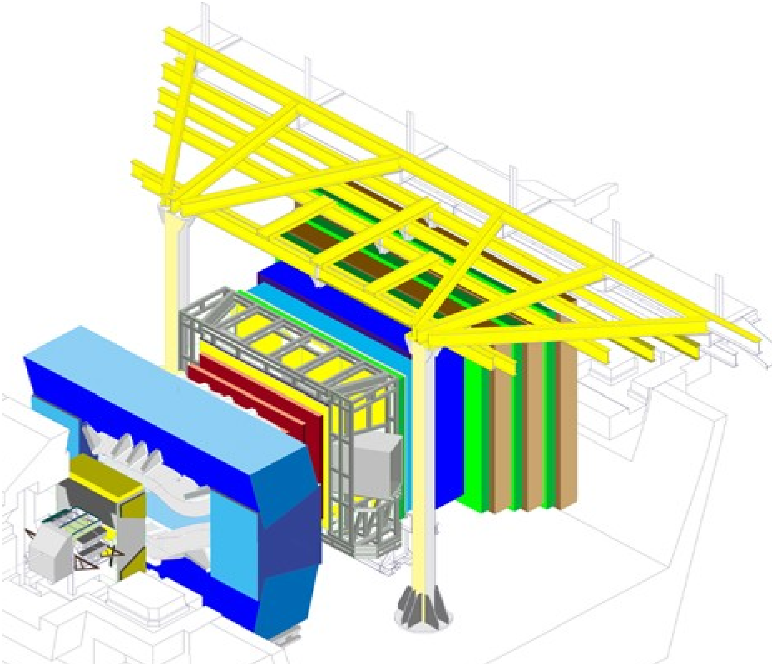
The LHCb Upgrade

Stéphane T'JAMPENS

on behalf of the LHCb collaboration



3rd KEK Flavor Factory workshop
KEK-FF 2014

February 13-15, 2014

KEK, Tsukuba, Japan

Outline

Motivation

LHCb experiment

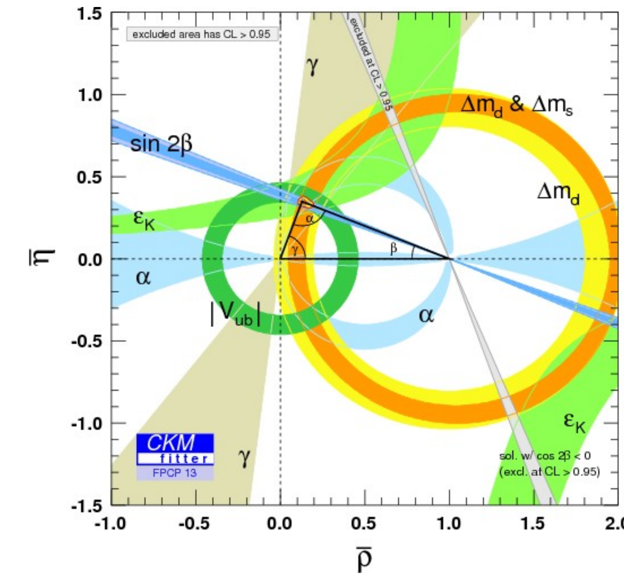
Upgrading LHCb

Challenges:

- Tracking
- Particle Identification
- Data Processing

Timeline and conclusion

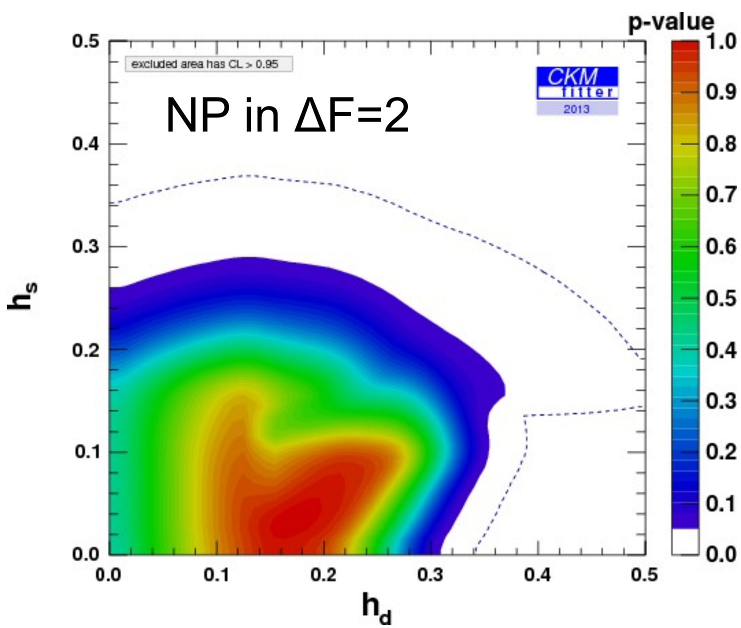
Motivation



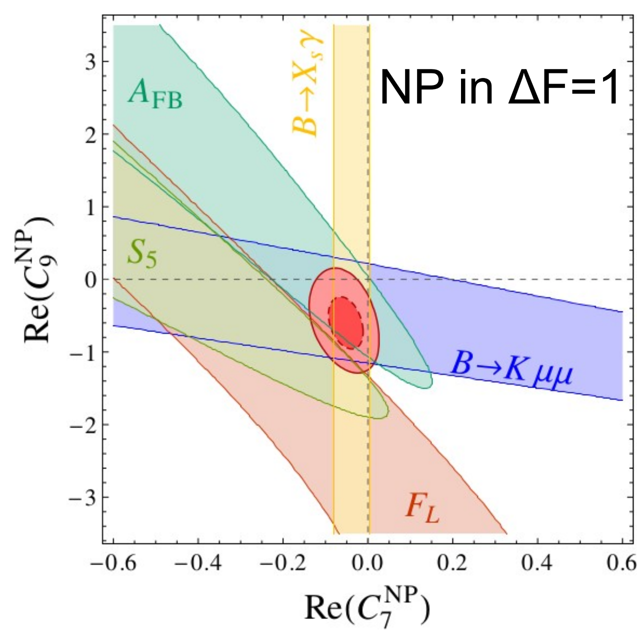
CKM matrix:

- dominant source of flavor and CP violation in flavor-changing processes
- Precision: ≤ 10%

NP effects are small but O(20%) contributions in most FCNC processes still allowed



arXiv:1309.2293



arXiv:1308.1501

➔ toward **high-precision** flavor physics

Top 9 theoretically clean observables

Need experimental precision and theoretical cleanliness to increase NP sensitivity

γ from tree ($B \to DK$, ...)	LHCb	Belle II
$\lvert V_{ub} \rvert$ from exclusive semi-leptonic B decays		Belle II
$B_{s,d} \to l^+ l^-$	LHCb	Atlas, CMS
CP violation in B_s mixing	LHCb	Atlas
$B \to K^{(*)} l^+ l^-, \nu\nu$	LHCb	Belle II, CMS
$B \to \tau\nu, \mu\nu$		Belle II
$K \to \pi\nu\nu$		NA62, KOTO, ORKA
CP violation in charm	LHCb	Belle II
Lepton flavor violation		MEG 3

[G. Isidori, European Strategy Preparatory Group, Krakow 2012]

- Need measurements in many different systems (K, D, D_s, B, B_s, B_c, Λ_b, …)
- Need to establish a pattern (correlations, ...)

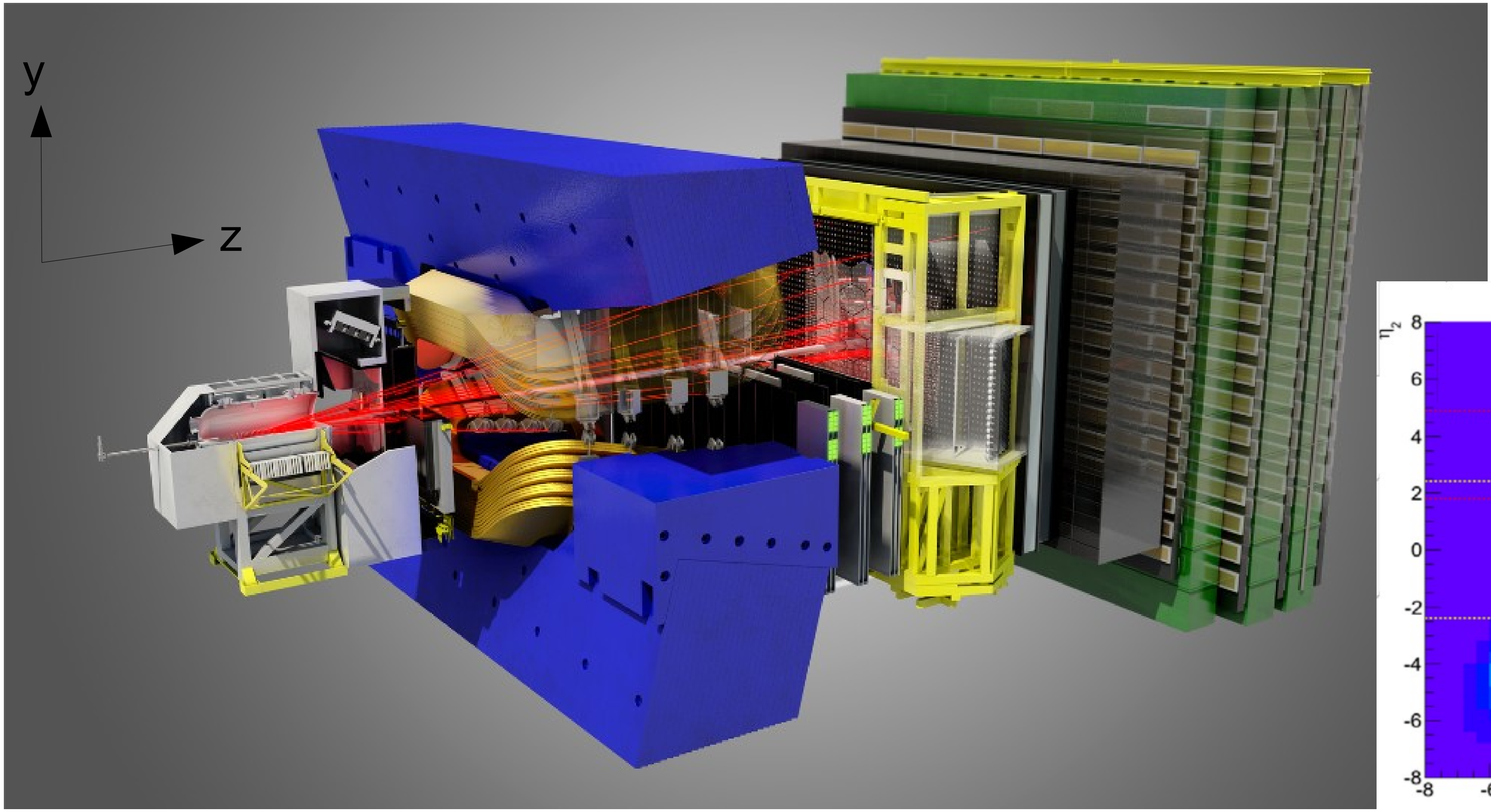
LHCb Experiment

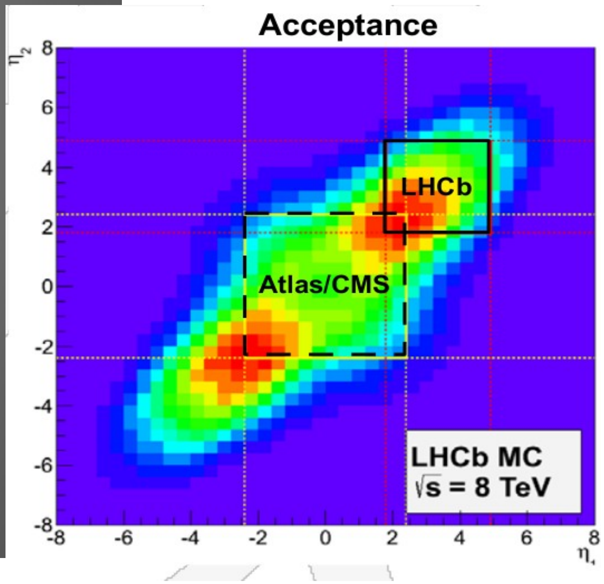
The LHCb detector

LHCb is a Forward General-Purpose Detector at the LHC:

- Single-arm forward spectrometer with unique coverage in pseudo-rapidity: $2 < \eta < 5$
- Catching ~30 % of heavy quark production cross-section with just 4% of solid angle
- Precision measurements in beauty and charm sectors

See Anton's and Diego's talks





The LHCb detector (point 8)

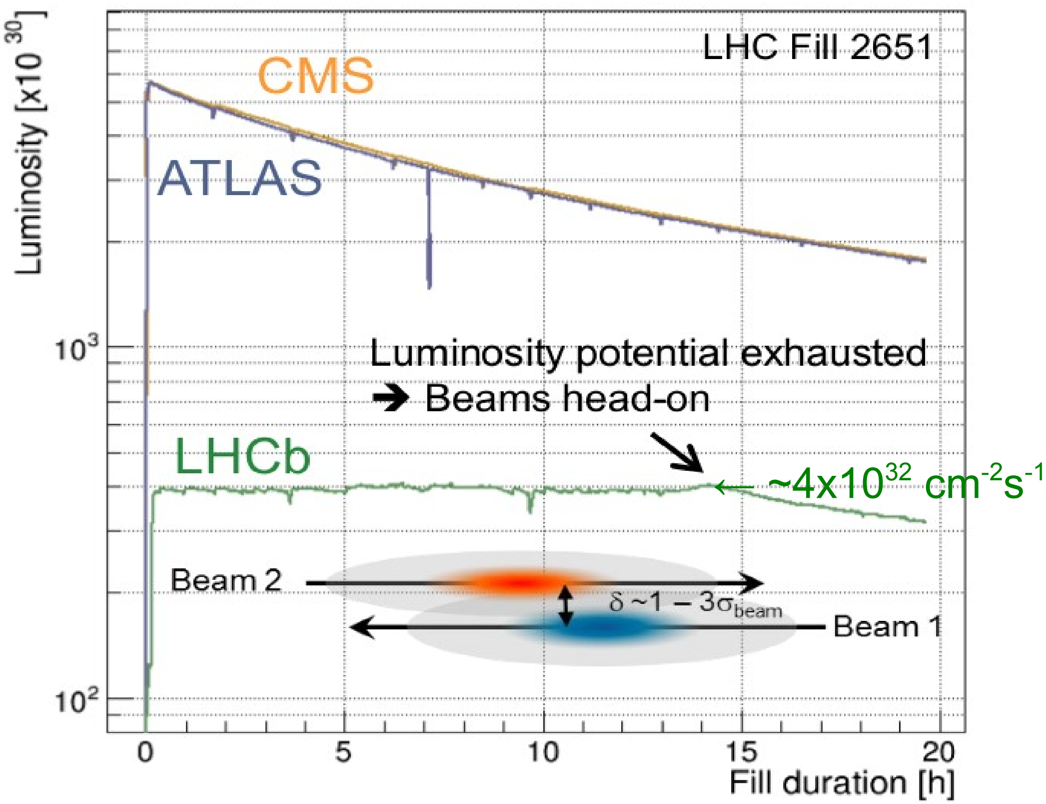
LHCb operation in 2011-2012

Design: L_{inst} = $2x10^{32}$ $cm^{-2}s^{-1}$ with pile-up=0.4 [2622 bunches, 25ns, 14 TeV]

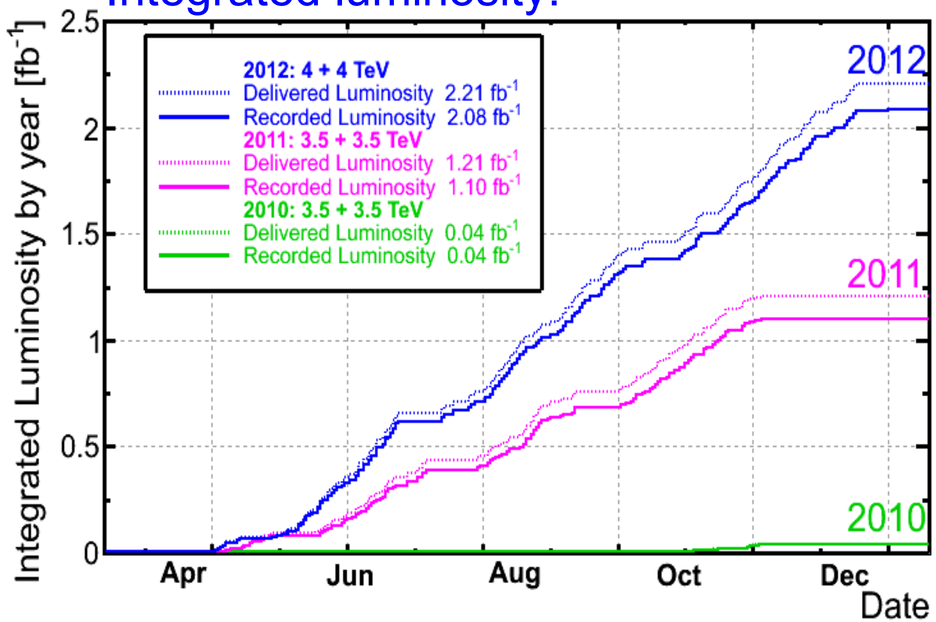
LHCb has excellent performance (beyond design)

Year	$\sqrt{s}$ [TeV]	$\mathcal{L} \times 10^{32}[\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	$\frac{\text{Interactions}}{\text{crossing}}$	HLT rate	L $[\mathrm{fb}^{-1}]$
2011	7	$2-4$	$0.4-2.5$	3 kHz	> 1.0
2012	8	4	1.6	5 kHz	> 2.0

Luminosity Levelling:



Integrated luminosity:



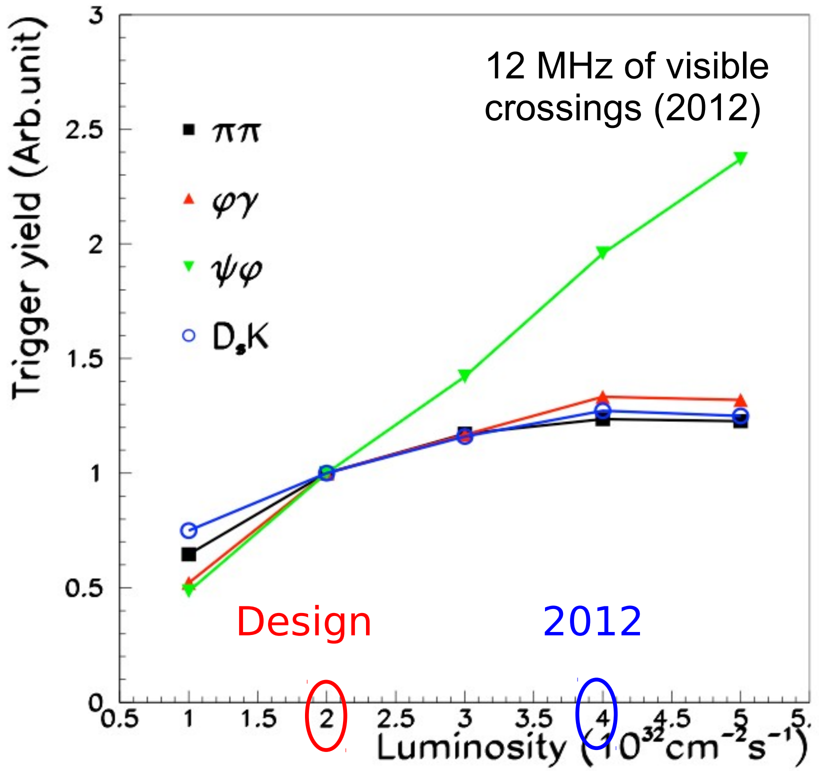
Upgrading LHCb

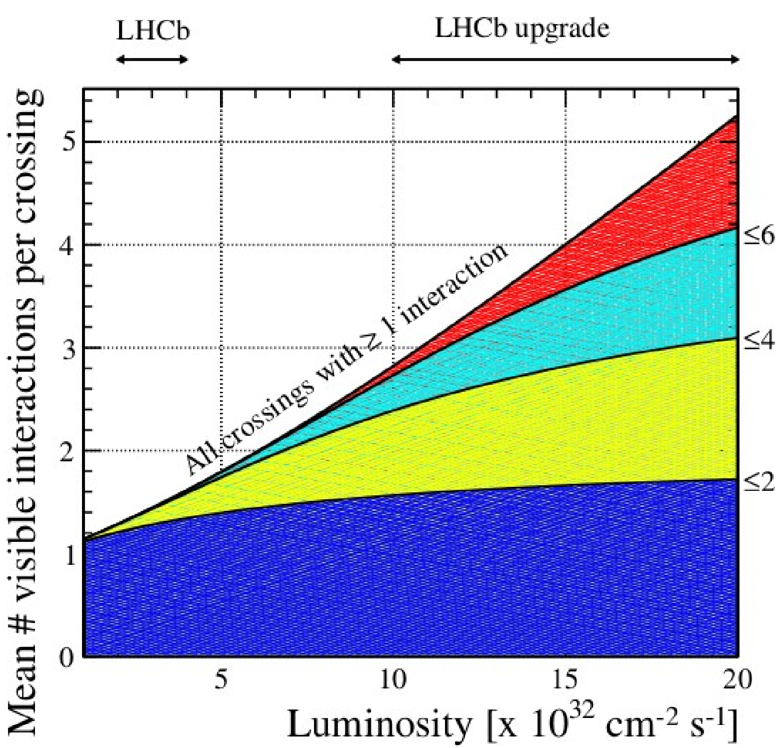
Current limitations

What prevents LHCb from running at higher luminosity already?

- Trigger limitation: L0 hardware trigger limited to 1.1 MHz (readout of Front-End electronics)
- Yield saturation: factor ~2 between di-muon events and fully hadronic decays

Saturation of the yields





At higher luminosities:

→ harsher cuts on p_T and E_T

→ More pile-up: events busier, reconstruction more difficult

→ Detector aging and degradation

for no real gain in statistics …

Upgrade strategy

Efficient selection requires IP and p_T of tracks

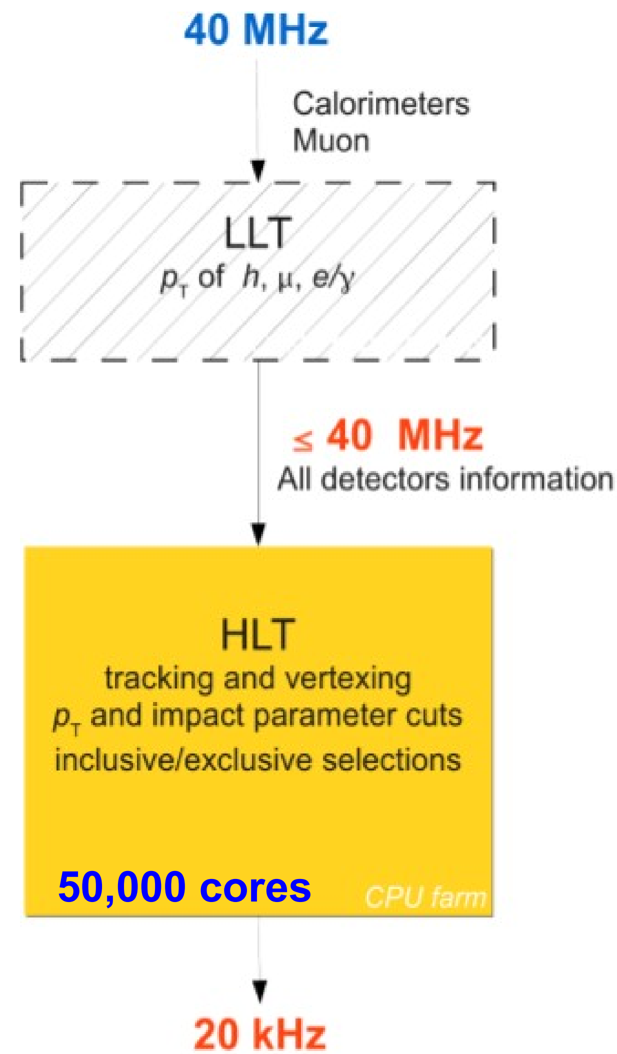
- **Remove L0 bottle neck** (almost → LLT (Low Level Trigger))

Implications of upgrade strategy:

- **Readout every LHC bunch crossing: 40 MHz** (instead of 1.1 MHz)
  - Trigger-less Front-End electronics
  - Multi-Tbit/s readout network
- **Fully software flexible trigger** (HLT)
  - output bandwidth~20kHz

Running Conditions:

- Design upgraded sub-detectors to sustain instantaneous luminosity up to $L_{inst} = 20 \times 10^{32}\ cm^{-2}s^{-1}$ [pile up=5.2, 2622 bunches, 25ns, 14 TeV]



► Collect ≥ **50 fb^{-1}** over 10 years (increase of Luminosity AND trigger efficiency)

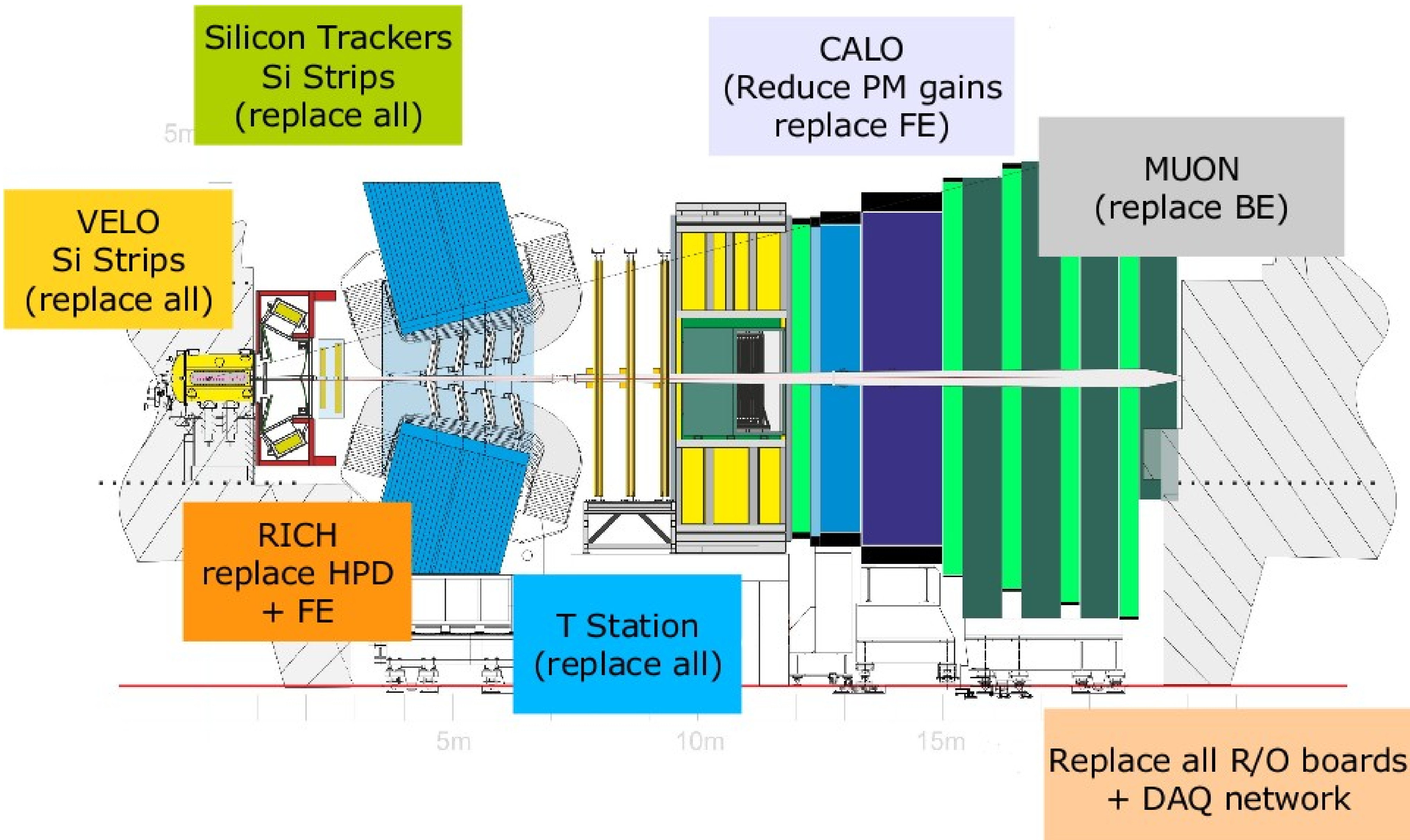
Statistical sensitivities

Comparable or better than theoretical uncertainties:

Observable	**Upgrade** [50 fb^{-1}] σ_{stat} / expected	Theory uncertainty σ_{theo} / expected
$\phi_s(B_s \to J/\psi\,\phi)$	**25%**	8%
q_0^2 de $A_{FB}(B^0 \to K^{*0}\mu\,\mu)$	**2%**	7%
$\mathrm{B}(B_s^0 \to \mu^+\mu^-)$	**5%**	8%
$\mathrm{B}(B^0 \to \mu^+\mu^-)/\mathrm{B}(B_s^0 \to \mu^+\mu^-)$	**40%**	5%
$\gamma(B \to D^{(*)}K^{(*)})$	**2%**	negligible

More observables in LHCb-PUB-2013-015

The 40 MHz detector



Tracking Challenges

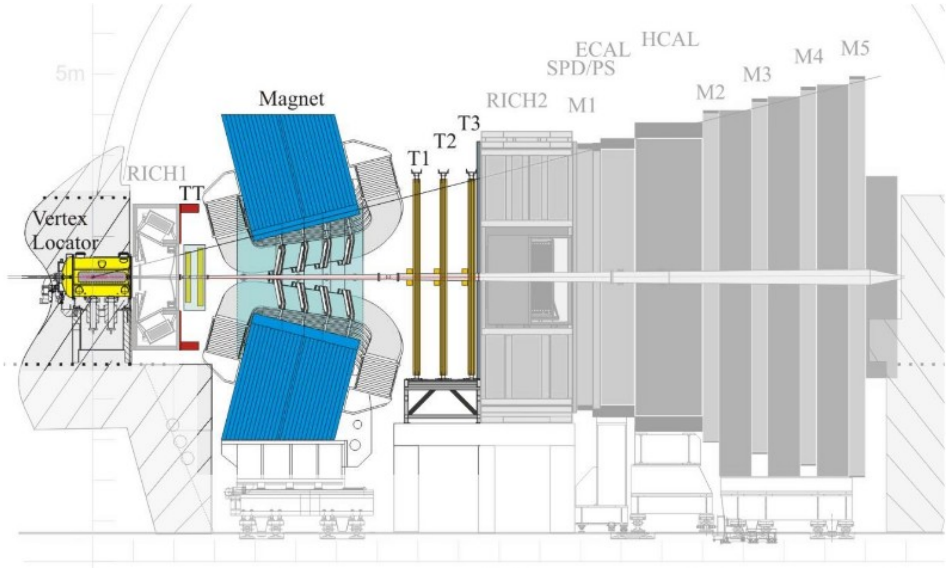
Tracking challenges

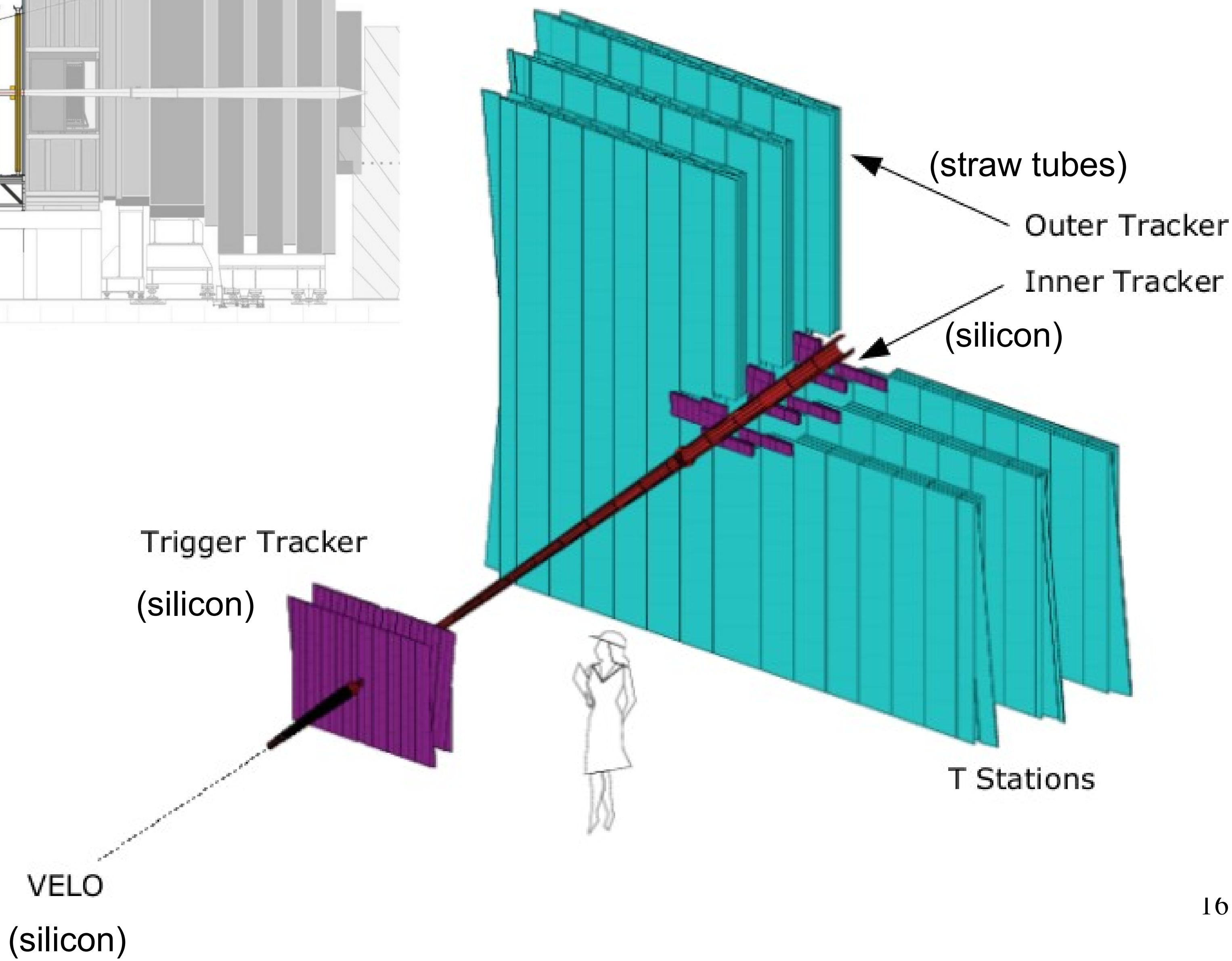
When the luminosity and the pile-up increase,
it is challenging to keep or even improve:

- High momentum resolution [$\sigma(p)/p = 4\times10^{-3}$ at 5 GeV/c]
- High IP resolution [20 μm at hight p_T]
- High Track efficiency [96% for long tracks]
- Low Ghost rate [~10%]
- Fast pattern recognition

Fast pattern recognition is a key issue for the upgrade
since it has to run in the software trigger.

Current LHCb tracking system



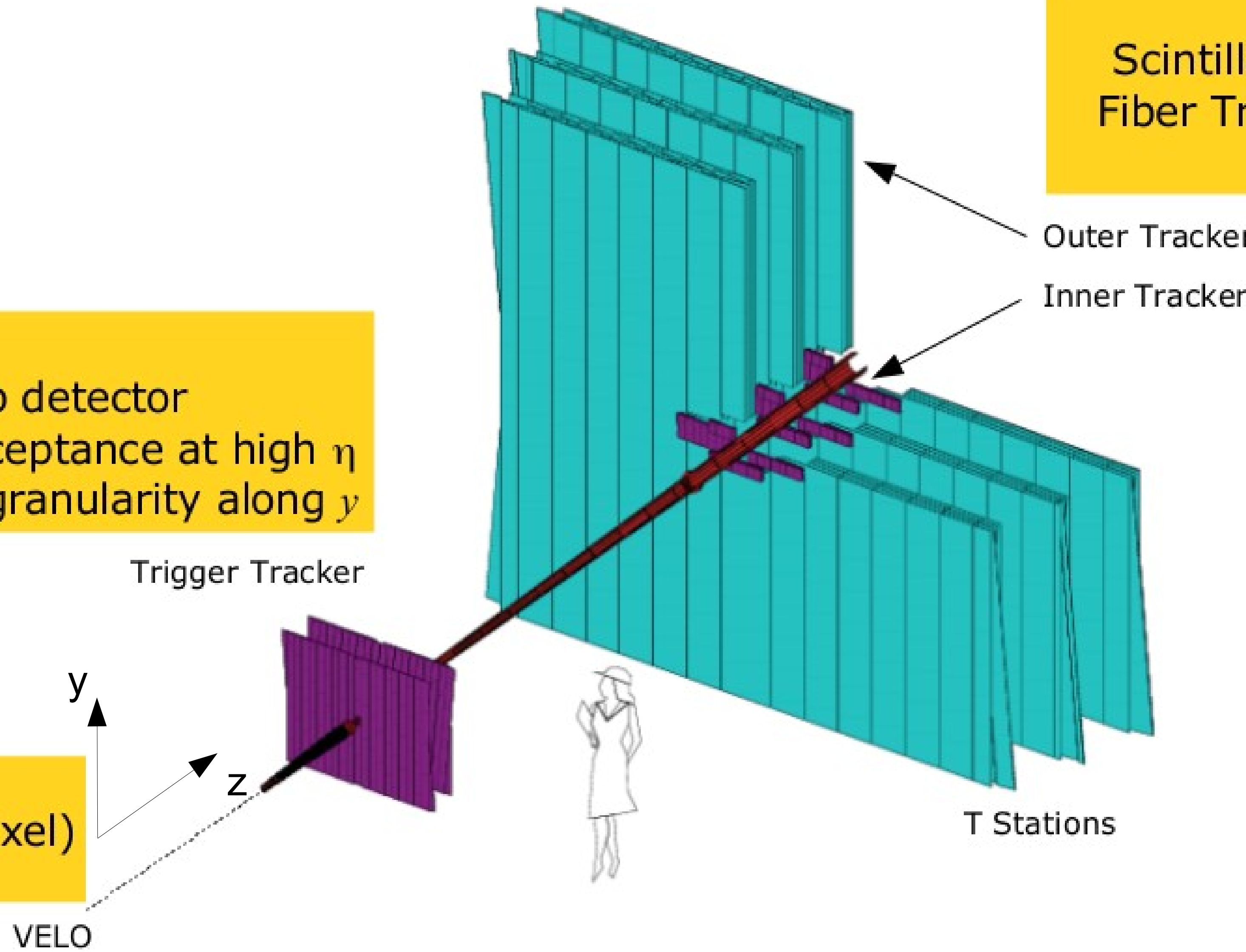


Upgraded LHCb tracking system

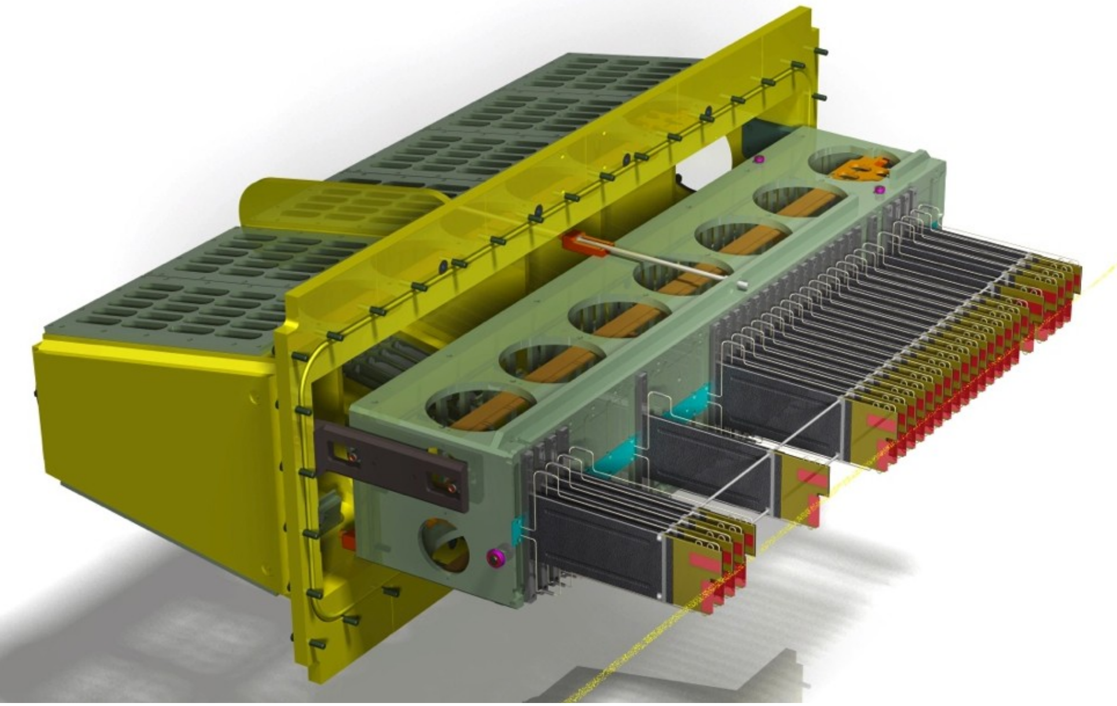
Scintillating Fiber Tracker

UT
Silicon strip detector
Enlarge acceptance at high η
Improved granularity along y

VELO (Pixel)

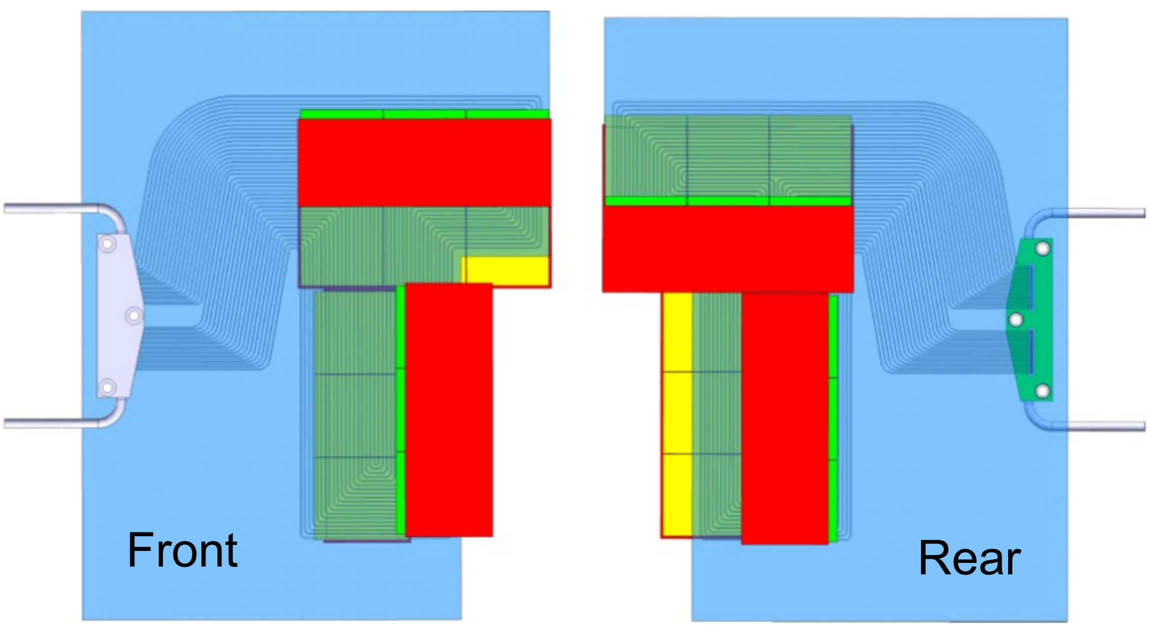


Upgraded LHCb Vertex Detector



Keep (improve) performance in harsher conditions:

- Lower material budget
  - Sensor thickness 300 → 200 μm
  - RF foil thickness: 300 → ≤ 250 μm
- Enlarge acceptance
  - Inner aperture: 5.5 mm → 3.5 mm



26 stations arranged perpendicularly along beam direction

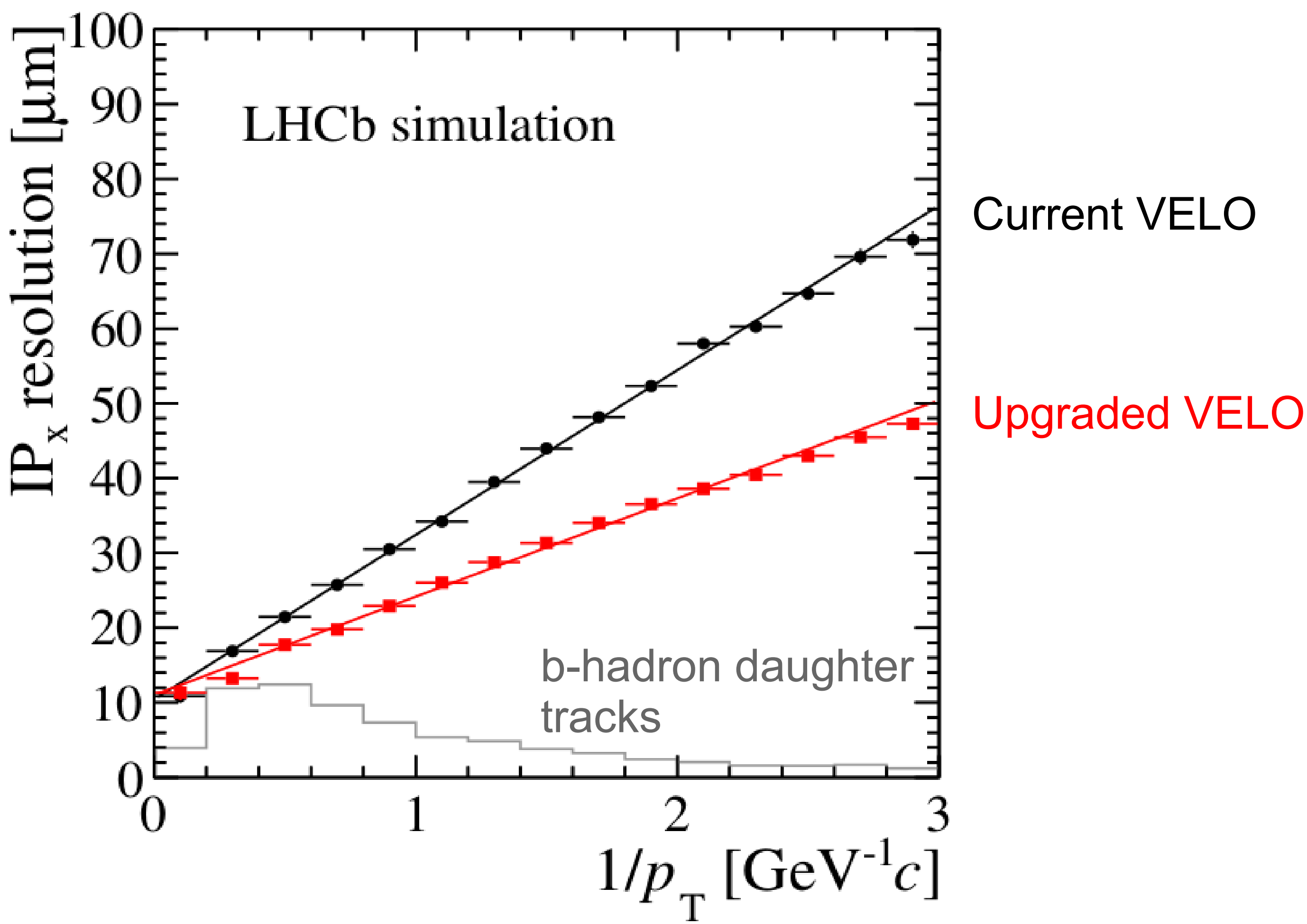
55x55 μm^2 pixels sensors with micro channels CO_2 cooling

41×10^6 pixels total

Radiation dose: up to 370 Mrad or 8×10^{15} 1 MeV n_{eq}/cm^2 for 50 fb^{-1}

Peak total data rate: 2.85 Tbit/s

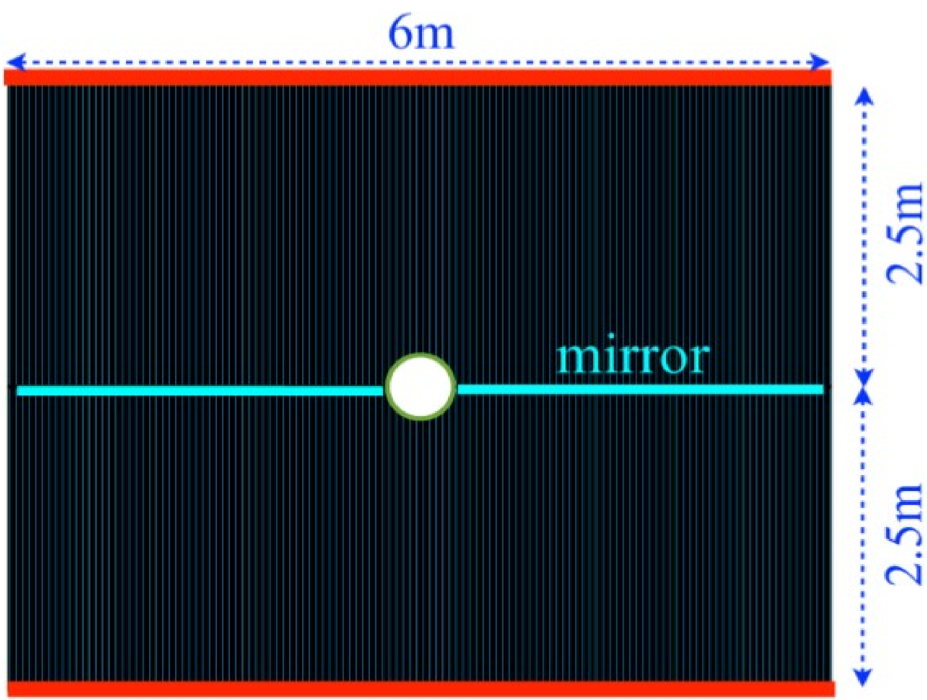
Expected performance

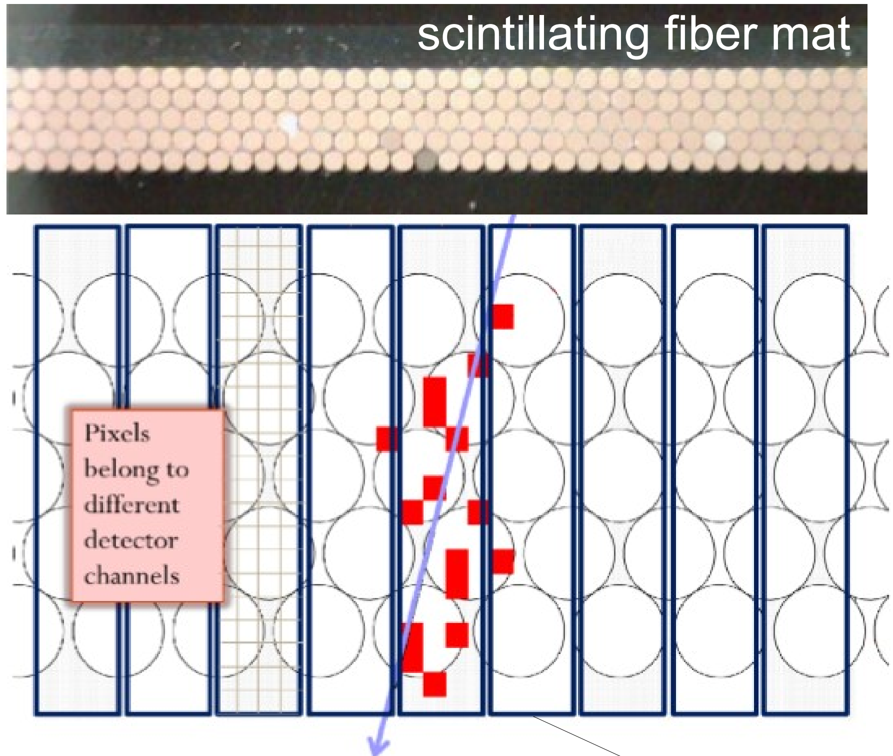


The resolutions in x and y are similar

More information in VELO TDR: CERN/LHCC 2013-021
http://cds.cern.ch/record/1624070/files/LHCB-TDR-013.pdf

T-station upgrade: fiber tracker





1 SiPM channel

3 stations of X-U-V-X scintillating fiber planes (≤5°) => 12 planes

Every plane is made of 5 layers of Ø250 μm fibers, 2.5 m long.

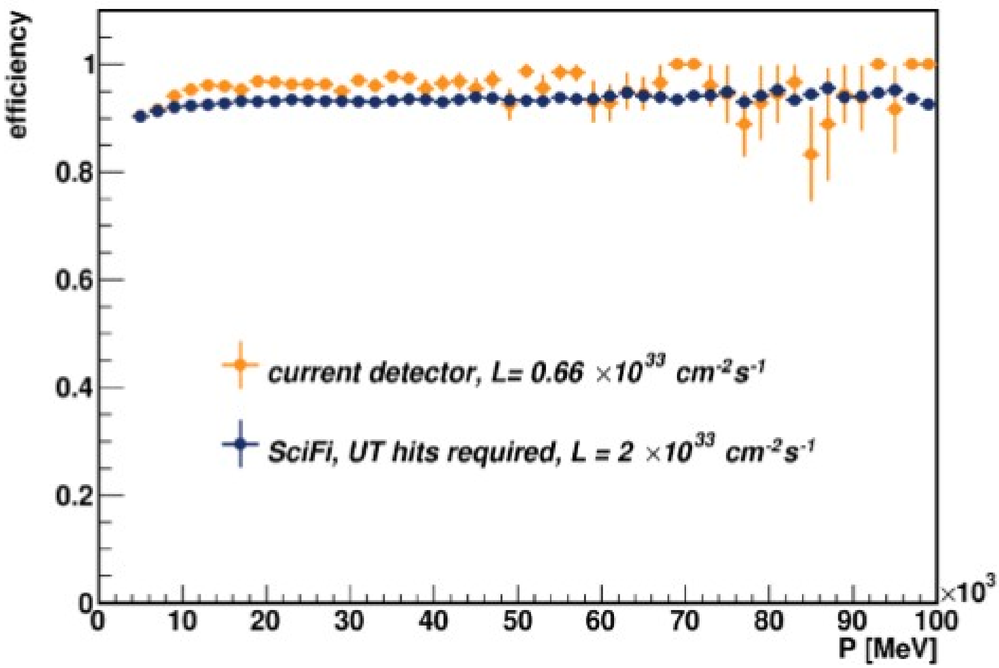
Read out by SiPM outside acceptance

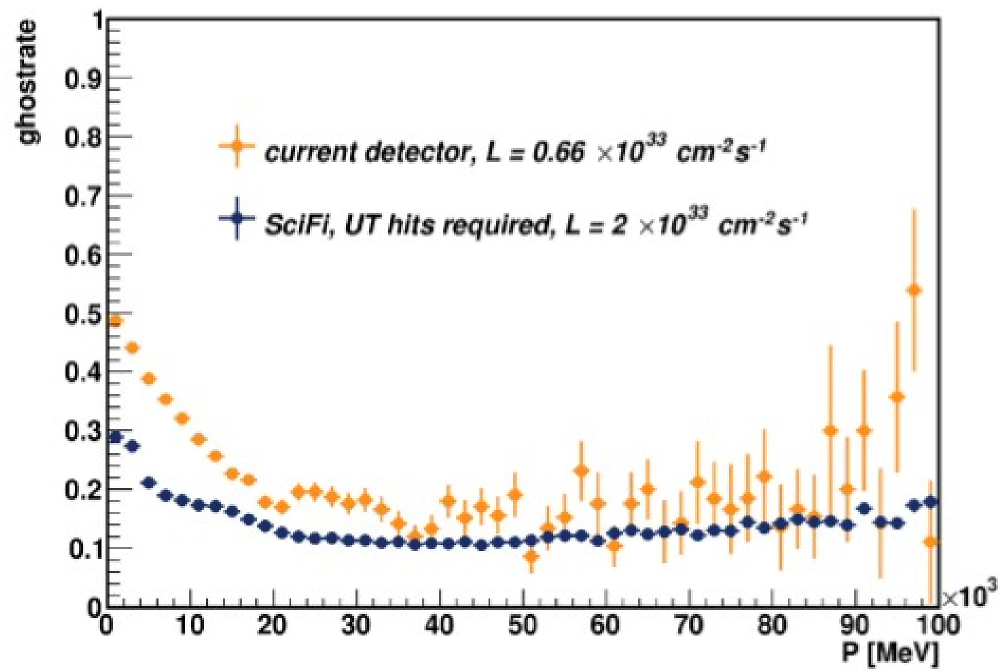
4608 SiPMs connected to specific ASIC (PACIFIC)

Challenge: radiation environment:

- Fibers → tested OK
- Neutron damage to SiPM → operate at -40 °C

Expected performance



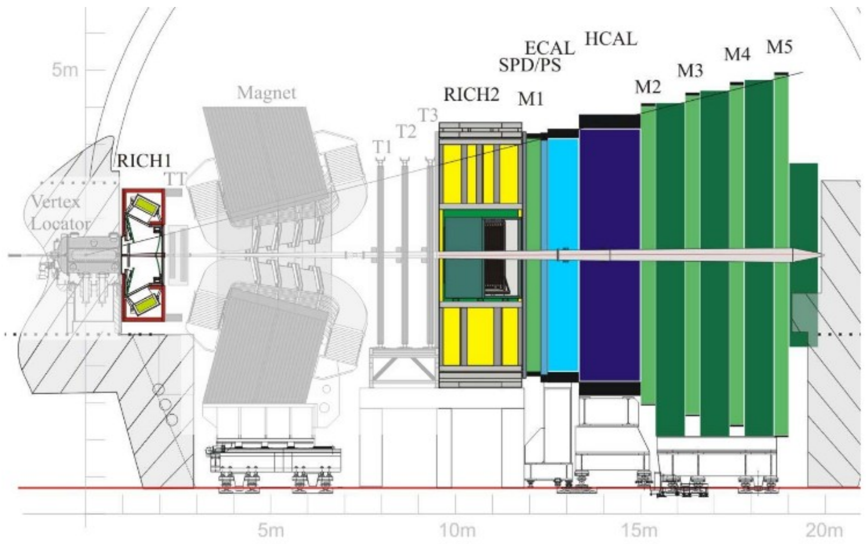


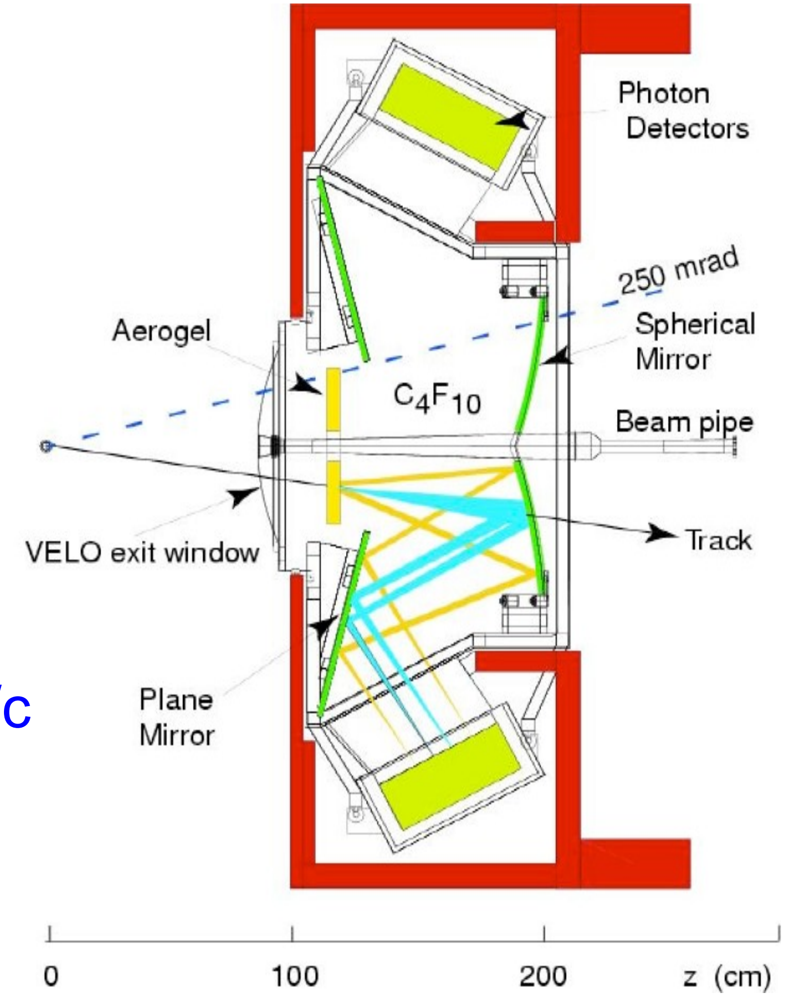
[TDR in preparation for March '14]

Particle Identification

Challenges

Current LHCb RICH system

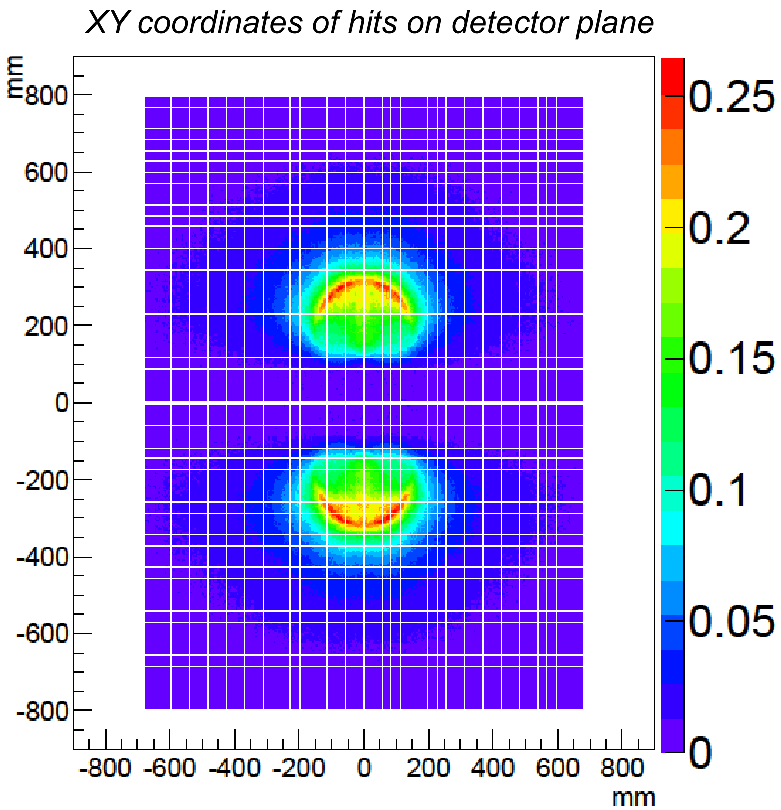




Particle identification from 2 to ~100 GeV/c

- 2 RICH detectors, 3 radiators:
  - RICH1: aerogel + C_4F_{10} (1-60 GeV/c)
  - RICH2: CF_4 (15-100 GeV/c)
- Readout by HPD (Hybrid Photon Detectors)

RICH upgrade



RICH 1: adapt to higher occupancies

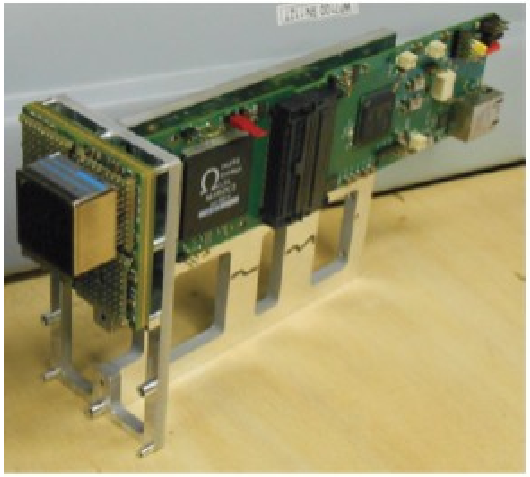
- Aerogel radiator removed
- New geometry to spread out Cherenkov rings
  - Spherical mirror with larger radius

RICH2: replace Hybrid Photon Detectors

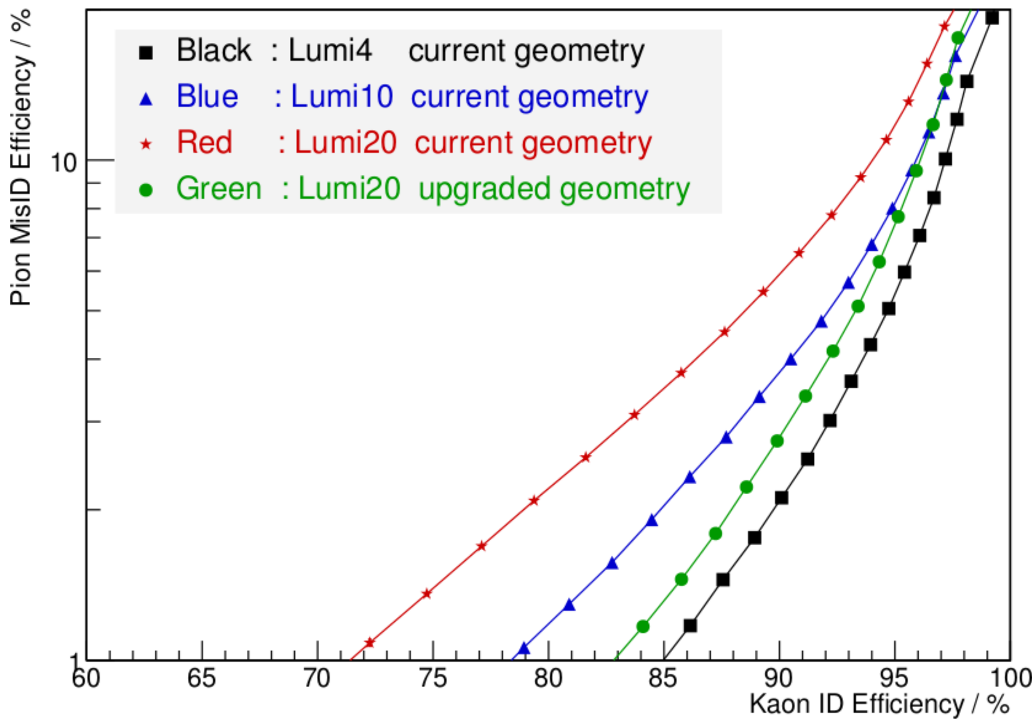
- embedded 1MHz R/O chip

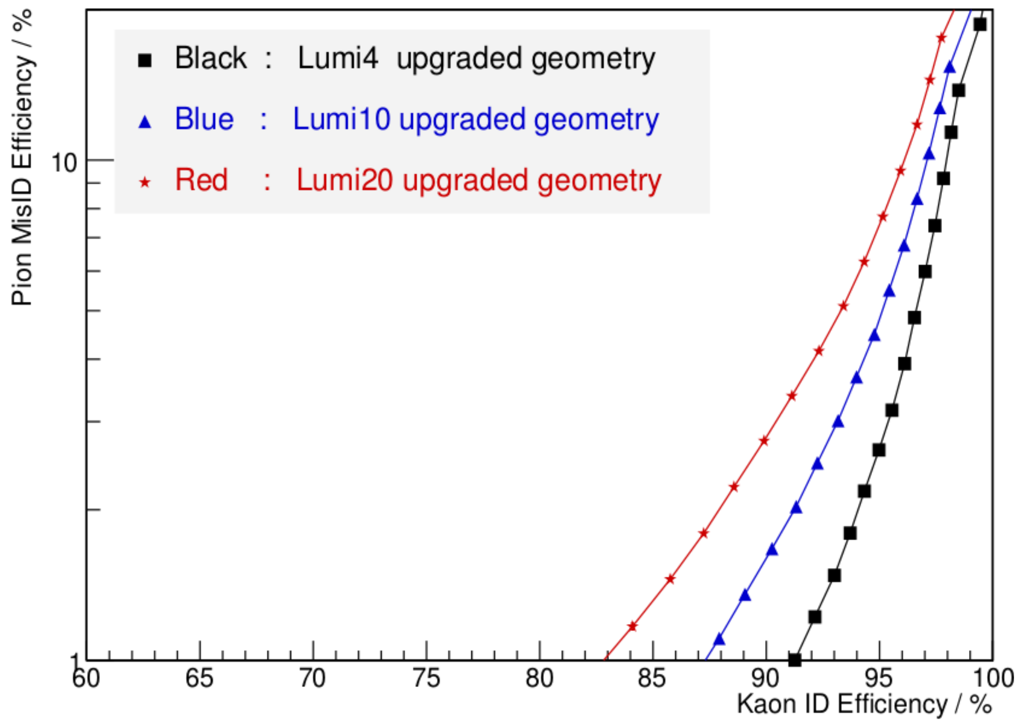
40 MHz readout:

- 64 channel Multi-anode PMTs
- Front-End: dedicated ASIC (CLARO)

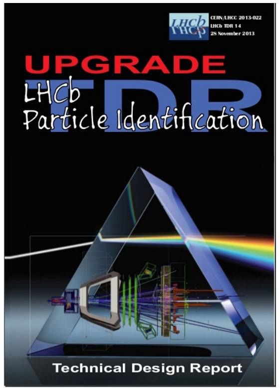


Expected performance





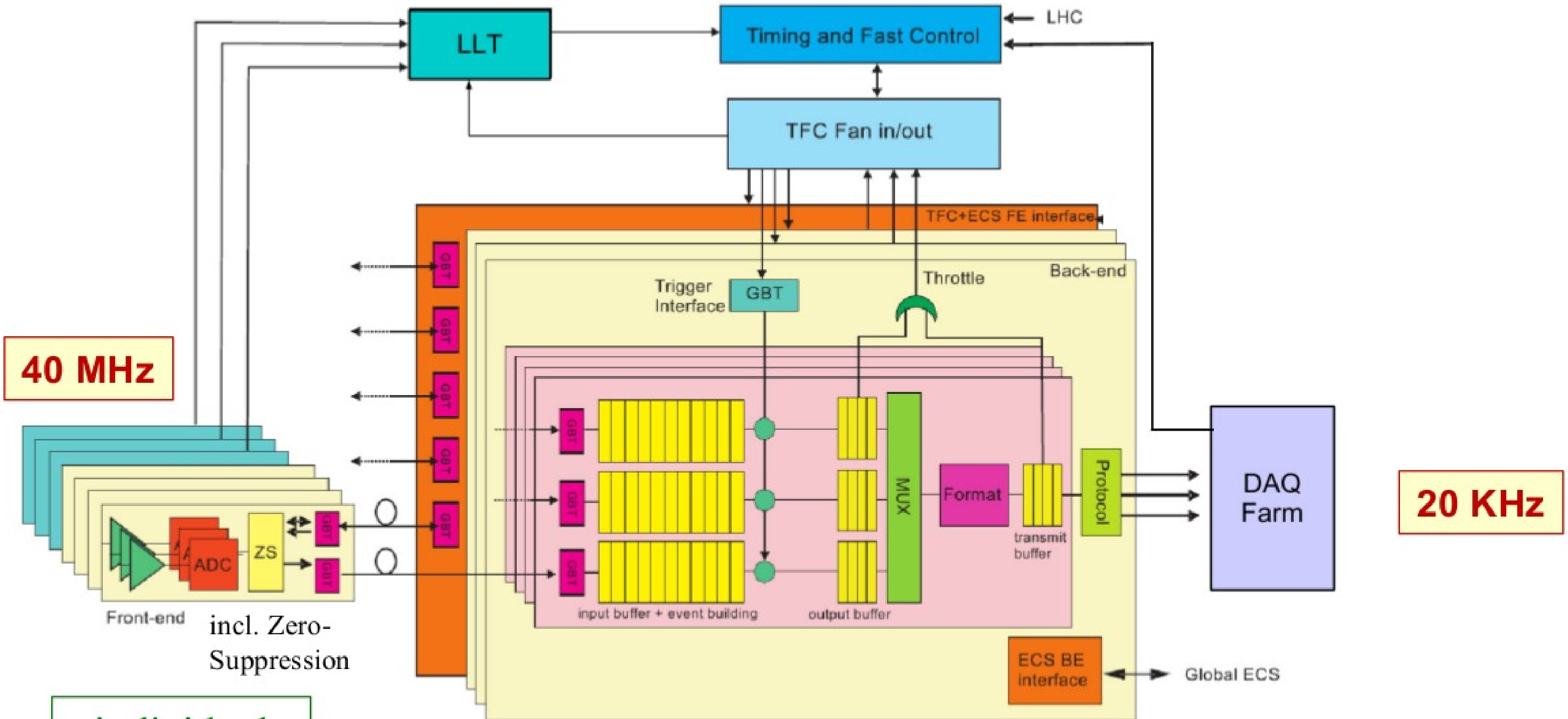
More information in PID TDR: CERN/LHCC 2013-022
http://cds.cern.ch/record/1624074/files/LHCB-TDR-014.pdf



Data Processing Challenges

40 MHz architecture overview

The main challenge is to build a cost-effective architecture

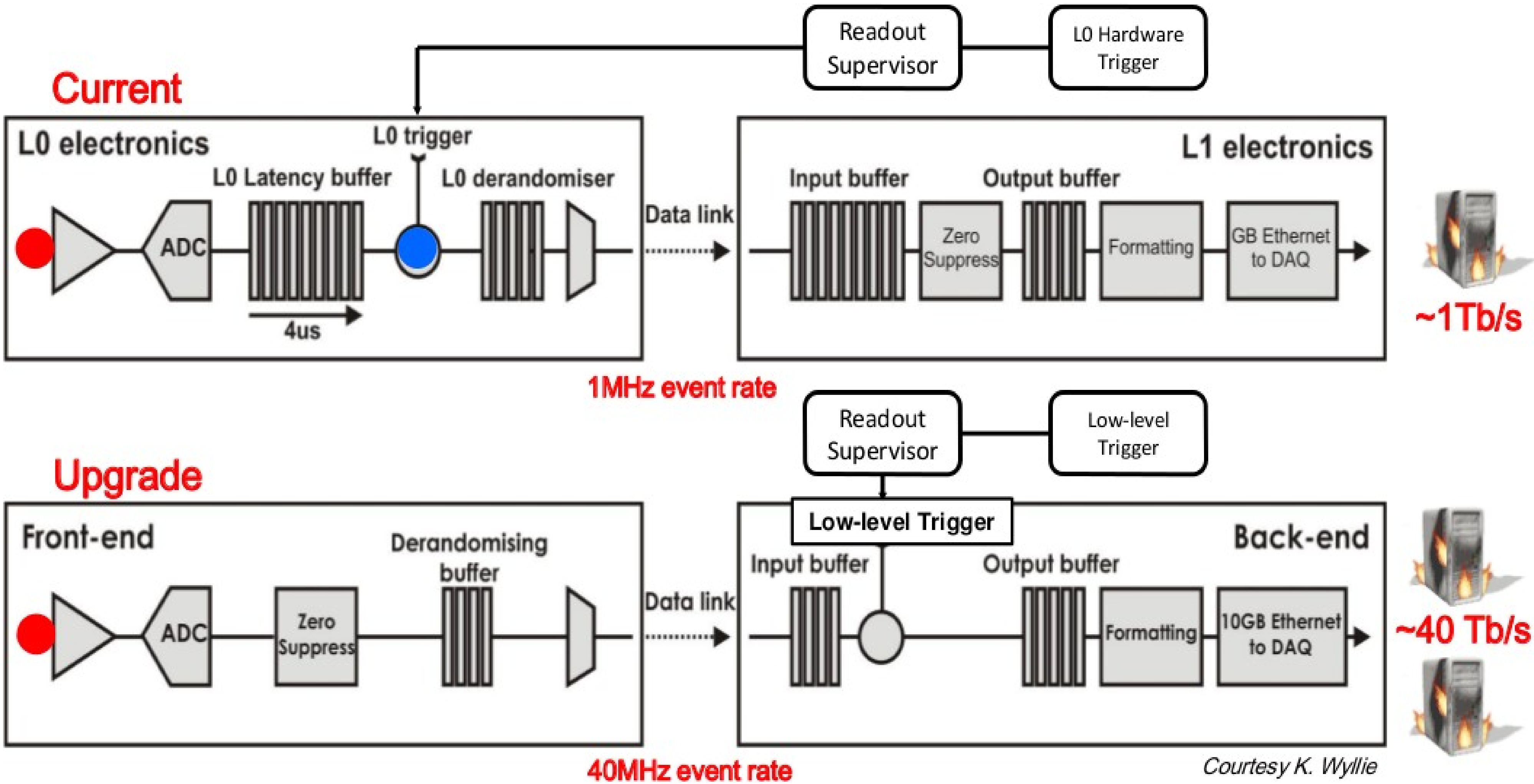


individual sub-systems Front-End electronics → optical link via GBT → common Back-End readout boards TELL40 [or PCI express] → event building & HLT

underground | ~300m | on surface

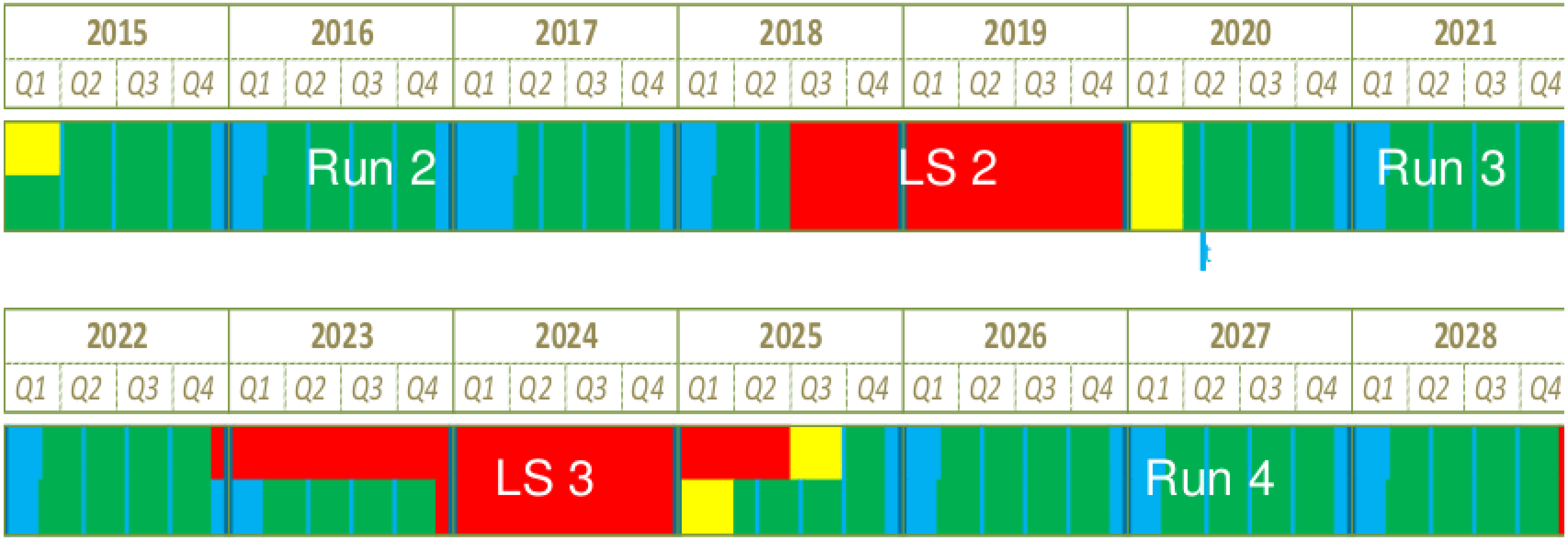
Upgraded Readout Architecture

Trigger-less Front-End electronics: transmit data every LHC bunch crossing (25ns)



40 Tb/s ~ 1050 DVDs per second!

LHC schedule beyond LS1



Run 2: LHCb should collect an additional 5 – 7 fb^{-1} of data

LS 2: upgrade of LHCb in one go (18 months shutdown)

Then take data: collect ≥ 50 fb^{-1} within ~ 10 years

http://cds.cern.ch/record/1333091/files/LHCC-I-018.pdf

http://cds.cern.ch/record/1443882/files/LHCB-TDR-012.pdf

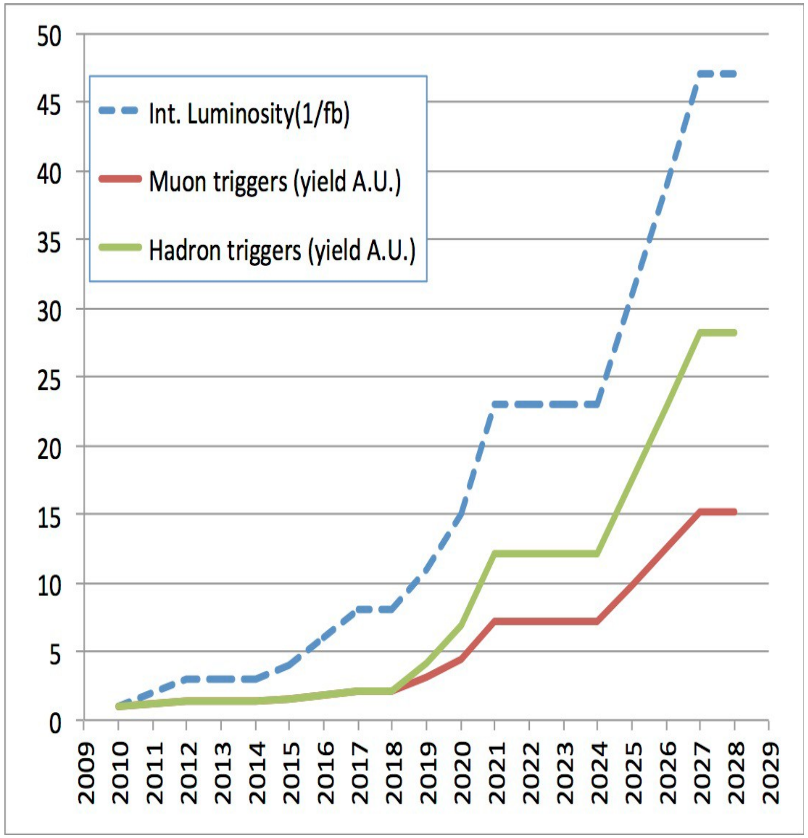
Conclusion

The LHCb Upgrade has been fully approved by CERN

Need to increase by at least an order of magnitude the amount of data to test the SM up to its theoretical uncertainties

► LHCb Upgrade (≥ 50 fb^{-1} in 10 years)

Read the detector at 40 MHz sustaining a levelled luminosity of $2 \cdot 10^{33}$ $cm^{-2}s^{-1}$



The LHCb Upgrade is a technologically challenging project and schedule is tight

► Extensive R&D ongoing, TDRs for December '13, March and June '14 .

The LHCb detector will be upgraded in one go during LS2 and then take data (> 2025: HL-LHC).


STOP

Statistical sensitivities

Table 3: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the expected sensitivity is given for the integrated luminosity accumulated by the end of LHC Run 1, by 2018 (assuming 5 fb^{-1} recorded during Run 2) and for the LHCb Upgrade (50 fb^{-1}). An estimate of the theoretical uncertainty is also given – this and the potential sources of systematic uncertainty are discussed in the text.

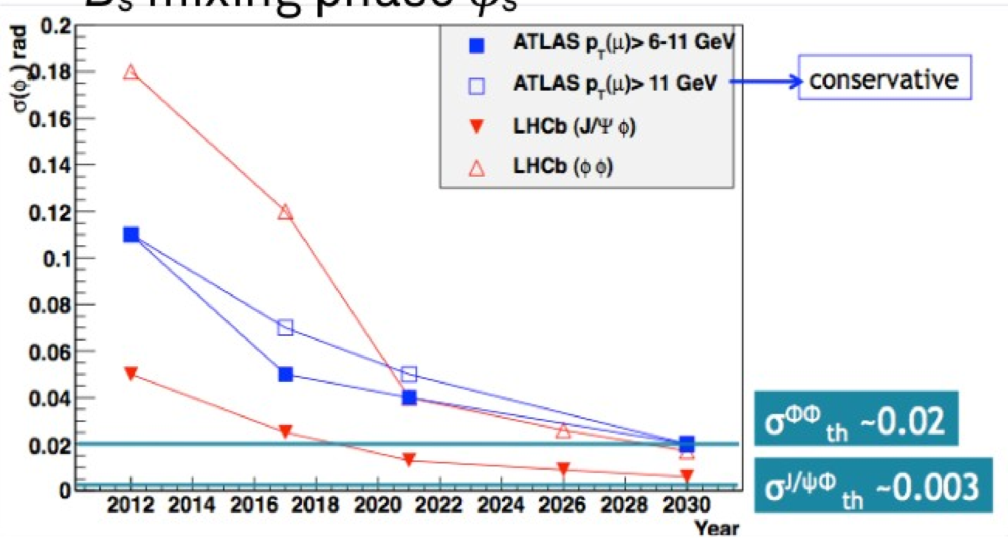
Type	Observable	LHC Run 1	LHCb 2018	**LHCb upgrade**	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.05	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\ f_0(980))$ (rad)	0.09	0.05	**0.016**	~ 0.01
	$A_{\rm sl}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic penguin	$\phi_s^{\rm eff}(B_s^0 \to \phi\phi)$ (rad)	0.18	0.12	**0.026**	0.02
	$\phi_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.029**	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.04**	0.02
Right-handed currents	$\phi_s^{\rm eff}(B_s^0 \to \phi\gamma)$	0.20	0.13	**0.030**	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.8%**	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
	$q_0^2\ A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim 7\%$
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.14	0.07	**0.024**	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%	**2.4%**	$\sim 10\%$
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (10^{-9})	1.0	0.5	**0.19**	0.3
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	220%	110%	**40%**	$\sim 5\,\%$
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	7°	4°	**1.1°**	negligible
	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.4°**	negligible
	$\beta(B^0 \to J/\psi\,K_S^0)$	1.7°	0.8°	**0.31°**	negligible
Charm CP violation	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.5**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.12**	–

Current Sensitivity limited by statistics, not theory

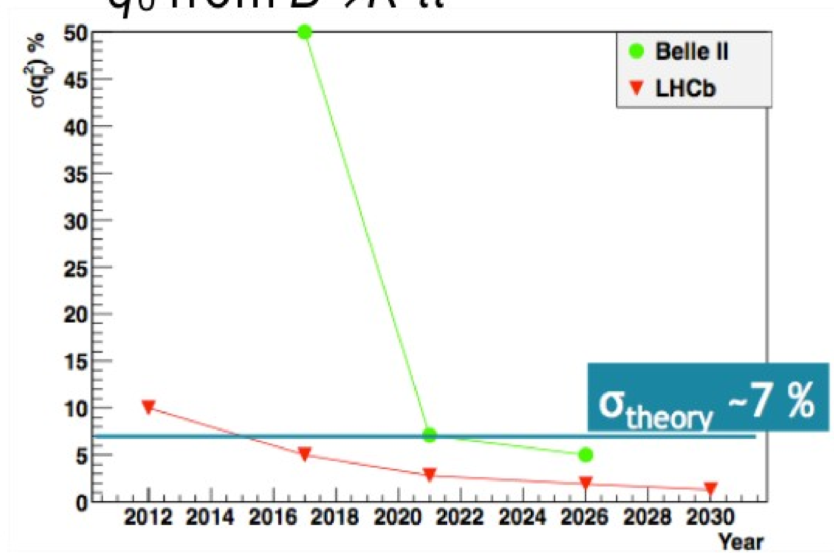
Upgrade: comparable to or better than the theoretical uncertainties

Comparison with other experiments

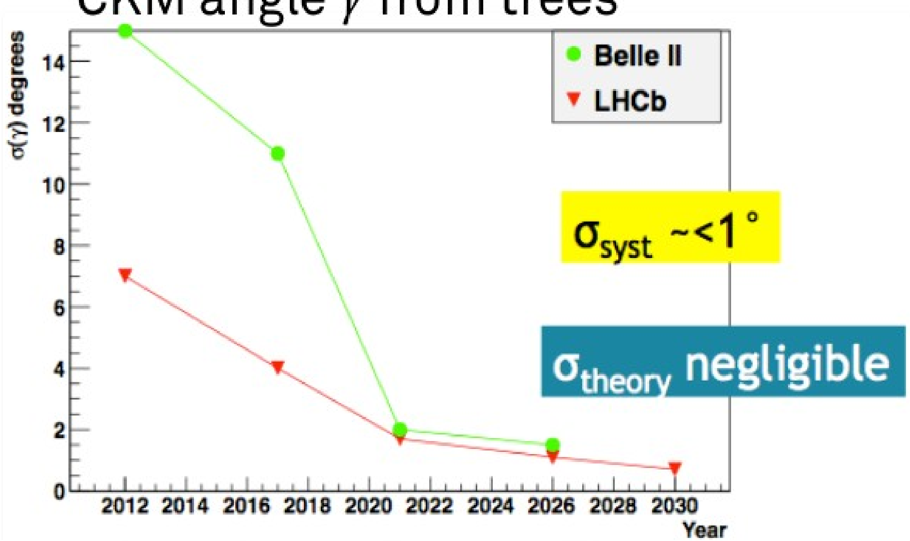
B_s mixing phase ϕ_s



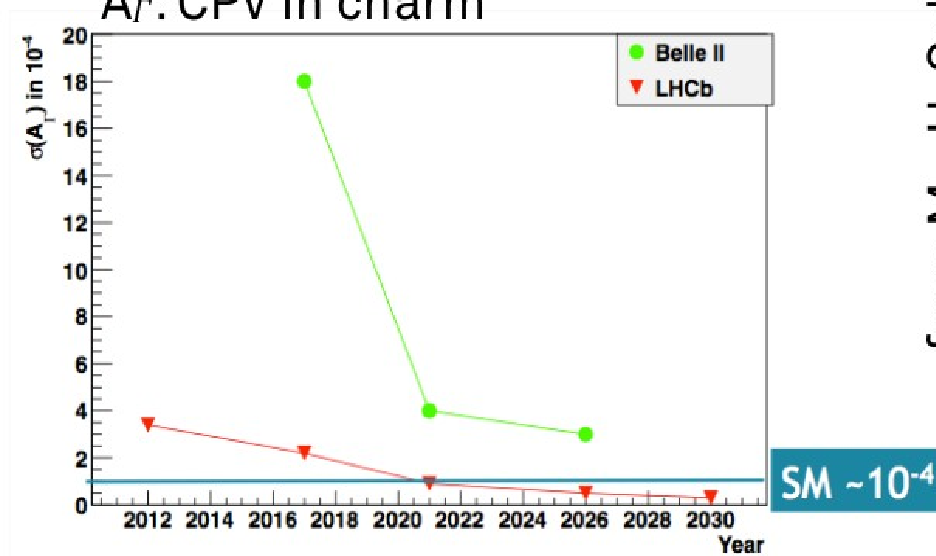
q_0 from $B \to K^*ll$



CKM angle γ from trees



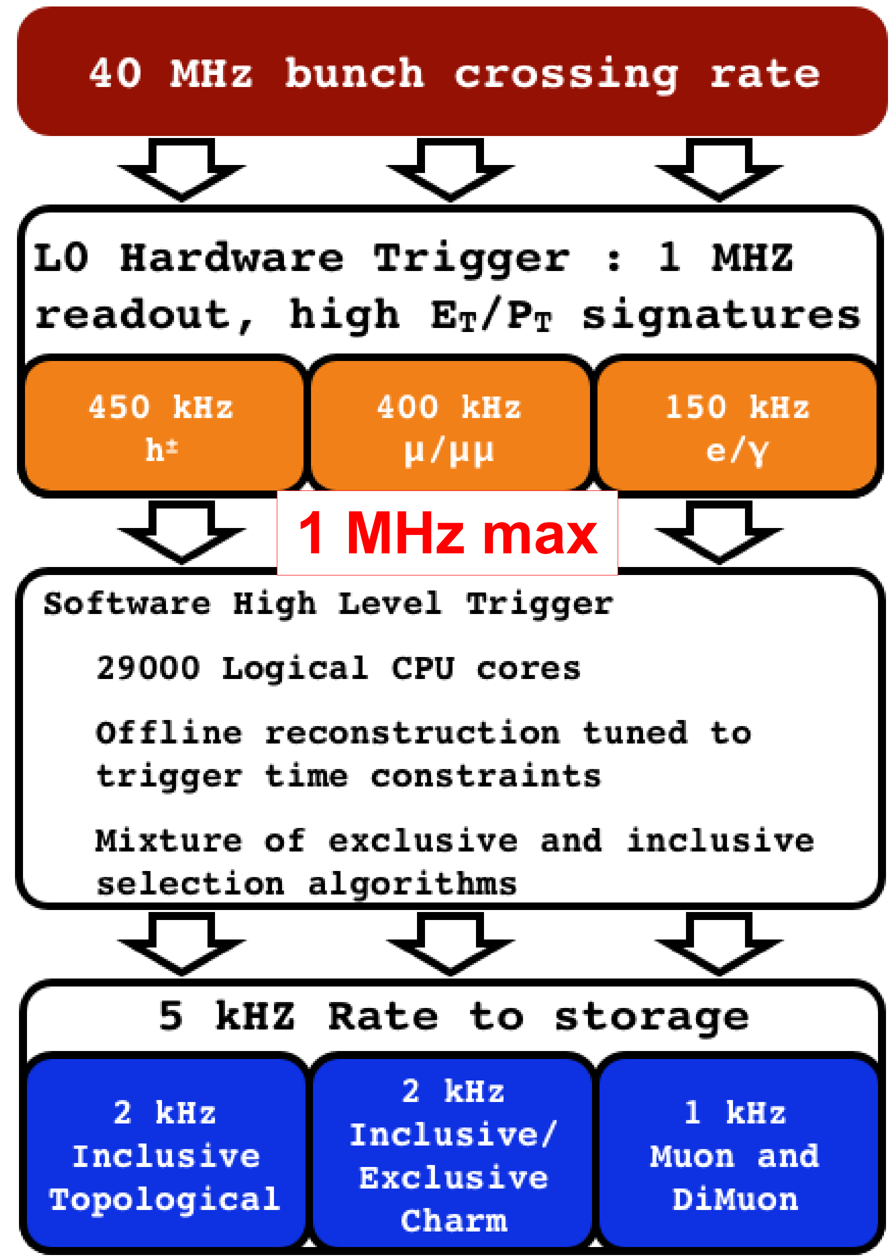
A_Γ: CPV in charm



from M. -H. Schune @ECFA HL-LHC 2013

Current Trigger Architecture

- Level-0 trigger: hardware
  - 4 μs latency @ 40MHz
  - "Moderate" E_T/p_T threshold:
    - $E_T(e/\gamma)>2.7$ GeV; $E_T(h)>3.6$ GeV
    - $p_T(\mu)>1.4$ GeV/c
- HLT trigger: software
  - ~30000 tasks in parallel on ~1500 nodes
  - Processing time available O(35-40 ms)
- Storage rate: 5 kHz
- Combined efficiency (L0+HLT):
  - ~90 % for di-muon channels
  - ~30 % for multi-body hadronic final states
  - ~10-20% for charm decays

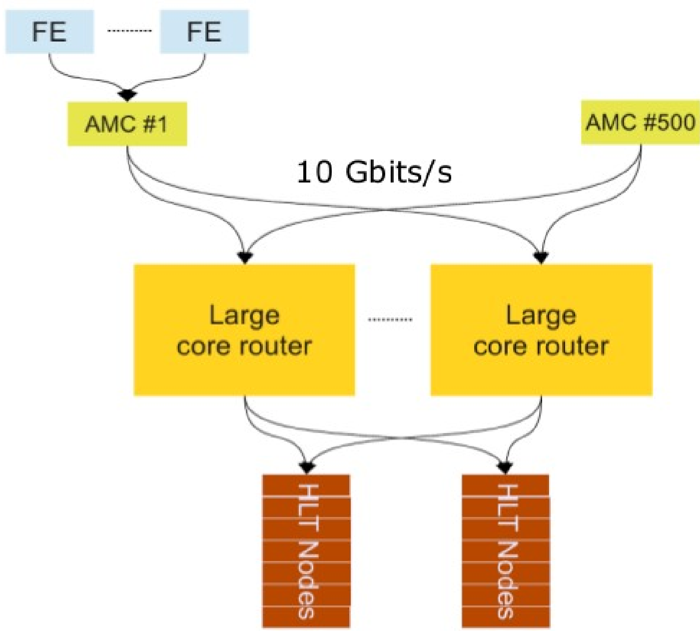


New LHCb DAQ

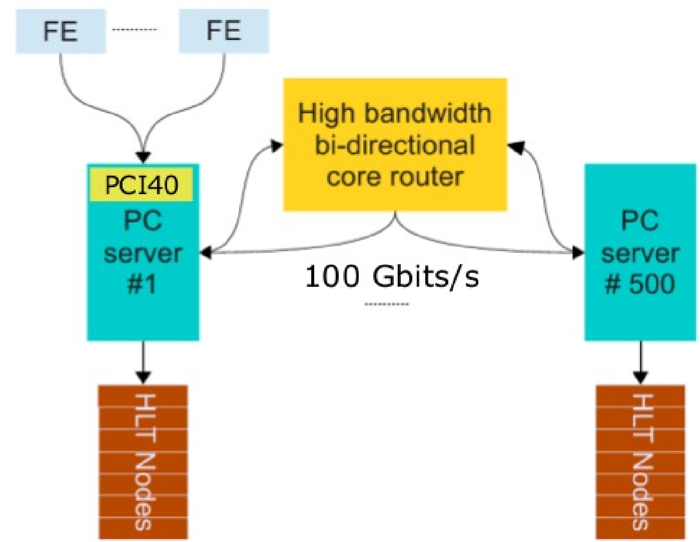
Two options: (decision end of February '14)

[TDR in preparation for June '14]

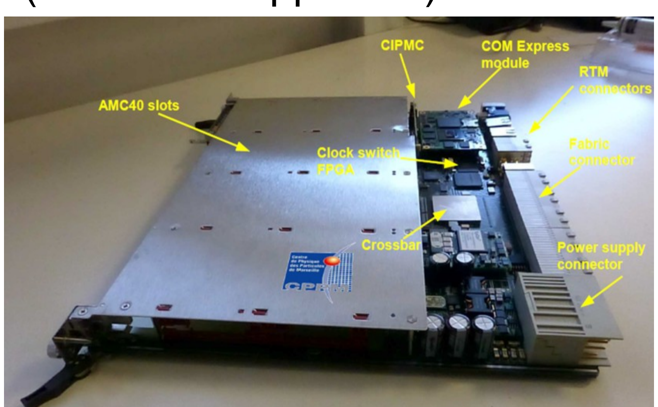
Fat-core event builder



Uniform event builder



FPGA-based ATCA card
(distributed approach)



PCIe Gen3 NIC card
(data-center approach)