LHC Detector Upgrades

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Outline and initial comments

Choice of material

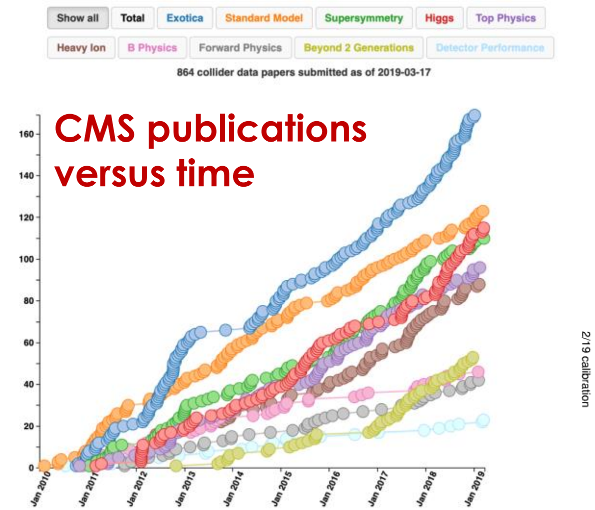
- Focus on ATLAS & CMS and LHCb
  - In line with the profile of the conference
  - Apologies for any bias in the choice of topics
  - Apologies to ALICE and other present and future LHC experiments
- Credits: colleagues in ATLAS, CMS and LHCb who provided material

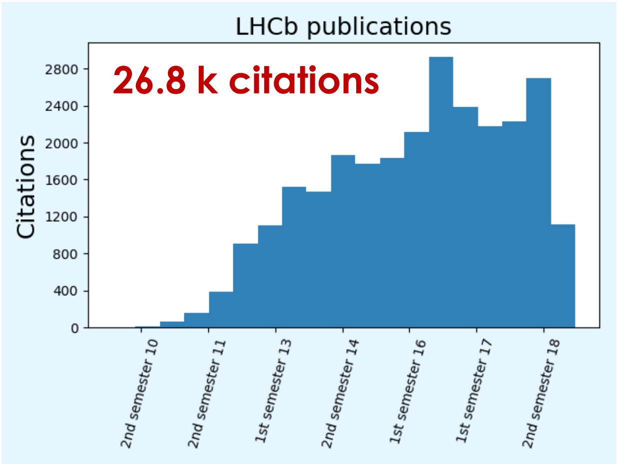
Outline of the talk and timeline of the upgrades

- Detector upgrades until now
- Upgrades in preparation
  - LS2, LS3 & LS4
- Conclusion

LHC Experimental achievements & status

- Seven years of physics data taking: 2010 – 2012, 2015 – 2018
- Recorded luminosity
  - ATLAS & CMS: 170 fb^{-1}
    - 500 pb^{-1} / good fill
  - LHCb: 9.1 fb^{-1}
    - 20 pb^{-1} / good fill
- Published papers
  - ATLAS: 844
  - CMS: 891
  - LHCb: 471
- Simplest argument for upgrading: $\sqrt{N}$
  - LHC has exceeded it design luminosity
  - Data doubling time (2018 performance)
    - ATLAS & CMS: 2.7 years
    - LHCb: 4.2 years





Timeline – Luminosity & upgrades

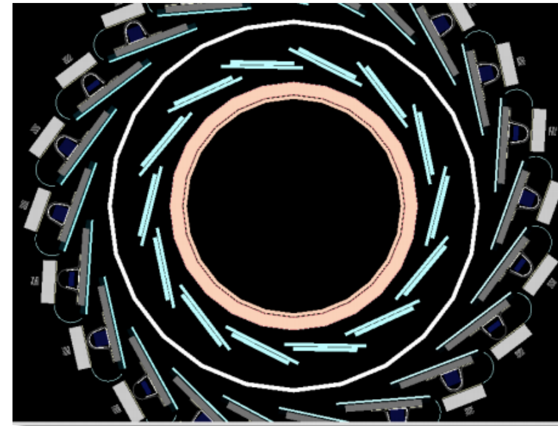
	Run 1	LS1	Run 2	LS2	Run 3	LS3	
Energy	7 TeV 8 TeV		13 TeV		14(?) TeV		
CMS & ATLAS	$\int \mathcal{L} = 21\ fb^{-1}$ $\mathcal{L} = 0 - 8 \times 10^{33}$	Upgrade phase I	$\int \mathcal{L} = 170\ fb^{-1}$ $\mathcal{L} = 1 - 2 \times 10^{34}$	Upgrade phase I	$\int \mathcal{L} = 380\ fb^{-1}$ $\mathcal{L}\ 2.5 \times 10^{34}$	Upgrade phase II	
	2010 2011 2012	2013 2014	2015 2016 2017 2018	2019 2020	2021 2022 2023	2024 2025	2026
LHCb	$\int \mathcal{L} = 3\ fb^{-1}$ $\mathcal{L} = 0 - 4 \times 10^{32}$		$\int \mathcal{L} = 9\ fb^{-1}$ $\mathcal{L} = 3 - 4 \times 10^{32}$	Upgrade 1	$\int \mathcal{L} = 23\ fb^{-1}$ $\mathcal{L} = 1 - 2 \times 10^{33}$	Upgrade 1b	

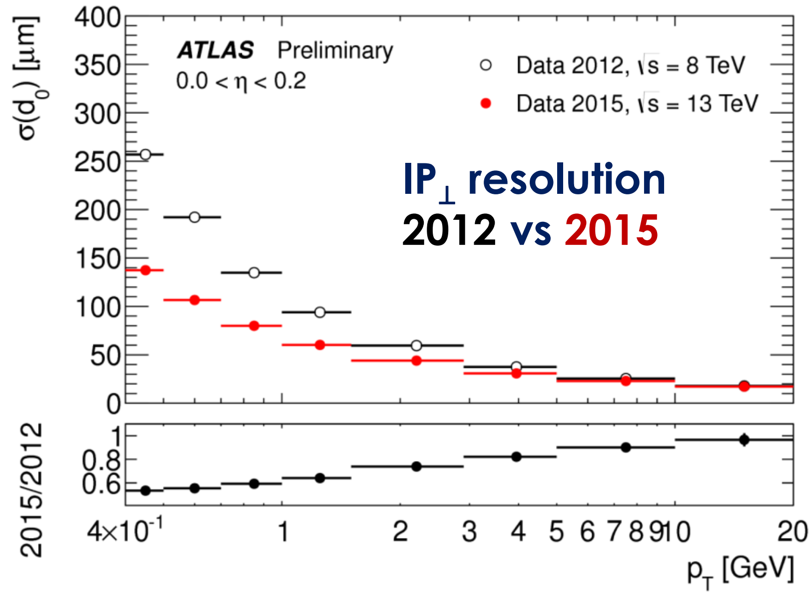
		Run 4	LS4	Run 5	LS5	Run 6
Energy		14 TeV		14 TeV		14 TeV
CMS & ATLAS		$\int \mathcal{L} = 1000\ fb^{-1}$ $\mathcal{L} = 3 - 5 \times 10^{34}$		$\int \mathcal{L} = 2000\ fb^{-1}$ $\mathcal{L} = 5 \times 10^{34}$		$\int \mathcal{L} = 4000\ fb^{-1}$ $\mathcal{L} = 5 - 7 \times 10^{34}$
	2026	2027 2028 2029	2030	2031 2032 2033	2034	2035 2036 2037
LHCb		$\int \mathcal{L} = 50\ fb^{-1}$ $\mathcal{L} = 2 \times 10^{33}$	Upgrade 2	$\mathcal{L} = 1 - 2 \times 10^{34}$		$\int \mathcal{L} > 300\ fb^{-1}$ $\mathcal{L} = 1 - 2 \times 10^{34}$

$[cm^{-2}s^{-1}]$

ATLAS phase I upgrade – during LS1

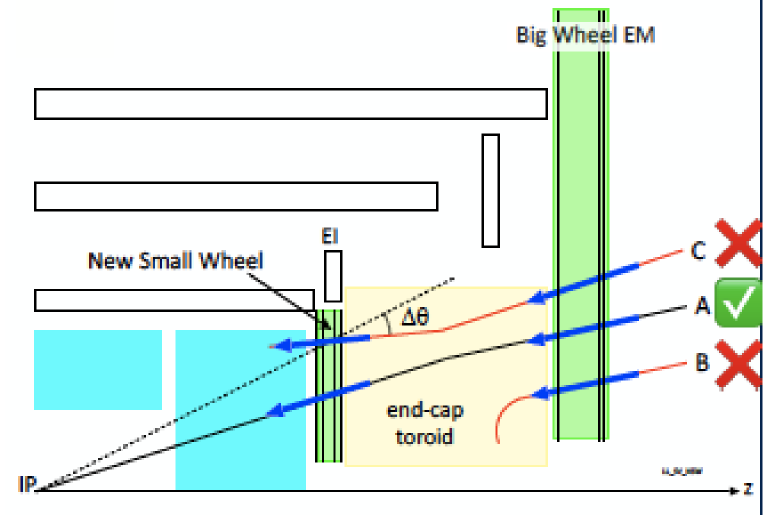
- Detector consolidation
  - Complete muon chamber installation
  - Repairs & improvements
- Insertable 4th pixel layer: IBL
  - 3.3 cm from beam axis
  - Improved IP resolution
    - B-tagging efficiency
- Trigger & DAQ improvements
  - L1 trigger, high-level trigger
  - Fast track trigger
- Software improvements
- Forward proton tagger



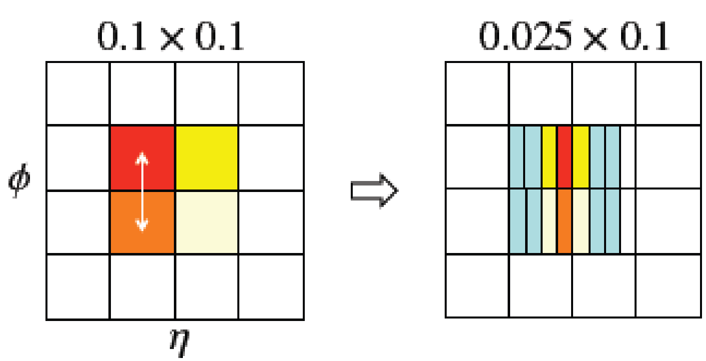


ATLAS phase I upgrades – LS2

- Replace first layer for endcap muon
  - New small wheel (NSW)
  - < 1 mrad angular resolution
    - Trigger vector capability
    - Reduces L1 muon rate up to 5 times
- TDAQ upgrade
  - L1 muon and calorimeter triggers
  - Topological triggers
  - High level trigger
  - Readout
- LAr readout electronics
  - Improved granularity
- Upgrades to the forward detector system
- Computing

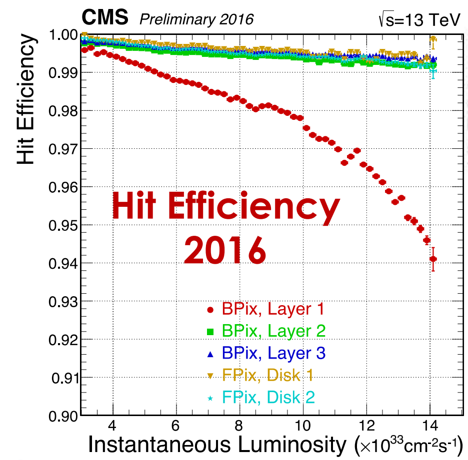


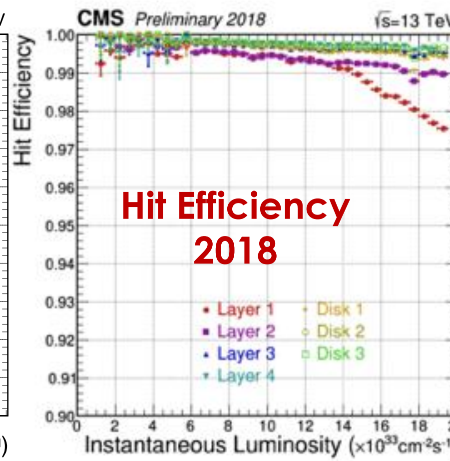
LAr readout cells



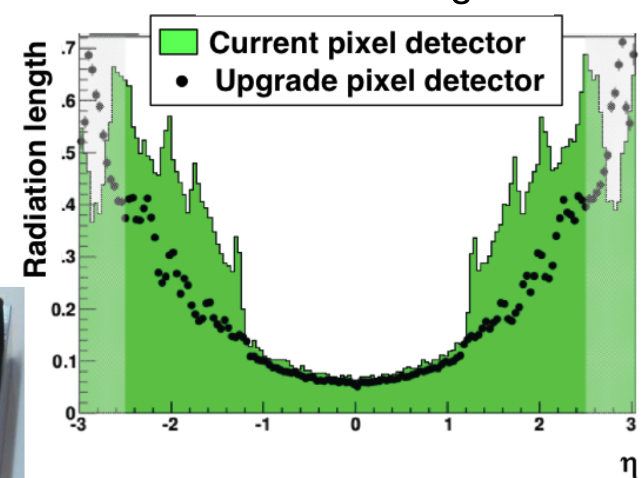
CMS phase I upgrade – until present

- L1 Trigger upgrade (2016)
  - Full system upgrade
- Pixel detector upgrade (2017)
  - Change 3 → 4 layers
  - Improved hit efficiency
  - Closer to the beam & less material
- Repairs of DC/DC converters (2018)
  - Adjusted operating procedure
- HCAL upgrade (2015-2018)
  - Photo detectors (HPD → SiPM)
  - Front- and backend electronics
  - Optimised readout

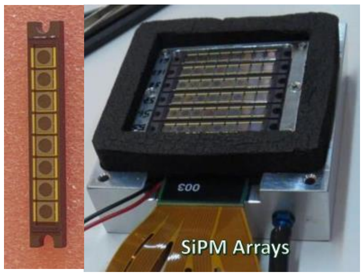




Material budget

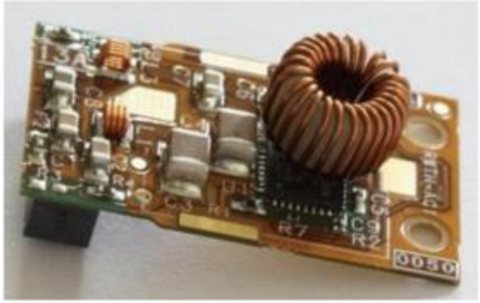


SiPM array

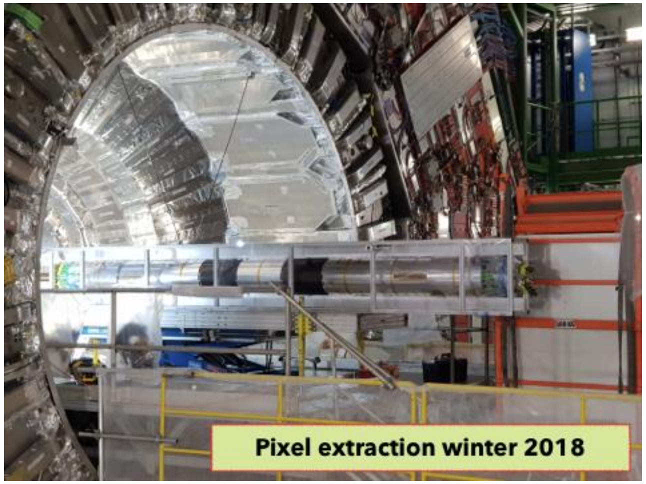


CMS phase I upgrades – LS2

- Complete repairs of the pixel detector
  - Permanent solution for the DC/DC converters
  - Redesign of the converter



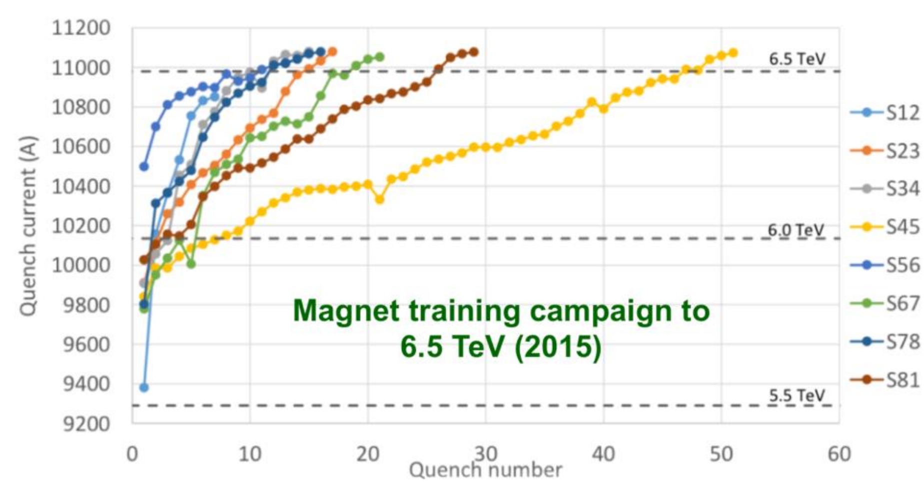
- Consolidation of previous upgrades
- Preparation for phase II upgrade
  - Infrastructure in the cavern
- Upgrades of the data readout
- Computing and trigger algorithm developments



LS2 – accelerator upgrades

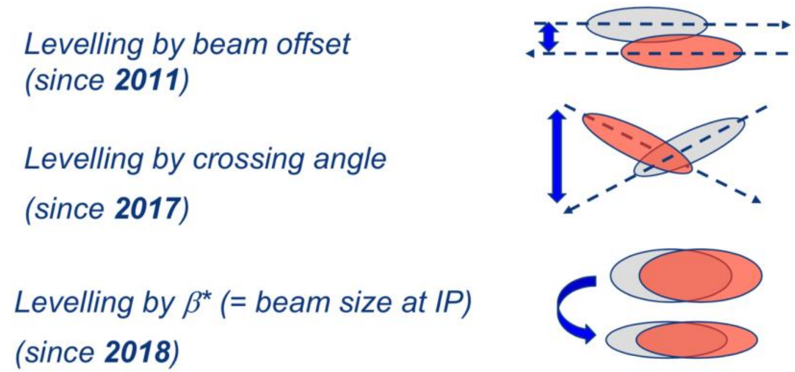
- Preparing for HL-LHC
  - Civil engineering
  - Consolidation work
- Upgrade of the injector chain
  - Increased brightness and intensity
  - Increased reliability and lifetime
- Increasing the CoM energy
  - Magnet training in 2016
    - 2 sectors reached 6.75 TeV
  - Estimate ~500 quenches to reach 14 TeV

Parameter	2018	Design	Run 3
Energy [TeV]	6.5	7.0	**7.0**
# bunches	2556	2808	~2760
Stored energy [MJ]	312	362	>500
β* [cm]	30-25	55	40-30
p/bunch [10^{11}]	1.1	1.15	1.8
Emittance [μm]	~1.8	3.75	1.5-2.0
Peak luminosity [10^{34}]	2.1	1.0	**3-4**
Crossing angle [μrad]	285	320	340

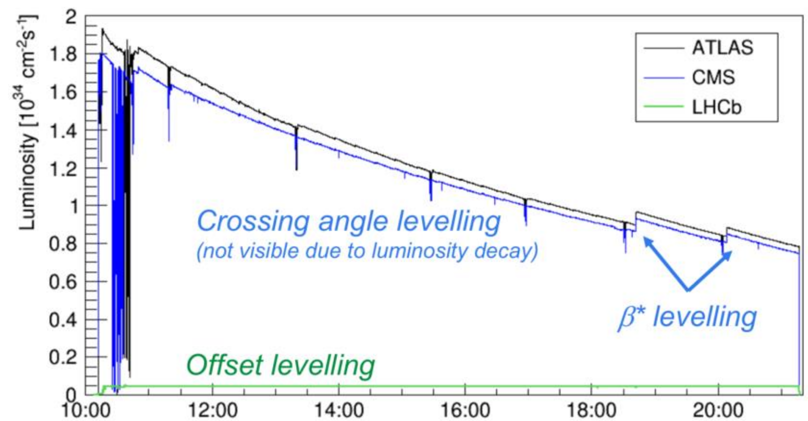


Luminosity levelling

- LHCb & ALICE take data at levelled luminosity since 2011
  - Stable optimal conditions
    - Optimal may be subjective!
- Three methods employed



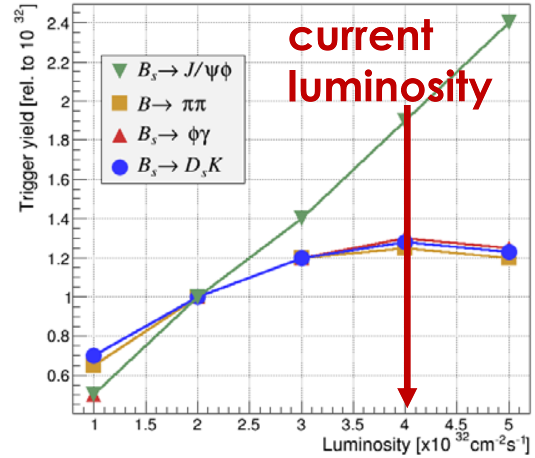
- ATLAS & CMS vs. LHCb in 2018
  - Nominal 12h long fill (average ~8h)
    - 50x peak luminosity
    - 30x integrated luminosity

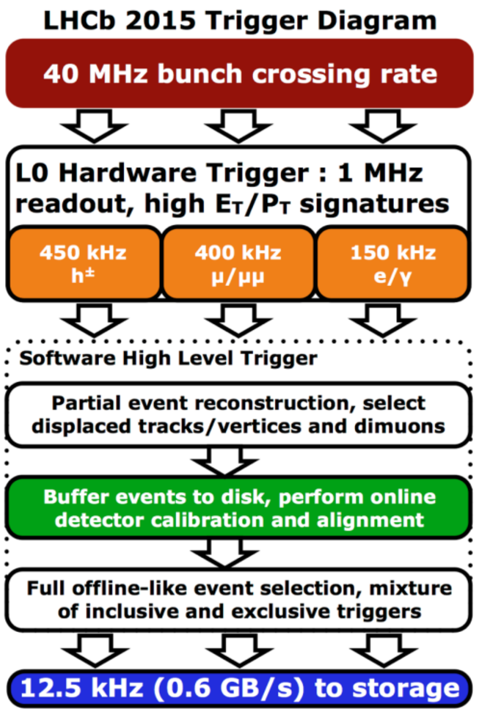


- Levelling for all experiments in Run III
  - Longer average fill lengths
  - More favourable conditions

LS2 – LHCb Upgrade – physics motivation

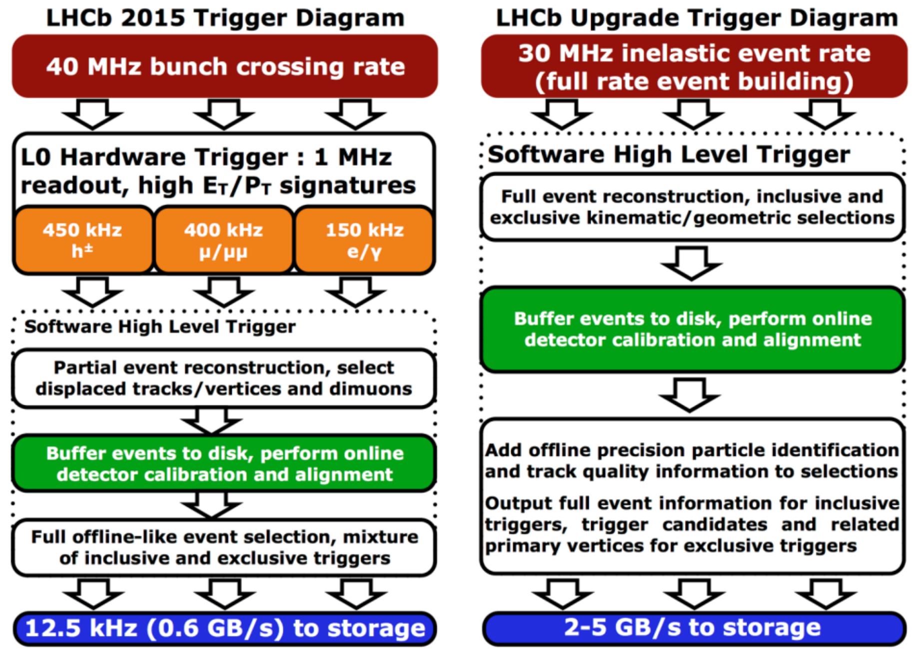
- LHCb – still statistics limited
  - Significant scope for improvements
- LHCb levels luminosity at $4x10^{32}$ $cm^{-2}s^{-1}$
  - Data doubling time 4.2 years
  - LHC can deliver higher luminosity
- Primary limitation: L0 trigger
  - Decision based on muons & calorimeters
    - Rate reduced from 40 MHz to 1 MHz
  - Signal yields in hadronic modes saturates
- Secondary limitation: occupancy
  - Currently 2x design luminosity
  - Requires detector upgrades



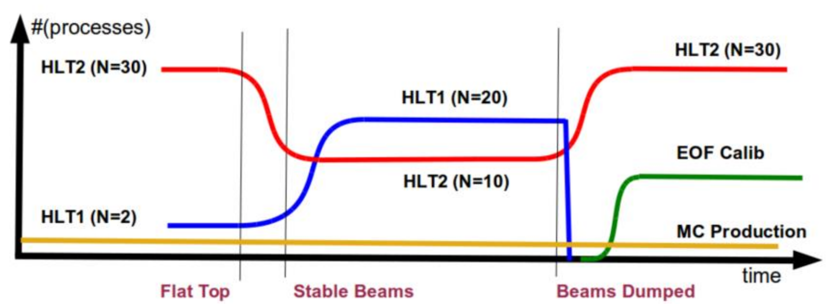


LHCb Upgrade – trigger

- LS1: Online reconstruction and trigger upgrade
  - HLT1 – partial reconstruction
    - 1 MHz → 100 kHz
  - Buffer for O(days)
    - Alignment & calibration
  - HLT2 – offline quality selections
    - Asynchronous – better use of computing resources



- LHCb upgrade trigger
  - Remove H/W trigger completely
    - Full detector readout @ 40 MHz
  - Continue current HLT1/HLT2 strategy
    - Even tighter online selections

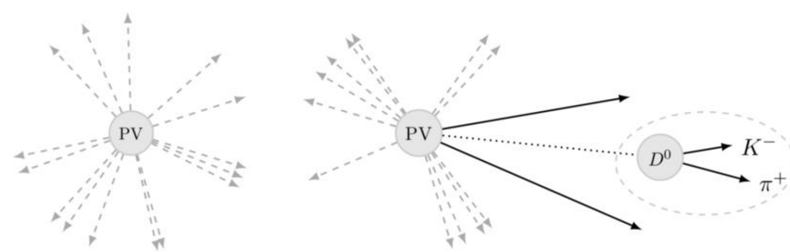


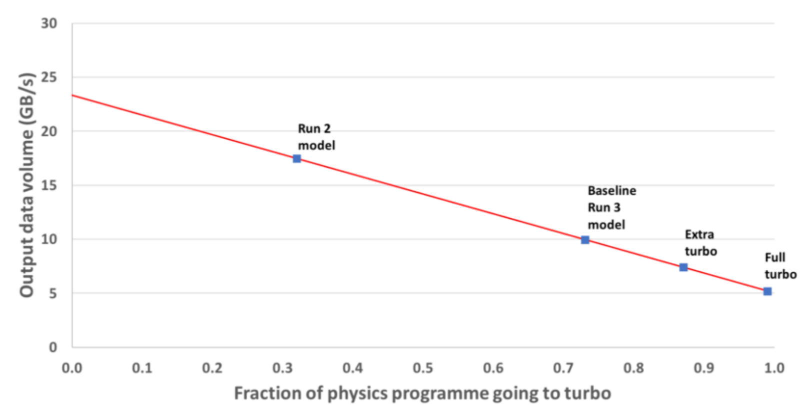
LHCb upgrade – data processing strategy

- Run II output streams from the HLT
  - Full stream: complete event information
    - Allows re-processing offline
    - Requires central pre-selections
  - Turbo stream: only physics objects
    - Data analysis directly on HLT output
  - Configurable persistence options
    - Only signal candidate → full event information
- LHCb upgrade processing
  - Employ same strategies – more aggressively
    - HLT output is already signal dominated
  - Increase fraction of Turbo to increase the output rate
    - Majority of analyses will use Turbo

2018 output rates & bandwidths

stream	event size (kB)	event rate (kHz)	rate fraction	throughput (GB/s)	bandwidth fraction
FULL	70	7.0	65%	0.49	75%
Turbo	35	3.1	29%	0.11	17%
TurCal	85	0.6	6%	0.05	8%
total	61	10.8	100%	0.65	100%





LS2 – LHCb Upgrade 1

UK contribution

Trigger, DAQ and timing system complexly replaced

- 40 Tb/s data read out to the trigger farm

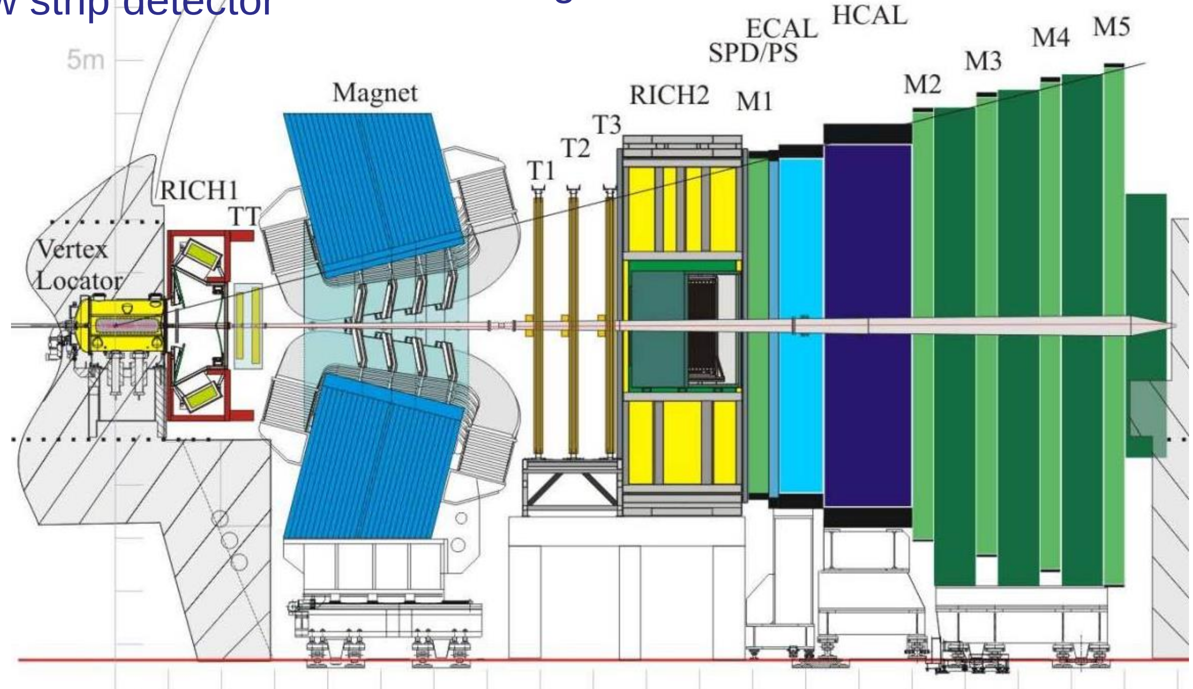
TT: replace with new strip detector

OT & IT: replace with scintillating fibre tracker

Muon system: replace FE electronics and remove M1

VELO: replace with new pixel detector

UK contribution



RICH: new photodetectors & electronics. Modified optics & mechanics

UK contribution

Calorimeters: replace FE electronics and remove PS/PSD

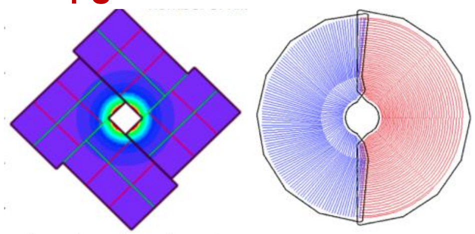
LS2 – LHCb Upgrade – VELO

- Si Pixel modules
  - VeloPix ASIC: 55x55 μm² pixels
    - Built on TimePix3
  - Silicon micro-channel cooling base
    - CO_2 cooling in 12x200 μm² channels
  - L-shaped modules
    - 5.1 mm from the beam

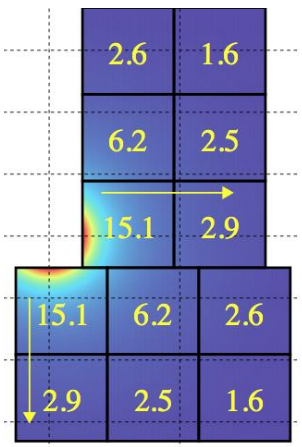
- 41M channels read out at 40 MHz
  - 15.1 Gb/s for hottest ASIC
  - 1040 data links (5.12 Gb/s)

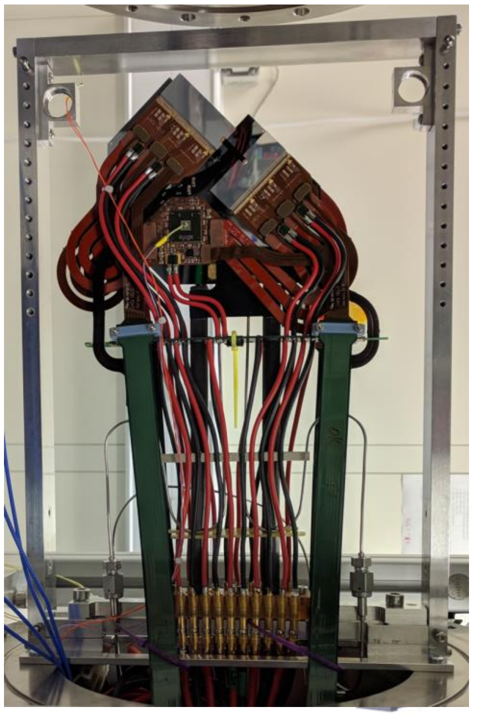
- Maintained or improved performance compared to current VELO

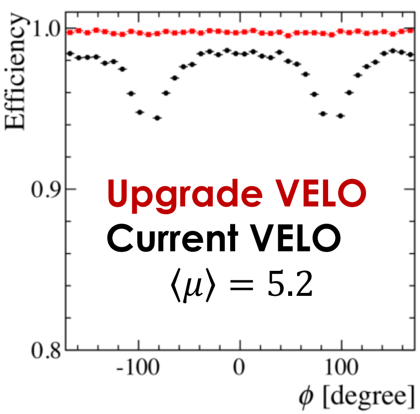
Upgrade Current



Peak data rates [Gbit/s/ASIC]



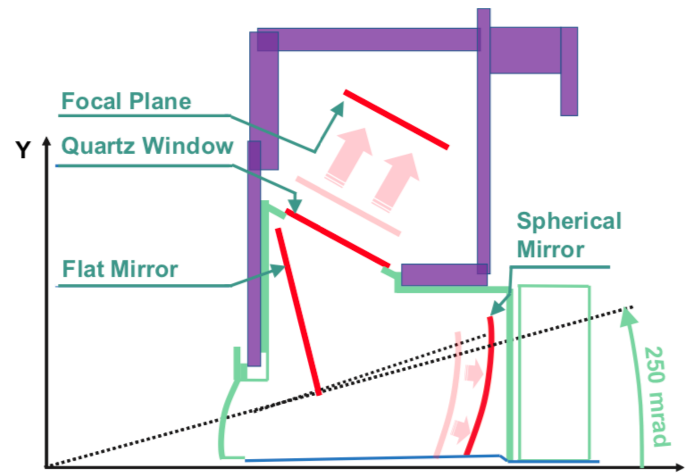




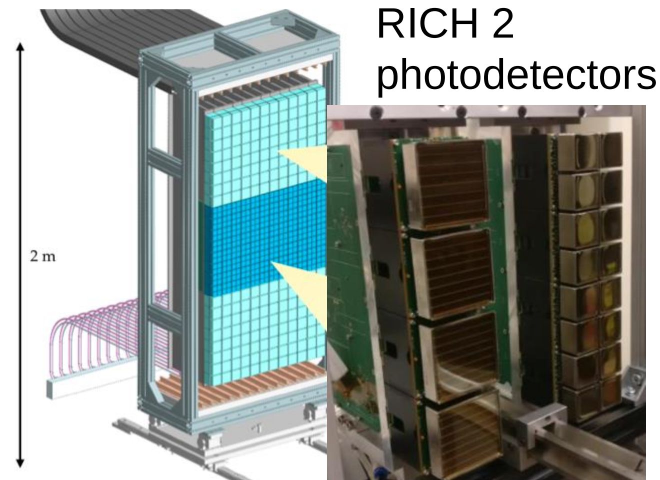
LS2 – LHCb Upgrade – RICH

- New RICH 1 mechanics & optics
  - Increase focal length
    - Reduced occupancy (<30%)
- Replace photodetectors
  - HPDs → 1" or 2" MaPMTs
    - Single-photon sensitivity
    - 8x8 pixel array
- 40 MHz readout
  - CLARO8 amplifier & discriminator
  - Digitiser board and GBTx high speed links
- Maintain current PID performance

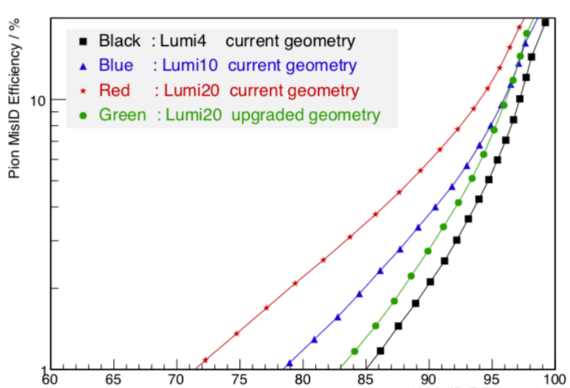
Upgraded RICH1



RICH 2 photodetectors



Photosensitive plane of the RICH2 detector



Timeline – Luminosity & upgrades

	Run 1	LS1	Run 2	LS2	Run 3	LS3	
Energy	7 TeV 8 TeV		13 TeV		14(?) TeV		
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		Run 4	LS4	Run 5	LS5	Run 6
Energy		14 TeV		14 TeV		14 TeV
CMS & ATLAS		$\int \mathcal{L} = 1000\ fb^{-1}$ $\mathcal{L} = 3 - 5 \times 10^{34}$		$\int \mathcal{L} = 2000\ fb^{-1}$ $\mathcal{L} = 5 \times 10^{34}$		$\int \mathcal{L} = 4000\ fb^{-1}$ $\mathcal{L} = 5 - 7 \times 10^{34}$
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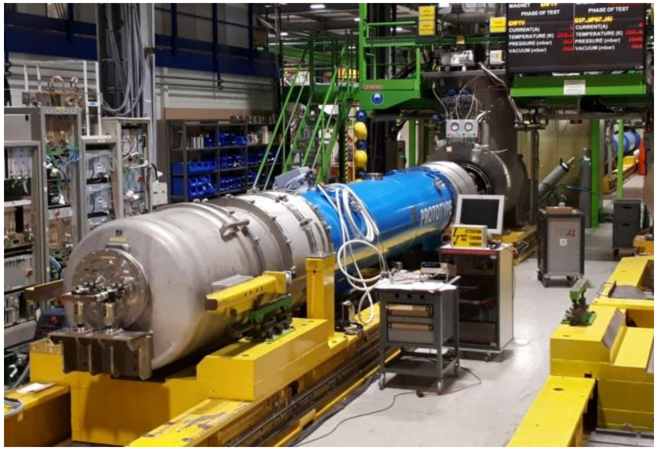
$[cm^{-2}s^{-1}]$

LHC machine upgrades in LS3

- The world's largest accelerator project
  - 1.2 km of the LHC to be replaced
  - Inner triplets a the IRs (Nb_3Sn)
  - Short 11 T dipoles (Nb_3Sn)
  - Crab cavities
  - Collimators
  - Machine protection
  - etc.



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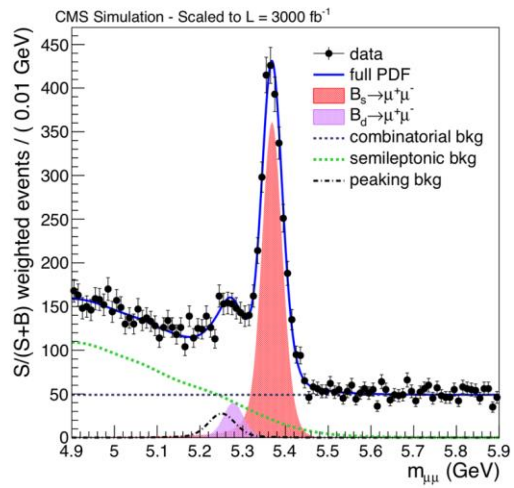
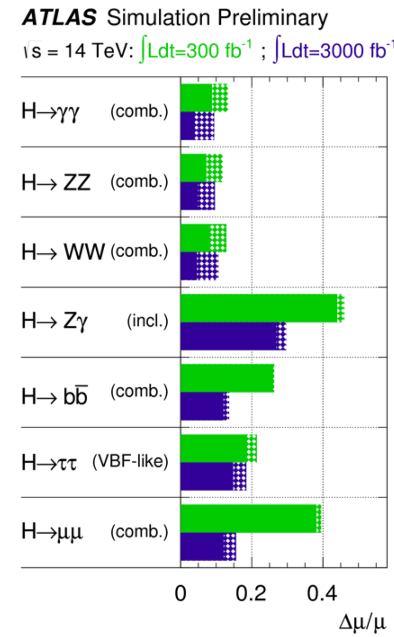
Stored energy [MJ]	312	362	>500	>650
β* [cm]	30-25	55	40-30	15
p/bunch [10^{11}]	1.1	1.15	1.8	2.2
Emittance [μm]	~1.8	3.75	1.5-2.0	2.5
Peak luminosity [10^{34}]	2.1	1.0	3-4	**5 levelled**
Crossing angle [μrad]	285	320	340	510

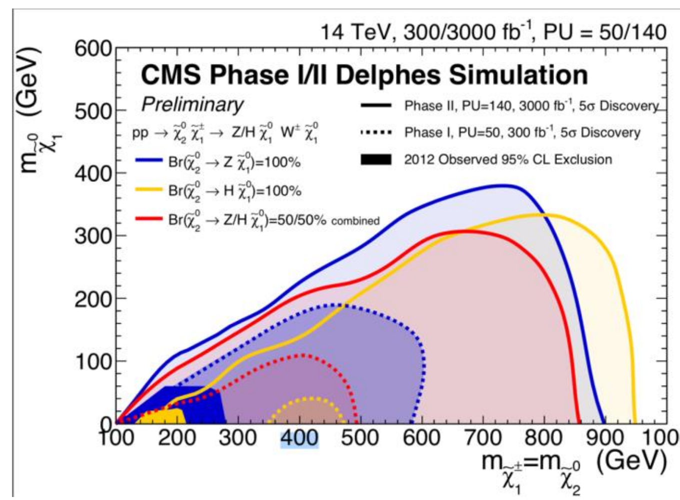
- Infrastructure
  - Civil engineering
  - Cryogenics
  - Vacuum
  - Cold powering

LS3 – ATLAS & CMS phase II – physics motivation

- The LHC is the energy frontier machine
  - Exploit its full potential
- Precision measurements
  - Higgs couplings
  - EW physics
  - Top physics
  - Flavour physics
- Direct searches
  - Extending the mass range
  - Sensitivity to rare signatures
- Detailed studies in the HL-LHC yellow reports

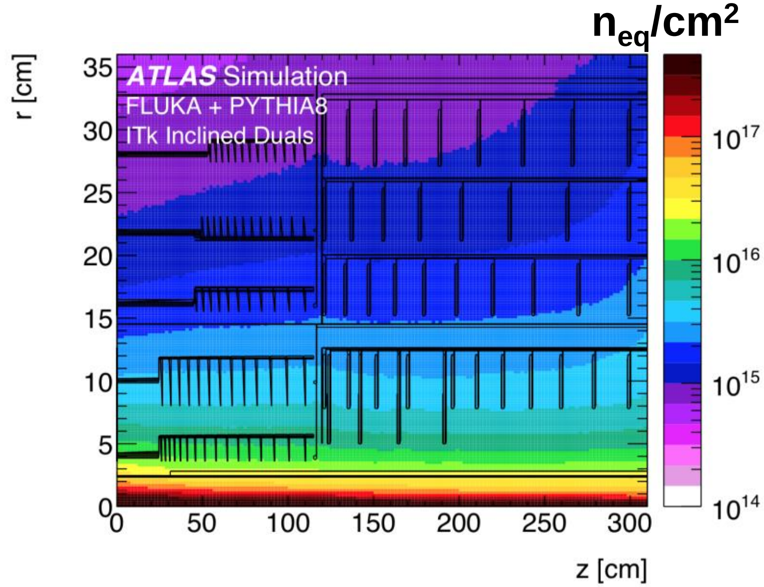


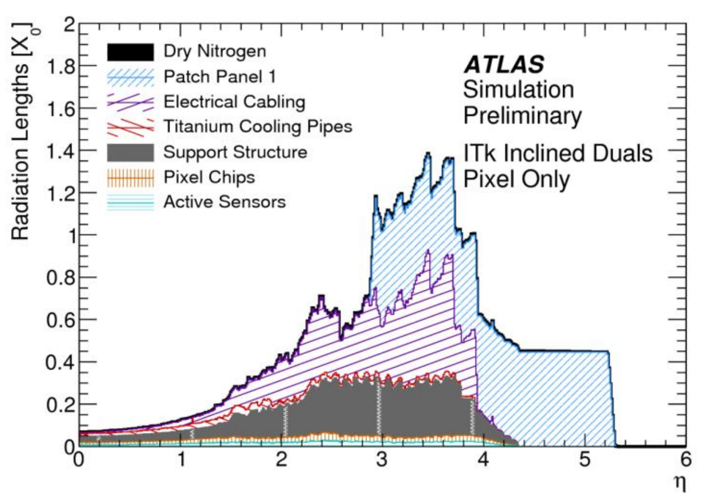




LS3 – ATLAS & CMS phase II - challenges

- Pile-up of 200 interactions / crossing
  - Increased track multiplicity
  - Event reconstruction
- Radiation damage
  - 10x dose compared to Run 3
  - 1st pixel layer: $2x10^{16}$ n_{eq}/cm^2 (3000 fb^{-1})
- Data readout
  - Data cables will become a significant part of the material budget
    - Serial powering, DC/DC & CO_2 cooling reduced material for LV cables and cooling
- Computing
  - Significant challenges for offline computing

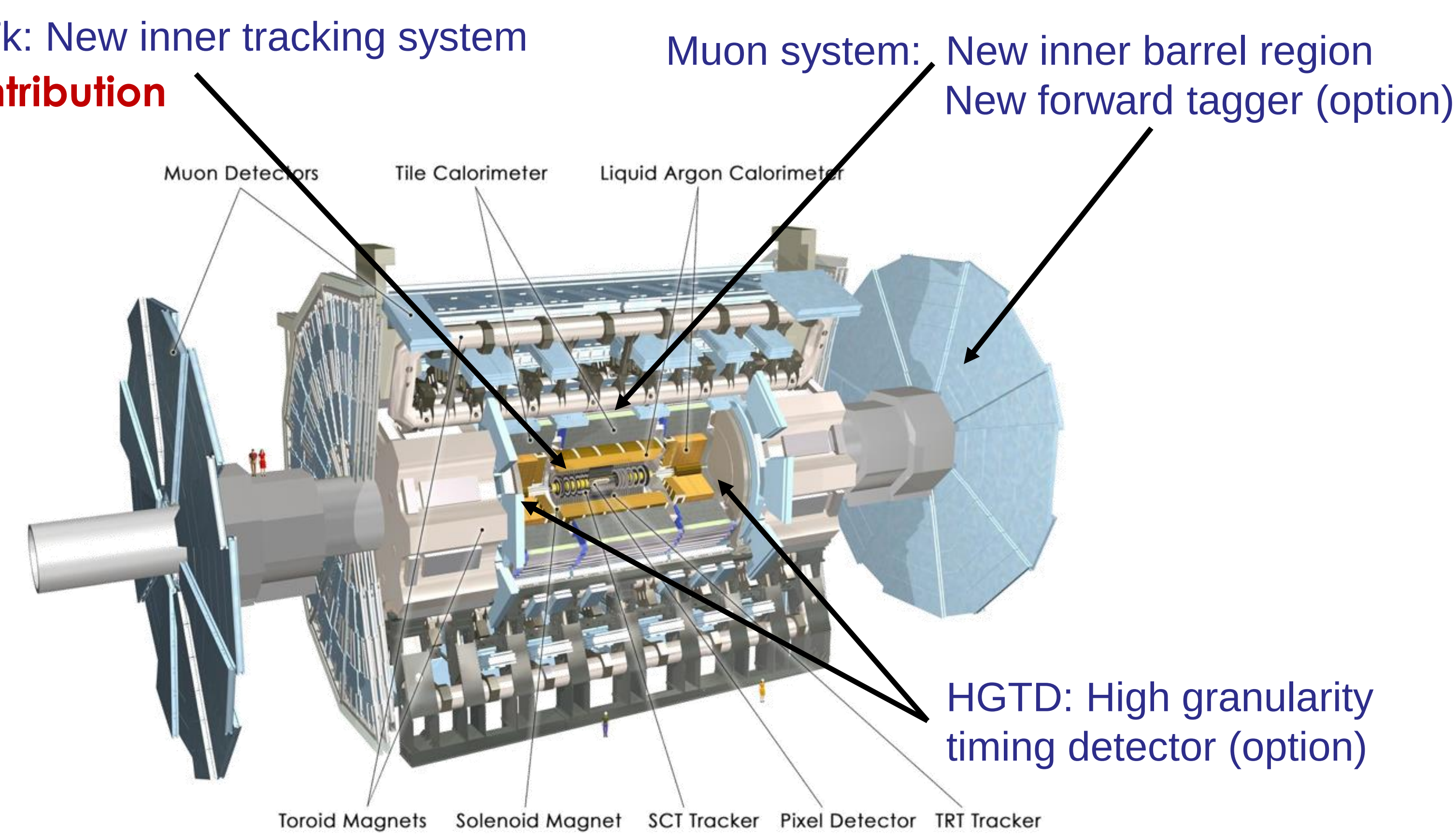




LS3 – ATLAS phase II – detector upgrades

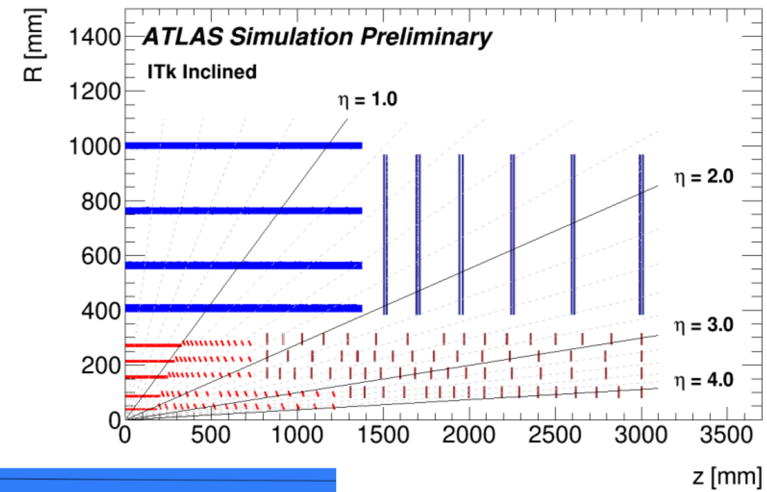
UK contribution TDAQ: new readout for ITk, LAr/Tile calorimeters & muons

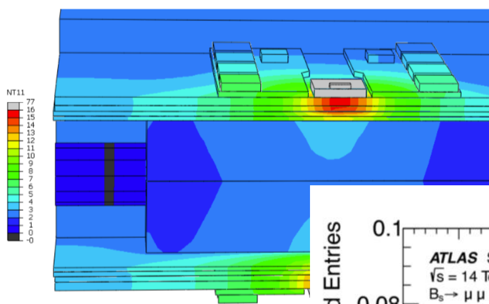
- H/W trigger output 1 MHz (data rate 42 Tbit/s)
- Trigger: L1, H/W track & calo triggers and event filter

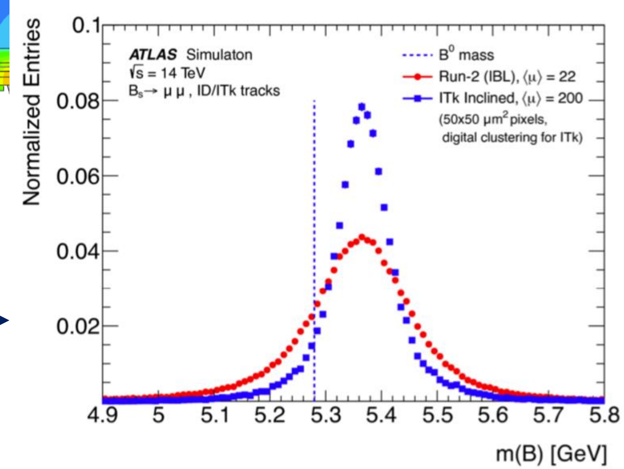


LS3 – ATLAS phase II – Inner tracking system

- All silicon tracker replaces ID
  - Pixels: 10 m^2 – 10 000 modules
    - Increase coverage |η| < 4
  - Strips: 165 m^2 - 17 888 modules
    - Mass-producibility & ease of integration
- 2-phase CO_2 cooling system
  - Higher efficiency, reduced mass
  - Careful thermal design
- Serial LV powering
  - Reduced mass in cables
- Data readout
  - High-speed electrical and optical links
- Improved performance
  - E.g. mass resolution in $B_s \rightarrow \mu^+\mu^-$

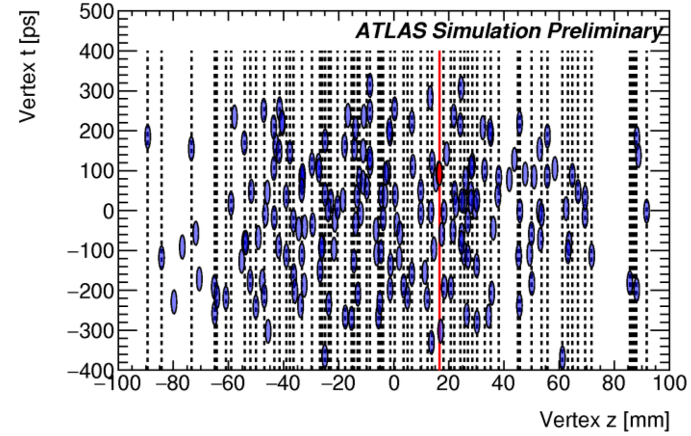


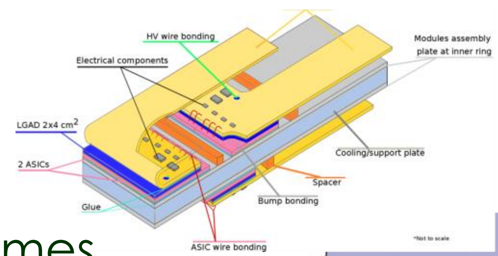


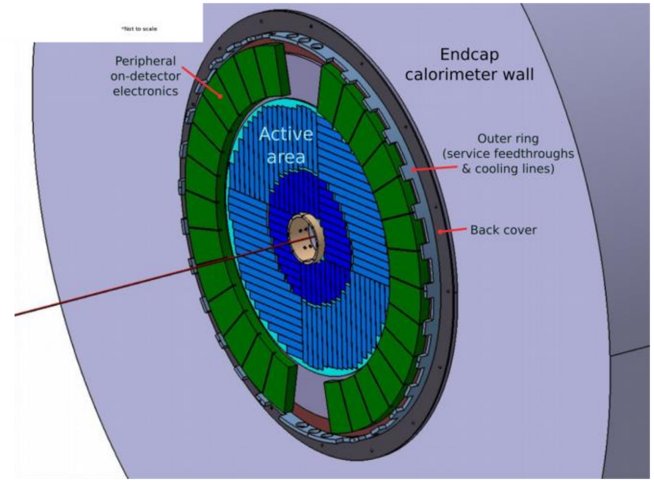


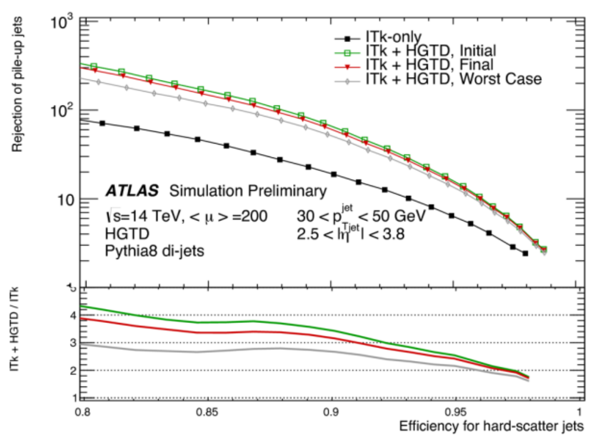
LS3 – ATLAS phase II – High granularity timing detector

- 4D reconstruction
  - Adding time information to tracks
- High granularity timing detector
  - Timing plane in front of endcap CALO
  - 4-layer LGAD detector
    - 1.3x1.3 mm² pads (<10% occupancy)
    - Timing resolution 30-50 ps
- Reduces the effects of pile-up
  - Light jet pile-up reduced up to 5 times









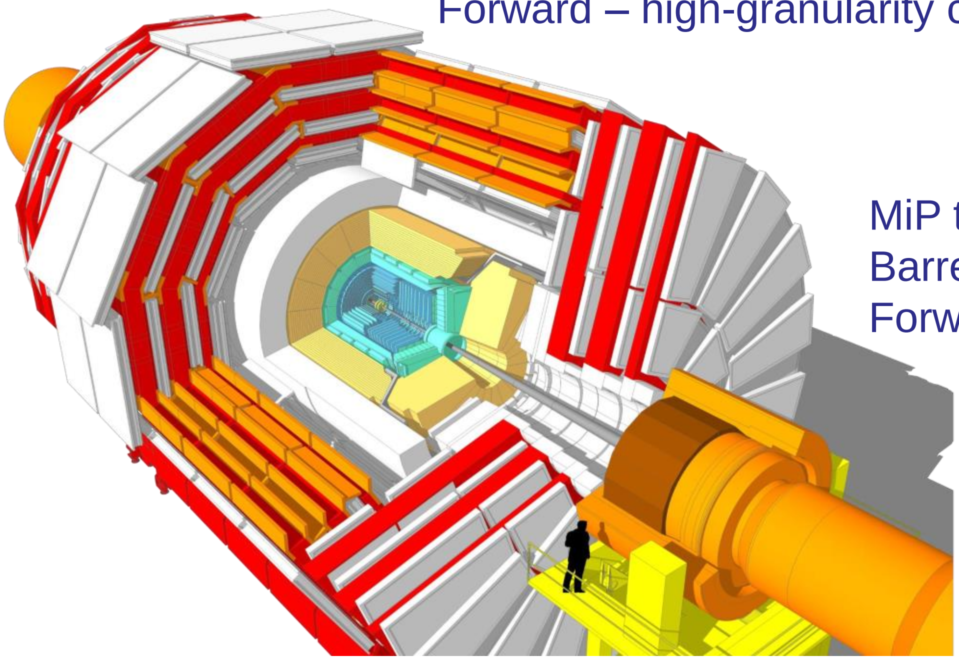
LS3 – CMS phase II – detector upgrades

Trigger & data acquisition **UK contribution**

- Full detector readout at 750 kHz (data rate ~50 Tb/s)
- Upgrade of the trigger system

UK contribution
Tracker: new full-silicon tracker

Calorimeters: **UK contribution**
Barrel ECAL – electronics for single-crystal R/O
Forward – high-granularity calorimeter

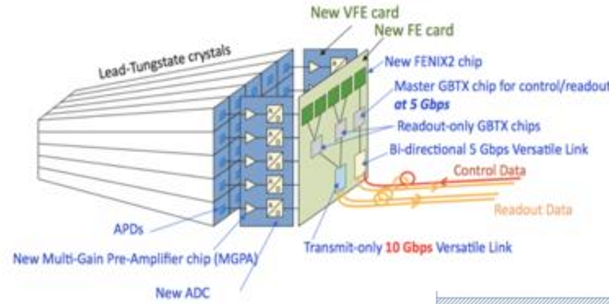


MiP timing detector:
Barrel – LYSO + SiPM
Forward – LGADs

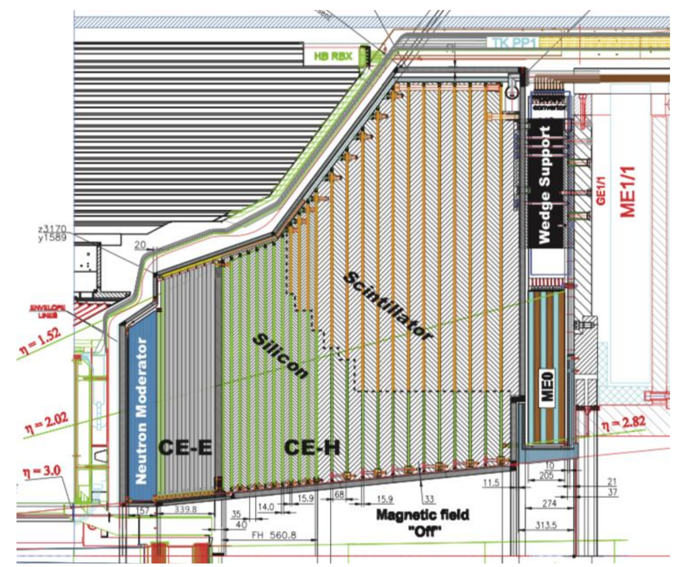
Muon system:
Extended coverage
New GEM chambers

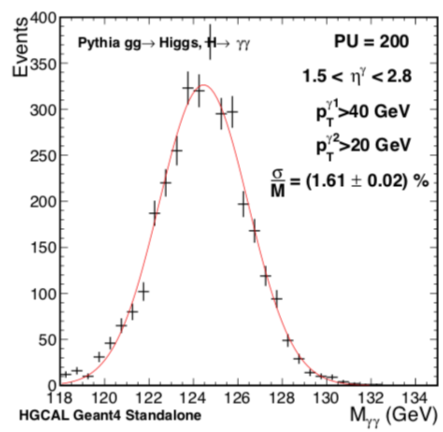
LS3 – CMS phase II – detector upgrades

- Barrel ECAL electronics
  - Single crystal readout
    - C.f. 5x5 crystals now

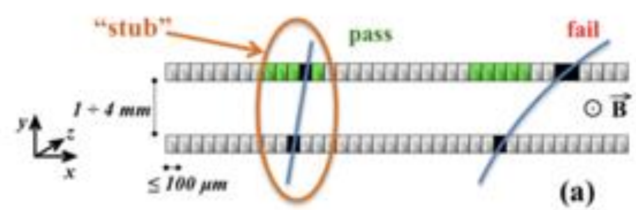


- Forward high-granularity calorimeter
  - ECAL: Silicon-W-Cu-Pb-Fe
  - HCAL: Silicon/Scintillator-Fe-Cu
  - Particle flow calorimetry





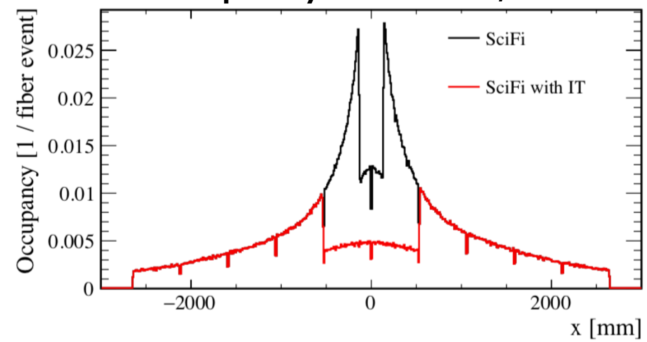
- Tracker upgrade
  - Increased granularity
  - Extended coverage
  - Stub-detecting module
    - Low-pT track rejection
    - 40 MHz input to trigger

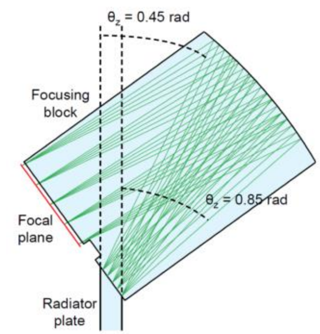


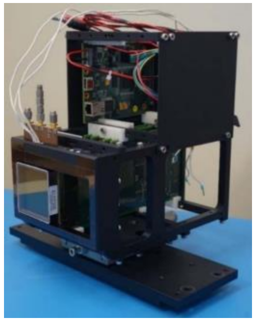
LS3 – LHCb Upgrade 1b

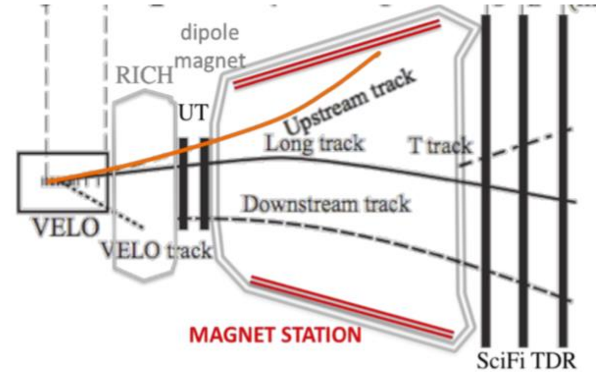
- Consolidation work of LS2 upgrade
  - Possibility to enhance performance in key areas
  - Several concepts under study
- New inner tracker
  - HV-CMOS tracker at the centre of SciFi
- TORCH – DIRC & ToF combined
  - Improved PID for p < 10 GeV
  - Prototyped in beam tests
- Magnet side stations
  - Increased acceptance for low momentum tracks

Run 4 occupancy with and w/o new IT









Timeline – Luminosity & upgrades

Energy	7 TeV 8 TeV		13 TeV		14(?) TeV	
	Run 1	LS1	Run 2	LS2	Run 3	LS3
CMS & ATLAS	$\int\mathcal{L}$ = 21 fb^{-1} $\mathcal{L}$ = 0 – 8 x 10^{33}	Upgrade phase I	$\int\mathcal{L}$ = 170 fb^{-1} $\mathcal{L}$ = 1 – 2 x 10^{34}	Upgrade phase I	$\int\mathcal{L}$ = 380 fb^{-1} $\mathcal{L}$ 2.5 x 10^{34}	Upgrade phase II
	2010 2011 2012	2013 2014	2015 2016 2017 2018	2019 2020	2021 2022 2023	2024 2025 2026
LHCb	$\int\mathcal{L}$ = 3 fb^{-1} $\mathcal{L}$ = 0 – 4 x 10^{32}		$\int\mathcal{L}$ = 9 fb^{-1} $\mathcal{L}$ = 3 – 4 x 10^{32}	Upgrade 1	$\int\mathcal{L}$ = 23 fb^{-1} $\mathcal{L}$ = 1 – 2 x 10^{33}	Upgrade 1b

Energy		14 TeV		14 TeV		14 TeV
		Run 4	LS4	Run 5	LS5	Run 6
CMS & ATLAS		$\int\mathcal{L}$ = 1000 fb^{-1} $\mathcal{L}$ = 3 – 5 x 10^{34}		$\int\mathcal{L}$ = 2000 fb^{-1} $\mathcal{L}$ = 5 x 10^{34}		$\int\mathcal{L}$ = 4000 fb^{-1} $\mathcal{L}$ = 5 – 7 x 10^{34}
	2026	2027 2028 2029	2030	2031 2032 2033	2034	2035 2036 2037
LHCb		$\int\mathcal{L}$ = 50 fb^{-1} $\mathcal{L}$ = 2 x 10^{33}	Upgrade 2	$\mathcal{L}$ = 1 – 2 x 10^{34}		$\int\mathcal{L}$ > 300 fb^{-1} $\mathcal{L}$ = 1 – 2 x 10^{34}

[cm^{-2}s^{-1}]

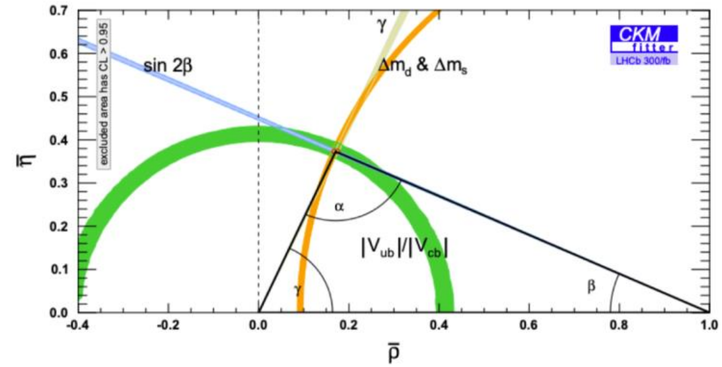
LS4 – LHCb Upgrade II – physics motivation

- Precision measurements of the SM
  - Flavour physics, spectroscopy, etc.
- Search for deviations from the SM
  - Rare decays, LFU, LFV, etc.

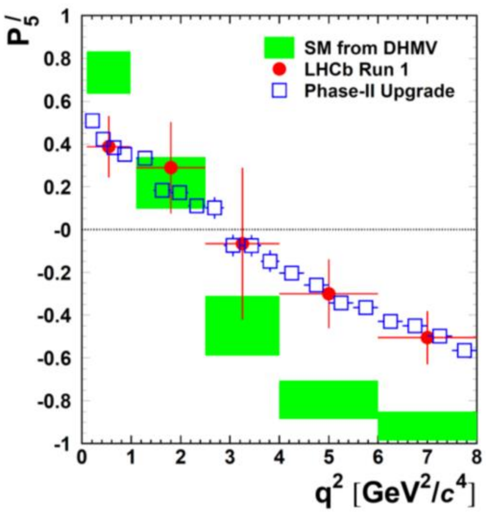
	2019 [5 fb^{-1}]	2025 [23 fb^{-1}]	Upgrade II [300 fb^{-1}]
$\sigma(R_K)$	6%	2.5%	0.7%

- LHCb upgrade is (still) not limited by the LHC
  - 1–2 x 10^{34} $cm^{-2}s^{-1}$ achievable at IP8
  - Exploit the full potential of LHC
    - > 300 fb^{-1} possible at IP8
- Belle II data taking 2019 – 2025
  - LHCb is the planned flavour experiment beyond 2026

CKM triangle with LHCb @ 300 fb^{-1}

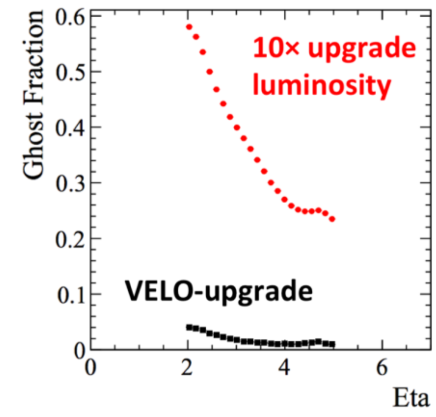


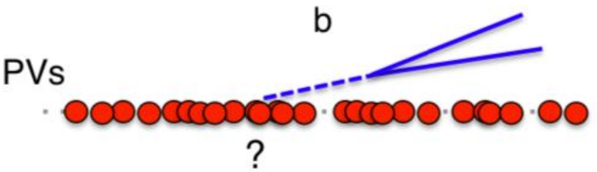
P_5' in $B^0 \to K^{*0}\mu^+\mu^-$ with LHCb @ 300 fb^{-1}



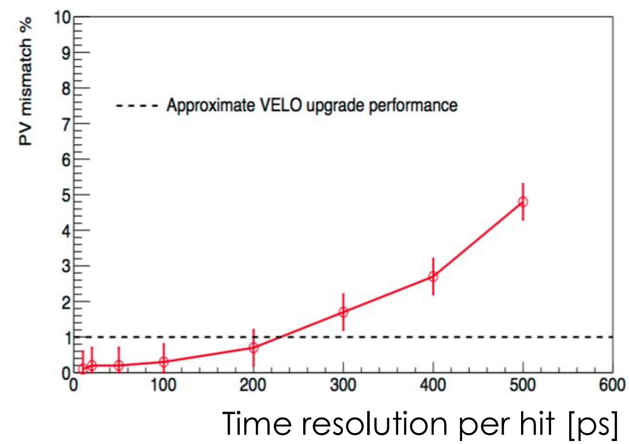
LS4 – LHCb upgrade II – detector concepts

- All detector systems will require upgrades
  - Increased granularity & rates
  - Calorimeters largely untouched in upgrade 1
    - Potential for significant physics gains
- Maintain or improve the performance
  - Keep 40 MHz triggerless readout
- 10x luminosity – 10x multiplicity
  - Tracking and reconstruction challenges
  - Favour physics – secondary vertices
- 4D tracking: add time information
  - Pattern recognition for tracking
  - Primary & secondary vertex association





PV mismatch vs. hit time resolution



LS4 - LHCb Upgrade II – detector concepts

- 6x integrated luminosity – 6x radiation damage
  - VELO upgrade 1: $8\text{x}10^{15}$ n_{eq}/cm^2 maximum
    - Is $5\text{x}10^{16}$ n_{eq}/cm^2 feasible?
    - Thinner sensors? Replaceable sensors?
    - New technologies?
- 10x luminosity – 10x data rates
  - MHz rate of $b\bar{b}$ at 10^{34} $cm^{-2}s^{-1}$
  - VELO upgrade 1: 4 x 5.12 Gbit/s for hottest ASIC
    - On-chip data transport challenging
  - Data links: 10x rate unlikely on electrical links
    - Optical direct from front-end
    - Silicon photonics possible option

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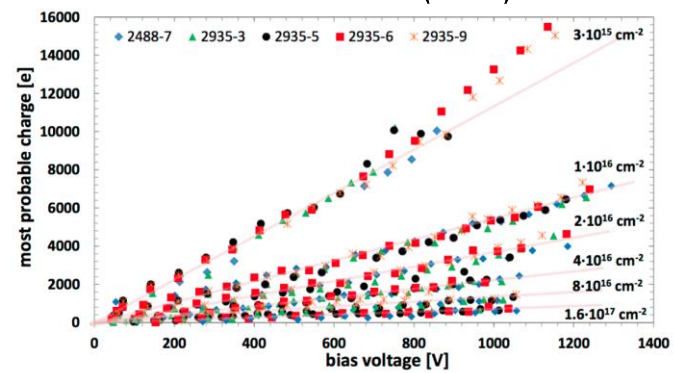

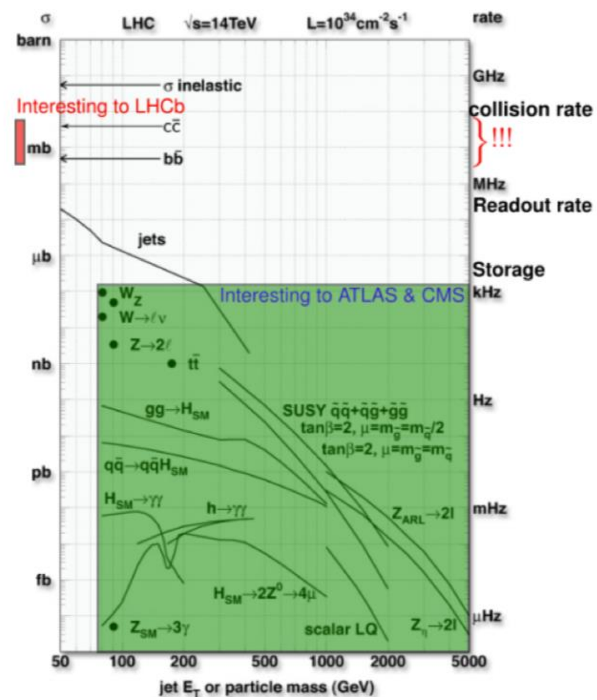

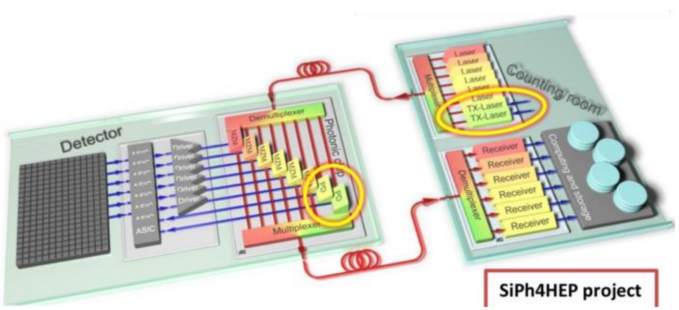

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Energy		14 TeV		14 TeV		14 TeV
		Run 4	LS4	Run 5	LS5	Run 6
CMS & ATLAS		$\int \mathcal{L} = 1000\ fb^{-1}$ $\mathcal{L} = 3 - 5 \times 10^{34}$		$\int \mathcal{L} = 2000\ fb^{-1}$ $\mathcal{L} = 5 \times 10^{34}$		$\int \mathcal{L} = 4000\ fb^{-1}$ $\mathcal{L} = 5 - 7 \times 10^{34}$
	2026	2027 2028 2029	2030	2031 2032 2033	2034	2035 2036 2037
LHCb		$\int \mathcal{L} = 50\ fb^{-1}$ $\mathcal{L} = 2 \times 10^{33}$	Upgrade 2	$\mathcal{L} = 1 - 2 \times 10^{34}$		$\int \mathcal{L} > 300\ fb^{-1}$ $\mathcal{L} = 1 - 2 \times 10^{34}$

Several future facilities are being discussed

energy upgrade: HE-LHC

ep collider: LHeC

$[cm^{-2}s^{-1}]$

Summary

- The LHC experiments have collected physics data since 2010
  - Produced an extraordinary set of results
- The upgrade programme started already in LS1 (2013-2014)
  - Continuous improvements during shut-downs
- Major accelerator and detector upgrades in preparation
  - LS2 (2019-2020): LHCb Upgrade 1
  - LS3 (2024-2025): ATLAS & CMS Phase II upgrades (LHCb Phase 1b)
  - LS4 (2030): LHCb Upgrade 2
- LHC will remain a major player in our field for at least 20 more years