Highlights and prospects on flavour physics at LHCb

Elena Graverini

École Polytechnique Fédérale Lausanne

Seminar at PSI, February 23, 2023

Swiss National Science Foundation

EPFL

LHCb

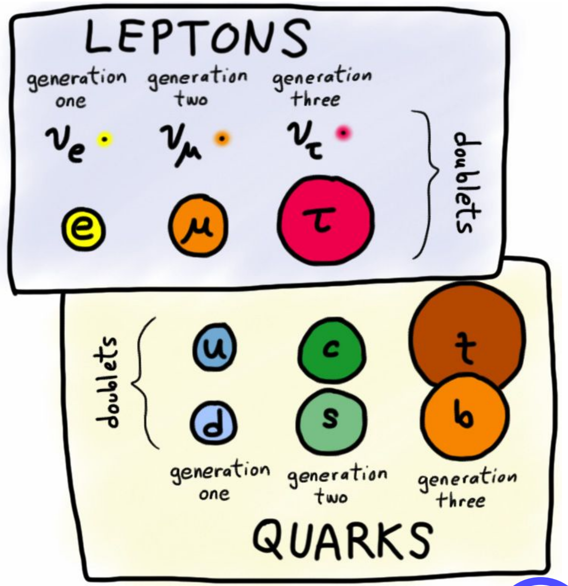
Outline of this seminar

- what is flavour physics?
- LHCb: why / what is that?
- selected measurements
  - charged current decays: $R\left(D^{(*)}\right)$
    - as a pretext to show how the LHCb detector works
  - physics with rare decays: the $b \to s\ell\ell$ example
- looking forward: the challenges ahead and the LHCb upgrade(s)

Meet Flavour Physics

Standard Model

- Successful recipe:
  - particle content of the universe
  - weak, strong & EM force:
    "gauge" bosons γ, $W^{\pm}$, Z^{0}, g
  - Higgs boson $\rightarrow$ masses
  - validated by countless experiments

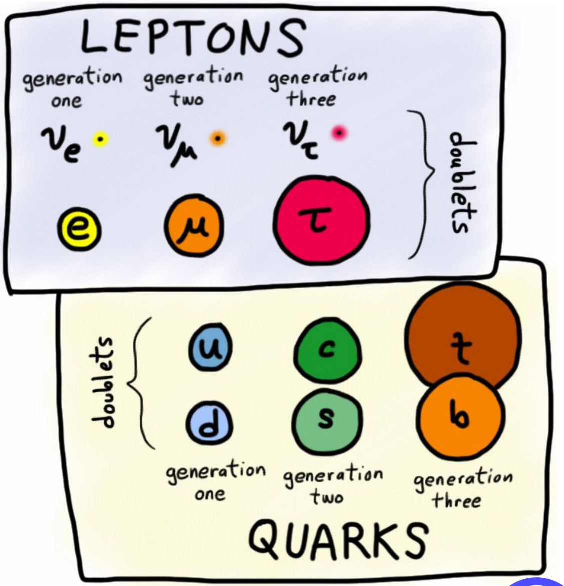


Standard Model

- Successful recipe:
  - particle content of the universe
  - weak, strong & EM force: “gauge” bosons γ, $W^{\pm}$, Z^0, g
  - Higgs boson $\rightarrow$ masses
  - validated by countless experiments

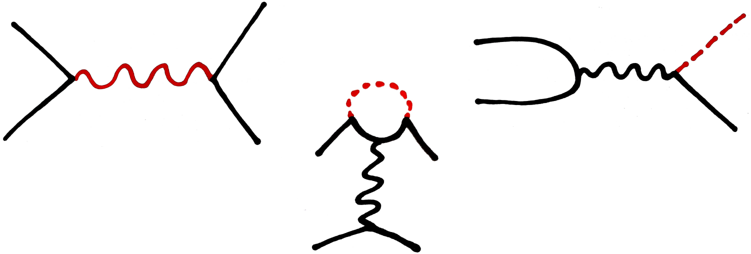
- **Problems!**
  - dark matter
  - neutrinos shouldn’t have mass
  - where did antimatter go?

“**New Physics**” out there?



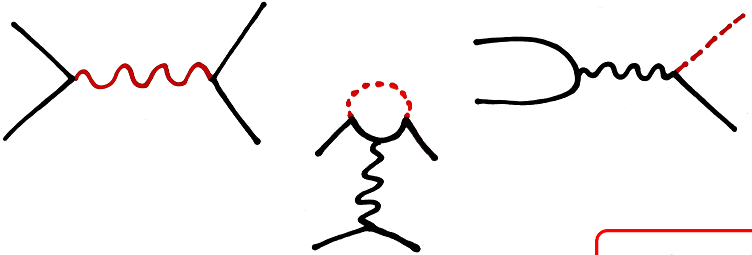
Where is New Physics?

- Too massive to be produced ⇒ larger collider
- Too weak to be detected ⇒ high intensity beam
- Can cause tensions between theory and observations ⇒ **flavour** physics



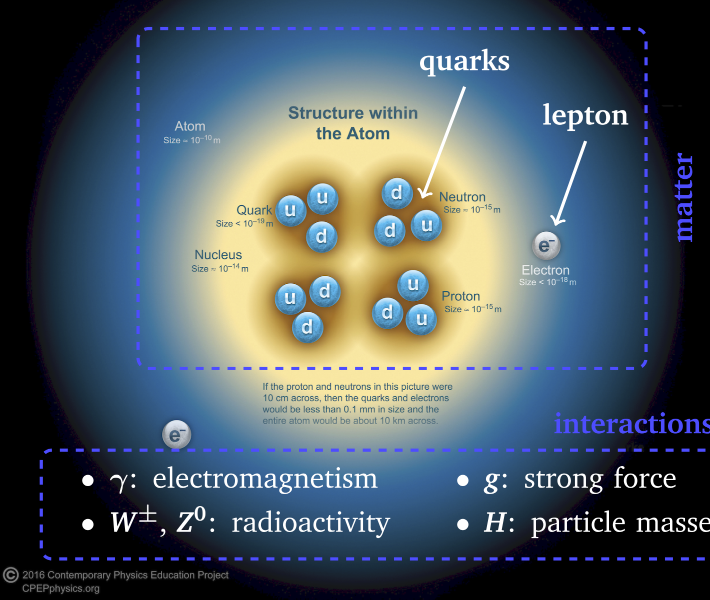
Where is New Physics?

- Too massive to be produced ⇒ larger collider
- Too weak to be detected ⇒ high intensity beam
- Can cause tensions between theory and observations ⇒ **flavour** physics



...what is **flavour**?

Fundamental particles of the Standard Model

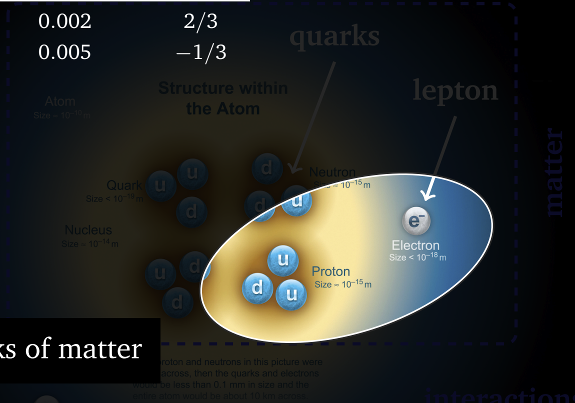


interactions

- γ: electromagnetism
- $W^{\pm}, Z^0$: radioactivity
- g: strong force
- H: particle masses

Fundamental particles of the Standard Model

Leptons			Quarks		
flavour	mass (GeV/c^2)	charge	flavour	mass (GeV/c^2)	charge
ν_e	$\lesssim 10^{-9}$	0	u	0.002	$2/3$
e	0.000511	-1	d	0.005	$-1/3$

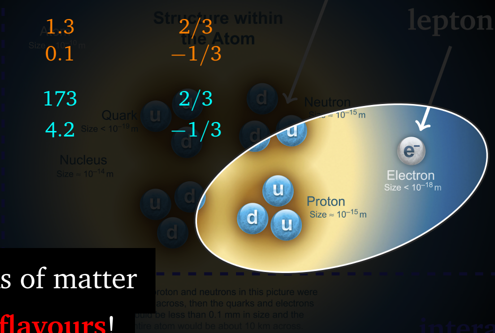


e, ν_e, u, d: fundamental building blocks of matter

interactions

- γ: electromagnetism
- g: strong force
- $W^\pm$, Z^0: radioactivity
- H: particle masses

Leptons			Quarks		
flavour	mass (GeV/c^2)	charge	flavour	mass (GeV/c^2)	charge
ν_e	$\lesssim 10^{-9}$	0	u	0.002	2/3
e	0.000511	−1	d	0.005	−1/3
ν_μ	$\lesssim 10^{-9}$	0	c	1.3	2/3
μ	0.106	−1	s	0.1	−1/3
ν_τ	$\lesssim 10^{-9}$	0	t	173	2/3
τ	1.777	−1	b	4.2	−1/3



e, ν_e, u, d: fundamental building blocks of matter

...coming in three “identical” copies: flavours!

Leptons			Quarks		
flavour	mass (GeV/c^2)	charge	flavour	mass (GeV/c^2)	charge
ν_e	$\lesssim 10^{-9}$	0	u	0.002	$2/3$
e	0.000511	-1	d	0.005	$-1/3$
ν_μ	$\lesssim 10^{-9}$	0	c	1.3	$2/3$
μ	0.106	-1	s	0.1	$-1/3$
ν_τ	$\lesssim 10^{-9}$	0	t	173	$2/3$
τ	1.777	-1	b	4.2	$-1/3$

Why are there three flavours?

Why are the masses so different?

Leptons			Quarks		
flavour	mass (GeV/c^2)	charge	flavour	mass (GeV/c^2)	charge
ν_e	$\lesssim 10^{-9}$	0	u	0.002	2/3
e	0.000511	−1	d	0.005	−1/3
ν_μ	$\lesssim 10^{-9}$	0	c	1.3	2/3
μ	0.106	−1	s	0.1	−1/3
ν_τ	$\lesssim 10^{-9}$	0	t	173	2/3
τ	1.777	−1	b	4.2	−1/3

Why are there three flavours?

Why are the masses so different?

...is there a more fundamental theory?

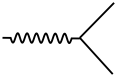
Flavour physics

Flavour physics is the study of different generations of fermions.

Flavour physics

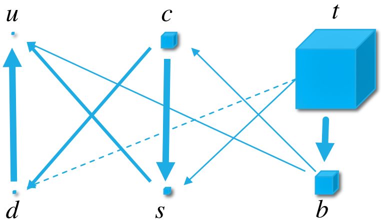
Flavour physics is the study of different generations of fermions.

- Experimentally, we observe a strong **hierarchy**:



$$= \frac{g}{\sqrt{2}} \left(\bar{u}_L^i \boldsymbol{V}_{\text{CKM}}\, \gamma^\mu d_L \right) W_\mu^\dagger$$

$$\boldsymbol{V}_{\text{CKM}} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ \lambda^3 & -\lambda^2 & 1 \end{pmatrix}$$

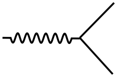


- $\boldsymbol{V}_{\text{CKM}}$ nearly diagonal, $V_{13} \sim V_{12} V_{23}$

Flavour physics

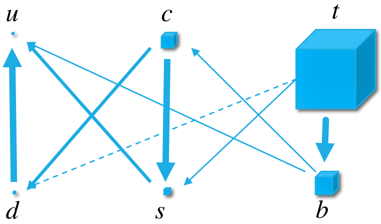
Flavour physics is the study of different generations of fermions.

- Experimentally, we observe a strong **hierarchy**:



$$= \frac{g}{\sqrt{2}} \left(\bar{u}_L^i \boldsymbol{V}_{\mathbf{CKM}} \gamma^\mu d_L \right) W_\mu^\dagger$$

$$\boldsymbol{V}_{\mathbf{CKM}} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ \lambda^3 & -\lambda^2 & 1 \end{pmatrix}$$

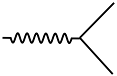


- $\boldsymbol{V}_{\mathbf{CKM}}$ nearly diagonal, $V_{13} \sim V_{12}V_{23}$ (*for no good reason*)

Flavour physics

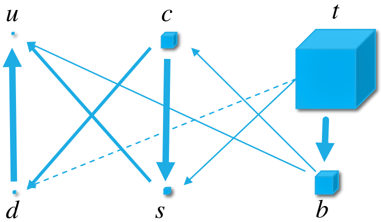
Flavour physics is the study of different generations of fermions.

- Experimentally, we observe a strong **hierarchy**:



$$= \frac{g}{\sqrt{2}} \left(\bar{u}_L^i \mathbf{V}_{\mathbf{CKM}} \gamma^\mu d_L \right) W_\mu^\dagger$$

$$\mathbf{V}_{\mathbf{CKM}} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ \lambda^3 & -\lambda^2 & 1 \end{pmatrix}$$

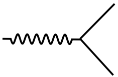


- $\mathbf{V}_{\mathbf{CKM}}$ nearly diagonal, $V_{13} \sim V_{12}V_{23}$ (*for no good reason*)
- transitions between different generations suppressed
- 3rd generation very isolated $\Longrightarrow$ tree-level b decays suppressed, long b lifetime

Flavour physics

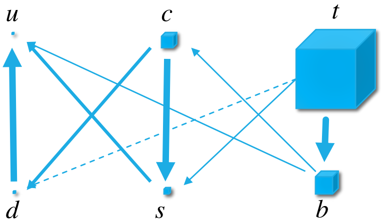
Flavour physics is the study of different generations of fermions.

- Experimentally, we observe a strong **hierarchy**:



$$= \frac{g}{\sqrt{2}} \left(\bar{u}_L^i \boldsymbol{V_{\mathrm{CKM}}} \gamma^\mu d_L \right) W_\mu^\dagger$$

$$\boldsymbol{V_{\mathrm{CKM}}} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ \lambda^3 & -\lambda^2 & 1 \end{pmatrix}$$

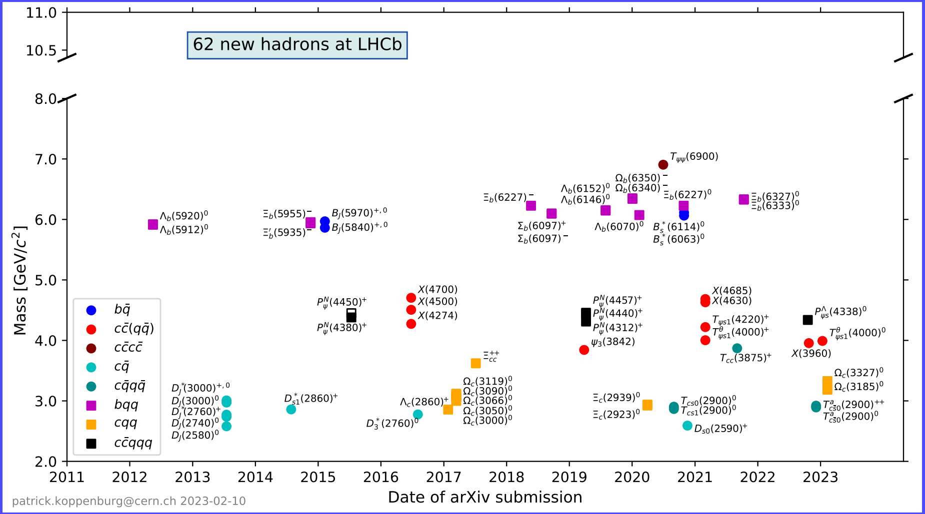


- $\boldsymbol{V_{\mathrm{CKM}}}$ nearly diagonal, $V_{13} \sim V_{12}V_{23}$ (*for no good reason*)
- transitions between different generations suppressed
- 3rd generation very isolated $\Longrightarrow$ tree-level b decays suppressed, long b lifetime
- probe high-mass virtual particles in loop-level decays

Flavour physics: areas of application

- **Spectroscopy:** better understand QCD in the low-E regime
  - tetraquarks, pentaquarks [hep-ex/2301.04899][hep-ex/2210.10346]
  - excited states, cc baryons [hep-ex/2302.04733][JHEP 05 (2022) 038]
- **CKM physics:** measure CP violating phases, unitarity triangle
  - first observation of $\not{CP}$ in charm [PRL 122 (2019) 211803]
  - overconstrain unitarity triangle [hflav.web.cern.ch]
- **Flavour-changing neutral currents:** great benchmarks for the SM
  - search for New Physics in SM-suppressed amplitudes
  - $B_s \to \mu\mu$, $B^0 \to \mu\mu$, $b \to s\ell\ell$ [Nature 522 (2015) 68][PRL 128 (2022) 041801][hep-ex/2212.09152]
  - search for LFV decays $\tau \to 3\mu$, $b \to e\mu$, ... [hep-ex/2207.04005][hep-ex/2209.09846]
- **Charged-current semileptonic decays:** "β decays" of B hadrons
  - strong and weak part factorize $\Rightarrow$ clean SM predictions
  - decays to e, μ well studied at B factories; room for NP in decays to τ
  - measure CKM parameters
  - $b \to c\ell\nu$ measurements sparking interest [see hflav.web.cern.ch]

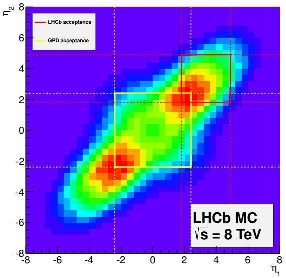
(Example: spectroscopy & exotic hadrons)

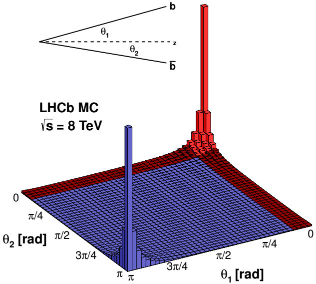


courtesy P. Koppenburg (nikhef.nl/~pkoppenb)

70 new hadrons observed at the LHC since 2012... **62 at LHCb!**

b physics at the LHC



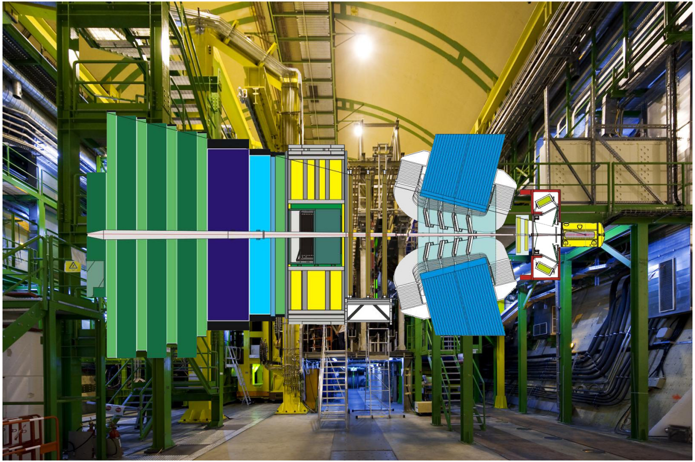


- large amount of b hadrons, produced with highly boosted CM frame
- central detector: **98%** solid angle coverage ⇒ **52%** acceptance
- forward detector: **3%** solid angle coverage ⇒ **27%** acceptance

The LHCb experiment

- forward-arm spectrometer dedicated to the study of heavy-flavoured hadrons
- tag B based on lifetime + distinguish decays $\Longrightarrow$ decay time resolution + PID

The LHCb detector in Run I+II



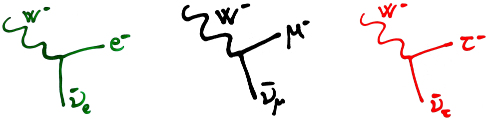
- 96% efficient tracking; 20μm and 45 fs IP and decay time resolution; $\delta p/p < 1\%$
- RICH 1, 2 + ECAL + muon chambers for PID (efficiency $> 90\%$)

Selected measurements

Lepton flavour in the Standard Model

Lepton generations differ **only in mass**.

- SM implies universality of lepton flavour (LFU): amplitude of processes with e, μ, τ identical (except phase space)
  - *e.g.* the decay $W \to \ell\nu$:



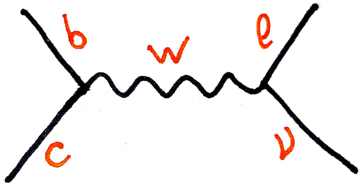
  - LFU well established in the decay of light mesons, *e.g.* $\pi \to \ell\nu$, $K \to \pi\ell\ell$, $J/\psi \to \ell\ell$
- Lepton Flavour Number is conserved (for massless ν): no $\ell_1 \leftrightarrow \ell_2$
  - stringent limits on LFV decays:

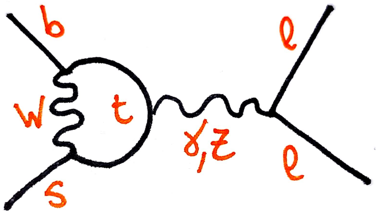
$\mu \to e\gamma$ ✘ ($\mathcal{B} \lesssim 10^{-13}$) [Eur.Phys.J.C76(2016)8,434]

$K \to \pi e\mu$ ✘ ($\mathcal{B} \lesssim 10^{-11}$) [Phys.Rev.D72(2005)012005]

- ~~**LFU**~~ or ~~**LFN**~~ $\longrightarrow$ unknown physics not accounted for
  - some SM extensions include particles that can cause ~~**LFU**~~ and/or ~~**LFN**~~ (*e.g.* LQ, Z')

Lepton flavour in b decays



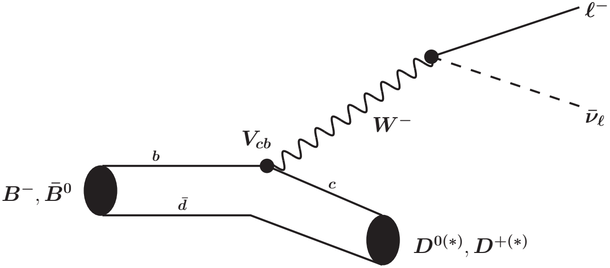


- **Charged current decays (CC):** "β decays" of B hadrons.
  - tree level, large $\mathcal{B} \sim$ few %
  - strong and weak part factorize $\Rightarrow$ clean SM predictions
- **Neutral current decays (NC):** great benchmarks for the SM
  - FCNC can only occur in loops: $\mathcal{B} \sim 10^{-7} \div 10^{-6}$
  - new particles can enhance SM-suppressed amplitudes

Example n° 1: charged-current decays

Lepton Universality in $b \to c\ell\nu$: R_{X_c}

Compare the $\mathcal{B}$ of $b \to c\tau\nu$ and $b \to c\mu\nu$ decays



- hadronic form factors constrained from measurements
- hadronic and experimental uncertainties cancel in ratios of $\mathcal{B}$'s
- in the Standard Model:

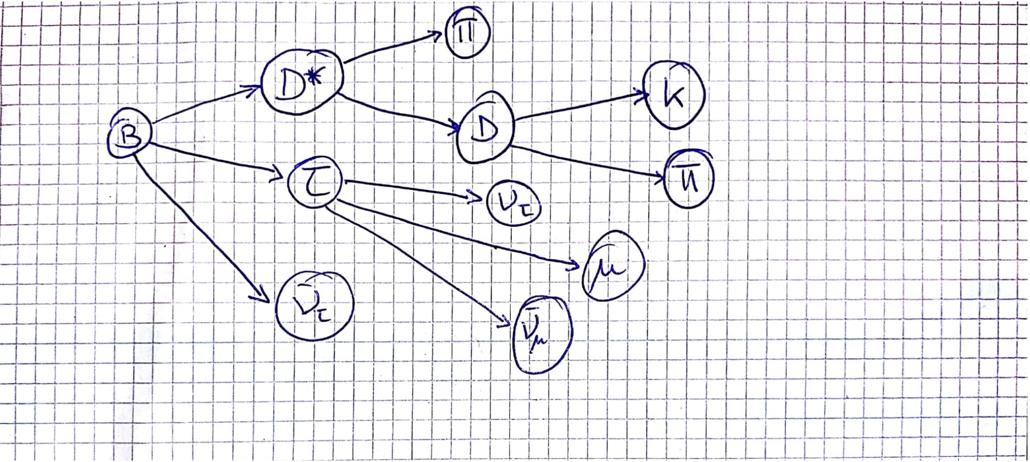
$$R_{D^*} \equiv \mathcal{B}(B \to D^*\tau\nu)/\mathcal{B}(B \to D^*\mu\nu) = 0.254 \pm 0.005$$

$$R_D \equiv \mathcal{B}(B \to D\tau\nu)/\mathcal{B}(B \to D\mu\nu) = 0.298 \pm 0.004$$

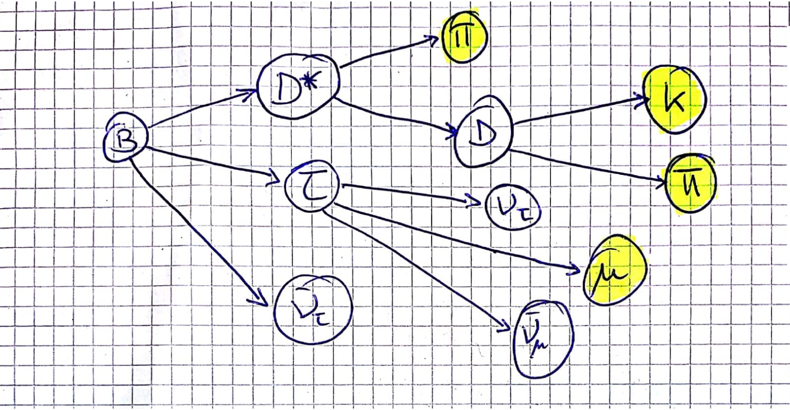
[hflav averages]

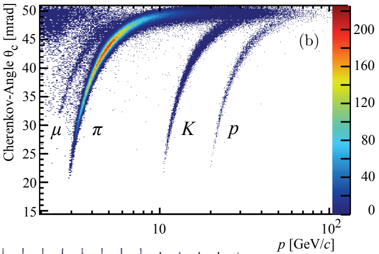
differ from unity only because $m_\tau \gg m_{e,\mu}$.

Detecting $B \to D^* \ell \nu$ at LHCb



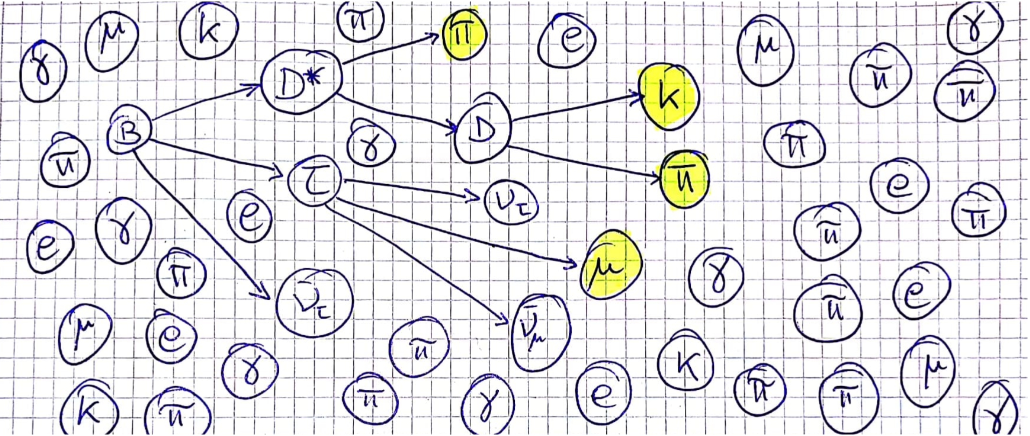
Detecting $B \to D^* \ell \nu$ at LHCb





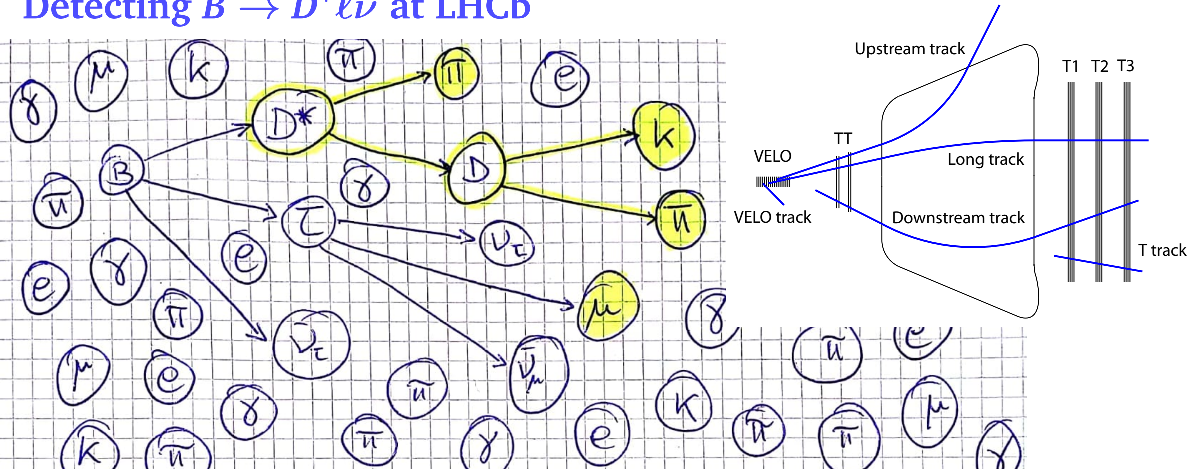
- π / K / p identification: RICH1 + RICH2 ($1 < p < 100$ GeV)
- μ identification: 5 muon chambers (triple GEM + MWPCs)
- e / γ / π^0: SPD (neutral *vs.* charged) + PS (position) + ECAL (E)

Detecting $B \to D^{*}\ell\nu$ at LHCb



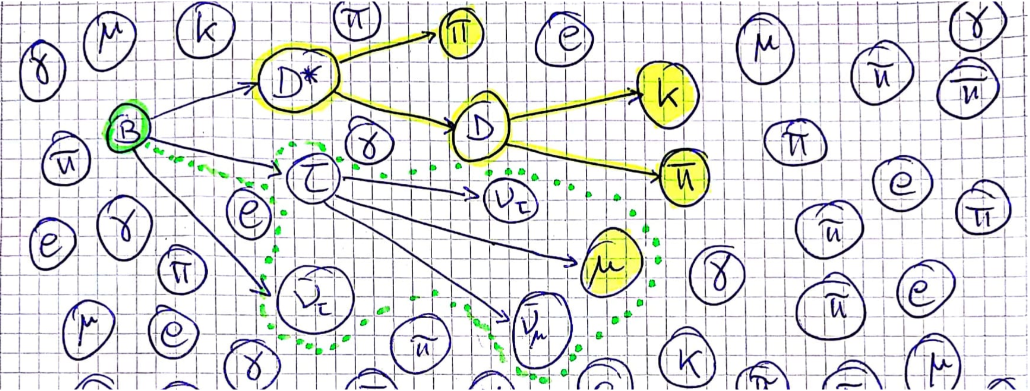
- Challenge: isolate signal from background

Detecting $B \to D^*\ell\nu$ at LHCb



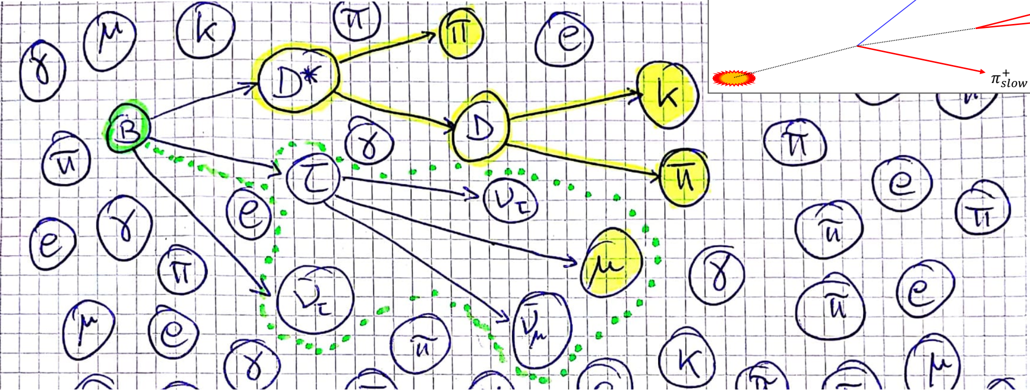
- Associate tracks and (partially) reconstruct candidates
- Use ML to isolate interesting tracks from the rest
- Use MC simulation and data-driven templates to study BG sources

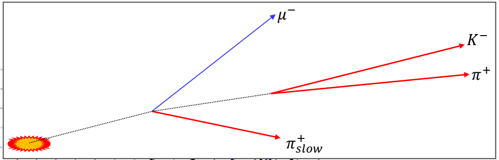
Detecting $B \to D^* \ell \nu$ at LHCb



- Challenge: missing momentum (1-3 neutrinos)
- D^* decays in place: B decay vertex known

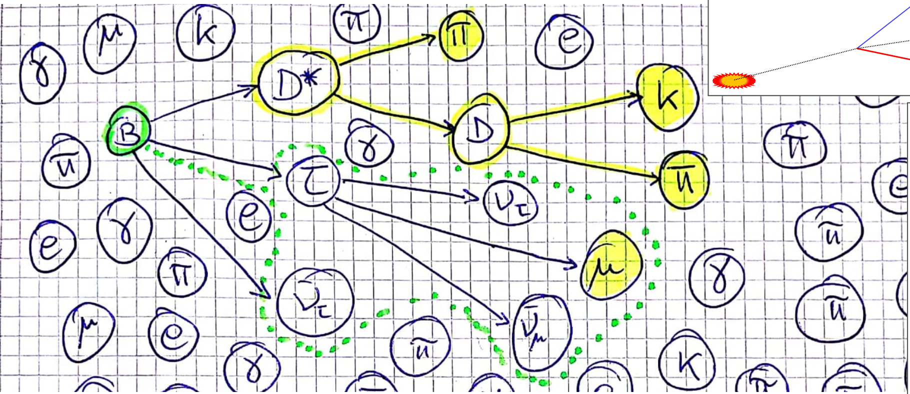
Detecting $B \to D^{*}\ell\nu$ at LHCb

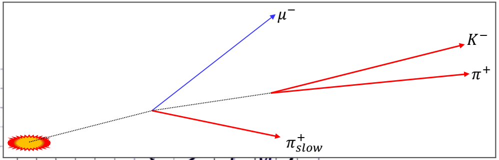


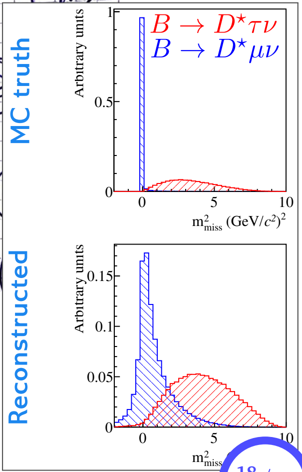


- Challenge: missing momentum (1-3 neutrinos)
- D^{*} decays in place: B decay vertex known
- Associate μ not pointing to the primary vertex

Detecting $B \to D^* \ell \nu$ at LHCb

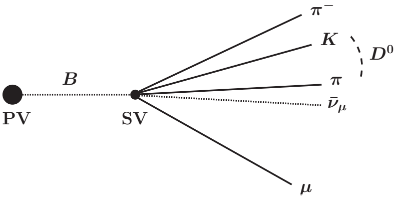


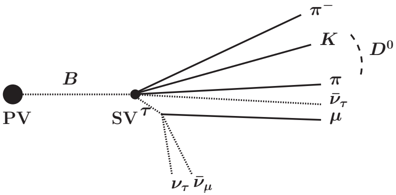




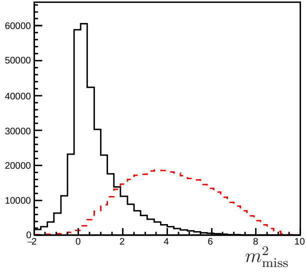
- Challenge: missing momentum (1-3 neutrinos)
- D^* decays in place: B decay vertex known
- Associate μ not pointing to the primary vertex
- Use approximations and the B flight direction to reconstruct p_B^μ

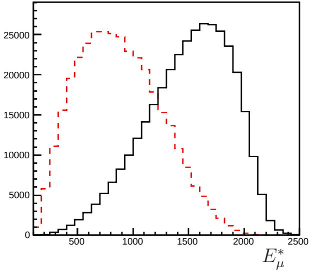
τ/μ separation

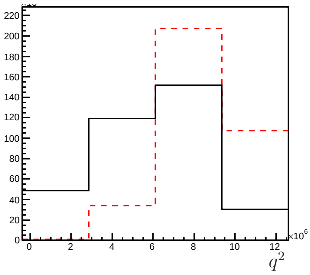




- with $\tau \to \mu\nu\nu$: 1–3 neutrinos in the final state
- separate μ from τ based on kinematics

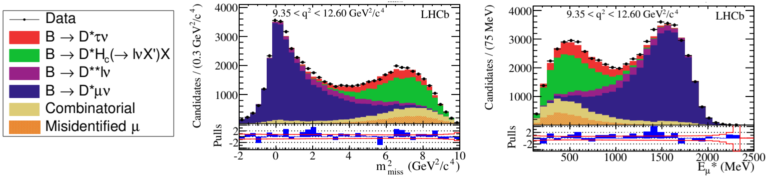


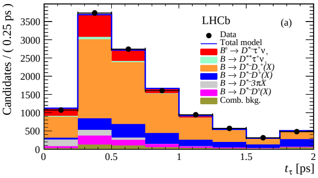




R_{D^*} results (2015–2018)

- with $\tau \to \mu\nu\nu$:
  - same visible final state as μ, with 1–3 neutrinos
  - 3D fit to kinematic variables to separate μ from τ
  - muonic $R_{D^*} = 0.336 \pm 0.027 \pm 0.030$, 2.1σ above the SM [3 fb^{-1}, PRL115(2015)111803]
- with $\tau \to \pi\pi\pi(\pi^0)\nu$:
  - normalize to $B \to D^*\pi\pi\pi$ and use known $\mathcal{B}(B \to D^*\pi\pi\pi)/\mathcal{B}(B \to D^*\mu\nu)$ to calculate R_{D^*}
  - background from prompt decays $\Longrightarrow$ use τ vertex displacement
  - hadronic R_{D^*} 1.1σ above the SM [PRL120(2018)171802]

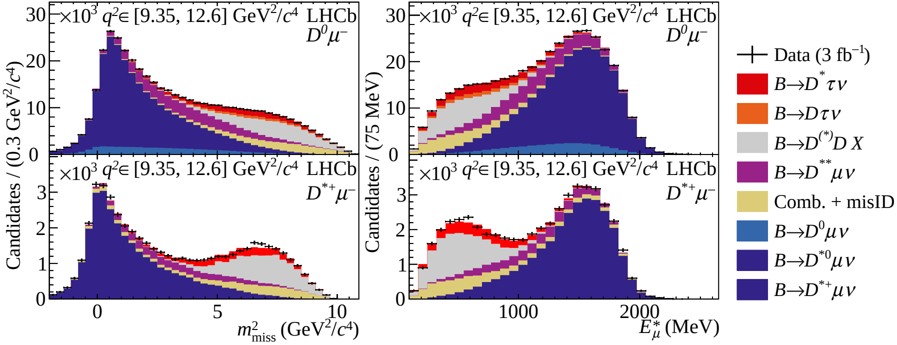




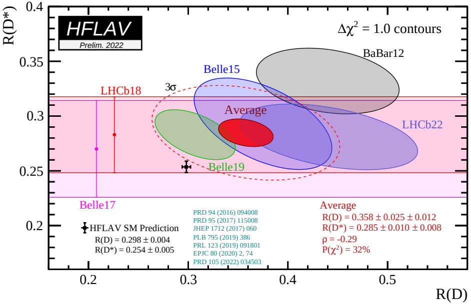
$R_{D^{(*)}}$ results (2022!)

[LHC seminar] [hep-ex/2302.02886]

- simultaneous measurement of R_D and R_{D^*} using $D^0\mu^-$ and $D^{*+}\mu^-$ final states
  - 2 disjoint signal samples + 6 control regions based on inverted isolation cut
  - trigger and selection redeveloped to boost acceptance for soft muons
- $R_{D^*} = 0.281 \pm 0.018 \pm 0.024$, $R_D = 0.441 \pm 0.060 \pm 0.066$ with $\rho = -0.43$
  - compatible with SM at 1.9σ, very small change in world average



$R_{D^{(*)}}$ combination

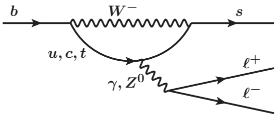


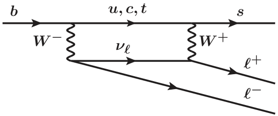
- combination of results from BaBar, Belle, LHCb
- R_D/R_{D^*} world average compatible with SM at **3.2σ** [hflav.web.cern.ch]
  - theory uncertainty related to $B \to D^{(*)}$ form factors
- LHCb: $R_{J/\psi}$ with B_c decays, $\sim 2\sigma$ above prediction [PRL120(2018)12,121801]
  - $R_{J/\psi}$ with B_c decays, $\sim 2\sigma$ above prediction [PRL120(2018)12,121801]
  - LFU test with **baryons** $R(\Lambda_c)$ compatible with SM [PRL 128 191803]

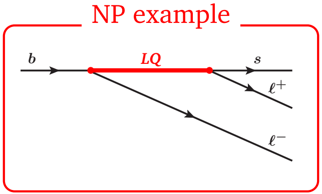
Example n° 2: neutral-current decays

Electroweak penguins

- Flavour Changing Neutral Current are powerful probes of NP
- LHCb can probe branching fractions 10^{-6} down to 10^{-10}
- forbidden at tree level in SM $\Longrightarrow$ NP contribution can be sizeable

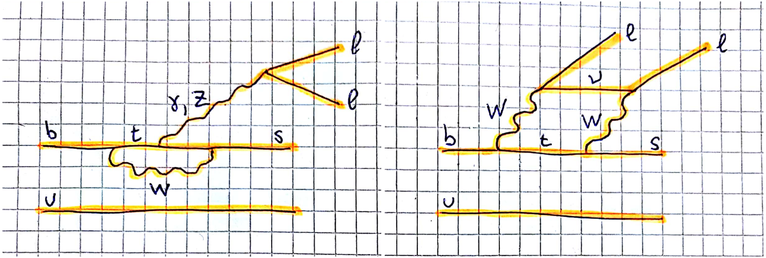






- $b \to s\ell^+\ell^-$ measurements present several tensions
  - pointing to either new mediators, or poorly known hadronic interaction
- sparked lively interest across both experimental and theory communities

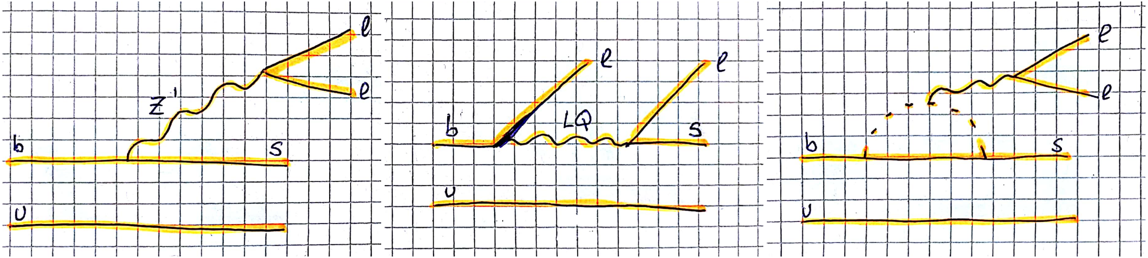
$b \to s\ell\ell$ as a test for the SM



- deviations from expectation can have various origins
- how to parametrize all possibilities?
- model-independent approach:

$$\mathcal{L} \propto \sum_i \mathcal{C}_i \mathcal{O}_i, \qquad \mathcal{C}_i \equiv \mathcal{C}_i^{SM} + \mathcal{C}_i^{NP}$$ "Wilson coefficients"

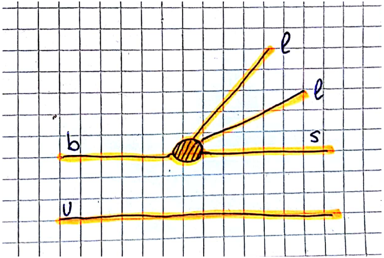
$b \to s\ell\ell$ as a test for the SM



- deviations from expectation can have various origins
- how to parametrize all possibilities?
- model-independent approach:

$$\mathcal{L} \propto \sum_i \mathcal{C}_i \mathcal{O}_i, \qquad \mathcal{C}_i \equiv \mathcal{C}_i^{SM} + \mathcal{C}_i^{NP} \qquad \text{“Wilson coefficients”}$$

$b \to s\ell\ell$ as a test for the SM



- deviations from expectation can have various origins
- how to parametrize all possibilities?
- model-independent approach:

$$\mathcal{L} \propto \sum_i \mathcal{C}_i \mathcal{O}_i, \qquad \mathcal{C}_i \equiv \mathcal{C}_i^{SM} + \mathcal{C}_i^{NP} \quad \text{“Wilson coefficients”}$$

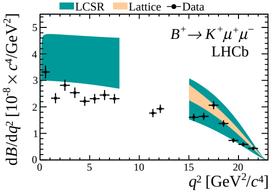
$b \to s\ell\ell$ measurements

Over the past decade, *tensions* with respect to the SM predictions accumulated in various observables:

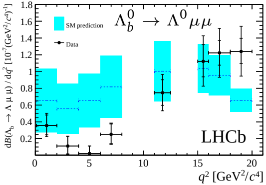
1. **Branching Fractions**
   $B \to K^{(*)}\mu^+\mu^-$, $B_s \to \phi\mu^+\mu^-$, $\Lambda_b \to \Lambda\mu^+\mu^-$
   suffer from uncertainties related to the hadronic matrix element
2. **Angular observables**
   $B \to K^{(*)}\mu^+\mu^-$, $\Lambda_b \to \Lambda\mu^+\mu^-$
   profit from cancellation of most form factors
3. **Ratios of branching fractions involving μ/e**
   $B^0 \to K^{*0}\ell^+\ell^-$, $B^+ \to K^+\ell^+\ell^-$
   all theoretical uncertaities cancel

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

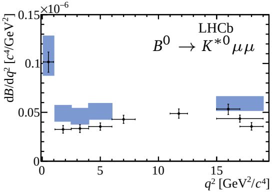
- differential branching fraction excluding $c\bar{c}$ resonances
- deficit with respect to theory predictions found in $B^{0,+} \to K^{0,+}\mu^+\mu^-$, $B^{0,+} \to K^{*0,+}\mu^+\mu^-$, $\Lambda_b^0 \to \Lambda^0\mu^+\mu^-$, $B_s^0 \to \phi\mu^+\mu^-$
- latest study of $B_s^0 \to \phi\mu^+\mu^-$ in agreement with Run 1, and 3.6σ tension with the SM



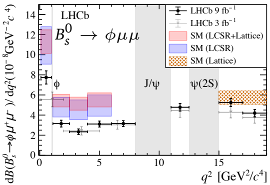
[JHEP 06 (2014) 133]



[JHEP 06 (2015) 115]



[JHEP 04 (2017) 142]

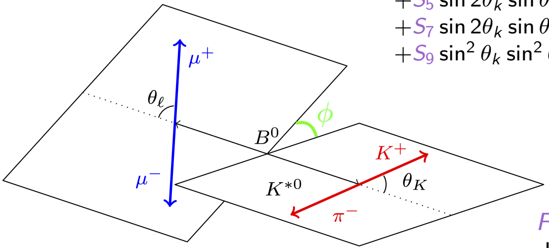


[PRL127 (2021) 151801]

Angular observables

- $P \to VV$ decay depends on q^2 and three decay angles
- angular analysis allow to probe the observables F_L, A_{FB}, S_i
- observables are sensitive to the Wilson coeffs.

$$\frac{1}{d(\Gamma+\bar{\Gamma})/dq^2}\frac{d^4(\Gamma+\bar{\Gamma})}{d\vec{\Omega}dq^2} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_L)\sin^2\theta_k + F_L\cos^2\theta_k + \tfrac{1}{4}(1-F_L)\sin^2\theta_k\cos 2\theta_\ell - F_L\cos^2\theta_k\cos 2\theta_\ell + S_3\sin^2\theta_k\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_k\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_k\sin\theta_\ell\cos\phi + \tfrac{4}{3}A_{FB}\sin^2\theta_k\cos\theta_\ell + S_7\sin 2\theta_k\sin\theta_\ell\sin\phi + S_8\sin 2\theta_k\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_k\sin^2\theta_\ell\sin 2\phi\Big],$$



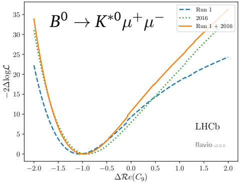
angular observables

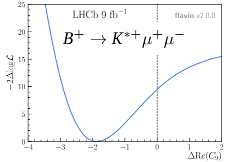
F_L, A_{FB}, $S_i = f(C_7, C_9, C_{10})$,
combinations of K^{*0} decay amplitudes

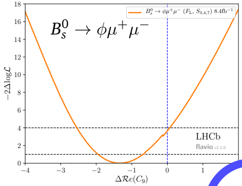
$b \to s\ell^+\ell^-$ angular observables

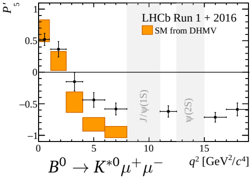
[PRL 125 (2020) 011802] [PRL 126 (2021) 161802] [JHEP 11 (2021) 043]

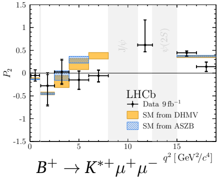
- measurements in several decay channels
- $B^0 \to K^{*0}\mu^+\mu^-$ [PRL 125 (2020) 011802]
  - local tension in P_5' confirmed by 2016 data
  - global tension of 3.3σ with SM
- $B^+ \to K^{*+}\mu^+\mu^-$: global 3.1σ tension with SM [PRL 126 (2021) 161802]
- $B_s^0 \to \phi\mu^+\mu^-$ consistent with SM at 1.9σ [JHEP 11 (2021) 043]
- coherent trends pointing at $\mathrm{Re}(\Delta\mathcal{C}_9) \simeq -1$
- new analyses based on unbinned amplitude fits ongoing

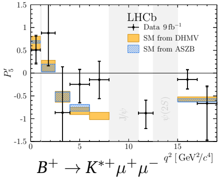








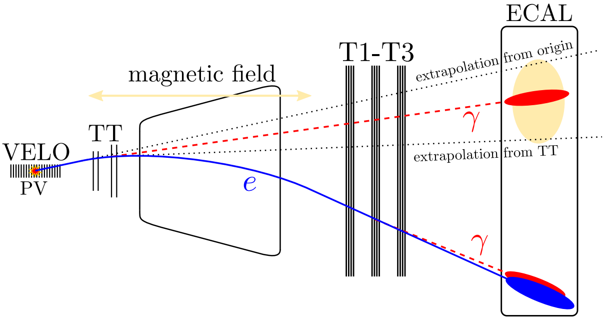


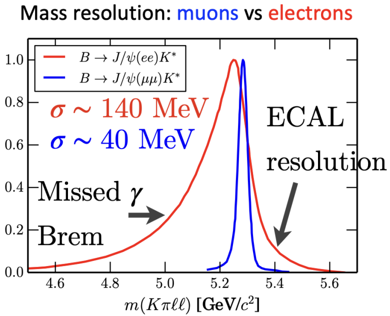


Electron *vs.* muons

- opportunity to test e *vs.* μ LFU in fully-reconstructed $B \to X_s \ell\ell$ decays
- $m_\ell \ll m_B \implies R_K^{\mathrm{SM}} = \left.\dfrac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}\right|_{[q^2_{\min},q^2_{\max}]} = \mathbf{1} \pm \mathcal{O}(10^{-2})_{(\mathrm{QED})} \pm \mathcal{O}(10^{-4})_{(\mathrm{QCD})}$

  [JHEP 12 (2007) 040] [EPJC 76 (2016) 440]
- electrons are the experimental limiting factor: ECAL trigger thresholds, resolution

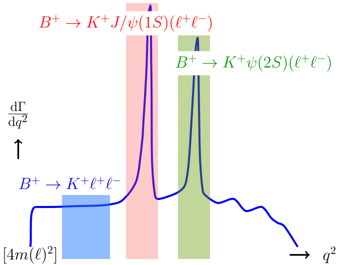




Common aspects: double ratio method

- the $X_s\ell^+\ell^-$ final state can also result from a $B^{(*)} \to X_s^{\pm} J/\psi$ decay
  $\longrightarrow$ measure R_{X_s} in a q^2 range that excludes $c\bar{c}$ resonances

- $B^{\pm} \to X_s^{\pm} J/\psi\,(\to \ell^+\ell^-)$ abundant and with topology similar to that of $B^{\pm} \to X_s^{\pm}\ell^+\ell^-$ signal
  $\Longrightarrow$ use them to reduce systematic uncertainties!



- R_X is measured as a double ratio:

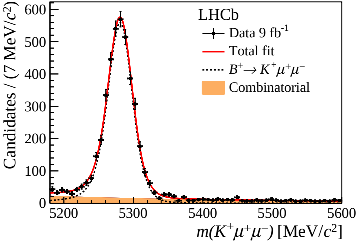
$$R_X \equiv \frac{\mathcal{B}\left(B \to X\,\mu^+\mu^-\right)}{\mathcal{B}\left(B \to X\,e^+e^-\right)} \Big/ r_{J/\psi}$$

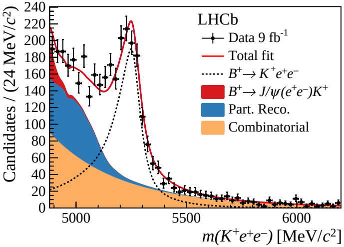
$$\equiv \frac{\mathcal{B}\left(B \to X\,\mu^+\mu^-\right)}{\mathcal{B}\left(B \to X\,J/\psi\,(\to \mu^+\mu^-)\right)} \frac{\mathcal{B}\left(B \to X\,J/\psi\,(\to e^+e^-)\right)}{\mathcal{B}\left(B \to X\,e^+e^-\right)}$$

- note: $J/\psi \to \ell\ell$ decays are lepton universal ($r_{J/\psi} = 1_{(SM)}$)

Common aspects: signal yield

- $\mathcal{B} \propto n_{evts} = n_{obs}/\varepsilon$
- ε from calibrated Monte Carlo simulations; n_{obs} from ML fit to dataset
- mass vetos and PID requirements bring peaking backgrounds to negligible levels
- BDT selection reduces combinatorial background
- residual backgrounds modelled in the fit
- systematics assessed by varying characteristics of signal model

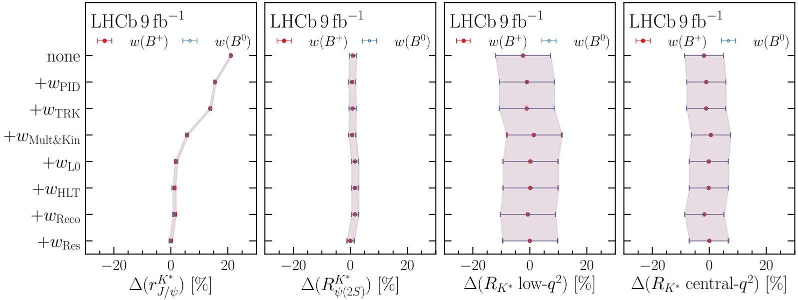




m_B lineshape constrained from simulation calibrated using resonant decays

Common aspects: efficiency

- Monte Carlo simulation imperfectly describes detector response and *pp* event
  - $B^+ \to K^+ J/\psi\,(\to \ell^+\ell^-)$ used to calibrate MC iteratively, with MVAs and tag&probe
- powerful cross-check to verify procedure:
  $r_{J/\psi} \equiv \mathcal{B}\left(B \to XJ/\psi\,(\to \mu\mu)\right) / \mathcal{B}\left(B \to XJ/\psi\,(\to ee)\right)$
  - assess absence of trends w.r.t. variables that distinguish rare from resonant decays

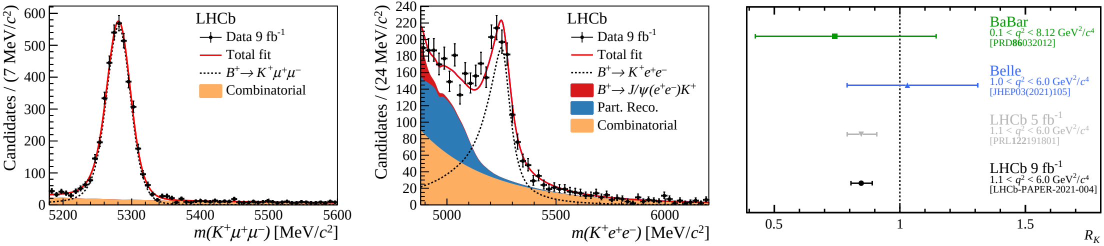


A (not so) short history of "cautious excitement"

- LHCb performed several measurements of LFU observables with FCNC decays
- $1\,\text{GeV}^2 \lesssim q^2 \lesssim 7\,\text{GeV}^2$ range is free from resonant contributions
- 2014: $R_K = 0.745^{+0.090}_{-0.074} \pm 0.036$, 2.6σ below 1 [PRL 113, 151601 (2014)]
- 2017: $R_{K^*} = 0.69^{+0.11}_{-0.07} \pm 0.05$, 2.5σ below 1 [JHEP 08 (2017) 055]
- 2019: $R_K = 0.846^{+0.060+0.016}_{-0.054-0.014}$ ($2\times$ data), 2.5σ [PRL 122, 191801 (2019)]
- 2019: $R_{pK} = 0.86^{+0.14}_{-0.11} \pm 0.05$ with Λ_b^0 decays, compatible with SM [JHEP 05 (2020) 040]
- 2021: $R_{K_S^0} = 0.66^{+0.20+0.02}_{0.14-0.04}$ and $R_{K^{*+}} = 0.70^{+0.18+0.03}_{-0.13-0.04}$, 2.0σ [PRL 128 (2022) 191802]

March 2021: ~~LFU~~ evidence?

[Nature Physics 18 (2022) 277-282]

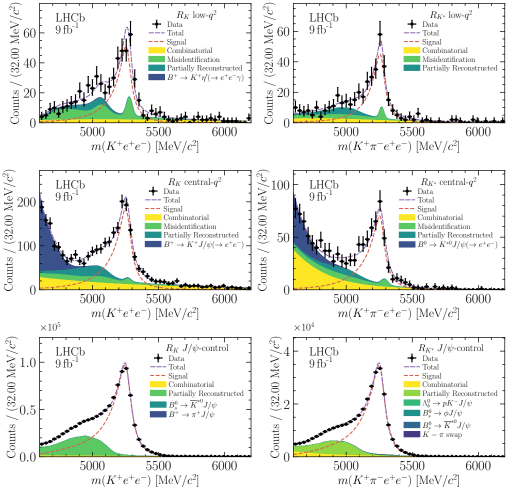


- "legacy" measurement using the whole 2011–2018 dataset
- $R_K = 0.846^{+0.042}_{-0.039}(\text{stat})^{+0.013}_{-0.012}(\text{syst})$
- main systematics: fit model, size of calibration samples
- p-value in SM hypotesys: 10^{-3}
  $\Longrightarrow$ 3.1σ evidence of LFU violation in $B \to K\ell\ell$ decays...

December 2022: LFU restored!

[hep-ex/2212.09152] [hep-ex/2212.09153]

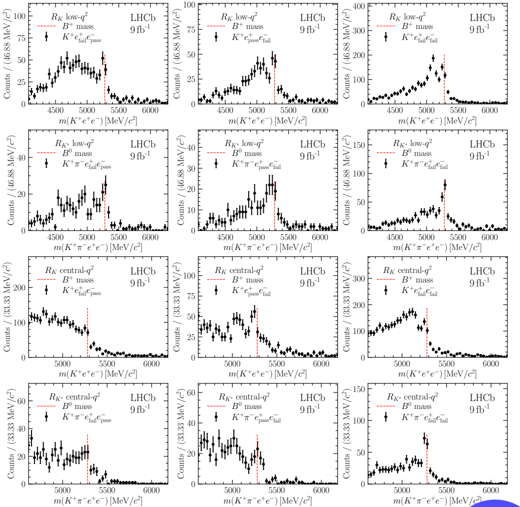
- simultaneous fit of $B^+ \to K^+\ell\ell$ and $B^0 \to K^{*0}\ell\ell$
- better understanding of cross-feeds



December 2022: LFU restored!

[hep-ex/2212.09152] [hep-ex/2212.09153]

- simultaneous fit of $B^+ \to K^+\ell\ell$ and $B^0 \to K^{*0}\ell\ell$
- better understanding of cross-feeds
- found dependency of result on PID cuts
- BGs from partially-reconstructed decays with $h \to e$ **misidentification**
- only present in rare mode electron data
- unknown Dalitz structure: constrain using data ("pass-fail" method)



December 2022: LFU restored!

[hep-ex/2212.09152] [hep-ex/2212.09153]

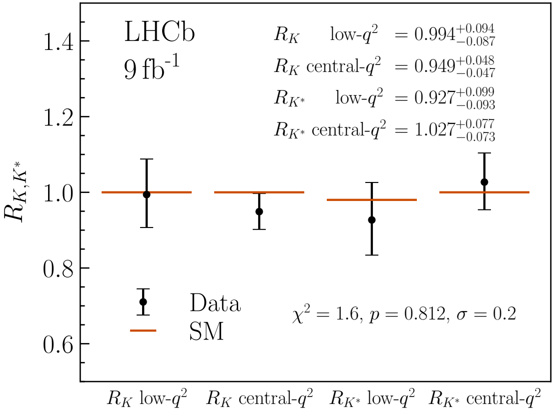
the electrons. More generally, however, any decay of the type $B^+ \to K^+\pi^-(\pi^0,\gamma)X$ or $B^0 \to K^{*0}\pi^-(\pi^0,\gamma)X$, where X is any number of other final state particles, can contribute. Not all particles from such processes are used to reconstruct the signal, therefore such backgrounds are characterized by low invariant masses.

Compared to previous LU measurements at LHCb, the tighter PID requirements used for electrons reduces the expected rates for pions and kaons to be misidentified as electrons.

It is essential to establish whether a significant number of misidentified background candidates pass the full selection criteria, and whether they create distinctive invariant mass distributions that cannot be absorbed by combinatorial or other background components. This task is complicated by the fact that there is a very large number of such backgrounds, many of which are poorly known. Even where the branching fractions of individual $B^+ \to K^+\pi^-(\pi^0,\gamma)X$ or $B^0 \to K^{*0}\pi^-(\pi^0,\gamma)X$ decays have been measured, their Dalitz structure is often unknown. A representative subset of these backgrounds is studied using simulation, and the expected contribution of each individual background found to be negligible. However, even if the contribution of any given background is small, the contribution of all these backgrounds taken together can be large and have a shape that differs from combinatorial background. These considerations lead to a data-driven

December 2022: LFU restored!

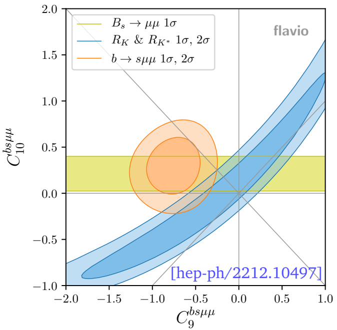
[hep-ex/2212.09152] [hep-ex/2212.09153]

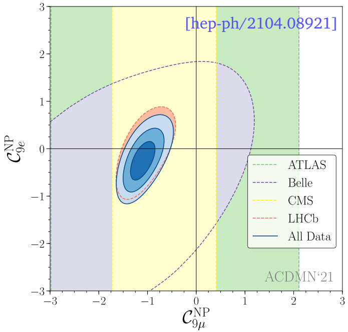


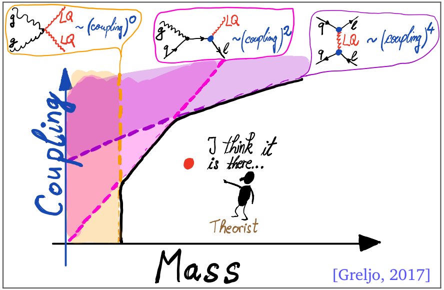
- muon mode consistent with previous measurement
- electron mode yield went down

$b \to s\ell\ell$ results interpretation

- previous LFU measurements favored the spawning of many ~~LFU~~ SM completions
- global fits retain high significance ($> 5\sigma$) for the NP hypotesis but now allow LFU NP
- significant preference for non-zero NP contribution to C_9
  - unless... incorrectly estimated charm-loop contribution

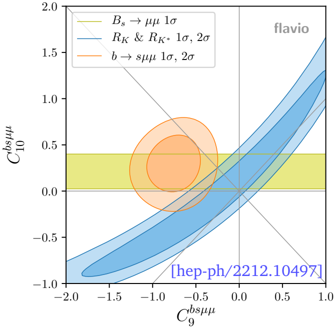


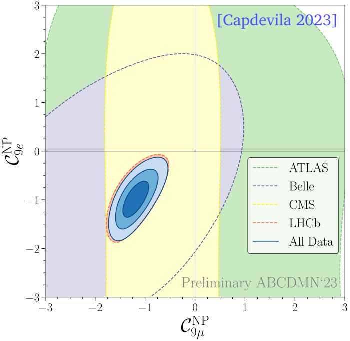


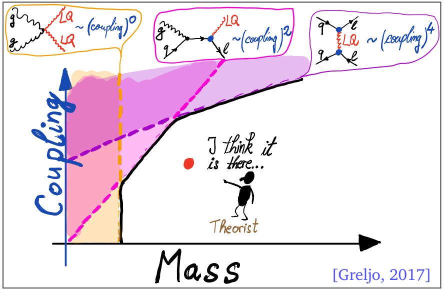


$b \to s\ell\ell$ results interpretation

- previous LFU measurements favored the spawning of many ~~LFU~~ SM completions
- global fits retain high significance ($> 5\sigma$) for the NP hypotesis but now allow LFU NP
- significant preference for non-zero NP contribution to C_9
  - unless... incorrectly estimated charm-loop contribution

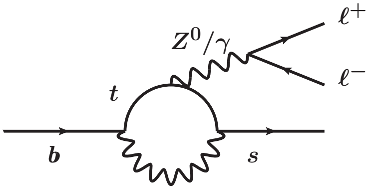






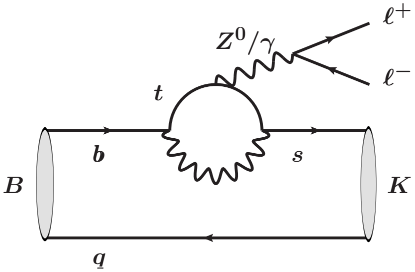
What can help?

[SNSF Ambizione PZ00P2_202065]



What can help?

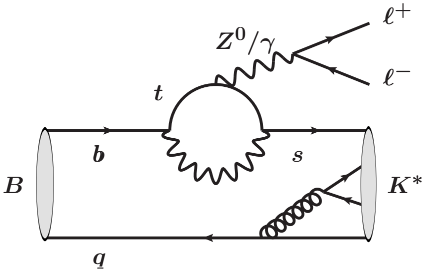
[SNSF Ambizione PZ00P2_202065]



- quarks do not exist unbound
  - study various *hadron* decays

What can help?

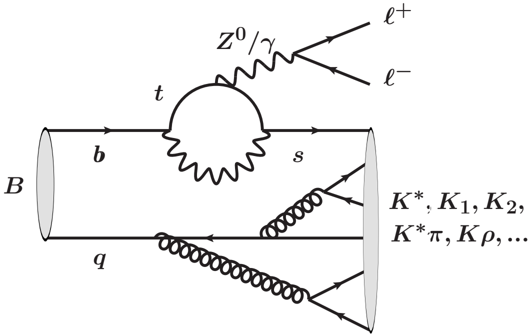
[SNSF Ambizione PZ00P2_202065]



- quarks do not exist unbound
  - study various *hadron* decays
- theoretical descriptions grow complex

What can help?

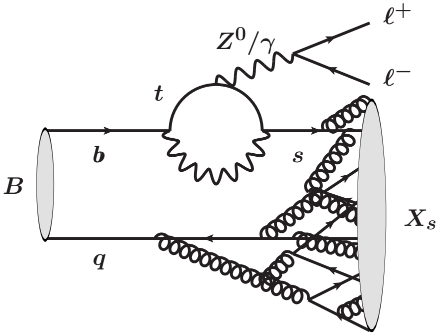
[SNSF Ambizione PZ00P2_202065]



- quarks do not exist unbound
  - study various *hadron* decays
- theoretical descriptions grow complex

What can help?

[SNSF Ambizione PZ00P2_202065]



- quarks do not exist unbound
  - study various *hadron* decays
- theoretical descriptions grow complex

➜ sum all decays together: easier theoretical treatment [PRD75(2007)034016] [JHEP 0(2020)88]

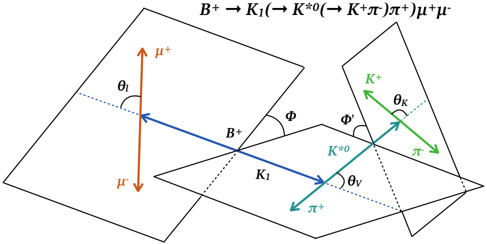
  - never done at a hadron factory

- extract maximum of information from **largest** data sample available

$$\frac{\mathrm{d}^2\Gamma\left(\mathcal{B}\to X_s\ell\ell\right)}{\mathrm{d}q^2\,\mathrm{d}\cos\theta} = \sum_{i<3} f_i\left(\cos\theta\right) g_i\left(q^2|C_7, C_9, C_{10}\right)$$

What else can help?

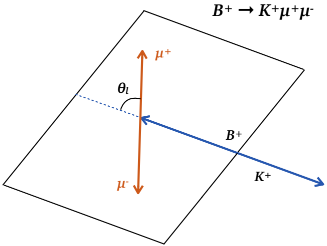
[SNSF Ambizione PZ00P2_202065]



- angular distributions carry crucial information
  - essential to explore more decays
  - while theory calculations advance
- complexity grows with multiplicity
- *e.g.* $B \to K\pi\pi\mu\mu$ decays: 8 d.o.f.

What else can help?

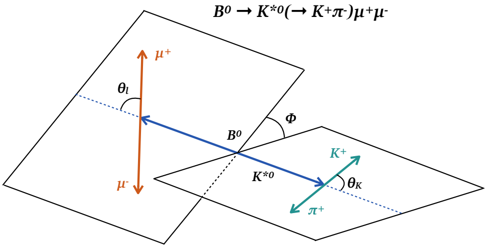
[SNSF Ambizione PZ00P2_202065]



- angular distributions carry crucial information
  - essential to explore more decays
  - while theory calculations advance
- complexity grows with multiplicity
- *e.g.* $B \to K\pi\pi\mu\mu$ decays: 8 d.o.f.

What else can help?

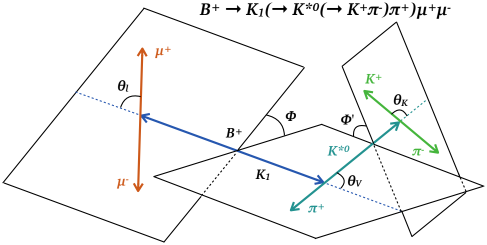
[SNSF Ambizione PZ00P2_202065]



- angular distributions carry crucial information
  - essential to explore more decays
  - while theory calculations advance
- complexity grows with multiplicity
- *e.g.* $B \to K\pi\pi\mu\mu$ decays: 8 d.o.f.

What else can help?

[SNSF Ambizione PZ00P2_202065]



- angular distributions carry crucial information
  - essential to explore more decays
  - while theory calculations advance
- complexity grows with multiplicity
- *e.g.* $B \to K\pi\pi\mu\mu$ decays: 8 d.o.f.

➜ method of moments

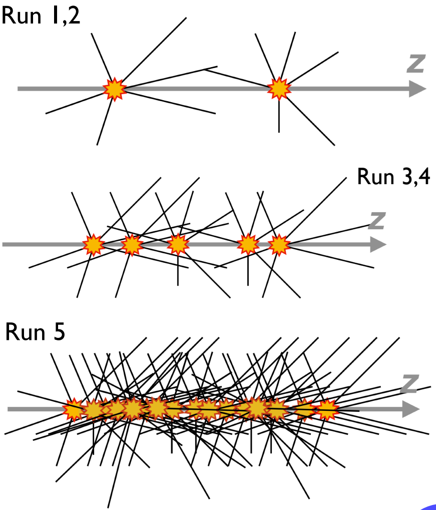
decompose multi-body decays in successive 2-body decays, parametrized in terms of spherical harmonics

The near and the far future

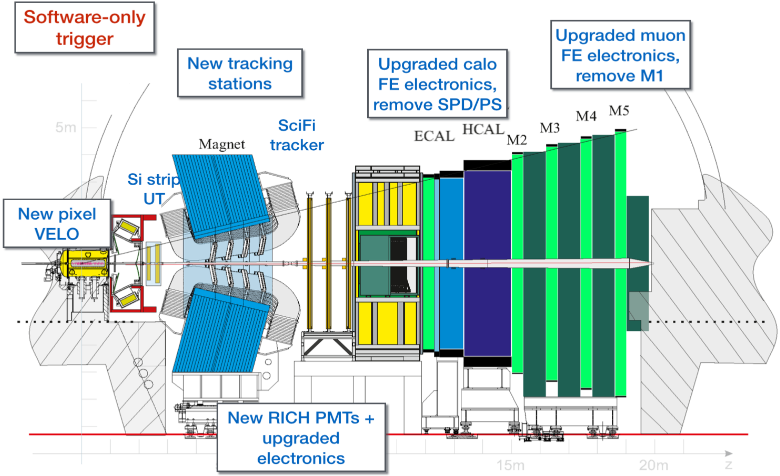
LHCb: the new challenges

Run	Year	Luminosity		PVs/bx
1	2011-12	3 fb^{-1}	4×10^{32}	~ 1
2	2015-18	8 fb^{-1}	4×10^{32}	~ 1
3	2022-25	22 fb^{-1}	2×10^{33}	~ 6
4	2029-32	50 fb^{-1}	2×10^{33}	~ 6
5	2035-??	300 fb^{-1}	1×10^{34}	~ 55

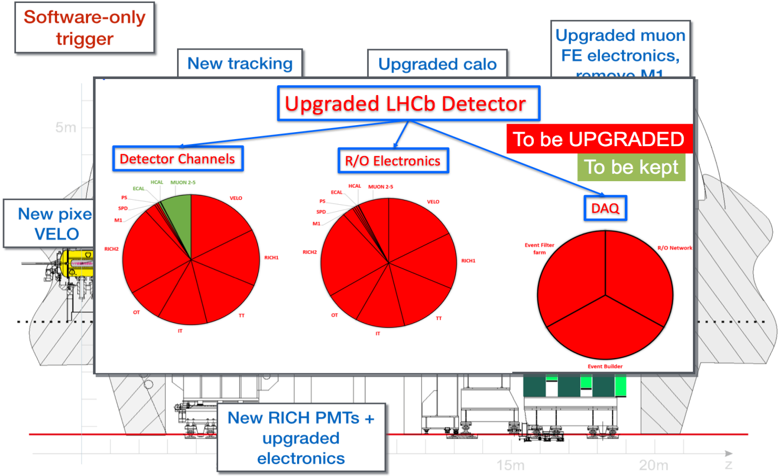
- acceptance/efficiency
- timing
- granularity
- radiation hardness
- upgrade in steps



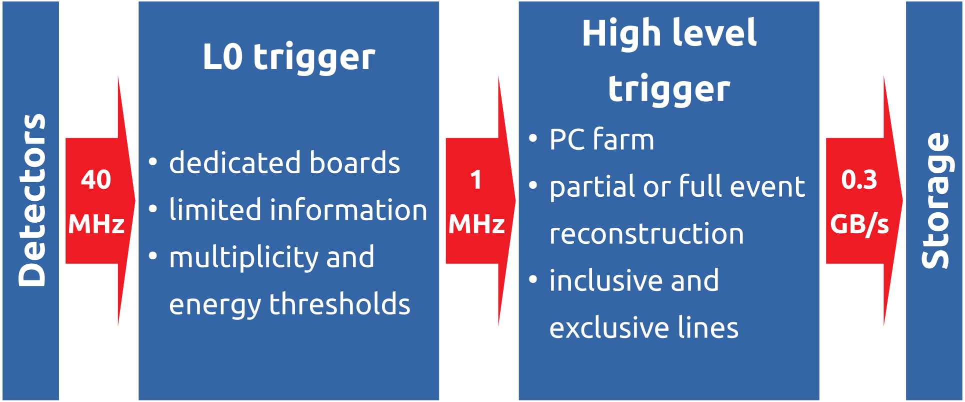
LHCb upgrade 1 (installed during LS2)



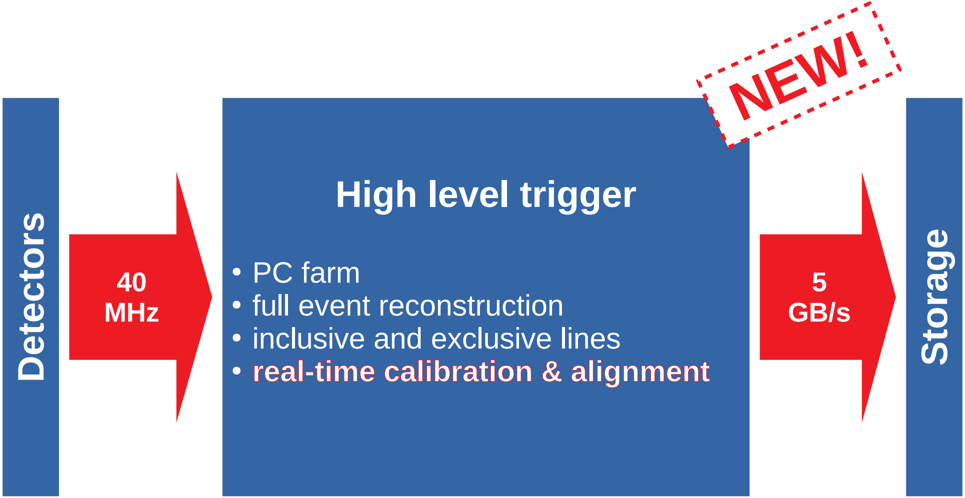
LHCb upgrade 1 (installed during LS2)



Real-time offline-quality event reconstruction



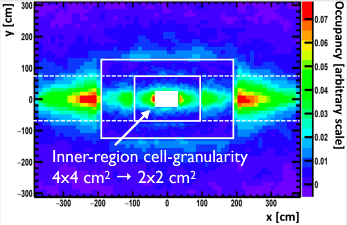
Real-time offline-quality event reconstruction



LHCb upgrade 1 consolidation (LS3, 2029)

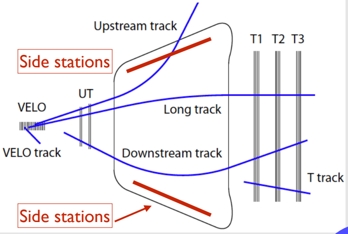
Calorimeters

- WLS and scintillator suffer radiation
- innermost part most affected
- crucial for decays with e, γ, π^0 etc.
- Tungsten: rad-hardness / timing
- opportunity to test Upgrade 2 design

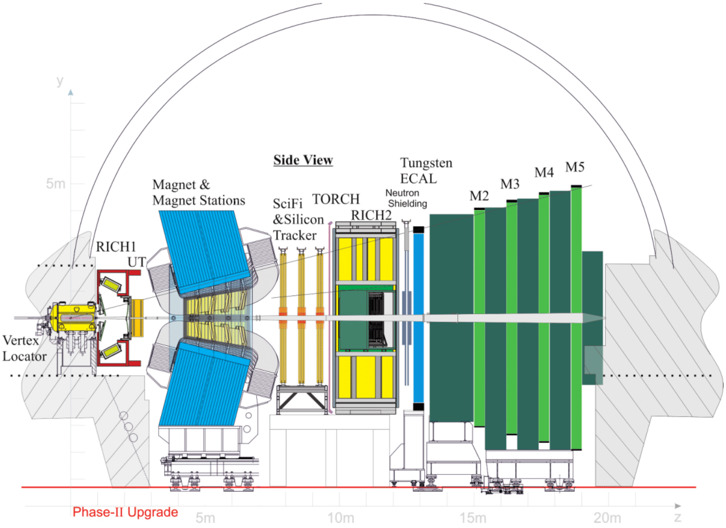


Magnet side stations

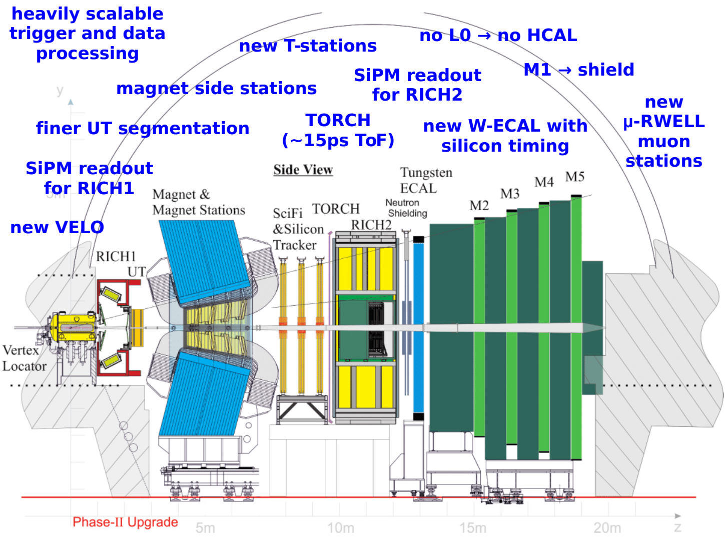
- upstream tracks: $\Delta p/p \sim 15\%$
- add 1 mm z−segmented tracker
- multibody b/c decays, heavy hadrons, slow π *e.g.* from D^*
- 10 to 50% gain
- can use SciFi technology



LHCb upgrade 2 (LS4, 2035)



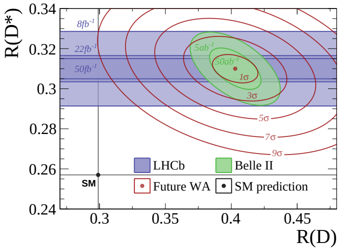
LHCb upgrade 2 (LS4, 2035)

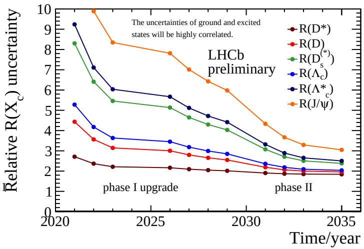


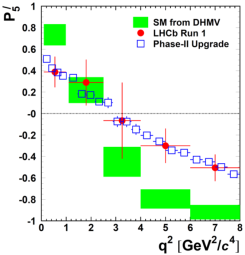
Physics potential of LHCb upgrades

[CERN-LHCC-2018-027] [CERN-LHCC-2017-003]

- new player in the game: Belle II
  - very different experimental conditions!
- at LHCb, many systematic uncertainties scale with $\sqrt{n}$
  - e.g. data-driven background templates
- reach $\sim$ 1-2% precision on R ratios
- better ECAL: access $\Delta S = S(\mu\mu) - S(ee)$ angular observables







Conclusions

- LHCb originally designed for CPV and rare decays
  - achieved much more! Multi-purpose experiment
  - selected measurements in CC and FCNC decays presented
- Recent results suggest possible avenue for flavour-hierarchic NP
  - more studies underway on other decay modes
- LHCb underwent major upgrade for Run 3
  - detector installed & commissioning ongoing
  - real time software-based trigger gretly improves flexibility
- Upgrade 2 (2035) framework TDR prepared [LHCC-2021-012]
  - potential to discover cracks in the SM and/or pave the way for NP searches!