Beyond The Upgrade VELO performance studies

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Theatre of Dreams: Beyond the LHCb Phase I Upgrade

Manchester, 6-7$^{\mathrm{th}}$ April 2016

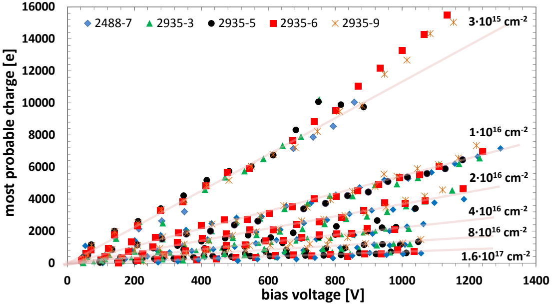
Introduction

- The high-luminosity environment 'Beyond the Upgrade' presents a number of challenges for a VELO Upgrade-style detector
- Express radiation dose in terms of the 1 MeV n_{eq} fluence (n_{eq})
- A detector with an inner radius of 5 mm (such as the VELO Upgrade) will be subject to $\sim 10^{17}$ n_{eq} over its lifetime
- Current sensor technology can cope with at most 10^{16} n_{eq} e.g. LHCb VELO Upgrade, ATLAS/CMS Upgrade
- Higher data rates will cause problems with occupancies, pattern recognition, tracking etc.

Moving to fluences above 10^{16} n_{eq}

- A detector with an inner radius of 5 mm will be subject to $\sim 10^{17}$ n_{eq} over its lifetime
- At 10^{17} n_{eq} the outlook is bleak with current technology:

- Maximum fluence for 4 ke$^-$ at 1000 V at 300 mm thickness is 1.6×10^{16}



G. Kramberger et al, JINST 8, 2013, P08004

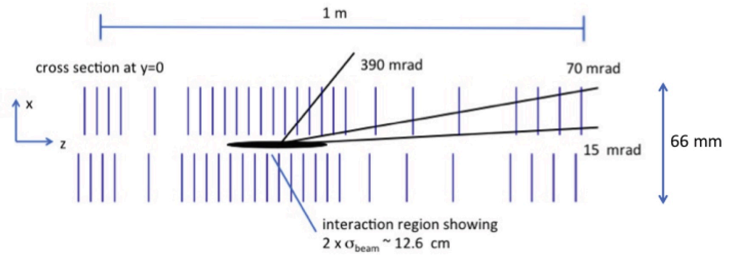
Options under study

- Consider two scenarios:
  - A) Conservative: Able to survive 10^{17} n_{eq} with no further improvements in technology
    → What would we need to change to remain below 10^{17} n_{eq} and how would this affect the physics?
  - B) Optimistic: A hypothetical detector with timing information:
    → What would be required to maintain current performance?
- Start with the more conservative approach

Scenario A: Conservative approach

Scenario A: The conservative view

- VELO Upgrade modules have to withstand 8×10^{15} n_{eq}
- Look at detector design that allows running for several years with technology able to take $\sim 10^{16}$ n_{eq}
- Assume design limitations/radiation requirements prevent regular replacement of sensors
- Fallback solutions if we hit brick walls in sensor development
  → Not advocating these as the best solutions



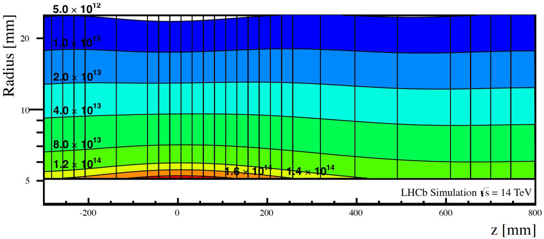
VELO Upgrade layout

Considerations

- Radiation dose scales approximately with radius squared
- Need to retract modules by square-root of number of years of running to maintain total maximum of 10^{16} $\mathrm{n_{eq}}$
- Last module position defined by position of fourth module from the end, which should record the highest η tracks at its inner radius
- For 5 years running: r_i = 11.4 mm and z_{-4} = 964 mm
  For 10 years: r_i = 16.1 mm and z_{-4} = 1313 mm
- But detector length is restricted to $<$ 1.2 m and need to allow for 3 more modules, i.e. an additional 75 mm

Shortening the detector

- Fluence lower at high z
  $\rightarrow$ Use smaller r_i for high z modules
- For $z > 600$ mm fluence is lower by 1/1.7
  $\rightarrow$ Can reduce r_i to give 5y: z_{-4} = 764 mm, 10y: z_{-4} = 1038 mm
- Still rather long, how much extra radiation do the modules have to take for a last module at 750 mm?
  $\rightarrow$ Have to go to r_i = 7.5 mm
  $\rightarrow$ Radiation increase by $(8.7/7.5)^2$ = 1.35 (5y scenario only)



VELO Upgrade fluence vs. r and z

Effect on impact parameter

- Increasing inner radius has implications on impact parameter resolution
- Extrapolation length more than doubles for first hit
- IP resolution approximately scales with the increase in sensor radius
  $\rightarrow$ factor of 2 degradation in IP resolution for sensors at 11.4 mm
- Degradation is η dependent if opting for compact geometry
  $\rightarrow$ Could retain current resolution for high η region

Geometry summary

- Limiting the detector to the total radiation dose of the upgrade era requires
  $\rightarrow$ increasing the inner radius to at least 11 mm
  $\rightarrow$ increasing the overall length of the detector to over 1 m
- With a variable inner radius a more compact design can be achieved ($<$ 850 mm)
- Allowing in addition for a moderate increase in radiation dose (1.1×10^{16} n_{eq}) a design with the same length of the current detector can be achieved (750 mm)
- IP resolution scales with increase in inner radius
  $\rightarrow$ varies between 50 – 100% VELO Upgrade depending on η

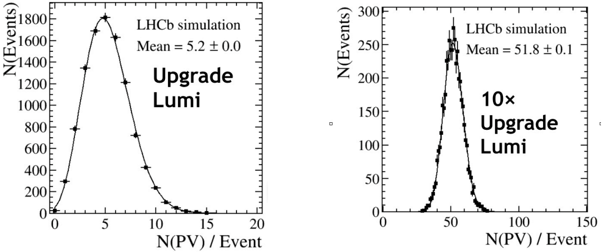
Scenario B: Optimistic approach

Upgrade VELO at $2 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

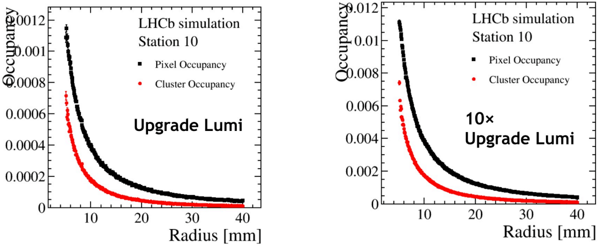
- Examine how the VELO Upgrade detector model copes with 10× upgrade luminosity
- Caveats:
  1) Limitations from radiation damage ignored
     → without further improvements in technology this could be achieved by replacing the sensors every year
  2) Current VELO Upgrade detector model - no changes to design (thinner sensors, smaller pixels, ...)
  3) Assume same collision conditions (except lumi), e.g. same beamspot size, same crossing angle
  4) Current pattern recognition algorithms: clearly not optimised for these multiplicities
- Details of simulated samples in backup

Sanity checks: Basic event information 1

➜ Number of true primary vertices



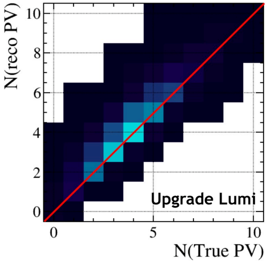
➜ Hit occupancies

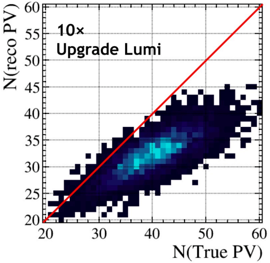


➜ Expect to see increase in ghost rate / reduction in track efficiency

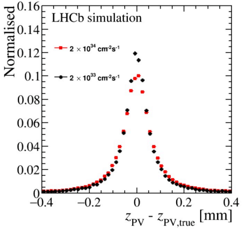
Sanity checks: Basic event information 2

- Number of reconstructed PVs



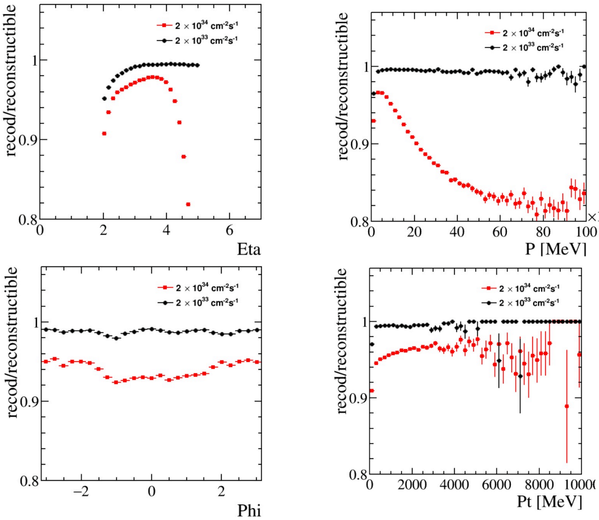


- PV z resolution
  $\rightarrow$ driven by lower track efficiency and degraded track resolution



Tracking efficiencies

➜ General degradation in tracking efficiencies



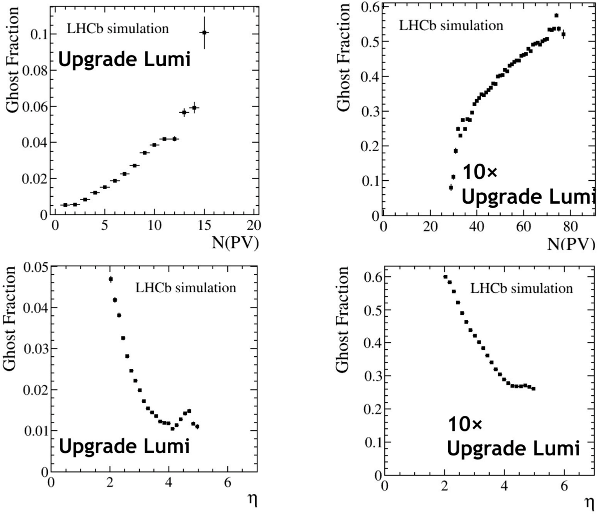
Integrated tracking efficiencies

➜ Summary of pattern recognition efficiencies for the two scenarios

	Upgrade lumi	10× upgrade lumi
Track-finding efficiency	98.7%	93.9%
Track purity	99.82%	99.25%
Hit efficiency	93.63%	91.68%

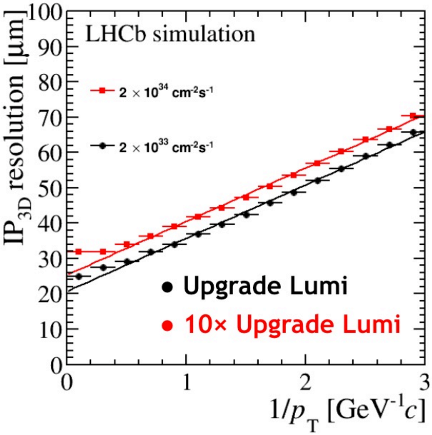
Ghost rates

- Huge increase in ghost rates
- Integrated ghost fraction for pixels: 1.9% → 42%



Impact parameter resolution

- Degradation in IP resolution: $\sim 5\mu$m over all p_T



- Driven by poorer PV reconstruction

PV misassociation at high $\mathcal{L}$

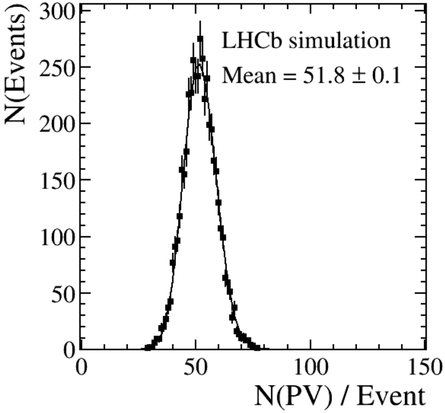
- Another key performance parameter is the rate of mis-association of heavy flavour particles to their corresponding PV
- Perform a toy study to estimate how bad this might get, and investigate if timing can resolve the problem
- With thanks to Vava Gligorov for the sharing of work previously presented at the Open TTFU Meeting

Conditions and assumptions

- Majority of input parameters modelled as distributions derived from the upgrade simulations discussed in previous slides:
  1) Number of interactions per bunch crossing
  2) Number of tracks per PV
  3) Number of hits per reconstructed track
- *B* kinematics, PV resolution, SV resolution, min-bias PV resolution and momentum resolution from Run 1 MC
- Upgrade beam parameters from VELO Upgrade TDR, assuming z and t resolution uncorrelated

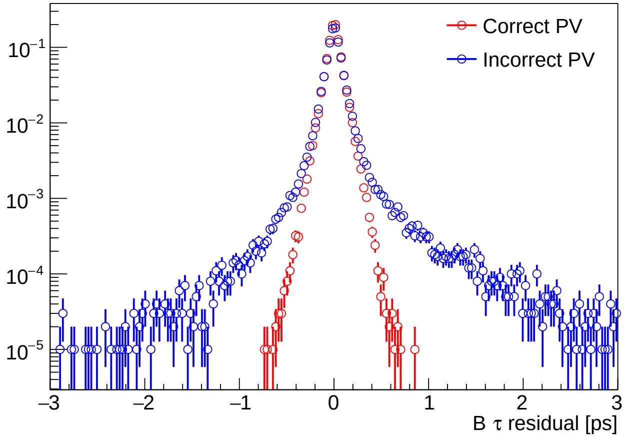
The problem

➜ At an increased luminosity of $2 \times 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$ there are $\sim$ 50 interactions per bunch crossing:



The problem

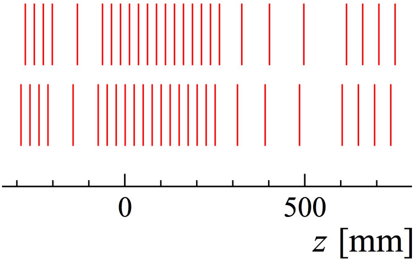
- A B that flies $\sim$1 cm is associated to the wrong PV 13% of the time, degrading the time resolution:



How can timing help?

- ➜ In a pixel detector with binary time resolution, hits would be collected in bins of time
- ➜ Consider time resolutions in the range 10 ps (highly optimistic!) to 500 ps (slightly pessimistic)

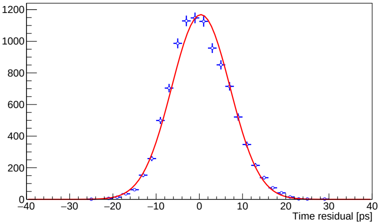
- ➜ Additional hits in other sensors improve the time resolution
- ➜ Additional hits in the same sensor do not



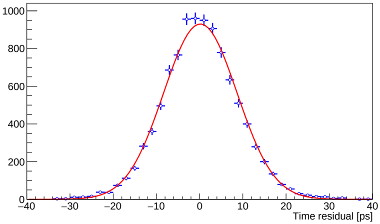
z-layout of sensors in the upgrade

Time resolutions for primary and secondary vertices

➜ With a 200 ps time resolution we obtain:



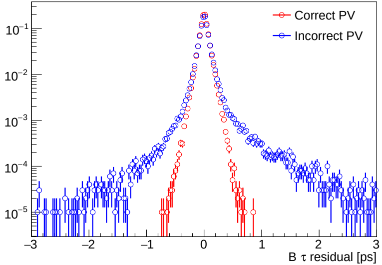
6.5 ps resolution for a PV

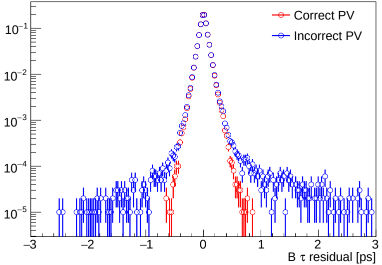


8.5 ps resolution for a 2-body SV

PV matching with timing

➜ If we match PVs according to their proximity in IP and time the *B* time residual is significantly improved:





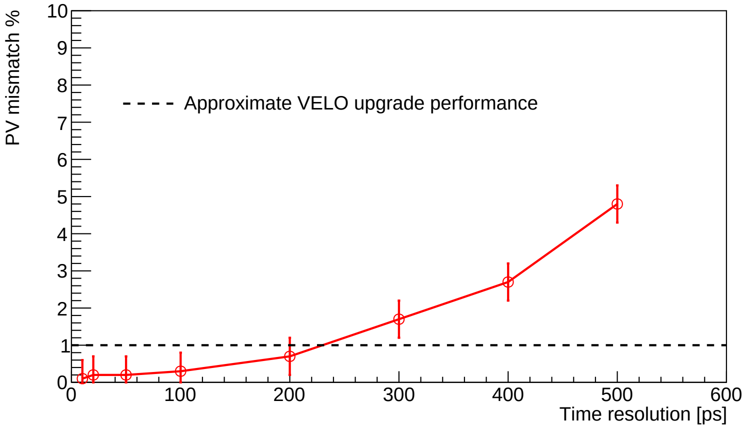
w/o timing: 13% mismatch

w/ timing: 1% mismatch

➜ c.f. a 1% mismatch in the VELO Upgrade using IP only

PV matching vs. time resolution

➜ Mismatching increases with degrading time resolution as expected

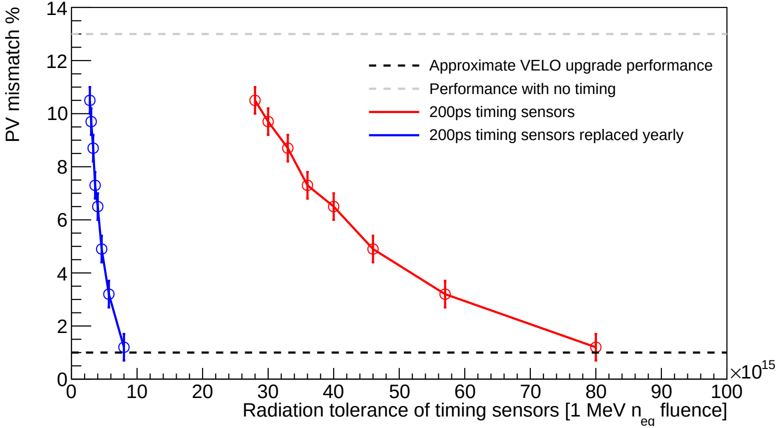


Constraints on use of timing from radiation damage

- Performance of sensors with timing under irradiation is largely unknown
  $\rightarrow$ Current studies to $\sim 10^{14}$ n_{eq}
- Could restrict use of timing to above a certain radius to limit radiation damage
- Replacing sensors on a yearly basis gains an additional factor 10 reduction in fluence
  $\rightarrow$ How feasible is this from an operations point of view?

PV matching vs. timing radiation hardness

- Even when replacing the sensors each year a radiation hardness of $\sim 10^{15}$ n_{eq} is required to maintain timing gains



Summary

- How could a VELO Upgrade-style detector be modified for Beyond the Upgrade?
  $\rightarrow$ To survive 5 years with current technology increase inner radius to $\sim$ 11 mm (could be z-dependent)
  $\rightarrow$ IP resolution 100 - 200% current value (η-dependent)
- Ignoring radiation damage effects the performance of the current upgrade model at 2×10^{34} is assessed (out-of-box algorithms)
  $\rightarrow$ Occupancies 10$\times$ higher, ghost rate is $\sim$ 40%
  $\rightarrow$ PV wrongly associated $\sim$ 13% of the time
- Adding timing information improves the situation
  $\rightarrow$ PV association at same level as upgrade with 200 ps resolution
  $\rightarrow$ Radiation damage on timing may have a significant effect
- Could benefit further from inclusion of additional improvements such as magnetic field that are yet to be studied

Backup

Simulated samples

- Two main samples:
  1) Standard upgrade conditions ($2 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$), based on official production:
     `$APPCONFIGOPTS/Gauss/Beam7000GeV-mu100-nu7.6-HorExtAngle.py`
     `$APPCONFIGOPTS/Gauss/Gauss-Upgrade-Baseline-20150522.py`
     `$APPCONFIGOPTS/Gauss/EnableSpillover-25ns.py`
  2) Exactly the same, except:
     `Gauss().Luminosity = 10.0*Gauss().Luminosity`
- Using: Gauss v48r0p1, Boole v29r7, Brunel v47r9
- With tags: `dddb-20150424`, `sim-20140825-vc-mu100`
- Include only VELO detector in simulation - no UT, SciFi, RICH, Calo, Muon

IP resolution determination

➜ $$\sigma_{IP}^2 = \frac{r_1^2}{p_T^2\sqrt{2}}\left(0.0136\sqrt{\frac{x}{X_0}}\left(1 + 0.038\ln\left(\frac{x}{X_0}\right)\right)\right)^2 + \frac{\Delta_{02}^2\sigma_1^2+\Delta_{01}^2\sigma_2^2}{\Delta_{12}^2}$$

$$\sigma_{IP}^2 = \sigma_{MS}^2 + \sigma_{extrapolation}^2$$

➜ Where:

r_1 = radius of first hit

$\frac{x}{X_0}$ = fraction of a radiation length before second hit

Δ_{xy} = the distance between points x and y

σ_x = the measurement error on hit x

More tracking efficiencies

- ➜ General degradation in tracking efficiencies