# *Flavor anomalies at LHCb*

Biplab Dey

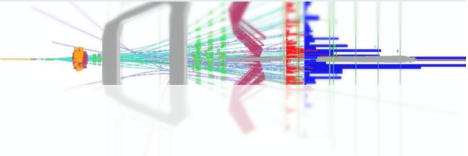
on behalf of the LHCb collaboration

(Re)interpreting the results of NP searches at the LHC,
May $14^{th}$–$16^{th}$ 2018, CERN

# Disclaimer

- Many interesting topics I won't have time to cover here...
  - $\phi_s$, $B^0_{(s)} \to \mu^+\mu^-$, radiative penguins, CPV in charm, ...
  - Dark photon and LLP searches. See also LHCb scenario and CODEX-$b$ talks at LLP workshop to follow.
- LHCb Public results page is our Data portal

The LHCb Public results



## LHCb publications

[to restricted-access page]

PUBLICATIONS PER WORKING GROUP

IONS AND FIXED TARGET

FLAVOUR TAGGING

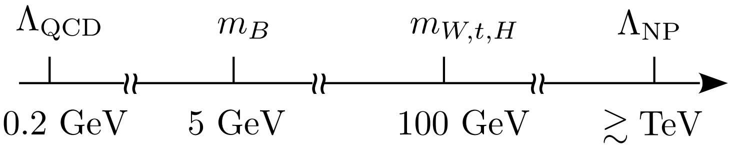
$b$-HADRONS AND QUARKONIA

List of papers (Total of 422 papers and 21902 citations) [plot]

| TITLE | DOCUMENT NUMBER | JOURNAL | SUBMITTED ON | CITED |
|---|---|---|---|---|
| Observation of the decay $\Lambda_b^0 \to \Lambda_c^+ p\bar{p}\pi^-$ | PAPER-2018-005 arXiv:1804.09617 [PDF] | PLB | 25 Apr 2018 | |

# NP hunting strategy in *b*-physics

- Multi-scale problem: QCD, hadronic form-factors, Electroweak, NP.




- Effective Field Theory: separate long and short distance scales. SM + a basis of dim-6 local operators, $\mathcal{O}_i$ and Wilson coefficients $C_i$

**Wilson coefficients encode short-distance physics after integrating over high mass SM particles**

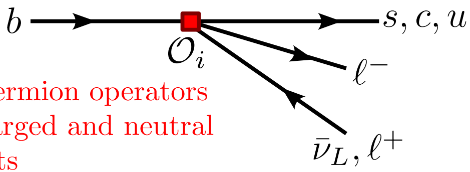
$$\mathcal{H}^{SM}_{\rm eff(6)} = -\frac{4G_F V}{\sqrt{2}} \sum_i C_i^{SM} \mathcal{O}_i$$

**generic non-SM flavor content**

$$\mathcal{H}^{NP}_{\rm eff(6)} = \sum_i \frac{C_i^{NP}}{\Lambda^2_{\rm NP}} \mathcal{O}_i,\ \Delta F = 1$$

- Sensitive to $\Lambda_{\rm NP} \gtrsim$ TeV scale thru' $C_i$. Need precision measurements.

# Operators for charged and neutral currents




Four-fermion operators for charged and neutral currents

- Charged current (SL tree-level):

  $b \to \{u, c\}\ell^- \overline{\nu}_\ell$, $\ell \in \{e, \mu, \tau\}$

  $V = \{V_{cb}, V_{ub}\}$, $\Lambda_{\rm NP} \sim 1$ TeV

$$\mathcal{O}_{V_{L,R}} = (\bar{c}\gamma^\mu P_{L,R} b)(\bar{\ell}\gamma_\mu P_L \nu_\ell)$$
$$\mathcal{O}_{S_{L,R}} = (\bar{c} P_{L,R} b)(\bar{\ell} P_L \nu_\ell)$$
$$\mathcal{O}_T = (\bar{c}\sigma^{\mu\nu} P_L b)(\bar{\ell}\sigma_{\mu\nu} P_L \nu)$$

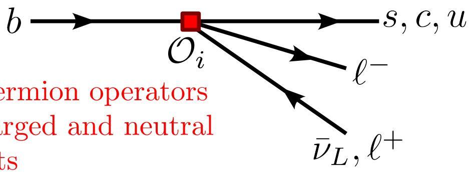
- Neutral FCNC (EWP loop-supp.):

  $b \to s\gamma_{\rm pol}$, $b \to s\ell^+\ell^-$, ...

  $V \sim \frac{\alpha}{4\pi} V_{ts}^* V_{tb}$, $\Lambda_{\rm NP} \sim$ 10-100 TeV

$$\mathcal{O}_{7\gamma}^{(\prime)} = \frac{m_b}{e}(\bar{s}\sigma^{\mu\nu} P_{R(L)} b) F_{\mu\nu}$$
$$\mathcal{O}_{9V}^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell)$$
$$\mathcal{O}_{10A}^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

# Operators for charged and neutral currents

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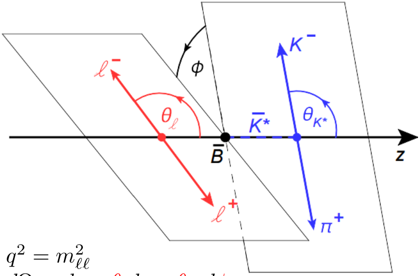
SM is (almost) purely left-handed

# $B^0 \to K^* \mu^+ \mu^-$ angular analysis




$q^2 = m^2_{\ell\ell}$
$d\Omega \equiv d\cos\theta_l d\cos\theta_K d\phi$

$$\frac{d\Gamma}{dq^2 d\Omega} = \frac{9}{32\pi} \sum_{i=1}^{17} J_i(q^2) f_i(\theta_l, \theta_K, \phi)$$

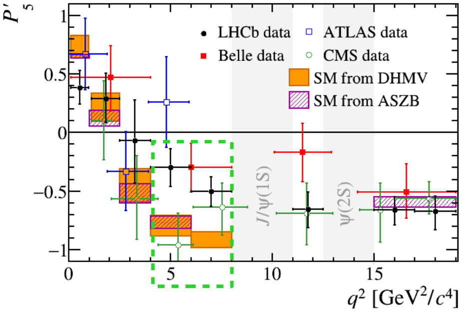
- $J_i$ are bilinears of the transversity amplitudes $A_0^{L,R}$, $A_\perp^{L,R}$, $A_\parallel^{L,R}$, $A_S^{L,R}$

- Both short- and long-distance parts enter the amplitudes:

$$A_\perp^{L(R)} \sim \left\{ [(C_9^{\text{eff}} + C_9'^{\text{eff}}) \mp (C_{10}^{\text{eff}} + C_{10}'^{\text{eff}})] \frac{V(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2}(C_7^{\text{eff}} + C_7'^{\text{eff}}) T_1(q^2) \right\}$$

- Reduced FF uncertainties at LO: $P_5' = \dfrac{J_5}{\sqrt{J_{1c}(1 - J_{1c})}}$, [1303.5794]

# STATUS OF $P_5'$ ANOMALY




Experiments:

LHCb: PRL111,191801(2013) (2011)
JHEP02(2016)104 (full Run1)
Belle: JHEP02(2016)104
ATLAS: ATLAS-CONF-2017-023 (2012)
CMS: CMS-PAS-BPH-15-008 (2012)

SM Theory (among *many*):

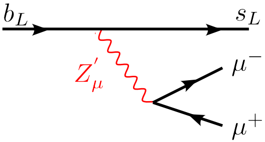
DHMV: 1407.8526
ASZB: 1411.3161, 1503.05534

(different treatment of the hadronic part)

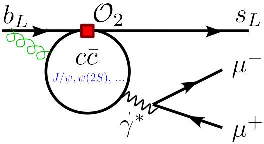
- 2.8 $\sigma$ and 3.0 $\sigma$ local deviations with DHMV in two $q^2$ bins. 3.4 $\sigma$ global discrepancy. Confirmation by Belle.

# NP or "brown muck" aka QCD?

- $\Delta C_{9\mu} = C_{9\mu}^{NP} < 0$ from a tree-level $Z'_\mu$ would explain the anomaly.
  [Altmannshofer'14, Crivellin'15,...]

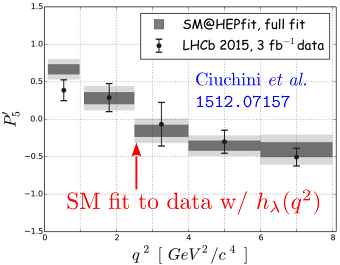



- Nasty issue for EWP: $\bar{c}c$ poles in the physical $q^2$ region (SL doesn't have this). Mimics $\Delta C_{9\mu}$.



# Non-factorisable power corrections

- SL and EWP $\mathcal{O}_{7,9,10}$ factorizes into $H_\mu L^\mu$. Allows FF formalism.
- Additional EWP 4-quark operators $\mathcal{O}_{1-6}$ factorizes only at $m_b \to \infty$ and $q^2 < 4m_c^2$ $c\bar{c}$ threshold.
- Perturbative corr: $C_9^{eff} = C_9 + Y_{\rm pert}(q^2)$, plus a long distance part.
- For each helicity amplitude $A_{\lambda\in\{0,\pm\}}$, additional power correction:
  $h_\lambda(q^2) = h_\lambda^{(0)} + q^2 h_\lambda^{(1)} + q^4 h_\lambda^{(2)}$
- $h_\lambda(q^2)$ can accommodate the data, but undesirably large ($> 100\%$) corrections.

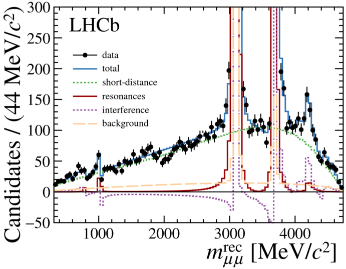


# $h_\lambda(q^2)$: DATA-DRIVEN APPROACHES AT LHCb - I

- Unbinned ML fits to data w/ external inputs as Gaussian constraints.
- $C_9^{NP}$ can't have $q^2$ dependence. $h_\lambda(q^2)$ same for $e/\mu$ cases.

1) [1709.03921] Assume $h_\lambda$ is a sum of relativistic Breit Wigners from $\{\rho^0, \phi, J/\psi, \psi(2S), \psi(3770), \psi(4040), \psi(4160)\}$ with floating strong phases. Entire $q^2$ range.

- Method shown to work for Run I $B^+ \to K^+\mu^+\mu^-$ [EPJC(2017)77:161]
- For $K^*$, complicated by exotics in $J/\psi\,\pi$ and $K\pi$ $S$-wave



# $h_\lambda(q^2)$: DATA-DRIVEN APPROACHES AT LHCb - II

2) [JHEP11(2017)176] Unbinned fit to $q^2 \in [0.1, 8]$ GeV$^2$.

- Power corrections: $A_\lambda \rightarrow A_\lambda \times (1 + a_\lambda + b_\lambda \frac{q^2}{6})$

3) [1707.07305] Use analyticity to control $h_\lambda(q^2)$ in $q^2 < m^2_{\psi(2S)}$.

- "$z$-expansion" with $J/\psi$ and $\psi(2S)$ poles removed:

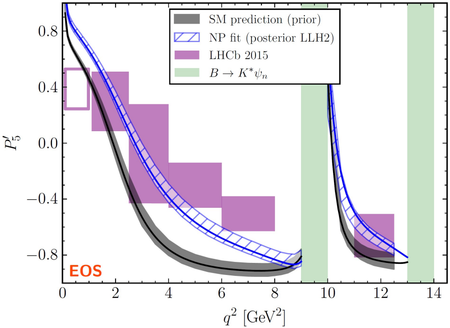
$$h_\lambda = \frac{1 - zz_{J/\psi}}{z - z_{J/\psi}} \frac{1 - zz_{\psi(2S)}}{z - z_{\psi(2S)}} \mathcal{F}(z) \left[ \sum_{i=0}^{N} a_i z^i \right]$$

- Extract $a_i$ from fit to data.

# $h_\lambda(q^2)$: DATA-DRIVEN APPROACHES AT LHCB - III

3) (cont.) Only theory connection is LCSR calculation in the unphysical $q^2 < 0$ region (Khodjamirian'10).

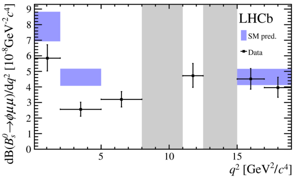
- Issues: $|z_{\rm max}| \sim 0.5$ is not truly small. Is the truncation error for expansion always under control?



# BF's systematically lower than SM

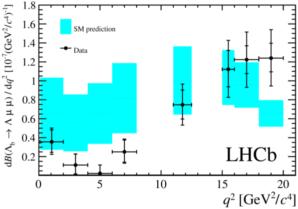
$B_s^0 \to \phi\mu^+\mu^-$

JHEP09(2015)179



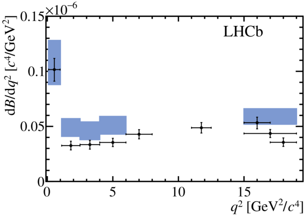

$\Lambda_b \to \Lambda\mu^+\mu^-$

JHEP06(2015)115

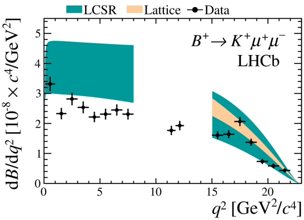


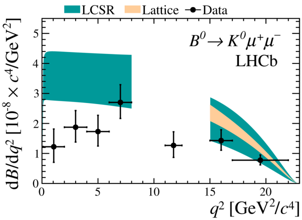

$B^0 \to K^*\mu^+\mu^-$

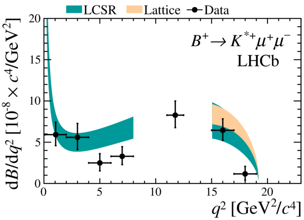
JHEP11(2016)047




- JHEP06(2014)133:

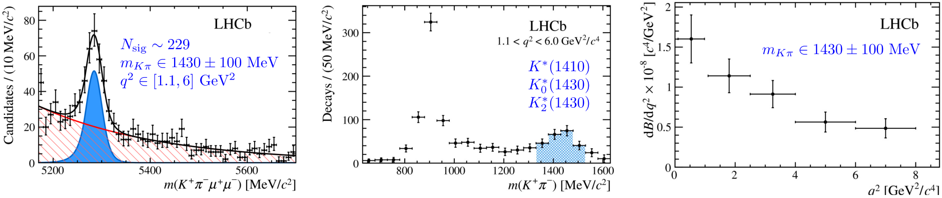


# Higher resonances for $b \to s\ell^+\ell^-$ JHEP12(2016)065

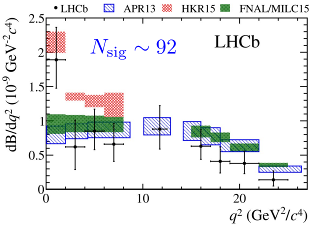
- Higher $K^*$ resonances region in $B^0 \to K^+\pi^-\mu^+\mu^-$ also probed.




- Angular analysis reveals a surprisingly suppressed $D$-wave $K_2^*(1430)$. At odds with other experiments in the $m_{K\pi} \sim 1430$ MeV region.
- $f_2(1525) \to K^+K^-$ tensor in $B_s \to K^+K^-\mu^+\mu^-$ being searched as well. The two modes can be connected by $SU(3)$.

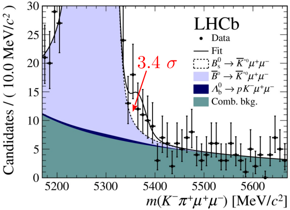
# RARE $b \to d$ FCNC TRANSITIONS

- For $b \to d$, two interfering amplitudes from $t/u$ quark in the loop.
- $V_{ub}V_{ud}^*$ and $V_{tb}V_{td}^*$ both are $\propto \lambda^3$ and have a relative phase.
- Excellent place to probe CKM structure of NP. SM is suppressed.



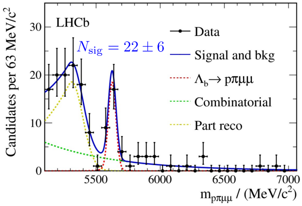

$B^+ \to \pi^+\mu^+\mu^-$

JHEP10(2015)034




$B_s^0 \to K^*\mu^+\mu^-$

1804.07167




$\Lambda_b \to p\pi^-\mu^+\mu^-$

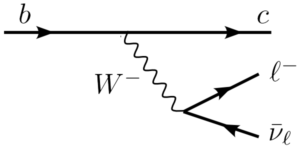
JHEP04(2017)029

# Lepton Flavor Universality (LFU) in SM

- Standard Model: three generations of leptons $\{e, \mu, \tau\}$ couple universally to the electroweak bosons. Only difference is in their mass.

## Semi-tauonic:

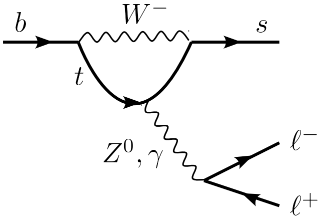
$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(B \to D^{(*)}\mu^-\bar{\nu}_\mu)}$$




- Tree-level and $R(D^{(*)}) < 1$ with large $\tau$-$\mu$ mass difference

## Electroweak penguins:

$$R(K^{(*)}) = \frac{\mathcal{B}(B \to K^{(*)}\mu^-\mu^+)}{\mathcal{B}(B \to K^{(*)}e^-e^+)}$$

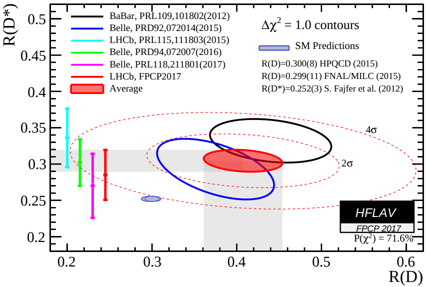



- Loop-level and $R(K^{(*)}) \sim 1$ upto small $e$-$\mu$ mass difference

# LFU Run I measurements

## Semi-tauonic:

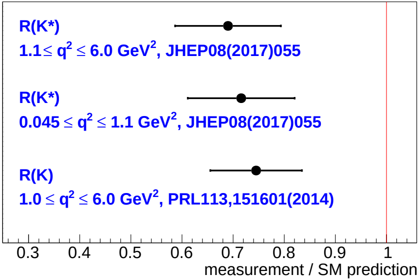
- Global $\sim 4.1\ \sigma$ tension w/ SM




- New $R(J/\psi)$ in $B_c^+ \to J/\psi \ell^- \overline{\nu}_\ell$ (PRL120,121801(2018)) within $2\ \sigma$ of SM

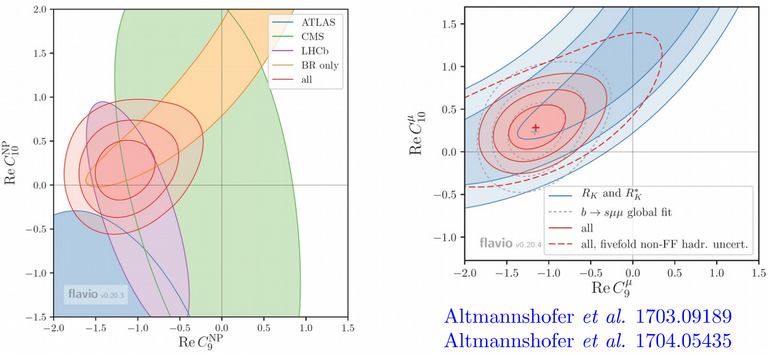
## Electroweak penguins:

- $2.1 - 2.6\ \sigma$ tension w/ SM



# $b \to s\ell^+\ell^-$ STATUS

- Many different global fits incorporating different $b \to s\ell^+\ell^-$, $b \to s\gamma$ measurements.

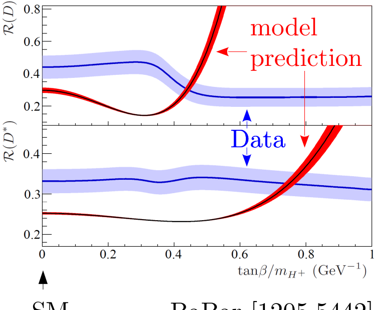



Altmannshofer *et al.* 1703.09189
Altmannshofer *et al.* 1704.05435

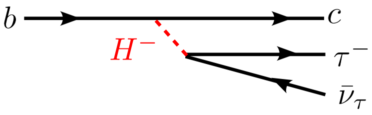
- Remarkable consistency:BF, angular, $R(K^{(*)})$ all point to $\Delta C_9^{\mu} \sim -1$.

# $b \to c\tau^-\bar{\nu}_\tau$ STATUS

- The most obvious one (charged Higgs), consistently disfavored



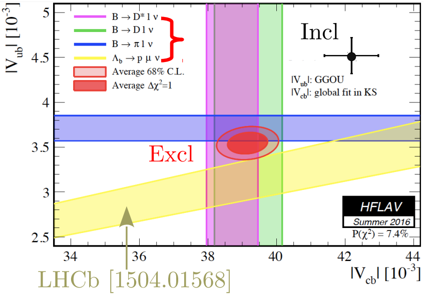

BaBar [1205.5442]




- Vector-like $\epsilon_{V_L} \sim 0.13$ (Grinstein) more viable.
- Could be good news since this should also affect $e/\mu$ modes where things are measurable

- Caveats: $\tau$'s are hard, $D^{**}$ backgrounds, ...

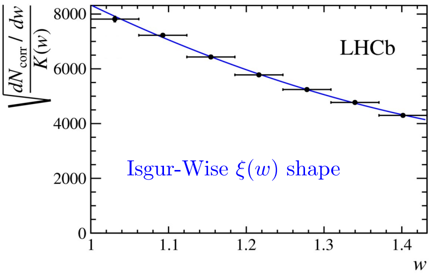
# $|V_{ub}|$-$|V_{cb}|$ tensions and FF's for $R(D^*)$

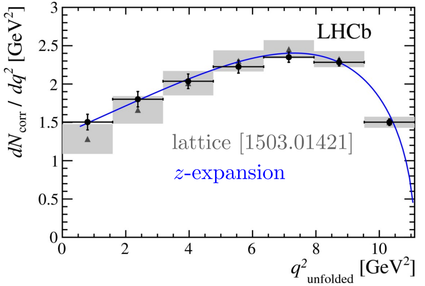



- Long known tension in the CKM parameters $|V_{ub}|$ and $|V_{cb}|$: inclusive and exclusive methods don't agree. $\sim 3\sigma$ discrepancy.
- Same FF's for $|V_{cb}|$ extraction from $\overline{B} \to D^* \ell^- \overline{\nu}_\ell$ enter $R(D^*)$

- FF parameterization (CLN) too constrained. Error budget underestimated (factor of $\sim 3$).
- Belle/BaBar data being re-analyzed with model-independent (BGL) FF [1702.01521, 1703.06124, 1703.08170, 1707.09509 ]

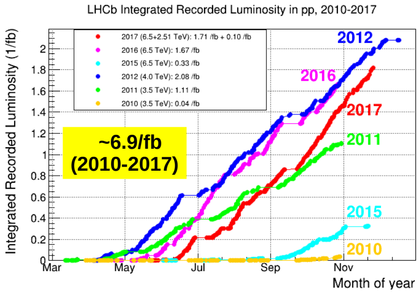
# FF shape in $\Lambda_b \to \Lambda_c^+ \mu^- \bar{\nu}$ PRD96,112005(2017)

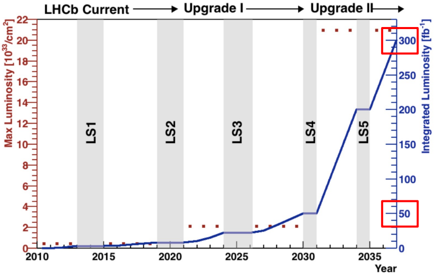



- FF shape for a baryonic $b \to c$ transition for the first time.
- Reasonable agreement with unquenched lattice.
- Full angular analysis not possible for SL decays. Resolution not good enough due to missing $\nu$.

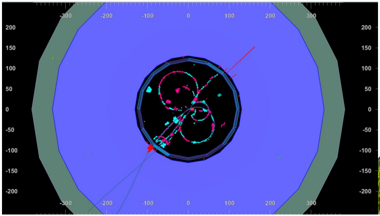
# The path ahead for LHCb...




- Aim to collect $> 2$/fb in 2018. Data-taking started.
- Many more $R(X)$, asymmetry measurements. TD-CPV in $B_s \to \phi\mu^+\mu^-$, $B^0 \to K_S^0\rho^0\gamma$, ...
- Major upgrade in LS2. Consolidation in LS3.
- 50/fb by 2030. Phase II upgrade for HL-LHC, aiming for 300/fb.

# Our friendly competitors at SuperKEKB




- First $e^+e^-$ collisions in Belle II on 26th April, 2018, after 7 years of preparation!
- $\sim 1.1$/ab of $B\bar{B}$ at Belle+*BABAR*. Aim for 50/ab at Belle II by 2024

- Different background, systematics. Entangled $B\bar{B}$ pairs, excellent flavor tagging, neutrino program, ...
- While, LHCb has large boost, access to all $b$-hadron species.

*Excellent overlap + complementarity between LHCb and Belle II*

# Outlook

**The Case for Future Hadron Colliders From $B \to K^{(*)}\mu^+\mu^-$ Decays**

**B.C. Allanach,**[a] **Ben Gripaios,**[b] **Tevong You**[1a,b]

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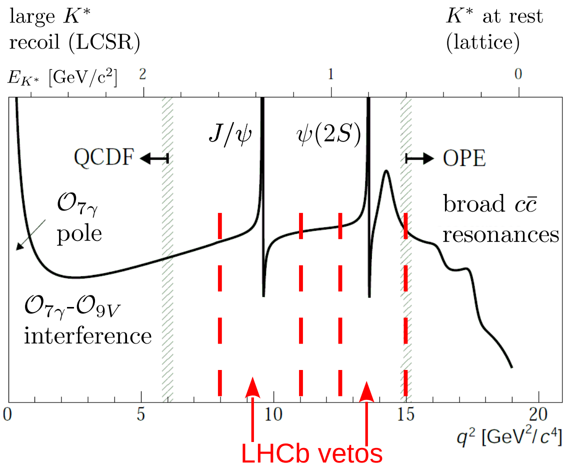
[b] *Cavendish Laboratory, University of Cambridge, J.J. Thomson Avenue, Cambridge, CB3 0HE, United Kingdom*

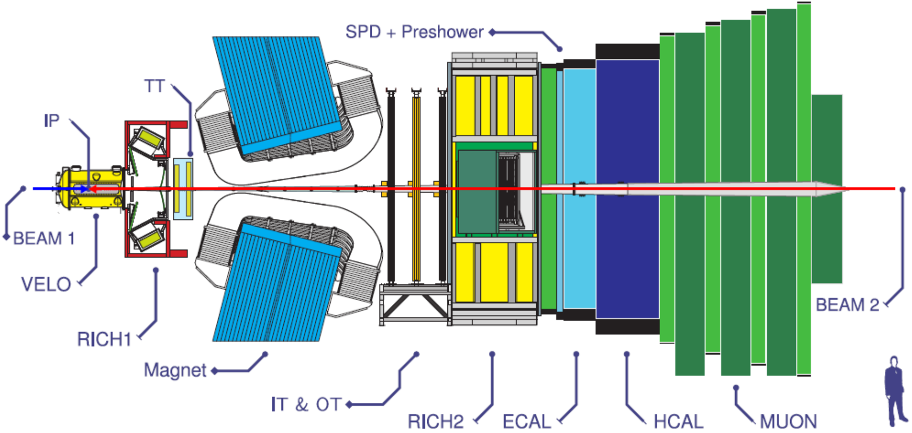
- *If* these flavor anomalies survive LHCb Run III and Belle II, strong motivation for a 100 TeV FCC-hh.

Backup slides

# $q^2$ DEPENDENCE



# The LHCb Detector components



# Phase II upgrade reach