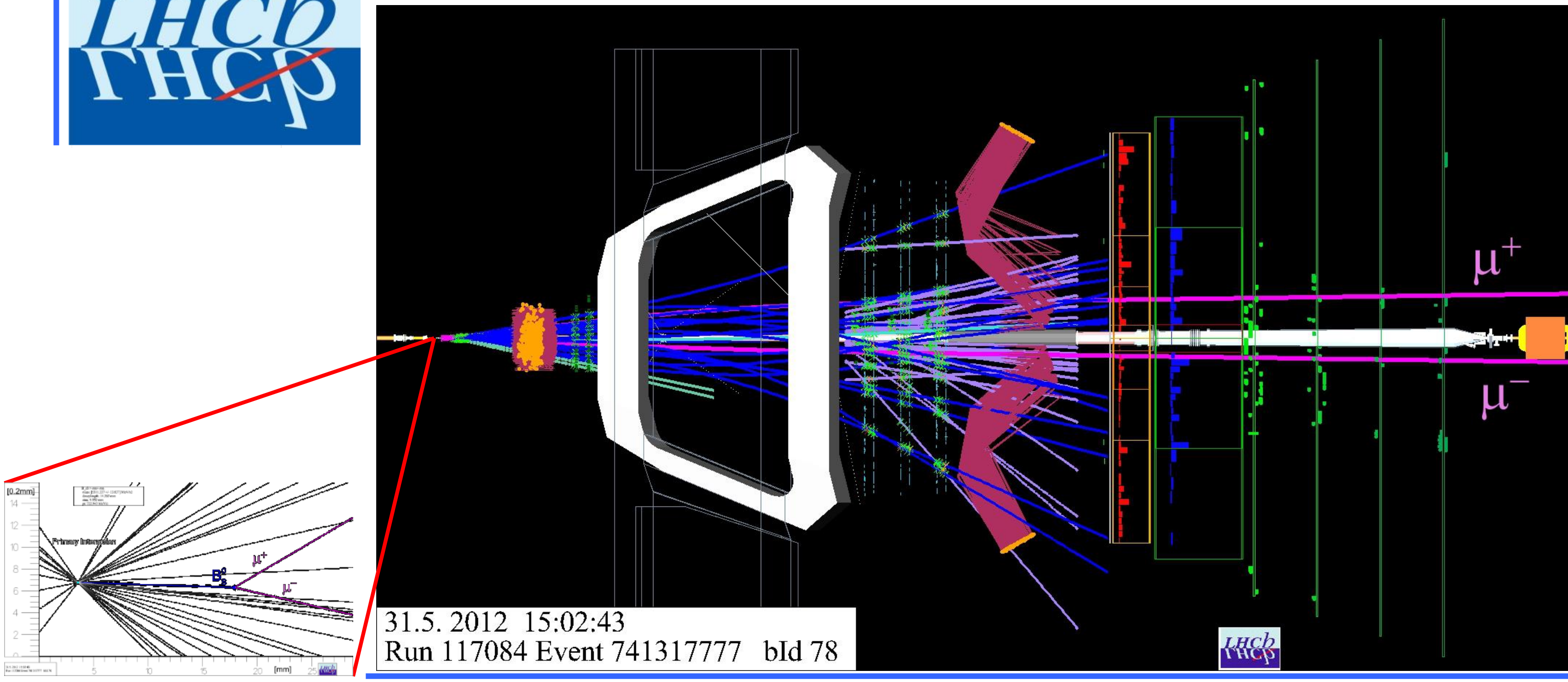


LHCb Upgrade(s)

Federico Alessio, CERN
on behalf of the LHCb Collaboration

HQL2021, Warwick - UK, 13-17 September 2021

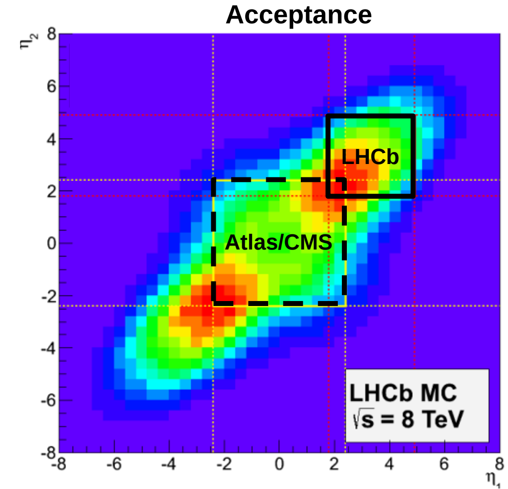
Outline

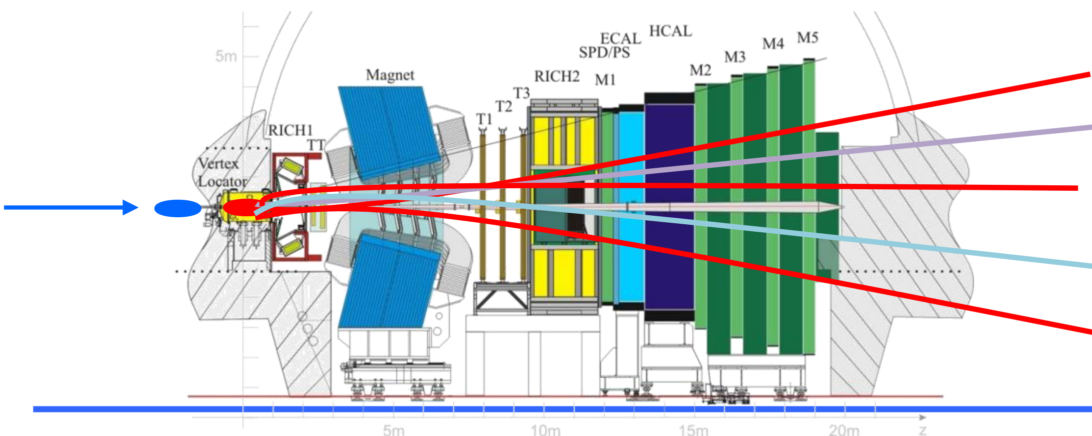
- LHCb as Forward General-Purpose Detector at the LHC
- Motivations for upgrading the detector
- Upgrade plans for the upcoming LHC Run3 and Run4
  - Readout System
  - Data processing and trigger
  - New detector technologies
    - Vertexing
    - Tracking
    - Particle ID
    - Calorimetry and Muon ID
  - SMOG2 and Fixed Target physics
- Conclusions

The LHCb detector at the LHC

LHCb proved itself to be the Forward General-Purpose Detector at the LHC:

- forward arm spectrometer with unique coverage in pseudorapidity (2 < η < 5)
- catching 40% of heavy quark production cross-section in 4% of solid angle
- precision measurements in beauty and charm sectors
  - ✓ $\Delta p / p = 0.5\%$ at < 20 GeV/c to 1.0% at 200 GeV/c
  - ✓ IP resolution $15+29/p_T$[GeV] μm for high-pT tracks
  - ✓ decay time resolution 45 fs for $B_s \rightarrow J/\psi\ \varphi$ and $B_s \rightarrow D_s\ \pi$
- Extended physics program to QCD, EW, direct searches
- Participation in heavy ion runs as well





Excellent performance in Run 1 and Run2
→ Benchmark for upgrades

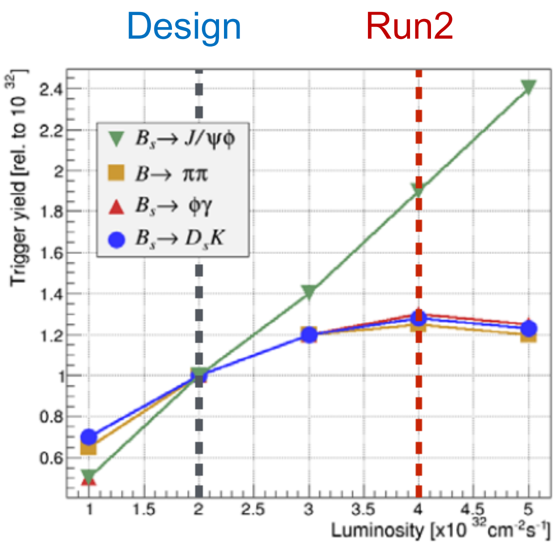
Int. J. Mod. Phys. A 30, 1530022 (2015)

Motivations for upgrading LHCb

Go beyond Flavor Physics: from exploration studies to precision studies

→ No significant signs of New Physics in Run1 and 2 but anomalies observed!

✓ R(D*), R(K), R(K*), angular analysis of $K^* \mu^+ \mu^-$ and more



Aim at more precision!

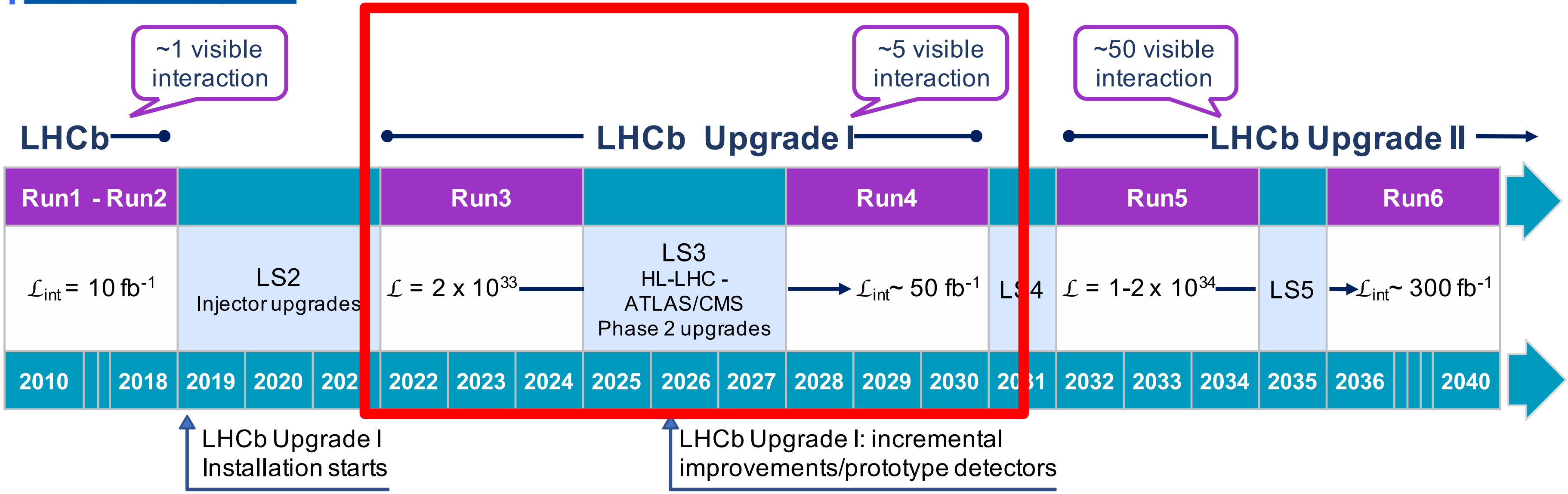
- *BR*($B_s \to \mu^+\mu^-$) down to ~10% of SM
- CKM γ angle to ~1°
- $2\beta_s$ to precision <20% of SM value
- charm CPV search below 10^{-4}

Only one way forward

→ remove limitations from hardware trigger!

- factor 2 yield between di-muon and fully hadronic decays
- remove necessary harsher cuts on p_T and E_T
- increase complexity of track reconstruction
- ageing and fast degradation of sub-detectors that needs replacing

LHCb upgrades plan & strategy



LHCb Phase-I upgrade ongoing now during LS2 for Run3 and Run4

- full software trigger and readout all detectors at 40MHz
- replace tracking detectors + PID + VELO and $\mathscr{L} \sim 2 \times 10^{33}$ sec^{-1} cm^{-2}
- Consolidate PID, tracking and ECAL during LS3

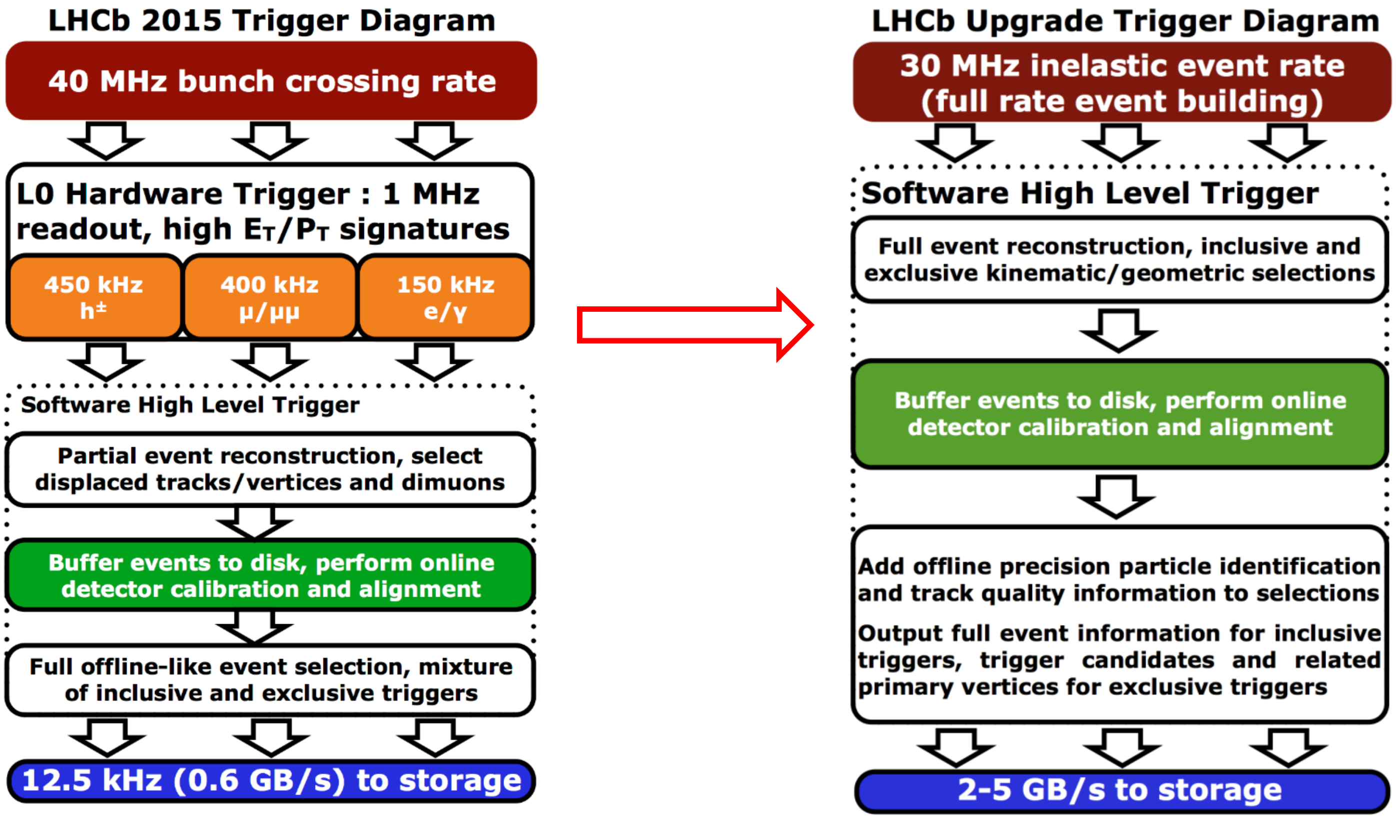
LHCb Phase-II upgrade during LS4 beyond Run4

- Use new detector technologies + timing to increase $\mathscr{L} \sim 1 \times 10^{34}$ sec^{-1} cm^{-2}

LHCb Upgrade-I challenges

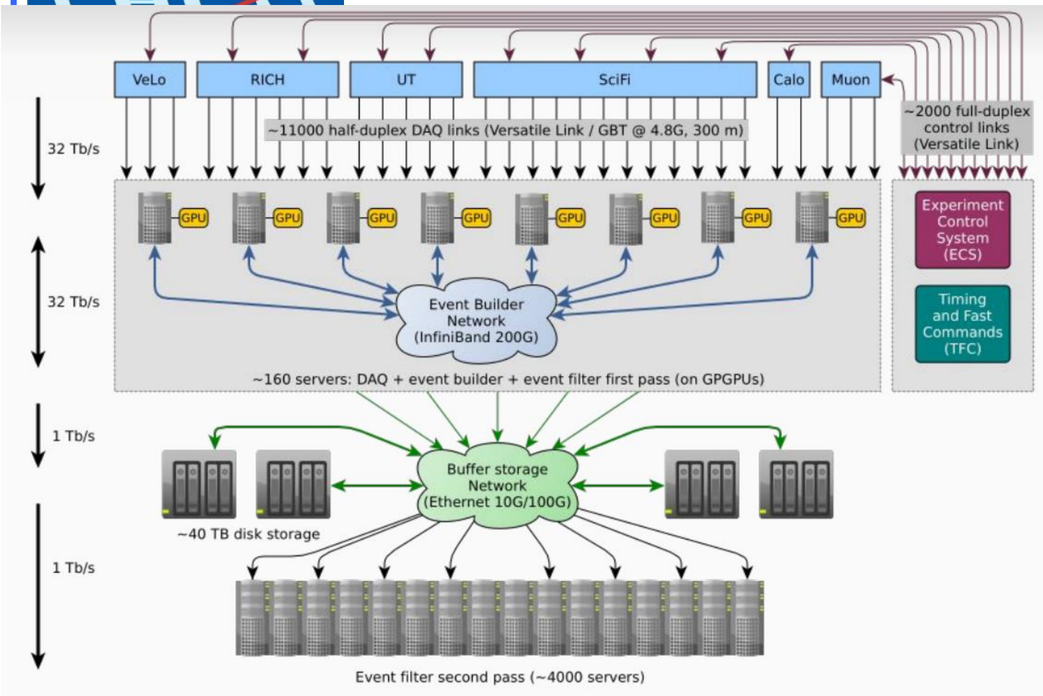
Remove L0 trigger!

Achieve same reconstruction performance in harsher environment
Record all bunch crossings with fully software trigger



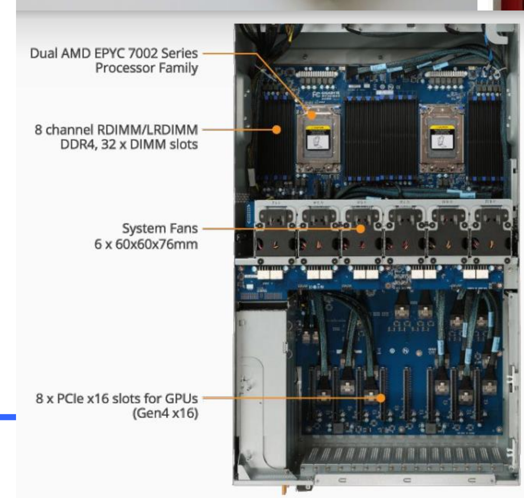
CERN-LHCC-2014-016

Trigger-less readout system



Modern Data center

Complex PCIe40 board

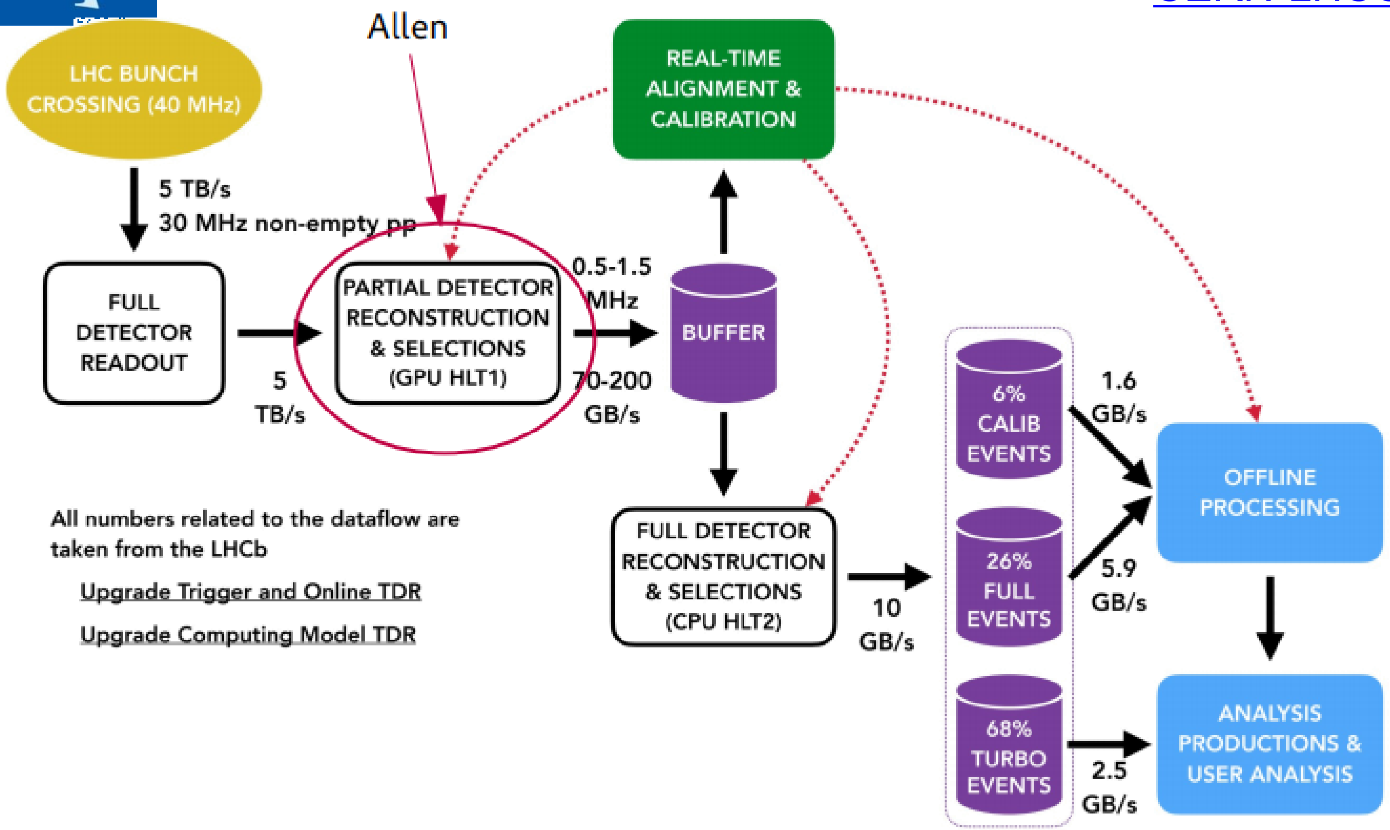


PCIe40+ GPU server

- Back-End electronics on surface in data center
- ~19000 long distance optical fibers (99.75% yield)
- Common Back-End boards (PCIe40)
  - ✓ Large FPGA and optical links (48 x 10 Gbps)
  - ✓ Flavor of firmware defines functionality
- Total effective bandwidth of 32 Tbps

Data processing and trigger

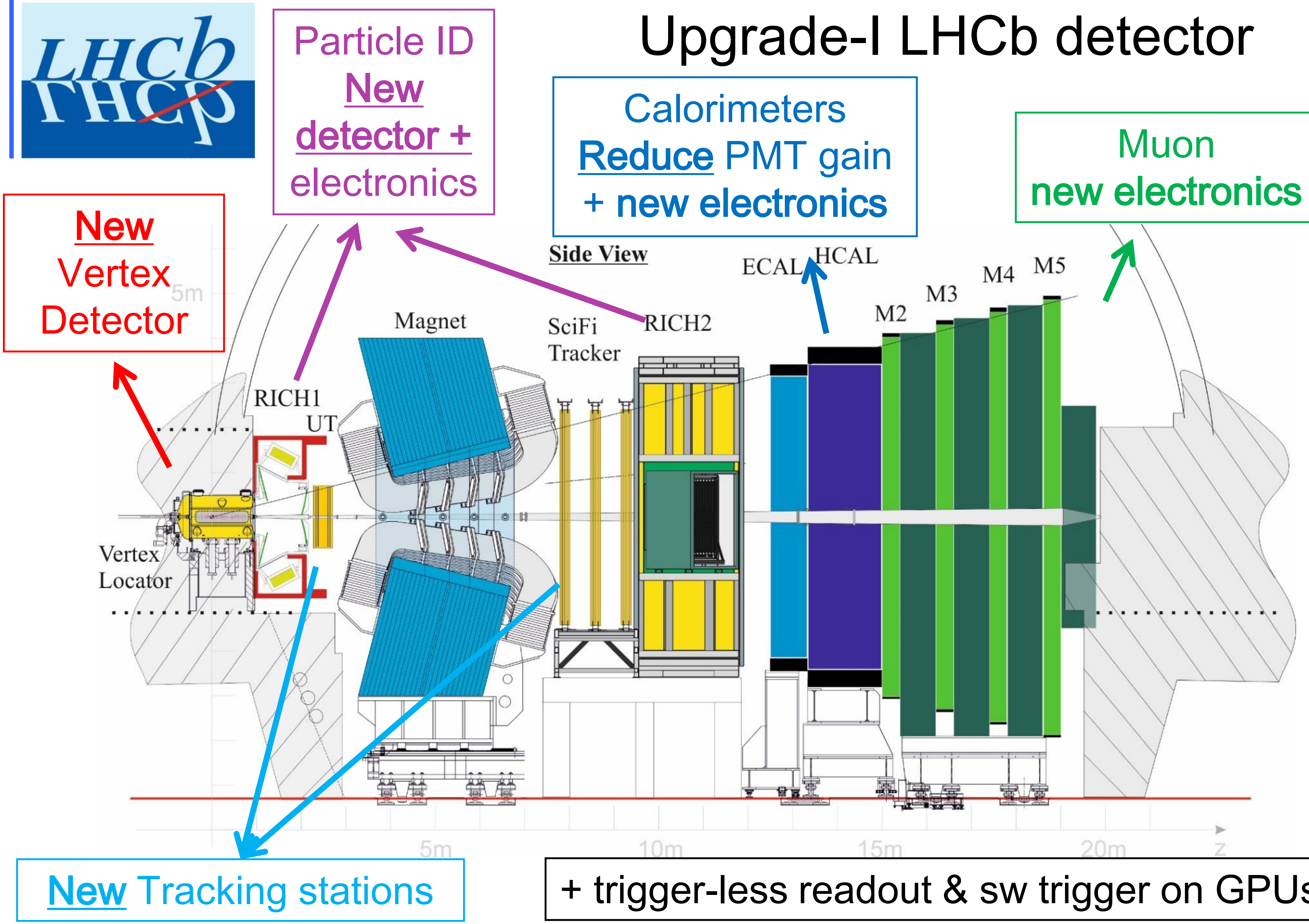
CERN-LHCC-2018-007



- HLT1 reconstruction in GPUs
- Offline reconstruction in HLT2
- TURBO model for exclusive selections

Comput. Phys. Commun. **208** 35-42
Run 2: 2019 *JINST* **14** P04013
GPU: Comput Softw Big Sci 4, 7 (2020)
TURBO: 2019 *JINST* **14** P04006

Upgrade-I LHCb detector



+ trigger-less readout & sw trigger on GPUs

Upgrade-I for Run 3

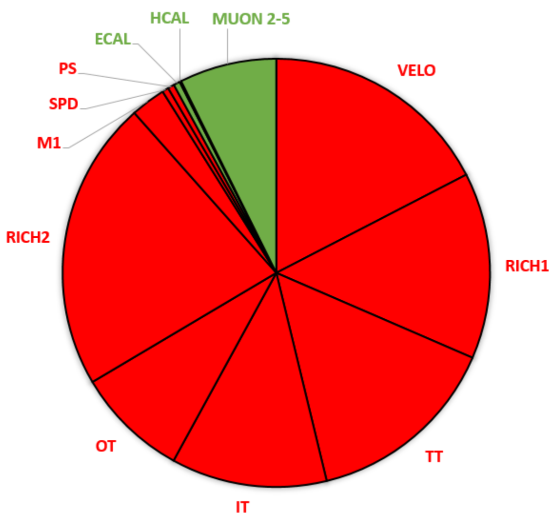
CERN-LHCC-2012-007

Upgraded LHCb Detector

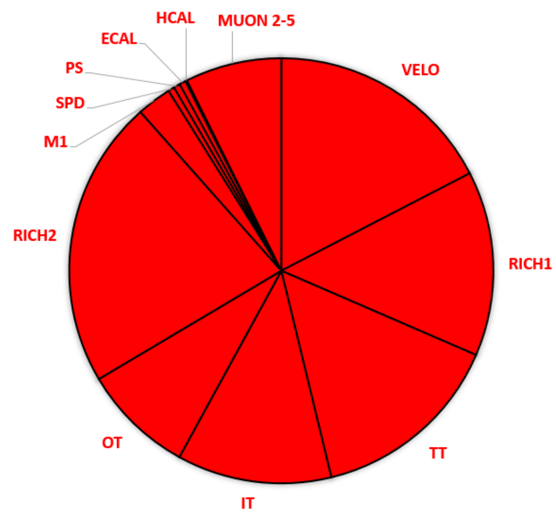
To be UPGRADED

To be kept

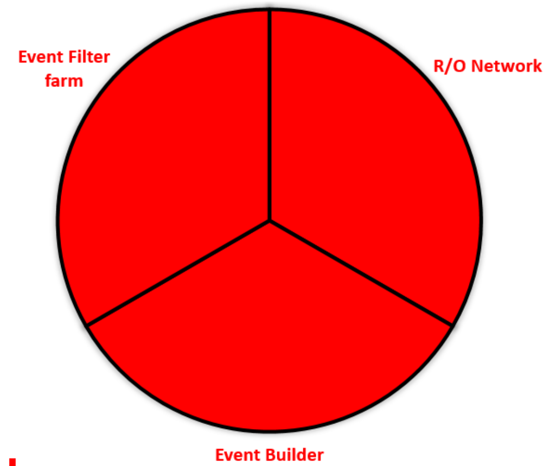
Detector Channels



R/O Electronics



DAQ



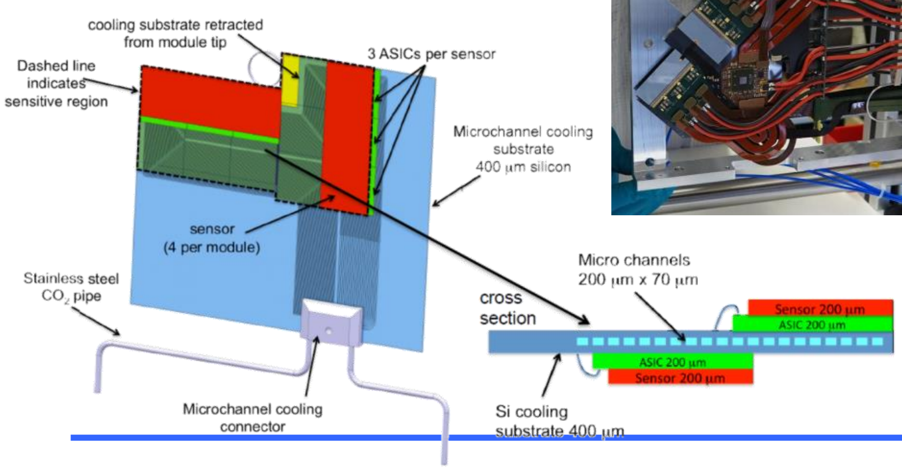
Major upgrade → it’s a new detector all together!

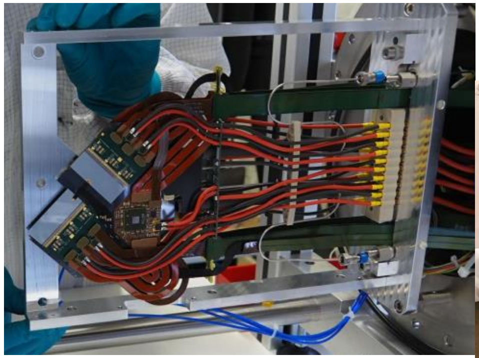
Upgraded Vertex Detector

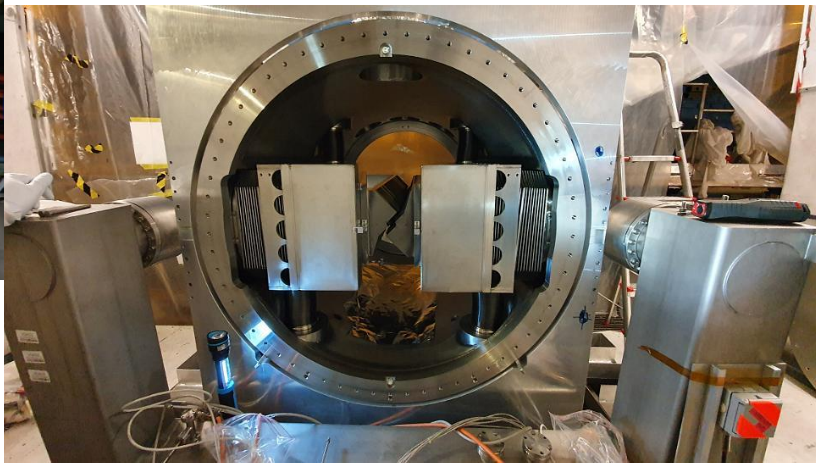
CERN-LHCC-2013-021

- Two movable halves: get closer to beam (5mm to 3.5mm) to improve IP resolution
  - ✓ 52 modules for a total of 41M pixels covering total area ~ 1.2 m^2
- Hybrid Pixel Silicon detector modules cooled down with fluid (bi-phase CO_2) which passes under the chips in etched micro-channels (T < - 20 C)
  - ✓ 200 µm n-on-p sensor tiles
- New ASIC VeloPix, ~20 Gbps in hottest ASIC and total of ~3 Tbps

VELO





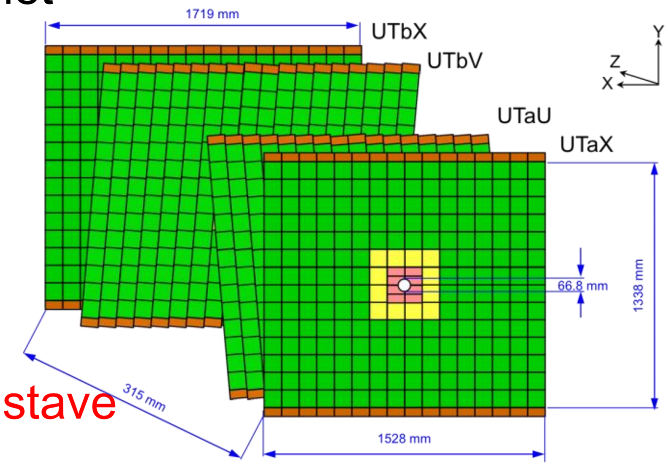


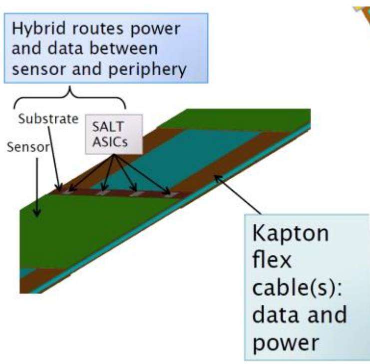
Upgraded Tracking System

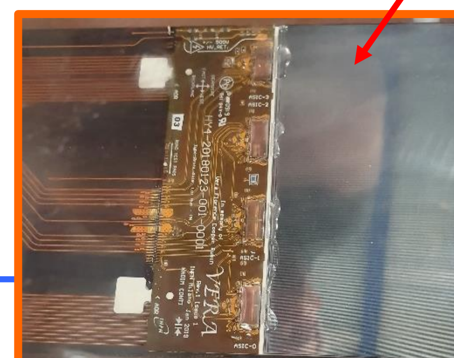
[CERN-LHCC-2014-001]

Upstream Tracker (UT)

- Silicon micro-strip detector
  - Four layers (x, u, v, x) upstream of magnet
  - with finer granularity and closer to beam
- Four types of sensors
  - n- and p-type with 512 or 1024 strips
  - 320/250 μm thick; 190/95 μm pitch
- Modules mounted on double-sided staves
  - Bi-phase CO_2 cooling pipe integrated in stave
- New read-out ASIC (SALT)
  - 128 channels with 6-bit ADC
  - Pedestal & common-mode subtraction, zero-suppression
- FE readout electronics mounted on detector frame
  - 1048 4-asic read-out sectors = 4192 ASICs







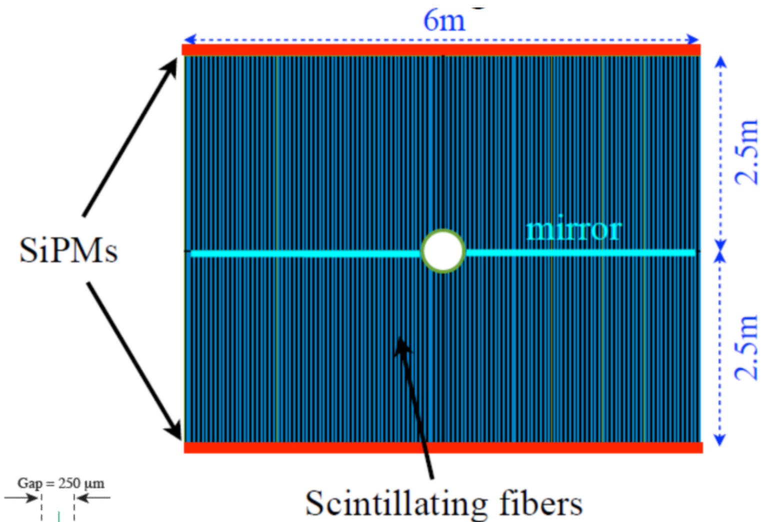
Upgraded Tracking System

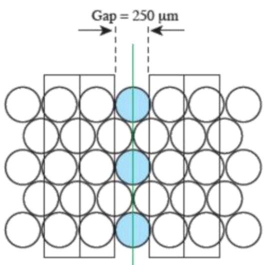
CERN-LHCC-2014-001

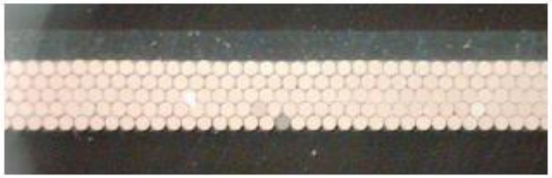
Scintillating Fibers (SciFi)

Completely new detector based on Scintillating Thin Fibers

- blue-emitting multi clad fibers, laid down as a mat
- 2.4m long, 250 um diameter (2.8 ns decay time)
- 12 layers of modules in different layout 3 x (x-u-v-x)
- read out with SiPM at -40C
- new ASIC, 64 channels 130 nm CMOS
  - ADC with 3 hardware thresholds
- FPGA on FE cluster board







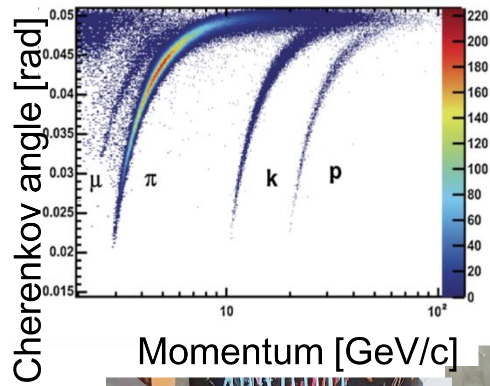
Upgraded Particle ID

CERN-LHCC-2013-022

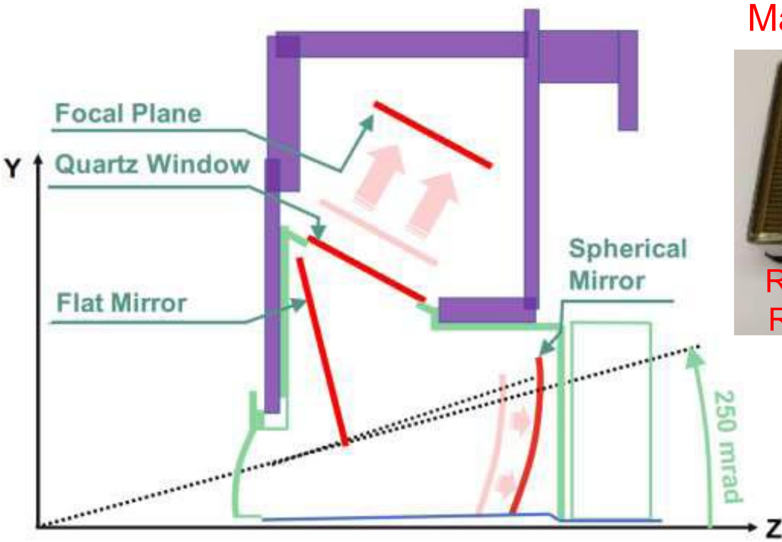
Ring-Imaging Cherenkov (RICH)

Maintain excellent Particle ID:

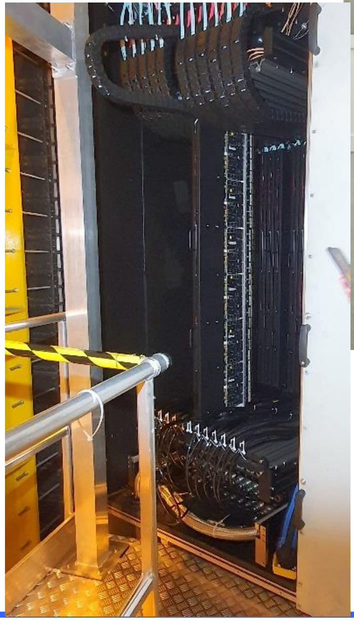
- RICH1 with C_4F_{10} (10-65 GeV/c)
- RICH2 with CF_4 (15-100 GeV/c)
  - ✓ Replace HPDs with MaPMTs
  - ✓ New Readout ASIC (CLARO)
  - ✓ FPGA on FE boards for serialization and latching of signal

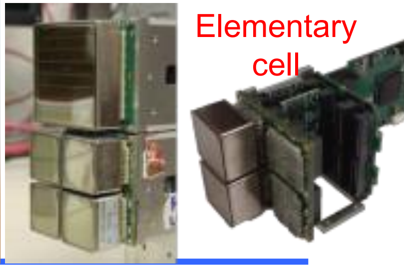


RICH2



MaPMTs (Hamamatsu)



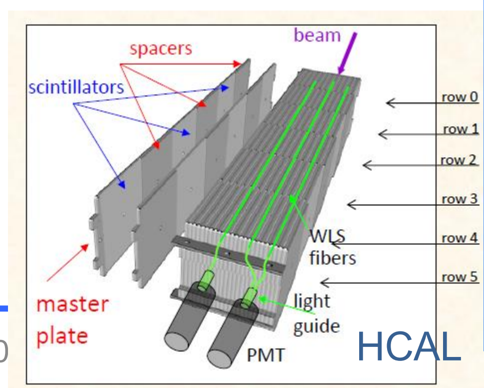


Calorimetry and Muon ID

ECAL + HCAL

Present Calorimeter detectors will be kept:

- ECAL (Shashlik 25 X_0 Pb + scintillator)
- HCAL (TileCal Fe + scintillator)
  - ✓ PS/SPD removed
- PMT gain reduced by a factor 5
- Front-End electronics redeveloped
  - For trigger-less readout and sending Non-Zero Suppressed data

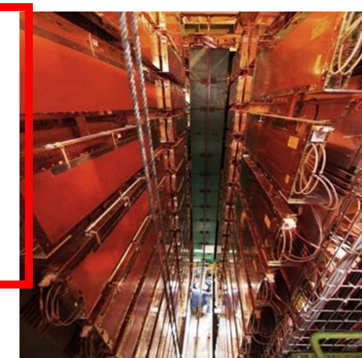


MUON

Present Muon detector will be kept:

- 4 layers (M2-M5) of Multi-Wire Proportional Chambers (MWPC)
  - ✓ first layer (M1 – used in first-level trigger, with GEMs) removed
- ✓ Front-End electronics redeveloped
  - For trigger-less readout

R&D to replace inner part of M2 (close to IP) with MWPC detector for higher-granularity and better efficiency

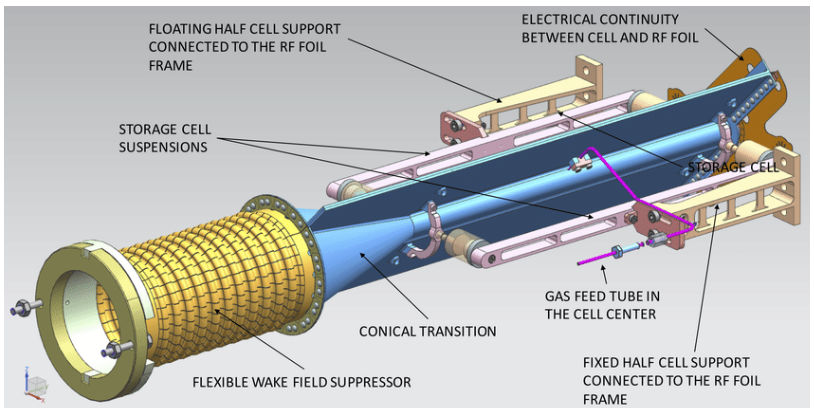


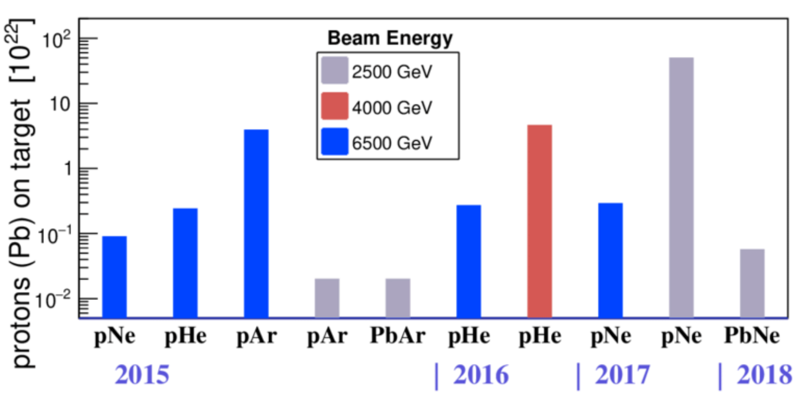
SMOG2 and Fixed Target physics

CERN-LHCC-2019-005

New SMOG2 system installed to inject various gas species in the LHCb IP

- Fixed Target physics at the LHC collider: in // with pp data taking
- Gas cell attached to VELO, displaced p-gas IP for easy distinction from pp data



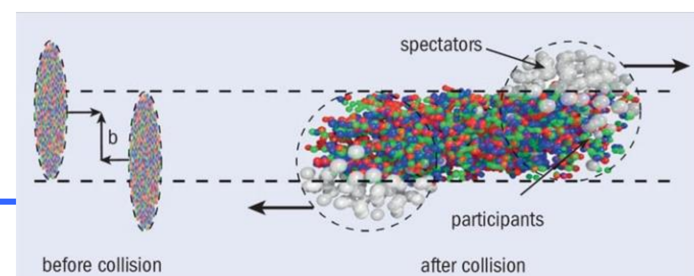


Physics program spans over:

- anti-proton production
- Central exclusive production
- X(3872)/ψ(2S)
- ψ(2S) / J/ψ
- Strangeness production
- Λc → pKπ

\+ LHCb participation in Heavy Ion runs
(PbPb and pPb data taking)

✓ Down to 30% centrality in LHCb in Run3!



LHCb physics reach with the Upgrade-I and Upgrade-II

Aim at collecting 50 fb^{-1} in Run3-4 and 300 fb^{-1} in Run5-6

✓ Collected ~9 fb^{-1} of data in Run1-2

arXiv:1808.08865

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II
EW Penguins				
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1	0.025	0.036	0.007
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1	0.031	0.032	0.008
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05
CKM tests				
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$	4°	–	1°
γ, all modes	$(^{+5.0}_{-5.8})^\circ$	1.5°	1.5°	0.35°
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04	0.011	0.005	0.003
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad	14 mrad	–	4 mrad
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad	35 mrad	–	9 mrad
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad	39 mrad	–	11 mrad
a_{sl}^s	33×10^{-4}	10×10^{-4}	–	3×10^{-4}
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6%	3%	1%	1%
$\boldsymbol{B_s^0, B^0 \to \mu^+\mu^-}$				
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90%	34%	–	10%
$\tau_{B_s^0 \to \mu^+\mu^-}$	22%	8%	–	2%
$S_{\mu\mu}$	–	–	–	0.2
$\boldsymbol{b \to c\ell^-\bar{\nu}_l}$ **LUV studies**				
$R(D^*)$	0.026	0.0072	0.005	0.002
$R(J/\psi)$	0.24	0.071	–	0.02
Charm				
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4}	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4}	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4}	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}
$x \sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}

Conclusion

The LHCb experiment successfully completed its first decade of data taking in the LHC Run1 and Run2

- LHCb established itself as the GPD in the forward region
- Physics program extended well beyond beauty and charm sectors

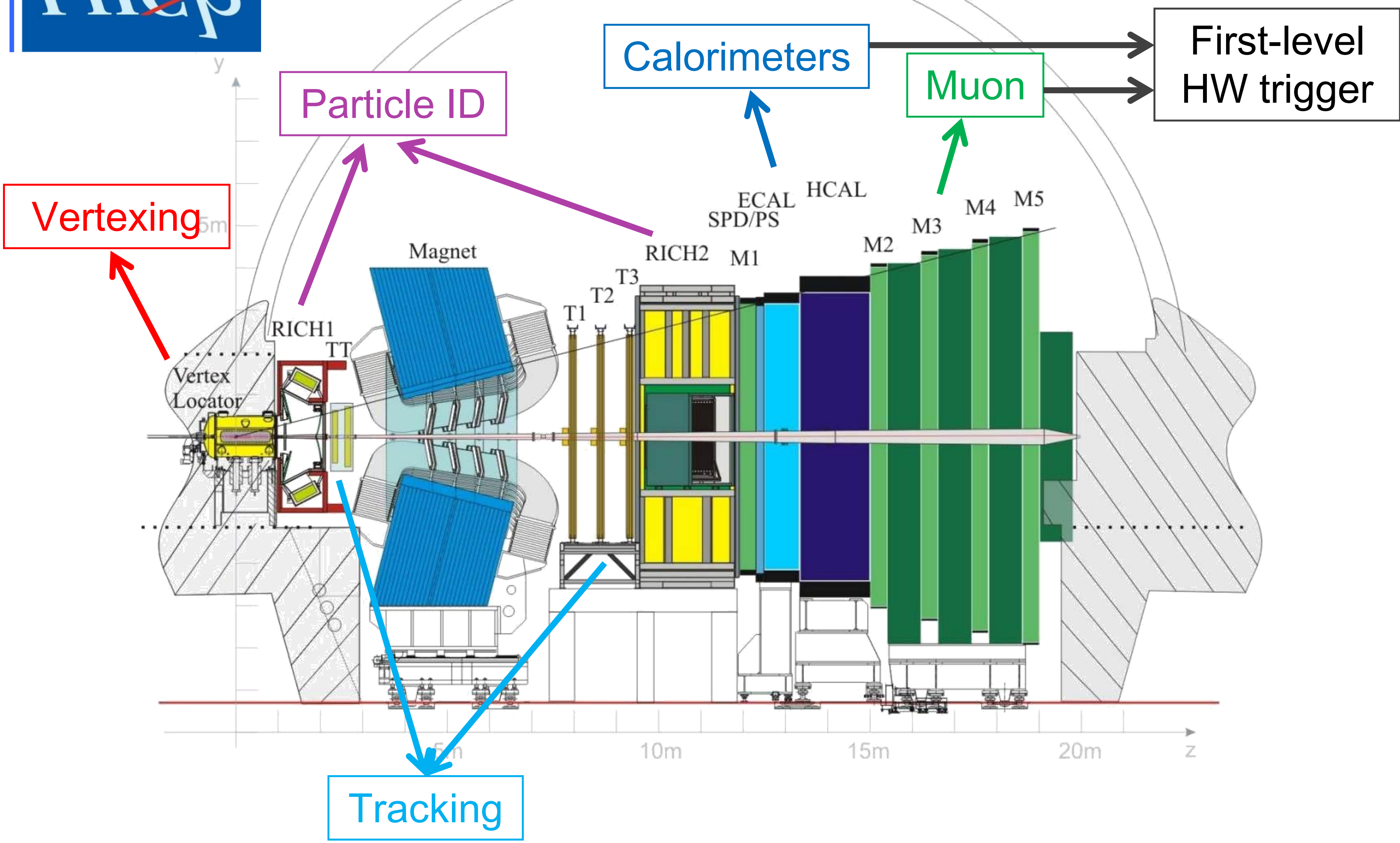
Currently preparing the upgrade of the detector in view of Run3 and Run4

- Aim at collecting at least 50 fb^{-1} by end of Run4
- New detectors and readout electronics to maintain performance at higher luminosities and collecting more data
  - Completely new readout system with common electronics and throughput of ~32 Tbps
  - Full software trigger on modern GPUs with ~170 GPGPUs (High-End)
  - Improved vertexing (VELO) and tracking systems (UT and SciFi)
  - New RICH detectors to maintain excellent Particle ID
  - New readout electronics for Calorimeters and MUONs
  - New SMOG2 system for injecting various gas species
    - ✓ Unique fixed target physics program
  - Participation in Heavy Ion runs

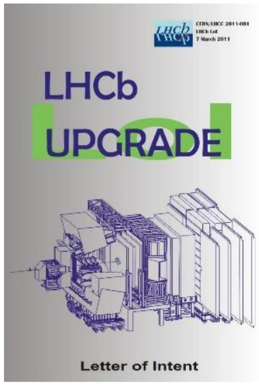
Exciting times ahead at LHCb!

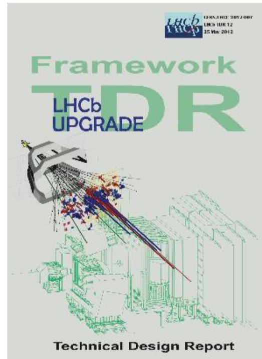
Backup

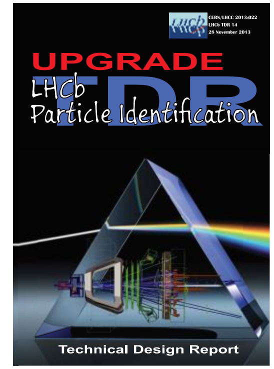
The LHCb detector in Run1 and Run2

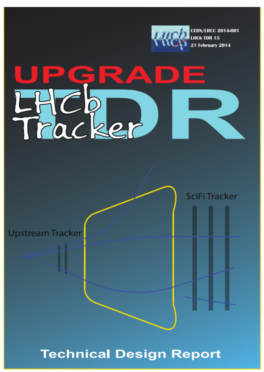


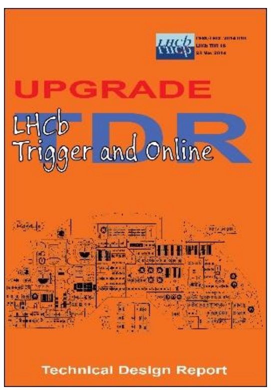
Upgrade I documents

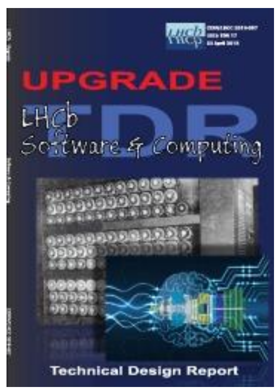






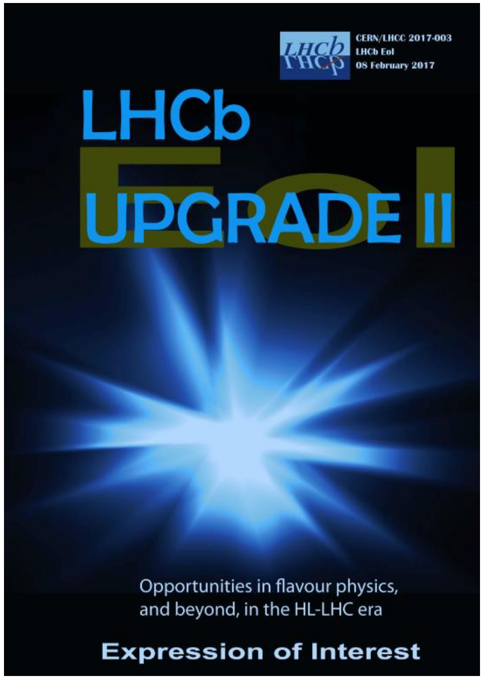


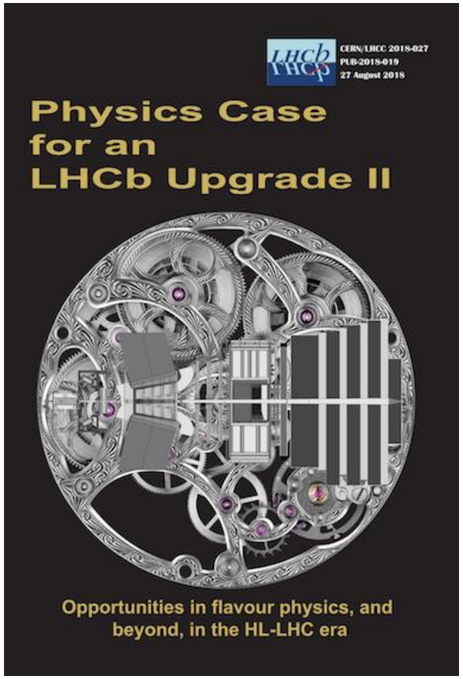




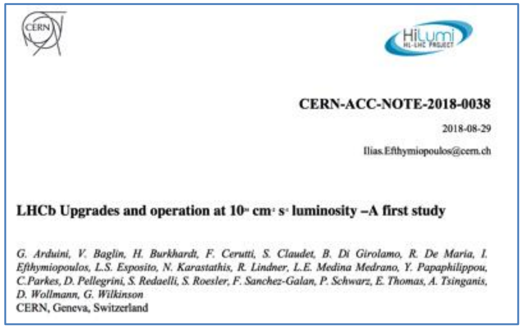
CERN-LHCC-2008-007
CERN-LHCC-2011-001
CERN-LHCC-2012-007
CERN-LHCC-2013-021
CERN-LHCC-2013-022
CERN-LHCC-2014-001
CERN-LHCC-2014-016
CERN-LHCC-2018-007
CERN-LHCC-2018-014
CERN-LHCC-2019-005

Upgrade II documents





CERN-LHCC-2017-003
CERN-LHCC-2018-027



CERN-ACC-NOTE-2018-0038

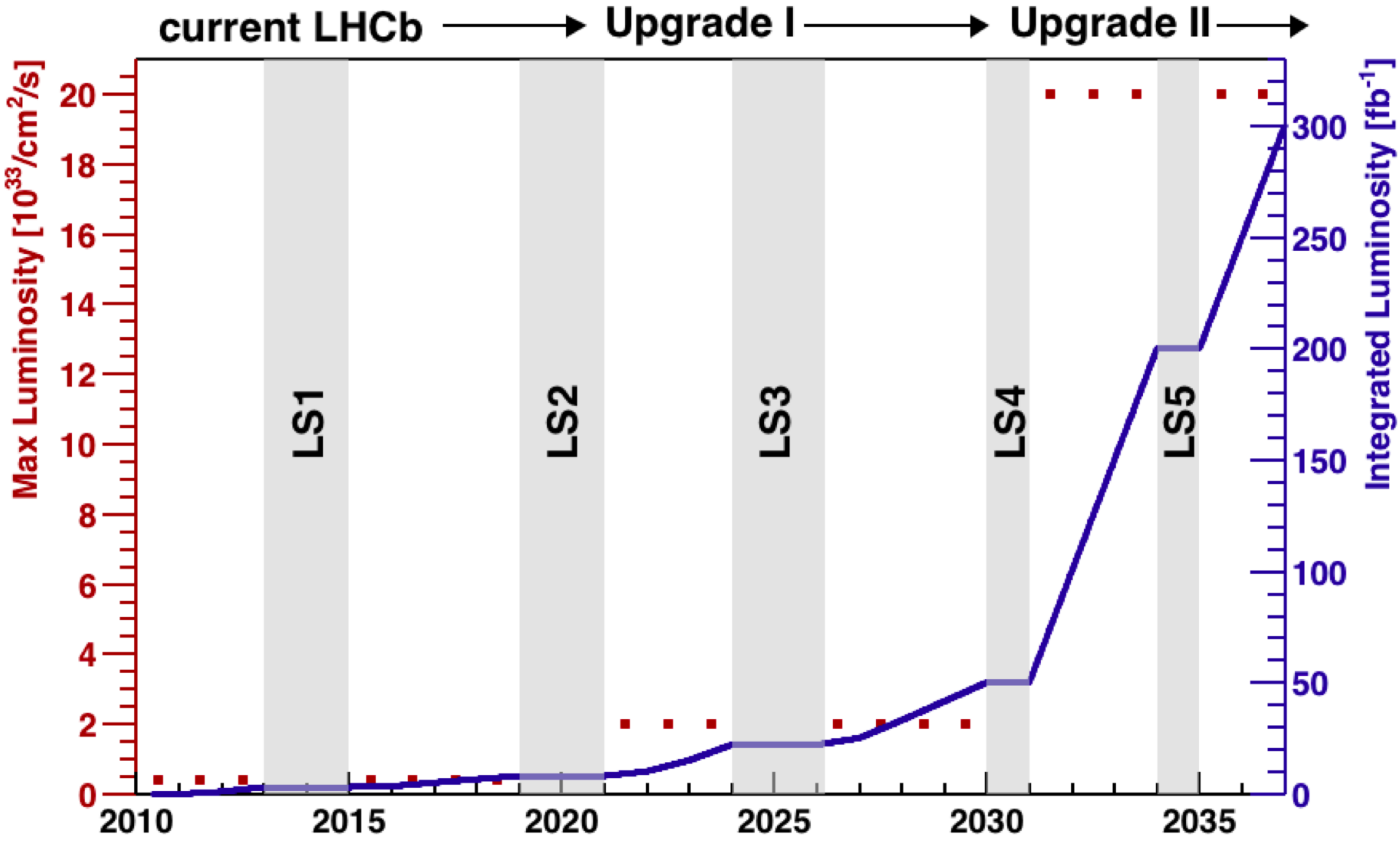
2018-08-29

Ilias.Efthymiopoulos@cern.ch

LHCb Upgrades and operation at 10 cm s luminosity –A first study

G. Arduini, V. Baglin, H. Burkhardt, F. Cerutti, S. Claudet, B. Di Girolamo, R. De Maria, I. Efthymiopoulos, L.S. Esposito, N. Karastathis, R. Lindner, L.E. Medina Medrano, Y. Papaphilippou, C.Parkes, D. Pellegrini, S. Redaelli, S. Roesler, F. Sanchez-Galan, P. Schwarz, E. Thomas, A. Tsinganis, D. Wollmann, G. Wilkinson
CERN, Geneva, Switzerland

Target luminosity



Phase-I Upgrade of LHCb

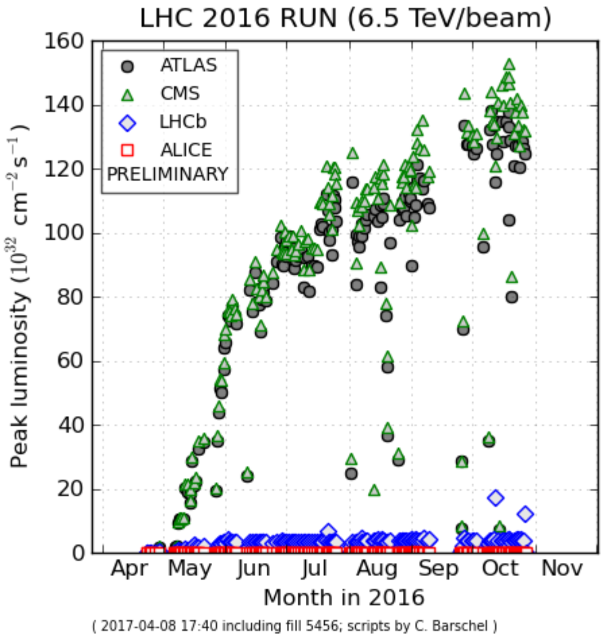
The amount of data and the physics yield from data recorded by the LHCb experiment was limited by its detector.

While LHC accelerator will keep steadily increasing …

- energy / beam (3.5 → 4 → 6.5 TeV → 7 TeV)
- luminosity (peak $8x10^{33}$ → $2x10^{34}$ $cm^{-2}s^{-1}$ → HL-LHC)

… but LHCb will stay limited in terms of

- data bandwidth: limited to 1.1 MHz / 40 MHz max
- physics yields for hadronic channels at the hardware trigge
- detectors degradation at higher luminosities

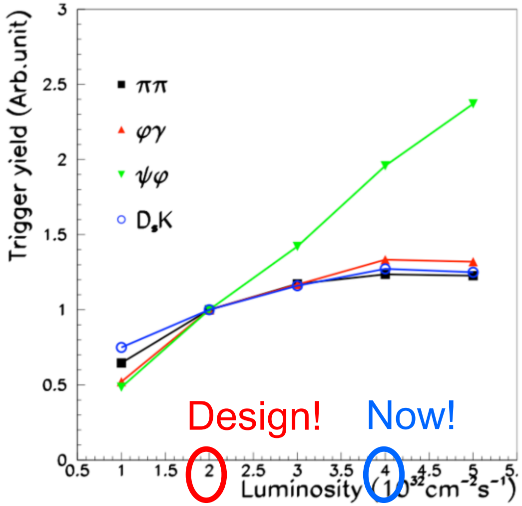


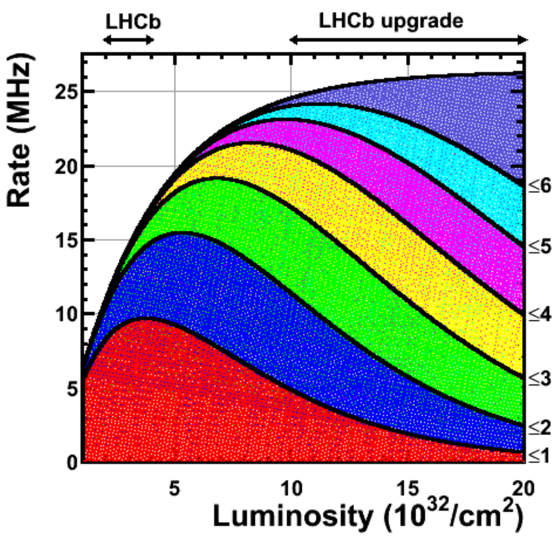
Factor ~40 between LHCb and ATLAS/CMS instantaneous luminosity!

Current limitations

First-level hardware trigger is limited at higher luminosities for hadronic channels:

- almost a factor 2 between di-muon events and fully hadronic decays
- due to trigger criteria based on p_T and E_T to reduce trigger rate to the bandwidth limited to 1.1 MHz



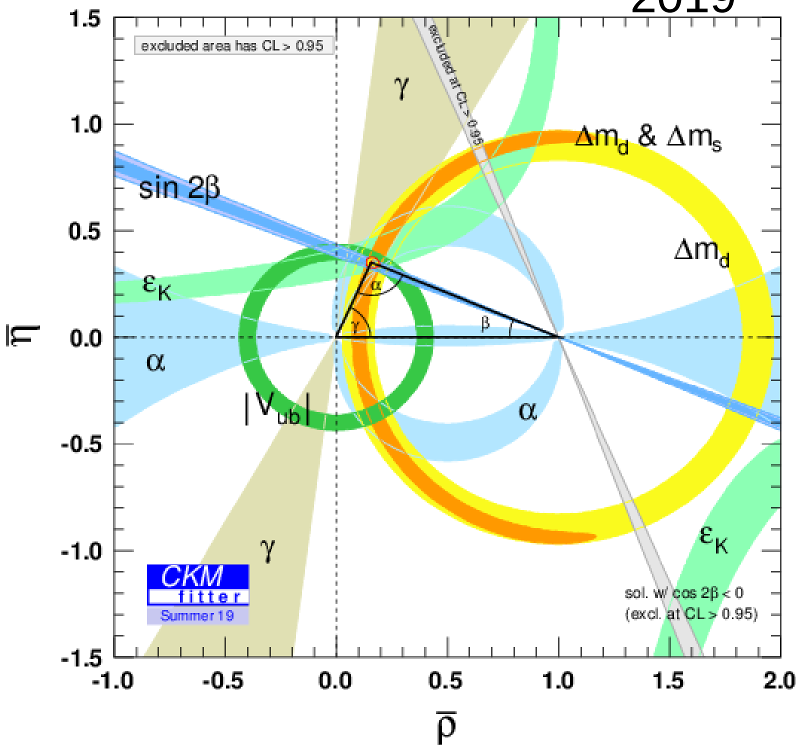


At higher luminosities → harsher cuts on p_T and E_T

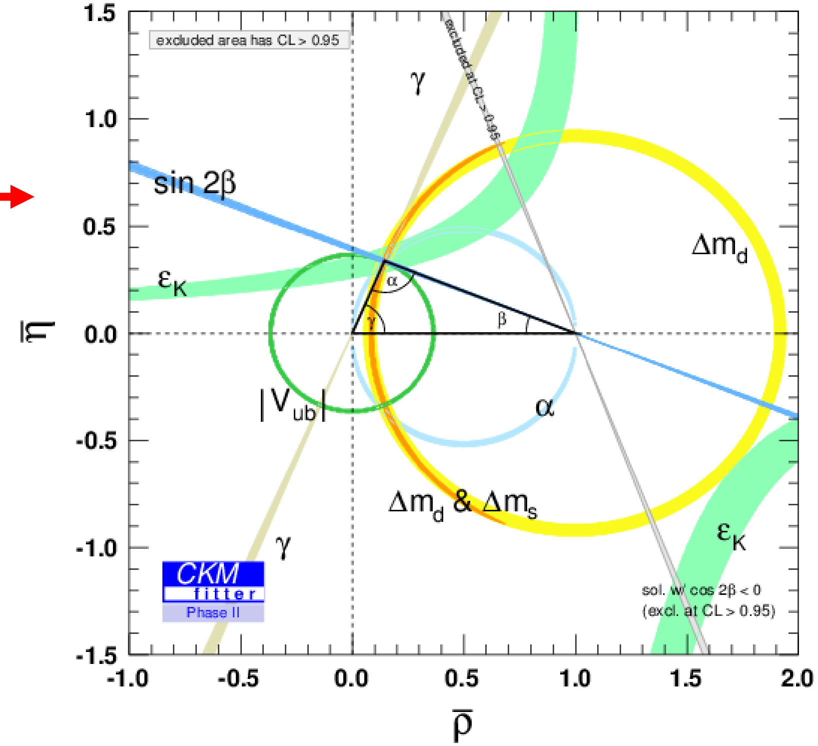
- waste luminosity while not retaining amount of data
- increases complexity of track reconstruction
  - higher computational times in processing farm
- ageing and fast degradation of sub-detectors
  - designed to operate 5 yr at $2x10^{32}$ $cm^{-2}s^{-1}$
  - currently reaching 5 years at $>3x10^{32}$ $cm^{-2}s^{-1}$ and still two years to go…

CKM measurements

2019



LHCb Phase-II

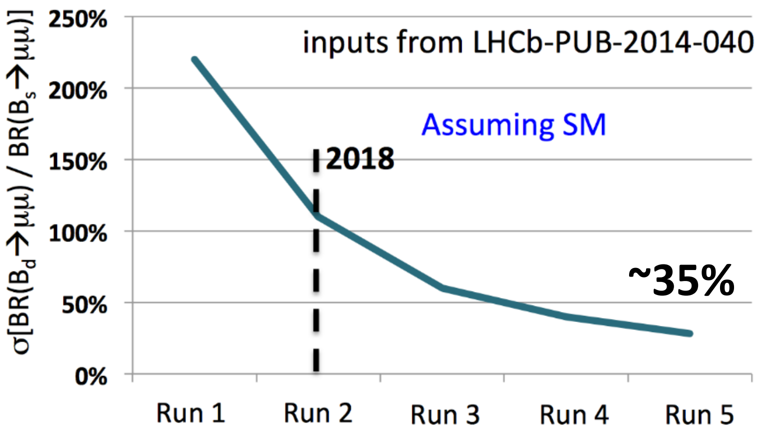


LHCb (300 fb^{-1}), Belle-II (50 ab^{-1})
ATLAS & CMS (3000 fb^{-1})

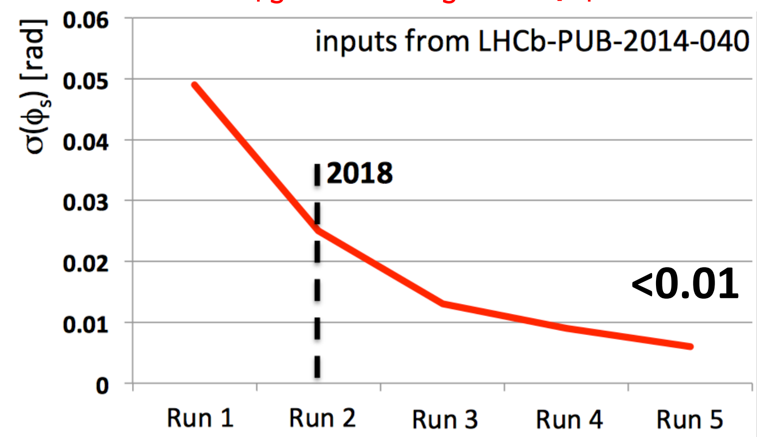
$\sigma_\gamma \approx 5°$ (2019) → 1° (Phase 1) → 0.35° (Phase 2)

LHCb physics reach with a Phase-I upgrade

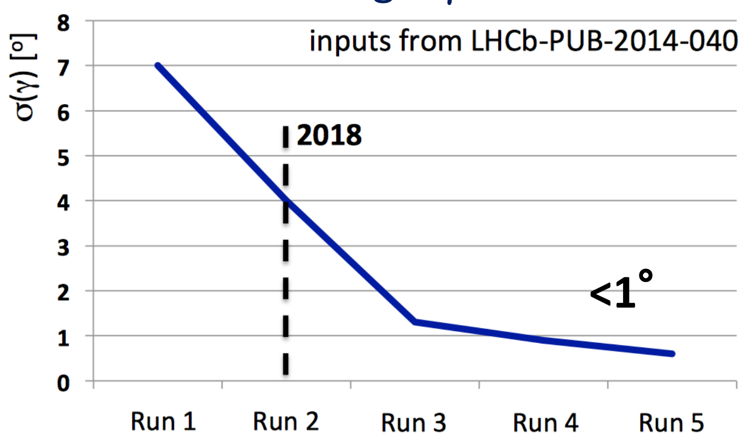
$\sigma(BR(B_d \to \mu\mu)/BR(B_s \to \mu\mu))$



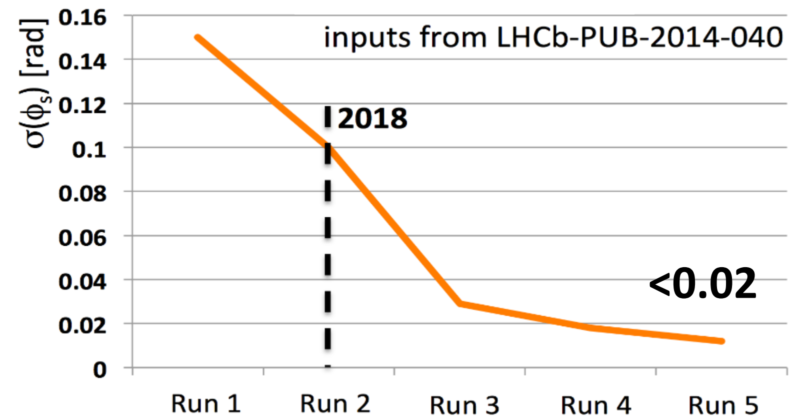
ϕ_s from $B_s \to J/\psi\phi$



CKM angle γ



ϕ_s from $B_s \to \phi\phi$



LHCb physics prospects for a Phase-I upgrade

Rare decays can give hints against Minimal Flavour Violation (MFV) hypothesis in case of significantly inconsistent measurements with the SM

→ Important to make sure that ratio of B (B^0 -> $\mu^+\mu^-$) / B (B_s → $\mu^+\mu^-$) since MFV predicts that this is given by its SM value, $|V_{td}/V_{ts}|^2$

Observation of B^0 -> $\mu^+\mu^-$ requires huge statistics and excellent control of background and can only be made by the upgraded LHCb background to the desired precision

Type	Observable	Current precision	LHCb 2018	Upgrade (50 fb^{-1})	Theory uncertainty
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [16]	8 %	2.5 %	$\sim$ 10 %
Higgs	$\mathcal{B}(B^0_s \to \mu^+\mu^-)$	1.5×10^{-9} [2]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
penguin	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$	–	$\sim 100\,\%$	$\sim 35\,\%$	$\sim 5\,\%$
Unitarity	$\gamma\ (B \to D^{(*)}K^{(*)})$	~ 10–$12°$ [19, 20]	4°	0.9°	negligible
triangle	$\gamma\ (B^0_s \to D_sK)$	–	11°	2.0°	negligible
angles	$\beta\ (B^0 \to J/\psi\, K^0_S)$	0.8° [18]	0.6°	0.2°	negligible
Charm	A_Γ	2.3×10^{-3} [18]	0.40×10^{-3}	0.07×10^{-3}	–
CP violation	ΔA_{CP}	2.1×10^{-3} [5]	0.65×10^{-3}	0.12×10^{-3}	–

LHCb physics prospects for a Phase-I upgrade

Type	Observable	Current precision	LHCb 2018	Upgrade ($50\,\mathrm{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s\ (B_s^0 \to J/\psi\ \phi)$	0.10 [9]	0.025	0.008	~ 0.003
	$2\beta_s\ (B_s^0 \to J/\psi\ f_0(980))$	0.17 [10]	0.045	0.014	~ 0.01
	$A_{\mathrm{fs}}(B_s^0)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
Unitarity	$\gamma\ (B \to D^{(*)}K^{(*)})$	~ 10–12° [19, 20]	4°	0.9°	negligible
triangle	$\gamma\ (B_s^0 \to D_s K)$	–	11°	2.0°	negligible
angles	$\beta\ (B^0 \to J/\psi\ K_S^0)$	0.8° [18]	0.6°	0.2°	negligible
Charm	A_Γ	2.3×10^{-3} [18]	0.40×10^{-3}	0.07×10^{-3}	–
CP violation	ΔA_{CP}	2.1×10^{-3} [5]	0.65×10^{-3}	0.12×10^{-3}	–

Primary goal of LHCb is to probe NP in B_s mixing

→ $B_s \to J/\psi\phi$ dominated by b -> c cbar s tree diagram and sensitive to the weak phase $\beta_s = \arg(-V_{ts}V_{tb}^* / V_{cs}V_{cb}^*)$

If no anomalous effect is seen in this channel, then it is necessary to control experimental systematics from an experiment point of view

→ LHCb upgrade will address such systematics

LHCb physics prospects for a Phase-I upgrade

Type	Observable	Current precision	LHCb 2018	Upgrade (50 fb^{-1})	Theory uncertainty
B_s^0 mixing	$2\beta_s\ (B_s^0 \to J/\psi\ \phi)$	0.10 [9]	0.025	0.008	~ 0.003
	$2\beta_s\ (B_s^0 \to J/\psi\ f_0(980))$	0.17 [10]	0.045	0.014	~ 0.01
	$A_{fs}(B_s^0)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_s^{\rm eff}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$	0.17 [18]	0.30	0.05	0.02
Right-handed	$2\beta^{\rm eff}(B^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	[illegible]	[illegible]	[illegible]	[illegible]
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	$\sim 100\,\%$	$\sim 35\,\%$	$\sim 5\,\%$
Unitarity triangle angles	$\gamma\ (B \to D^{(*)}K^{(*)})$	~ 10–12° [19, 20]	4°	0.9°	negligible
	$\gamma\ (B_s^0 \to D_s K)$	–	11°	2.0°	negligible
	$\beta\ (B^0 \to J/\psi\ K_S^0)$	0.8° [18]	0.6°	0.2°	negligible
Charm CP violation	A_Γ	2.3×10^{-3} [18]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [5]	0.65×10^{-3}	0.12×10^{-3}	–

Charmless hadronic B decays highly sensitive to NP

→ Rare decay topologies such as penguin diagrams

→ Big experimental challenge to control SM uncertainties to the necessary precision

LHCb physics prospects for a Phase-I upgrade

Type	Observable	Current precision	LHCb 2018	Upgrade (50 fb^{-1})	Theory uncertainty
B_s^0 mixing	$2\beta_s$ ($B_s^0 \to J/\psi\,\phi$)	0.10 [9]	0.025	0.008	~ 0.003
	$2\beta_s$ ($B_s^0 \to J/\psi\, f_0(980)$)	0.17 [10]	0.045	0.014	~ 0.01

Only the LHCb upgrade will provide the huge statistics needed to reach the precision that is necessary to remove the SM uncertainty in NP searches.

→ γ measurement is ideally suited for LHCb as it's largely based on analyses

1. that do not require flavour-tagging
2. that exploit LHCb's unique capability to trigger on fully hadronic decay modes.

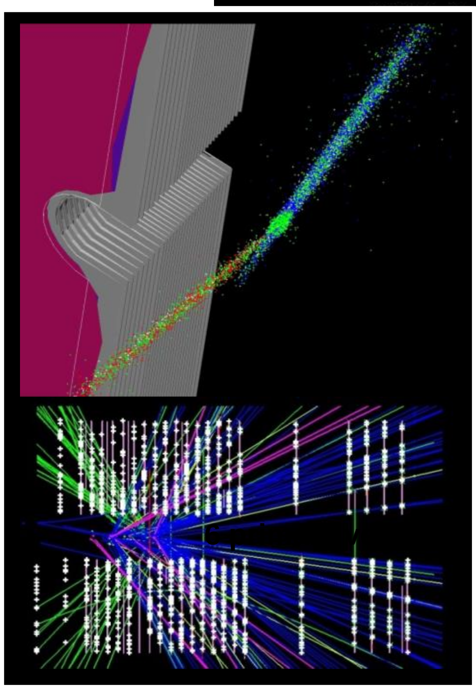
→ With 50 fb^{-1}, γ will be determined to better than 1° precision

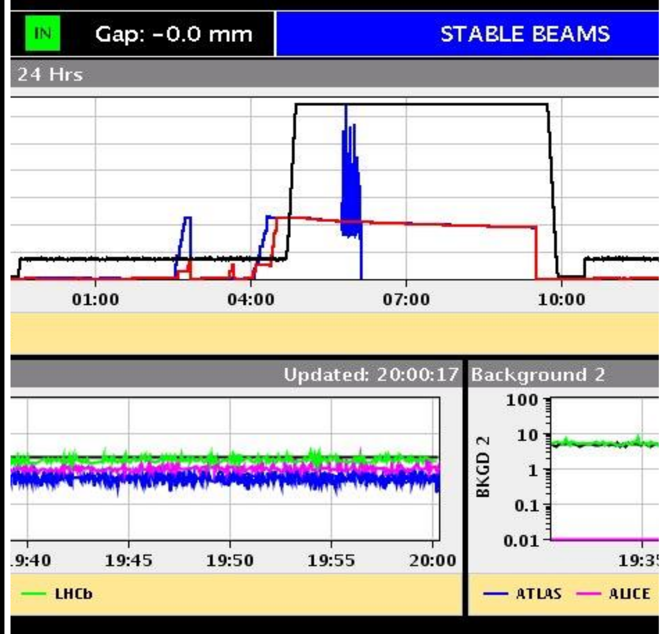
Type	Observable	Current precision	LHCb 2018	Upgrade (50 fb^{-1})	Theory uncertainty
penguin	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	$\sim 100\,\%$	$\sim 35\,\%$	$\sim 5\,\%$
Unitarity	γ ($B \to D^{(*)}K^{(*)}$)	$\sim$ 10–12° [19, 20]	4°	0.9°	negligible
triangle	γ ($B_s^0 \to D_s K$)	–	11°	2.0°	negligible
angles	β ($B^0 \to J/\psi\, K_S^0$)	0.8° [18]	0.6°	0.2°	negligible
Charm	A_Γ	2.3×10^{-3} [18]	0.40×10^{-3}	0.07×10^{-3}	–
CP violation	ΔA_{CP}	2.1×10^{-3} [5]	0.65×10^{-3}	0.12×10^{-3}	–

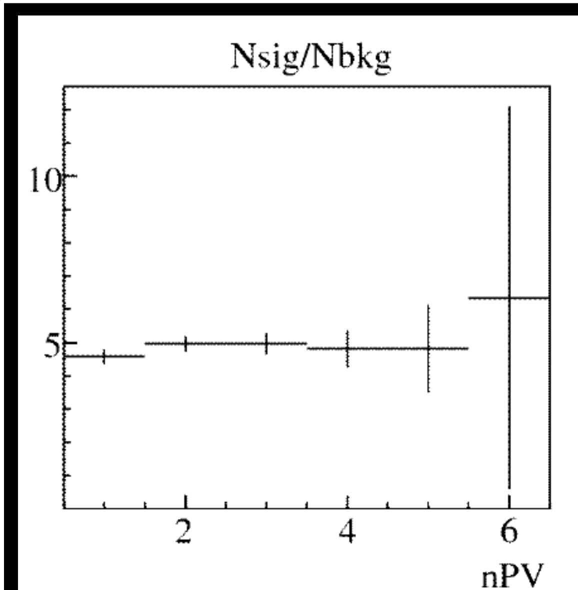
Is it feasible?

YES! We already tried in 2012: took some data at 10^{33} (5x designed values)

04-Dec-2012 20:00:17 Fill #: 3374 Energy: 4000 GeV I(B1): 2.03e+14 I(B2): 2.01e+14	ATLAS	ALICE	CMS	LHCb
Experiment Status	PHYSICS	PHYSICS	PHYSICS	Upgrade!
Instantaneous Lumi [(ub.s)^-1]	5460.0	6.595	5604.2	999.1
BRAN Luminosity [(ub.s)^-1]	5494.5	4.272	5521.6	1123.1
Fill Luminosity (nb)^-1	27394.6	30.5	28708.4	2803.3
BKGD 1	0.723	0.982	2.195	1.615
BKGD 2	102.929	0.000	4.883	5.478
	1.792	7.130		





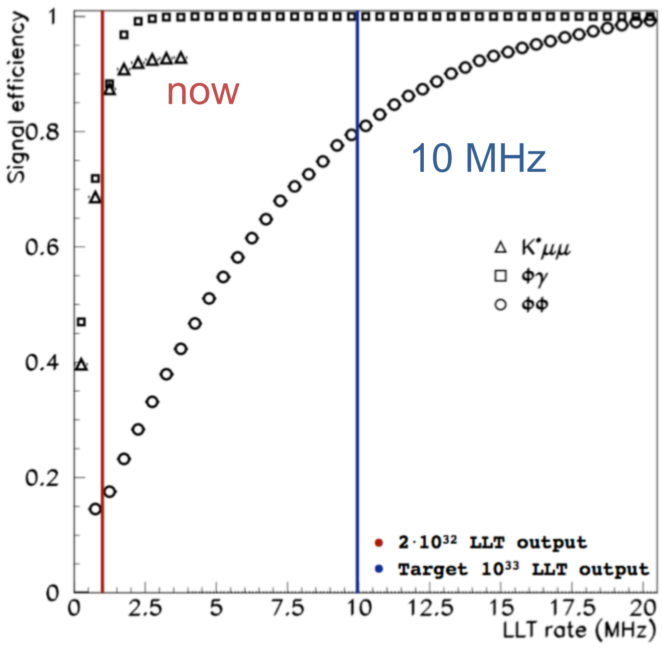


B S/N almost independent of pileup
D S/N shows some degradation vs pileup.

Implications of upgrade strategy

Removal of first-level hardware trigger implies

- read out every LHC bunch crossing
  - trigger-less Front-End electronics
  - multi-Tb/s readout network
- fully software flexible trigger
  - full event information available to improve trigger decision
  - maximize signal efficiencies at high events rate



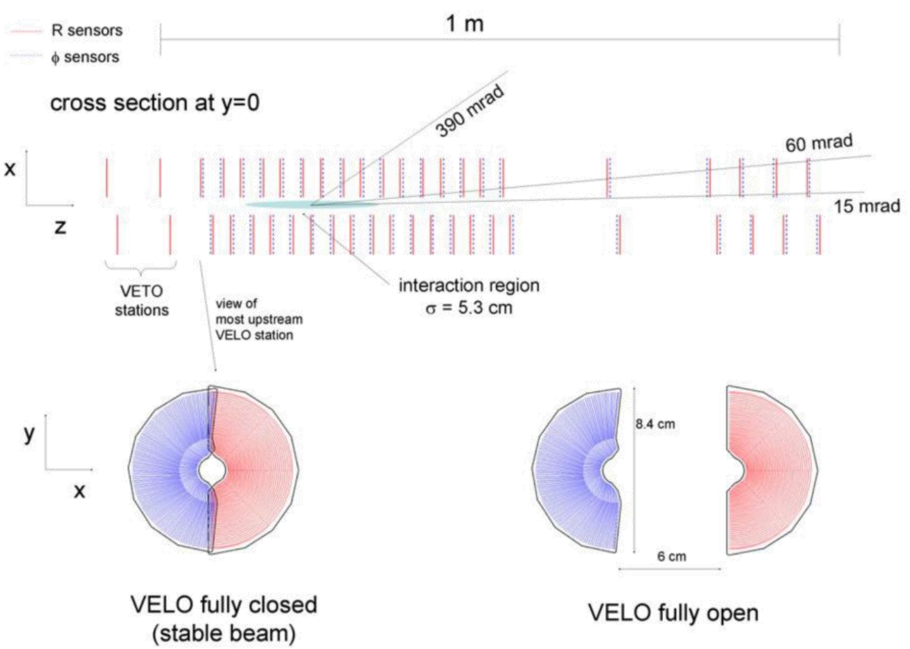
→ higher luminosities: **redesign (incompatible) sub-detectors for a peak luminosity of $2x10^{33}$ $cm^{-2}s^{-1}$** (x5-x10 more than today)

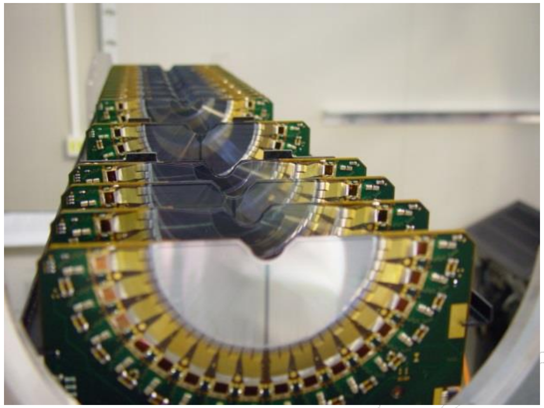
→ more data by increasing bandwidth: redesign readout architecture to record 40 MHz events

Current LHCb Vertex Detector

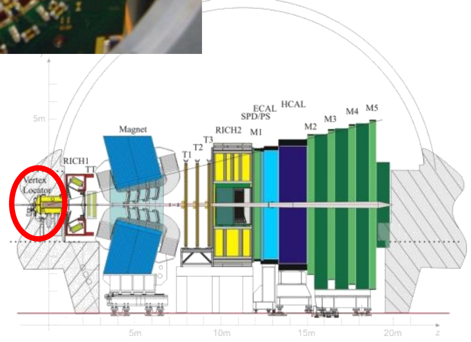
Current Vertex Detector (VELO) is at the heart of LHCb tracking, triggering and vertexing

- Excellent performance, reliable, cluster efficiency >99.5%, best hit resolution down to <4μm
- Movable device! ~50mm to ~5mm close to LHC beams when in collisions (autonomously…)





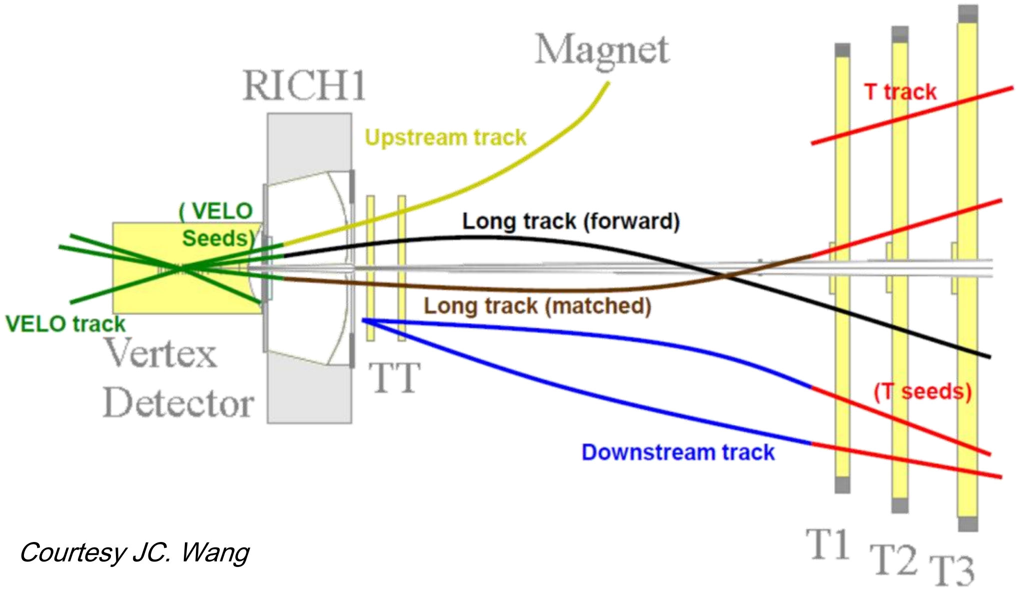
Si-strips measuring r and ϕ



Current LHCb Tracking system

Present Tracking System will be upgraded:

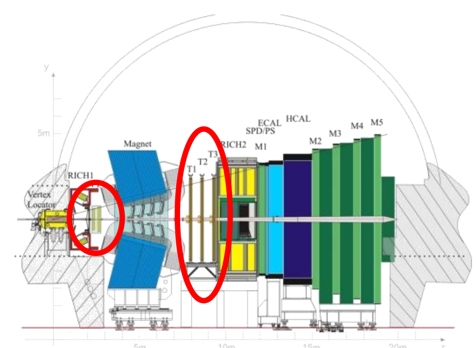
- VELO + TT (Si-strip) + DIPOLE (no change) + IT (2% inner area, Si) / OT (Straw Tubes)



Courtesy JC. Wang

Current pattern-recognition based on current tracking system would not be efficient in upgraded scenario

- Too high occupancy in central region
- R&D for different solutions
  - → for downstream and upstream tracking



Sidenote: R&D in increasing Dipole field (x1.8 Bdl)

New LHCb Vertex Detector

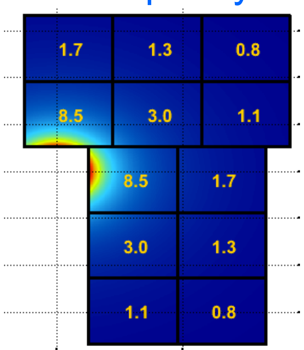
Future VELO must maintain same performance, but in harsher conditions

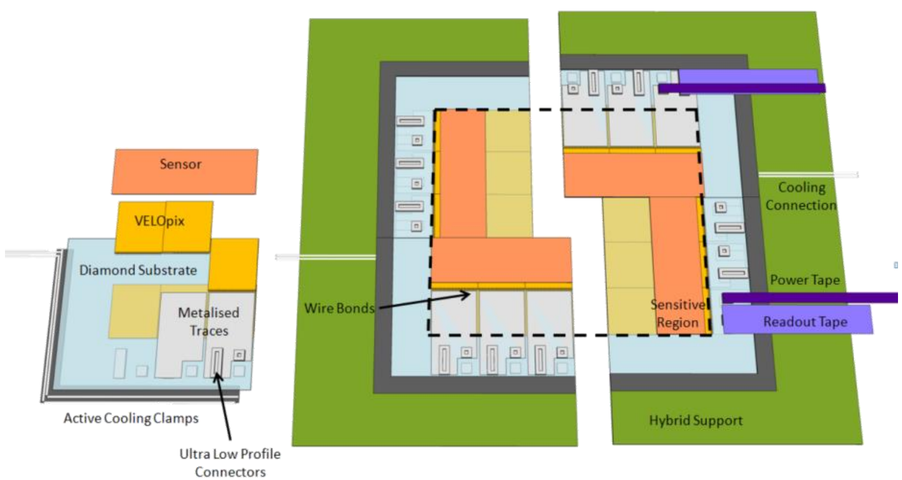
- Low material budget, cope with > radiation damage, deal with > multiplicities
- Trigger-less readout ASICs and provide fast and efficient reconstruction at HW level

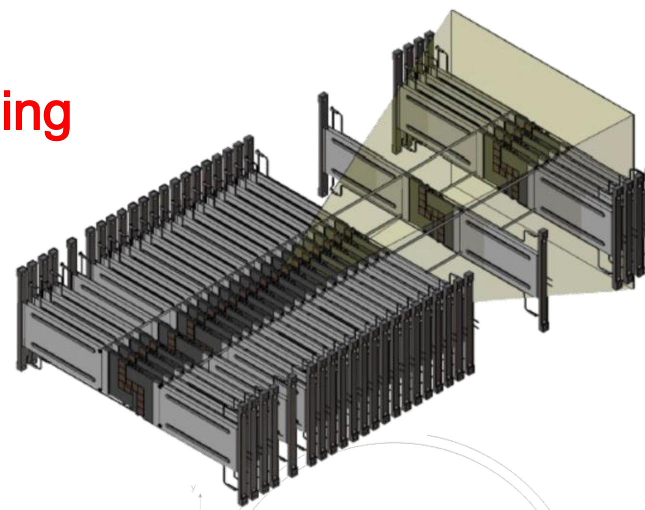
→ Recent technology reviews favored the choice of a

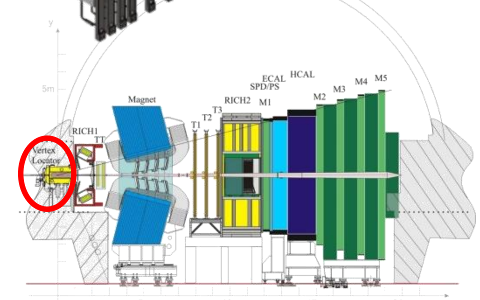
Si-pixel detector with microchannel cooling

occupancy



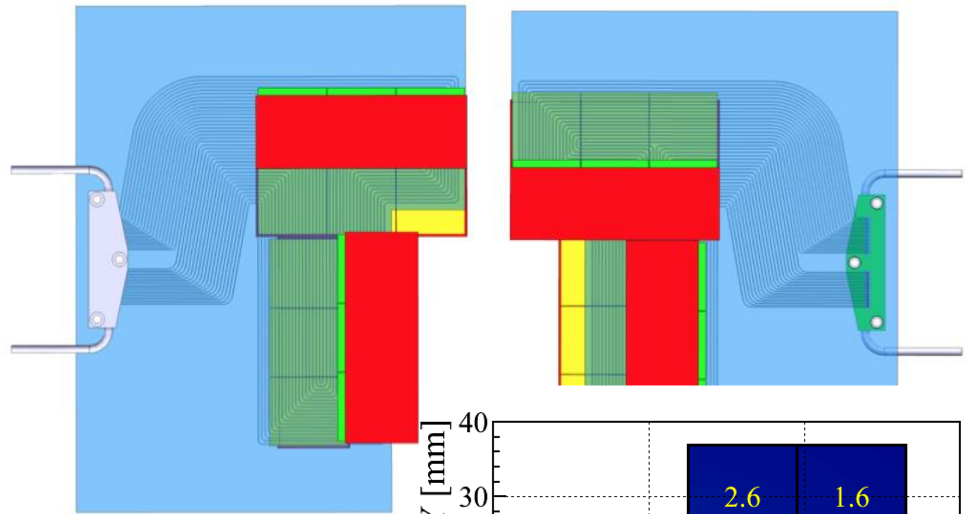


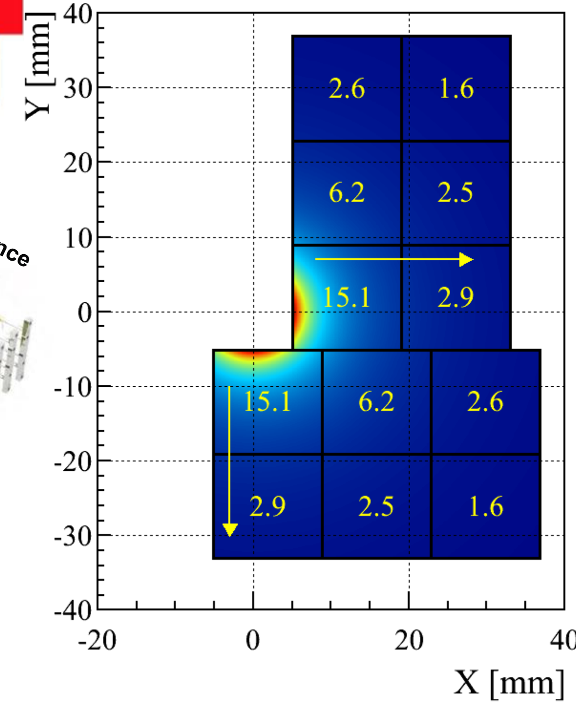


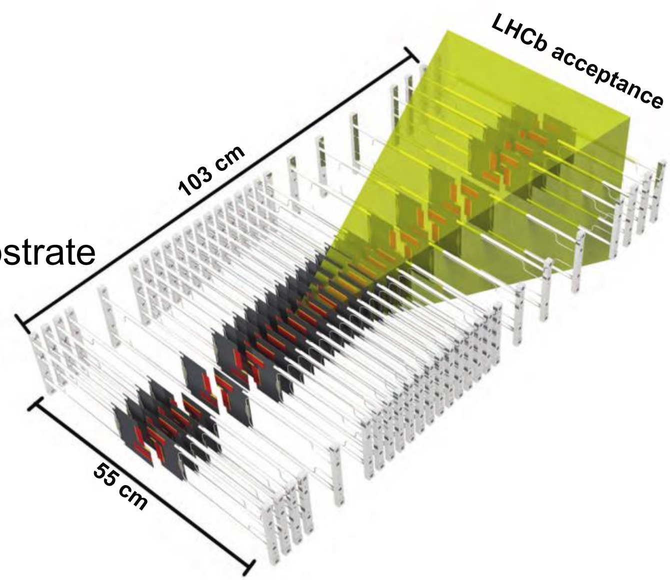


Upgraded VELO

- Hybrid pixel detector
  - Easier pattern recognition
  - Thinner sensors (300 µm → 200 µm)
- Move closer to beam
  - First measurement: 8.13 mm → 5.1 mm
- New RF foil
  - Reduce material before first measurement
- New ASIC (VeloPix)
  - Based on Medipix/TimePix
  - 256x256 (55 µm x 55 µm)
  - 12 per module
- Non-uniform irradiation
  - Extremely high data rates
  - Micro-channel cooling in substrate

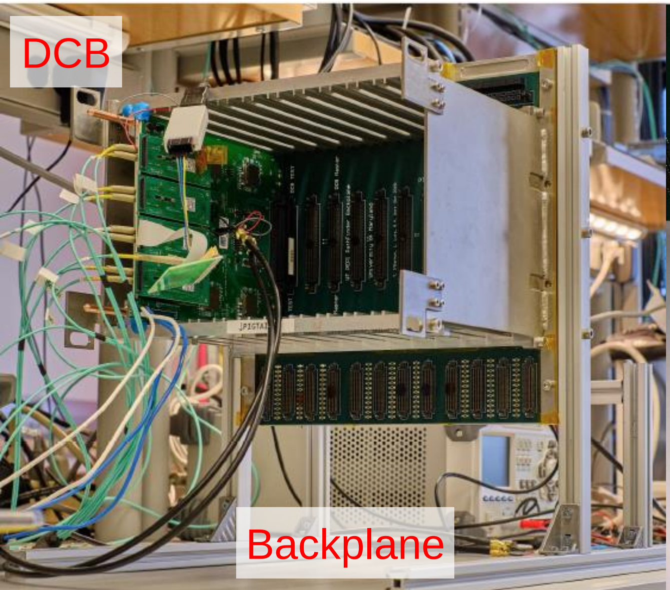


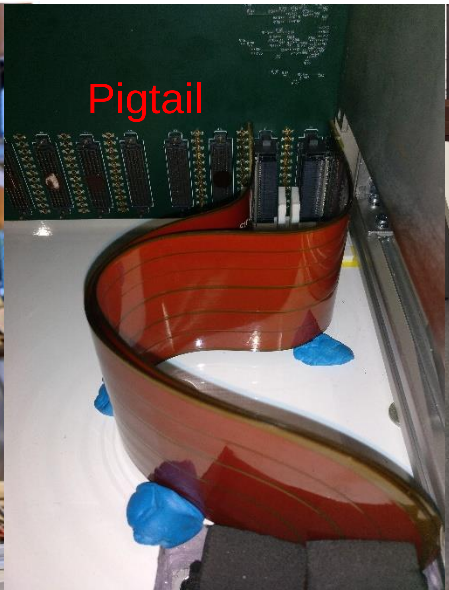




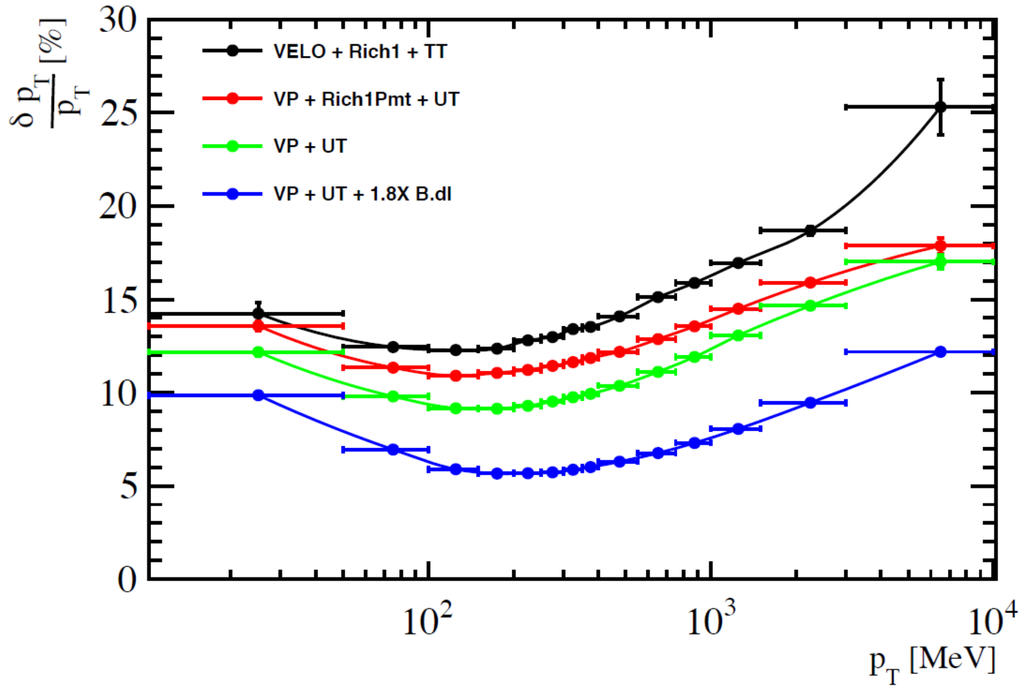
UT

- Near-detector electronics outside acceptance.
  - Distributes TFC&ECS signals.
  - Collects serial data from ASICs (320 Mbps).
  - Transmits optical serial data via GBTx/VTTx (~4.8 Gbps).
  - Connected to stave via pigtail flex cables.
- Two versions of read-out ASIC (SALT).
  - Problems found in previous iterations have been solved.
    - Analogue power issues, 40 MHz oscillations.
  - 4- (8-) ASIC modules assembled with SALT v3.5 (v3.8).
- Full read-out chain validated in system test.
  - First tests with final powering and grounding scheme.
  - CO_2 cooling tests at −30°C.



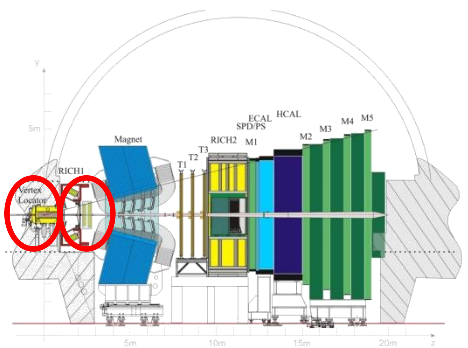


New UT + Phase-I VELO

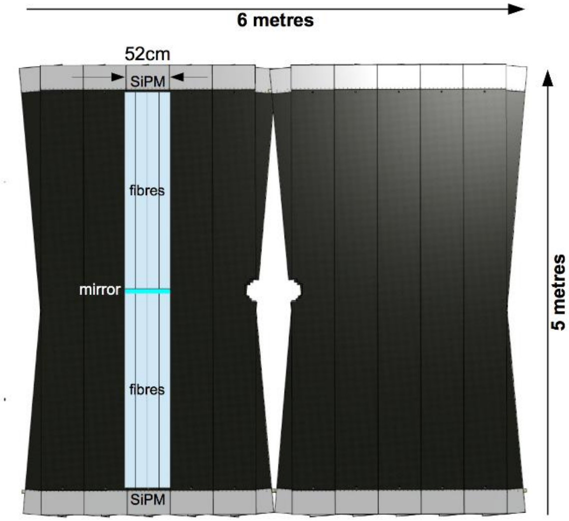


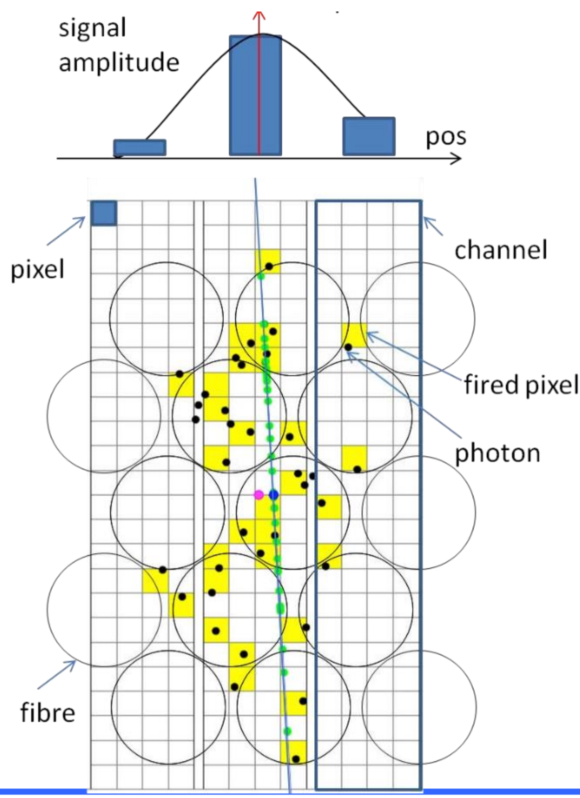
better p_T resolution
+
drastic reduction in ghost rate
+
large gain in reconstruction time!

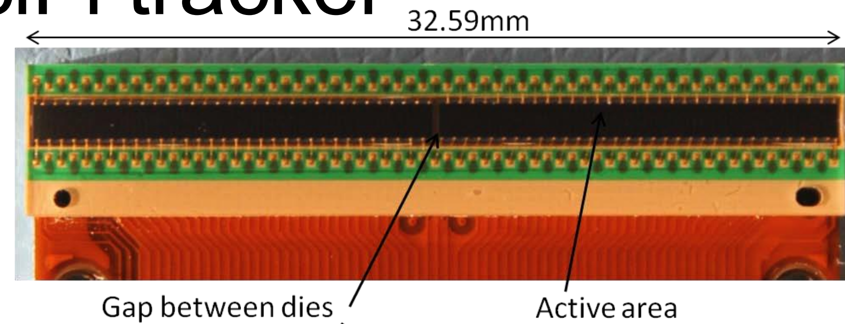
	ϵ(%)	GR(%)	t(ms)	err	range	min_{p_T} (MeV)
No p-estimate	96.3	52.1	25.7			1100
$\delta p/p = 0.0$	96.7	2.9	3.0	0.06	60	1245
$\delta p/p = 0.1$	96.7	3.4	5.2	0.17	60	1000
$\delta p/p = 0.2$	96.7	4.9	8.2	0.28	60	750
$\delta p/p = 0.3$	96.7	7.2	16.6	0.39	60	500

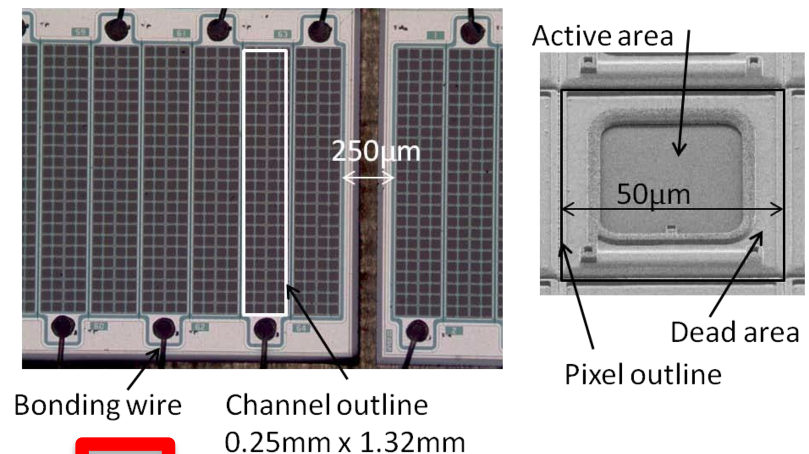


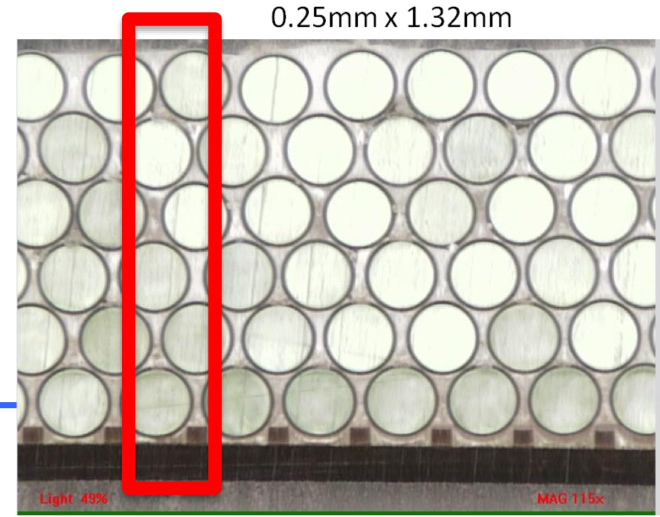
SciFi tracker











RICH

RICH1:
Change everything but the magnetic shielding

- mirrors, gas enclosure, quartz windows
- Photon detectors, electronics, detector mechanics

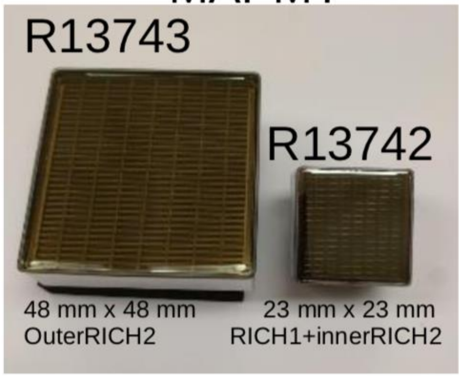
=> 22 columns

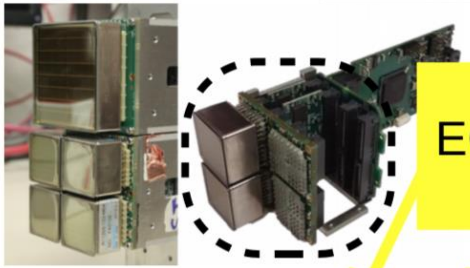
RICH2:
Change only detectors

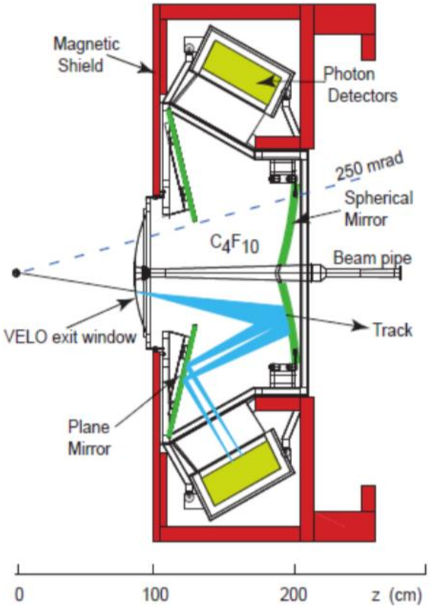
- Photon detectors, electronics, detector mechanics

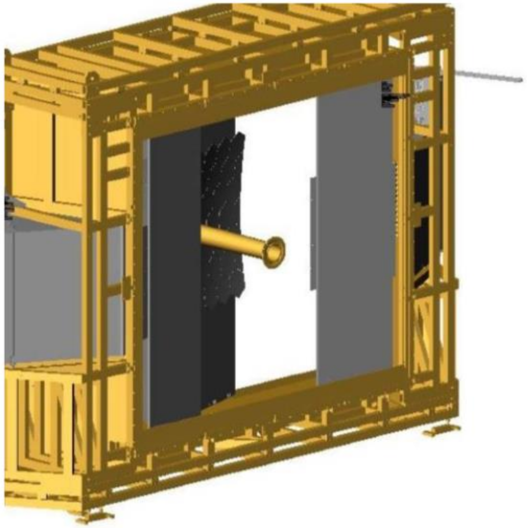
=> 24 columns

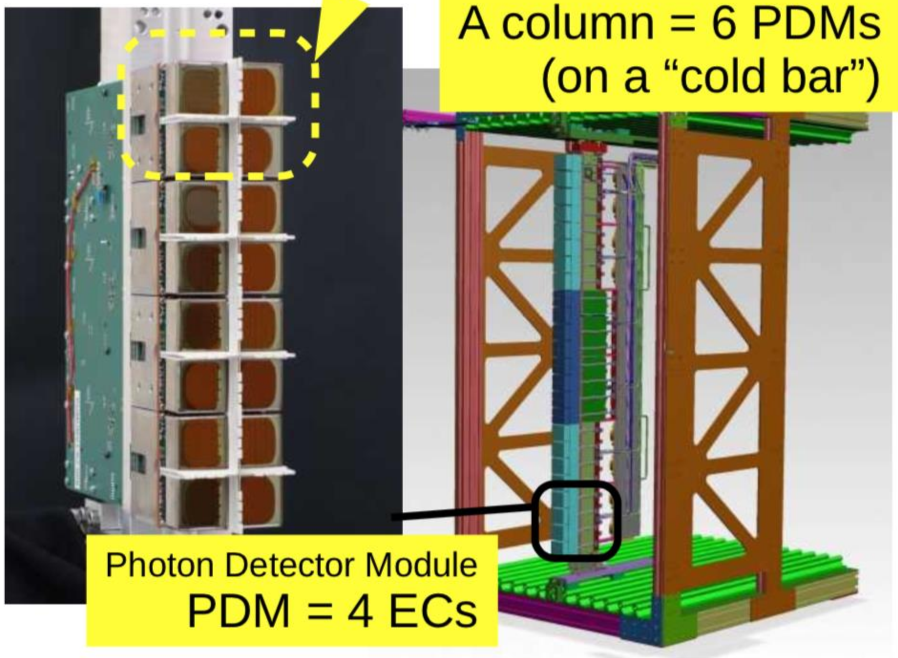
MAPMT











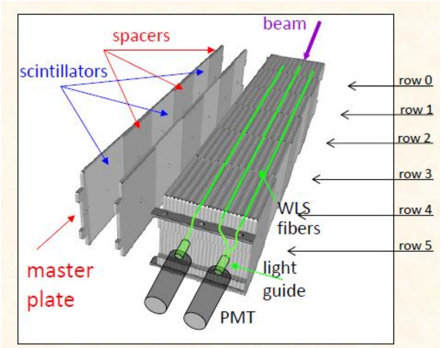
Upgraded Calorimeters

Present Calorimeters detectors will be kept:

- ECAL (Shashlik 25 X_0 Pb + scintillator)
- HCAL (TileCal Fe + scintillator)

→ PreShower / ScintillatingPadDetector (PS/SPD) will be removed

HCAL



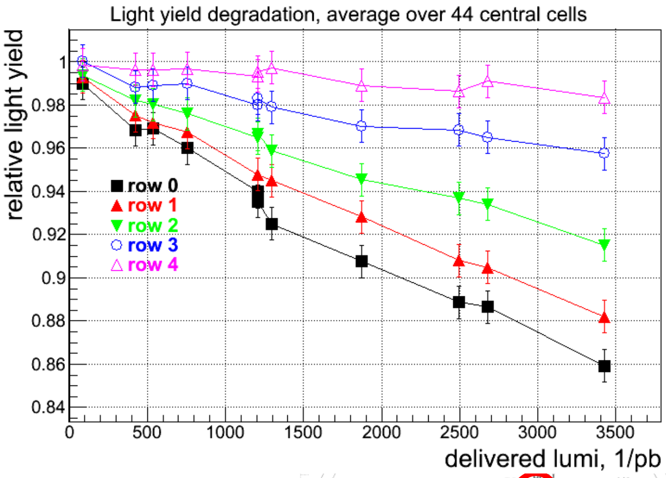
Main changes:

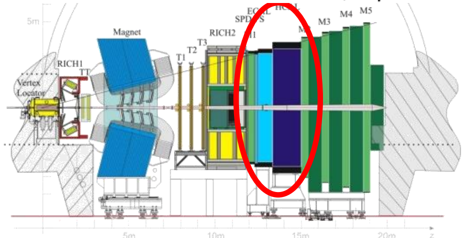
PMT gain will be reduced by a factor 5

- to reduce ageing due to higher luminosities

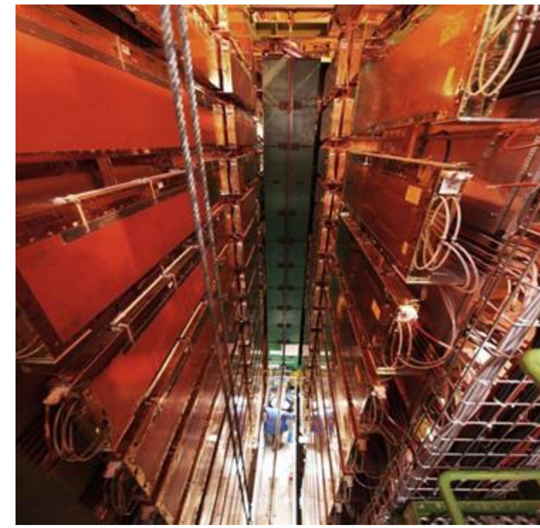
Front-End electronics will be redeveloped

- to be compatible with the reduced gain (R&D)
- to be compatible with trigger-less readout





Upgraded Muon Detectors



Present Muon detector will be kept:

- 4 layers (M2-M5) of Multi-Wire Proportional Chambers (MWPC)

→ first layer of Muon Detector (M1 – used in first-level trigger, with GEMs) will be removed

Main changes:

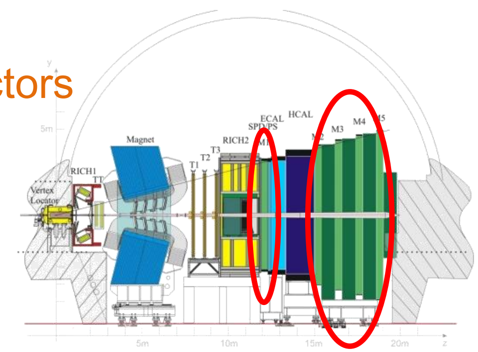
Front-End electronics will be redeveloped

- to be compatible with trigger-less readout

R&D:

Replace inner part of M2 (closest to IP) with RWEL and GEMs detectors

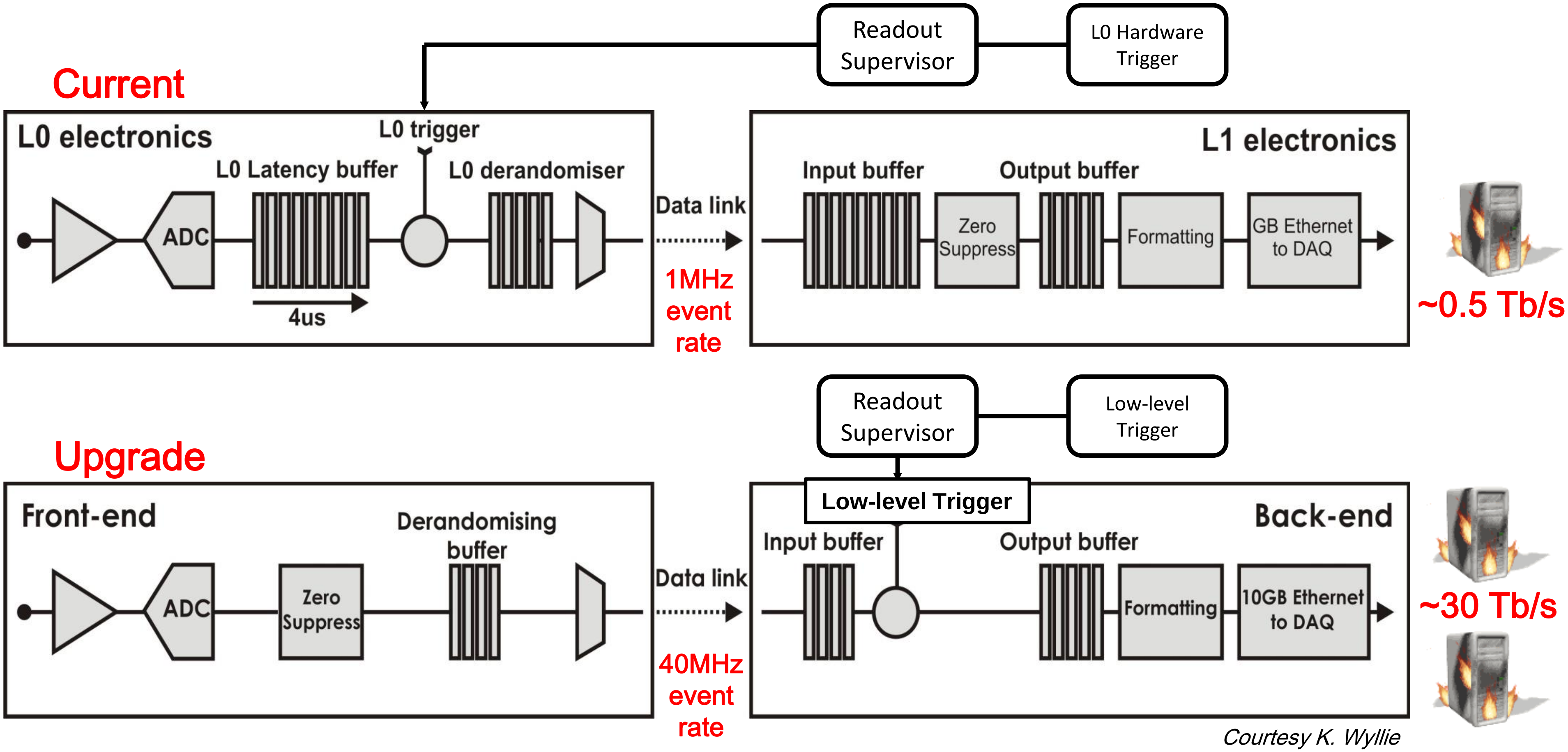
- to have higher-granularity



Upgraded Readout Architecture

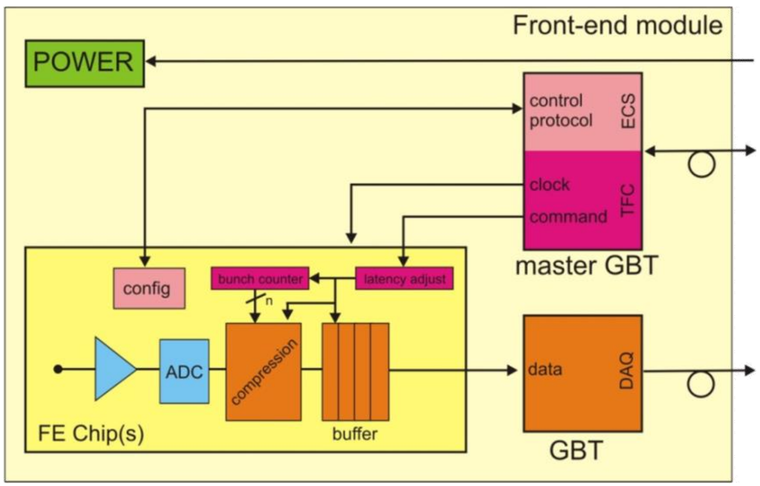
Reminder: remove the first-level hardware trigger

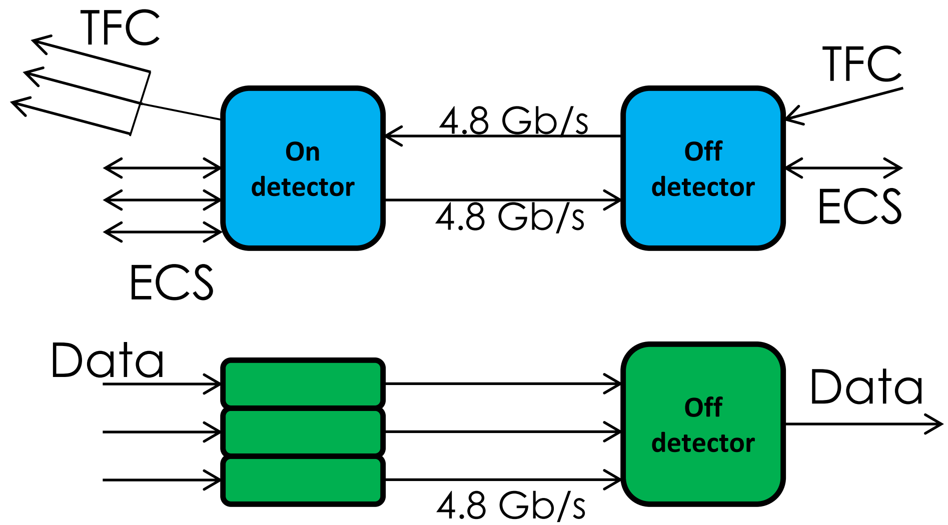
→ accept all LHC bunch crossing: trigger-less Front-End electronics!



Courtesy K. Wyllie

Trigger-less Front-Ends





1. Need to compress (zero-suppress) data already at the FE to reduce data throughput
   - reduce # of links from ~80000 to ~12500 (20 MCHF to 3.1 MCHF)
2. Use separate link bandwidth efficiently for data
   - Pack data across data link continuously with elastic buffer before link
3. Compact links merging Timing, Fast (TFC) and Slow Control (ECS).
   - Extensive usage of the CERN GBT development

→ Support data driven readout (asynchronous) + big latencies!

Readout & DAQ

Future LHC DAQs in numbers

	Event-size [kB]	Rate [kHz]	Bandwidth [Gb/s]	Year [CE]
ALICE	20000	50	8000	2019
ATLAS	4000	200	6400	2022
CMS	2000	200	3200	2022
LHCb	100	40000	32000	2019

Courtesy N. Neufeld

- Exploit the economies of scale → try to do what everybody does but smarter!
- Some overlapping trends across experiments, at least conceptually
  - custom-made Readout Boards with fast optical links and big&powerful FPGAs
    - ✓ ideally with fast interface to PCs (PCIe Gen3 or future…)
    - ✓ ideally with some co-processing (GPUs…)
  - commercial network technologies following market trends in terms of BW & costs
    - ✓ distributed vs data-center-like network. Ethernet vs InfiniBand.

Full HLT1 trigger is called Allen

LHCB-TDR-016

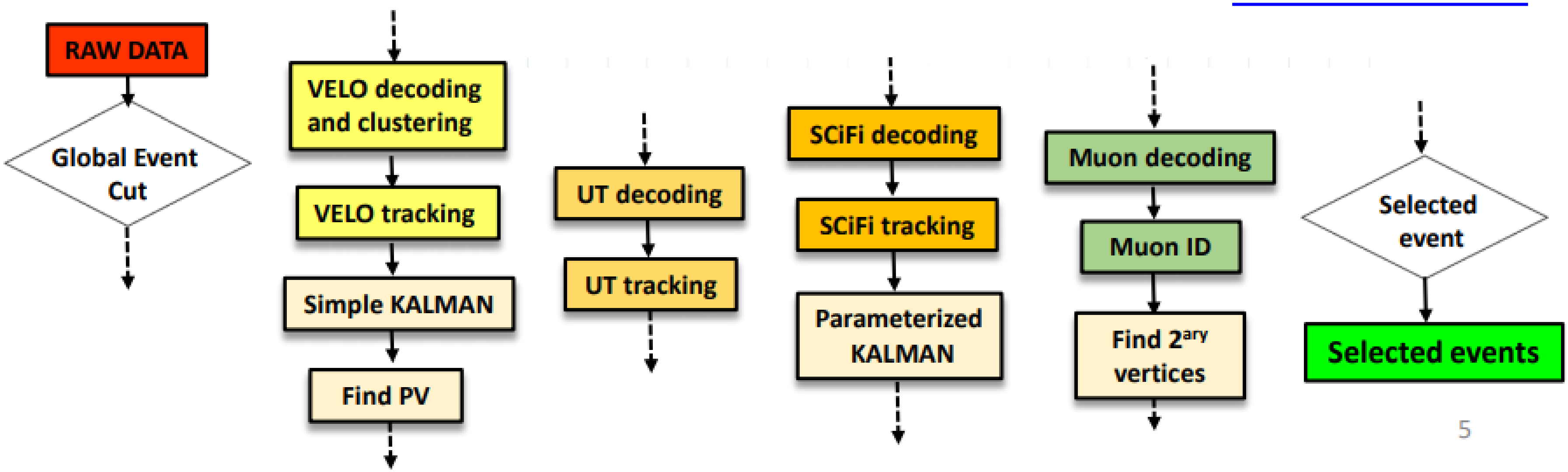
Allen project for fully software trigger on GPUs

- Implemented on C++, CUDA and python
- Running also for CPU and HIP (AMD, experimental)
- It can run standalone
- Continuously improving
- Getting ready to be commissioned

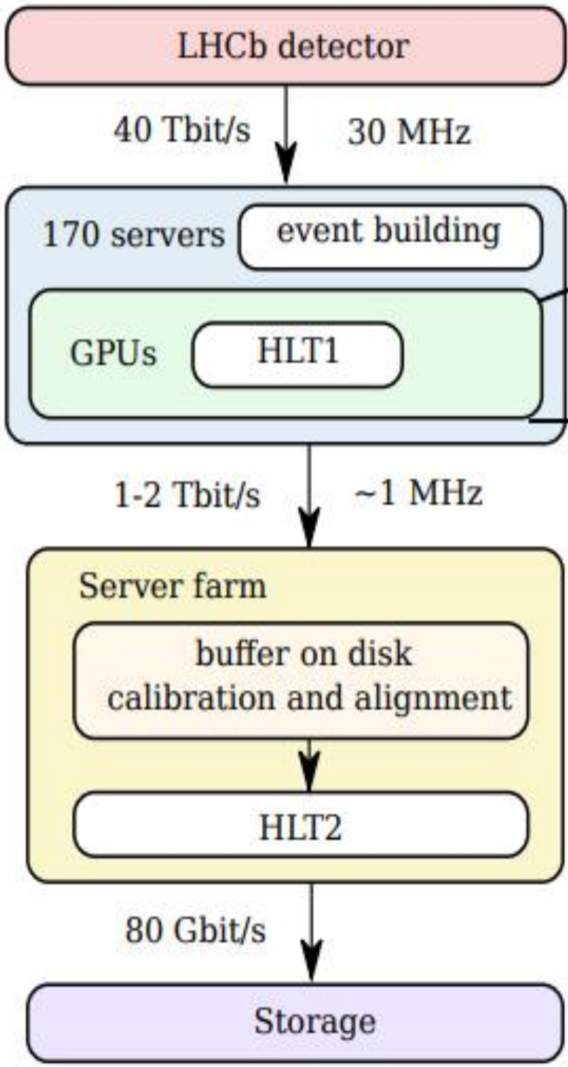
Technical design and performance of a GPU HLT1

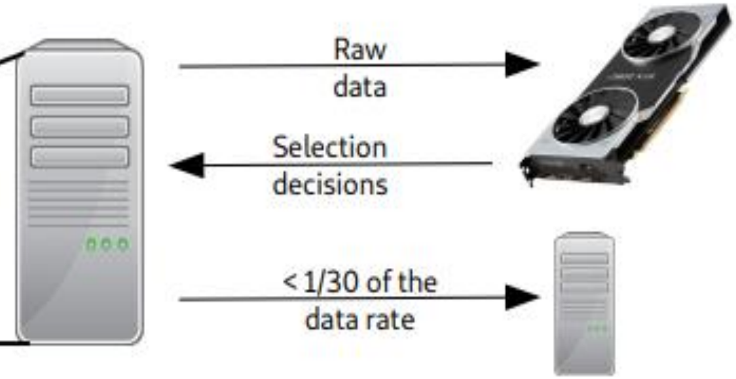
R. Aaij[1], J. Albrecht[2], M. Belous[a,3], P. Billoir[6], T. Boettcher[4], A. Brea Rodríguez[5], D. vom Bruch[6], D. H. Cámpora Pérez[b,7], A. Casais Vidal[5], T. Colombo[7], D. C. Craik[4], P. Fernandez Declara[c,7], L. Funke[2], V. V. Gligorov[6], B. Jashal[9], N. Kazeev[a,3], D. Martínez Santos[5], X. Mayo López[5], F. Pisani[d,e,7], D. Pliushchenko[f,3], S. Popov[a,3], R. Quagliani[6], M. Rangel[10], F. Reiss[6], C. Sánchez Mayordomo[9], R. Schwemmer[7], M. Sokoloff[11], H. Stevens[2], A. Ustyuzhanin[a,3], X. Vilasís-Cardona[8], M. Williams[4], L.Zhang[12]

LHCB-TDR-021

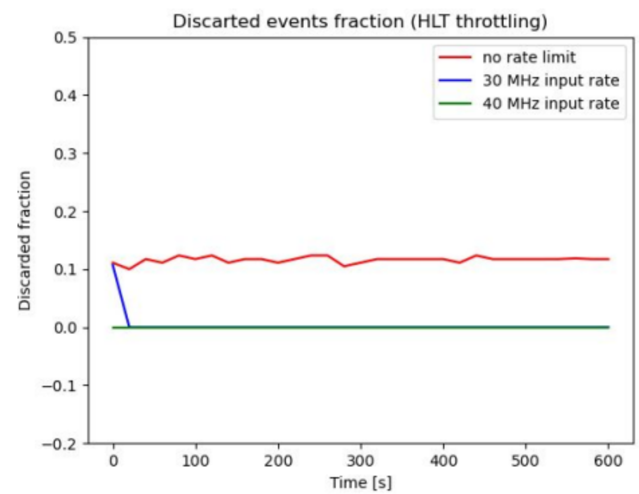


Full HLT1 on GPUs



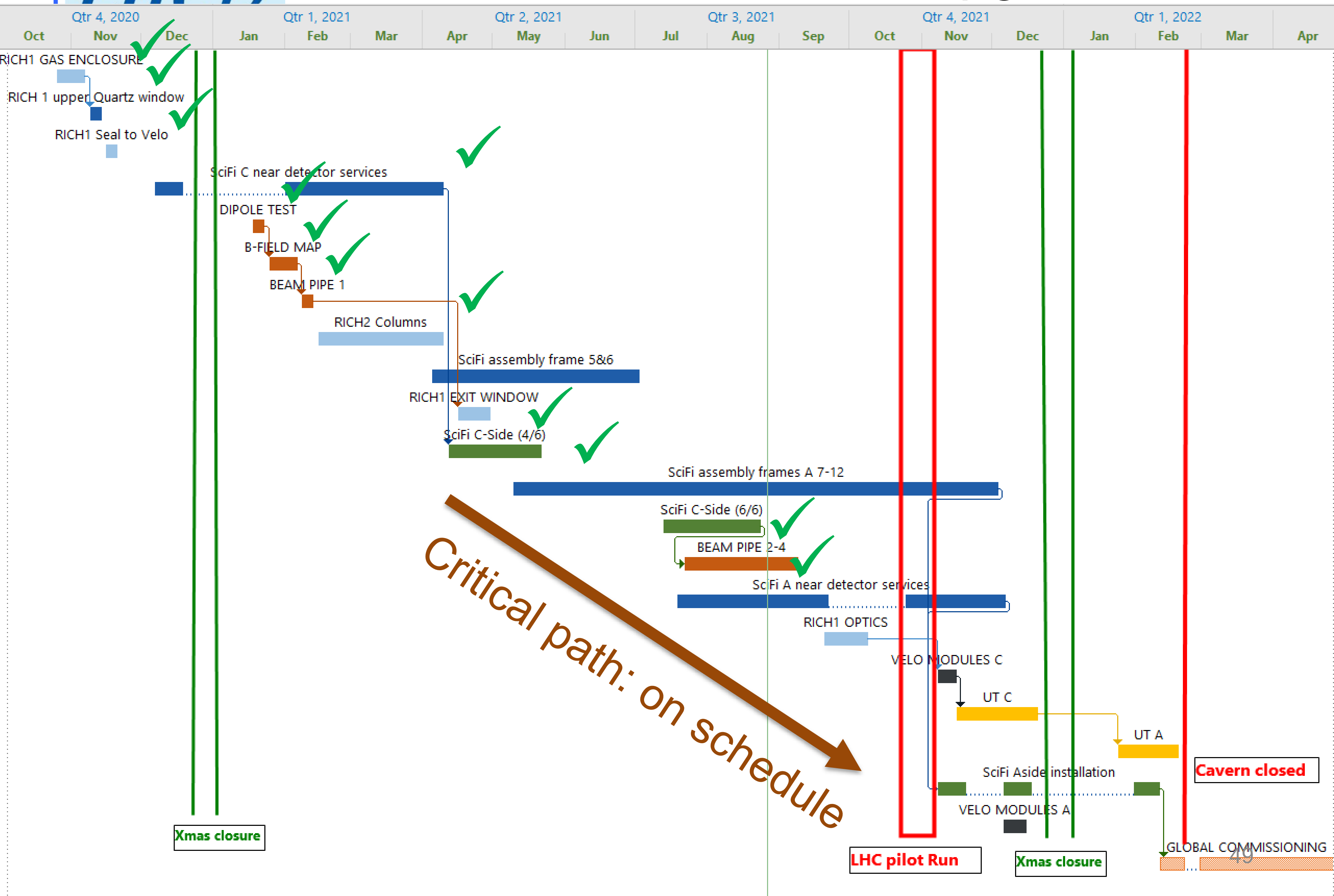


HLT1 (*Allen*):
partial & fast reconstruction + selections
→ runs at visible collision rate



Current performance already adequate!
→ No events discarded at 40 MHz.

Installation schedule Upgrade-I



Installation

RICH 1 mechanics installed:

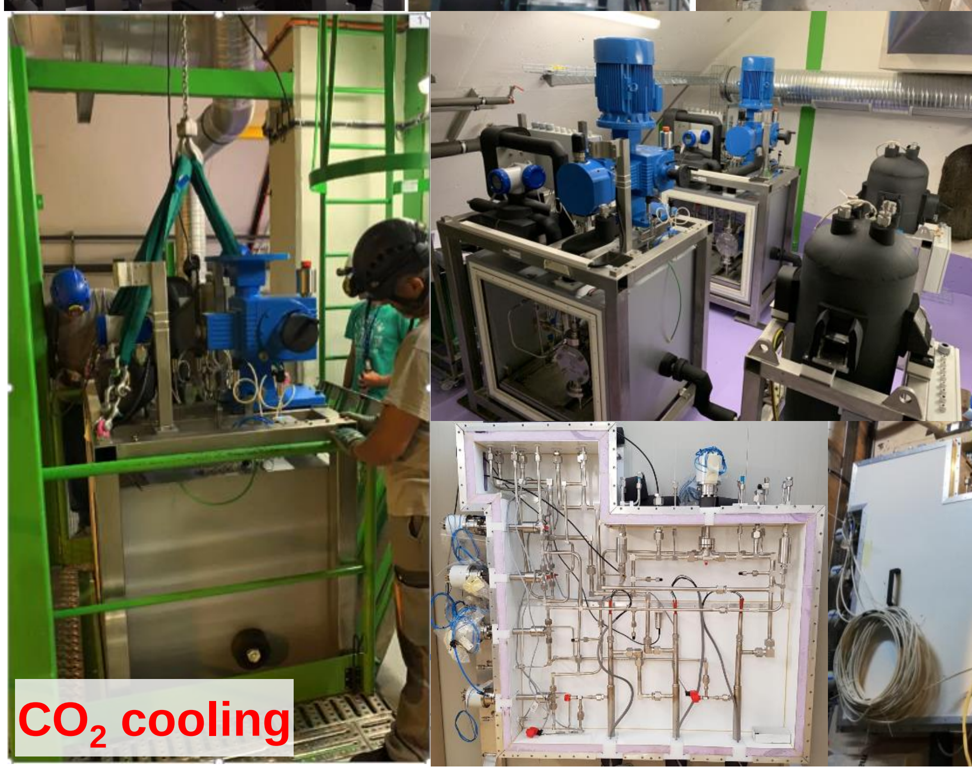
- Magnetic shielding shelves, MaPMT supports, gas enclosure.

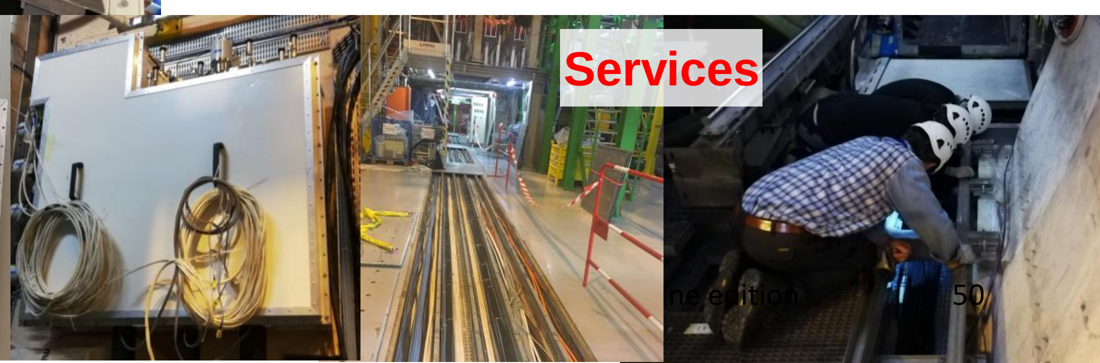
Detector Services:

- 100% of long distance copper cables installed.
- 100% of optical fibres installed & tested.
  - Few fibres with power loss > threshold.
- 100% of long distance pipes installed.

CO_2 cooling plants (VELO & UT):

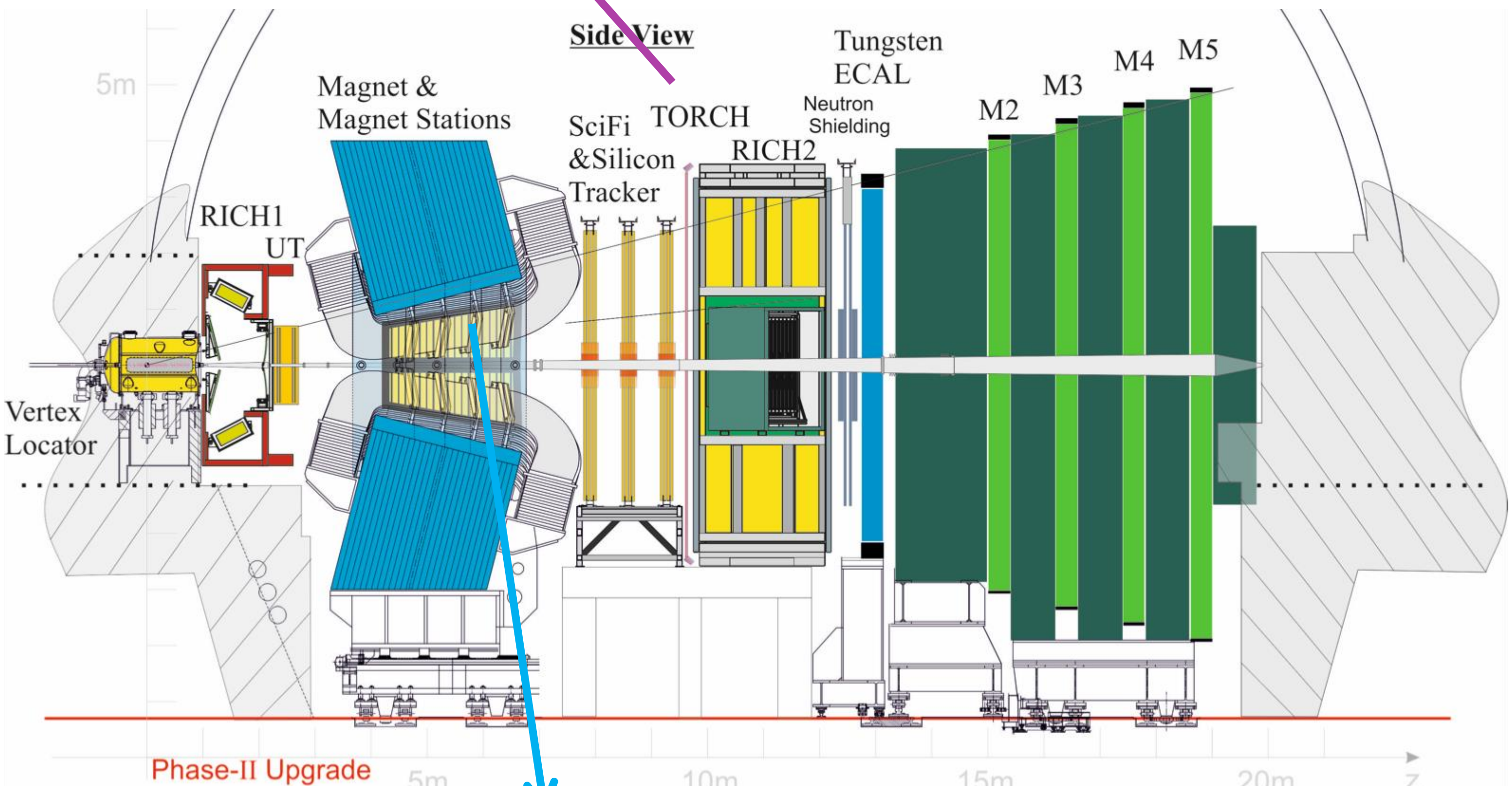
- CO_2 cooling plants and distribution boxes installed.
- Connections and first tests performed.
- Cleaning required to remove “oil”.





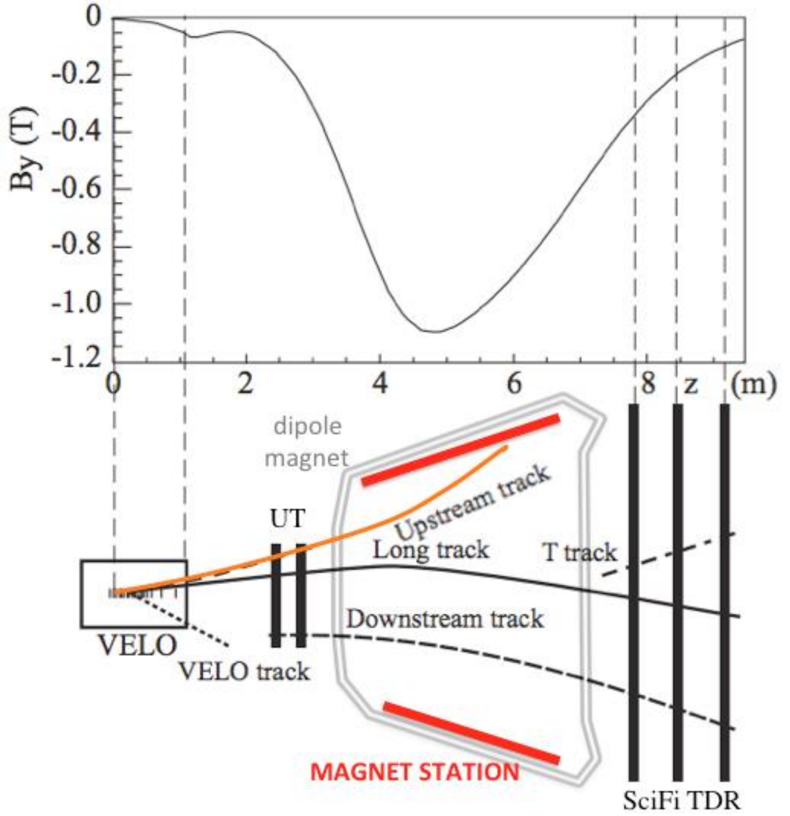
Phase-Ib consolidation (still R&D phase)

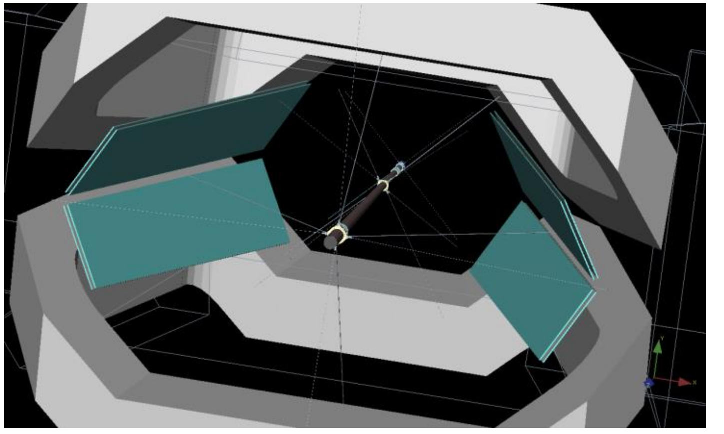
Add TORCH detector in front of RICH2

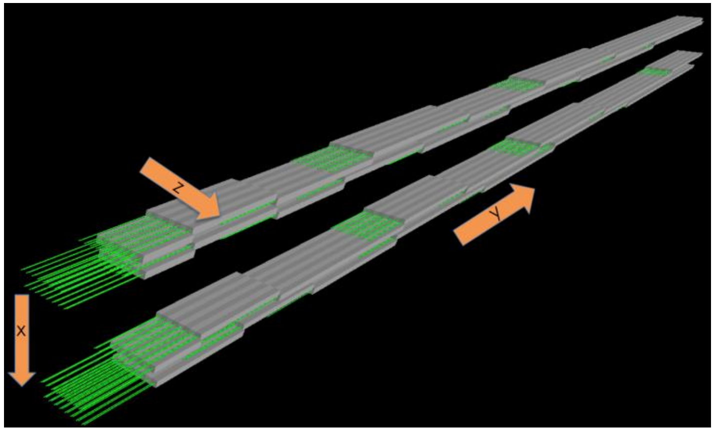


Additional Tracking stations in the magnet

Tracking stations in the magnet







- Reconstruction low momentum tracks
- Scintillator bars read out with SiPMs outside acceptance
  - Re-use existing SciFi Tracker electronics (ASIC, read-out boards, etc)

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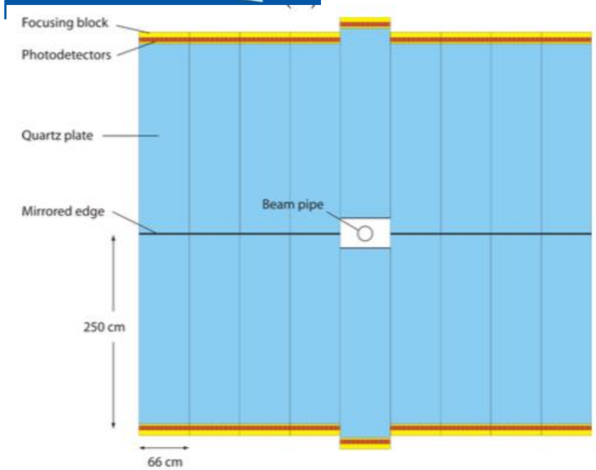
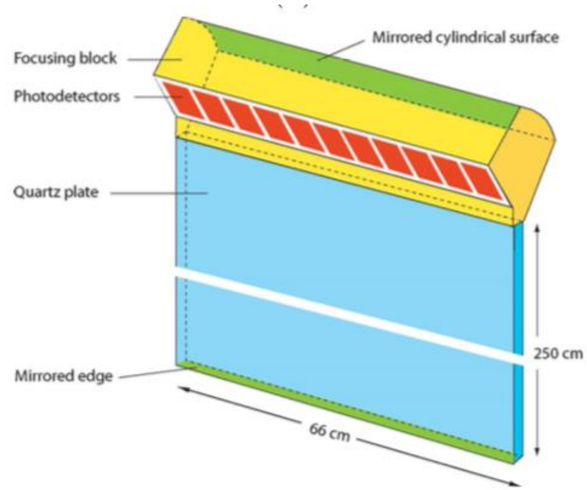
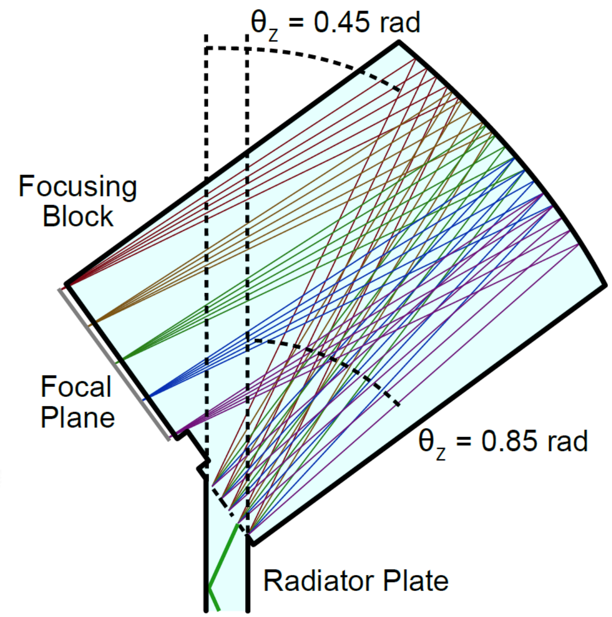
TORCH







- Time Of internally Reflected CHerenkov light
  - Large area time-of-flight detector
  - Provide PID in momentum range 1 – 10 GeV/c
- Cherenkov light produced in quartz plates
  - Photons travel to detector plane via total internal reflection
- Focusing block focuses image on detection plane
- Multichannel plate PMTs with 35 ps time resolution
  - Resolutions of 88 – 130 ps achieved in test beams

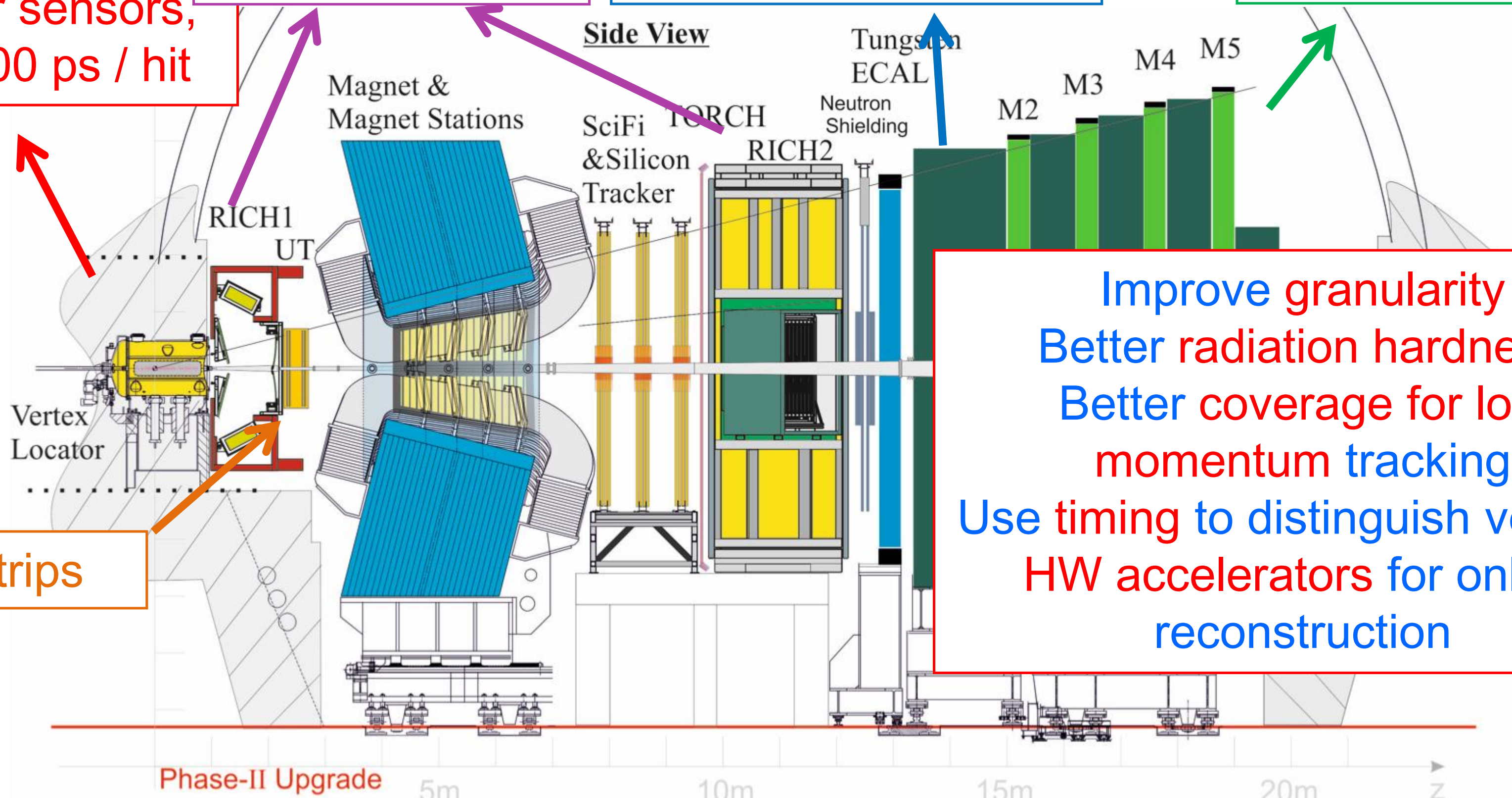
Phase-II upgraded LHCb detector

New Vertex Detector II
Smaller pixels, thinner sensors,
$\sigma_t < 200$ ps / hit

RICH with new photon detectors
$\sigma_t < 100$ ps / photon

ECAL with finer segmentation and timing with
$\sigma_t \approx 20 - 50$ ps

MUON with MPGD (μ-RWELL), modified shielding



Si-strips

Improve granularity
Better radiation hardness
Better coverage for low momentum tracking
Use timing to distinguish vertices
HW accelerators for online reconstruction

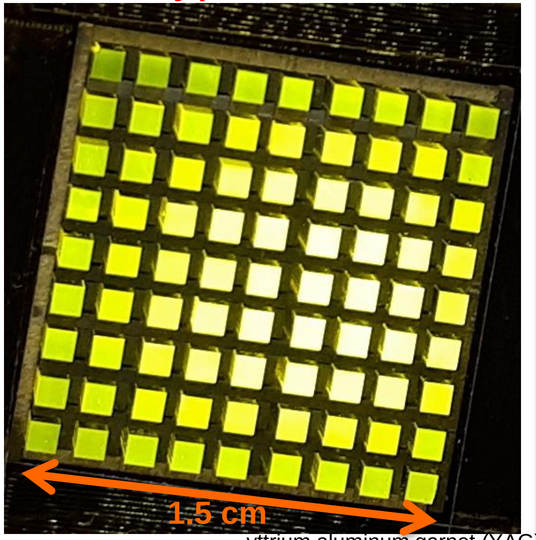
+ trigger-less readout (PCIe Gen4++) & accelerators for online reconstruction

Detector technologies for Run4++

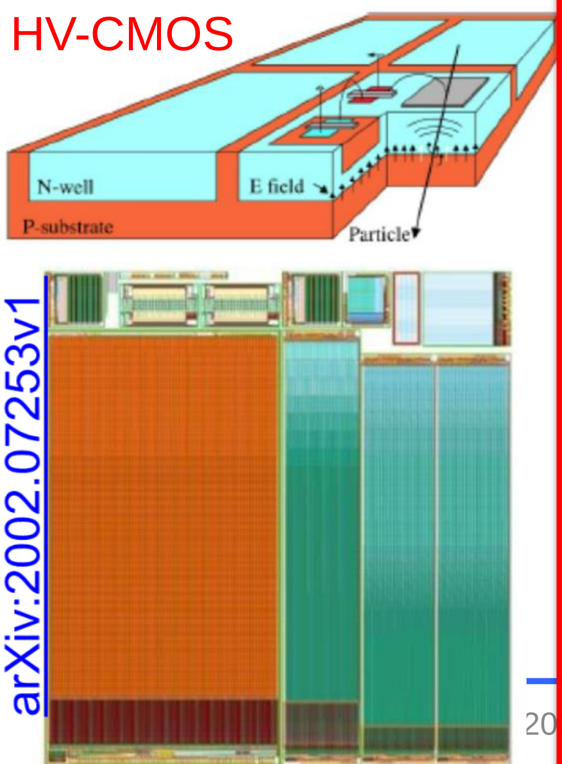
Ongoing R&Ds across collaboration

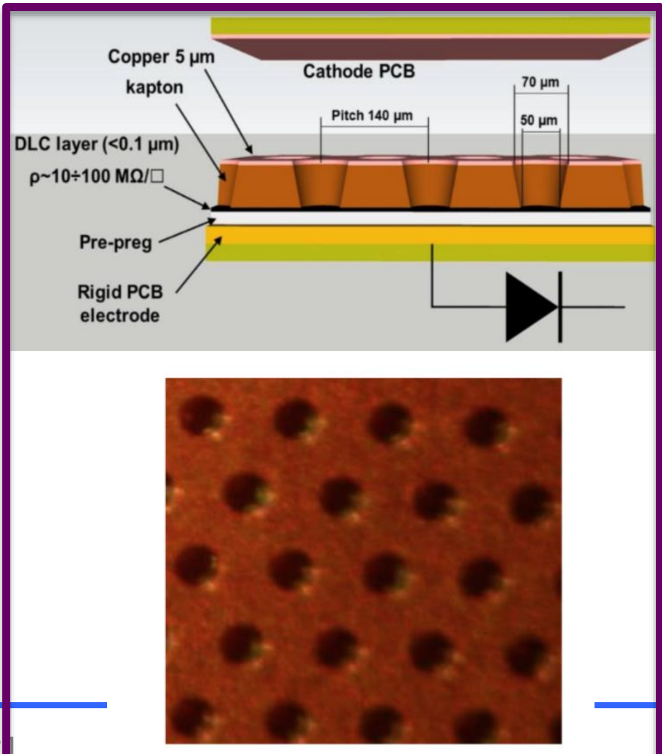
- SPACAL with crystal fibers
- CMOS tracker chip in design
- Silicon with timing capabilities
- Photon sensors with timing
- New MPGDs for high-rate MUON detection

Prototype CALO cell

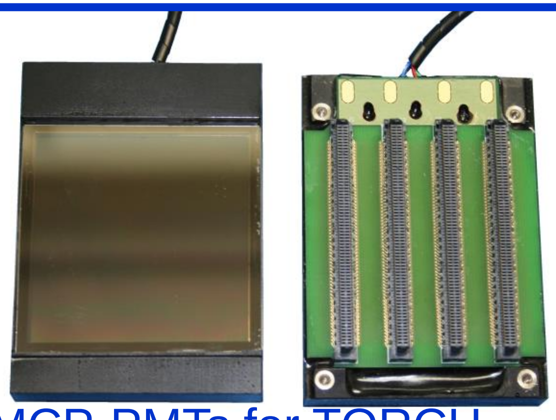


HV-CMOS





The µ-RWELL amplification stage



MCP-PMTs for TORCH

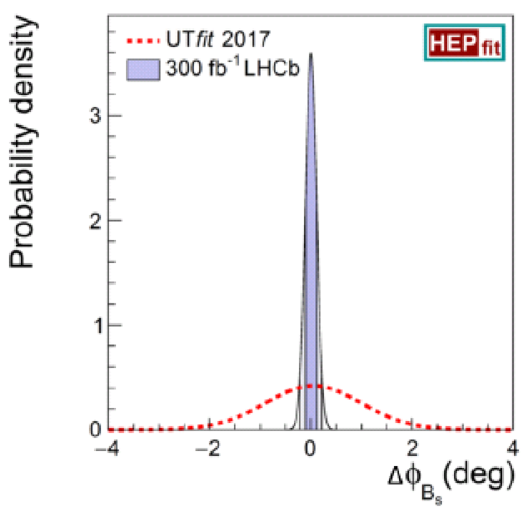
LHCb Phase-II upgrade

Just recently submitted an EoI to install an upgraded LHCb detector that can operate up to a peak instantaneous luminosity of **2×10^{34} cm^{-2}s^{-1}**

- between x50-x100 more than today and x10 more than Phase-I upgrade
- to be ready for LHC Run V and to fully exploit HL-LHC

Improve even more the Phase-I LHCb precision:

- Comprehensive measurement programme of observables in a wide range of b->s l^+l^- and b-> d l^+l^- employing both muon and electron modes
- Measurement of the CP-violation phases γ and ϕ_s with a precision of 0.4° and 3 mrad



NP contribution to ϕ_s

(dark blue 68%, light blue 95%)

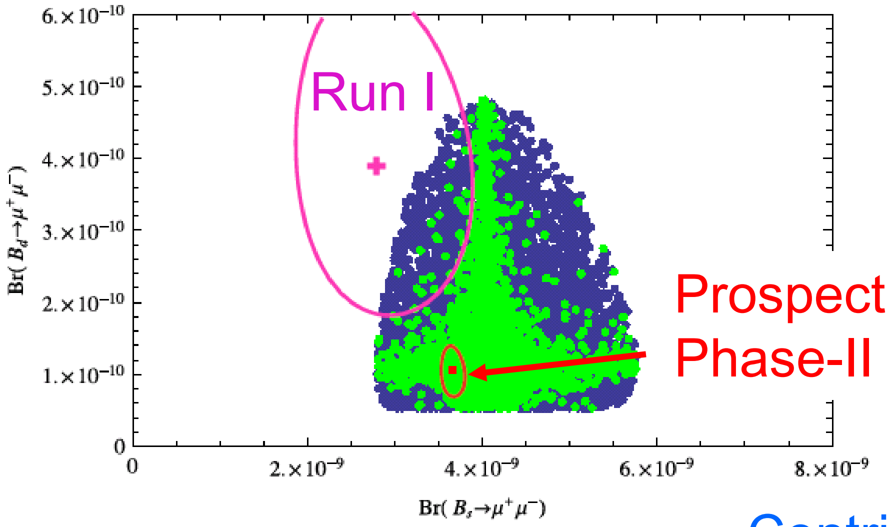
LHCb Phase-II upgrade

For an exhaustive list see CERN-LHCC-2017-003

Improve even more the Phase-I LHCb precision:

- Measurement of B ($B^0 \to \mu^+\mu^-$) / B ($B_s \to \mu^+\mu^-$) with 20% uncertainty
- CP-violation studies in charm with 10^{-5} precision
- Exotica searches, dark photons?

Close up on $B^0 \to \mu^+\mu^-$ and $B_s \to \mu^+\mu^-$ with 14% precision on ratio



Contribution to knowledge of $|V_{ub}/V_{cb}|$