The LHCb Upgrade and beyond

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on behalf of the LHCb Collaboration

AGH-University of Science and Technology

XIII International Conference on Heavy Quarks and Leptons (HQL)

22/05 – 27/05/2016,Virginia Tech Blacksburg, USA

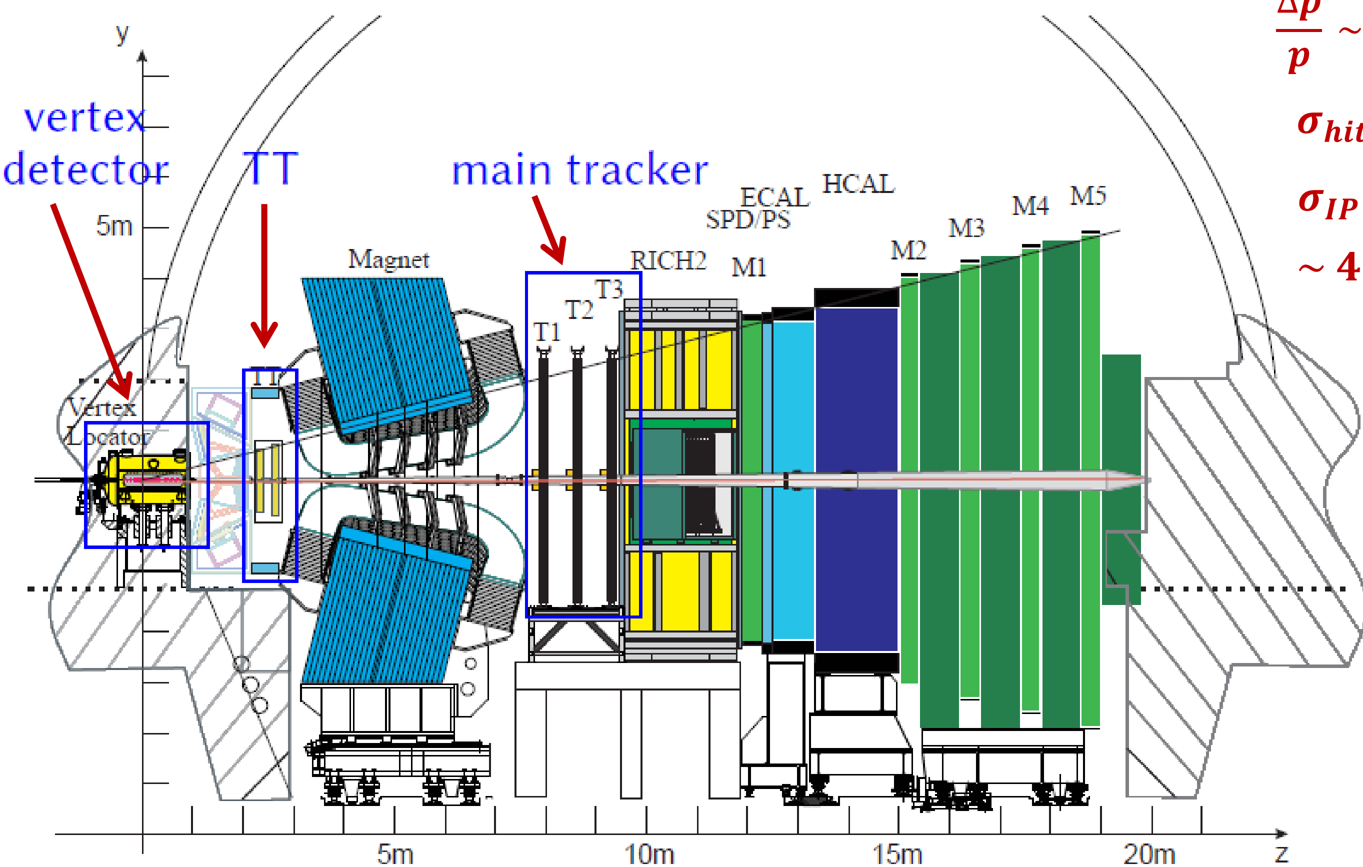
- ❑ Outline
- ❑ LHCb Detector @ RUNI and RUN II
- ❑ Upgrade Plans
- ❑ Theatre of Dreams – going beyon RUN III
- ❑ Summary

Introduction – LHCb detector

- **LHCb** is dedicated for studying **heavy quark flavour physics**
- It is a **single arm forward spectrometer** (**$2 < \eta < 5$**)
- Excellent tracking capabilities provided by:
  - Vertex detector **VELO**
  - Upstream and downstream tracking stations
  - 4 Tm warm dipole magnet
- Particle identification done by:
  - RICH detectors
  - Calorimeters
  - Muon stations
- Partial information from calorimeters and muon system contribute to **L0 trigger** (hardware) that works at LHC clock – **40 MHz**
- **Full** detector readout at **1 MHz**

Introduction – LHCb detector

- Tracking system – precise momentum reconstruction, vertexing, decay time resolution
- Excellent PID using RICH detectors (cover different momentum range), calorimeters and muon chambers in concert



$\frac{\Delta p}{p} \sim 0.5 - 1.0\,\%$

$\sigma_{hit} \approx 4\,\mu m$

$\sigma_{IP} \approx 13\,\mu m$

$\sim 40 - 50\,fs$

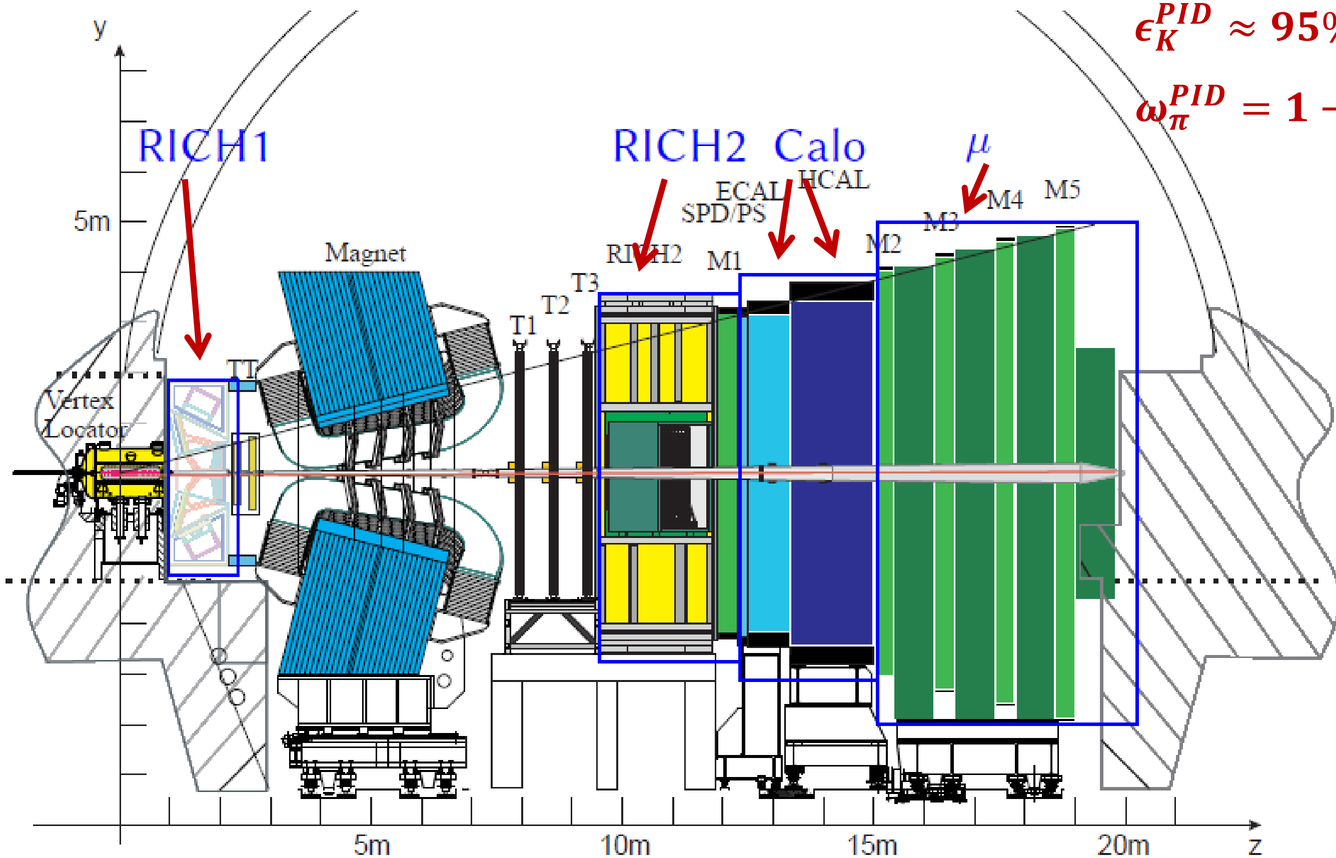
[JINST 3 (2008) S08005]

Introduction – LHCb detector

- ❑ Tracking system – precise momentum reconstruction, vertexing, decay time resolution
- ❑ Excellent PID using RICH detectors (cover different momentum range), calorimeters and muon chambers in concert

$\epsilon_K^{PID} \approx 95\%$

$\omega_\pi^{PID} = 1 - \epsilon_\pi^{PID} \approx 10\%$



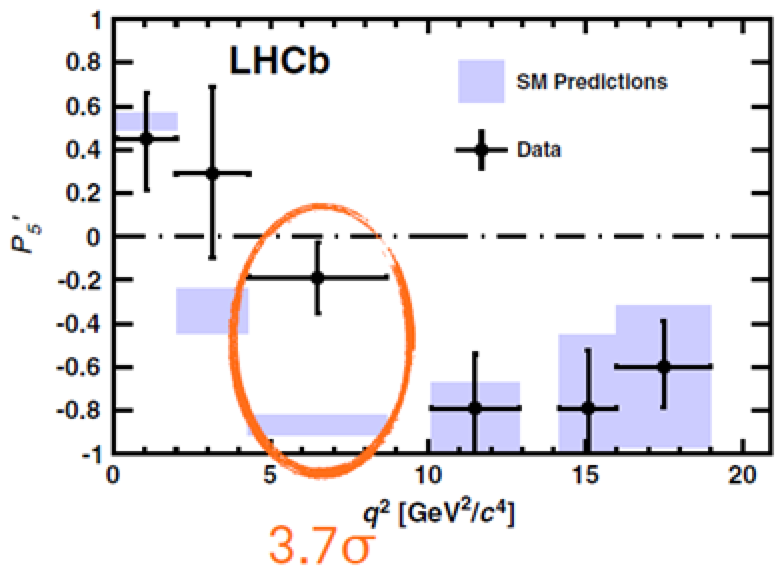
[JINST 3 (2008) S08005]

Are these interesting times – cracking the SM (I)

$B^0 \rightarrow K^*\mu^+\mu^-$: **NP in loops**

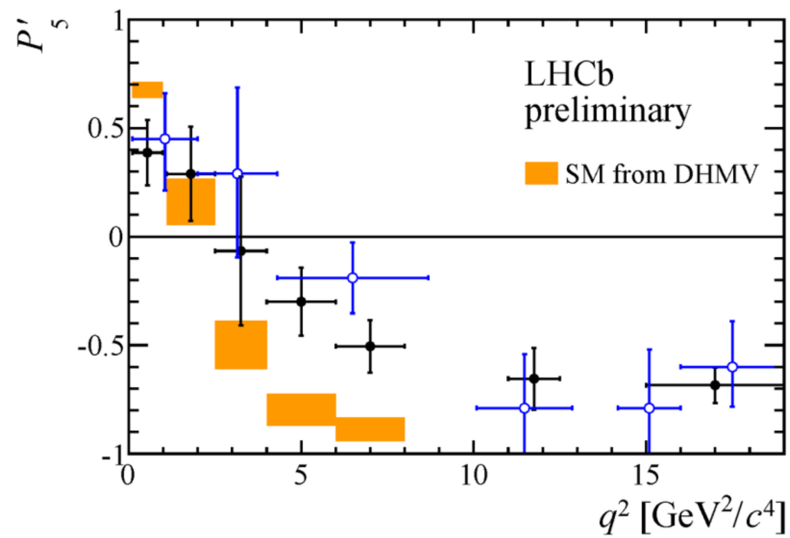
- In order to limit the hadronic uncertainties (form factors) a new base of observables proposed
- Analysis done in 2013 and repeat in 2015 with the full RUN I data sample
- Observed discrepancy may be a hint of new heavy neutral Z' particle
- Belle reported very similar result @ LHCSki'16 conference!

2013



(PRL 111, 191801 (2013))

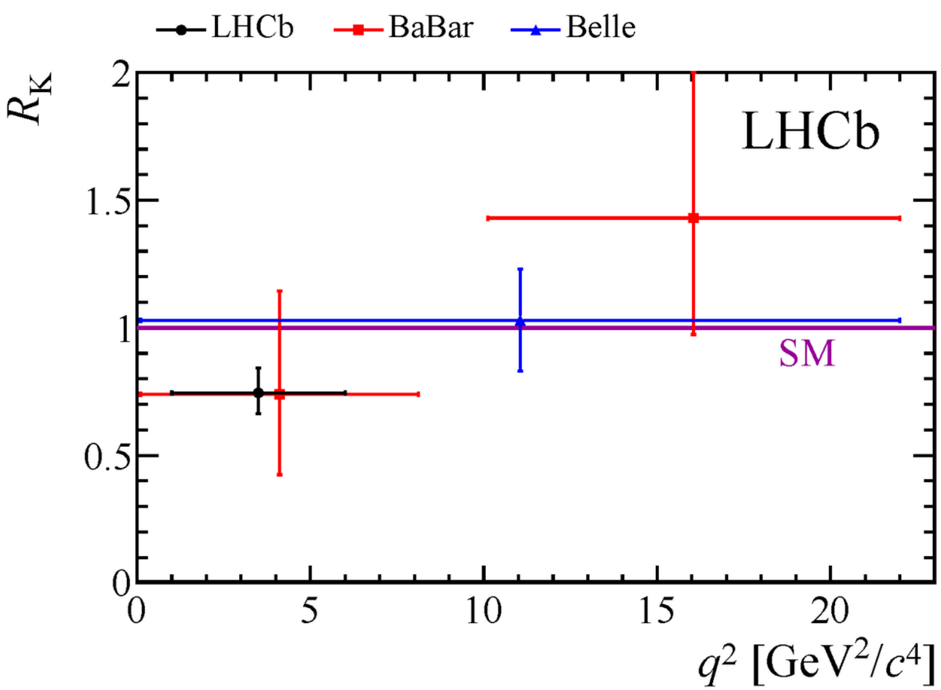
2015



Are these interesting times – cracking the SM (II)

LFU Violation

- In the SM the **couplings** between the intermediate bosons and all lepton families **should be the same**
- Any departure from this would be a signal of New Physics
- LHCb studied the ratio, R_k, using two rare decay channels
- Very sensitive to new particles exchanged in the virtual loops



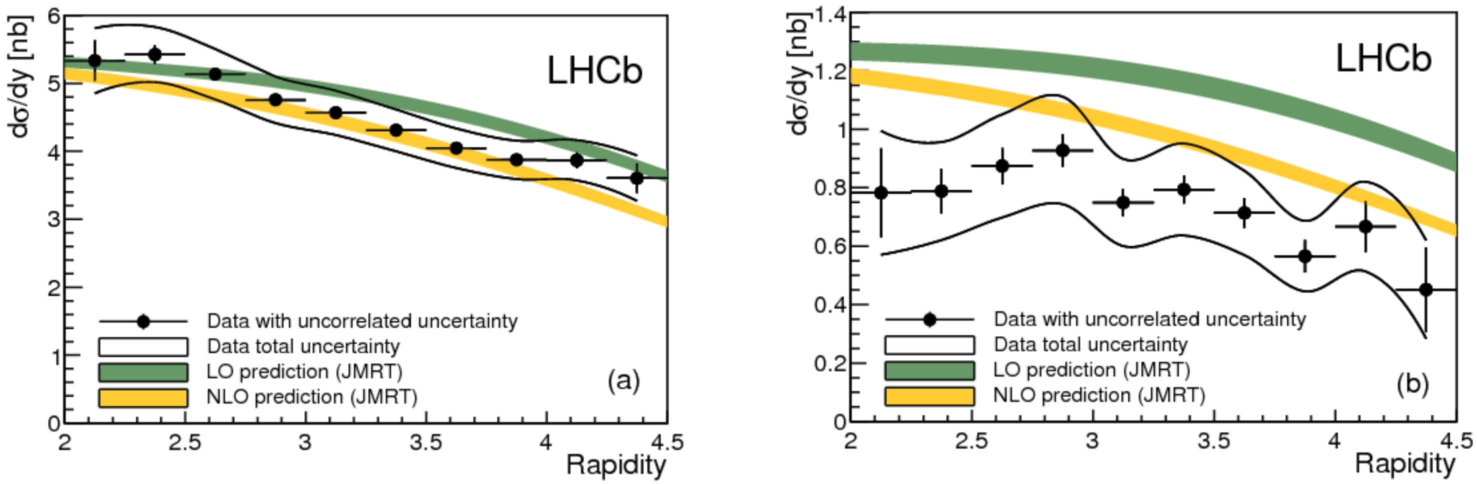
$$R_k = \frac{\mathcal{B}r(B^+ \to K^+\mu^-\mu^+)}{\mathcal{B}r(B^+ \to K^+e^-e^+)}$$

$$R_K = 0.745^{+0.090}_{-0.074} \pm 0.036$$

(PRL 113, 151601 (2014))

LHCb can also participate in 'exotic' physics…

- Spectroscopy – some world best measurement
- Penta-quarks
- Electro-weak physics in forward region
- Ion runs – this is actually awesome…
- Soft QCD – exclusive production



$$\boxed{\sigma_{J/\psi\to\mu^+\mu^-}(2 < \eta_{\mu^+}\eta_{\mu^-} < 4.5) = 291 \pm 7(stat.) \pm 19(sys.)pb}$$

$$\boxed{\sigma_{\psi(2S)\to\mu^+\mu^-}(2 < \eta_{\mu^+}\eta_{\mu^-} < 4.5) = 6.7 \pm 0.9(stat.) \pm 0.4(sys.)pb}$$

J. Phys. G 41 (2014) 055002

Overall summary of Run I

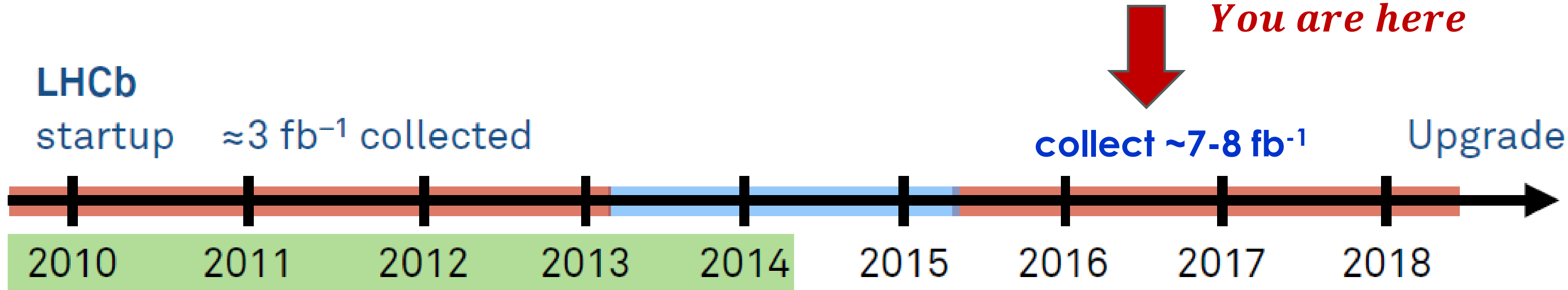
LHCb:

- Superb performance – greatly exceeded any expectations
- Stable operation at inst. luminosity **100%** higher than nominal
- **General purpose detector in forward direction**
- Many world leading results
- **Over 250 papers published!**

Still waiting for a crack in the SM

- No conclusive BSM physics discovered
- There is still room for NP!
- Need push **precision** to the limits in order to challenge theoretical predictions
- **We are taking more data as we speak – hope for new fantastic resutls soon!**

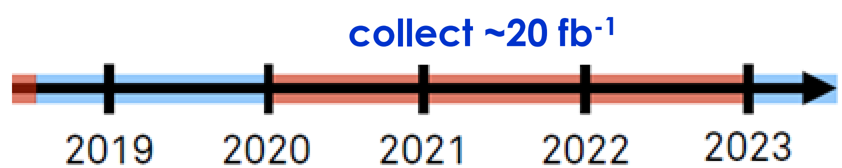
Data taking road map for LHCb (RUN I – RUN III)



LHC Run I
- *pp* runs @50 ns
  - 7 TeV (2010,2011)
  - 8 TeV (2012)
- Pb Pb run @2.76 TeV
- *p* Pb run @5 TeV

LHC LS1
- repair splices
- consolidation

LHC Run II
- *pp* runs 13 TeV @25 ns
- L_{peak} 2x10^{34} cm^{-2} s^{-1}



LHC LS2

LHC Run III
- *pp* runs 14 TeV @25 ns

LHC LS3
HL-LHC

Upgrade Plans

Why upgrade (i.e., what's wrong with the current design…?)

Superb performance – but **1 MHz** readout is a **sever limit**

- can collect **~ 2 fb^{-1}** per year, **~ 8 fb^{-1}** for Run I and II of the experiment
- this is not enough if we want to move from **precision** exp to **discover**y exp
- cannot gain with increased luminosity – trigger yield for **hadronic events saturates**

Upgrade plans for LHCb do not depend on the LHC machine

- we use fraction of the luminosity at the moment

Upgrade P I target

- full event read-out@30 MHz (flexible approach)
- completely new front-end electronics needed (on-chip zero-suppression)
- redesign DAQ system
- **HLT output@2 – 5 GB/s, more than 50 fb^{-1} Run III and IV (Upgrade P I b)**
- increase the yield of events (up to 10x for hadronic channels)
- **experimental sensitivities close or better than the theoretical ones**
- expand physics scope to: lepton flavour sector, electroweak physics, exotic searches and QCD

Installation ~ 2018 - 2020

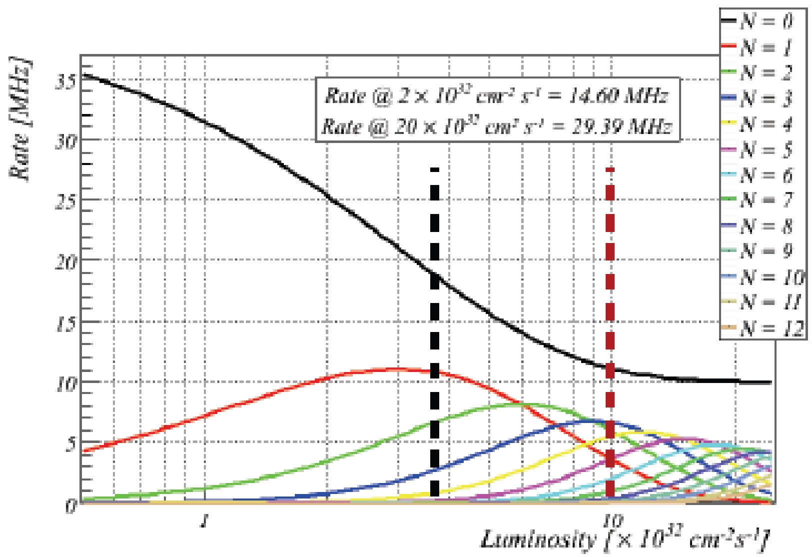
Sensitivities to key flavour observables

(for more see: **LHCb Upgrade: Technical Design Report**, **LHCb-TDR-12**)

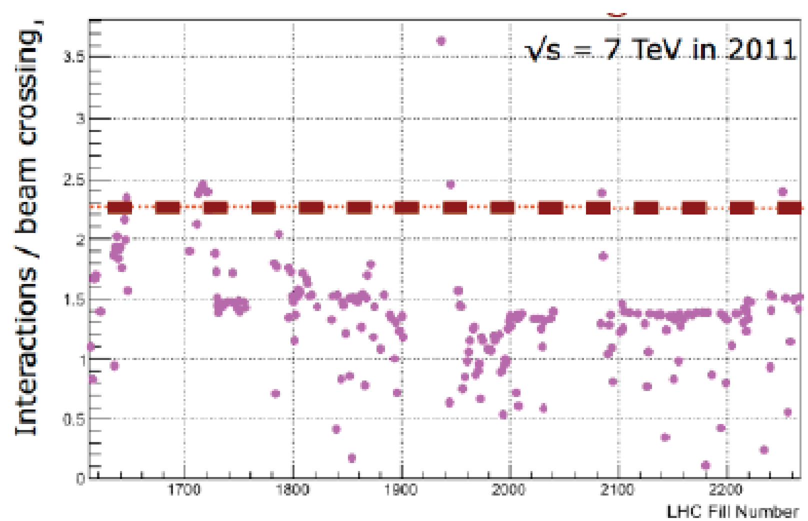
Type	Observable	Current precision	LHCb (5 fb^{-1})	Upgrade (50 fb^{-1})	Theory uncertainty
Gluonic penguin	$S(B_s \to \phi\phi)$	-	0.08	0.02	0.02
	$S(B_s \to K^{*0}\bar{K}^{*0})$	-	0.07	0.02	< 0.02
	$S(B^0 \to \phi K^0_S)$	0.17	0.15	0.03	0.02
B_s mixing	$2\beta_s\ (B_s \to J/\psi\phi)$	0.35	0.019	0.006	~ 0.003
Right-handed currents	$S(B_s \to \phi\gamma)$	-	0.07	0.02	< 0.01
	$\mathcal{A}^{\Delta\Gamma_s}(B_s \to \phi\gamma)$	-	0.14	0.03	0.02
E/W penguin	$A_T^{(2)}(B^0 \to K^{*0}\mu^+\mu^-)$	-	0.14	0.04	0.05
	$s_0\, A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	-	4%	1%	7%
Higgs penguin	$\mathcal{B}(B_s \to \mu^+\mu^-)$	-	30%	8%	$< 10\%$
	$\frac{\mathcal{B}(B^0 \to \mu^+\mu^-)}{\mathcal{B}(B_s \to \mu^+\mu^-)}$	-	-	$\sim 35\%$	$\sim 5\%$
Unitarity triangle angles	$\gamma\ (B \to D^{(*)}K^{(*)})$	$\sim 20^\circ$	$\sim 4^\circ$	0.9°	negligible
	$\gamma\ (B_s \to D_s K)$	-	$\sim 7^\circ$	1.5°	negligible
	$\beta\ (B^0 \to J/\psi\, K^0)$	1°	0.5°	0.2°	negligible
Charm CPV	A_Γ	2.5×10^{-3}	2×10^{-4}	4×10^{-5}	-
	$A_{CP}^{dir}(KK) - A_{CP}^{dir}(\pi\pi)$	4.3×10^{-3}	4×10^{-4}	8×10^{-5}	-

Projected running conditions for the upgrade

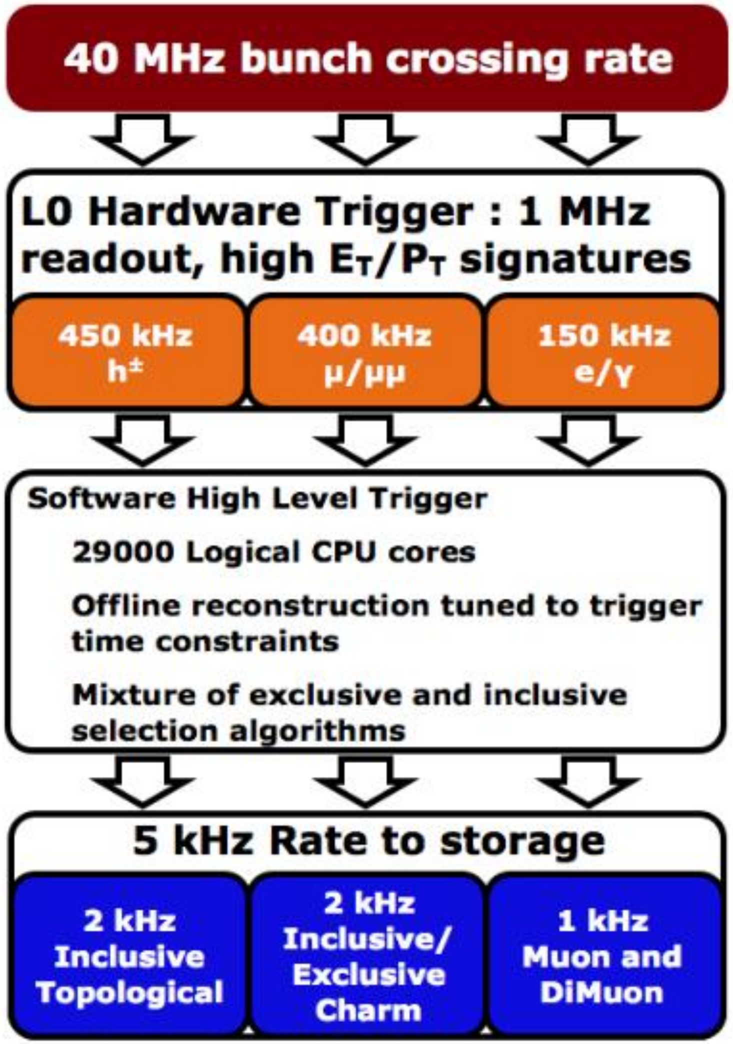
- Operational luminosity up to L_{inst} = **2 x 10^{33}** [cm^{-2}s^{-1}]
- 25 ns bunch time spacing
- Average number of visible interaction per x-ing $\mu \approx 2.6$
- Challenging environment for tracking and reconstruction
- Radiation damage

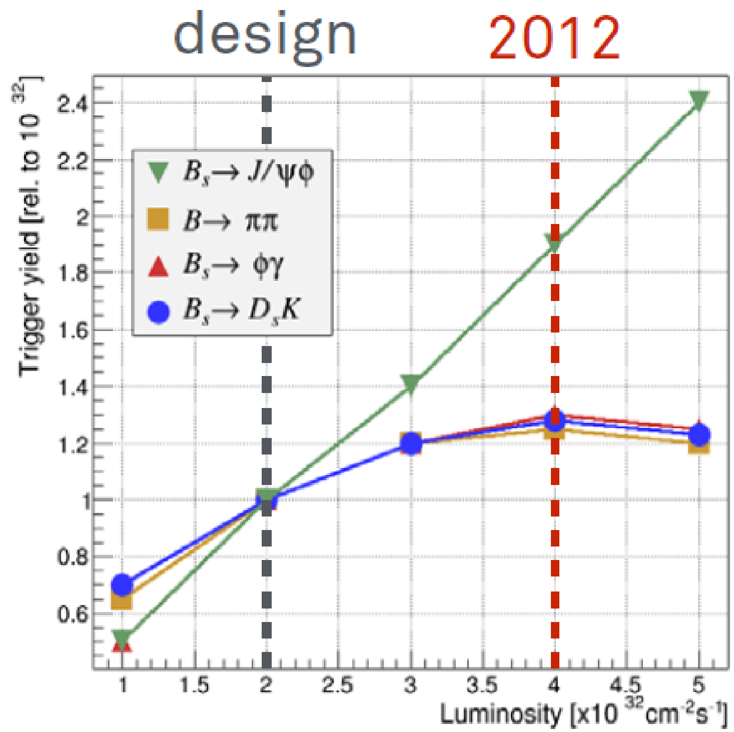


High μ already seen in LHCb!



RUN I – the beggining 2kHz readout

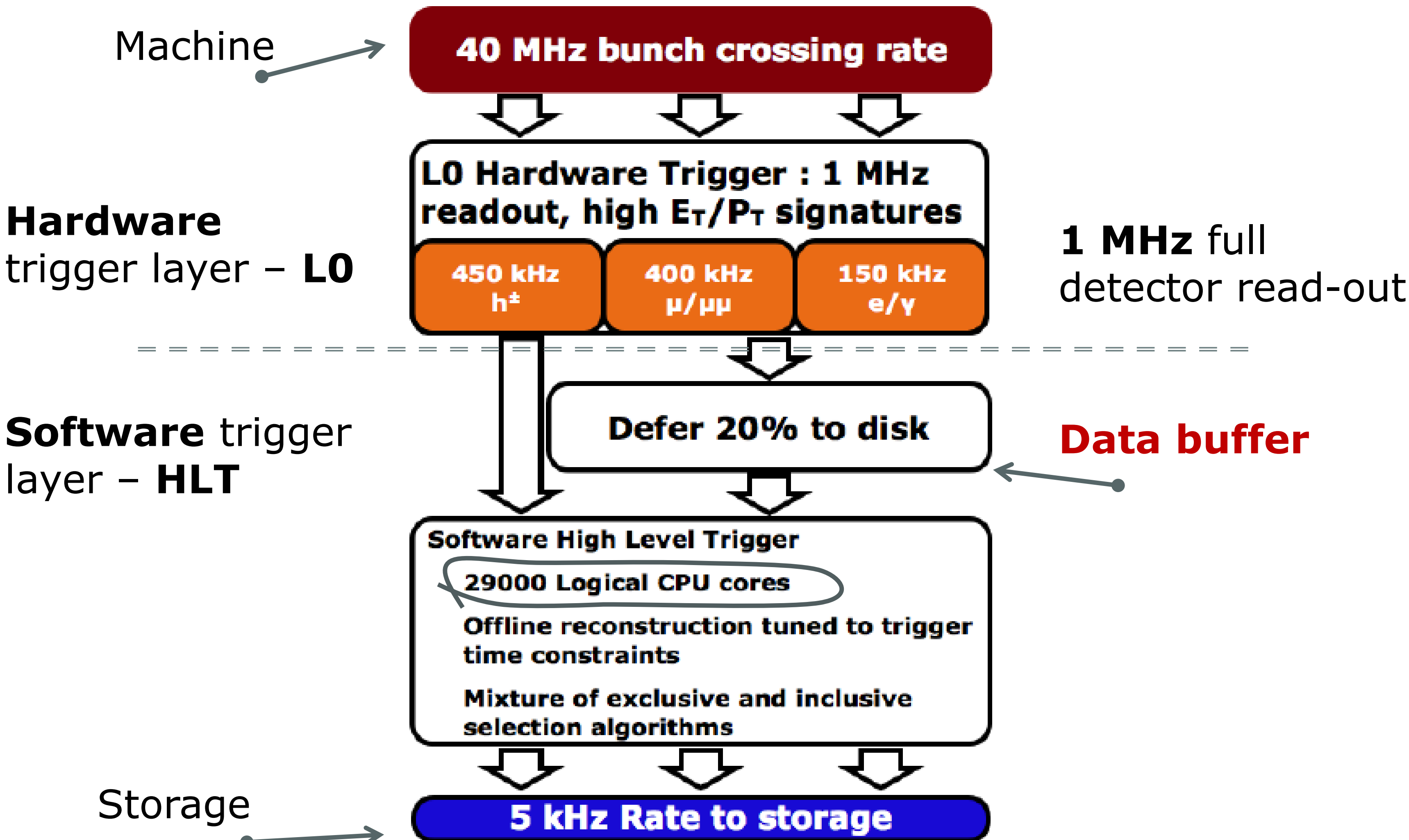




Problem for hadronic channels:

- ❑ saturation with increasing luminosity
- ❑ no gain in event yields

RUN I – evolution – 5kHz readout



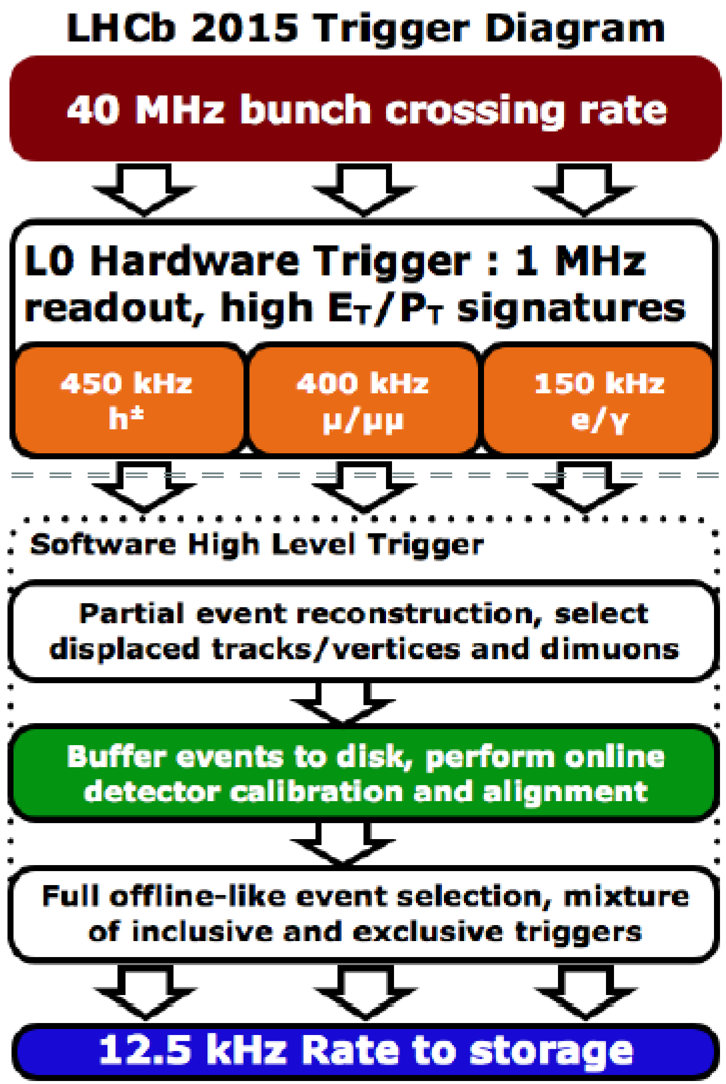
Revolution in HEP data acquisition system a.k.a. RUN II LHCb Trigger

Machine

Hardware
trigger layer – **L0**

1 MHz full
detector read-out

Splitted– HLT



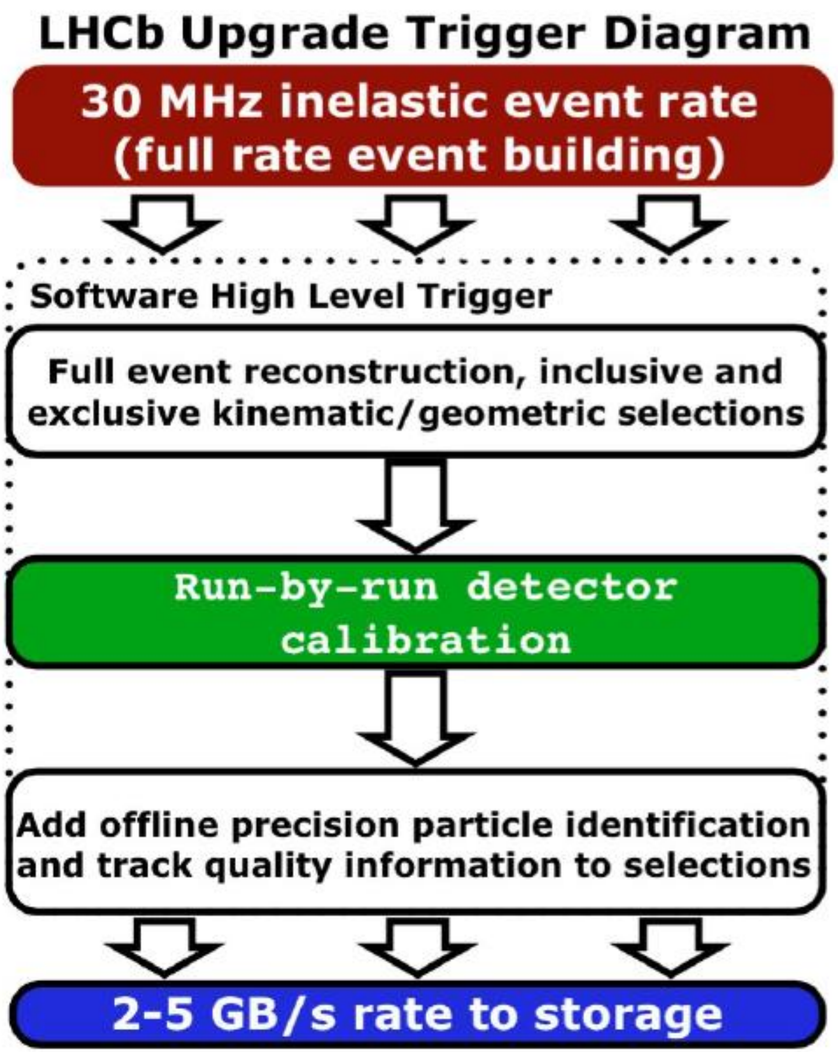
Data buffer

~ 5 PB

Storage

RUN III a.k.a. upgraded LHCb Trigger

Machine



1-30 MHz full detector read-out

L0 completely removed!

Storage

Tracking is at heart of the current LHCb success

- Upgrade cannot compromise this performance
- This is not an easy task

At high luminosity we are expecting

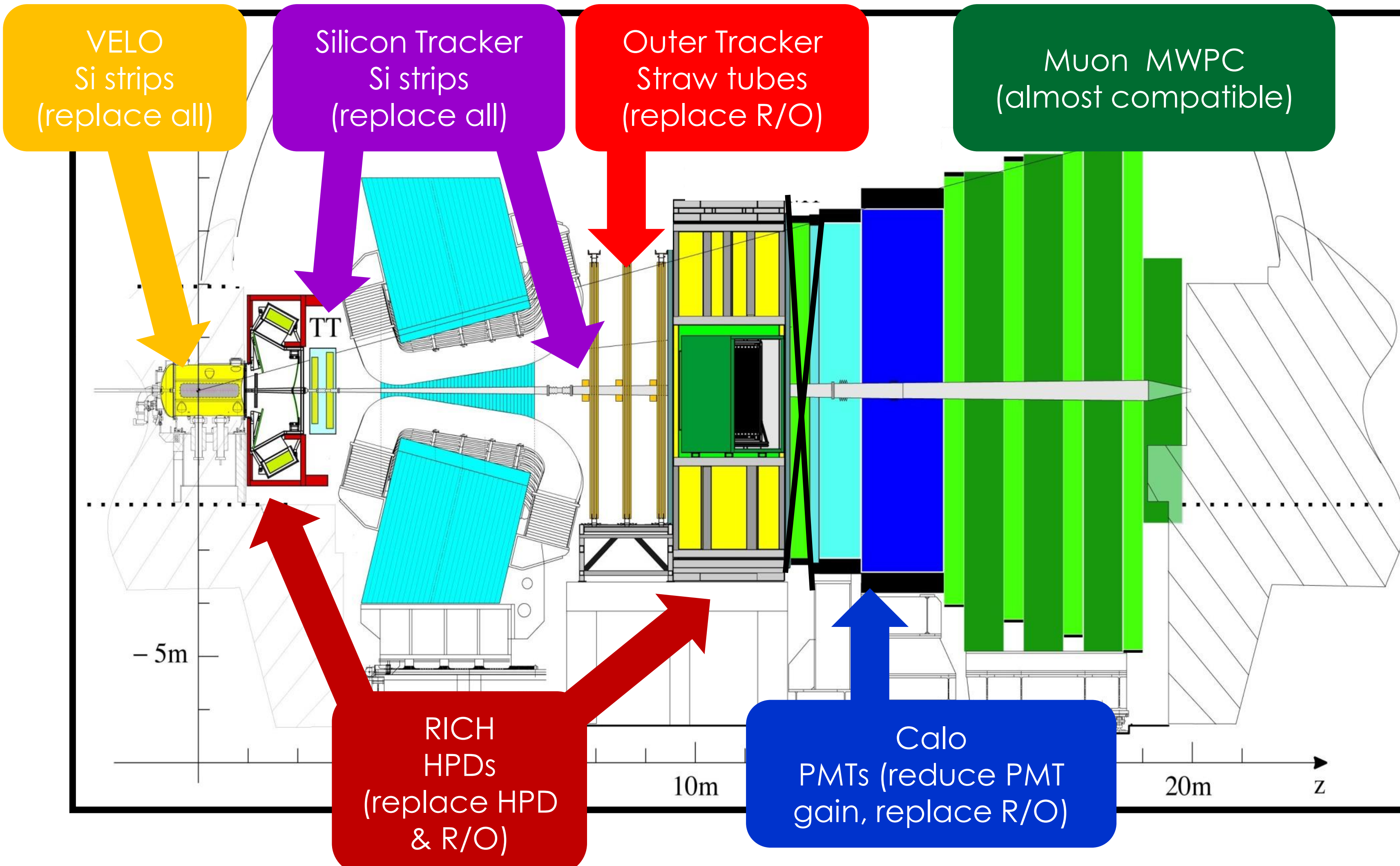
- More interactions per x-ing
- Higher track multiplicities, more vertices, higher detector occupancy
- More ghosts (scary and dangerous in many ways…)
- Spill-over

We need to maintain

- High tracking efficiency (~ 90% for p > 5 GeV)
- High relative momentum resolution (~ 3.5×10^{-3})
- Ghost rate as low as possible (less than ~ 10 %)
- Single event processing time in HLT as short as possible (~ 25 ms)
- And do not add to the material budget…

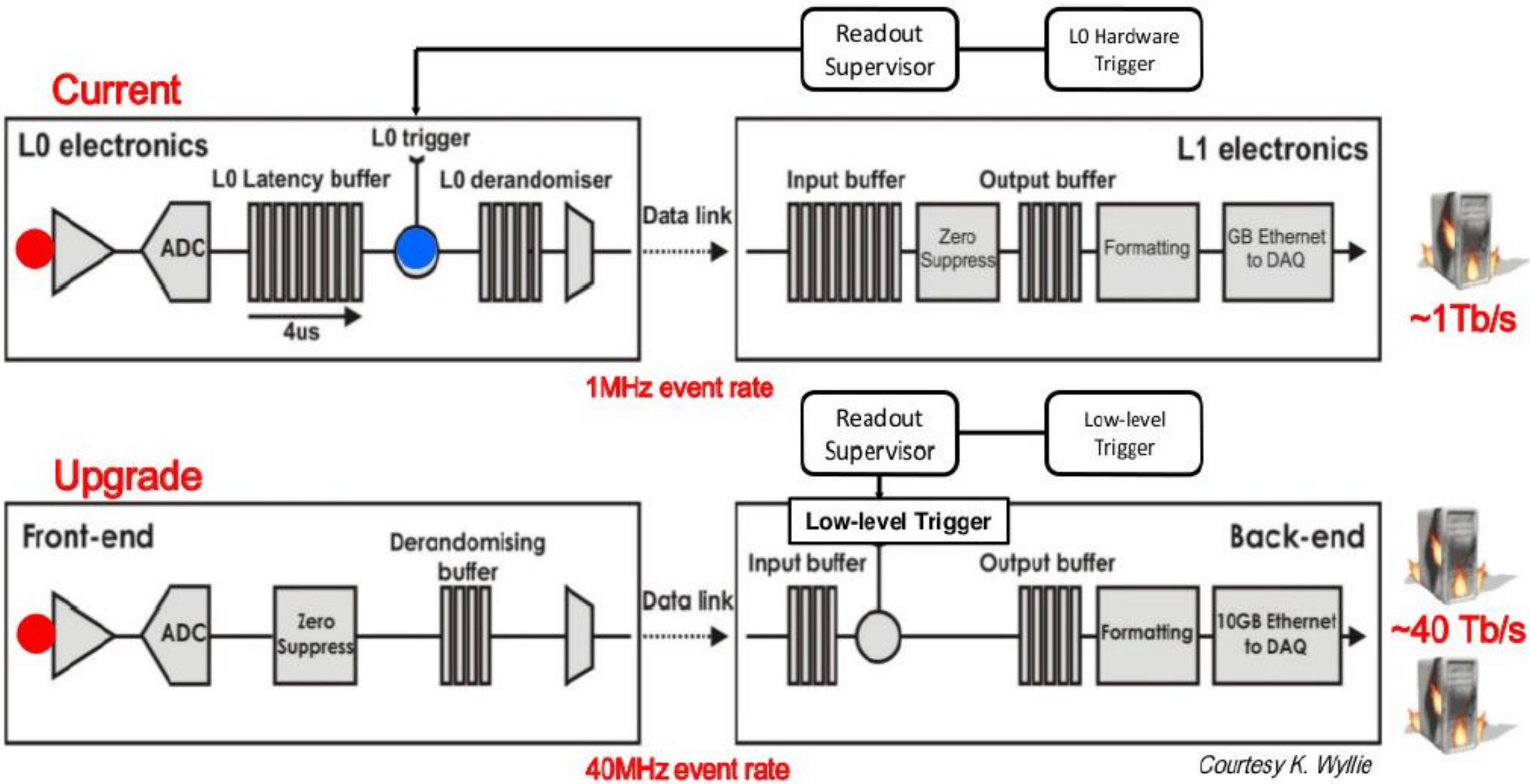
And in addition all of this using full detector information@40 MHz

What we must change to cope with the 40 MHz read-out

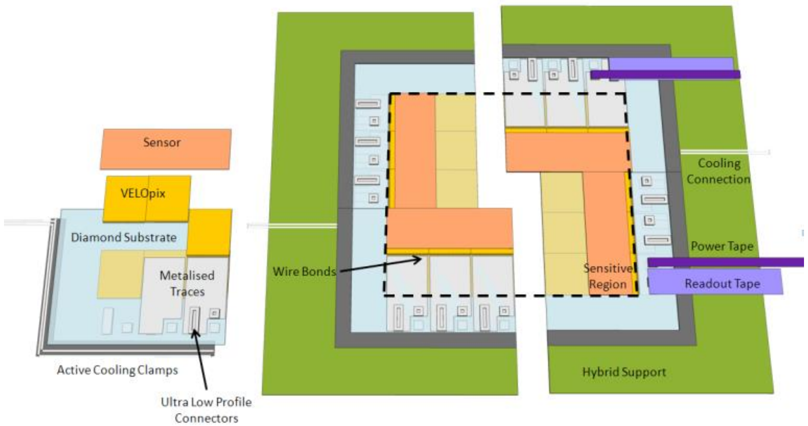


New front-end electronics

- ❑ Trigger-less
- ❑ Sends out data with the machine frequency
- ❑ On chip zero-suppression (SoC)



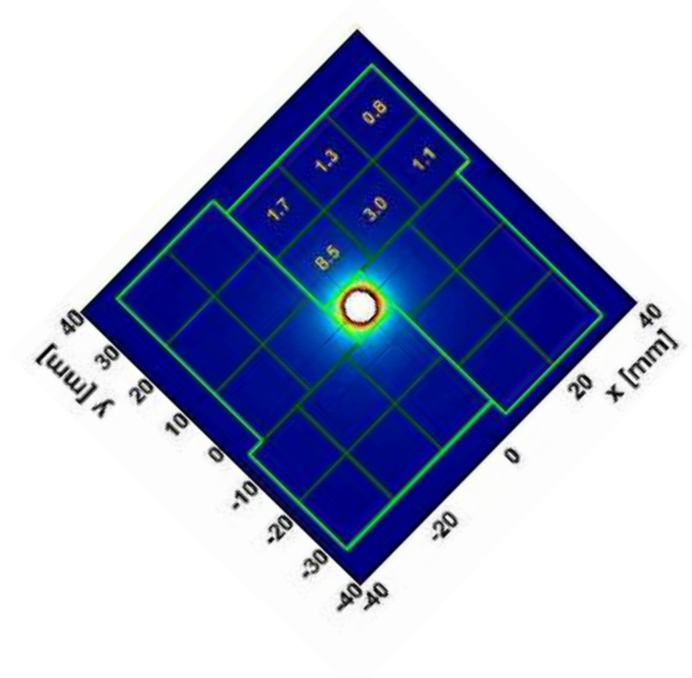
VErtex LOcator VELO2



- Current design: R-Φ geometry Si strip sensors with pitch between 38 – 100 μm
- To be replaced with pixel based device
  - ❑ low occupancy
  - ❑ much easier patter recognition
  - ❑ easier to control alignment
  - ❑ radiation hardness
  - ❑ extremely high data rate ~ **12 Gbit/s**
  - ❑ un-uniform data rates/radiation damage
  - ❑ **micro-channel** CO_2 cooling

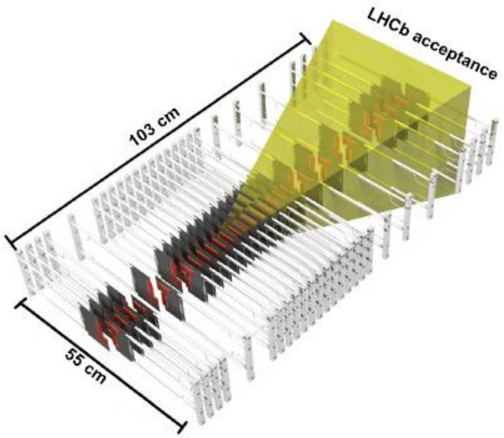
Read-out ASIC, VeloPix, based on TimePix/Medipix chip

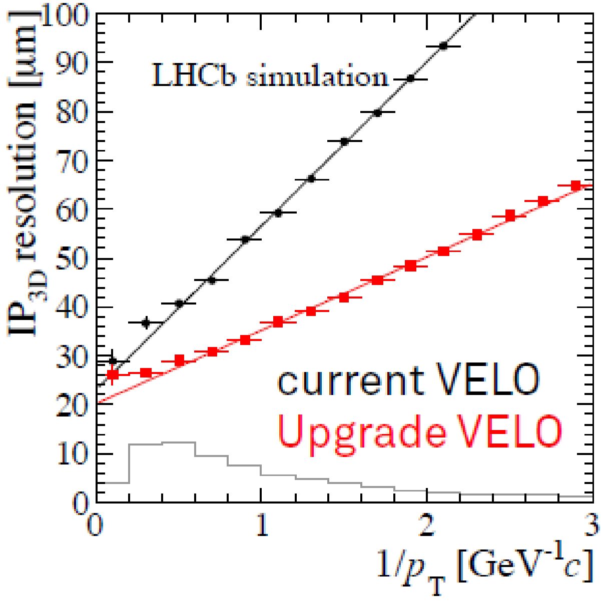
- ❑ 256x256 pixel matrix
- ❑ equal spatial resolution in both directions
- ❑ IBM 130 nm CMOS process
- ❑ great radiation hardness potential ~ 500 Mrad

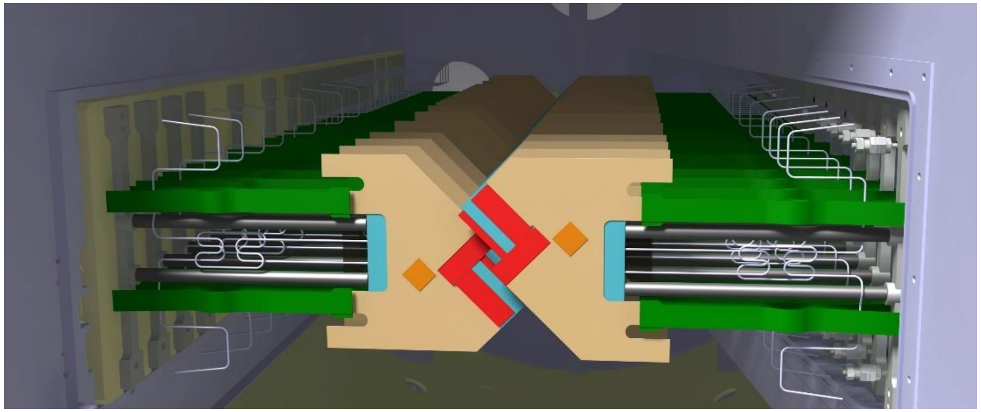


VErtex LOcator VELO2

- ❑ Predicted performance superior in almost any aspect w.r.t the current VELO
- ❑ **This is essential for physics performance of the upgraded spectrometer**
- ❑ TDR document is out!

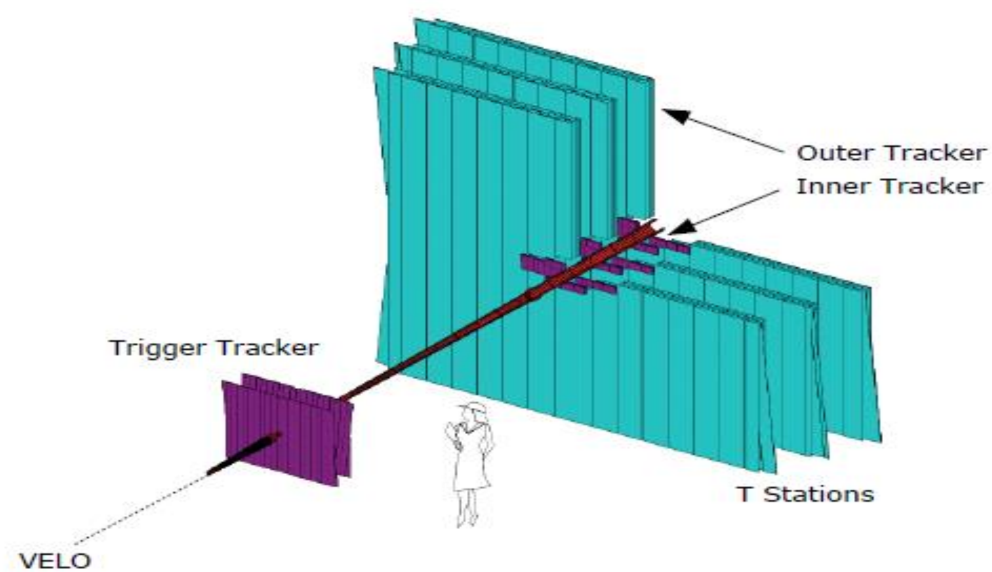


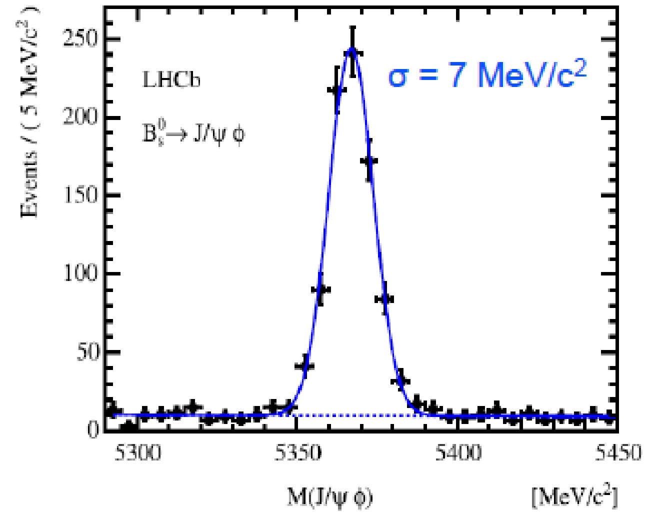




(VELO Upgrade: Technical Design Report, LHCb-TDR-13)

TT and T (IT + OT) trackers



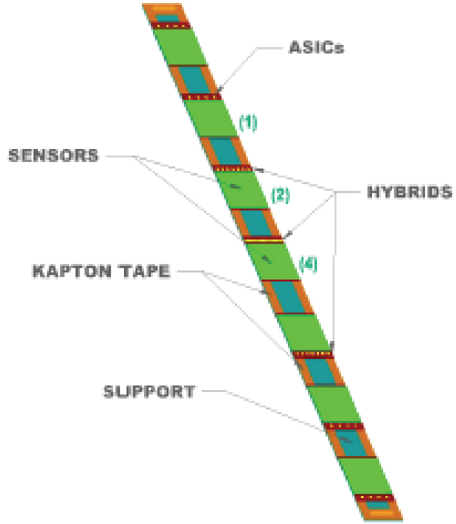


- TT and IT part of the T stations are Si strips based detectors
  - pitch 200 μm
  - long strips 11, 22 and 33 cm

- OT is a gaseous detector
  - very long (2.4 – 5 m)
  - and thin straws (5 mm)
  - occupancy limited to ~ 10 – 25 %

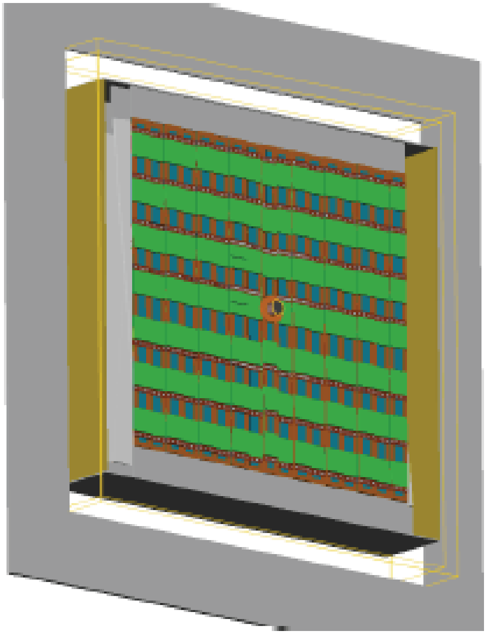
World's best b hadrons mass measurement!

TT tracker upgrade



Features after the upgrade

- ❑ high momentum track on-line selection (part of the trigger)
- ❑ reconstruct long lived particles decaying outside the VELO
- ❑ momentum estimate for slow particles
- ❑ improved matching with VELO segments



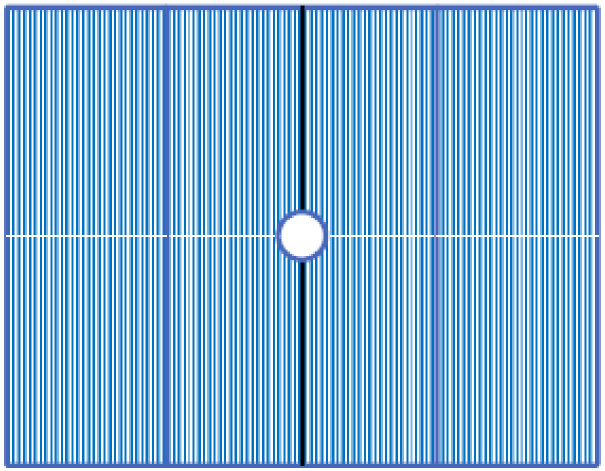
Upgrade technology

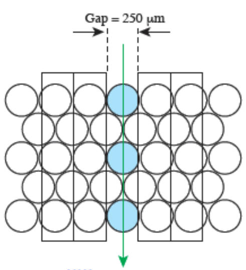
- ❑ 4 – 6 detector planes of Si strip detectors
- ❑ reduced silicon thickness 500 → 300 μm
- ❑ strip length 2.5 – 10 cm
- ❑ increase acceptance at low η
- ❑ **new read-out electronics with on-chip zero-suppression SALT chip**

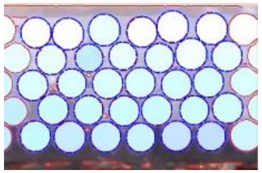
(Tracking Upgrade: Technical Design Report, **LHCb-TDR-15**)

T stations upgrade

Full Fibre Tracker







- Fiber Tracker
  - ❑ IT and OT removed completely and replaced with scintillating fibres
  - ❑ Six layers of 2 x 2.5 m long fibres with diameter of 250 μm
  - ❑ Readout with SiPM (Silicon Photo Multipliers)
  - ❑ SiPM cooled to -40 deg due to neutron radiation
  - ❑ Low mass
  - ❑ Hit efficiency better than 99%
  - ❑ Fast track reconstruction
  - ❑ Spatial resolution about 75 μm

(Tracking Upgrade: Technical Design Report, LHCb-TDR-15)

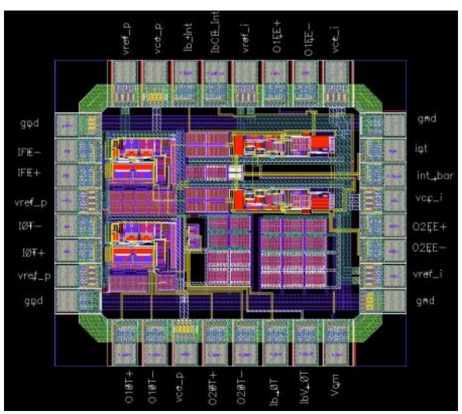
Particle ID and Calorimeters

MaPMTs by Hamamatsu

Both RICH1 and RICH2 remains

- ❑ new photo detectors (MaPMTs)
- ❑ square design to increase coverage
- ❑ 40 MHz read-out ASIC
- ❑ remove aerogel (cannot operate at expected luminosities)

ASIC prototype



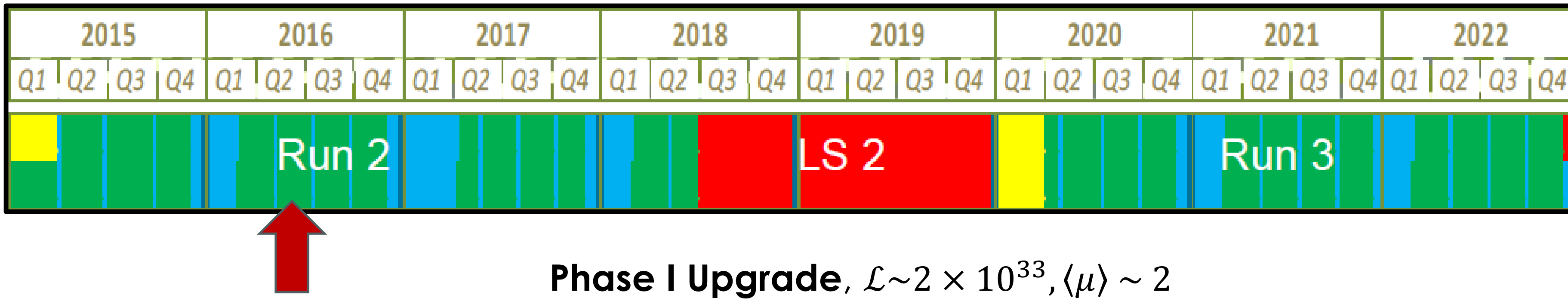
Calorimeters (ECAL and HCAL) are maintained

- ❑ PS/SPD removed (no L0!), e/γ separation provided by tracker (worked out in HLT)
- ❑ inner modules of the ECAL may be replaced due to radiation damage (LS3)
- ❑ front-end electronics adapted to 40 MHz read-out
- ❑ first prototype ready – under study
- ❑ lower gain

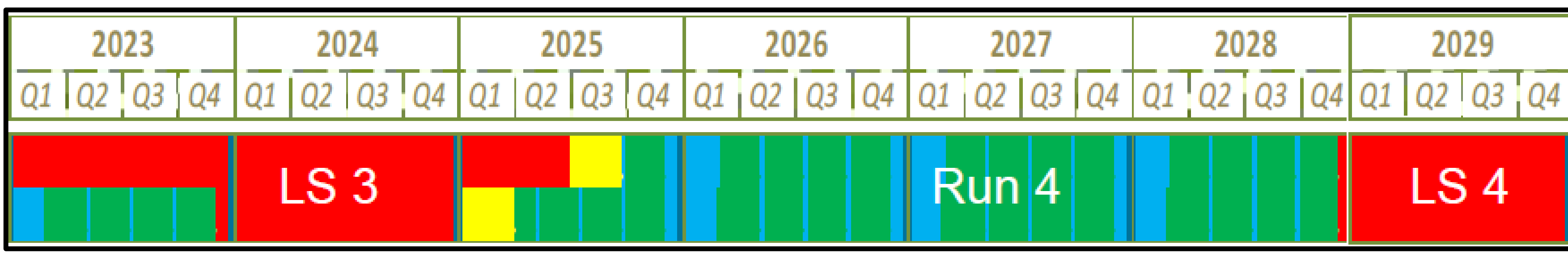
(**PID Upgrade: Technical Design Report**, **LHCb-TDR-14**)

Beyond year 2023

- ❑ Ok, some vocabulary first, i.e., phases, years and luminosities…

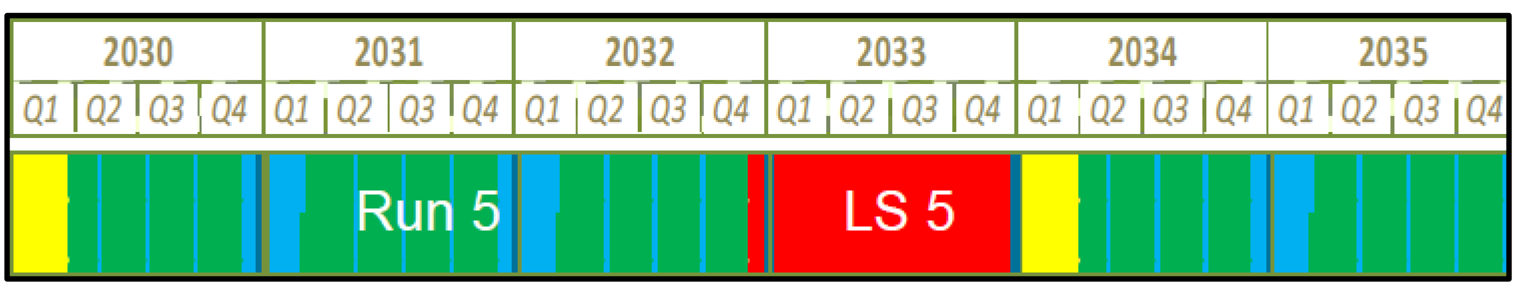


Phase I Upgrade, $\mathcal{L}{\sim}2\times10^{33}, \langle\mu\rangle\sim2$



Phase Ib Upgrade, $\mathcal{L}{\sim}2\times10^{33}, \langle\mu\rangle\sim2$

Phase II Upgrade, $\mathcal{L}{\sim}2\times10^{34}, \langle\mu\rangle\sim50$



Beyond year 2023

- A dedicated workshop regarding the long term plans after the RUN III
- **Theatre of Dreams** (see ToD web page)

THEATRE OF DREAMS

MANCHESTER 1824

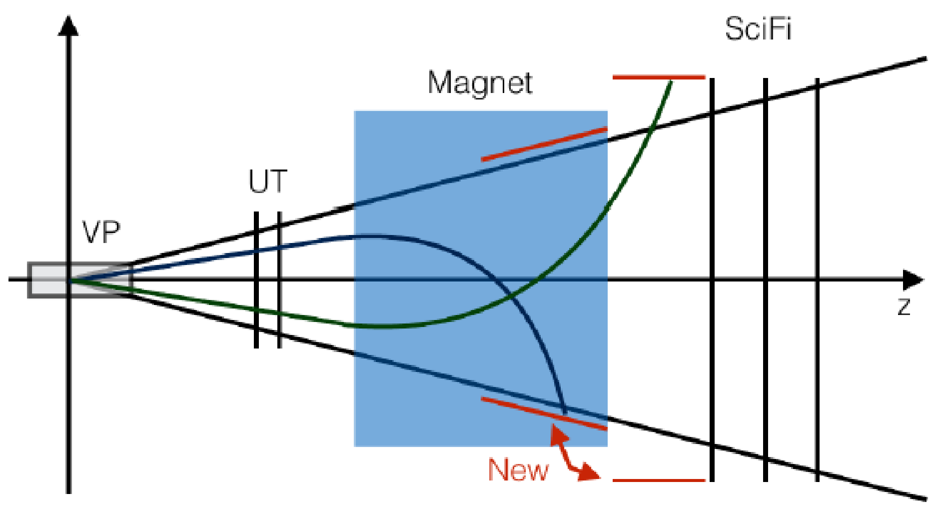
- **Main topics**
  - LHC evolution beyond 2020
  - Prospects for various experiments
  - LHCb upgrade Phase Ib/II
    - Vertex detector – 4D pixels (timing)
    - Tracking
    - Calorimetry and PID
    - Muons
    - Physics prospects

SuperVELO

Beyond year 2023

- By the end of RUN III LHCb would collect $\sim 30\ fb^{-1}$ of data
- After Phase Ib/II (RUN IV/RUN V) we could get $\sim 50/300\ fb^{-1}$

- **Phase Ib upgrade** – low cost improvement of the Phase I detector:
  - Improved tracking for low momentum particles – **new stations** installed inside magnet
  - **New muon stations** around magnet (using the yoke as shielding)
  - **HCAL** must be replaced
  - **ECAL** innermost part to be replaced
  - Some parts of the **SciFi** may be replaced due to radiation damage



Beyond year 2023

- **Phase II upgrade** – search for new technologies
- LHCb must be able to cope with instantaneous luminosities $\sim\mathbf{2} \times \mathbf{10^{34}}\ 1/s \cdot cm^2$

- **VELO**
  - Could re-use the Phase I design – must increase separation from the beam (from 5 to 11 mm) and increase the length
  - New design based on thinner sensors with timing information, new mechanics, new RF foil and smaller pixels
- **Tracker**
  - SciFi design in principle can be used also for Phase II, probably need to put silicon detector for the innermost region
  - Tracking software challenge – need careful tuning
- **Calorimeter**
  - The inner region must be replaced (rad damage)
  - New technologies & higher granularity
- **Muon**
  - Rate too high in inner region – can be reduced by replacing the HCAL by an iron shielding wall (~ 50% less hits)
  - Also seek out new technologies and increase the number of channels

Summary

- **Superb performance of the LHCb experiment during Run I**
- Large number of world's best physics results
- **More than 250 papers published**

- We did not make any considerable dents on the Standard Model
- Upgrade of the present detector essential for discovery potential of the LHCb – **origin of the CP violation and NP**
- Can collect ~ **50 fb^{-1}** of data between 2019 and 2028
- Base-line technologies of the upgrade have been chosen
- Respective TDRs have been/are being submitted to the LHCC

- **We also plan for time beyond the RUN III**