/0}$

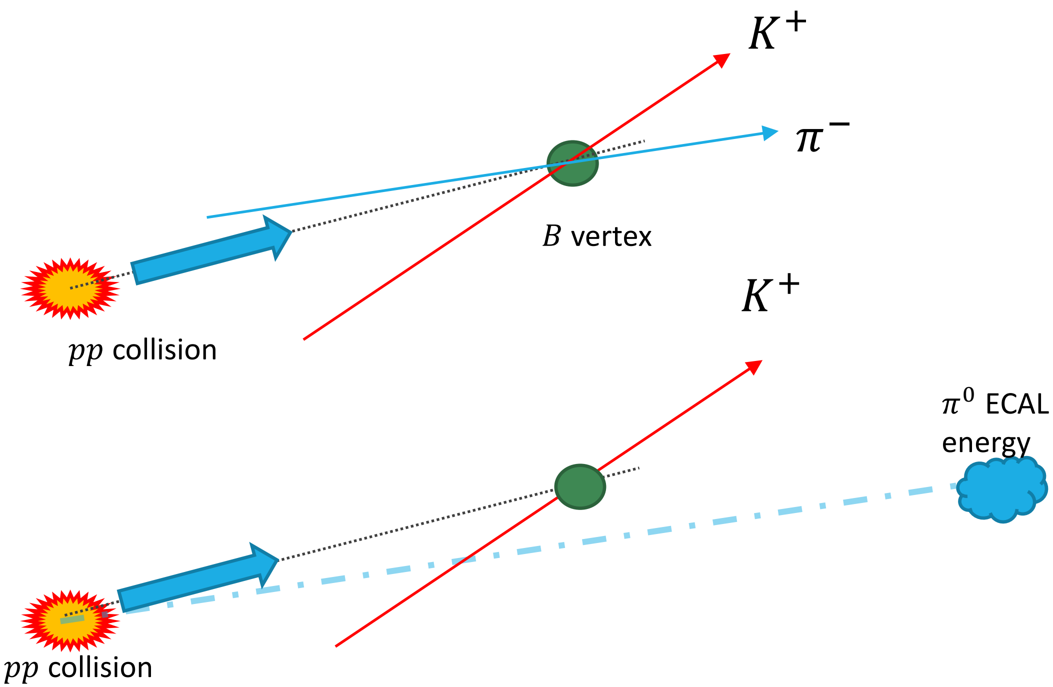



- LHCb's power lies in the ability to separate b-hadron decays from the direct proton-proton collision fragments ("underlying event")
  - Beauty-hadron secondary vertex is usually *essential* for analyses at LHCb
- $B \rightarrow K^{+}\pi^{-}$ is "easy" at LHCb, but understanding the related mode $B \rightarrow K^{+}\pi^{-}$ is important
  - *Is there a way to identify the signal without knowing the trajectory of the 2nd daughter particle?*

# LHCb Events & $B \to K^+\pi^{-/0}$



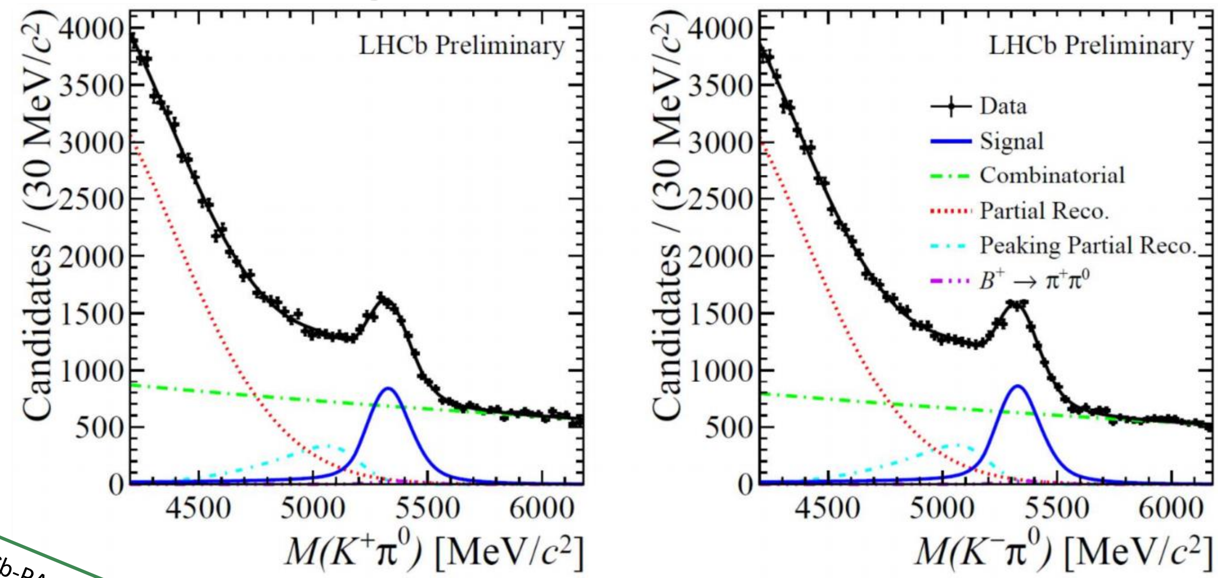

- LHCb's power lies in the ability to separate b-hadron decays from the direct proton-proton collision fragments ("underlying event")
  - Beauty-hadron secondary vertex is usually *essential* for analyses at LHCb
- $B \to K^+\pi^-$ is "easy" at LHCb, but understanding the related mode $B \to K^+\pi^-$ is important
  - *Is there a way to identify the signal without knowing the trajectory of the 2nd daughter particle?*
  - *Construct intersection of 3-momentum vector (origin at PV) and Kaon flight trajectory!*

# Result: A Clear Signal!

- With combination of the new technique and efficient selection of events *without additional nearby tracks* (“isolation”)

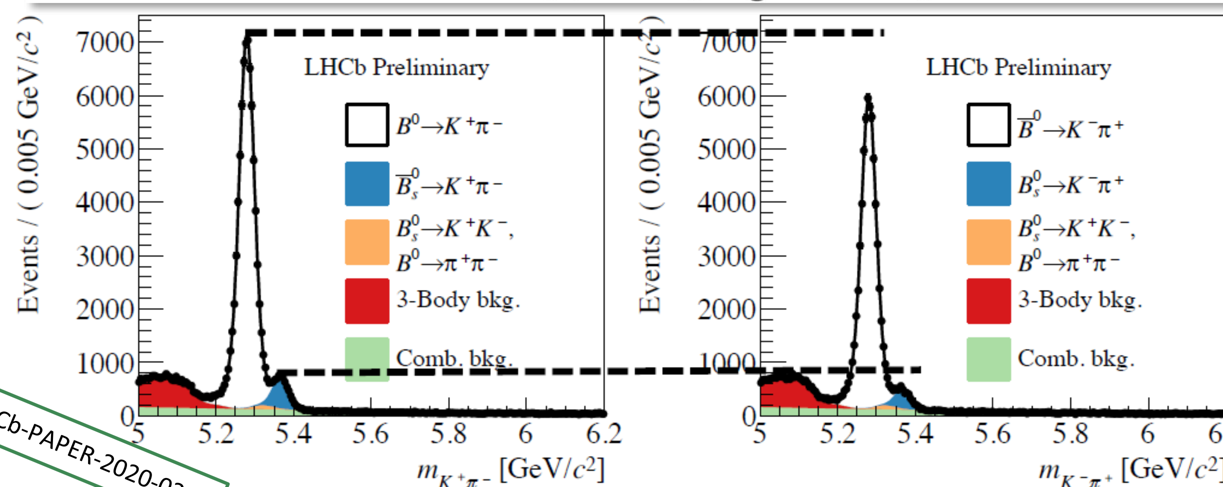
- Word-leading measurement of the asymmetry in this “impossible” mode!

- Note the much-smaller asymmetry here compared to all-charged mode (lower)
  - Naively should be similar. Something to learn here!




LHCb-PAPER-2020-040

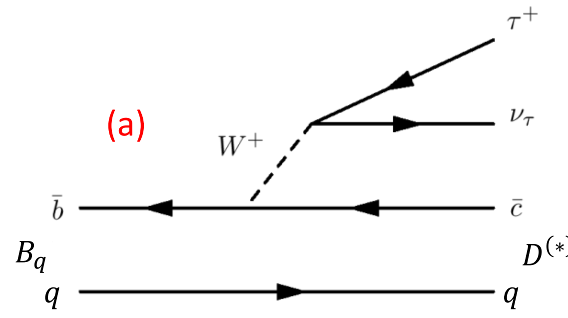
- $A_{raw} = 0.005 \pm 0.022$ (Magnet Up),
  $0.019 \pm 0.021$ (Magnet Down)




LHCb-PAPER-2020-029

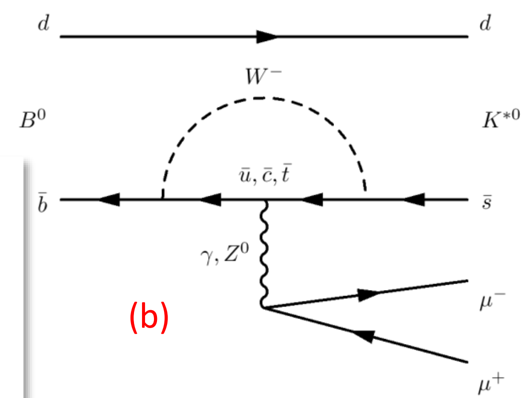
# Physics with final-state leptons

- Test for the presence of new forces which distinguish the leptons $(e^{\pm}, \mu^{\pm}, \tau^{\pm})$
  - In the Standard Model *only* the Higgs does this
  - Beyond the Standard Model: extra scalar bosons? Leptoquarks?



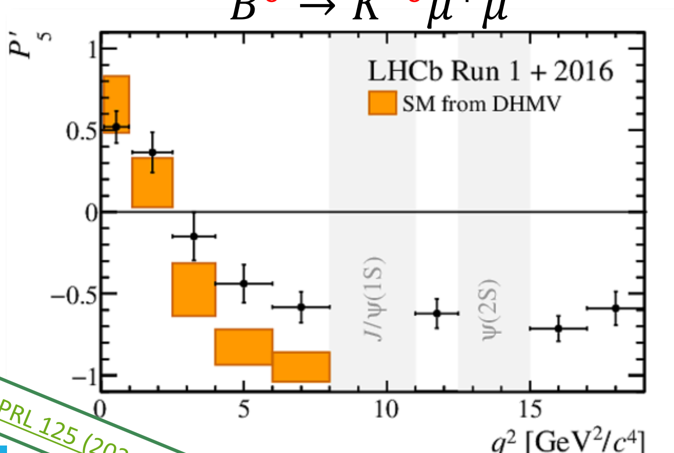

- Several suggestive deviations exist in both tree-level (a) and loop-level (b) decays:
  the much-discussed "B hadron anomalies"
  - Work underway for improved measurements in the tree-level modes R(D), R(D*) in Run1&2
  - $R_K, R_{K^*}$ with full dataset in progress
  - Meanwhile, analysis of both in other b-hadrons unique to LHCb

Diagrams from C. Elsasser's FDL



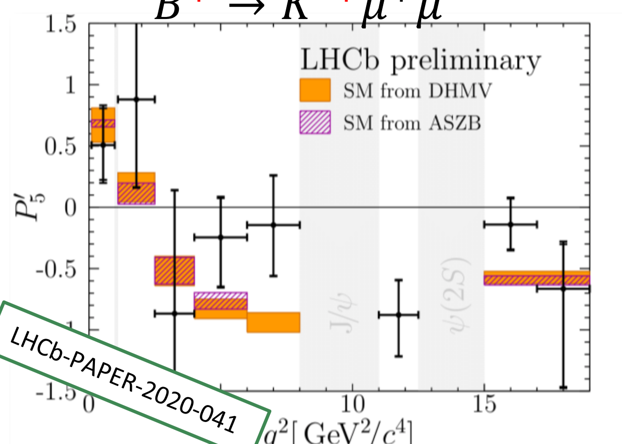

- Continuing to see deviations from Standard Model calculations for the angular distributions of the muons in the neutral-current muon modes.

$B^0 \to K^{*0}\mu^+\mu^-$




PRL 125 (2020) 011802

$B^+ \to K^{*+}\mu^+\mu^-$




LHCb-PAPER-2020-041

# Next Steps for LHCb

HEAVY FLAVOR IN RUN3 AND BEYOND

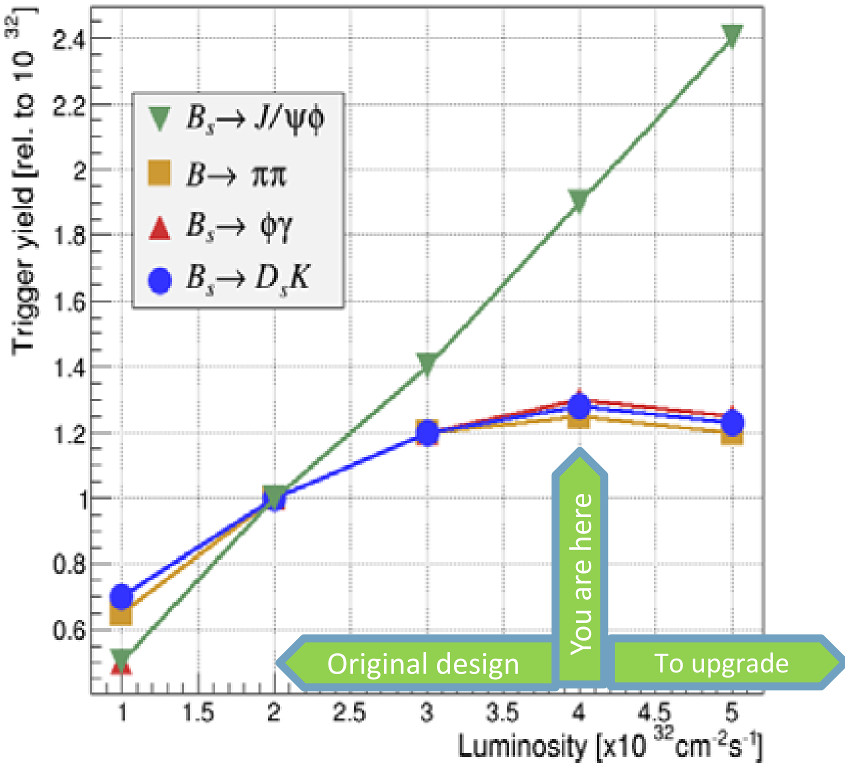
# Challenges at high luminosity

- Cannot increase luminosity any further in Run2 trigger scheme
  - Fixed-bandwith hardware decisions limit output rate and only access limited event info
  - Increasingly strict requirements select *against* heavy-flavour events

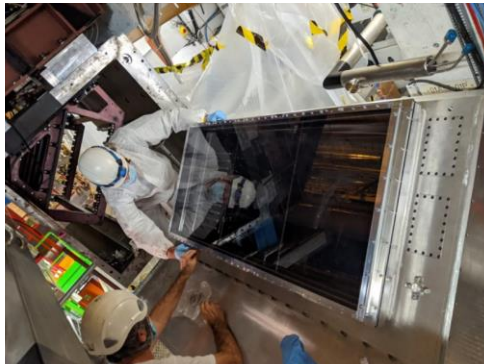
- LHCb Upgrade Concept:
  - Completely rebuilt detector readout to be synchronous with LHC beam crossings
  - Real-time analysis style event selection
    - Fast event reconstruction with GPU technology
    - Can identify candidate B hadrons and interesting tracks *before* making the decision!

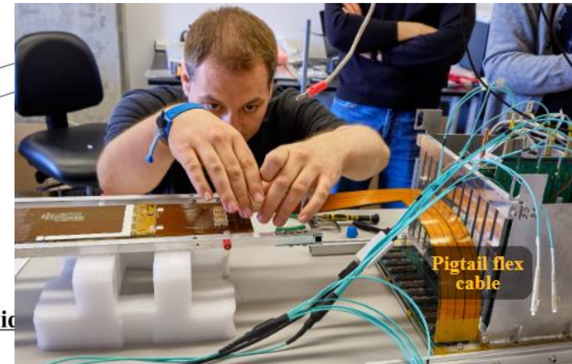
- Result: Order-of-magnitude increase in dataset

- Require significant increase in segmentation to deal with $\sim 5\ pp$ collisions per event
  - All new charged-particle trackers
  - Re-optimized and rebuilt particle identification subdetectors

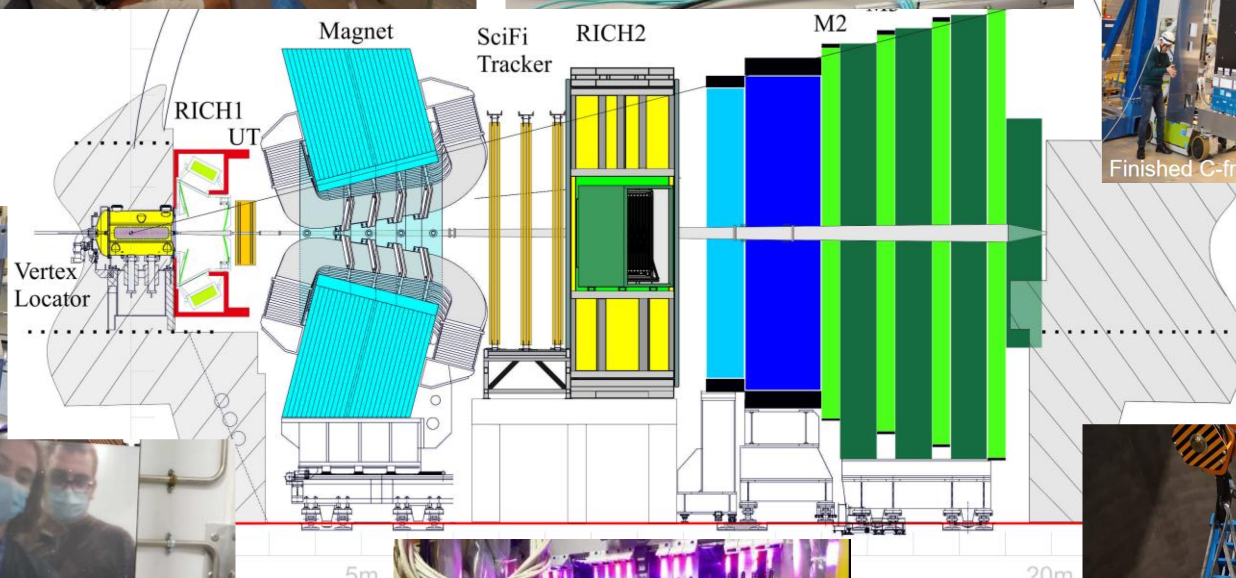


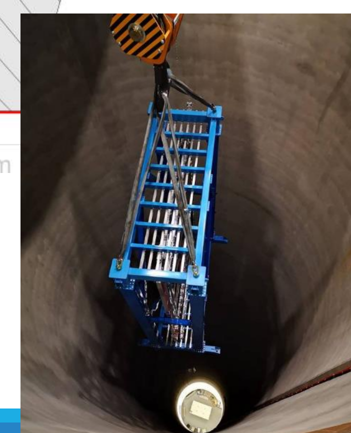
# Upgrade outside the nutshell









# Summary

- LHCb has had an extremely successful Run1 & Run2, and much of the original detector has been decommissioned to make way for the upgrade
  - Many thanks to LHC machine colleagues, and we look forward to resumed high-quality collisions in our upgraded detector!

- Despite COVID-19 and challenging LS2 upgrade schedule, the physics program continues to produce a wide variety of impactful results
  - Best determination of difficult CKM parameter $\gamma$
  - Establishment of time-dependent matter-antimatter asymmetries in $B_s$ decays
  - Discovery of matter-antimatter asymmetries in the decay of charm mesons
  - Unexpected exotic states which may help illuminate the internal dynamics of hadrons
  - Studies in unique fixed-target data-taking modes, as well as p-Pb collisions

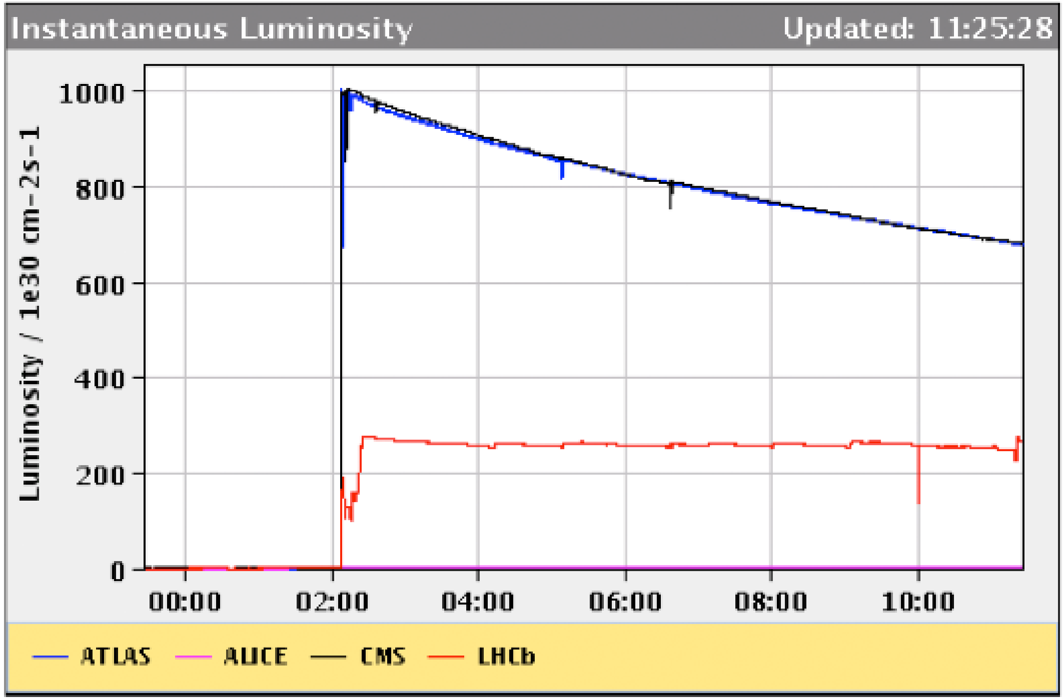
- After a successful Run2 exposure, MoEDAL will continue it's search for unexpected new phenomena in Run3 alongside LHCb

- Upcoming in 2021: technical design for a *second* LHCb upgrade to fully exploit HL-LHC point 8

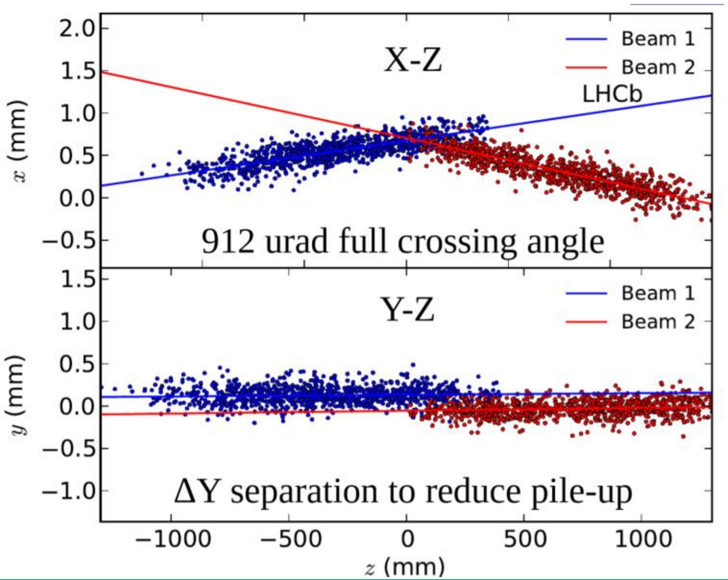
**Farewell to a busy 2020!**

# Backup Slides

# LHCb Datataking




- LHCb requirements:
  - Lower peak Lumi $(2 - 4 \times 10^{32})$
  - Stable intra-fill pileup
- LHC machine solution: Lumi levelling scheme at point 8
  - Possible use in high-pt experiments in HL-LHC



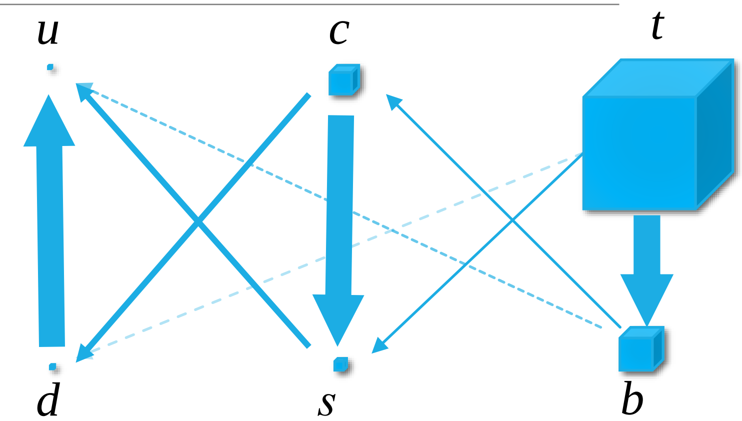
# Why LHCb

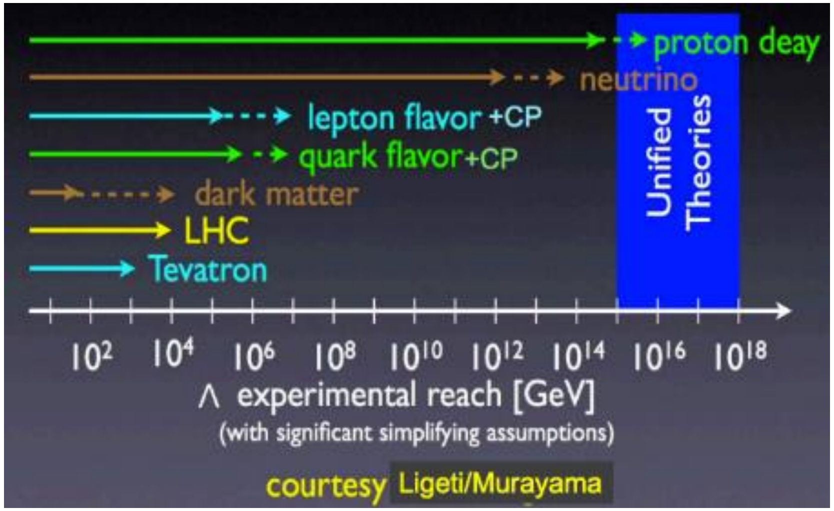
- CKM mechanism is integral part of standard model governing quark flavor transitions

- Striking feature: matrix covering transitions is nearly diagonal and hierarchical by generation (mass)
  - Transitions mixing different generations suppressed
  - 3rd generation especially "isolated"

- b-quark *has no kinematically allowed decays with O(1) CKM factors* ($|V_{cb}|^2 \sim 10^{-3}$)
  - Makes B physics quite sensitive to new physics generically misaligned with CKM
  - Also leads to long $b$ quark lifetime: $c\tau_B \sim 400\mu m$! (= about 2x charm lifetime) key for measurements at LHC

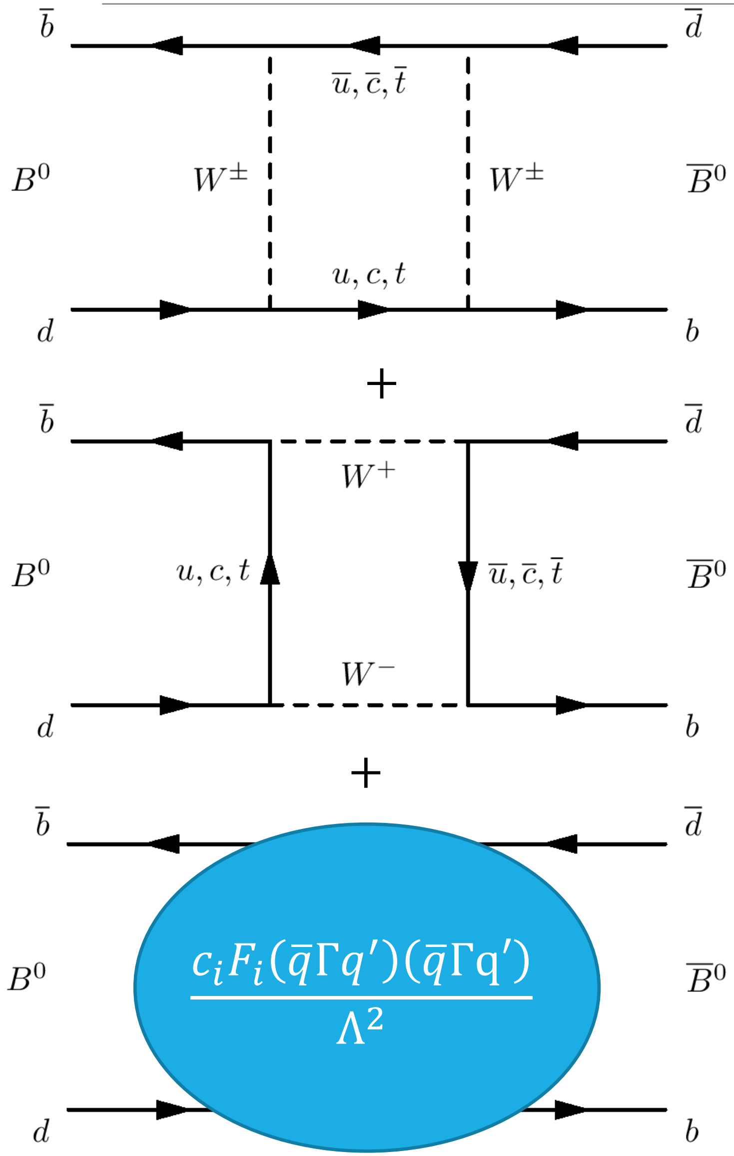
- Violation of CP symmetry required for baryon-antibaryon asymmetry of the universe
  - Single complex phase in CKM violates CP symmetry
  - SM CPV extremely overconstrained



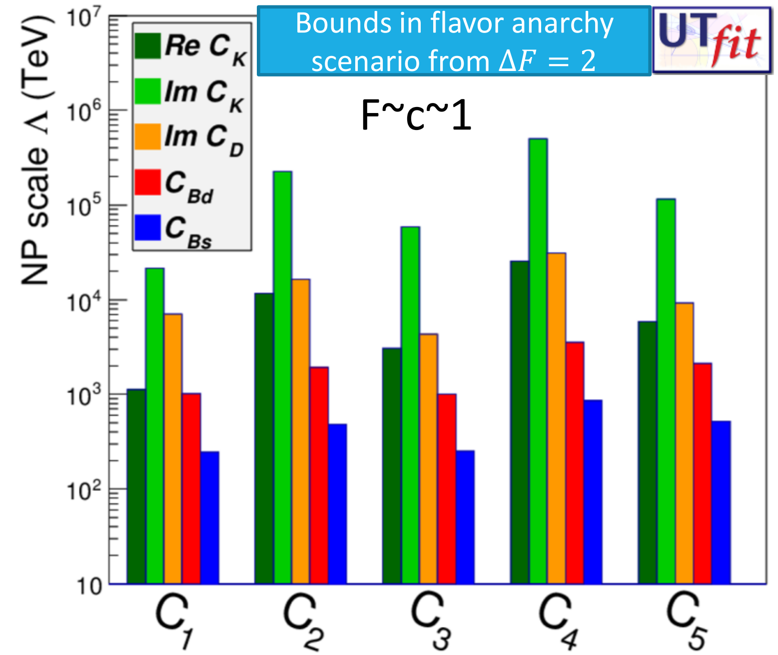




H. Weerts, intensity frontier workshop

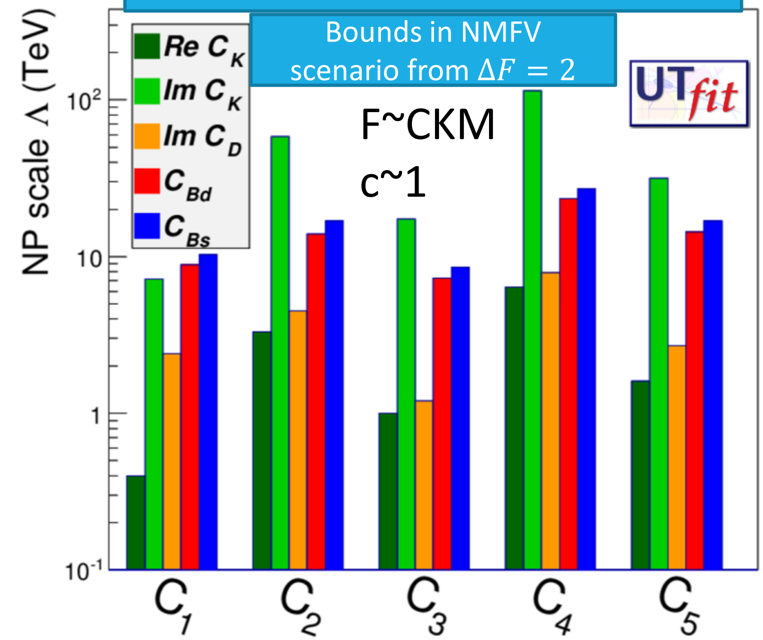
# Flavor Physics Reach




Diagrams from C. Elsasser's FDL




UTFit collaboration arXiv:1710.09644

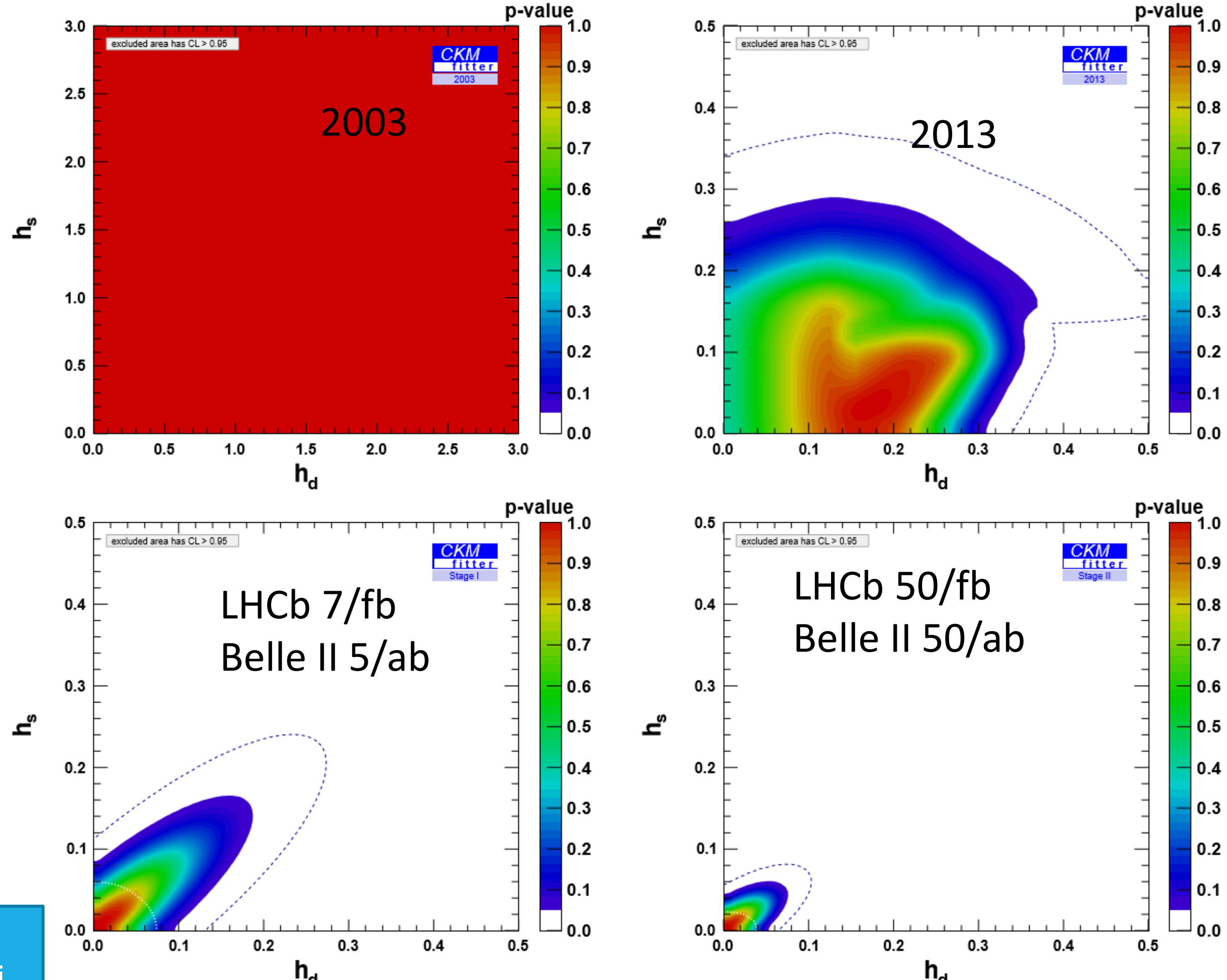


# Constraining NP in B mixing

Constraints on model independent parametrization of new physics in B mixing

$M \sim M_{SM}(1 + he^{i\sigma})$

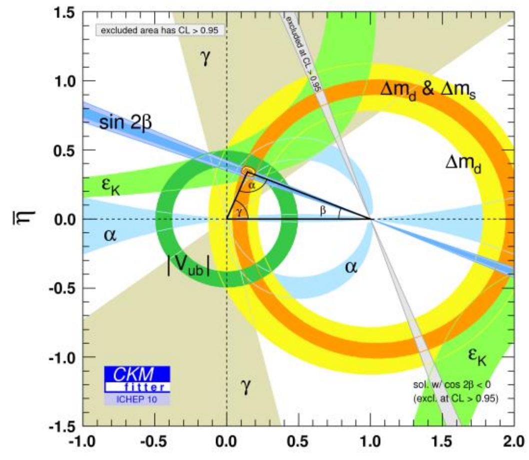
for $B_d (= B^0)$ vs $B_s$



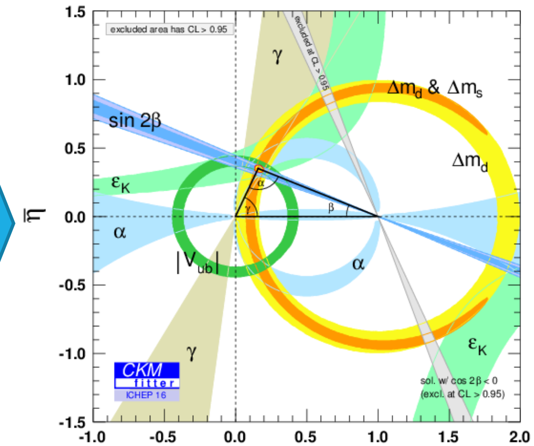

J. Charles, S. Descotes-Genon, Z. Ligeti, S. Monteil, M. Papucci, K. Trabelsi
arxiv 1309.2293

# Impact of flavor at LHC

- CKM uncertainties steadily shrinking – huge impact on knowledge of $\gamma$

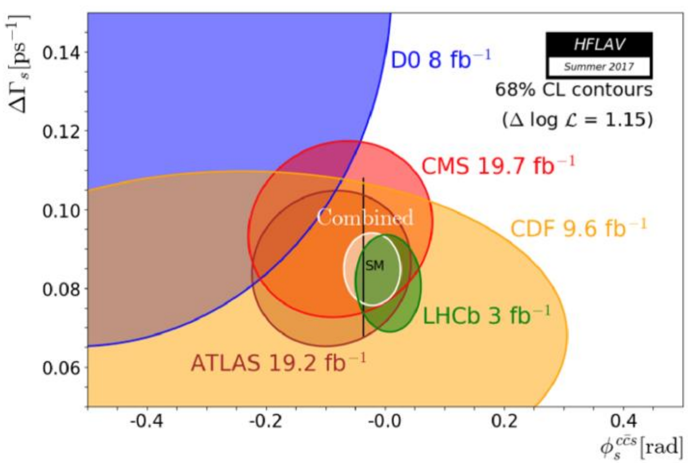



2010




2016

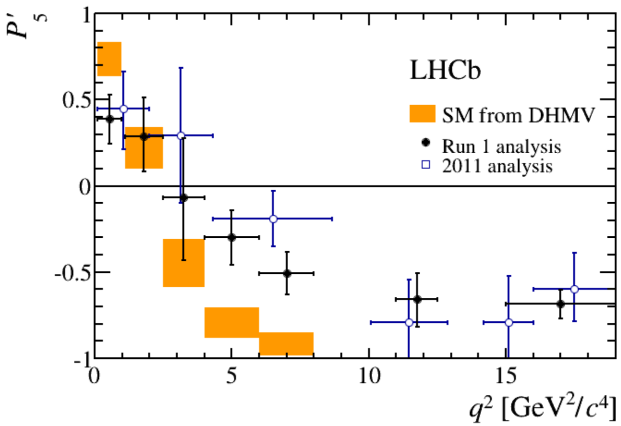
- $B_s^0$ mixing parameters and NP contributions to becoming steadily more constrained, plus competitive contributions to $B^0$ mixing parameters



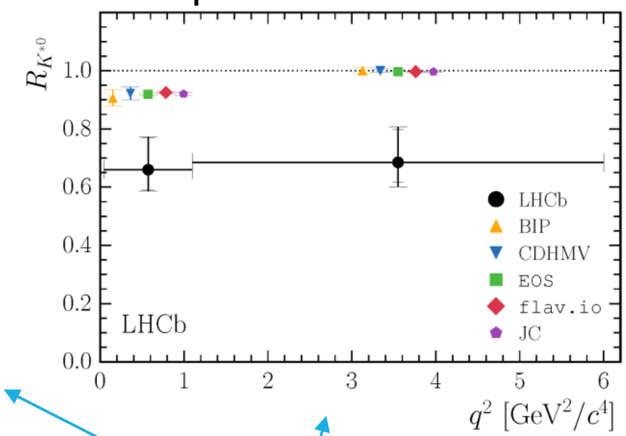

$B_s 2\mu\mu$ goes here

# B hadron anomalies

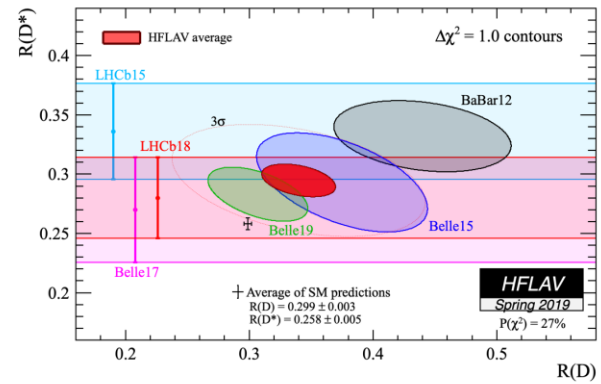
Angular distributions in $B^0 \to K^* \mu^+ \mu^-$



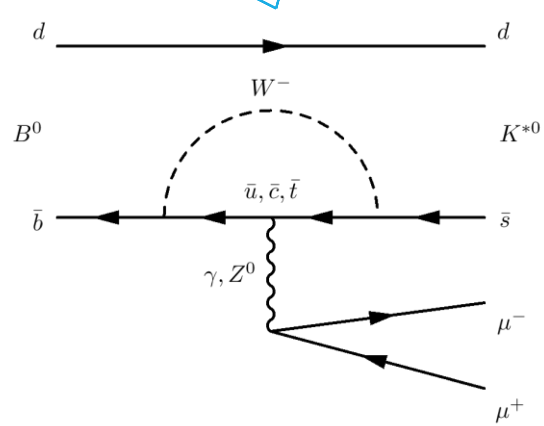

Deficit of $B \to K^{(*)}\mu\mu$ compared to $B \to K^{(*)}ee$

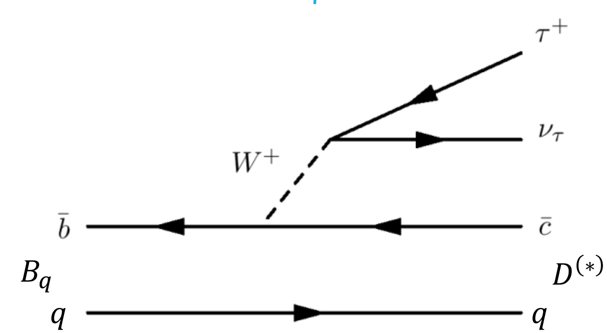



$B \to D^{(*)}\tau\nu$ excess




Quick acknowledgement: Much of this has been covered in more detail at previous workshops by Mitesh Patel, Paula Alvarez Cartelle, and Lucia Grillo, from which I'm borrowing a lot. See their linked slides for more!

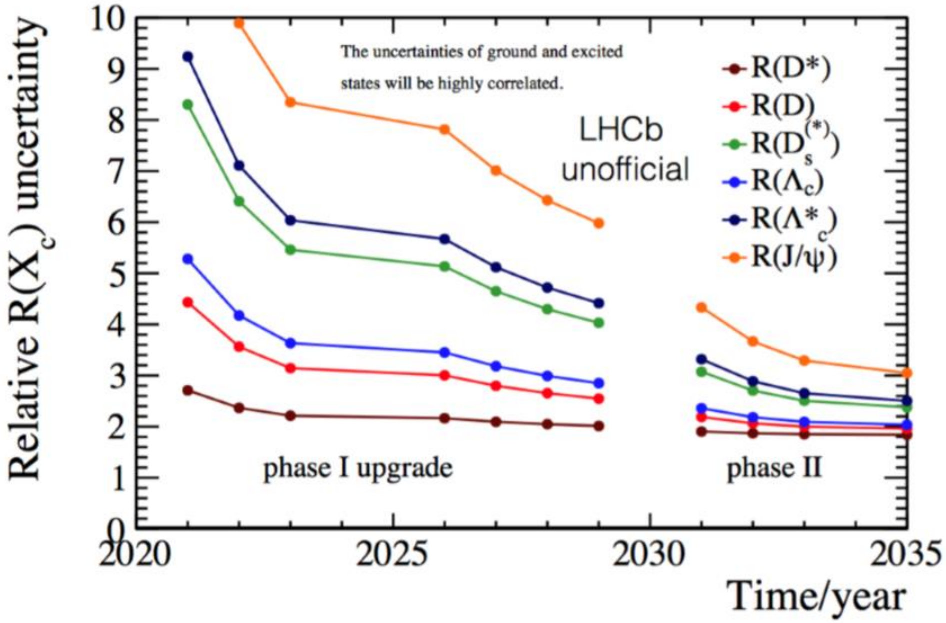



Diagrams from C. Elsasser's FDL

# LFU Ratio prospects

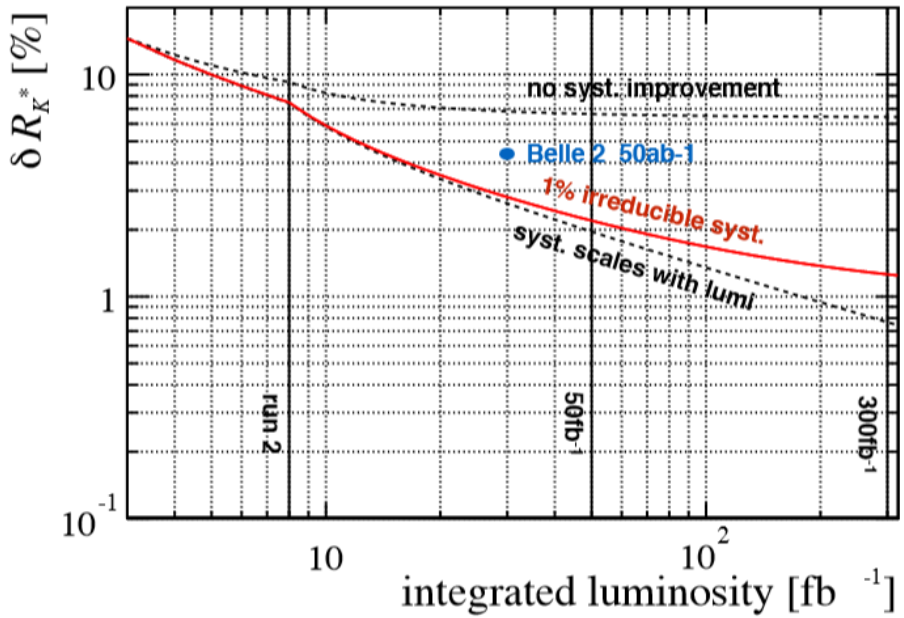
- General prospects for increasing precision of core observables ($R(X_c)$) are relatively well-established
  - Ultimate sensitivity depends on what systematics become limiting
  - Large datasets -> large control samples -> most systematics can be reduced

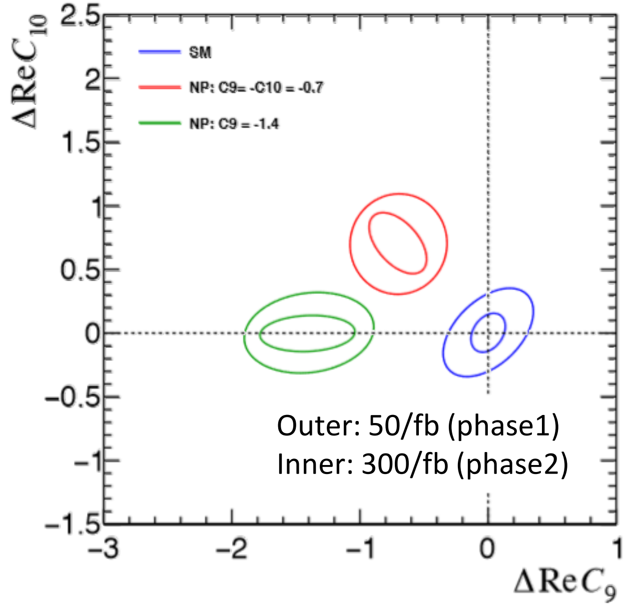



- Right: projections if limiting systematics become combinatorial background shapes, PID efficiencies, data/MC corrections

- Absolutely crucial that computing keep up with data (need simulation ~4x data to keep up)
  - Raw power/architecture improvements?
  - Improved FastMC? (systematics?)

# LFU plus angular observables

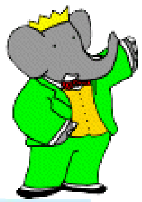


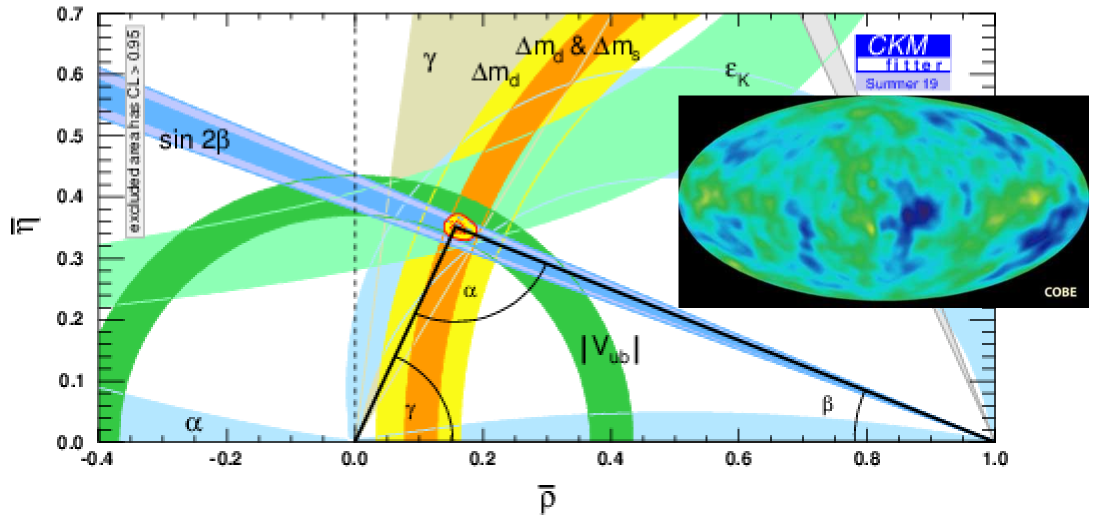

- Powerful idea going forward will be measuring LFU-violating differences in angular observables
  - Best of both worlds, potentially a very powerful probe to characterize what other observables may be presently hinting at

- Will require improvements to LHCb ECAL for Phase-II to boost $e^{\pm}$ performance and bremsstrahlung recovery

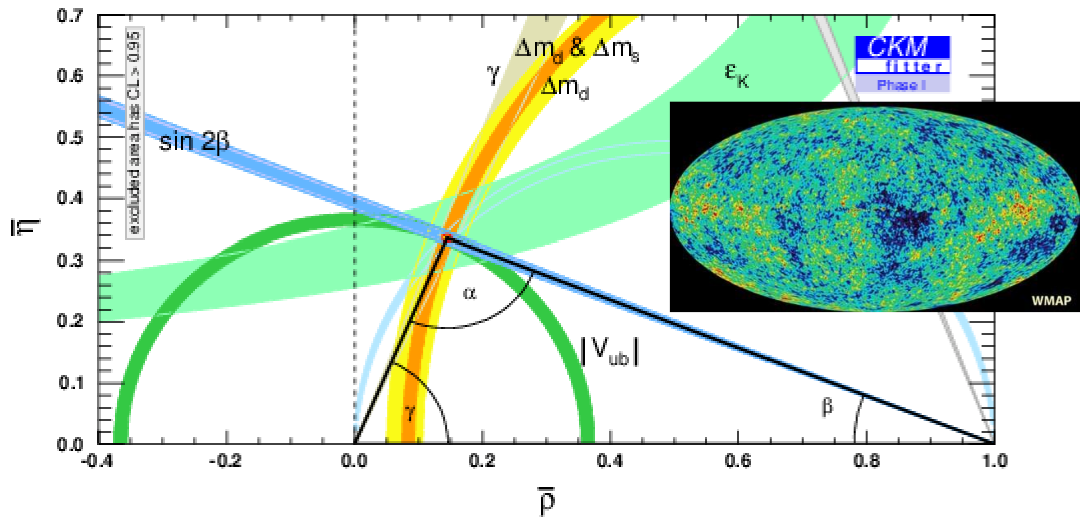
# "Why keep doing flavor in the 2020s?"



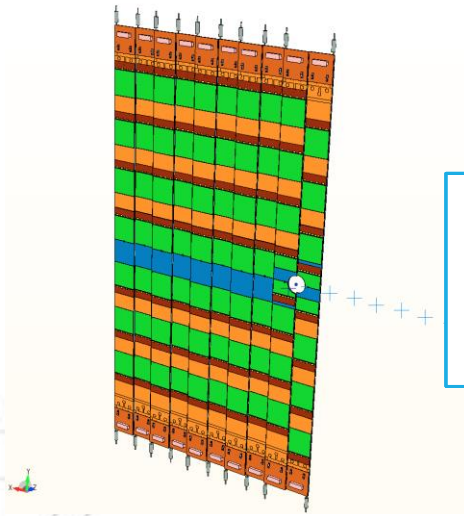
2019



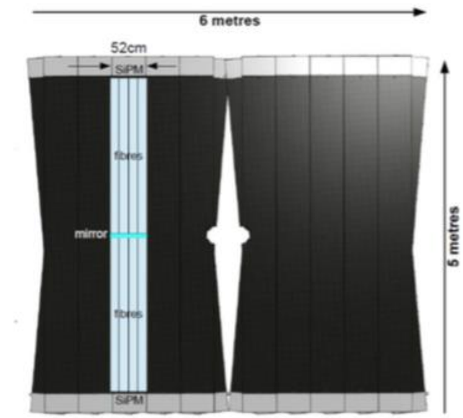

2030

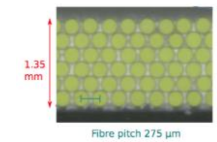


# LHCb Upgrade Hardware

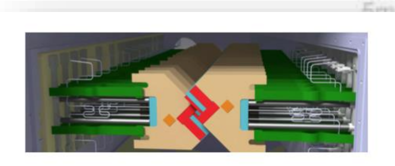


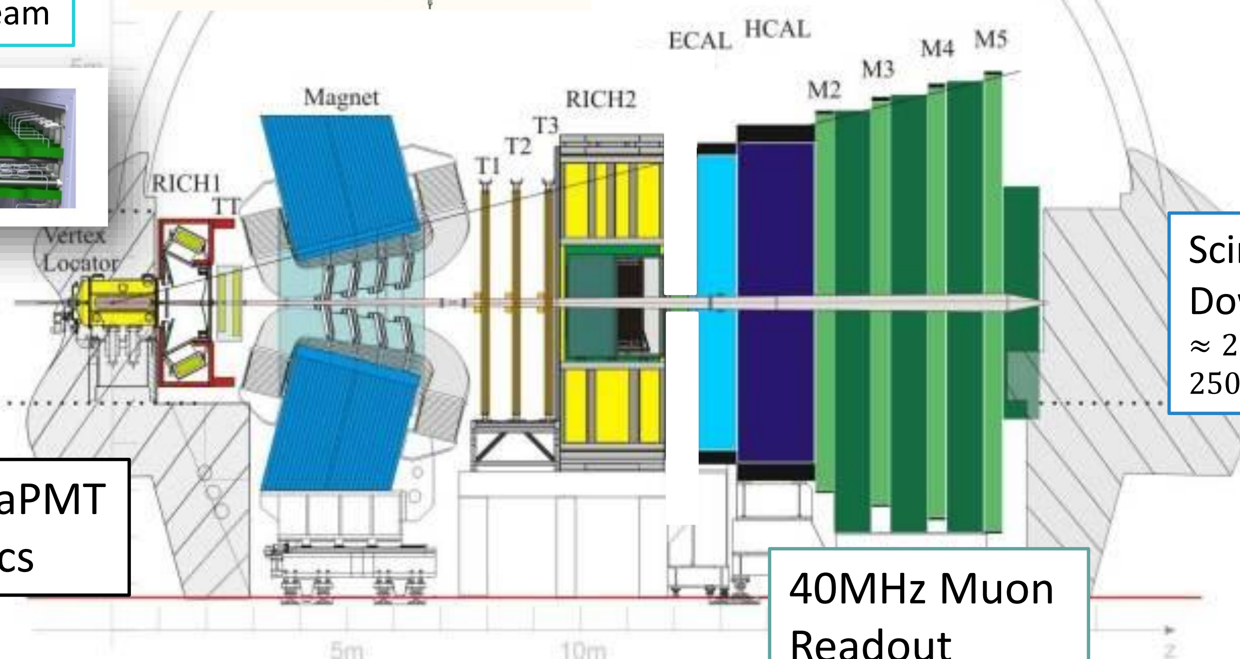
**Upstream Tracker**
Silicon Strips
$\approx 190\mu m$ outer,
$95\mu m$ inner




**Pixel Velo**
$55\mu m$ square
@ 3.5mm from beam






**Scintillating Fibre Downstream Tracker**
$\approx 275\mu m$ fiber pitch,
$250\mu m$ pitch SiPM sensors

**New RICH MaPMT sensors+optics**

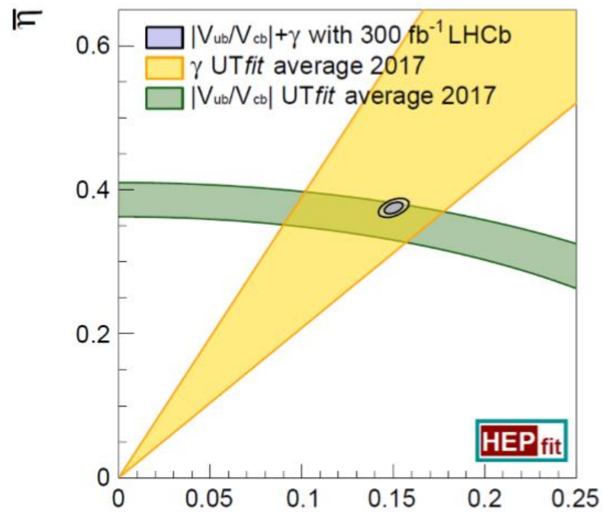
**40MHz Muon Readout**

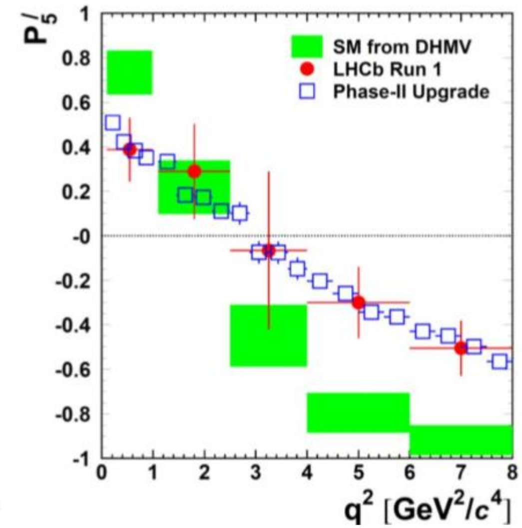
# Flavor frontiers beyond LS4

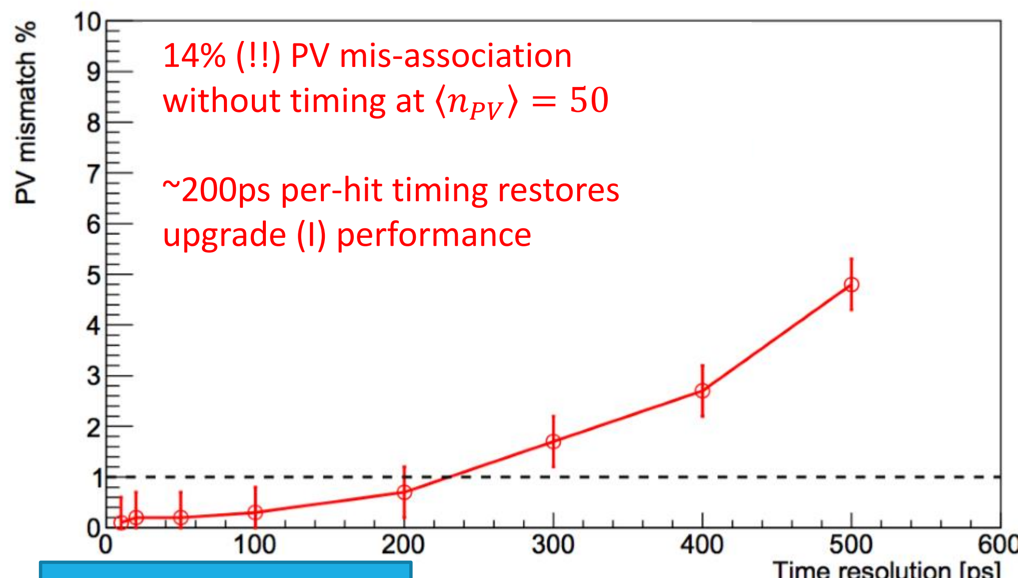
- LHCb ‘phase-II’ upgrade currently under study to record 300/fb
  - Second leap forward in flavor observables?

- Requires second rebuilding of the LHCb detector
  - Pileup of 50 in forward direction -> timing is essential to associate tracks->PVs (bottom)

- Expression of interest well-received by LHCC, work underway to sharpen physics case

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