Physics at the LHC and Beyond
Quy Nhon, Aug 10-17, 2014

The LHCb Upgrades

Olaf Steinkamp

on behalf of the LHCb collaboration

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Universität Zürich[UZH]

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The LHCb LS2 Upgrade

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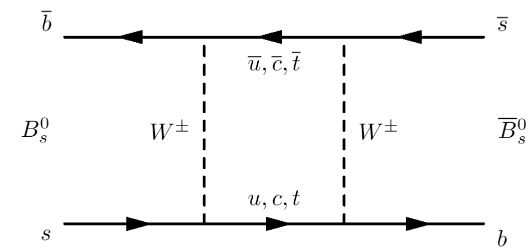
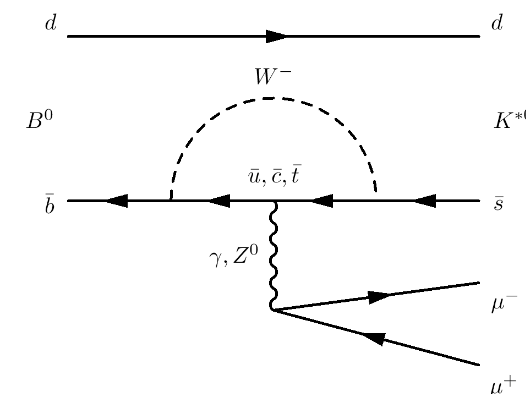
LHCb Motivation

- **primary goal: "indirect" search for New Physics**
  - new heavy particles can enter in internal loops and have sizeable effect on observables
  - *CP* violating phases, rare *FCNC* decays



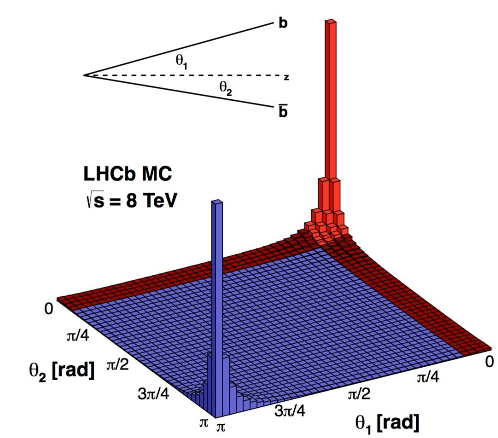
- **B^0 and B^0_s systems are an ideal hunting ground**
  - rich phenomenology, precise predictions from theory



- **LHCb: confront predictions with precise measurements**

  `[see also Ulrik Egede's talk on Wednesday]`

- ***$b\bar{b}$* production at LHC peaks at small polar angles**
  - LHCb layed out as forward dipole spectrometer
- **forward geometry offers additional advantages:**
  - larger Lorentz boost → better decay time resolution
  - higher momentum for same p_T → lower p_T thresholds



- **extra benefit: unique potential for production studies in forward direction**

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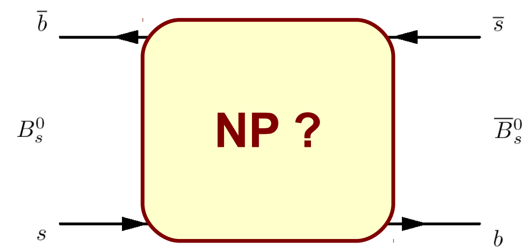

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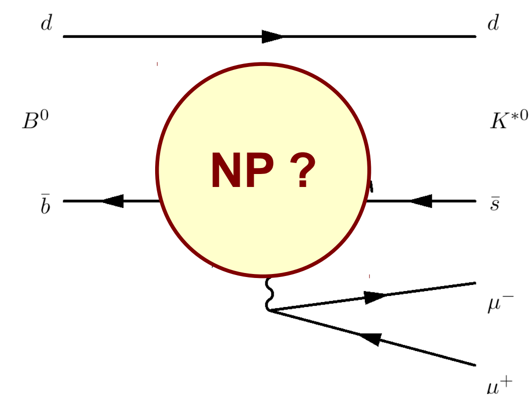

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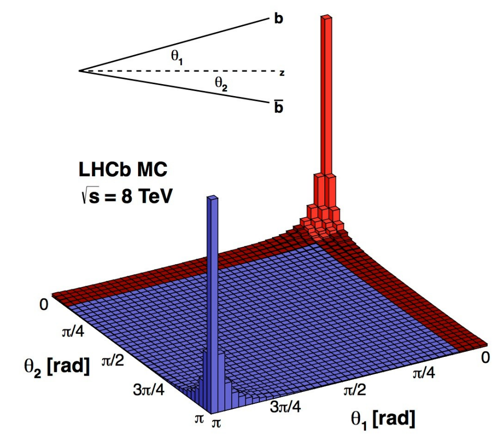

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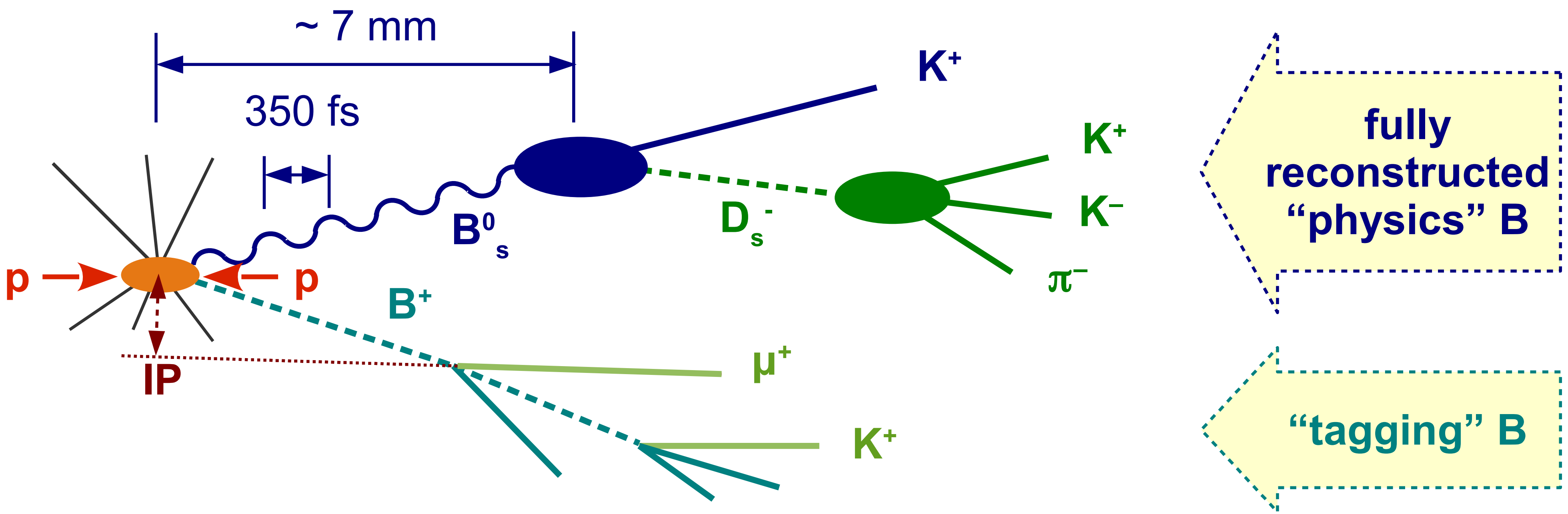
Requirements



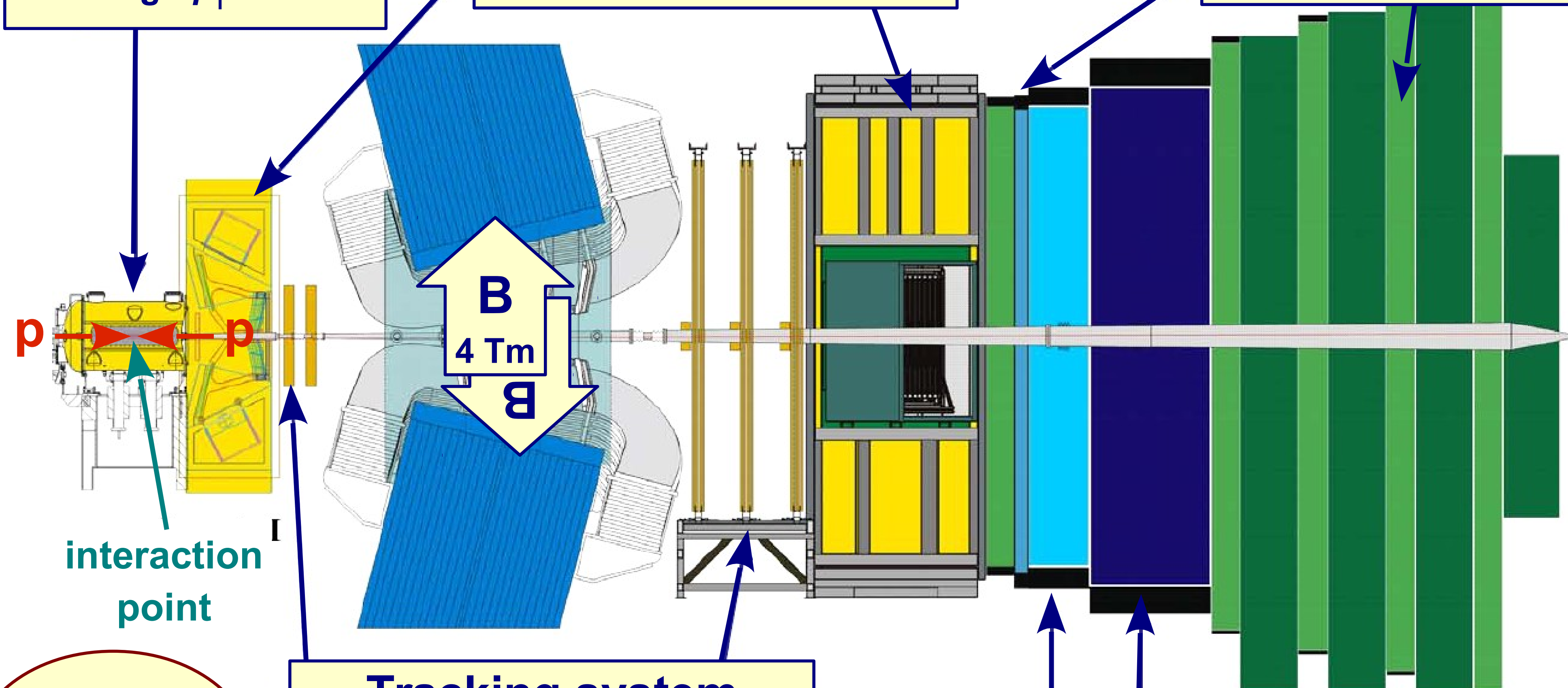
- **impact parameter resolution**
  - to identify secondary vertices
- **proper time resolution**
  - to resolve fast B^0_s-$\overline{B}^0_s$ oscillations
- **momentum & invariant mass resolution**
  - to suppress combinatorial backgrounds
- **K/π separation**
  - to suppress peaking backgrounds
  - for flavour tagging
- **selective and efficient trigger, also for hadronic final states**

Run I/II Detector

VErtex LOcator
$\sigma_{IP} \sim 20\ \mu m$
for high-p_T tracks

RICH detectors
$\varepsilon(K \to K) \sim 95\ \%$
for 5 % $\pi \to K$ mis-id

Muon system
$\varepsilon(\mu \to \mu) \sim 97\ \%$
for 1-3 % $\mu \to \pi$ mis-id



Acceptance
$2 < \eta < 5$

Tracking system
$\Delta p/p = 0.4\ \%$ @ 5 GeV/c to
0.6 % @ 100 GeV/c

Calorimeters
ECAL: $\sigma_E/E \sim 1\ \% \otimes 10\ \% / \sqrt{E\ (GeV)}$

[JINST 3 (2008) S08005]

2012 Trigger

40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures

450 kHz $h^{\pm}$	400 kHz $\mu/\mu\mu$	150 kHz e/γ

Software High Level Trigger

- 29000 Logical CPU cores
- Offline reconstruction tuned to trigger time constraints
- Mixture of exclusive and inclusive selection algorithms

5 kHz Rate to storage

2 kHz Inclusive Topological	2 kHz Inclusive/ Exclusive Charm	1 kHz Muon and DiMuon

Hardware level (L0):

- maximum output rate 1 MHz
- typical thresholds

  $E_T(e/\gamma) > 2.7$ GeV

  $E_T(h) > 3.6$ GeV

  $p_T(\mu) > 1.4$ GeV

Software level (HLT):

event reconstruction similar to offline

Combined efficiency L0+HLT (2012):

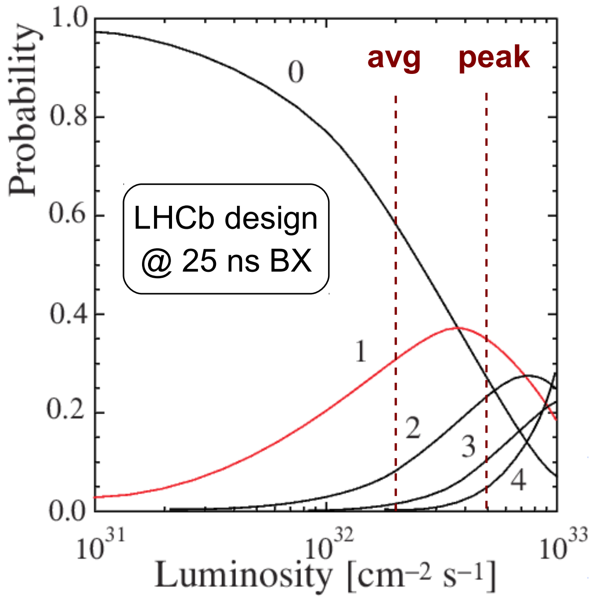
~ 90 % for di-muon channels

~ 30 % for multi-body hadronic final states

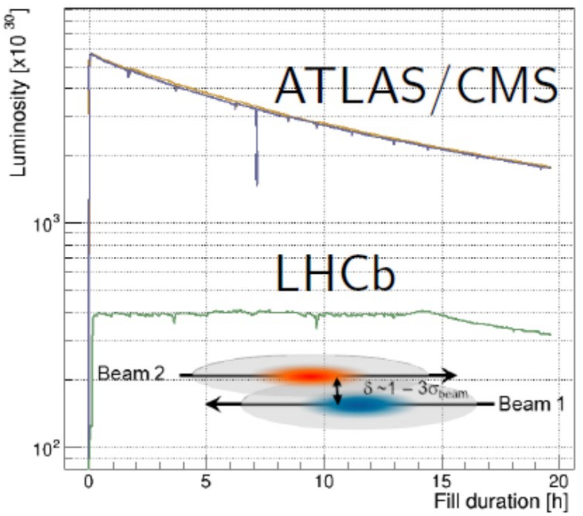
[LHCb run II trigger: Karol Hennessy's talk earlier today]

Luminosity

- **LHCb designed to operate at lower instantaneous luminosity than ATLAS/CMS**
  - very high particle density in forward region
  - large pile-up could affect reconstruction performance (e.g. *B* decay length, flavour tagging)
- **achieved by displacement of LHC beams**
  - luminosity leveling: adjust displacement throughout fill, operate at constant instantaneous luminosity
  - optimal use of beams + stable operation conditions

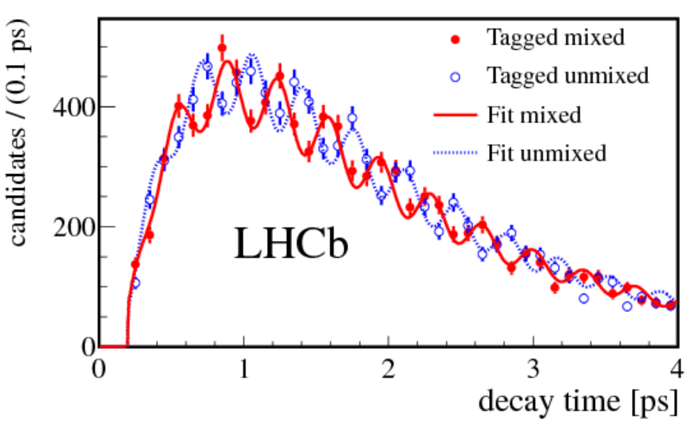


2011:	**1 fb^{-1} *pp* at 7 TeV**
2012:	**2 fb^{-1} *pp* at 8 TeV**
2013:	**1.6 nb^{-1} *p*Pb / Pb*p***

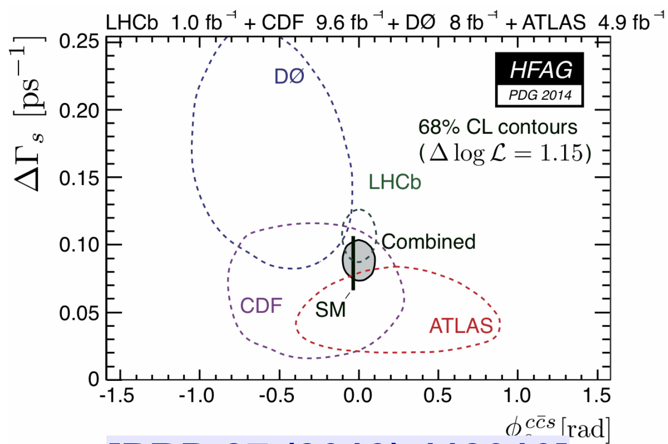


[run I performance: Giacomo Graziani's talk on Monday]
[run I operation: Clara Gaspar's talk on Monday]

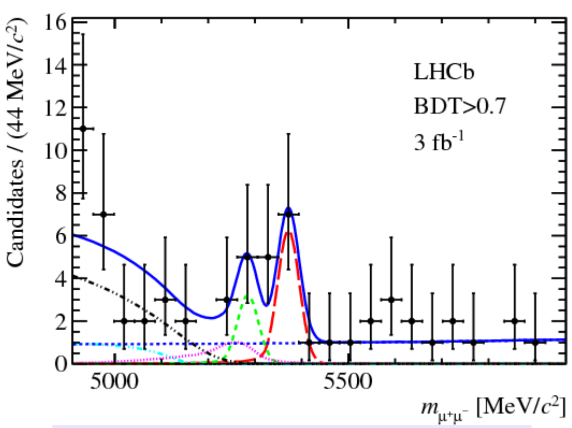
- **200+ submitted papers and counting**
  - CP violating phases, rare heavy-quark decays
  - production & spectroscopy, exotics searches, Lepton Flavour Violation, …



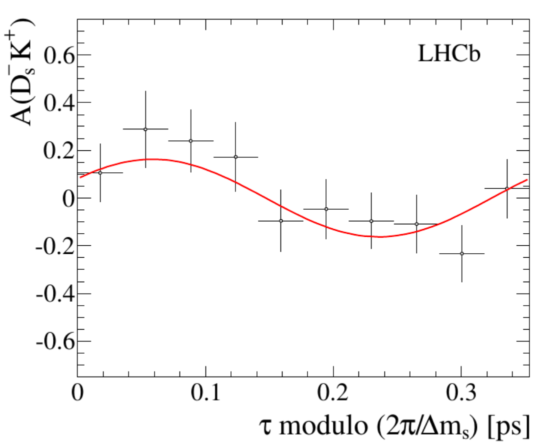
[NJP 15 (2013) 053021]



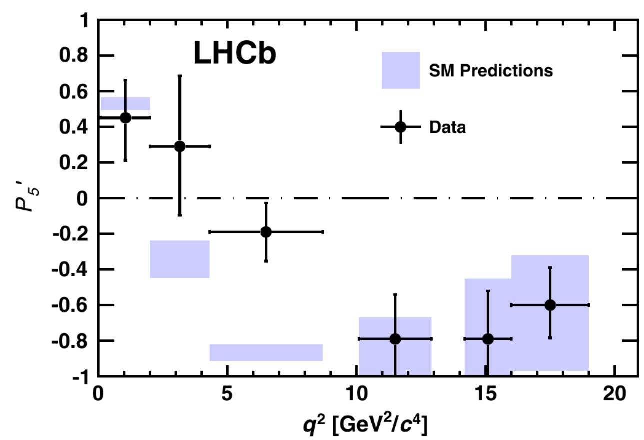
[PRD 87 (2013) 112010]



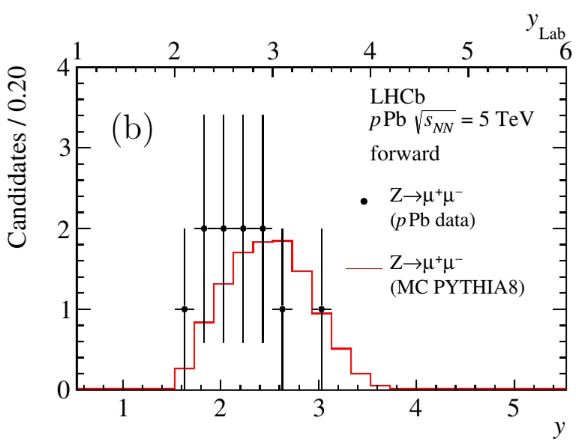
[PRL 111 (2013) 101805]



[arXiv:1407.6127]



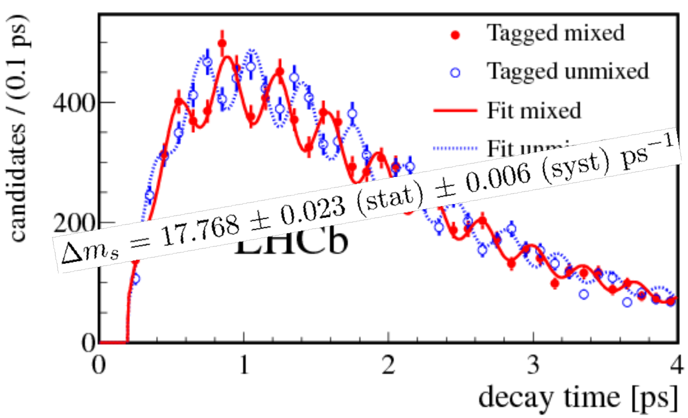
[PRL 111 (2013) 191801]



[arXiv:1406.2885]

Run I Physics Output

- **200+ submitted papers and counting**
  - CP violating phases, rare heavy-quark decays
  - production & spectroscopy, exotics searches, Lepton Flavour Violation, …



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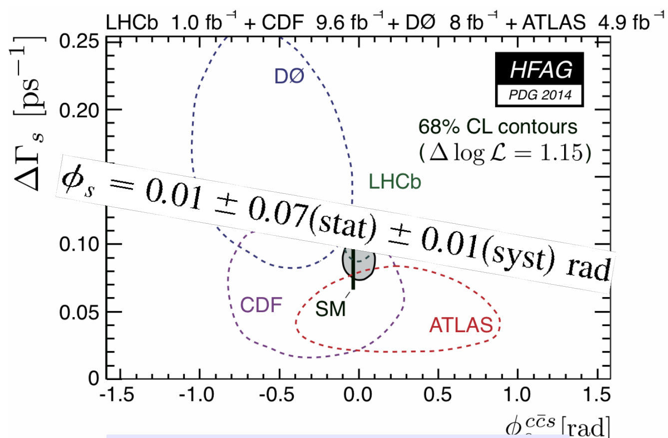

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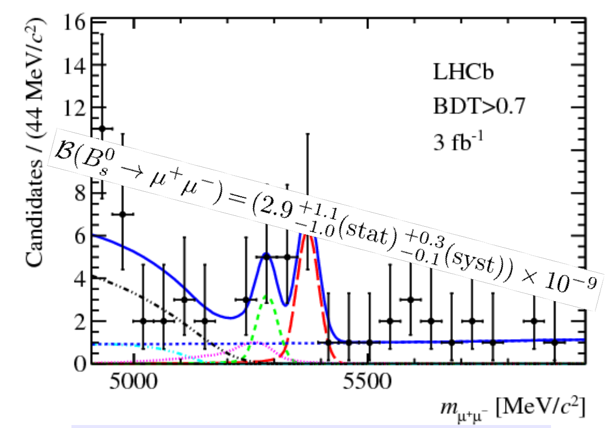

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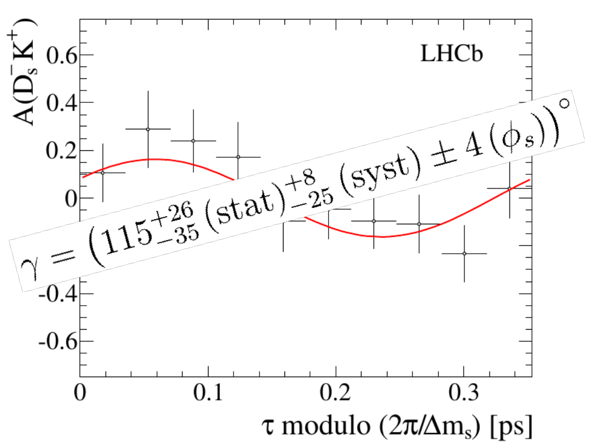

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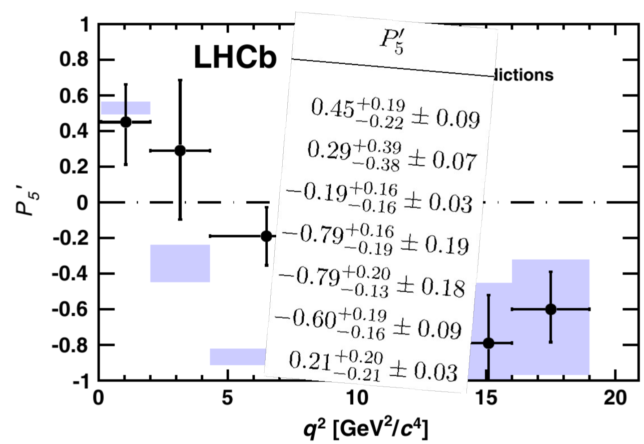

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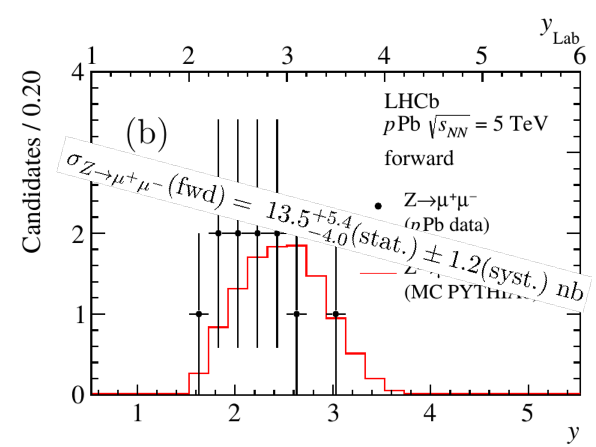

[arXiv:1406.2885]

LHCb Upgrade

- **run 1 has been a great success for the LHC, LHCb, ... and the Standard Model**
  - but current measurement precision in the flavour sector still allows significant contributions from New Physics
- **precision of most LHCb results will still be limited by statistics after run 2**
  - leading systematic uncertainties will often decrease with available statistics
- **after run 2 would need > 10 years with current LHCb to double precision again**

LHCb upgrade after run 2
increase annual event yields by
- increasing instantaneous luminosity
- increasing trigger efficiencies

2010	run 1	0.037 fb^{-1} @ 7 TeV
2011		1 fb^{-1} @ 7 TeV
2012		2 fb^{-1} @ 8 TeV
2013	LS 1	minor maintenance work
2014		
2015	run 2	5 fb^{-1} @ 13 TeV
2016		
2017		
2018	LS 2	LHCb upgrade
2019		
2020	run 3	15 fb^{-1} @ 14 TeV
2021		
2022		
2023	LS 3	?
2024		
2025		
2026++	run 4	5 fb^{-1} / year @ 14 TeV

“Physics” Goal

- **approach theory uncertainties in quark flavour sector, e.g.:**

	LHCb up to LS2		LHCb upgrade		Theory
	Run 1	Run 2	Run 3	Run 4	Theory uncertainty
Integrated lumi	$3\ fb^{-1}$	$8\ fb^{-1}$	$23\ fb^{-1}$	$46\ fb^{-1}$	
$\frac{Br(B_d\to\mu\mu)}{Br(B_s\to\mu\mu)}$	-	110 %	60%	40%	5%
$q_0^2 A_{FB}(B_d \to K^{*0}\mu\mu)$	10%	5%	2.8%	1.9%	7%
$\phi_s(B_s \to J/\psi\phi, B_s \to J/\psi\pi\pi)$	0.05	0.025	0.013	0.009	0.003
$\phi_s(B_s \to \phi\phi)$	0.18	0.12	0.04	0.026	0.02
γ	7°	4°	1.7°	1.1°	negl.
$A_\Gamma(D^0 \to KK)$	$3.4\ 10^{-4}$	$2.2\ 10^{-4}$	$0.9\ 10^{-4}$	$0.5\ 10^{-4}$	-

[M.H.Schune at Heavy Flavour in the HL-LHC Era, Aix les Bains, 2013]

- **ALSO: reinforce LHCb as a general purpose forward detector**
  - **e.g. electroweak boson production, exotic searches, proton-ion physics**

Collect them all …

Final Upgrade TDR submitted and under review – all others are approved

[CERN-LHCC-2011-001]

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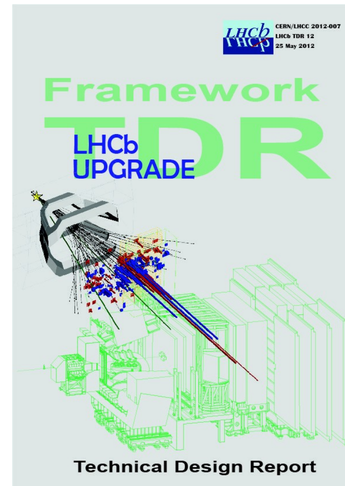

[CERN-LHCC-2012-007]

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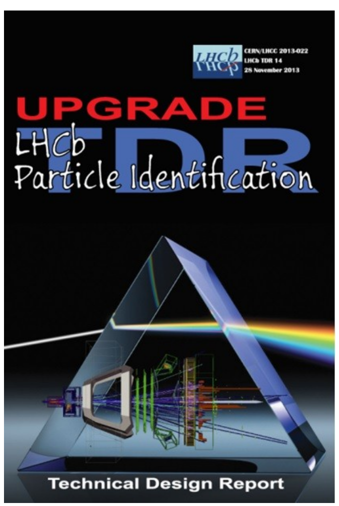

[CERN-LHCC-2013-001]

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[CERN-LHCC-2013-021]

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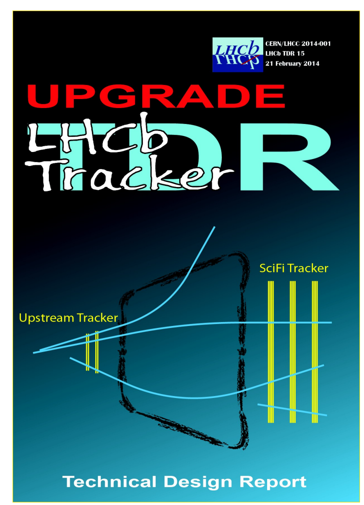

[CERN-LHCC-2014-001]

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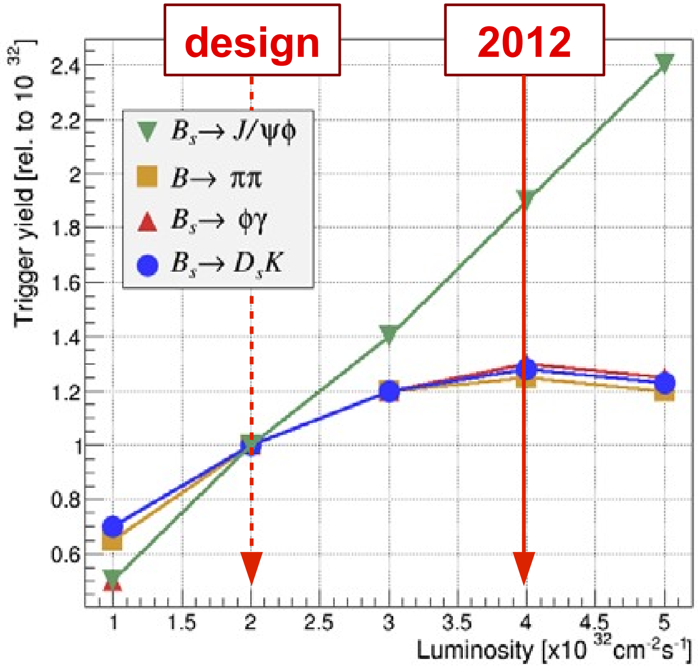
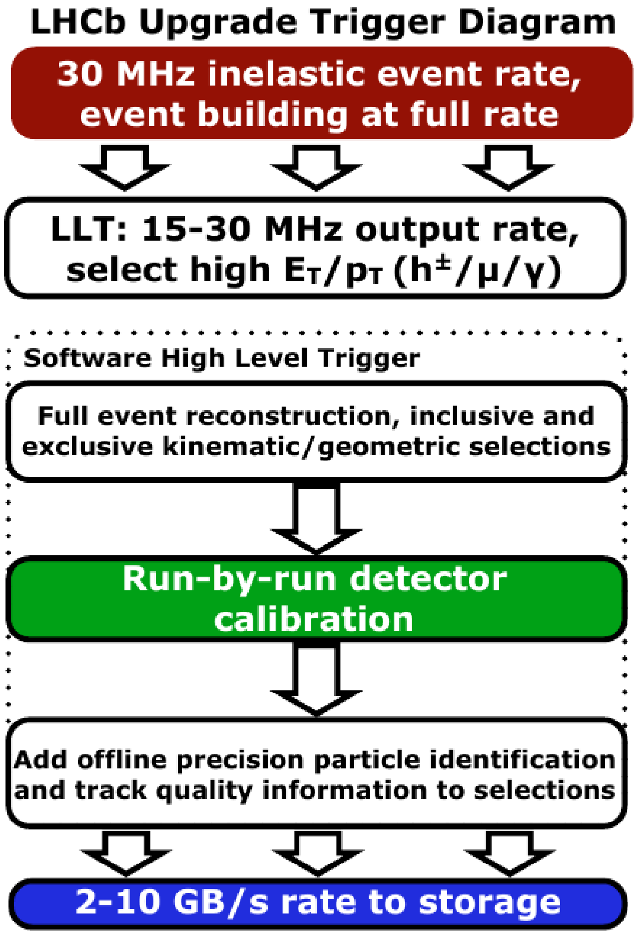
[CERN-LHCC-2014-016]

Trigger

- to collect 5 fb^{-1} / year: operate at up to 5 × higher instantaneous luminosity
- final states with muons: event yields scale linearly with luminosity
- fully hadronic final states: in current trigger scheme have to increase p_T thresholds to stay within 1 MHz limit of L0 trigger → no further gain in yield



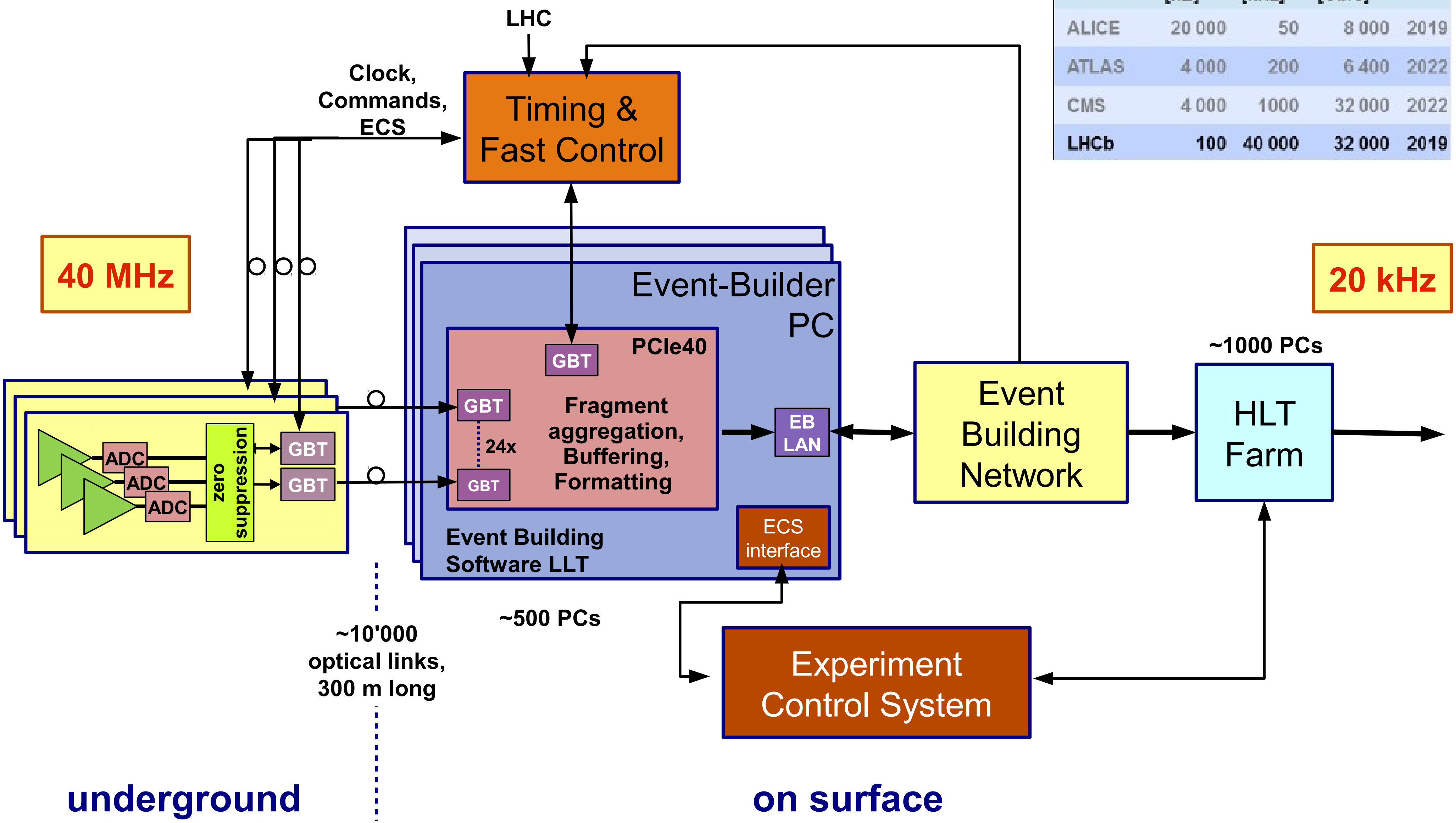


readout full detector at 40 MHz
full software trigger with 20 kHz output rate

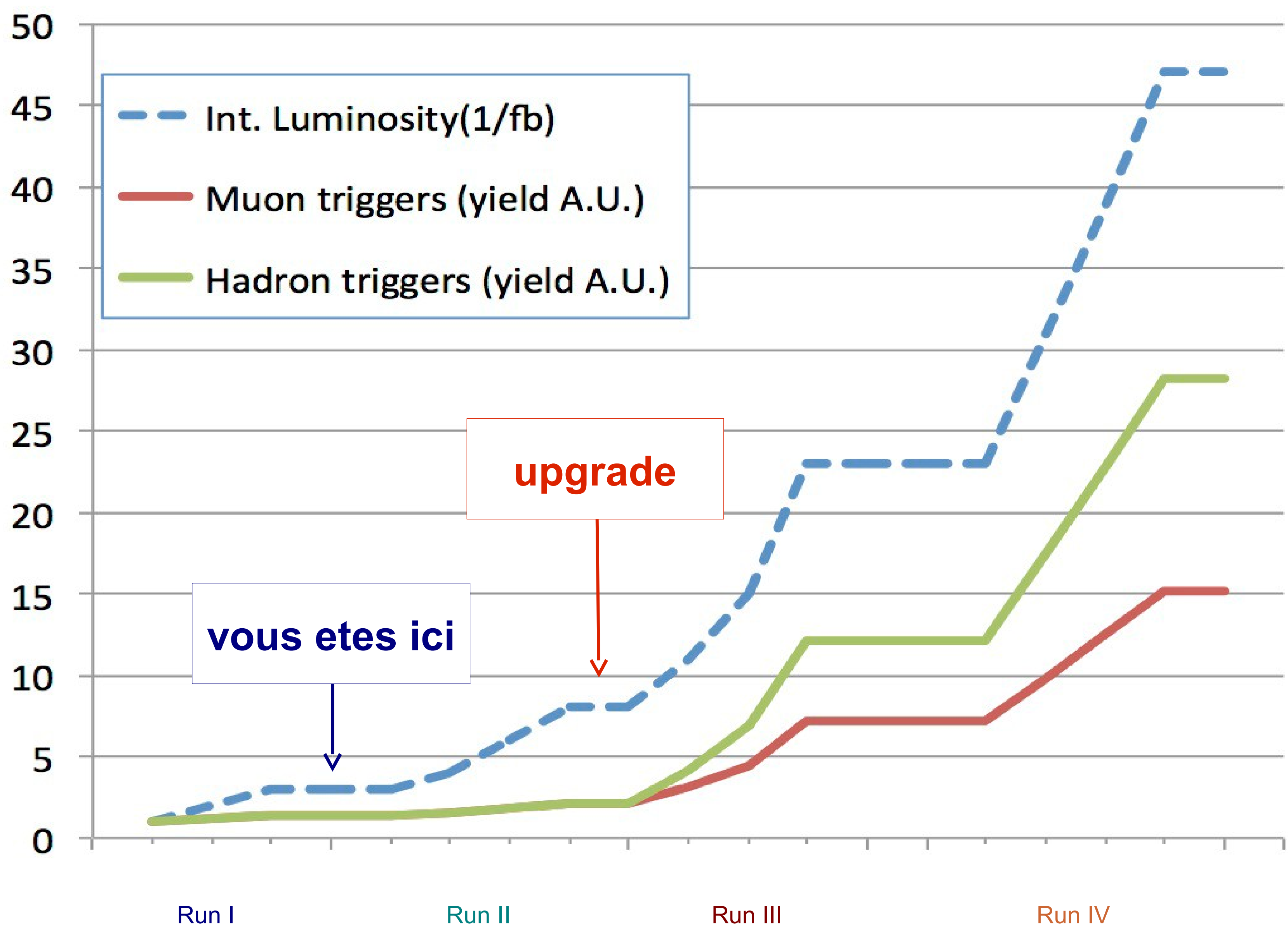
40 MHz Readout

[status: ECFA-Workshop 10/2013]

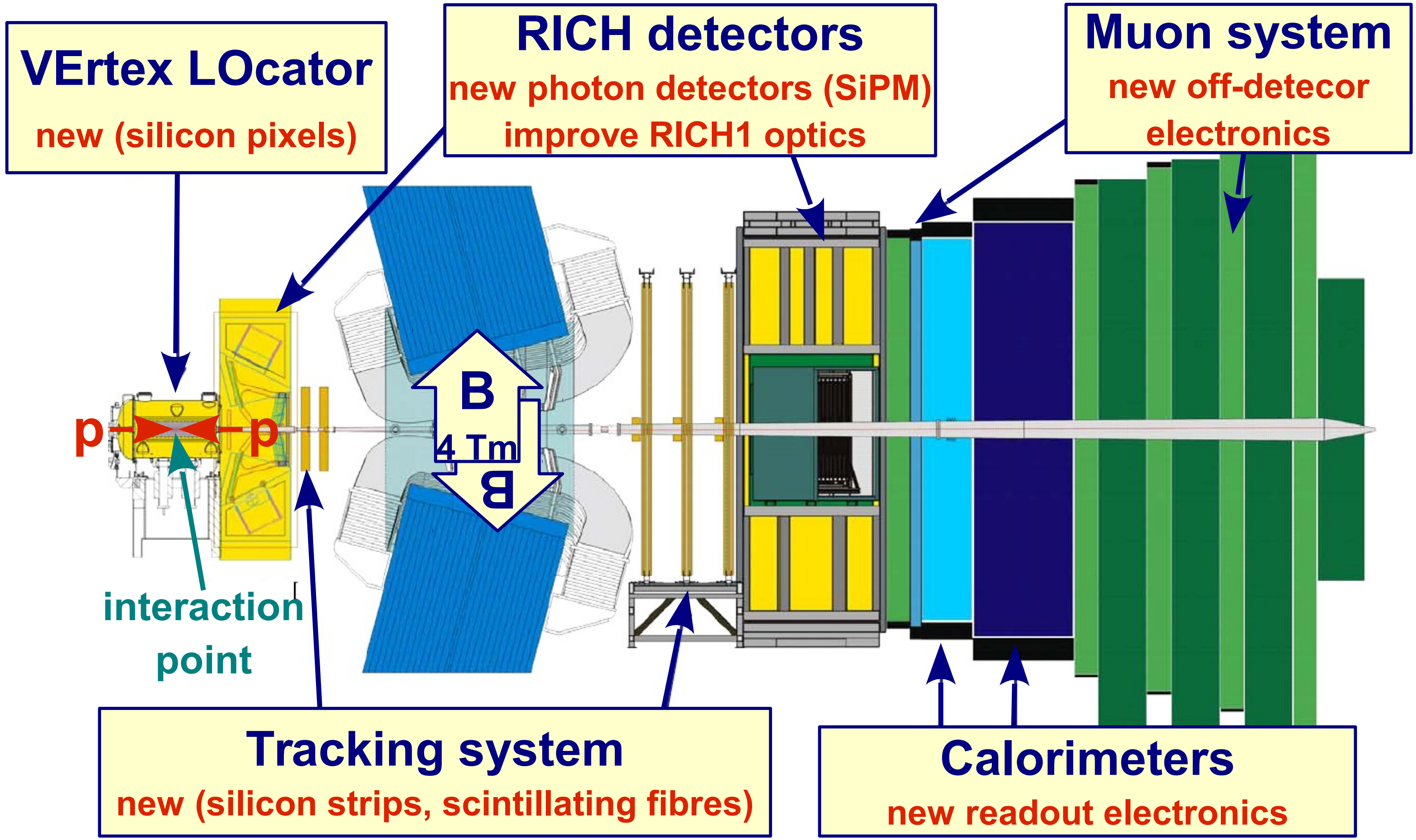
	Event-size [kB]	Rate [kHz]	Bandwidth [Gb/s]	Year
ALICE	20 000	50	8 000	2019
ATLAS	4 000	200	6 400	2022
CMS	4 000	1000	32 000	2022
LHCb	**100**	**40 000**	**32 000**	**2019**



Estimated Yields



Detector



- **upgrade to 40 MHz front-end electronics**
  - need to replace sub-systems with embedded front-end electronics
- **adapt where needed to maintain excellent performance at 5× higher luminosity**

VErtex LOcator

Run I/II: silicon micro-strip detectors

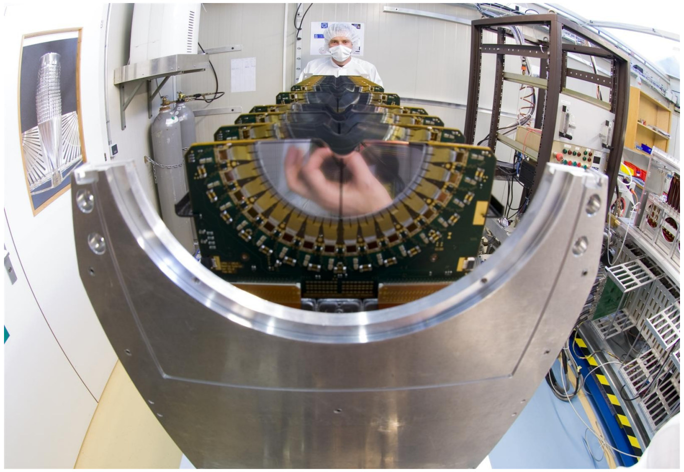
- r/ϕ strip geometry, strip pitch 83-101 μm

Operating in secondary vacuum inside LHC vessel

- 300 μm Al foil separates detector from beam vacuum

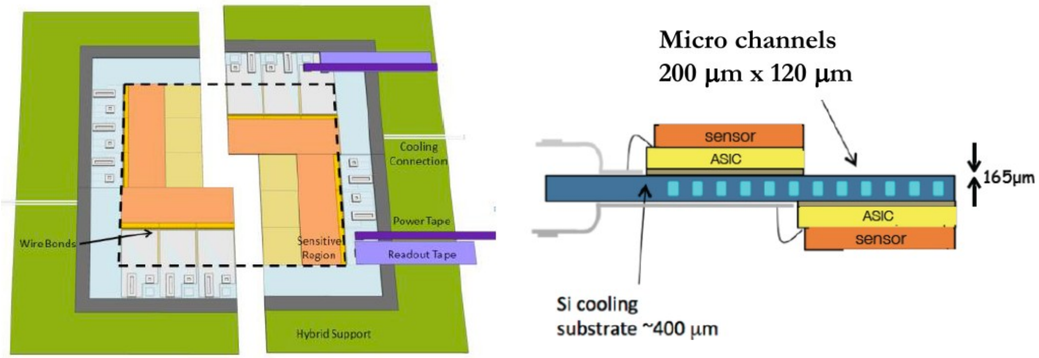
Two retractable halves

- silicon at 7 mm from beam during data taking



Upgrade challenges and goals:

- **cope with increased radiation level**
  - up to 8×10^{15} n_{eq} / cm^2 for 50 fb^{-1}, highly non-uniform across surface
- **improve current performance**
  - decrease material budget (thinner Al foil)
  - get even closer to beam (→ 5.5 mm)



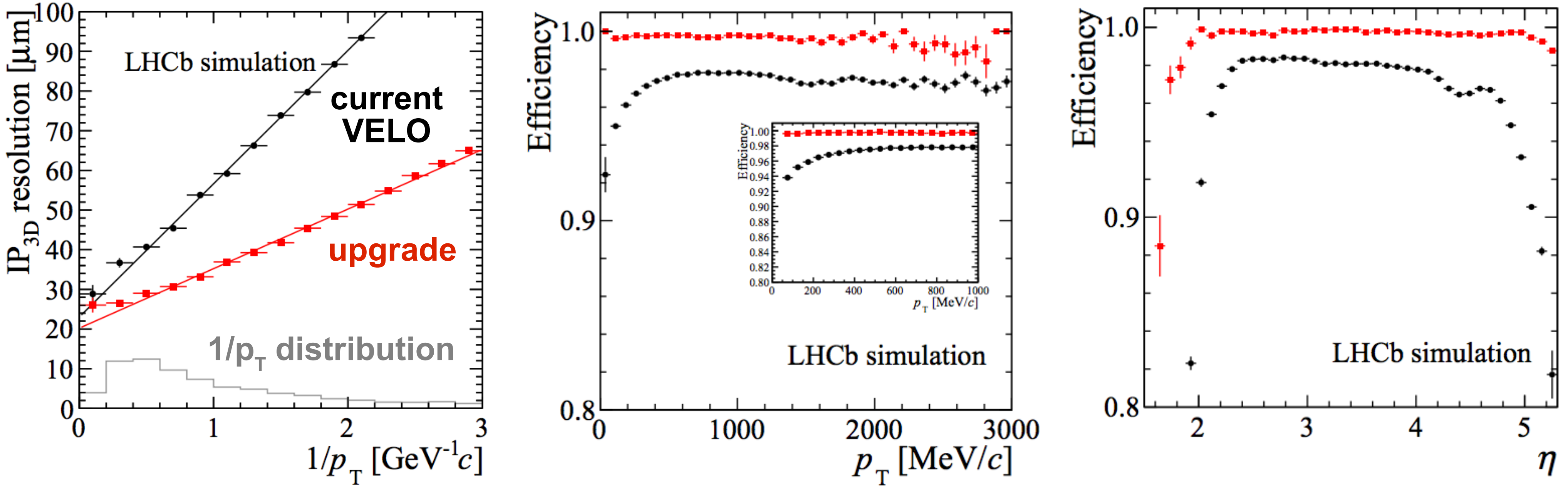
55×55 μm² silicon pixel detector

- Velopix readout chip (evolution of TimePix chip)
- micro-channel CO_2 cooling

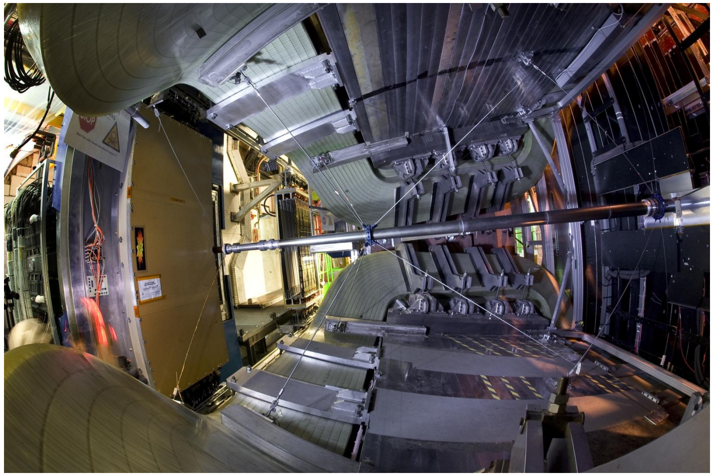
Expected Vertexing Performance

Expect superior performance in essentially every aspect compared to current VELO operating at high luminosity

- better impact parameter resolution due to reduced material budget
- reduced ghost rate due to pixels
- improved efficiency over full range in p_T, ϕ, η

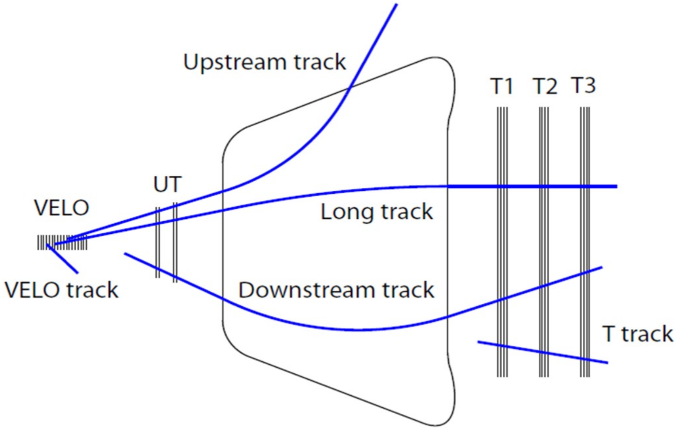


Main Tracker



Run I/II: silicon micro-strips upstream of magnet, silicon and 5 mm ∅ straw drift tubes downstream

- granularity / segmentation across detector surface adjusted to forward peaked particle densities
- excellent momentum resolution due to small material budget → crucial for background suppression



Upgrade challenges and goals:

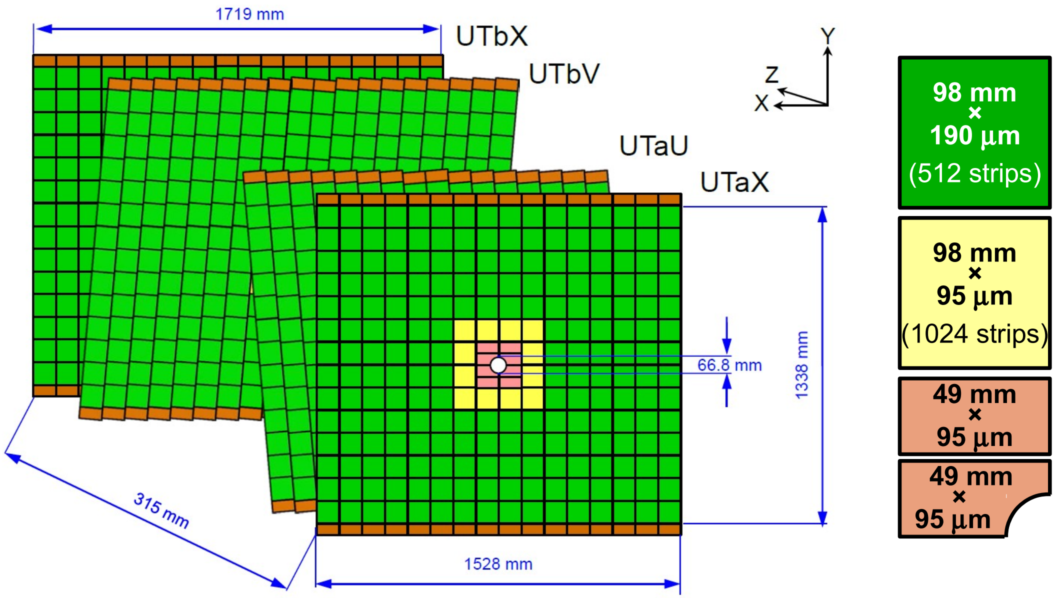
- **cope with increased particle density**
  - too high in inner region of straw detector
- **improve speed of track reconstruction**
  - crucial for trigger performance
- **improve forward acceptance in upstream station**
  - approach closer to beam pipe

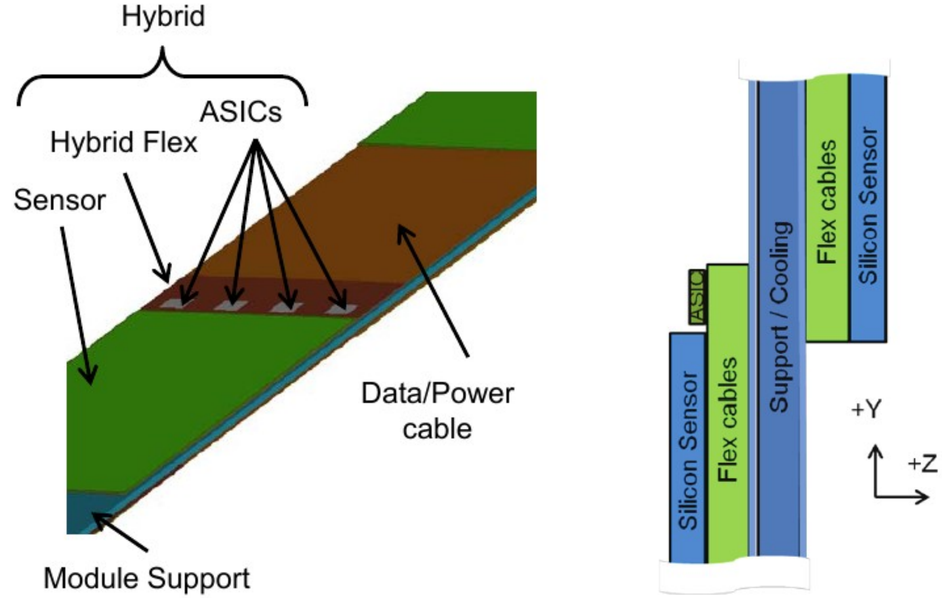
keep current setup with 1+3 stations
upstream: **silicon strip detector with finer readout granularity**
downstream: **scintillating fibres**

Main Tracker - Upstream

Upstream Tracker (UT)

- **four layers of 250 µm thin silicon micro-strip detectors**
  - three readout strip geometries, adapted to particle densities across detector surface
- **new 40 MHz readout chip**
- **silicon sensors and readout chips mounted on 130 cm long "staves"**
  - detectors on both sides of stave to avoid gaps in acceptance
- **bi-phase CO_2 cooling**
  - thin cooling pipes in stave supports

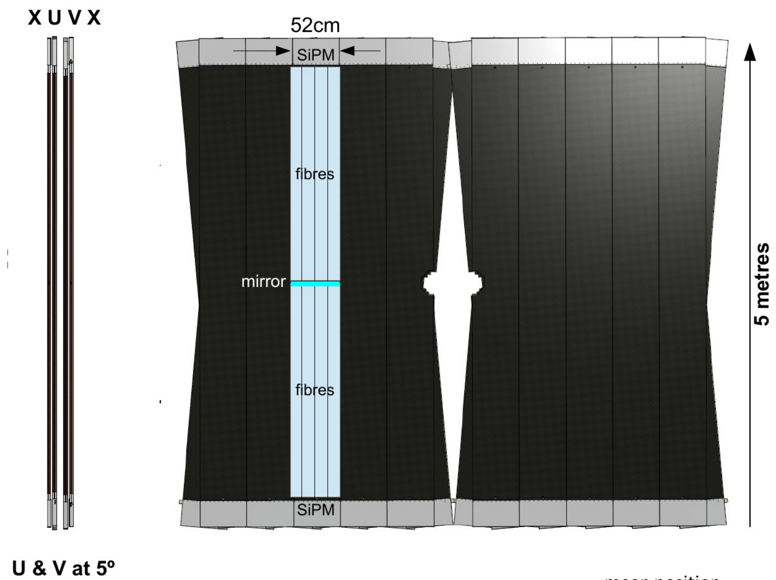


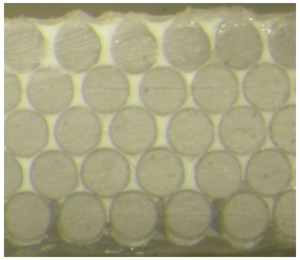


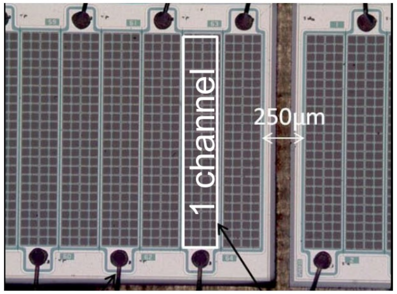
Main Tracker - Downstream

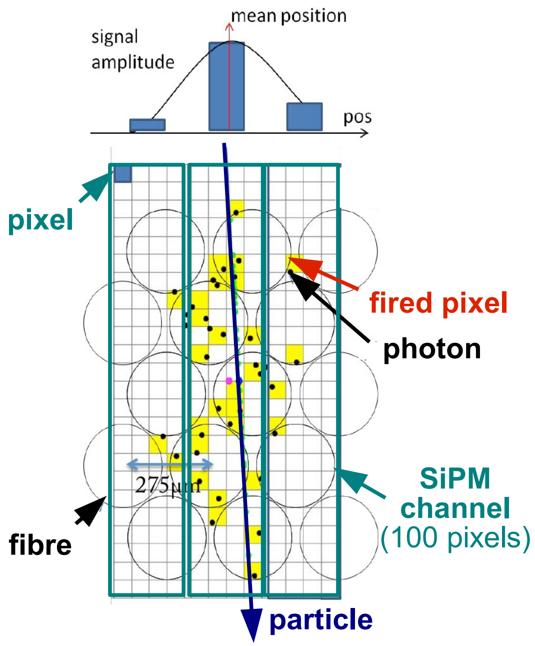
Scintillating Fibres (SciFi) with Silicon Photo-Multiplier (SiPM) readout

- **2.5 m long fibres with 250 μm ∅**
- **each detection plane = five fibre layers to ensure full efficiency**
  - typically 15-20 photo-electrons
- **single technology advantageous for fast track reconstruction in trigger**
  - uniform material distribution
  - avoid “left-right ambiguities” of straws
- **region close to beam pipe might need further optimization for occupancy**
- **SiPM need to be cooled to –40ºC to mitigate effects of radiation damage**
- **fibres look okay up to 50 fb^{-1}**



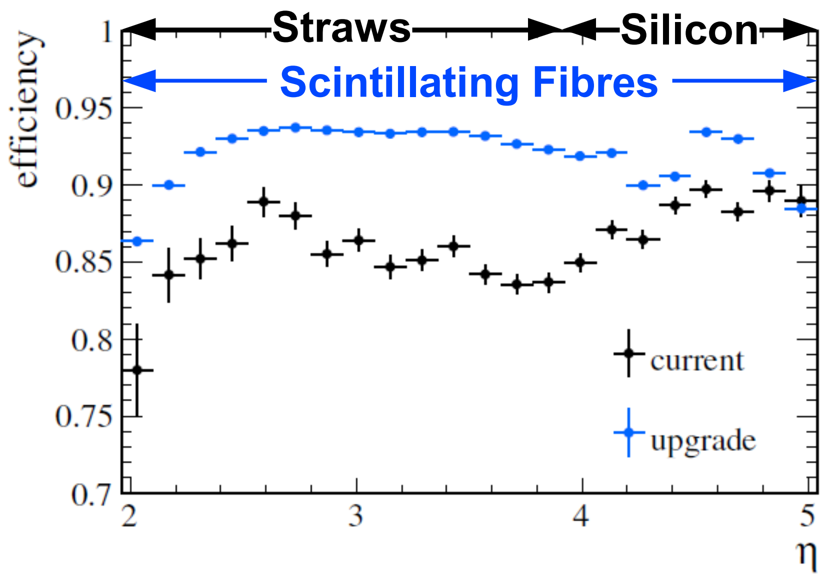




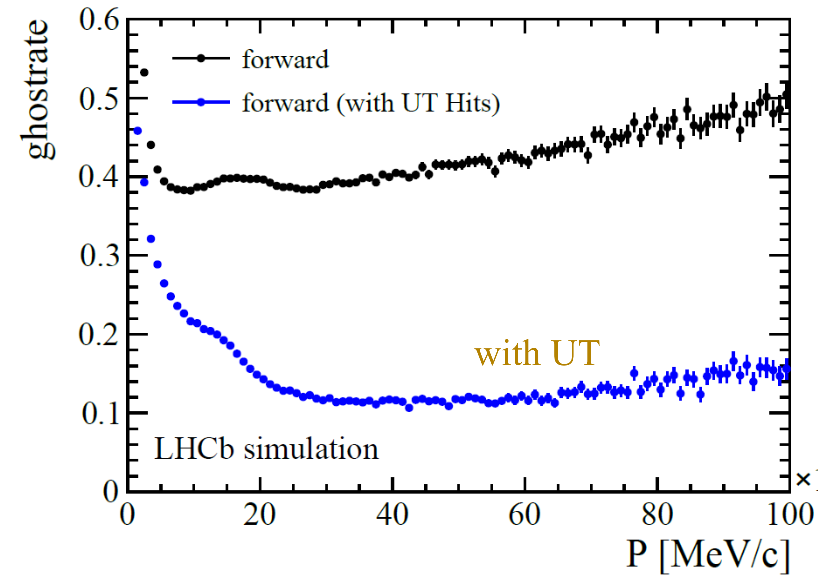


Expected Tracking Performance

Improved efficiency from SciFi compared to existing Silicon/Straw combination



Reduction of rate of fake tracks (ghosts) from use of UT hits in track reconstruction



Track reconstruction fits into 50 % of estimated HLT time budget of 13 ms

- assumes 10 × current CPU farm
- option to further speed up by applying Global Event Cuts (GEC) on hit multiplicities to veto small fraction of very high multiplicity events

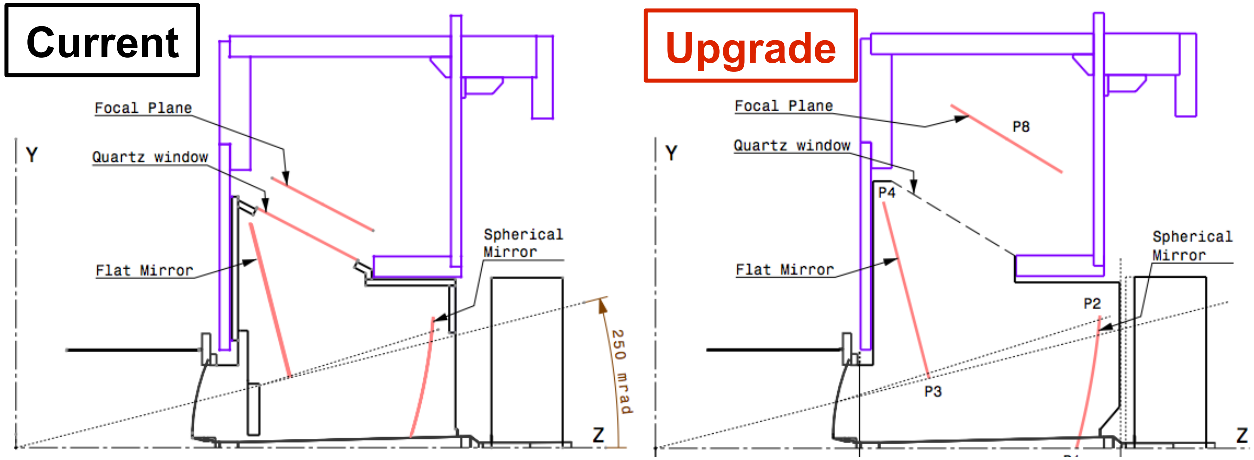
	CPU time[ms]	
Tracking Algorithm	No GEC	GEC = 1200
VELO tracking	2.3	2.0
VELO-UT tracking	1.4	1.3
Forward tracking	2.5	1.9
PV finding	0.40	0.38
Total @29 MHz		5.6
Total	6.6	5.4

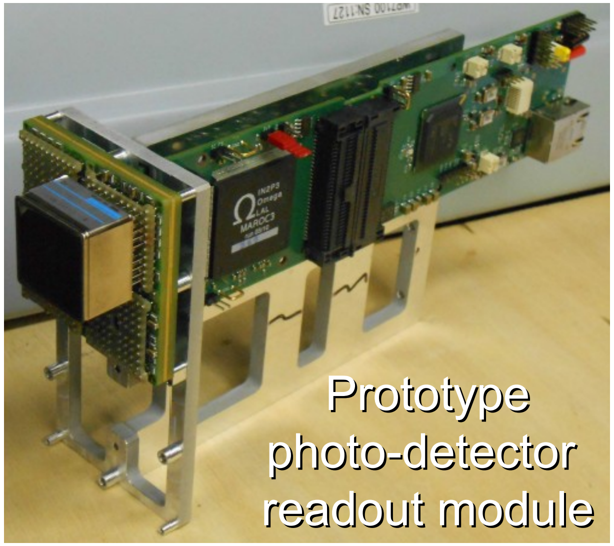
Run I/II: Hybrid photon detectors (HPD) with embedded 1 MHz front-end readout electronics

- need to be replaced for 40 MHz readout

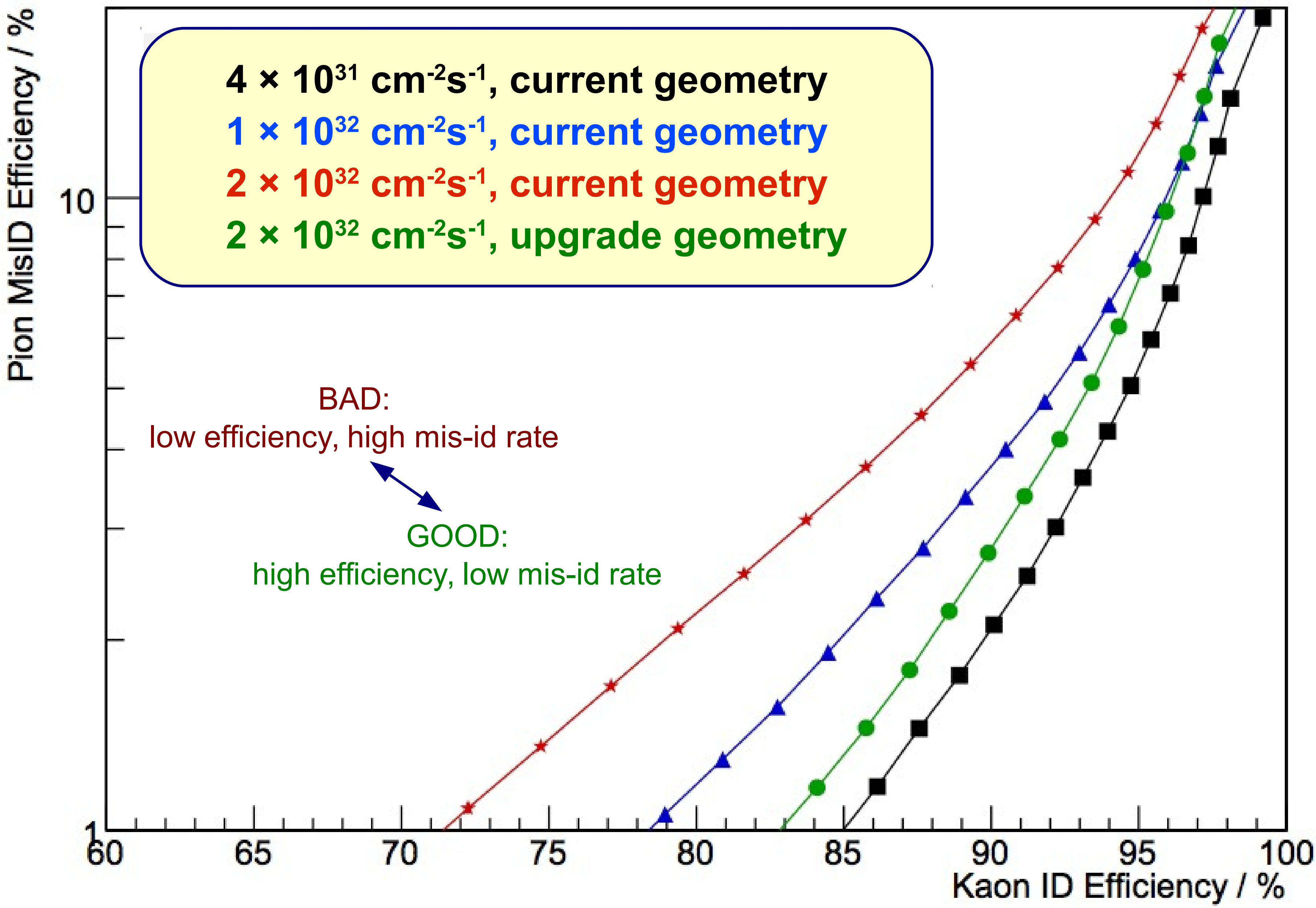
Upgrade:

- **replace HPDs with commercial Multi-Anode PMTs**
- **re-optimize RICH1 mirror optics**
  - spread out rings to compensate for higher occupancy
  - but stay within current gas enclosure





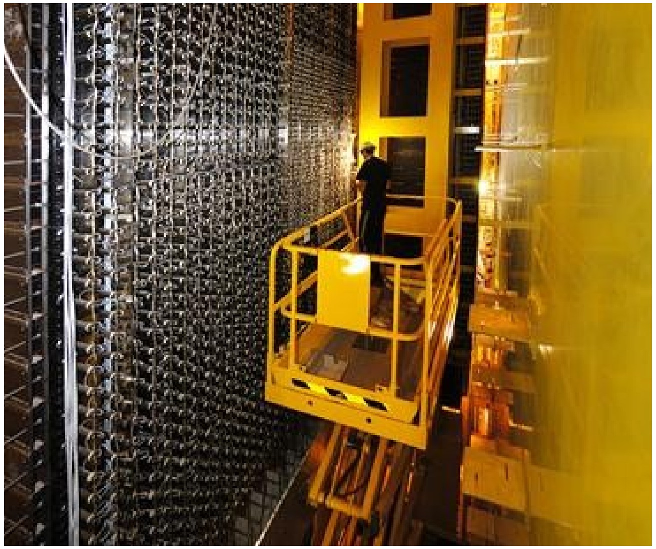
Expected K/π performance



Calorimeters

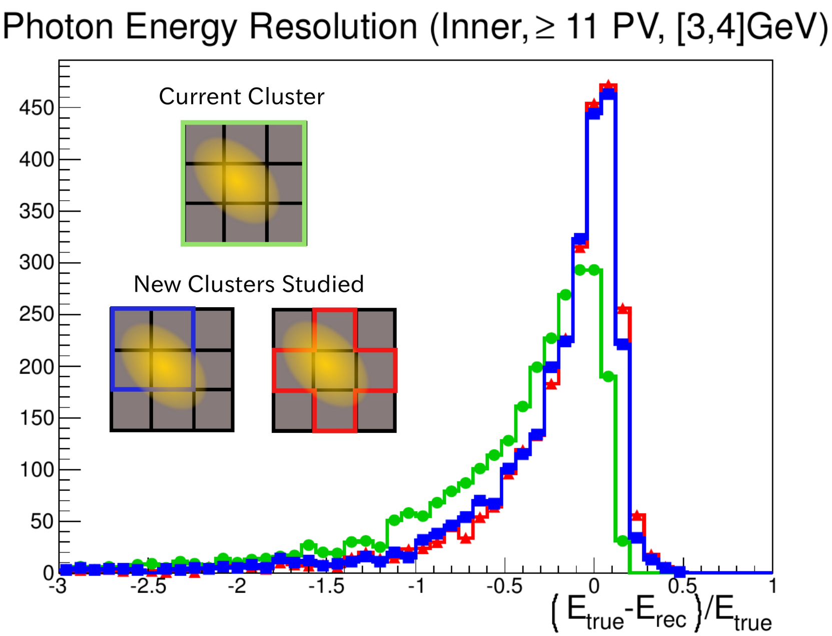
Run I/II: L0 trigger and e/γ reconstruction

- robust sampling calorimeters: absorber and scintillating fibres with photo-multiplier readout



Upgrade:

- **remove pre-shower (PS) and scintillating pad detector (SPD)**
  - not needed without L0 trigger
- **replace readout electronics for 40 MHz**
- **compensate for higher occupancy**
  - reduce photo-multiplier gains
  - revise cluster definition
- **radiation damage**
  - consider replacing innermost ECAL cells during LS3, otherwise okay up to 50 fb^{-1}



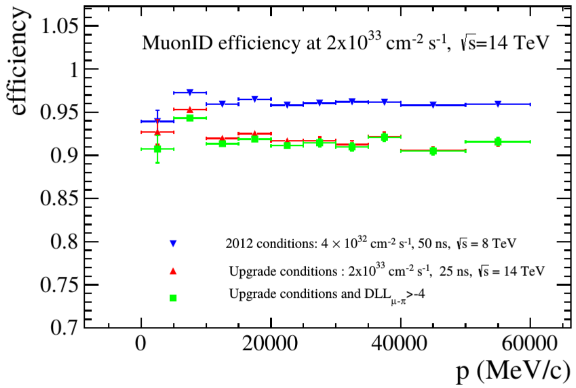
Muon System

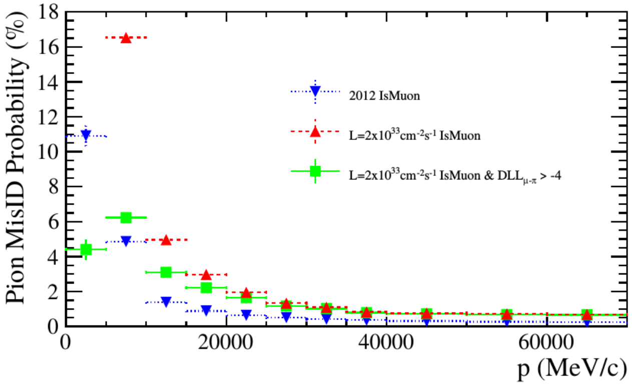
Run I/II: L0 trigger and muon identification

- five detector stations (M1-M5) interleaved with absorber walls (M1 upstream of calorimeters)
- multi-wire proportional chambers, triple-GEMs in regions of highest particle density
- detectors read out at 40 MHz for L0 trigger

Upgrade:

- **no need to change front-end readout ;-)**
- **remove M1 in front of calorimeters**
  - too high occupancies, not crucial for muon ID
- **add more shielding between HCAL and M2**
  - to reduce background rate in innermost region
- **possible replacement of detectors in innermost regions of M2 and M3 under consideration**





Summary / Outlook

- **excellent LHCb performance is leading to world best measurements in the beauty and charm quark sectors and many other interesting results**
- **expect to increase available data sample from 3 fb^{-1} to ~8 fb^{-1} by 2018**
  - will allow LHCb to find or rule-out large sources of flavour symmetry breaking at the TeV scale
- **LHCb upgrade is then mandatory to reach measurement precisions of the order of current theoretical uncertainties**
  - goal is to collect ≥ 50 fb^{-1} within ~10 years, with improved selection efficiency
  - software-only trigger with access to the full detector information
  - detector upgrade to 40 MHz readout, able to sustain a levelled luminosity of $2 \times 10^{33}\ cm^{-2}\ s^{-1}$ at 25 ns bunch spacing
- **LHCb upgrade is fully approved, the last TDR is under review**
  - to be installed in LS2 and operational at the beginning of 2020


THANK YOU !

Roadmap Towards the Upgrade

2011 LoI submitted & encouraged to proceed to TDRs

2012 "Framework TDR" submitted, endorsed & approved

□ **"LHCb upgrade approved to be part of the long-term exploitation of the LHC"**

2012 Submission of MoU for Common Projects

2012 /13 R&D towards technical choices

2013 Technical reviews & choice of technologies

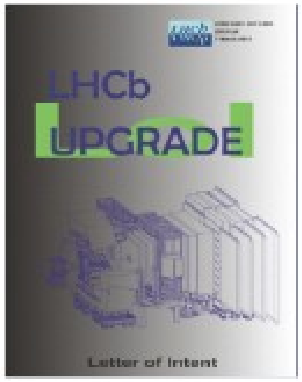
2013/14 Technical Design Reports & MoUs of sub-systems

2014 Prototype validation & Engineering Design Reviews

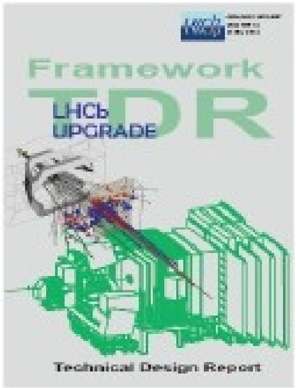
2014-16 Tendering & serial production

2016-17 Quality control & acceptance tests

2018/19 18 months installation during LS2



CERN-LHCC-2011-001



CERN-LHCC-2012-007

[A. Schopper at Heavy Flavour in the HL-LHC Era, Aix les Bains, 2013]

Complementarity LHCb / Belle II

LHCb

ATLAS & CMS

- Rare decays: $B_{d,s} \to \mu\mu$
- B_s system
- b-baryons
- Spectroscopy
- CKM phases (β, γ)
- Gluonic penguins
- EW penguins
- Charm physics
- Semileptonics: Mixing, A_{SL}
- Semileptonics: V_{xb}
- $B\to\tau\nu$, $D\tau\mu$,
- $B\to K^*\nu\nu$
- τ-physics

Some only LHCb, some only Belle II

On-going

Belle II

*) Caveat: I am probably missing "your" favored channel/field

[U.Uwer at Flavour Physics Conference, Quy Nhon, 2014]

DAQ Numbers

Event rate	40 MHz
Mean nominal event size	100 kBytes
Readout board bandwidth	up to 100 Gbits/s
CPU nodes	up to 4000

LHC BX frequency

PCIe Gen3 protocol

power, cooling, space constraints

Instantaneous luminosity	$2 \times 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
Pile-up	7.6
Input rate	30 MHz
Maximum processing time per event	13 ms
Output bandwidth	$20\,\mathrm{kHz} \times 100\,\mathrm{kB} = 2\,\mathrm{GByte/s}$

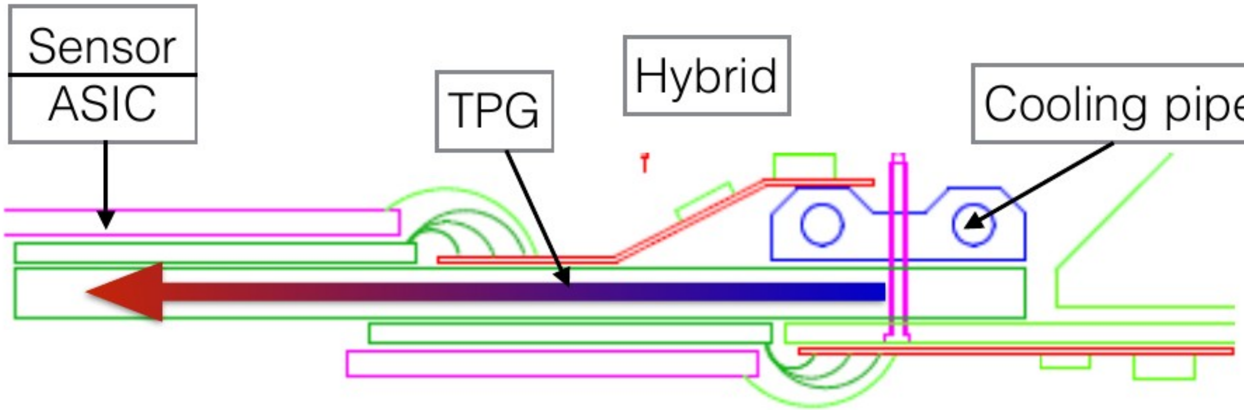
⟨pp collisions⟩ per BX

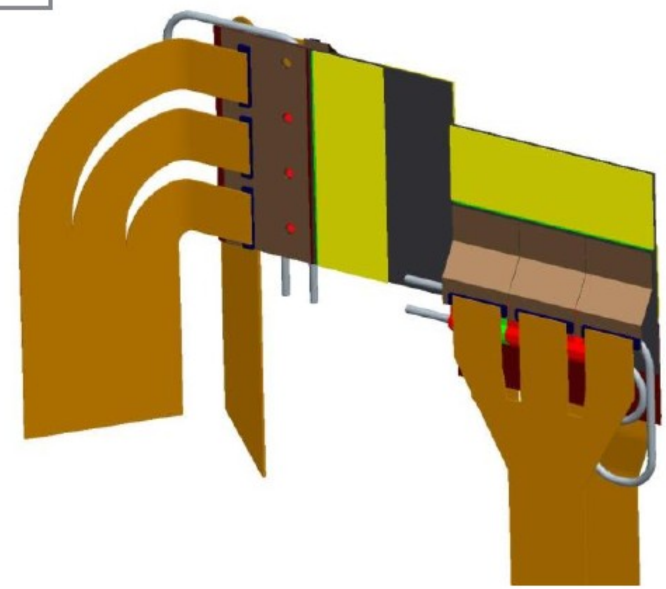
non-empty BX

CPU × CPU power (assume 2011 × 16)

Versatile Links for DAQ	8800
Mean nominal total event-size	100 kB
PCIe40 boards for DAQ	500
Versatile Links / readout board (DAQ)	up to 48
Event builder-PCs	500
PCIe40 boards for ECS and TFC (SOL40)	77
Core switch ports (100 Gbit/s)	500
Event-filter nodes	up to 4000
Output rate	20 kHz
Nominal instantaneous output rate	2 GB/s

Thermal pyrolytic graphite (TPG)





Heat sources | Cooling

Too much ΔT in simulations and thermal mock-up.
Too much thermal expansion difference (delamination). 😱

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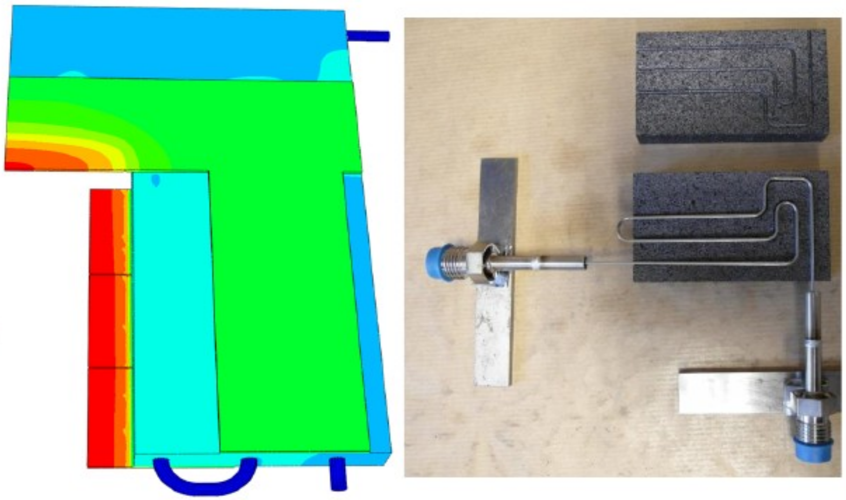
Micro-Channel Cooling

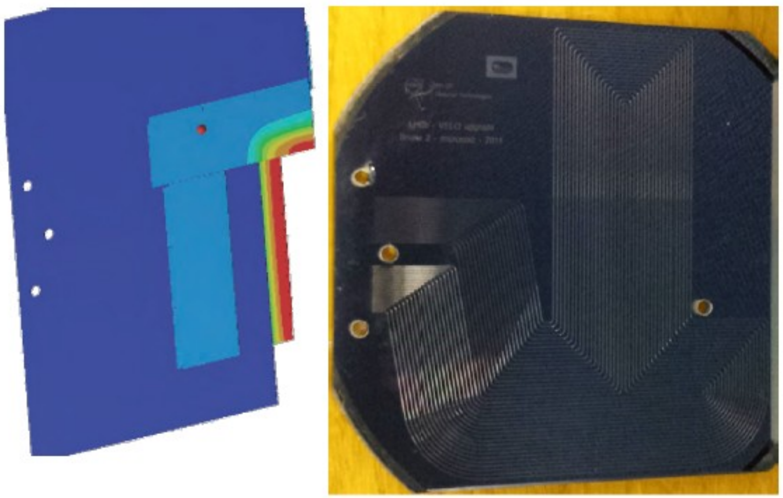
New approach: the cooling is underneath the heat source

Pocofoam®



Cooling pipes surrounded by carbon foam

Micro-channel



CO_2 passes through channels etched in a silicon plate

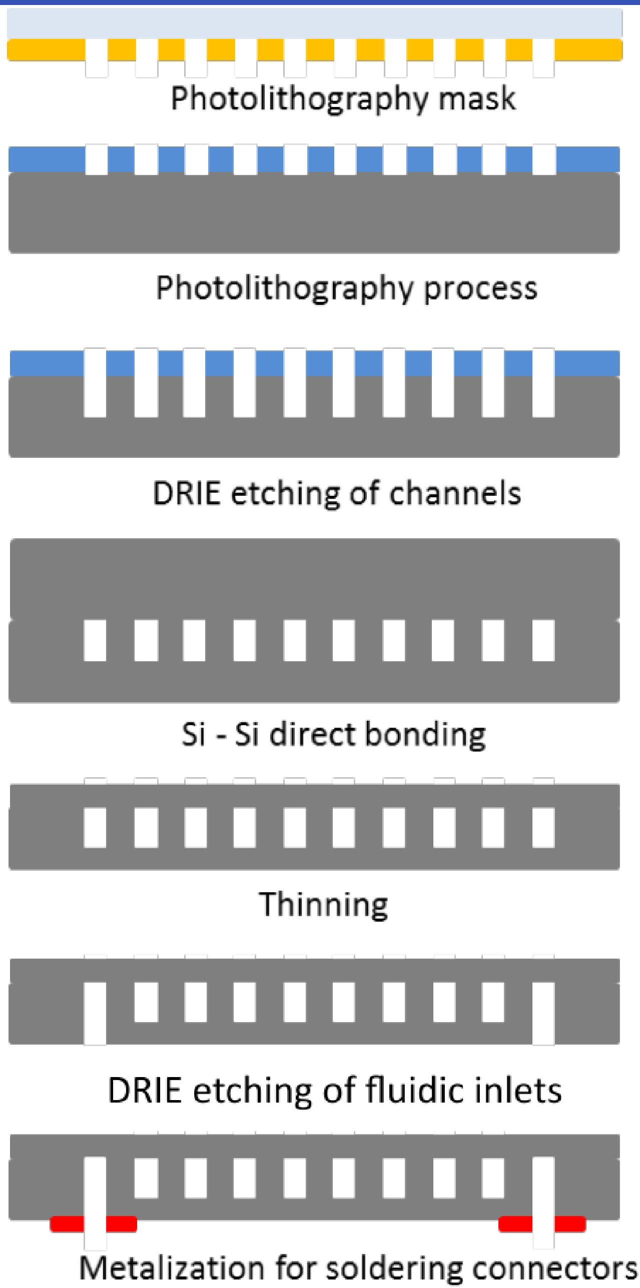
Both satisfy the cooling requirements.

Both acts as mechanical support.

Micro-channel showed better IP resolution:

- Lower material budget.
- Thinner modules.

Micro-Channel Cooling



<u>Fabrication</u>

- Etch trenches into the surface of silicon wafer.
- Atomic bond a cover wafer to create the capillaries.
- Practice exit and entry holes.
- Attach the connectors & electronics.

<u>Advantages</u>

- Cooling is exactly under the heat source.
- Large heat exchange surface (many parallel channels).
- Small thermal gradients across the module (no heat path through the hybrid/sensor plane).
- Minimal material budget (thin silicon layer).
- No CTE difference between heat source and heat sink.

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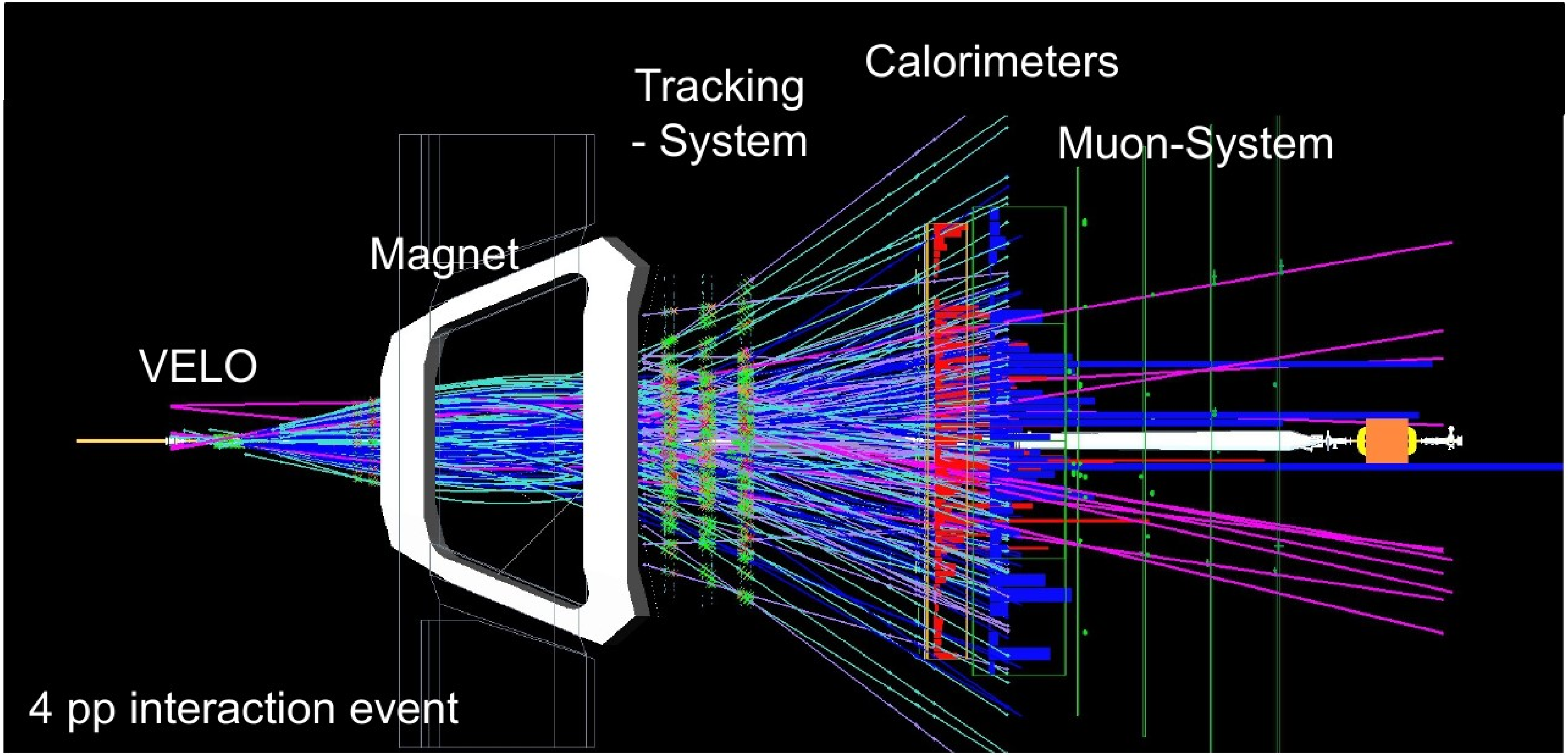
Multiplicities



Number of visible pp interactions per BX Poisson distributed with

2012: $\langle\mu\rangle = 2$ ⟶ upgrade: $\langle\mu\rangle = 5$

Average number of tracks for $b\bar{b}$ events

2012: 72 ⟶ upgrade: 180

Fluence and Dose in UT

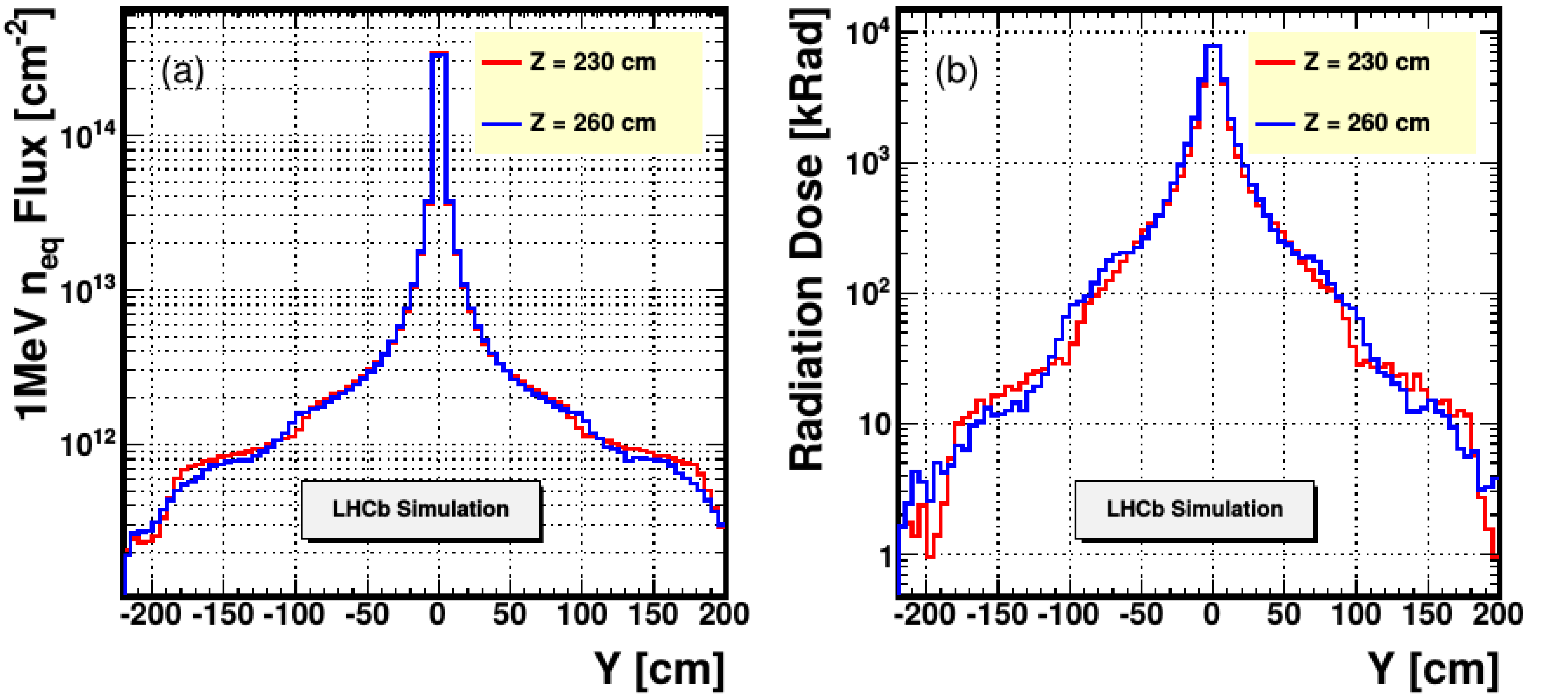


Figure 2.6: Expected fluence profile (left) and dose profile (right) after $50\,\mathrm{fb}^{-1}$ of total integrated luminosity as a function of the vertical coordinate Y for X=0. (The LHCb coordinate system is a right handed Cartesian system with the positive Z-axis aligned with the beam line and pointing away from the interaction point and the positive X-axis following the ground of the experimental area, and pointing towards the outside of the LHC ring.) This slice represents the highest fluence region throughout the UT system.

SALT Chip

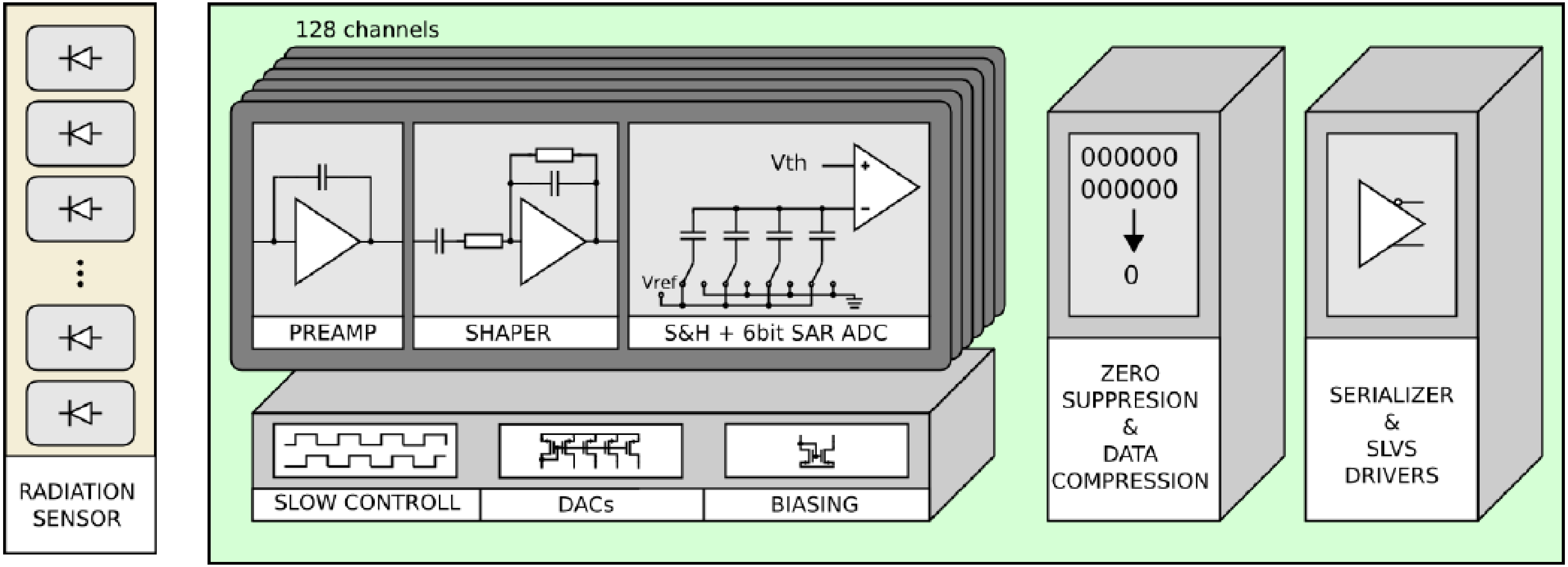
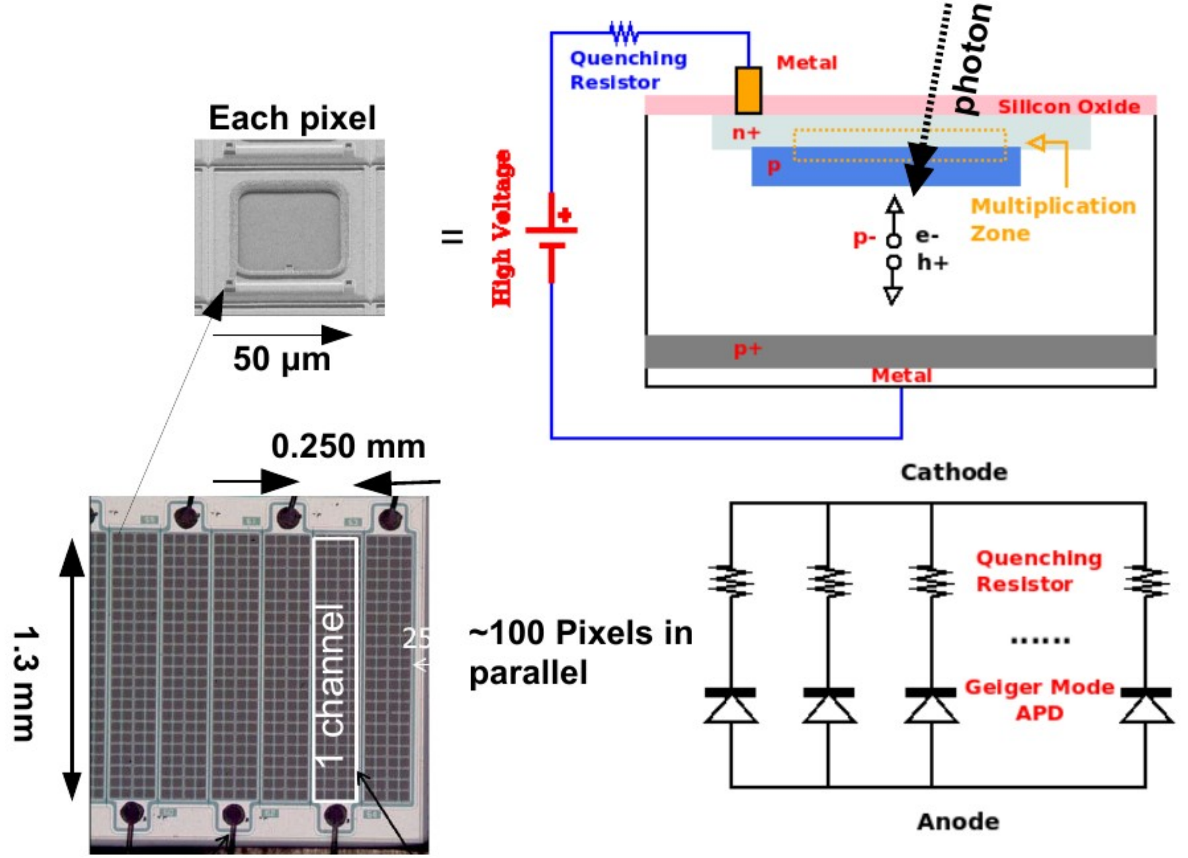


Figure 2.19: The SALT ASIC block diagram.

Silicon Photo Multiplier

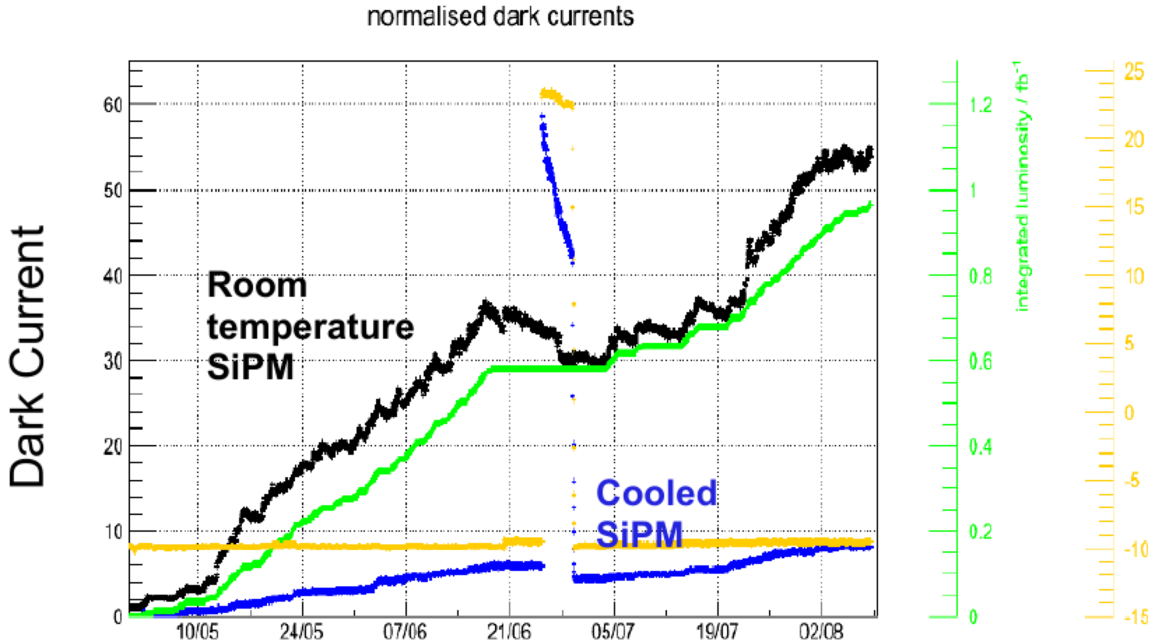
- The SiPM pixel is a photo-diode (reverse-biased, above breakdown)
- a single free electron/hole-pair can trigger an avalanche of electrons
- 10^6—10^7 gain
- 40-50% photon detection efficiency



Sketches from Wei Shen, PhD Thesis Uni Heidelberg

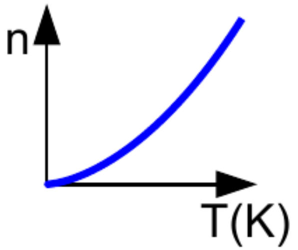
Radiation Damage in SiPM

- SiPMs create single photo-electron signals from thermal electrons, cross-talk between pixels makes 1 photo-electron look like 2+
- Neutron damage to silicon worsens thermal problem, expect 10^{12} neutrons/cm^2



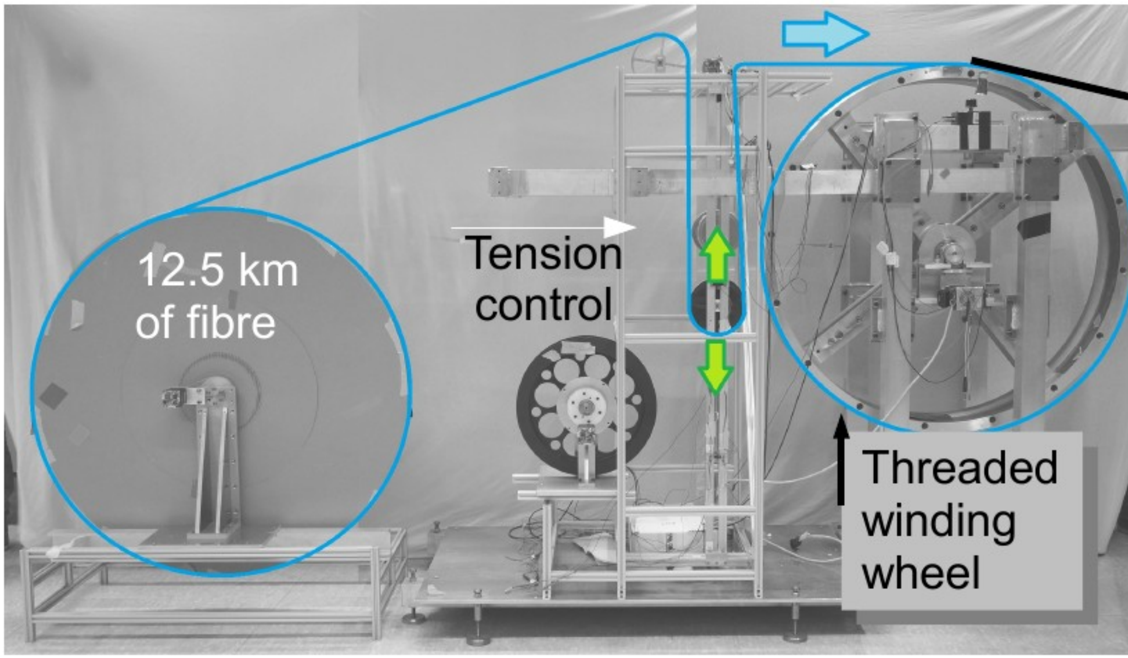
- Acceptable cluster rates require -40C cooling and +40C annealing

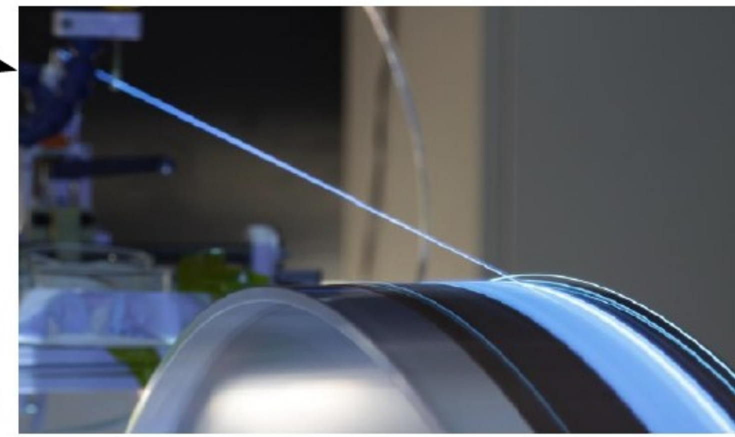
$$dark\ noise \propto T^2 \exp\left(\frac{-E_g}{2k_B T}\right)$$

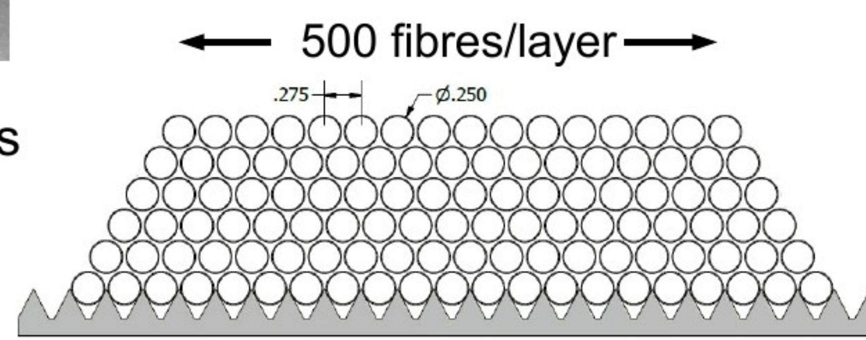


Production of Fibre Mats

Fibre mats are produced from winding a single fibre onto a threaded wheel.



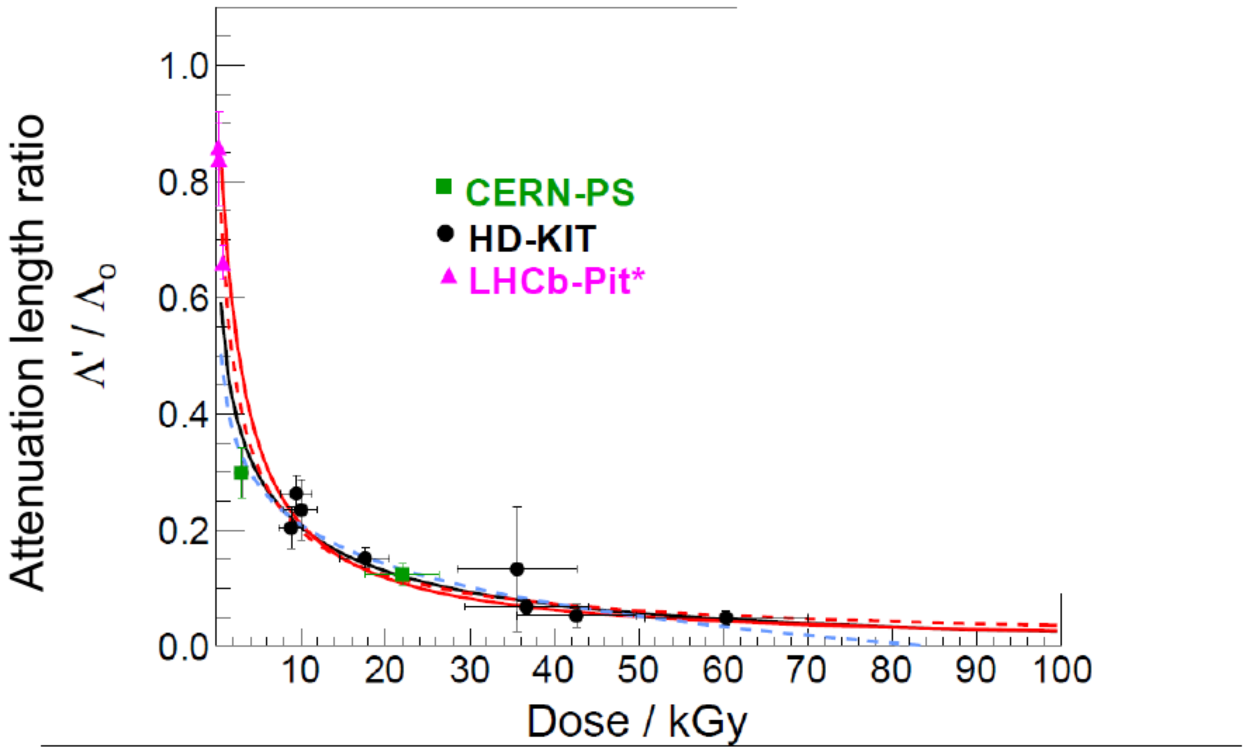




- Need about 8km of fibre for one mat of 6 layers 2.5 metres long
- 10,000 km of fibre in total ...

Radiation Damage in Fibres

- The scintillating fibres darken with radiation (up to 35 kGy expected near the beam pipe over the upgrade lifetime)



June 6, 2014 Blake D. Leverington - TIPP 2014 22/27