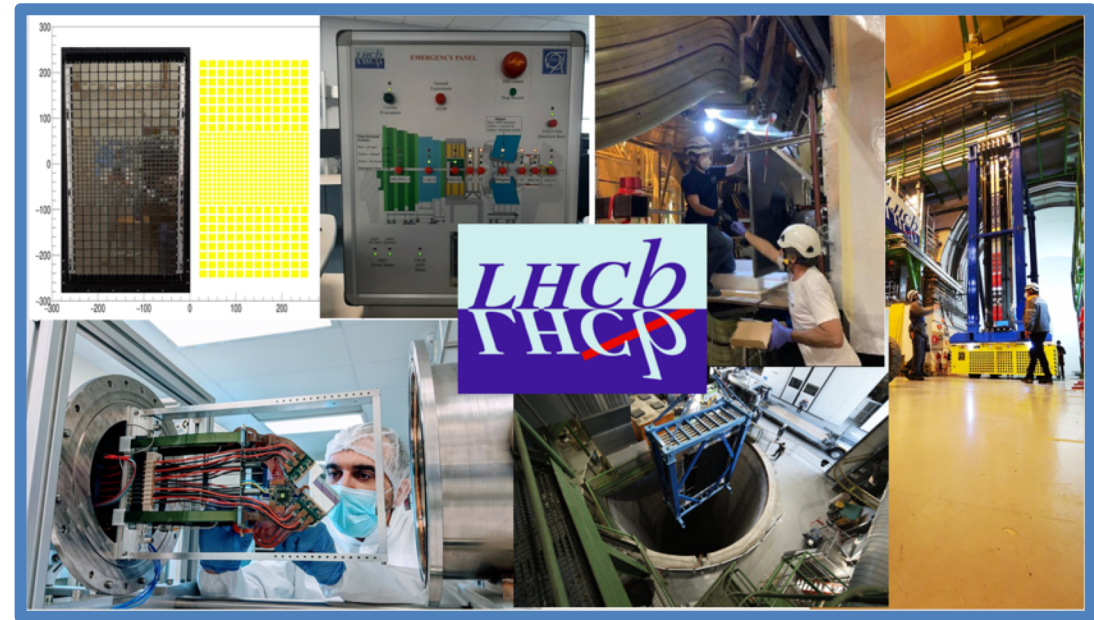


LHCb: Highlights & Perspectives

LHCP, 7th June 2021

- Selected Recent Physics Results
- Upgrade I Installation
- Upgrade II Preparation



Chris Parkes
on behalf of the LHCb Collaboration

- LHCb was originally designed for matter antimatter asymmetry measurements (CP Violation) and studying rare decays
 - of course it has achieved much more
 - **Heavy ions, fixed target programme, QCD, Electroweak, long-lived particles...**
- Report on recent highlights from the core programme and beyond

More than 50 hadrons discovered

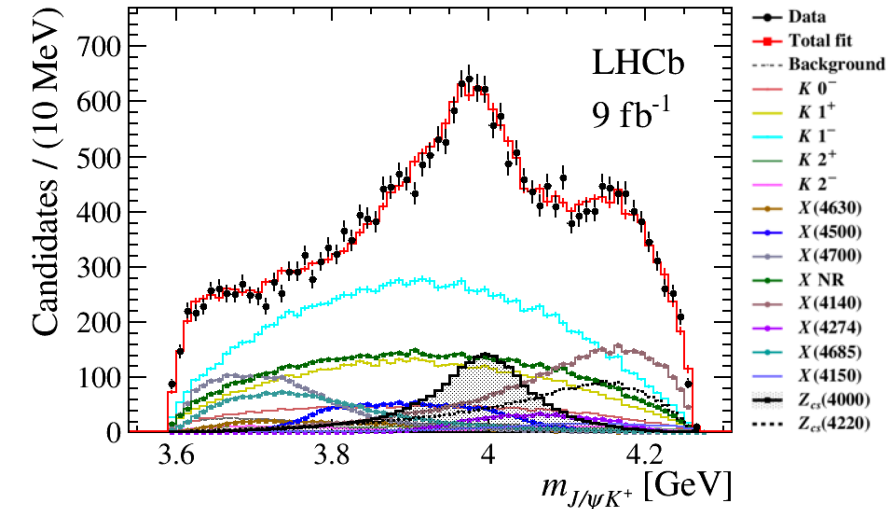
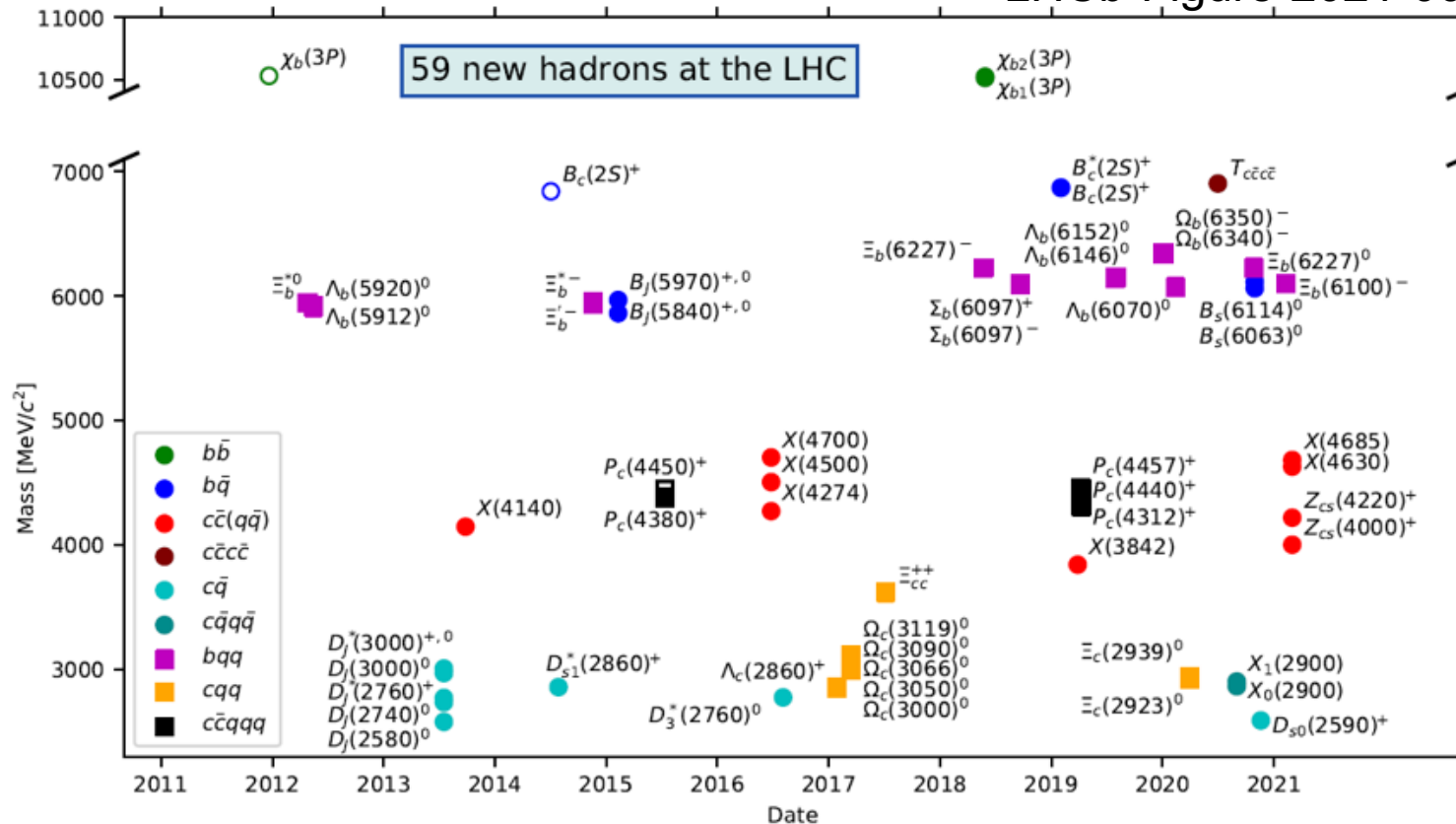
Oscillations: B_s and D^0

Rare decays: $b \rightarrow s l^+ l^-$ anomalies

LHC > 50 Hadrons Discovered

- Observation of two $\bar{c}cu\bar{s}$ tetraquarks and two $\bar{c}du\bar{s}$ tetraquarks, open strangeness
 - $Z_{cs}(4000)^+$, $Z_{cs}(4220)^+$, $X_0(2900)$, $X_1(2900)$

LHCb-Figure-2021-001

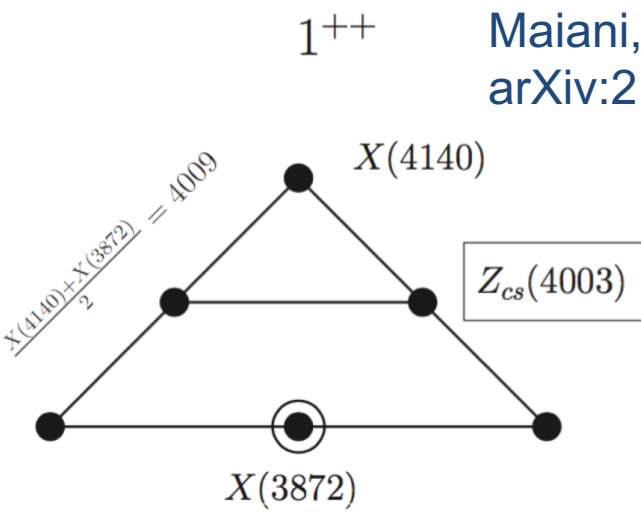


- For the 50th anniversary of hadron colliders the LHC has now discovered more than **50 hadrons !**
- 52 discovered by LHCb

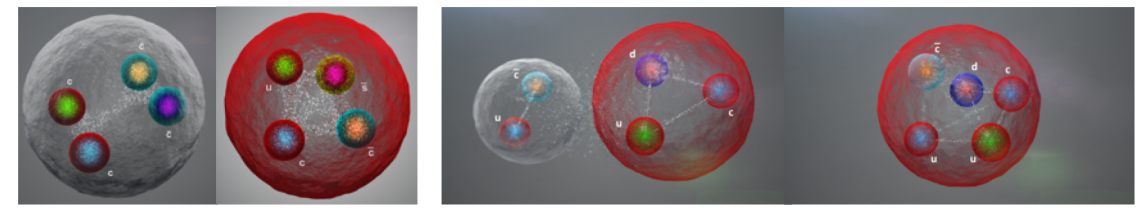
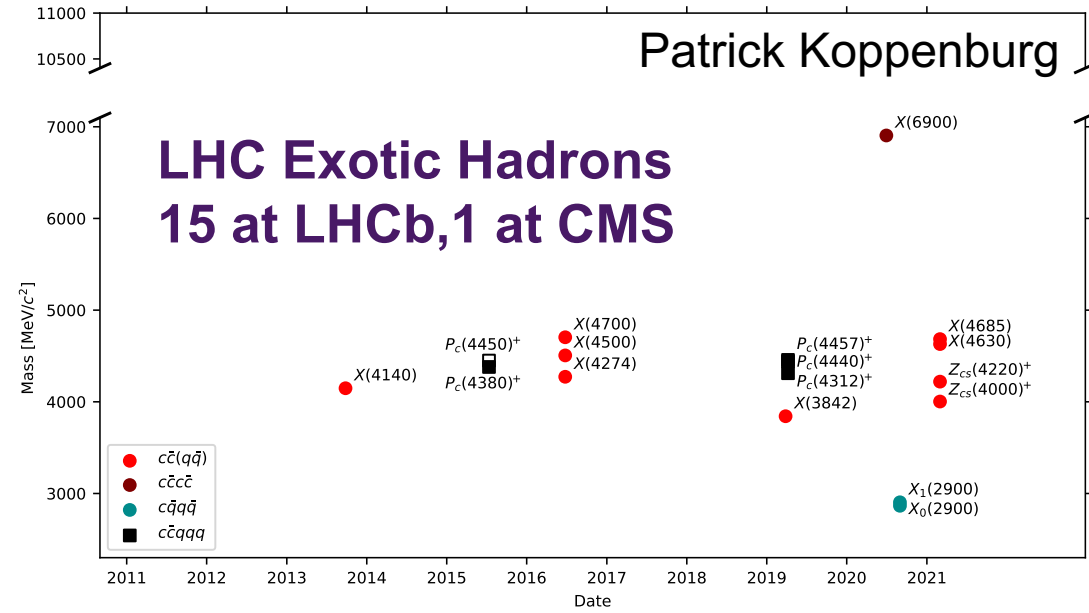
“New Wave” of Exotic Hadrons



- Many exotic hadrons (four, five quark states) discovered in recent years
 - Some of the highest cited papers in LHCb & particle physics
 - Compact & molecular interpretations
 - Clarity starting to emerge ?
- **Formation of multiplets**



Results in:
 Elisabetta Norella
 Thursday 14:33
 Jibo He, Thursday 13:36



Ω_c Lifetime : $\Lambda_c^+(udc), \Xi_c^+(usc), \Xi_c^0(dsc)$ and $\Omega_c^0(ssc)$

New

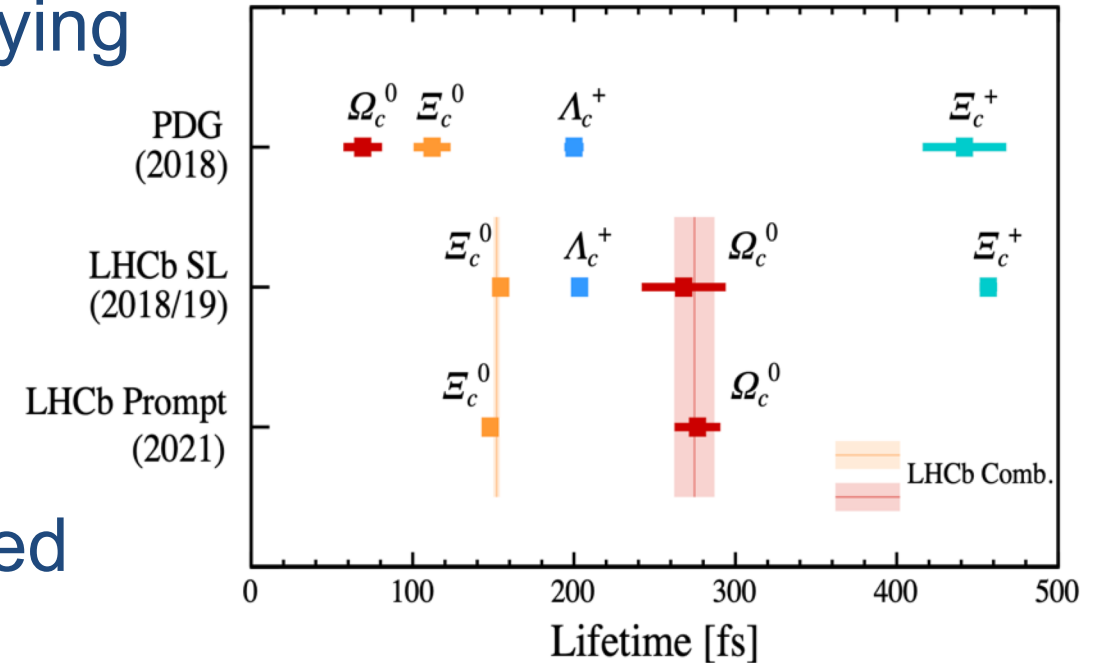
Jibo He, Thursday 13:36

LHCb-PAPER-2021-021

- Ground-state baryons weakly decaying
- Lifetime hierarchy long thought:
 $\tau(\Omega_c^0) < \tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Xi_c^+)$
- LHCb results in production from b decays challenged this
- New results using promptly produced baryons improve measurements & confirm new hierarchy

$$\tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Omega_c^0) < \tau(\Xi_c^+)$$

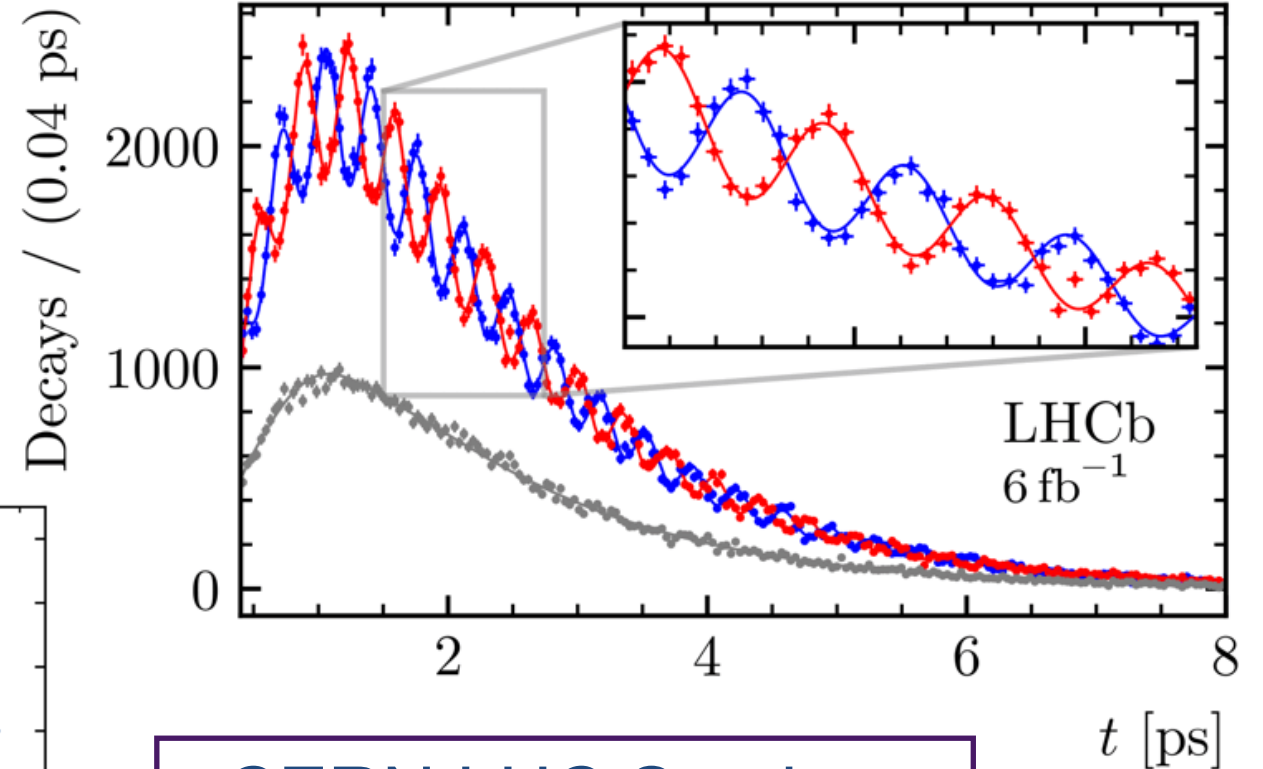
Ω_c^0 lifetime nearly four times larger than PDG (2018)



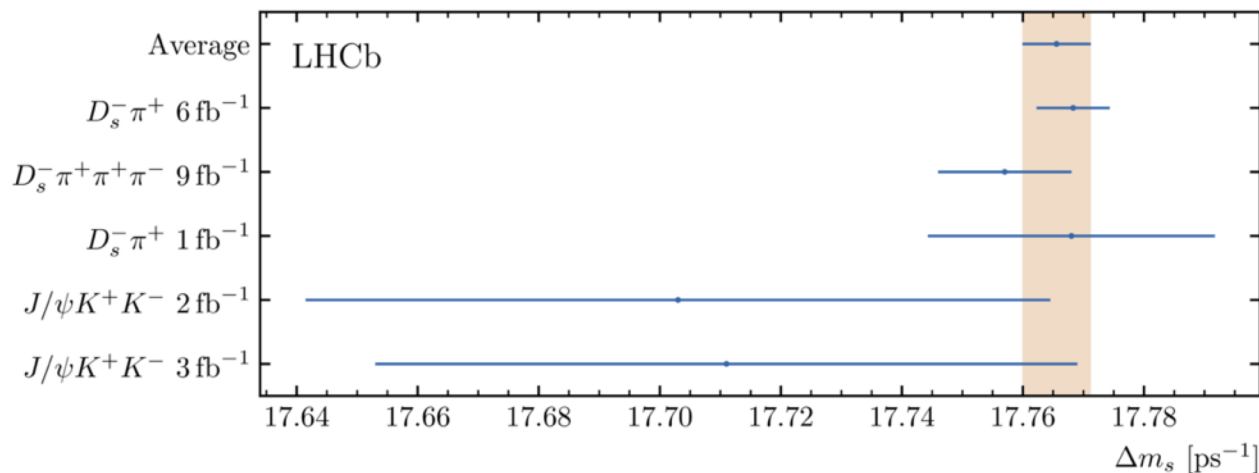
Alessandro Bertolin, Wednesday 15:48

- $B_s \rightarrow D_s^- \pi^+$
- Rate of oscillations controlled by mass difference between eigenstates
- Precision: 3×10^{-4} , Run 2 Legacy Δm_s

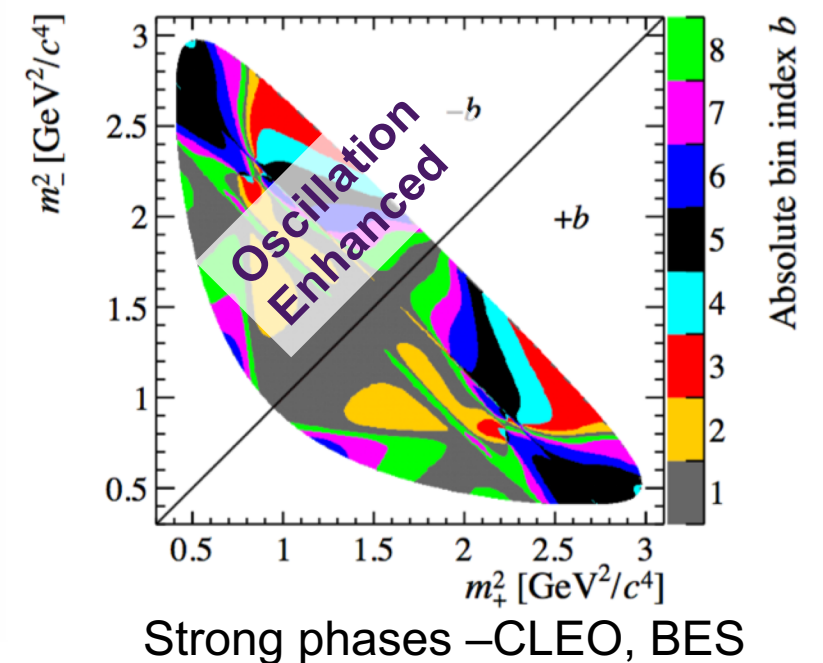
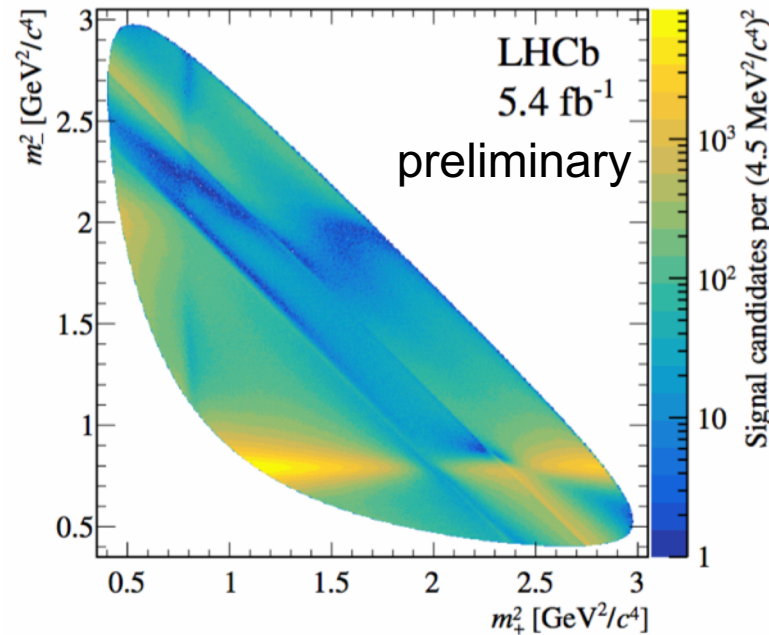
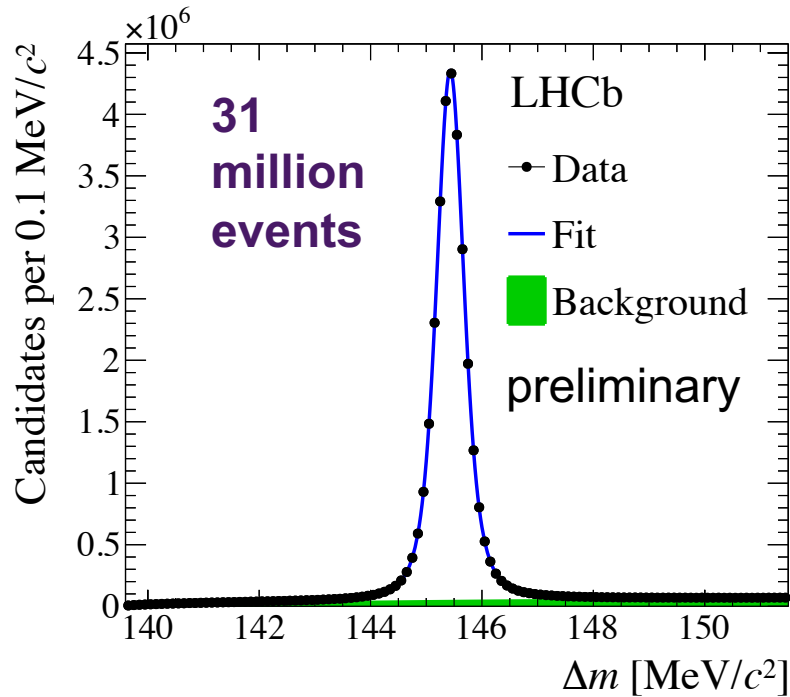
— $B_s^0 \rightarrow D_s^- \pi^+$ — $\bar{B}_s^0 \rightarrow D_s^- \pi^+$ — Untagged



CERN LHC Seminar
10:30 CEST 8th June



- “Golden Channel”: $D^0 \rightarrow K_S \pi^+ \pi^-$
- Analyse decay time evolution of Dalitz plot
- Divide Dalitz plane into bins of similar strong phase
- Ratios utilising symmetry of Dalitz plot reduce efficiency dependence



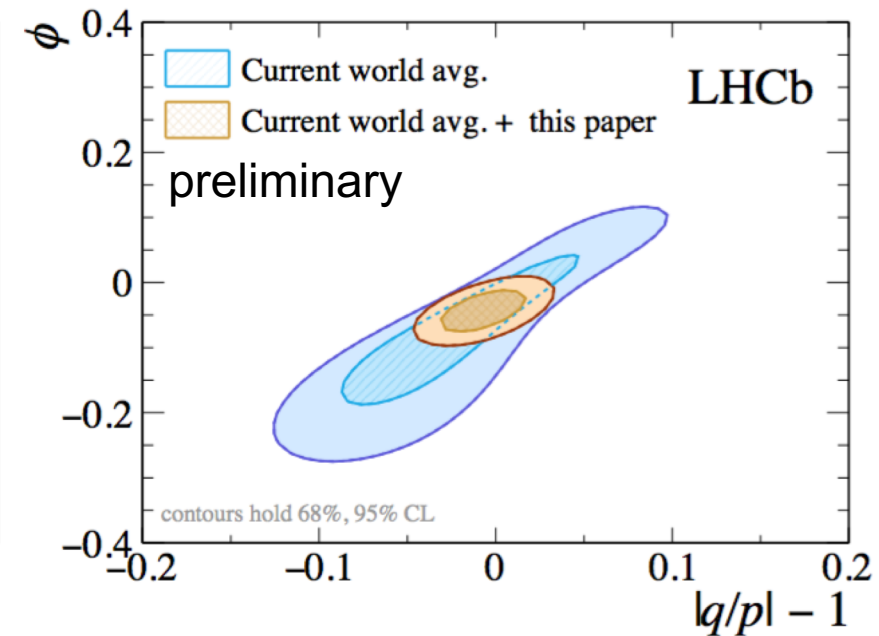
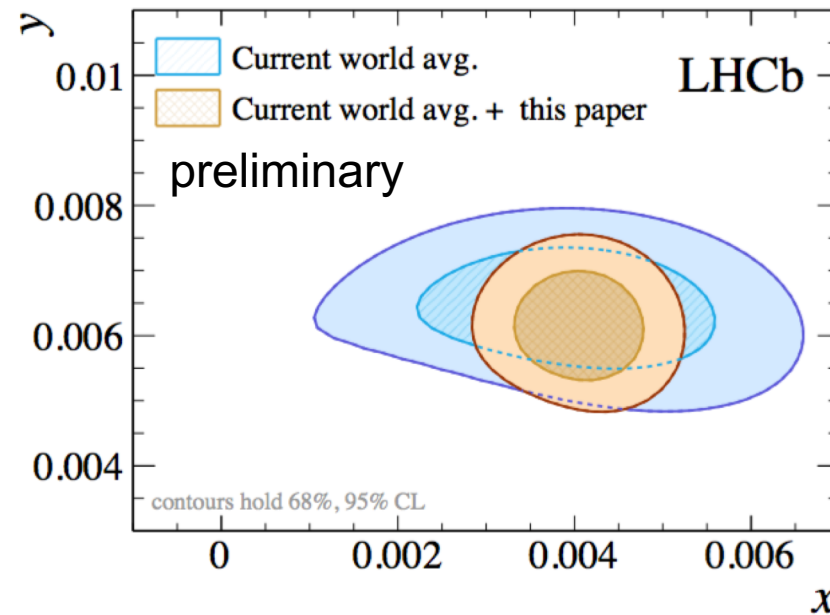
Observation of Mass Difference in D Eigenstates

New

LHCb-PAPER-2021-009

- $x = (m_1 - m_2) / \Gamma$
- $y = (\Gamma_1 - \Gamma_2) / 2\Gamma$
- CPV: q/p and ϕ

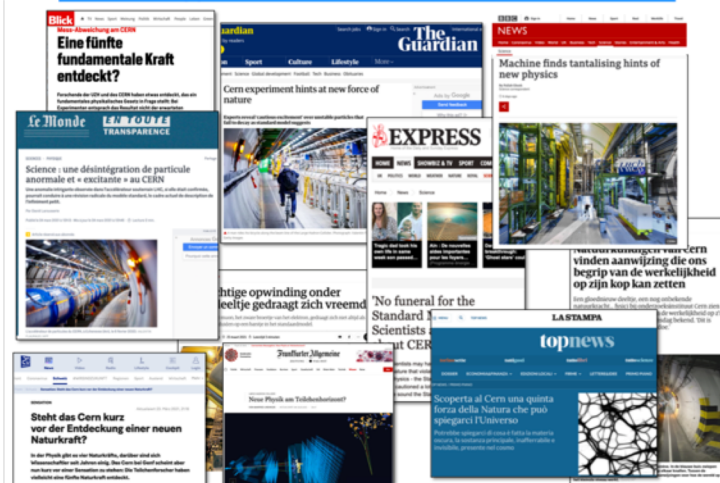
Parameter	Value
$x [10^{-3}]$	$3.98^{+0.56}_{-0.54}$
$y [10^{-3}]$	$4.6^{+1.5}_{-1.4}$
$ q/p $	0.996 ± 0.052
ϕ	$-0.056^{+0.047}_{-0.051}$



- **First Observation (7σ) of mass difference between D_1, D_2 eigenstates**
- CERN LHC Seminar 10:30 CEST 8th June

$b \rightarrow s l^+ l^-$: an extensive programme

FCNC decay powerful probe for New Physics



Title	Observ.	Comment
2020		
Search for the lepton flavour violating decay $B^+ \rightarrow K^+ \mu^- \tau^+$ using B^{*0}_{s2} decays	Limit	Lepton Flavour Viol.
Search for the rare decays $B^0_s \rightarrow e^+ e^-$ and $B^0 \rightarrow e^+ e^-$	Limit	Rare decay
Measurement of CP -averaged observables in the $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decay	P_5'	Angular asymmetry
Strong constraints on the $b \rightarrow s \gamma$ photon polarisation from $B^0 \rightarrow K^{*0} e^+ e^-$ decays	C_7'	Wilson coefficient
Angular analysis of the $B^+ \rightarrow K^{*+} \mu^+ \mu^-$ decay	P_5'	Angular asymmetry
2021		
Test of lepton universality in beauty quark decays	R_K	Lepton Flavour Non-Univ.
Improved measurement of $B^0_{(s,d)} \rightarrow \mu^+ \mu^-$ decays	BR	Rare decay
Measurement of $B^0_s \rightarrow \mu^+ \mu^-$ and search for $B^0 \rightarrow \mu^+ \mu^-$ and $B^0_s \rightarrow \mu^+ \mu^- \gamma$ decays	BR	Rare decay
Differential branching fraction of $B^0_s \rightarrow \varphi \mu^+ \mu^-$ and search for $B^0_s \rightarrow f'_2 \mu^+ \mu^-$	$d\Gamma/dq^2$	Decay rate
Updated angular analysis of the rare decay $B^0_s \rightarrow \varphi \mu^+ \mu^-$	F_L, A_{FB}	Angular asymmetry
Search for the $\Xi_b \rightarrow \Xi \gamma$ radiative decay	Limit	Rare decay



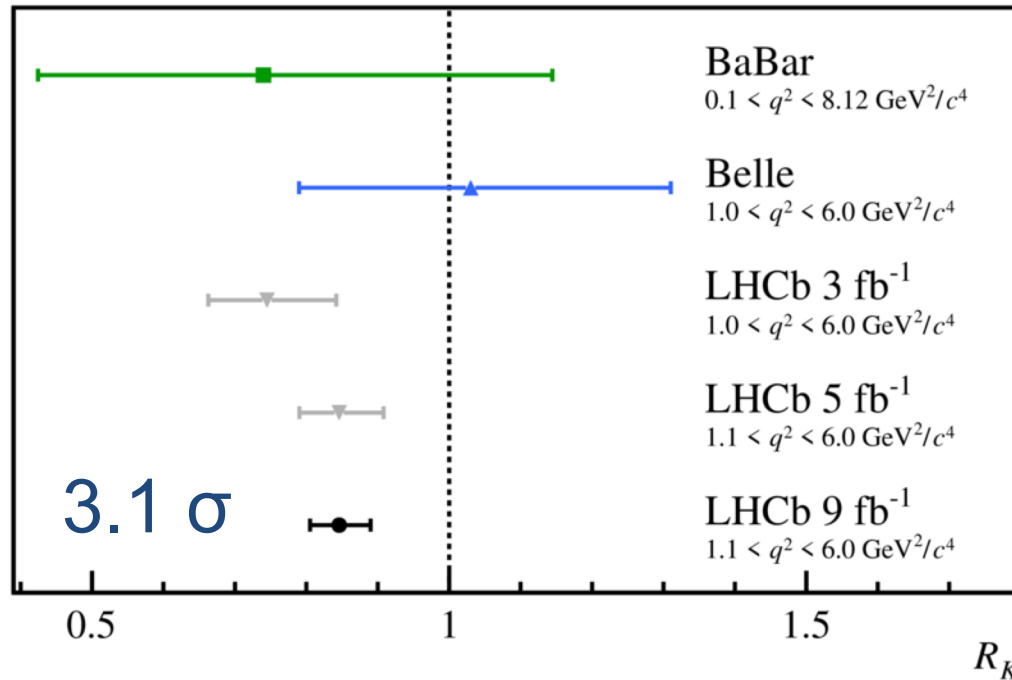
- $b \rightarrow s l^+ l^-$ processes generated a lot of #CautiousExcitement recently
- For us it has become a notable part of our programme over the last decade (first two papers in 2011, six already this year)

– Ratios, Angular asymmetries, Branching Fractions, LFV Searches

$b \rightarrow s l^+ l^- : R_K \text{ \& } B_s \rightarrow \mu^+ \mu^-$

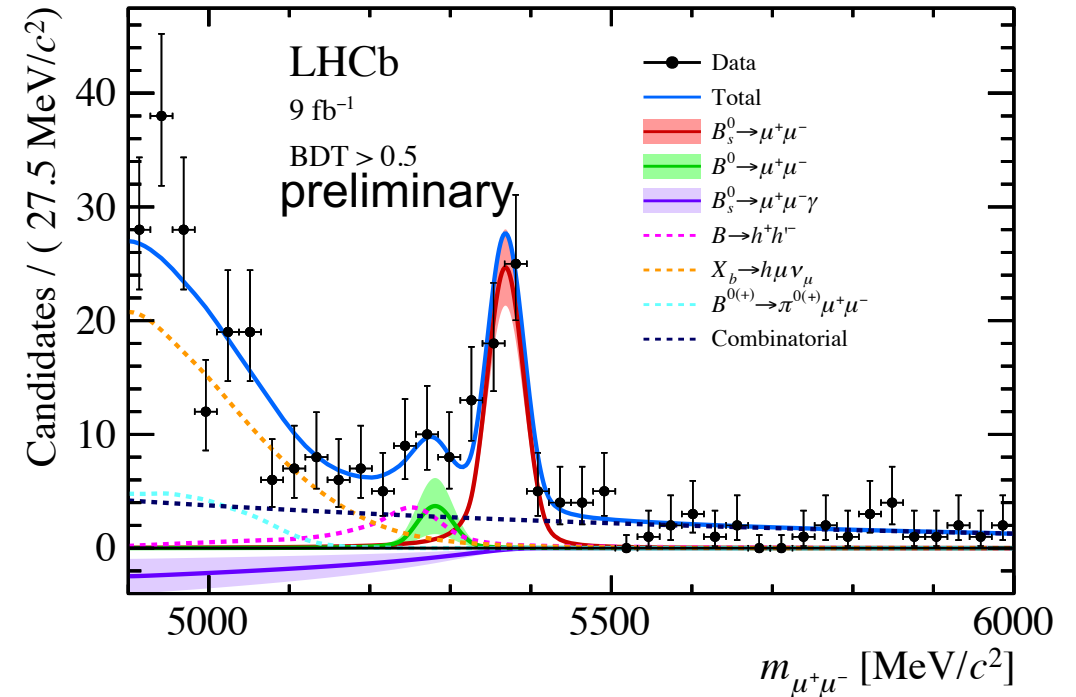
Jacco De Vries, Tuesday 15:27 Yanting Fan, Tuesday at 14:51

- Full LHCb data set, theoretically clean observables



$$R_K = 0.846^{+0.044}_{-0.041}$$

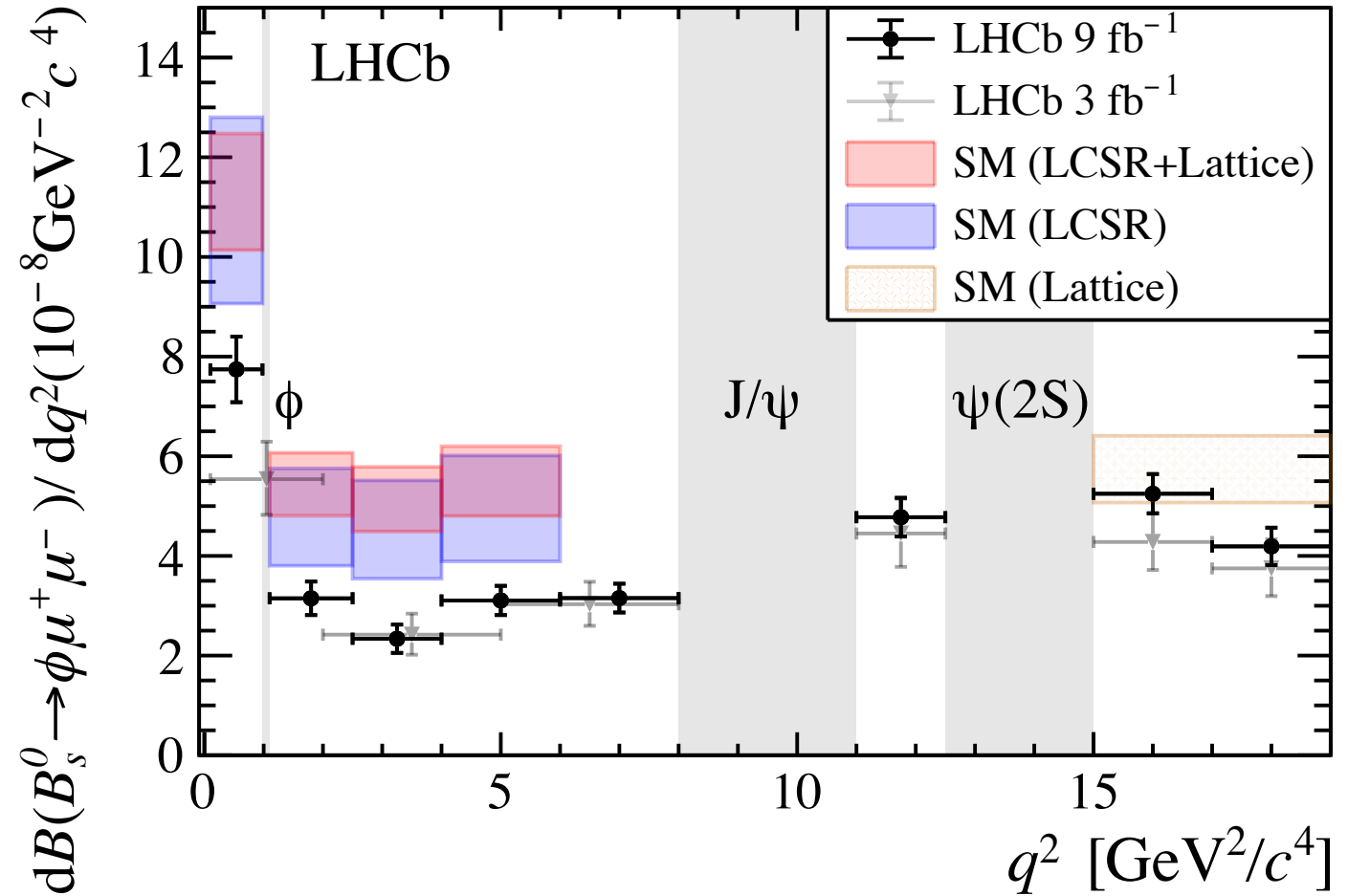
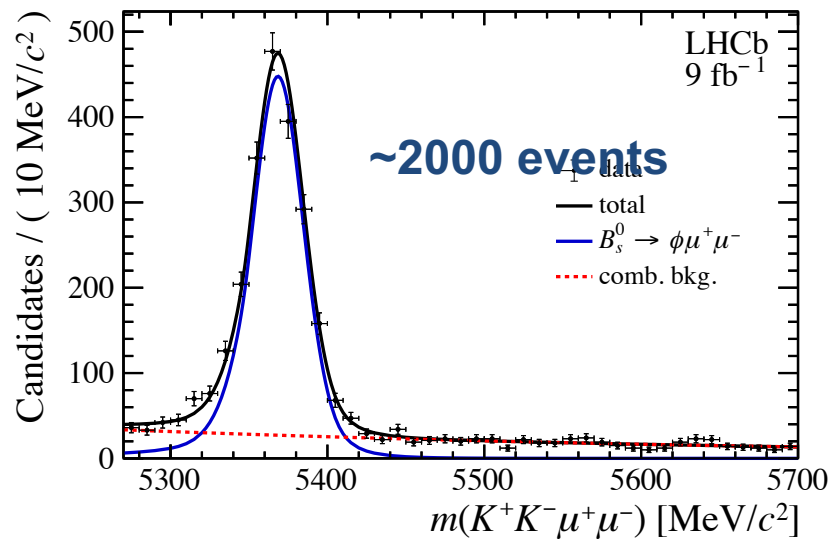
$$R_K = \frac{\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \rightarrow J/\psi(\rightarrow \mu^+ \mu^-) K^+)} \bigg/ \frac{\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)}{\mathcal{B}(B^+ \rightarrow J/\psi(\rightarrow e^+ e^-) K^+)}$$



$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9}$$

R_K 66 citations,
effective field theory Wilson coefficient fits

- Full LHCb data set
- Tension with respect to SM prediction:
 - 3.6σ LCSR+Lattice
 - 1.8σ LCSR only
- Again, lack of muons



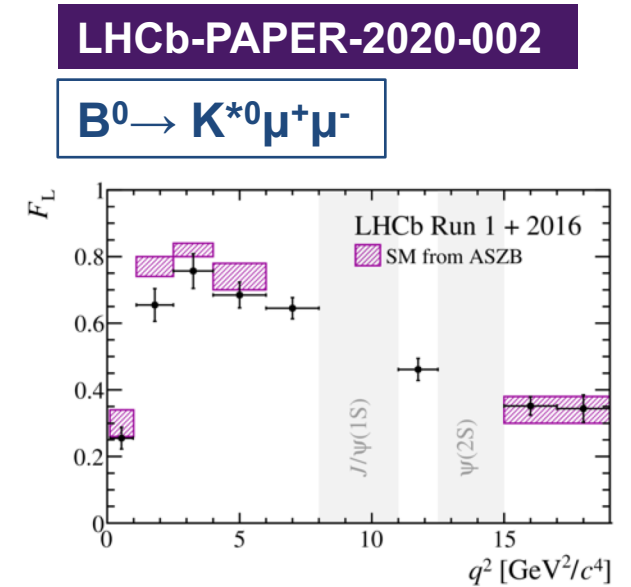
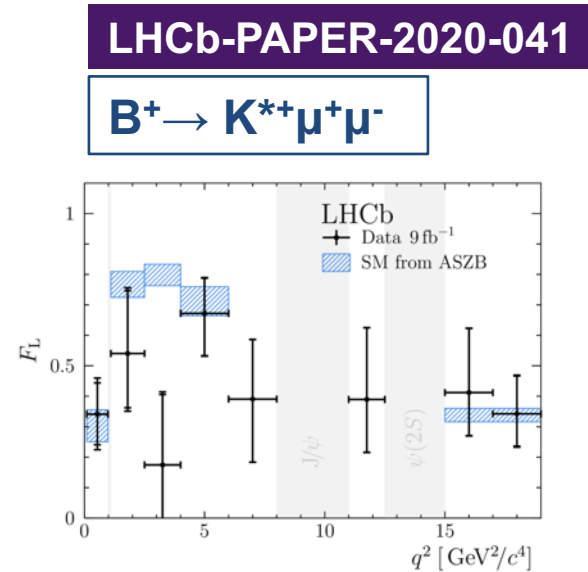
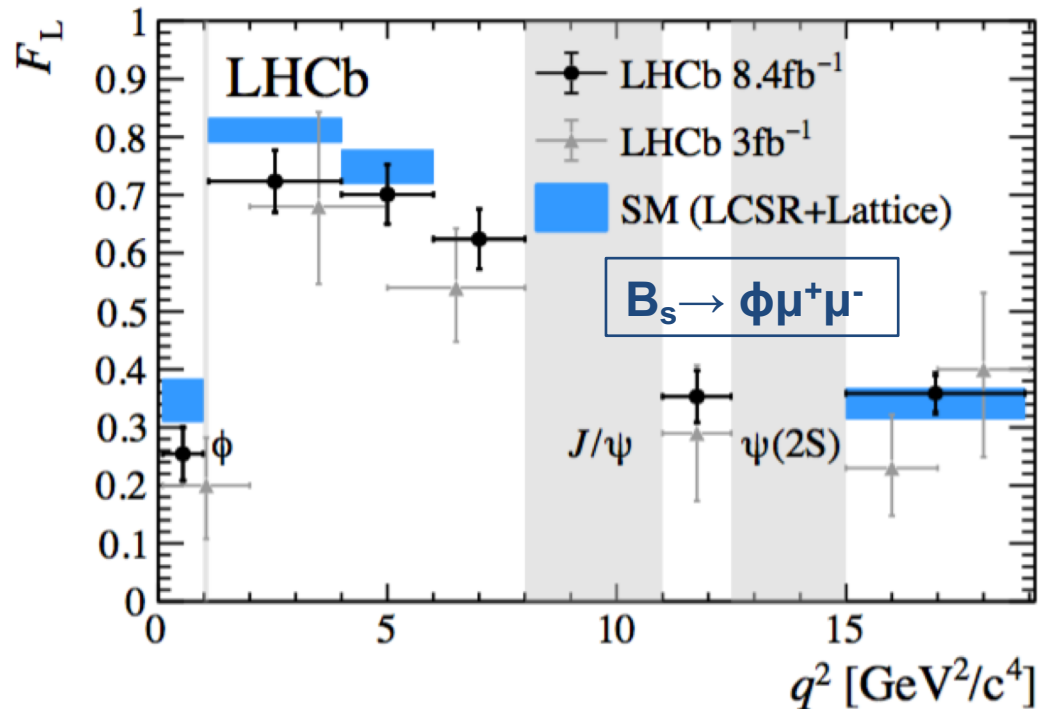
$b \rightarrow s l^+ l^- : B_s \rightarrow \phi \mu^+ \mu^-$ Angular Analysis

LHCb-PAPER-2021-022

New

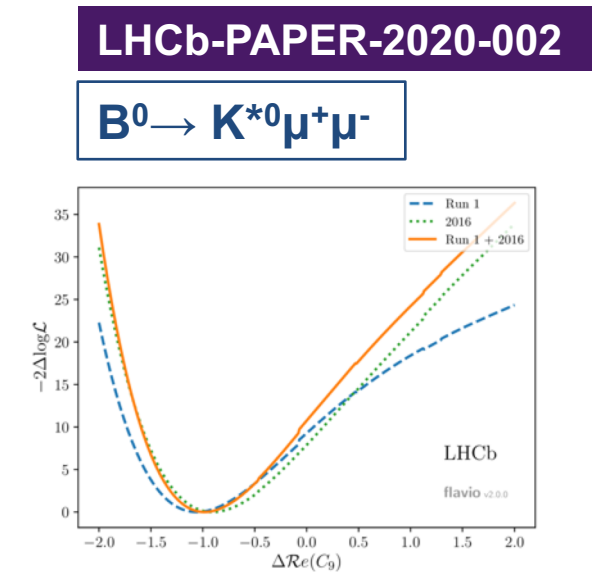
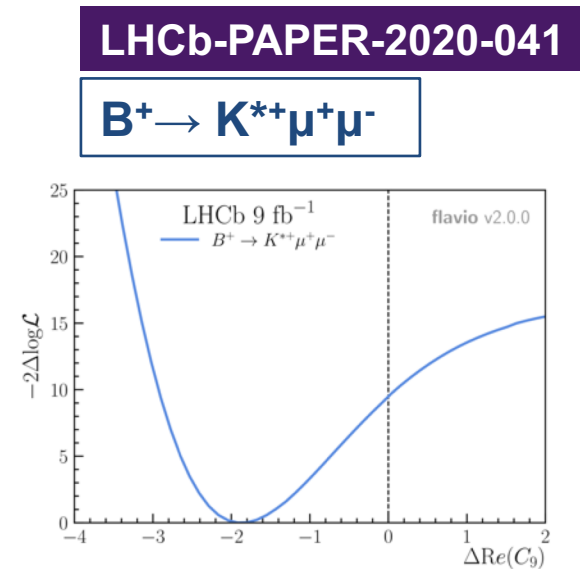
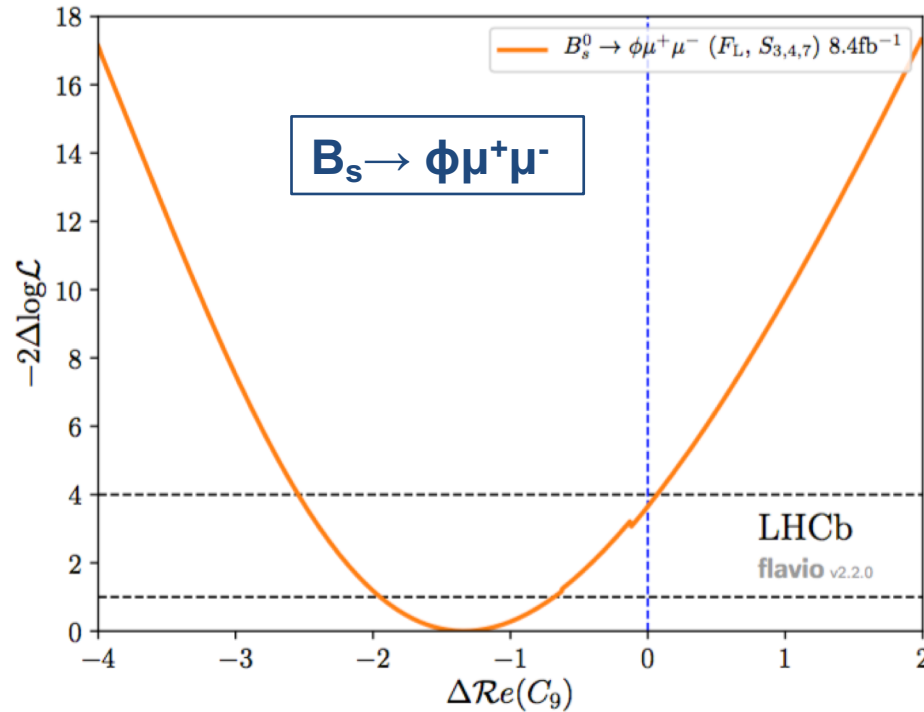
- Full LHCb data set

Yanting Fan, Tuesday at 14:51



- F_L somewhat below SM at low q^2
 - Same pattern as $B^+ \rightarrow K^{*+} \mu^+ \mu^-$ & $B^0 \rightarrow K^{*0} \mu^+ \mu^-$
 - Effective field theory Wilson coefficient best $Re(C_9)$ fit 1.9σ over SM
- P_5' is CP-average and not accessible here as mode not self tagged

- Full LHCb data set



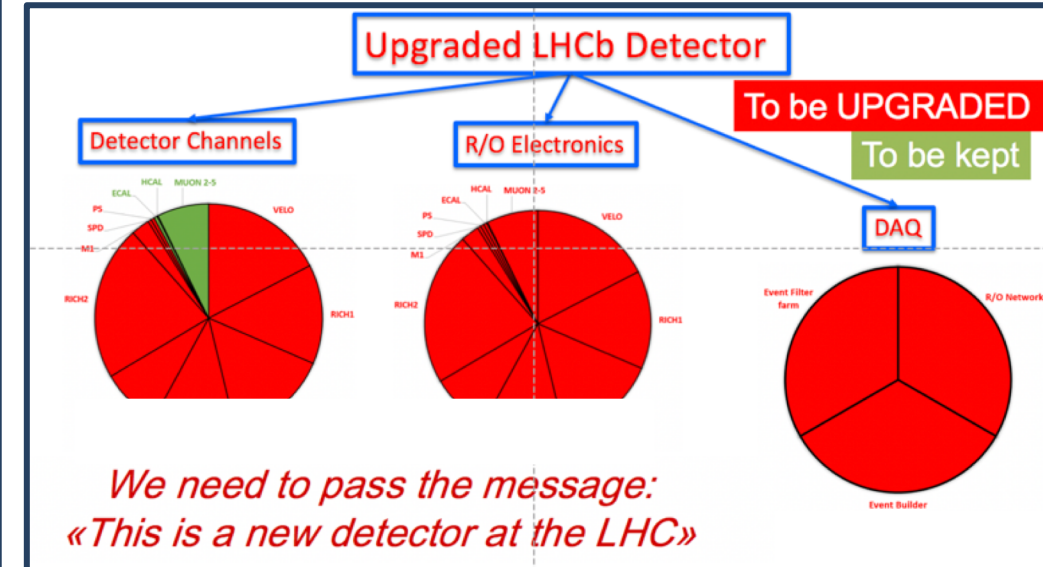
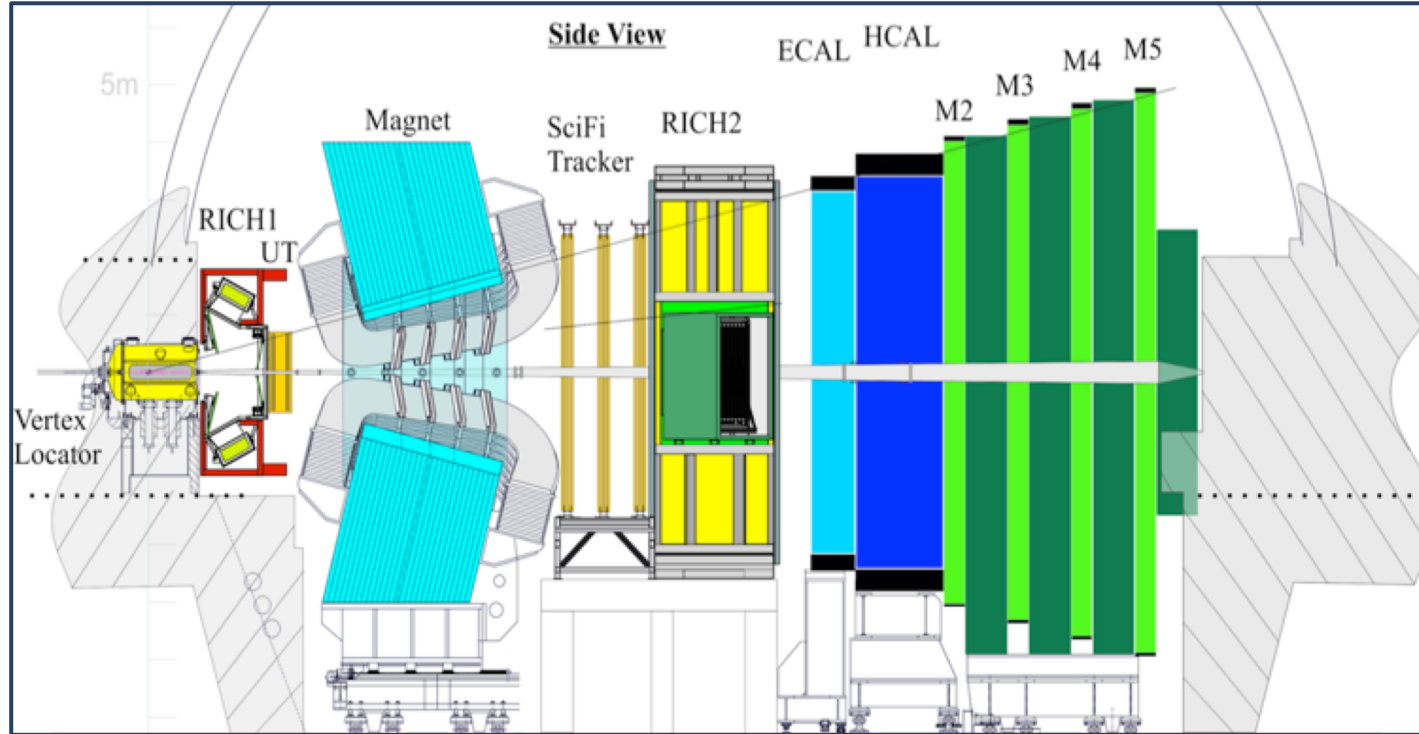
- F_L somewhat below SM at low q^2
 - Same pattern as $B^+ \rightarrow K^{*+}\mu^+\mu^-$ & $B^0 \rightarrow K^{*0}\mu^+\mu^-$
 - Effective field theory Wilson coefficient best $\text{Re}(C_9)$ fit 1.9σ over SM
- P_5' is CP-average and not accessible here as mode not self tagged

Upgrade I: Reminder

- All sub-detectors read out at 40 MHz for a **fully software trigger**

Tomasz Szumlak,
Wednesday 17:42

with new data centre



*We need to pass the message:
«This is a new detector at the LHC»*

- Pixel detector **VELO** with silicon microchannel cooling 5mm from LHC beam
- New **RICH** mechanics, optics and photodetectors
- New silicon strip upstream tracker **UT** detector
- New **SciFi** tracker with 11,000 km of scintillating fibres
- New electronics for **muon** and **calorimeter** systems

Major project
being installed
currently for
operation in Run 3



VELO

VELO Modules: first half completed

Half Assembly: expected to start soon

Travel & quarantine delays to problem solving and components

SciFi

Four (of 12) assembled frames & cable chains installed

Travel of significant part of team resumed despite restrictions



UT

Modules: main type production nearly complete

Mounting to start mid-July

Travel restrictions & issues delayed mounting



LHCb Upgrade I: Particle Identification [RICH, CALO, Muons]

RICH: commissioning

RICH1 Enclosure
installed and leak tested

RICH2 Photodetector
arrays installed, first new
sensors

Key expert travel allowed
& excellent progress



CALO: commissioning started

Front-end board installation in progress

Issues at production companies
resolved

Muons: commissioning

All electronic boards installed

Commissioning progressing well

Excellent progress made

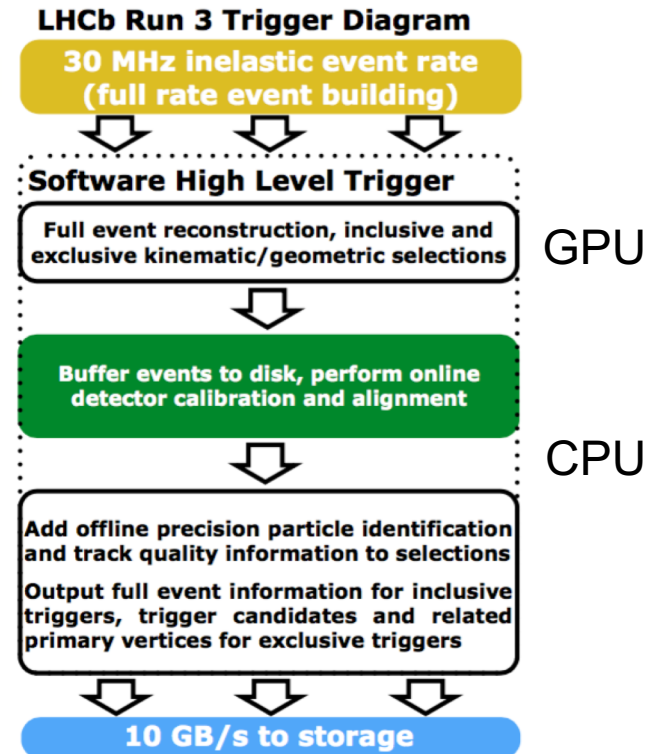
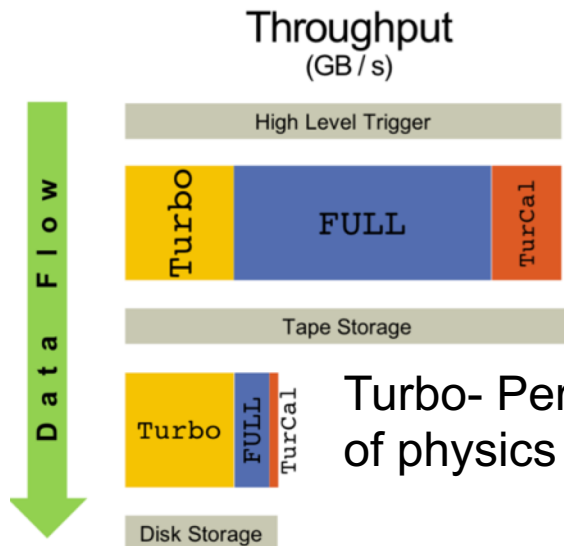


LHCb Upgrade I: Computing, Online & Trigger



- Installation of Event builder PC servers & their FPGA DAQ cards completed
- Event builder network >100 Tbit/s (200xRun2) achieved
- Commissioning of Muon, RICH, CALO underway

- Event reconstruction in trigger achieved in single GPU card
- Full reconstruction in trigger achieved CPU event rate requirement

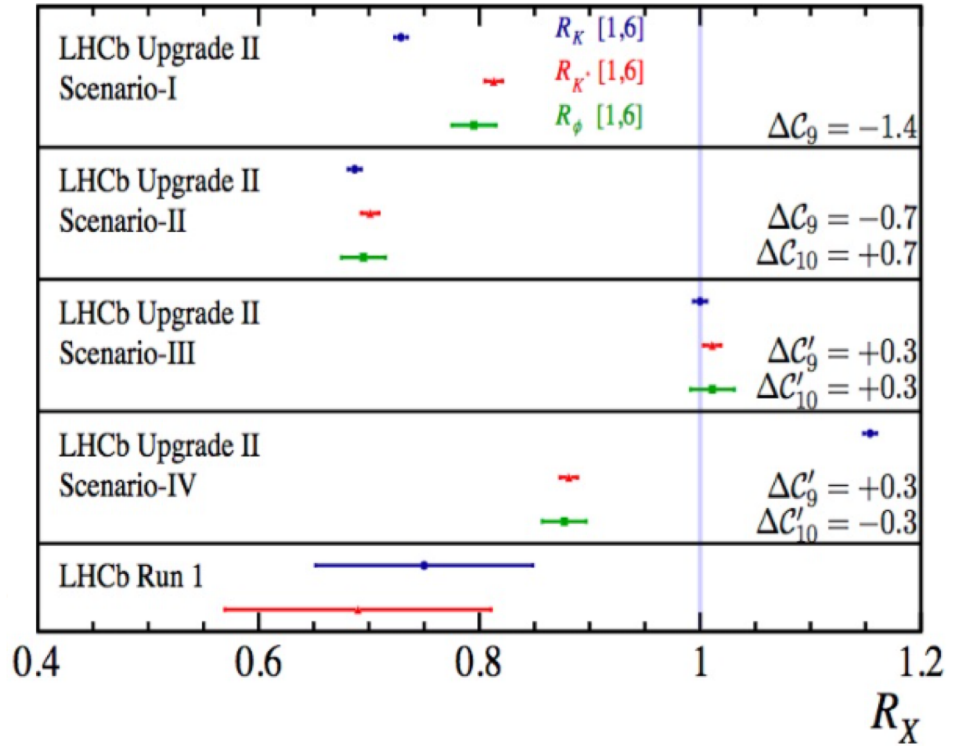


LHCb Upgrade II : Framework TDR

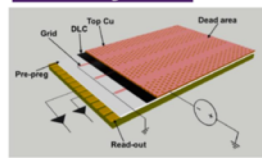


Francesca Dordei, Monday 17:54 Silvia Gambetta, Wednesday 14:39

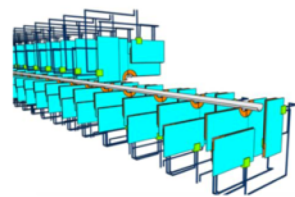
- **Fully exploit LHC facility for flavour physics & beyond, for LS4**
 - Expression of interest (2017), Physics Case (2018)
 - Strong support in European Strategy (2020)
- **Framework Technical Design Report**
 - Options to achieve physics programme
 - Drafting in progress, for delivery later this year



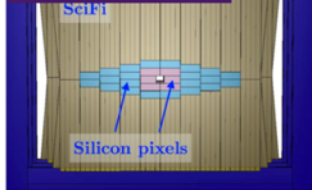
Muon system



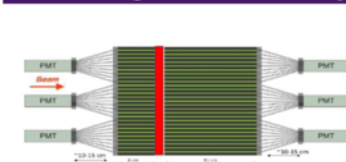
Vertex Detector (VELO)



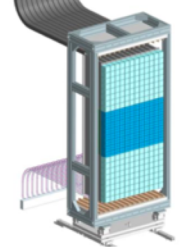
Tracking System



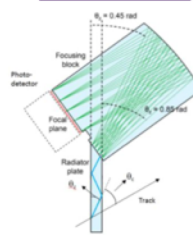
Electromagnetic Calorimetry



RICH



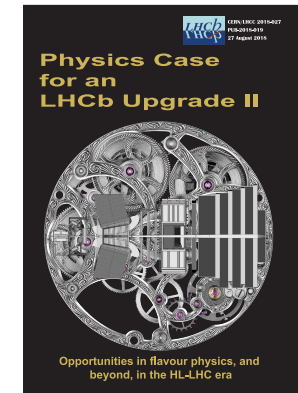
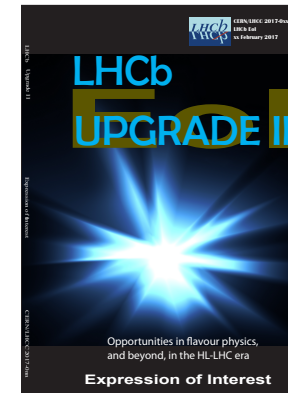
TORCH ToF



Trigger & DAQ system

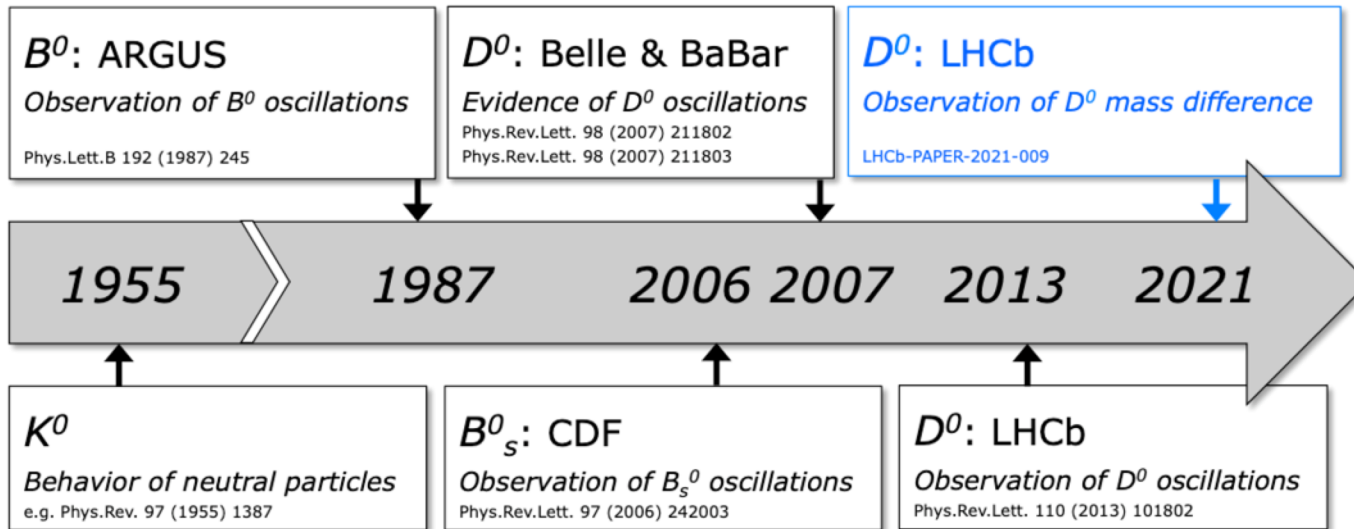


Technology synergy with future projects



Summary

- New results include:
 - Mass difference in D eigenstates, further tensions with SM in $b \rightarrow s|^{+}|^{-}$ processes
- Significant progress made on Upgrade I, schedule tension remains
 - Advanced production → installation → commissioning
- Upgrade II Framework TDR in drafting phase

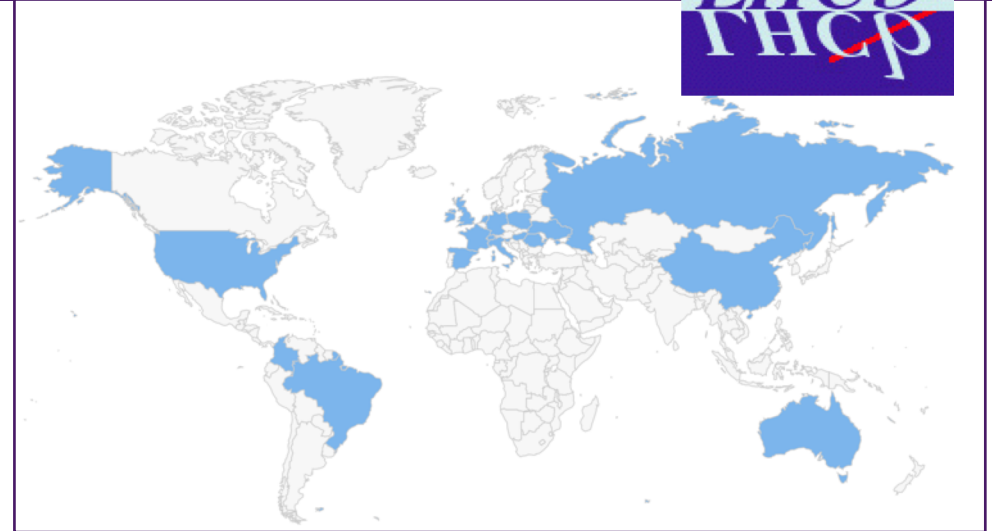


Backup

Collaboration



- Exceeded 1000 authors
 - 1009 authors, 1482 members
- 88 institutes, 19 countries



Growing Collaboration

Ambitious future upgrade plans with strong synergies with future collider projects

Extensive physics programme beyond flavour

LHCb Recent Results: Key Legacy Measurement



LHCb-PAPER-2021-007

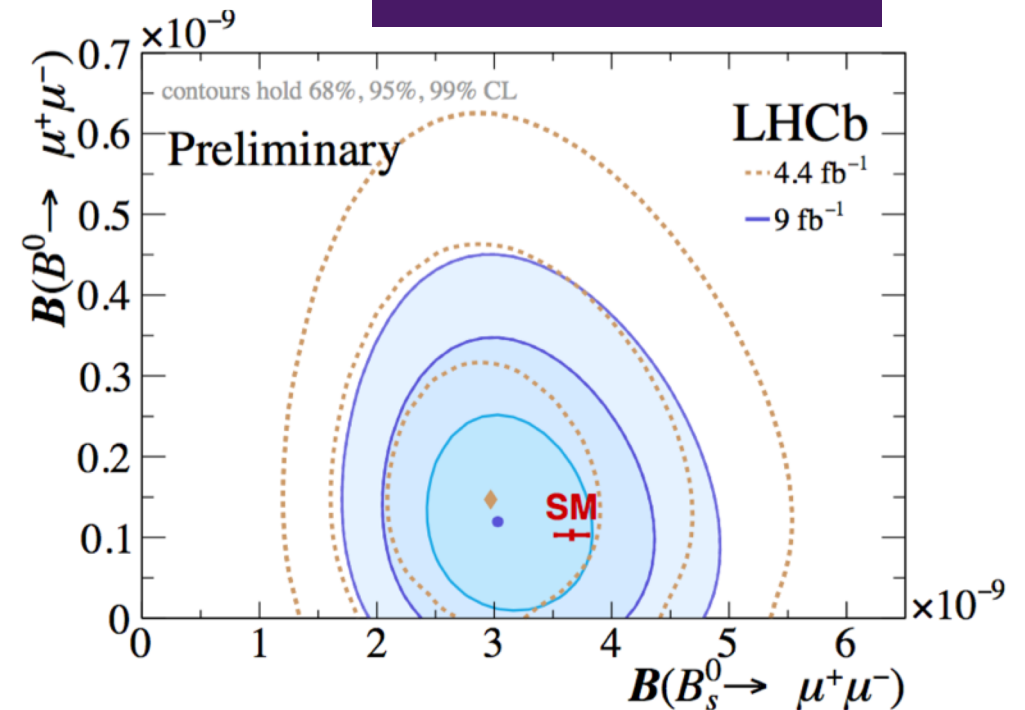
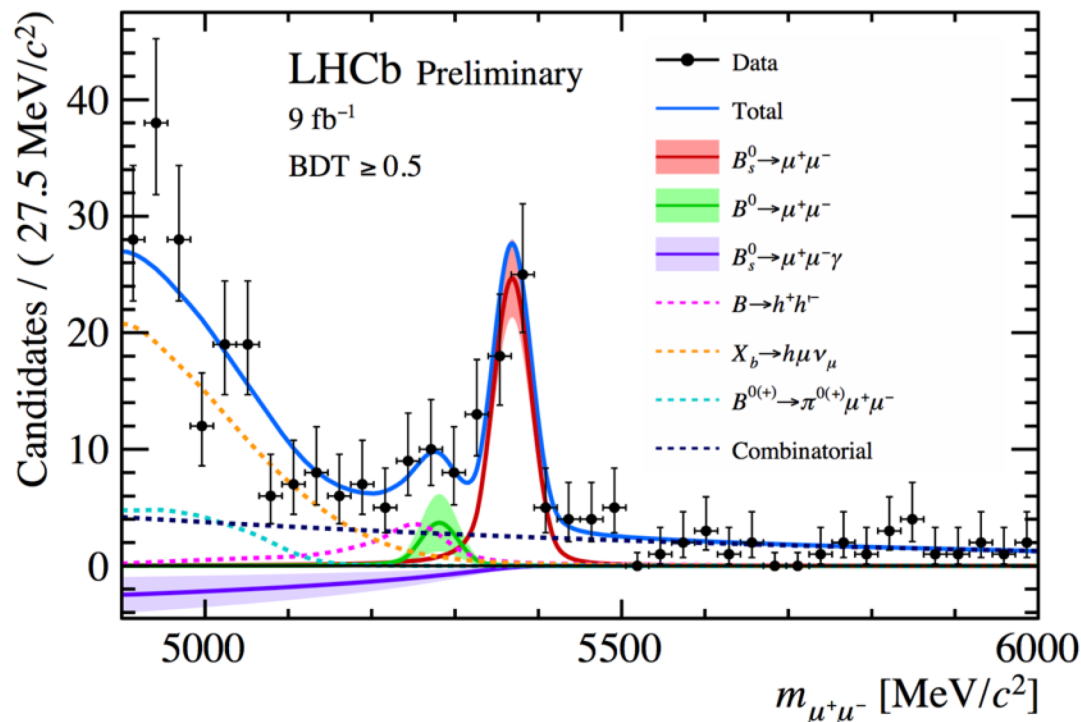
$B_s \rightarrow \mu^+ \mu^-$

- Results with full data set
- Best single expt measurement
 - A key process to constrain new physics, for example extended Higgs sectors
 -and including models related to the next slide...

New measurement f_s/f_d provides important input

● $\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9} \quad (10.8\sigma)$

LHCb-PAPER-2020-046



LHCb Recent Results – Lepton Flavour Universality



LHCb-PAPER-2021-004

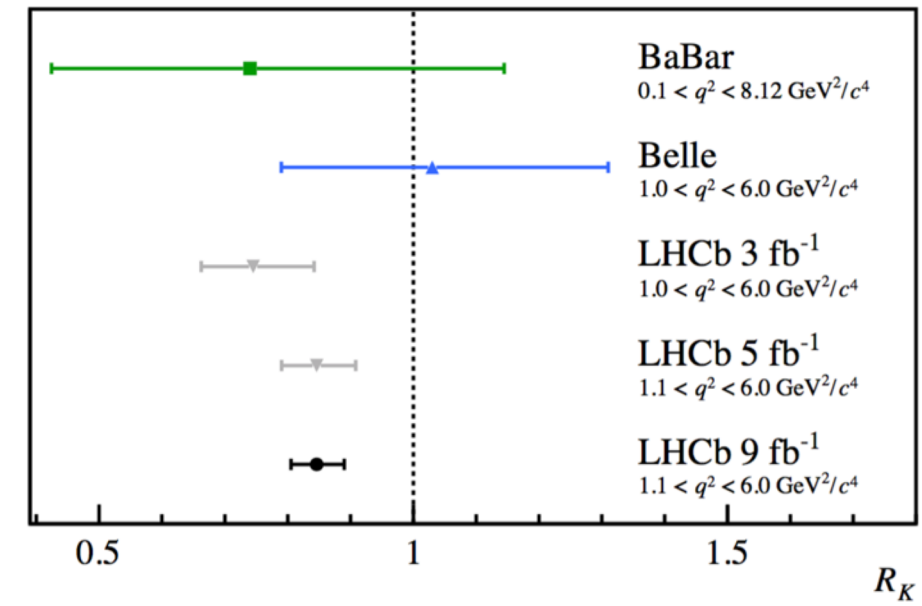
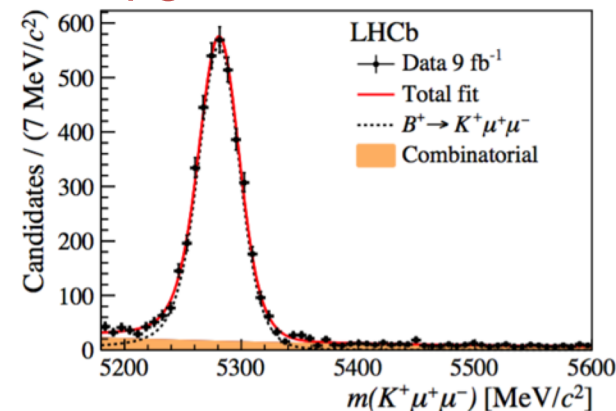
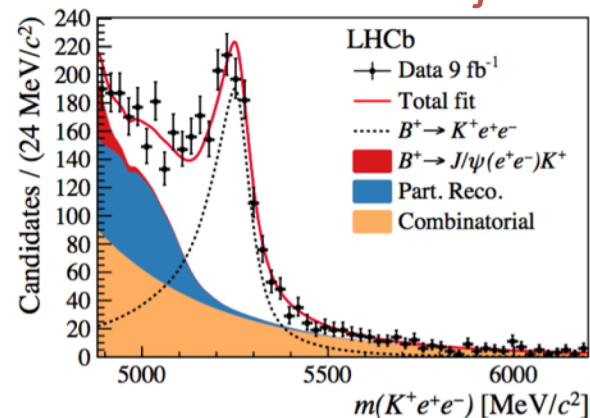
- Standard Model predicts identical electroweak couplings of e, μ
 - Intriguing hints from LHCb in recent years at $2.1\text{-}2.5\sigma$ level of deviations from SM in $b \rightarrow s l^+ l^-$ ratios, also in angular distributions and branching fractions.

Rare B decay process:
 $B \rightarrow K \mu^+ \mu^-$, $B \rightarrow K e^+ e^-$,
 Count and compare, expect same numbers of decays

$$R_H \equiv \frac{\int_{q_{\min}^2}^{q_{\max}^2} \frac{d\mathcal{B}(B \rightarrow H \mu^+ \mu^-)}{dq^2} dq^2}{\int_{q_{\min}^2}^{q_{\max}^2} \frac{d\mathcal{B}(B \rightarrow H e^+ e^-)}{dq^2} dq^2}$$

$$R_K(1.1 < q^2 < 6.0 \text{ GeV}^2/c^4) = 0.846^{+0.042}_{-0.039} {}^{+0.013}_{-0.012}$$

- 3.1σ deviation from Standard Model
 - Additional measurements with existing data set will provide further information, then data from the current major LHCb Upgrade for Run 3



Operation: Computing



- Extensive use of fast simulation techniques has increased the number of events produced by a **factor of four** with only a **30% increase** in CPU resources

