LHCb upgrade – the essentials

Flavour and the fourth family, IPPP, Durham

Guy Wilkinson
University of Oxford
on behalf of the LHCb collaboration

Outline

- Current experiment: experience and performance

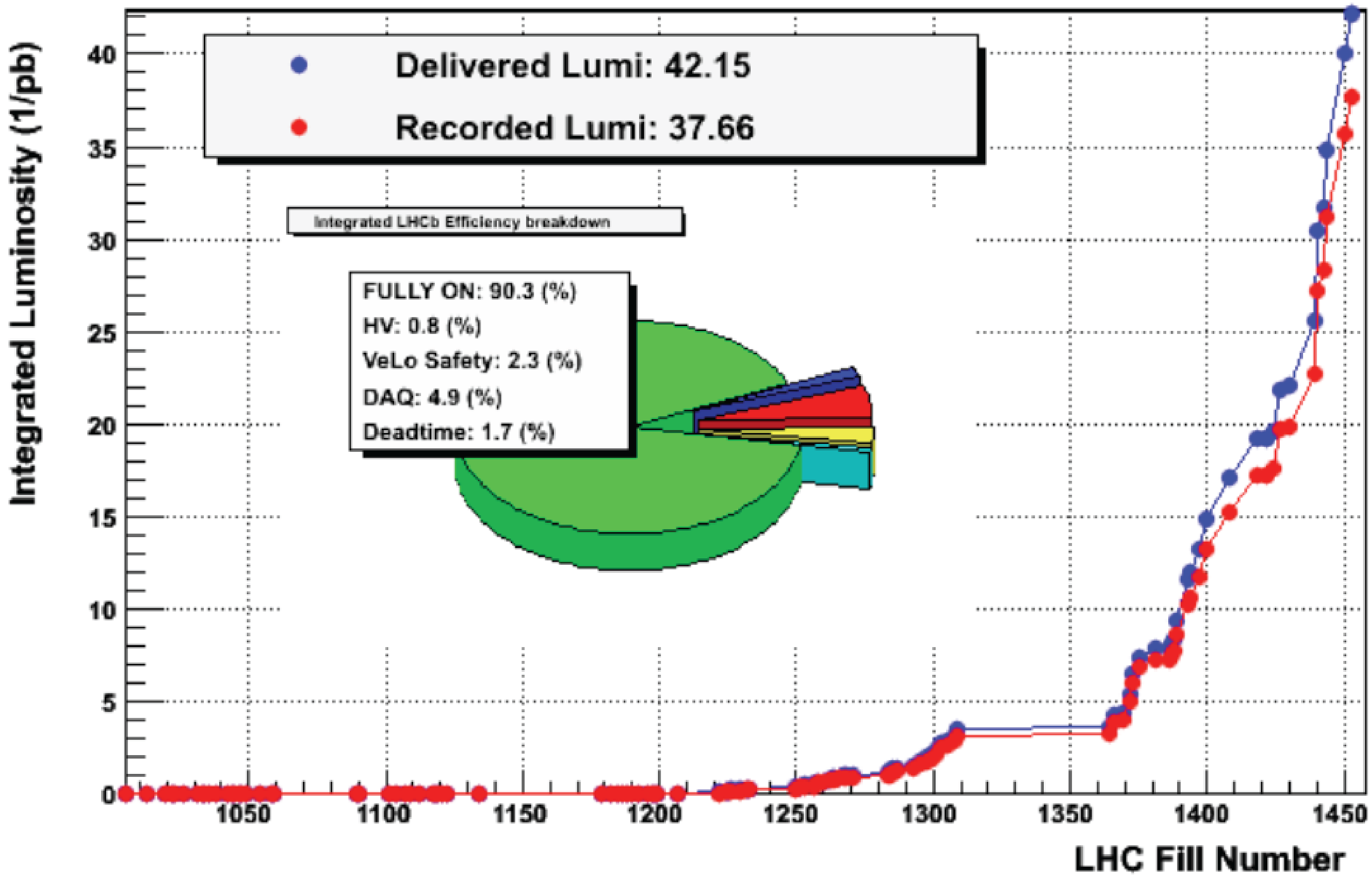
- Path to the upgrade

- Selected flavour physics goals:
  2010, 2011+ and during upgrade era

- Physics beyond flavour

- Summary

Integrated luminosity in 2010

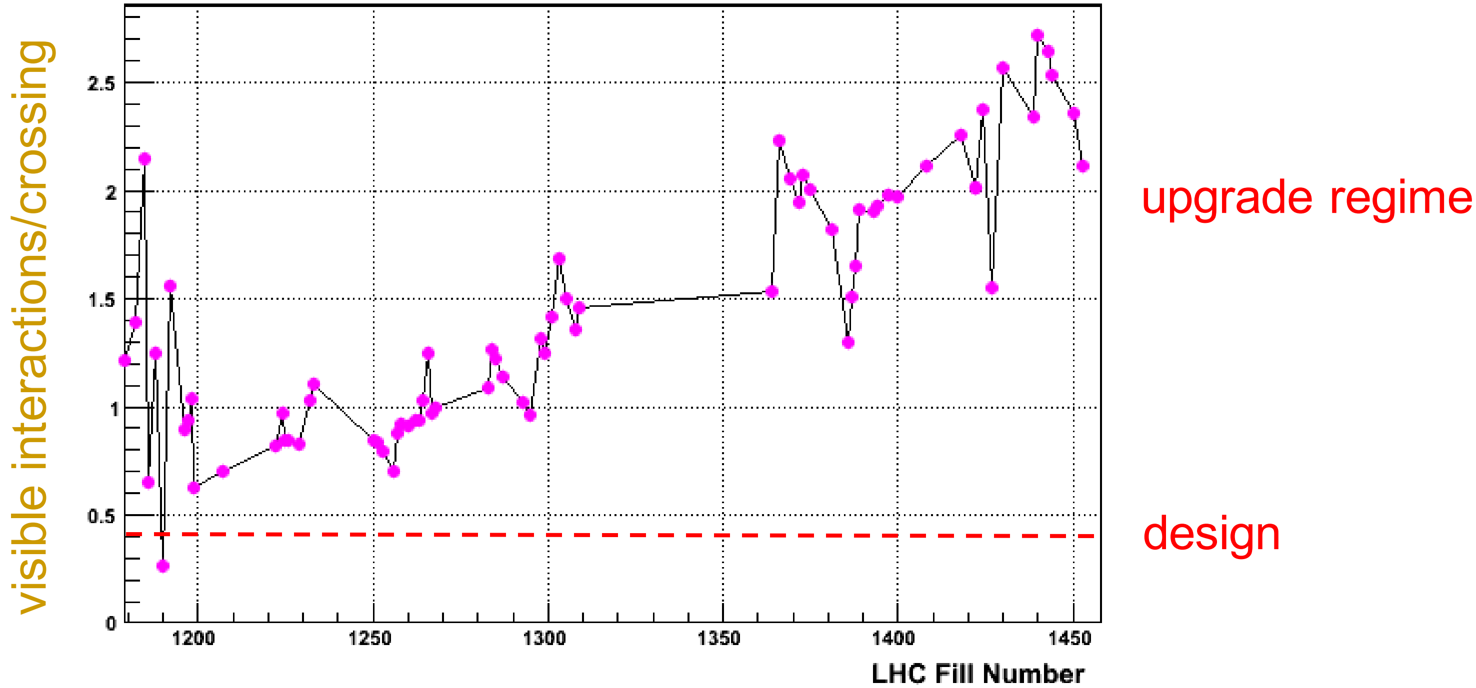


Design luminosity 2 x 10^{32} cm^{-2} s^{-1}. Almost there at end of run!

2010 running conditions

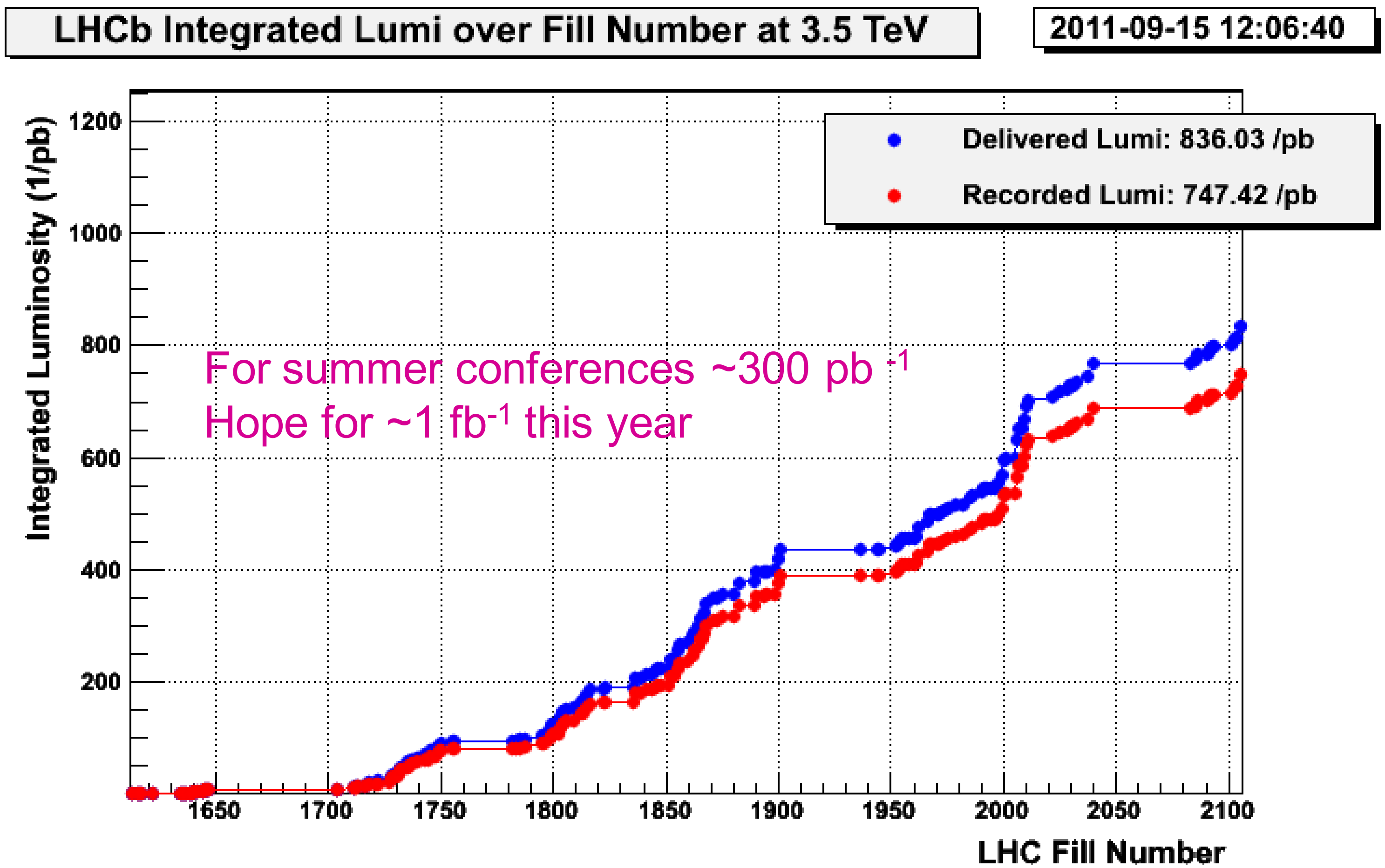
LHCb designed for luminosity of ~2 x 10^{32} cm^{-2} s^{-1} and ~0.4 interaction/crossing

In 2010 machine quickly went to (above) nominal in emittance and bunch charge, whilst still having only a few hundred bunches. It was therefore necessary to run at > 2 interactions/crossing in order to obtain acceptable luminosity.



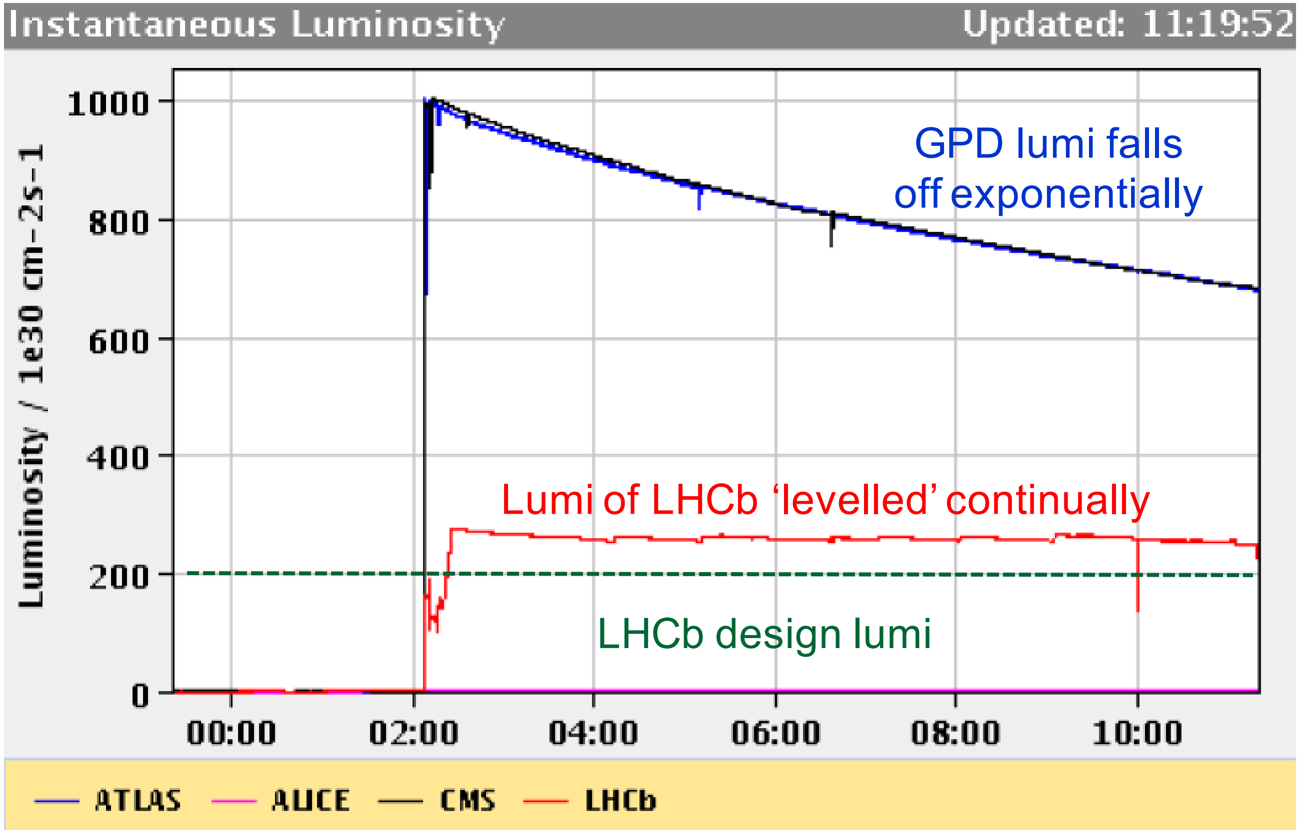
These are the conditions foreseen for upgrade – the experiment performed well!

2011 so far: the dream machine



LHCb running strategy in 2011

Fill from 24/5/11: 912 bunches, LHCb μ (=visible interactions/xing) set to ~1.6

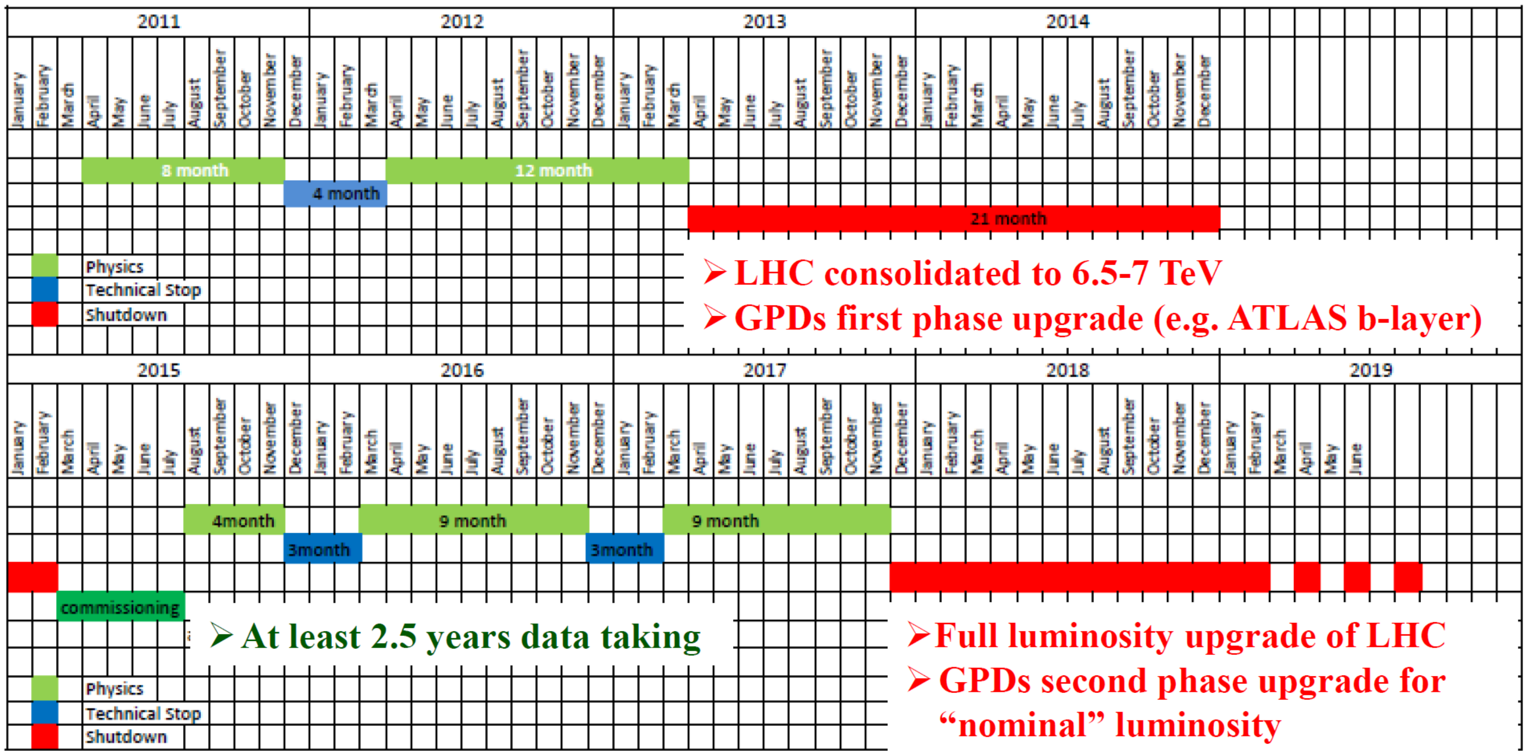


← upgrade regime

LHCb lumi can be raised with # bunches &/or chosen value of μ value
Max. value for safe detector operation is assumed to be ~4 x 10^{32} $cm^{-2}s^{-1}$

LHC planning

Disclaimer: this is not an official schedule, just a plausible scenario under discussion



- ➢ LHC consolidated to 6.5-7 TeV
- ➢ GPDs first phase upgrade (e.g. ATLAS b-layer)
- ➢ At least 2.5 years data taking
- ➢ Full luminosity upgrade of LHC
- ➢ GPDs second phase upgrade for "nominal" luminosity
- ➢ LHCb full upgrade to 40MHz R/O

4-5 years of data taking with natural window for upgrade in 2nd long shutdown

LHCb, now and in the future

Present experiment:

Collect ~5 fb^{-1} of data integrated over ~5 years at L ~ 3 x 10^{32} $cm^{-2}s^{-1}$ with detector performing as expected (even above nominal !). Then, rather than continuing to accumulate at the same rate, we will take a more rewarding path...

Essentials of upgraded LHCb:

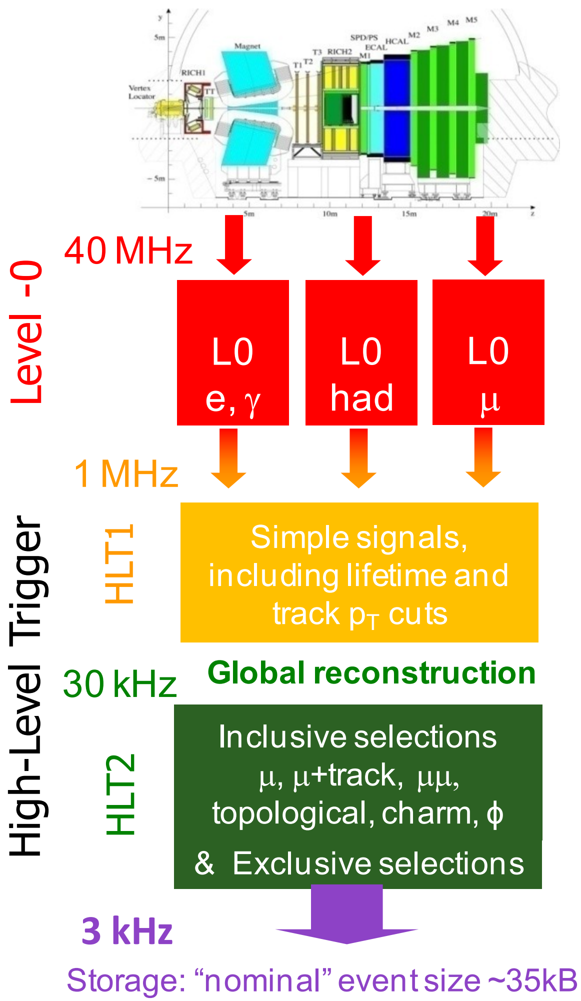
Raise luminosity to 10^{33} $cm^{-2}s^{-1}$:
Easy - LHC has already reached this performance!

Upgrade readout of all subdetectors + DAQ architecture to 40 MHz (driven by full-software trigger – see next slide)

New readout necessitates changes for some subdetectors (VELO, RICH photodetectors, TT/IT) – good opportunity to benefit from new technologies

Collect ~5 fb^{-1} / year, with more efficient and flexible trigger

LHCb trigger – strengths and limitations



Present strategy:

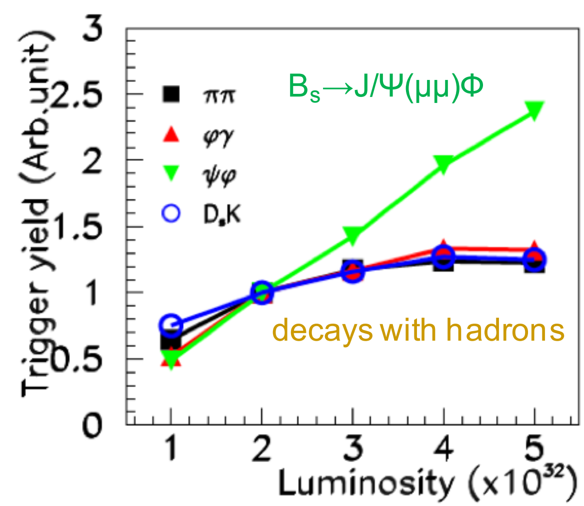
- hardware high p_T signal at earliest level – robust
- *inclusive** signature in HLT – very efficient

Performance even better than anticipated, but yield in hadronic channels does not scale with luminosity

Must raise p_T cuts to stay within 1 MHz readout limit

Decays to leptons - linear gain

Hadronic final states – yield flatlines...



Upgrade solution:

Readout at 40 MHz & use s/w trigger *throughout*

* 'inclusive' = ~ anything LHCb can reconstruct will be selected by trigger

Selected flavour physics goals: from 37 pb^{-1} to 5 fb^{-1} to 50 fb^{-1}

Here cover only the most obvious topics. Many other items already identified, and analysis targets will certainly evolve with time.

Today:

- $B^0_{s,d} \to \mu\mu$
- CPV in B^0_s mixing ("Φ_s")
- $B^0 \to K^*\mu\mu$
- B decays to charm – measurement of γ
- Charm physics

Selected flavour physics goals: from 37 pb^{-1} to 5 fb^{-1} to 50 fb^{-1}

Here cover only the most obvious topics. Many other items already identified, and analysis targets will certainly evolve with time.

Other topics:

- Charmless B-decays (incld. gluonic Penguins)
- Rare hadronic B-decays
- Flavour specific asymmetries
- Semileptonic decays
- Other CKM angles: α, β
- $b \to s\gamma^{(*)}$ exclusive
- $B \to D^*\tau\nu$
- LFV τ decays
- Sterile Majorana neutrinos

Searching for New Physics at LHCb

Search for (and then characterise) New Physics with two classes of measurement.

Exploration

Focus on decay modes or observables a priori very sensitive to New Physics, but which have not (really) been accessible to previous experiments

e.g.
- Search for $B_s \to \mu\mu$ down to SM value
- Search for mixing induced CPV in B_s system down to SM value
- Look for non-SM behaviour in A_{FB} of $B^0 \to K^*\mu\mu$

Precision studies

Measurement of known parameters with improved sensitivity, to allow for more precise comparisons with theory.

e.g.
- Measure CKM angle γ to 3-4^o to permit meaningful CKM tests
- Search for CPV in charm

Searching for New Physics at LHCb upgrade

Search for (and then characterise) New Physics with two classes of measurement.
New exploration topics appear, and existing studies migrate to precision studies

Exploration

Focus on decay modes or observables a priori very sensitive to New Physics, but which have not (really) been accessible to previous experiments

e.g.
- Search for $B^0 \rightarrow \mu\mu$
- Study new kinematical observables in $B^0 \rightarrow K^*\mu\mu$, e.g. $A_T^{(2)}$
- High sensitivity CPV studies with gluonic Penguins, e.g. $B_s \rightarrow \Phi\Phi$

Precision studies

Measurement of known parameters with improved sensitivity, to allow for more precise comparisons with theory.

e.g.
- Measure BR($B_s \rightarrow \mu\mu$) to precision of ~10% (assuming SM value)
- Measure Φ_s to <20% of SM value
- Measure γ to <1^o to match anticipated theory progress
- Charm CPV search below 10^{-4}

The golden mode: $B_s \to \mu\mu$

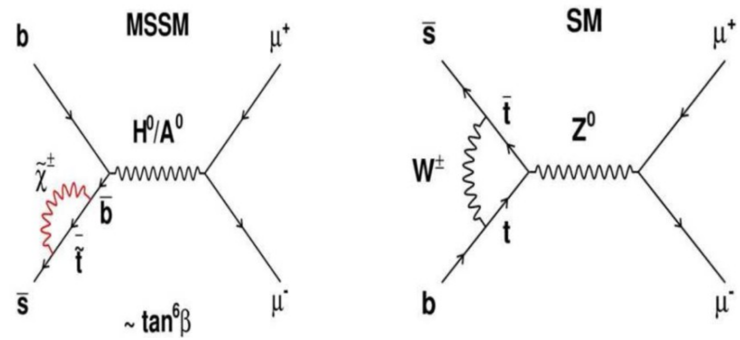
B physics rare decay par excellence:

$BR(B_s \to \mu\mu)_{SM} = (3.35 \pm 0.32) \times 10^{-9}$

(Blanke et al., JHEP 0610:003,2006)

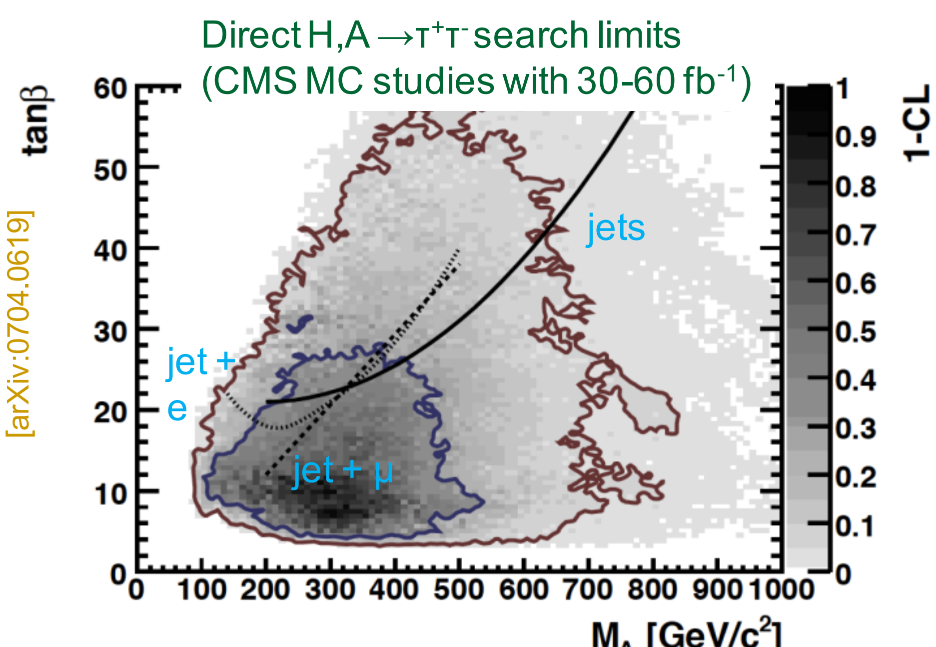
Precise prediction (which will improve) !

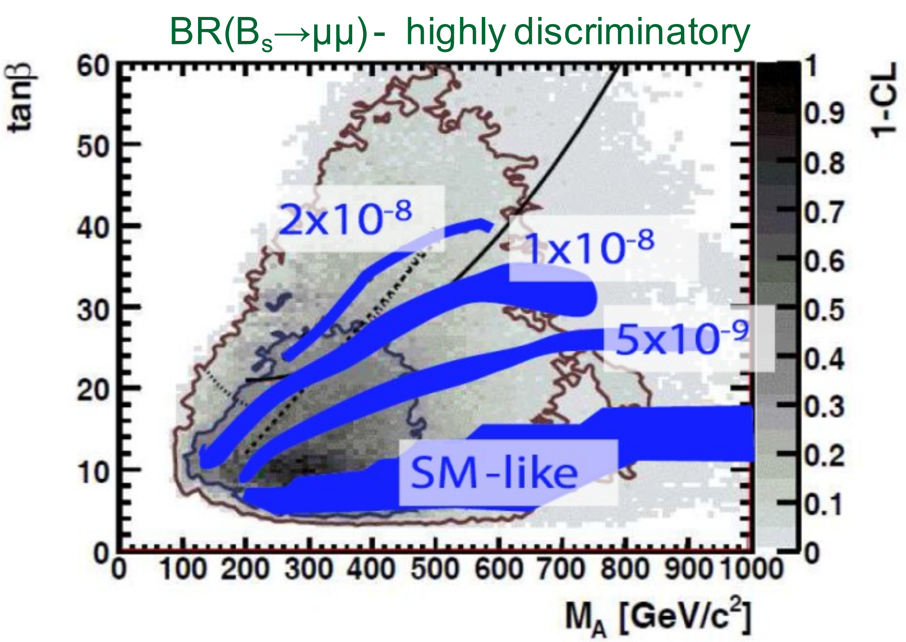
Very high sensitivity to NP, eg. MSSM:



$$Br^{MSSM}(Bq \to l^+l^-) \propto \frac{m_b^2 m_l^2 \tan^6\beta}{M_{A0}^4}$$

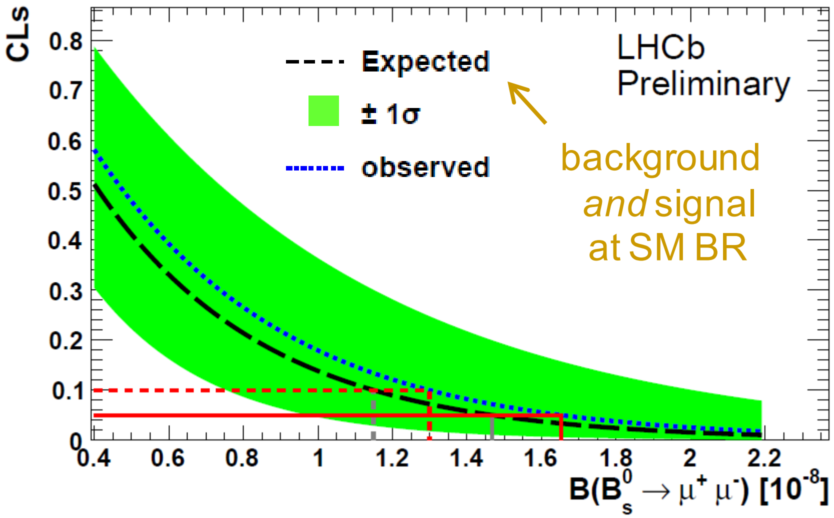
One example [O. Buchmuller et al, arXiv:0907.5568] : NUHM (= generalised version of CMSSM)

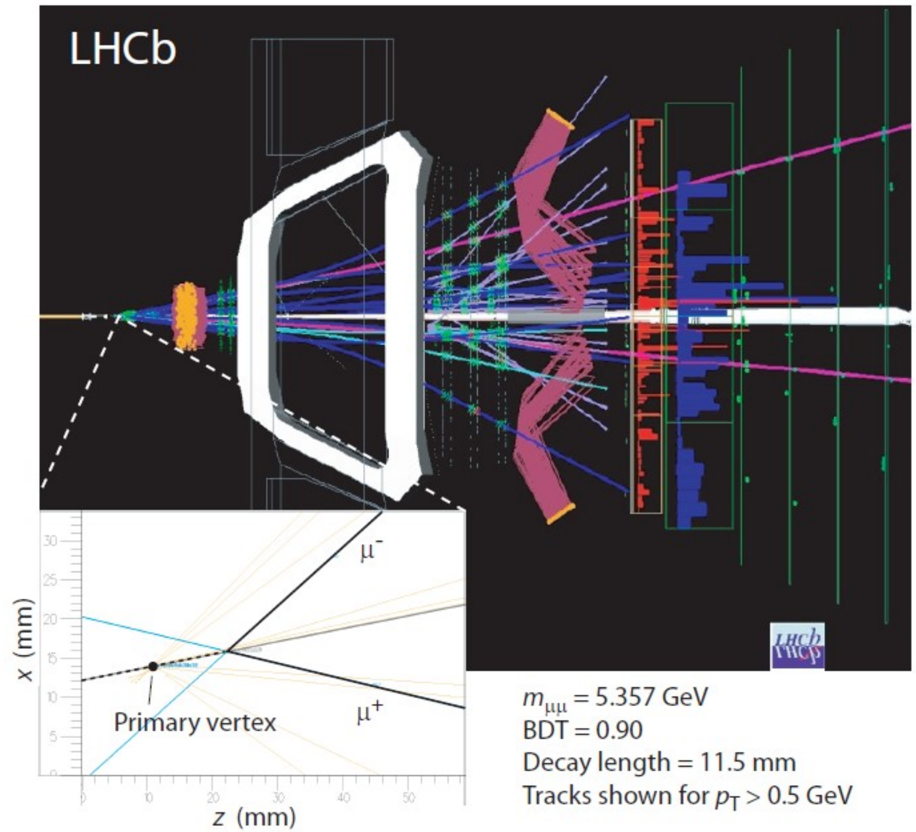




$B_s \to \mu\mu$ at LHCb with 300 (+37) pb^{-1}

No excess seen... but plausible candidates now being observed





LHCb-CONF-2011-037

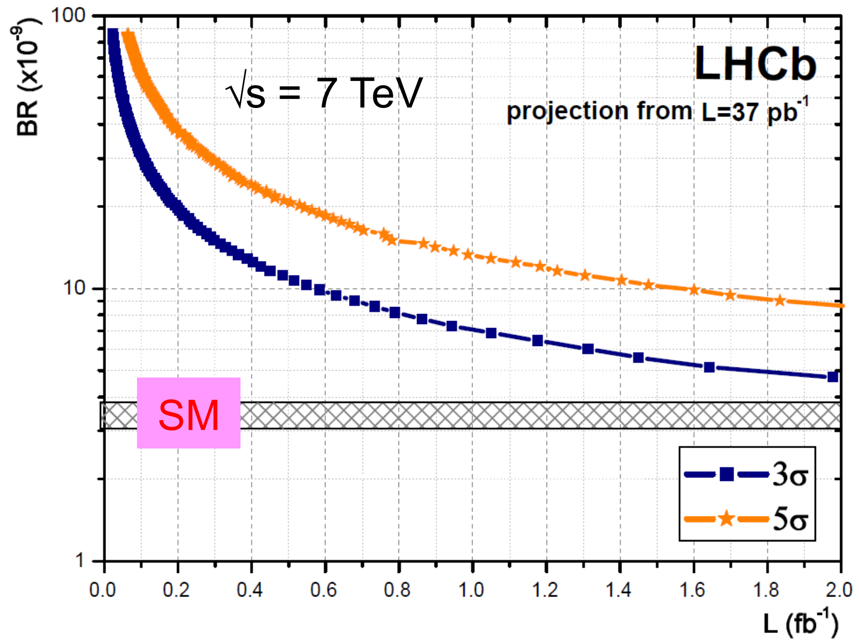
Observed limit at 95% (90%) C.L.
(including 37 pb^{-1} from with 2010):

1.5 (1.2) x 10^{-8}

Around ~5x SM BR, and closing fast...

$B_{s,d} \to \mu\mu$ at upgrade

2011-12 discovery prospects



Current LHCb will reveal NP if large-ish...

...but bigger sample required to look for more subtle effects, and indeed to be certain of reaching SM sensitivity.

Present experience indicates that bckgd and systematics will be manageable e.g. f_s/f_d – *already* measured at LHCb ~ well as at LEP & better than Tevatron

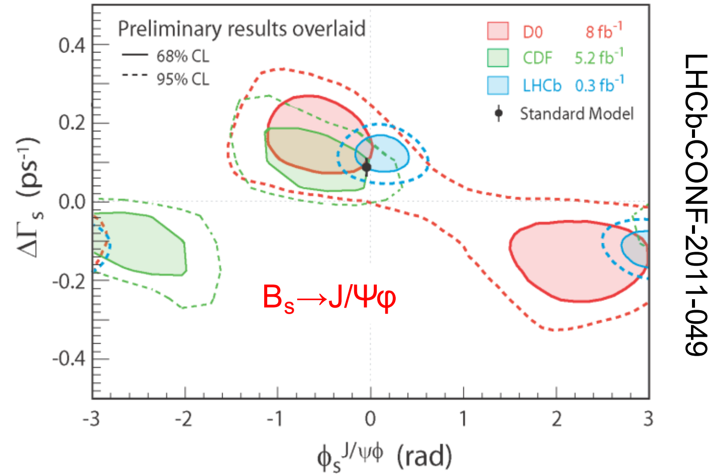
If at SM value, and present analysis, we will measure BR with ~8% precision with 50 fb^{-1}. Very important consequences for flavour structure of NP, & invaluable constraint on SUSY parameter space, whether or not SUSY discovered at GPDs.

Another goal of upgraded LHCb: possibility to measure $B_d \to \mu\mu$ and get first information on ratio of $B_d \to \mu\mu / B_s \to \mu\mu$, which is critical checkpoint for MFV

Φ_s with >> 5 fb^{-1}

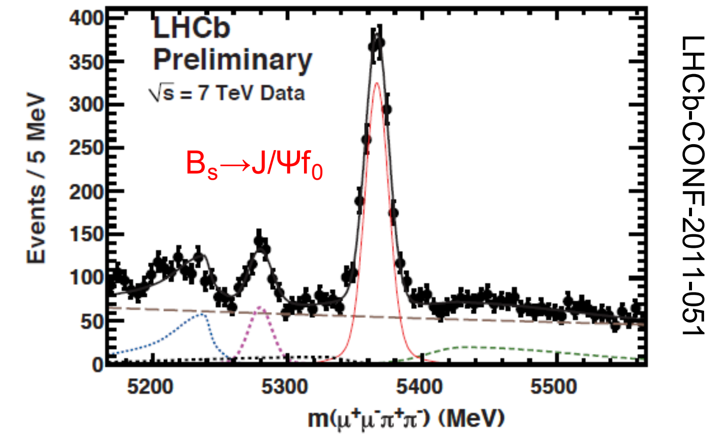
LHCb combination for Lepton-Photon [LHCb-CONF-2011-056]:

$$\phi_s = 0.03 \pm 0.16\,(\text{stat}) \pm 0.07\,(\text{sys})\ \text{rad}$$



High hopes of finding non-SM CPV in $B_s \to J/\Psi\Phi$, but know already effect will not be very large. Precision measurement will be needed to distinguish it from SM & characterise its nature.

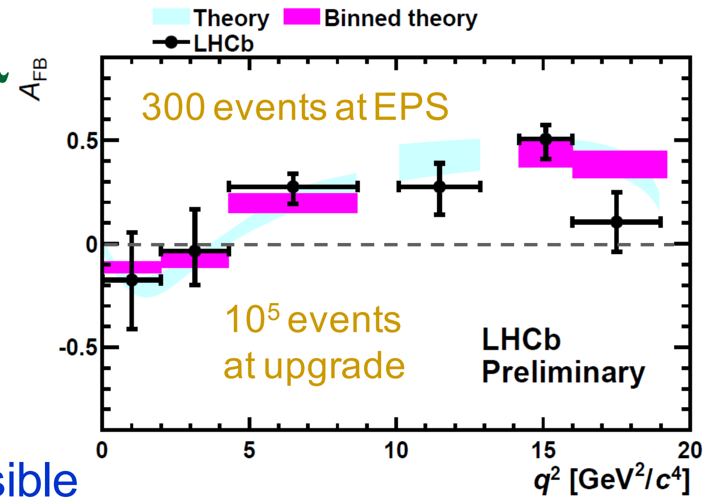
→ With a few fb^{-1} measurement uncertainty similar in size to SM value – much more data are needed !



Associated benefits and related issues with 50 fb^{-1}

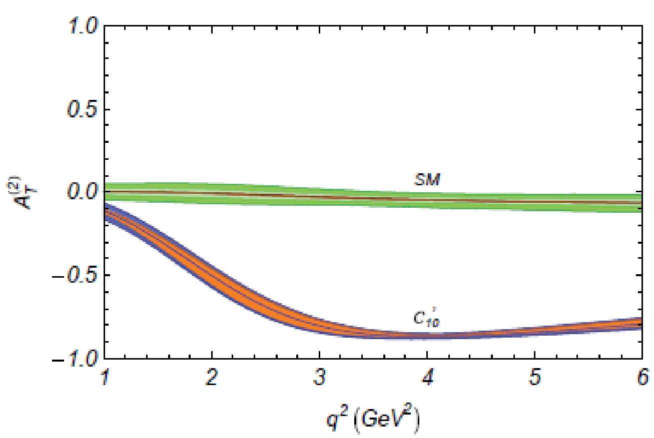
- Make precise and experimentally more robust measurements with CP-eigenstate modes e.g. $D_s^+D_s^-$ and $J/\Psi f_0$.
- Combat Penguin uncertainties in SM prediction:
  - Bound from data with $B_s \to J/\Psi K^{(*)0}$ decays
  - Use Penguin free channel $B_s \to D^0\Phi$ (s/w trigger will help!)

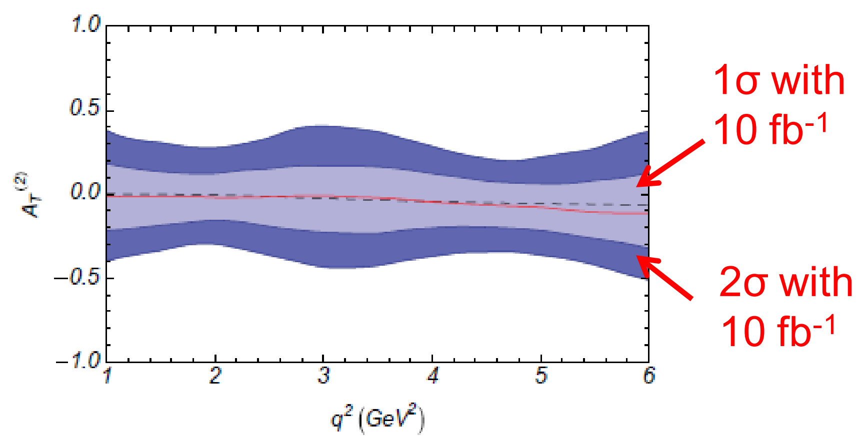
Opportunities with $B^0 \to K^* \mu\mu$



Angular distributions sensitive to helicity structure of NP. Principal task for current LHCb is to map out A_{FB} curve, & in particular determine 'crossing point'. (B-factories/CDF statistics inadequate)

But several other asymmetries will only be accessible at upgrade, e.g. transversity asymmetry, $A_T^{(2)}$ – highly sensitive to RH currents



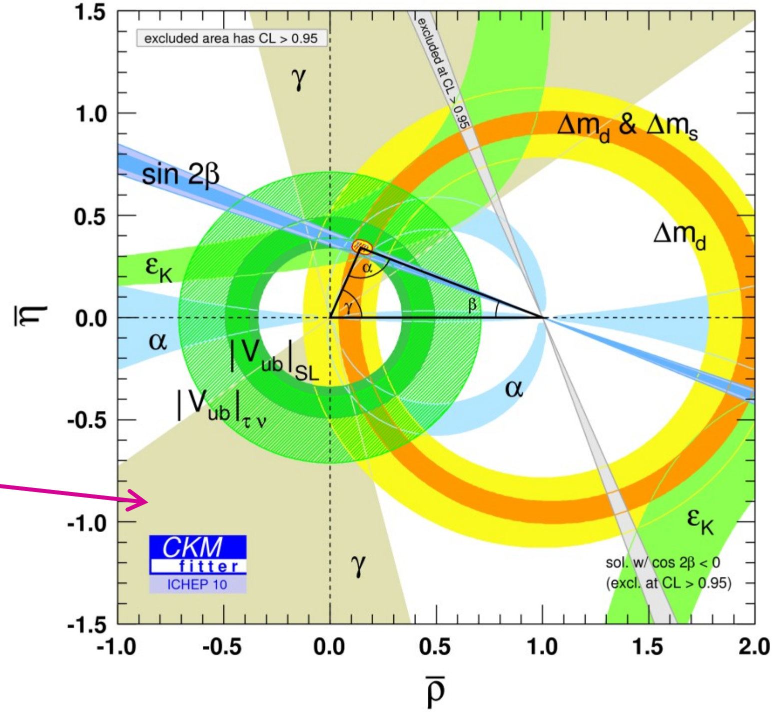


Other modes also become available: $B^0 \to K_2^{*0}\mu\mu$, $B_s \to \Phi\mu\mu$, $B_s \to K^*\mu\mu$, $\Lambda_b \to \Lambda^{(*)}\mu\mu$ (and ~5000 $B^0 \to K^* e^+ e^-$ events, neglecting trigger improvements)

Precision CKM-metrology: the next challenge

B-factories (& others) have done a great job in mapping out unitarity triangle.

But progress demands improved knowledge of angle γ (a.k.a. φ_3)



LHCb goal in short term:

Measure γ to a few degrees (~3o?) – more than sufficient to match precision of indirect prediction coming from other constraints

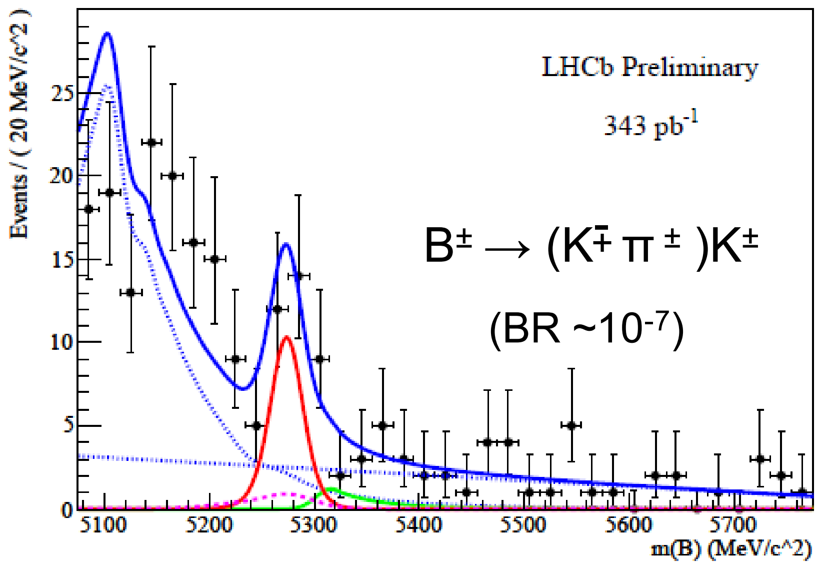
Goal for upgrade:

Exploit increased luminosity and improved trigger efficiency to aim for sub-degree precision – necessary to match anticipated improvements in prediction from, e.g. lattice QCD

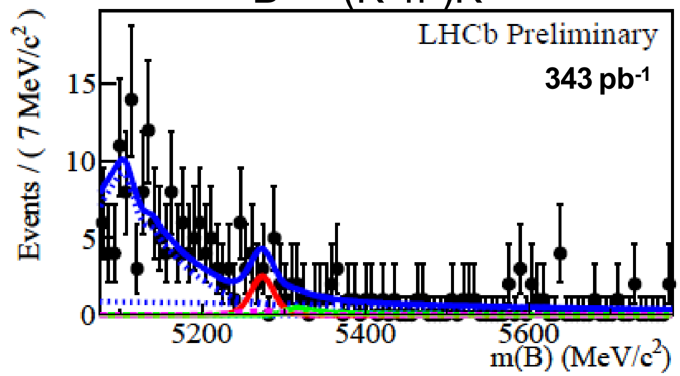
The road to γ: evidence for suppressed ADS mode

Signal seen with 4.0σ significance, & hint of asymmetry, consistent with previous results

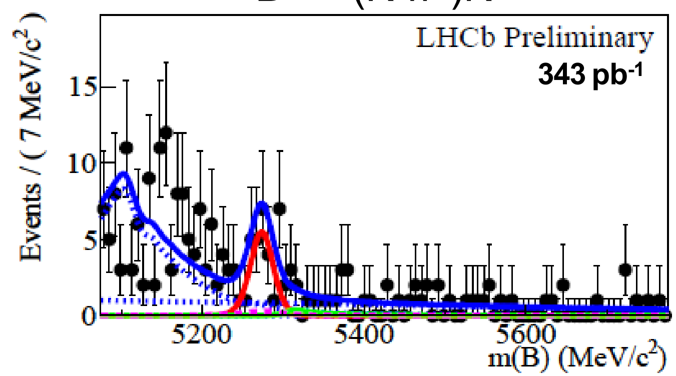
LHCb-CONF-2011-044



$B^- \to (K^+\pi^-)K^-$



$B^+ \to (K^-\pi^+)K^+$



Ratio to favoured mode:

$$\boxed{R_{ADS}^{DK} \quad = \quad (1.66 \pm 0.39 \pm 0.24) \times 10^{-2}}$$

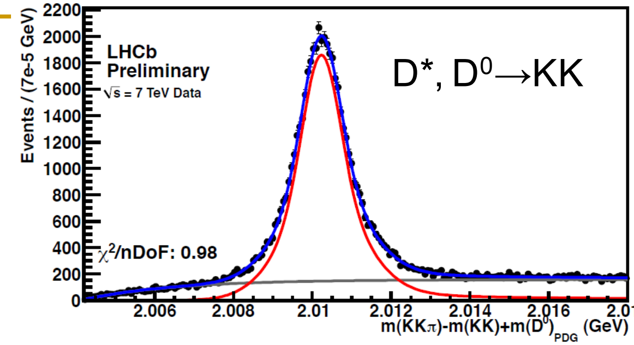
World Average (without LHCb) $(1.6 \pm 0.3) \times 10^{-2}$

Asymmetry:

$$\boxed{A_{ADS}^{DK} \quad = \quad -0.39 \pm 0.17 \pm 0.02}$$

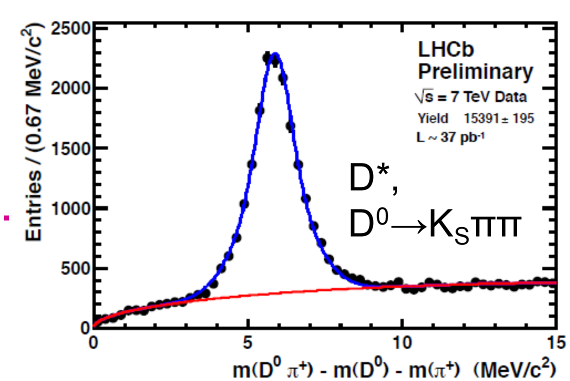
World Average (without LHCb) -0.58 ± 0.21

Charm: now & future



LHCb 2010 yields in low multiplicity D decays already comparable to B-factories (x-sec ~ 6 mb* !)

e.g. 1.2 x 10^5 D*, $D^0 \to KK$ with 37 pb^{-1}
c.f. 1.1 x10^5 with 540 fb^{-1} [Belle, PRL 98 (211803) 2007]

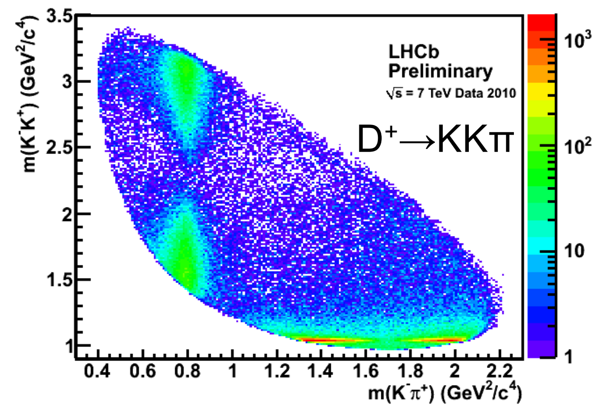


Already in 2011 have 20x this number! HLT selection now in place for $K^0_S\pi\pi$ to ensure high yields here also.

First 2010 data measurement - difference in time integrated CP asymmetry in $D^0 \to KK$ & $D^0 \to \pi\pi$

$$\Delta A_{CP} = (-0.28 \pm 0.70 \pm 0.25)\%^{+}$$

(NB syst.error is itself statistical in nature)



Also available: y_{CP}, A_Γ and $D \to KK\pi$ CPV search

LHCb strategy: rare decay searches and CPV studies with 2,3,4 body final states targeting experimentally robust measurements

Upgrade particularly beneficial for high multiplicity charm due to full s/w trigger !

* pp at $\sqrt{s}$= 7 TeV: LHCb-CONF-2010-013
+ LHCb-CONF-2011-023

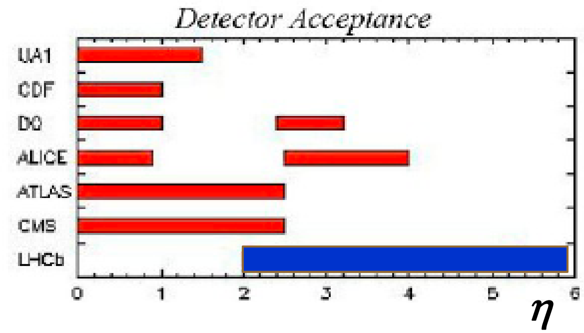
Beyond flavour

Many possibilities – only one example shown here, but suitable topics encompass any LHC phenomena which have forward specific features &/or benefit from precise vertexing / good PID / flexible trigger

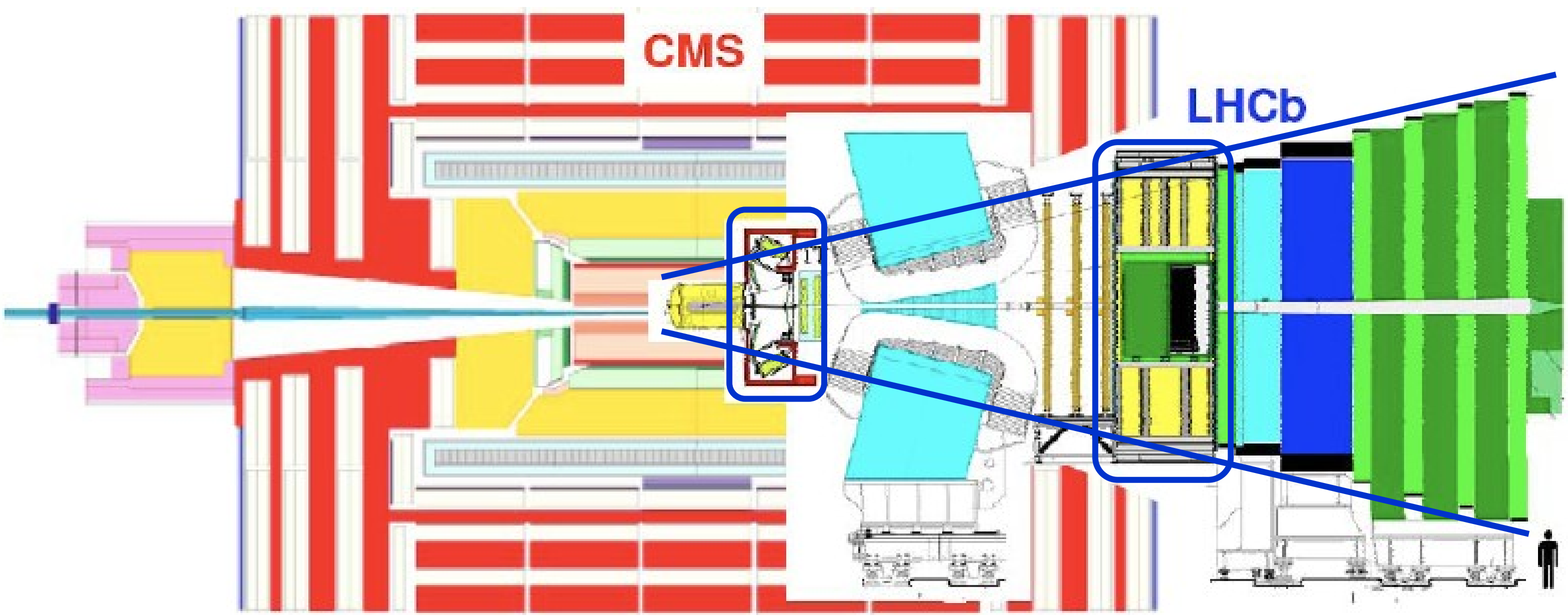
- EW physics

[Other topics include: onia, QCD (e.g. central exclusive production), forward top physics, search for long lived new particles...]

A GPD in the forward direction



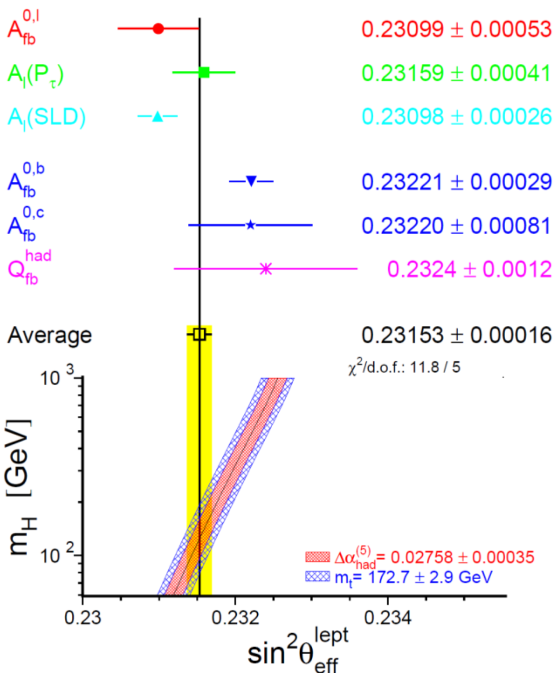
LHCb is as well instrumented as ATLAS and CMS (+ has excellent hadron PID)



but covers a unique pseudorapidity and also has acceptance down to $p_T \sim 0$

$\sin^2\theta_{eff}^{lept}$ and A_{FB}

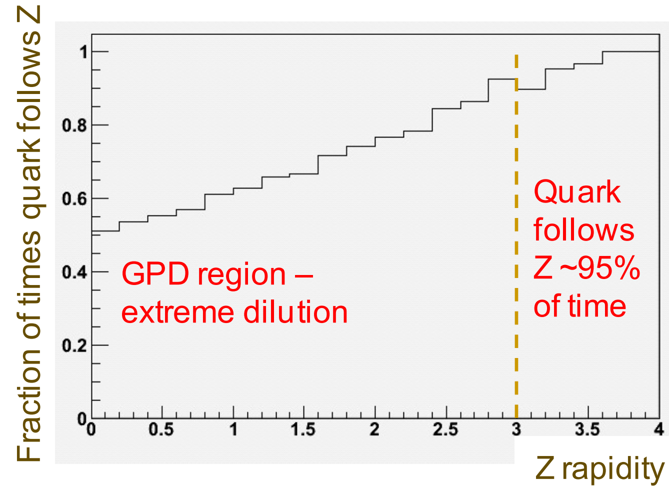
Weak mixing angle a fundamental parameter of EW theory, but no significant progress since LEP/SLD



Note also infamous internal tension between various measurements...

Measure A_{FB} at LHC as was done at LEP, but now initial state is q-qbar...

...need to assign direction to axis – this much easier at LHCb than in GPDs due to dominant valence-sea collisions



(also reduced contribution at LHCb from poorly known s-sbar & c-cbar collisions)

with 50 fb^{-1} can measure $\sin^2\Theta_{eff}$ with stat precision ~2x better than LEP/SLD

Status of approval

LoI on upgrade submitted in March

Positive feedback from LHCC
'..arguments for flavour physics with 50 fb^{-1} very compelling.'

Approved at LHCC June meeting
→ green light to 2 year R&D period + TDR

Summary – looking beyond

Current LHCb experiment collects ~1 fb^{-1}/ yr and will accumulate ~5 fb^{-1} by 2017.
Compelling case to extend flavour programme to ~50 fb^{-1}

- enormous samples of exclusive b- & c-decays, particularly in the B_s sector
- take initial LHCb studies to higher order of precision, and open new frontiers

Unique acceptance of LHCb, & detector capabilities, opens up possibilities in topics beyond flavour, which adds extra dimension to long-term LHC physics programme

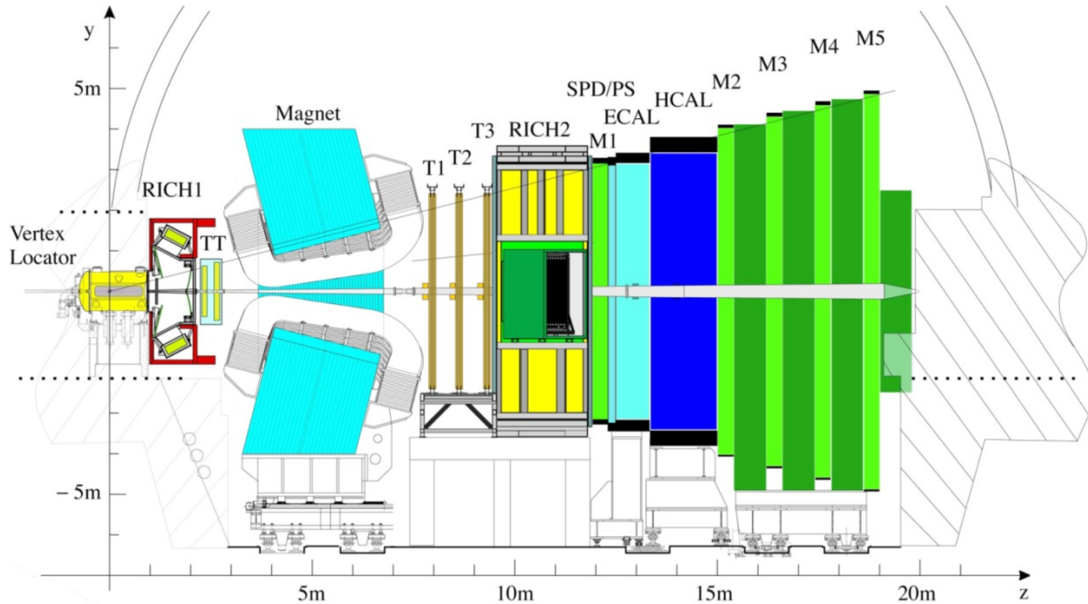
What then is needed?

- Nothing new from the machine !
- Detector which can run at ~10^{33} $cm^{-2}s^{-1}$
- Changing to 40 MHz readout and flexible full software trigger (→ higher efficiency in many modes)

LHCC approval granted in June. Aim to install in 2^{nd} long shutdown (~2018)

Backups

LHCb: differences w.r.t. ATLAS & CMS

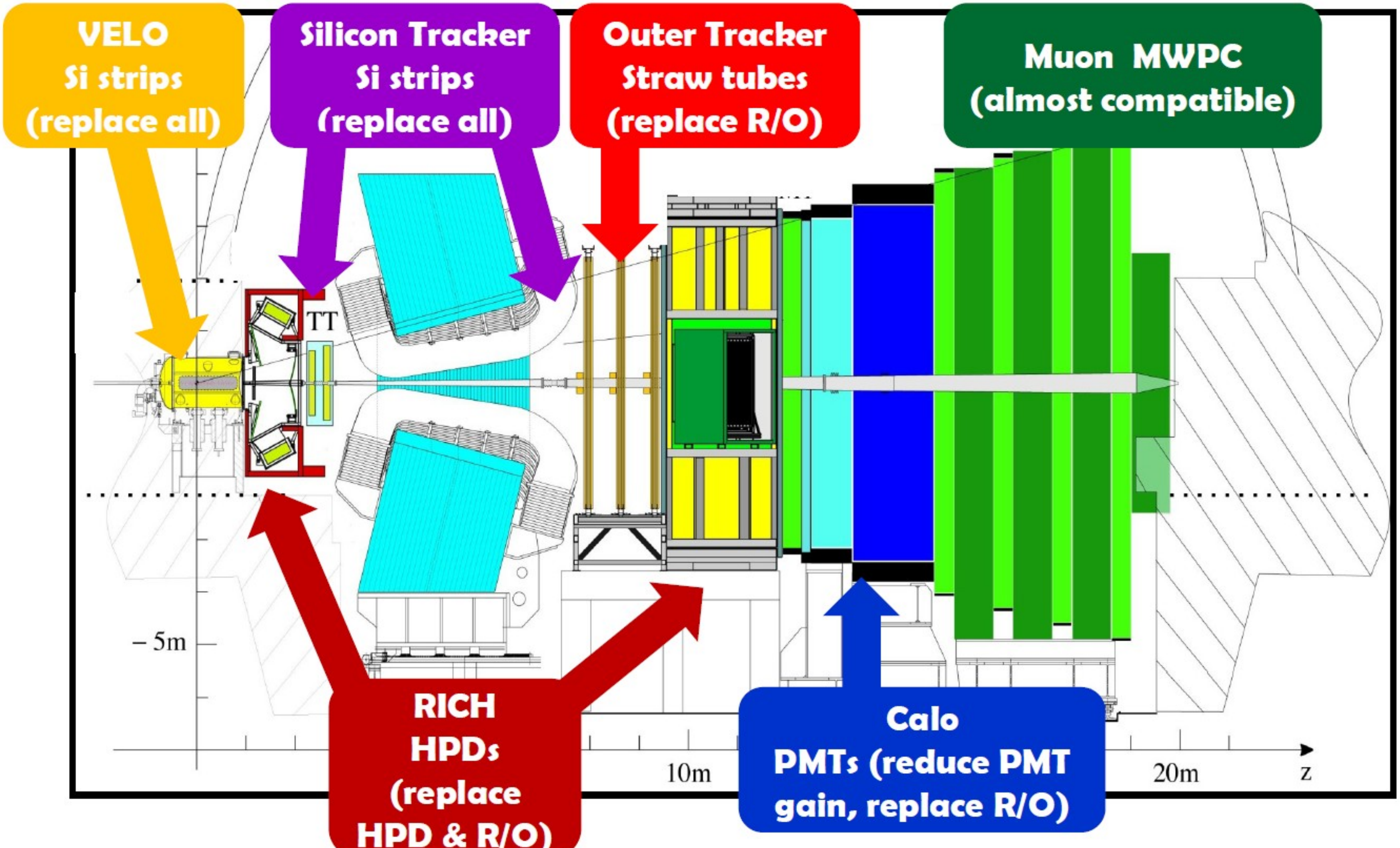


Optimised for flavour physics:

- forward acceptance ($2 < \eta < 5$)
- high bandwidth trigger (3 kHz output)
- acceptance down to low p_T
- precise vertexing (VELO)
- hadron identification (RICHes)

Unique acceptance and high quality instrumentation opens up possibilities in other physics areas!

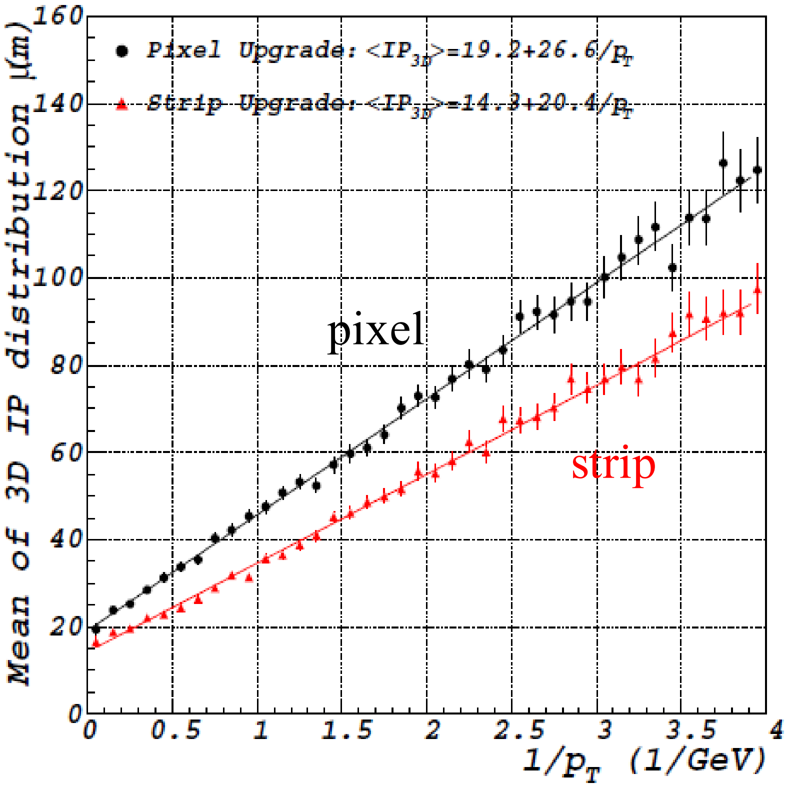
Upgrade of LHCb subsystems



VELO Upgrade

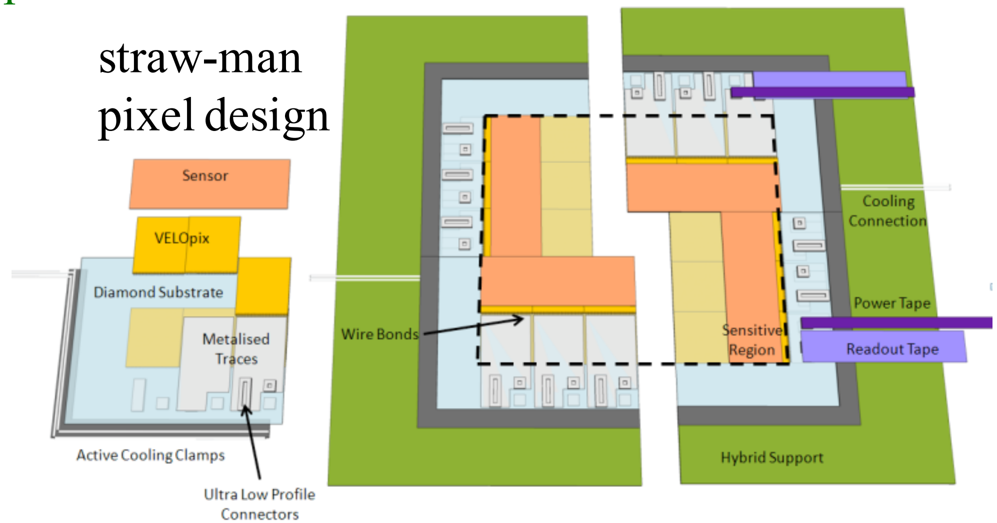
Two options:

- **pixel detector**: VELOPIX based on Timepix chip with 55 µm x 55 µm pixel size advantageous for pattern recognition
- **strip detector**: based on proven design, but with reduced strip pitch and increased number of strips



IP resolution vs $1/P_T$

straw-man pixel design



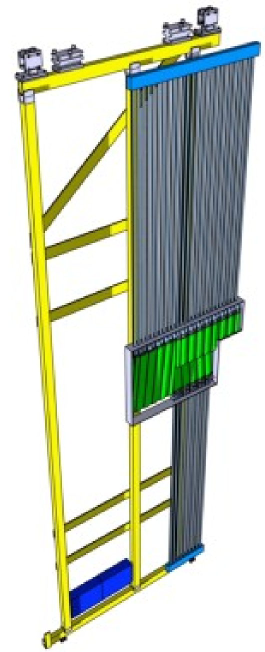
R&D program :

- module structure (X_0)
- sensor options: Planar Si, Diamond, 3D
- CO_2 cooling
- electronics
- RF-foil of vacuum box

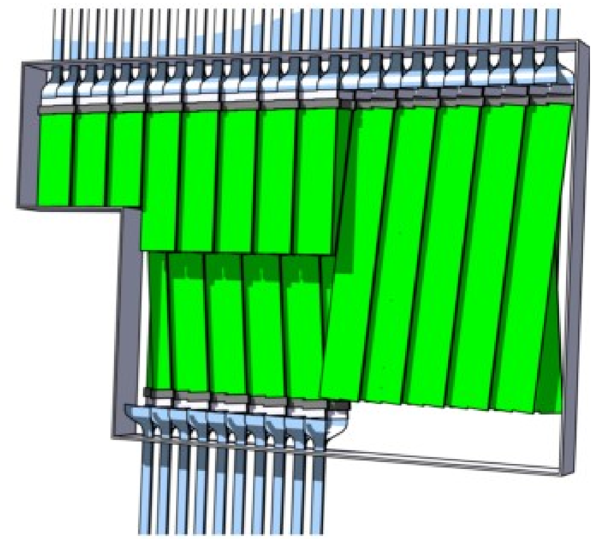
Main Tracker upgrade: OT, IT, TT

IT and TT detectors must be replaced:
(1 MHz electronics integrated)

Two options:
- Silicon strips (current technology, but R/O outside acceptance?)
- 250 µm Scintillating Fiber Tracker (new technology)

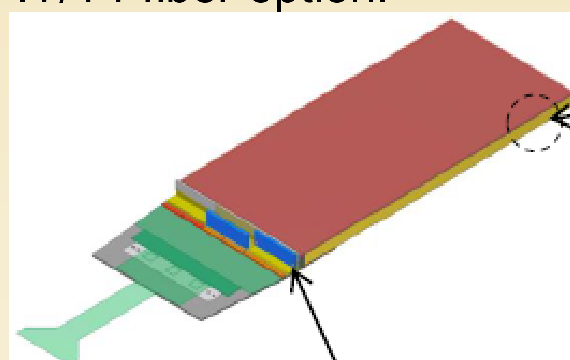


IT-fiber detector layout:

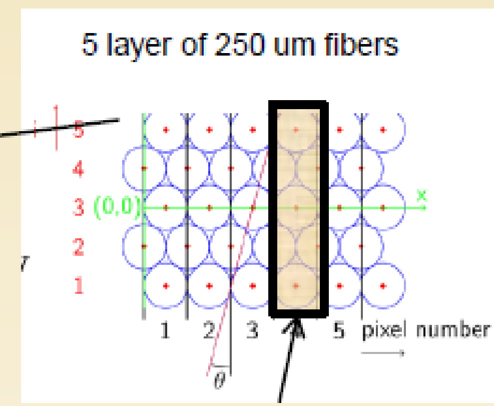


R&D started:
- 250µm scint. fibres (8 layers)
- fibres coupled to SiPM
- SiPM radiation tolerance?
- ASIC investigation started

IT/TT fiber option:



SiPM array



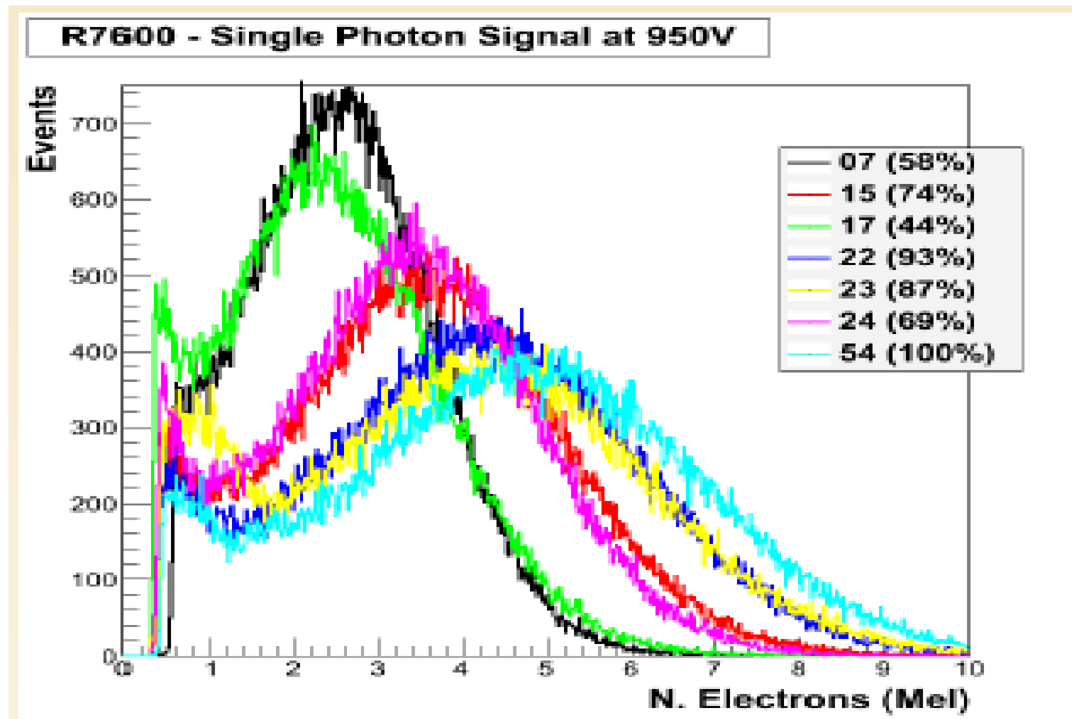
SiPM cell coverage

PID upgrade: RICH detectors

RICH-1 and RICH-2 detectors remain:

- baseline option: replace pixel HPDs by MaPMTs & readout out by 40 MHz ASIC
- alternative: new HPD with external readout

MaPMT (baseline) option



Prototyping using MAROC3:

- Gain compensation
- Binary output

Digital functions in ACTEL

PID upgrade: TORCH

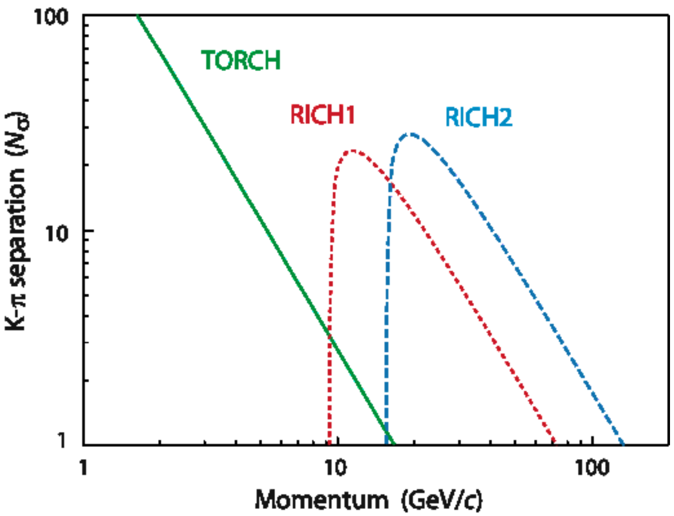
Low momentum tracks:

replace Aerogel by Time-of-Flight detector "TORCH"

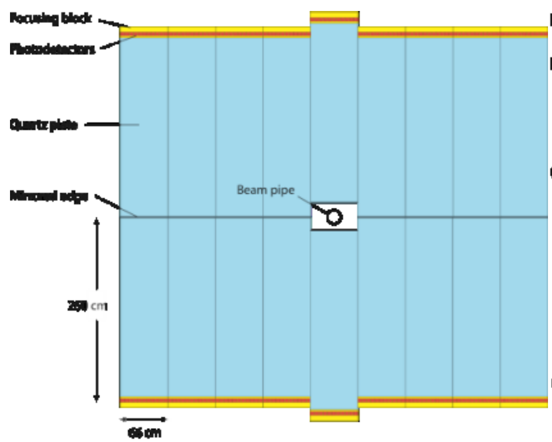
(TORCH=Time Of internally Reflected Cherencov light)

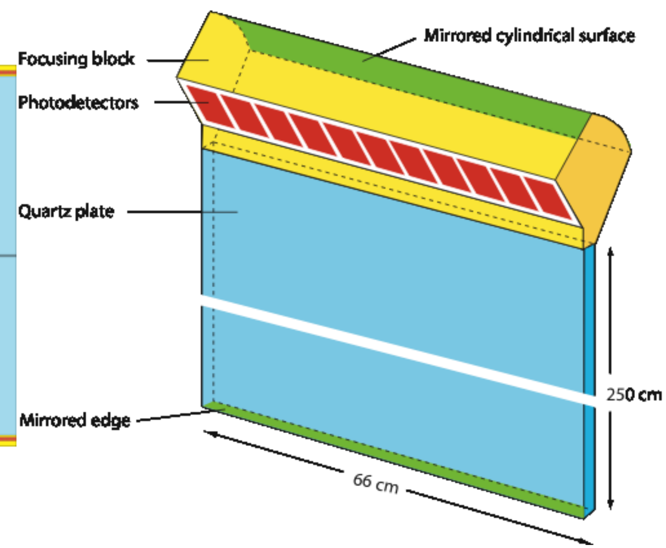
- 1 cm thick quartz plate combining technology of time-of-flight and DIRC
- measure ToF of tracks with 10-15 ps (~70 ps per photon).

K-π separation vs p in upgrade:



TORCH detector:





→ could be installed later than 2018!

Physics strategy – illustrative examples

	Exploration	Precision studies
Current LHCb	Search for $B_s \to \mu^+\mu^-$ down to SM value Search for mixing induced CP violation in B_s system ($2\beta_s$) down to SM value Look for non-SM behaviour in forward-backward asymmetry of $B^0 \to K^*\mu^+\mu^-$ Look for evidence of non-SM photon polarisation in exclusive $b \to s\gamma^{(*)}$	Measure unitarity triangle angle γ to $\sim 4°$ to permit meaningful CKM tests Search for CPV in charm
Upgraded LHCb	Search for $B^0 \to \mu^+\mu^-$ Study other kinematical observables in $B^0 \to K^*\mu^+\mu^-$, e.g. $A_T(2)$ CPV studies with gluonic penguins e.g. $B_s \to \phi\phi$ Measure CP violation in B_s mixing (A^s_{fs})	Measure $\mathcal{B}(B_s \to \mu^+\mu^-)$ to a precision of $\sim 10\%$ of SM value Measure $2\beta_s$ to precision $< 20\%$ of SM value Measure γ to $< 1°$ to match anticipated theory improvements Charm CPV search below 10^{-4} Measure photon polarisation in exclusive $b \to s\gamma^{(*)}$ to the % level

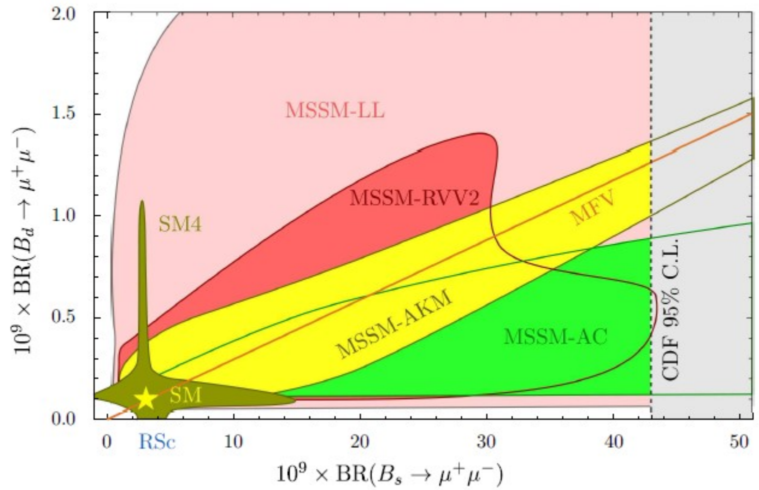
Impact on New Physics Models

LHCb upgrade will provide measurements essential to understand physics landscape that the coming decade will unveil. Lets consider two popular ideas.

Minimal Flavour Violation (MFV) hypothesis

All sources of flavour- and CP-violation in quarks will be same as SM. In this case searches for NP will be fruitless in CPV, but not in rare decays

e.g. In MFV $BR(B_s \to \mu\mu)$ *can* differ from SM but *not* $BR(B_d \to \mu\mu)/BR(B_s \to \mu\mu)$



SM with 4-families (SM4)

Add 2 new quarks (t', b') plus 5 new quark-mixing parameters

New CPV possibilities that could show up in D^0, B^0 and B_s system

Both proposals can be disproved / strongly constrained with improved flavour data