

# LHCb Summary

Michael McCann  
**on behalf of LHCb**

Imperial College London

30 November 2016  
128<sup>th</sup> LHCC meeting: Open Session

# Introduction

LHCb  
Summary

Michael  
McCann  
on behalf of  
LHCb

Busy few months for LHCb, this talk will cover:

- 2016 Operations
  - General improvements
  - $pp$  running
  - $pPb$ – $Pbp$  running
  - EYETS
- Physics program
  - Overview
  - Highlights
    - Including **new results** at CKM
- LS2 upgrade program

# New control room and automation

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- Purpose built control room
- Pleasure to spend time there
- Dedicated meeting room
- **Four coffee machines!**



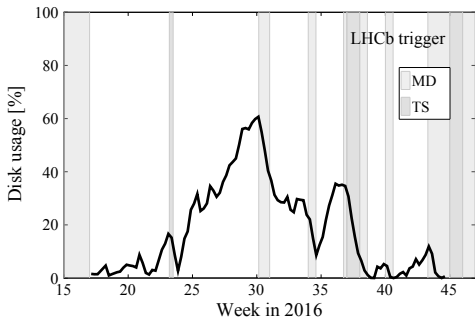
- High levels of automation
- Experiment run by two shifters
- Often only need to accept handshakes
- Backed up by dozens of experts and piquets

# HLT (software trigger)

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- HLT split into two stages
  - HLT1: Uses basic event info
  - HLT2: Fully calibrated and reconstructed event info
- HLT1 output parked until HLT2 run
  - 10 PB disk buffers available
- HLT2 runs when HLT1 isn't using full resources
- Tuned adaptively to conditions for maximum efficiency





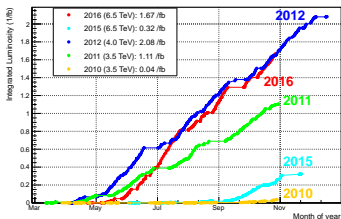
# pp running

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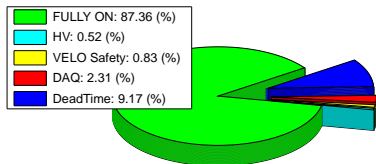
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- LHC 2016  $pp$  program now complete
- Very successful period for LHCb
  - 1.7  $\text{fb}^{-1}$  taken
  - Including 2015 1.99  $\text{fb}^{-1}$  total, equal to 2012 but much higher cross-sections  $\sim \times 2b\bar{b}$
- Luminosity levelling to  $\mu \sim 1.1$  effective
- Thanks to LHC for excellent running

LHCb Integrated Luminosity in pp collisions 2010-2016



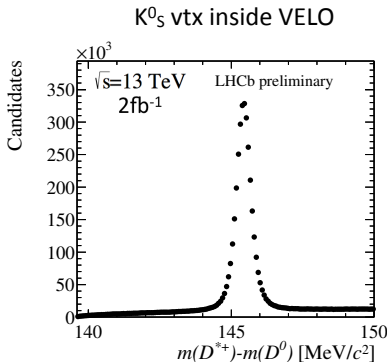
LHCb Efficiency breakdown in 2016



Av. rec. lumi. =  $0.3 \text{ nb}^{-1}\text{s}^{-1}$ ,  
better with more bunches

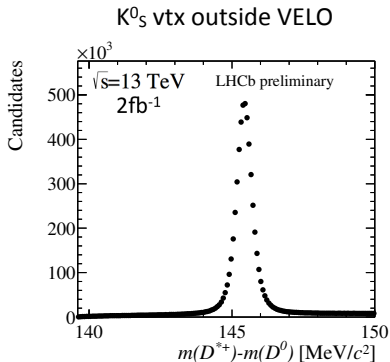
## Excellent online charm reconstruction and yields

$$D^0 \rightarrow K_S^0 \pi^+ \pi^-$$



$N_D \approx 3.2 \times 10^6$  (1.6M/fb)

Run1: 0.3M/fb



$N_D \approx 5.0 \times 10^6$  (2.5M/fb)

Run1: 0.4M/fb

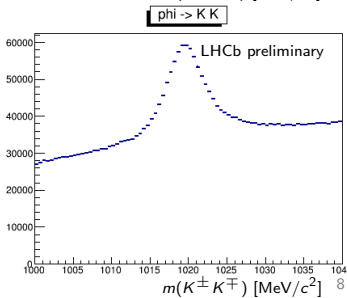
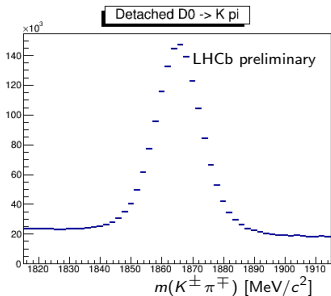
Factor of  $\sim 5$  ( $/\mathcal{L}$ ) w.r.t run 1

# Ion running

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- LHC 2016 ion program now in progress
  - Big thank you for agreeing to our requests
- Requested  $10 \text{ nb}^{-1}$  per direction  $\sqrt{s_{NN}} = 8 \text{ TeV}$ 
  - LHCb asymmetric
- Smooth data taking  $p\text{Pb}$ :
  - 5 TeV taken  $\sim 2 \text{ nb}^{-1}$
  - 8 TeV taken  $\sim 13 \text{ nb}^{-1}$
  - 95% efficiency
- $\text{PbP}$  taken  $\sim 10 \text{ nb}^{-1}$
- All reconstructed online
- Online plots from  $p\text{Pb} \rightarrow$



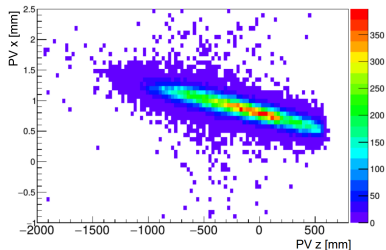


# SMOG

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- Can inject He into beam pipe
  - Acts as fixed target experiment
- SMOG injected during 5 TeV  $p\text{Pb}$
- Physics goals
  - $\bar{p}$  cross sections
  - Charm production



**Collisions and fixed target at the same time!!**

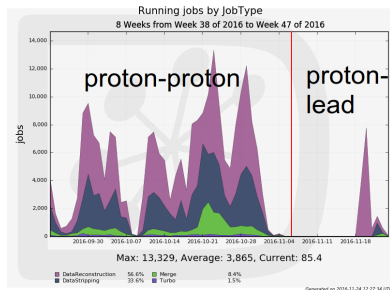
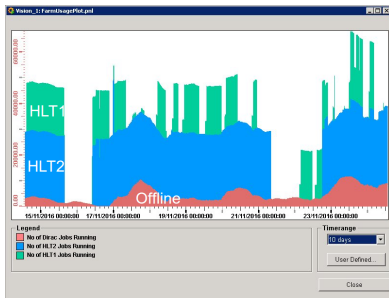
# Offline Computing

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## ■ Status of Data Processing

- 2016 proton-proton collision processing finished
- proton-lead processing currently ongoing



- Further resource usage optimization by running HLT and offline simulation workloads **concurrently** in the trigger farm

- E.g. **during pPb Run** not all resources needed for software trigger

## Limited at LHCb by crane maintenance after 24 Jan ready for detector upgrade in LS2

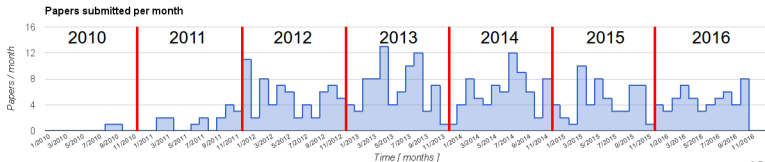
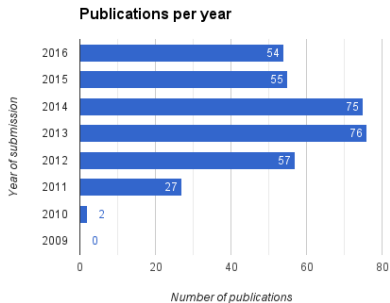
- Program of detector maintenance (Minor work)
  - Installation of upgrade cooling lines
  - Minor repairs to silicon tracker bonding
  - Scintillator replacements in Herschel
  - Photodetector replacements in both RICHes
- Program of infrastructure maintenance (Major work)
  - Replacement of main crane in cavern
  - Replacement of main lift to cavern

# Physics overview

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- 346 papers submitted (total)
  - 20 further papers within the Editorial Board
- 16 conference notes with preliminary results (2016)
- 40 other analyses under review



- **Search for decays of neutral beauty mesons into four muons [arXiv:1611.07704]**
- Evidence for the two-body charmless baryonic decay  $B^+ \rightarrow p\bar{\Lambda}$  [arXiv:1611.07805]
- **Measurements of charm mixing and CP violation using  $D^0 \rightarrow K^\pm\pi^\mp$  decays [arXiv:1611.06143]**
- **Measurement of the CKM angle  $\gamma$  from a combination of LHCb results [arXiv:1611.03076]**
- Measurement of CP asymmetry in  $D^0 \rightarrow K^-K^+$  decays [arXiv:1610.09476]
- **Observation of the annihilation decay mode  $B^0 \rightarrow K^+K^-$  [arXiv:1610.08288]**

cont. . .

- **Measurement of forward  $\bar{t}t$ ,  $W + \bar{b}b$  and  $W + \bar{c}c$  production in  $pp$  collisions at  $\sqrt{s} = 8$  TeV [arXiv:1610.08142]**
- New algorithms for identifying the flavour of  $B^0$  mesons using pions and protons [arXiv:1610.06019]
- Observation of the decay  $B_s^0 \rightarrow \phi\pi^+\pi^-$  and evidence for  $B^0 \rightarrow \phi\pi^+\pi^-$  [arXiv:1610.05187]
- Search for the CP-violating strong decays  $\eta \rightarrow \pi^+\pi^-$  and  $\eta'(958) \rightarrow \pi^+\pi^-$  [arXiv:1610.03666]
- Measurements of prompt charm production cross-sections in  $pp$  collisions at  $\sqrt{s} = 5$  TeV [arXiv:1610.02230]
- Observation of  $B^+ \rightarrow J/\psi 3\pi^+ 2\pi^-$  and  $B^+ \rightarrow \psi(2S)\pi^+\pi^+\pi^-$  decays [arXiv:1610.01383]

# Important conference on going

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## CKM2016

### 9<sup>th</sup> International Workshop on the CKM Unitarity Triangle

TIFR, Mumbai  
Nov. 28 – Dec. 2, 2016

#### International Advisory Committee

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- Thomas Browder (Hawaii)
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- Anjan Giri (IIT, Hyderabad)
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Image: [https://en.wikipedia.org/wiki/Bandra-Worli\\_Sea\\_Link\\_Newscenter\\_phillips.com](https://en.wikipedia.org/wiki/Bandra-Worli_Sea_Link_Newscenter_phillips.com)  
Designed by Saurabh Sandilya

CKM2016  
Department of High Energy Physics  
Tata Institute of Fundamental Research  
Homi Bhabha Road, Colaba  
Mumbai 400 005 India  
Tel# +91 22 2278 2359/2147 Fax# +91 22 2280 4610 (Attn: CKM2016)

# Conference talks (CKM)

LHCb  
Summary

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- Measurement of  $CP$  asymmetry in  $B_s^0 \rightarrow D_s^\mp K^\pm$  decays
- Measurement of time-dependent  $CP$  violating asymmetries in  $B^0 \rightarrow \pi^+\pi^-$  and  $B_s^0 \rightarrow K^+K^-$  decays at LHCb
- **Study of the decay  $B^\pm \rightarrow DK^{*\pm}$  with  $D^0 \rightarrow K^-\pi^+$ ,  $K^-K^+$ ,  $\pi^-\pi^+$ ,  $\pi^-K^+$  final states**
- Search for the  $B_s^0 \rightarrow \eta'\phi$  decay
- Search for  $CP$  violation in the rare  $\Lambda_b^0 \rightarrow pK^-\mu^+\mu^-$  decay
- **First observation of a non-tree  $B_c^+$  transition with  $B_c^+ \rightarrow D^0K^+$  decays**
- Measurement of  $J/\psi$  pair production cross-section in  $pp$  collisions at  $\sqrt{s} = 13$  TeV
- First observation of  $B_s^0 \rightarrow \eta_c h^+ h^-$  decays



# Conference talks (CKM)

LHCb  
Summary

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- Observation of triply charmed  $B_c^+$  decays  
 $B_c^+ \rightarrow J/\psi D^{(*)} K^{(*)}$
- Measurement of the  $B^\pm$  production asymmetry and the  $CP$ -violating asymmetry in the decay  $B^\pm \rightarrow J/\psi K^\pm$
- Observation of the  $\Xi_b^- \rightarrow J/\psi \Lambda K^-$  decay
- Search for long-lived scalar particle in  $B^+ \rightarrow K^+ \chi(\mu\mu)$  decay
- Measurement of the branching fraction ratio and  $CP$  asymmetry difference of the decays  $B^- \rightarrow J/\psi \pi^-$  and  $B^- \rightarrow J/\psi K^-$
- Observation of the rare baryonic decay  $\Lambda_b^0 \rightarrow p \pi^- \mu^+ \mu^-$
- **Measurement of the phase difference between the short- and long-distance amplitudes in the  $B^+ \rightarrow K^+ \mu^+ \mu^-$  decay**

# Selected physics analyses

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**The following analyses are grouped into:**

- CP violation analysis
- Rare decays
- EW production

# CKM angle $\gamma$ LHCb combination

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- CKM  $\gamma \equiv \arg[-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*]$ 
  - Least well known angle of the CKM unitarity triangle
  - Measured from tree level processes
- Can combine 5  $B \rightarrow DKX$  LHCb results to improve  $\gamma$  estimate
  - $DK$  combination: 71 observables and 32 parameters
  - $DK/\pi$  combination: 89 observables and 38 parameters
- Included analyses:
  - $B^+ \rightarrow DK^+$
  - $B_d^0 \rightarrow DK^{*0}$
  - $B_d^0 \rightarrow DK^+\pi^-$
  - $B^+ \rightarrow DK^+\pi^+\pi^-$
  - Parameterised by  $\gamma$  and nuisances  $r_B^{DK^{(*)}}$  &  $\delta_B^{DK^{(*)}}$
  - Time dependent  $B_s^0 \rightarrow D_s^\mp K^\pm$
  - $B^+ \rightarrow D\pi^+$  (additional combination)
  - $B^+ \rightarrow D\pi^+\pi^-\pi^+$  (additional combination)

[arXiv:1611.03076]

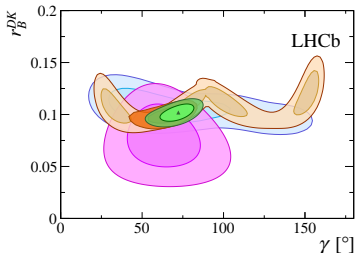
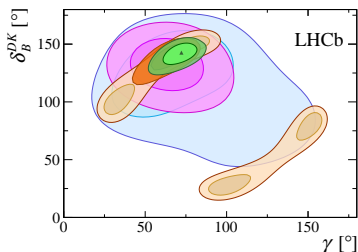
# CKM angle $\gamma$ LHCb combination


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Combined likelihood formed from all observables

## Just $B^+$ projections



  $B^+ \rightarrow DK^+, D \rightarrow h3\pi/hh'\pi^0$

  $B^+ \rightarrow DK^+, D \rightarrow K_s^0 hh$

  $B^+ \rightarrow DK^+, D \rightarrow KK/K\pi/\pi\pi$

 All  $B^+$  modes

 Full LHCb Combination

## Final result

$$\gamma = (72.2_{-7.3}^{+6.8})^\circ \text{ (c.f. prev. } 73_{-10}^{+9} \text{ LHCb 2014)}$$

$$\gamma \in [55.9, 85.2]_{95\%}^\circ$$

[arXiv:1611.03076]

# $B^\pm \rightarrow DK^{*\pm}$ from run II data (CKM conference)

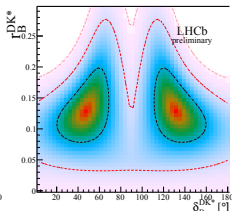
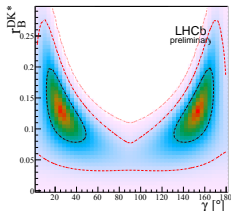
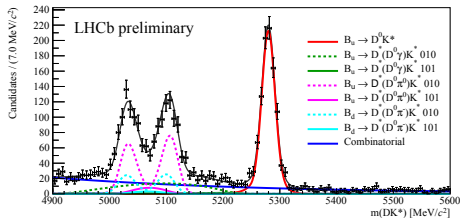
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- Decay with same parameterisation
- Run 1:  $3 \text{ fb}^{-1}$   
+ Run 2:  $1 \text{ fb}^{-1}$
- First CP in  $B/D$  measurement using Run 2 data
- More inputs to  $\gamma$
- Consistent with  $\gamma$  combination

[LHCb-CONF-2016-014]

## Extraordinarily clean peak

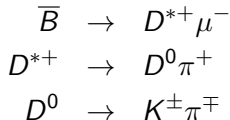


# Mixing and CP violation in $D^0 \rightarrow K^\pm \pi^\mp$

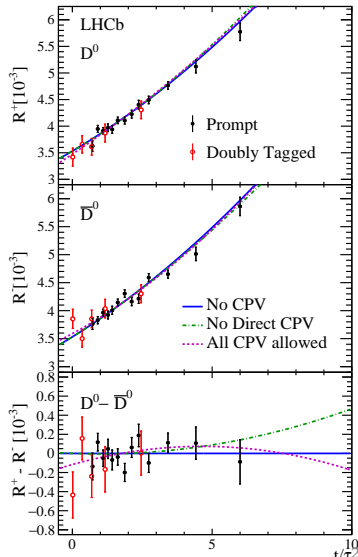
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- **Reminder:** mixing obvious in LHCb (first  $5\sigma$  obs.)
- Previous analysis used  $D^0$  from  $pp$  collision (prompt)
- Add short decay time sample from



- **Double tagged** through charge of muon and pion
  - Consistent with no CPV
- [arXiv:1611.06143]



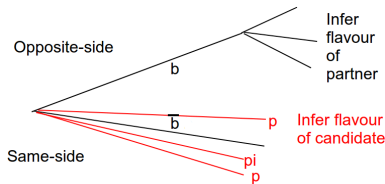
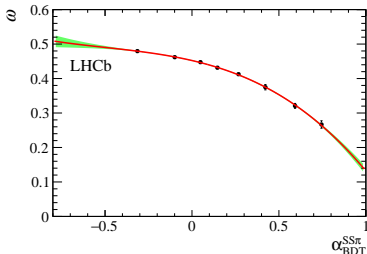
# New algorithms for identifying the flavour of $B^0$

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- Time dependent CP analyses require initial flavour of  $B^0$
- Same-side flavour tagging using pions and protons
- MVA trained and optimised on  $B^0 \rightarrow D^- K^+$ 
  - Kinematics and quality of  $\sim 2$  associated pions and protons and  $B^0$  candidate
- 60% improvement in tagging power (eff 38%  $\rightarrow$  84%)

$\omega$  mistagging rate

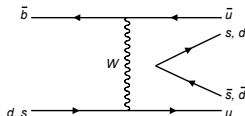
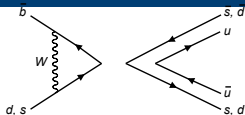


[arXiv:1610.06019]

# Observation of $B^0 \rightarrow K^+ K^-$

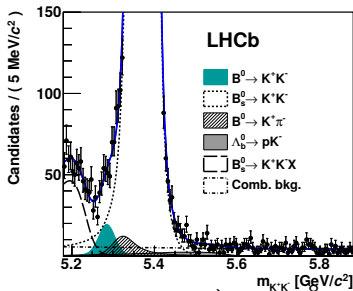
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Diagrams contribute to dominant mode

- Run 1:  $3 \text{ fb}^{-1}$  data
- Control of systematics
- $> 5\sigma$  significance
- First observation, rarest purely hadronic decay
- Improved measurement of  $B_s^0 \rightarrow \pi^+ \pi^-$



$$B(B^0 \rightarrow K^+ K^-) = (7.80 \pm 1.27 \pm 0.81 \pm 0.21) \times 10^{-8}$$

$$B(B_s^0 \rightarrow \pi^+ \pi^-) = (6.91 \pm 0.54 \pm 0.63 \pm 0.19 \pm 0.40) \times 10^{-7}$$

[arXiv:1610.08288]

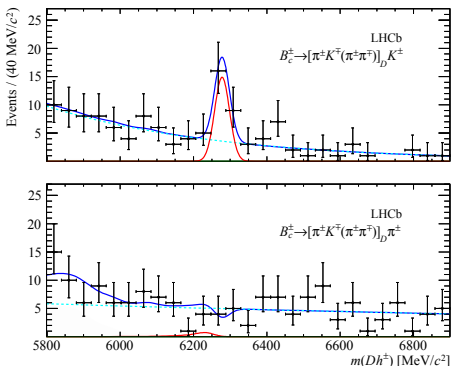


# $B_c^+ \rightarrow D^0 K^+$ (CKM conference)

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- Run 1:  $3 \text{ fb}^{-1}$
- Expectation  
 $\frac{f_c}{f_u} \times \mathcal{B} \sim \mathcal{O}(10^{-9})$
- First  $b \rightarrow s$  penguin  
decay of  $B_c$   
observed
- $5.1\sigma$  significance



$$\frac{f_c}{f_u} \times \mathcal{B}(B_c^+ \rightarrow D^0 K^+) = (9.3_{-2.5}^{+2.8} \pm 0.6) \times 10^{-7}$$

[PAPER-2016-058]

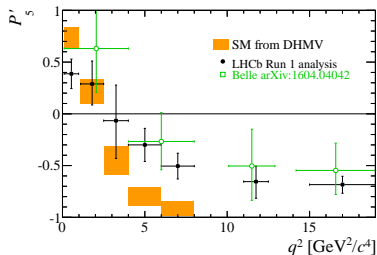
# Brief aside: $P_5'$

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Interest in angular observable in  $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ ,  $P_5'$

- Discrepancy between prediction and data in dimuon invariant mass squared,  $q^2$
- Could be explained by new vector, or poorly understood charm loops
- $q^2$  spectrum can distinguish between cases
- $c\bar{c}$  resonances enter the the  $q^2$  spectrum
  - Unknown phases between resonances and nonresonant mode



[JHEP 02 (2016) 104]

# Amplitude phase differences in $B^+ \rightarrow K^+ \mu^+ \mu^-$ decay (CKM conference)

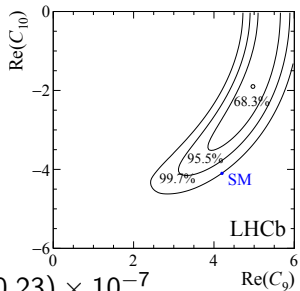
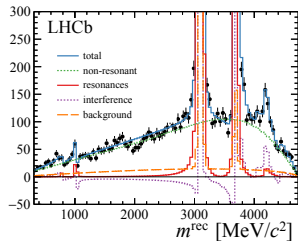
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- $q^2$  distribution of  $B^+ \rightarrow K^+ \mu^+ \mu^-$  is separated from the resonant components
- Resonances: BW with phase
- Nonresonant:  $C_9, C_{10}$
- 4 degenerate solutions  $\pm\pi/2, \pm\pi/2$
- Same tools can be applied to  $B^0 \rightarrow K^{*0} \mu^+ \mu^-$
- Also BF measurement

$$\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-) = (4.37 \pm 0.15 \pm 0.23) \times 10^{-7}$$

[PAPER-2016-045]

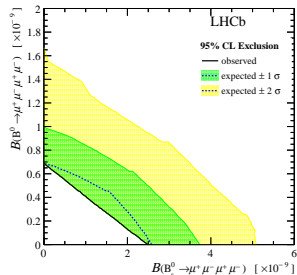
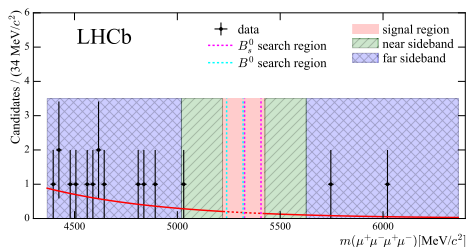


$$B_{(s)}^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-$$

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## Search for the non-resonant mode in run 1 data (and MSSM scalar+pseudoscalar)



No candidates seen  $\rightarrow$  limits set

$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-) < 2.5 \times 10^{-9} \text{ (95\% CL)}$$

$$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-) < 6.9 \times 10^{-10} \text{ (95\% CL)}$$

[arXiv:1611.07704]

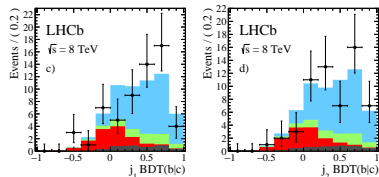
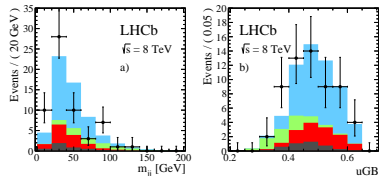
# $\bar{t}t$ , $W + \bar{b}b$ and $W + \bar{c}c$ production

LHCb  
Summary

Michael  
McCann  
on behalf of  
LHCb

- Run 1:  $2 \text{ fb}^{-1} \sqrt{s} = 8 \text{ TeV}$
- $W + q\bar{q}$  test of perturbative QCD
- $W + c\bar{c}$  measurement first of its kind
- Reconstructed as two jets + isolated lepton
- Simultaneous fit to  $e^\pm, \mu^\pm$ , in four variables, mass of jets, and three jet flavour MVA classifiers
- $b$ -tag 1/5 mistag of GPDs

Fit to  $\mu^+$  data



■  $W+b\bar{b}$  ■  $t\bar{t}$  ■  $W+c\bar{c}$  ■ Background

[arXiv:1610.08142] (arXiv:1504.07670, arXiv:1211.4462)

# $\bar{t}t$ , $W + \bar{b}b$ and $W + \bar{c}c$ production

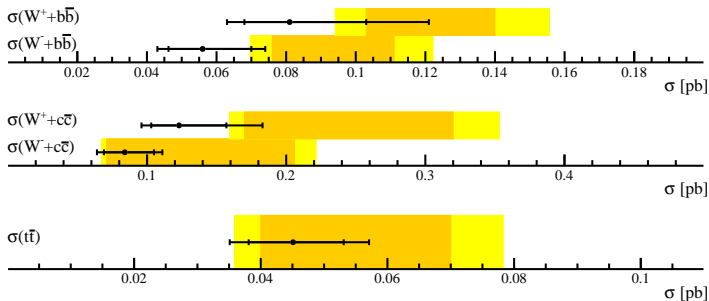
LHCb  
Summary

Michael  
McCann  
on behalf of  
LHCb

LHCb,  $\sqrt{s} = 8$  TeV

• MCFM CT10

■ Data<sub>stat</sub>  
■ Data<sub>tot</sub>



All measurements consistent with SM  
EW measurements complementary to GPDs

[arXiv:1610.08142]

# Coming soon

LHCb  
Summary

Michael  
McCann  
on behalf of  
LHCb

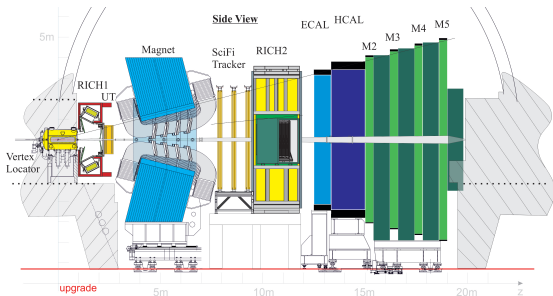
- Time-dependent  $B^0 \rightarrow \pi^+\pi^-$  and  $B_s^0 \rightarrow K^+K^-$  CP violation with full Run-1 data
  - To be shown on Thursday at CKM
  
- Time-dependent  $B_s^0 \rightarrow D_s K$  CP violation with full Run-1 data
  - To be shown on Thursday at CKM
  
- Lepton non-universality tests
  - $R(K)$ ,  $R(K^*)$  &  $R(D^*)$
  
- Plus many more

# Upgrade overview

LHCb  
Summary

Michael  
McCann  
on behalf of  
LHCb

## After LS2 detector read out at 40MHz, software trigger



- Velo: Si pixels
- UT: Si strips
- SciFi: scint. fibre tracker
- RICH: photon detectors & optics
- CALO: gain & readout
- Muons: shielding & readout



# Upgrade progress

LHCb  
Summary

Michael  
McCann  
on behalf of  
LHCb

- Upgrade construction phase **started**
- Delivery of components **started**  
(e.g. RICH MaPMTs, SciFi fibres)
- Many important tenders completed or ongoing  
(e.g. SciFi SiPMs)
- PRR for crucial components in the coming month  
(e.g. VELO/UT sensors)
- All front-end ASICs have **passed EDR**, some PRR
- Some components on critical path:
  - Closely monitoring them and taking any urgent action  
(e.g. microchannel cooling)
- Internal comprehensive review of whole upgrade project
  - Planned for 30 January – 1 February 2017
  - Focus on critical aspects, organization of construction and preparation for installation

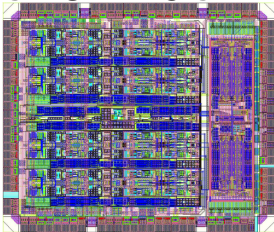
**Now for some evidence...**

# Upgrade progress

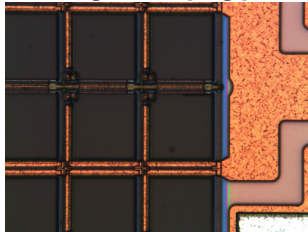
LHCb  
Summary

Michael  
McCann  
on behalf of  
LHCb

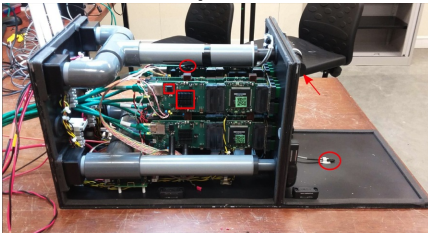
## CALO FE ASIC



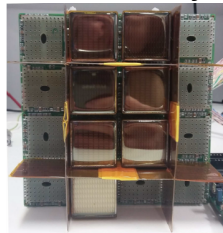
## SiPM for SciFi



## RICH QA setup



## RICH PD array



# Upgrade test beams

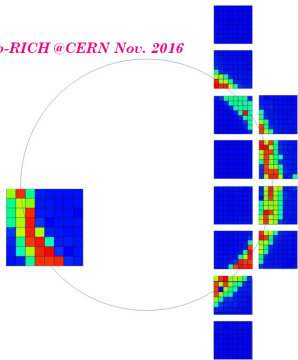
LHCb  
Summary

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McCann  
on behalf of  
LHCb

Test beam period early November

- Testing:
  - Sensors
  - Electronics
  - DAQ chain
- Involving:
  - Velo
  - UT
  - SciFi
  - RICH
  - Calorimeter

*LHCb-RICH @CERN Nov. 2016*



**Cherenkov ring using new  
RICH photon detectors and  
electronics**

## Thank you to LHC for making this a great year

- Operations
  - Automation makes running the detector very easy
  - Excellent performance during  $pp$  program
  - $pPb$  program ahead of expectation
- EYETS
  - Planning complete
  - Several upgrade activities already planned
- Physics
  - On course to improve on last year's paper count
  - Still interesting results coming out of run 1
  - First results from run 2
- Upgrade
  - Many items in production
  - On course for LS2

# Backup

LHCb  
Summary

Michael  
McCann  
on behalf of  
LHCb

# Dead time

LHCb  
Summary

Michael  
McCann  
on behalf of  
LHCb

- Cause (in general)
  - Veto of consecutive triggers
  - Readout time of high occupancy events
  - Processing time of large events
- LHCb readout limited to 1 MHz events
- Can trigger nicer events with more bunches
  - Dead time will reduce with more bunches
  - Hopefully achieved next year

# VELO microchannel cooling

LHCb  
Summary

Michael  
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on behalf of  
LHCb

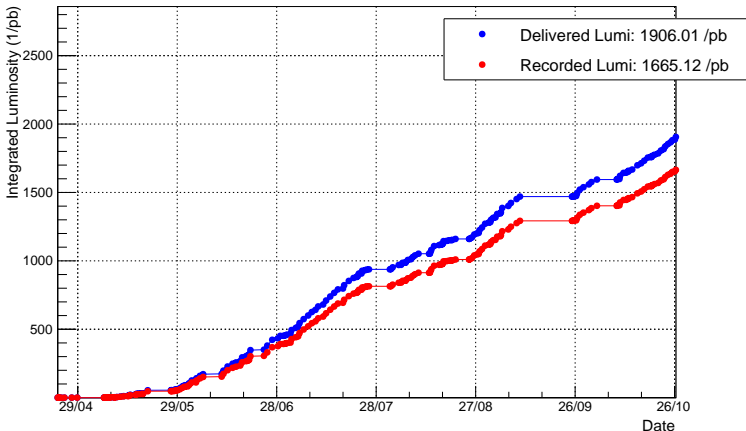
- Initial slip in schedule
  - No further slips
- Prototype preproduction run for early next year
  - Performance check
  - Production yield check
  - Determine total cost
- Plan B in place
  - Using capillaries
- On schedule, but limited scope for delays

# $pp$ running

LHCb  
Summary

Michael  
McCann  
on behalf of  
LHCb

## LHCb Integrated Luminosity in p-p in 2016





## LHCb Average Mu in p-p in 2016

