LHCb upgrade: plans and potential

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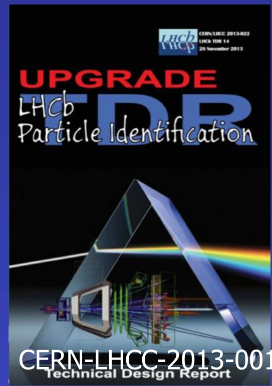
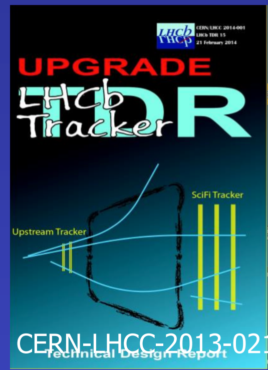
On behalf of the LHCb collaboration

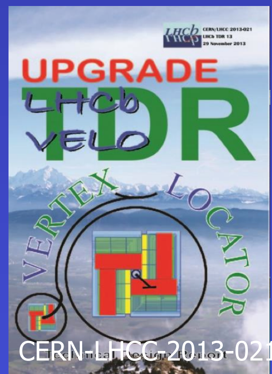
Outline

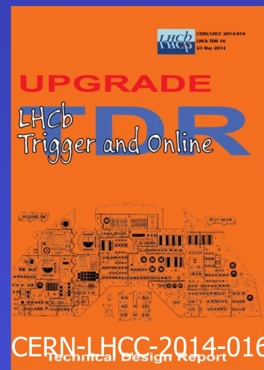
- **LHCb**
  - Performance
  - Highlights/plans
- **LHCb Upgrade**
  - Motivation
  - Trigger
- **LHCb Upgrade Physics Potential**
  - Rare decays
  - CP violation
  - Non-Flavour physics
- **Detector upgrades**
  - Trackers VELO, UT and SciFi
  - Particle ID RICH, CALO and Muon
- **Conclusions**

More information, see LHCb Ugrade TDRs



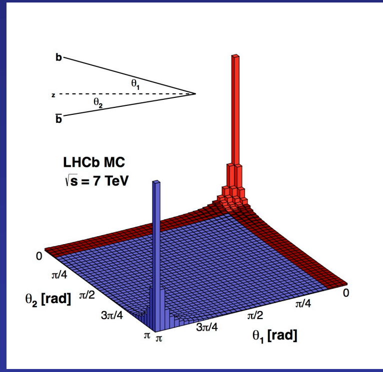






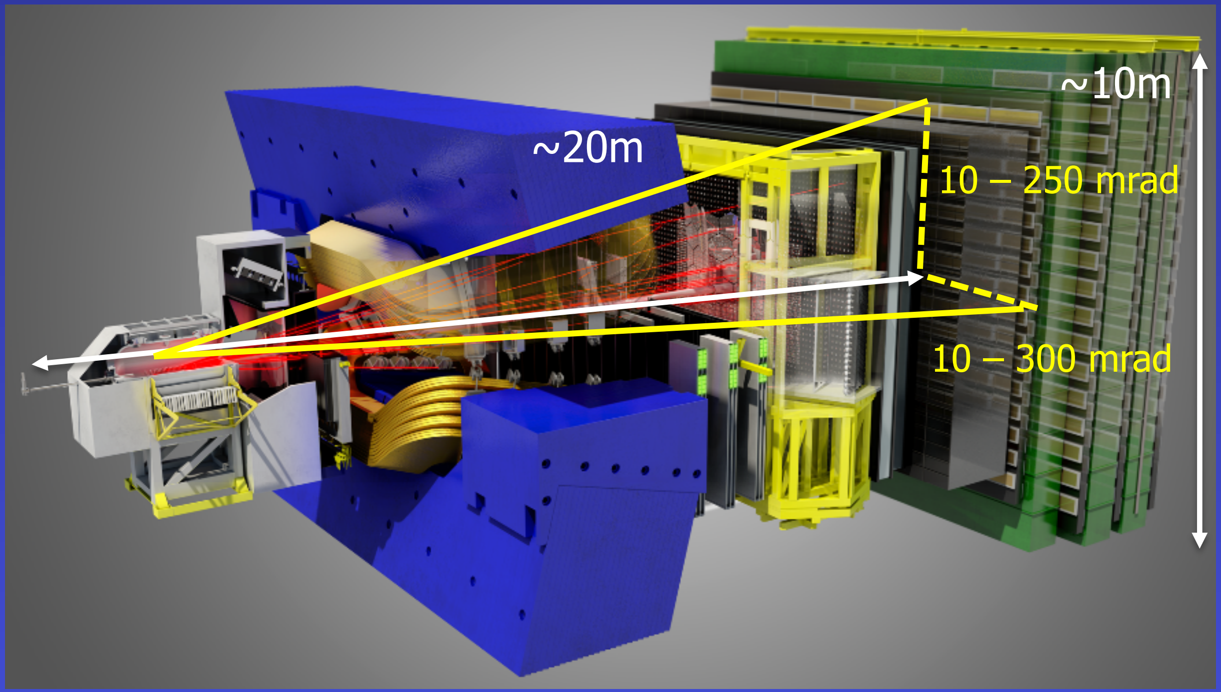
LHCb Experiment

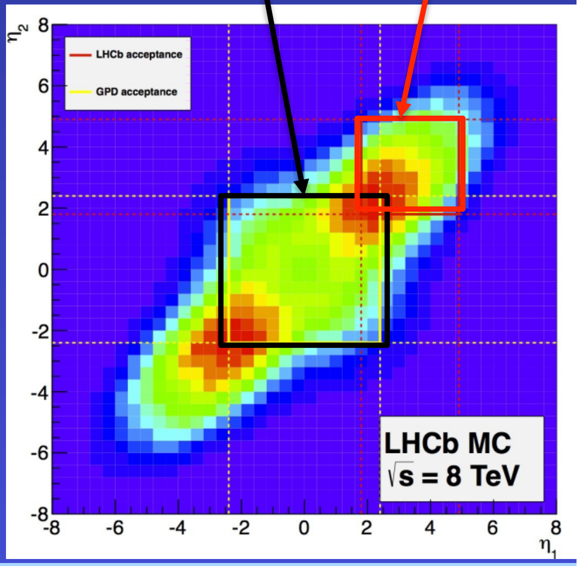
- **LHC is a flavour factory**
  - beauty quark cross section σ_{bb} ~ 300 μb at 7 TeV
  - Very large charm cross section σ_{cc} ~ 20 σ_{bb} ~ 6 mb
- **LHCb**
  - dedicated experiment for heavy flavour physics



ATLAS & CMS region | η | < 2.5

LHCb region 2 < η < 5



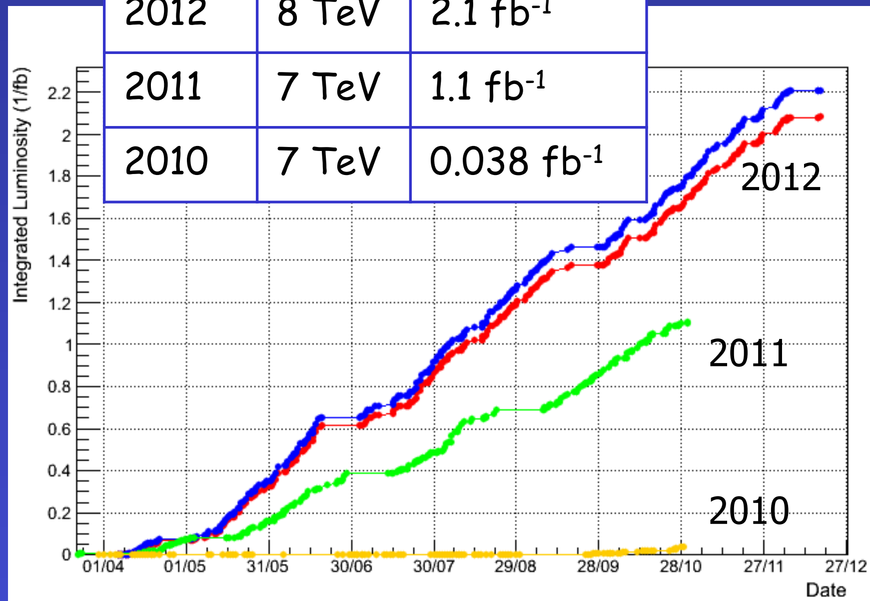


LHCb Performance

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

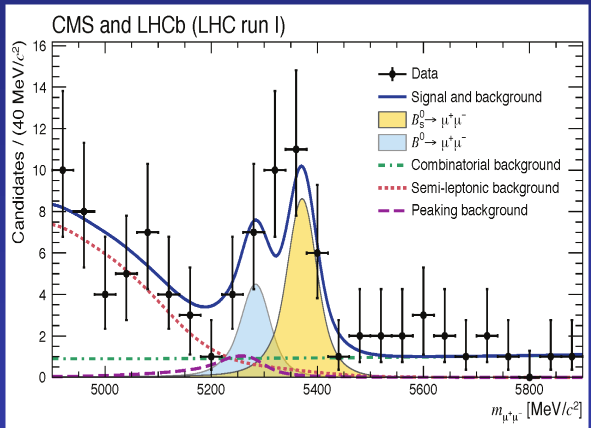
- **Very successful in LHC run 1**
  - LHCb operated at luminosities up to $L = 4 \times 10^{32}\ cm^{-2}\ s^{-1}$
  - 2x design luminosity
  - Average # of visible interactions/crossing $\mu = 1.4$ (nominal $\mu = 0.4$)
  - Recorded $\int Ldt \sim 3\ fb^{-1}$

2012	8 TeV	$2.1\ fb^{-1}$
2011	7 TeV	$1.1\ fb^{-1}$
2010	7 TeV	$0.038\ fb^{-1}$



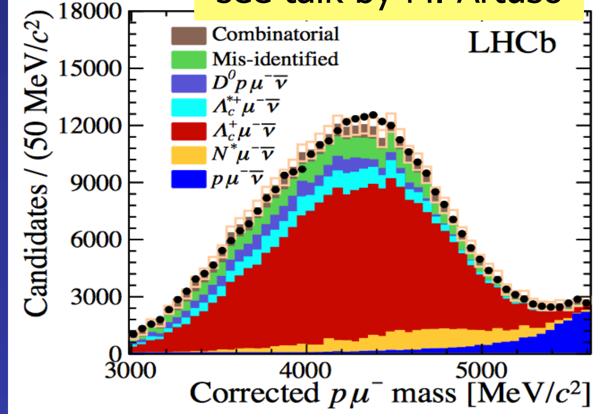
Highlights of LHCb results

Observation of $B_s \to \mu\mu$



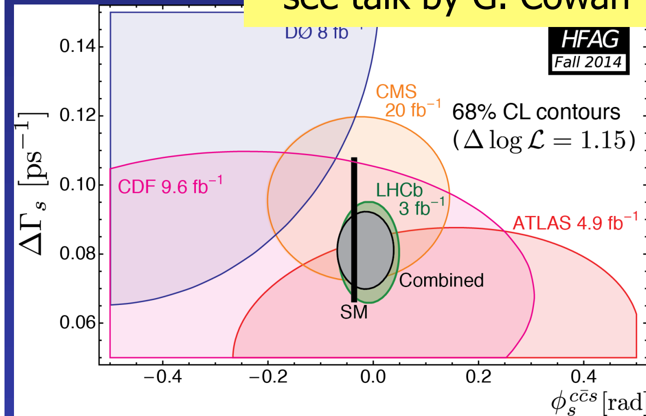
Measurement of V_{ub} in $\Lambda_b \to p\mu\nu$

see talk by M. Artuso

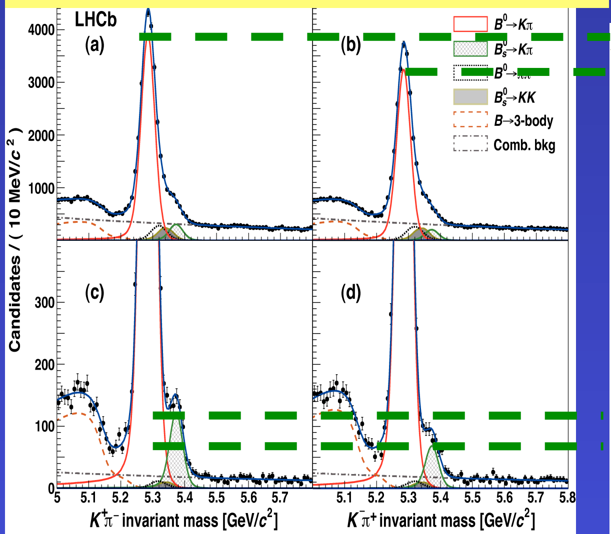


Measurement of φ_s in $B_s \to J/\psi\varphi$

see talk by G. Cowan

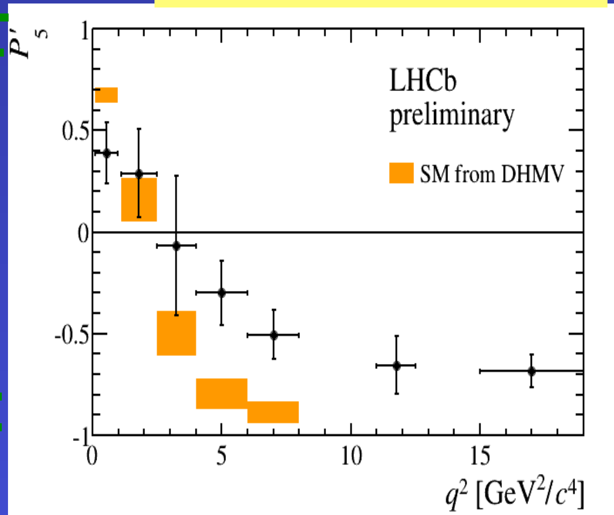


Observation of direct CP violation at a hadron collider



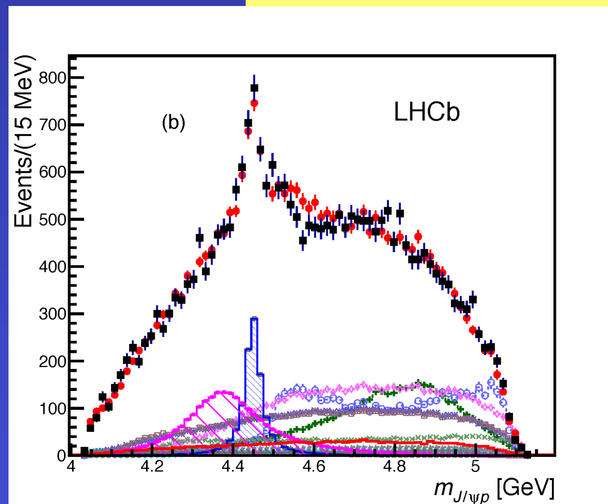
Angular analysis in $B^0 \to K^{*0}\mu\mu$

see talk by S. Coquereau



Observation of pentaquarks

see talk by S. Stone



LHCb Plans/Upgrade

First LHCb results from the 13 TeV LHC data

see talk by I. Komarov

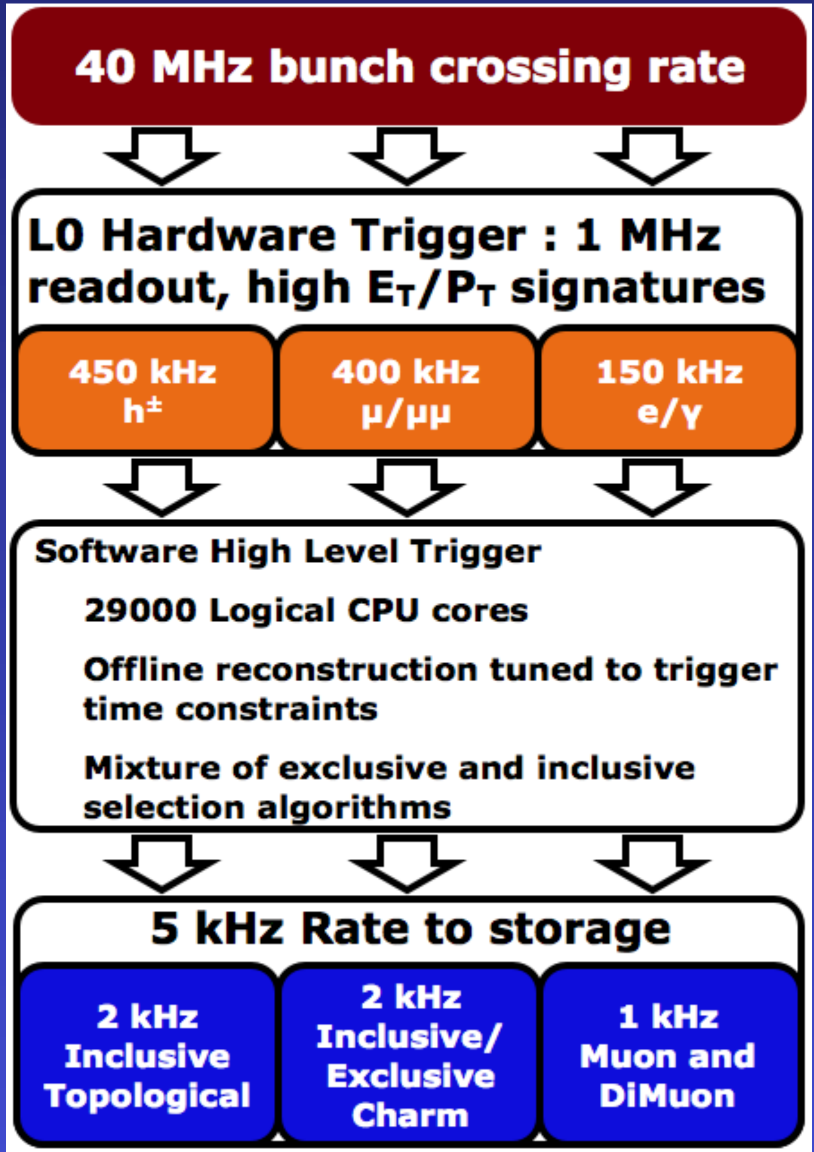
- **LHC Run 2 - collect ~5 fb^{-1} of data**
  - 7, 8 → 13 (14) TeV: nearly double b and c production
  - Precision measurements of unitarity triangles
  - Measure rare decays
  - Probe/measure New Physics at 10% level in key measurements
  - Be prepared for the unexpected → follow the data
  - Current detector limited to 1 MHz readout by Level-0 trigger
- **LHCb upgrade**
  - Upgrade detectors to be able to readout at 40 MHz
  - Operate detector at luminosities of ~2 x 10^{33} cm^{-2} s^{-1}
  - Install upgraded LHCb in long shutdown LS2 2019/20

LHC era			HL-LHC era	
Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2021-23)	Run 4 (2025-28)	Run 5+ (2030+)
3 fb^{-1}	8 fb^{-1}	23 fb^{-1}	46 fb^{-1}	100 fb^{-1}

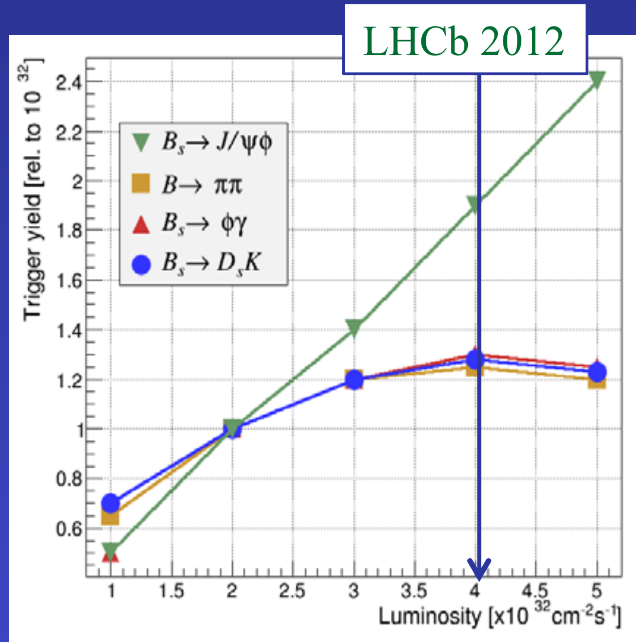
LHCb Upgrade Motivation

- **Excellent results from LHCb**
  - Demonstrated potential of Flavour Physics at the LHC
  - Many world's best measurements, severely constrain new physics
- **LHCb upgrade physics reach**
  - Unique for NP searches in B_s system, very competitive for B_d
  - Unprecedented B-baryon and charm yields
  - Potential for non-flavour physics
- **LHCb upgrade will fully exploit LHC physics in forward region**
  - General purpose experiment with forward geometry
  - LHCb upgrade will operate at higher luminosity
  - is compatible with high luminosity LHC phase, but does not require it
  - Complementary to direct searches at ATLAS and CMS
- **If new particles are discovered**
  - LHCb upgrade will measure flavour couplings through loop diagrams
- **If no new particles are found**
  - LHCb upgrade will probe NP at multi-TeV energy scale

LHCb Trigger

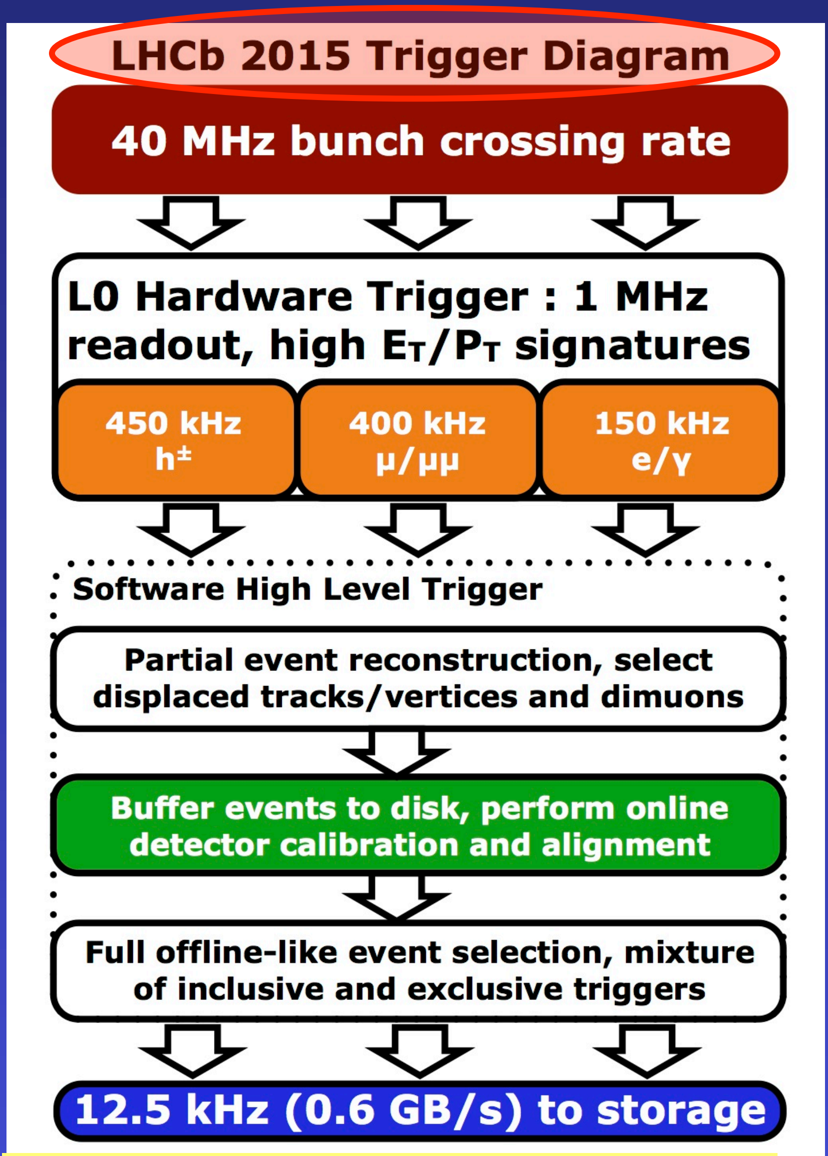


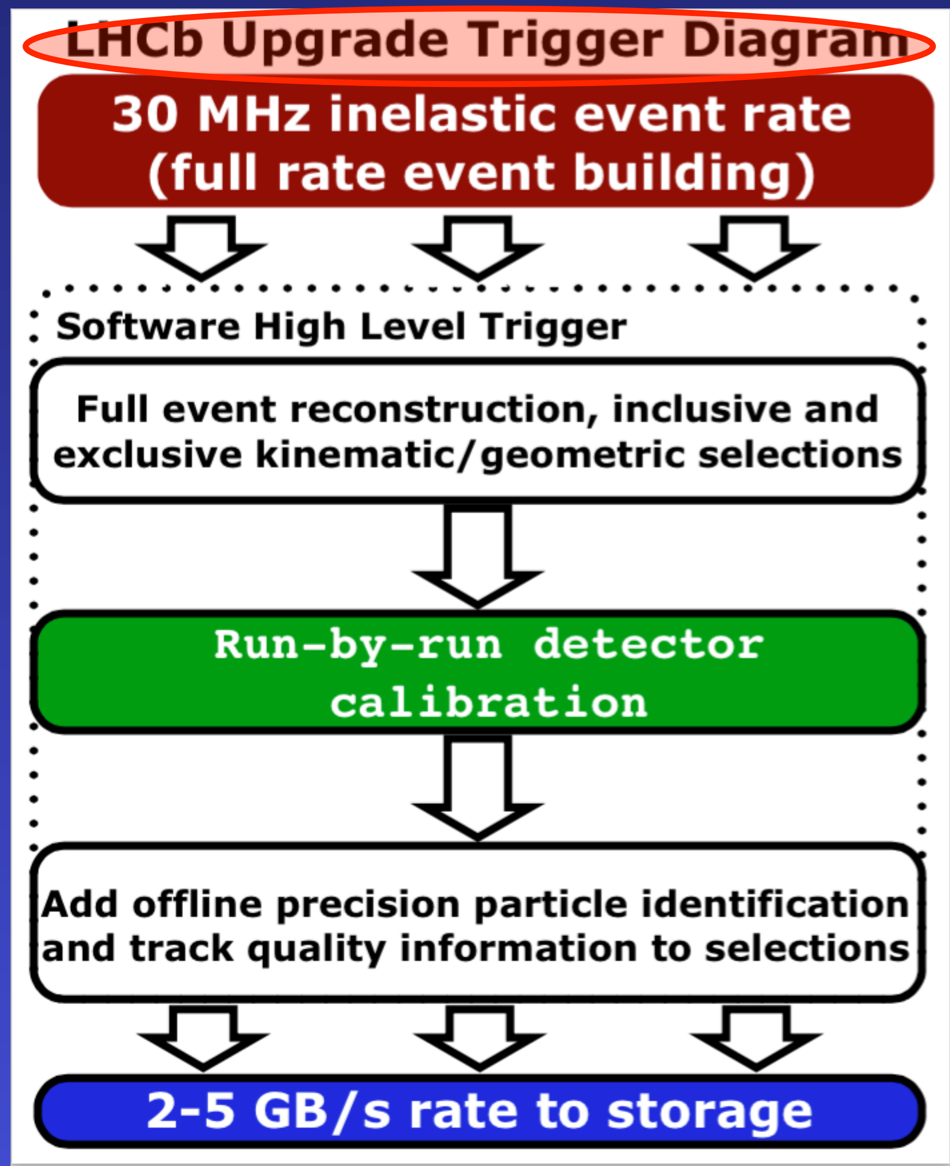
- **Level-0 Hardware trigger**
  - limited to 1 MHz output
  - Event yields saturate for hadronic channels



- **HLT Software trigger**
  - Implemented in CPU farm

LHCb Trigger Upgrade





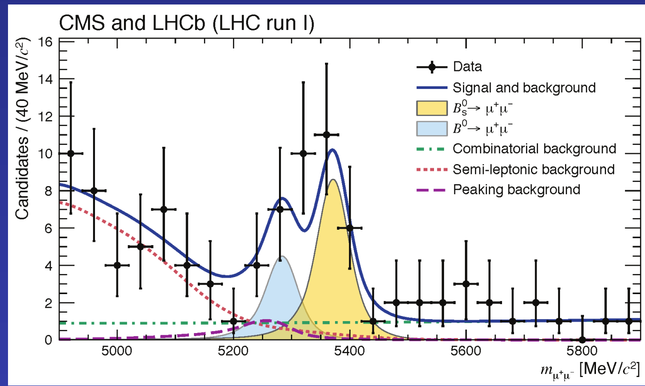
HLT and real-time calibration in LHCb Run II

see talks by S. Stahl and P. Seyfert

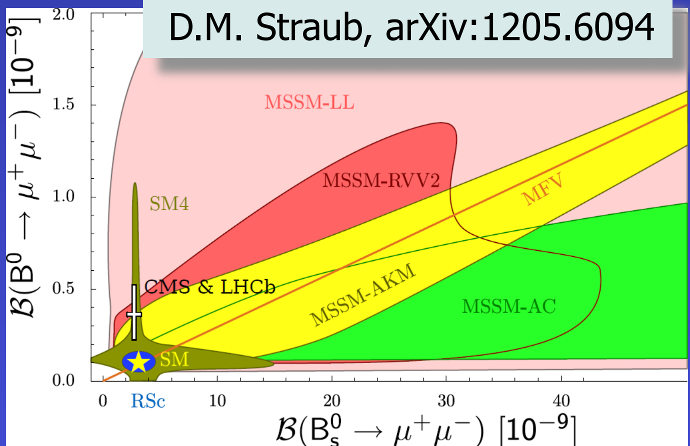
Rare decay $B_s \to \mu^+\mu^-$

Phys. Rev. Lett. 111 (2013) 101805
Nature 522, 68–72

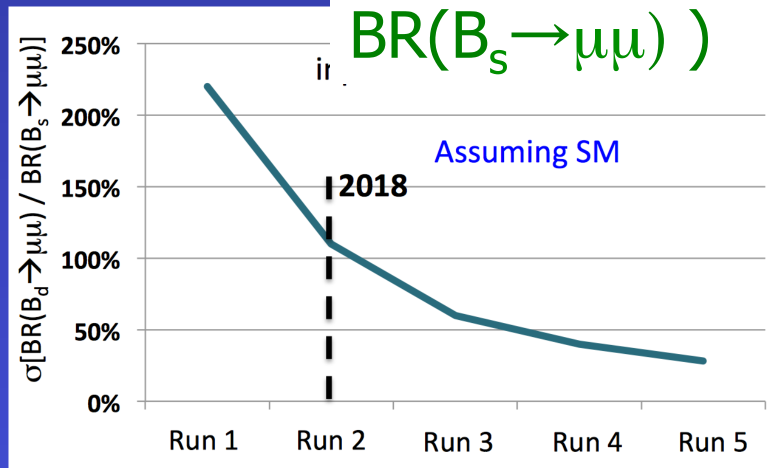
- **LHCb**
  - Observed $B_s \to \mu^+\mu^-$, with CMS at 6.2σ significance
  - $BR(B_s \to \mu^+\mu^-) = (2.8 +0.7-0.6) \times 10^{-9}$
  - 3σ evidence for $B_d \to \mu^+\mu^-$
  - NP SUSY models with large tan β ruled out
- **LHCb upgrade**
  - Precision measurement of $BR(B_s \to \mu^+\mu^-)$
    - 50 events/year at SM
  - Measure $BR(B_d \to \mu^+\mu^-)/BR(B_s \to \mu^+\mu^-)$
  - Very sensitive to NP models



D.M. Straub, arXiv:1205.6094



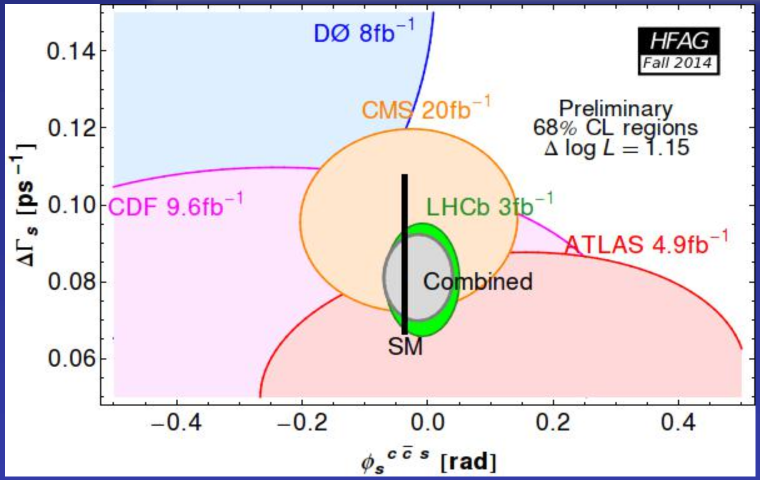
σ(BR(B_d→μμ)/BR(B_s→μμ))



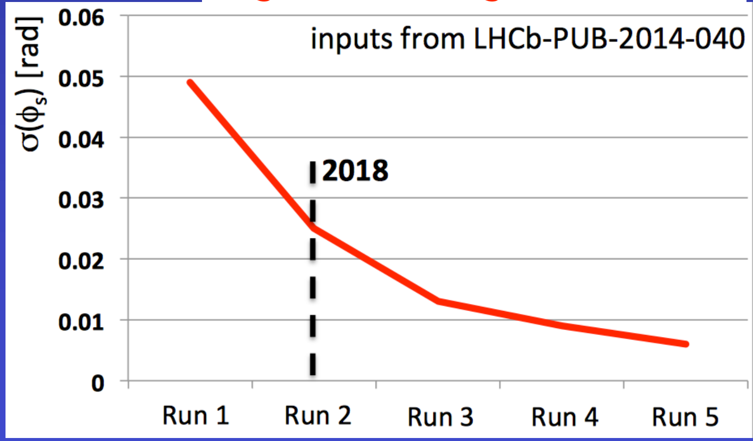
CP Violation in $B_s \to J/\psi\phi$

- **Weak phase ϕ_s**
  - Small and precise SM prediction
  - SM ϕ_s = -36.3 ± 1.3 mrad
  - Sensitive to new physics in B_s mixing and decay amplitude
- **LHCb**
  - Golden mode $B_s \to J/\psi K^+K^-$
    ϕ_s = -58 ± 49 ± 6 mrad
  - Additional modes $B_s \to J/\psi\pi^+\pi^-$ and $B_s \to D_s^+D_s^-$
  - LHCb dominates world average
    ϕ_s = -15 ± 35 mrad
- **LHCb upgrade**
  - Sensitivity $\sigma(\phi_s)$ ~ 10 mrad
  - Compare to $\sigma(\phi_s$, theory) ~3 mrad

Phys. Rev. Lett. 114 (2015) 041801



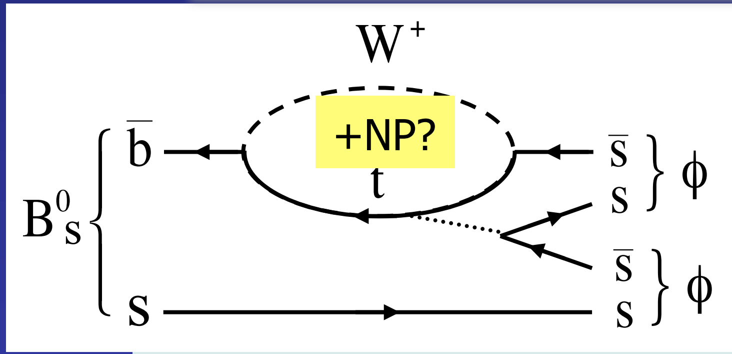
ϕ_s from $B_s \to J/\psi\phi$



CP Violation in $B_s \to \phi\phi$

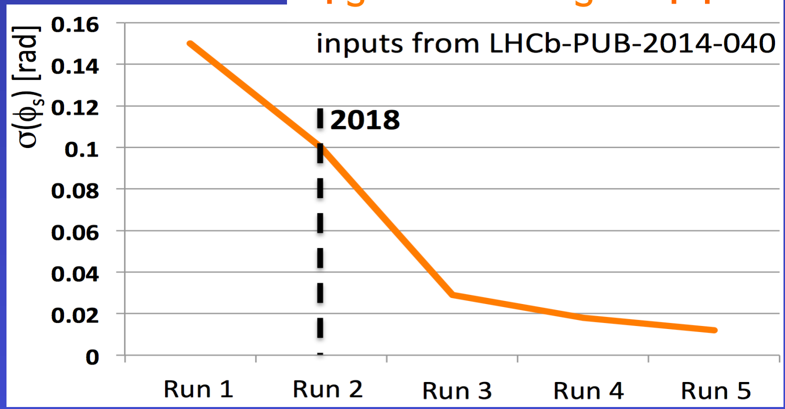
- **$B_s \to \phi\phi$ is golden mode for upgrade**
  - probe CP violating weak phase ϕ_s in hadronic B_s penguin decays
  - Sensitive to new physics in decay amplitude
  - Prediction for ϕ_s very close to zero
- **LHCb results on $B_s \to \phi\phi$**
  - ϕ_s = -170 ± 150 ± 30 mrad
- **LHCb upgrade**
  - Sensitivity $\sigma(\phi_s)$ ~0.02
  - Comp. to $\sigma(\phi_s$, theory) ≤ 0.02
  - Non zero ϕ_s result ➔ New Physics

Phys. Rev. D 90 (2014) 052011



M. Raidal, arXiv:hep-ph/0209091
M. Bartsch et al., arXiv:0810.0249

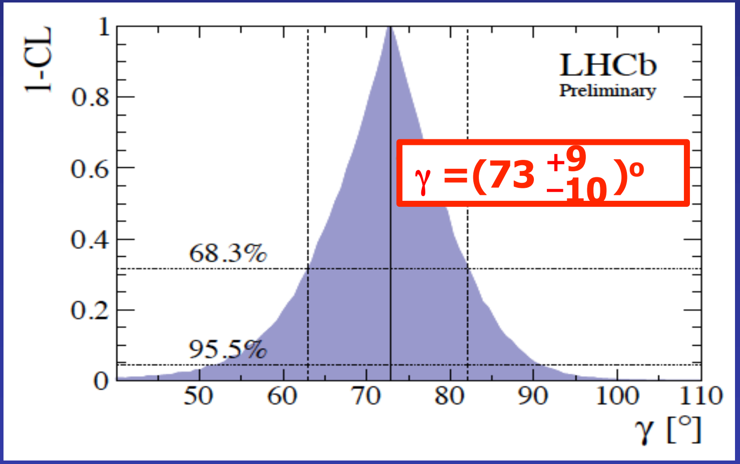
ϕ_s from $B_s \to \phi\phi$



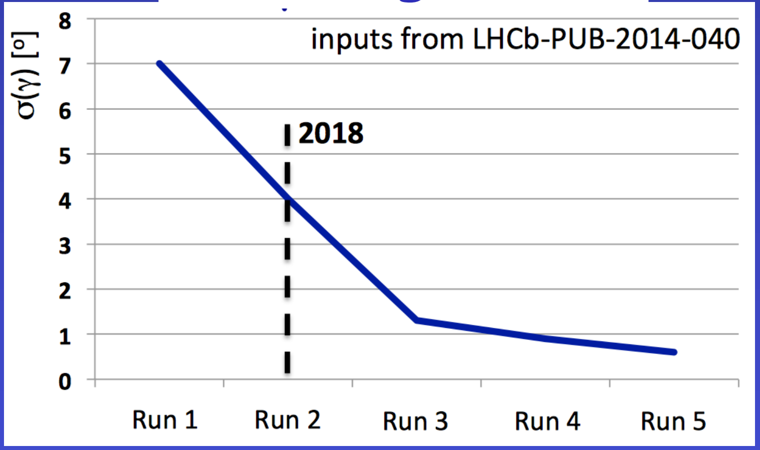
CKM angle γ

LHCB-CONF-2014-004

- **B factories**
  - Excellent progess during last decade
  - Babar $\gamma = 69 +17 -16\ °$
  - Belle $\gamma = 68 +15 -14\ °$
- **LHCb**
  - Combining many methods ADS, GLW, GGSZ, $B_S \rightarrow D_S K$
  - Starting to dominate γ world average
  - Expect 4° uncertainty on γ at end of run 2
- **LHCb upgrade**
  - Aiming for < 1° precision on γ

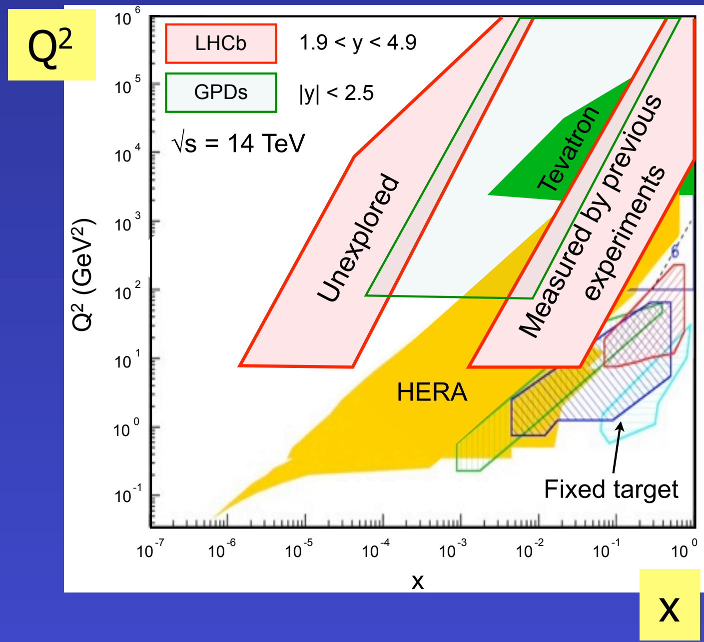


CKM angle γ



Non-Flavour Physics

- **Electroweak**
  - $\sin^2\theta_{eff}^{lepton}$: measure A_{FB} of leptons in Z-decays
  - Top quark forward-backward asymmetry
- **QCD**
  - Constraints on PDFs, unexplored region at low x
  - Flavour tagging of jets
- **Central Exclusive Production**
  - $pp \to p + X + p$ with rapidity gap
  - Central exclusive χ_b production
- **Exotics**
  - Tetra- and Pentaquarks
  - Hidden Valley long-lived particles
- **Heavy Ions**
  - pA, Ap and AA collisions in forward region
- **Higgs**
  - $H \to cc$ and $H \to bb$ in VBF

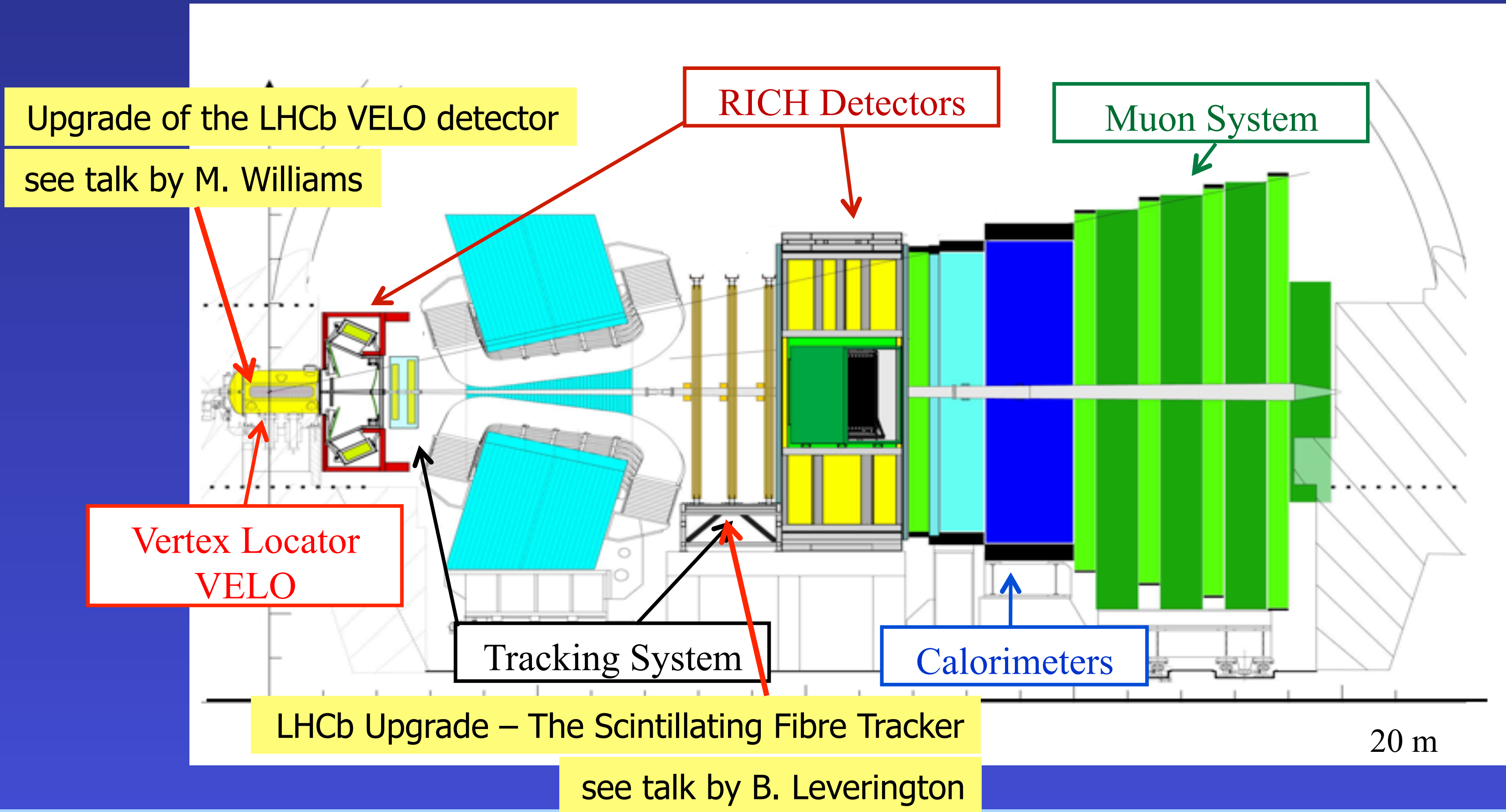


LHCb Upgrade Physics Reach

Type	Observable	Current precision	LHCb 2018	**Upgrade** ($50\,\text{fb}^{-1}$)	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
	$A_{\text{fs}}(B_s^0)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_s^{\text{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\text{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\text{eff}}(B^0 \to \phi K_S^0)$	0.17 [18]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\text{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\text{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	$5\,\%$	$1\,\%$	$0.2\,\%$
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.08 [14]	0.025	0.008	0.02
	$s_0\,A_{\text{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	$25\,\%$ [14]	$6\,\%$	$2\,\%$	$7\,\%$
	$A_{\text{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.25 [15]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	$25\,\%$ [16]	$8\,\%$	$2.5\,\%$	$\sim 10\,\%$
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [2]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	$\sim 100\,\%$	$\sim 35\,\%$	$\sim 5\,\%$
Unitarity triangle angles	$\gamma\ (B \to D^{(*)}K^{(*)})$	~ 10–$12°$ [19, 20]	$4°$	$0.9°$	negligible
	$\gamma\ (B_s^0 \to D_sK)$	–	$11°$	$2.0°$	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}	–

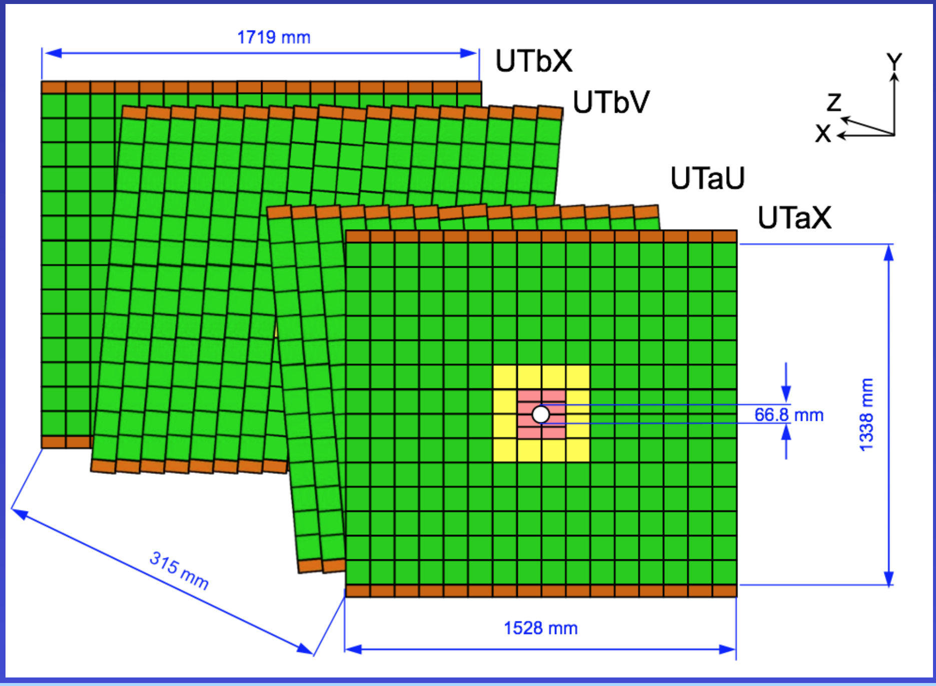
Detector upgrade

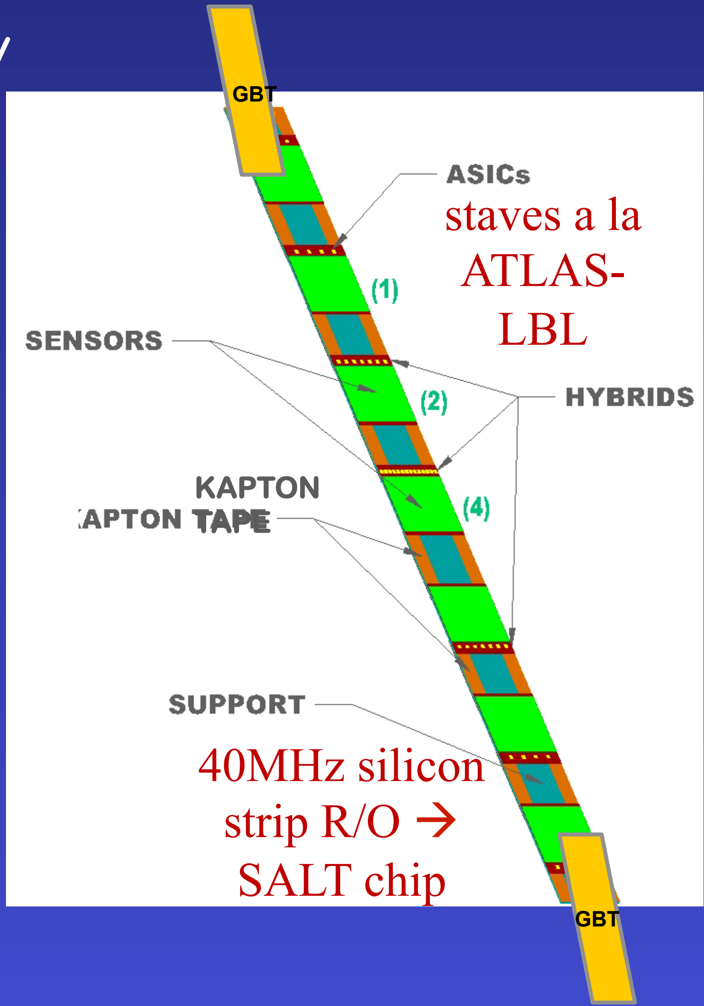
- **Replace or adapt sub-systems to 40 MHz readout**
  - Approved by LHCC & funding agencies, have Technical Design Reports
  - Construction phase from 2015 to 2018, installation in LS2



Upstream tracker - UT

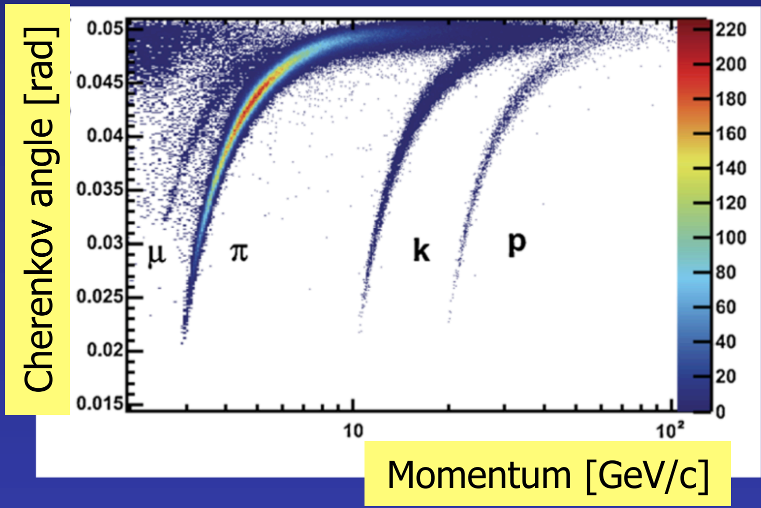
- **UT replaces TT tracker**
  - Silicon strip sensors with finer granularity in high occupancy region
  - Improved coverage at small polar angles
  - Readout and Signal processing at 40 MHz
  - Improved radiation hardness

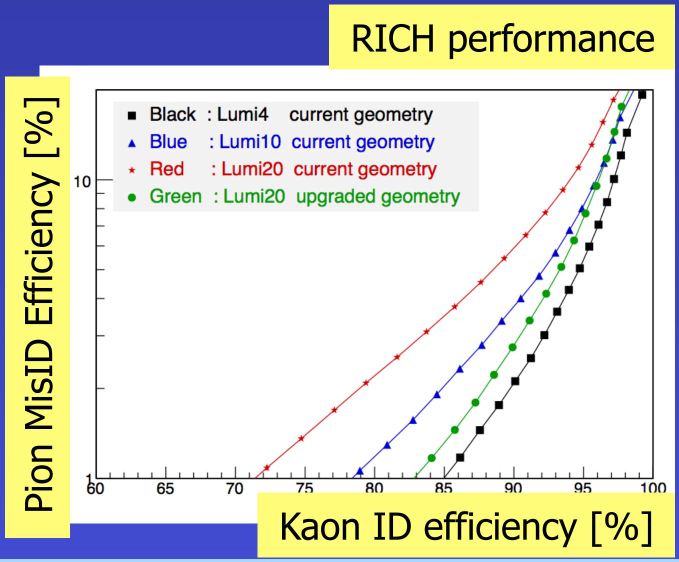


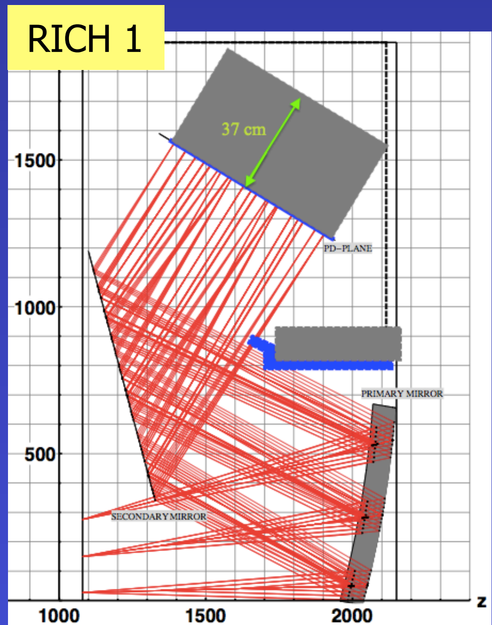


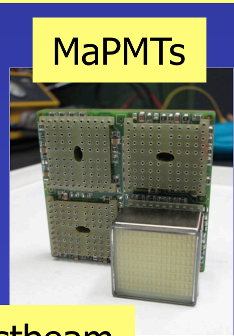
RICH PID upgrade

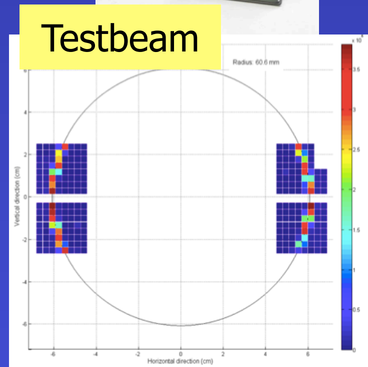
- **Maintain excellent charged PID**
- **RICH photon detectors**
  - MaPMTs replace HPDs
- **Upgraded RICH**
  - Remove aerogel radiator
  - RICH 1 optimised to reduce hit occupancy





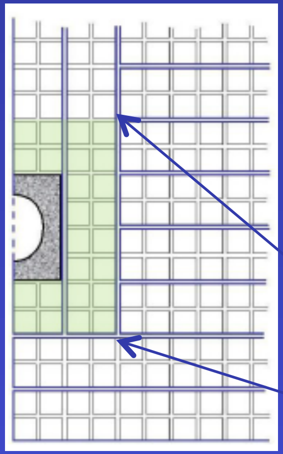


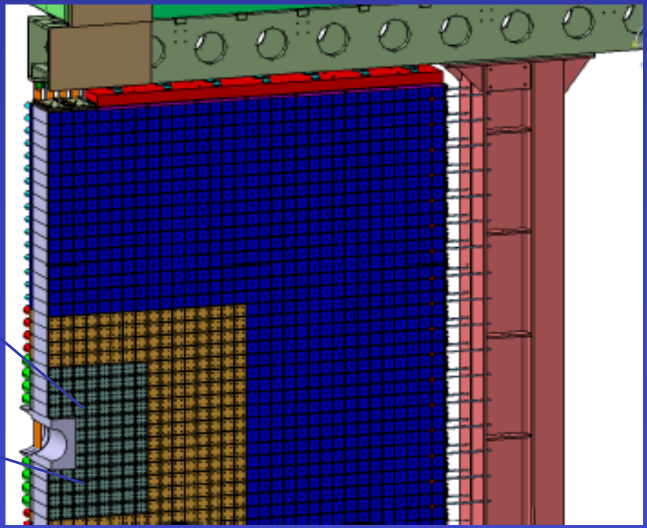




Calorimeter & Muon Upgrade

- **HCAL & ECAL**
  - HCAL modules ok up to ~50 fb-1
  - Inner ECAL modules need to be replaced after ~20 fb-1 (LS3)
  - Keep detector modules and PMTs
  - Reduce PMT gain, increase FE amplification
  - Modify 40 MHz FE electronics
- **Muon Spectrometer**
  - Keep muon chambers & FE electronics
  - Replace off-detector electronics
  - Remove first station (M1)
  - Install shielding





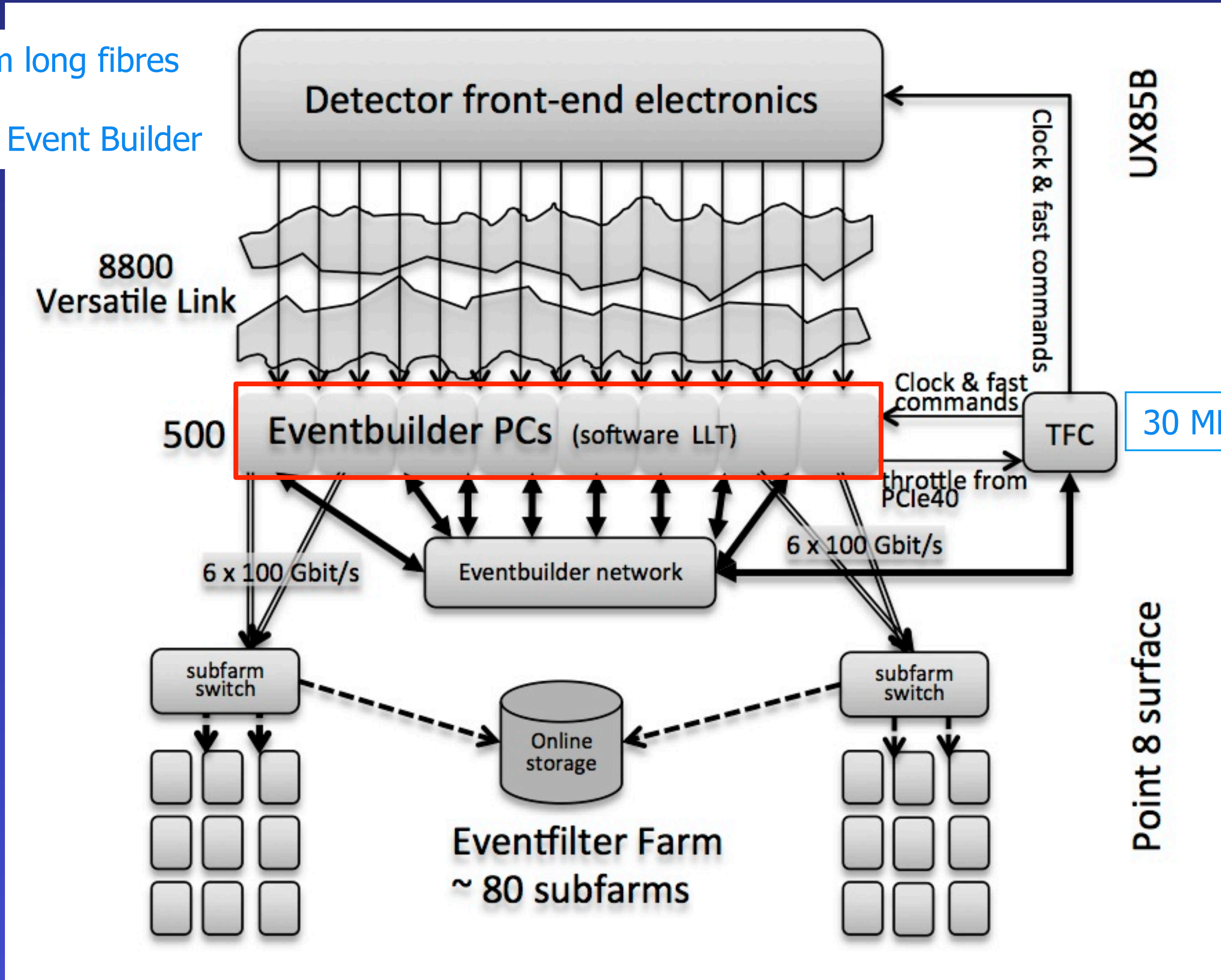
Conclusions

- LHCb and Flavour physics at the LHC are a huge success
  - Large NP ruled out in many flavour physics observables
  - Large increase in statistics required to investigate small NP deviations
- LHCb upgrade is approved and progressing well
  - Key element is 40 MHz readout of all sub-detectors
  - Full Software Trigger increases trigger efficiency significantly in hadronic channels
  - LHCb key performance parameters are retained
    - Vertex Resolution, Track reconstruction efficiency, Particle Identification
  - Installation of upgraded LHCb in Long Shutdown LS2 in ~2019/20
  - Operation in LHC Run 3 and Run 4 (HL-LHC)
- LHCb Upgrade is General Purpose Experiment for Forward region
  - Beauty, Charm, LFV, Electroweak, QCD, Exotica, Heavy Ion
  - Probe/measure New Physics at the percentage level

Backup

Readout Architecture

5 Gb/s , 300 m long fibres
from the FEE
directly to the Event Builder



30 MHz × 100 kB/evt

Charm physics

- A_Γ, WS $K\pi$, ΔA_{CP}
  - measurements with small systematics due to cancellations
  - No limiting uncertainty known so far
- $y_{CP} \equiv \tau_{K\pi}/\tau_{KK} - 1 \approx y$
  - Comparison of two different final states
- LHCb upgrade
  - Will collect unprecedentedly large charm samples
  - Scaling sensitivities with $\sqrt{N}$

Run	x [10^{-3}]	y [10^{-3}]	|q/p| [10^{-3}]	ϕ [mrad]
1	1.22	0.53	59	89
2	0.92	0.37	44	70
3	0.42	0.15	20	33
4	0.25	0.09	**12**	**20**

LHCb far future

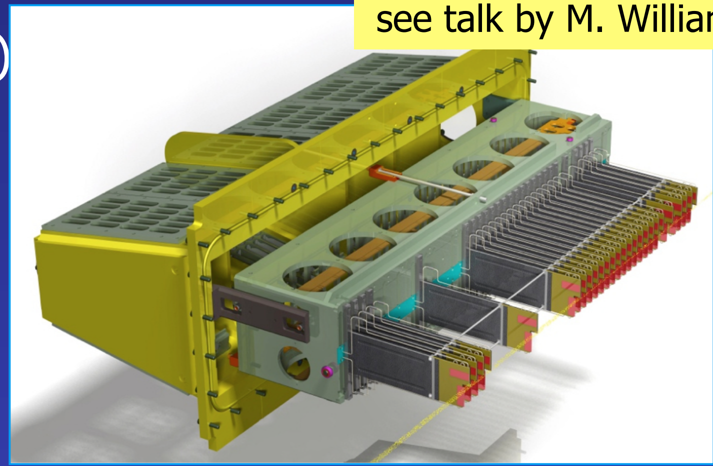
- **Scope of LHCb upgrade**
  - Plan to collect data set of 50/fb by Long Shutdown LS4
- **LHC will continue to operate**
  - beyond LS4 into 2030s
  - HL-LHC will be most copious source of heavy flavour particles
- **Physics case for LHCb in 2030s**
  - forward spectrometer operating at $O(10^{34}/cm^2/s)$
  - accumulate O(500/fb)
  - ECFA HL-LHC studies give mandate to discuss
  - Many flavour observables will become systematics or theory limited
  - Ideas: $B_s \to \mu\mu$ effective lifetime, $H \to cc$
  - Will hopefully get guidance from data in Run 2
  - Need to leave no stone unturned

VELO upgrade

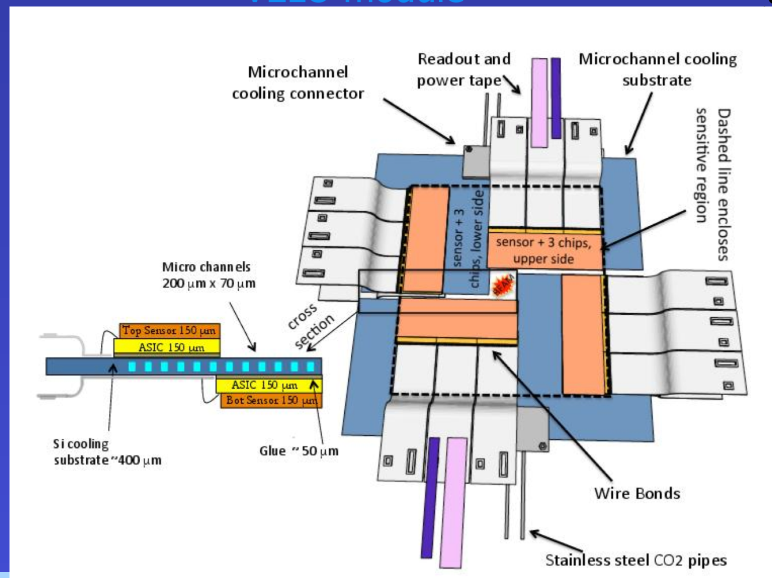
- **Key Issues and challenges**
  - increased radiation (highly non-uniform) $8 \cdot 10^{15}\ n_{eq}/cm^2$ for 50 fb^{-1}
  - handle high data volume
  - improve current performance
  - lower material budget
  - enlarge acceptance
- **VELO pixel detector**
  - Silicon pixels sensors of 55 × 55 μm^2
  - Sensor thickness: 300 μm → 200 μm
  - Aluminum RF foil: 300 μm→ ≤ 250 μm
  - 40 MHz VeloPix chip based on CMOS 130 nm technology
  - Radiation hard up to 400 MRad
  - Micro channel CO_2 cooling

Upgrade of the LHCb VELO detector

see talk by M. Williams



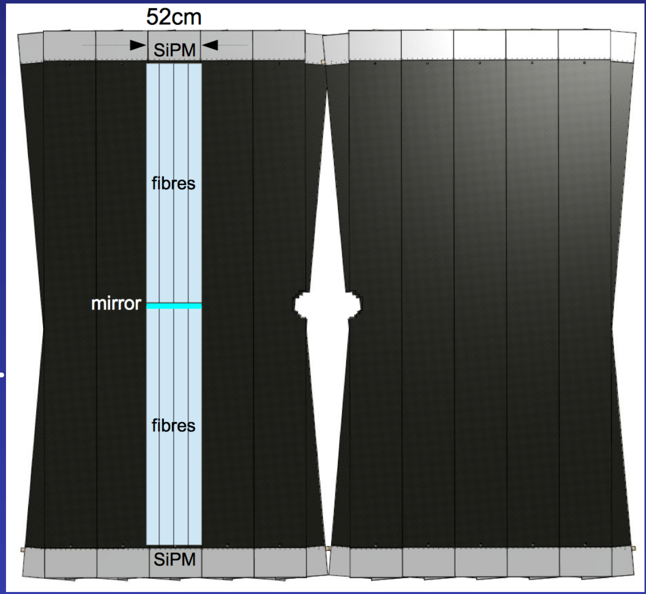
VELO module

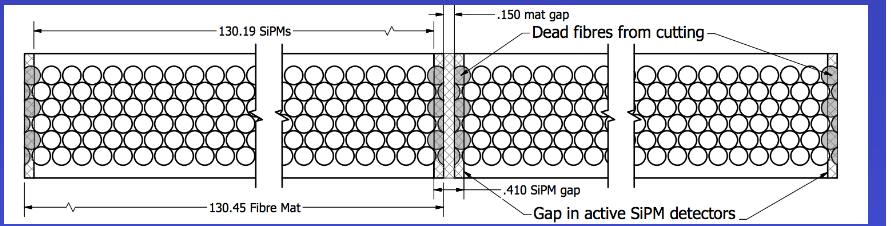


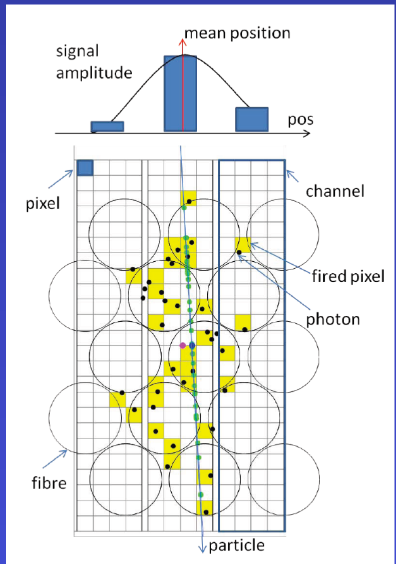
http://cds.cern.ch/record/1624070/files/LHCB-TDR-013.pdf

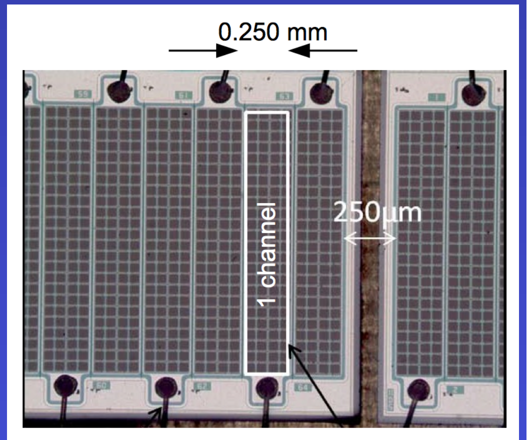
Downstream tracker - TT

- **Scintillating Fibre Tracker**
  - single technology will replace Straw (OT) and silicon IT tracker
  - Covering full acceptance: 5 × 6 m^2
  - Uniform material budget: $X/X_0 = 2.6\%$ per st
  - multiple layers of 2.5 m long scintillating fibres of 250 μm diameter
- **Readout**
  - The fibres are read by SiPM
  - SiPMs cooled to -40°C.
  - 60 – 100 μm spatial resolution









The End