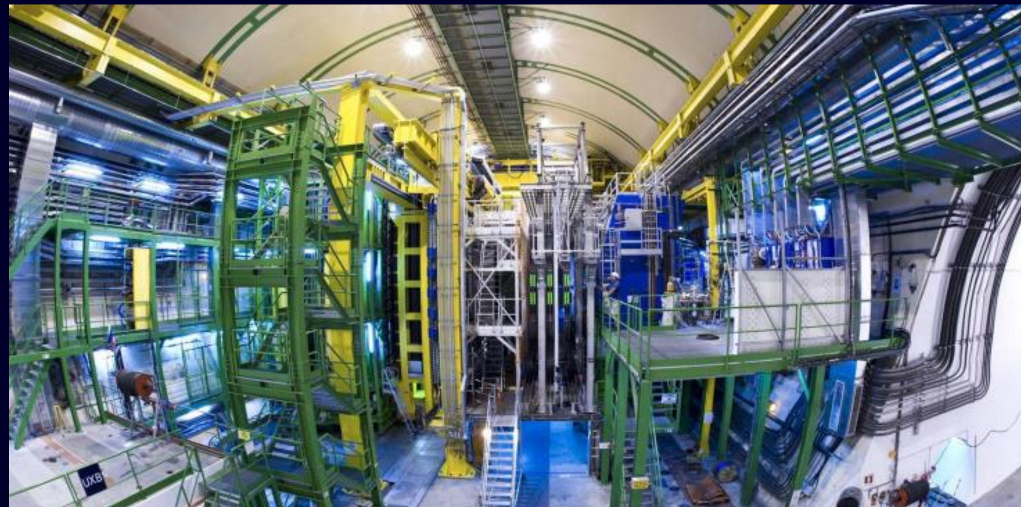


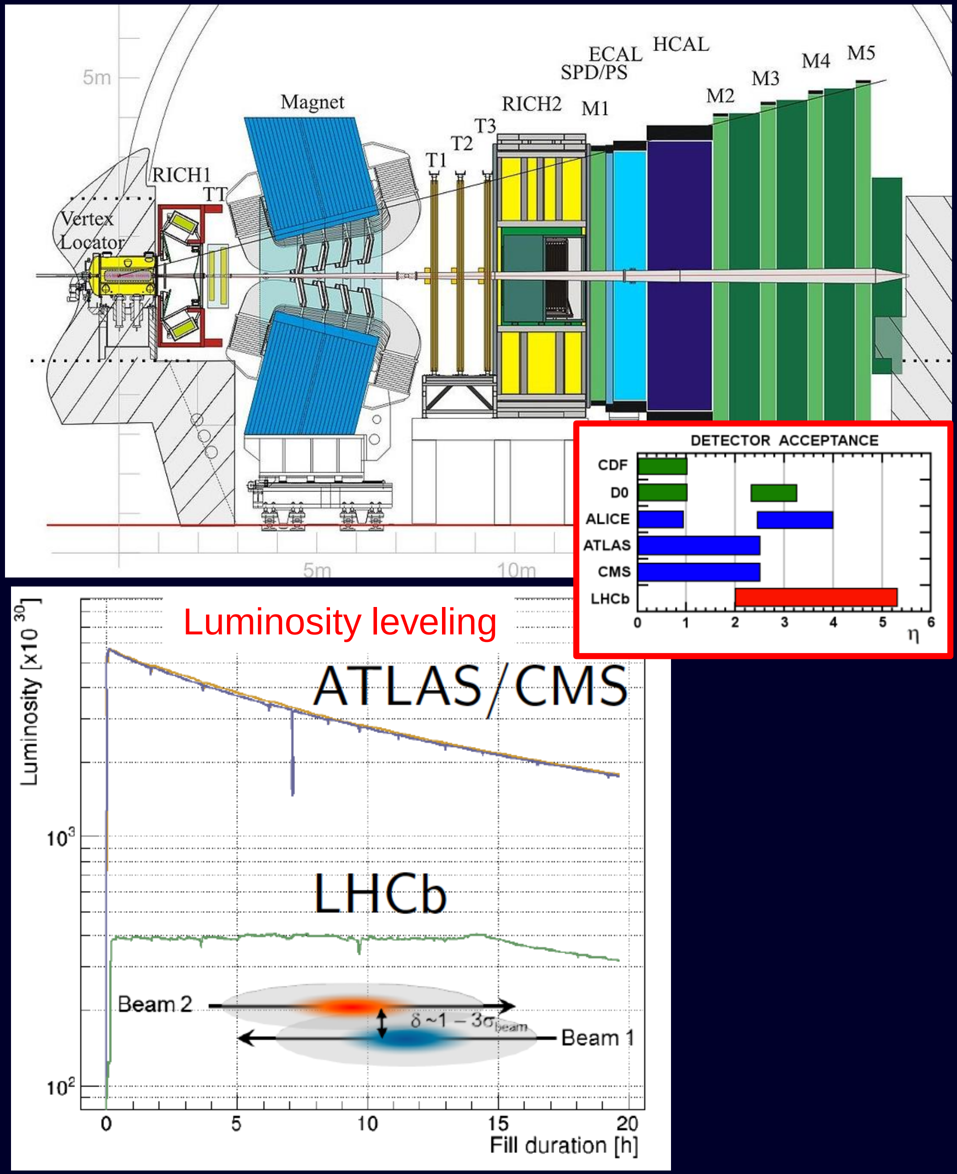
The LHCb Upgrade
Plans and Potential

Alessandro Cardini / INFN Cagliari, Italy

on behalf of the LHCb Collaboration

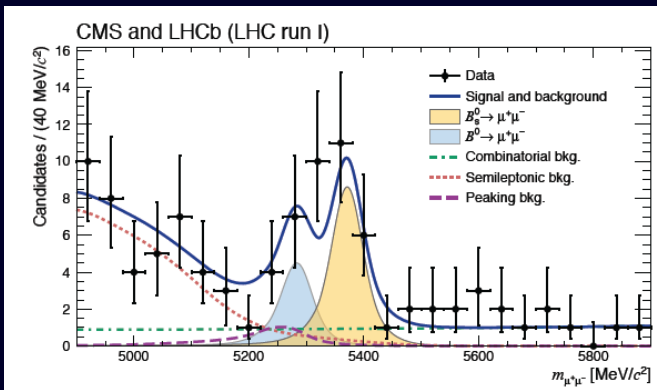
The LHCb “way” to Flavor Physics

- Our purposes
  - study rare *b*- and *c*- hadron decays
  - measure the CP-violation in *b* sector
  - Measure SM CKM parameters
  - Perform indirect searches for New Physics
  - Spectroscopy, charm physics, QCD, EW, exotica, …
- How
  - Use a forward spectrometer, exploiting the huge production of beauty-pairs at small angles
  - Operate at fixed instantaneous luminosity

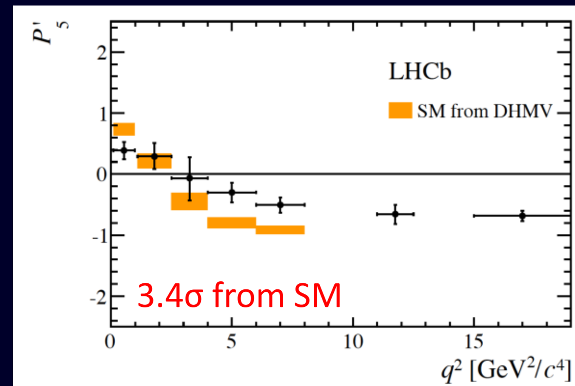


A few Physics Highlights from Run1

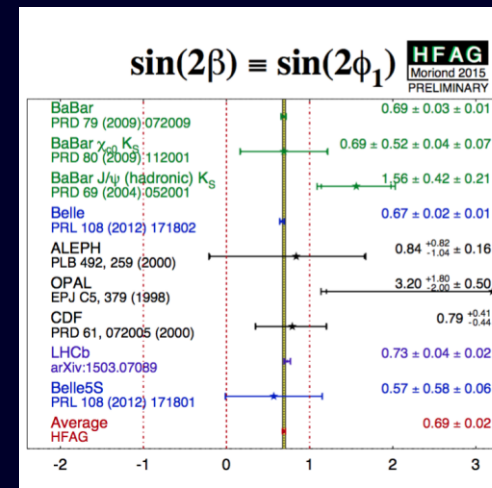
$B_s \rightarrow \mu^+\mu^-$, $B^0 \rightarrow \mu^+\mu^-$
Nature 522 (2016) 68



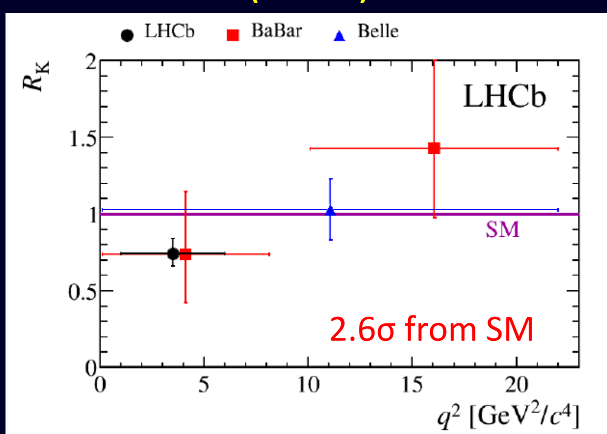
FCNC decay $B^0 \rightarrow K^{*0}\mu^+\mu^-$
JHEP 2 (2016) 104



CPV in $B^0 \rightarrow J/\psi\ K_s$
PRL 115 (2015) 3 031601



Lepton Universality R_k
PRL 113 (2014) 151601



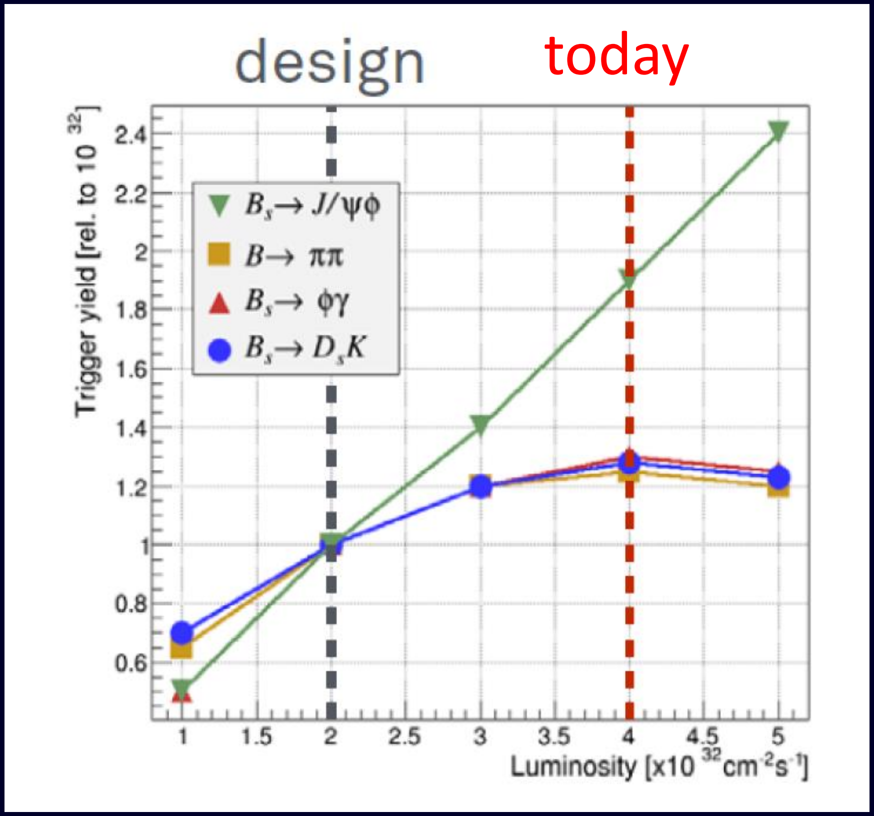
LHCb surpassed Run1 performance expectations!

- Huge physics output, much more than its “core” business
- Modes with neutrinos (thought to be impossible)
- Pentaquarks
- … and many others

Why upgrade?

CERN-LHCC-2011-001
CERN-LHCC-2012-007

- No evidence for New Physics (yet)
  - ➔ Look for tiny deviation from SM predictions
  - ➔ More (x10) data required
- The current 1 MHz level-0 trigger output is a severe limitation!
- If luminosity increases
  - – trigger yield of hadronic events saturates
  - – need harder cuts on P_t and E_t due to the 1 MHz bandwidth limit
    - ➔ no gain in statistics
    - ➔ limited to ~5 fb^{-1} in Run2
- Our upgrade luminosity does not depend on (now approved!) LHC upgrade, we only use a fraction of the available luminosity (i.e. what is used by ATLAS and CMS)



Upgrade HOWTO

CERN-LHCC-2011-001
CERN-LHCC-2012-007

- Remove the level-0 hardware trigger
  - Readout an event at every bunch crossing (40 MHz)
  - New front-end electronics (with on-chip zero suppression) and New DAQ system
- Use an efficient fully software trigger accessing complete event information, running at the bunch crossing rate, performing a full online event reconstruction
- Redesign several detectors to cope with increased occupancies
- Data taking conditions
  - Leveled L = $2{\cdot}10^{33}/cm^2/s$
  - 30 MHz collisions
  - 20-100 kHz to disk
  - ~5 fb^{-1} per year
- Challenges
  - High pile-up
  - Large occupancies
    - Difficult event reconstruction
    - More difficult PID
  - Huge Data Rate
  - Radiation damage

LHC era → HL-LHC era

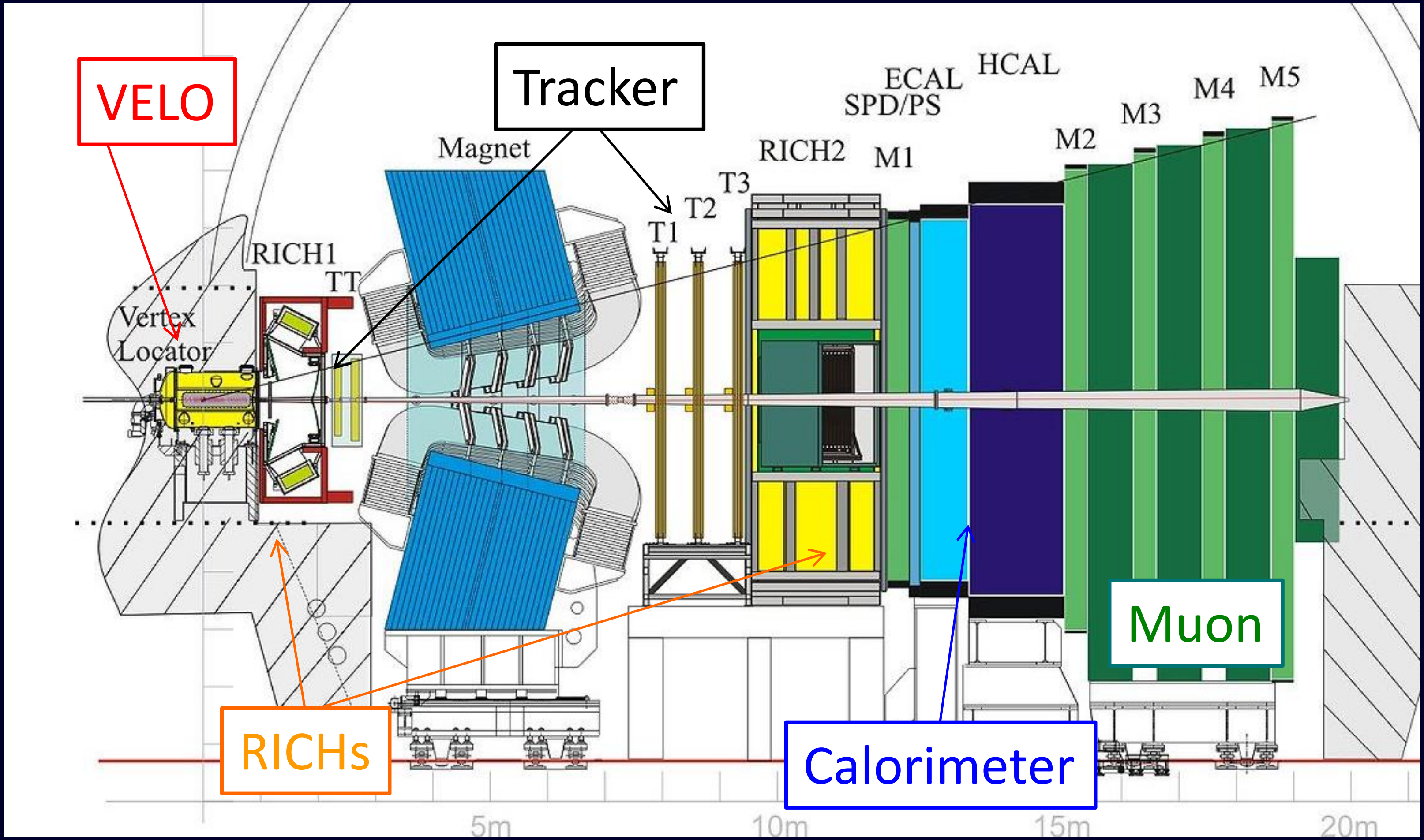
Run (years)	Run 1 (2010-2012)	Run 2 (2015-2018)	Run 3 (2021-2023)	Run 4 (2027-2029)
Integrated luminosity	3 fb^{-1}	8 fb^{-1}	25 fb^{-1}	50 fb^{-1}
Instantaneous luminosity	4×10^{32} $cm^{-2}s^{-1}$		2×10^{33} $cm^{-2}s^{-1}$	

Current LHCb → | LS2 LHCb Upgrade | Upgraded LHCb →

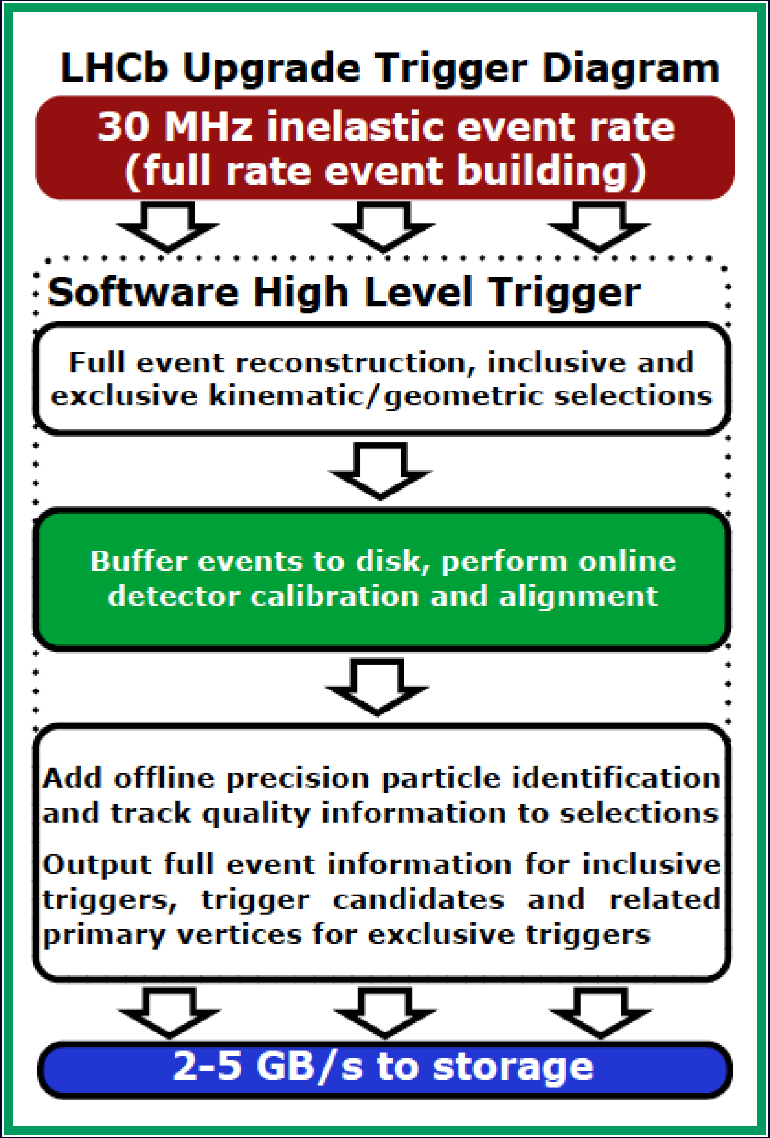
The LHCb Upgrade

CERN-LHCC-2011-001
CERN-LHCC-2012-007

Fully software trigger + new DAQ + …



The upgraded (software) trigger

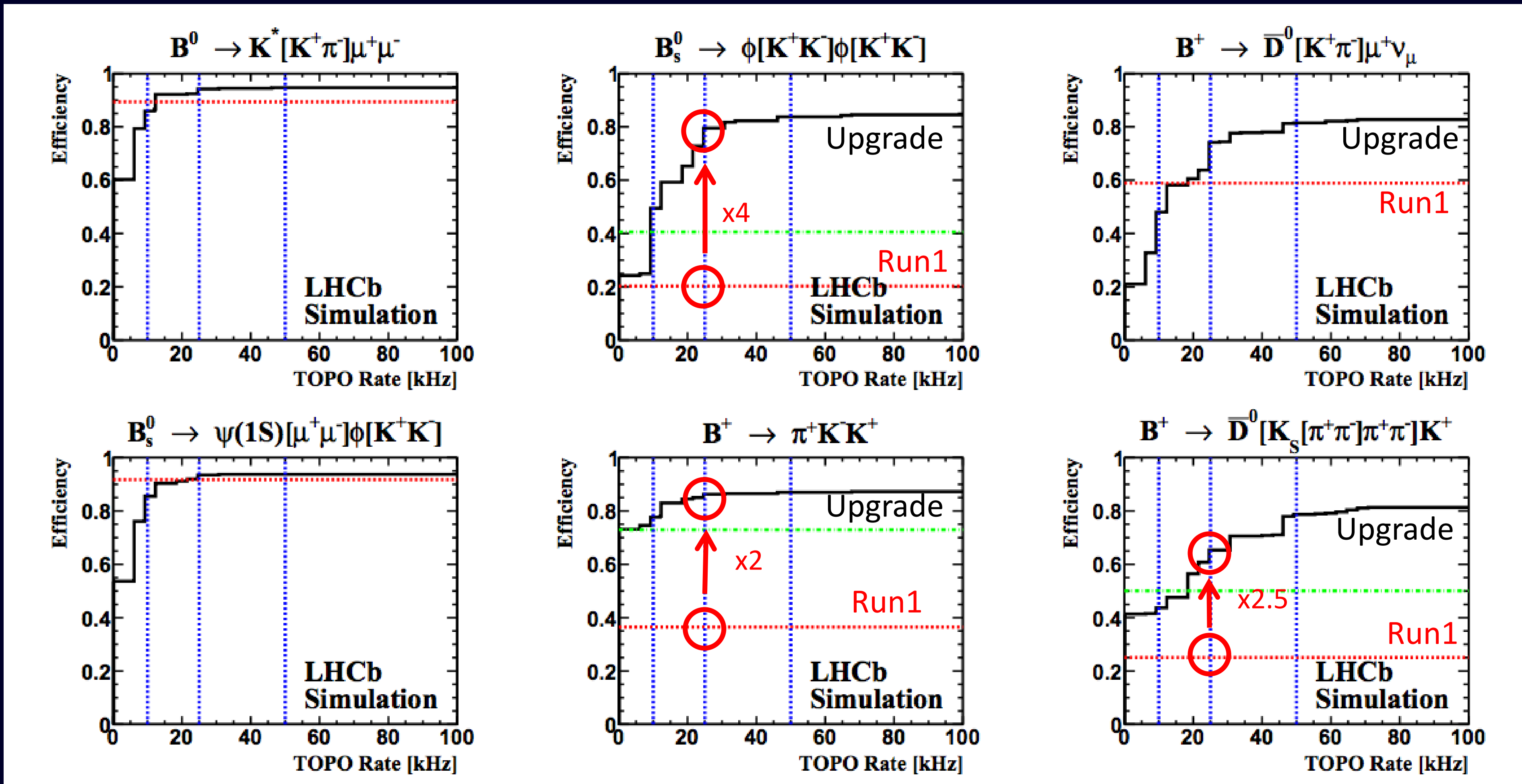


CERN-LHCC-2014-016; LHCb-TDR-016

- Trigger farm: 50k logical CPU cores
- Offline-like reconstruction tuned to available time constraints
- Mixture of exclusive and inclusive selection algorithms
- (Optional) Low Level Trigger (LLT) with output rate progressively increasing as trigger farms grows

Trigger Performance

CERN-LHCC-2014-016; LHCb-TDR-016



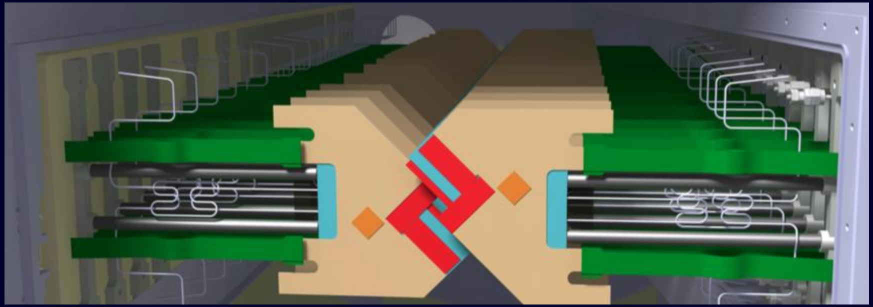
Very important improvement for hadronic channels!

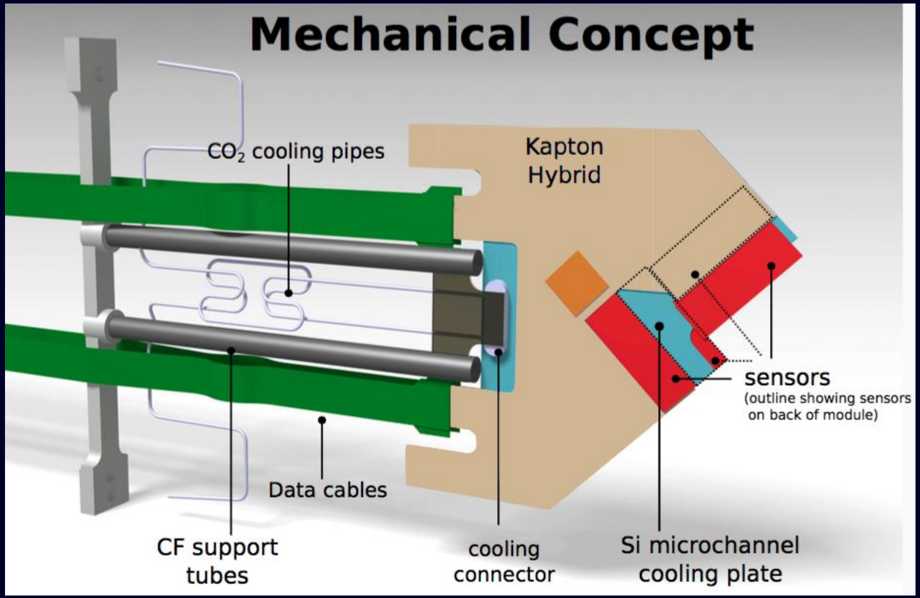
Upgraded VELO

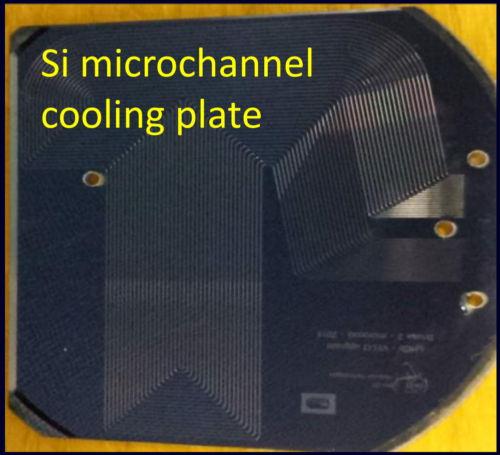
CERN-LHCC-2013-021; LHCb-TDR-013

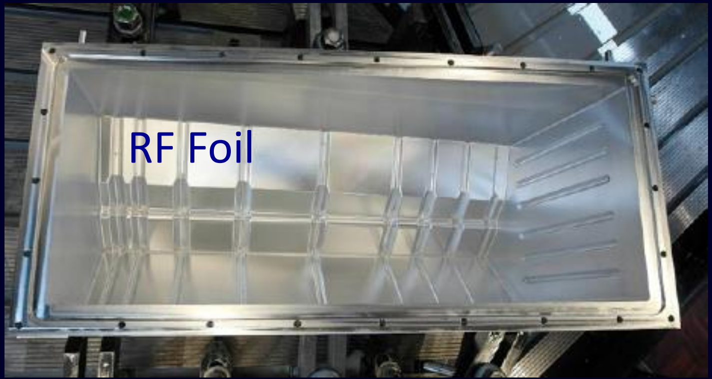
- Two moveable halves in secondary vacuum
- 26 stations, 1 module per side, 4 sensors per module
- Pixel (55x55 μm^2) silicon sensors
- Velopix ASIC (Timepix3 evolution, x8 faster)
- Detector at 5.1mm from beam (now 8.1mm)

- 40 MHz readout → up to 2.85 Tbit/s
- Micro-channel CO_2 cooling
- Non-uniform radiation damage, up to 8 10^{15} 1-MeV n_{eq}/cm^2 after 50 fb^{-1}
- 250 µm thick RF foil to separate VELO from LHC vacuum
- Very low material budget







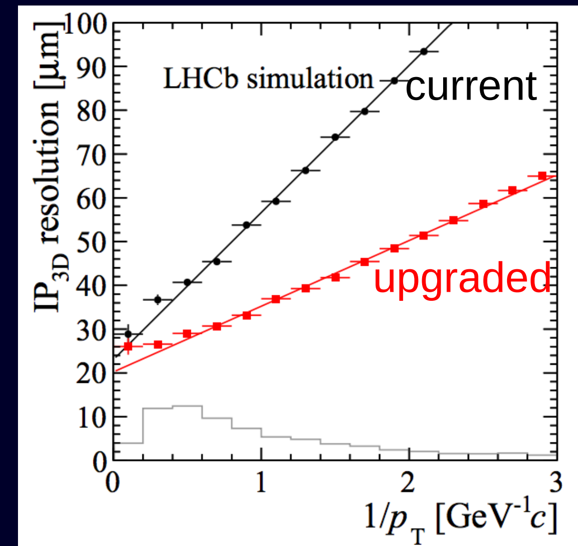


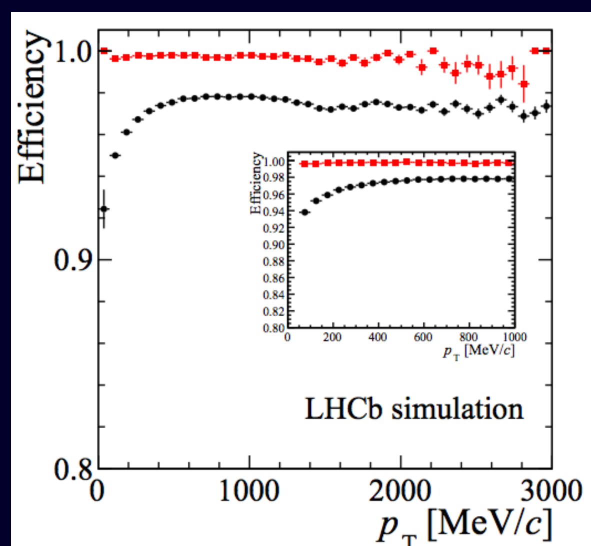
Upgraded VELO - Performance

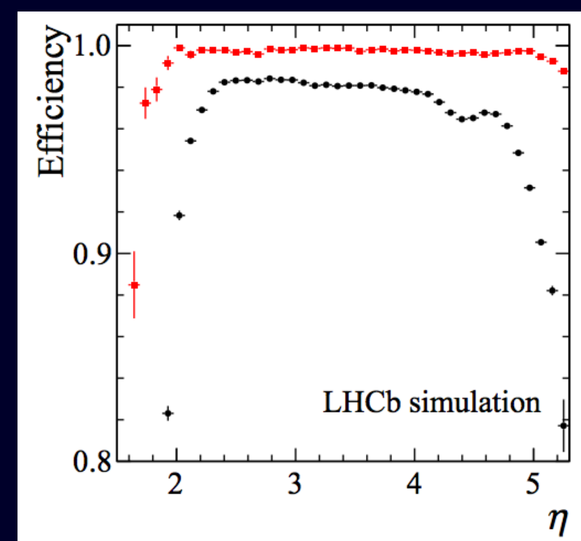
CERN-LHCC-2013-021; LHCb-TDR-013

Predicted performances at $2{\cdot}10^{33}/cm^2/s$ are superior in almost every aspect with respect to the current VELO operating at upgrade luminosity

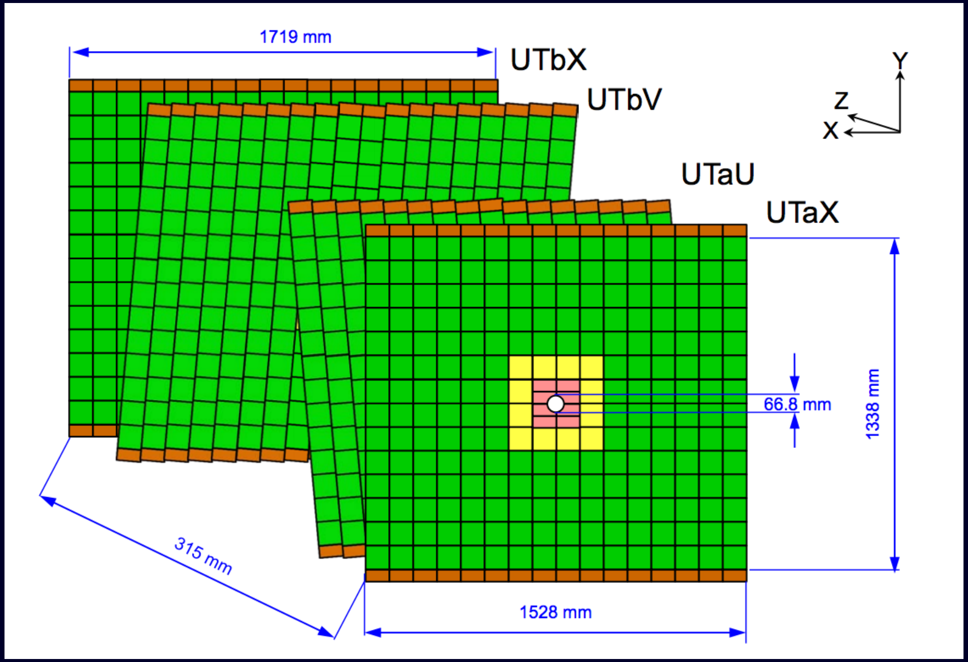
Decay time resolution [fs]	$B_s^0 \to \phi\phi$	$B^0 \to K^{*0}\mu^+\mu^-$
Current VELO	48.3 ± 0.5	41.2 ± 0.5
Upgraded VELO	43.4 ± 1.6	35.3 ± 0.3



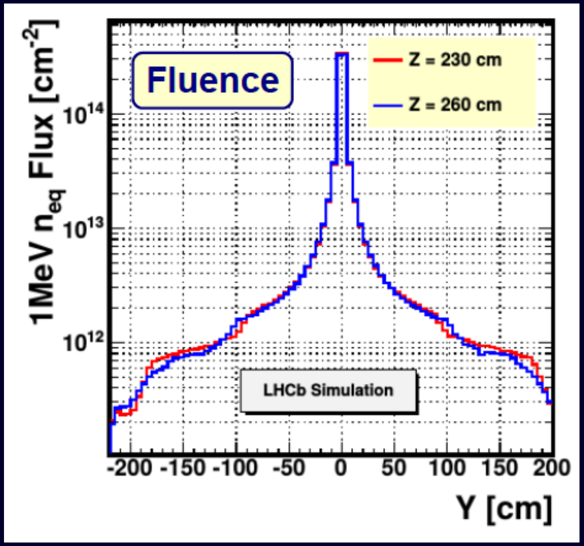


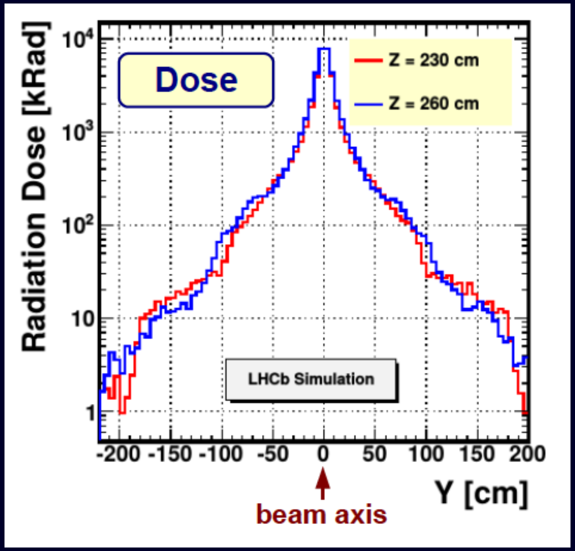


Upstream Tracker (UT)



CERN-LHCC-2014-001; LHCb-TDR-015



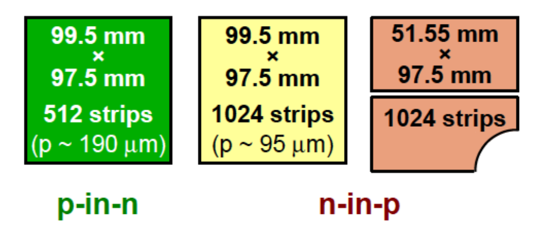


- 4 detection planes, stereo $\pm 5^{\circ}$
- Rad-hard silicon strip detector, 250 μm thick
- up to 5 10^{14} 1-MeV n_{eq}/cm^2 and up to 40 Mrad after 50 fb^{-1}

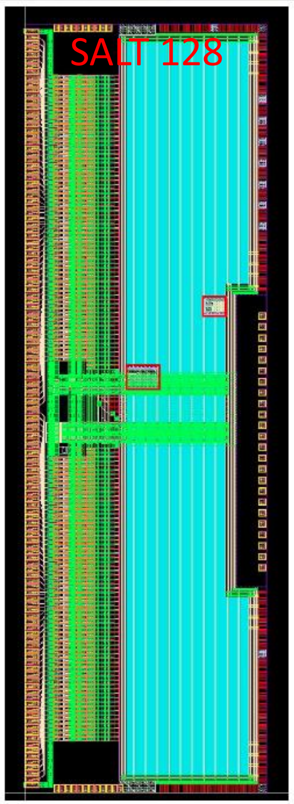
Upstream Tracker (UT)

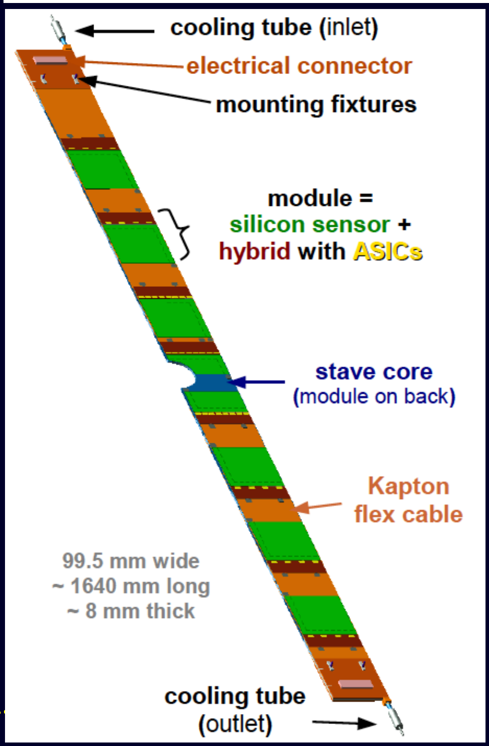
CERN-LHCC-2014-001; LHCb-TDR-015

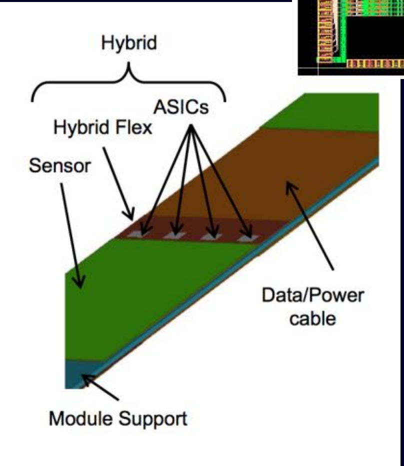
- To mitigate radiation damage, operate at -5C
- Sensor segmentation and technology chosen according to expected dose and occupancy:
  - n^+-in-p in inner region
  - p^+-in-n elsewhere to reduce cost
- Detector modules mounted on both side of a stave, providing:
  - Precise position of modules
  - Cooling of sensors and FEE
- 40 MHz R/O via SALT ASIC (https://cds.cern.ch/record/1604837/files/Poster-2013-283.pdf)



Property	Sensors A	Sensors B,(C,D)
Technology	p^+-in-n	n^+-in-p
Thickness	250 µm	250 µm
Physical dimensions	98 mm X 98 mm	98 mm X 98 (49) mm
Length of read-out strip	98 mm	98 (49) mm
Number of read-out strips	512	1024
Read-Out strip pitch	190 µm	95 µm
Sensor number (needed)	888	48 (16,16)





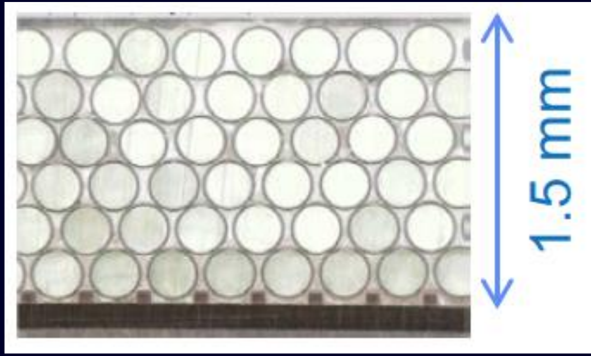


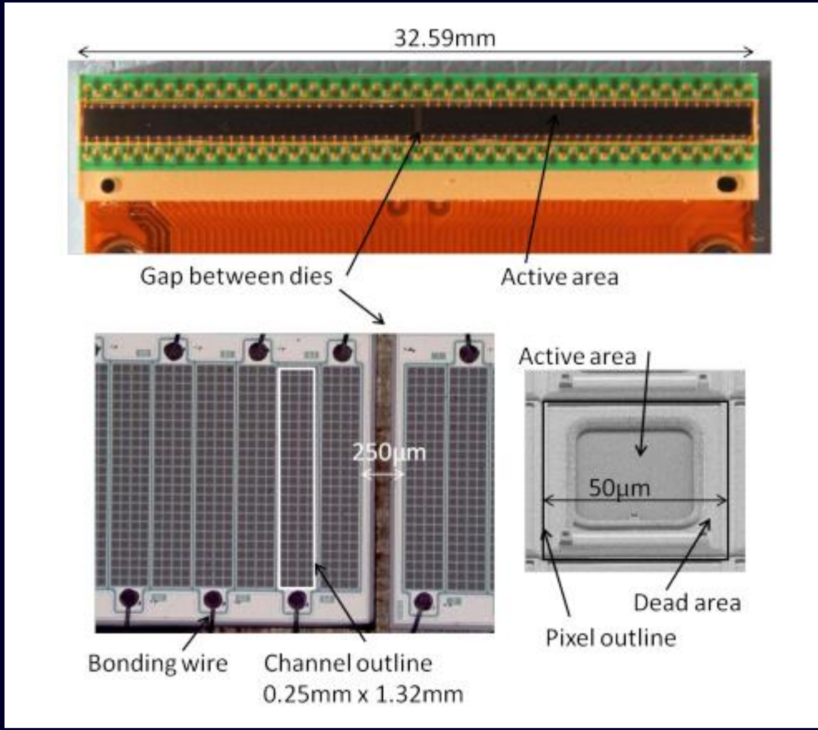
Fiber Tracker (FT) technology

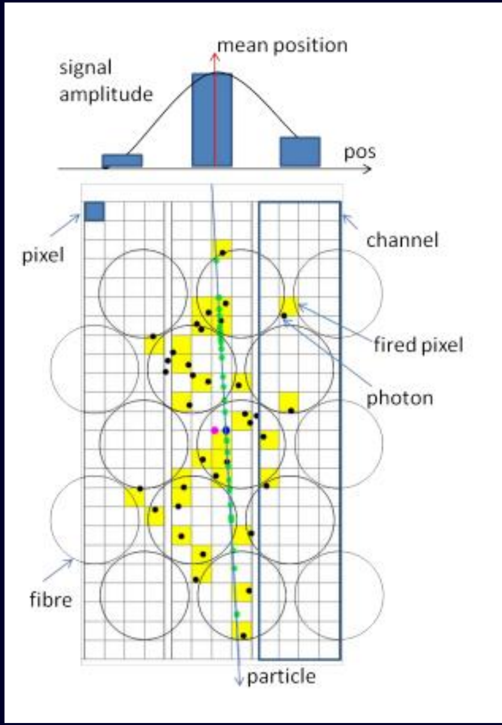
- Scintillating fiber mats
- 250 µm diameter scintillating fibres
- R/O via 2x64 channel SiPM array
  - ➔ 17 photo-electrons / m.i.p.

- R/O by 128 channels 40 MHz PACIFIC ASIC

CERN-LHCC-2014-001; LHCb-TDR-015



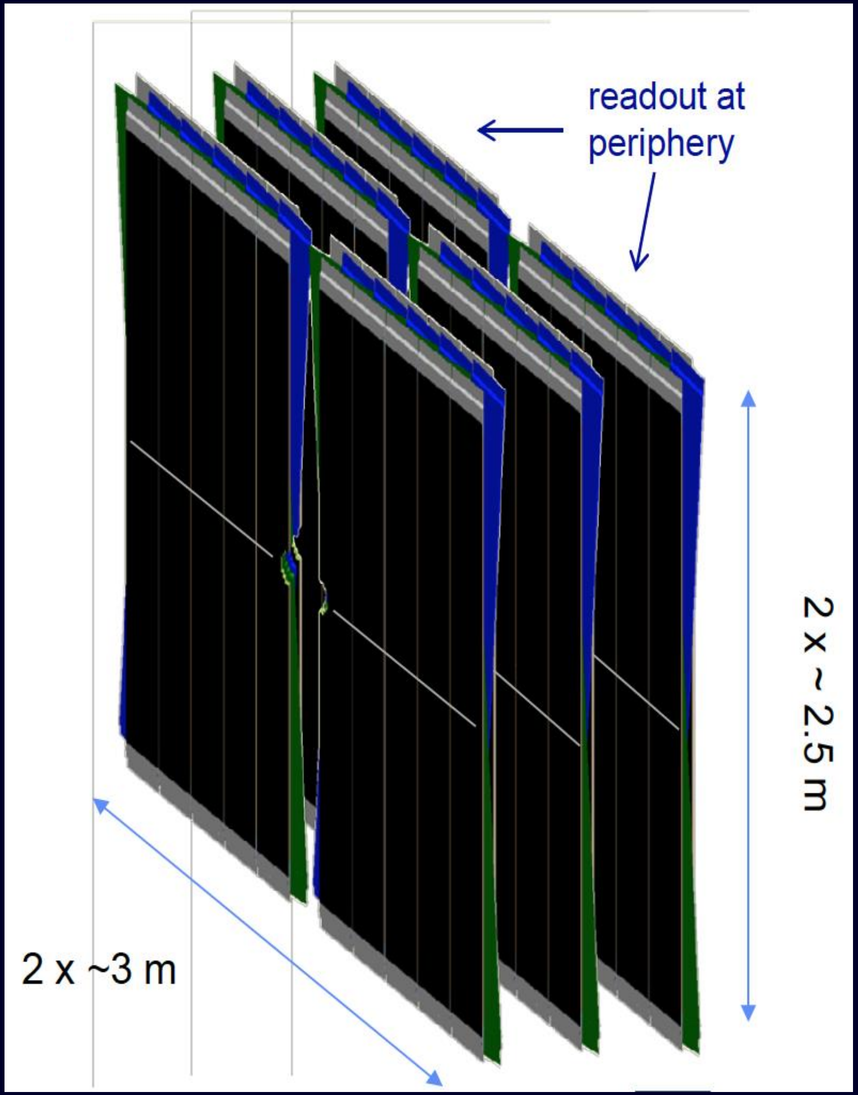




FT Design

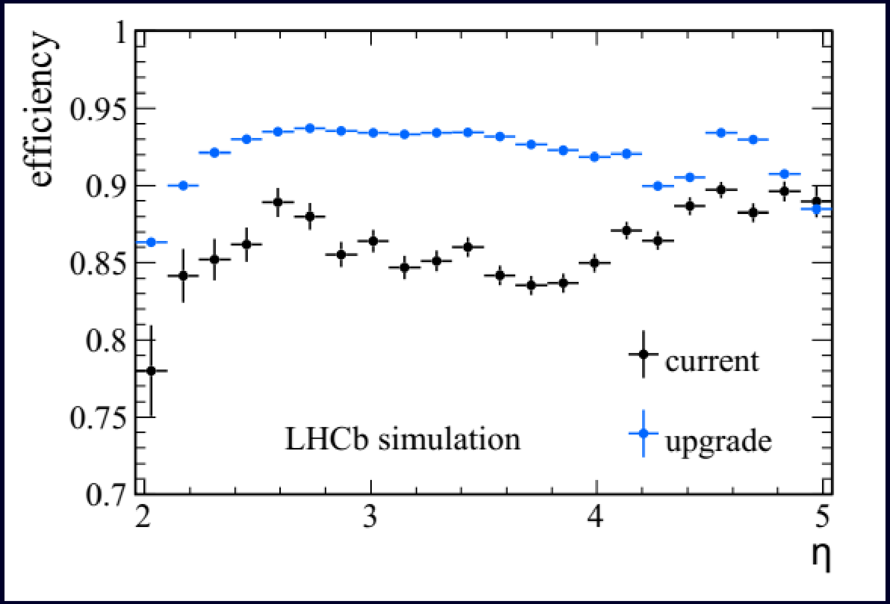
CERN-LHCC-2014-001; LHCb-TDR-015

- 12 detection layers in 3 stations
- Each station has *XUVX* layers (*U,V*: ±5°)
- Advantages
  - Single technology easy to operate
  - High granularity gives excellent x-position resolution
  - Uniform material budget
  - SiPM & R/O outside detector acceptance
- Challenges
  - Radiation damage to fiber → tested, ok
  - SiPM rad. damage → operate @ -40° C and shielding with Polyethylene loaded with 5% boron
- Performance
  - Spatial resolution better than 70 μm
  - Single-hit efficiency > 99%

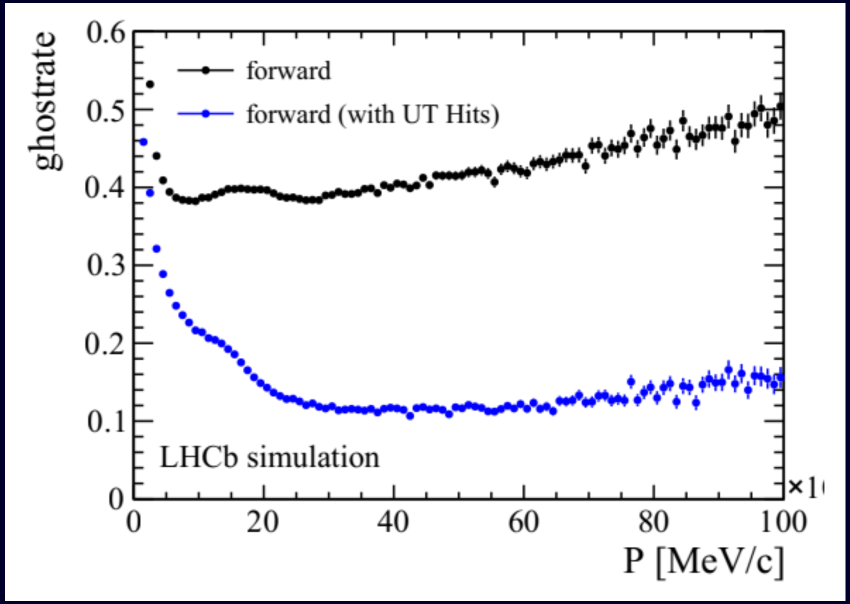


Overall Tracker Performance

Efficiency for $B_s \rightarrow \varphi\varphi$



Ghost rate (long tracks) for $B_s \rightarrow \varphi\varphi$



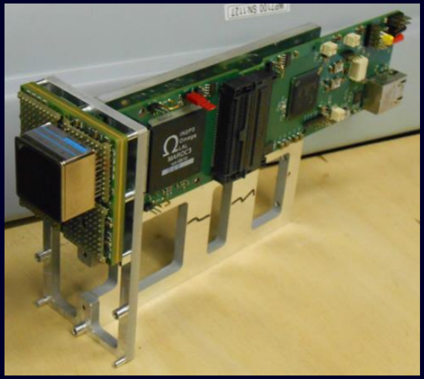
CERN-LHCC-2014-001; LHCb-TDR-015

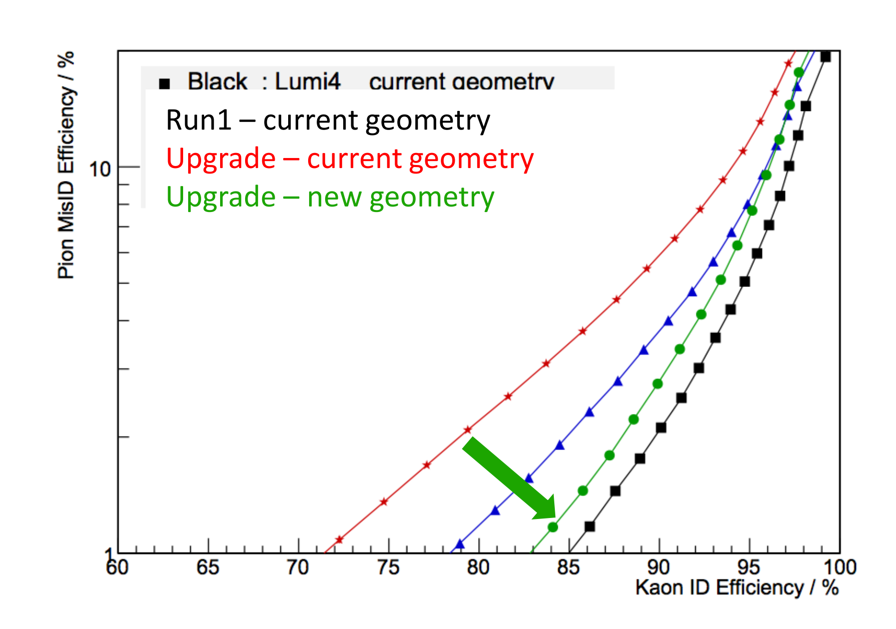
Fiber Tracker ➔ Improved tracking efficiency

Upstream Tracker ➔ Improved background rejection

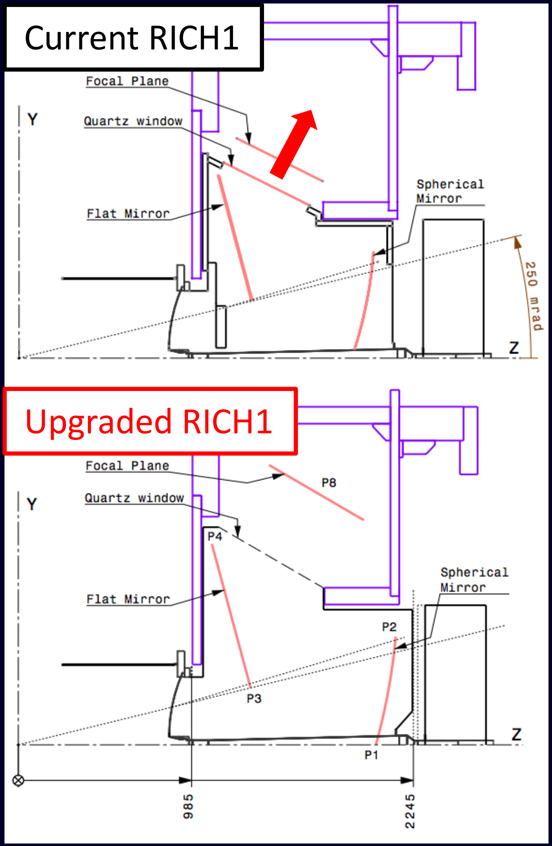
RICH Upgrade

- New R/O: 64 channel multi-anode PMTs
- 40 MHz CLARO front-end ASIC
- In addition, for RICH1 ➔ improve optics to spread out Cherenkov rings on the focal plane





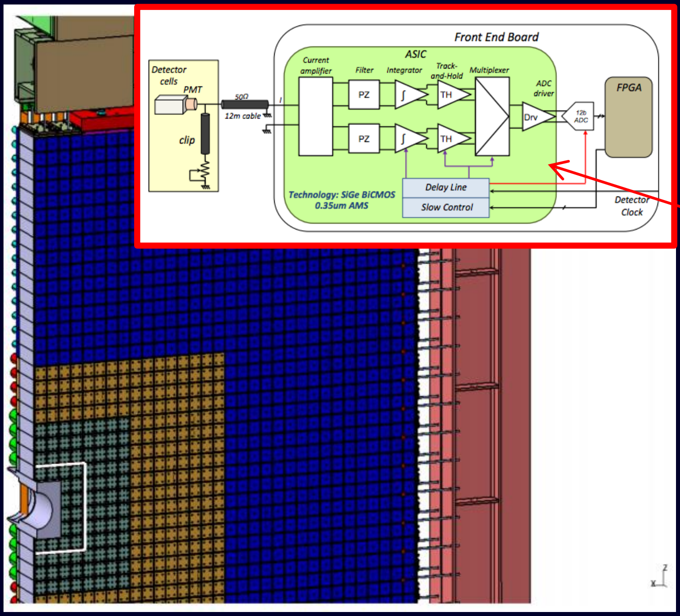
CERN-LHCC-2013-022; LHCb-TDR-014

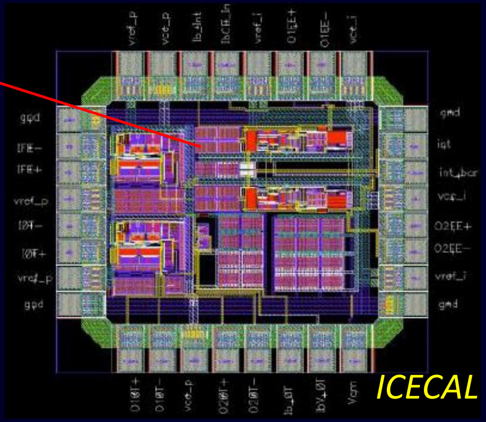


CALO/MUON Upgrades

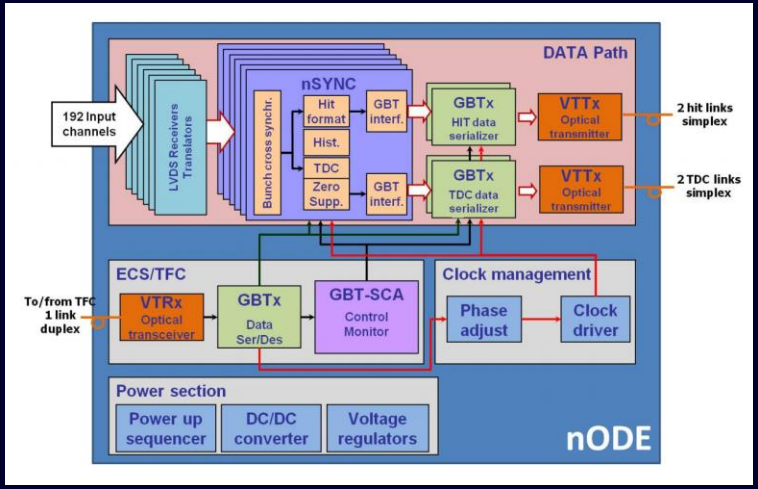
CERN-LHCC-2013-022
LHCb-TDR-014

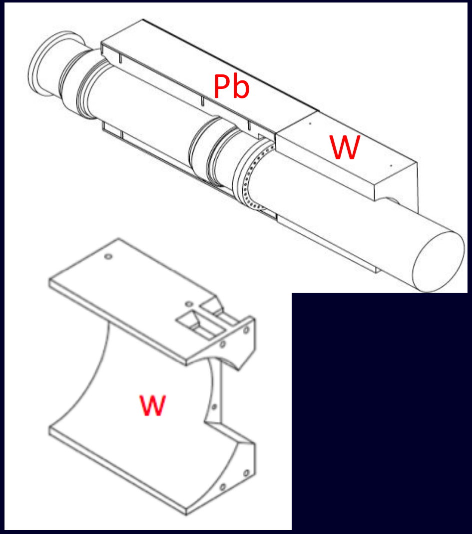
- CALORIMETER
  - Remove PS and SPD
  - Lower PMTs gain
  - New FEE (ICECAL)
  - ECAL (HCAL) expected to be fine up to 20fb^{-1} (50 fb^{-1})





- MUON
  - Remove M1
  - New Readout boards
  - Additional shielding





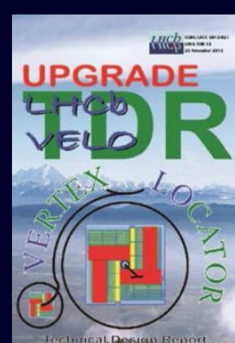
Physics Potential after the upgrade

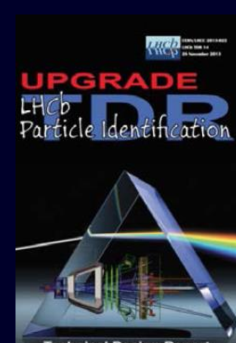
Type	Observable	LHCb 2018	**Upgrade** (50 fb^{-1})	Theory uncertainty
B_s^0 mixing	$2\beta_s(B_s^0 \to J/\psi\phi)$	0.025	0.008	$\sim$0.003
	$2\beta_s(B_s^0 \to J/\psi\, f_0(980))$	0.045	0.014	$\sim$0.01
	$a_{\rm sl}^s$	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguins	$2\beta_s^{\rm eff}(B_s^0 \to \phi\phi)$	0.17	0.03	0.02
	$2\beta_s^{\rm eff}(B_s^0 \to K^{*0}\overline{K}^{*0})$	0.13	0.02	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\rm eff}(B_s^0 \to \phi\gamma)$	0.09	0.02	$<$0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5 %	1 %	0.2 %
Electroweak penguins	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.025	0.008	0.02
	$s_0 A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	6 %	2 %	7 %
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.08	0.025	$\sim$0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	8 %	2.5 %	$\sim$10 %
Higgs penguins	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	$\sim$100 %	$\sim$35 %	$\sim$5 %
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	4°	0.9°	negligible
	$\gamma(B_s^0 \to D_s K)$	11°	2.0°	negligible
	$\beta(B^0 \to J/\psi K_S^0)$	0.6°	0.2°	negligible
Charm *CP* violation	A_Γ	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	0.65×10^{-3}	0.12×10^{-3}	–

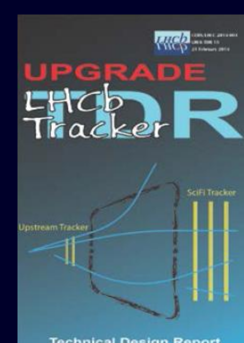
Eur. Phys. J. C (2013) 73:2373

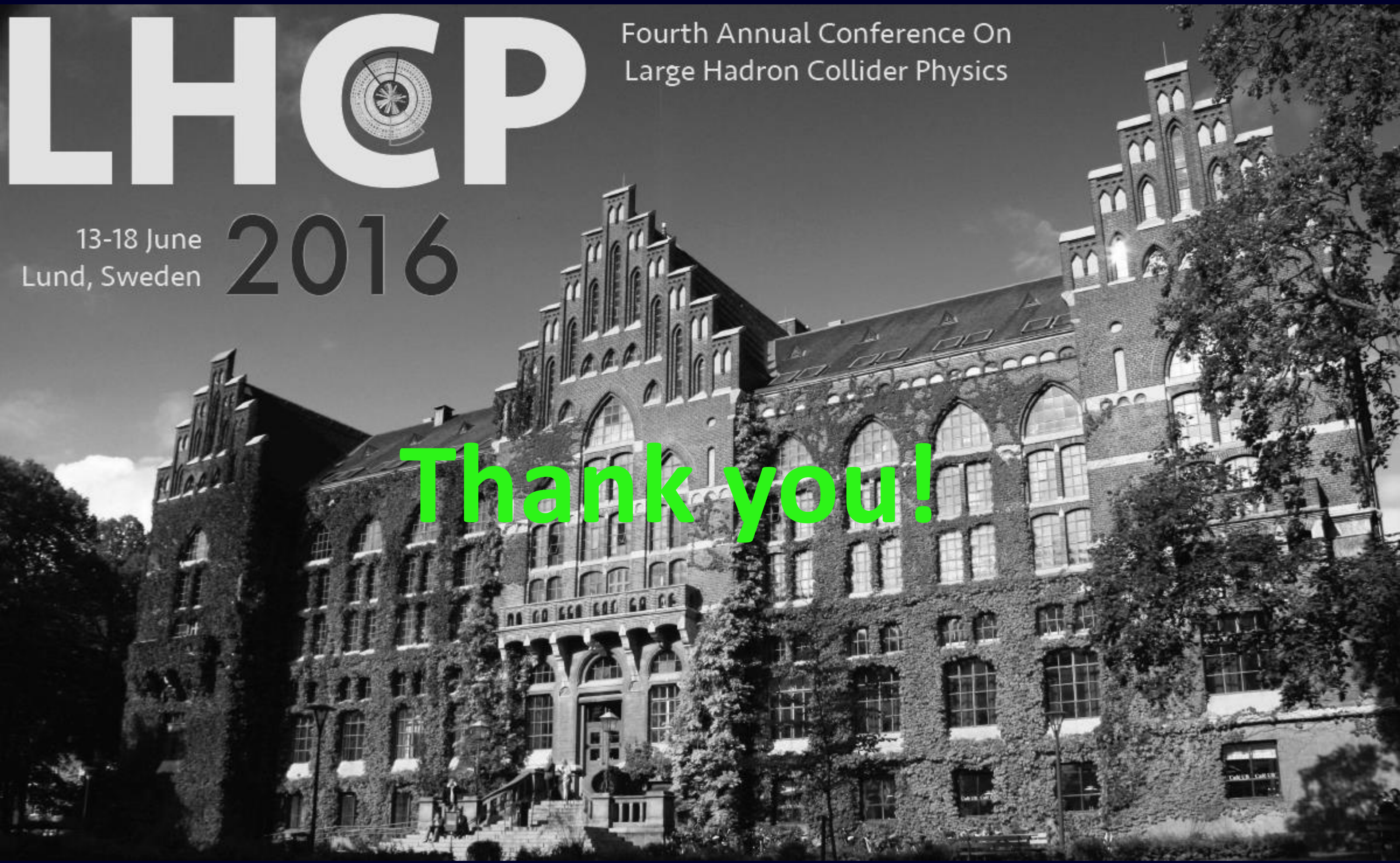
Summary

- Thanks to its excellent performance LHCb is producing world best measurements in the beauty and charm sector
- An already improved detector started taking data for Run2
- The Upgraded LHCb trigger-less scheme, guaranteeing event processing at 40 MHz, will allow to collect 5 fb^{-1} per year
- The upgrade will be performed in 2019-20 during LS2; data taking will start in 2021
- <u>The LHCb upgrade is mandatory to reach experimental precision of the order of theoretical uncertainties</u>
- The LHCb upgrade is fully approved and work ongoing





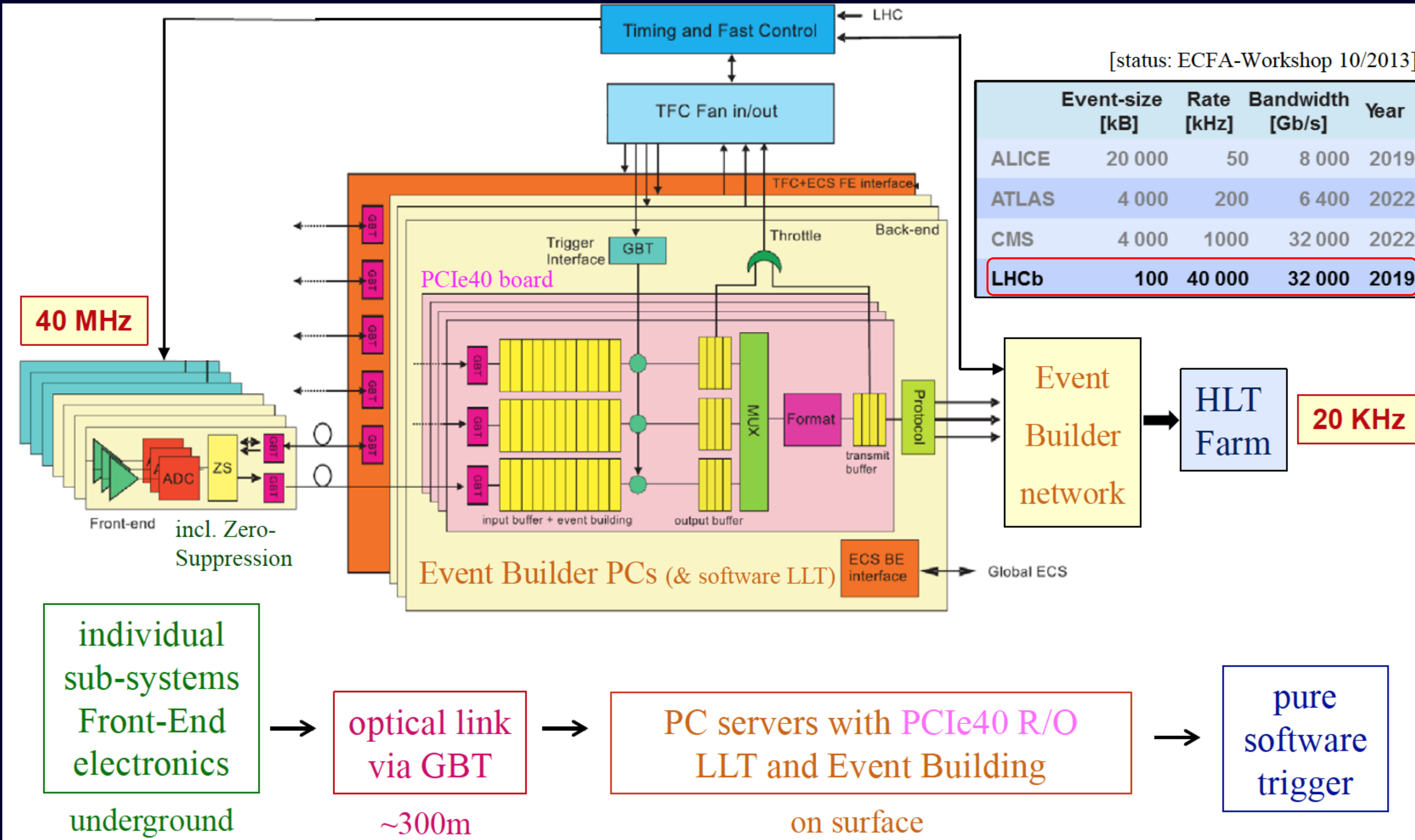



LHCP
Fourth Annual Conference On
Large Hadron Collider Physics
13-18 June
Lund, Sweden
2016
Thank you!

Backup slides

The 40 MHz R/O architecture

CERN-LHCC-2014-016; LHCb-TDR-016

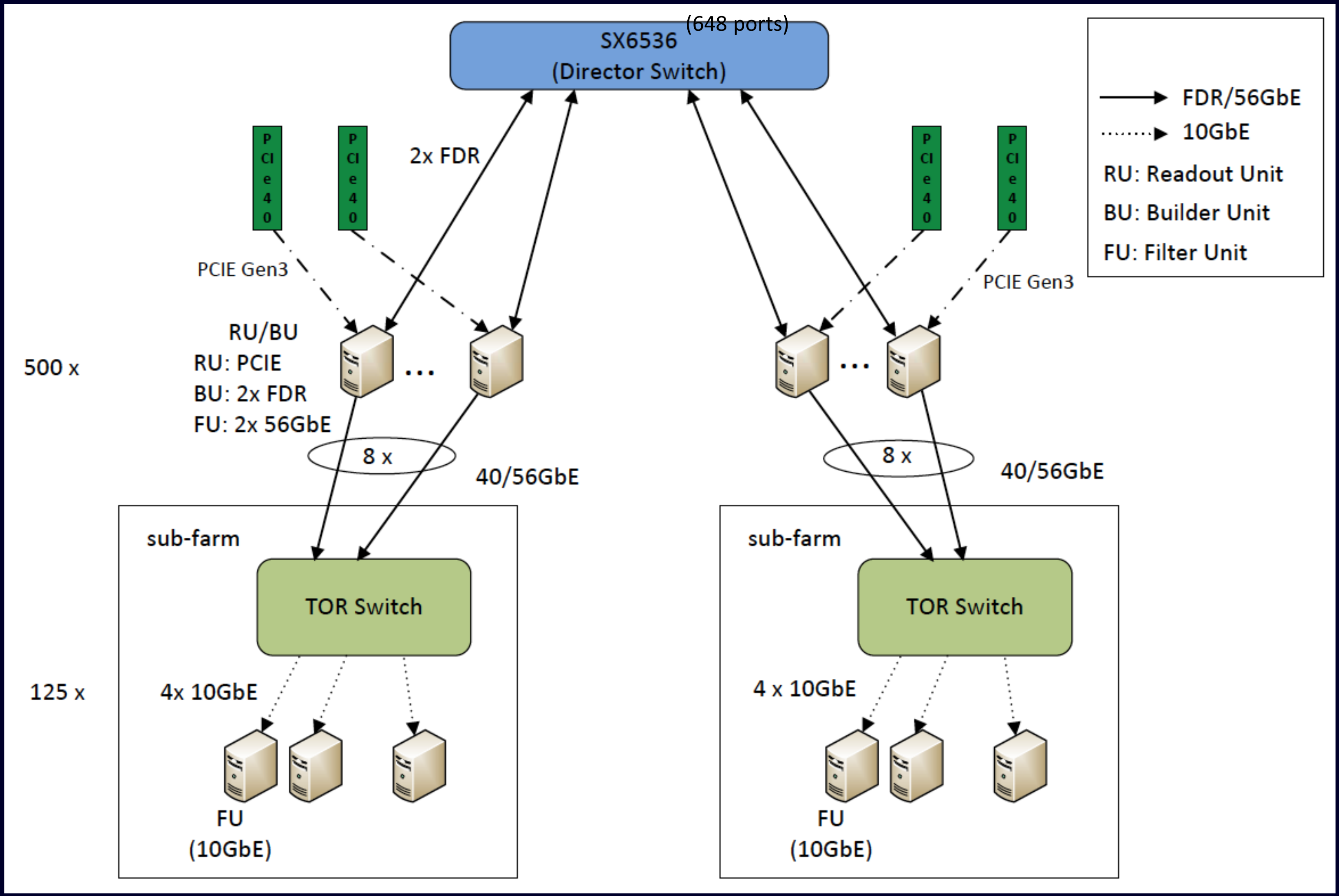


[status: ECFA-Workshop 10/2013]

	Event-size [kB]	Rate [kHz]	Bandwidth [Gb/s]	Year
ALICE	20 000	50	8 000	2019
ATLAS	4 000	200	6 400	2022
CMS	4 000	1000	32 000	2022
LHCb	**100**	**40 000**	**32 000**	**2019**

Upgraded data flow

CERN-LHCC-2014-016; LHCb-TDR-016



Bidirectional event-building scheme uses FDR Infiniband for event-building and Ethernet for event distribution

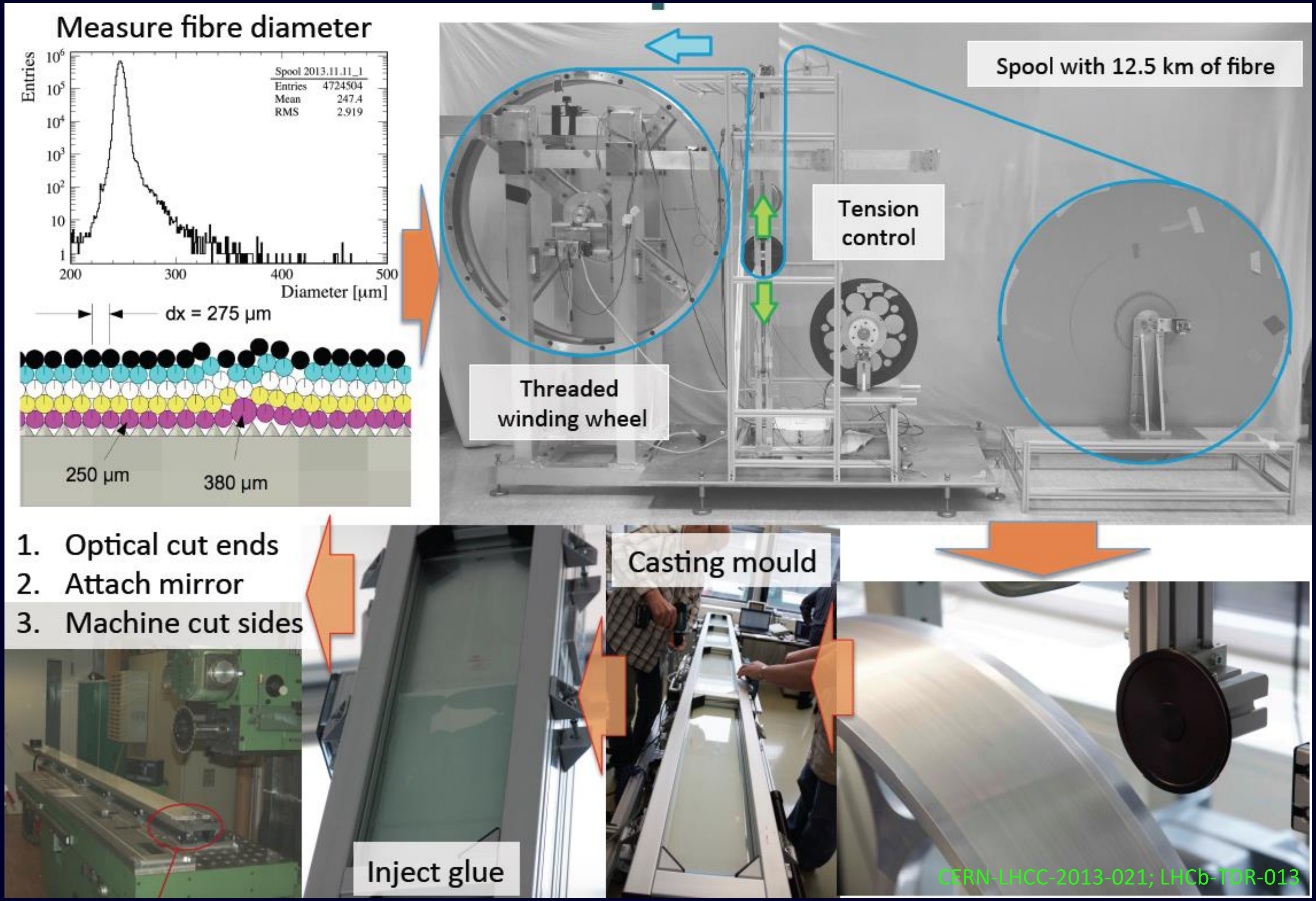
Tracker Upgrade

CERN-LHCC-2014-001; LHCb-TDR-015

- Requirements
  - Detection performance
    - Hit efficiency > 98%, Noise rate < 10% signal rate (in every region)
    - 100 μm spatial resolution in bending plane
  - Material budget: $X/X_0 < 1\%$ per detection plane
  - Readout at 40 MHz
  - Capable of sustain an integrated luminosity of 50 fb^{-1}

- How / Why
  - Replace TT with Upstream Tracker
    - Too high occupancies & too high radiation damage in current TT
  - Replace both IT and OT with Fiber Tracker
    - Occupancy too high in current OT and readout is limited to 1 MHz

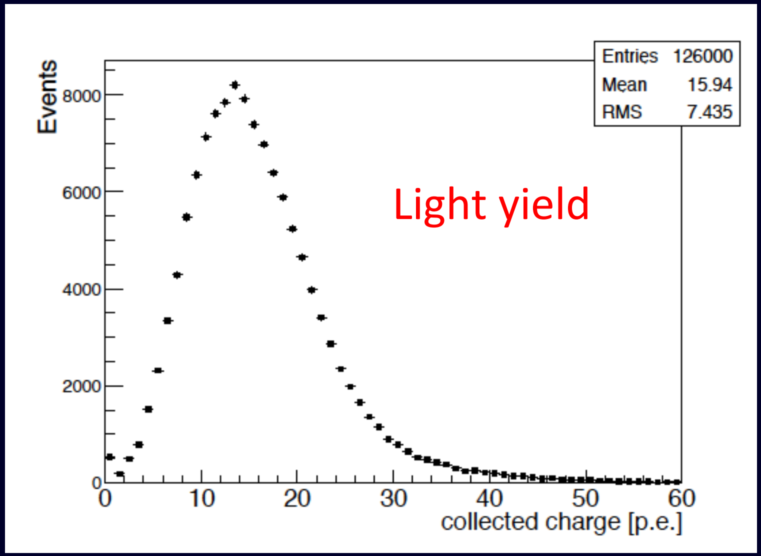
Fiber Mat Production

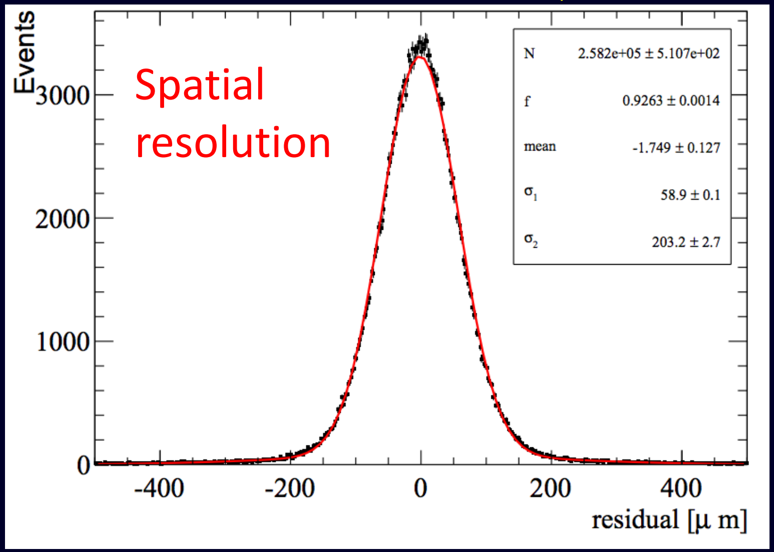


1. Optical cut ends
2. Attach mirror
3. Machine cut sides

FT Performance

CERN-LHCC-2014-001; LHCb-TDR-015





- Light yield from m.i.p. @ mirrored end = 17 p.e.
- Spatial resolution better than 70 μm
- Single-hit efficiency > 99%