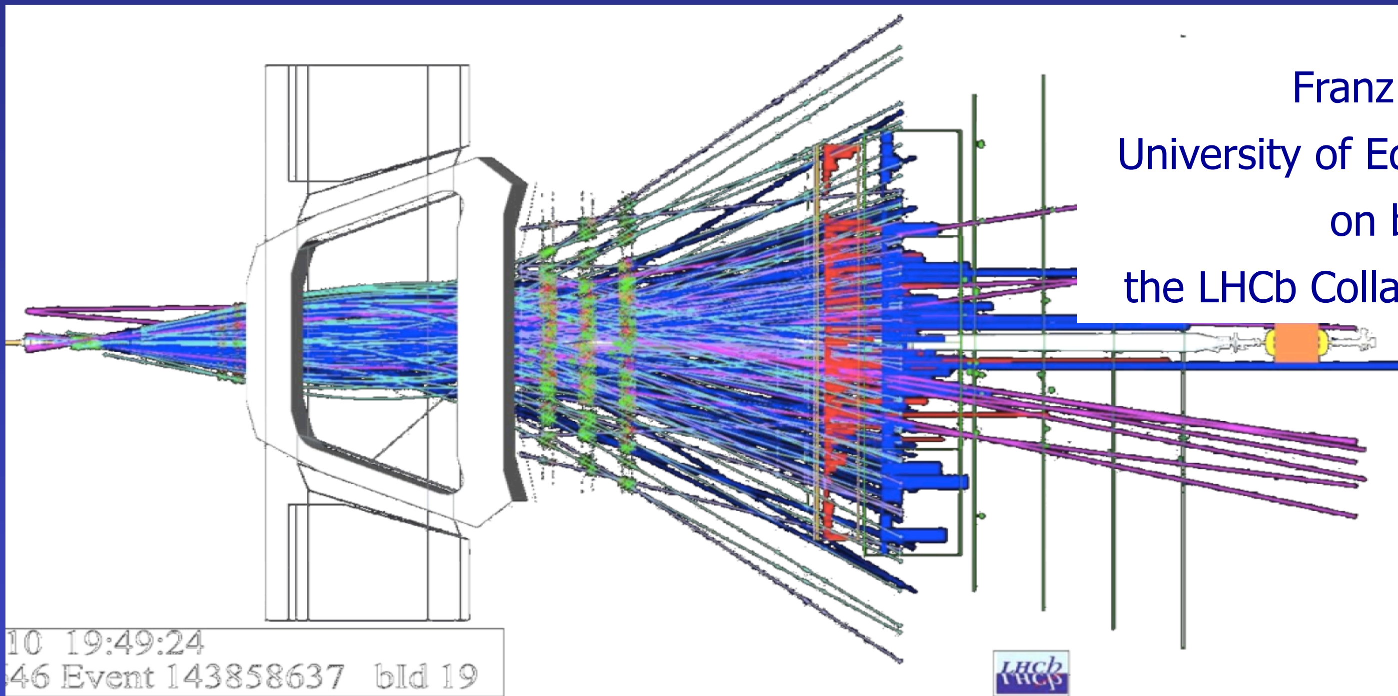
The LHCb Upgrade
Beyond the Energy Frontier



Franz Muheim
University of Edinburgh
on behalf of
the LHCb Collaboration

ICHEP2012 Melbourne
36th International Conference on High Energy Physics
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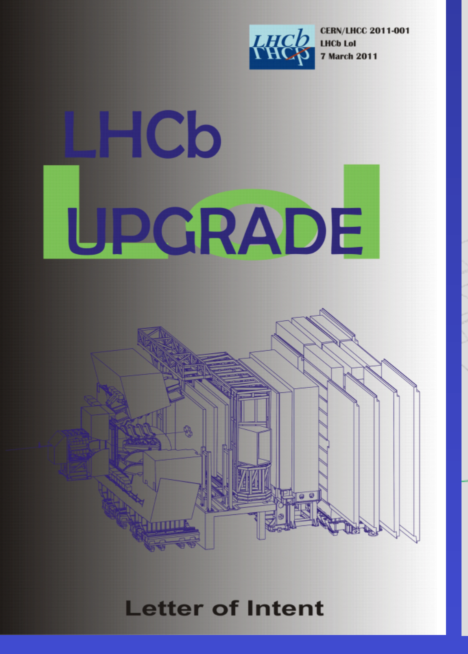
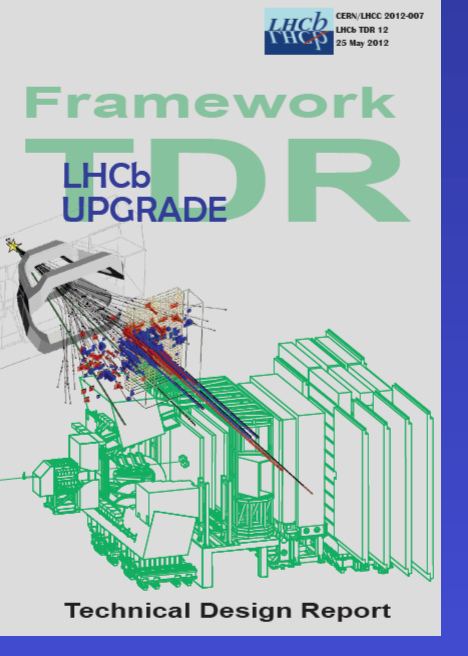
Outline

- LHCb Experiment Performance
- Physics Motivation for LHCb Upgrade
- LHCb Detector Upgrade
  - Trigger
  - Vertex Detector
  - Tracker
  - Particle Identification
- Conclusions

More information available
LHCb Upgrade LoI,
CERN/LHCC-2011-001
LHCb Upgrade Framework TDR,
CERN/LHCC-2012-007

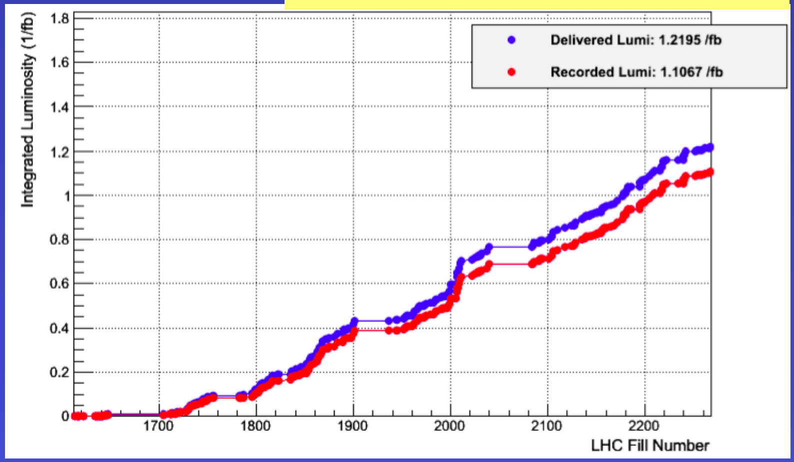




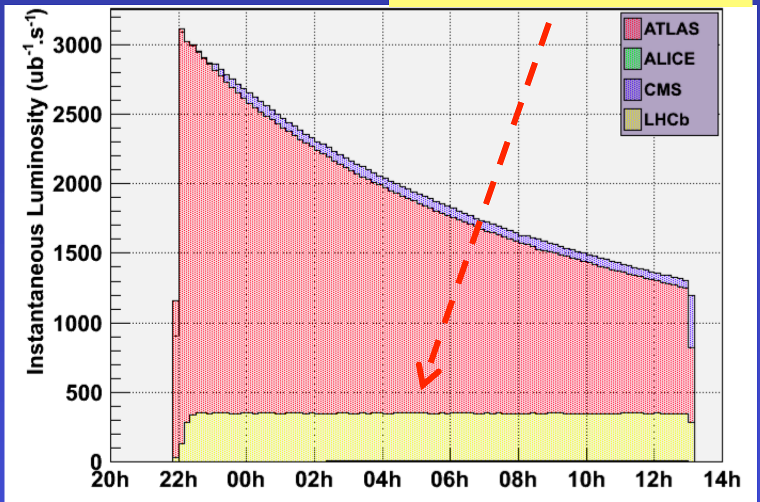
LHCb Performance

- **Very successful 2011 run**
  - LHCb operated at luminosities up to L =4 x 10^{32} cm^{-2} s^{-1}
    2x design luminosity
  - Average # of visible interactions/crossing μ = 1.4 (nominal 0.4)
  - Integrated $\int Ldt$ > 1.0 fb^{-1} on tape
  - Luminosity levelling, great LHC performance
  - 91% data taking efficiency, 99% of channels operational
  - 3 kHz of physics data to tape

LHCb Integrated Luminosity

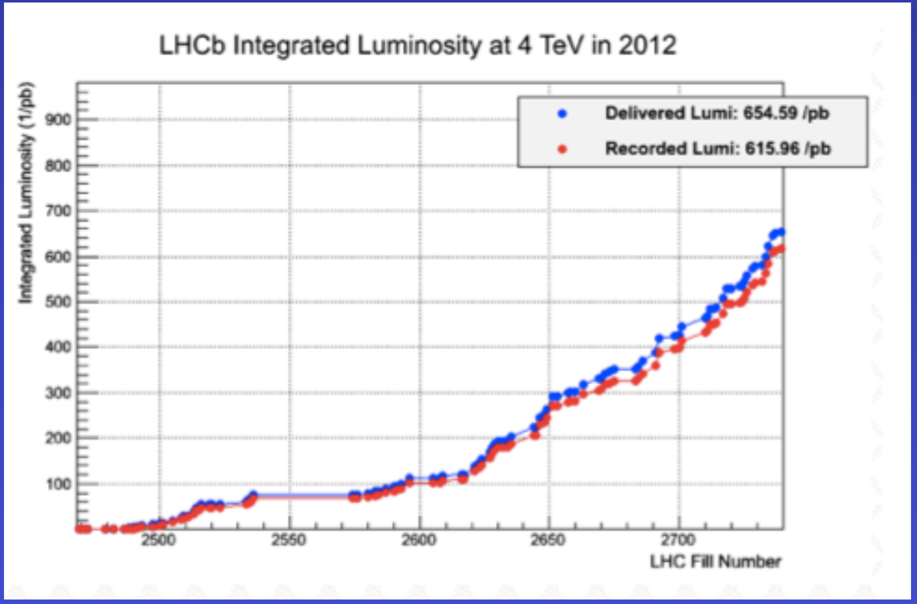


Luminosity levelling



LHCb Operations 2012

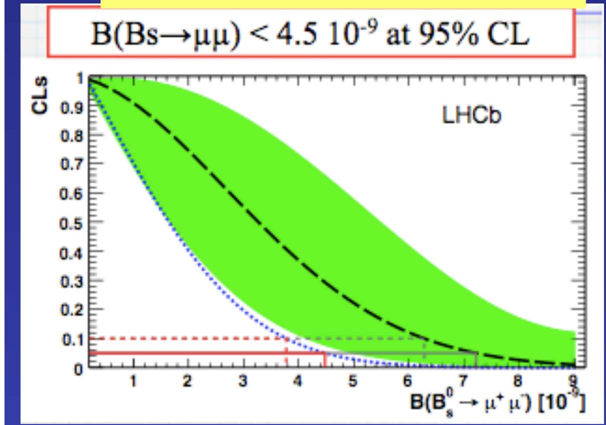
- **Excellent running in 2012 run**
  - Increased beam energy of 4.0 TeV results in ~15 % increase of $b\bar{b}$ cross section
  - Luminosity L = 4 x 10^{32} cm^{-2} s^{-1}
  - Average # of visible interactions per crossing μ = 1.6
  - Keep high data taking efficiency and quality
  - High Level Trigger (HLT) upgraded farm
  - HLT output increased from 3 to 4.5 kHz
  - Recorded > 0.6 fb^{-1} in 2012
  - Expect ~ 1.5 fb^{-1} of data in 2012



LHCb Physics Highlights

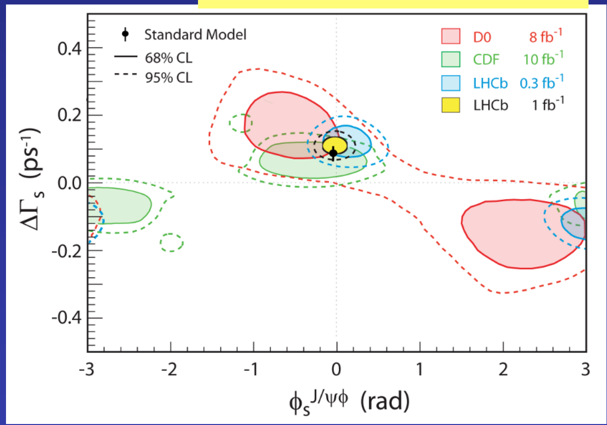
Best upper limit for $B_s \to \mu\mu$

see talk by M. Perrin-Terrin



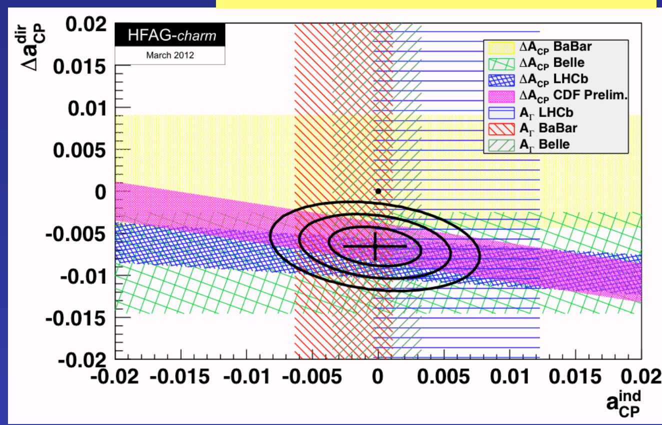
Best measurement of ϕ_s in $B_s \to J/\psi\phi$

see talk by G. Cowan



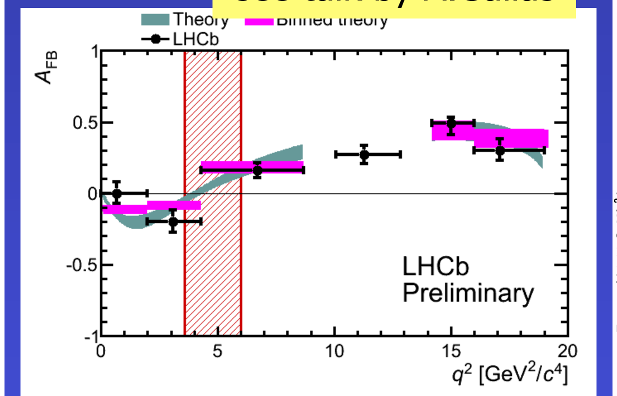
Evidence for CP violation in charm

see talk by J. Garra Tico



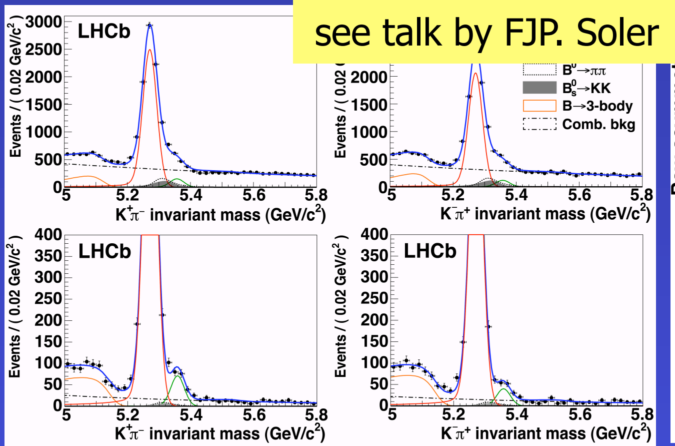
Best measurement of A_{FB} in $B^0 \to K^{*0}\mu\mu$

see talk by A.Gallas



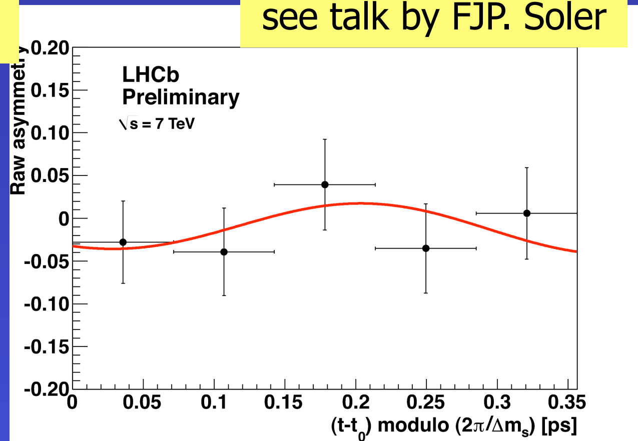
First observation of direct CP violation at a hadron collider

see talk by FJP. Soler



First measurement of CP violation in $B_s \to KK$

see talk by FJP. Soler



LHCb Plans/Upgrade

- **Collect > 5 fb^{-1} data sample over next five years**
  - 13 (14) TeV → double b and c production
  - Precision measurements of unitarity triangles
  - Measure rare hadronic decays
  - Probe/measure New Physics at 10% level in key measurements
  - Be prepared for the unexpected → follow the data
- **LHCb upgrade**
  - Current detector limited to 1 MHz trigger Level-0 trigger
  - Upgrade detectors to 40 MHz readout
  - Implement first level software trigger for all detectors
  - Operate detector at luminosities up to 2×10^{33} cm^{-2} s^{-1}
- **Expected annual physics yield with LHCb upgrade**
  - Increase x10 in decays with muons
  - Increase at least x20 in hadronic channels
  - Collect ~50/fb
- **Install upgraded LHCb in long shutdown of ~2018**

LHCb Upgrade Motivation

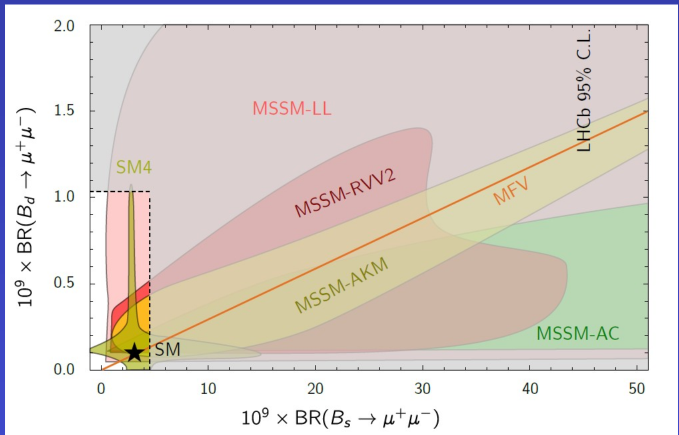
- **Excellent results from LHCb**
  - Many world's best measurements, severely constrain new physics
  - Demonstrated potential of Flavour Physics at the LHC
- **LHCb upgrade physics reach**
  - Unique for NP searches in B_s system, very competitive for B_d
  - Unprecedented charm yields
  - General purpose experiment with forward geometry has potential for non-flavour physics
- **LHCb upgrade will fully exploit LHC physics in forward region**
  - LHCb upgrade is compatible with high luminosity LHC phase but does not require it
  - Complementary to ATLAS / CMS direct searches
- **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

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

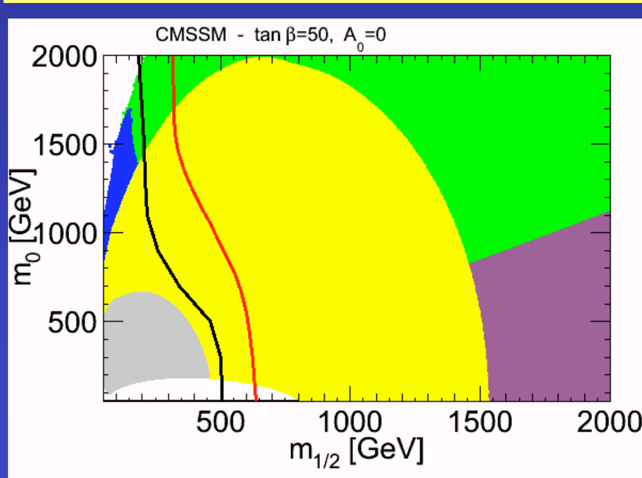
1.0 fb^{-1}, Phys. Rev. Lett. 108 (2012) 231801

- **LHCb**
  - Closing in on SM prediction $BR(B_s \to \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9}$
  - New physics 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

green – allowed regions
black/red – exclusion limits from CMS
yellow - exclusion region from LHCb $B_s \to \mu\mu$ result



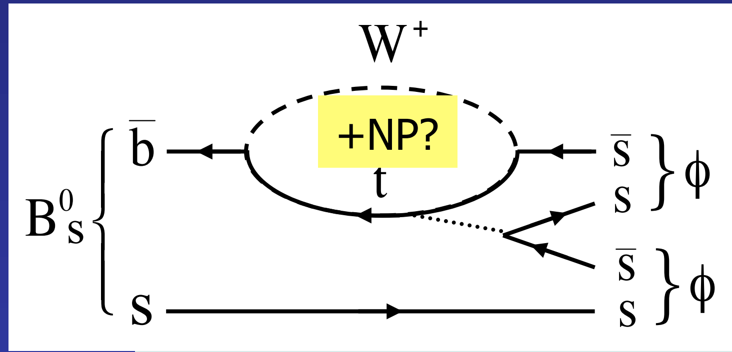
D.M. Straub, Moriond EW 2012



N. Mahmoudi, Moriond QCD 2012

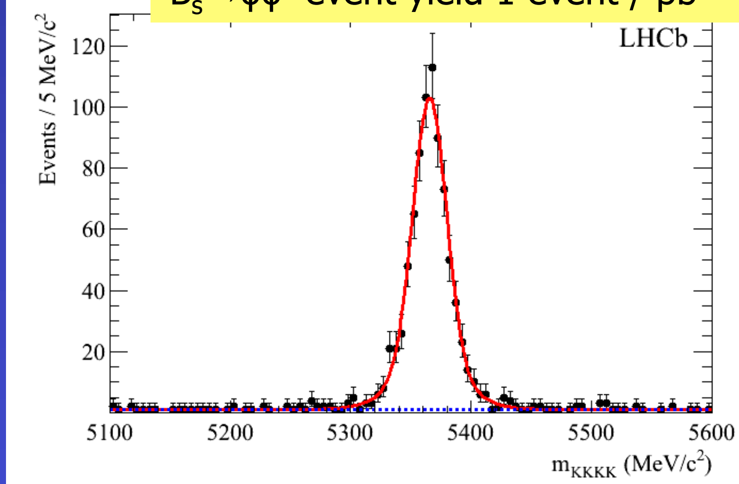
CP Violation in $B_s \to \phi\phi$

- **$b \to q\bar{q}s$ penguin transitions**
  - Rare hadronic decay
  - Sensitive to new physics in decay amplitude
- **$B_s \to \phi\phi$ is golden mode for upgrade**
  - For probing CP violating weak phase ϕ_s in hadronic B_s decays
  - In Standard Model cancellation between decay and mixing phases
  - Prediction for ϕ_s very close to zero
- **LHCb upgrade**
  - Sensitivity $\sigma(\phi_s)$ ~0.03
  - Comp. to $\sigma(\phi_s$, theory) ≤ 0.02
  - Non zero ϕ_s result ➔ New Physics



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

$B_s \to \phi\phi$ event yield 1 event / pb^{-1}



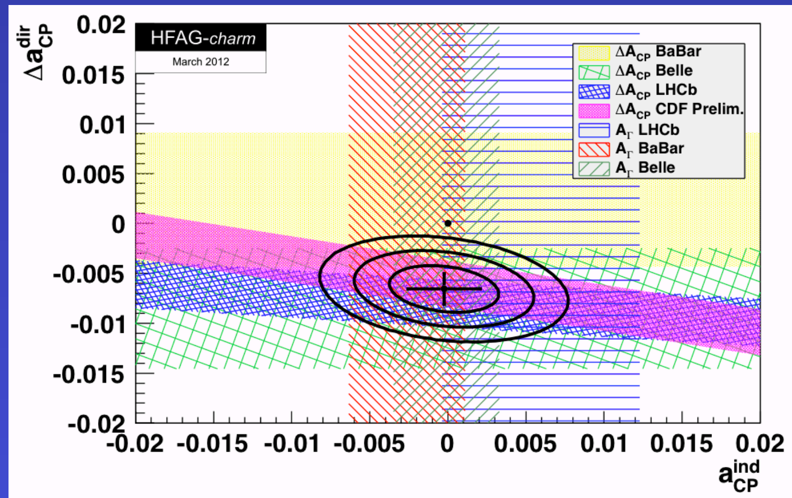
1.0 fb^{-1}, Phys. Lett. B713 369-377 (2012)

CP Violation in Charm

- **CP violation in charm**
  - Was expected to be < 0.1%
- **Evidence for direct CPV in D→hh**
  - $\Delta A_{CP} \equiv A_{CP}(KK) - A_{CP}(\pi\pi)$ experimentally favourable
  - Measure $\Delta A_{CP} = (-0.82 \pm 0.21 \pm 0.11)\%$
  - Recently confirmed by CDF
  - Further LHCb studies underway
  - Theory community is reconsidering
- **LHCb upgrade**
  - Will collect unprecedentedly large charm samples
  - Expected sensitivity $\sigma(\Delta A_{CP}) \sim 0.12 \times 10^{-3}$

0.6 fb^{-1}, PRL 108, 111602 (2012)

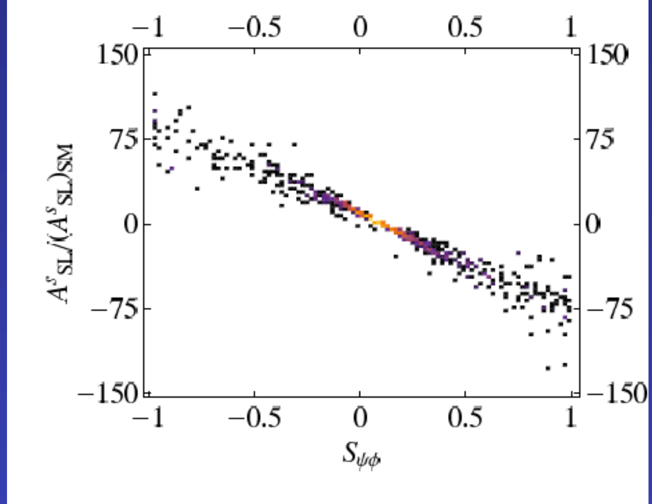
ΔA_{CP} versus a^{ind}_{CP}



LHCb Upgrade Physics Reach

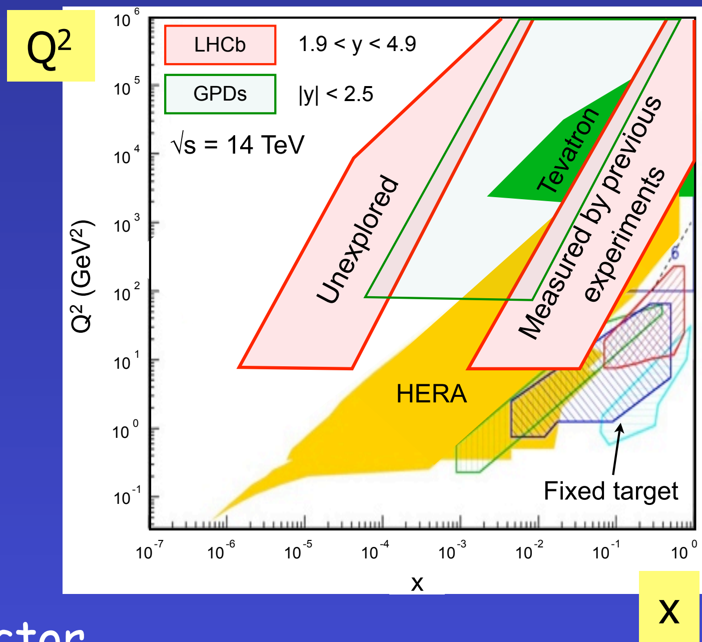
- **Electroweak penguins**
  - $B^0 \to K^{*0}\mu^+ \mu^-$
  - Upgrade will allow to make precise measurements of asymmetries A_I, S_3, …
- **B_s mixing**
  - $B_s \to J/\psi\phi$ very precise $\sigma(\phi_s)$ ~0.008
  - A_{sl} sensitivity 0.2×10^{-3}
- **Gluonic penguins**
  - $B_s \to K^{*0}\overline{K^{*0}}$ probes CPV phase ϕ_s in same way as $B_s \to \phi\phi$
  - Sensitivity $\sigma(\phi_s)$ ~0.02 matches theoretical uncertainty
- **Unitarity triangles**
  - $\sigma(\gamma)$ ~ 0.9 degrees

M. Blanke et al., arXiv0809.1073



Non-Flavour Physics

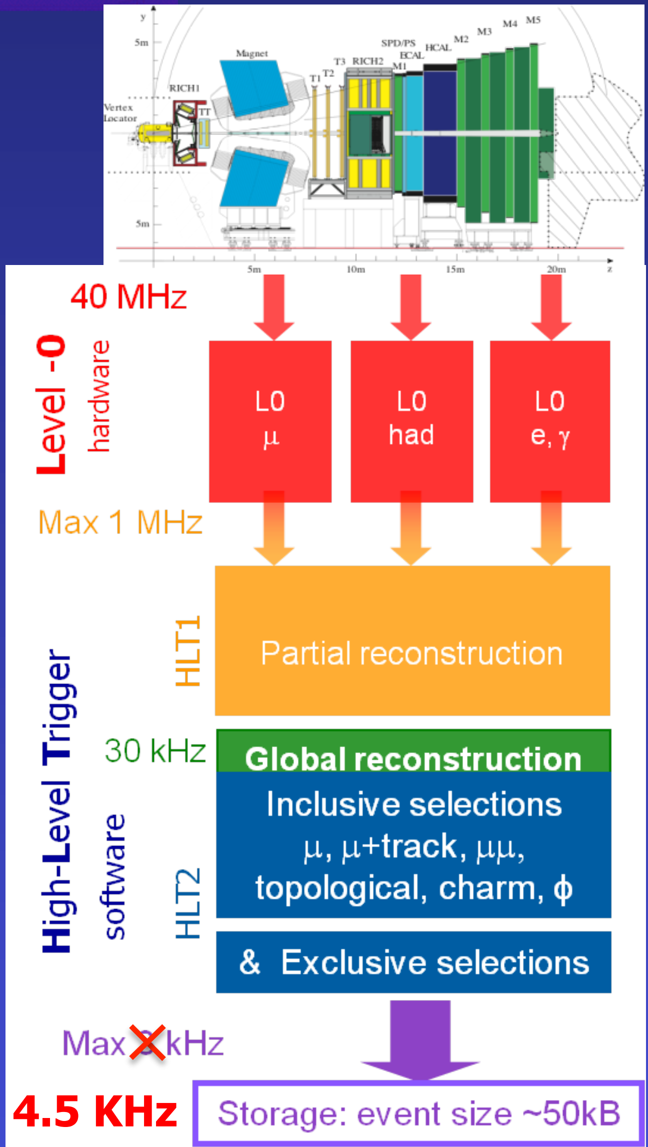
- **Electroweak**
  - Boson follows quark direction in forward region
  - $\sin^2\theta_{eff}^{lepton}$: measure A_{FB} of leptons in Z-decays
  - Top quark forward-backward asymmetry
- **QCD**
  - Constraints on PDFs
  - Unexplored region at low x
  - Flavour tagging of jets
- **Central Exclusive Production**
  - pp → p + X + p with rapidity gap
  - Central exclusive χ_b production
  - Pomeron/ photon exchange
- **Hidden Valley particles**
  - long-lived, decay in LHCb vertex detector



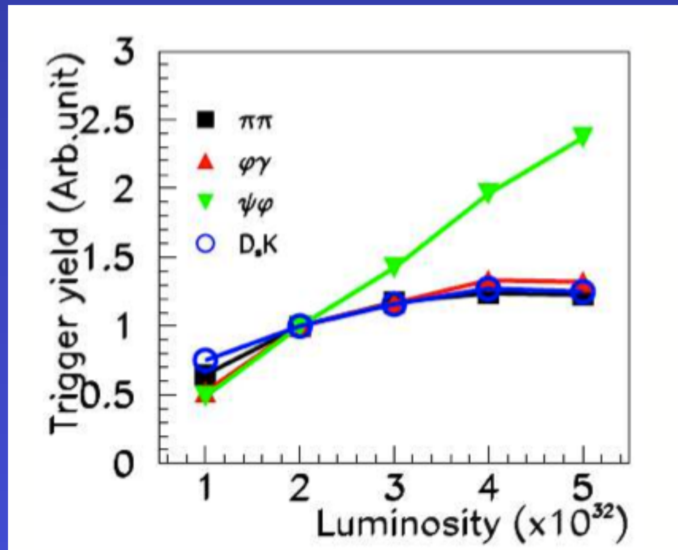
Performance Benchmarks

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
	$A_{\rm fs}(B_s^0)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_s^{\rm eff}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$	0.17 [18]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\rm eff}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	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
	$s_0\,A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [14]	6 %	2 %	7 %
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	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}	–

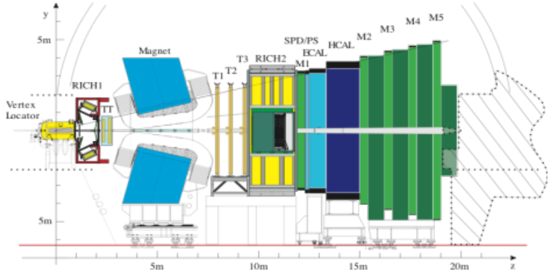
Current LHCb Trigger



- **Level-0 Hardware trigger**
  - limited to 1 MHz output
- **HLT Software trigger**
  - Implemented in CPU farm
- **Luminosity upgrade**
  - Event yields saturate for hadronic channels



Trigger for LHCb Upgrade



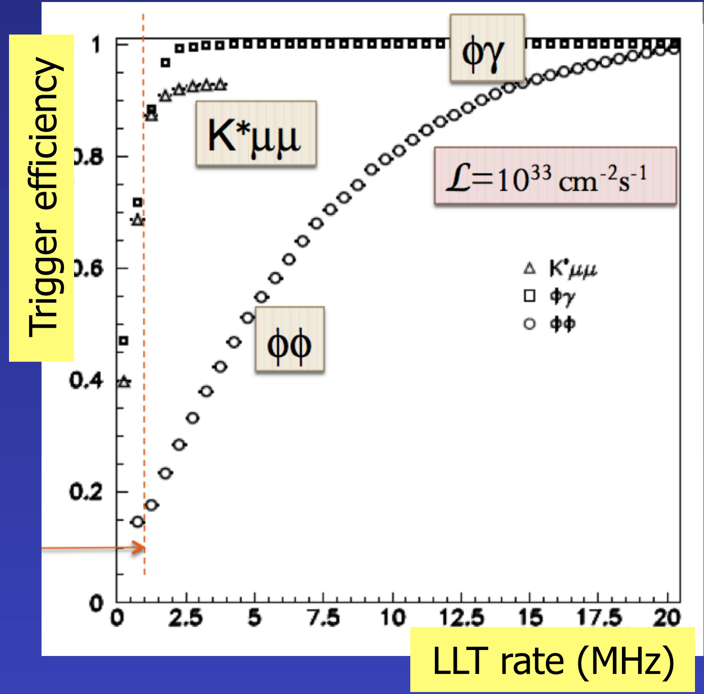
40 MHz

Optional
Low Level Trigger
throttle
1-40 MHz

HLT
Tracking and vertexing
Impact Parameter cuts
Inclusive/Exclusive selections

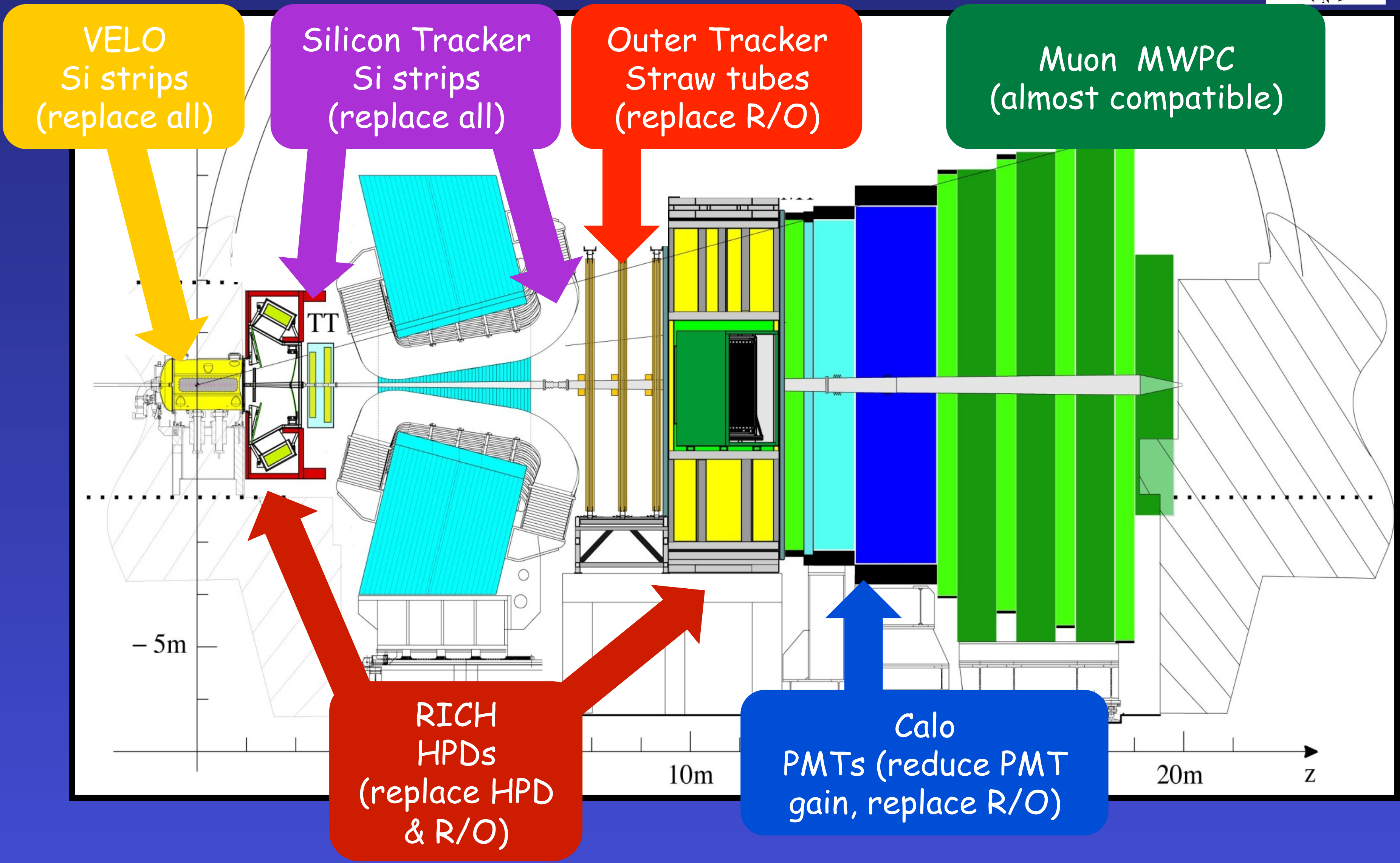
to tape

20 kHz



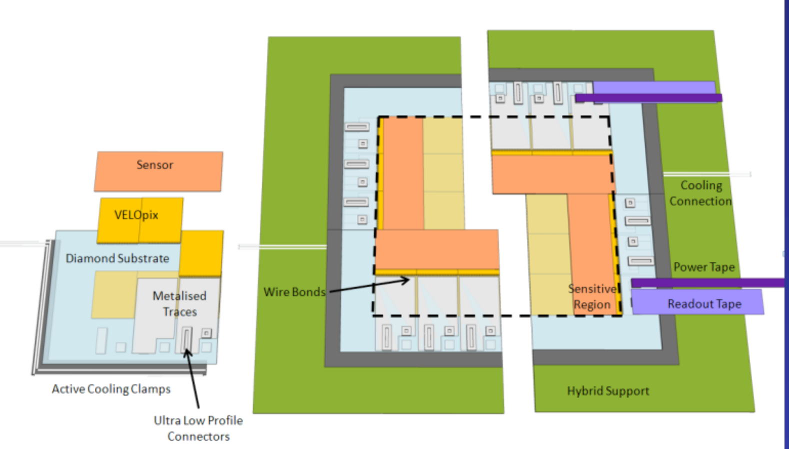
Efficiency	Farm Size = 5 x 2011	Farm Size = 10 x 2011
$B_s \to \phi\phi$	29%	50%
$B^0 \to K^*\mu\mu$	75%	85%
$B_s \to \phi\gamma$	43%	53%

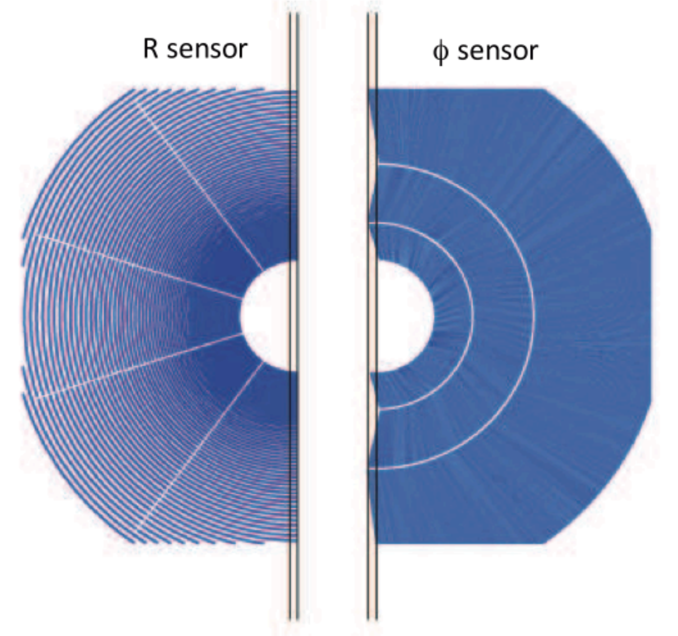
LHCb Upgrade to 40 MHz



VELO Upgrade

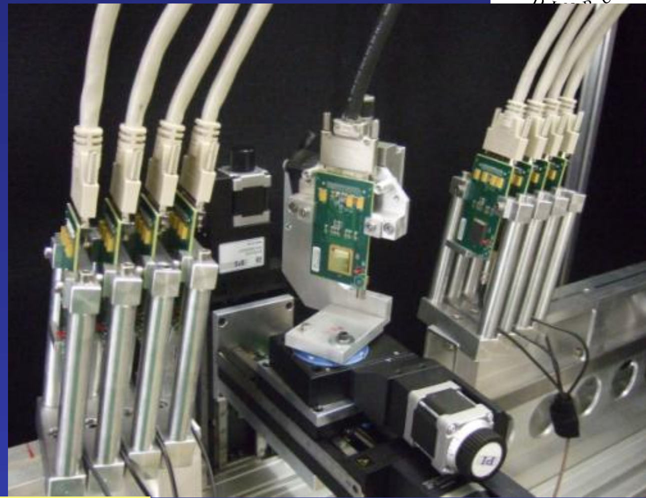
- **New VELO at 40 MHz readout**
  - Pixel detector (VELOPIX) read out with Timepix chip
    - 55 µm x 55 µm pixel size
  - Strip detector
    - New F/E chip
- **R&D programme**
  - Module structure (X_0)
  - Sensor options
    - planar Si, pixel
  - Radiation hardness
  - Electronics
  - CO_2 cooling
  - RF-foil



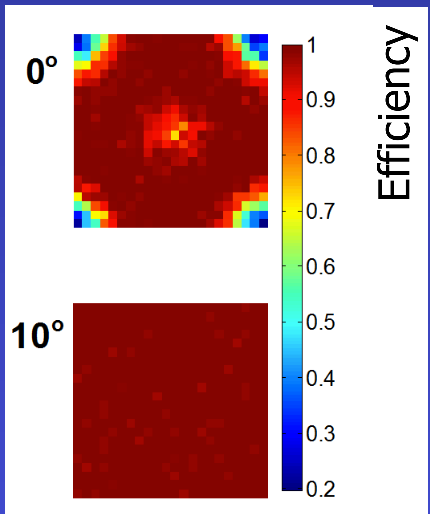


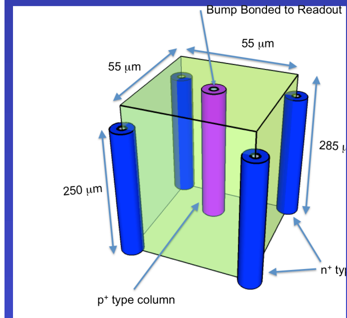
VELO R&D

- **Testbeam telescope**
  - based on TimePix chip
  - Excellent resolution O(μm)
  - High rate capability

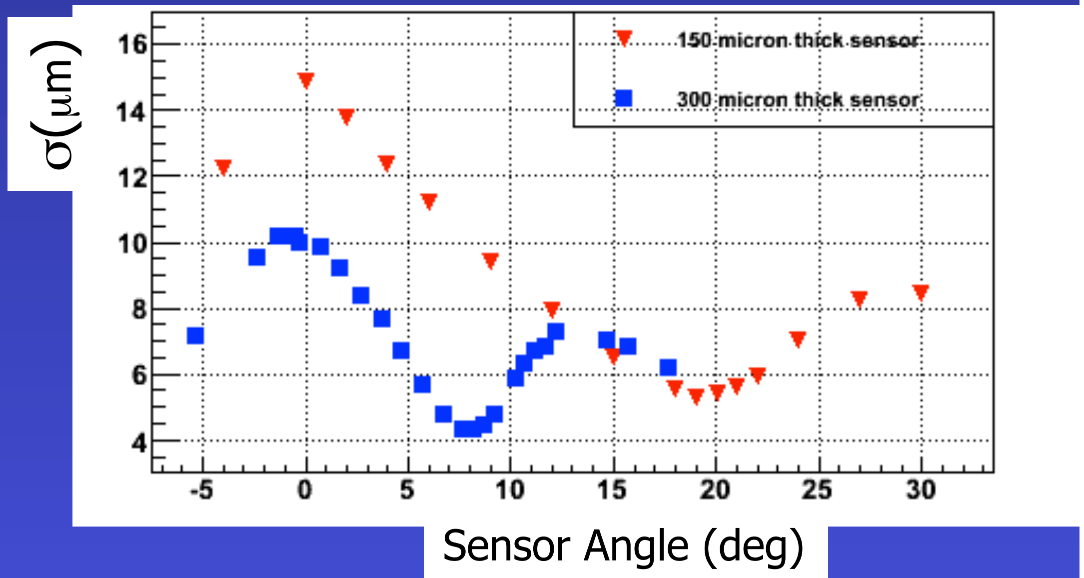


3D sensor studies



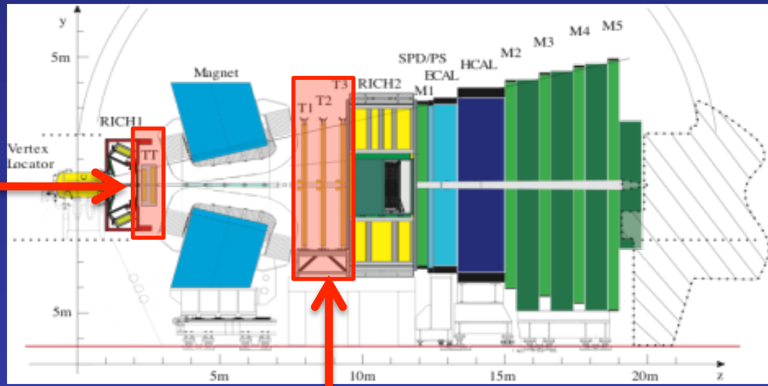


Planar sensor studies

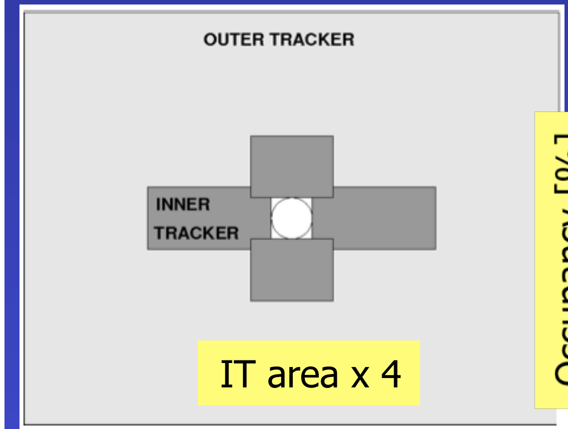


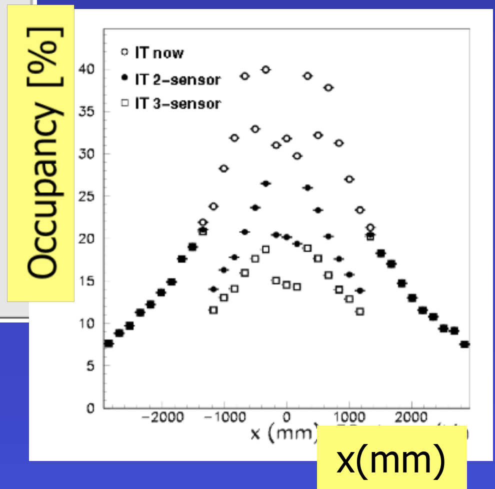
LHCb Tracker Upgrade

- **TT tracking station**
  - Silicon strip detector
  - Upgrade - Redesign silicon strips
  - Share FE chip with strip VELO



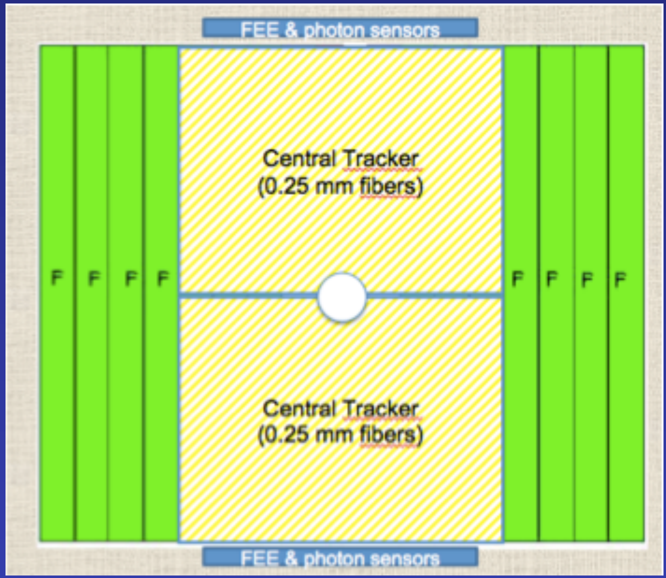
- **Current tracking system**
  - Inner tracker (IT) - Silicon strip
  - Outer tracker (OT) - Straw tubes
- **Tracker upgrade - Option A**
  - Same technologies
  - Increase IT area by factor of 4
  - Decrease mass
  - Reduces occupancy in OT straw tubes to < 20%

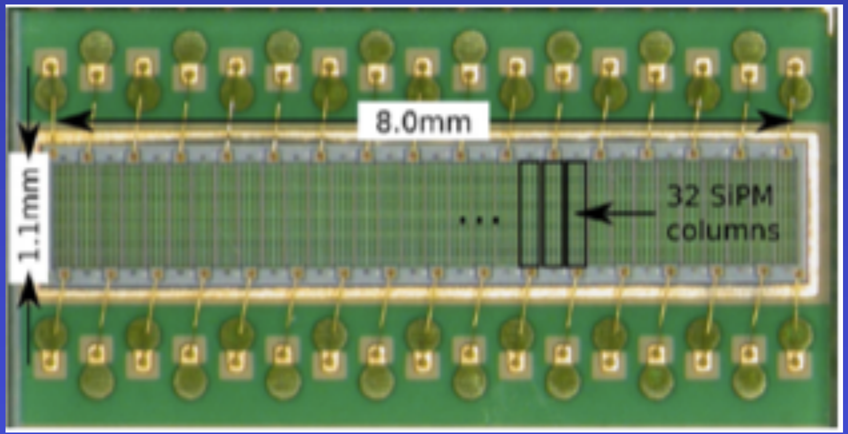


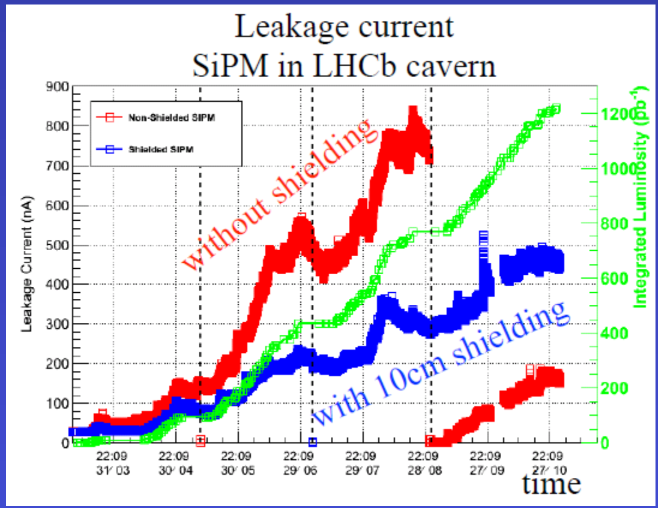


LHCb Tracker Upgrade

- **Tracker upgrade – Option B**
  - Scintillating fibre Central Tracker
  - Straw tube outer tracker
- **Central Tracker**
  - Modules with 5 layers of scintillating fibres, 2.5 m long
  - Read out with silicon photomultipliers

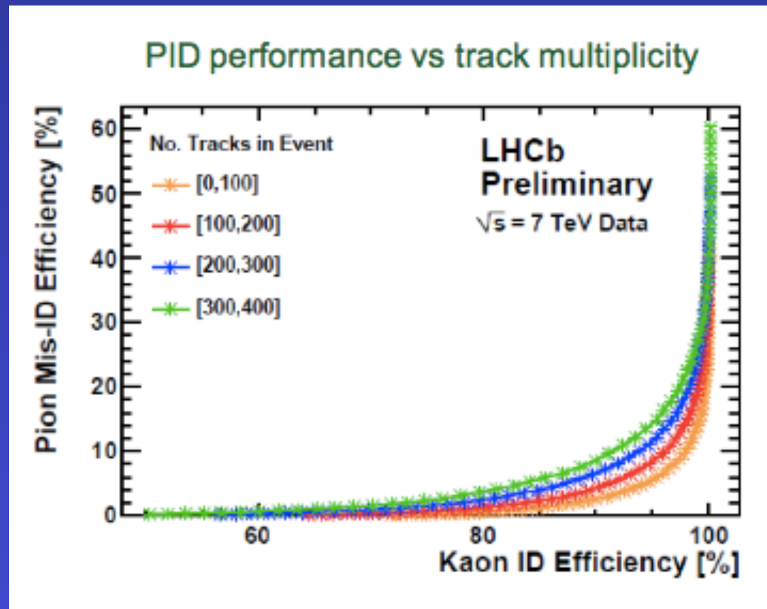






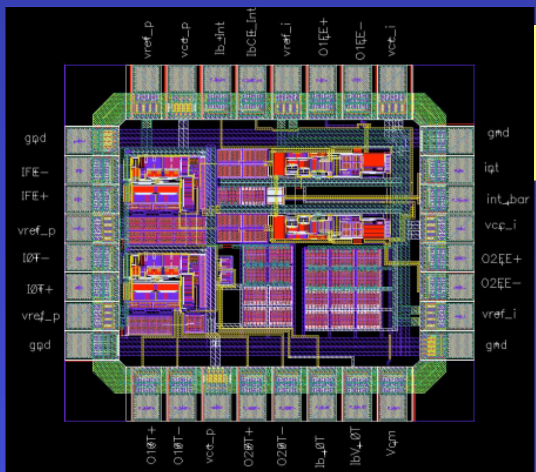
RICH Upgrade

- **RICH Photo detectors**
  - HPDs - encapsulated readout electronics
  - Need to be replaced
  - Hamamatsu R11265 MaPMT
    - baseline
    - 80% area coverage
- **RICH1 and RICH2**
  - Remove aerogel radiator due to occupancy
  - Investigate change of RICH1 optics to reduce occupancy in central region
- **Performance studies**
  - Pattern recognition works well up to 2×10^{33} cm^{-2} s^{-1}

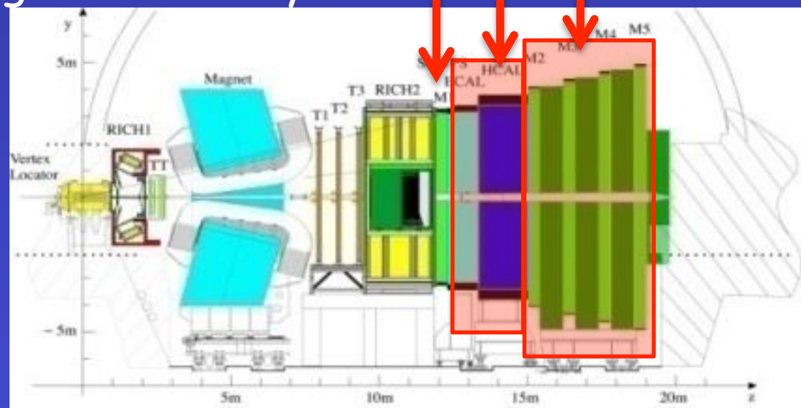


Calorimeter & Muon Upgrade

- **HCAL & ECAL**
  - Keep detector modules and PMTs
  - Reduced PMT gain, increased FE amplification
  - Modified 40 MHz FE electronics
- **Muon Spectrometer**
  - Keep chambers & FE electronics
  - Remove first station (M1)
  - High occupancy performance and aging under study



Calorimeter FrontEnd ASIC prototype



Conclusions

- LHCb and 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 plan is mature
  - Key element is 40 MHz Readout of all sub-detectors
  - Full Software Trigger increases trigger efficiency
    at least x2 in hadronic channels
  - LHCb key performance parameters are retained
    - Vertex Resolution, Track reconstruction efficiency, Particle Identification
- Installation of upgraded LHCb detectors in Long Shutdown 2018
- LHCb Upgrade is General Purpose Experiment for Forward region
  - Beauty, Charm, LFV, Electroweak, QCD, Exotica
  - Probe/measure New Physics at the percentage level

Backup Slides

Challenge: Data Rates

- Full detector read-out @ 40 MHz
  - Current Vertex Locator: 225 G samples/s (analogue)
  - Upgraded Vertex Locator: 2-3 Tbit/s (digital)
- On-detector zero-suppression
  - Replace (almost) all FE electronics
- Massive read-out infrastructure