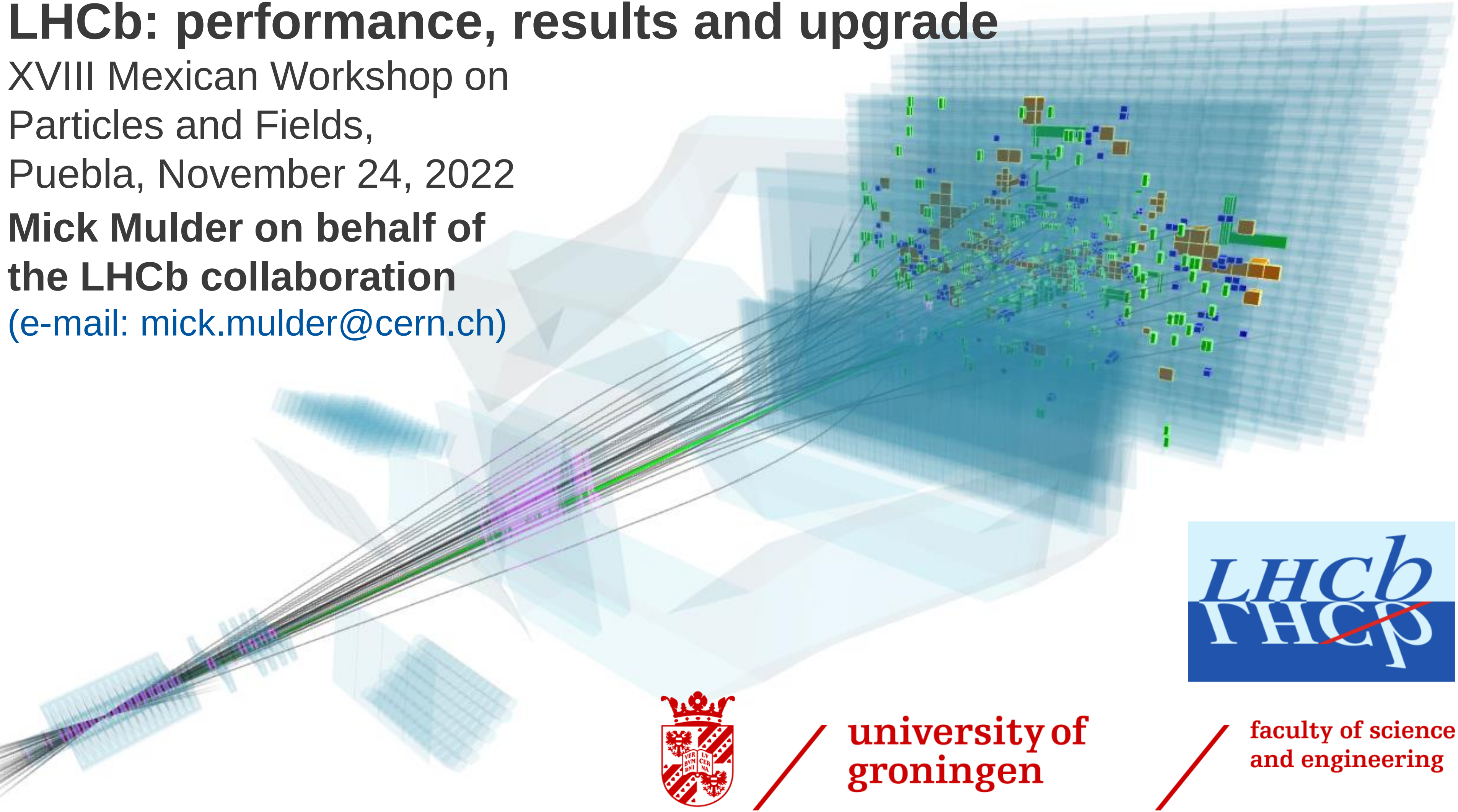
LHCb: performance, results and upgrade

XVIII Mexican Workshop on
Particles and Fields,
Puebla, November 24, 2022

**Mick Mulder on behalf of
the LHCb collaboration**
(e-mail: mick.mulder@cern.ch)



LHCb

university of groningen

faculty of science and engineering

Outline for today

Antojito	LHCb detector and performance
Comida	Physics results
Postre	LHCb Upgrade

LHCb physics programme

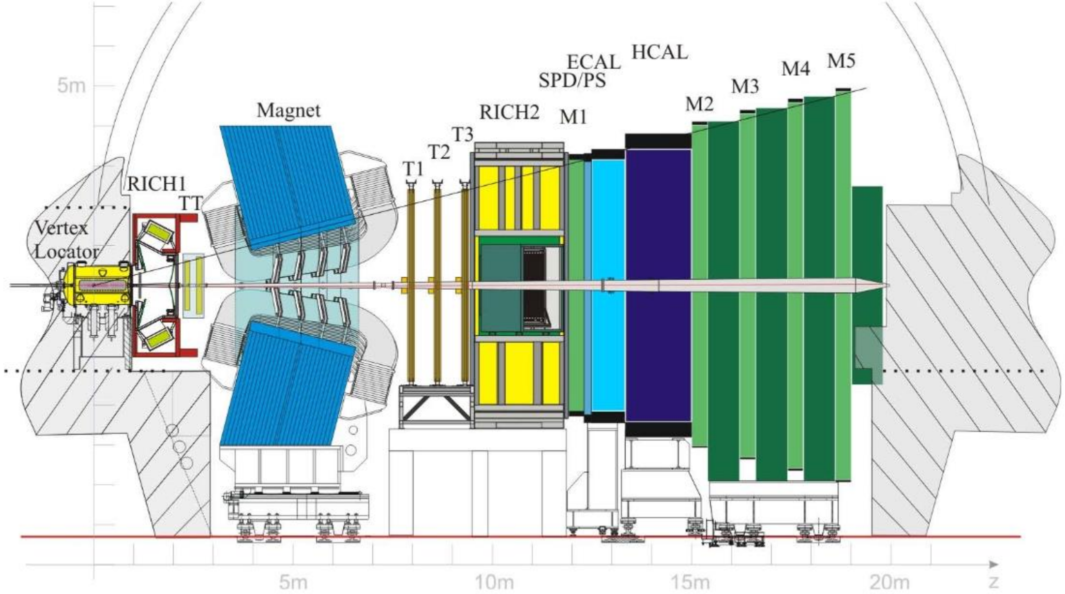
- LHCb explicitly designed for
  - Mixing and CP violation in B decays

LHCb technical proposal (1998)

Since its discovery, CP violation has been detected only in the decay amplitude of K_L mesons. Experimental efforts in the kaon sector will continue for some time. In the B-meson system there are many more decay modes available, and the Standard Model makes precise predictions for CP violation in a number of these. The B-meson system is therefore a very attractive place to study CP violation, and to search for a hint of new physics.

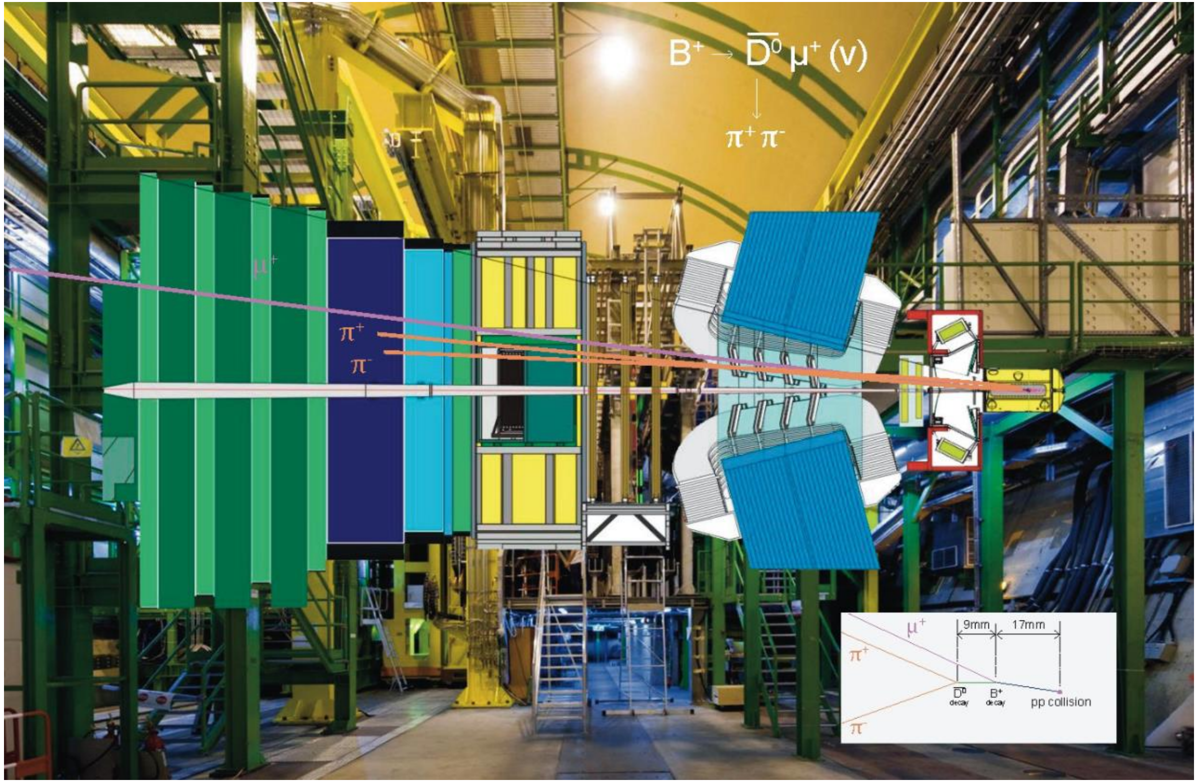
LHCb experiment

- Forward spectrometer at the LHC, optimised for b-hadrons
- $\mathrm{b\bar{b}}$ cross section $= 154.3 \pm 1.5\ \mu\mathrm{b}$ at $\sqrt{s}$ =13 TeV in acceptance $2 < \eta < 5$
- $\mathrm{O}(10^5)\ \mathrm{b\bar{b}}$ pairs/s in LHC Run 1 & 2 (and 20 x more $\mathrm{c\bar{c}}$)



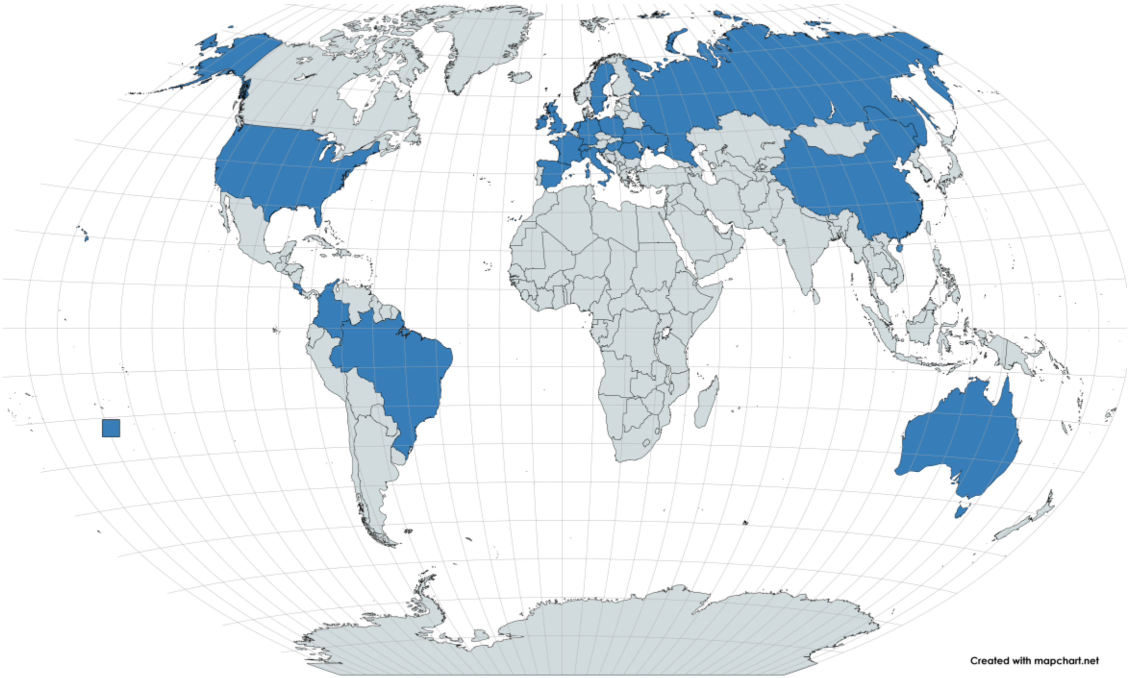
LHCb detector

LHCb detector



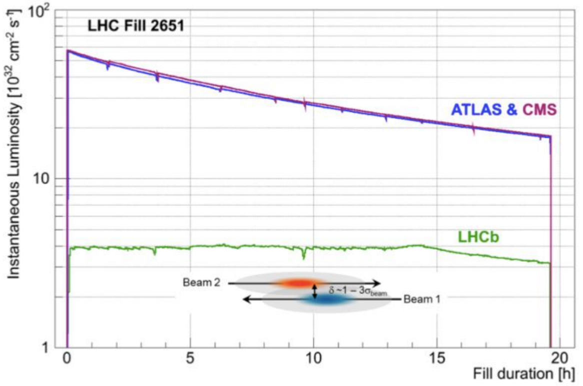
LHCb collaboration

LHCb collaboration

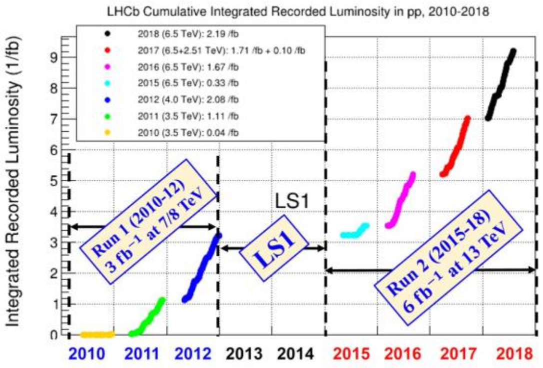


LHCb Run 1 & 2 data taking

- Running with LHC luminosity levelling ($\mathcal{L} = 4 \times 10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, 2x design luminosity)
- Corresponds to 1.5 interactions per bunch crossing

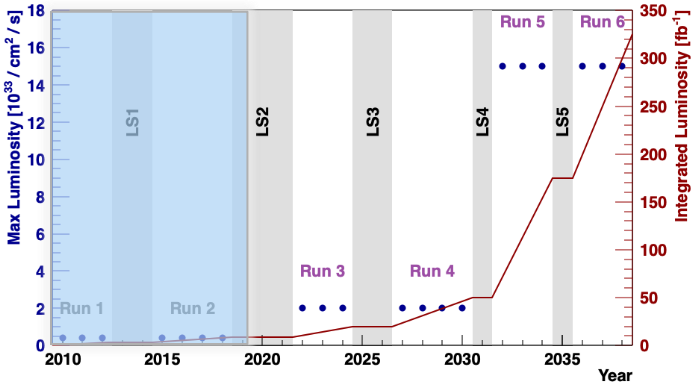


- Total of $9\ \mathrm{fb}^{-1}$ collected from 2011 to 2018
- Around $3 \cdot 10^{12}\ \mathrm{b\bar{b}}$ pairs produced in Run 1 & 2!

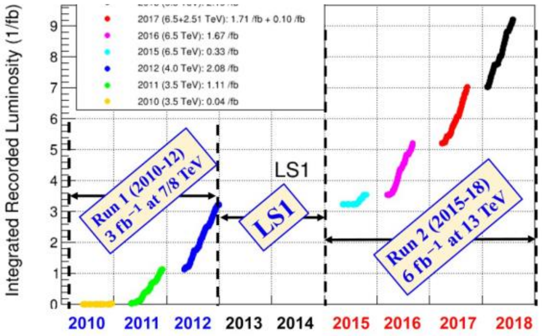


LHCb Run 1 & 2 data taking

- Running with LHC luminosity levelling
  ($\mathcal{L} = 4 \times 10^{32} \mathrm{cm}^{-2} \mathrm{s}^{-1}$, 2x design luminosity)
- Corresponds to 1.5 interactions
  per bunch crossing

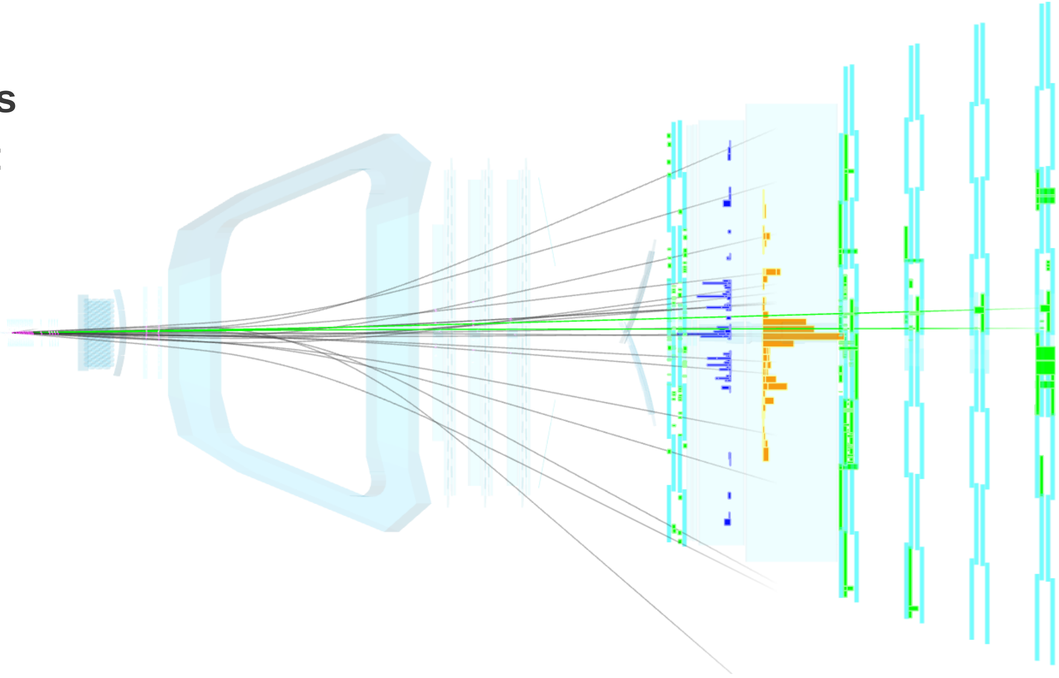


- Total of $9\ \mathrm{fb}^{-1}$ collected from 2011 to 2018
- Around $3 \cdot 10^{12}\ \mathrm{b\bar{b}}$ pairs produced in Run 1 & 2!
  Only the beginning (more later in this talk ☺)



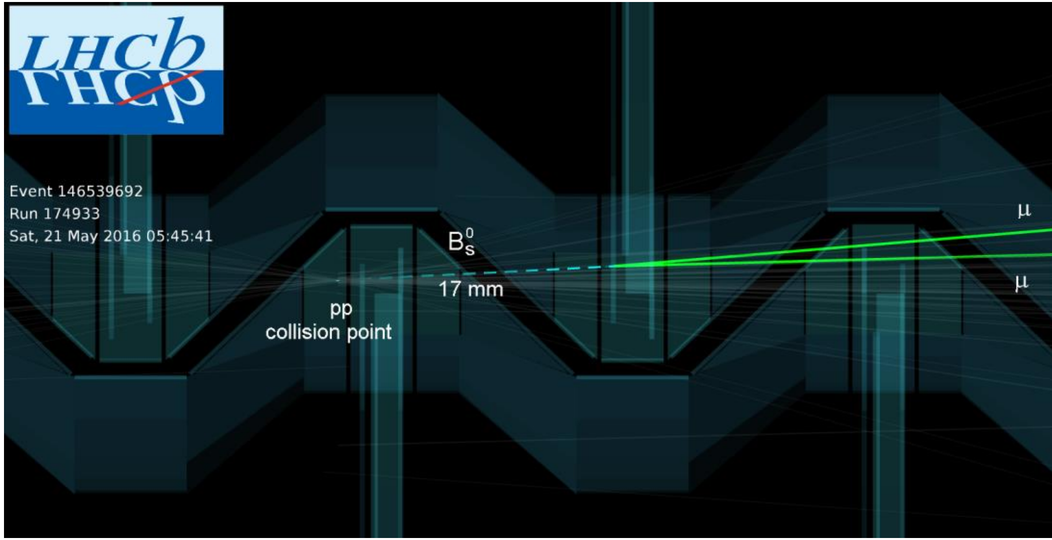
LHCb performance

- Very good momentum resolution
  ($\Delta p/p = 0.5 - 1.0\%$)
  → **Sufficient to separate $\mathbf{B_s^0, B^0}$ decays**
- Excellent charged particle identification:
  μ ID ~ 97 % w. 1-3% $\pi \rightarrow \mu$ mis-id
  e ID ~ 90 % w. ~ 5% $h \rightarrow e$ mis-id
  → **required to reject hadronic B decays & separate $\mathbf{\pi, K, p}$**



LHCb performance

- Very good momentum resolution ($\Delta p/p = 0.5 - 1.0\%$)
  → **Sufficient to separate B_s^0, B^0 decays**
- Excellent charged particle identification:
  μ ID ~ 97 % w. 1-3% $\pi \rightarrow \mu$ mis-id
  e ID ~ 90 % w. ~ 5% $h \rightarrow e$ mis-id
  → **required to reject hadronic B decays & separate π, K, p**
- Clear separation of
  B hadron decay vertex, pp collision:
  45 fs decay time resolution ≅3% of B lifetime
  → **essential to reduce backgrounds**



LHCb physics programme

- LHCb explicitly designed for:
  - Mixing and CP violation in B decays

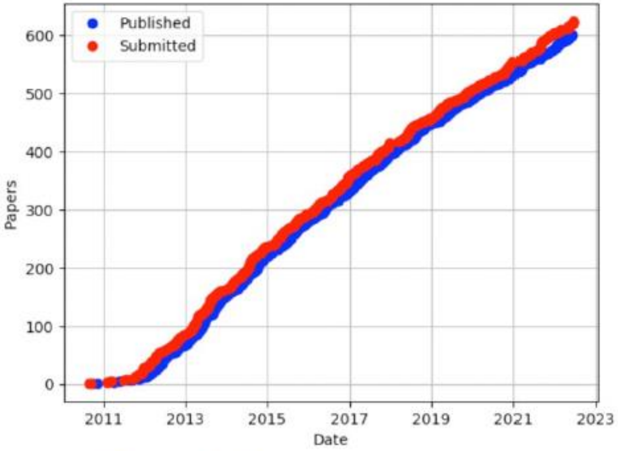
[LHCb technical proposal (1998)]

Since its discovery, CP violation has been detected only in the decay amplitude of K_L mesons. Experimental efforts in the kaon sector will continue for some time. In the B-meson system there are many more decay modes available, and the Standard Model makes precise predictions for CP violation in a number of these. The B-meson system is therefore a very attractive place to study CP violation, and to search for a hint of new physics.

LHCb physics programme

- LHCb explicitly designed for:
  - Mixing and CP violation in B decays
- But LHCb has found general purpose:
  - Rare B decays
  - Charm decays
  - Semileptonic B decays
  - Spectroscopy and exotic hadrons
  - Hadron production (B and quarkonia)
  - Heavy ion physics, fixed target
  - Electroweak physics, QCD
  - Exotics (dark matter, long-lived particles)

LHCb publication page

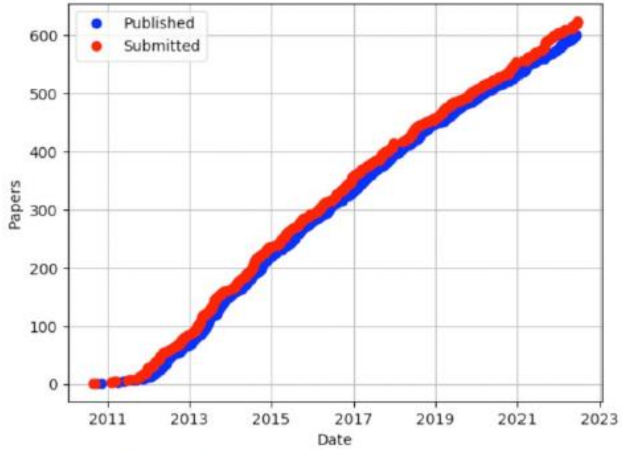


Over 600 published papers

LHCb physics programme

- LHCb explicitly designed for:
  - **Mixing and CP violation in B decays**
- But LHCb has found general purpose:
  - **Rare decays**
  - **Charm decays**
  - **Semileptonic B decays**
  - **Spectroscopy and exotic hadrons**
  - **Hadron production (B and quarkonia)**
  - Heavy ion physics, fixed target
  - Electroweak physics, QCD
  - Exotics (dark matter, long-lived particles)
- **Today: selected results from LHCb Run 1 and 2**

LHCb publication page

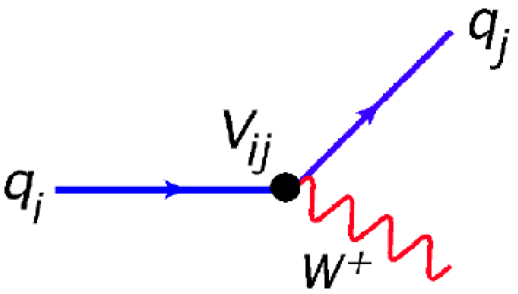


Over 600 published papers

Mixing and CP violation

CKM matrix

- Mass and flavour eigenstates of quarks are not equal → W boson transforms quarks



CKM matrix

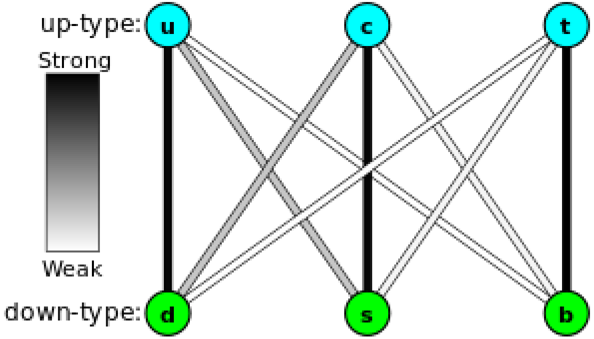
- Mass and flavour eigenstates of quarks are not equal → W boson transforms quarks
- Probabilities described with 3x3 unitary CKM matrix (**almost diagonal, almost real)**

$$\underbrace{\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}}_{\text{weak states}} = \underbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}}_{\text{CKM matrix}} \underbrace{\begin{pmatrix} d \\ s \\ b \end{pmatrix}}_{\text{mass states}}$$

CKM matrix

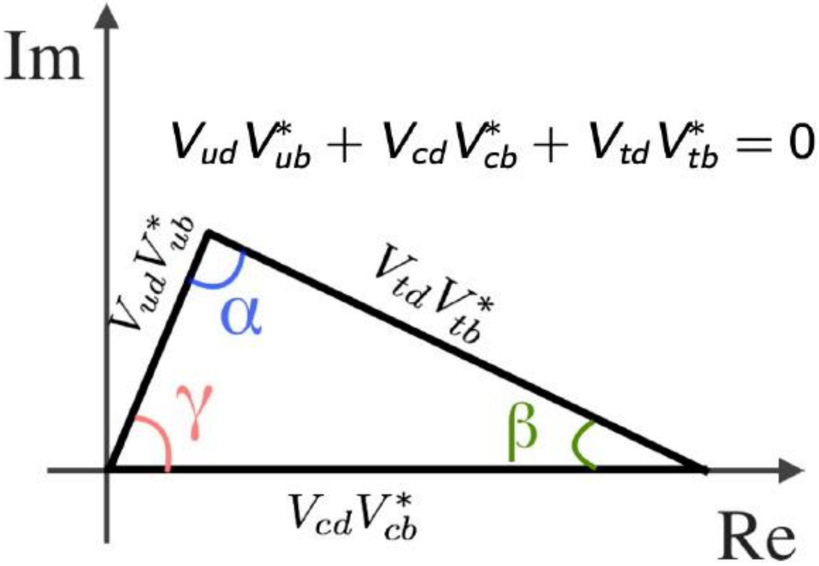
- Mass and flavour eigenstates of quarks are not equal → W boson transforms quarks
- Probabilities described with 3x3 unitary CKM matrix (**almost diagonal, almost real)**
- Only three real, one imaginary parameter remain in SM (due to unitarity)
- **Imaginary element causes CP violation** (opposite phase for particle, anti-particle)

$$\underbrace{\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}}_{\text{weak states}} = \overbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}}^{\text{CKM matrix}} \underbrace{\begin{pmatrix} d \\ s \\ b \end{pmatrix}}_{\text{mass states}}$$



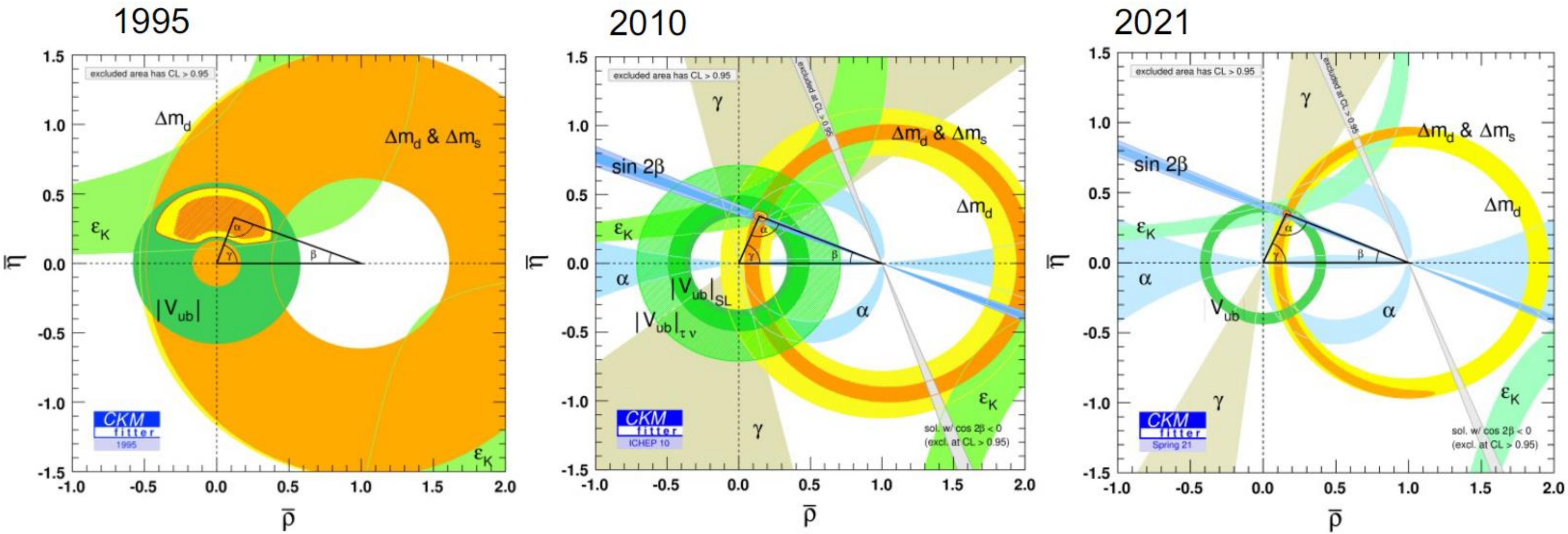
Unitarity triangle

- Unitarity of CKM matrix leads to two types of conditions: real, $\Sigma_i V_{ij} V_{ij}^* = 1$, orthogonal, $\Sigma_i V_{ij} V_{ik}^* = 0$
- **Unitarity triangles** formed with orthogonal relations
- **In case of New Physics, unitarity conditions are broken!** → test consistency of unitary triangles with measurements testing each angle and side



Constraining the unitarity triangle

Significant progress over last decades with crucial role for LHCb (since 2011)



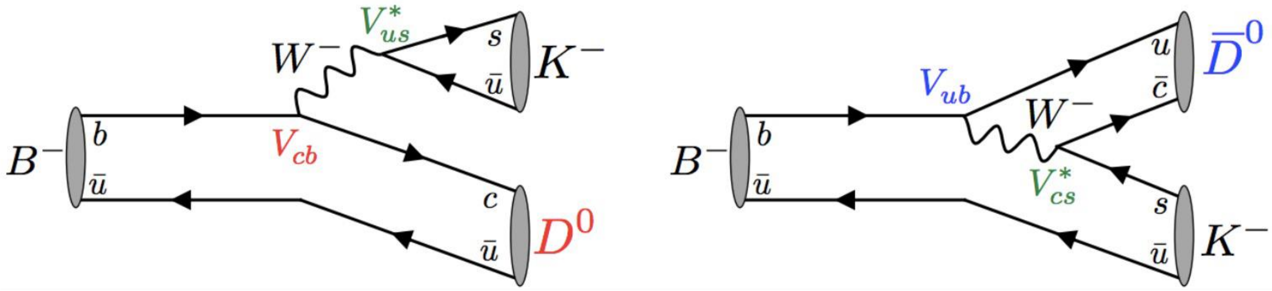
Any sign of inconsistency could point to New Physics

CKMfitter.in2p3.fr

CKM angle γ

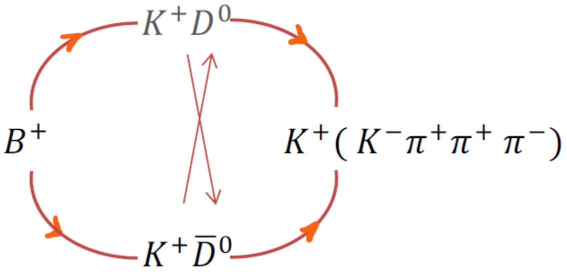
$$\gamma \equiv \arg(-V_{ud}V_{ub}^{*}/V_{cd}V_{cb}^{*})$$

- Only angle accessible in tree-level decays
- Theoretically clean measurements
- Use **interference** of $b \to c$ and $b \to u$ diagrams



- Interference only possible using $D^0, \overline{D}^0$ decays to same final state
- Extraction of γ from combination of $B^{\pm} \to Dh^{\pm}$ decay measurements

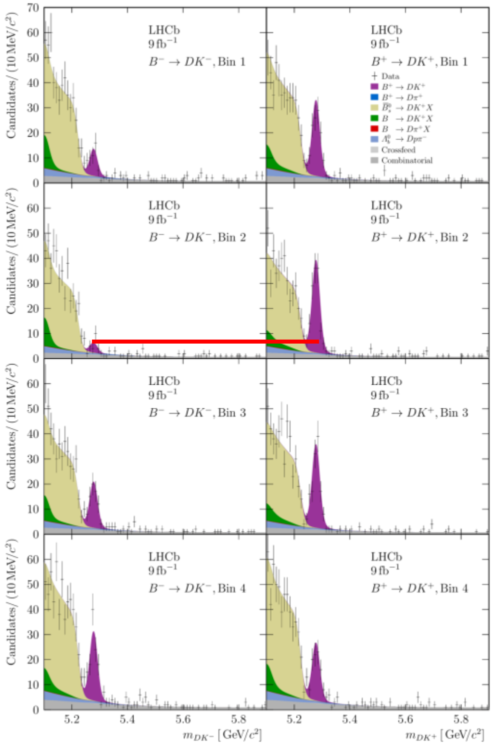
New γ measurement



[arXiv:2209.03692]

Largest CPV
ever measured (85%)!

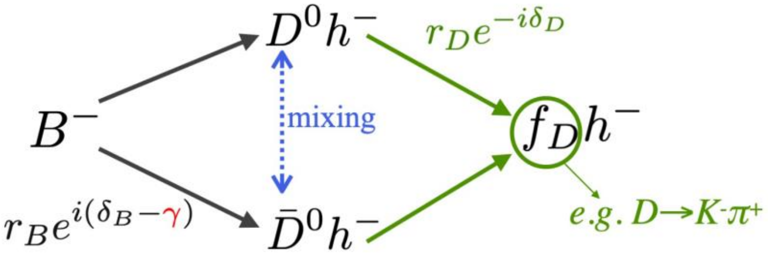
- Model-independent determination in bins of *D* phase space
- Second most precise measurement from a single *D* mode:
  $\gamma = \left(54.8^{+6.0+0.6+6.7}_{-5.8-0.6-4.3}\right)^\circ$
  using inputs from BESIII/CLEO



New γ combination

LHCb-CONF-2022-003;
update to [JHEP 12(2021)141]

- Combination of 173 observables to determine 52 parameters
- Simultaneous determination of γ and charm mixing parameters
- External inputs from BESIII & CLEO

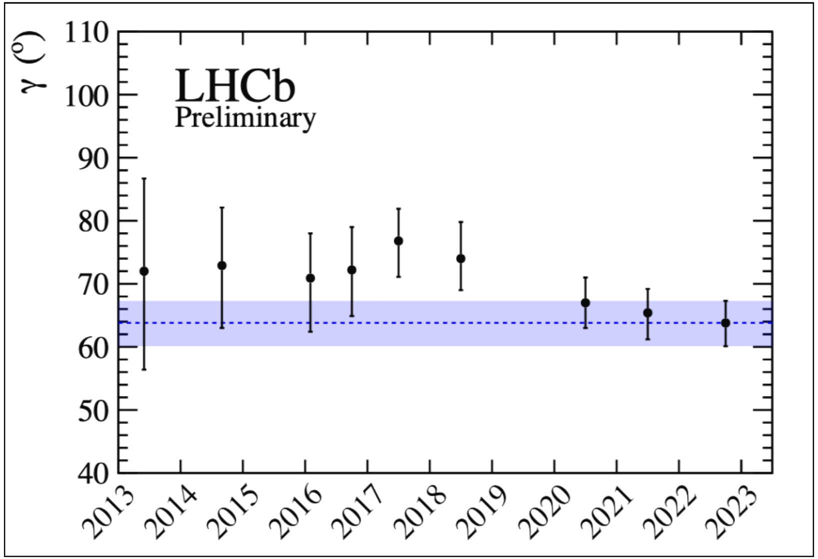


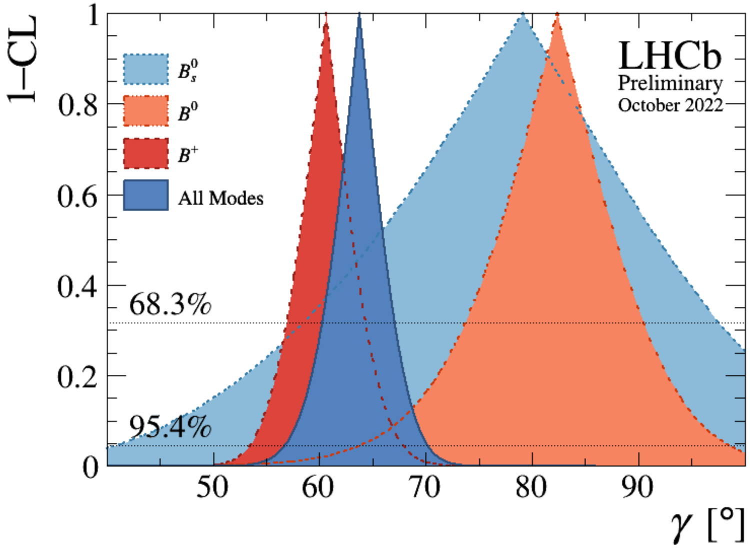
B decay	D decay	Ref.	Dataset	Status since Ref. [14]
$B^\pm \to Dh^\pm$	$D \to h^+h^-$	[29]	Run 1&2	As before
$B^\pm \to Dh^\pm$	$D \to h^+\pi^-\pi^+\pi^-$	[30]	Run 1	As before
$B^\pm \to Dh^\pm$	$D \to K^\pm\pi^\mp\pi^+\pi^-$	[18]	Run 1&2	**New**
$B^\pm \to Dh^\pm$	$D \to h^+h^-\pi^0$	[19]	Run 1&2	**Updated**
$B^\pm \to Dh^\pm$	$D \to K^0_S h^+h^-$	[31]	Run 1&2	As before
$B^\pm \to Dh^\pm$	$D \to K^0_S K^\pm\pi^\mp$	[32]	Run 1&2	As before
$B^\pm \to D^*h^\pm$	$D \to h^+h^-$	[29]	Run 1&2	As before
$B^\pm \to DK^{*\pm}$	$D \to h^+h^-$	[33]	Run 1&2(*)	As before
$B^\pm \to DK^{*\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	[33]	Run 1&2(*)	As before
$B^\pm \to Dh^\pm\pi^+\pi^-$	$D \to h^+h^-$	[34]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to h^+h^-$	[35]	Run 1&2(*)	As before
$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^+\pi^-$	[35]	Run 1&2(*)	As before
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	[36]	Run 1	As before
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^-\pi^+\pi^+$	[37]	Run 1	As before
$B^0_s \to D_s^\mp K^\pm$	$D_s^+ \to h^+h^-\pi^+$	[38]	Run 1	As before
$B^0_s \to D_s^\mp K^\pm\pi^+\pi^-$	$D_s^+ \to h^+h^-\pi^+$	[39]	Run 1&2	As before
D decay	**Observable(s)**	**Ref.**	**Dataset**	**Status since Ref. [14]**
$D^0 \to h^+h^-$	ΔA_{CP}	[24, 40, 41]	Run 1&2	As before
$D^0 \to K^+K^-$	$A_{CP}(K^+K^-)$	[16, 24, 25]	Run 2	**New**
$D^0 \to h^+h^-$	$y_{CP} - y_{CP}^{K^-\pi^+}$	[42]	Run 1	As before
$D^0 \to h^+h^-$	$y_{CP} - y_{CP}^{K^-\pi^+}$	[15]	Run 2	**New**
$D^0 \to h^+h^-$	ΔY	[43–46]	Run 1&2	As before
$D^0 \to K^+\pi^-$ (Single Tag)	$R^\pm$, $(x'^\pm)^2$, $y'^\pm$	[47]	Run 1	As before
$D^0 \to K^+\pi^-$ (Double Tag)	$R^\pm$, $(x'^\pm)^2$, $y'^\pm$	[48]	Run 1&2(*)	As before
$D^0 \to K^\pm\pi^\mp\pi^+\pi^-$	$(x^2+y^2)/4$	[49]	Run 1	As before
$D^0 \to K^0_S\pi^+\pi^-$	x, y	[50]	Run 1	As before
$D^0 \to K^0_S\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	[51]	Run 1	As before
$D^0 \to K^0_S\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	[52]	Run 2	As before
$D^0 \to K^0_S\pi^+\pi^-$ (μ^- tag)	x_{CP}, y_{CP}, Δx, Δy	[17]	Run 2	**New**

New γ combination

LHCb-CONF-2022-003;
update to [JHEP 12(2021)141]

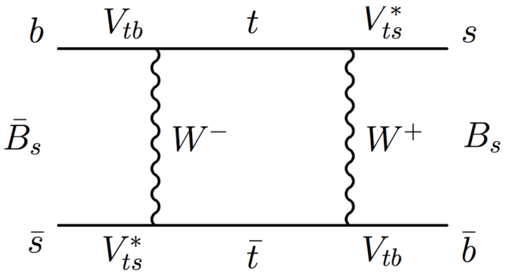
- Most precise single experiment determination $\gamma = (63.8^{+3.5}_{-3.7})^{\circ}$
- Agrees with previous result and global fits: $\gamma_{\mathrm{UTFit}} = (65.8 \pm 2.2)^{\circ}$, $\gamma_{\mathrm{CKMFitter}} = (65.5^{+1.1}_{-2.7})^{\circ}$
- Tension between $\mathbf{B^+}$ and $\mathbf{B^0}/\mathbf{B^0_s}$ modes remains (around 2σ)

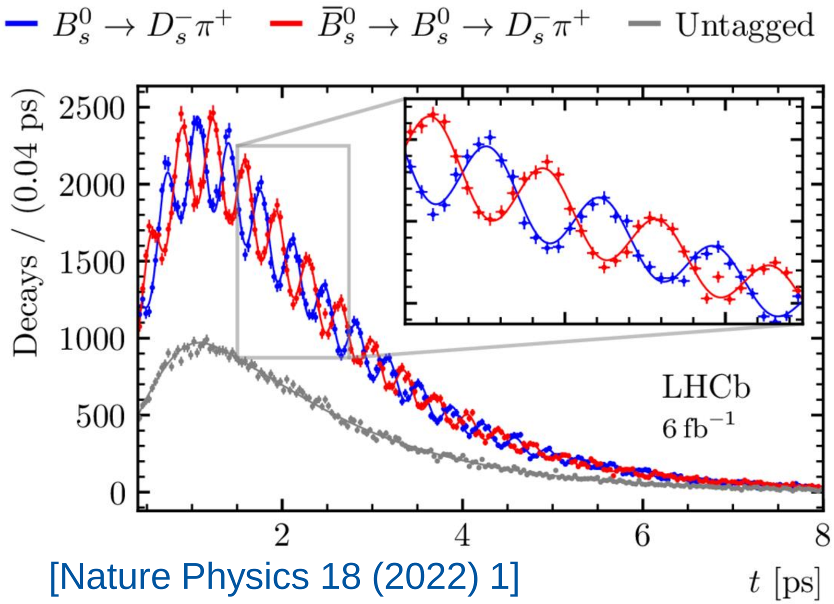




B_s^0 mixing

- Neutral B_s^0 mass(~CP) eigenstates characterised by sizeable difference in decay width and mass!
  $\Delta\Gamma_s/\Gamma_s = 0.124 \pm 0.008$, $\Delta m_s/\Gamma_s \approx 30$
- To **measure oscillation**, need to know **B_s^0 state at production (flavour tagging)** and **B_s^0 state at decay**!
- Recent LHCb measurement of Δm_s uses $B_s^0 \to D_s^- \pi^+ / \overline{B}_s^0 \to D_s^+ \pi^-$:
  B_s^0 state at decay fixed by final state
- **Most precise measurement of Δm_s**
  $\Delta m_s = 17.7683 \pm 0.0051 \pm 0.0032\ ps^{-1}$ ps



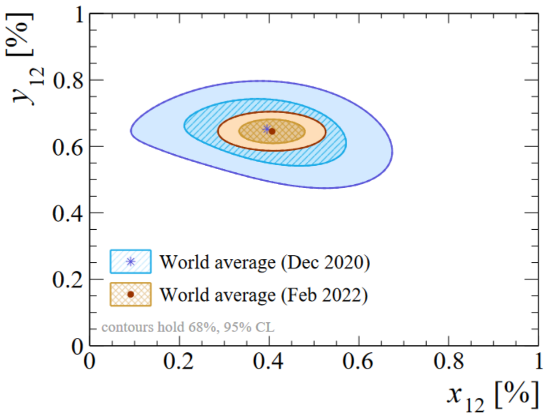


[Nature Physics 18 (2022) 1]

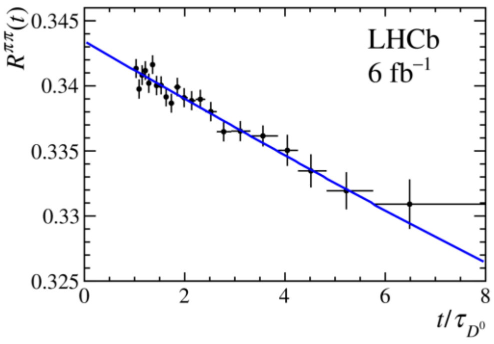
Charm mixing

[PRL 127 (2021) 111801, PRD 105 (2022) 092013]

- Until very recently (2020), no observation yet of charm mixing (**extremely difficult**)
- Recent measurements have observed mass $\left(D^0 \to K_S^0\pi^+\pi^-\right)$, lifetime difference



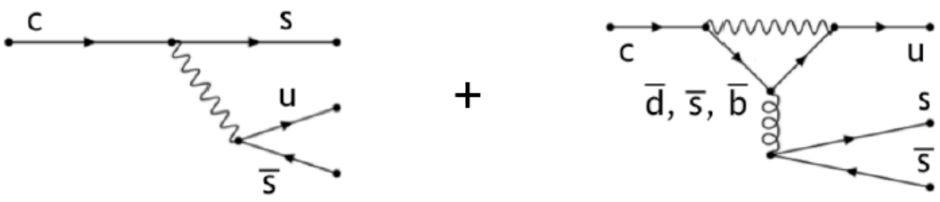
- **New measurement today: very precise determination of lifetime difference**
- Study two-body D^0-meson decays
- Decay $D^0 \to K^-\pi^+$ is CP-mixed state: $\tau(D^0 \to K^-\pi^+) \approx 1/\Gamma$
- Decay $D^0 \to h^+h^-$ $(h \in [\pi, K])$ is CP-even state $\tau(D^0 \to h^-h) < \tau(D^0 \to K^-\pi^+)$
- **From difference in lifetimes determine** $\boldsymbol{y = \frac{\Delta\Gamma}{\Gamma} = (6.96 \pm 0.26 \pm 0.13) \times 10^{-3}}$



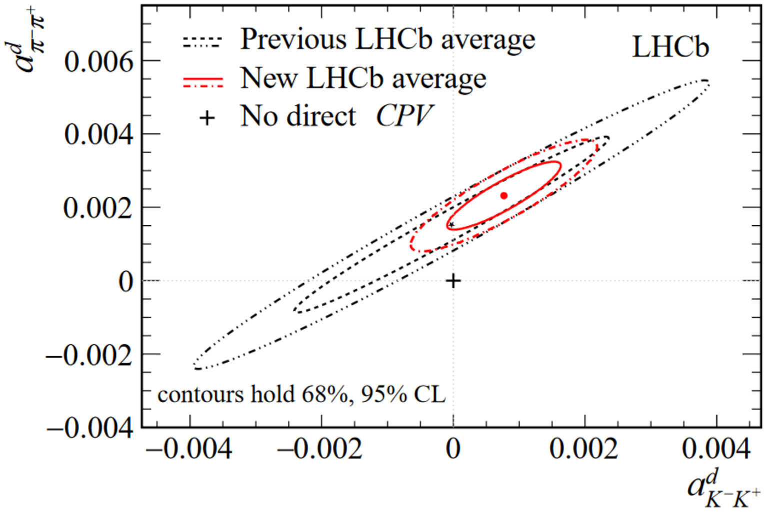
Charm CPV

[PRL 122 (2019) 211803]; [arXiv:2209.03179]

- Unique test of CP violation (up-type quarks), asymmetries $\leq 0.1\%$!
- Uncertainties dominated by long-distance contributions
- Interferences between tree and penguin diagrams
- **CPV discovery in charm in 2019:** difference in time-integrated CP asymmetries comparing $D^0 \to K^+K^-, D^0 \to \pi^+\pi^-$
- New today: dedicated time-integrated asymmetry in $D^0 \to K^+K^-$



$$a^d_{K^-K^+} = (7.7 \pm 5.7)\times 10^{-4} \quad (1.4\sigma)$$
$$a^d_{\pi^-\pi^+} = (23.2 \pm 6.1)\times 10^{-4} \quad (3.8\sigma)$$



Summary

LHCb has provided stringent tests of CP violation and CKM matrix

- Strongest constraints on CKM angle γ (closing the triangle)
- Most precise mixing measurement Δm_s
- Observation of mixing and CP violation in charm decays

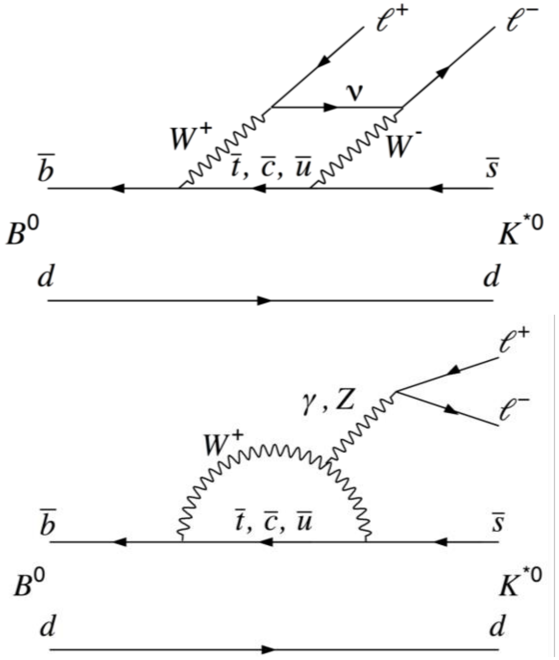
But also unique measurements in:

- $\mathrm{B}_s^0 \rightarrow \mathrm{J}/\psi\phi$: world-leading β_s (angle in B_s^0 unitarity triangle)
- CP violation in mixing with semileptonic $B_{(s)}^0$ decays
- $|\mathrm{V}_{\mathrm{ub}}|, |\mathrm{V}_{\mathrm{cb}}|$ tests with semileptonic decays ($\mathrm{B}_s^0, \Lambda_\mathrm{b}^0 \rightarrow \mathrm{X}_{\mathrm{u,c}}\mu\nu$)

Rare decays and lepton universality

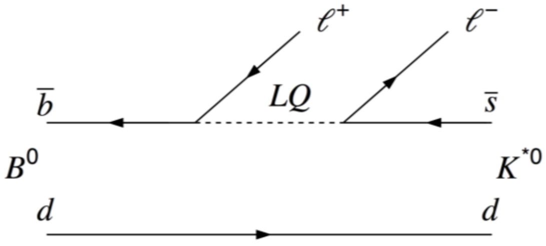
Rare B decays: $b \to s(d)ll$

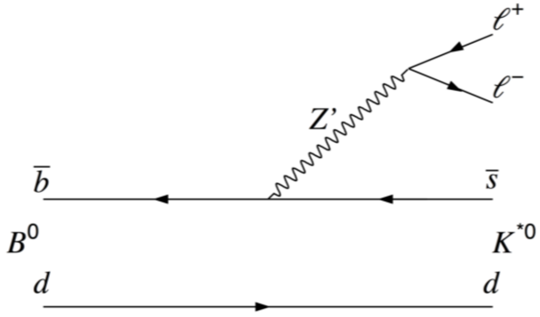
- Test Standard Model with weak interaction loop diagrams (Flavour Changing Neutral Currents)



Rare B decays: $b \to s(d)ll$

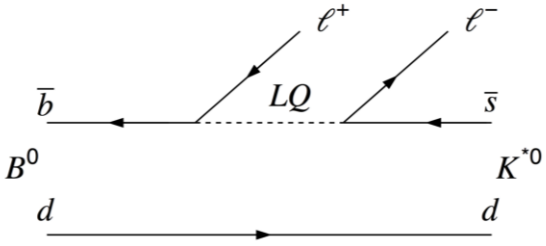
- Test Standard Model with weak interaction loop diagrams (Flavour Changing Neutral Currents)
- Transition uncommon in Standard Model, **sensitive to small contributions from heavy new particles**!

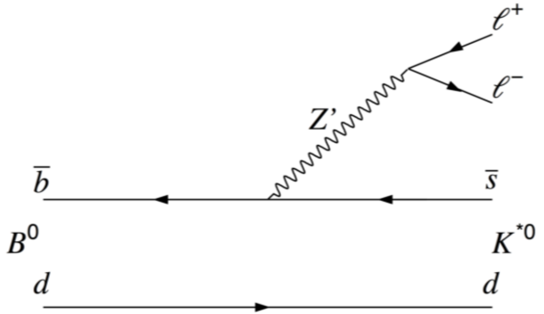




Rare B decays: $b \to s(d)ll$

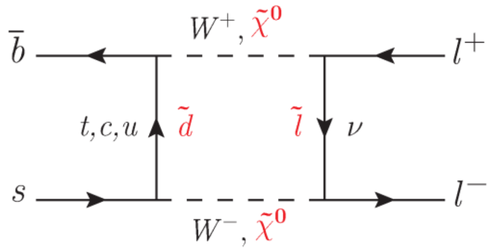
- Test Standard Model with weak interaction loop diagrams (Flavour Changing Neutral Currents)
- Transition uncommon in Standard Model, **sensitive to small contributions from heavy new particles**!
- Observables:
  - Branching fractions
  - Angular distributions
  - Lepton universality
- Large variety of channels and observables (many B hadrons with many decay modes)





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

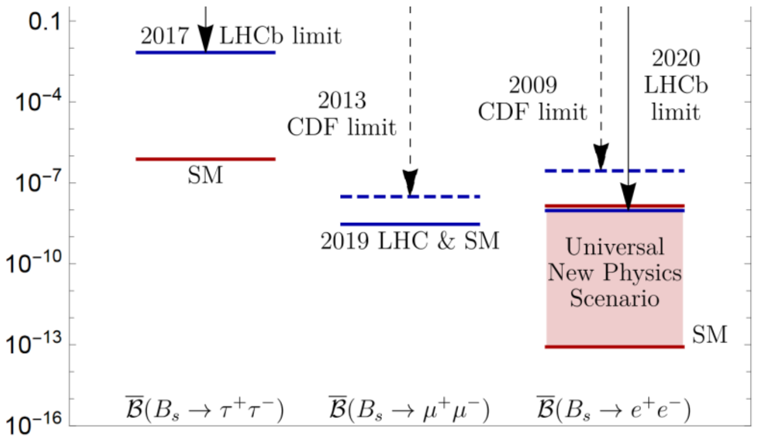
- Excellent decays to study $b \to s(d)ll$ transition
  - **Precise theory predictions (4% uncertainty)**
  - Helicity suppression: **very rare in SM**
  - **Scalar contributions not helicity suppressed → enhanced relative to SM!**
- Only $B^0_{(s)} \to \mu^+\mu^-$ in current experimental reach



Fleischer et al., JHEP 05 (2017) 156

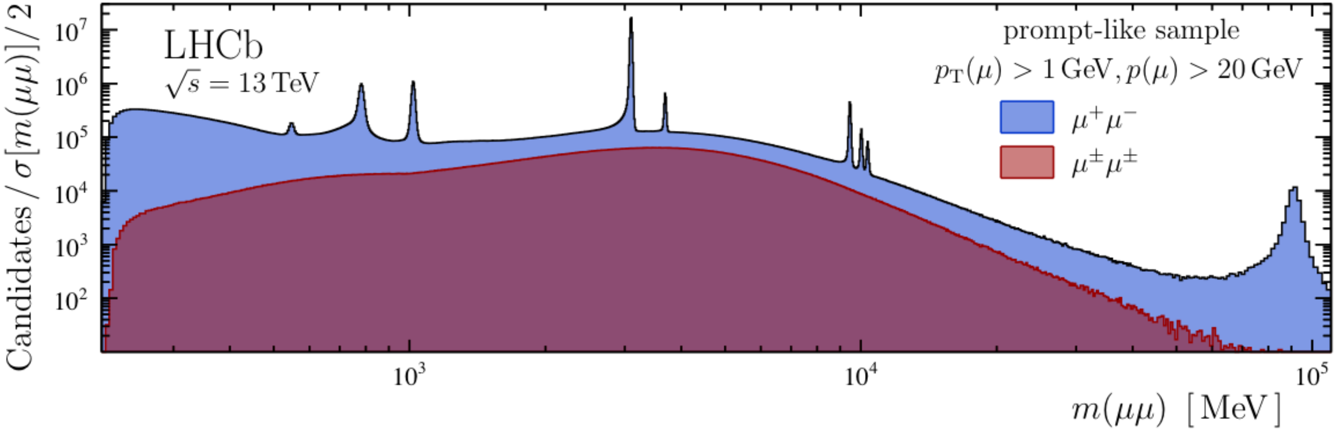
Bobeth et al. PRL 112 (2014) 101801
Beneke et al. JHEP 10 (2019) 232

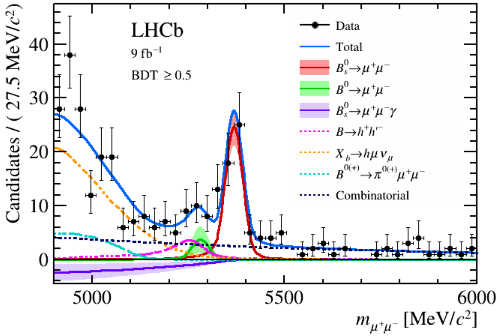
- Predictions
  - $B(B^0_s \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$
  - $B(B^0 \to \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}$
  - $\frac{B(B^0 \to \mu^+\mu^-)}{B(B^0_s \to \mu^+\mu^-)} = 0.0281 \pm 0.0006$ (extra clean test)



Searching for $B_s^0 \to \mu^+\mu^-$

[PRL 120 (2018) 061801]



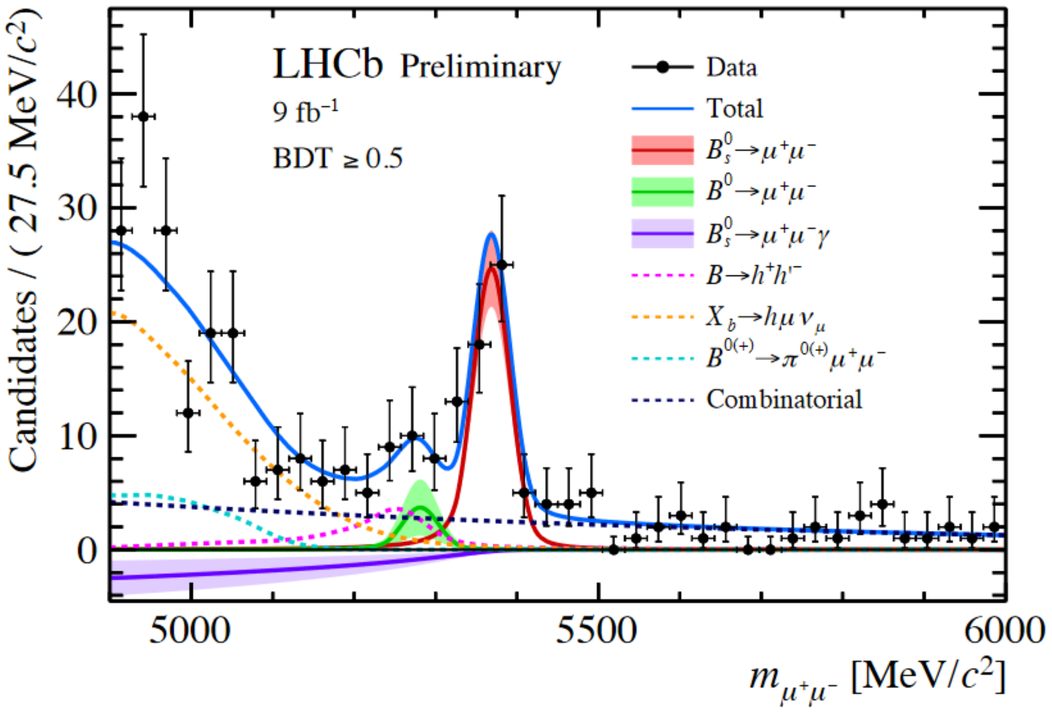


Branching fraction of $B_s^0 \to \mu^+\mu^-$

[LHCb-PAPER-2021-007]

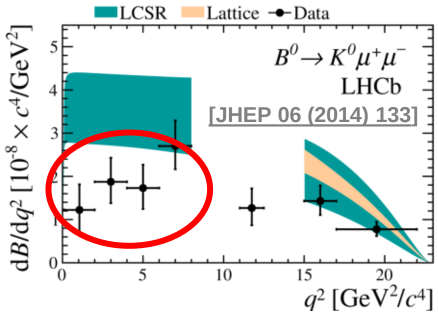
- $\boldsymbol{B(B_s^0 \to \mu^+\mu^-)} =$ $\boldsymbol{(3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9}}$ **with significance > 10σ**
- **Similar uncertainty to previous LHC combination**

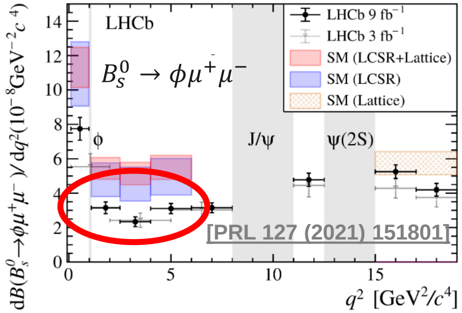
- $B^0 \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-\gamma$ compatible with background-only at 1.7σ, 1.5σ
- Measurement of $\tau(B_s^0 \to \mu^+\mu^-)$ is testing CP state of decay (more data needed)

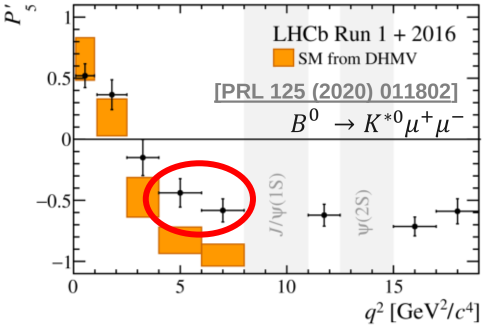


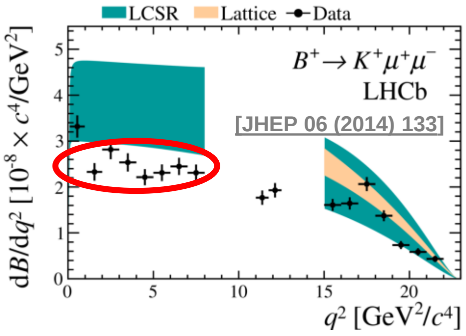
Semileptonic rare B decays: anomalies

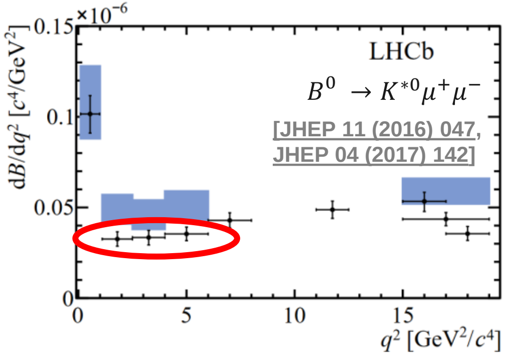
Measurements of semileptonic rare B decays deviate from predictions….

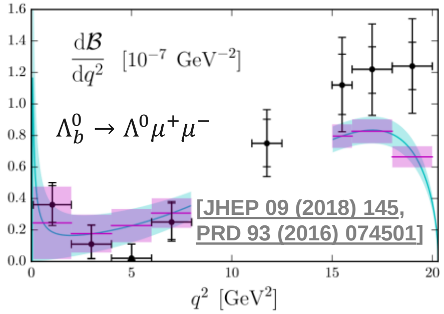










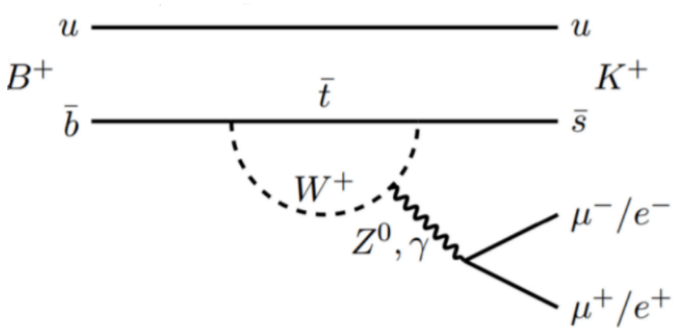


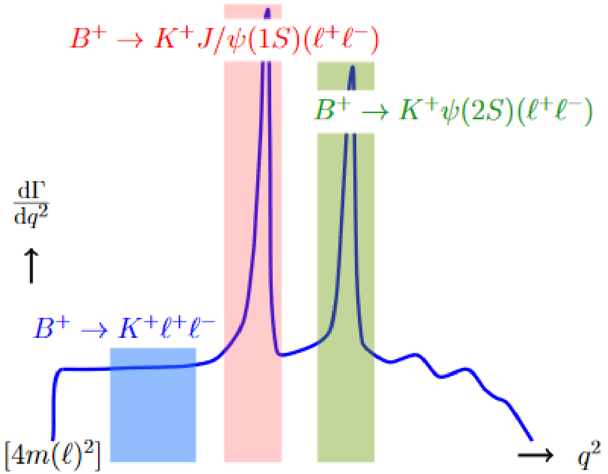
Note: consistent deviations (interpreted in EFT framework, see backup)

[Nature Physics 18 (2022) 277-282]

Lepton universality and R_K

- **Lepton universality: only difference between muons, electrons is mass**
- Strong test of lepton universality with $R_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e)} \cong 1$ (in SM) for $q^2 > 0.1\ \mathrm{GeV}$
- Uncertainty of $O(1\%)$ in SM (from QED)
- **Any significant deviation in R_K is clear sign of New Physics**

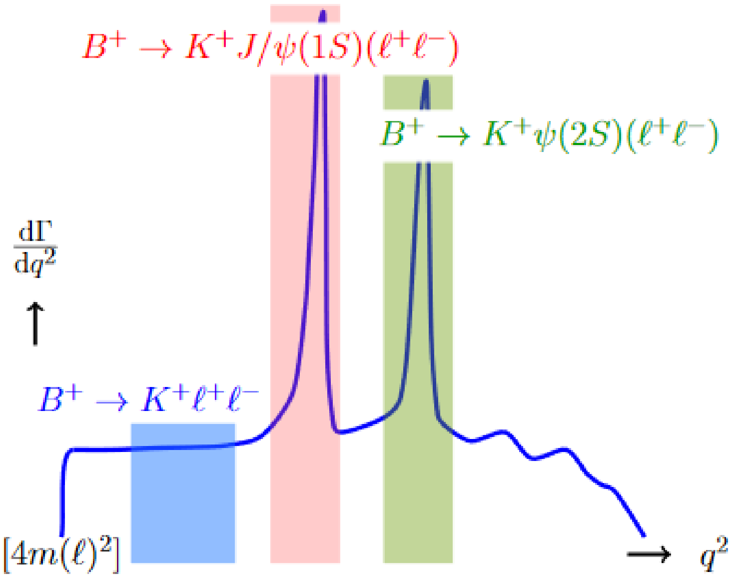




Lepton universality strategy

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+J/\psi(\mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to K^+J/\psi(e^+e^-))} = \frac{N^{\mathrm{rare}}_{\mu^+\mu^-}\ \varepsilon^{J/\psi}_{\mu^+\mu^-}}{N^{J/\psi}_{\mu^+\mu^-}\ \varepsilon^{\mathrm{rare}}_{\mu^+\mu^-}} \times \frac{N^{J/\psi}_{e^+e^-}\ \varepsilon^{\mathrm{rare}}_{e^+e^-}}{N^{\mathrm{rare}}_{e^+e^-}\ \varepsilon^{J/\psi}_{e^+e^-}}$$

- **Electrons behave very differently from muons at LHCb! (material interactions → missing momentum)**
- **Measure R_K as double ratio (relative to $B^+ \to K^+ J/\psi$)**
- Rare and J/ψ modes share identical selections but for q^2
- J/ψ modes also used for calibration
- **Essential to validate with cross-checks!**



[Nature Physics 18 (2022) 277-282]

Cross-checks: $r_{J/\psi}$ and $R_{\psi(2S)}$

- **To ensure efficiencies are well calibrated, determine single ratio:**

$$r_{J/\psi} = \frac{\mathcal{B}(B^+ \to K^+ J/\psi(\mu^+\mu^-))}{\mathcal{B}(B^+ \to K^+ J/\psi(e^+e^-))} = 1$$

known to hold within 0.4%

- **Requires direct control of muons versus electrons**
- Result:

$$r_{J/\psi} = 0.981 \pm 0.020\ (\text{stat} + \text{syst})$$

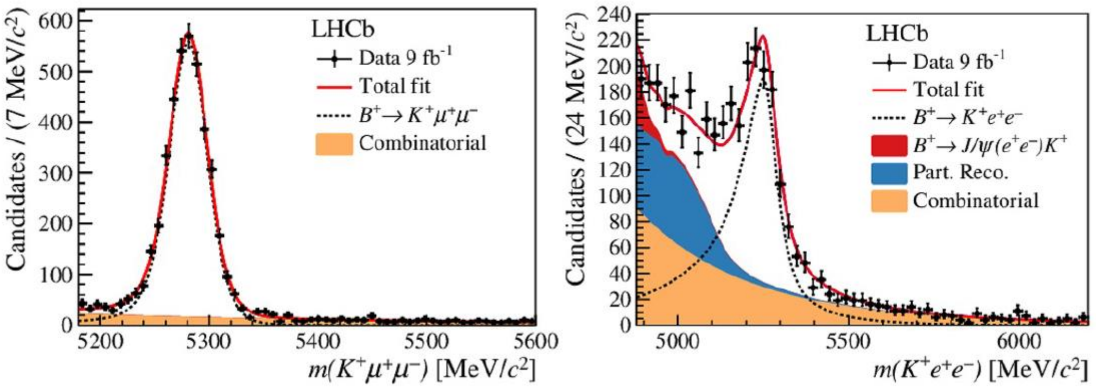
compatible with expectation per subsample

- Additional checks: $r_{J/\psi}$ does not vary versus variables of interest, double ratio of $\psi(2S)$ wrt J/ψ: $R_{\psi(2S)} = 0.997 \pm 0.011\ (\text{stat} + \text{syst})$

R_K results

- R_K measured with double ratio $\frac{N^{\text{rare}}_{\mu^+\mu^-}}{N^{J/\psi}_{\mu^+\mu^-}}\frac{\varepsilon^{J/\psi}_{\mu^+\mu^-}}{\varepsilon^{\text{rare}}_{\mu^+\mu^-}} \times \frac{N^{J/\psi}_{e^+e^-}}{N^{\text{rare}}_{e^+e^-}}\frac{\varepsilon^{\text{rare}}_{e^+e^-}}{\varepsilon^{J/\psi}_{e^+e^-}}$

$$\boldsymbol{R_K = 0.846^{+0.042+0.013}_{-0.039-0.012}}$$

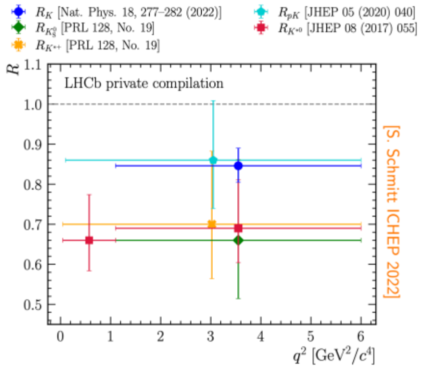


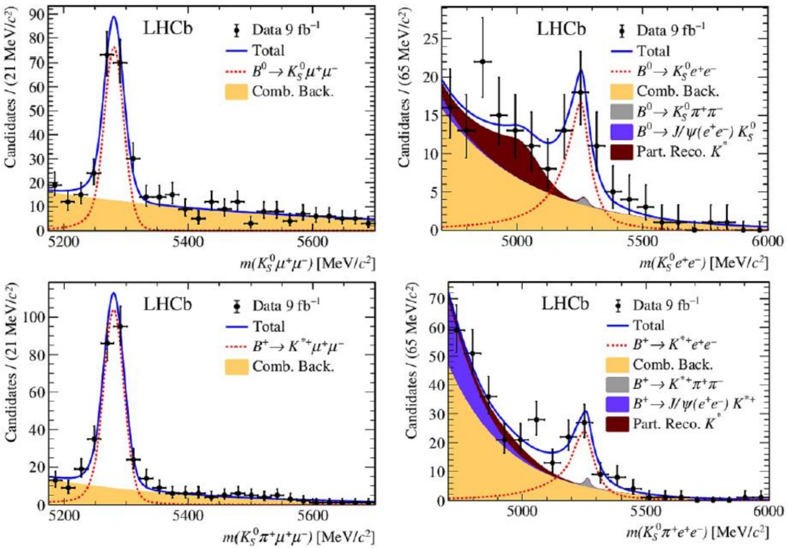
- Systematic uncertainties (~1%) from fit model, calibration samples size
- Evidence of LFU breaking with significance of 3.1σ
- Determined using $\mathrm{B}(B^+ \to K^+\mu^+\mu^-)$ measurement, $\mathrm{B}(B^+ \to K^+e^+e^-)$ is fully consistent with SM → **New Physics only affects muons!**

$R_{K_S^0}$ and $R_{K^{*+}}$

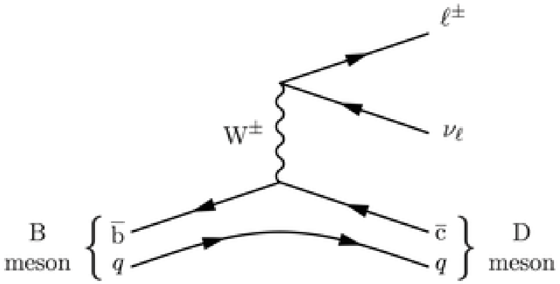
[PRL 128 (2022) 191802]

- Tests of lepton flavour universality with $b \to s l^+ l^-$ decays (μ/e)
- $R_{K_S^0} = 0.66^{+0.20}_{-0.15}(\text{stat})^{+0.02}_{-0.04}(\text{syst})$
- $R_{K^{*+}} = 0.70^{+0.18}_{-0.13}(\text{stat})^{+0.03}_{-0.04}(\text{syst})$
- Both around 1.5σ from SM $(= 1)$
- Consistent deviations from SM; more coming up!





Semileptonic decays & LFU



- Semileptonic $b \to cl\nu$ most common decay mode!
- **Include neutrino in final state → missing mass**
- Still, used at LHCb for
  - b-hadron production measurements
  - Mixing and CP violation tests
  - $|V_{ub}|, |V_{cb}|$ measurements
- **Test lepton universality: τ vs. μ, e rates**

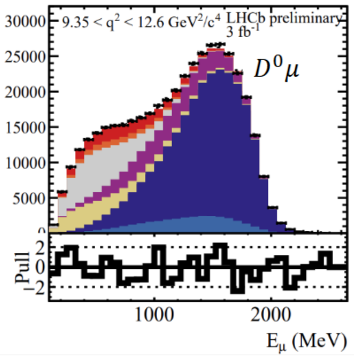
$$R(D^{(*)}) \equiv \frac{\mathcal{B}(\bar{B}^0 \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{(*)}\mu^-\bar{\nu}_\mu)}$$

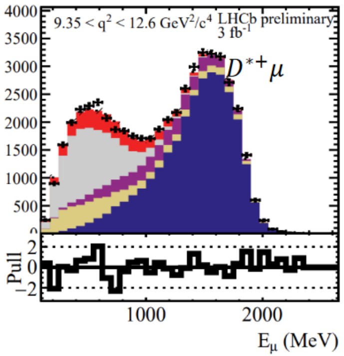
- Precise SM prediction available
- **By definition τ will decay at least 1 neutrino: more missing mass**
- LHCb does $\tau^- \to \mu^-\nu_\tau\bar{\nu}_\mu$ or $\tau^- \to 3\pi^-\nu_\tau$

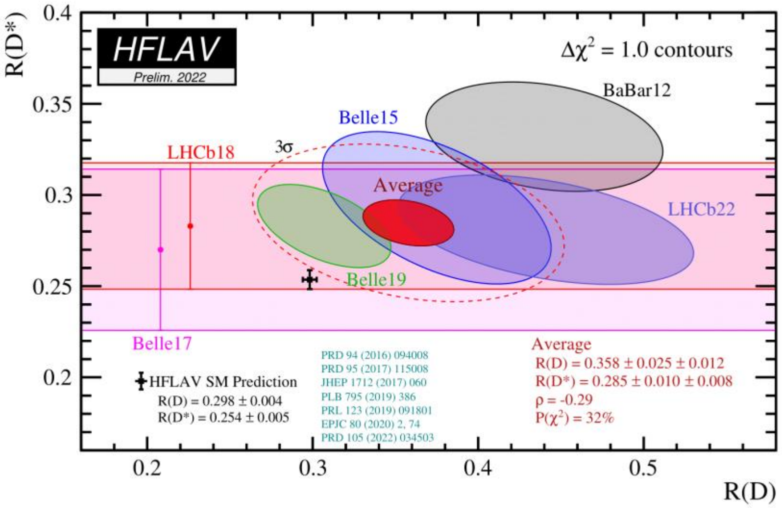
$R(D) - R(D^*)$ leptonic

LHCb-PAPER-2022-039,
in preparation

- Simultaneous $R(D), R(D^*)$ determination with Run 1 data
- Uses $\tau^- \to \mu^- \nu_\tau \bar{\nu}_\mu$,
  very challenging (3 neutrinos)!
- Multidimensional fit in
  3 variables (m^2_{miss}, E_μ, q^2)
- $R(D^*) = 0.281 \pm 0.018 \pm 0.024$
  $R(D) \; = 0.441 \pm 0.060 \pm 0.066$
- By itself 1.9σ from SM predictions,
  preliminary average $3.3\sigma \to 3.2\sigma$
- Work on extension to Run 2 ongoing



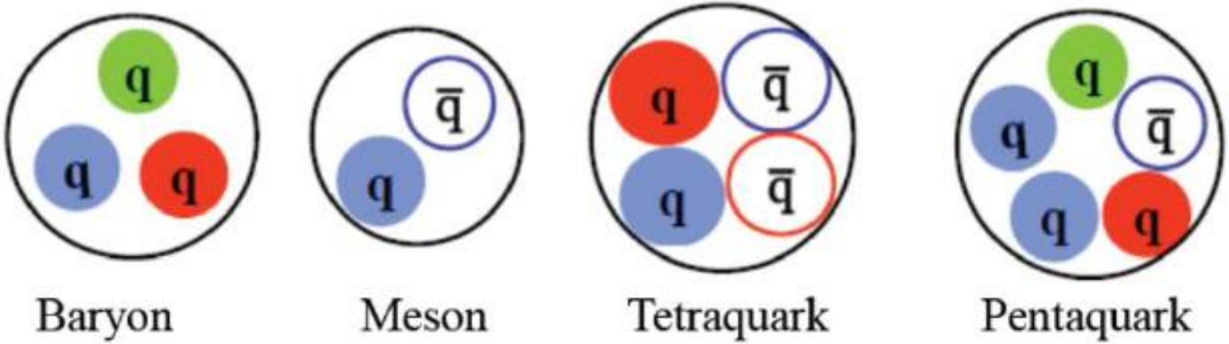




Summary

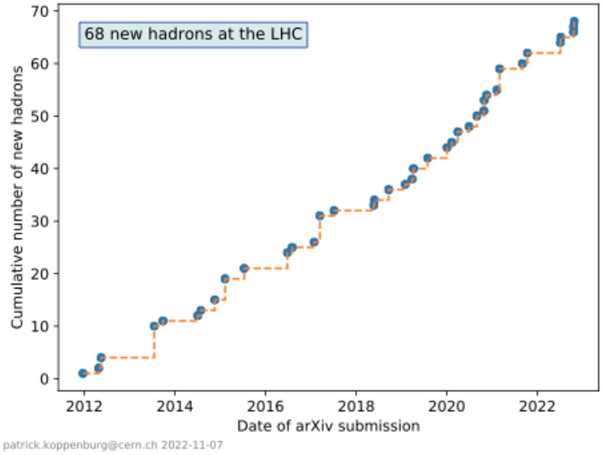
- Deviations found in $b \to s\mu\mu$ decays
  (branching fraction and angular observables)
- Lepton universality deviations in
  semileptonic loop-level decays: $b \to see/b \to s\mu\mu$;
  (consistent with New Physics in $\mathrm{b} \to s\mu\mu$ only)
  semileptonic tree-level decays: $b \to c\tau\nu/b \to cl\nu$;
  (consistent with New Physics in $b \to c\tau\nu$ only)
- Consistent interpretations possible (with EFT)
- Eagerly awaiting new results…
- (and much more done: strange decays; LFV, BNV and LNV;)

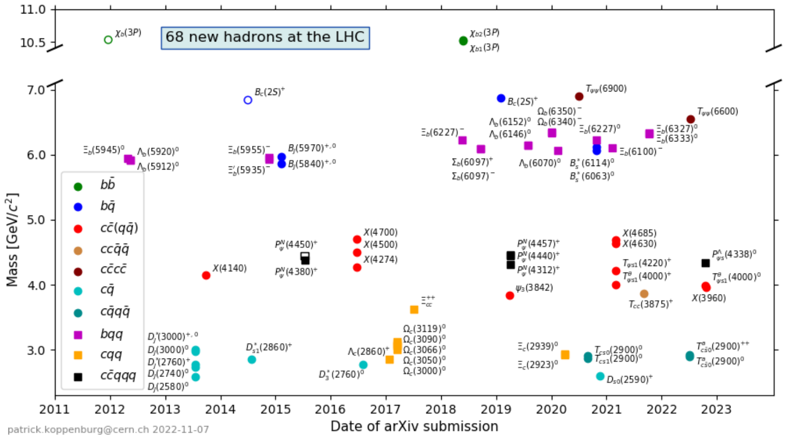
Spectroscopy and exotic hadrons



Spectroscopy

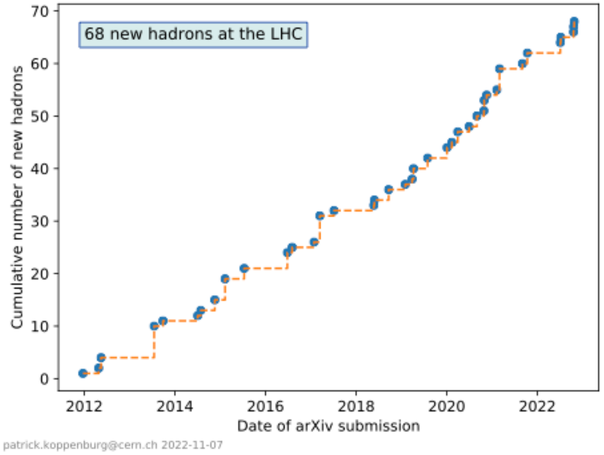
- Many new hadrons discovered at LHC: 68 total, 60 at LHCb

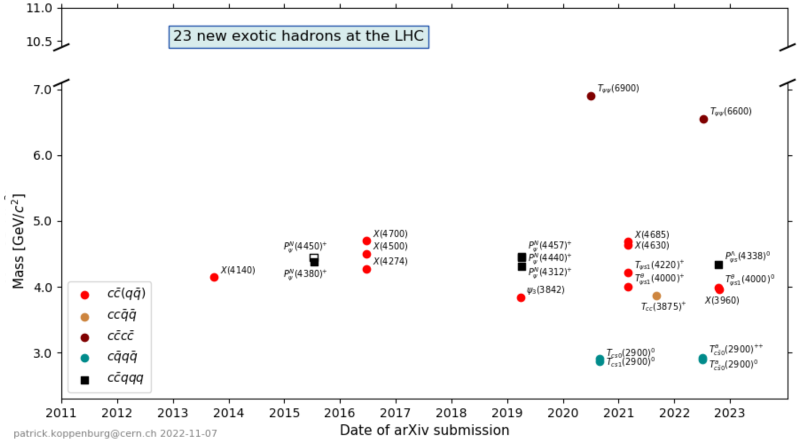




Spectroscopy

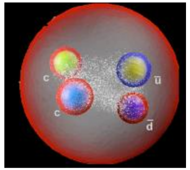
- Many new hadrons discovered at LHC: 68 total, 60 at LHCb

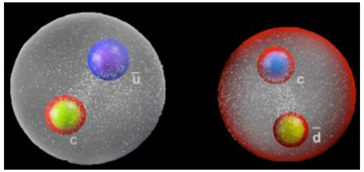




- **23 new hadrons are exotic states: tetra- or pentaquarks.**
- Nature of exotic states still unclear:
  tightly or loosely-bound (hadronic molecule)?
- Key to study of non-perturbative QCD
- New naming scheme proposed by LHCb: [arXiv:2206.1523]

tightly or loosely-bound?

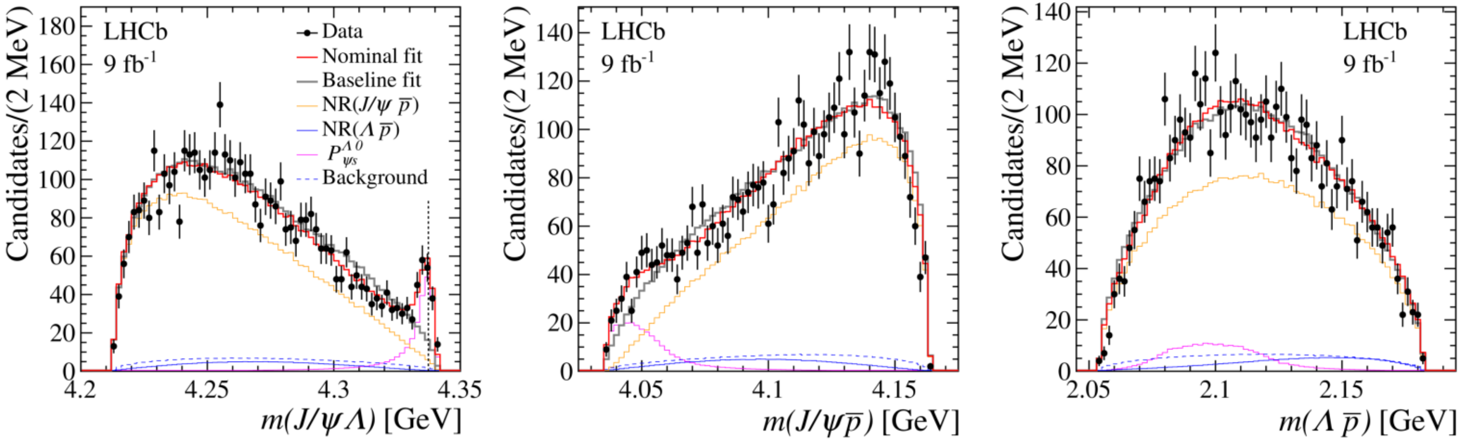




Pentaquark in $B^0 \to J/\psi\Lambda\bar{\mathrm{p}}$

[arXiv:2210.10346]

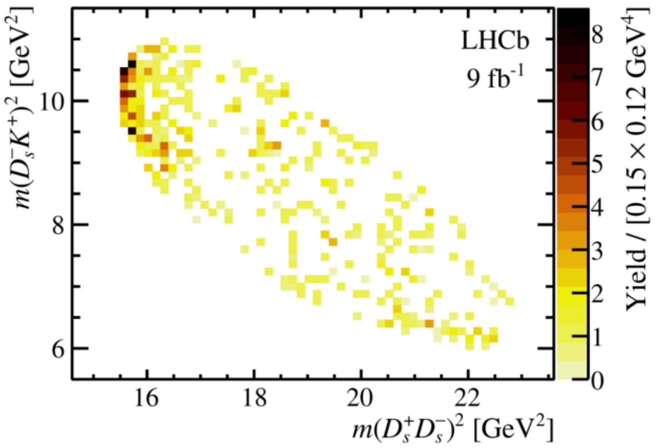
- Amplitude analysis of 4400 $B^0 \to J/\psi\Lambda\bar{\mathrm{p}}$ candidates
- Resonance near $\Xi_c^+ D^-$ threshold observed: $P_{\psi s}^{\Lambda}(4438)^0$
- Minimal quark content $c\bar{c}sud$: **first observation of strange pentaquark**

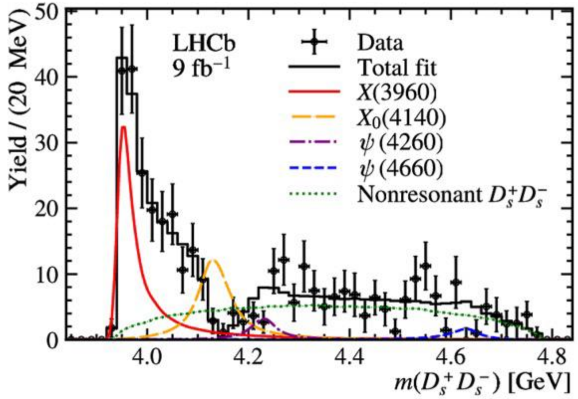


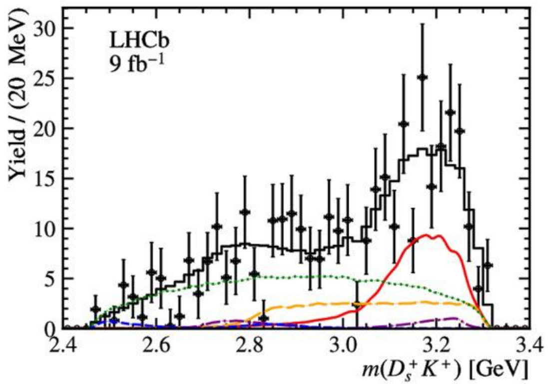
Tetraquark in $B^+ \to D_s^+ D_s^- K^+$

[arXiv:2210.15153]

- Amplitude analysis of 360 $B^+ \to D_s^+ D_s^- K^+$ candidates
- X(3960) resonance near $D_s^+ D_s^-$ threshold; consistent with $c\bar{c}s\bar{s}$
- X(4140) causes dip in mass (interference)



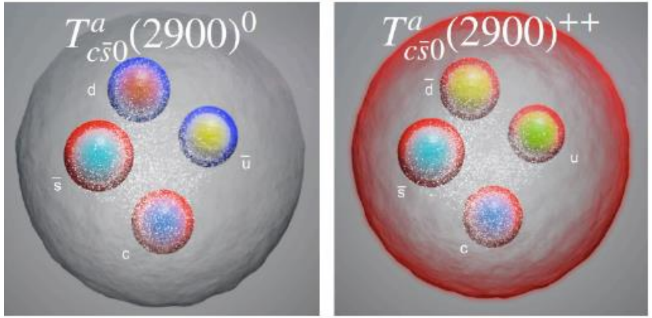


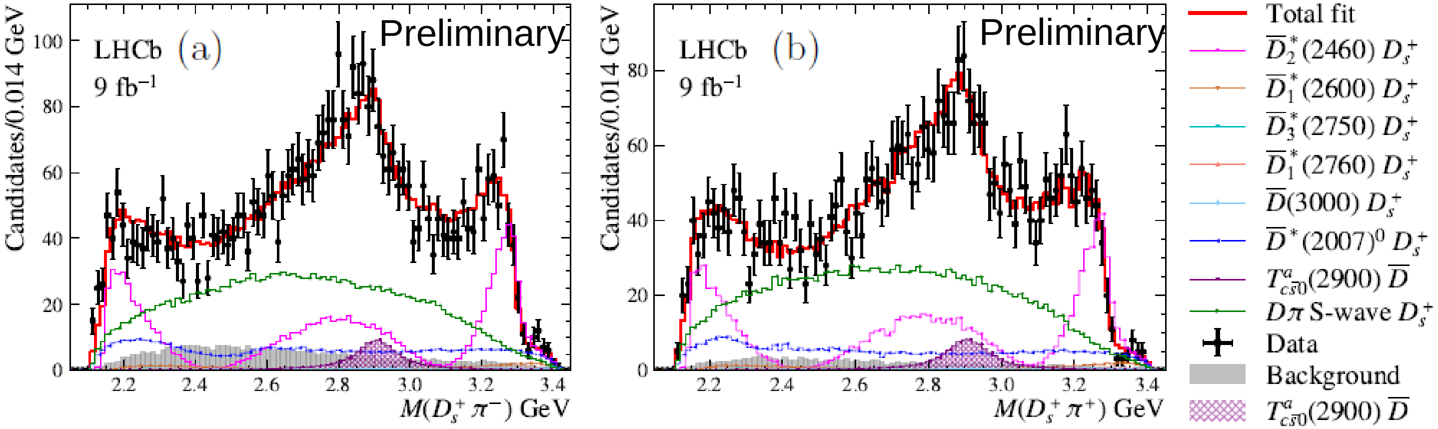


New tetraquarks

LHCb-PAPER-2022-026,
LHCb-PAPER-2022-027,
in preparation

- Amplitude analysis of $B^+ \to D^- D_s^+ \pi^+, B^0 \to \overline{D}^0 D_s^+ \pi^-$
- Observed isospin pair $T^a_{c\bar{s}0}(2900)^0, T^a_{c\bar{s}0}(2900)^{++}$
- **First tetraquarks containing $c\bar{s}\bar{u}d, c\bar{s}u\bar{d}$**
- Significance >9σ, Spin-parity: $J^P = 0^+$, M~2.9 GeV, Γ~136MeV

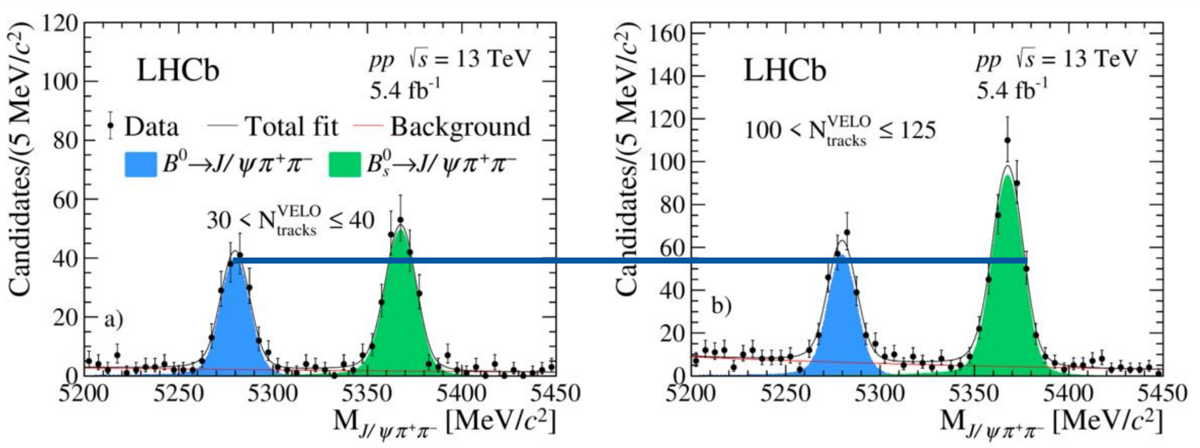




B hadron production

LHCb-PAPER-2022-001

- First test of B hadron production dependence on occupancy
  - Previously encountered in charm hadrons (ALICE)
  - Sample divided in number of VELO tracks
  - Use B_s^0, and B^0 hadrons decaying to same final state $J/\psi\pi^+\pi^-$
- **Observation of dependence of B_s^0/B^0 production on occupancy!**



Summary

- Many new regular and exotic states observed at LHC(b)!

- Interpretation of many states still unclear,
goal is to fill up this exotic particle zoo to find answers!

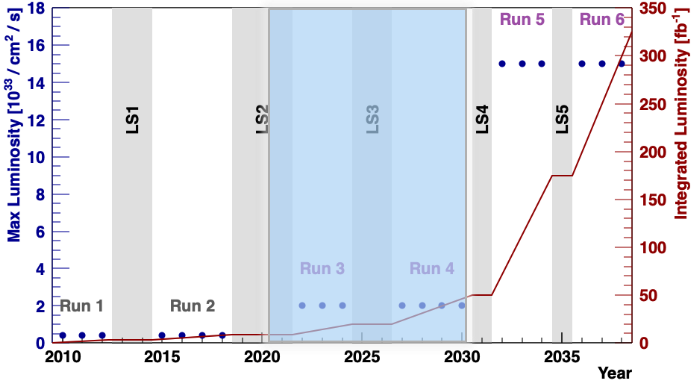
- Interesting results also on hadron production
(e.g. observations of B_s^0/B^0 and $X(3872)/\psi(2S)$ production dependence on multiplicity)

LHCb detector upgrades

LHCb Upgrade 1

Goals:

- **Luminosity increase by factor 5**;
  collect additional $14\ \mathrm{fb}^{-1}$ by 2025, $41\ \mathrm{fb}^{-1}$ by 2031
- **Hardware trigger removed →**
  2x efficiency in hadronic/electronic modes



Requires

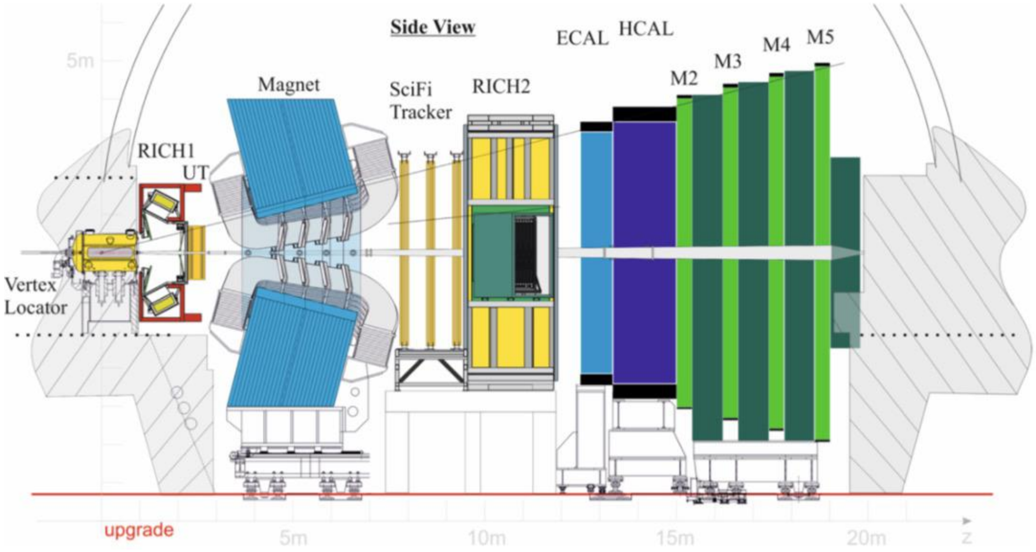
- Upgrade of most detectors (higher granularity)
- Full readout and DAQ replacement to read out detector at 40 MHz

Installation completed, commissioning ongoing

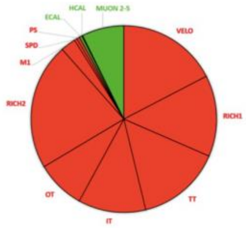
LHCb Upgrade 1 detector

CERN-LHCC-2011-001

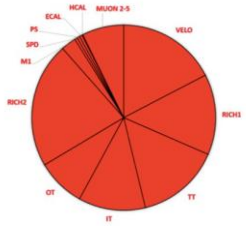
A whole new detector!



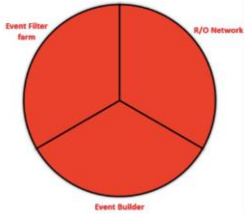
Detector channels



Readout

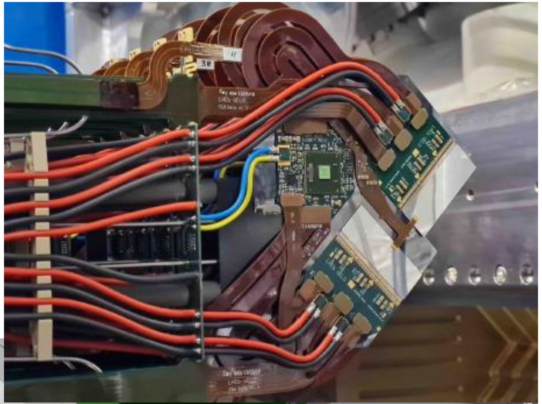


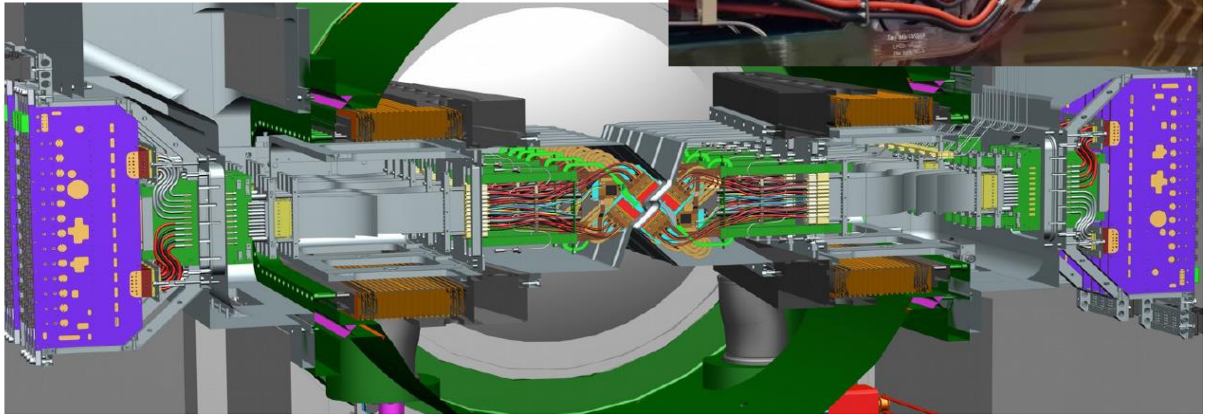
DAQ



VELO

CERN-LHCC-2013-021

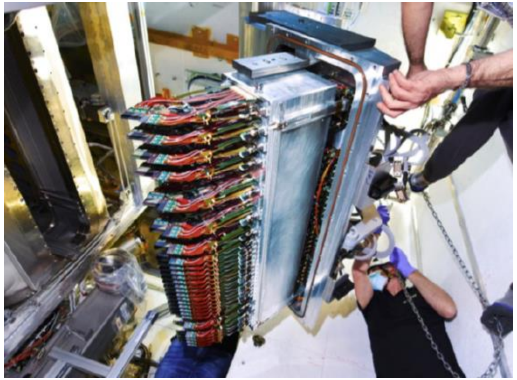




- **New pixel detector** (replacing strips)
- 52 modules, 41M pixels, 55x55 μm^2; dedicated ASIC (read out at 40 MHz)
- Within vacuum of LHC beam pipe; 2 moveable halves (5.1 mm from beam closed, 30 mm open)
- Dedicated RF foil for protection
- Microchannel CO2 cooling (-30 c)
- Very radiation hard
- Data rate: 3 Tbit/s

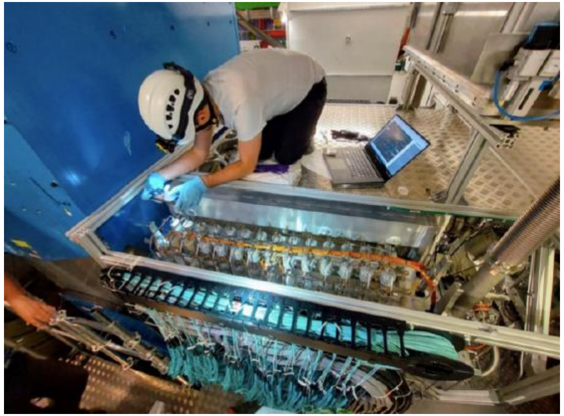
VELO

CERN-LHCC-2013-021



Ongoing commissioning:

- Installed in March, May 2022
- In-situ ASIC calibration, spatial + time alignment
- Tracks, vertices and beam position reconstructed
- **Closed for first time end of October**

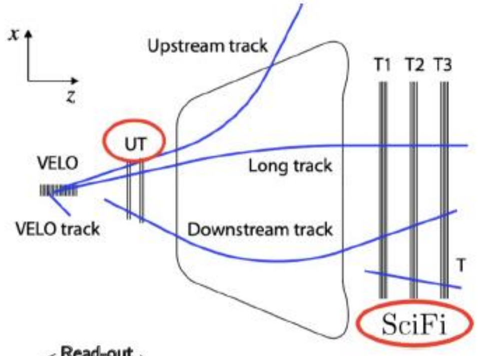


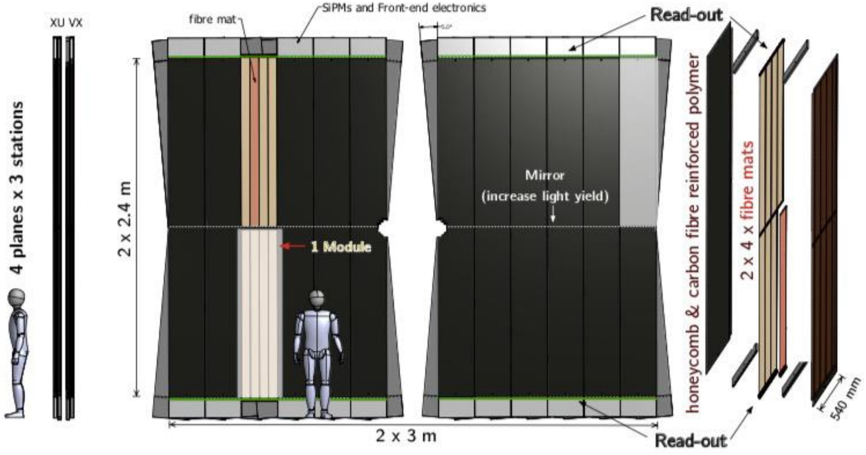
SciFi

CERN-LHCC-2014-001

Scintillating Fibretracker developed for high occupancy

- Fibres of 250 mum of 2.5m length
- Read out by Silicon Photomultipliers cooled to -40 C (!)
- 128 modules (0.5 x 5 m), arranged in 12 planes.
- Each plane has 30 m2.
- Spatial resolution 80 µm
- Hit efficiency > 99%.

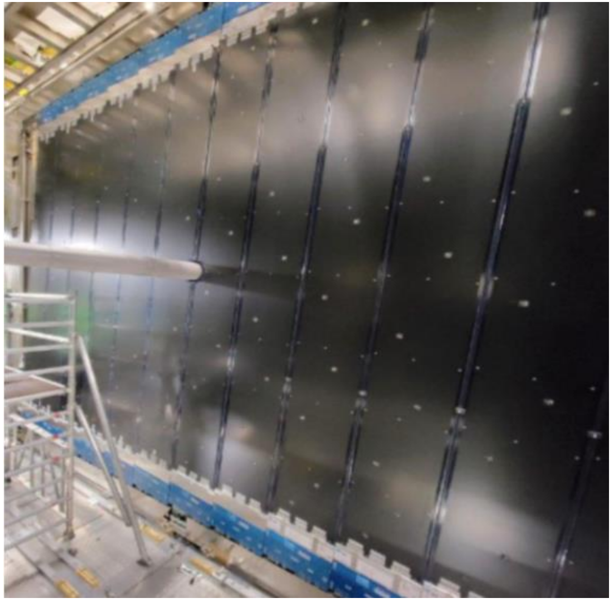




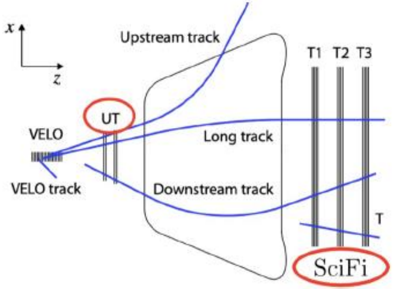
SciFi

CERN-LHCC-2014-001

- The Scintillating Fibre tracker was installed and is being commissioned:
  - Very stable, working on alignment
  - **Participates in global data taking**

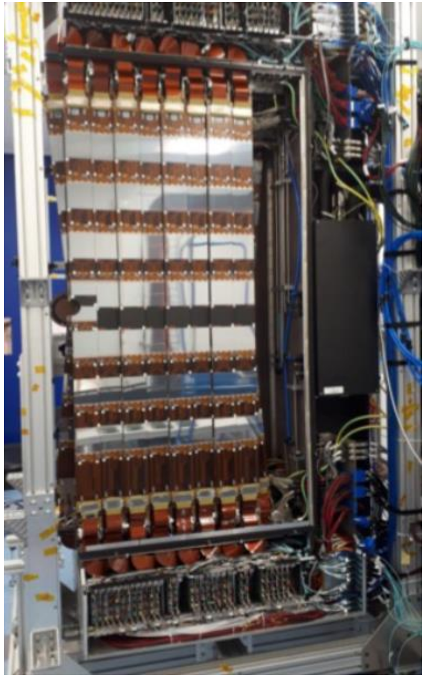


Upstream Tracker



CERN-LHCC-2014-001

- 4 planes made of **silicon strips** with finer segmentation and improved acceptance
- Reconstruction role:
  - Fast pT determination for track extrapolation, reduce ghost tracks
  - Detect long-lived particles decaying after VELO (K_S^0, Λ^0)
- 68 staves with silicon strips and integrated cooling
- 4 planes, vertical and —5°
- Half installed, assembly going on at the surface
- **Preparing services for installation, to finish early next year**

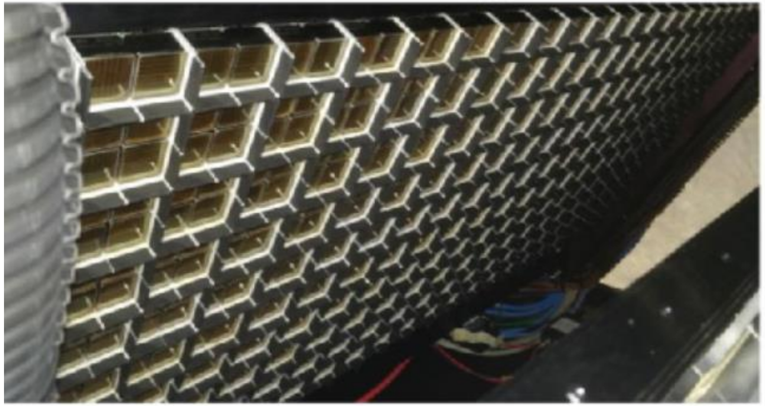


RICH1 and RICH2

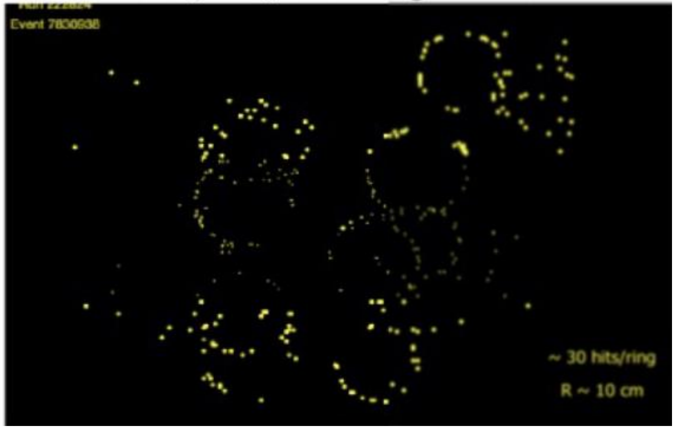
CERN-LHCC-2013-022

- Ring Imaging Cherenkov detctors: unique eparticle identification capability
  - RICH1: new mirrors with increased focal length, to halve the occupancy.
  - RICH1 and 2: new photodetectors MaPMTs with increased granularity, 40 MHz readout
  - Installation successfully completed in February.
  - Detectors commissioned, in global data taking

RICH1: MaPMTs installed upper side



RICH2: first rings acquired during LHC october test



Calorimeters and Muon

CERN-LHCC-2013-022

Present detectors withstand increased Run 3/4 luminosity

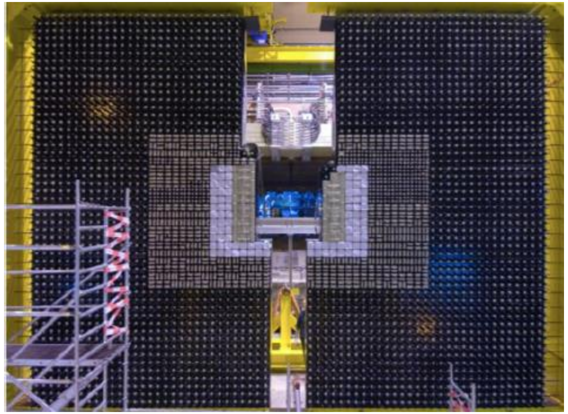
Shashlik calorimeters:

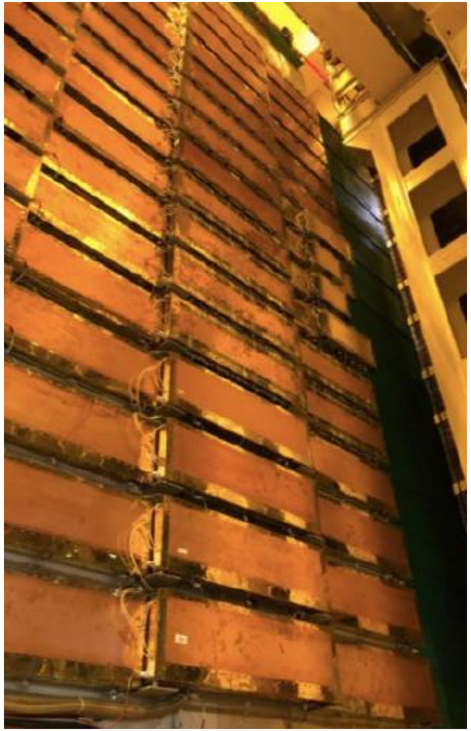
- PMT gain reduced to deal with higher occupancy
- New front-end electronics: improved S/N, 40 MHz readout

Muon stations:

- 4 walls equipped with MWPCs and interleaved with iron filters
- Front-end electronics upgraded for 40 MHz readout
- Granularity increased on first station to reduce occupancy

Both in global data taking





Plume and SMOG

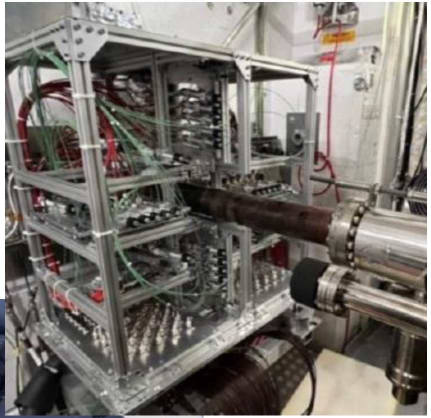
CERN-LHCC-2021-002

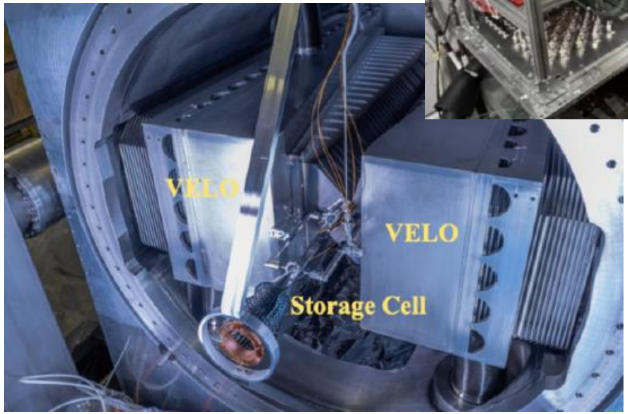
Probe for LUminosity MEasurement (PLUME): new dedicated luminometer

- Quartz tablets + PMTs for online+offline per-bunch luminosity measurement
- **Installed and taking data**

SMOG2 gas system for fixed-target physics

- New storage cell for the gas upstream of the nominal interaction point
- Gas density increased by up to two orders of magnitude → much higher luminosity
- Gas targets: He, Ne, Ar (+ possibly H2, D2, N2, Kr, Xe)
- Simultaneous p-p and p-gas data taking
- **First data taken at beginning of November!**



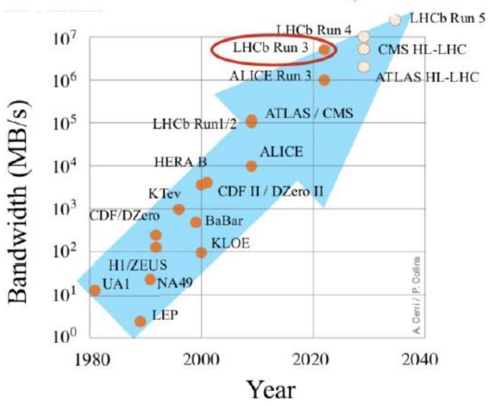


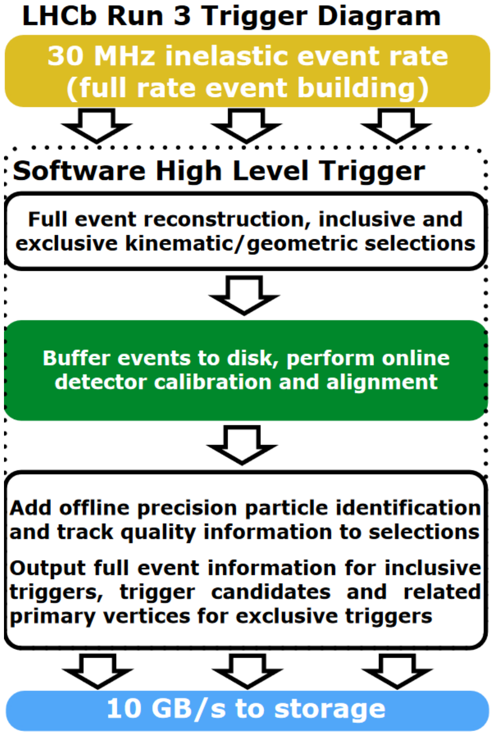
CERN-LHCC-2019-005

Trigger

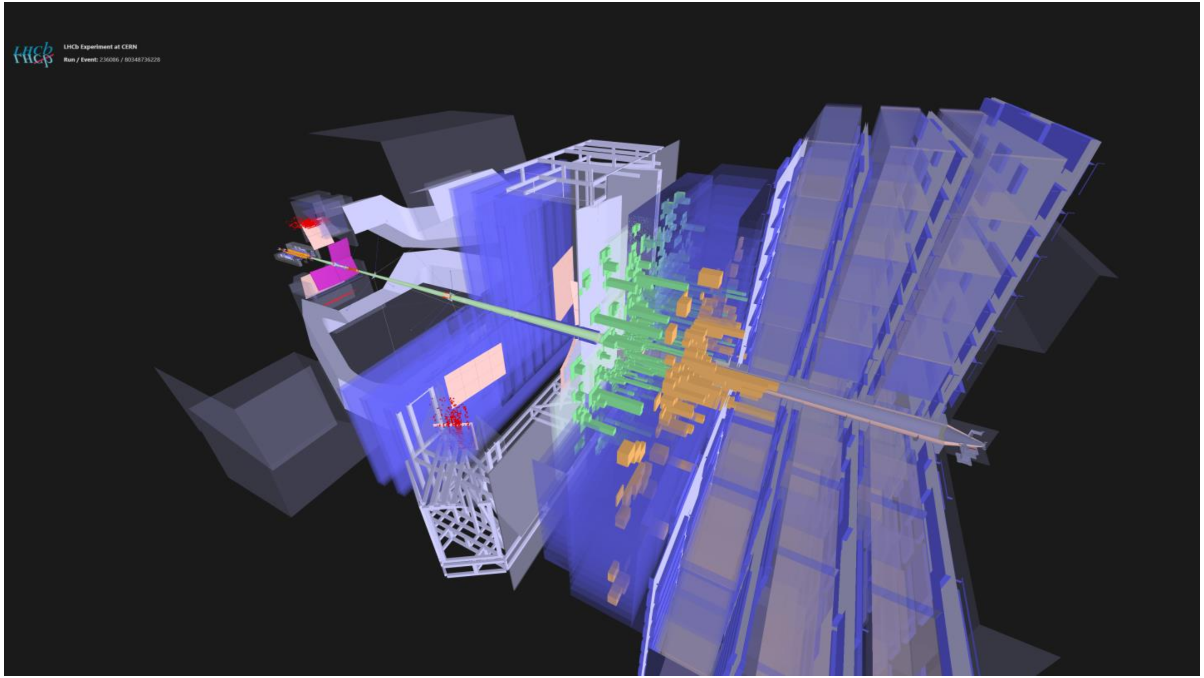
CERN-LHCC-2014-016
CERN-LHCC-2020-006

- All subdetectors are read out at 40 MHz – Real Time Analysis with software trigger
- 30 MHz reduced to 1 MHz by HLT1 using partial event reconstruction (tracking, vertexing, muon ID)
- Running on GPUs in new data centre on surface
- Hadronic yield $/\mathrm{fb}^{-1}$ is 2x that of Run 2
- **40 Tbit/s is highest throughput of all LHC**

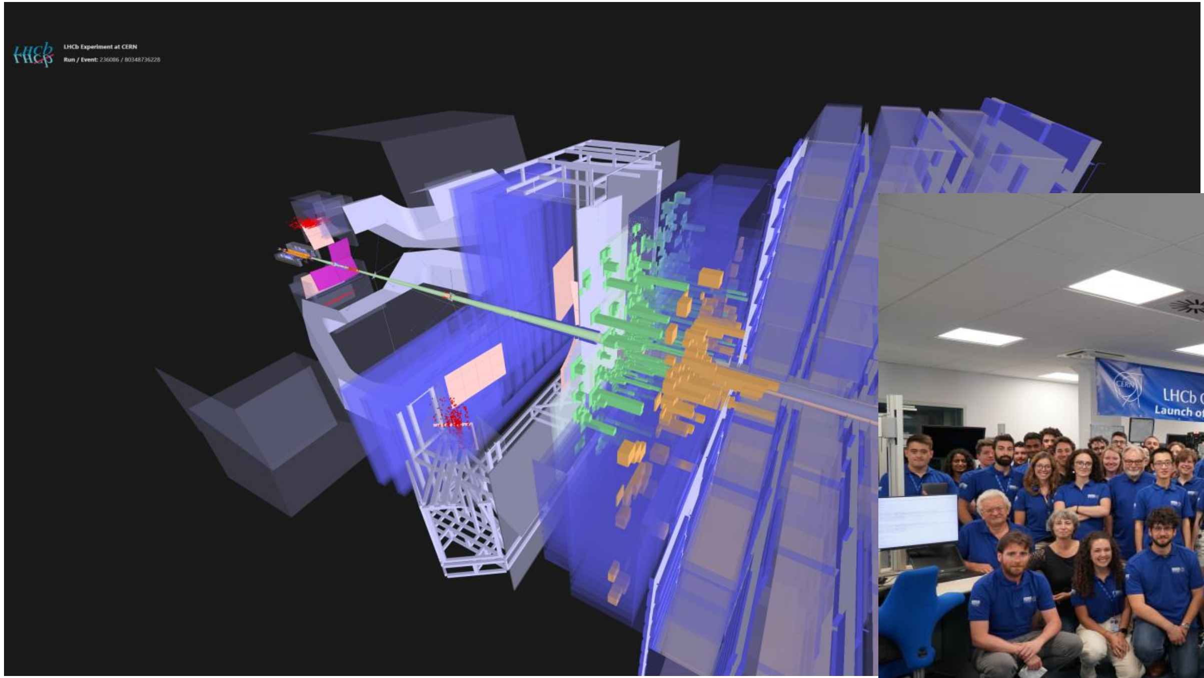




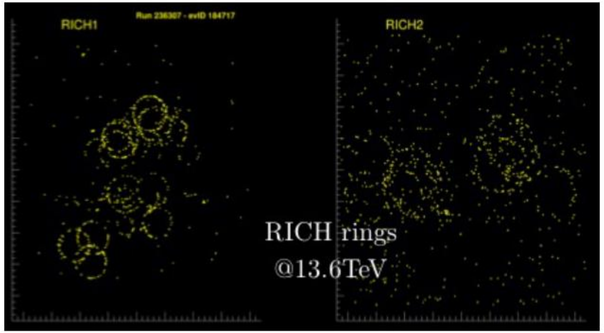
First collisions! (July 5th 2022)

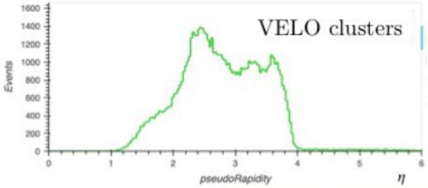


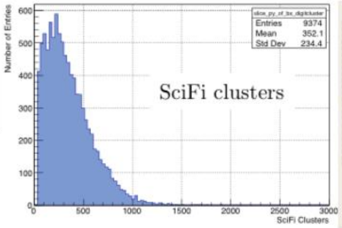
First collisions! (July 5th 2022)

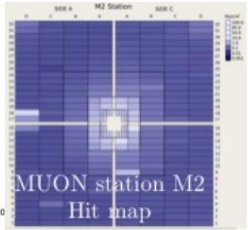


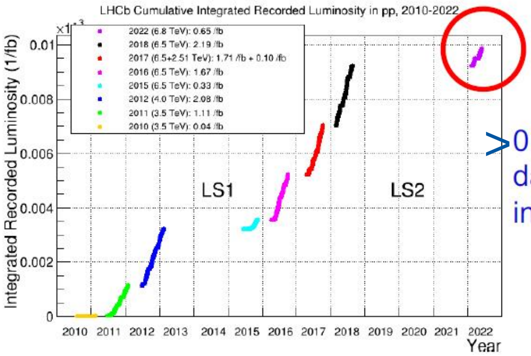
Data taking impressions



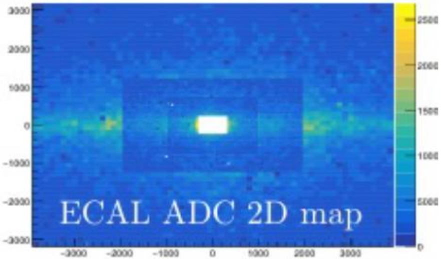




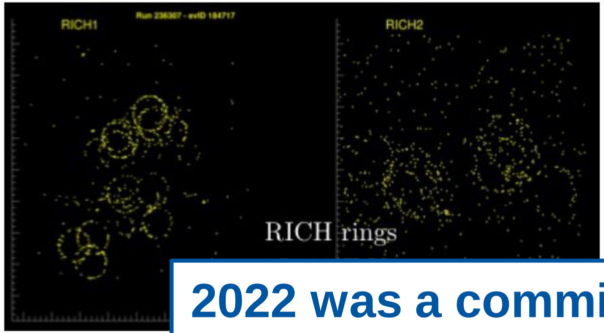


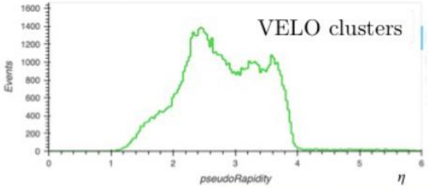


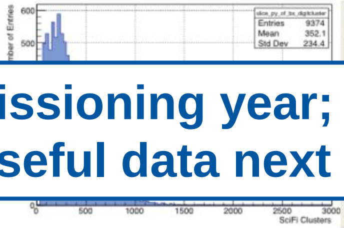
> 0.65 fb^{-1} of data recorded in Run 3.

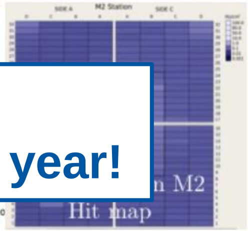


Data taking impressions

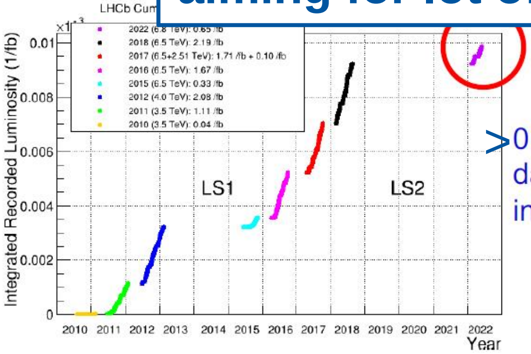




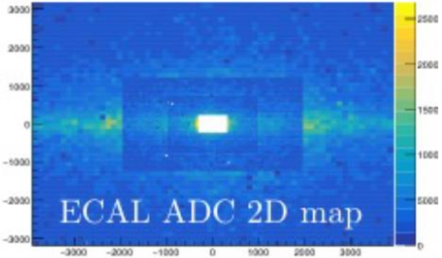




2022 was a commissioning year;
aiming for lot of useful data next year!

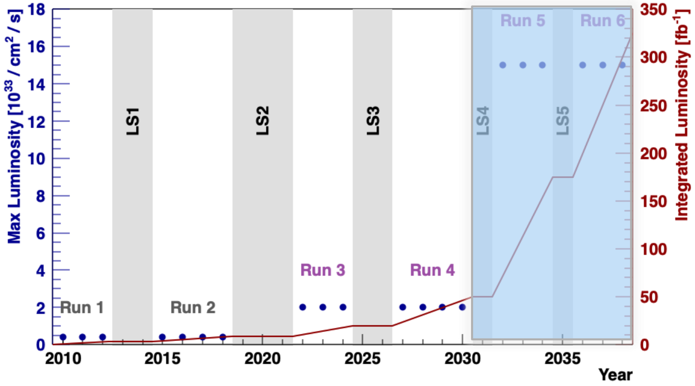


>0.65 fb^{-1} of data recorded in Run 3.



Upgrade 2

Goal: increase of luminosity by factor 7.5; aim for 300 fb-1 after Run 6



Upgrade 2

Goal: increase of luminosity by factor 7.5; aim for 300 fb-1 after Run 6

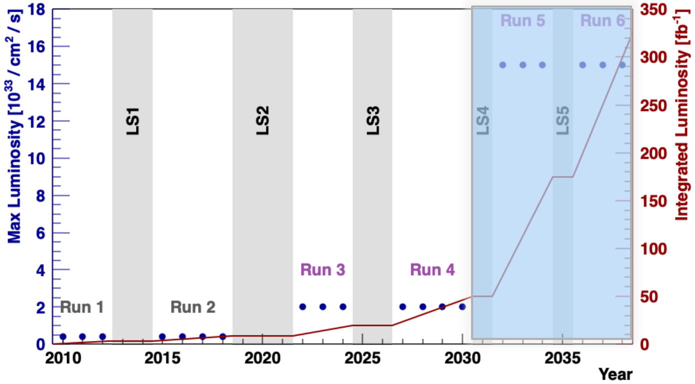
- Will reach unprecedented precision

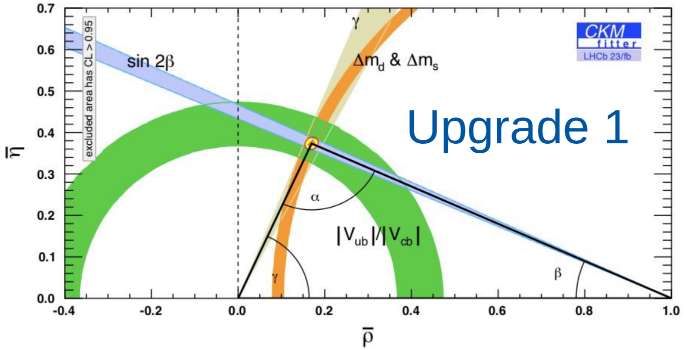
Detector environment will be challenging:

- Pile-up ~40 interactions.
- 200 Tb/s of produced data.

Detector upgrades: performance in harsher environment

- Better granularity
- Fast timing (~10 ps)
- Radiation hardness





Upgrade 2

Goal: increase of luminosity by factor 7.5; aim for 300 fb-1 after Run 6

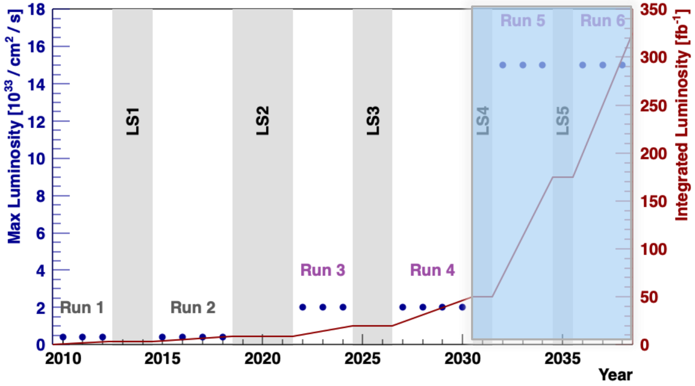
- Will reach unprecedented precision

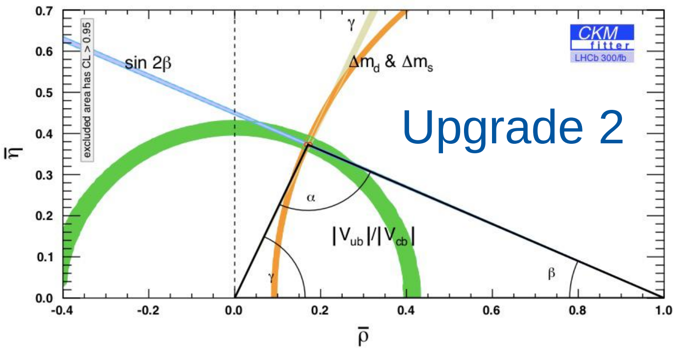
Detector environment will be challenging:

- Pile-up ~40 interactions.
- 200 Tb/s of produced data.

Detector upgrades: performance in harsher environment

- Better granularity
- Fast timing (~10 ps)
- Radiation hardness





Conclusions

- **LHCb achieved excellent performance over Runs 1 and 2**, collecting $9\ \text{fb}^{-1}$ at $\sqrt{s} = 13\text{TeV}$

- **Unitarity triangle tested to high precision;** Standard Model still holds on, but New Physics more and more constrained
- Rare decays and lepton universality tests strongly probe new heavy particles; **eagerly awaiting new results to resolve hints of New Physics**
- **Fantastic set of spectroscopy results, many of which were never expected**

- **Need to turn up the luminosity to make the next step in precision!** Upgrade 1 detector installed and being commissioned; work for Upgrade 2 is ongoing

¡Gracias por su atención!

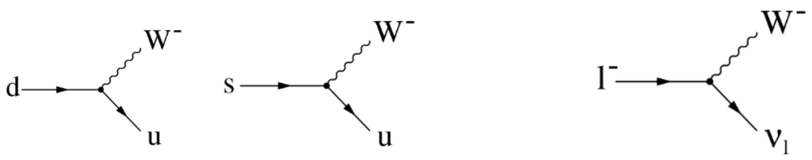
Question, comments: mick.mulder@cern.ch

Advantages of b-hadrons

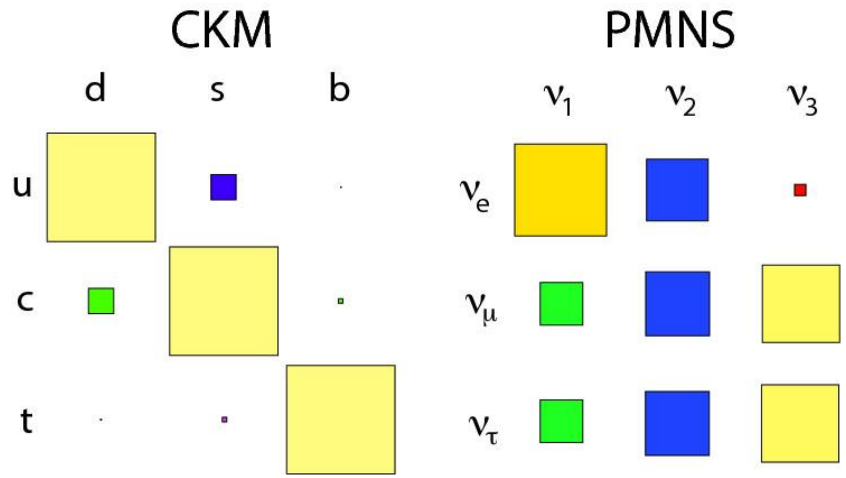
- Heaviest quark forming hadrons decaying weakly
- Many possible decay modes,
  and even more observables!
  - Very rich spectrum of possibilities!
  - O(600) modes (incl. searches) for B^+/B^0, O(100) for B_s^0, Λ_b^0
- Weak decay of b-hadron crosses generations:
  - No large branching fractions (largest 5%)
  - Sensitive to small SM and Beyond the SM effects!
- Lifetime and boost at LHCb give decay length of $\mathrm{O}(1\ \mathrm{cm})$; precise lifetime measurement possible

Flavour puzzle: fermion mixing

Quark mixing caused by separate eigenstates for
Higgs, weak interaction →
4 parameters for quarks,
4 parameters for leptons

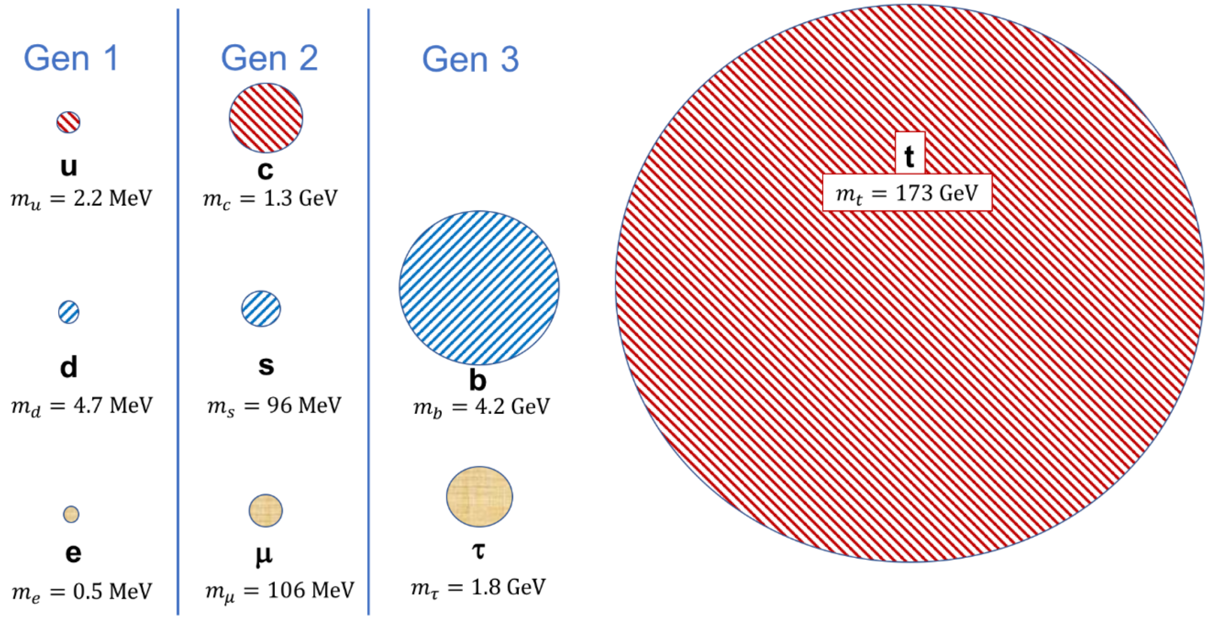


Why do mixing parameters for quarks look hierarchical and anarchical for neutrinos?



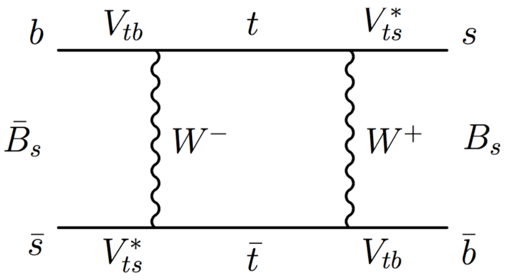
To solve flavour puzzle:
study third generation
→ rare decays of beauty quarks

Impression of mass hierarchy



Meson mixing

- Neutral flavoured mesons (K, D, B) only have non-zero quantum numbers
that are not invariant for weak interaction!



- Very dependent on meson system
- Described with Hamiltonian,
oscillation frequency Δm
and lifetime difference $\Delta\Gamma$

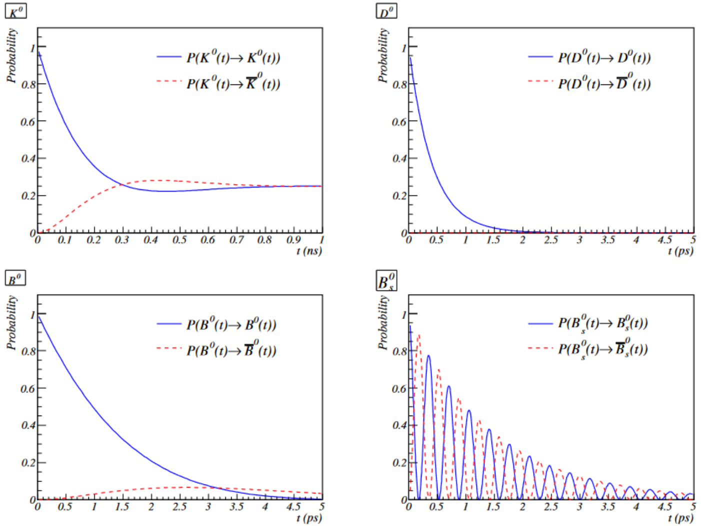
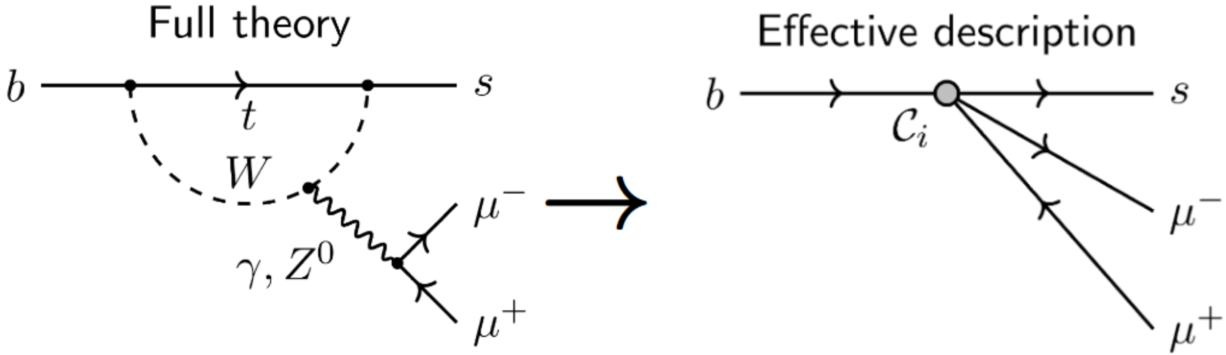


Figure 3.3: *If one starts with a pure P^0-meson beam the probability to observe a P^0 or a $\bar{P}^0$-meson at time t is shown,* $\text{Prob}(t) = \frac{e^{-\Gamma t}}{2}\left(\cosh \frac{1}{2}\Delta\Gamma t \pm \cos \Delta m t\right)$.

Effective field theory

- Are anomalies consistent with each other?
- **Use effective field theory at B-hadron scale, just like beta decay four-point interaction!**

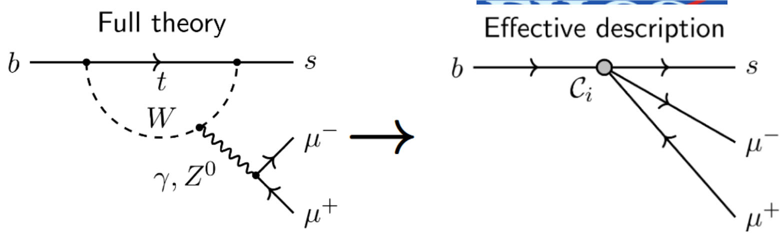


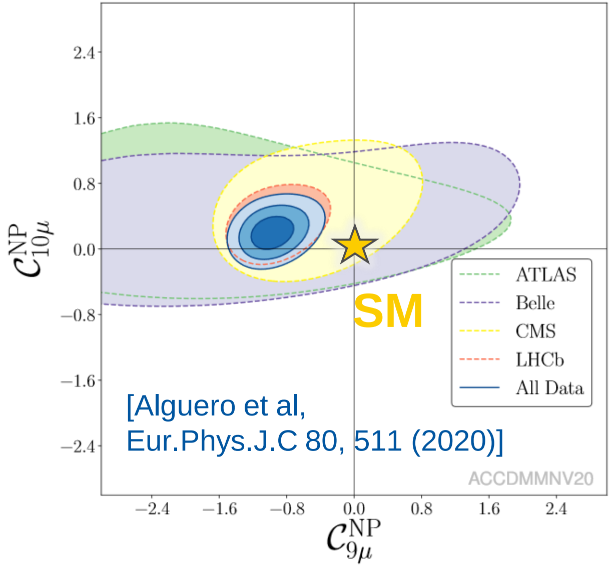
Effective field theory

- An EFT probes different couplings:

$$\mathcal{H}_{\text{eff}} = -\frac{G_F}{\sqrt{2}} V_{\text{CKM}} \sum_i \mathcal{C}_i \mathcal{O}_i$$

- Fermion operators O_i, Wilson coefficients C_i
- Grouped by leptonic current: (SM,NP)
    - C_7 photon penguin
    - $(C_{10})C_9$ (axial) vector
    - $(C_P)C_S$ (pseudo) scalar
- Note: operators, coefficients with opposite quark current handedness from SM marked with O_i',C_i' (negligible in SM)
- **Global fits indicate consistent deviation: reduction of C_9 for muons** (perhaps also in C_{10})?



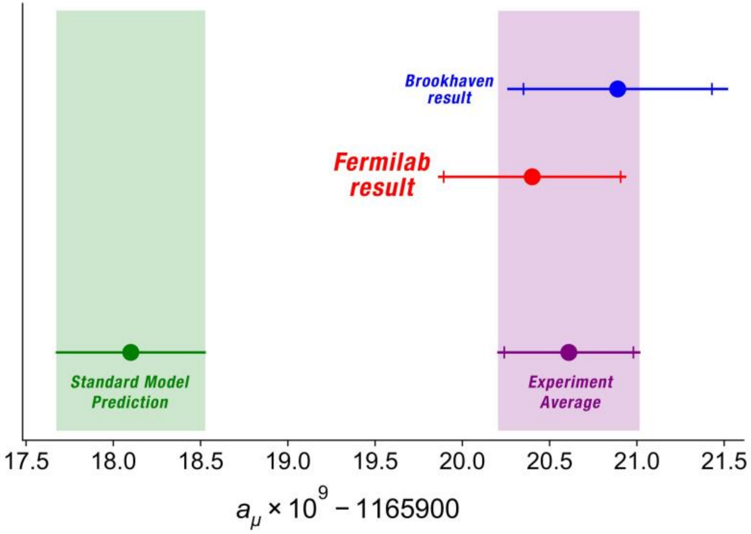


[Alguero et al, Eur.Phys.J.C 80, 511 (2020)]

Link with $(g-2)_\mu$?

- Muon magnetic moment, $(g-2)_\mu$:
  - Lower energy observable, **many possible contributions**
- **A month ago: $(g-2)_\mu$ deviation confirmed by Fermilab, currently at 4.2 sigma from SM**
- **Experimental uncertainty will reduce by ~3 w. full data**
- **Reduction of theory uncertainty essential to confirm deviation**

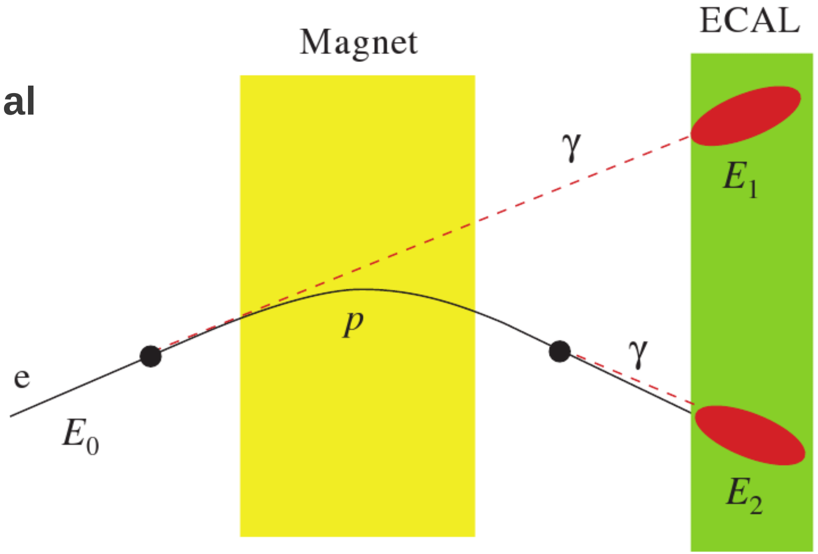
- General interest in $(g-2)_\mu$, many different models:
  - Adding one or two particles ‘ad hoc’ (leptoquark or Z’)
  - Supersymmetry models
  - Flavour-specific gauge interactions
- **Can be explained together with B anomalies with single vector leptoquark or scalar leptoquark + charged scalar**
- **Not required to solve flavour puzzle, but could be related**



Measurements with electrons at LHCb

[arXiv:2103.11769]

- **Electrons provide extra challenge in LHCb, because of significant bremsstrahlung in material**
- If bremsstrahlung is emitted before magnet, momentum is underestimated
- Recover bremsstrahlung by searching for photon clusters in calorimeter
- If found, correct electron momentum
- **Still, mass shape worse for electron modes**

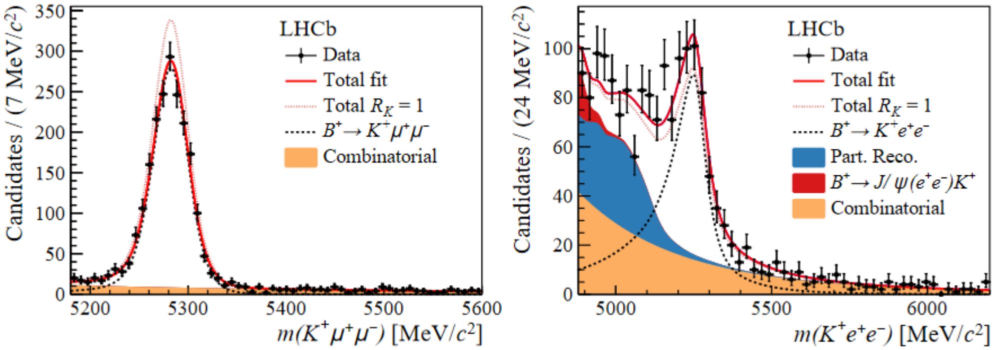


Measurements with electrons at LHCb

[arXiv:2103.11769]

- **Electrons provide extra challenge in LHCb, because of significant bremsstrahlung in material**
- If bremsstrahlung is emitted before magr momentum is underestimated
- Recover bremsstrahlung by searching for photon clusters in calorime
- If found, correct electron momentum
- **Still, mass shape worse for electron m**

From previous result, LHCb [PRL122(2019)191801]



- **Additionally, electrons more difficult for hardware trigger (than muons)**
- Electron sample divided based on hardware trigger category: electron, rest-of-event, or hadron trigger

f_s/f_d combination: introduction

[arXiv:2103:06810]

- At LHCb, produce many types of b-hadrons: B^0 , B^+ , B_s^0, Λ_b^0, $\Xi_b^{0/-}$, B_c^+, …
- **Essential rare decay measurements include branching fractions of B_s^0 mesons,** such as $\boldsymbol{B(B_s^0 \to \mu^+\mu^-)}$, $\boldsymbol{B(B_s^0 \to \phi\mu^+\mu^-)}$
- **Determine B_s^0 branching fractions relative to B^0 or B^+ mode with known branching fraction** (with efficiency-corrected yield n_{corr} from experiment):

$$\frac{n_{\text{corr}}(B_s^0 \to X)}{n_{\text{corr}}(B^{0(+)} \to Y)} = \frac{\mathcal{B}(B_s^0 \to X)}{\mathcal{B}(B^{0(+)} \to Y)} \frac{f_s}{f_{d(u)}}$$

- **Need to know B_s^0/B_d^0 production ratio = f_s/f_d!**
- f_s/f_d is interesting as well as probe of hadronisation, previously found to depend on p_T (not on η)

- **Measure f_s/f_d using modes with prediction of branching fraction ratio**
- Five previous LHCb measurements (2011 to 2020)**:** **today, show combination to determine single value with higher precision**

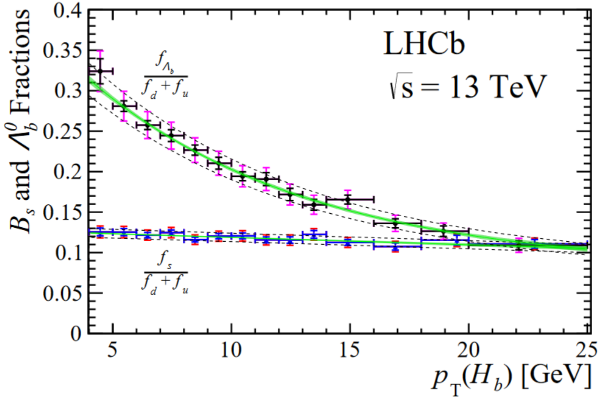
f_s/f_d combination: input measurements

- Measurements at main energies (7, 8, 13 TeV), full LHCb acceptance ($p_T \in [0.5, 40]$ GeV, $\eta \in [2, 6.4]$)

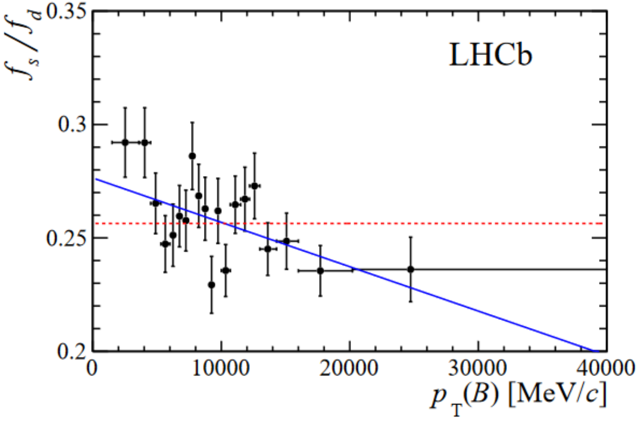
- Three decay modes: $B \to D\mu X$, $B \to Dh$, (both with predictions), $B \to J/\psi X$ (no prediction $\to$ dependence)
- **Update external inputs for predictions (e.g. D branching fraction, B lifetimes): significant improvement in sensitivity!**

[arXiv:2103:06810]

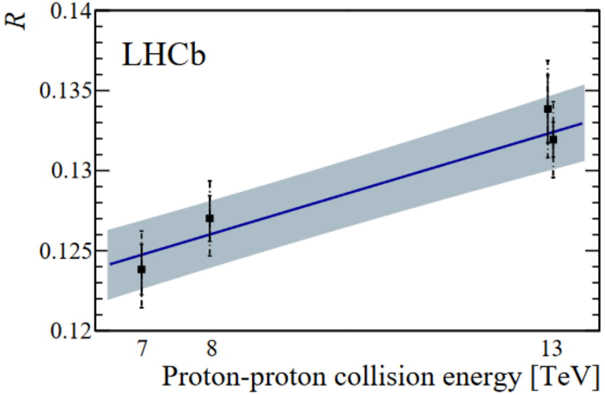
$B \to D\mu X$, 13 TeV



$B \to Dh$, 7 TeV



$B \to J/\psi X$, various $\sqrt{s}$

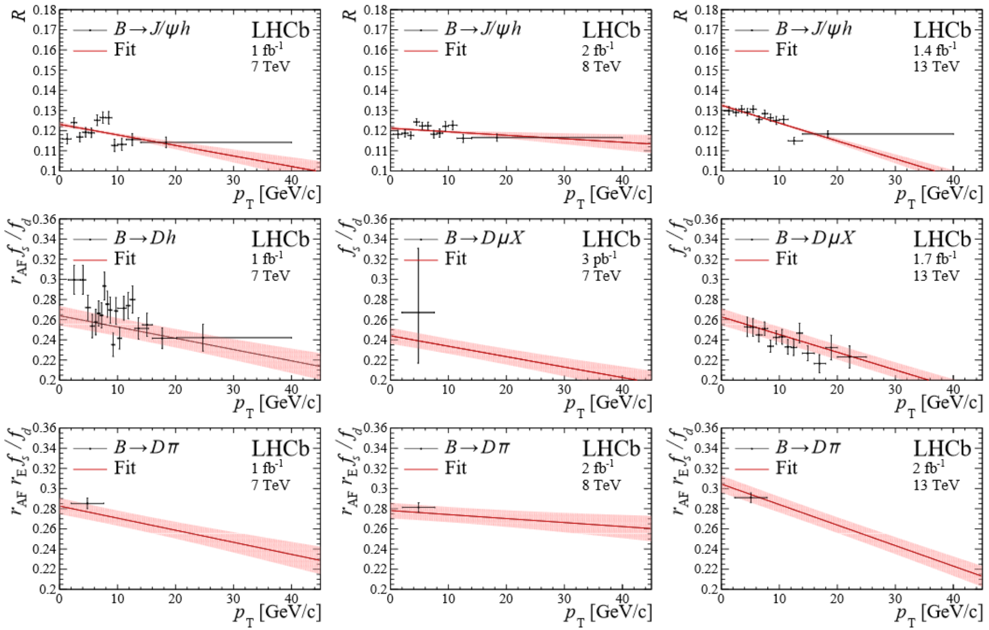


Combination of $B_s^0/B^{0/+}$ production measurements

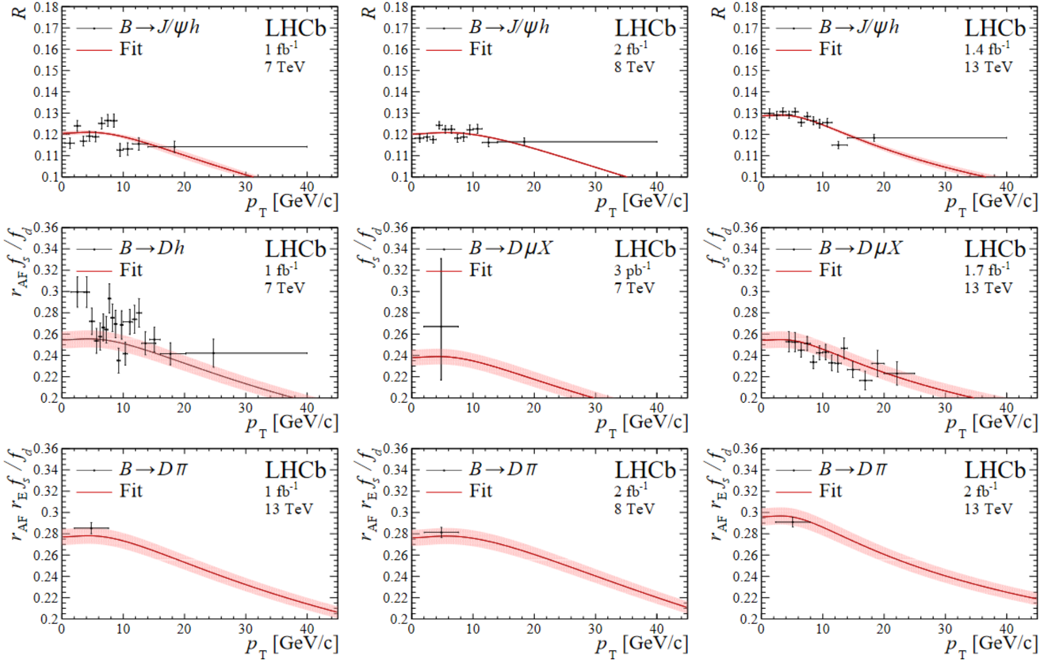
[arXiv:2103:06810]

$$\frac{n_{\text{corr}}(B_s^0 \to X)}{n_{\text{corr}}(B^{0(+)} \to Y)} = \frac{\mathcal{B}(B_s^0 \to X)}{\mathcal{B}(B^{0(+)} \to Y)} \frac{f_s}{f_{d(u)}}$$

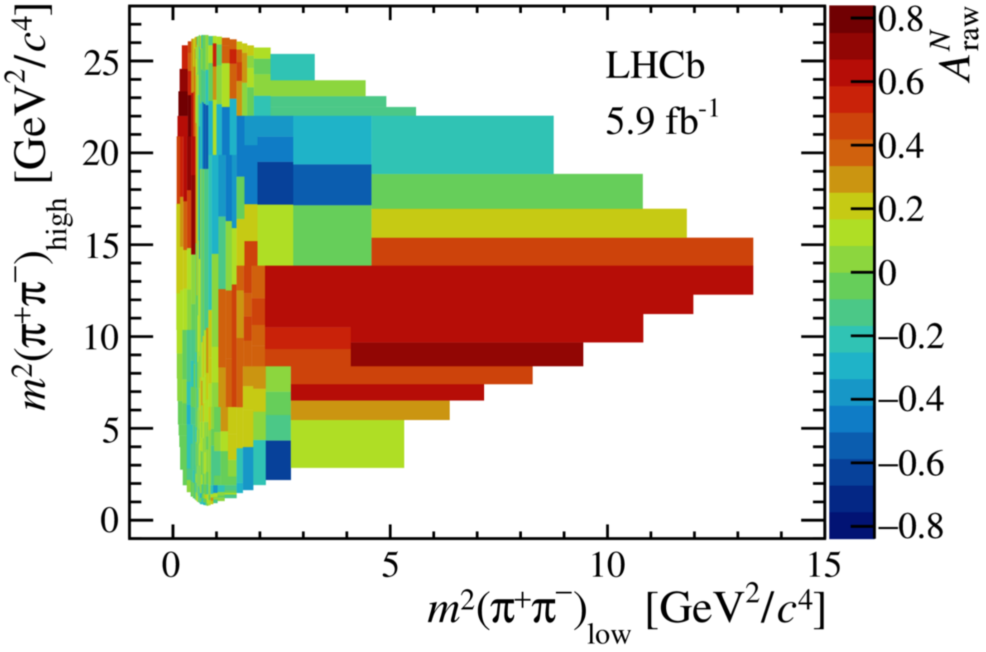
- Combination of five previous LHCb measurements
- Integrated value (13 TeV) in LHCb acceptance: $\frac{f_s}{f_d} = 0.2539 \pm 0.0079$
- **Uncertainty reduced by ~factor 2 to 3.1%**
- **Essential improvement for** $\boldsymbol{B(B_s^0 \to \mu^+\mu^-), B(B_s^0 \to \phi\mu^+\mu^-)}$! (and all other B_s^0 modes)

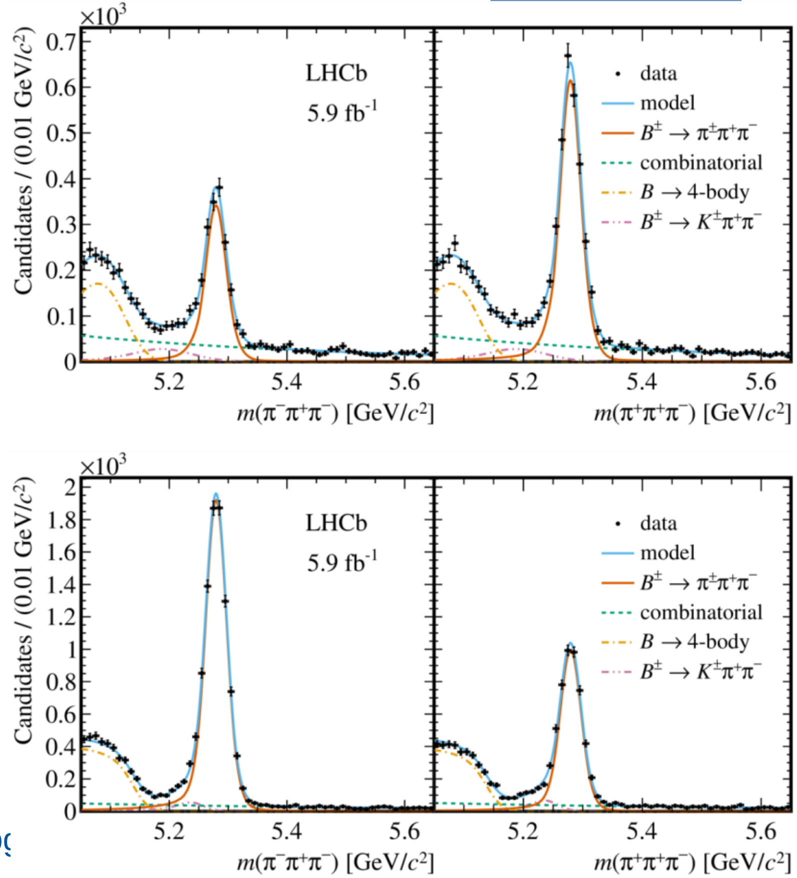


Fit with Tsallis function



CP violation in $B^+ \to h^+ h'^+ h''^-$



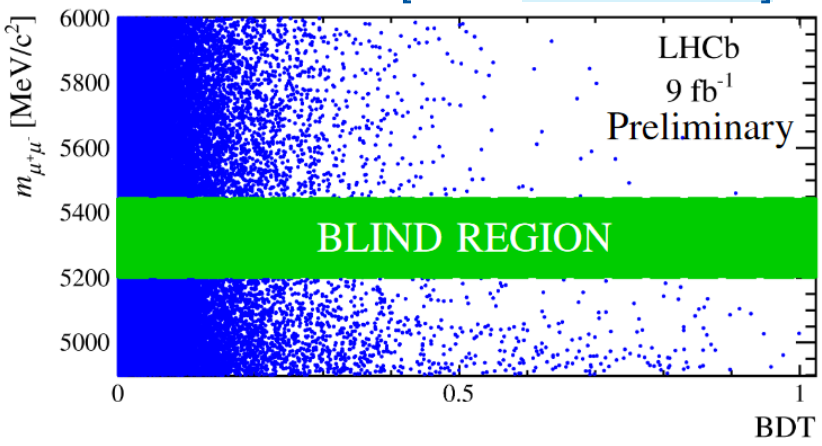


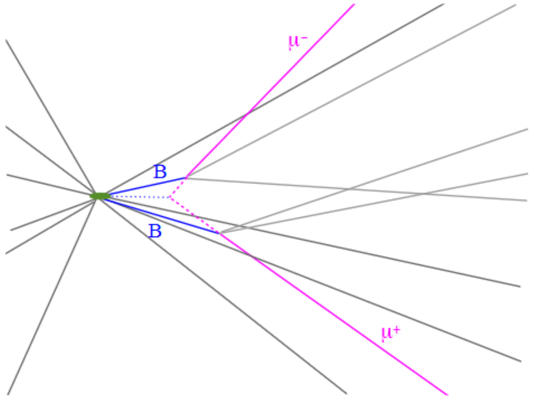
[LHCb-PAPER-2021-007]

Analysis strategy

- **Similar strategy to previous analysis, strongly improved calibration**
- Use full Run 1 + Run 2 data
- Muon pairs with $m_{\mu^+\mu^-} \in [4.9, 6.0]$ GeV with good displaced vertex
- Signal region blind until analysis is finalised
- Suppress misID with tight PID cut

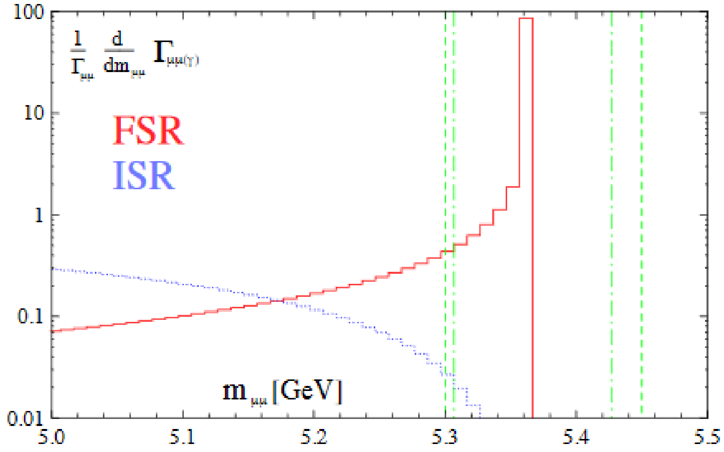
- Main background: combinatorial
- Rejected with multivariate classifier, namely Boosted Decision Tree (BDT)
- **Determine signal from fit to $\mathbf{m_{\mu\mu}}$ and BDT**





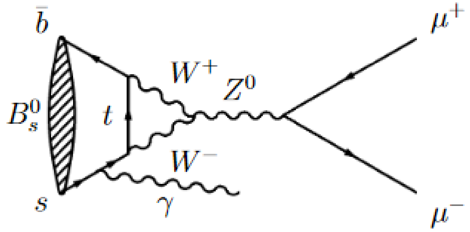
$B^0_{(s)} \to \mu^+\mu^-$ and photon radiation

- Initial State Radiation: photon emitted from quarks, **sensitive to $\boldsymbol{C_9}$ and $\boldsymbol{C_{10}}$,**
  here referred to as $B^0_{(s)} \to \mu^+\mu^-\gamma$
- **New observable in this analysis,**
  without reconstructing photon for $m_{\mu^+\mu^-} > 4.9\ \mathrm{GeV}$
- SM prediction $O(10^{-10})$
  [JHEP 11 (2017) 184, PRD 97 (2018) 053007]
- Final State Radiation:
  soft photons emitted from muons,
  sensitive to $\boldsymbol{C_{10}}$ only,
  included in $B^0_s \to \mu^+\mu^-$ via PHOTOS

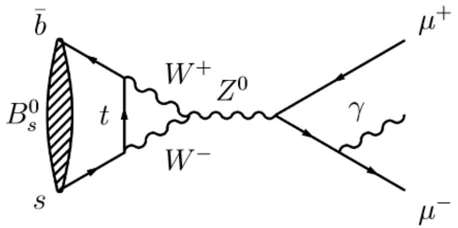


[PRL 112 (2014) 101801]

Initial State Radiation



Final State Radiation



Backgrounds

[LHCb-PAPER-2021-007]

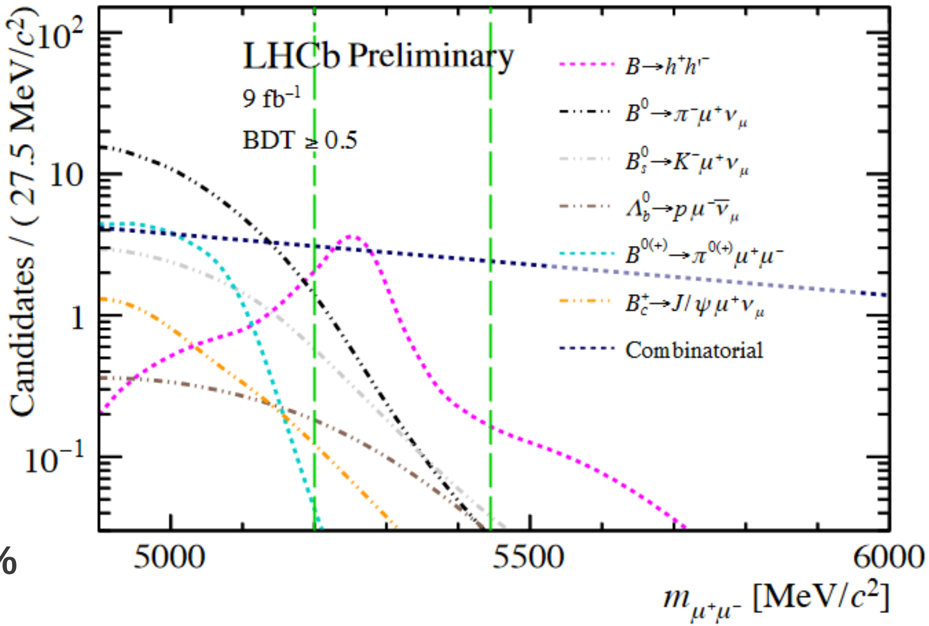
Three types of backgrounds in fit:

1. Combinatorial, over full mass spectrum (free in fit)
2. Mis-identified backgrounds:
   $B^0 \to \pi^- \mu^+ \nu_\mu$, $B_s^0 \to K^- \mu^+ \nu_\mu$,
   $B_{(s)}^0 \to h^+ h'^-$, $\Lambda_b^0 \to p \mu^- \overline{\nu_\mu}$
3. Real muons:
   $B^{0/+} \to \pi^{0/+} \mu^+ \mu^-$, $B_c^+ \to J/\psi \mu^+ \nu_\mu$

Calibrate on corrected simulation samples

Cross-check with fit to $B_{(s)}^0 \to h^+ h'^-$ data with one hadron mis-identified, consistent within 10%

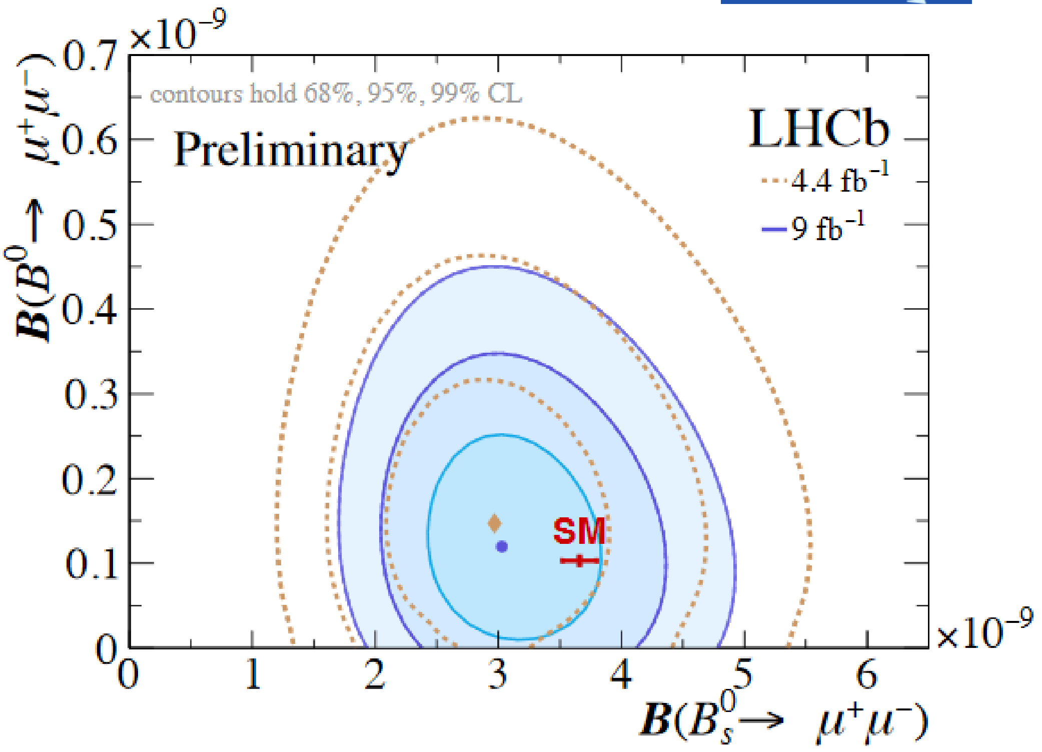
Everything calibrated, time to fit!



Results: compatibility with SM

[LHCb-PAPER-2021-007]

- 2D likelihood contour of $B(B_s^0 \to \mu^+\mu^-)$ vs. $B(B^0 \to \mu^+\mu^-)$: **result compatible with SM (<1σ) and previous LHCb result**
- Correlation is small (-7%)

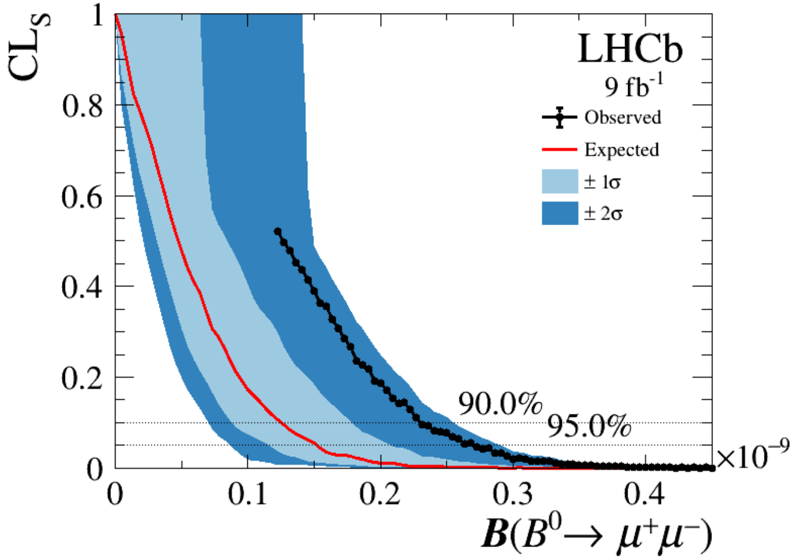


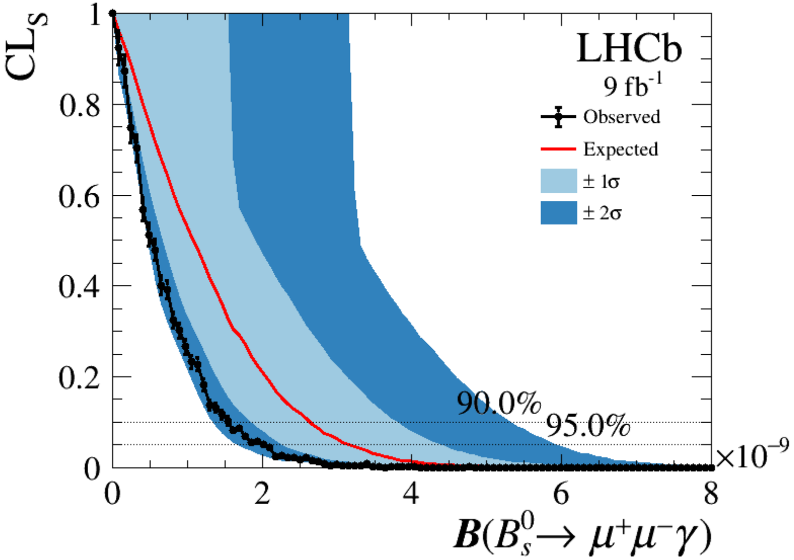
Results: limits (CLs method)

[LHCb-PAPER-2021-007]

$B(B^0 \to \mu^+\mu^-) < 2.3(2.6) \times 10^{-10}$ at 90(95)% CL

$B(B^0_s \to \mu^+\mu^-\gamma) < 1.5(2.0) \times 10^{-9}$
for $m_{\mu^+\mu^-} > 4.9$ GeV at 90(95)% CL

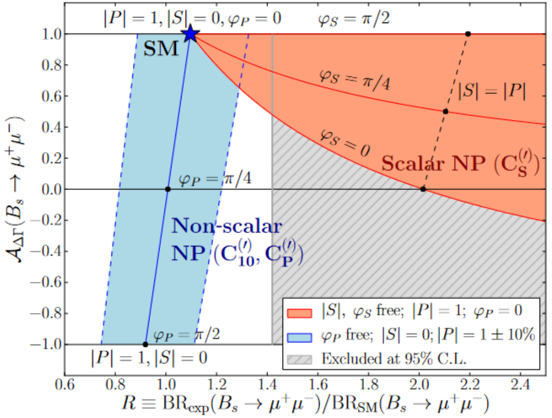




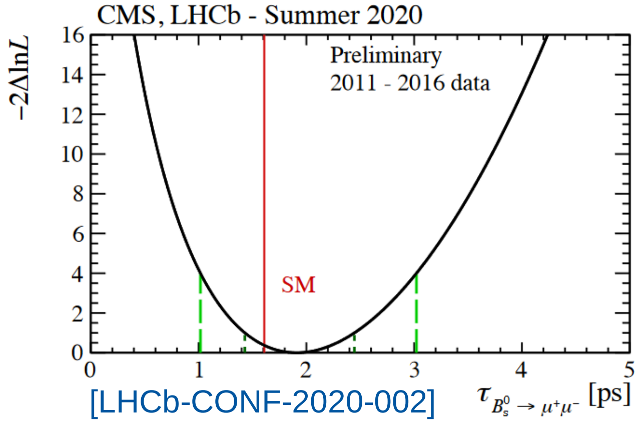
[PRL 109 (2012) 041801]

Effective lifetime of $B_s^0 \to \mu^+\mu^-$

- Neutral $B_{(s)}^0$ mesons undergo mixing, propagate as CP-odd and CP-even eigenstates
- Only CP-odd state contributes to $B_{(s)}^0 \to \mu^+\mu^-$ in SM: CP amplitude asymmetry $A_{\Delta\Gamma_s}^{\mu\mu} = +1$
- Neutral B_s^0 mass(~CP) eigenstates characterised by sizeable difference in decay width, $\Delta\Gamma_s/\Gamma_s = 0.124 \pm 0.008$
- **Measure effective lifetime τ_{eff} to test for CP-even contribution, scalar NP (C_s, C_P)!**



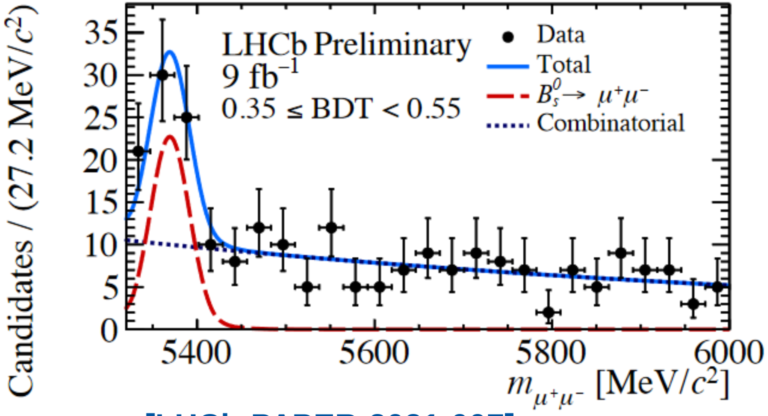
- Combination of first LHCb, CMS measurements: $\tau_{\rm eff}(B_s^0 \to \mu^+\mu^-) = \left(1.91^{+0.37}_{-0.35}\right)$ ps (dominated by statistics)



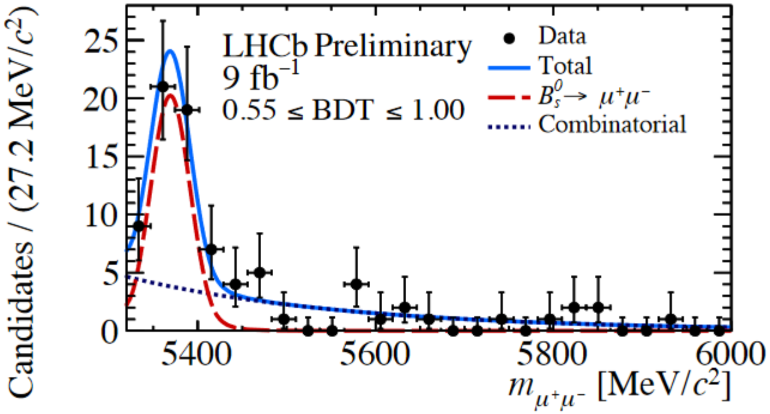
[LHCb-CONF-2020-002]

Effective lifetime strategy

- $B_s^0 \to \mu^+\mu^-$ **measurement only: separate optimisation**
  - Smaller mass window (>5.32 GeV): contains only B_s^0, combinatorial
  - Looser PID requirements
- Procedure:
  1. Mass fit in two BDT bins to subtract background (with sWeights) [NIM A555 (2005) 356–369]
  2. Calibrate lifetime acceptance on simulation, test with $B^0 \to K^+\pi^-, B_s^0 \to K^+K^-$ decays
  3. Fit lifetime distribution including acceptance to determine effective lifetime



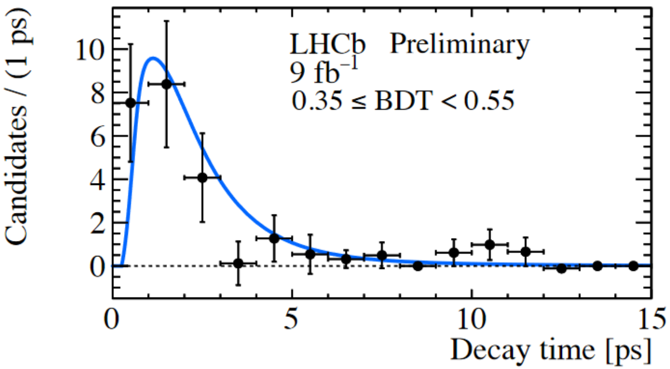
[LHCb-PAPER-2021-007]

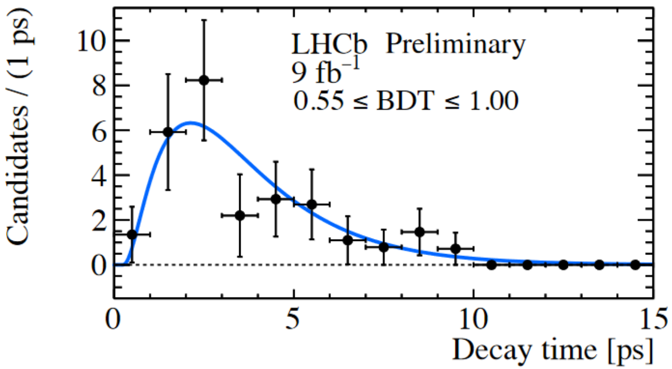


Effective lifetime

[LHCb-PAPER-2021-007]

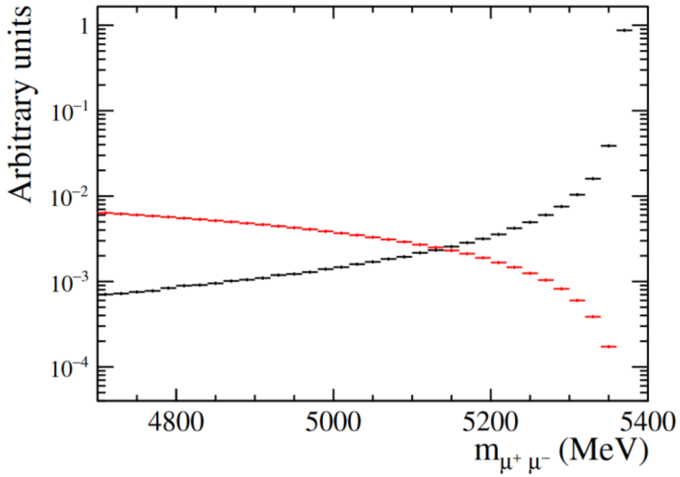
- $B^0_{(s)} \to \mu^+\mu^-$ decay proceeds through CP-odd state in SM;
- CP-even, CP-odd states of B^0_s have different lifetime → **measure effective lifetime τ_{eff} to test CP-even contribution, scalar NP**
- $\boldsymbol{\tau(B^0_s \to \mu^+\mu^-) = 2.07 \pm 0.29 \pm 0.03}$ **ps** (previously $2.04 \pm 0.44 \pm 0.05$ ps)
- 1.5 sigma from SM, 2.2 sigma from extreme non-SM
- **Run 3 data needed to start providing significant constraints**



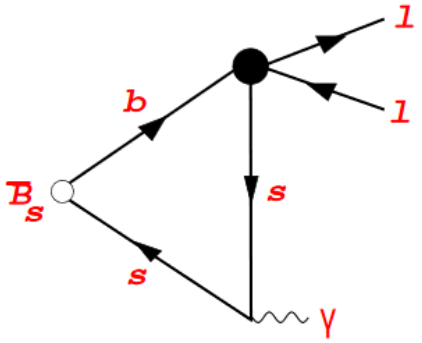


$B_s^0 \to \mu^+\mu^-\gamma$: ISR/FSR

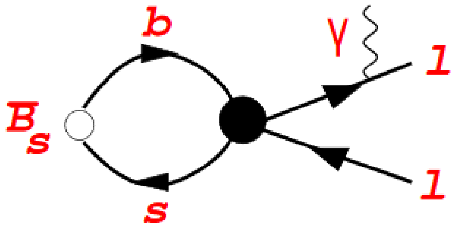
- ISR: photon from b, s quarks, effectively three-body semileptonic B decay (vs q^2): **partially reconstructed background for $B_s^0 \to \mu^+\mu^-$ reconstruction**
- FSR: soft photons from muons, same Wilson coefficients: **additional tail for $B_s^0 \to \mu^+\mu^-$, modelled with PHOTOS**



Initial State Radiation



Final State Radiation



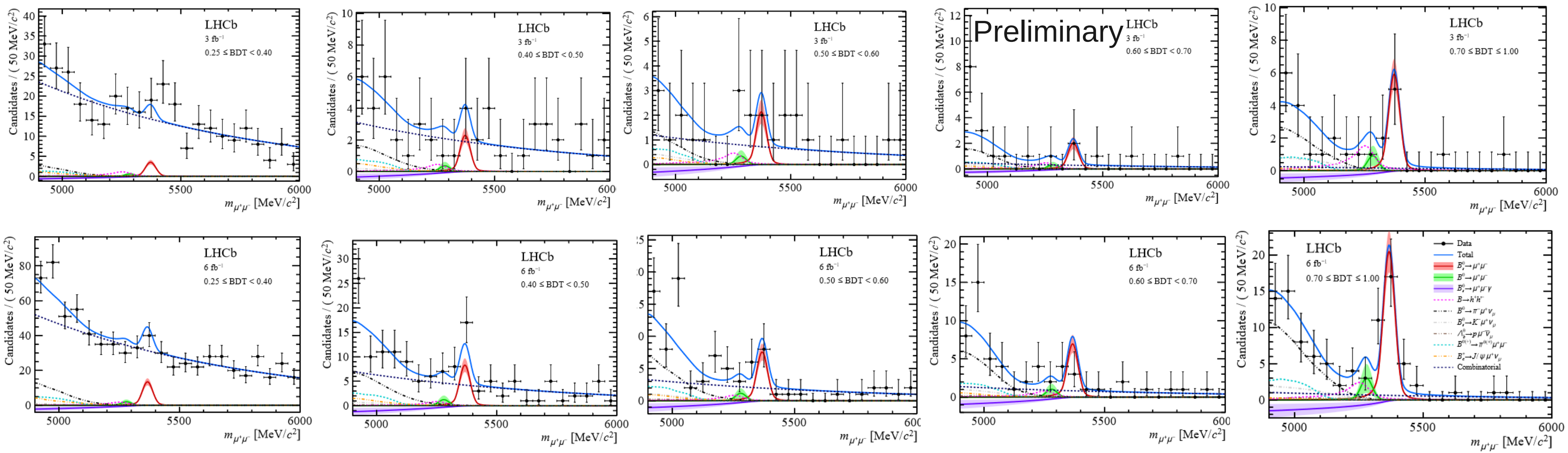
Results: mass fit in all BDT bins

[LHCb-PAPER-2021-007]

BDT [0.25,0.4] | BDT [0.4,0.5] | BDT [0.5,0.6] | BDT [0.6,0.7] | BDT [0.7,1.0]

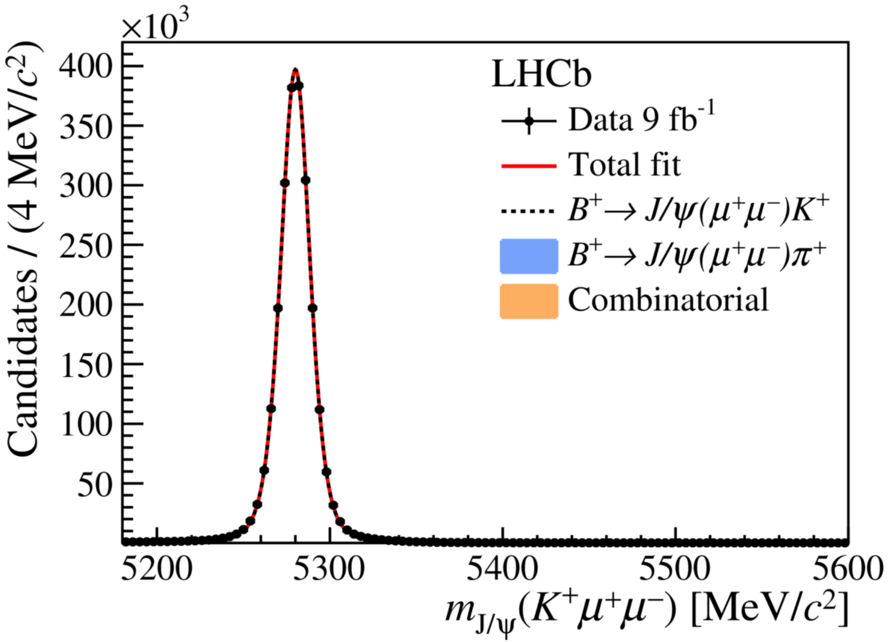
Run 1

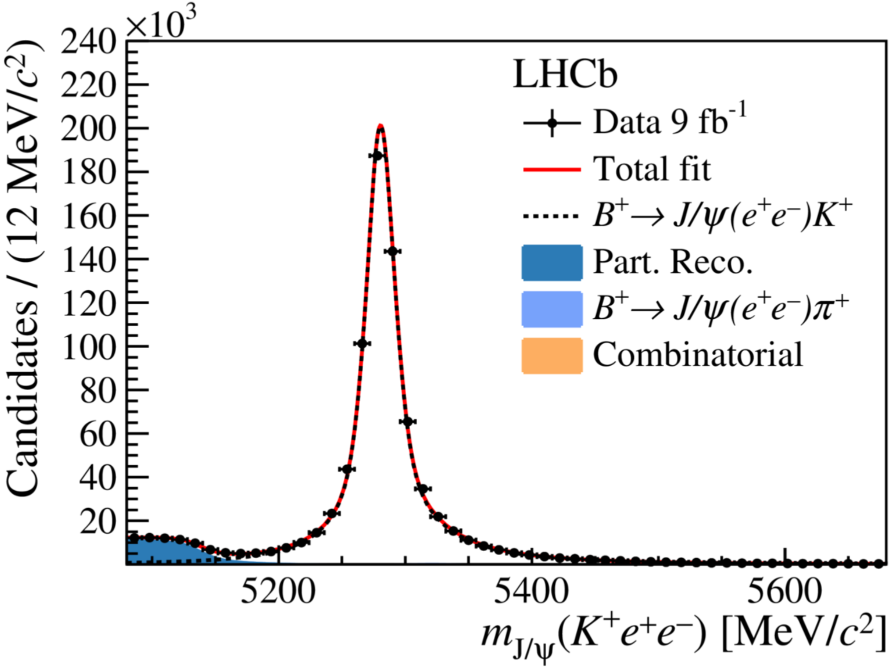
Run 2



RK: Mass fits for calibration modes

[arXiv:2103.11769]

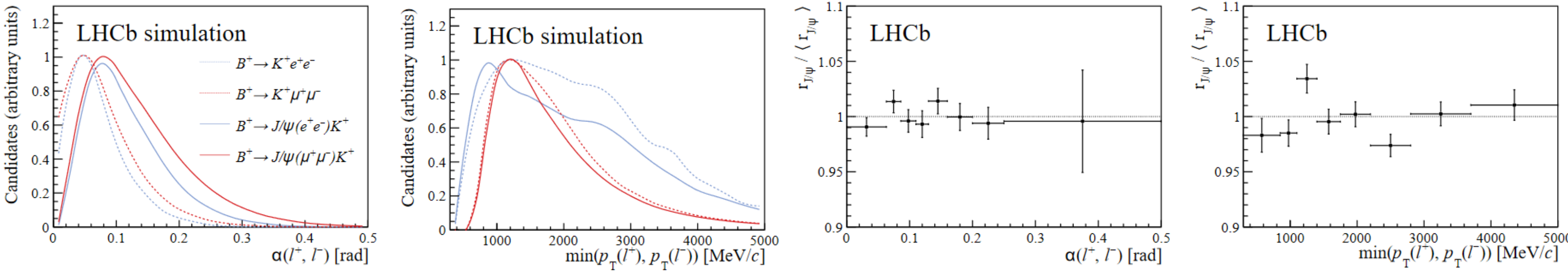




RK cross-checks: differential $r_{J/\psi}$

[arXiv:2103.11769]

- **Validate $r_{J/\psi}$ is flat to ensure efficiency transfers to rare mode in various variables (e.g. kinematics, lepton opening angle)**



- Taking largest observed departure from flatness as genuine effect, bias on R_K is 0.1%

RK cross-check: $R_{\psi(2S)}$

[arXiv:2103.11769]

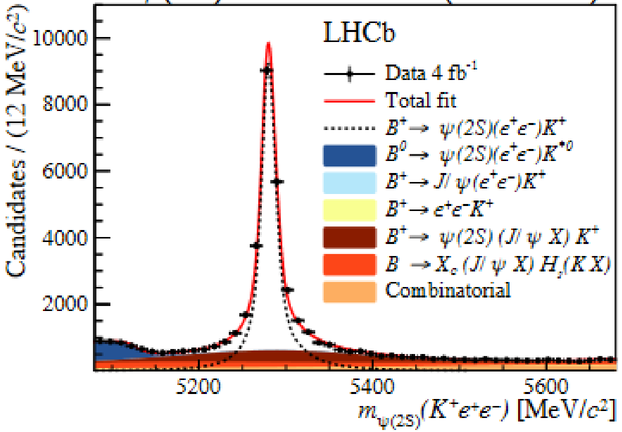
- Measurement of double ratio

$$R_{\psi(2S)} = \frac{\mathcal{B}(B^+ \to K^+\psi(2S)(\mu^+\mu^-))}{\mathcal{B}(B^+ \to K^+J/\psi(\mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^+ \to K^+\psi(2S)(e^+e^-))}{\mathcal{B}(B^+ \to K^+J/\psi(e^+e^-))}$$

- **Independent validation of double-ratio procedure**
- **Result well compatible with unity:**

$$R_{\psi(2S)} = 0.997 \pm 0.011\ (\text{stat} + \text{syst})$$

Use $\psi(2S)$ constrained $m(K^+\ell^+\ell^-)$



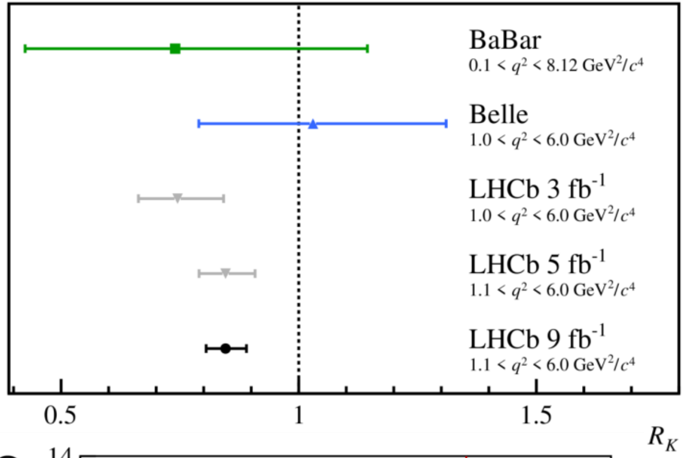
Results: R_K

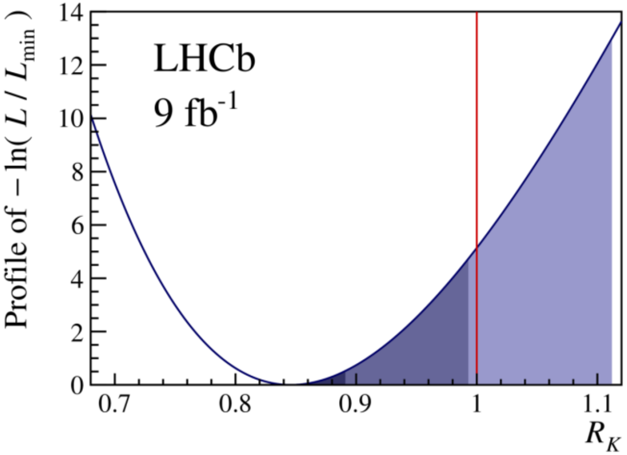
[arXiv:2103.11769]

$$R_K = 0.846^{+0.042+0.013}_{-0.039-0.012}$$

- Exact same central value as before
- Main systematic uncertainties (~1%)
  from fit model, statistics of calibration samples

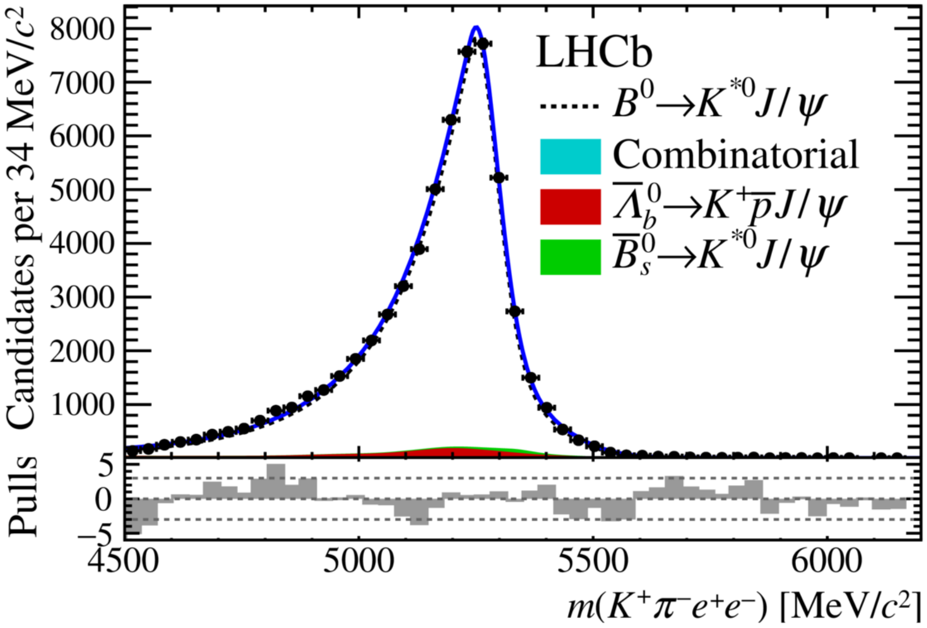
- Compatibility with SM determined from integration of profile likelihood
  (including uncertainty on SM prediction of 1%)
- SM hypothesis p-value: 0.0010,
  evidence of lepton universality violation at 3.1σ





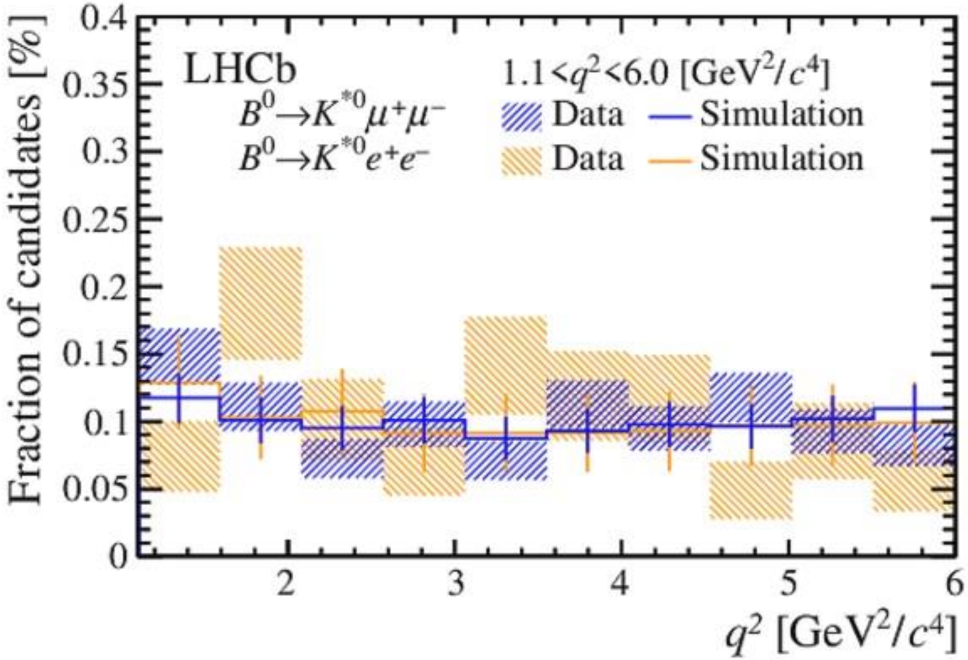
R_{K^*}: example fit without J/ψ mass constraint

[JHEP 08 (2017) 055]



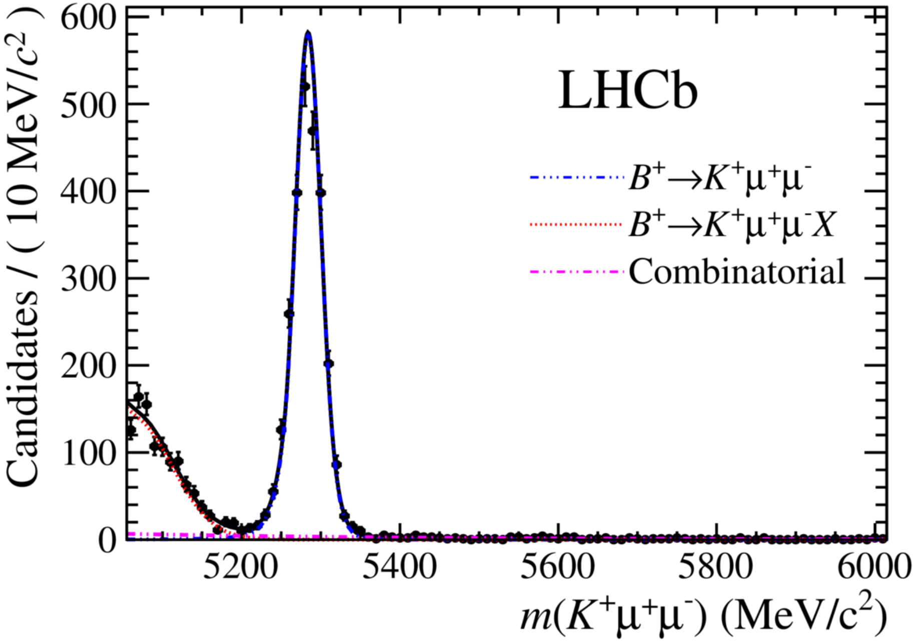
R_{K^*}: q^2 dependence in main bin

[JHEP 08 (2017) 055]



RK: Dimuon fit w. partially reconstructed bkg

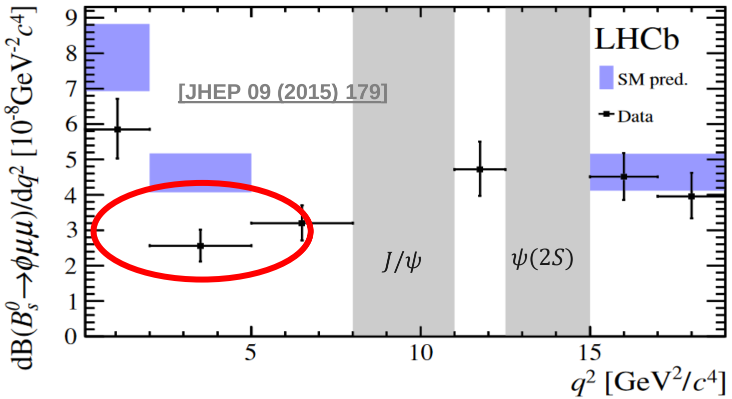
[JHEP 10 (2015) 034]

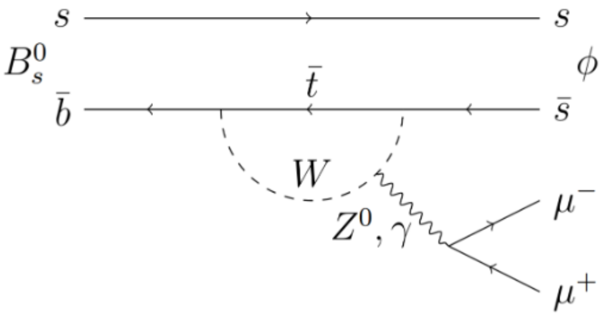


$B(B_s^0 \to \phi\mu^+\mu^-)$

- Semileptonic rare B decay with s spectator quark
- Run 1 result at 3σ tension with SM

- Update with full Run 1 + Run 2 data
- Similar strategy to R_K analysis (but with single ratio)
- Normalise to $B_s^0 \to J/\psi\phi$ decay (same final state) with improved uncertainty from f_s/f_d combination

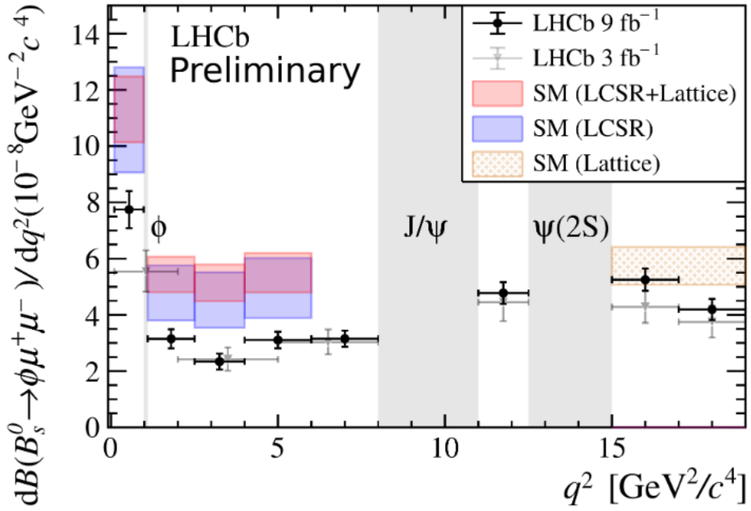




$B(B_s^0 \to \phi\mu^+\mu^-)$: results

- New results: **similar central values, uncertainty reduced by factor 2**
- Main systematic uncertainty: physics model (incl. $\Delta\Gamma_s$)

- Tension with SM at 1.8, 3.6σ, resp. for Light Cone Sum Rules(LCSR)-only or LCSR+Lattice predictions
  $\rightarrow$ **better understanding required**
- Looking forward to inclusion in global fits



[JHEP 08 (2016) 098, EPJC 75 (2015382), arXiv:1810.08132, PRL 112 (2014) 212003, PoSLATTICE2014 (2015) 372]