The LHCb Upgrade

- Introduction/Overview
- LHCb & Upgrade physics programme
- Trigger/DAQ Upgrade
- Detector Upgrade
- R&D Plan
- Conclusions

Franz Muheim
University of Edinburgh
On behalf of the LHCb collaboration

LHCC meeting CERN 22/23 Sept 2008

Introduction/Overview

- Expression of Interest for an LHCb Upgrade
  - Submitted to LHCC on 22nd April 2008
    document CERN/LHCC/2008-007
- Why is upgrade required?
  - Physics rationale
- How can experiment be improved?
  - Identify issues of running at higher luminosity
  - 40 MHz is the only way forward
- Strategy for upgrade plan
  - How to implement 40 MHz readout
  - Consistency with LHC Schedule

Status of LHC Physics in ~2013

- LHCb
  - will be producing lots of excellent physics results
  - may or may not observe New Physics beyond Standard Model
  - Flavour physics will constrain New Physics models
- ATLAS/CMS
  - will discover Standard Model Higgs (if it exists)
  - may or may not observe New Physics beyond Standard Model
- Branch point
  - Discovery or not of NP at TeV scale
- New Physics beyond the Standard Model
  - will contribute to flavour observables

⇒ Better flavour physics sensitivity will be required to measure/probe New Physics flavour structure

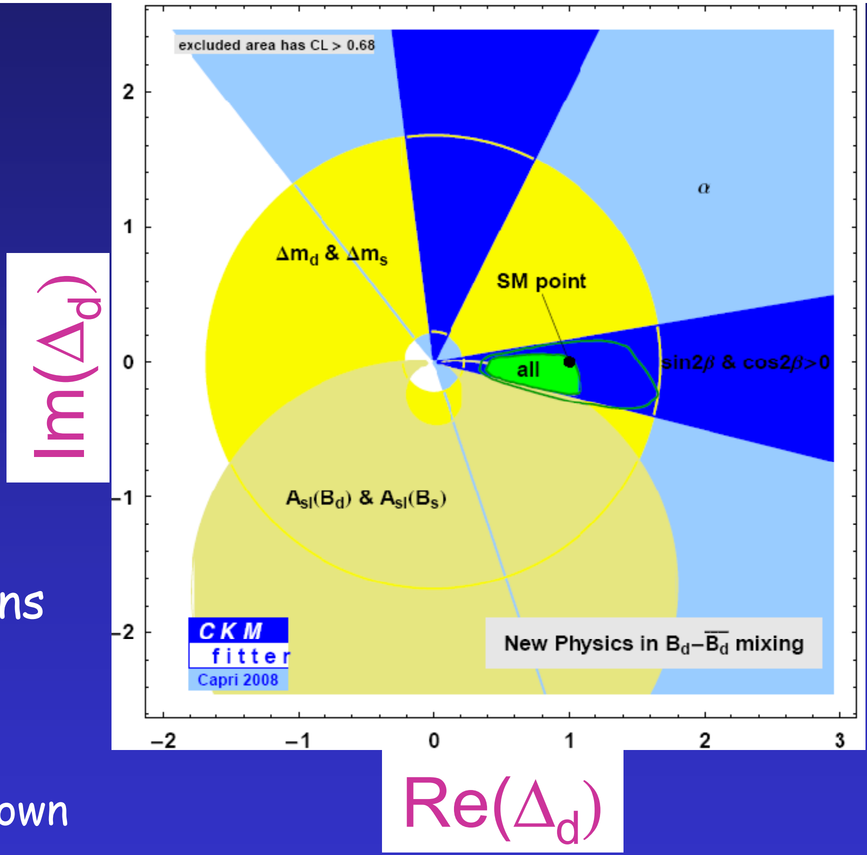
Limits on New Physics from B^0

- Is there NP in B^0-$\bar{B}^0$ mixing?
  - Assume NP in tree decays is negligible

$$\mathrm{Re}(\Delta_q)+i\mathrm{Im}(\Delta_q)=\frac{\langle B^0|H^{full}|\bar{B}^0\rangle}{\langle B^0|H^{SM}|\bar{B}^0\rangle}$$

- Existing Measurements
  - Vub, Vcb, angles α, β, γ, Δm_d ...
- All quantities expressed as functions of CKM parameters η & ρ
- Fit to η, ρ, $\mathrm{Re}(\Delta_d)$, $\mathrm{Im}(\Delta_d)$
  - Caveat: only 68% CL regions are shown due to large errors

"Next to minimum flavor violation"

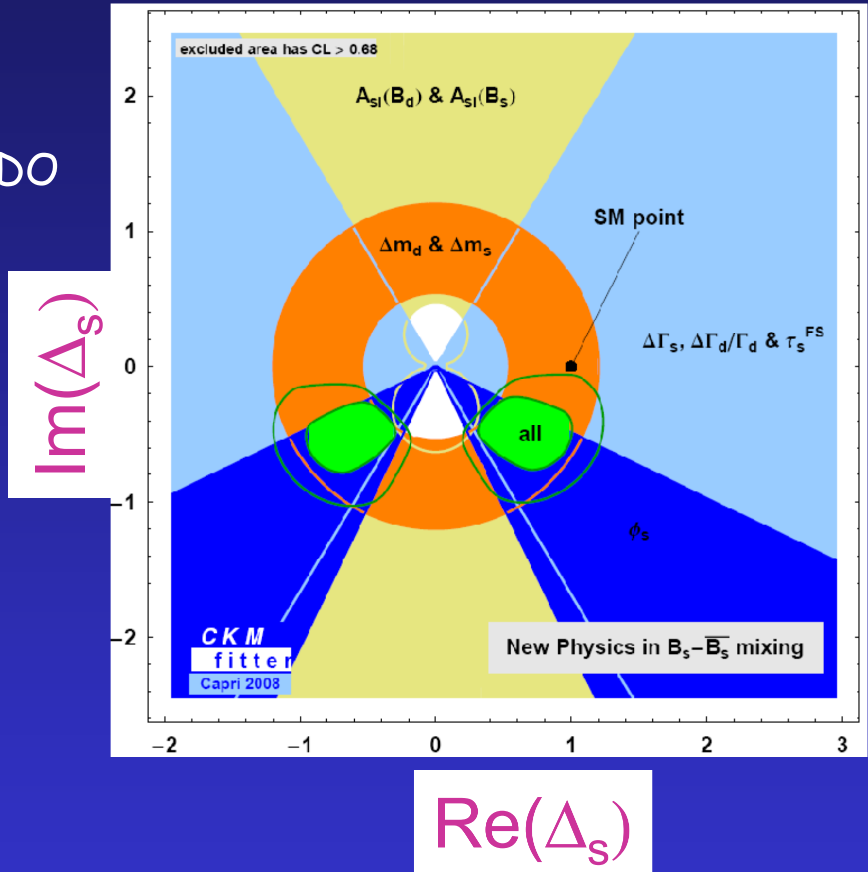


From Jérôme Charles, Capri, June 2008

- Large Range of NP still allowed

Limits on New Physics from B_s

- Similar study for B_s decays
  - including ΔM_s and ϕ_s measurements from CDF and DO
- Limits much weaker
  - phase in B_s mixing ϕ_s is not well measured yet
  - Caveat: only 68% CL regions are shown due to large errors
- Latest results on ϕ_s
  - Large central values
  - SM prediction close to zero
  - SM CL is at 7%



▪New Physics could be around the corner!

LHCb Physics Prospects

- **LHCb – first five years**
  - Accumulate 10 fb^{-1} data sample
- **Sensitivities**
  - Weak mixing phase ϕ_s in $B_s \to J/\psi\phi$
    If $\phi_s \gg 0 \to$ NP discovery
  - NP search in rare decays
    $B_s \to \mu^+\mu^-$ down to SM level
  - $B_s \to \phi\phi$ probe NP in hadronic penguins
  - Precision measurements of
    CKM angles $\sin 2\beta$, γ and α
  - Significant improvement for angle γ

Sensitivities for integrated lumi of 2 fb^{-1}

	Decay	Precision
γ	$B_s^0 \to D_s^{\mp} K^{\pm}$	$\sigma(\gamma) \sim 10°$
	$B^0 \to \pi^+\pi^-$	$\sigma(\gamma) \sim 5°$
	$B_s^0 \to K^+K^-$	
	$B^0 \to D^0(K^-\pi^+, K^+\pi^-)K^{*0}$	$\sigma(\gamma) \sim 6° \quad 10°$
	$B^0 \to D^0(K^+K^-, \pi^+\pi^-)K^{*0}$	
	$B^- \to D^0(K^-\pi^+, K^+\pi^-)K^-$	$\sigma(\gamma) \sim 6° - 10°$
	$B^- \to D^0(K^+K^-/\pi^+\pi^-)K^-$	
	$B^- \to D^0(K_S^0\pi^+\pi^-)K^-$	$\sigma(\gamma) \sim 15°$
α	$B^0 \to \pi^+\pi^-\pi^0$	$\sigma(\alpha) \sim 8.5°$
	$B^{+,0} \to \rho^+\rho^0, \rho^+\rho^-, \rho^0\rho^0$	
β	$B^0 \to J/\psi K_S^0$	$\sigma(\sin 2\beta) \sim 0.015$
Δm_s	$B_s^0 \to D_s^-\pi^+$	$\sigma(\Delta m_s) \sim 0.007\ ps^{-1}$
ϕ_s	$B_s^0 \to J/\psi\phi$	$\sigma(\phi_s) \sim 0.023$ rad
	$B_s^0 \to \phi\phi$	$\sigma(\phi_s) \sim 0.11$ rad
Rare	$B_s^0 \to \mu^+\mu^-$	
Decays	$B^0 \to K^{*0}\mu^+\mu^-$	$\sigma(s_0)) \sim 0.46\ GeV^2$
	$B^0 \to K^{*0}\gamma$	$\sigma(A_{CP}) \sim 0.01$
	$B_s^0 \to \phi\gamma$	

- **10 fb^{-1} data sample**
  - Probe/measure NP at 10% level

LHCb Upgrade

- **What is LHCb Upgrade?**
  - Run at ten times the design luminosity, namely at 2×10^{33}
  - Needs detector and trigger upgrade
  - Increase trigger efficiencies for hadrons by at least a factor two
  - Accumulate data sample of 100 fb^{-1}
- **Sensitivities**
  - LHCb upgrade will provide us with a very powerful microscope
  - Use theoretically clean observables
  - **Probe/measure NP at percent level**

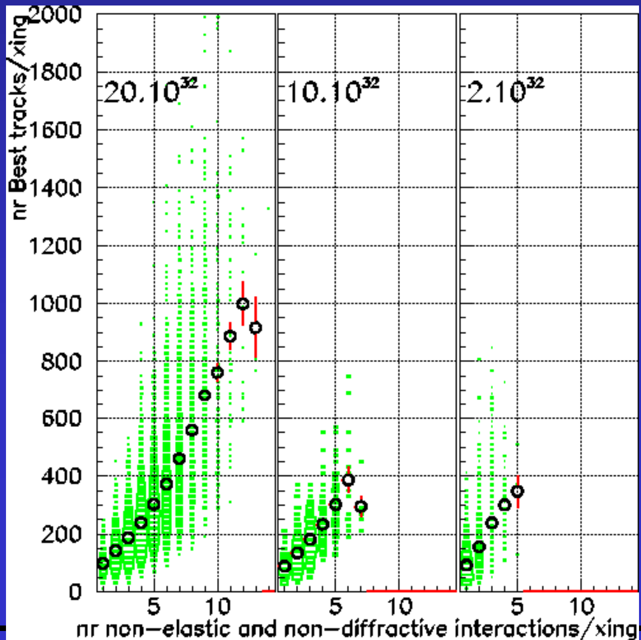
Sensitivities for integrated lumi of 100 fb^{-1}

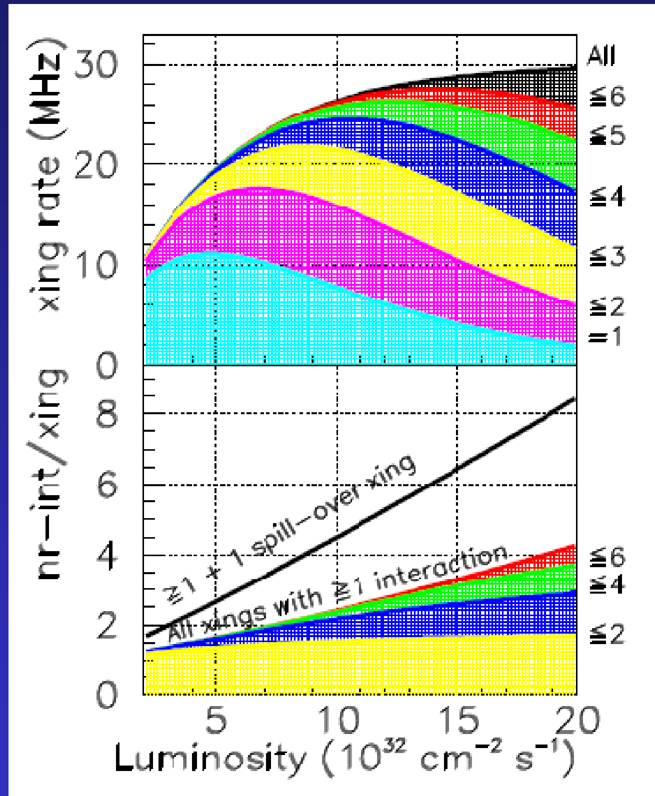
Observable	Sensitivity
$S(B_s \to \phi\phi)$	$0.01 - 0.02$
$S(B_d \to \phi K^0_S)$	$0.025 - 0.035$
$\phi_s\ (J/\psi\phi)$	0.003
$\sin(2\beta)\ (J/\psi K^0_S)$	$0.003 - 0.010$
$\gamma\ (B \to D^{(*)}K^{(*)})$	$< 1^\circ$
$\gamma\ (B_s \to D_s K)$	$1 - 2^\circ$
$\mathcal{B}(B_s \to \mu^+\mu^-)$	$5 - 10\%$
$\mathcal{B}(B_d \to \mu^+\mu^-)$	3σ
$A_T^{(2)}(B \to K^{*0}\mu^+\mu^-)$	$0.05 - 0.06$
$A_{\rm FB}(B \to K^{*0}\mu^+\mu^-)\ s_0$	$0.07\ \mathrm{GeV}^2$
$S(B_s \to \phi\gamma)$	$0.016 - 0.025$
$A^{\Delta\Gamma_s}(B_s \to \phi\gamma)$	$0.030 - 0.050$
charm x'^2	2×10^{-5}
mixing y'	2.8×10^{-4}
CP y_{CP}	1.5×10^{-4}

Also studying Lepton Flavour Violation in $\tau \to \mu\mu\mu$

Interactions vs Luminosity

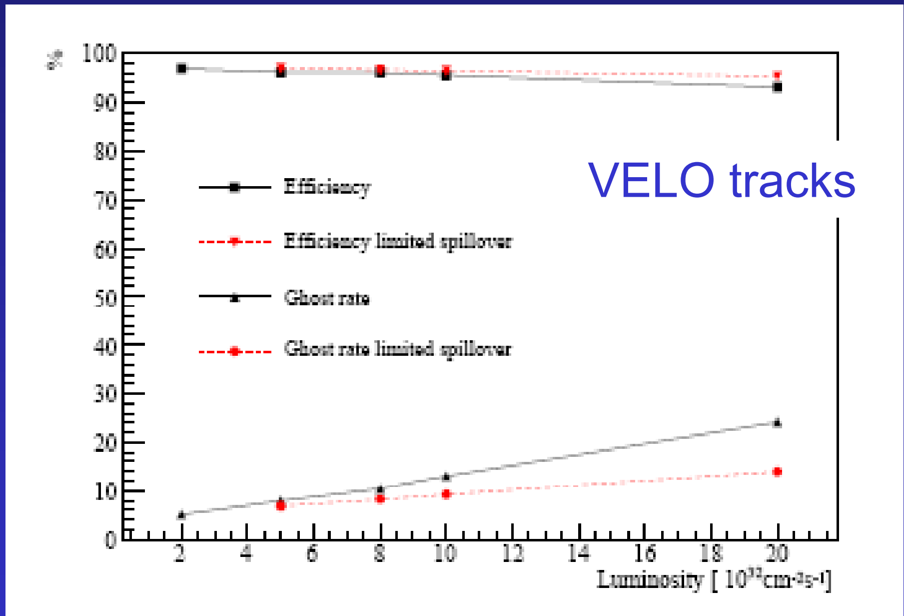
- At 2×10^{32} ~10 MHz crossings with ≥ 1 interactions
- At 10^{33} ~26 MHz crossings with ≥ 1 interactions
- At $>10^{33}$ linear increase with lumi



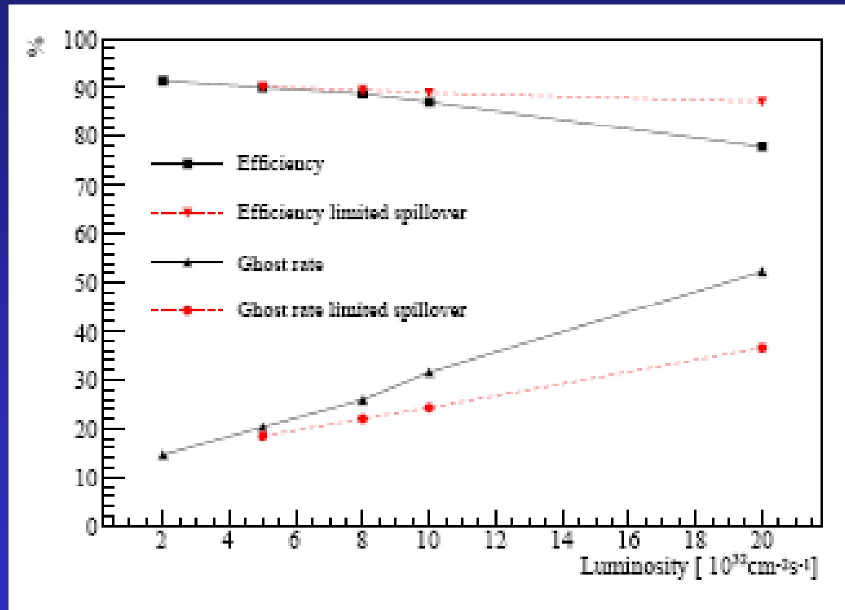


Detector Performance vs Luminosity

- Tracking
  - Efficiencies and Ghost rate



Long Tracks



- Preliminary studies show that LHCb detectors can operate up to 1×10^{33}
- Detectors designed for 20 fb^{-1} (except VELO: 6 to 8 fb^{-1})

LHCb Trigger

Detector

40 MHz

pt ~ 1 GeV μ
pt ~ 3 GeV e,h

L0: high p_T (μ, e, γ, *h*) [hardware]

1 MHz

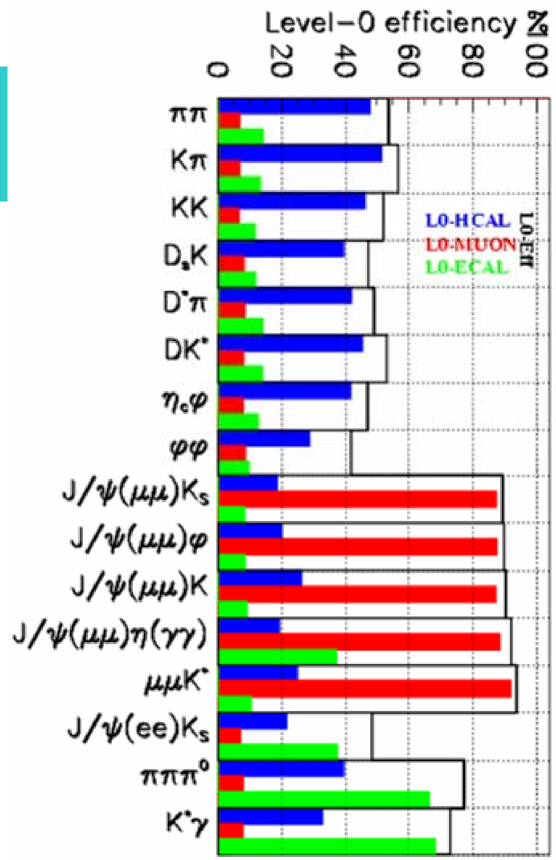
CPU farm

HLT: L0 confirmation + high IP [software]
then full reconstruction of event

2 kHz

Storage (event size ~ 35 kB)

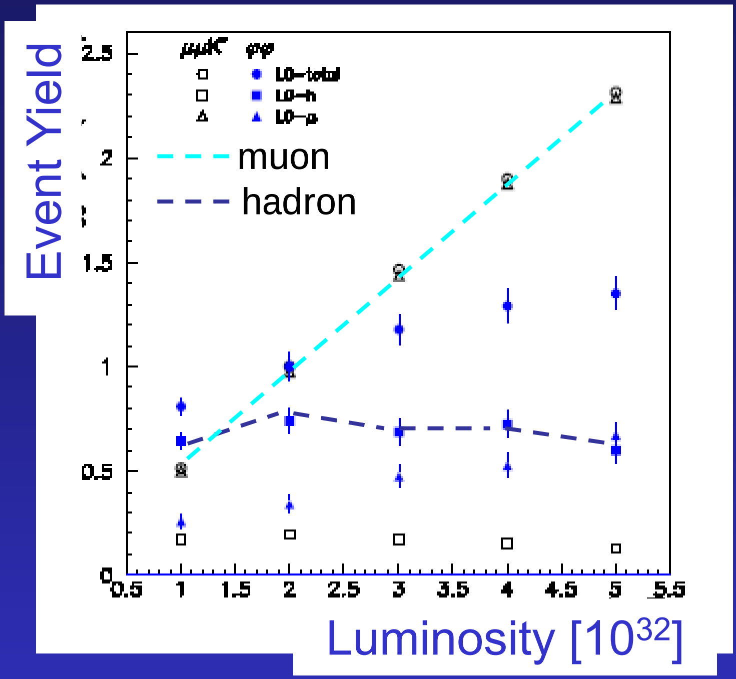
L0 efficiency

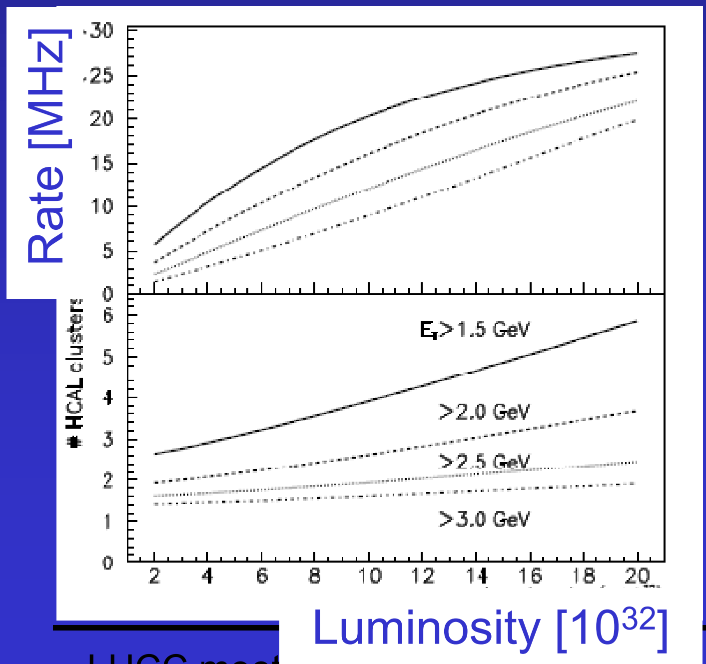


- L0 typically is 50% efficient on fully hadronic final states
- HLT1 is 60% on D_SK^-
- HLT2 is 85% on D_SK^-
- Product is 25%, room for improvement

L0 Trigger vs Luminosity

- L0 hadron trigger
  - Is bandwidth limited
  - Rate of HCAL triggers with $E_T > 2$ GeV increases from 4 to 25 MHz when lumi from 2 to 20x 10^{32}





- L0 muon trigger
  - ~90% efficiency, scales with luminosity
- L0 hadron trigger
  - Only ~50% efficient
  - does not scale with luminosity

LHCb Upgrade Strategy

- Current LHCb experiment
  - L0 trigger bandwidth cannot exceed 1.1 MHz
  - At 2×10^{33} rate of interesting hadron seeds is ~25 MHz
- **Strategy**
  - Significant gains possible for LHCb upgrade when **reading out data from detector at 40 MHz**
- Example Illustration - $B_s \to \phi\phi$
  - At luminosity of 2×10^{33}
  - Trigger efficiency = 85% at 2×10^{33}
    for HCAL cluster > 2 GeV
    24 MHz of rate & 4.2 clusters/event

LHCb Upgrade Strategy

- **LHC Machine Upgrade** (LHCC upgrade session 1th July 2008)
  - Tentative LHC schedule
  - Phase 1 - IR Upgrade, new triplets, 8 months shutdown in 2012/13
  - Phase 2 – ATLAS & CMS replace inner detectors
    18 months shutdown in 2017
  - Propose two-step approach consistent with LHC schedule
    (LHCb upgrade does not require SLHC)
- **LHCb Upgrade Phase 1**
  - Upgrade all front-end detector electronics to 40 MHz by 2014
    do not run in 2013 (Nov 2012 – Mar 2014 with 12 months access)
  - Run at 1×10^{33} until Phase 2 shutdown
  - **Increase hadron data sample by factor ~10**
  - reach detector design lumi of ~20 fb^{-1} (except VELO)
- **LHCb Upgrade Phase 2**
  - Upgrade all detectors such that LHCb can operate at a luminosity
    of at least 2×10^{33} during 18 months shutdown in 2017
  - Operate at highest possible luminosity for five years

Luminosities and Yields

Year	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Running time [10^6 s]	3.3	6.6	6.6	6.6		3.3	6.6	6.6		3.3	6.6	6.6	6.6	6.6
<L> [10^32]	2.0	2.0	5.0	5.0		10.0	10.0	10.0		30.0	30.0	30.0	30.0	30.0
Int L dt [fb-1]	0.7	1.3	3.3	3.3		3.3	6.6	6.6		9.9	19.8	19.8	19.8	19.8
Total Int L dt [fb-1]	0.7	2.0	5.3	8.6	8.6	11.9	18.5	25.1	25.1	35.0	54.8	74.6	94.4	114.2
hadron yield [a.u.]	0.5	1.0	1.0	1.0		5.0	10.0	10.0		15.0	30.0	30.0	30.0	30.0
Int hadron yield [a.u.]	0.5	1.5	2.5	3.5	3.5	8.5	18.5	28.5	28.5	43.5	73.5	103.5	133.5	163.5
hadron years for 2x stats	1.0	1.5	2.5	3.5		1.7	1.9	2.9		2.9	2.5	3.5	4.5	5.5
muon yield [a.u.]	0.5	1.0	2.5	2.5		2.5	5.0	5.0		7.5	15.0	15.0	15.0	15.0
Int muon yield [a.u.]	0.5	1.5	4.0	6.5	6.5	9.0	14.0	19.0	19.0	26.5	41.5	56.5	71.5	86.5
muon years for 2x stats	1.0	1.5	1.6	2.6		3.6	2.8	3.8		3.5	2.8	3.8	4.8	5.8

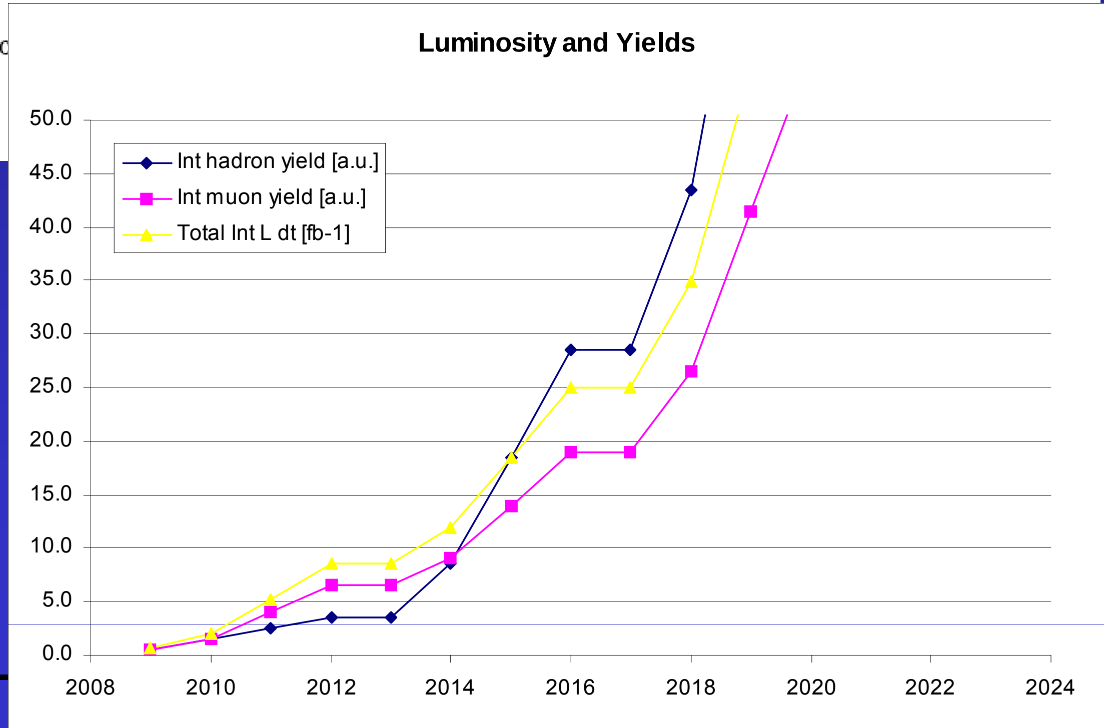
Notes:

One year = 6.6x10^6 s corresponding to 152 days at 50% efficienc

Peak Lumi after FE replacement: 10^33

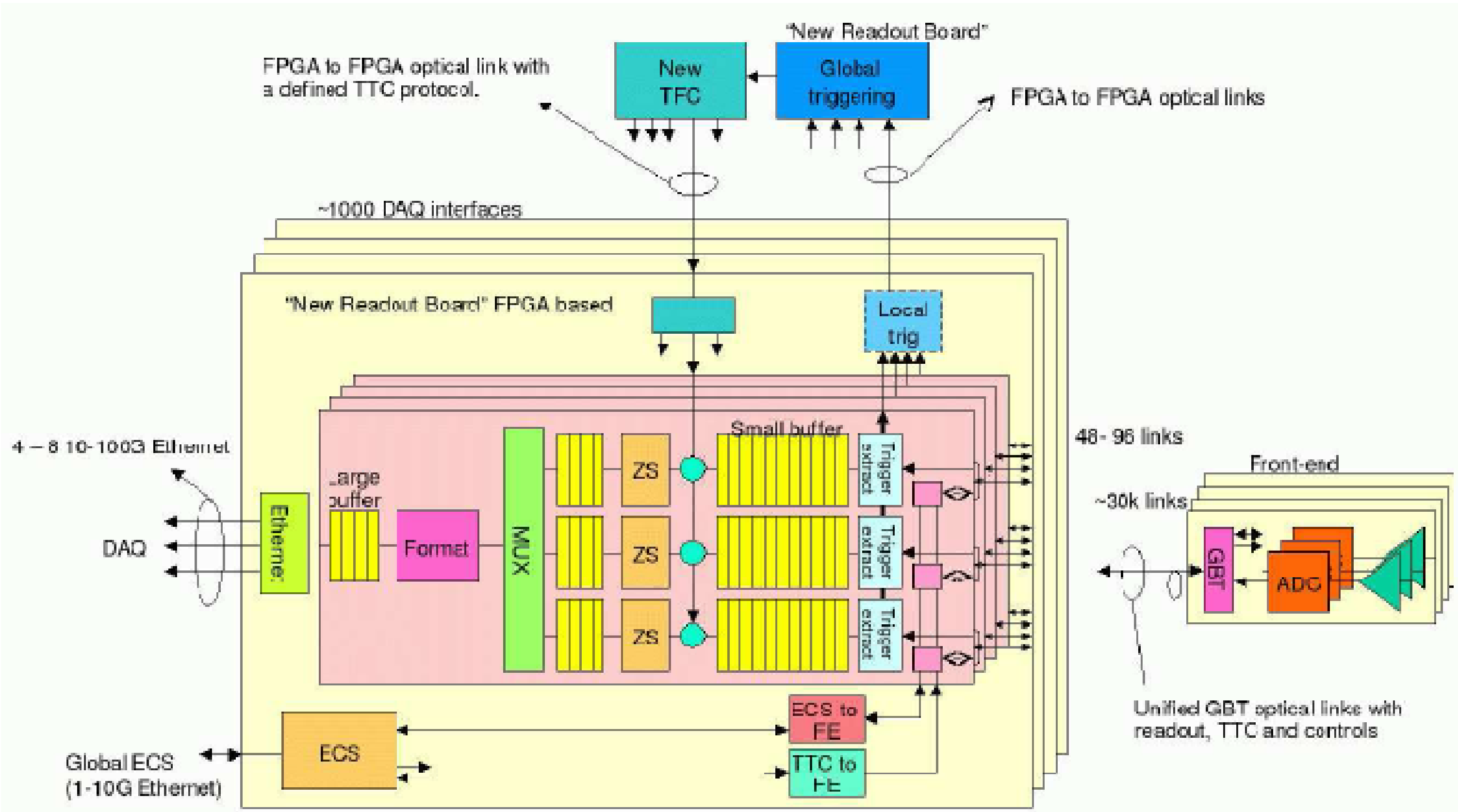
Peak Lumi after 2017: 3x10^33

hadron and muon yields are normalised to a full year at 2x10^32



DAQ/Readout Architecture

- At 40MHz from on-detector front-ends to the DAQ
  - High but constant rate readout from front-ends to DAQ interface
  - Complexity in the counting room
  - Requires 30000 optical links at 40 MHz and 2.56 Gbit/s



Data Rate

- Challenge
  - Need to demonstrate that we can collect signal at >10 times current rate
- We have decided on 40 MHz readout
  - We can do this using 10 GB/s technology
  - At 2x 10^{33} Interaction rate is ~100 MHz, so up to 100 x the data flow
    - What we have now are 1 GB/s links
    - At the source upgrade to "New Readout Board" send data on one or several 10 GB/s links
    - On the way: Switches/routers receive data at up to 10 GB/s speed
    - At the destination: Servers receive data at up to 10 GB/s speed
    - 10-40 GB/s technology already exists in some form, certainly by 2013: (Eithernet, Myrinet, Infiniband)

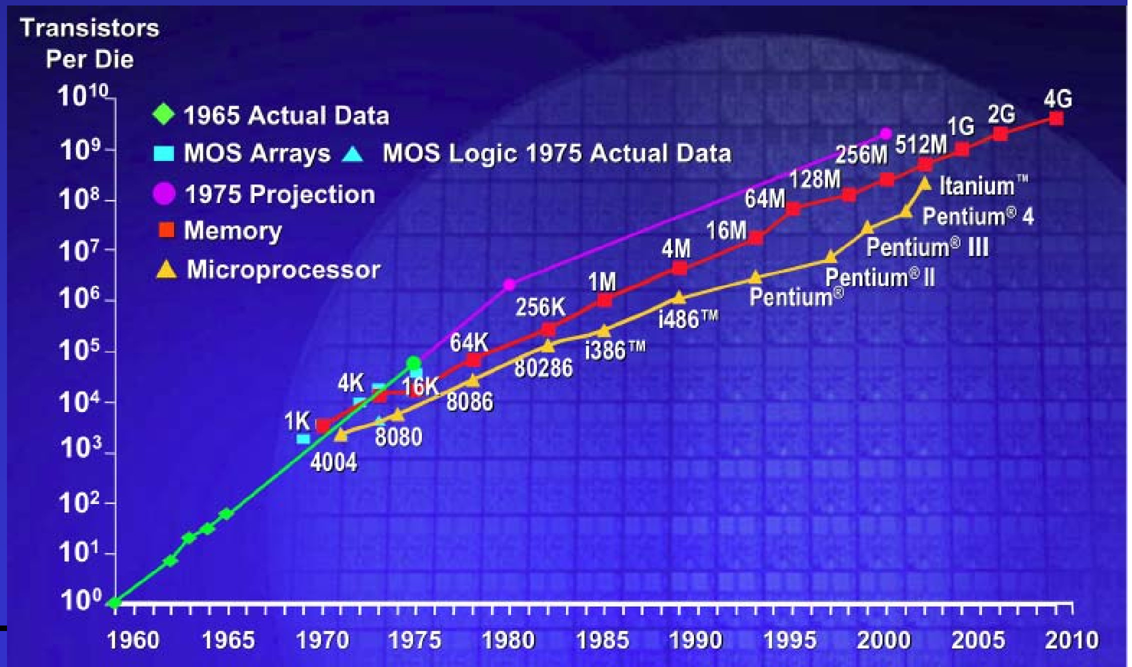
Data Rate II

- Data Storage
  - We cannot permanently store data at the crossing rate, but in 2013 10 kHz is feasible & in 2017 20 kHz, compared to 2 kHz now
  - We store data temporarily in cheap "circular" buffer outside of radiation area
- Can we process this amount of data? (offline)
  - LHCb computing TDR: Event processing time 8 sec (B event) on 1 GHz Pentium III
  - Now available 3 GHz quad-core (~12 GHz equivalent) already not a problem

Data Storage

- Can we store the events?
  - Full DST 125 kB/B event
  - 10 kHz corresponds to 12 PB per 10^7 s
  - 247 PB systems now commercially available

    http://h18006.www1.hp.com/storage/xparrays.html
- Therefore 10 kHz or 20 kHz data output is feasible

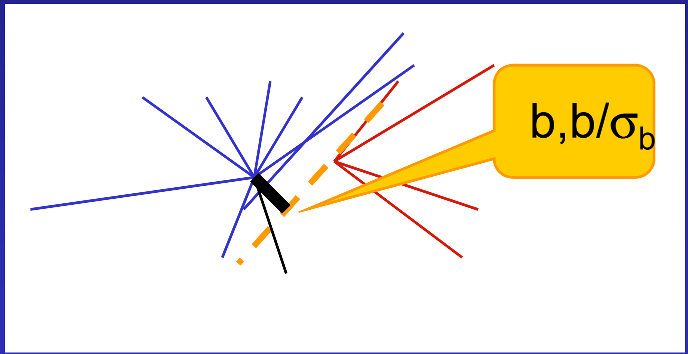


Trigger Specifications

- Projected online farm
  - Is 16,000 processors/cores
  - Original spec was 1 GHz and 1600 processors
  - We have 25 ns *16,000 = 0.4 ms to make a decision (probably will have >10 GHz cores)
- Trigger strategy
  - Must execute in ⟨0.4 ms⟩
  - Should be maximally efficient on signal and reduce the background to an acceptable level
  - Minimum bias must be reduced from 100 MHz to <10 kHz, reduction factor is 100,000 to get 1 kHz background rate; ~same as now ⇒ goal can be met adopting current trigger strategy, but we want to do better!
  - Not so useful rate of 100 kHz B's >90% must also be eliminated
- Goal
  - To increase hadron trigger efficiency by a factor of 2 to 3

Trigger Strategies at 40 MHz

- First level detached vertex trigger
  - Key point is to trigger on tracks which do not originate from a primary vertex
  - e.g. use impact parameter and its significance



  - p_T information on tracks is crucial to defeat multiple scattering Need to reject tracks with P_t<250 MeV
    - Match VELO tracks to downstream tracker
    - or can put VELO in magnetic field

Trigger Strategies at 40 MHz

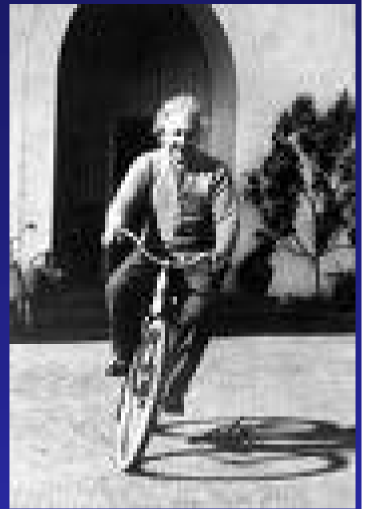
- Dimuon trigger
  - For muon channels
  - also used to add efficiency for hadron trigger & cross checks
- Calorimeter triggers
  - Use existing triggers selecting high E_T events
  - Can be tuned as a function of higher lumi and lower thresholds
  - Can be implemented as a "rate control trigger"
- Next level
  - vertex trigger achieves factor of ~100 rejection, so we have about 10x more time per event
  - Here we fully reconstruct tracks & fit for common vertex; goal is to get another factor of 10-100
- Final level
  - Now we have enough time to reconstruct the B candidate & keep if useful. This gains us the remaining factor of 10-100, so full minimum bias rejection is 10^5.

Electronics

- **40 MHz Front-end chip**
  - work is starting now
  - Must be adaptable to variety of conditions
    - Geometry: Si strips, pixels, photo detectors…
    - Should be capable of zero suppression
    - Should have ≥3 bit ADC to get best position resolution
- Off-Detector Electronics R&D
  - GBT chip - push for the highest possible link speed
  - "New Readout Board"
    - with at least 40 Gbit/s output bandwidth,
    - process ~ 400 Gbit/s of input data
  - New TFC based on GBT and "New Readout Board"
  - 10 Gbit DAQ based on 10 Gigabit Ethernet of Infiniband
  - L0 trigger for rate control between 30 and 1 MHz

VELO → VESPA

- VErtex LOcator replacement called VESPA
- Solution for first upgrade phase (2013)
  - Keep mechanical structure and silicon strip sensors
  - Replace FE chip with 40 MHz readout
  - This device will be rad hard to ~20 fb^{-1} and will collect data until 2017



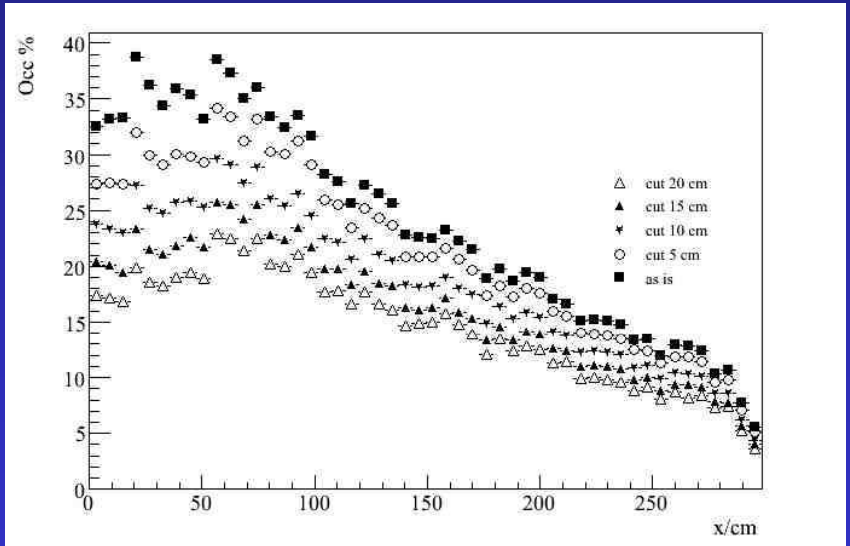
- Solution for 2017 will be a complete overhaul
  - Pixels/3D detectors
    - better resolution
    - lower occupancy
  - Possible magnetic field to improve trigger by taking advantage of improved pattern recognition
  - Remove bulky RF shield and replace with wires? Could use liquid N_2 cooling with cold fingers to create good vacuum, making VESPA a cryo-pump at the LHC

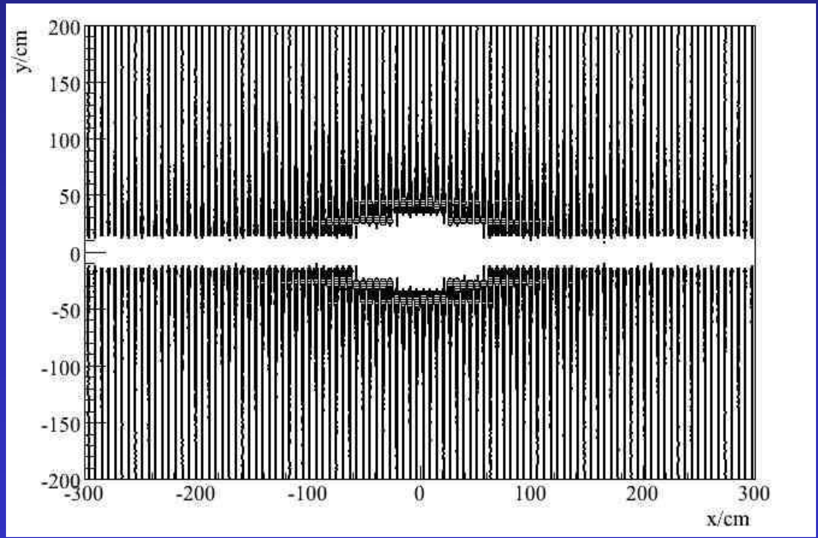
Tracking Systems

- 40 MHz upgrade
  - All Si systems have readout chips bonded on hybrid
  - Will need to be replaced by 2013
    (IT≡inner tracker, TT≡trigger tracker)
- Ghost tracks
  - are an issue, especially at higher lumi
  - generally thought to be false matches between VELO and tracking systems
- Spillover
  - Can be reduced with faster gas in Outer Tracker (OT)
  - Reduce timing from 75 to 50 ns
- Occupancies
  - Okay for silicon trackers
  - Okay up to 10^{33} in OT
  - Increases to 38% near horizontal plane at $2x10^{33}$
  - Reduce material

Tracking Systems

- Possible solution for very high luminosity > 10^{33}
  - Cut horizontal section of OT & increase IT size
  - Likely requires replacing OT
    rebuild or scintillating-fibre tracker



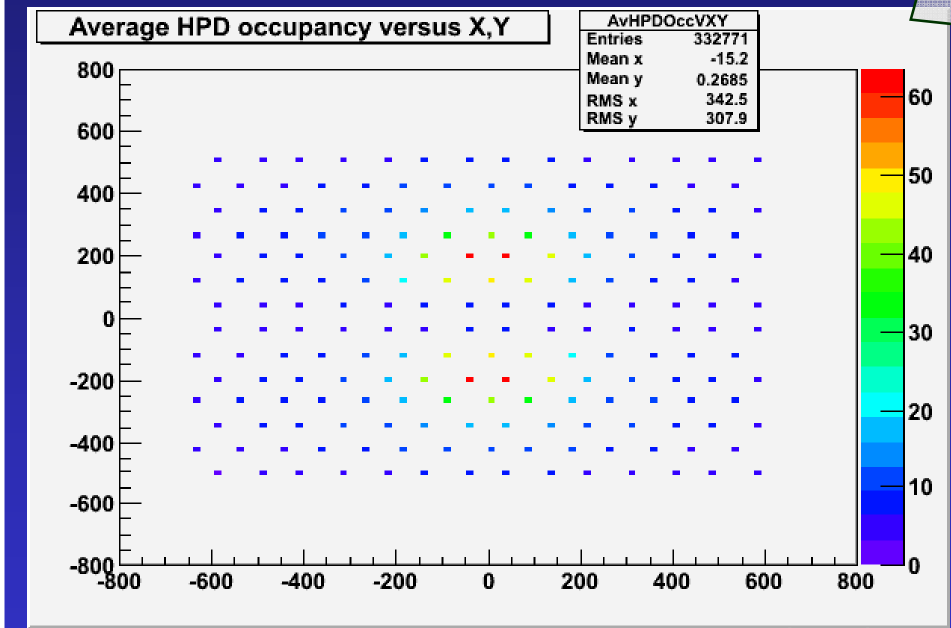


- Front-end electronics
  - Needs to be adapted to 40 MHz

RICH1/RICH2 Occupancies at 2×10^{33}

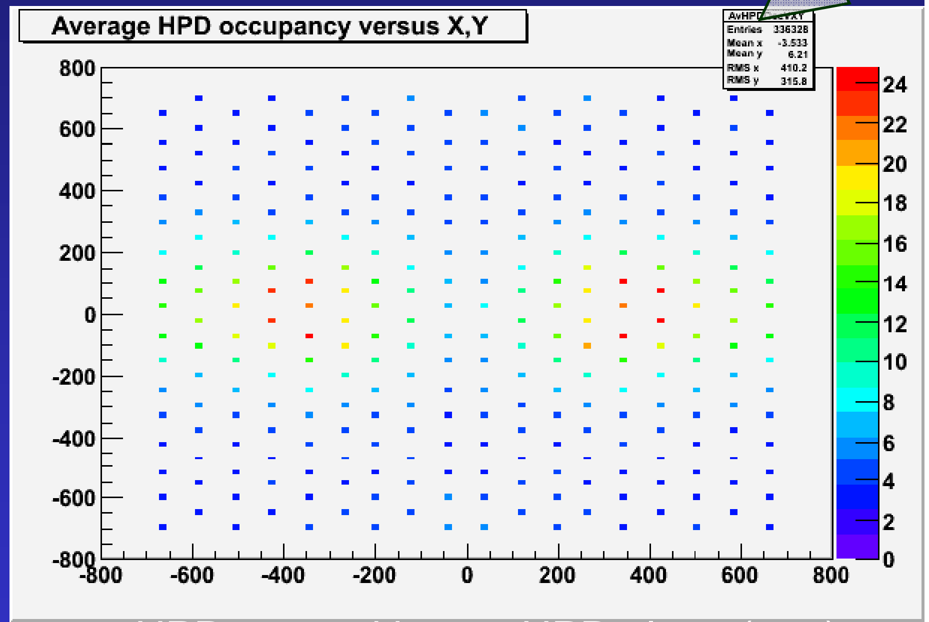
Plots show average no. of pixels hit per HPD ≈ Average event occupancy/1000

- RICH-1



HPD x,y position on HPD plane (mm)

- RICH-2

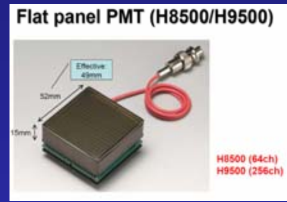


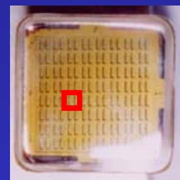
HPD x,y position on HPD plane (mm)

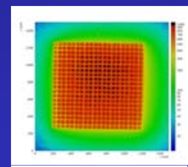
- Maximum average occupancy in RICH-1 is ~6%
- Maximum average occupancy in RICH-2 is ~2.5%

RICH Upgrade

- 40 MHz Readout
  - The readout chip is encapsulated inside the HPD
  - therefore all photon detectors will need to be replaced
- Choice of Photo sensitive device
  - HPD with 40 MHz pixel chip
  - Vacuum PMTs - Flat-panel MaPMT, MCP
  - Si-photomultiplier
  - Choice must be made soon





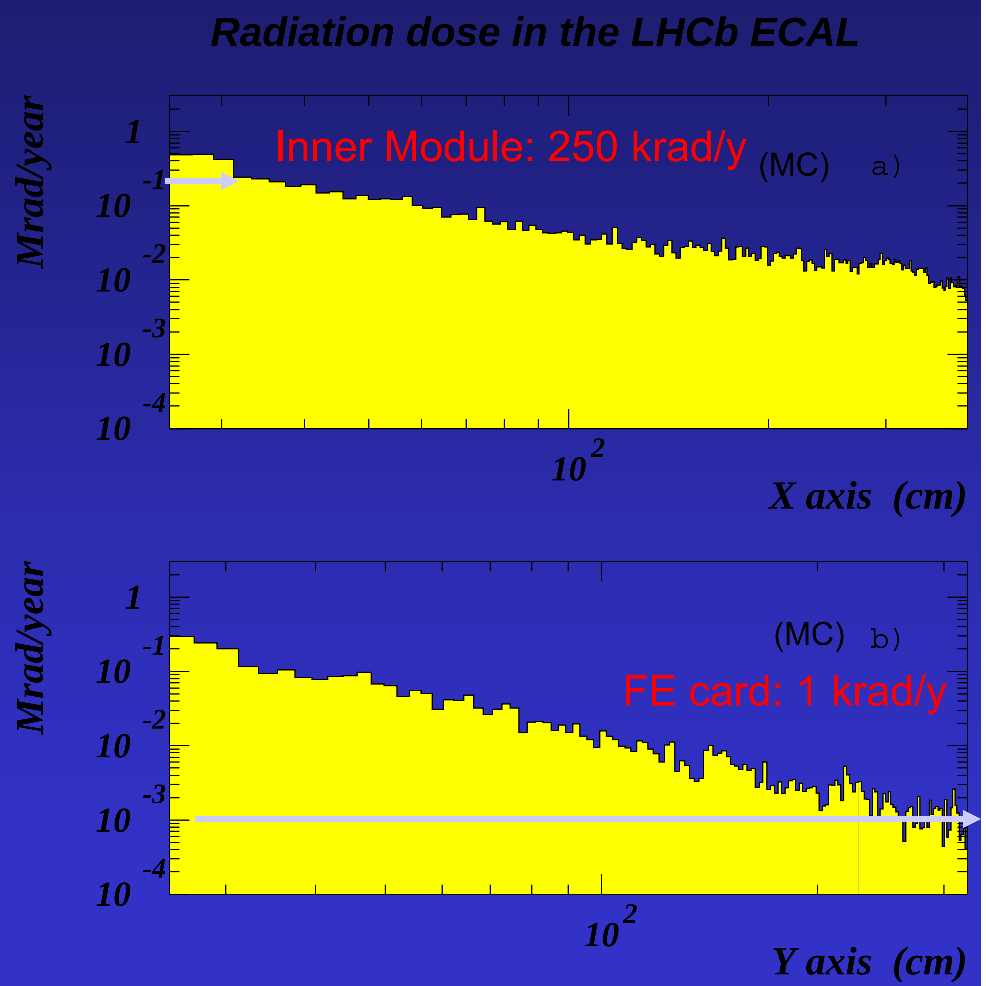


- FE electronics
  - development of pixel chip at 40MHz
  - or external front-end chip for commercial devices
- Option
  - Remove RICH1, replace with ~few ps TOF?
  - Reduces material for tracking

Electromagnetic Calorimeter

- Signal efficiency
  - Preliminary studies show only minor degradation for $B_s \to \phi\gamma$
- Radiation damage
  - At 2×10^{33} the worst place has 2.5 Mrad/year, projected useful life is only 3 years
  - Clearly need a replacement with rad hard technology for inner part for >2017
  - Also useful would be increased segmentation in inner part
- Front-end Board
  - need to be adapted to 40 MHz

Dose at L = 2×10^{32}



Hadron Calorimeter

- Present HCAL will be maintained
  - Should be able to last with some degradation in resolution
  - 2 years running at 2x 10^{33} resolution will degrade constant term from 10% to 15%
- Front-end Board
  - need to be adapted to 40 MHz

Muon System

- The major part of the muon detector can very likely operate at 2×10^{33} for 5 years
  - Muon detector electronics is already at 40 MHz
- Upgrade of M1 station is not required, it will likely be removed
  - Momentum of muon candidates determined by tracking stations
- Aging
  - Okay for up to 100 fb^{-1} with the possible exception of region M2R1
  - technology presently adopted for region M1R1 (triple-GEM) will work
- Further studies are required
  - to understand the effects of a larger occupancy of the muon detector on the tracking and the purity of muon identification.

R&D Plan

- Develop 40 MHz readout electronics
  - FE chip for tracking and VESPA
  - FE chip for RICH
  - Are assembling team of electronics engineers
  - OT, ECAL, HCAL require adaptations of off-detector electronics
- Create strawman detectors for 2013 & 2017
  - Quantify the gain in useful signal events for L = 10^{33} (2013) & 2×10^{33} (2017) using targeted simulations on specific modes such as $B_S\rightarrow\phi\phi$, $B\rightarrow K^*\mu^+\mu^-$, $B_S\rightarrow\mu^+\mu^-$, $\tau^-\rightarrow\mu^-\mu^+\mu^-$
- Start R&D on each individual detector now
  - Highest R&D priority is to make detectors 40 MHz compatible
  - Top priority is getting physics out of current detector
  - R&D effort will benefit from synergies with ATLAS/CMS on common items

Conclusions

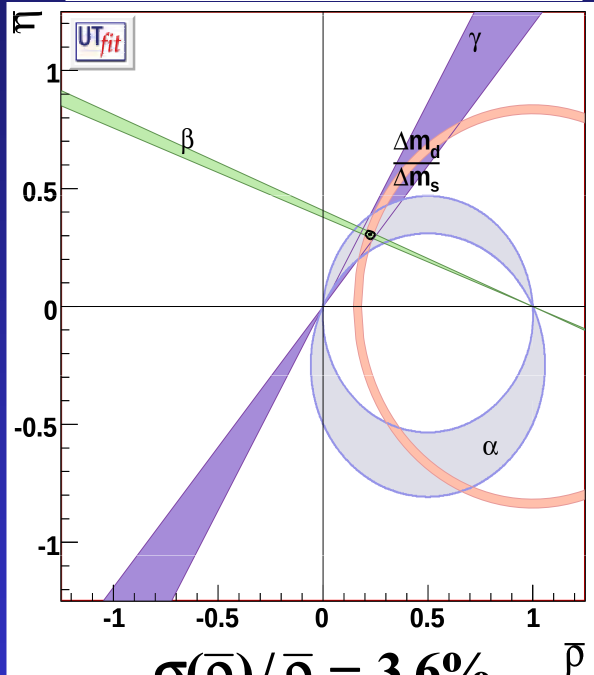
- LHCb Collaboration submitted EoI for LHCb Upgrade
- Physics case
  - Probing/measuring NP at percent level
- LHCb Upgrade Strategy
  - Upgrade to 40 MHz FE electronics first to run at 10^{33} (2014)
  - Upgrade all detectors such that LHCb can operate at luminosity of at least $2x10^{33}$ in ~ 2017
- R&D plan is evolving fast
  - Design of FE chips for 40 MHz read out
  - Vertex detector upgrade well on track
  - Other subsystems gaining momentum

Backup Slides

LHCb Physics Prospects

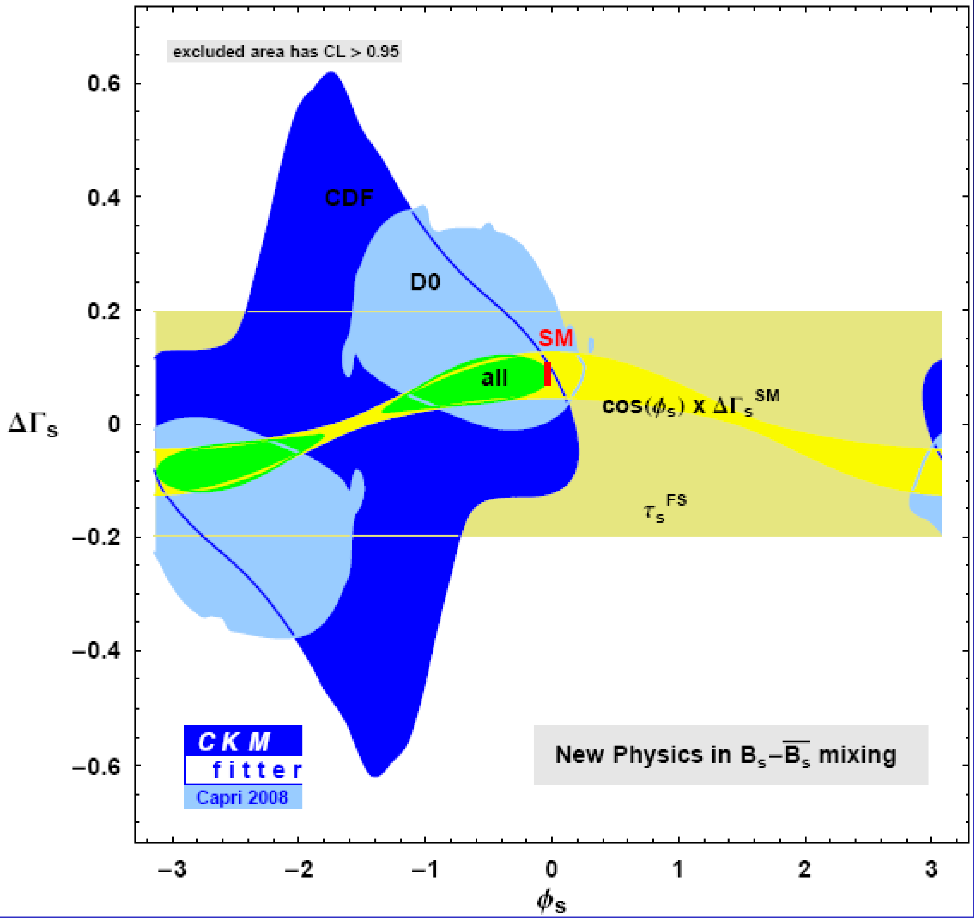
- **LHCb – first five years**
  - Lots of opportunities to test SM
  - Accumulate 10 fb^{-1} data sample
  - Weak mixing phase ϕ_s in $B_s \rightarrow J/\psi\phi$
    If $\phi_s \gg 0 \rightarrow$ NP discovered in mixing
  - NP search in rare decays
    $B_s \rightarrow \mu+\mu-$ down to SM level
  - $B_s \rightarrow \phi\phi$ if $\phi_s(J/\psi\phi) \neq \phi_s(\phi\phi)$
    or $\sin2\beta^{eff} \neq \sin2\beta \rightarrow$ NP in penguins
- **CKM Unitarity Triangle with 2 fb–1, 10 fb–1**
  - $\sigma(\sin(2\beta))$ = 0.02, 0.01
  - $\sigma(\gamma)$ = 4.2°, 2.4°
  - $\sigma(\alpha)$ = 10°, 4.5°
  - At precision to probe NP at 10% level
  - Requires theoretical progress
    |Vub| and Lattice QCD (mixing)

10 fb^{-1} ~2013



$$\sigma(\bar{\rho})/\bar{\rho} = 3.6\%$$
$$\sigma(\bar{\eta})/\bar{\eta} = 1.8\%$$

CDF & D0 May See



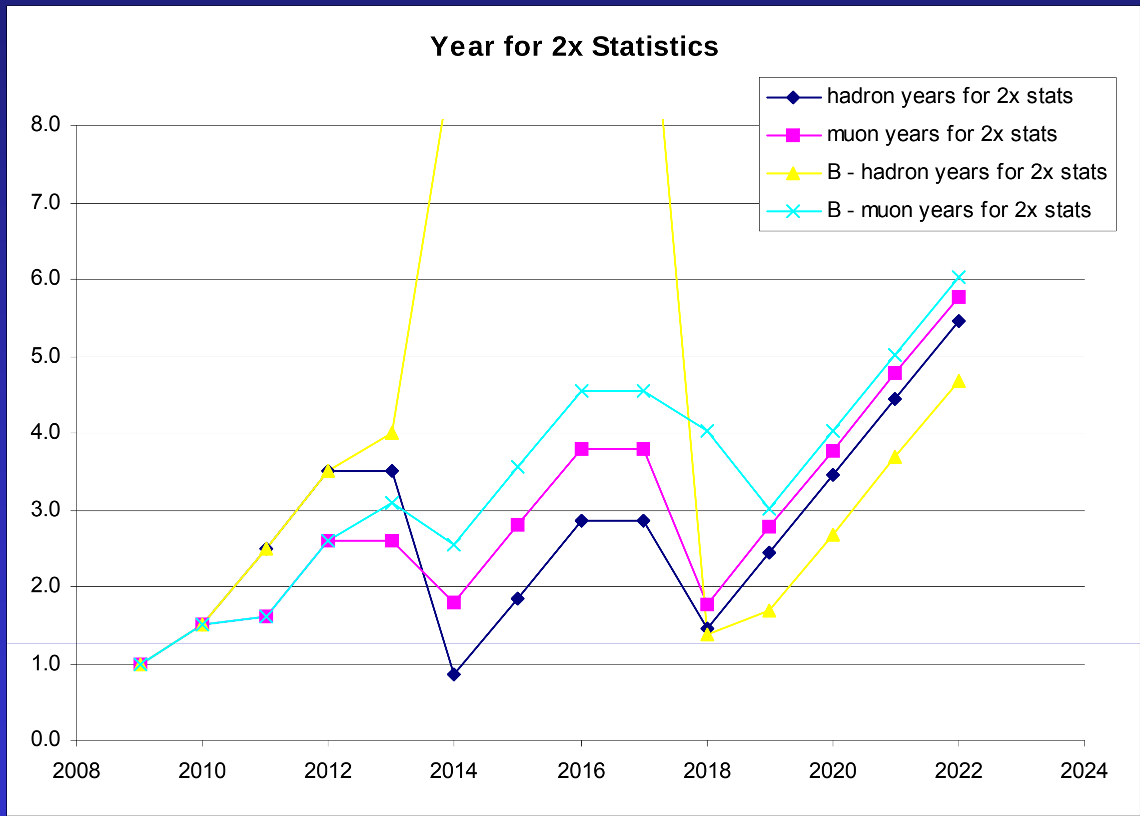
using all $(\phi_s, \Delta\Gamma_s)$ inputs, $\phi_s = -2\beta_s$ is excluded at 2.4σ, while the 2D hypothesis $\phi_s = -2\beta_s$, $\Delta\Gamma_s = \Delta\Gamma_s^{SM}$ is excluded at only 1.9σ (wrt to 1.4σ from FC treatment by CDF)

very transparent analysis: all theoretical uncertainties are contained in the SM prediction $\Delta\Gamma_s^{SM} = 0.090^{+0.017}_{-0.022}$ ps (red line)

- From Jérôme Charles, Capri, June 2008
- Similar results from UTfit, Silverstrini

Time to double dataset

- Proposal vs no Phase 1 upgrade (B)
  - Running on muon trigger at 10^{33} until Phase 2 upgrade



Proposed R&D - Electronics

- GBT chip
  - active LHCb involvement is highly recommended, in particular to push for the highest possible link speed
- "New Readout Board"
  - with at least 40 Gbit/s output bandwidth and the possibility to process ~ 400 Gbit/s of input data.
- New TFC
  - based on GBT and "New Readout Board"
- 10 Gbit DAQ
  - Based on 10 Gigabit Ethernet of Infiniband
- L0 trigger
  - For rate control between 30 and 1 MHz

The End