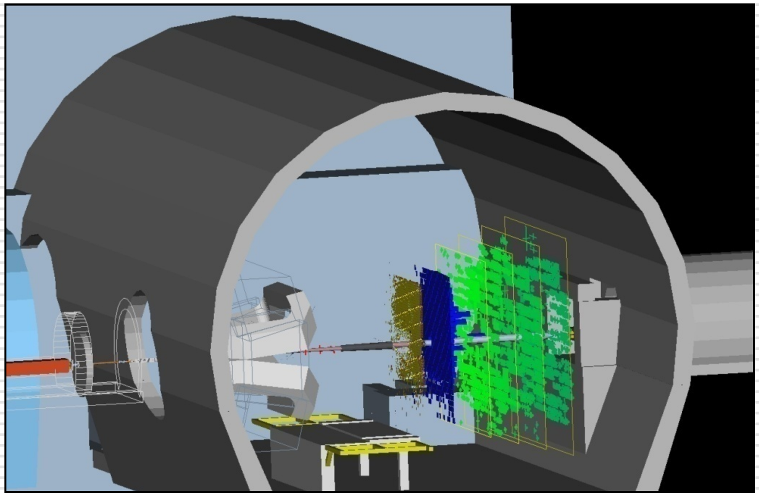
The LHCb upgrade

Technology and Instrumentation in Particle Physics 2011
Chicago 9-14 June 2011

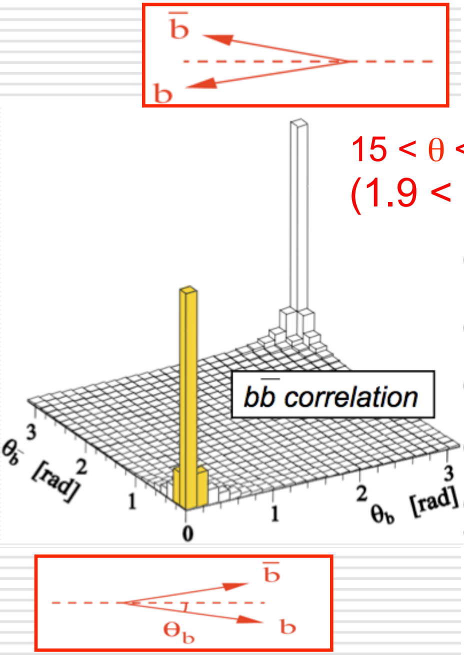


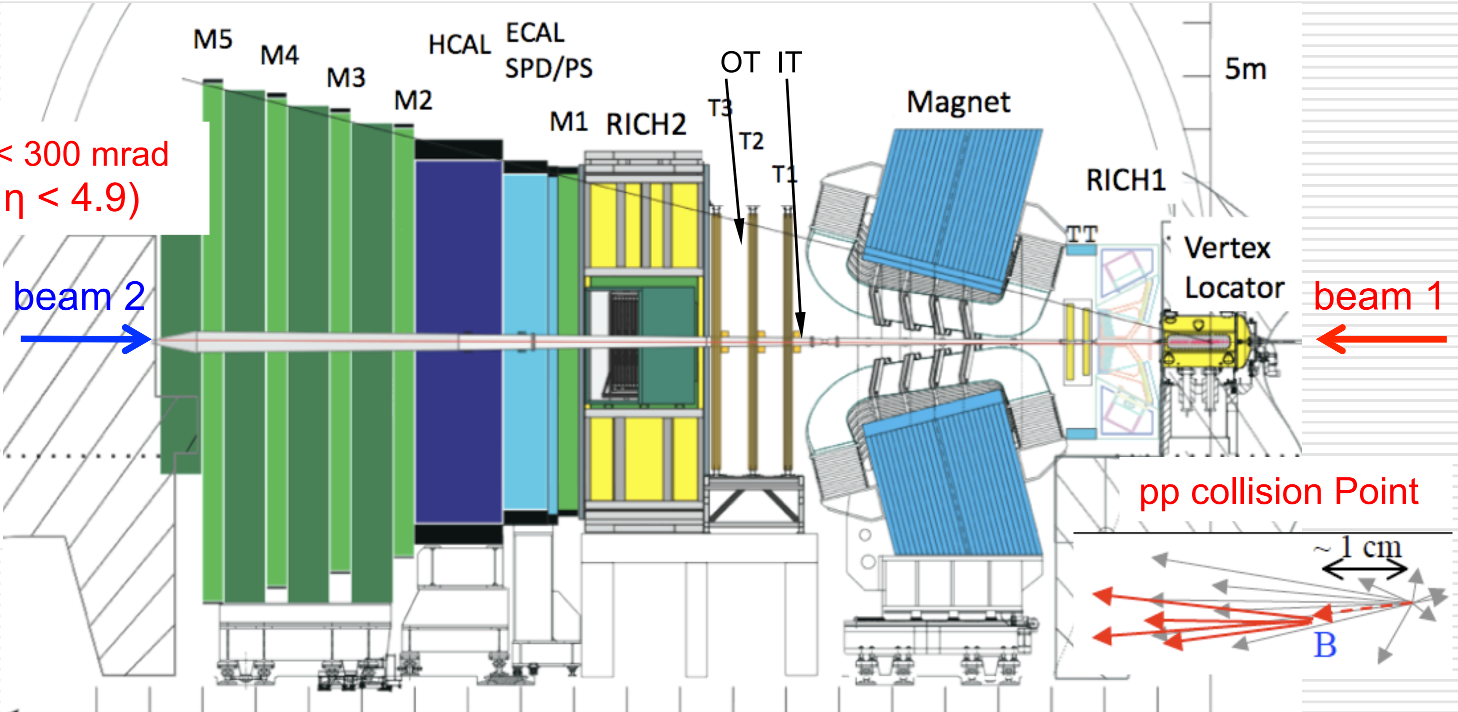
Abraham Gallas for the LHCb Collaboration

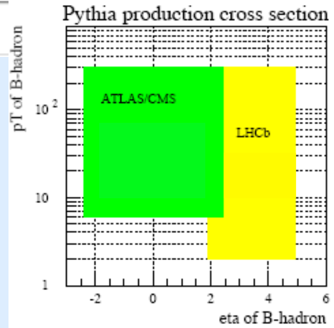
Outline:

- Current LHCb performance
- LHCb upgrade plan & main issues
- Overview of the sub-detector modifications
- Summary & Conclusions

Current LHCb

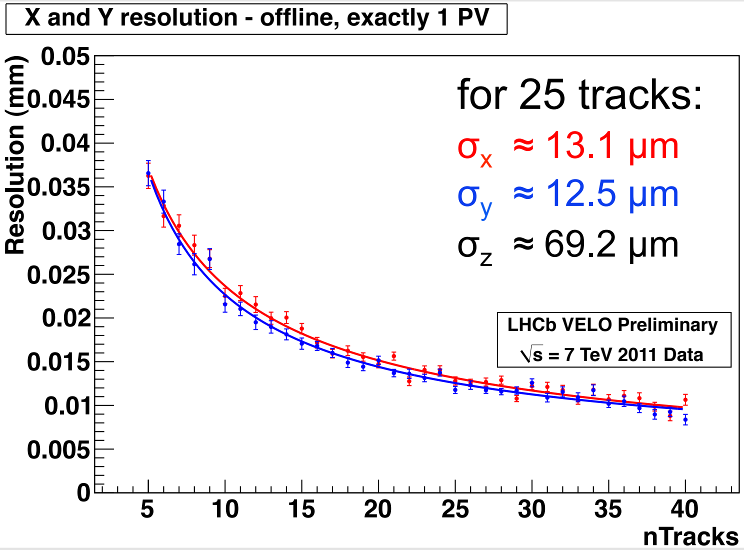


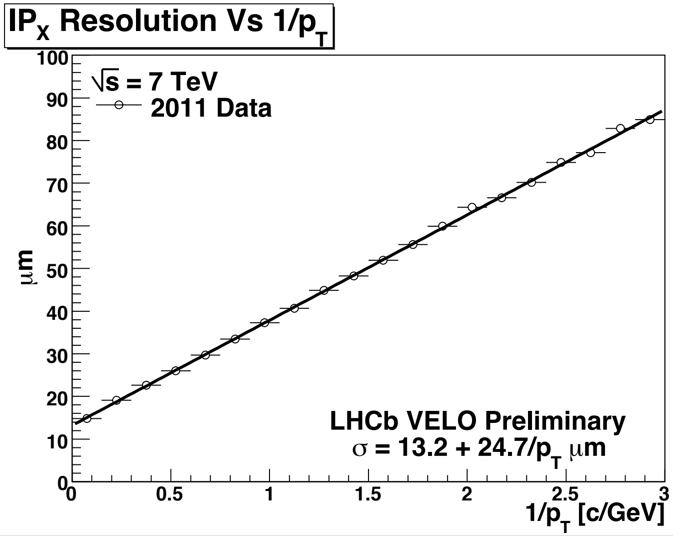




- Current LHCb goals:
  - Indirect search for new physics via CP asymmetries and rare decays
  - Focus on flavor physics with b and c decays
- Forward spectrometer designed to exploit huge $\sigma_{b\bar{b}}$ @ LHC
  - 10^{12} $b\bar{b}$ pairs produced per 2 year of data taking @ $\mathcal{L} = 2\times10^{32}$ cm^{-2}s^{-1}
  - Access to all b-hadrons: B_d, B_u, B_s, b-baryons and B_c
- Big experimental challenge: $\sigma_{b\bar{b}} < 1\%$ σ_{inel} total, Bs of interest BR < 10^{-5}
- Current LHCb : Collect ~5 fb^{-1} before 2nd LHC shutdown 2017

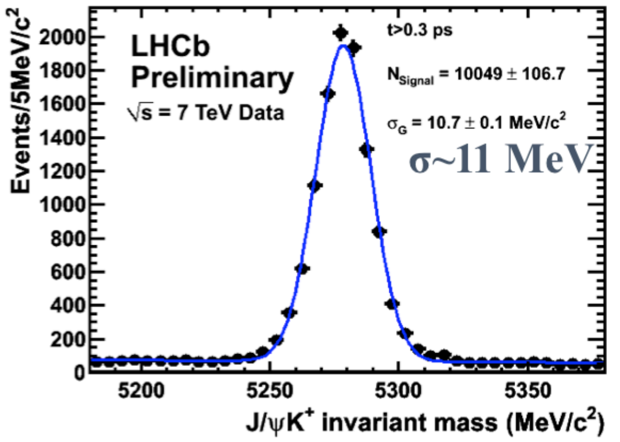
Detector performance: vertexing & mass resolution





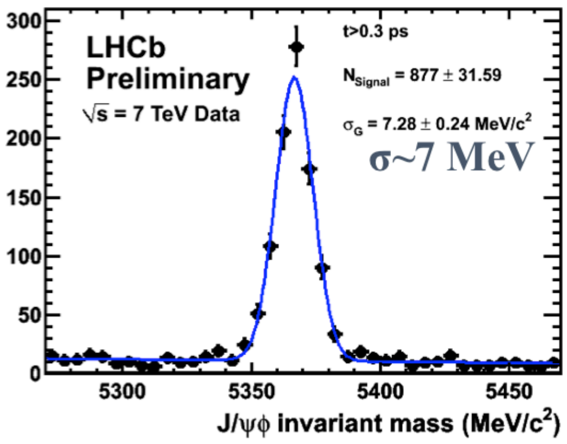
$B_u^+ \rightarrow J/\psi K^+$

$B_s^0 \rightarrow J/\psi \varphi$



- very good mass resolution
- very low background

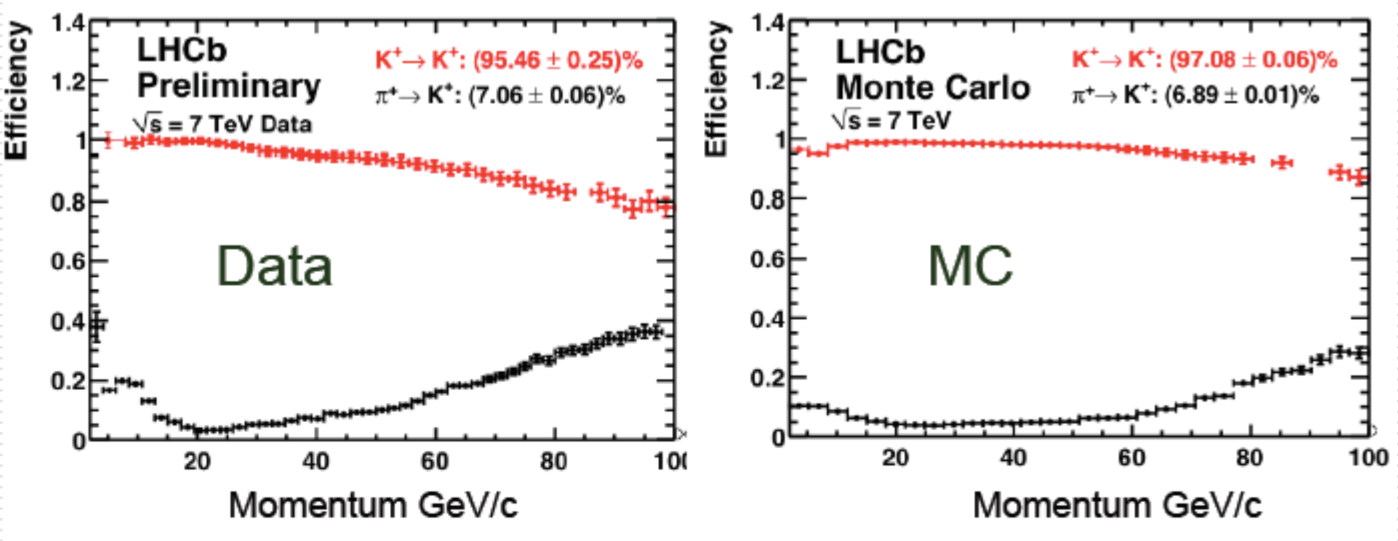
(comparable to e^+e^- machines)



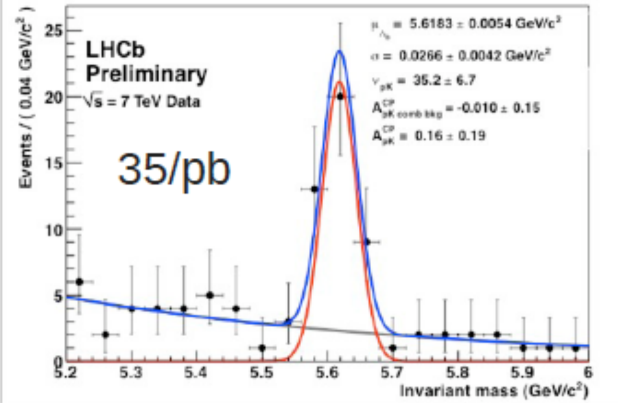
Comparison GPDs:

- CMS: σ~16 MeV
- ATLAS: σ~26 MeV

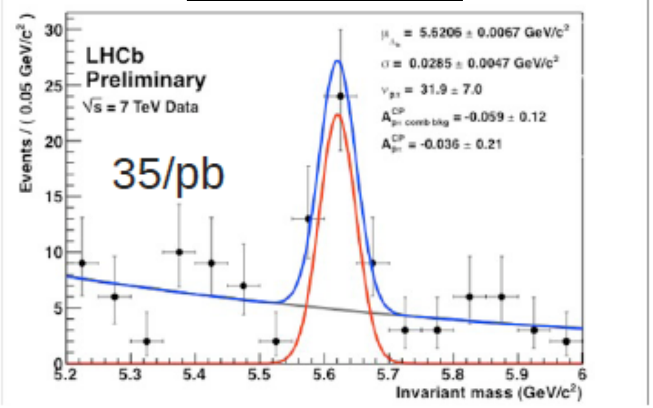
Detector performance: hadron PID



$\Lambda_b \to p\,K$

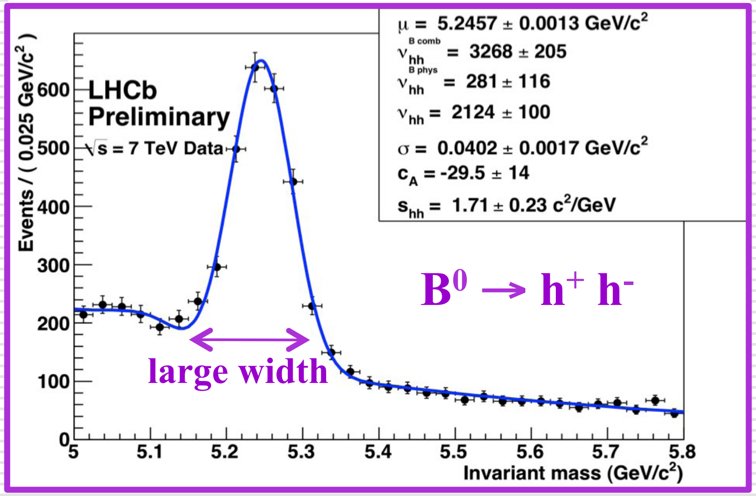


$\Lambda_b \to p\,\pi$

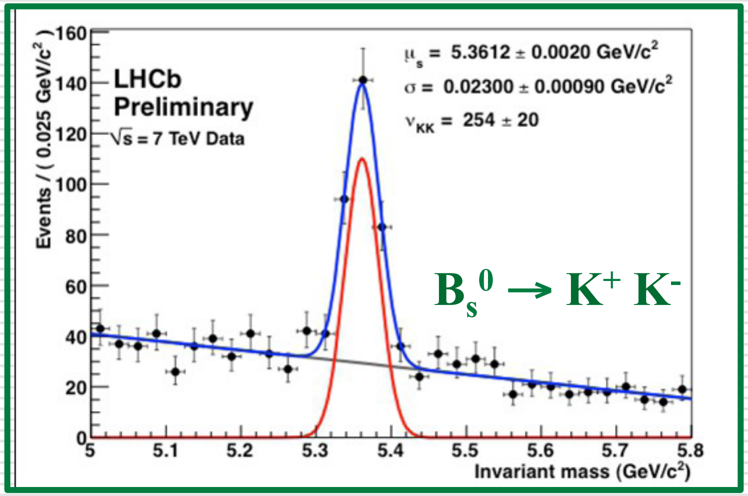


Detector performance: Particle Identification on B➔ hh

No particle identification → any 2 hadrons!

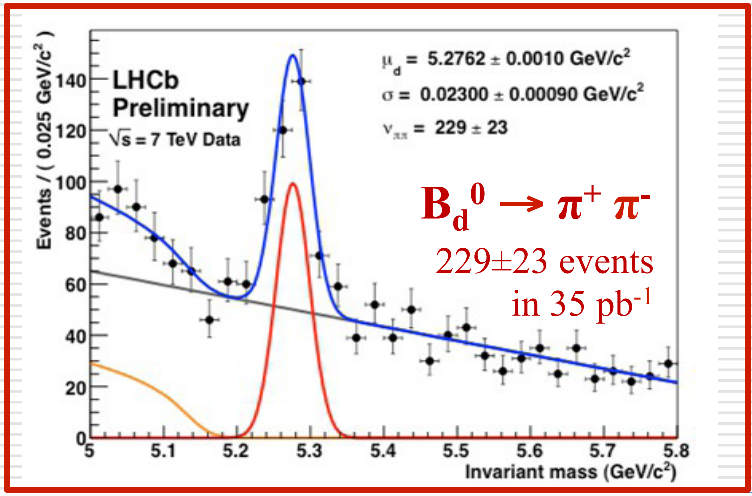


particle identification of 2 Kaons



particle identification of 2 π

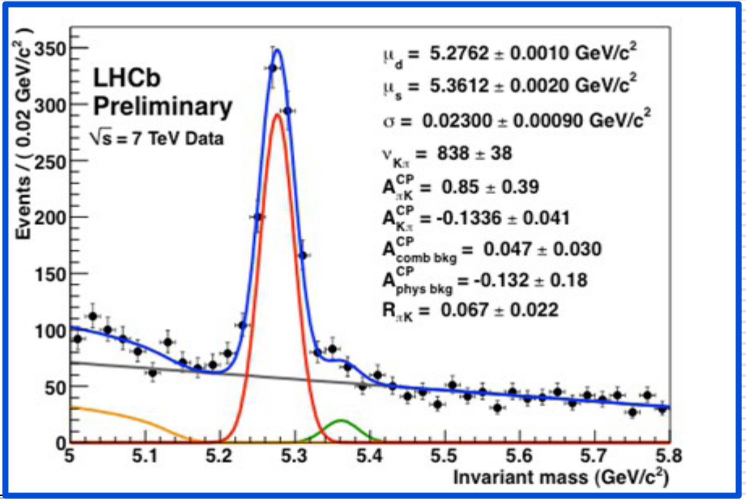
BR(B→$\pi^+\pi^-$) = 5 x 10^{-6} !



particle identification of 1 π and 1 K

$B_d^0 \to K\pi$ & $B_s^0 \to K\pi$

(will get as many Kπ in <1 fb^{-1} as Belle in 1000 fb^{-1})



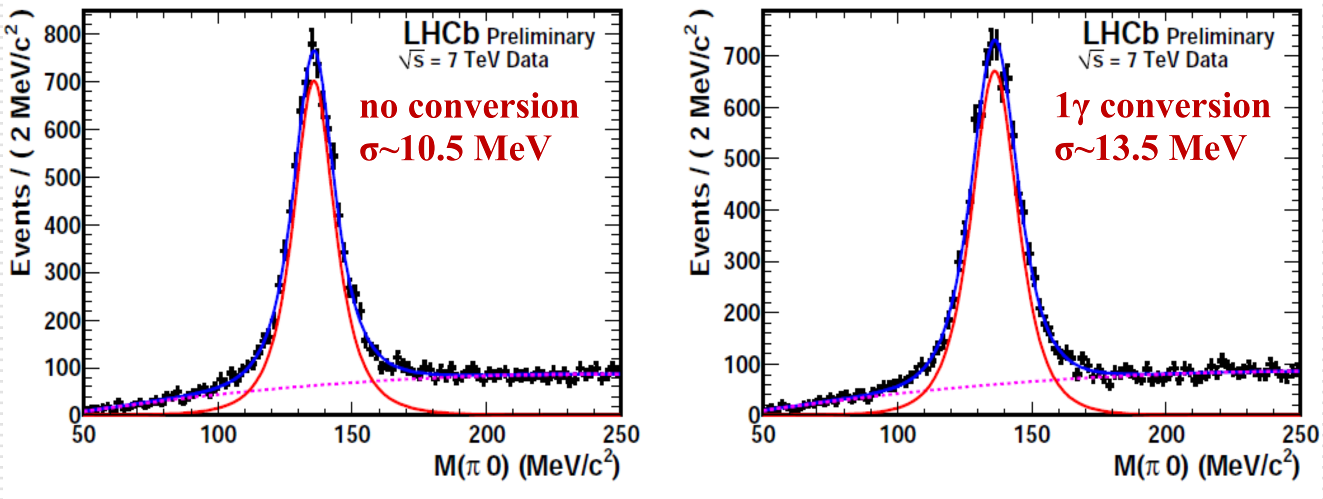
Expectations 2011:

LHCb: 6500 ev./fb^{-1}

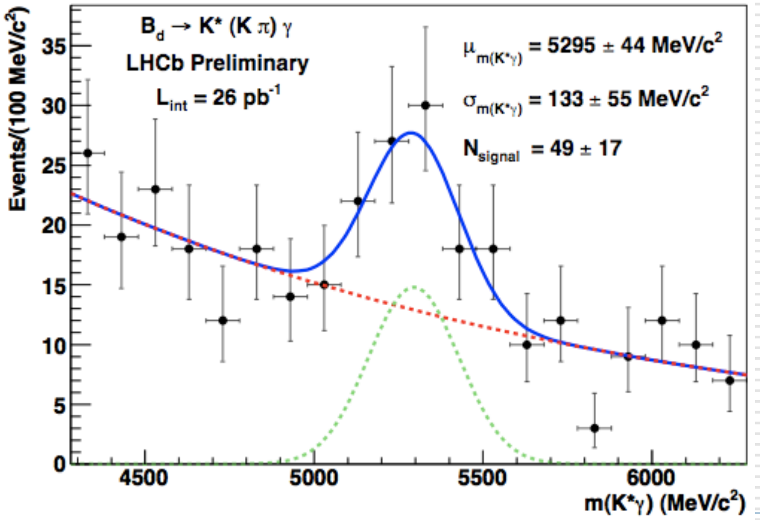
(CDF: 1100 ev./fb^{-1})

Detector performance: photon PID

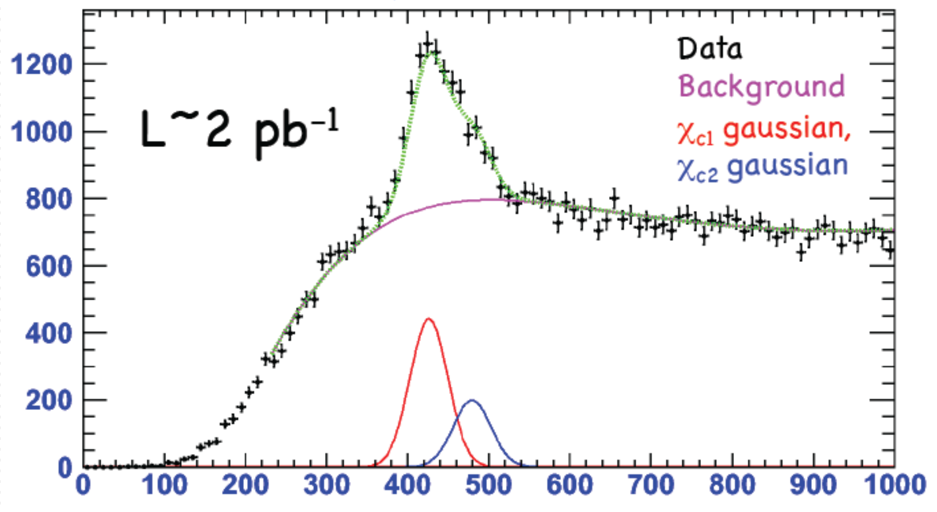
π^0 reconstruction performance



$B^0 \rightarrow K^* \gamma$

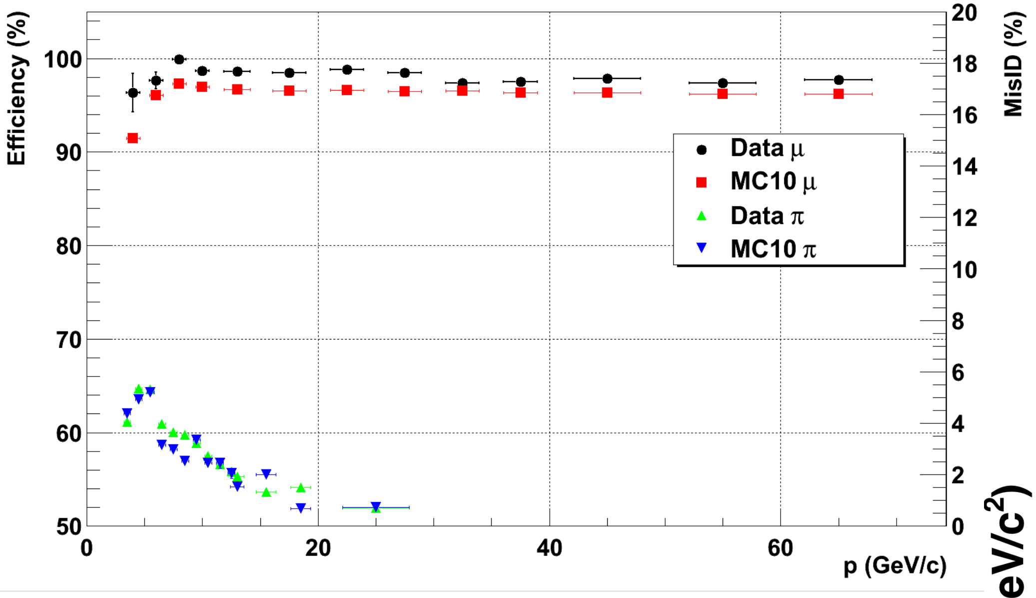


$\chi_c \rightarrow J/\psi\ \gamma$

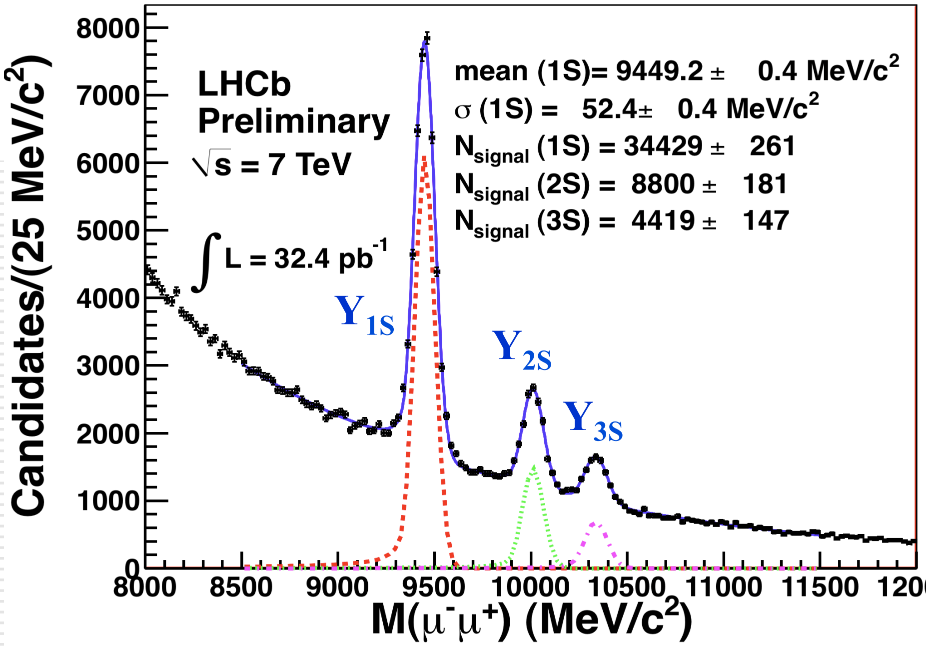


See talk by Frédéric Machefert

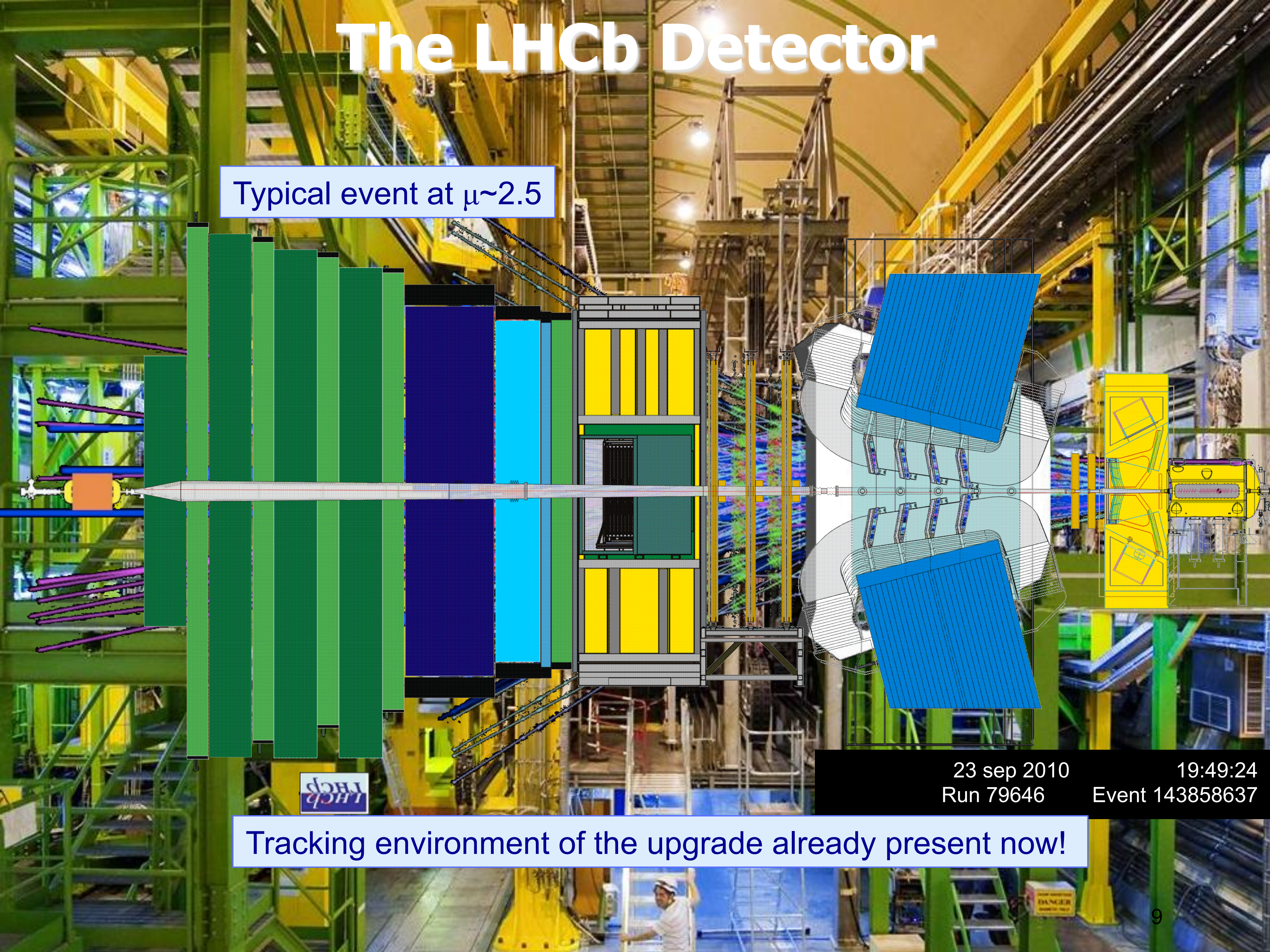
Detector performance: muon PID performance



- ➢Muons: key ingredient for many LHCb physics analyses!



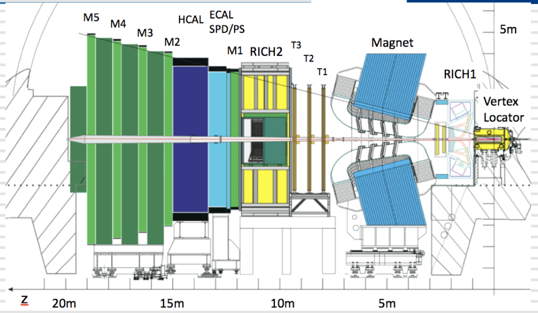
The LHCb Detector



Typical event at μ~2.5

Tracking environment of the upgrade already present now!

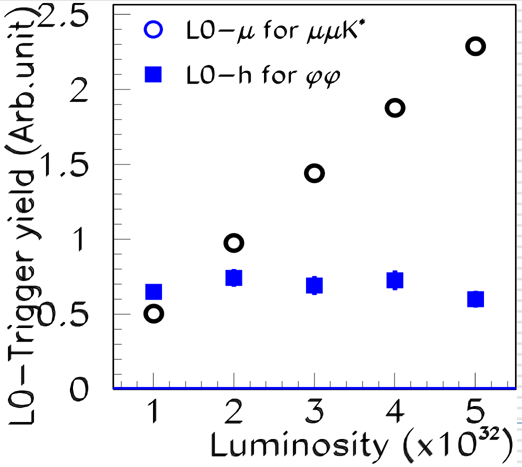
Future LHCb: Upgrade



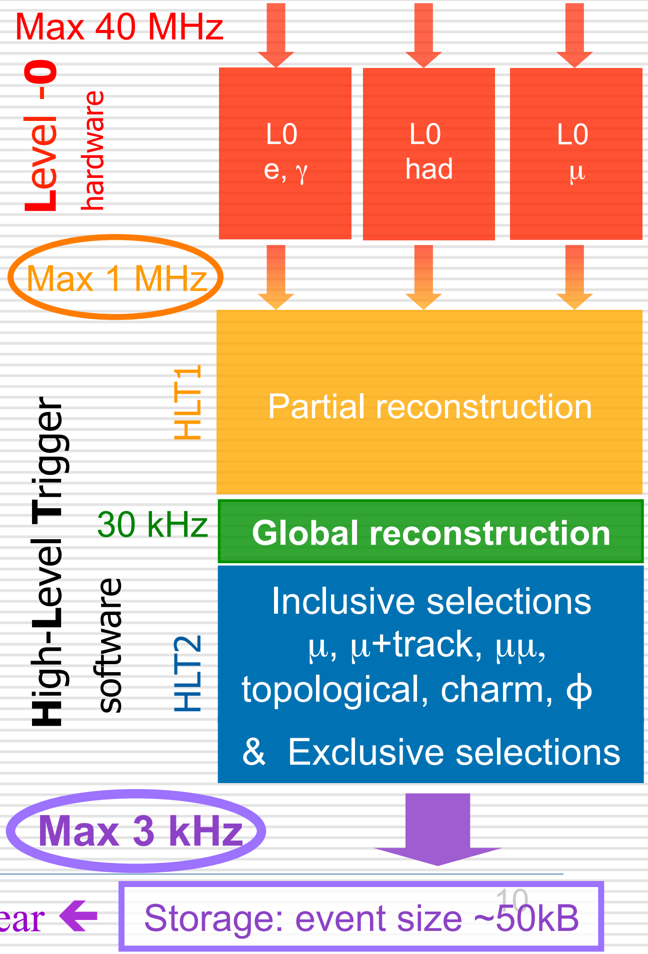
- Excellent performance of current detector in hadronic environment demonstrated:
  - vertexing, mass resolution, PID
  - High selectivity and low background
  - Very efficient trigger

2010	Muon trigger (J/ψ)	Hadron trigger (D^0)
Data	94.9±0.2%	60±4%
MC	93.3±0.2%	66%

- After recording ~5 fb^{-1} time to double stats is too slow ➔ increase $\mathcal{L}$ ➔ Level-0 trigger loses efficiency because the DAQ readout limited to 1MHz, E_T -cut raised...



Solution:
40MHz DAQ readout rate
Fully software trigger


Max 40 MHz

Level -0 hardware

L0 e, γ

L0 had

L0 μ

Max 1 MHz

HLT1 Partial reconstruction

30 kHz

Global reconstruction

High-Level Trigger software

HLT2 Inclusive selections
μ, μ+track, μμ,
topological, charm, ϕ
& Exclusive selections

Max 3 kHz

Storage: event size ~50kB

accumulate ~1fb⁻¹/year ←

Upgrade plot and strategy

- LHCb detector readout at 40MHz with a fully software based trigger:
  - ➢ Upgrade of all sub-detector Front-End electronics to 40 MHz readout
- Rebuild of all silicon detectors attached to the current 1MHz electronics
  - ➢ VELO, IT, TT, RICH photo-detectors
- Remove some detectors due to increased occupancies or no necesity at higher luminosity
  - ➢ RICH1-aerogel, M1, possibly PS&SPD
- Eventually improved PID a low momenta:

- Tight time schedule → try to optimize:
  - ➢ Cost
  - ➢ Manpower
  - ➢ Time (R&D, production, installation)

- Re-use existing electronics & infrastructure as much as possible
- Develop common solutions for use by all sub-detectors
  - ➢ e.g.: use GBT @ 4.8 Gbit/s with zero suppression ~ 13,000 links with 8,300 optical fibers already installed in LHCb

Upgraded LHCb

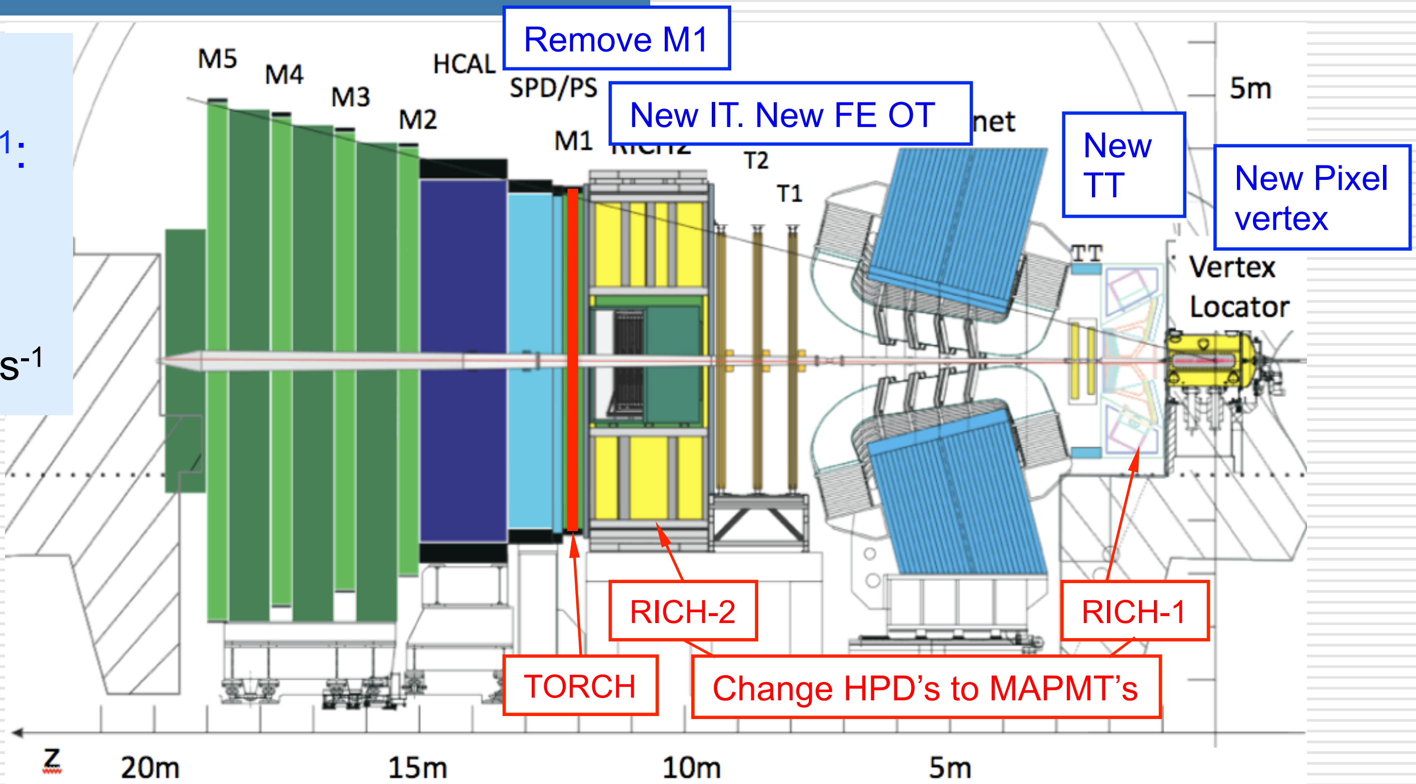
LHCb Upgrade:

- Collect 50 fb^{-1}:

  ~5 fb^{-1}/year

  $\sqrt{s}$ = 14 TeV

  $\mathcal{L} = 10^{33}\ \text{cm}^{-2}\text{s}^{-1}$



Remove M1

New IT. New FE OT

New TT

New Pixel vertex

RICH-2

RICH-1

TORCH

Change HPD's to MAPMT's

- Mission of upgrade LHCb:
  - General purpose detector in the forward region with a 40 MHz Readout and a full software trigger.
  - Quark flavour physics main component but expand physics program to include:
    - Lepton flavour physics
    - Electroweak physics
    - Exotic searches
  - Possible due to full software trigger

Upgraded LHCb environment: $\mathcal{L}$ & Pile-up

LHCb operation (design):

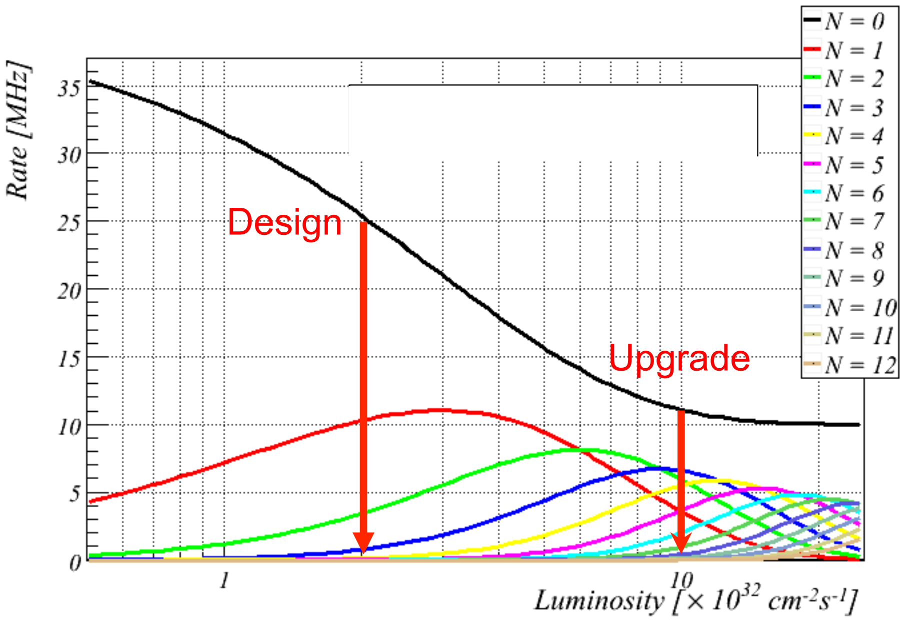
- $\mathcal{L} \sim 2 \times 10^{32}$ cm^{-2}s^{-1} with 25ns BX-ings
  - → ~ 10 MHz xings with ≥ 1 interaction
  - → $\mu^{*} \sim 0.42$

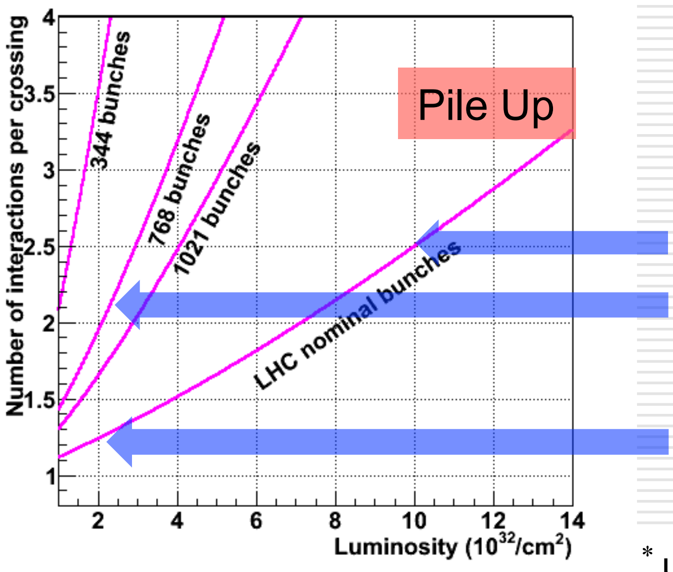
Upgrade operation:

- $\mathcal{L} \sim 1 \times 10^{33}$ cm^{-2}s^{-1} with 25ns BX-ings
  - → ~ 26 MHz xings with ≥ 1 interaction
  - → $\mu \sim 2.13$

Current operation:

- LHC has < 2622 bunches so the μ ~2

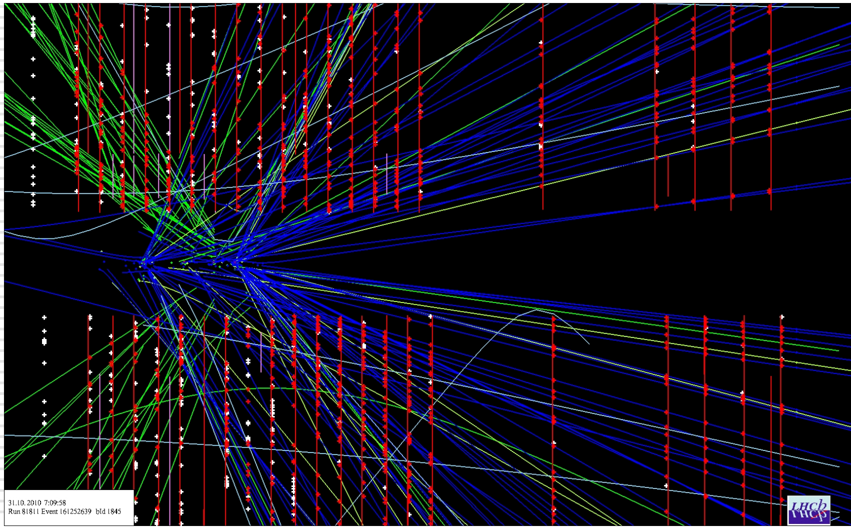




Upgrade

Current

Design



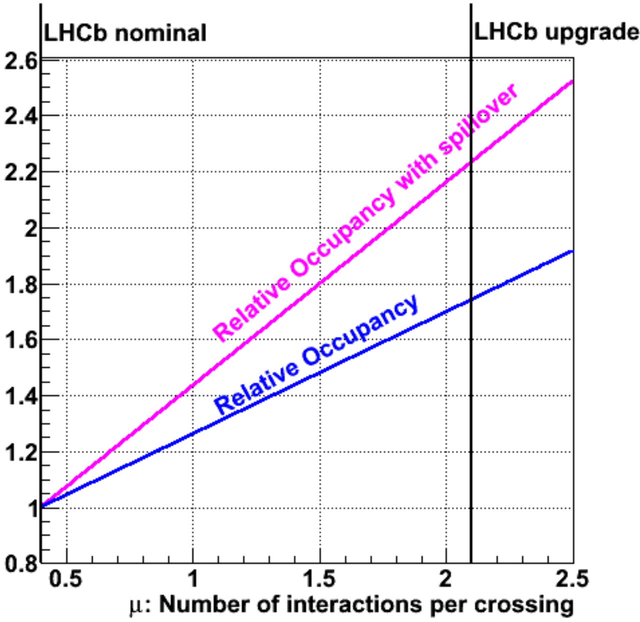
* μ = number of visible pp collisions per bunch crossing

Upgraded LHCb environment: Occupancies & Irradiation

Tracking and Occupancy:

- Si can be operated without spillover
- Outer Tracker straws: occupancy at limit
- Good PR experience now from 50 ns running
- Increase area coverage of IT and use faster gas
- Move to scintillating fibres

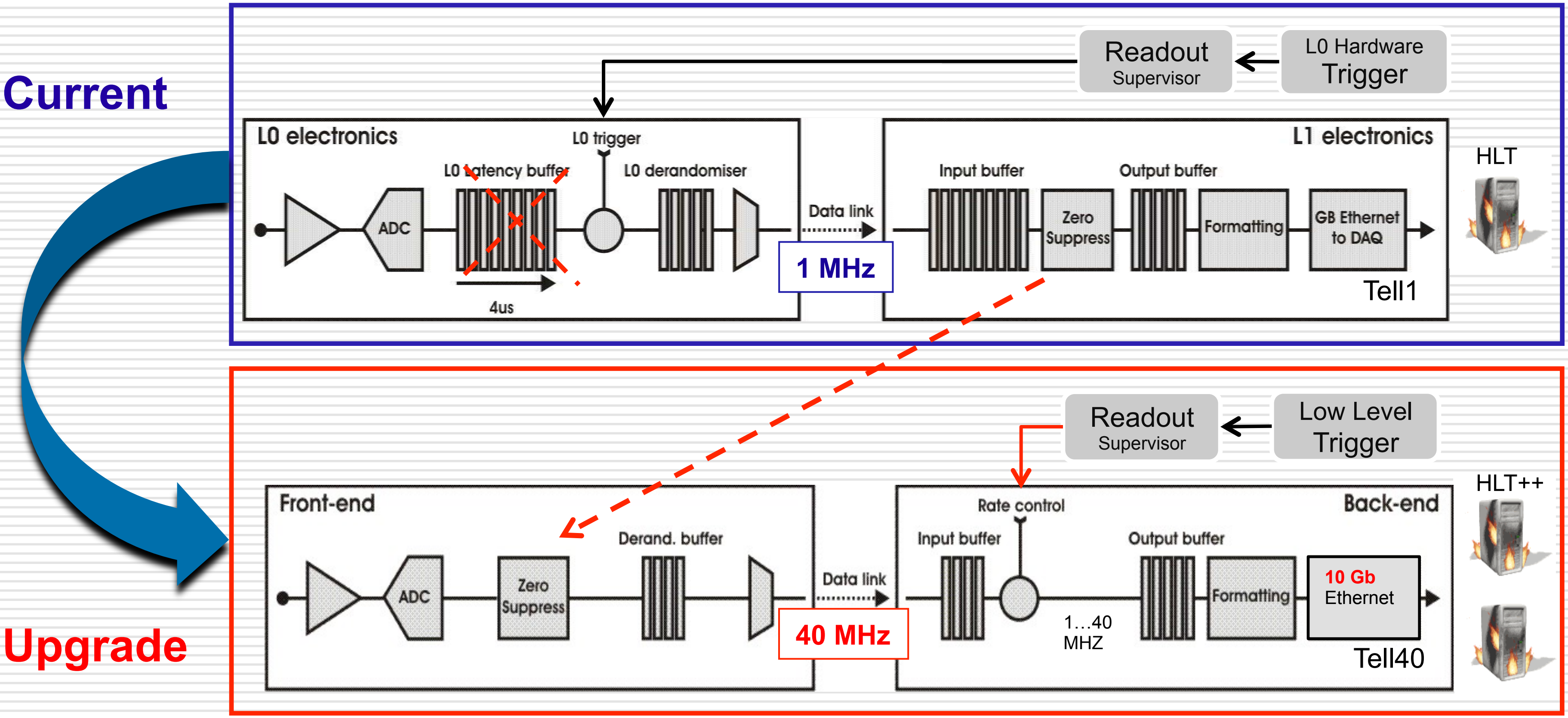
Material Budget an important issue (occupancy, momentum resolution)



Irradiation:

- Integrated dose up by a factor 10
- Affects mainly large η (trackers, inner part of calorimeter)
- Silicon will anyway be replaced and cooling optimised
- Experience from current experiment will guide decisions

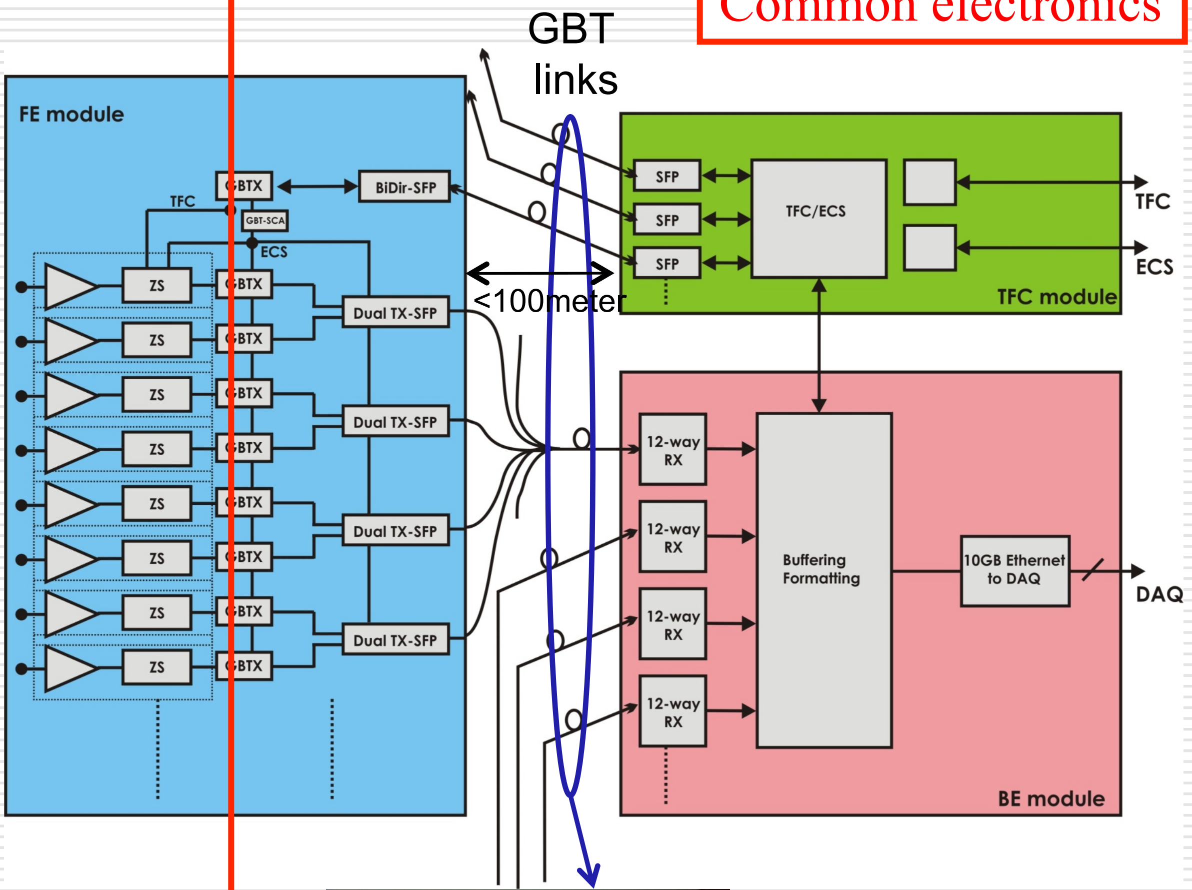
Common DAQ architecture



- Front-end electronics should:
  - Transmit collision data @ 40 MHz
  - Zero-suppress to minimize data bandwidth
- The L0 hardware trigger is re-used to reduce the event rate to match the installed router and CPU farm capacity (staging). Initially run at 5~10 MHz

Generic sub-detector readout &control:

Common electronics



Bundle of 8 x 12 way ribbon

- Number of GBT links:

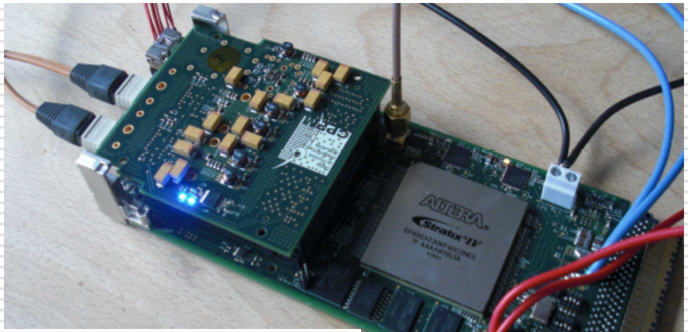
	Data	TFC/ ECS
Velo	2496	52
OT	3456	72
ST	1200	~100
RICH	2476	~200
Calo	952	238
Muon	1248	104
Total =	11684	766

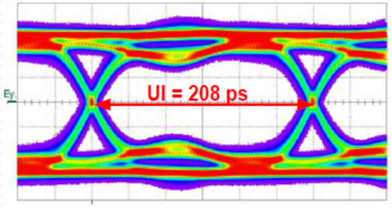
- Total optical links required ~ 13000
- Current LHCb has already 8300 links installed

Common developments

TELL40: Common **Back-End** readout **module**:

- Modular mezzanine-based approach (diff tasks)
- Processing in FPGAs
- Format: Advanced-TCA motherboard (under investigation)
- Tests of high-speed links on proto-board: 12-way Optical I/Os (12 x > 4.8 Gb/s), GBT compatible
- 24 channels/mezzanine ➔ up to 96/BE module
- Transmission to the DAQ using 10 Gb Ethernet

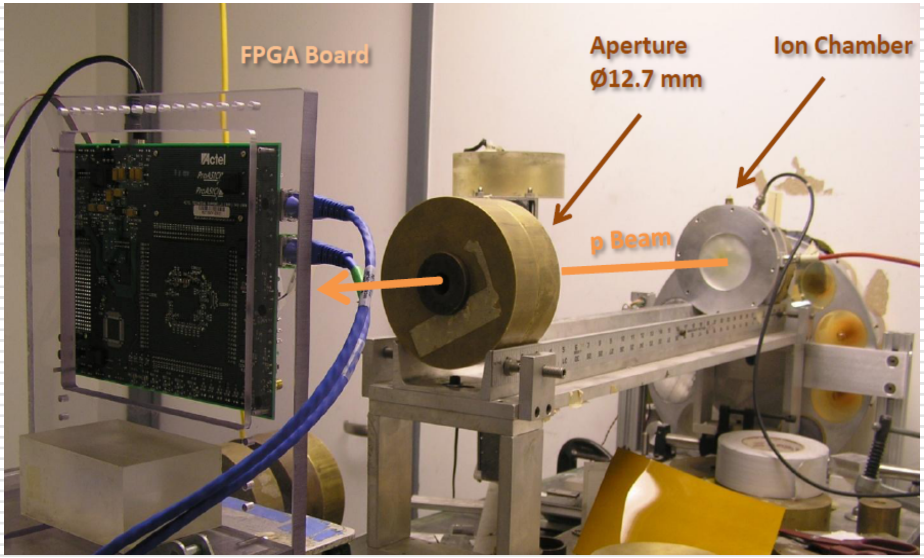




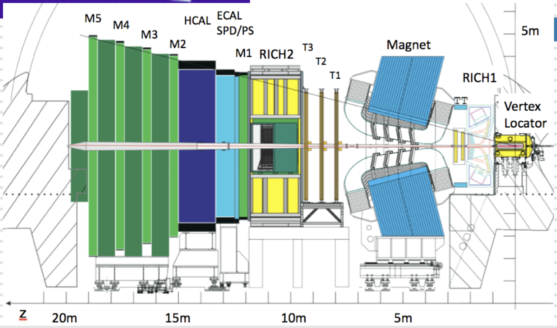
Eye-diagram from one channel @ 4.8 Gbit/s

ACTEL Flash FPGA for front-end modules

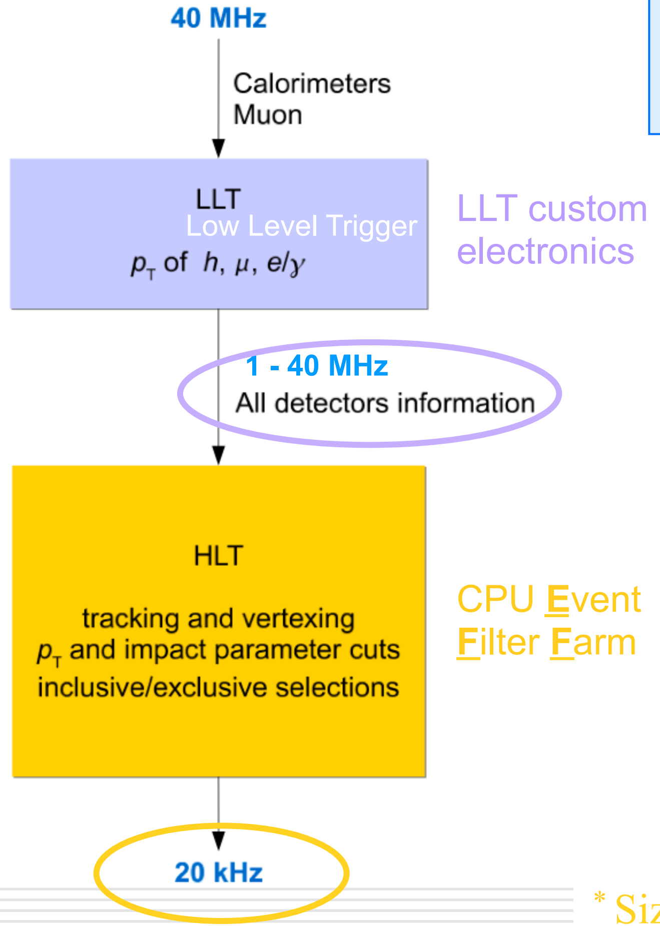
- Advantages over ASICs: re-programmable, faster development time.
- Can they survive the radiation?
- Irradiation program started on A3PE1500
  - Preliminary results up to 30 krad ok.



Upgrade LHCb Trigger *



- ✓ flexible software trigger with up to **40 MHz input rate and 20 kHz output rate**
- ✓ trigger has all the event information
- ✓ runs in a stageable Event Filter Farm
- ✓ run at **5 times LHCb** luminosity (→ $\mathcal{L} = 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$)
- ➢ big gain in signal efficiency with **up to factor 7** for hadronic modes



40 MHz

Calorimeters
Muon

LLT
Low Level Trigger
p_T of h, μ, e/γ

LLT custom electronics

1 - 40 MHz
All detectors information

HLT

tracking and vertexing
p_T and impact parameter cuts
inclusive/exclusive selections

CPU Event Filter Farm

20 kHz

Signal efficiencies

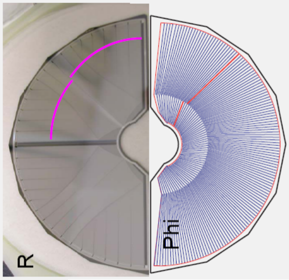
LLT-rate (MHz)	1	5	10
$B_s \to \phi\phi$	0.12	0.51	0.82
$B^0 \to K^*\mu\mu$	0.36	0.89	0.97
$B_s \to \phi\gamma$	0.39	0.92	1.00

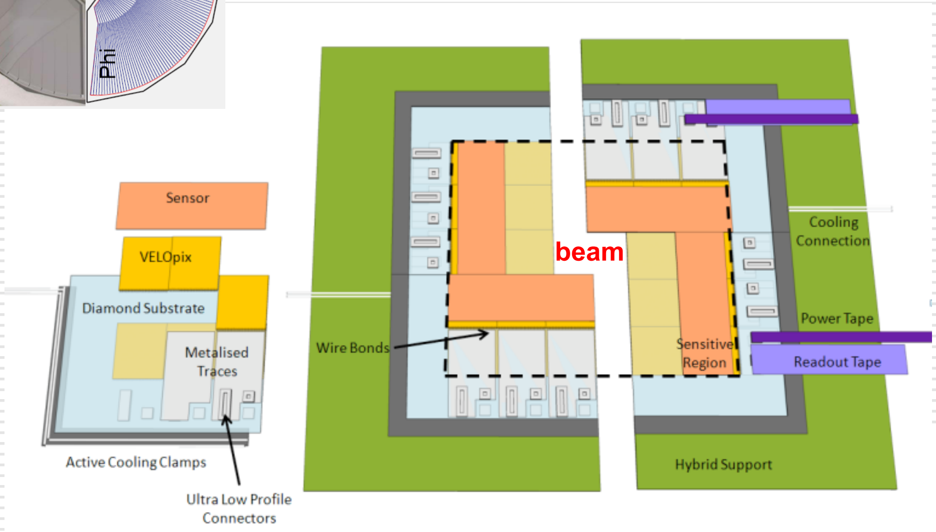
EFF size *	5×2011	10×2011
LLT-rate (MHz)	5.1	10.5
HLT1-rate (kHz)	270	570
HLT2-rate (kHz)	16	26
Total signal efficiency		
$B_s \to \phi\phi$	0.29	0.50
$B^0 \to K^*\mu\mu$	0.75	0.85
$B_s \to \phi\gamma$	0.43	0.53

* See talk by Roel Aaij

* Size of the Event Filter Farm available for the 2011 run

VELO UPGRADE*



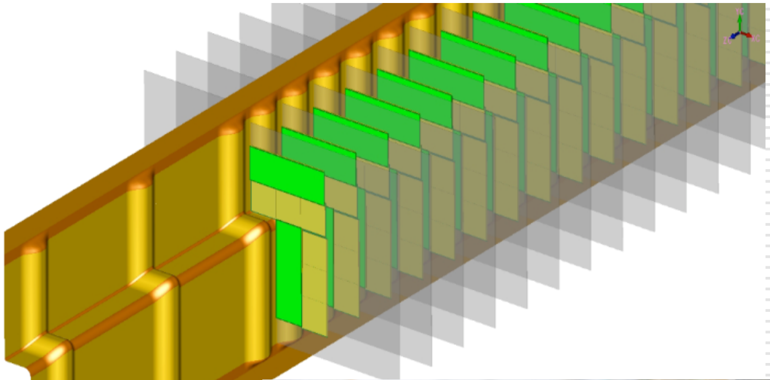


NEW VELO @ 40MHz Readout

- Challenges: Data rates $<rate_{max}> = 200MHz\ cm^{-2}$
  Irradiations$_{max}$= 5.10^{15} 1 MeV $n_{eq}cm^{-2}$
  Low material budget
- PIXEL Detector: VELOPIX based on TimePix
  - 55 µm x 55 µm pixel size
  - CVD Diamond substrate
- Strip detector: minimum pitch 30 µm improved geometry

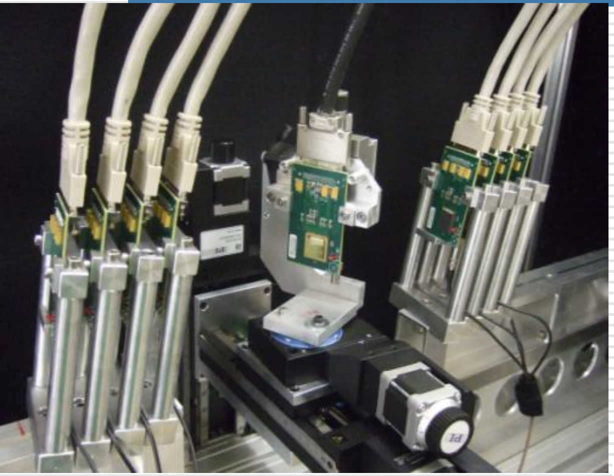
R&D ongoing

- Module layout and mechanics
- Sensor options:
  - Planar Si, 3D, Diamond
- CO_2 cooling
- FE electronics
- RF-foil of vacuum box

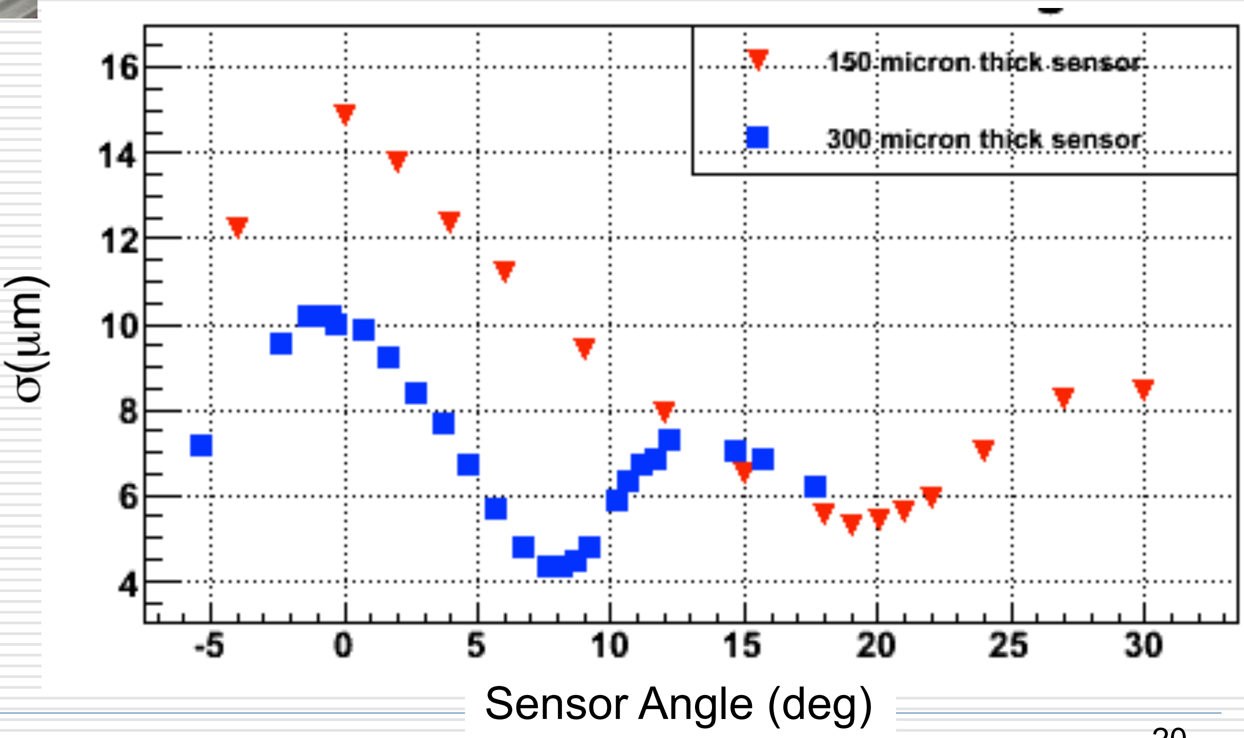


* See talk by Daniel Hynds

VELO-Pixel R&D

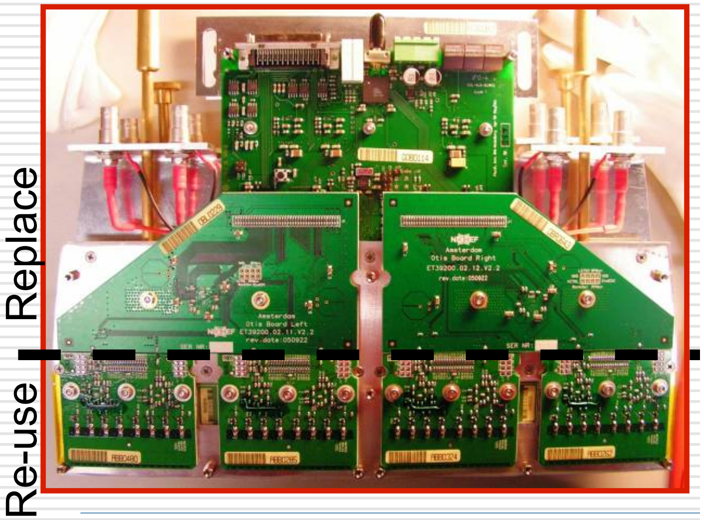


- Test Beam TimePix Telescope
- Results:
  - 2011 *JINST* **6** P05002 doi: 10.1088/1748-0221/6/05/P05002
  - arXiv:1103.2739v2 [physics.ins-det]

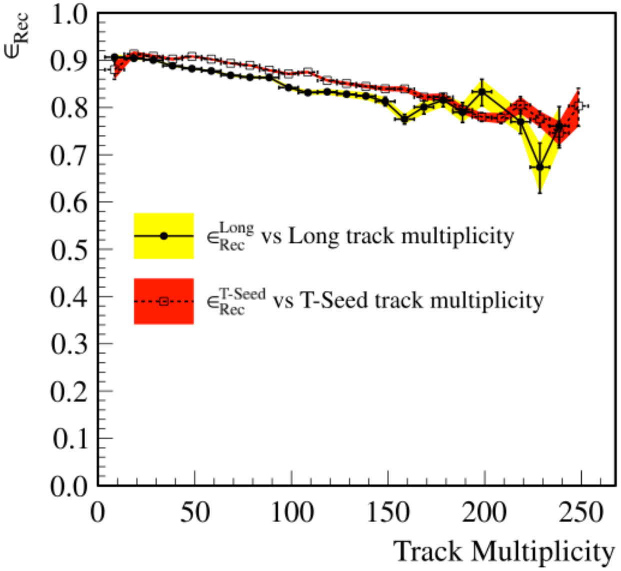


Main Tracker stations upgrade: OT, IT, TT

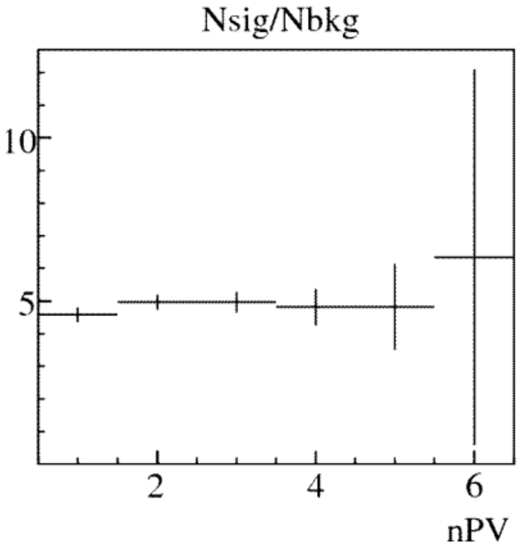
- Current tracker works already with upgrade level pile-up (but not yet with spill-over)
- OT straw detector remains
  - ➢ Detector aging in hot area is still under investigation
  - ➢ Consider module replacements with 1mm Scintillating Fiber Tracker in hottest region, increase granularity. In conjunction with IT replacement.
  - ➢ Replace on-detector electronics by 40 MHz version (FPGA-TDCs):
    - ➢ re-use front-end
    - ➢ implement TDC (1ns) in ACTEL ProASIC FPGA
    - ➢ prototype already working



tracking efficiency vs. multiplicity

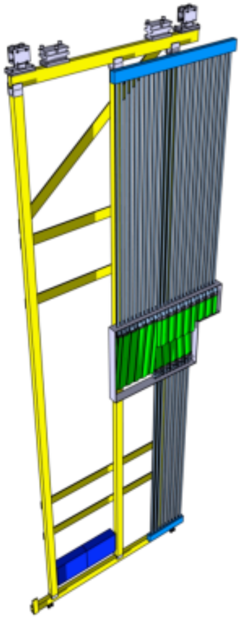


Nsig/Nbkg for B→J/ψK^+

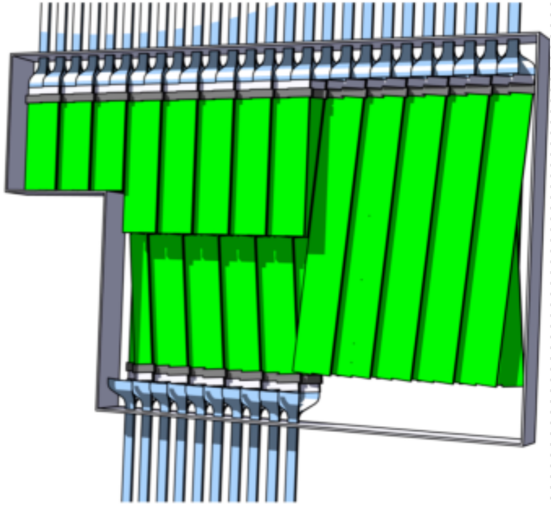


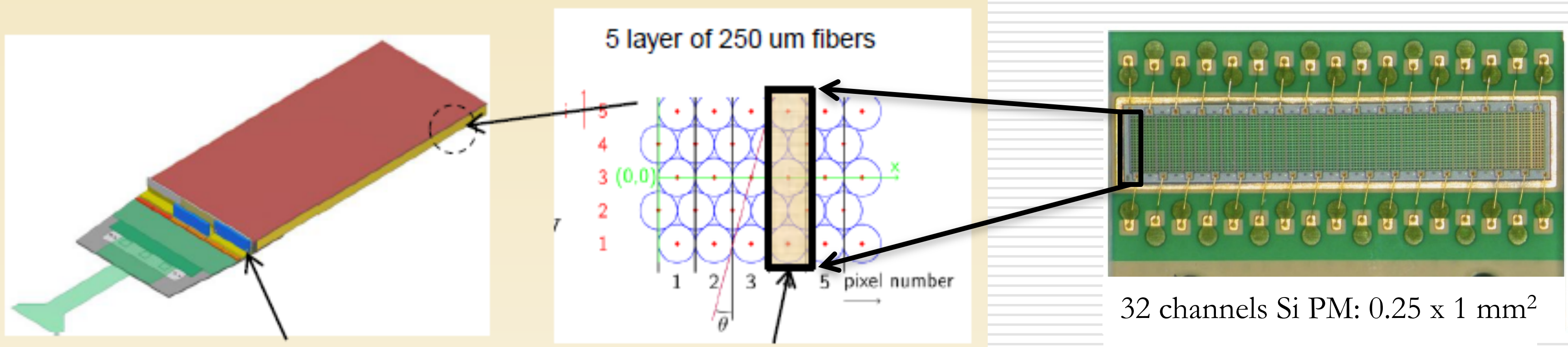
Main Tracker stations upgrade: OT, IT, TT

- Current IT and TT Si-strip detectors must be replaced:
  - 1 MHz Readout electronics integrated
- Two technologies:
  - Silicon strips:
    - Development of a new rad-hard FE chip @ 40MHz
  - 250 µm Scintillating Fiber Tracker
    - 8 layers (same X_0 as the Si-strip option)
    - Fibers coupled to a Silicon Photo-Multiplier (SiPM)
    - Signals outside acceptance with clear fibers:
      - SiPM shielding
      - Cooling, electrical components
    - SiPM radiation tolerance under investigation
    - ASIC to read out the SiPM under investigation



IT-fiber detector layout:





SiPM array

SiPM cell coverage

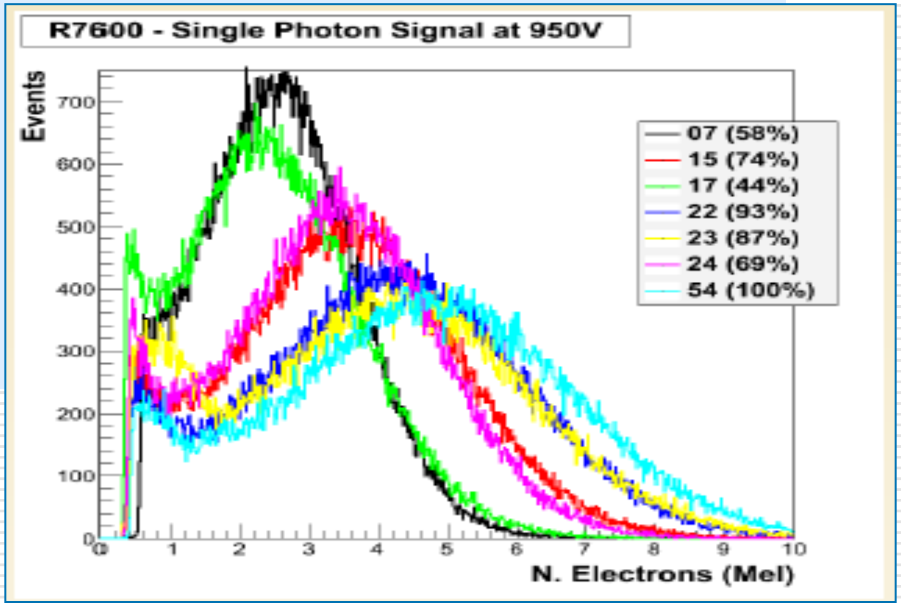
32 channels Si PM: 0.25 x 1 mm^2

128 channels SiPM available

PID upgrade: RICH detectors

- RICH-1 and RICH-2 detectors are retained, replace HPDs (1 MHz internal Readout):
  - ➢ Baseline readout: replace pixel HPDs by MaPMTs & readout with 40 MHz custom ASIC
- Baseline MaPMTs (Hamamatsu):

Under development @ Hamamatsu



R7600 vs R11265 (baseline):

8x8 pixels, 2.0x2.0 mm^2, 2.3 mm pitch (2.9 mm)
18.1x18.1 mm^2 active area (23.5x23.5 mm^2)
CE (simulation) : 80% (90%)
Fractional coverage: 50% (80%)

Prototyping using 40 MHz Maroc-3 RO chip:

- Gain compensation
- Binary output

Digital functions in ACTEL Flash FPGA FE module.

R7600 characterization:

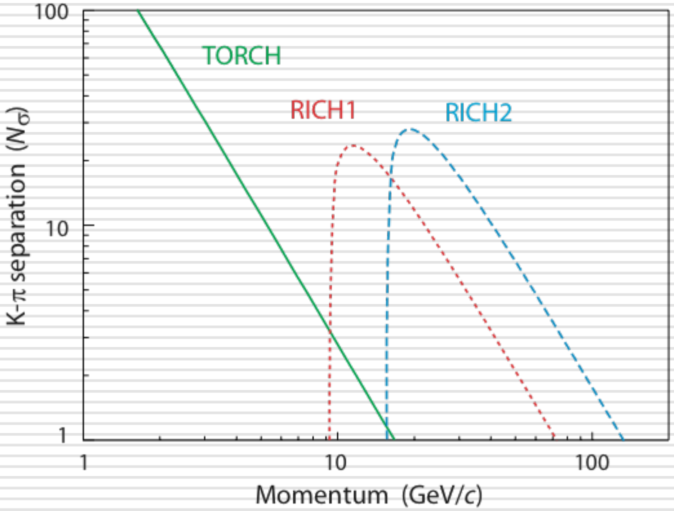
- Channel to channel gain variation (correction in FE)
- Excellent cross-talk (below 1%)
- ~10% gain reduction in 50 gauss B_L-field (25 gauss max B_L-field in LHCb)

3712 R7600/R11265 units for RICH1&2 ~238k #

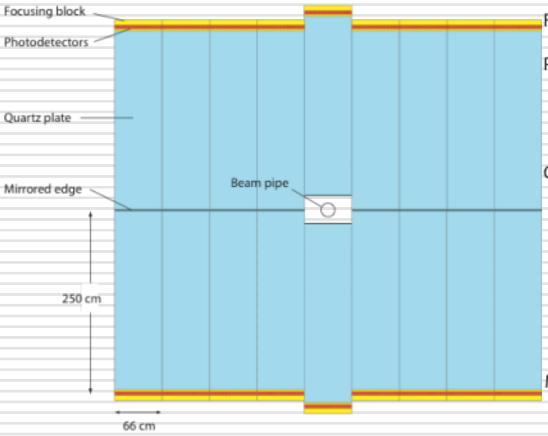
PID upgrade: TORCH

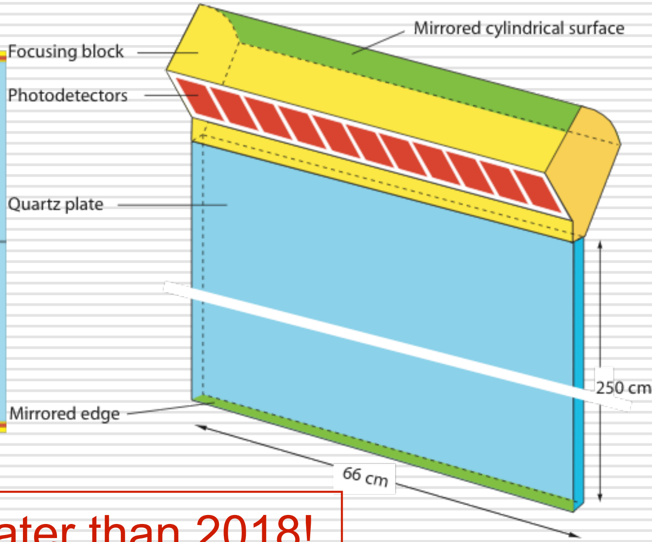
- Time of Flight detector based on a 1 cm quartz plate, for the identification of p<10 GeV hadrons (replacing Aerogel) combined with DIRC technology:
  - ➢ TORCH=Time Of internally Reflected Cherencov light*
  - ➢ reconstruct photon flight time and direction in specially designed standoff box
  - ➢ Measure ToF of tracks with ~15 ps (~70 ps per photon)

K-π separation vs p in upgrade:



TORCH detector:





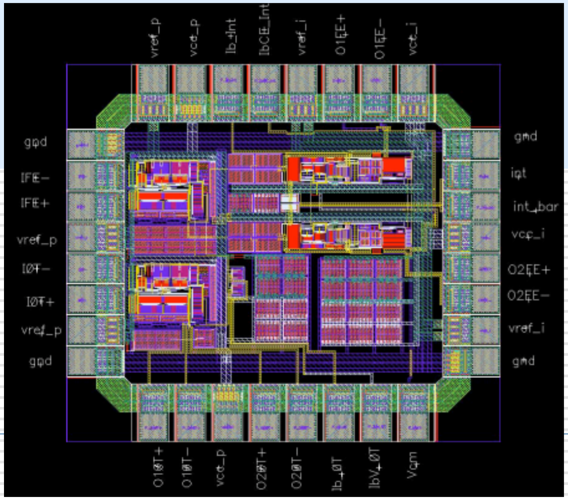
→ could be installed later than 2018!

* See talk by Neville Harnew

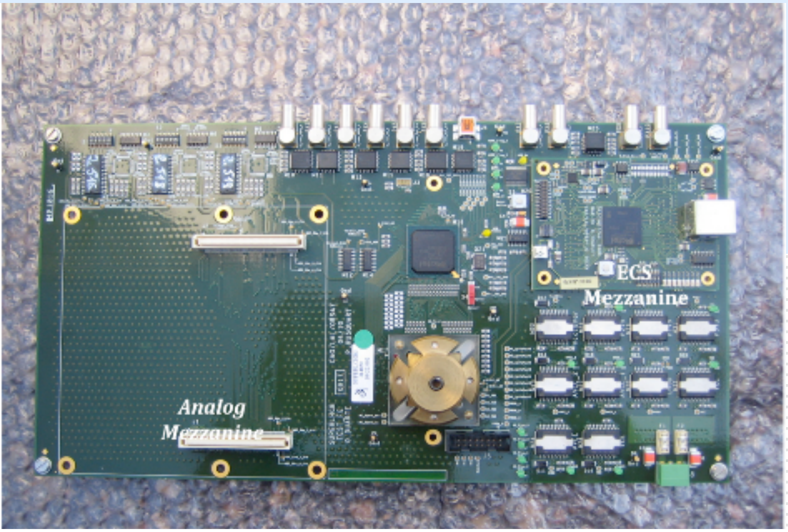
Calorimeters Upgrade

- ECAL and HCAL remain
  - ➢ Keep all modules & PMTs
    - ➢ Radiation tolerance of inner modules being assessed @ LHC tunnel
  - ➢ Reduce the PMTs gain by a factor 5 to keep same <current>
- PS and SPD might be removed (under study)
  - ➢ (e/γ/hadron separation later in HLT with the whole detector info.)
- New FEE to compensate for lower gain and to allow 40 MHz readout:
  - ➢ Analogue part: ASIC or Discrete* components solutions (keeping noise ≤1 ADC cnt (ENC < 5-6 fC))
  - ➢ Digital part: prototype board to test FPGAs (flash/antifuse) for:
    - ➢ Radiation tolerance
    - ➢ Packing of Data @ 40 MHz

ASIC prototype



New digital electronics prototype



* See poster by Carlos Abellán

Muon Detector Upgrade

- Muon detectors are already read out at 40 MHz in current L0 trigger
  - Front-end electronics can be kept
  - Remove detector M1 (background and upgraded L0(LLT), room for TORCH)
- Investigations:
  - MWPC aging :
    - tested at two sites up to 0.25 C/cm and 0.44 C/cm with no loss of performance
    - 1C/cm is considered as an upper limit for safe operation of MWPC chambers
  - Rate limitations of chambers and FE:
    - High-rate performance tested @ CERN-GIF no saturation effect up to 30nA/cm^2 (factor 2 for 10^{33})
    - No deterioration in the FE electronics up to 1MHz

Accumulated charge (C/cm) for 50 fb^{-1}

	R1	R2	R3	R4
M2	0.67	0.42	0.10	0.02
M3	0.17	0.08	0.02	0.01
M4	0.22	0.06	0.01	0.004
M5	0.15	0.03	0.01	0.003

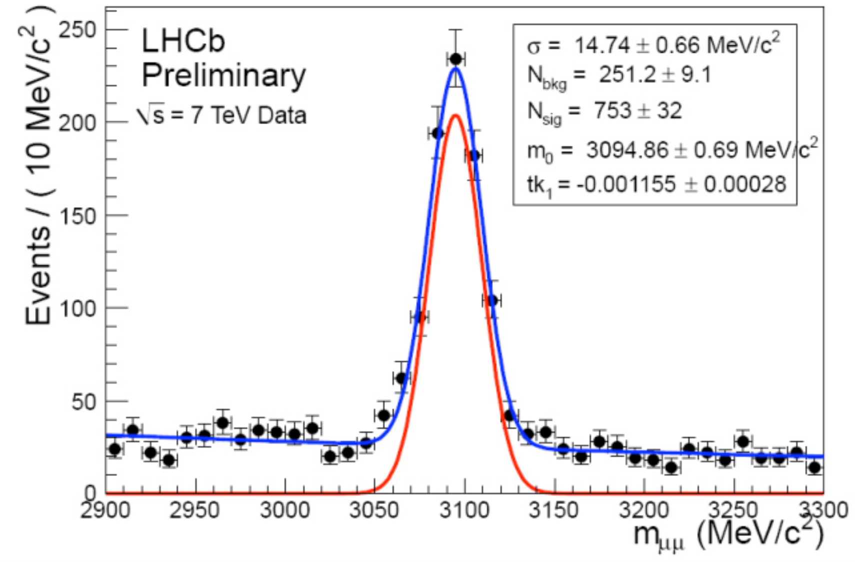
Maximum rates/channel MHz @ 10^{33} cm^{-2}s^{-1}

	R1	R2	R3	R4
M2	0.81	0.55	0.12	0.10
M3	0.24	0.11	0.03	0.04
M4	0.09	0.07	0.04	0.03
M5	0.07	0.07	0.04	0.02

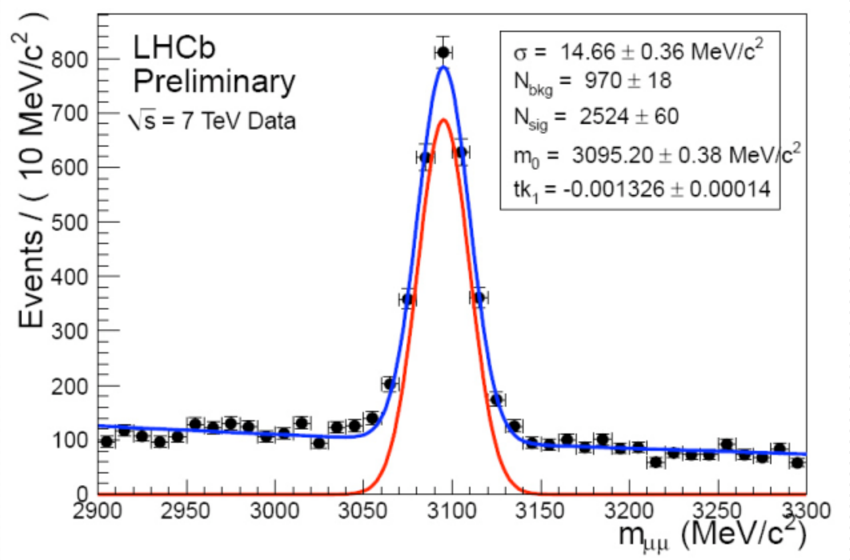
Muon Detector Upgrade

- Performance at higher occupancy: OK
  - Studied with real data July-October 2010 <PV> ≥ 2.
  - After retuning the Muon ID algorithm the J/ψ :
    - Worsening S/B ≤ 15%
    - Efficiency loss ≤ 5%

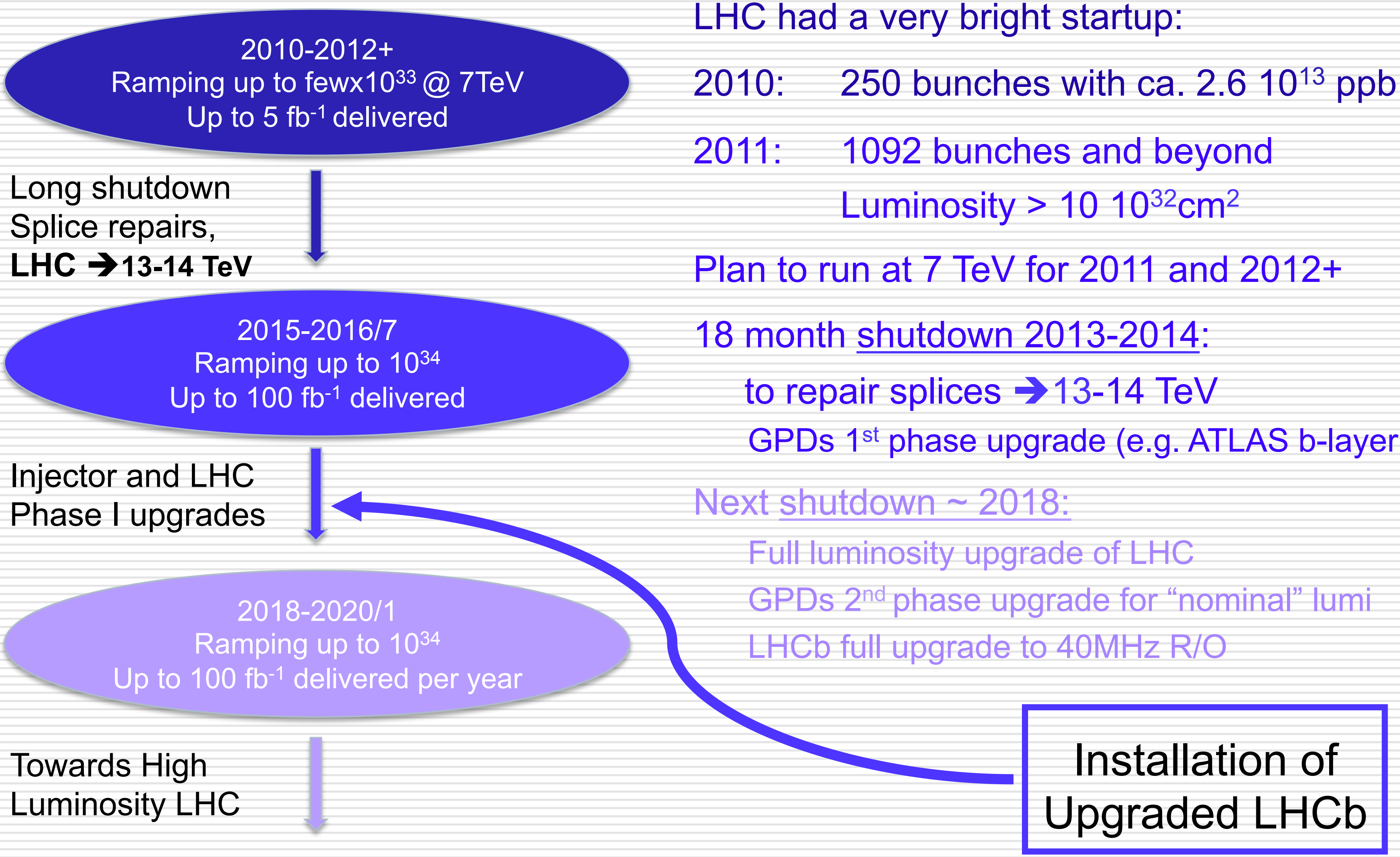
J/ψ → $\mu^+ \mu^-$ for single PV events



J/ψ → $\mu^+ \mu^-$ for events with <PV>=2.3



A possible schedule*



2010-2012+
Ramping up to fewx10^{33} @ 7TeV
Up to 5 fb^{-1} delivered

Long shutdown
Splice repairs,
LHC → 13-14 TeV

2015-2016/7
Ramping up to 10^{34}
Up to 100 fb^{-1} delivered

Injector and LHC
Phase I upgrades

2018-2020/1
Ramping up to 10^{34}
Up to 100 fb^{-1} delivered per year

Towards High
Luminosity LHC

LHC had a very bright startup:

2010: 250 bunches with ca. $2.6\ 10^{13}$ ppb

2011: 1092 bunches and beyond
Luminosity > $10\ 10^{32}$cm^2

Plan to run at 7 TeV for 2011 and 2012+

18 month shutdown 2013-2014:

to repair splices → 13-14 TeV
GPDs 1st phase upgrade (e.g. ATLAS b-layer)

Next shutdown ~ 2018:

Full luminosity upgrade of LHC
GPDs 2nd phase upgrade for "nominal" lumi
LHCb full upgrade to 40MHz R/O

Installation of
Upgraded LHCb

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* Different scenarios under discussion at present between CERN and Experiments

Summary

- The LHCb experiment has demonstrated very successful operation in a hadronic and high multiplicity environment in 2010 & 2011:
  - Excellent vertexing, PID and tracking performances give confidence that the upgrade will be successful
- LHCb has a firm plan to upgrade in 2018:
  - Read out entire detector at 40 MHz with a fully software-based trigger @ $\mathcal{L} \sim 10^{33}$ cm^{-2} s^{-1}
  - Massive statistical power
  - Independent of the LHC luminosity upgrade
  - No major detector changes needed, except for VELO, ST and RICH
  - The sub-detectors electronic developments are well underway
- Given its forward geometry, its excellent tracking and PID capabilities and the foresee flexible software-based trigger, the upgraded LHCb detector:
  - is an ideal detector for the next generation of quark flavour physics experiments
  - provides unique and complementary capabilities for New Physics studies beyond flavour physics
- Submitted upgrade LOI to LHCC beginning of March [CERN-LHCC-2011-001]

Back-up slides

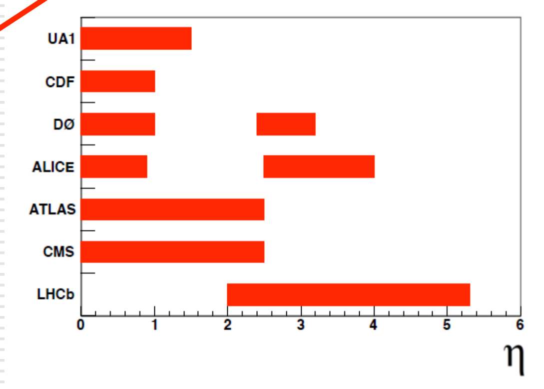
LHCb Upgrade Physics program

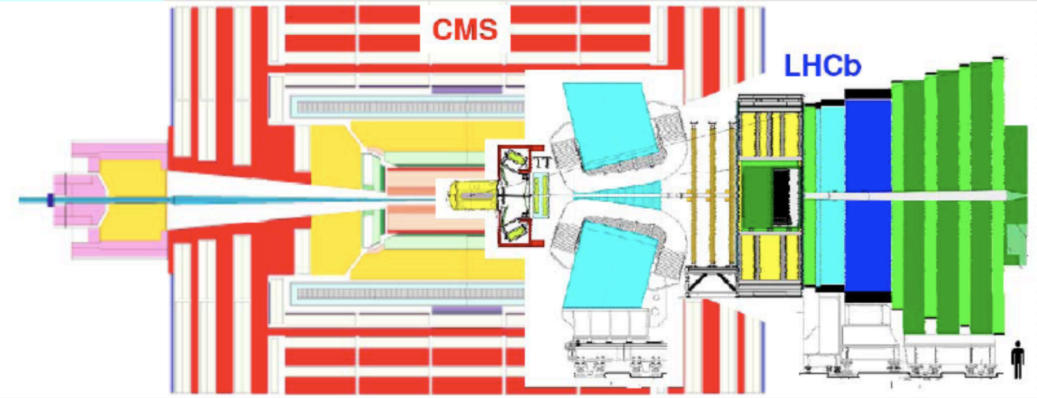
- Quark Flavour Physics
  - CPV in b-decays:
    - in B_s oscillations
    - in charmless hadronic decays
    - measurement of gamma
  - Rare b-decays
  - Charm Physics

- Lepton Flavour Physics
  - Searches for Majorana neutrinos
  - Lepton Flavour Violating tau decays

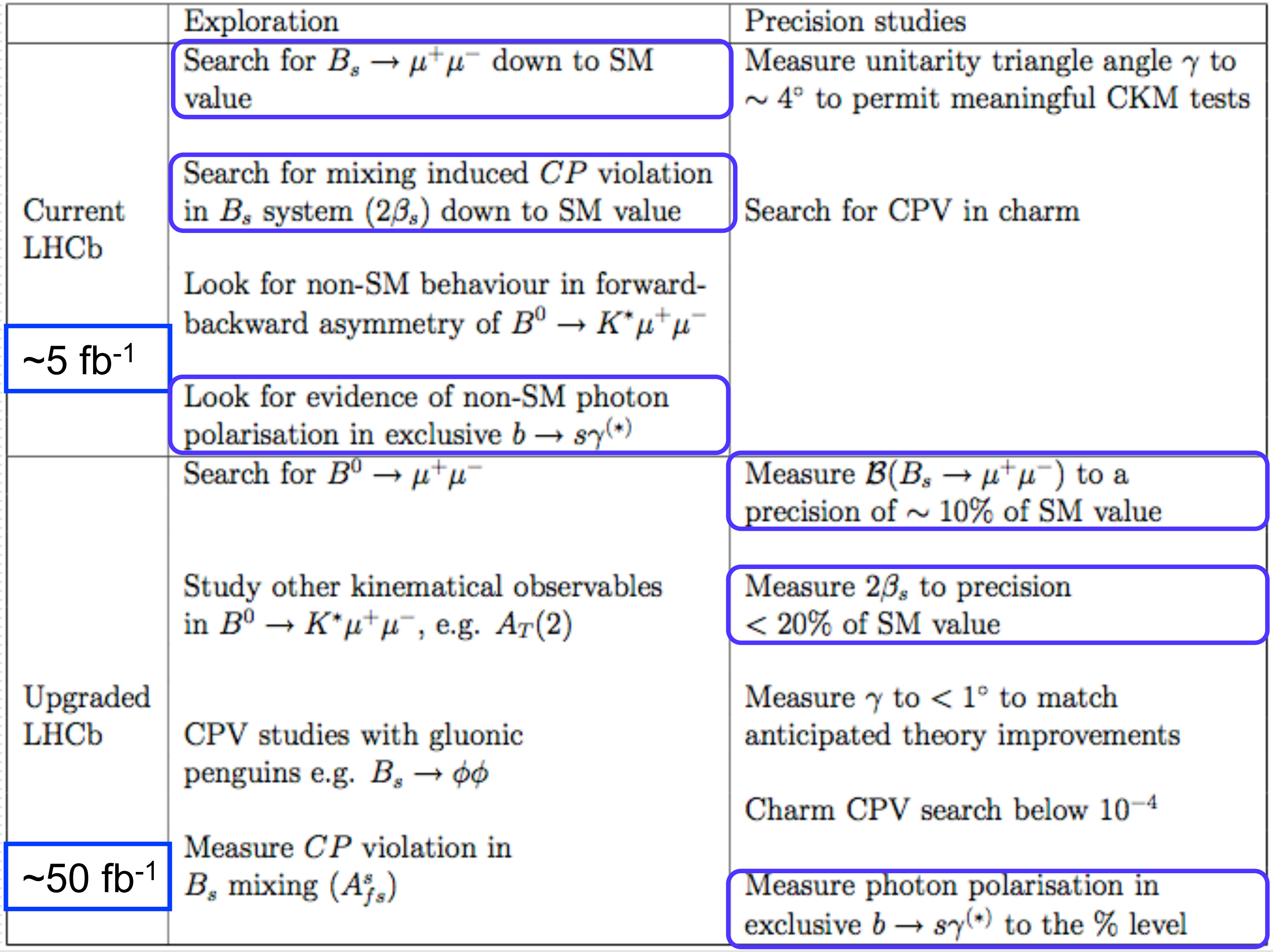
- Physics Beyond Flavour
  - Electroweak Physics
  - Exotics
  - Central Exclusive Production

Complementary Acceptance
+
Excellent vertexing and PID
+
Software-based trigger





Quark flavour physics goals overview



	Exploration	Precision studies
Current LHCb ~5 fb^{-1}	Search for $B_s \to \mu^+\mu^-$ down to SM value	Measure unitarity triangle angle γ to $\sim 4^\circ$ to permit meaningful CKM tests
	Search for mixing induced CP violation in B_s system ($2\beta_s$) down to SM value	Search for CPV in charm
	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 $b \to s\gamma^{(*)}$	
Upgraded LHCb ~50 fb^{-1}	Search for $B^0 \to \mu^+\mu^-$	Measure $\mathcal{B}(B_s \to \mu^+\mu^-)$ to a precision of $\sim 10\%$ of SM value
	Study other kinematical observables in $B^0 \to K^*\mu^+\mu^-$, e.g. $A_T(2)$	Measure $2\beta_s$ to precision $< 20\%$ of SM value
	CPV studies with gluonic penguins e.g. $B_s \to \phi\phi$	Measure γ to $< 1^\circ$ to match anticipated theory improvements
		Charm CPV search below 10^{-4}
	Measure CP violation in B_s mixing (A^s_{fs})	Measure photon polarisation in exclusive $b \to s\gamma^{(*)}$ to the % level