The LHCb Upgrade

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For the LHCb collaboration

- Flavour Physics goals at the LHC.
- Performance vs Pileup.
- The Trigger.
- The upgrade in a nutshell.
- Upgrading the detector:
  - FE-electronics.
  - Tracking detectors.
  - PID detectors.
- Conclusions.

Physics Goals in a Nutshell

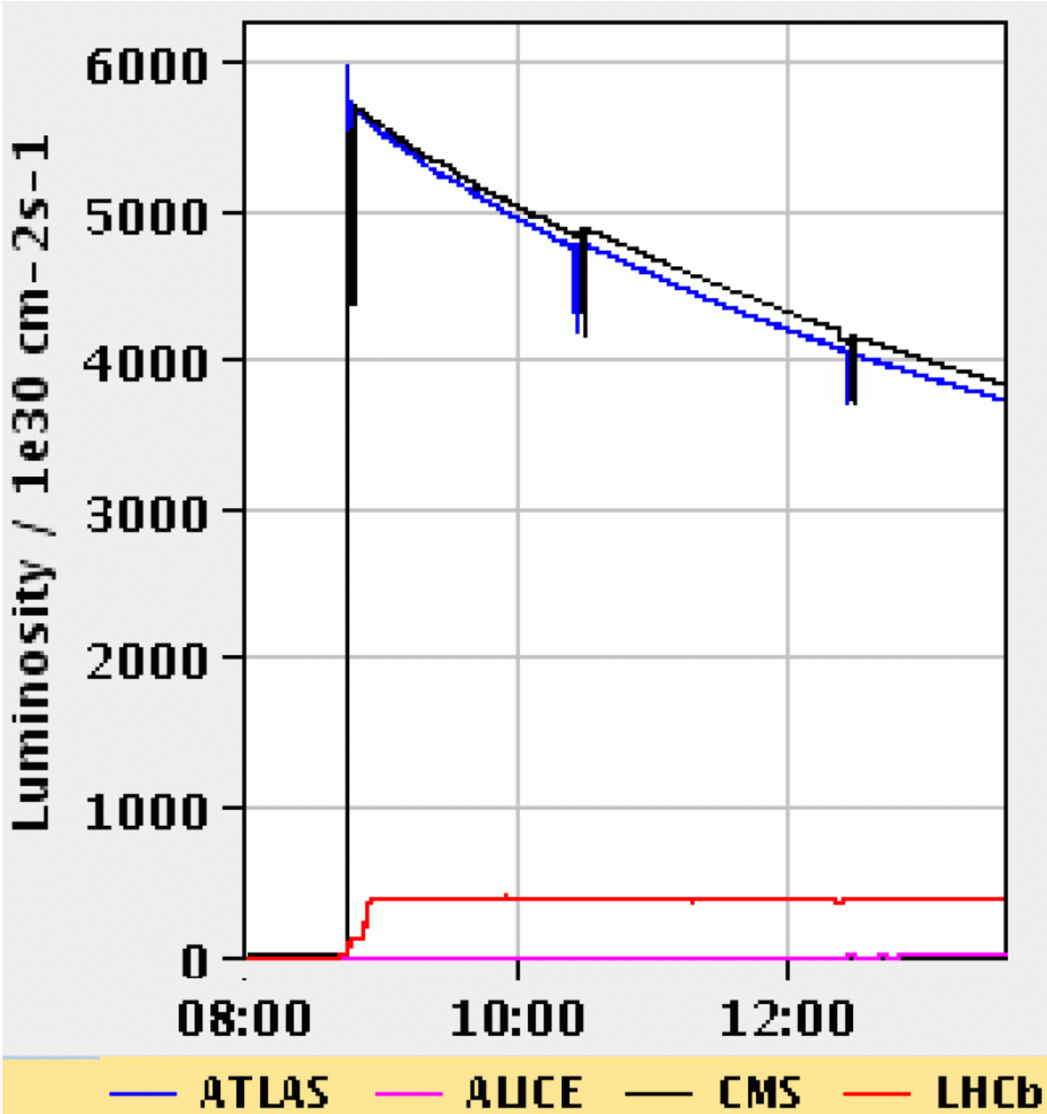
- 2011: LHCb Upgrade LOI
  http://cdsweb.cern.ch/record/1333091/files/LHCC-I-018.pdf
- Current→upgrade: $\int L =\sim\ 5 \to 50\text{fb}^{-1}$

	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

LHCb and LHC

Snapshot LHC status "page 1":

- Much lower lumi than GPDs
- No lumi-decay in LHCb:
  - Squeeze to β^*=3 m, but offset beams.
  - Reduce offset every 10-15 min to keep same lumi.
  - Run at $4 \times 10^{32}\text{cm}^{-2}\text{s}^{-1}$ for ~ 15 h.
- LHC could deliver $> 10^{33}\text{cm}^{-2}\text{s}^{-1}$ at LHCb already today.
- Can LHCb take this today?



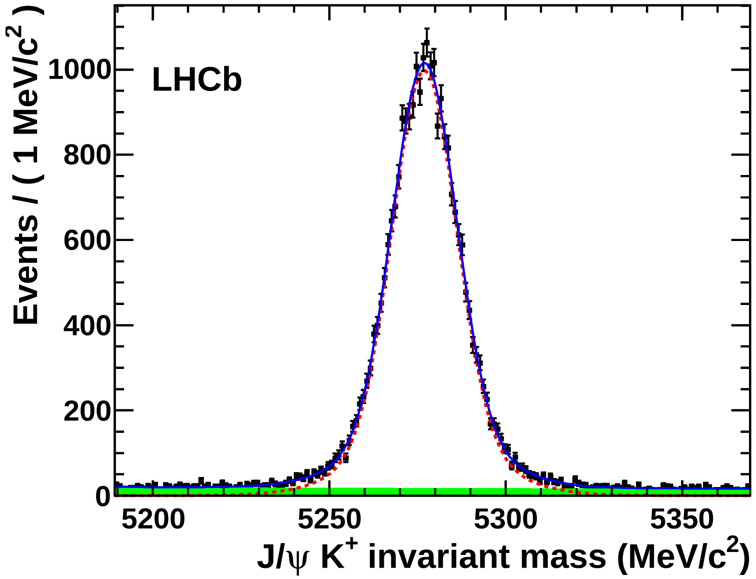
Performance and Pileup

Very clean signal-background separation:

- σ(PV): x,y$\sim 10\ \mu$m, z$\sim 60\ \mu$m
  $90\ \%$ of PV distributed over 20 cm in z.
- $\sigma(\tau_B) \sim 40$ fs, compared to $\tau_B = 1.5$ ps.
- $\Delta p/p$: 0.4-0.6 $\%$.
- RICH-PID:
  $\varepsilon(\mathrm{K} \rightarrow \mathrm{K}) \sim 95\ \%$, mis-ID $(\pi \rightarrow \mathrm{K}) \sim 5\ \%$.
- Muon-PID:
  $\varepsilon(\mu \rightarrow \mu) \sim 97\ \%$, mis-ID $(\pi \rightarrow \mu) \sim 1-3\ \%$.
- $\Delta(E_\gamma)/E_\gamma \sim 0.1/\sqrt{E} \oplus 0.01$ (E in GeV).

B S/N almost independent of pileup

D S/N shows some degradation vs pileup.



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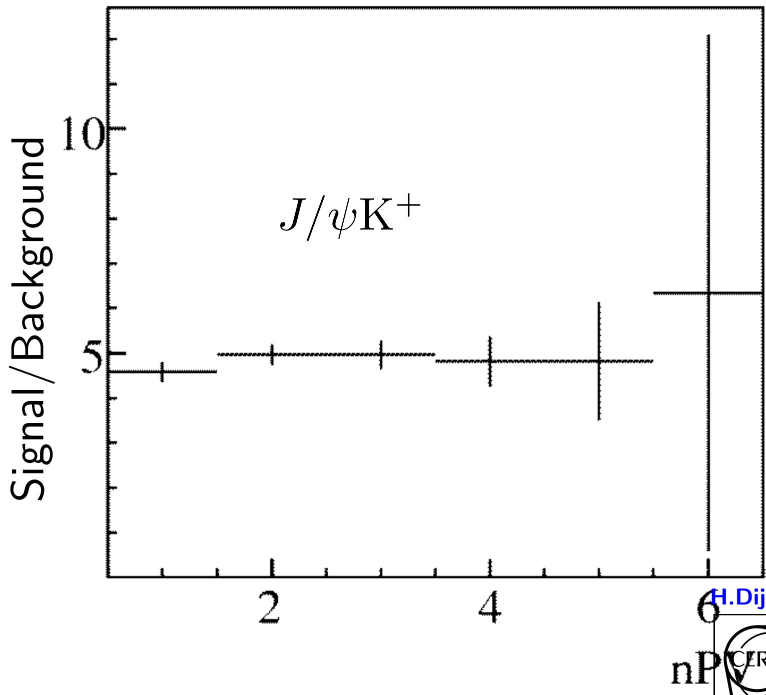

CERN/LHCC 2011-001

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Pileup Events

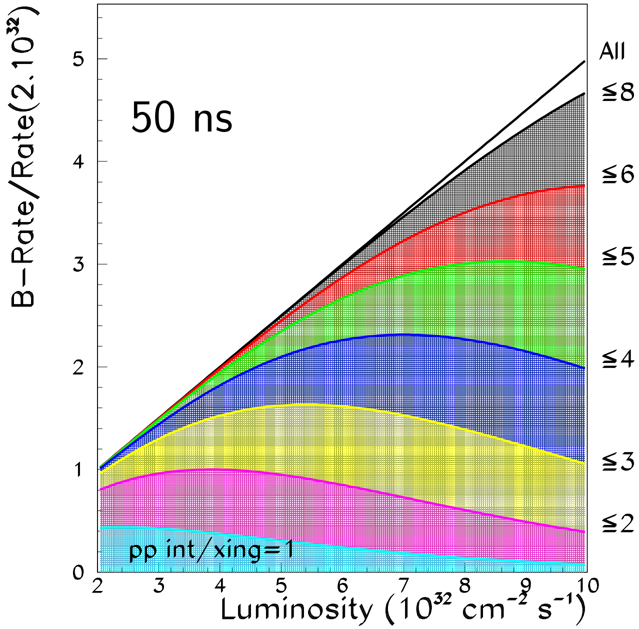
Now: LHC has 50 ns bunch spacing.

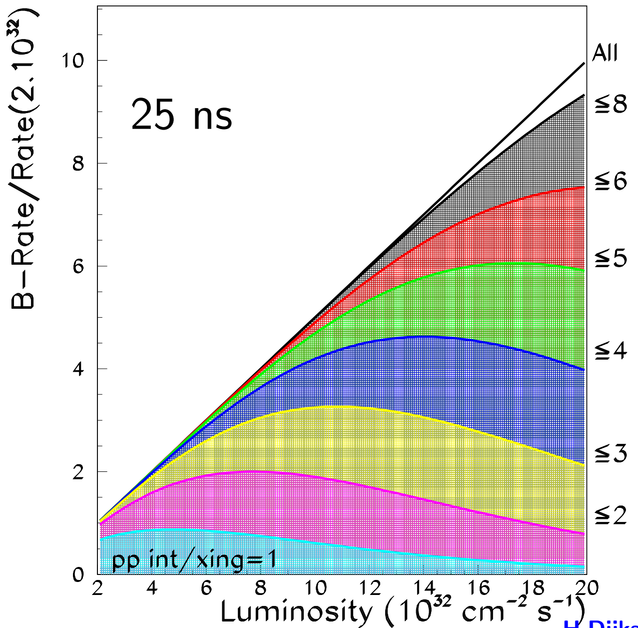
- 1262 colliding bunches in LHCb.
- $@4 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$ nr pp-int/xing with $b\bar{b}$ is ≤ 6.
- $@10^{33}\text{cm}^{-2}\text{s}^{-1}$:
  90 % of xings ≤ 6, hence total B-rate 80 % larger!

≥2015: LHC will go to 25 ns bunch spacing.

- ~2500 colliding bunches in LHCb.
- $@8 \times 10^{32}\text{cm}^{-2}\text{s}^{-1}$ nr pp-int/xing with $b\bar{b}$ is ≤ 6.
- $2 \times @10^{33}\text{cm}^{-2}\text{s}^{-1}$:
  90 % of xings ≤ 6, hence total B-rate 80 % larger!
- $@2 \times @10^{33}\text{cm}^{-2}\text{s}^{-1}$: pileup similar to "now".

Hence: why not run at much larger L already now?





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Trigger Yield as a function of Luminosity

First Level Trigger:

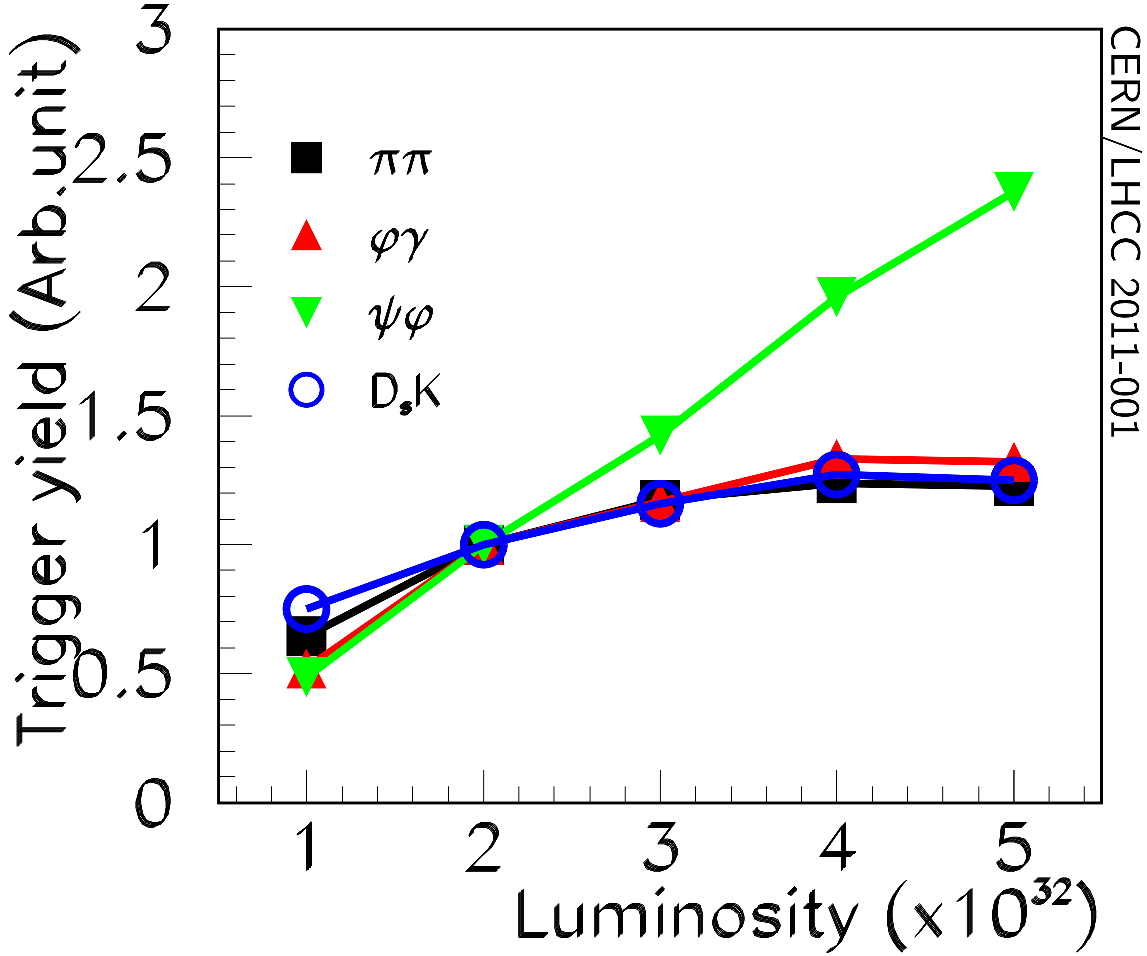
- hadronic-channels:
  $L^{\rm peak} \geq 3 - 4.10^{32}$
  no gain, and eventually will loose.
- μ-channels: yield $\propto \int L$

In addition:
Radiation:

- designed for $\int L \leq 20 \text{ fb}^{-1}$.
- Affects mainly large η.

Tracking & Particle-ID:

- Si tracking not a problem.
- Straws: $L^{\rm peak} \geq 10^{33}$
  spillover becomes a problem.
- PID: OK for $L^{\rm peak} \leq 10^{33}$,
  then some degradation.



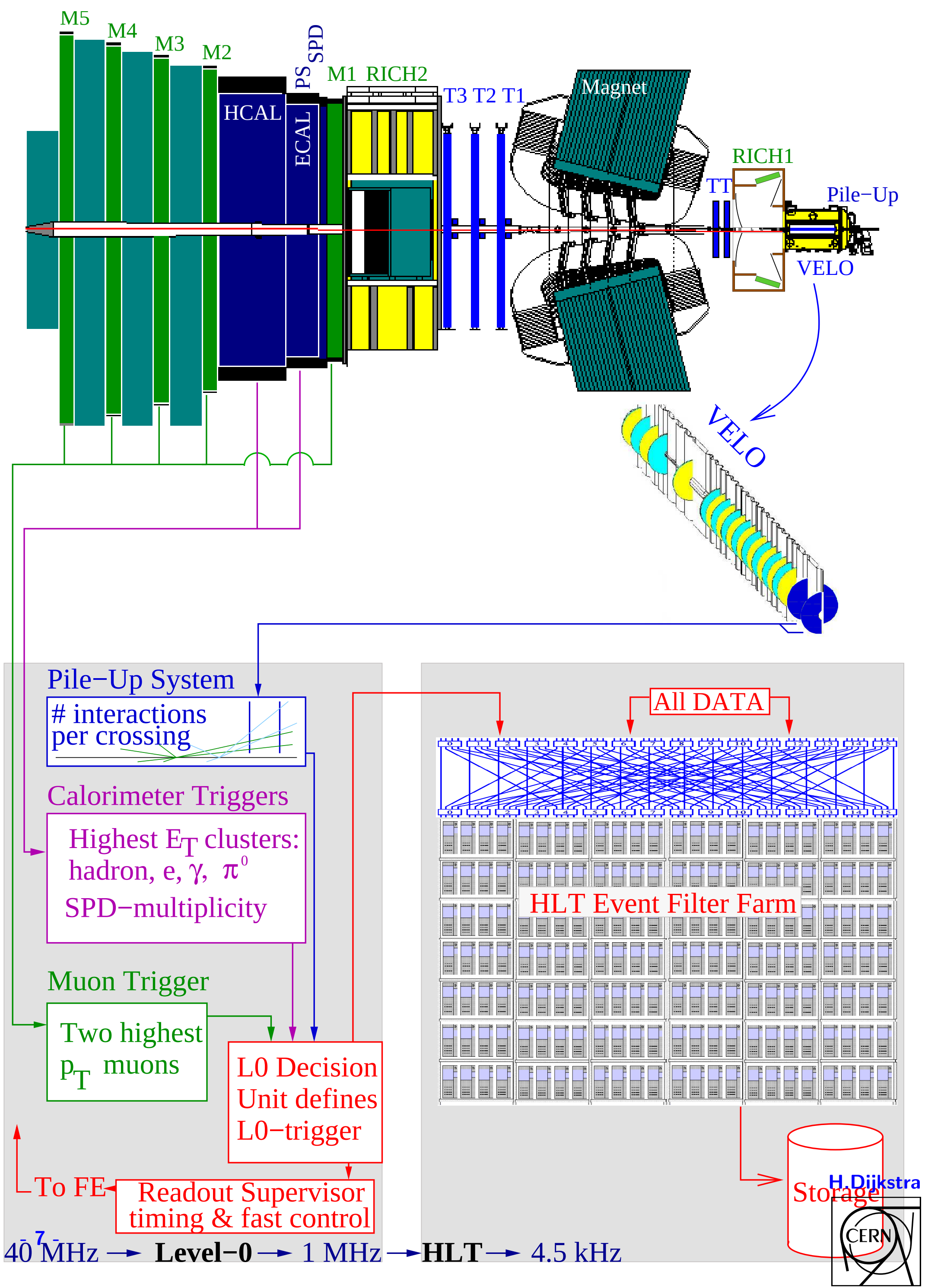
Trigger Overview

Level-0 (hardware):

- Largest E_T hadron, e(γ) and μ.
  Typical thresholds: 3.5, 2.5, 1.5 GeV.
- Bottleneck: 1 MHz max-output rate.
- L0 limiting yield for larger L^{peak}:
  - $@L > 2.10^{32}$: L0-retention $\sim 10\%$
  - $@L > 10^{33}$: L0-retention $\sim 3\%$
  - Result: E_T threshold $\gg \mathrm{M_B}$.

High Level Trigger (software):

- Access to all detector info.
- Limitation: CPU (brain?) power.
- Will improve
  with Moore's law "automatically".
- This year: 20-30% more CPU power,
  by storing events,
  and processing in inter-fill gaps.

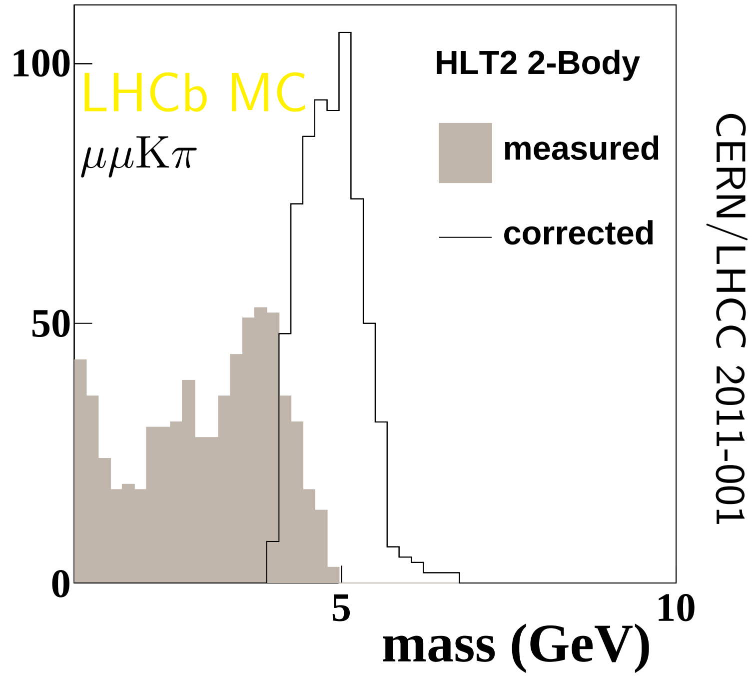


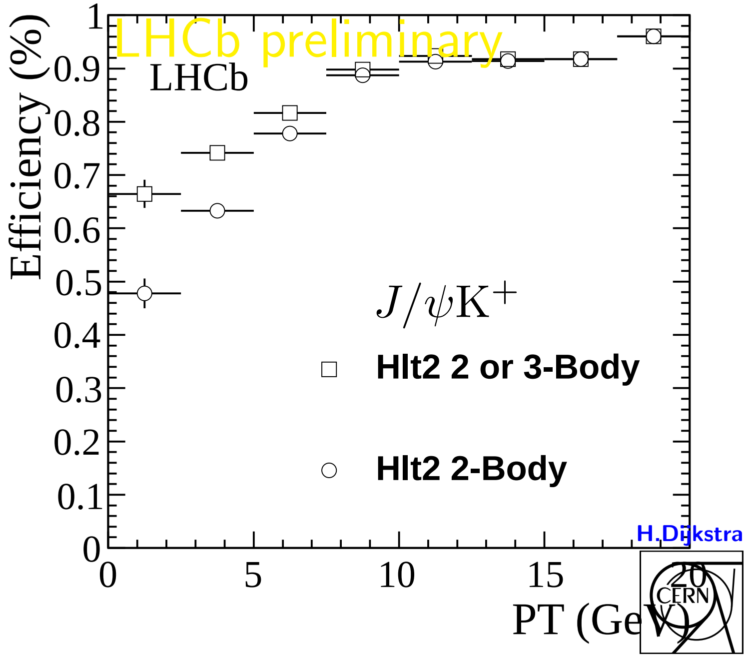
HLT Inclusive Trigger

HLT strategy:

- Reconstruct all PVs.
- HLT1:
  - Select tracks with significant IP to any PV.
  - Reconstruct p_T of these tracks.
  - Select $\sim 10\ \%$ events with at least one track with significant IP,p_T.
- HLT2:
  - Reconstruct p of all tracks with $p_T > 0.5$ GeV.
  - Built secondary vertices, with 2,3,4 tracks.
  - Calculate "corrected-mass" using PV↔secondary-vertex pointing constraint. Example: MC: $B^0 \to \mu\mu K\pi$, using 2-tracks.
  - Data: $B^+ \to J/\psi K^+$ with 2 tracks only.
  - (Leptonic decays: use leptons)

HLT already very efficient, just based on topology.

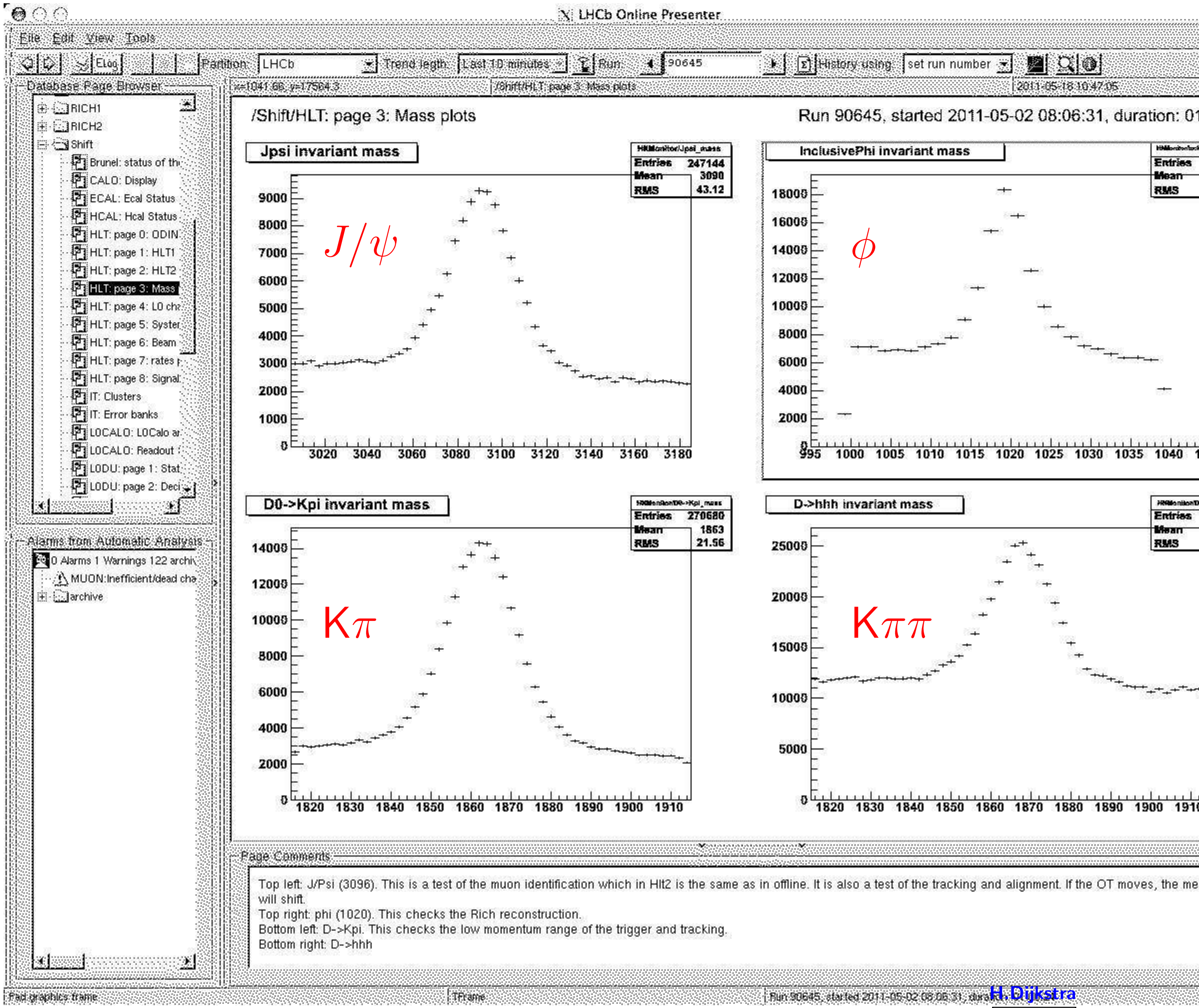




HLT Exclusive Triggers

☺ Charm "background" overwhelming!

- Inclusive charm triggers → high rate.
- Use exclusive reconstructed channels.
- Use RICH PID.
- Charm as on-line monitor. few min snapshot of on-line display.



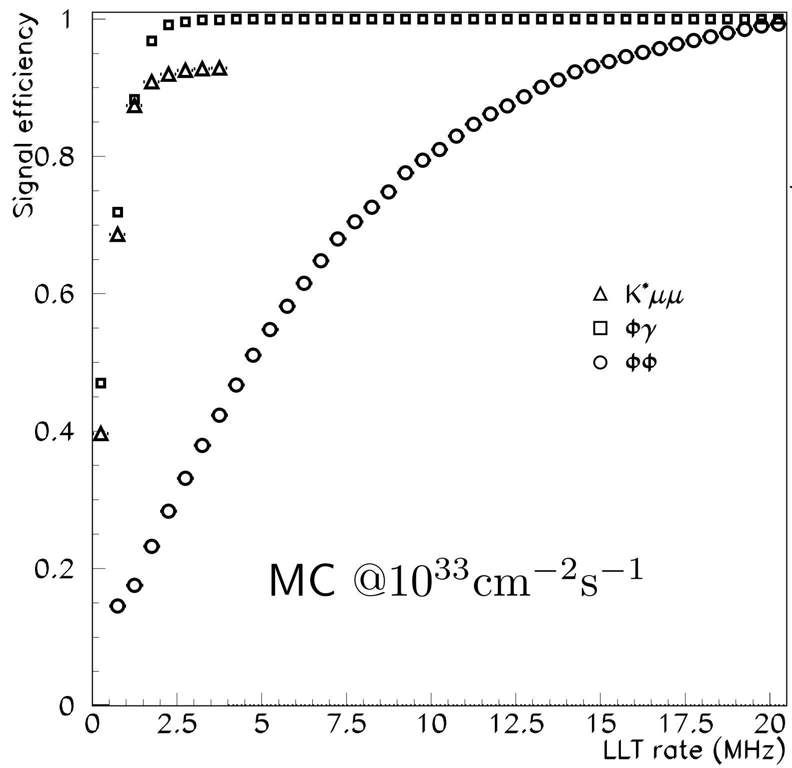
Upgrade the Trigger

Higher lumi bottleneck is 1 MHz L0 trigger!
Improve: need both IP and p_T of tracks in first level
Two ways investigated:

1) Put more information in L0, keep 1 MHz:
   - L0-latency is 4 μs, of which 2.5 μs for trigger.
   - Add VELO+TT, calculate IP,p_t in FPGA etc..
   - 2.5 μs is show stopper, also very inflexible.

2) "Remove" L0, all software trigger:
   - Readout FE at 40 MHz, iso 1 MHz now.
   - Move all data for every xing to EFF.
   - Very flexible trigger.
   - Keep L0-like Low Level Trigger (LLT) to "stage" rate to CPU-farm.

LHCb decided on 2).



CERN/LHCC 2011-001

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

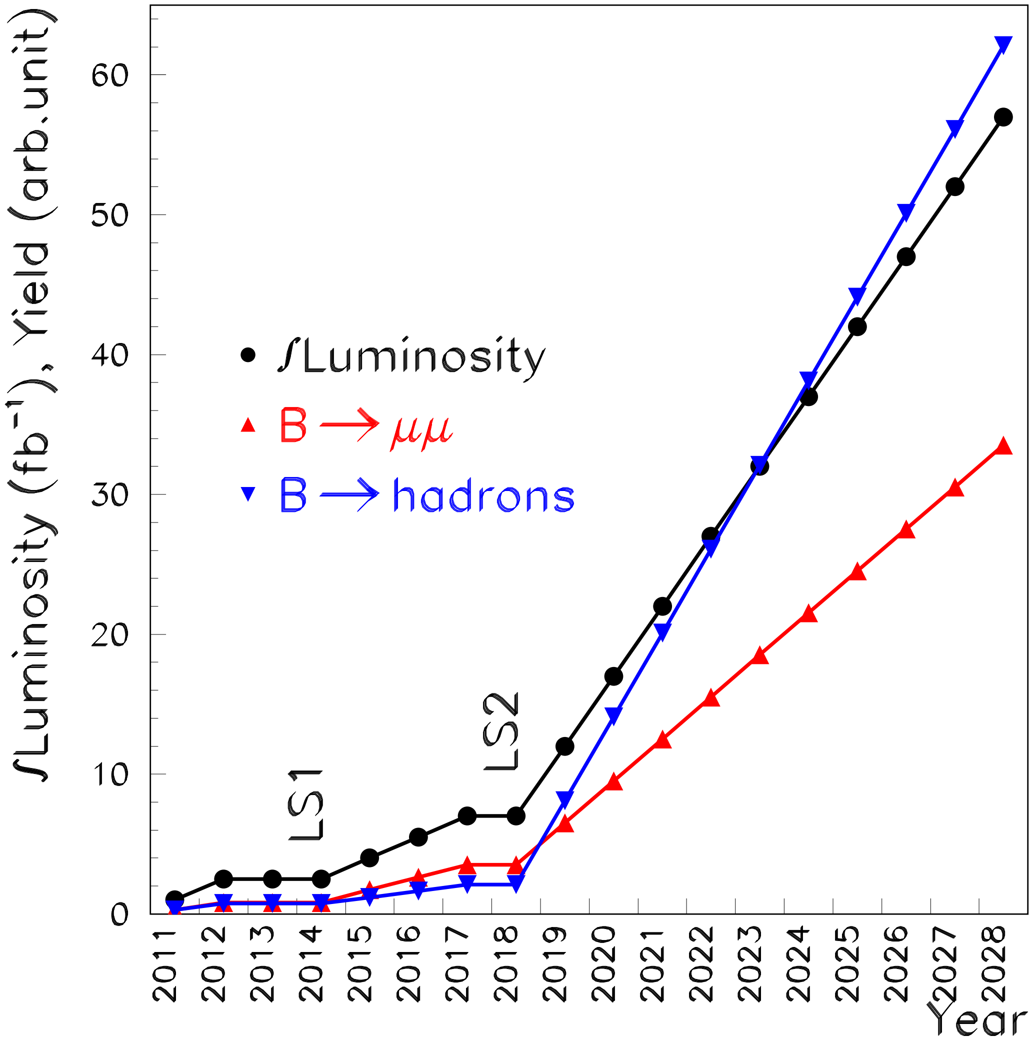
Strategy and Expected Performance

Upgrade Strategy:

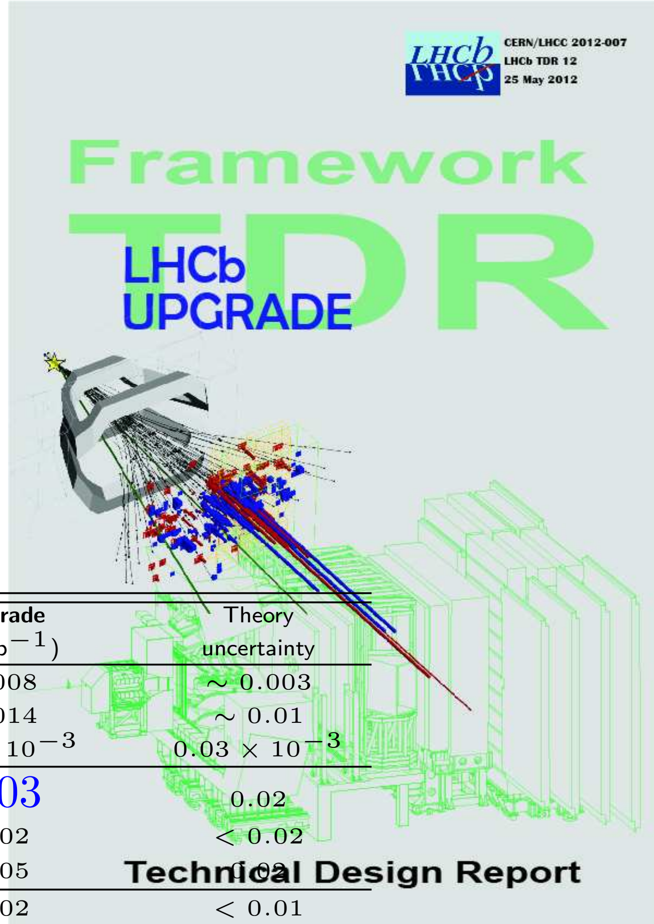
- Change FE-electronics to be able to move all data of every xing into a large Event Filter Farm (EFF).
- Install in LS2 (2018)
- Target luminosity $10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$.
- Sub-detectors which require replacement should sustain $2 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

Simulated LLT and "present" HLT:

- Assume flat $10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$.
- 5 fb^{-1}/year.
- For charm improve even more.
- More EFF-power (algorithms, GPU, ?), will improve even further.



Expected Upgrade Sensitivities



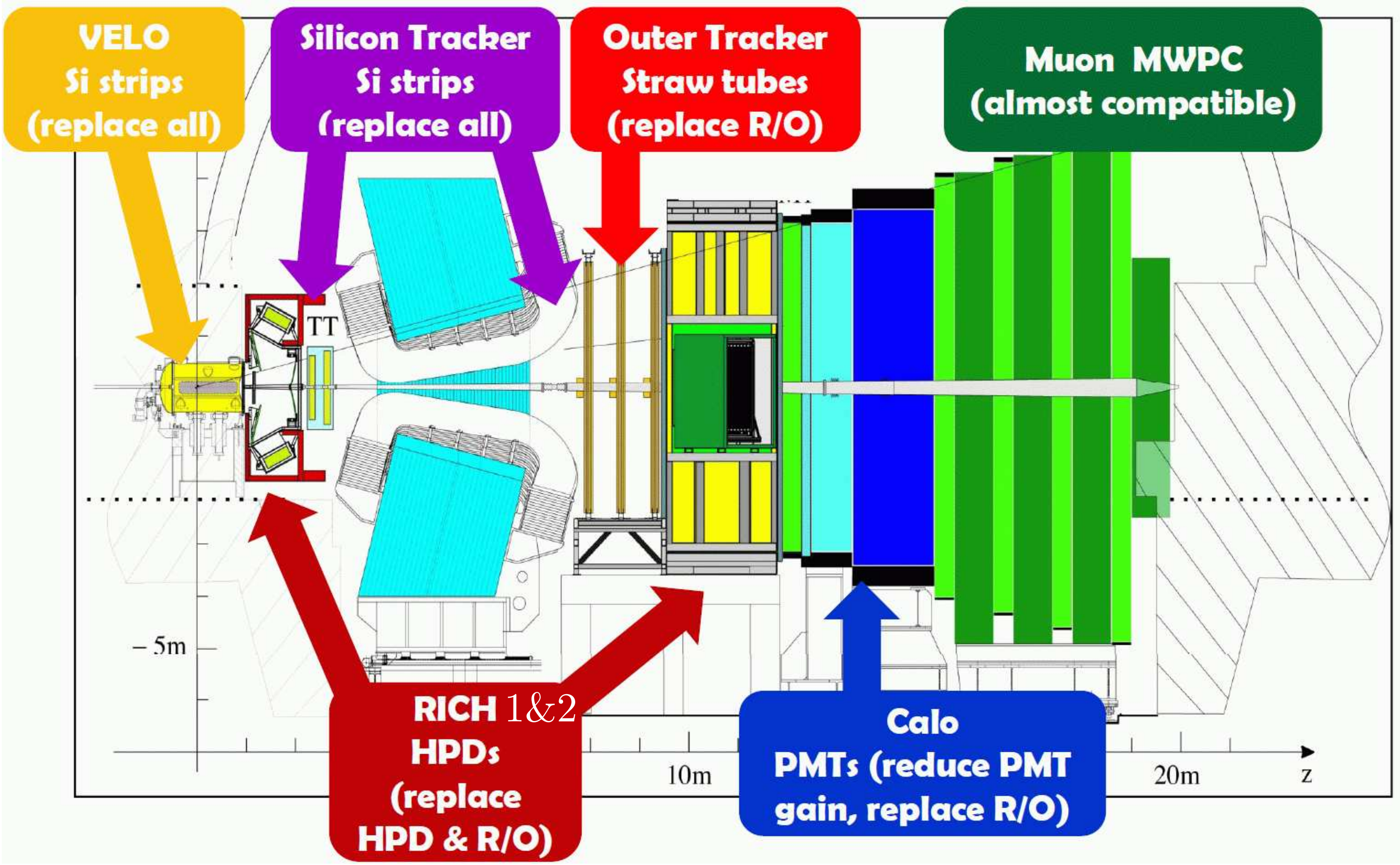
2012: LHCb Upgrade Framework TDR
http://cdsweb.cern.ch/record/1443882/files/LHCB-TDR-012.pdf

- 2018: expect $\int L = 5\ \mathrm{fb}^{-1}$
- 2028: expect $\int L = 50\ \mathrm{fb}^{-1}$

Type	Observable	Current precision	LHCb 2018	**Upgrade** ($50\,\mathrm{fb}^{-1}$)	Theory uncertainty
B^0_s mixing	$2\beta_s\ (B^0_s \to J/\psi\ \phi)$	0.10	0.025	0.008	~ 0.003
	$2\beta_s\ (B^0_s \to J/\psi\ f_0(980))$	0.17	0.045	0.014	~ 0.01
	$A_{\mathrm{fs}}(B^0_s)$	6.4×10^{-3}	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta^{\mathrm{eff}}_s(B^0_s \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta^{\mathrm{eff}}_s(B^0_s \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\mathrm{eff}}(B^0 \to \phi K^0_S)$	0.17	0.30	0.05	0.02
Right-handed currents	$2\beta^{\mathrm{eff}}_s(B^0_s \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\mathrm{eff}}(B^0_s \to \phi\gamma)/\tau_{B^0_s}$	–	5 %	1 %	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.08	0.025	0.008	0.02
	$s_0\ A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 %	6 %	2 %	7 %
	$A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.25	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 %	8 %	2.5 %	~ 10 %
Higgs penguin	$\mathcal{B}(B^0_s \to \mu^+\mu^-)$	1.5×10^{-9}	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	$\gamma\ (B \to D^{(*)}K^{(*)})$	~ 10–12°	4°	0.9°	negligible
	$\gamma\ (B^0_s \to D_s K)$	–	11°	2.0°	negligible
	$\beta\ (B^0 \to J/\psi\ K^0_S)$	0.8°	0.6°	0.2°	negligible
Charm CP violation	A_Γ	2.3×10^{-3}	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3}	0.65×10^{-3}	0.12×10^{-3}	–

Upgrading LHCb

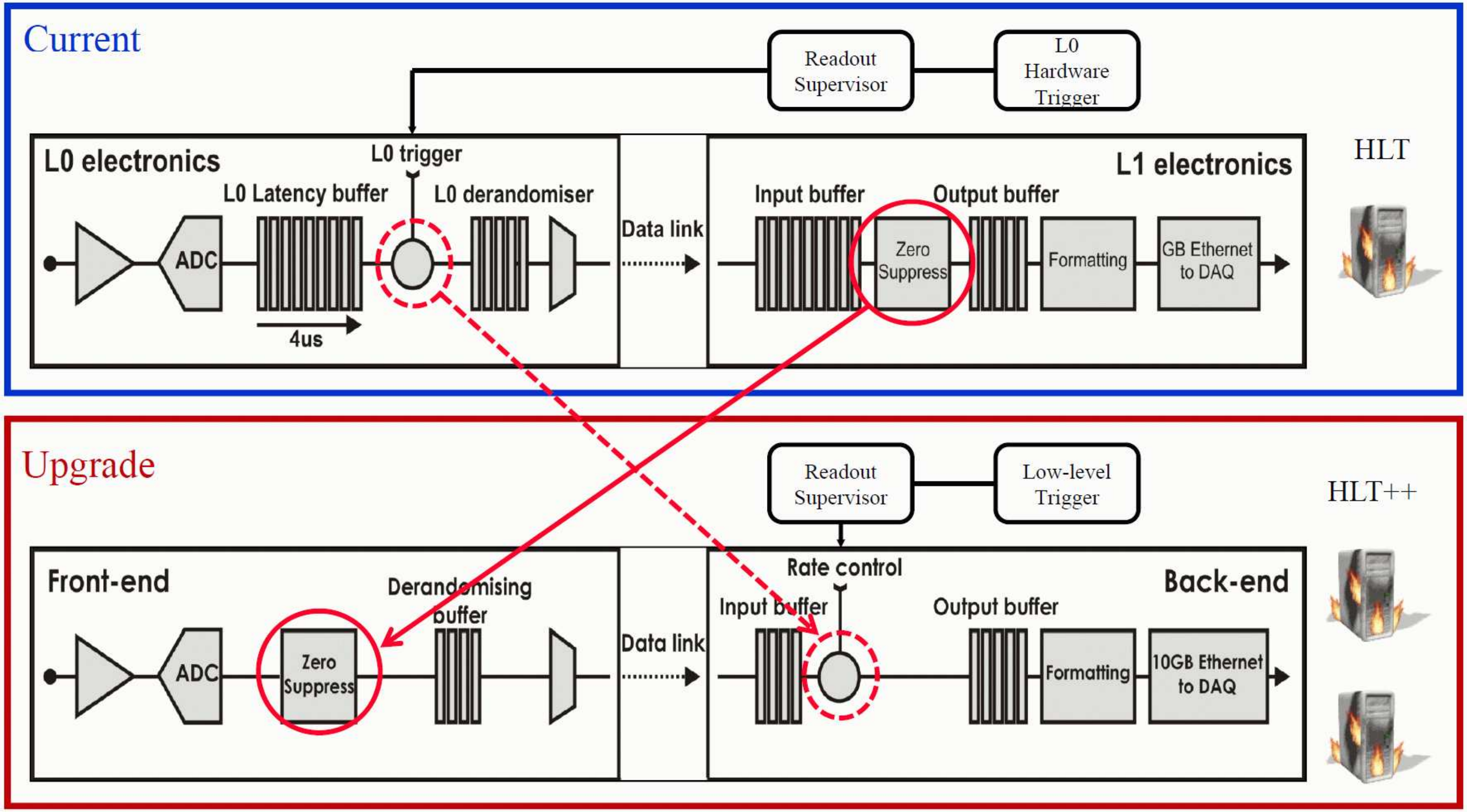
- Upgrading "all" FE-electronics to readout FE at 40 MHz.
- Upgrading Tracking detectors.



- Upgrading PID detectors.

FE-electronics $1 \rightarrow 40$ MHz

Current: FE latency-buffer, and zero-suppress after L0 trigger



Upgrade: zero-suppress in FE, no trigger→FE, LLT in back-end.

Upgrading Trackers

Aim: cope with $2 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

VELO (now Si-strixels):

- Two options being studied: pixels and strixels
- Main challenges (common!): cooling and data rates
- Improve σ_{IP}: reduce Si distance to beam.

TT (now Si-strips):

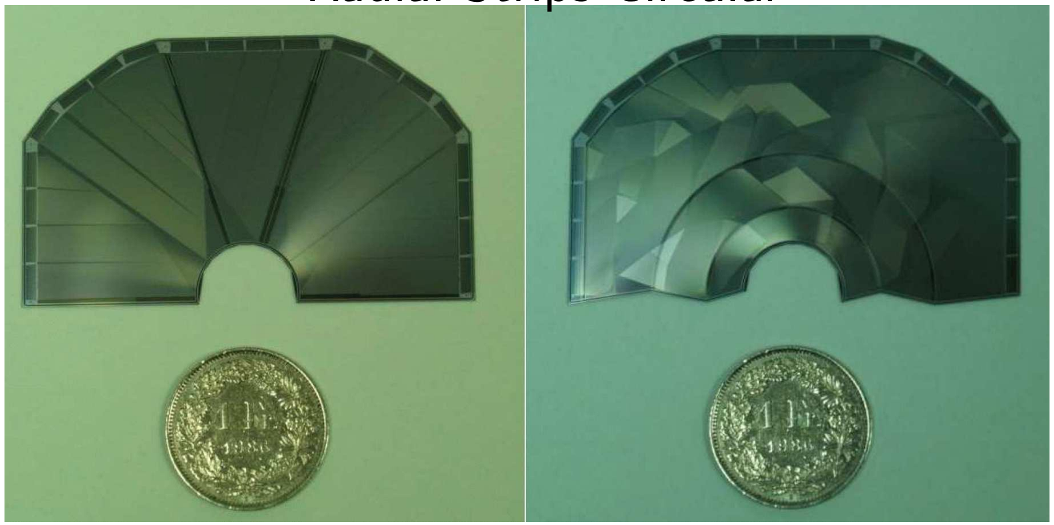
- Si-strips. Reduce strip size at large η.
- Main challenges: cooling (radiation dose) and material budget.
- Closer to 10 mrad beam-pipe.

T-stations (now 5 mm straw tubes with Si-strips close to beam-pipe):

- Straw: 40 MHz read-out, and further away from beam-pipe.
- Near beam-pipe: Scintillating Fibre or larger Si-strip detector.
- SciFi tracker challenges: radiation hardness of fibres and SiPM read-out.
- Si tracker: material budget.

Velo Upgrade

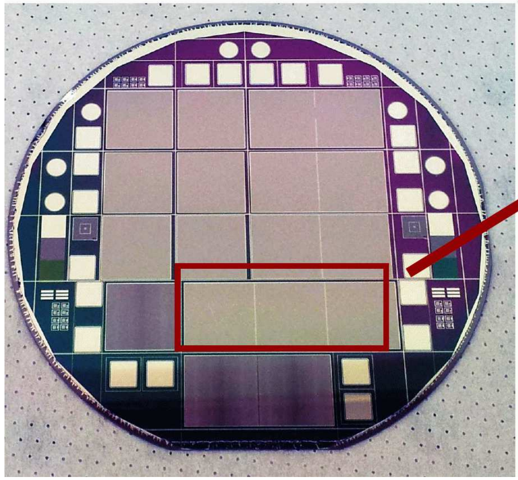
Radial Strips Circular

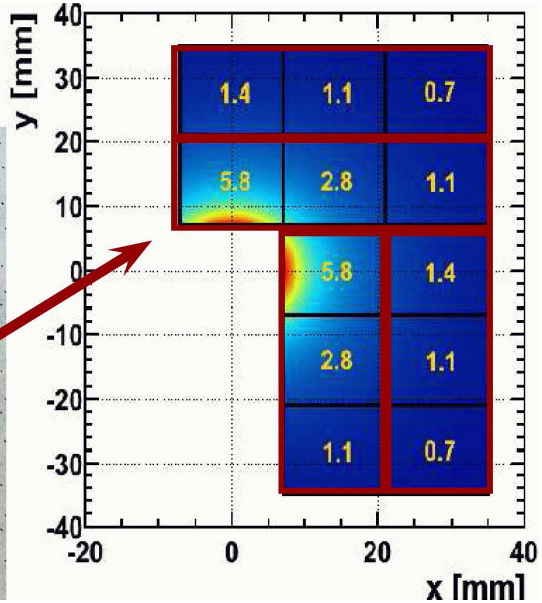


Strixels:

- Prototype sensors being tested: 200 μm thick, n-in-p. Smallest pitch: $30 \rightarrow 25$ μm.
- FE-chip: common development for all Si-strip detectors in LHCb

Pixel wafer





Pixels:

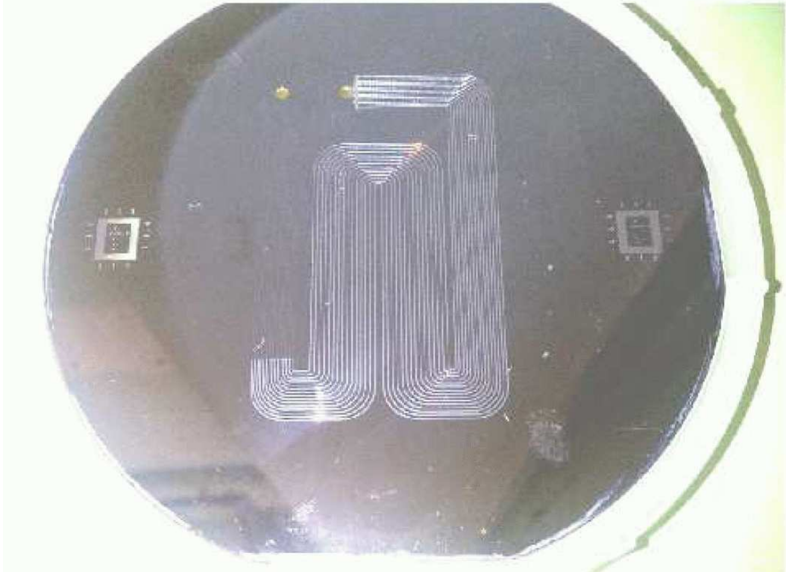
- Prototype sensors: 200 μm thick. pixel: $55 \times 55\ \mu\mathrm{m}^2$
- FE-chip: Velopix being developed based on Timepix3 (spinoff from Medipix3), 256×256 pixels/chip.

Velo Cooling

Close to beam: $\sim 5 \times 10^{15}\ \mathrm{n_{eq}cm^{-2}}$

- Keep T$< -10\ ^{o}\mathrm{C}$ to prevent thermal runaway.
- Present Velo:
  evaporative CO_2 cooling, and TPG substrate
  to connect sensor with cooling manifold:
- Upgrade cooling:
  - Like now: TPG→diamond?
  - Move CO_2 to sensors: micro-channel cooling
    Bond Si with micro-channels on sensor.
    Can remove 13 W from $40 \times 17\ \mathrm{mm}^2$ area.

Microchannel cooling

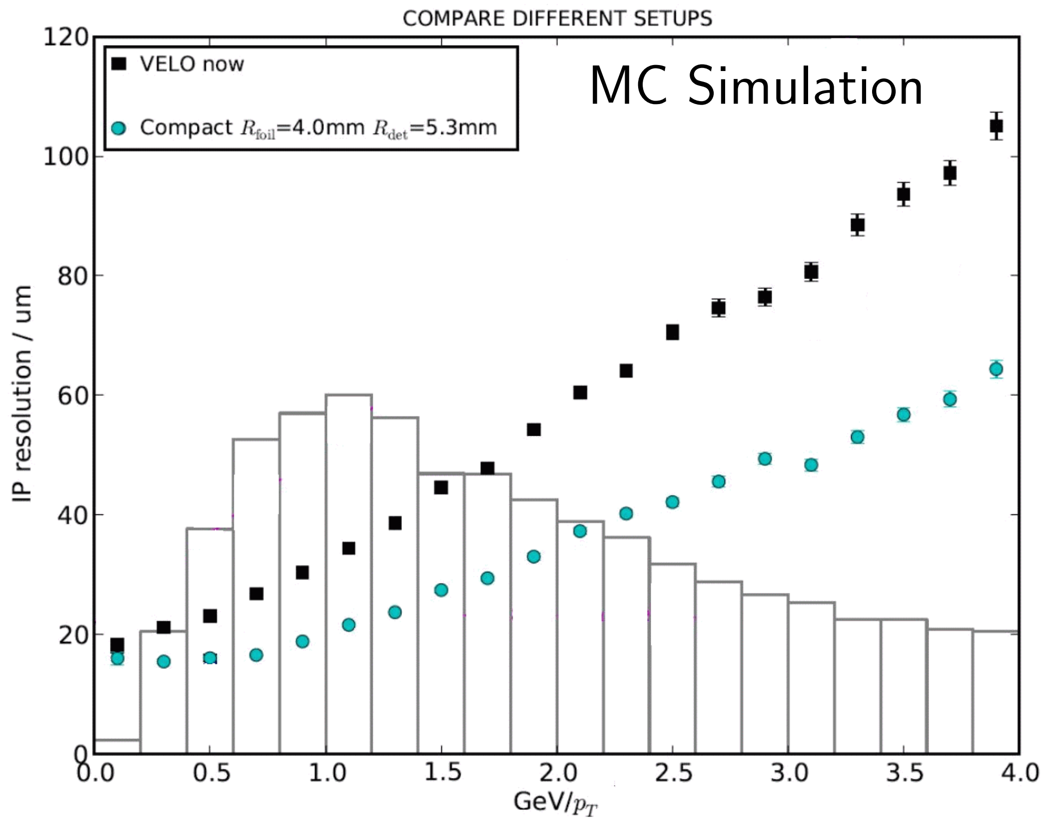


Velo Inner Radius

Velo is a moveable detector.
It closes around the beam every LHC fill.

- 300 μm thick Al RF-foil @ r =5.5 mm
- First Si-strip at @ r =8.2 mm.

LHC beam stable (few μm) during Fill.



Upgrade:

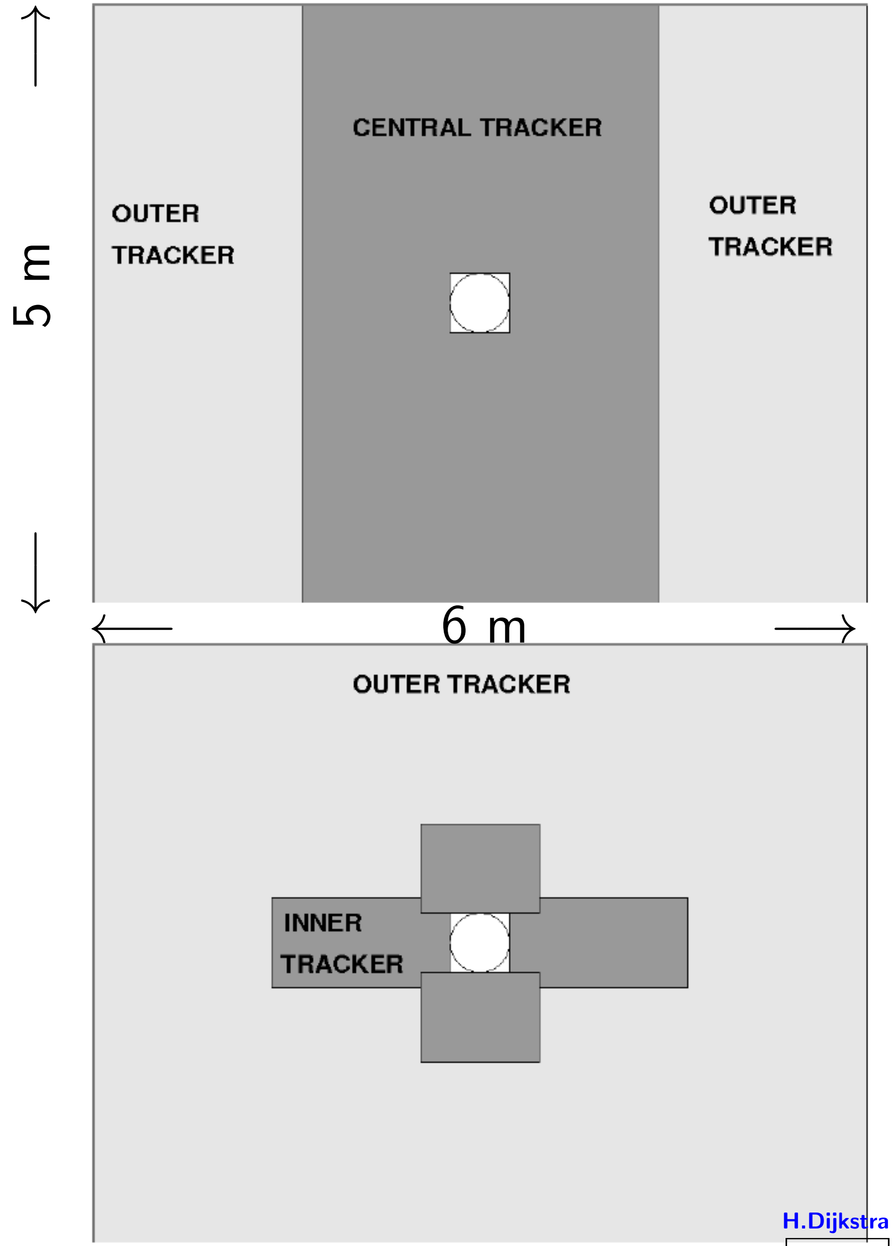
- Thinner RF-foil and closer to beam.
- Si closer to RF foil,
  reduce guard ring, better resolution.
- $\rightarrow$ large gain in IP-resolution.

Tracker Stations

Now:

OT 24 straws planes, 5 mm $\varnothing$, $\int$50 ns

IT 12 Si-strips planes close to beam.



Two options to decrease OT occupancy in center:

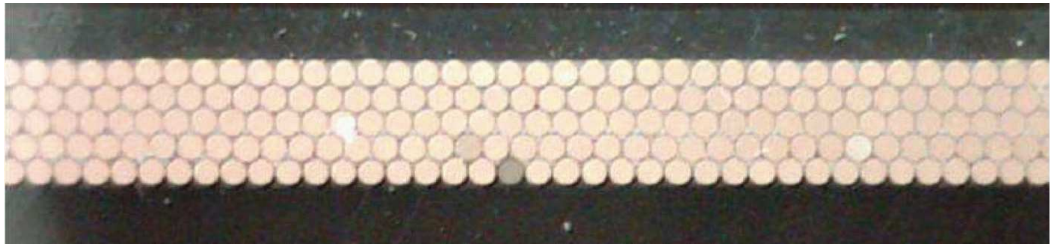
1 Replace center with Scintillating Fibres

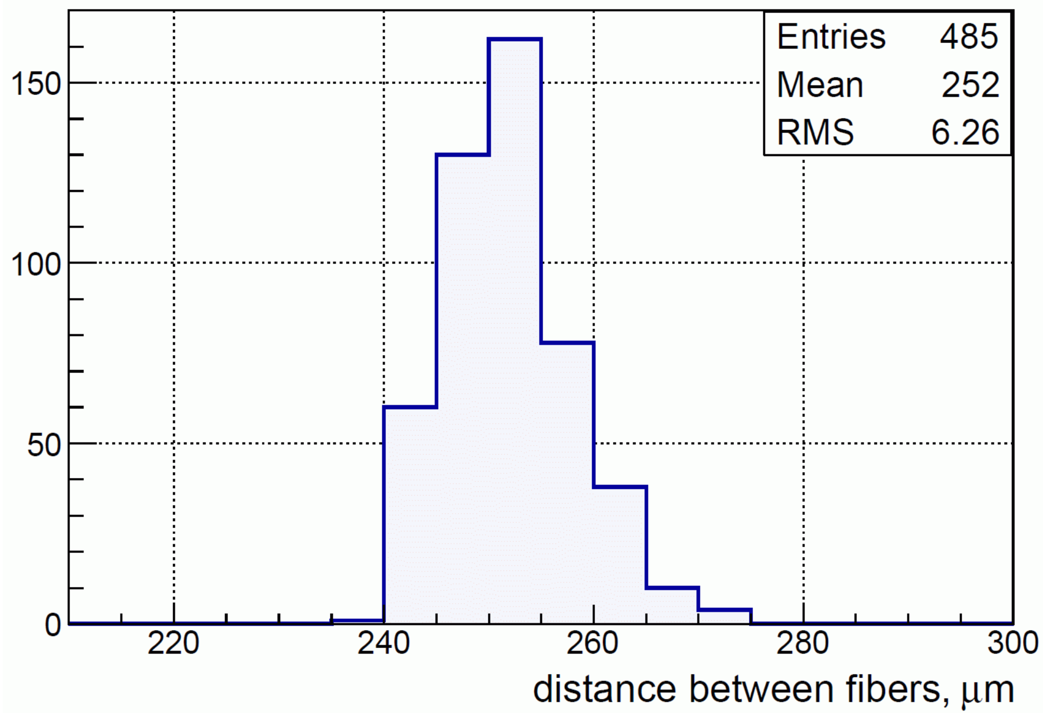
2 Larger Si-IT close to beam.

1+2 Mix SciFi with Si-IT

Scintillating Fibres

- 250 μm $\varnothing$ fibres.
- X/X0 = 0.7 % per layer of 5 fibres.
- 2.5 m long modules produced.
- excellent spacial precision achieved.
- ~ 50 μm precision/cluster.

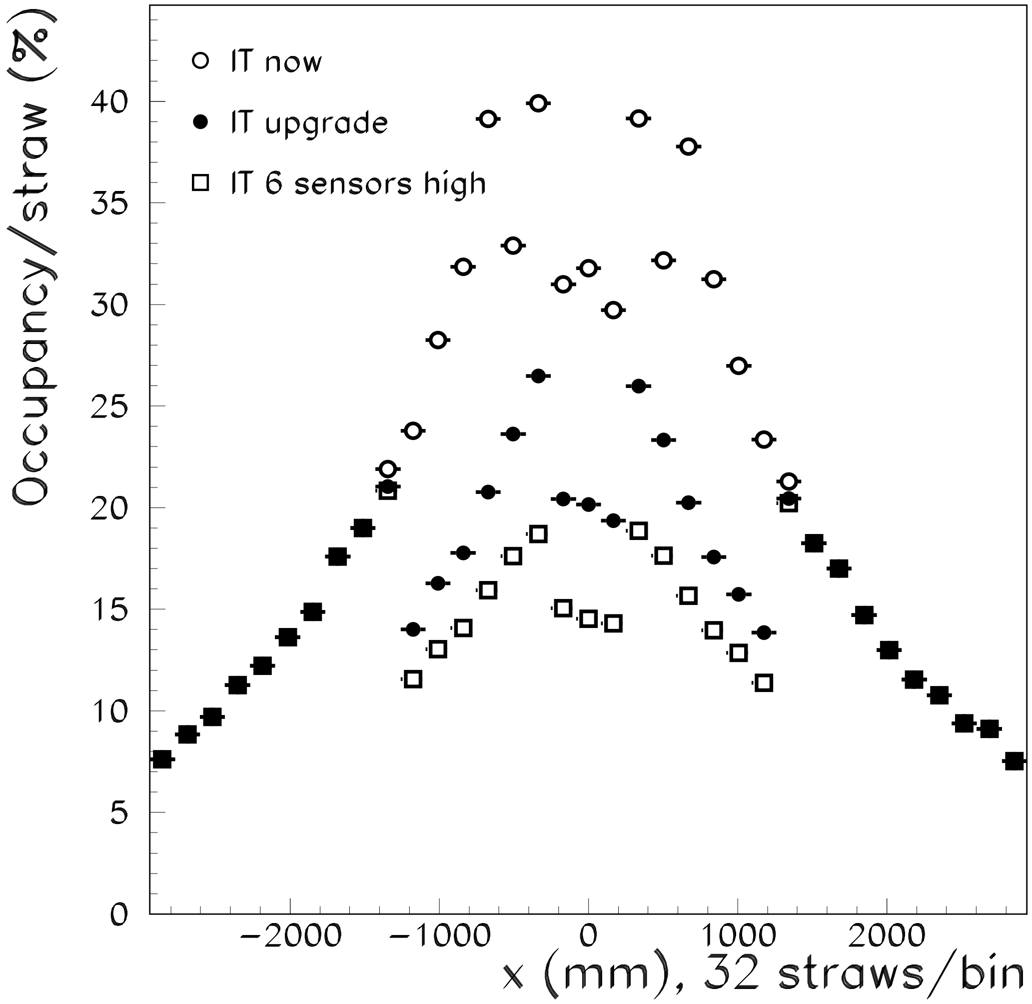




- Radiation:
  - SiPM: need shielding+cooling. Test (in situ) ongoing.
  - Fibre attenuation near beam-pipe: campaign of irradiation tests.

Silicon IT

- Si-IT size driven by OT occupancy.
- Aim: $2 \times 10^{33} \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Pattern recognition deteriorates $> 20\ \%$ occupancy.
- OT occupancy dominated by secondaries, hence:
  - New Be beam-pipe support (LS1)
  - Lighter IT, using air cooling. Radiation: $\lesssim 5^{\circ}\mathrm{C}$
  - Less $(12 \rightarrow 10)$ IT layers?
  - Move IT behind OT.
  - Use faster OT gas.



PID Upgrade

Muon system:

- Vital input for LLT, HLT and off-line μ-identification.
- M1 (before Calorimeters) will be removed. Provides improved momentum resolution for L0, not needed in LLT.
- FE already read-out at 40 MHz. Needs some modifications to comply with upgrade scheme.
- Present M2-M5 can cope with $1 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. At higher rates too much dead-time close to beam. Several options under study: shielding, smaller pads, faster FE.

Calorimeter system:

- LLT on γ, electron and hadrons. Off-line γ resolution.
- Now: Scintillating Pad Detector (e/γ separation) and Pre-Shower (π suppression): not needed in LLT. Remove and improve ECAL resoluton.
- Radiation: studies ongoing, module in tunnel with $5\times$ highest flux. Expect mild resolution degradation at highest doses. Could replace innermost cells.
- Lower PMT gain $\rightarrow$ new FE being developed.

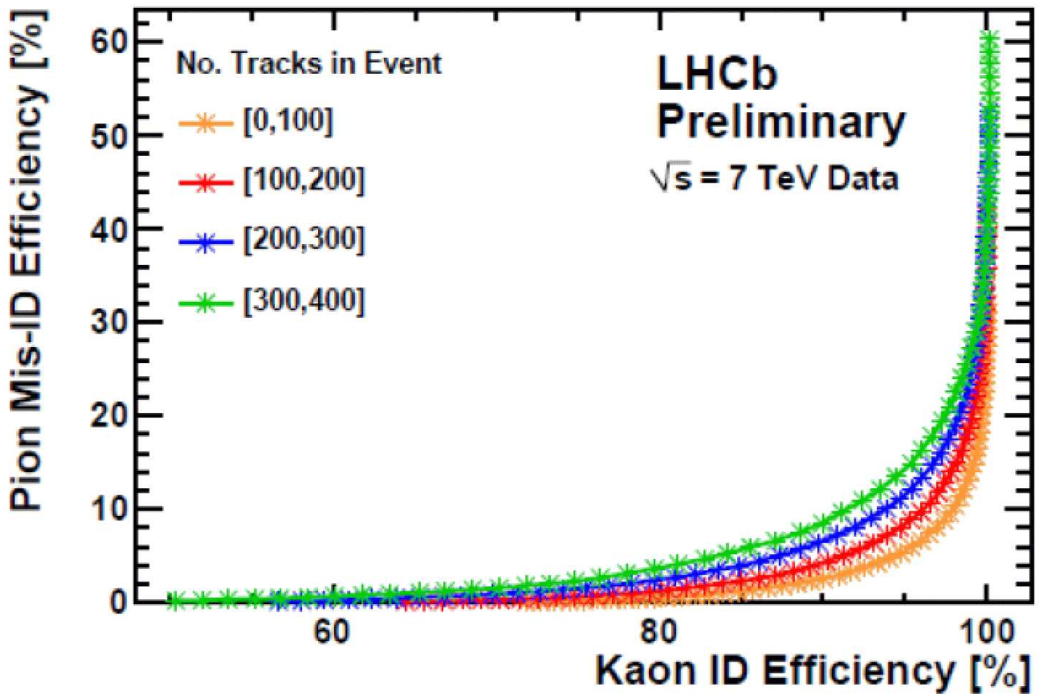
RICH system:

- Next slides..

RICH Upgrade (baseline)

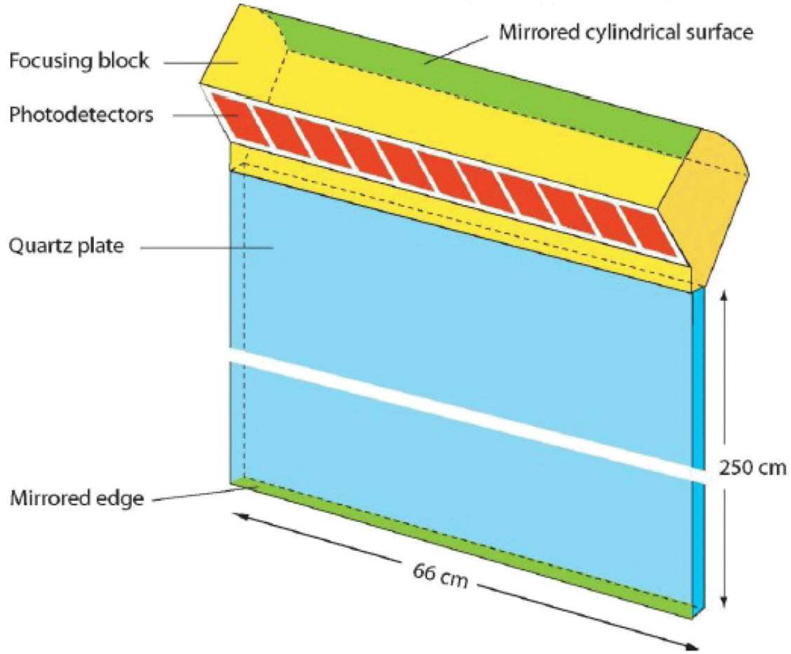
- Keep present arrangement, i.e. RICH1 and RICH2
- Remove aerogel (low p coverage) from RICH1: too few photons/ring to reconstruct at high lumi.
- Need to replace photon detectors (HPD) with 40 MHz read-out system. Several possibilities unser study.
- Existing PID pattern recognition functions well, even at 2×10^{33}.

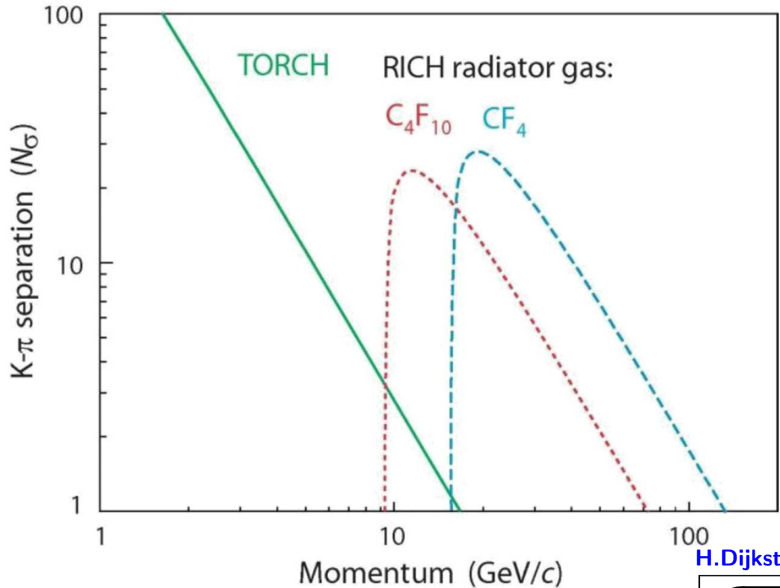
PID performance vs track multiplicity



RICH Upgrade: R&D→ 2020++?

- Time Of internally Reflected Cherenkov light.
- Measure TOF of Cherenkov photons produced in 1 cm thick 6×5 m^2 quartz plate.
- Located after T-stations.
- Cover low momentum range (lost due to aerogel removal) Important for tagging with $K^{\pm}$.





Conclusions

- Proven record to be able to do high precision flavour physics at LHC.
- LHCb needs to upgrade the trigger to be able to profit from larger LHC luminosity.
- LHCb decided to move to full software trigger at first level. Very flexible trigger to adapt to needs a decade from now.
- All sub-detectors $\mathrm{R\&D}$ underway, some options, final decisions Q1-2013.
- Install during LS2 (2018).
- $\int L \sim 5\ \mathrm{fb}^{-1}$ by 2018, then collect $\int L \sim 5\ \mathrm{fb}^{-1}$/year with much improved (hadron) trigger.
- Expect improved sensitity by factor 3-6 compared to no upgrade, depending on channel.
- Allows exploration of new observables.