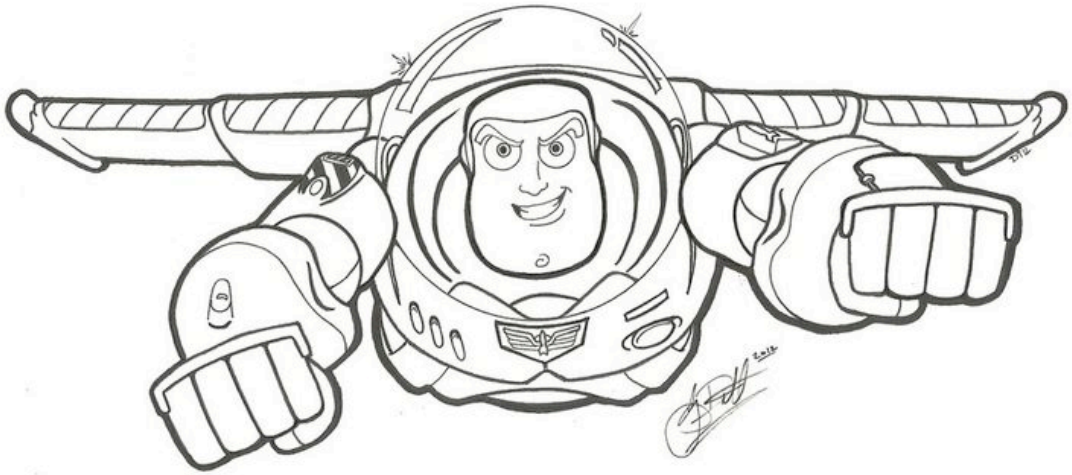
MANCHESTER 1824
The University of Manchester

# LHCb: To Infinity and Beyond

## LHCb Longterm Plans / Dreams

Chris Parkes
on behalf of the
LHCb Collaboration

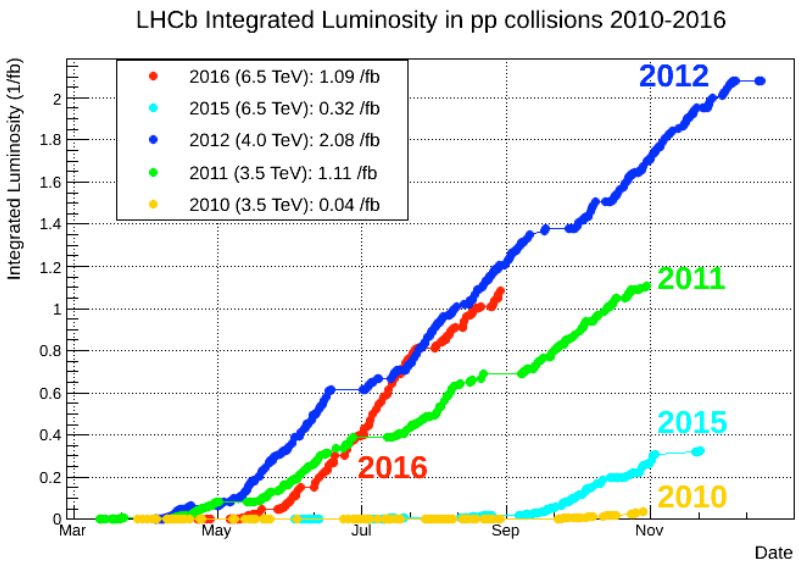


# LHCb Timeline

- LHC Run-I (2010-2013)
  - The results you know and love, several new this week
- LHC Run-II (2015-2018)
  - Trigger computing increased. First results…
- LHC Run-III, Run-IV (2021-2023, 2026-2029)
  - Major 'New' Experiment: **LHCb Upgrade [Phase I(a), I(b)]**
- LHC Run-V (2031-)
  - Major 'New' Experiment

**LHCb Upgrade Phase II**

– May be only general heavy flavour expt on this timescale



# Physics Programme

## Limited by Detector

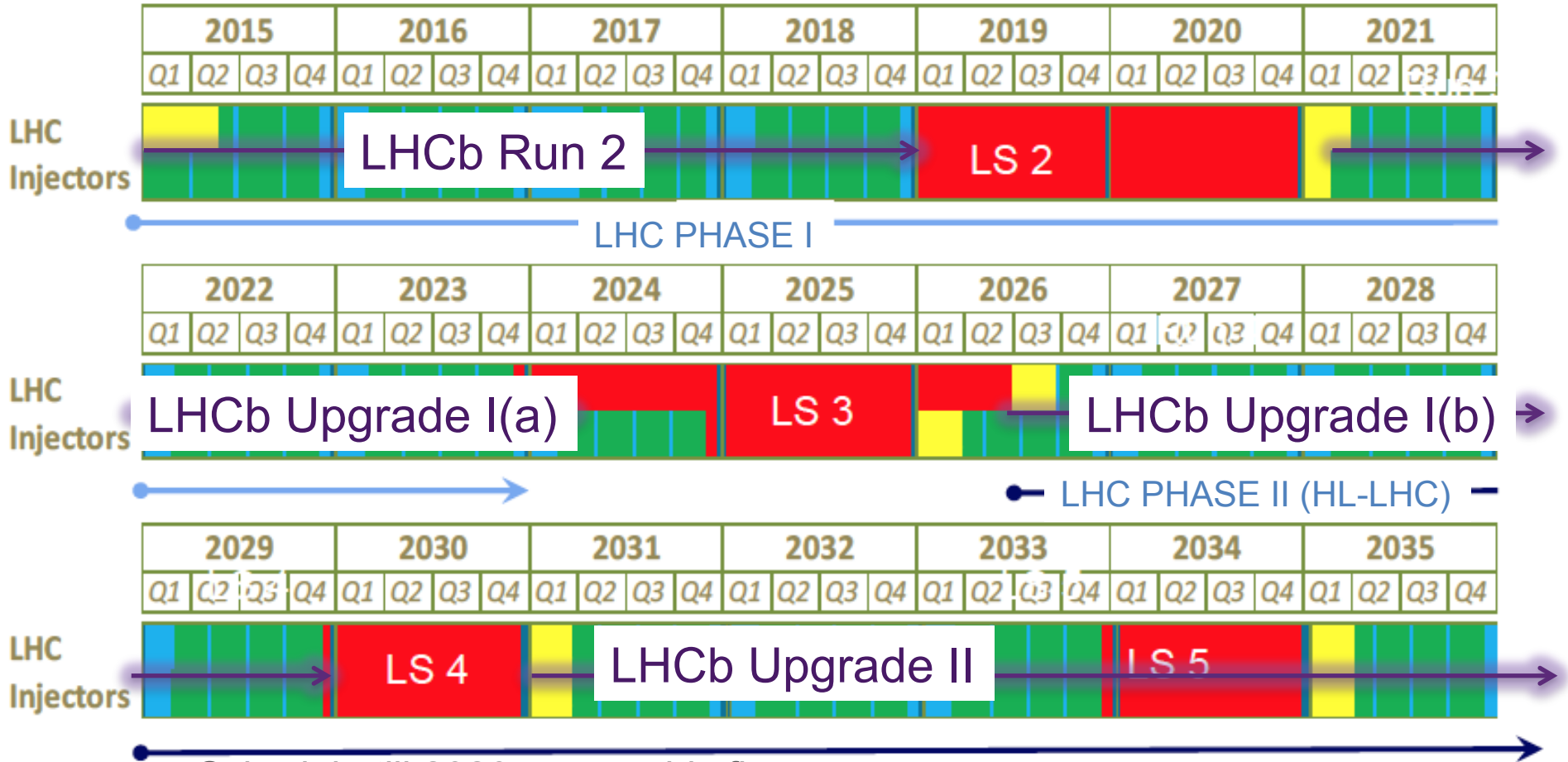
## But **NOT** Limited by LHC

- Upgrade to extend Physics reach
  - Exploit advances in detector technology
    - Displaced Vertex Trigger, **40MHz readout**
  - Better utilise LHC capabilities
- Upgrade I(a/b) Collect >50 $fb^{-1}$ data
  - $L \sim 2x10^{33}\ cm^{-2}\ s^{-1}$
- Upgrade II Collect > 300 $fb^{-1}$ data
- Modest cost compared with existing accelerator infrastructure

Upgrade I
- HL-LHC not needed
- But compatible With HL-LHC phase

Upgrade II
- Utilise HL-LHC phase luminosities

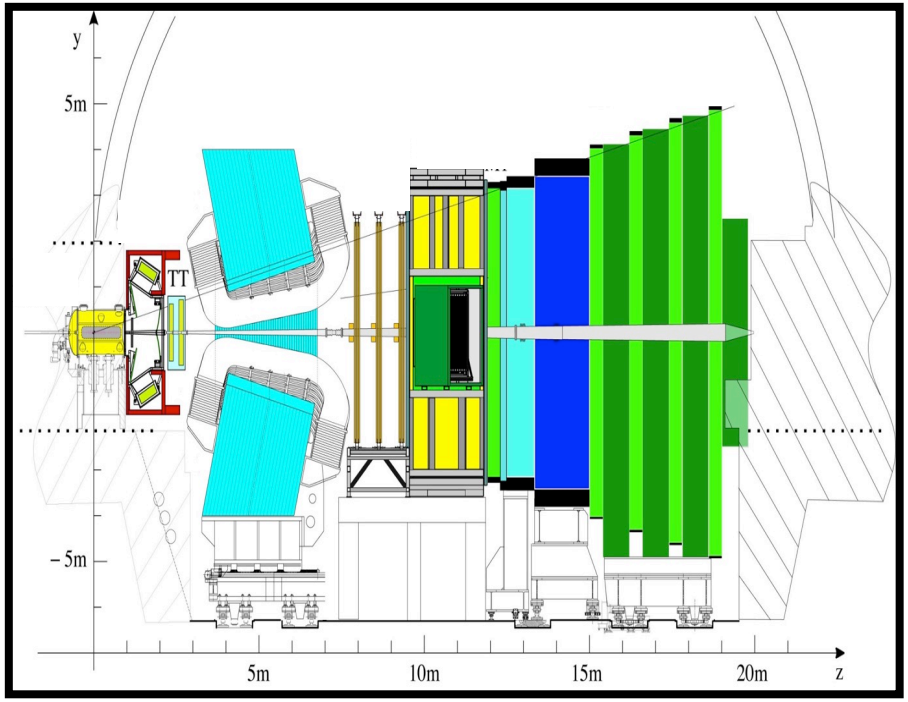
# LHC Schedule & LHCb




- Schedule till 2020 reasonably firm
- GPD main upgrades (phase II) scheduled for LS3
- HL-LHC upgrade in LS3
- **Belle II finishes ~ 2025**

Physics
Shutdown
Beam commissioning
Technical stop

# LHCb Upgrade I(a)
# 25ns readout, software only triggering




VELO
Pixel
Detector

Upgrade Tracker
Silicon strips

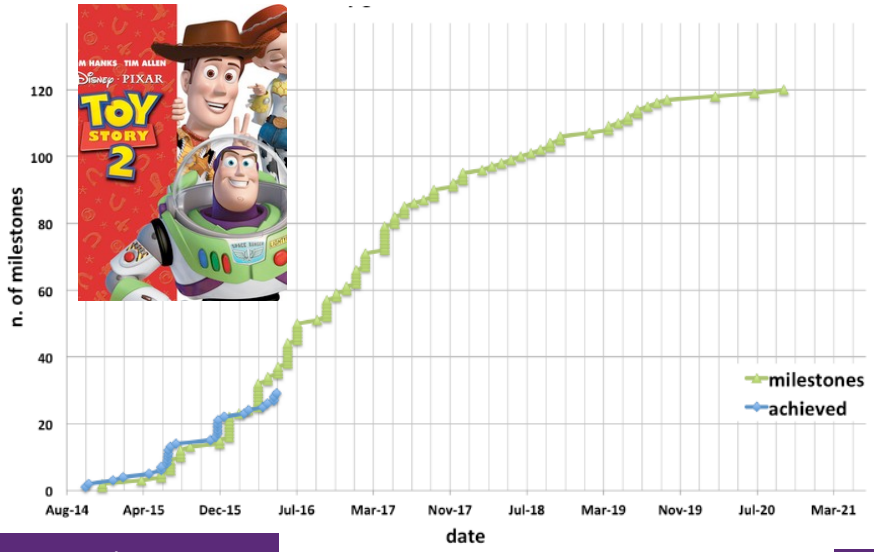
Outer Tracker
Scintillating Fibres

RICH
Photon Detectors &
(partial) mechanics

Calo
PMTs (reduce PMT
gain, replace R/O)

Muon MWPC
(almost compatible)

- Construction project on milestone schedule
- Prototypes exist for most major elements
- Major industrial orders placed



# Phase 1(b) – Consolidate & Enhance

- LS3: 2½ year shutdown in the middle of LHCb Upgrade I operations
  - Utilise this to consolidate upgrade experiment
    - Phase I(b), same luminosity
  - Enhance physics programme
    - Pathways to Phase II
  - Financial/ personnel resources limited

Not many new toys

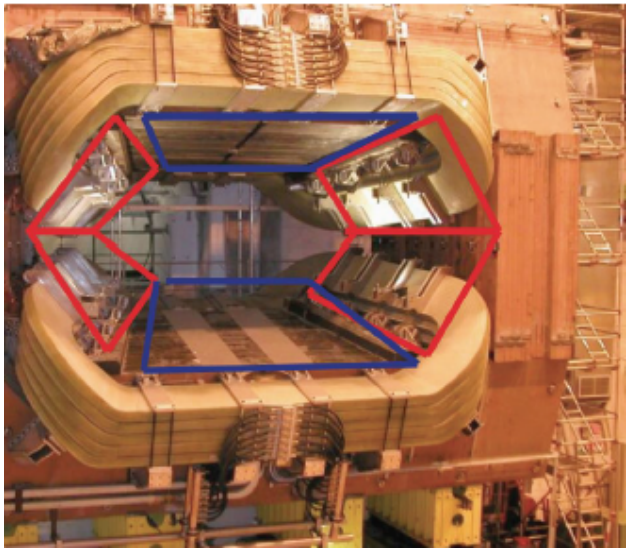
Same timescale:

ATLAS EXPERIMENT Upgrade Phase II

CMS Upgrade Phase II

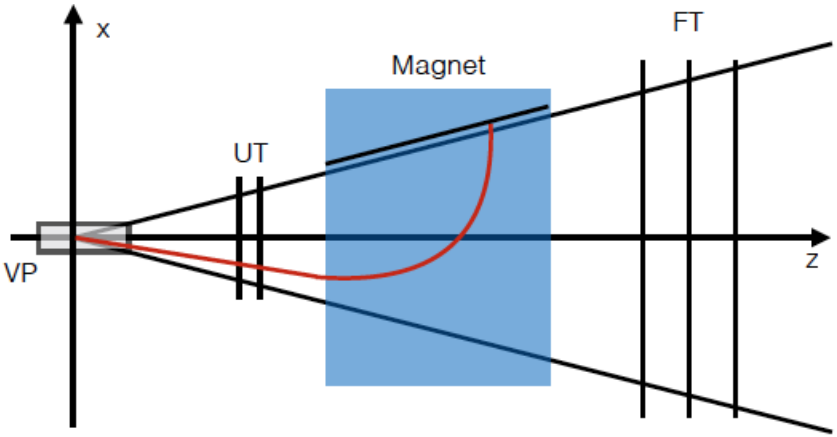
DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

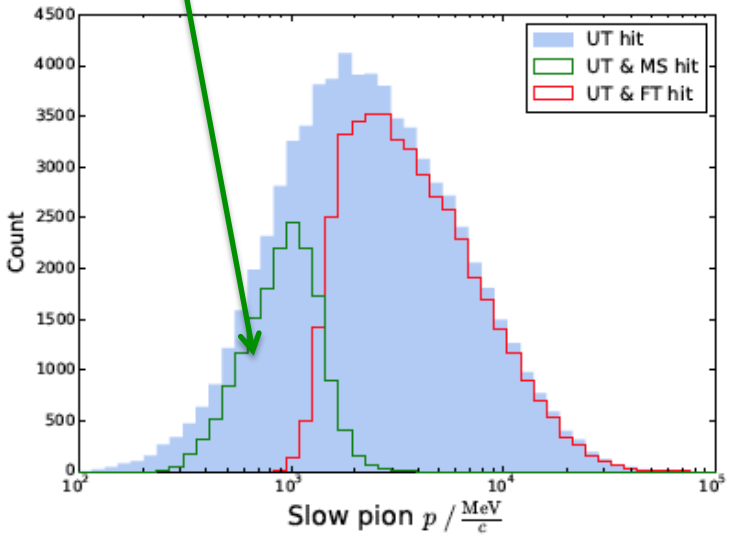
# Phase 1(b) e.g. – Magnet Side Stations



- Improve tracking acceptance for low momentum particles
  - Install tracking stations on the dipole magnet internal sides

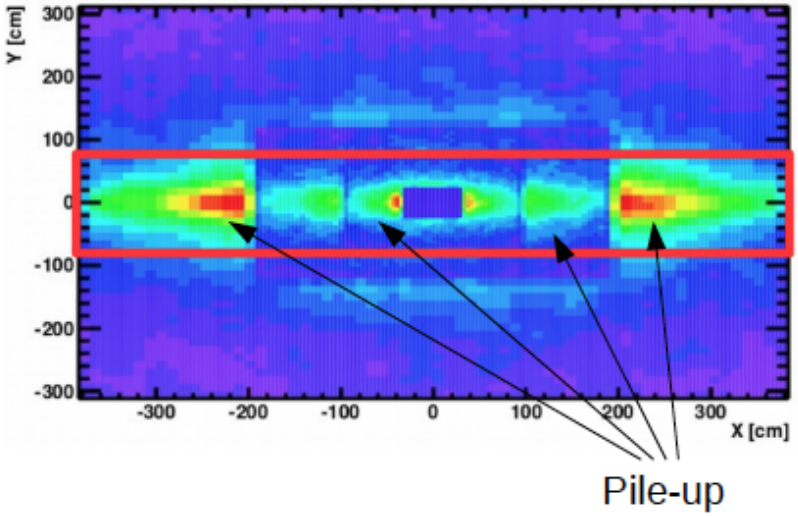
e.g. $D^{*+} \rightarrow D\ \pi_s^+$, 40% extra slow pions

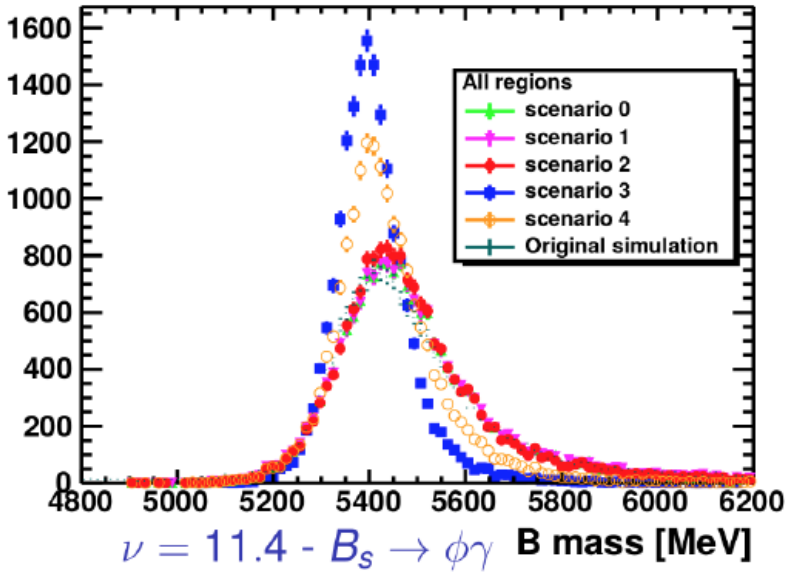


# Phase 1(b) e.g. – E'magnetic Calorimeter

- Inner ECAL replacement required due to radiation damage
  - Partial replacement only
- Strong Physics Interest: $\gamma, \pi^0, e^-$
- Improve performance with new technologies ?
- Improve energy/position resolution
  - Reduced Moliere radius, cell granularity



# Phase II – Major new Upgrade

"Formal approval of High luminosity LHC…secures CERN's future until 2035" CERN DG, June 2016

Secure Flavour Physics future

Target Luminosity: > 300 $fb^{-1}$, > $2x10^{34}$ $cm^{-2}$ $s^{-1}$
HL-LHC experiment: ~50 events/interaction pile-up

1. Physics case
2. LHC capabilities
3. Detector feasibility

# Phase II – Major new Upgrade

"Formal approval of High luminosity LHC…secures CER

Sec

Critics Consensus: Deftly blending comedy, adventure, and honest emotion, *Toy Story 3* is a rare second sequel that really works.

$cm^{-2}$ $s^{-1}$

bile-up

1. Physics case
2. LHC capabilities
3. Detector feasibility


# Physics Case - ask the analysts….

## Phase-2 upgrade: benchmarking topics

- *CP* violation in the interference between $B_s$ mixing and decay
- *CP* violation in $B_c$ and *b*-baryon decays
- *CP* violation in charm mixing and decay
- Determination of the angle $\gamma$
- Semileptonic asymmetries
- Electroweak penguin decays
- Rare and radiative decays
- Lepton universality tests
- Lepton flavour violation
- Search for Majorana neutrinos
- Forward Higgs production
- Dark photon searches
- Spectroscopy and exotic states

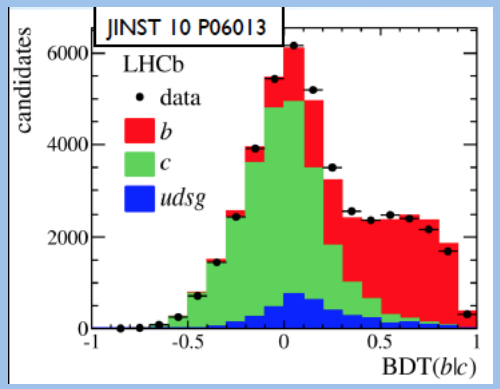
V. Vagnoni, Theatre of Dreams, April 2016

# Physics Case - ask the analysts….

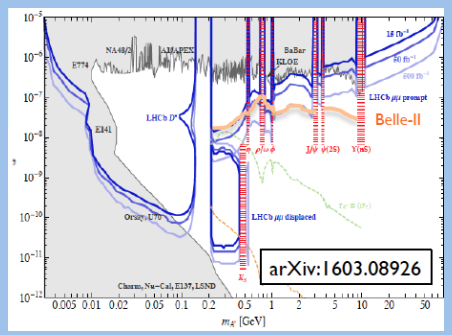
## Phase-2 upgrade: benchmarking topics

- *CP* violation i… …ixing and decay
- *CP* violation i…
- *CP* violation i…
- Determinatio…
- Semileptonic…
- Electroweak …
- Rare and radi…
- Lepton universality tests

Everything we currently do and a few more for good measure



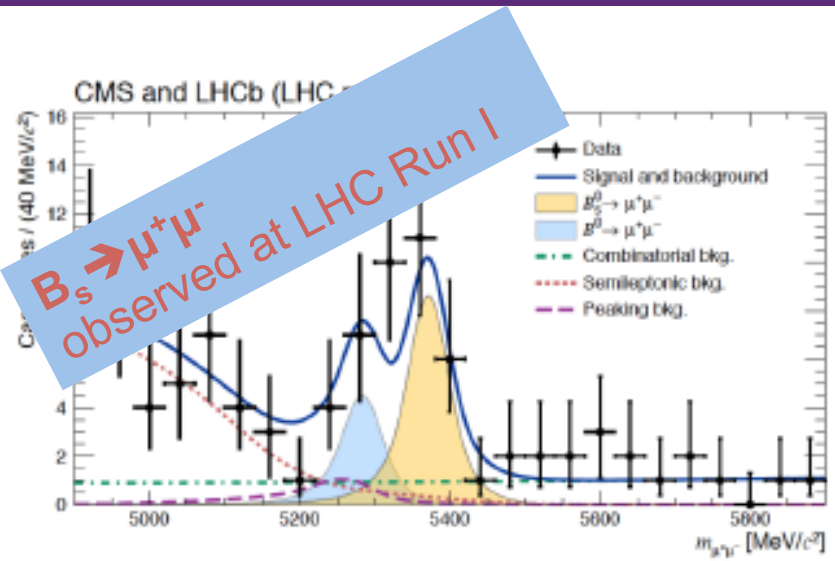

Phase II towards SM sensitivity for **H→c$\bar{c}$?**




Dark photon A'→μμ

best sensitivity

# Physics: Very Rare Decays Examples




$B_s \rightarrow \mu^+\mu^-$ observed at LHC Run I

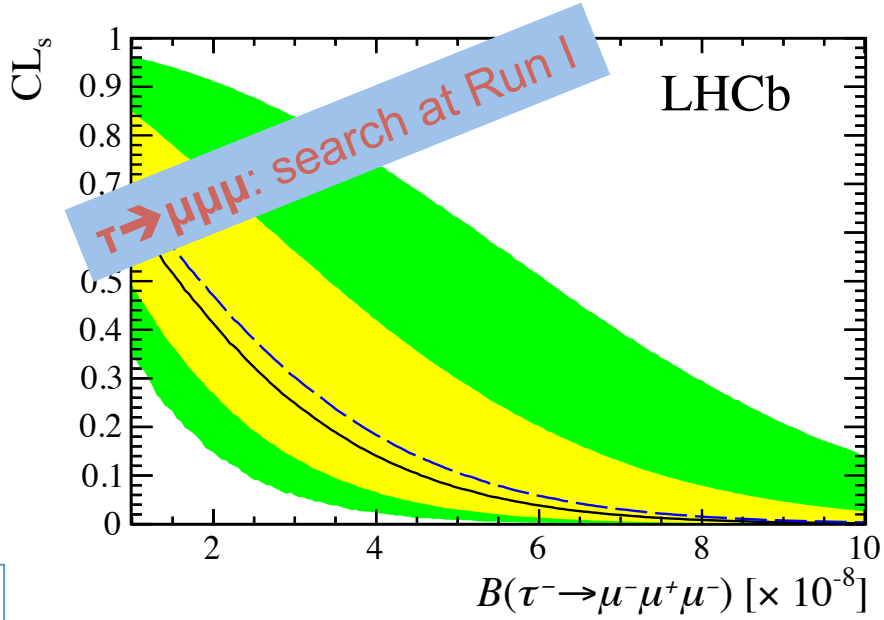
Next Target:

$$R = BR(B_d \rightarrow \mu^+\mu^-)/BR(B_s \rightarrow \mu^+\mu^-)$$

$\sigma(R)/R$ < 10% for Phase II

300 fb$^{-1}$ 2400 $B_s$ and 240 $B^0$
Effective lifetime ~ 2%
Test for CPV

- CLFV decays – strong interest: Neutrino mass linked to SM Higgs ?
- **$\tau \rightarrow \mu\mu\mu$: a classic e+e- B-factory mode**
- Phase II LHCb precision comparable with Belle II ~ O($10^{-9}$)

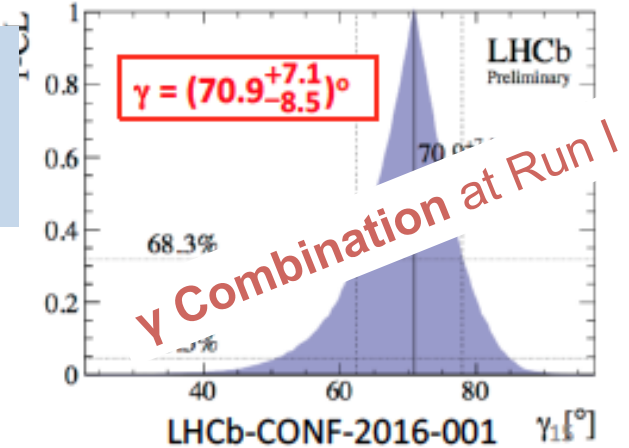


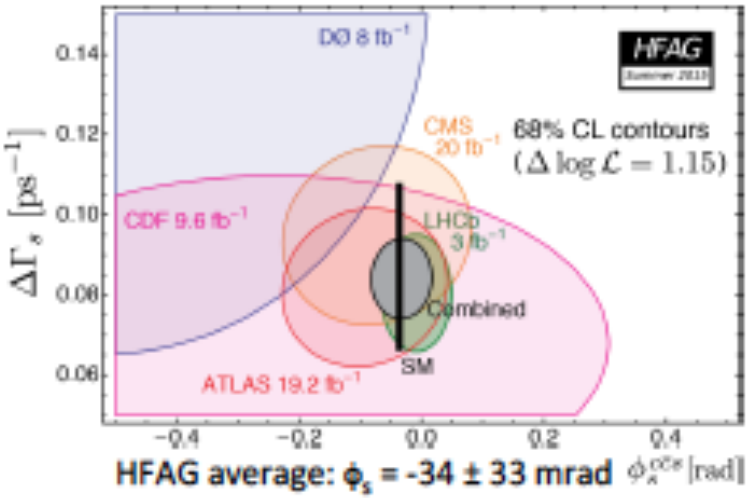

- Future Charm Rare Decays
- e.g. $D^0 \rightarrow l^+l^-$, $D_{(s)}^+ \rightarrow h^+l^+l^-$, $D^0 \rightarrow h^+h^-l^+l^-$ with $l^+ = \mu^+$ **and $e^+$**

# CPV Examples

- Time dependent measurements
  - more difficult in high pile-up environment

- Tree level determination of γ
- Phase II: 0.1° uncertainty in reach !




- $\phi_s$ in $b \rightarrow c\bar{c}s$ ($B_s \rightarrow J/\psi X\ldots$)
- Phase II: 4 mrad
  - **SM level !**
- $\phi_s$ in $b \rightarrow s\bar{s}s$ ($B_s \rightarrow \phi\phi$)
- Phase II: 7 mrad

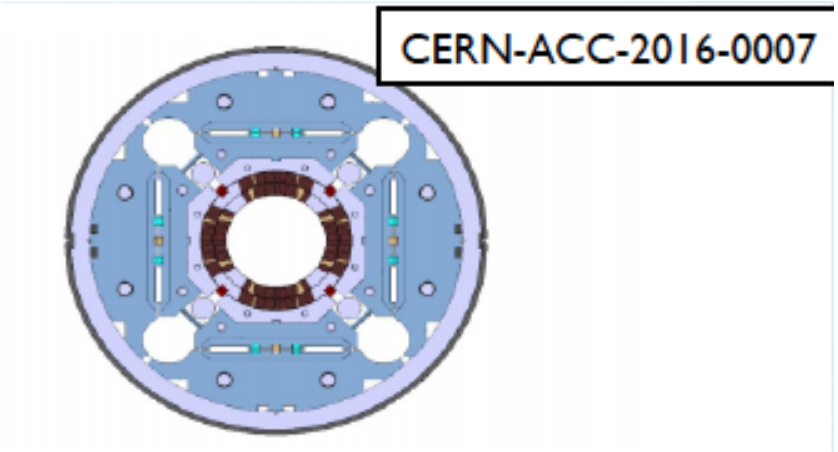
- Charm: $y, A_\Gamma, \Delta A_{CP}$ no limiting systematics known
- Observe SM level CPV

# Accelerator: Can LHCb Phase II run ?

Riccardo de Maria @ Theatre of Dreams (April 2016) — Preliminary

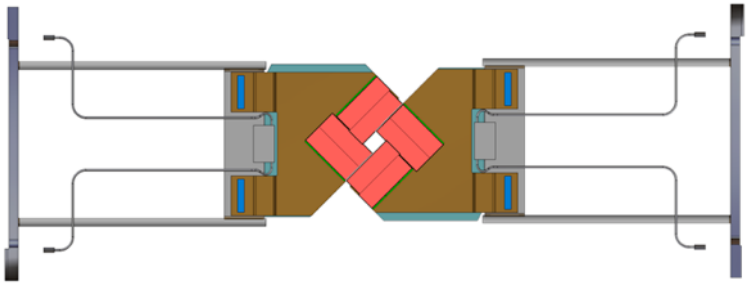
| Levelled luminosity LHCb [ $10^{34}$ $cm^{-2}s^{-1}$ ] | Opt fill length (IP1/5) [h] | Integrated luminosity ATLAS/ CMS [$fb^{-1}$/y] | Integrated luminosity LHCb [$fb^{-1}$/y] | β* IP8 [m] | Levelling time IP8 [h] |
|---|---|---|---|---|---|
| 0.2 (nom.) | 9.3 | 261 | 10.4 | 3 | 9 |
| 2 | 8.5 | 253 | 70 | 1 | 2 |

- LHCb collect > 50 $fb^{-1}$ per year **without** affecting ATLAS/CMS

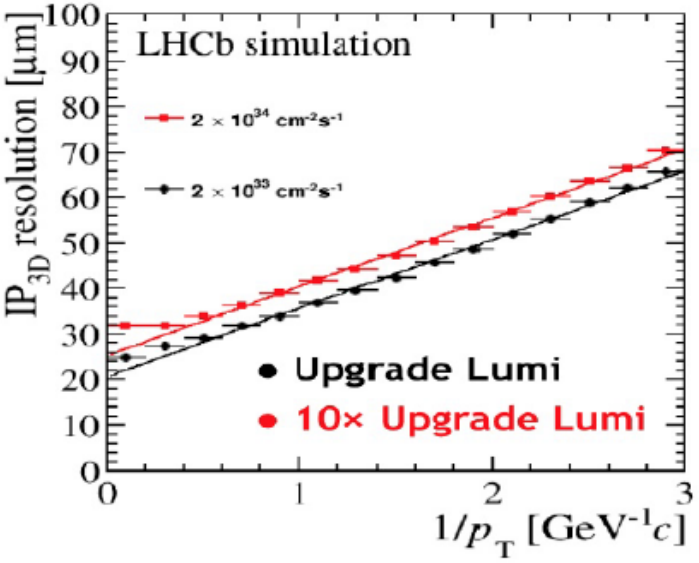


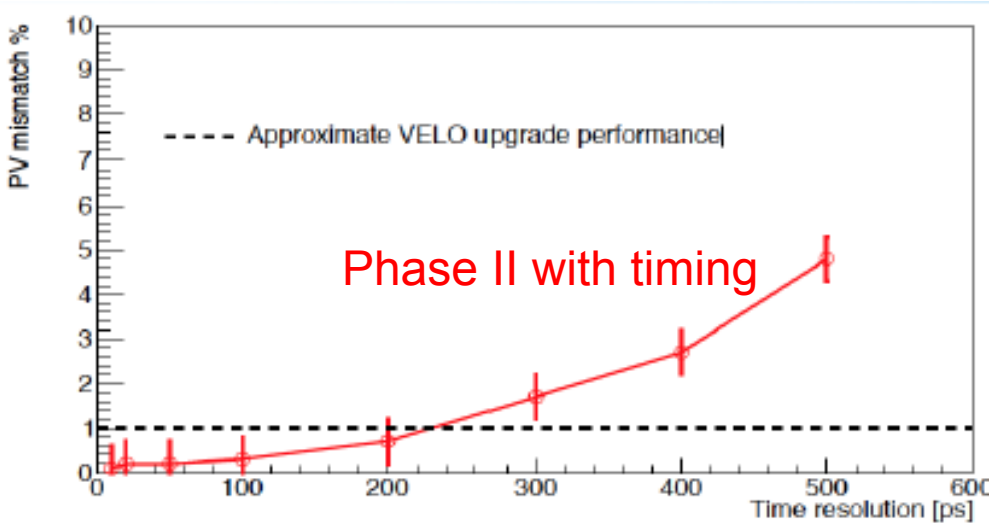

- LHCb IP not designed for HL-LHC experiment
- Inner Triplet quadropole need to be replaced at **~300 $fb^{-1}$**
  - Probably prohibitively expensive
- LHC side impressive studies on
- additional requirements
  - **No showstoppers !**

# Vertex Detector: VELO



- Radiation Damage
  - Dose at $10^{17}$ 1 MeV $n_{eq}$ / $cm^2$ level for full lifetime
  - Replace / increase inner radius
- Pile-up
  - Mismatch b/c decays to wrong PV
  - 4D: Timing at 200ps level required



# Particle Identification: RICH

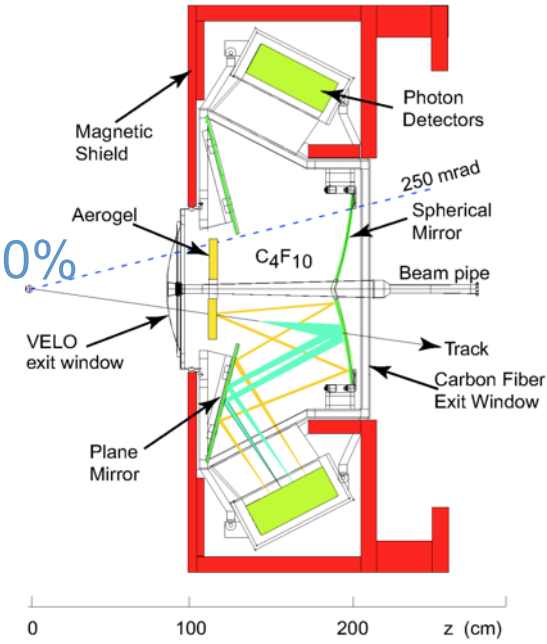
- Granularity
- Phase II RICH I peak occupancies would exceed 100%
  - Increase pixel granularity 7mm$^2$ ➔ 1mm$^2$

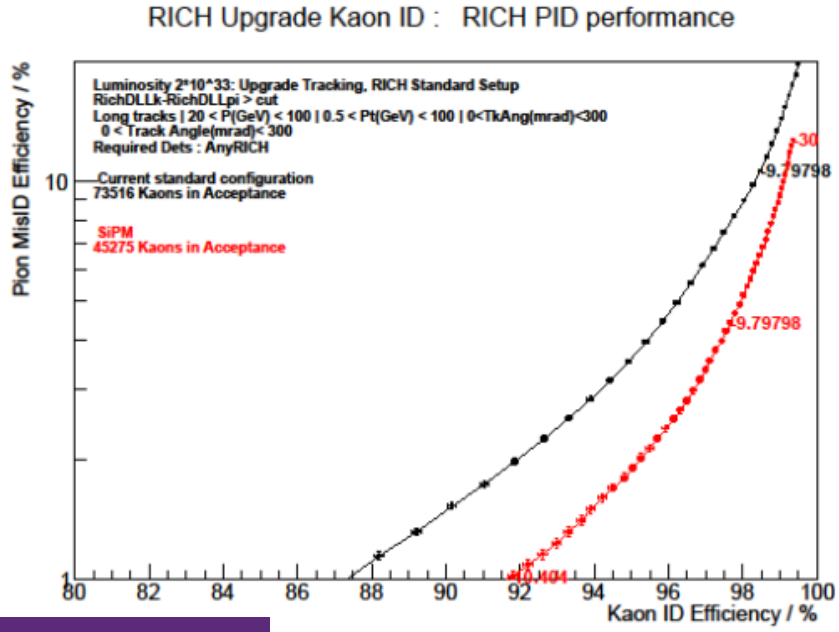
- Time resolution
  - Disentangle busy events

- Use B-field insensitive photodetectors
  - SiPM or MCP

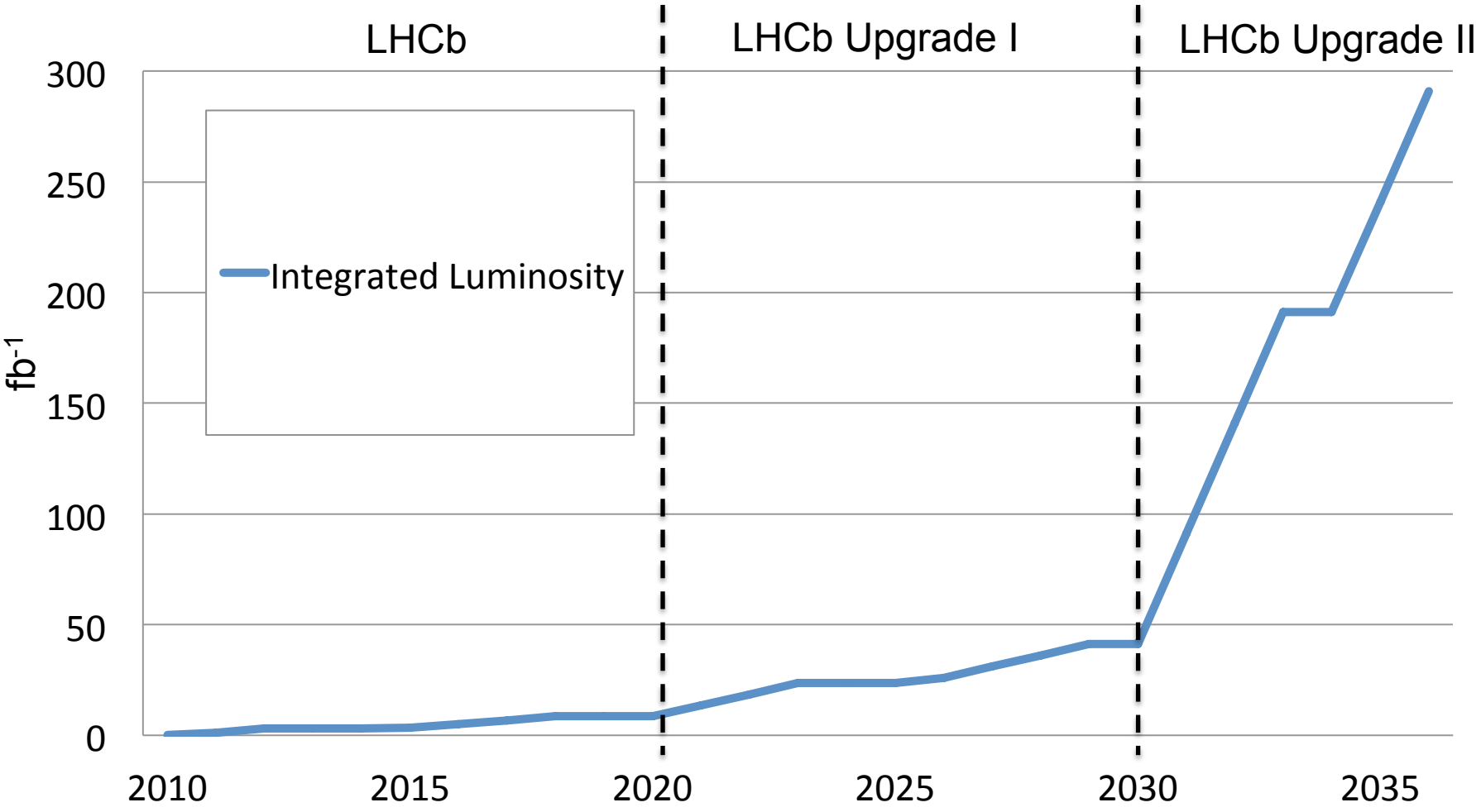
- Concepts for improving
- Optical and chromatic uncertainty

- Equip central region for **Phase 1(b)** ?



# LHCb Statistics- Timeline



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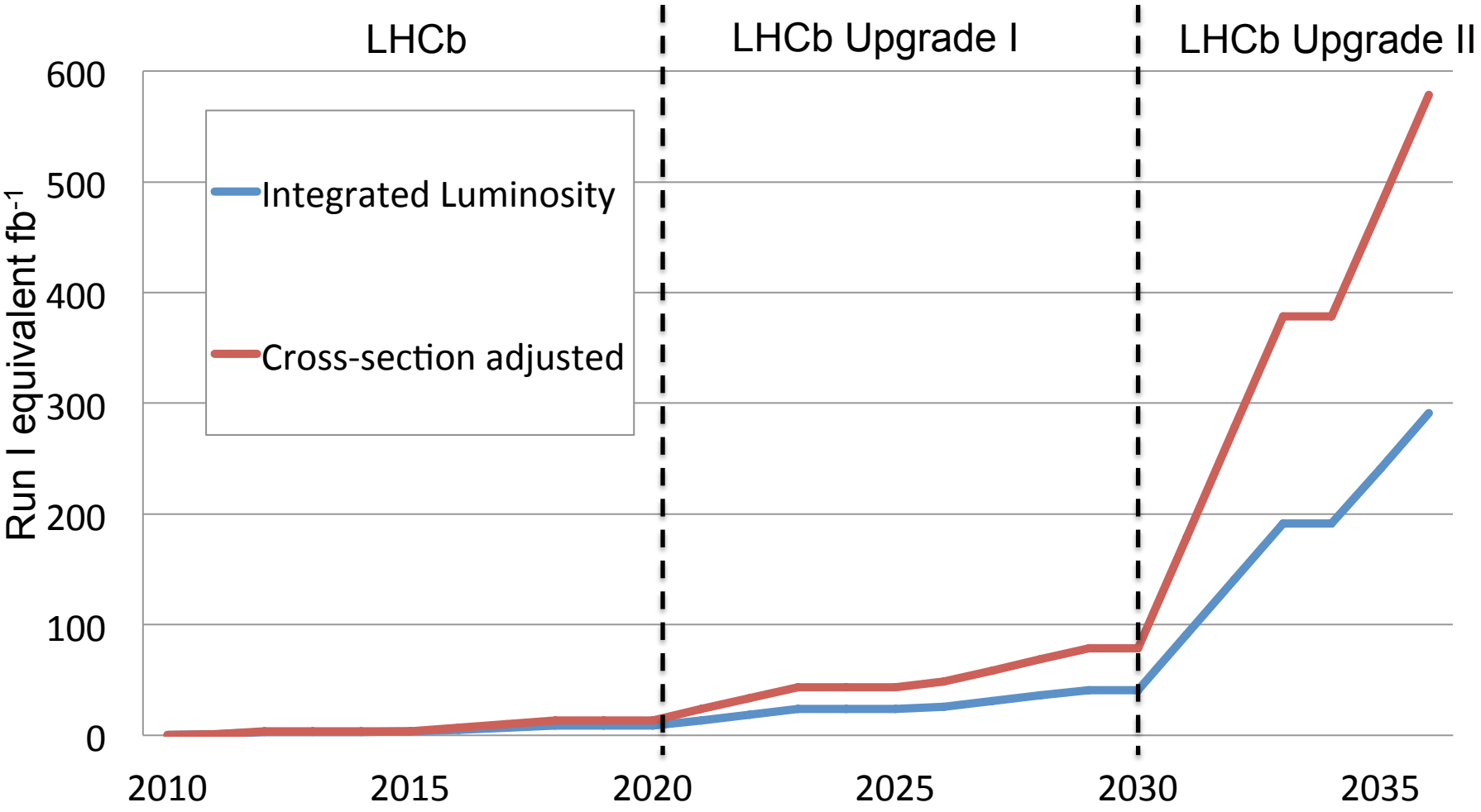
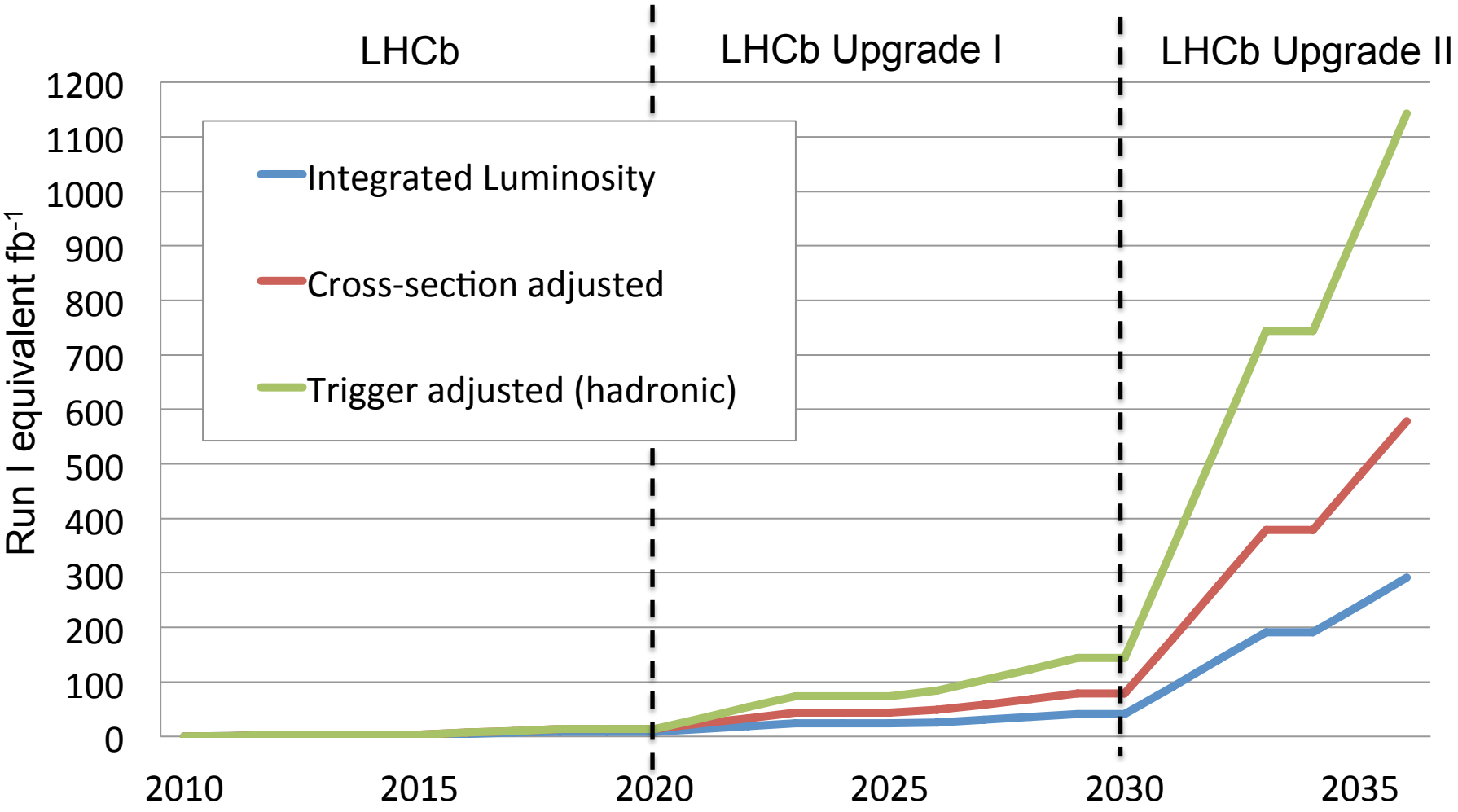



- Adjustment for 7/813/14 TeV cross-sections

# LHCb Statistics- Timeline




- Assumptions made on relative trigger efficiencies have significant uncertainty

# Summary - Take Home Message

- 2021: LHCb Upgrade I construction on track
- 2025: Phase I(b) Upgrade: consolidate & enhance
  - Same luminosity as upgrade phase 1(a)
- 2030: Phase II Upgrade
  - Challenging project
  - Physics – systematic / theoretical limit not reached
  - Detector – timing information may be key to coping with pile-up
  - Factor ten increase in luminosity
    - LHC can provide

# Backup

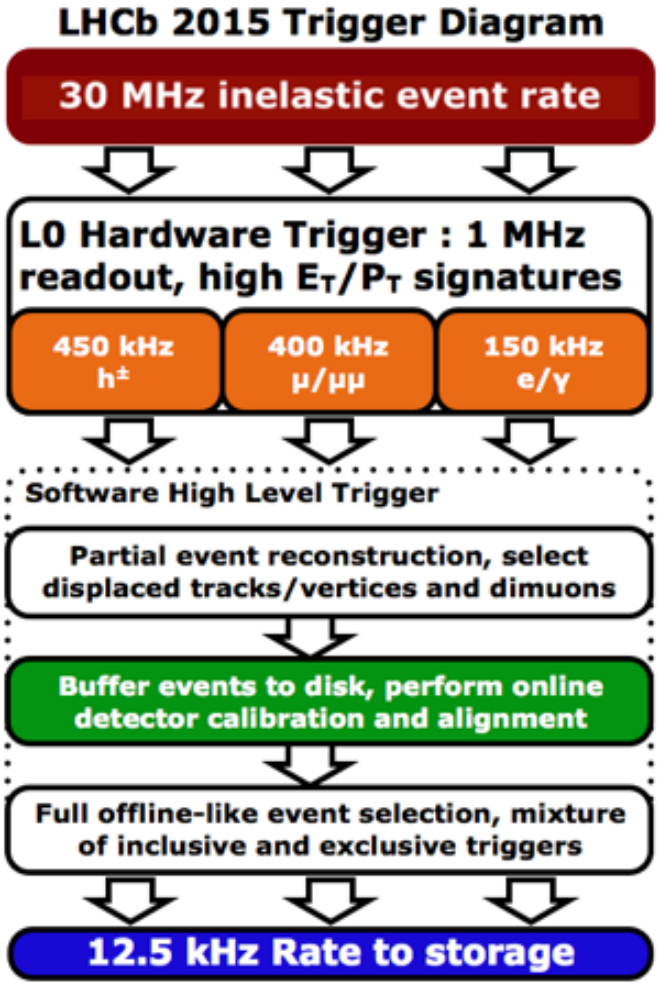
# LHCb Upgrade I(a)

- Letter Of Intent, 2011
- Framework Technical design Report 2012
- Subsystem TDRs, 2014

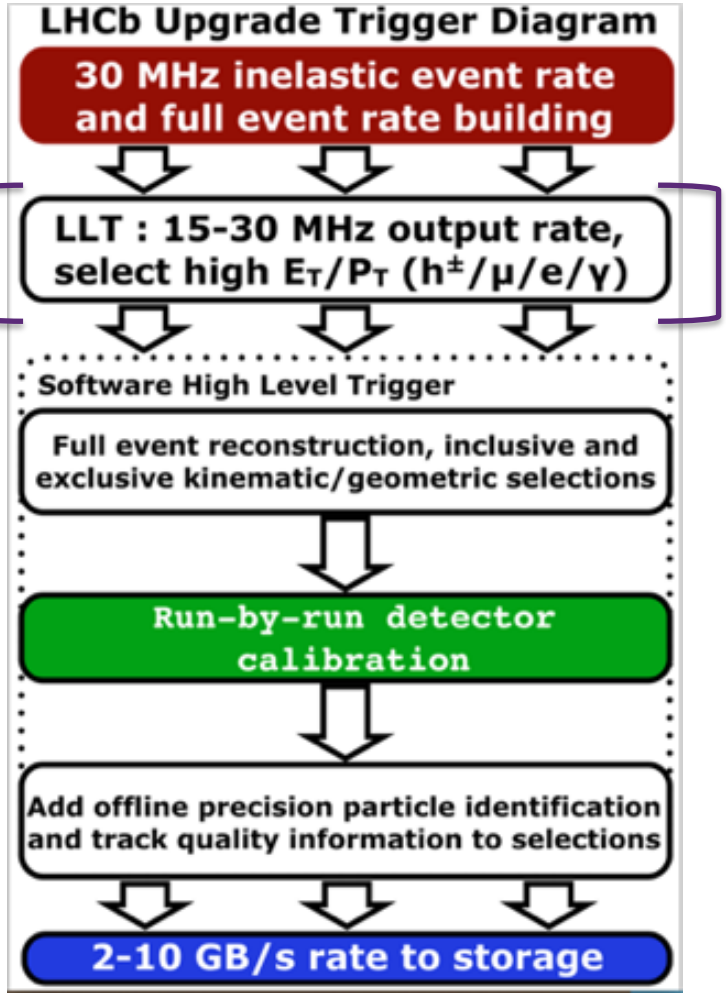

- Funding largely in place from end 2014
  - Upgrade I(a) Construction
  - Assumed ~ 10 years running

# Trigger Evolution – Upgrade I

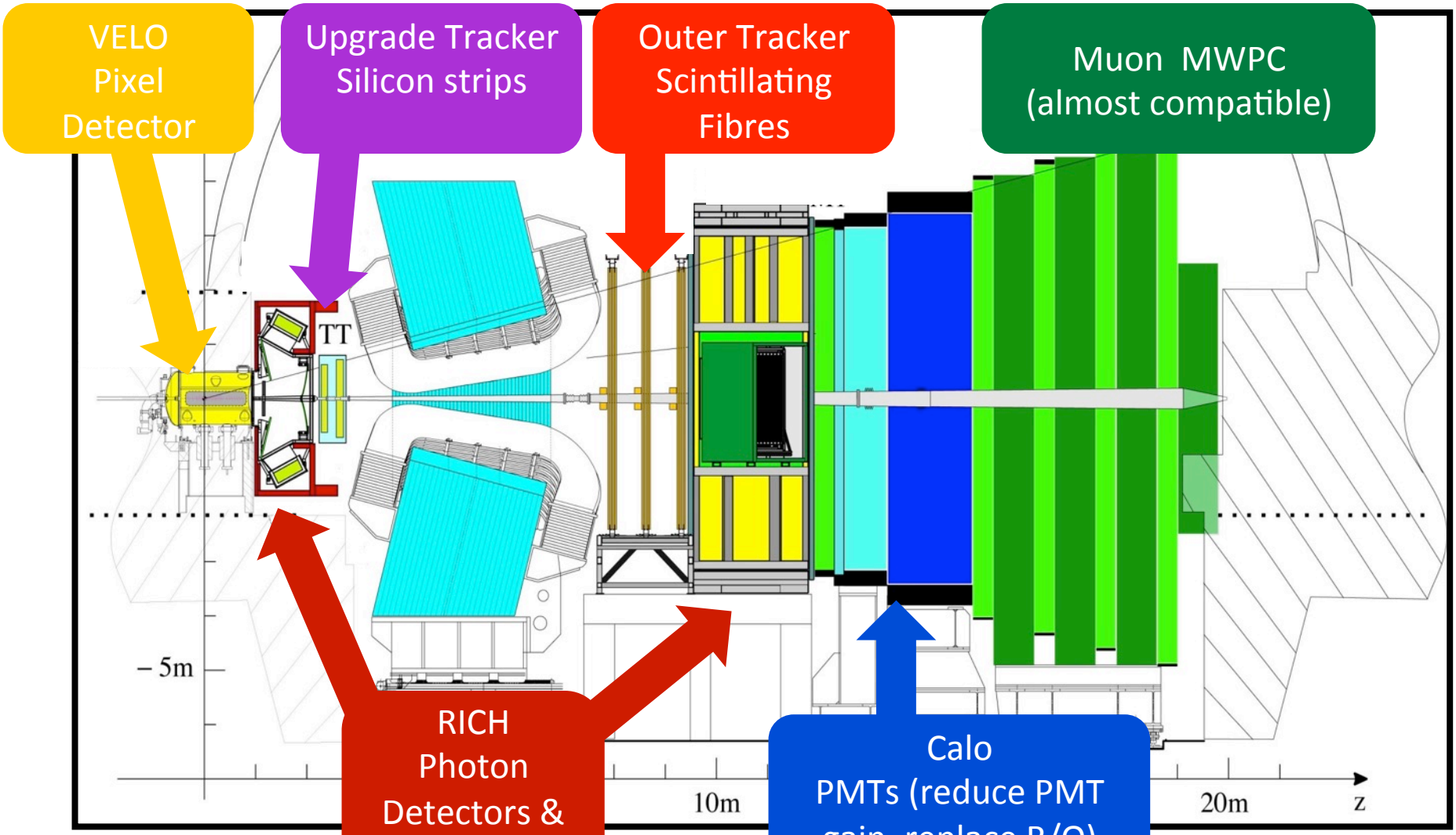
## Run II



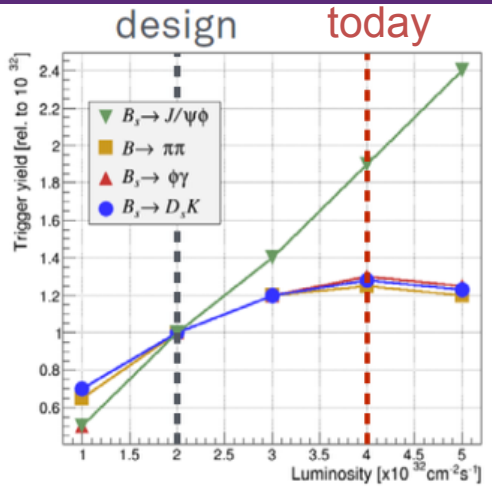

## Upgrade I

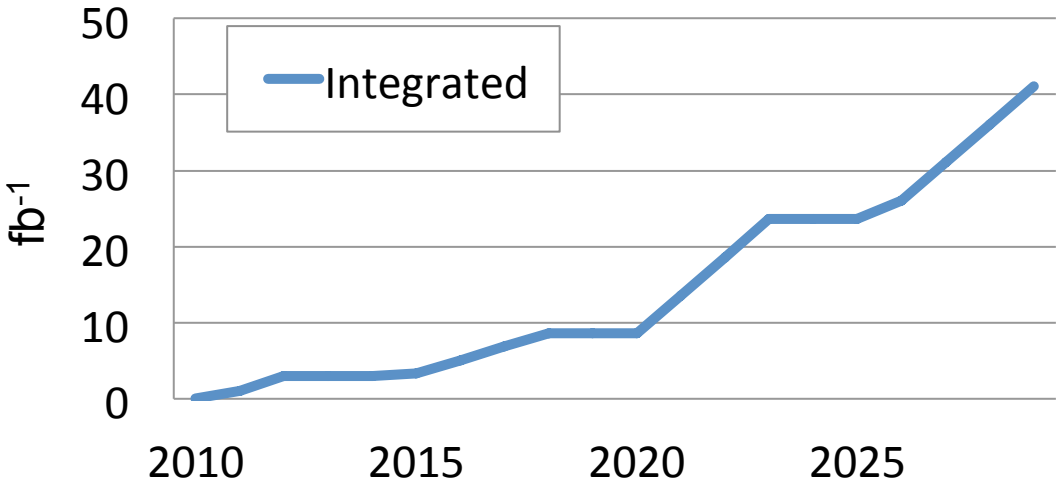


# LHCb Upgrade I
# 25ns readout, software only triggering



# Upgrade I – Beyond the Energy Frontier




- Hardware 1st Level Trigger ➔ Fully Software Trigger
- Increase Lumi to $2\times10^{33}$ $cm^{-2}s^{-1}$ to collect 50 $fb^{-1}$
- General purpose detector in forward region

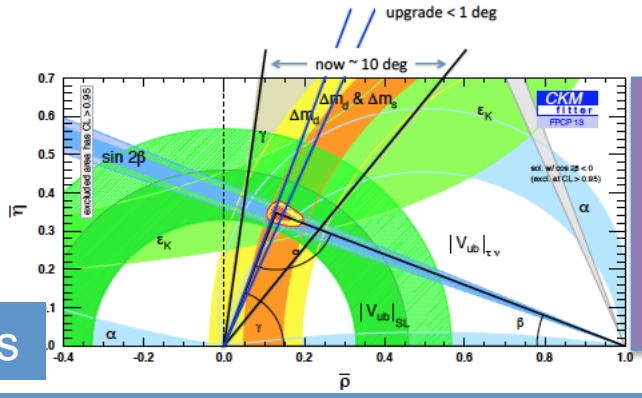
New Physics in Rare Decays

New Physics in CP Violation

New Physics in Charm

Electroweak & QCD Physics

Long Lived Stable Particle Searches, Dark Photon Searches

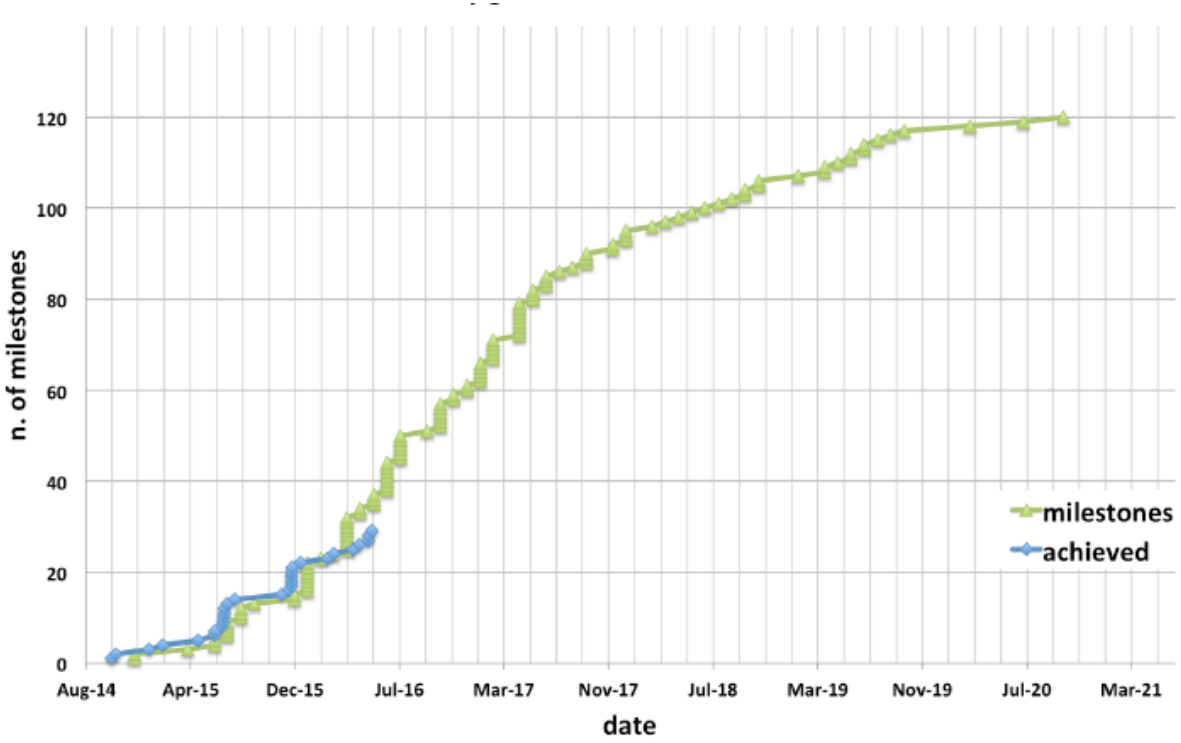



Probe **100 TeV** for tree-level couplings

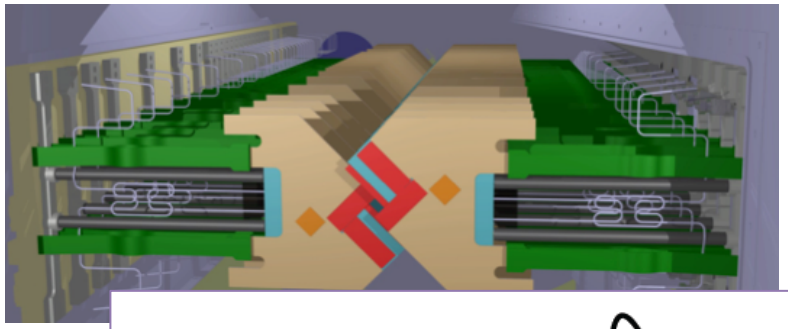
Eur. Phys. J. C (2013) 73:2373

# LHCb Upgrade I - Status

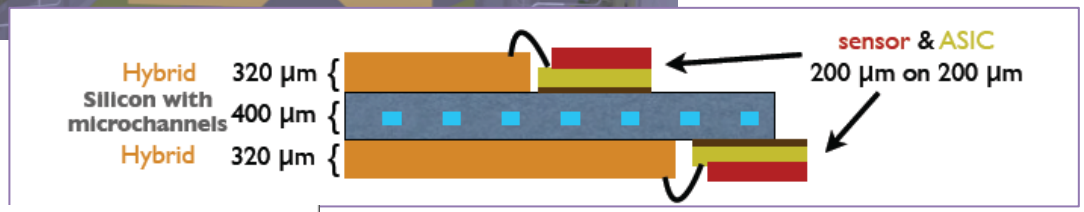
- Construction project on milestone schedule
- Prototypes exist for most major elements
- Engineering Design Reviews being conducted
- Major industrial orders placed



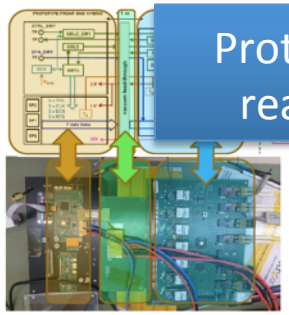
# LHCb Upgrade I: Vertex Locator



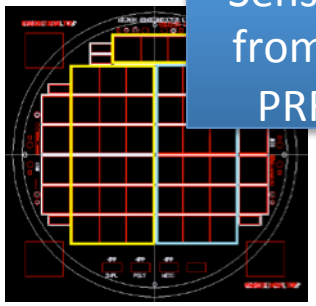
- Pixel Detector
  - 55×55 μm pixels
  - In vacuum




ASIC (VeloPix) received in last weeks



Prototypes full readout chain



Sensor prototypes from two vendors PRR this month

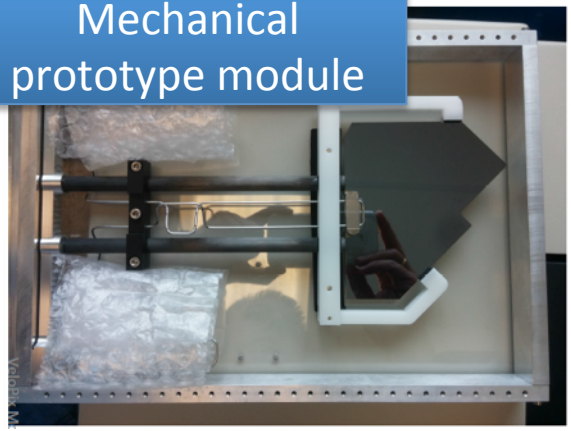
- 5mm from beam
  - $10^{16}$ $n_{eq}/cm^2$
  - Retracted for filling

Bi-phase $CO_2$ cooling

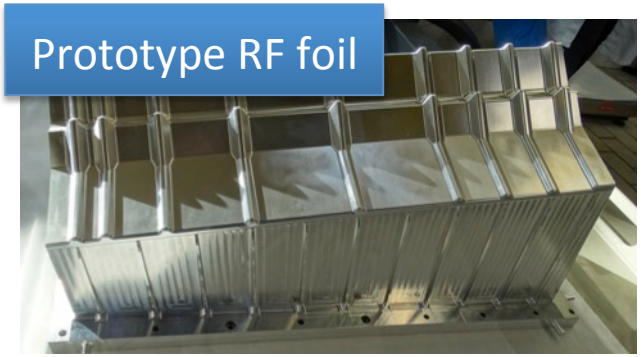
Si Microchannel

- back-up: pipes in TPG/ carbon fibre also under study

Mechanical prototype module



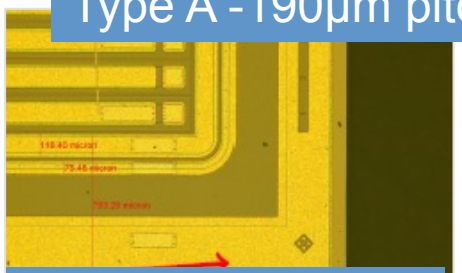
Prototype RF foil



# LHCb Upgrade I: Upstream Tracker

- Silicon detector before magnet
  - Critical for tracking in trigger

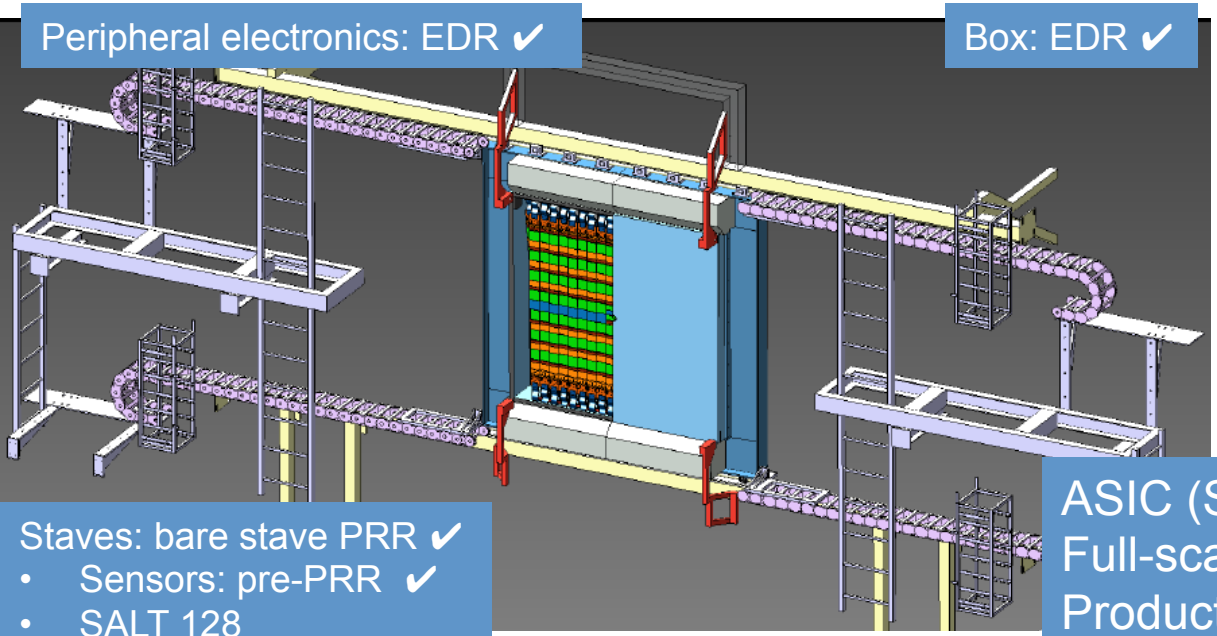
Type A -190μm pitch

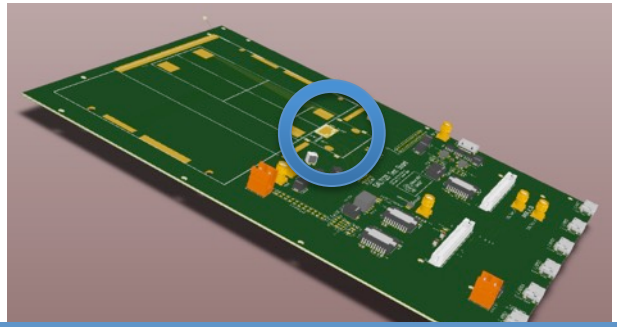


Sensor pre-PRR ✔

Peripheral electronics: EDR ✔

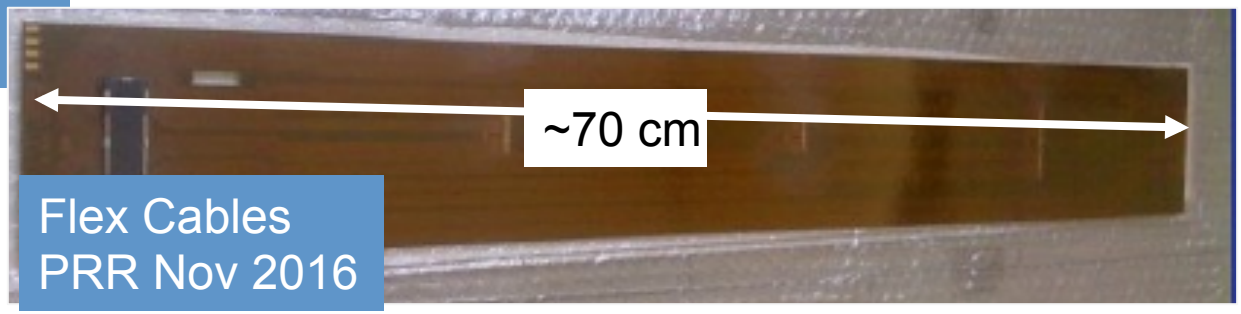
Box: EDR ✔





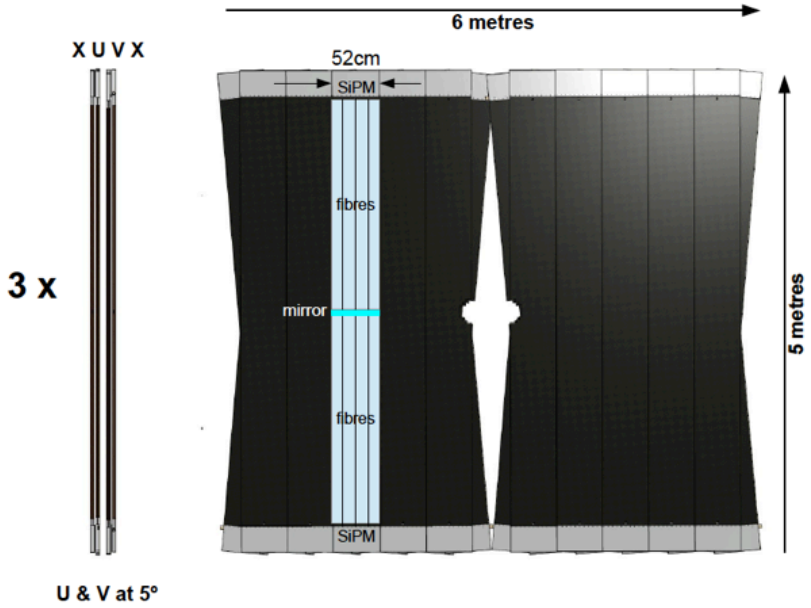
Staves: bare stave PRR ✔
- Sensors: pre-PRR ✔
- SALT 128
- Hybrids
- Flex cables

ASIC (SALT) 8 channel version tested.
Full-scale version received last month.
Production Q2 2017

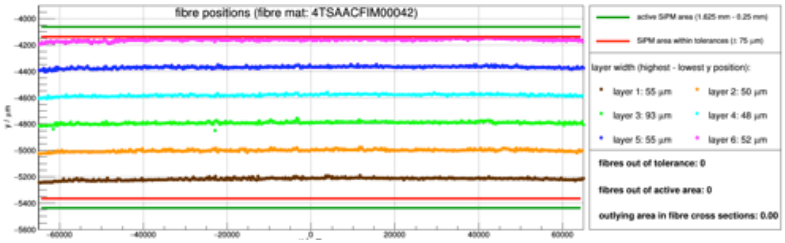


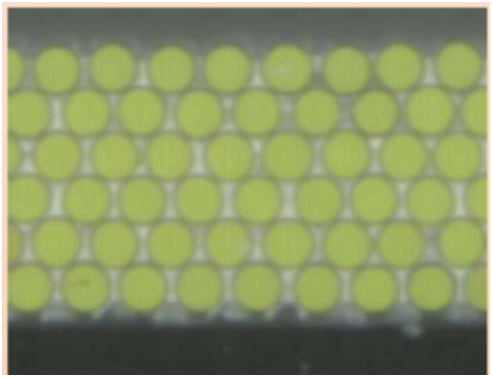

Flex Cables
PRR Nov 2016

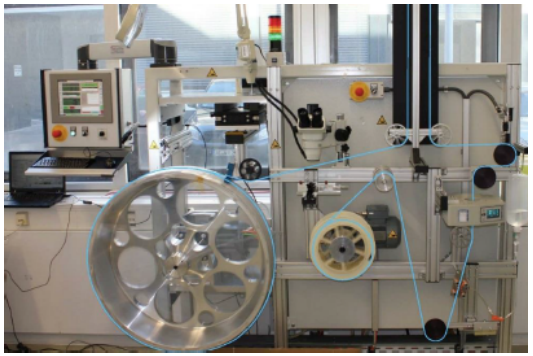
# LHCb Upgrade I : Scintillating Fibre Tracker




- Mat made from
  - 250μm diameter fibres
  - SiPM readout
- **Mat production underway**
- 11,000 km fibre !
  - 1300km received





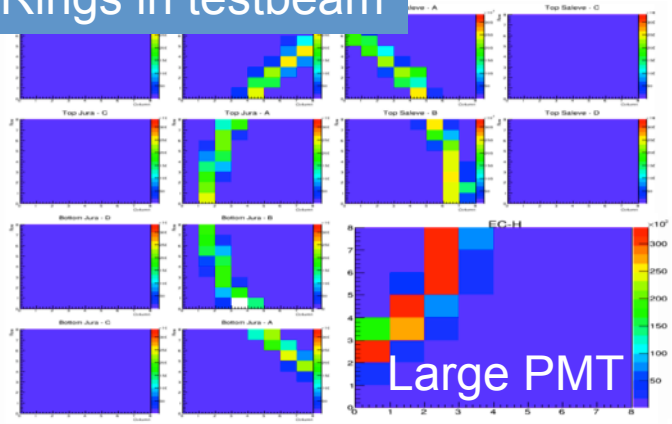
- Bumps in fibre within spec.
- "debumping" procedure applied

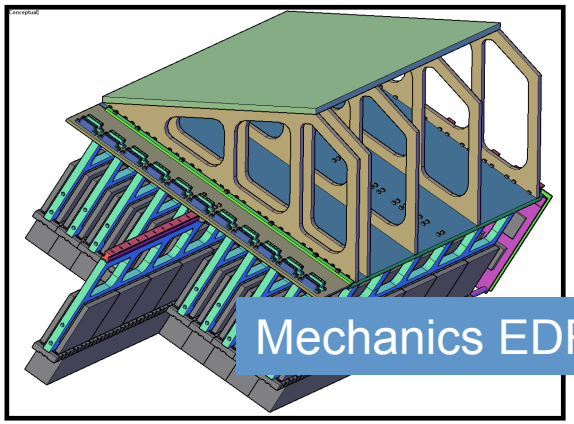
- Fibre positions in spec.
- Cold box for SiPM EDR ✔

# LHCb Upgrade I : RICH 1&2

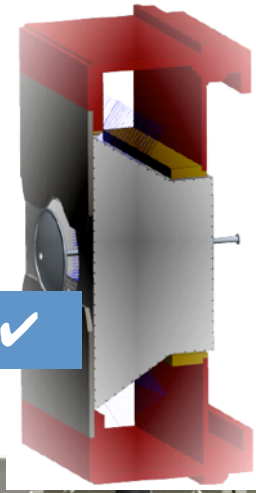
- π/K separation critical to physics
- MaPMT pre-series received and qualified
  - mass production to start

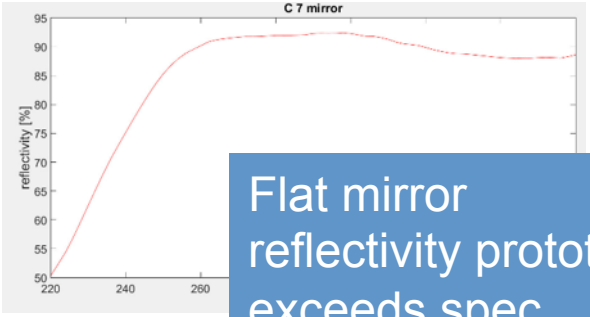
Rings in testbeam



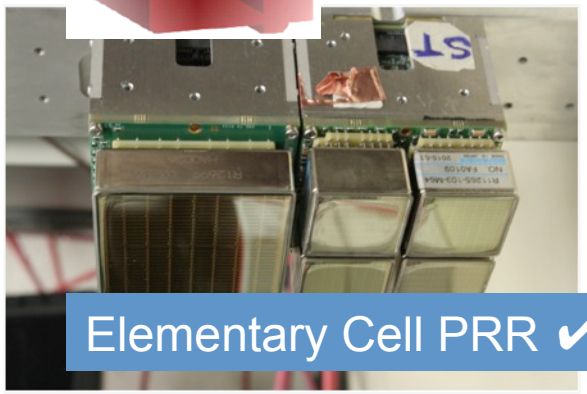
Mechanics EDR ✔





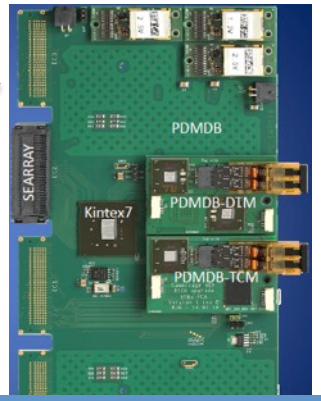

Flat mirror reflectivity prototype exceeds spec.


ASIC (CLARO) PRR
Radiation qualified ✔



Elementary Cell PRR ✔

4x EC




Digital Board EDR ✔

# LHCb Upgrade I : Calorimeters

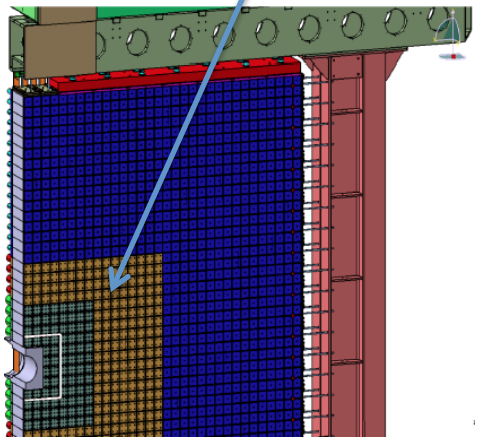
- 1st level hardware trigger role removed
- …but intriguing hints of Lepton non-universality (also physics with $\pi^0$, radiative decays)

further emphasize need for good ECAL

Prototype FE board +HV / Calibration produced and tested

ASIC (ICECAL) extensively tested – including radiation PRR in October

Innermost Cell replacement not needed till LS3

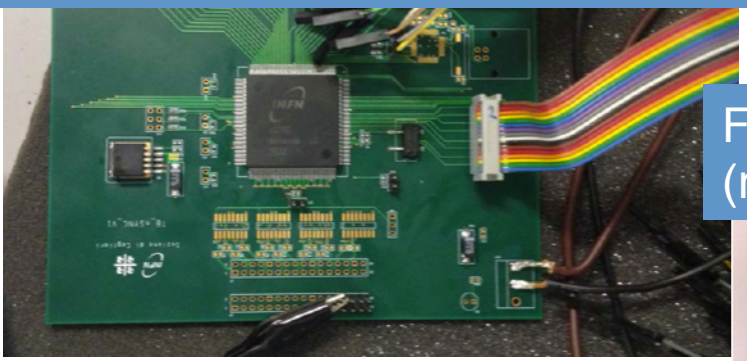


- Reduce gain by factor five, compensate in FE elec.
- Planning for initial layer (SPD/PS) dismantling (not needed in trigger)

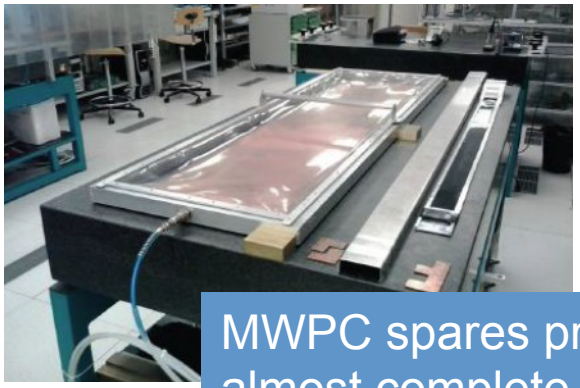
# LHCb Upgrade I : Muon

- New off-detector readout for 40MHz
- Additional shielding

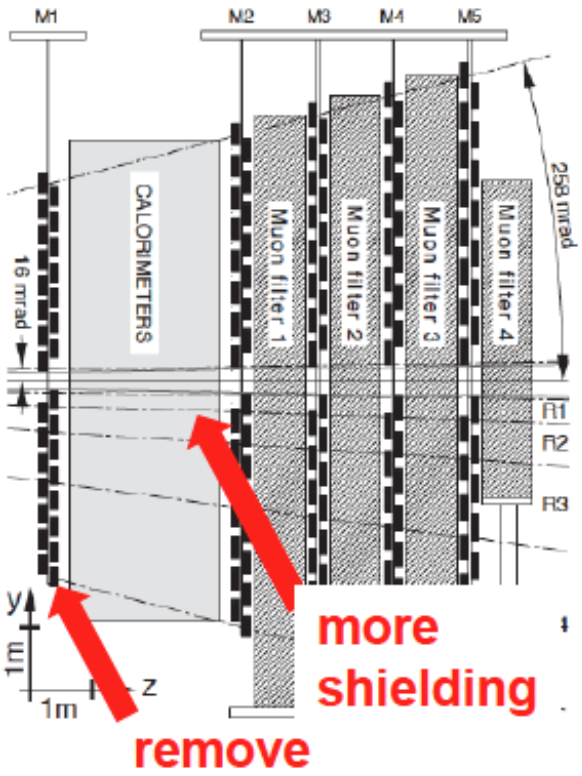
New Off Detector electronics ASIC (nSync) under test



FE control & test board (nSB) prototype produced

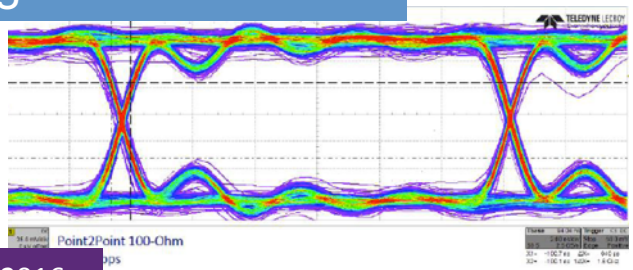


MWPC spares production almost complete

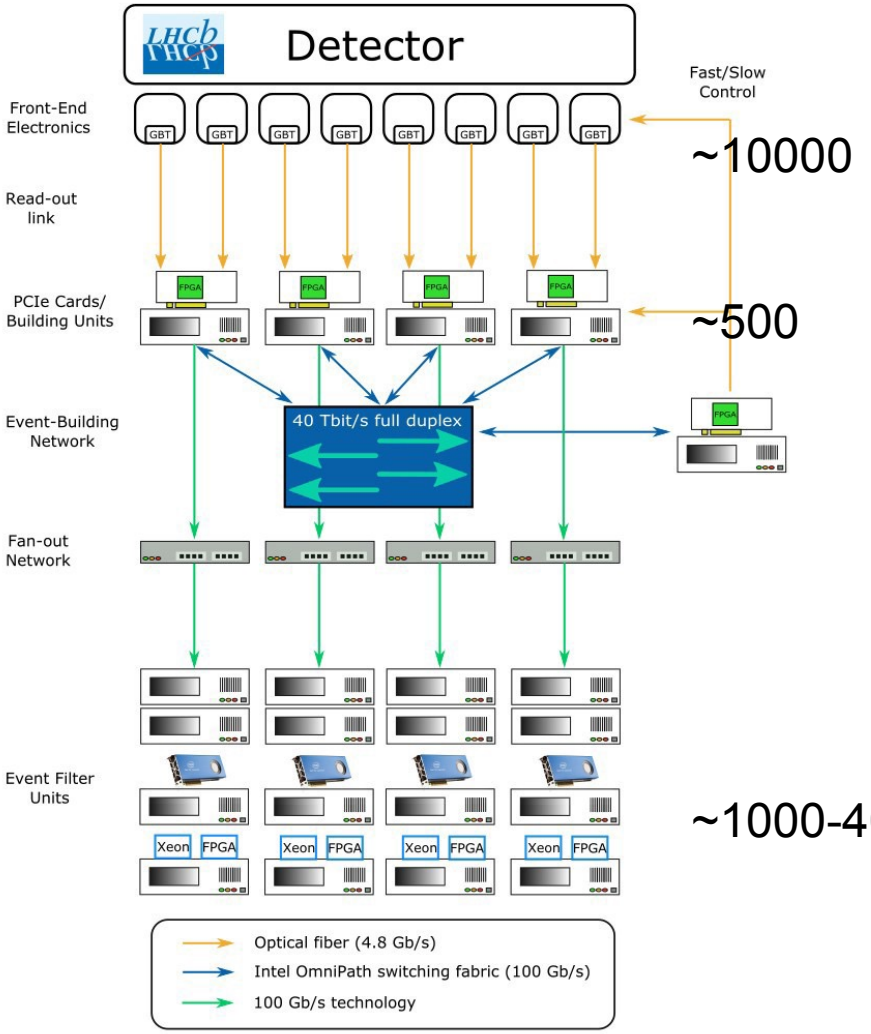



not needed in trigger

High speed backplane design & tests

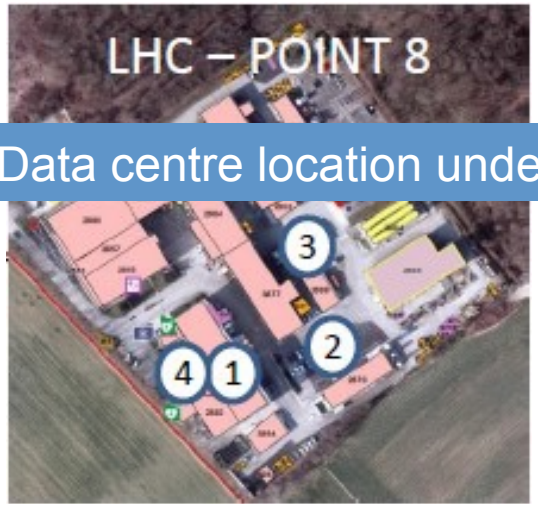


# LHCb Upgrade I : Online & Computing




Common DAQ,ECS,TFC board for all detectors (PCIE40)
2nd prototype received

Firmware developed

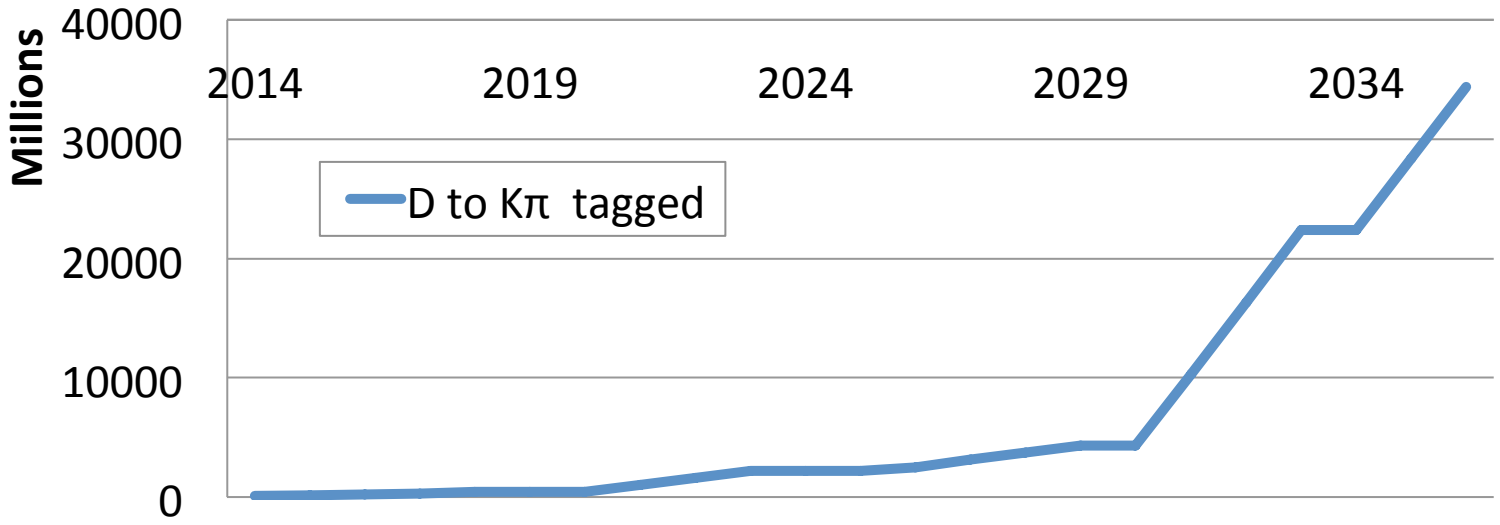



Data centre location under discussion

- Computing TDR Q1 2017
  - Pioneering using reconstruction in trigger in Run2 to reduce event size (online calibration “turbo” stream)

# Physics: Charm mixing & CPV

- Negatives:
- Lower momentum, shorter lifetime than B-sector
- Positives:
- $y, A_\Gamma, \Delta A_{CP}$ – no limiting systematics yet known

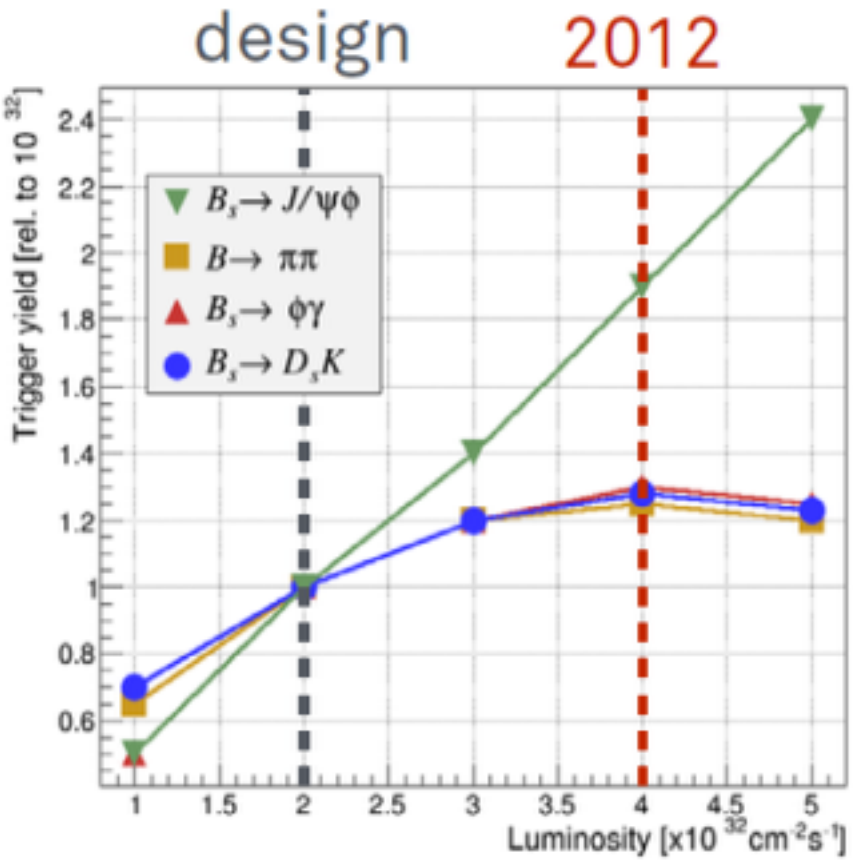



- ~30MHz of charm events produced in acceptance!

Observe SM level CPV at LHCb Phase II Upgrade

# LHCb Trigger: the key to higher Lumi

- Aim: Increase integrated luminosity from 2 $fb^{-1}$ to 5 $fb^{-1}$ per year
  Increase instantaneous luminosity to $2x10^{33}$ $cm^{-2}$ $s^{-1}$



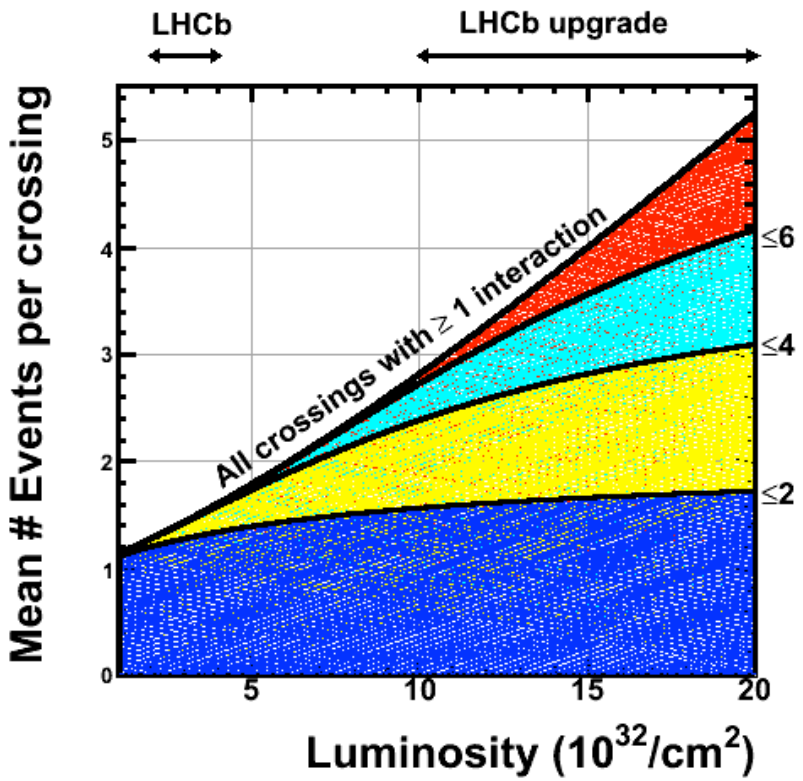

Current First Trigger Level:
Hardware Muon/ECAL/HCAL
1.1 MHz readout

Performance:
Muon channels scale
Hadronic channels saturate bandwidth

- No gain in hadronic channels with current trigger

# Solution: Upgrade to 40MHz readout

- Read out full detector at 40MHz
  - Major detector changes
  - Front-end electronics must change
- Use fully software trigger
  - Increased flexibility
- Maintain (improve) current detector performance
  - At increased multiple Interactions
    - Occupancies
    - Radiation damage



# Phase 1(b) Upgrade Ideas

- Improving the muon shielding by replacing HCAL with iron
- Building new, high rate, muon chambers for busy regions
- Replacing central region of RICH1 photodetector plane with new high granularity SiPMs
- Replacing inner SciFi modules with SciFi/ silicon
- Adding side chambers in magnet
- TORCH for fast-timing and PID purposes
- Replacing some of ECAL with high performant technology

# Physics Performance Assumptions

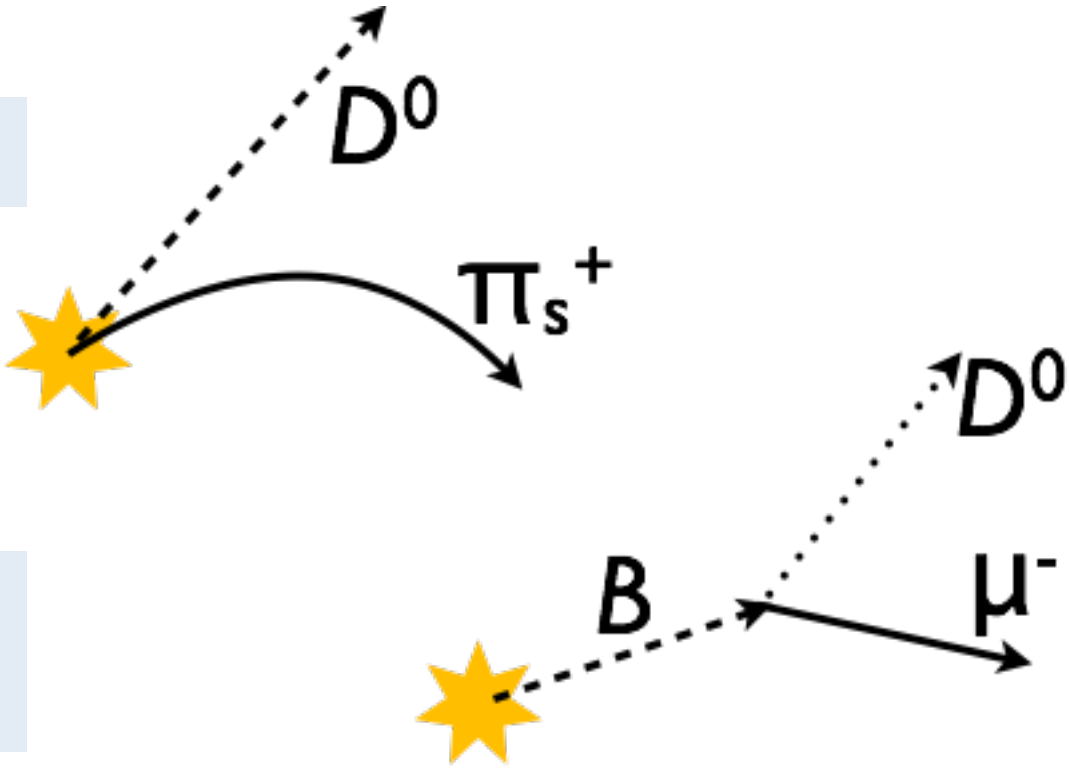
- Run-2
  - Cross-section increases linearly with $\sqrt{s}$
  - Non-muon trigger efficiency suffers from tighter thresholds, but benefits from increased trigger eff.
  - 1.75 $fb^{-1}$ per full year, ~5$fb^{-1}$ in total for run II
- Upgrade Phase I
  - Removal of hardware trigger brings factor 2 efficiency boost for non-muon triggered events
  - 5$fb^{-1}$ per year
- Upgrade Phase II
  - Same trigger eff. as upgrade (an upper limit?)
  - 50 $fb^{-1}$ per year

# Sources of Charm

## Prompt charm

Run I D➔Kπ: 100M

Offline selected D* tagged




## Semileptonic B-hadron decays

Run I D➔Kπ: 20M

Offline selected D* tagged

Hadronic B decays
Not only useful to measure CKM γ
Also revealed first spin-3 charm state

→ LHCb collaboration, Phys. Rev. Lett. 113 (2014) 162001

# Physics Coverage / Limitations

- Inclusive charm trigger selections are not feasible
  - Upgrade I will produce **800 kHz** of analysable charm-hadron events
  - **80 GB/s** with current data format – hence turbo stream approach
    - can keep **2-10 GB/s** for ALL LHCb physics
- Have to decide in advance what to keep
  - Cabibbo favoured modes prescaled ?
  - Purely exclusive selection – trigger is offline selection
- Limits of physics programme not yet reached
  - Use of neutrals
  - understanding production/detection asymmetries

$D^0 \to \pi^-\pi^+\pi^0$

2yrs LHCb Run 1= 80 yrs B factory v1