LHCb Future Upgrades & Prospects

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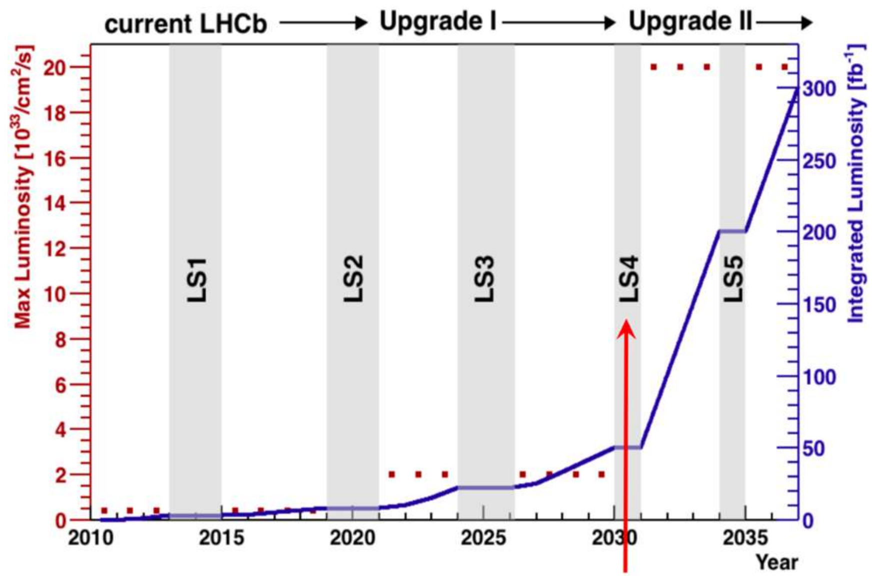
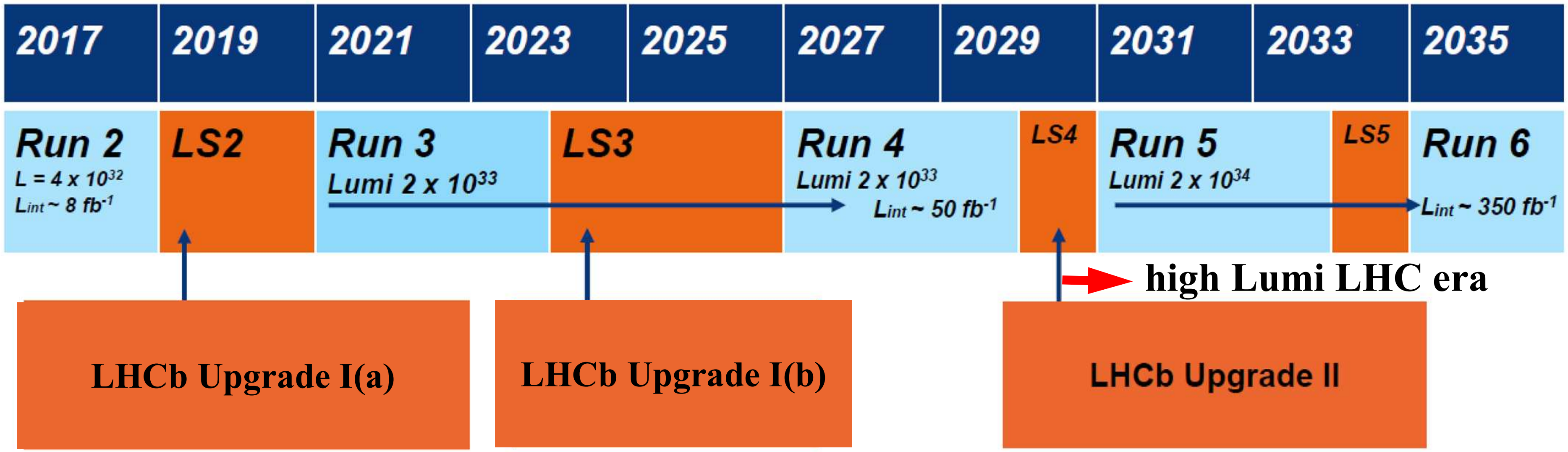
Overview of the timeline

- LHC Run-I (2010-2013) & LHC Run-II (2015-2018)
- LHC Run-III, Run-IV (2021-2023, 2026-2029)
  - based on LHCb Upgrade [I(a), I(b)]
- LHC Run-V (2031-)
  - based on LHCb Upgrade II





Why upgrades ?

- **We need more data to explore the unknown**

Physics Case for an LHCb Upgrade II, CERN-LHCC-2018-027

Observable	Current LHCb
EW Penguins	
R_K	$0.745 \pm 0.090 \pm 0.036$
$R_{K^{*0}}$	$0.69 \pm 0.11 \pm 0.05$
CKM tests	
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$
γ, all modes	$(^{+5.0}_{-5.8})^\circ$
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad
a_{sl}^s	33×10^{-4}
$\lvert V_{ub}\rvert / \lvert V_{cb}\rvert$	6%
$B_s^0, B^0 \to \mu^+\mu^-$	
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90%
$\tau_{B_s^0 \to \mu^+\mu^-}$	22%
$S_{\mu\mu}$	
$b \to c\ell^-\bar{\nu}_l$ **LUV studies**	
$R(D^*)$	0.026
$R(J/\psi)$	0.24
Charm	
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4}
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4}
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4}

σ(stat)/σ(sys)	Largest source of systematic
2.5	Mass shape & trigger eff
2.2	MC correction & residual bkgd
3	Δm_s, time res, tagging, det asymmetry
-	
8	Decay time: bias and efficiency
8	Angular efficiency
8	Decay time resolution
5	Acceptance (angular and time)
1.3	Track reco asymmetry
0.5	External BR(Λ_c)
6	f_d/f_s
9	Decay time acceptance
1	MC sample size
1	F($B_c \to J/\psi$) form factor
2.7	Mass model
2.8	Contribution from sec b→D*X decays
2	Contribution from sec b→D*X decays

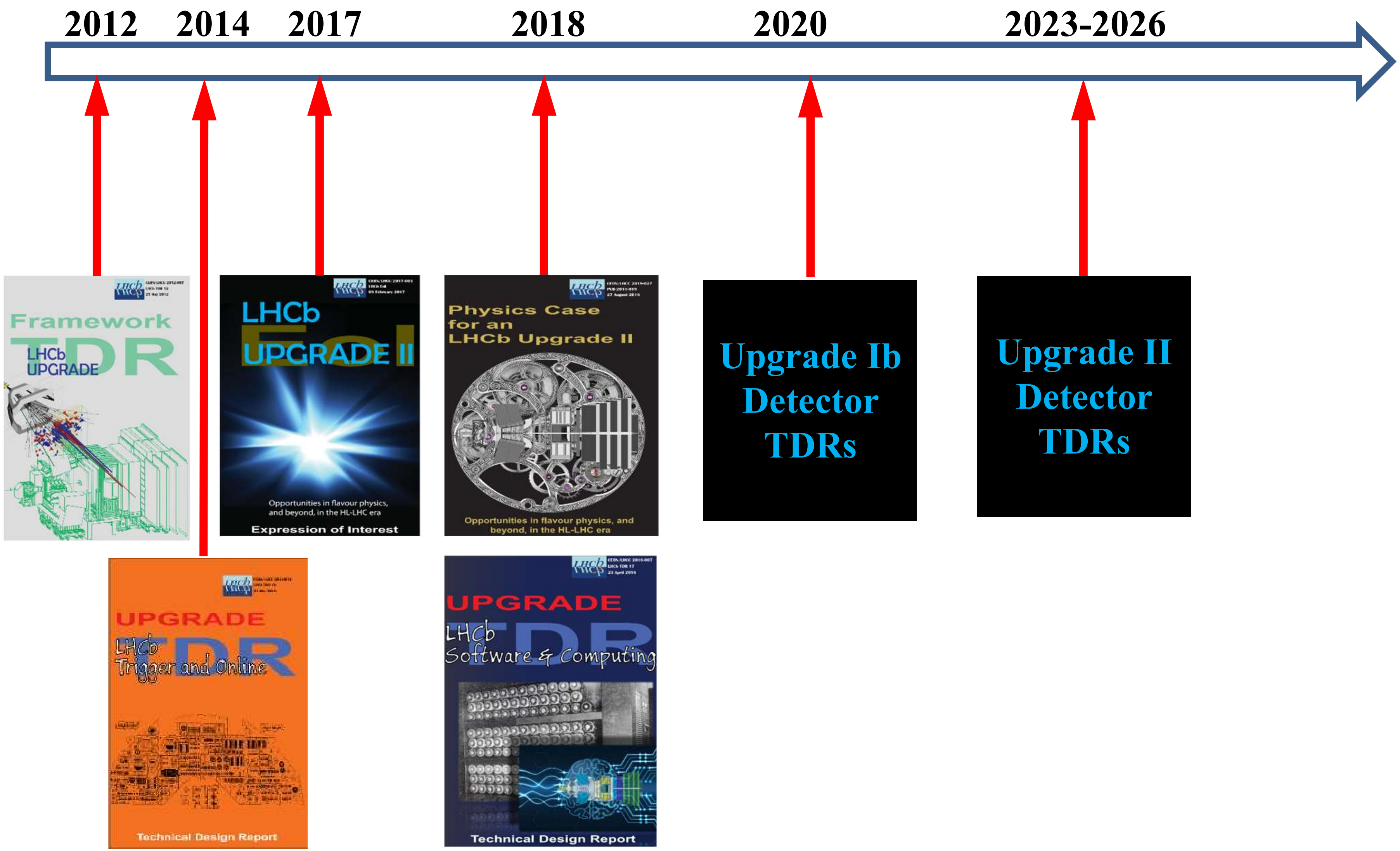
What we can get ?

- **Order of magnitude better precision in Upgrade II:**

Upgrade I precision

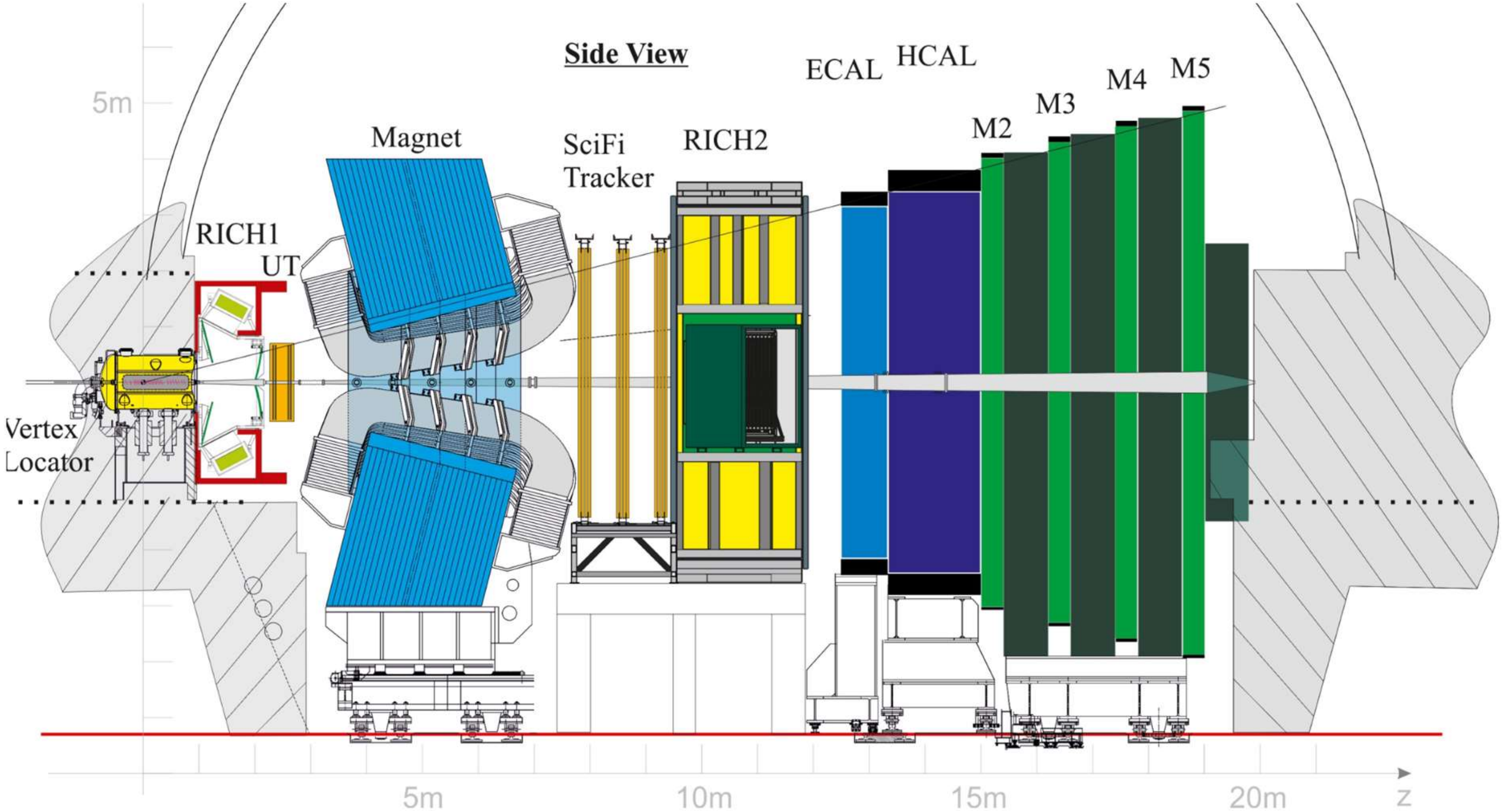
Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II
EW Penguins				
R_K $(1 < q^2 < 6\,\text{GeV}^2c^4)$	0.1	0.025	0.036	0.007
R_{K^*} $(1 < q^2 < 6\,\text{GeV}^2c^4)$	0.1	0.031	0.032	0.008
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05
CKM tests				
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$	4°	–	1°
γ, all modes	$(^{+5.0}_{-5.8})^\circ$	1.5°	1.5°	0.35°
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04	0.011	0.005	0.003
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad	14 mrad	–	4 mrad
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad	35 mrad	–	9 mrad
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad	39 mrad	–	11 mrad
a_{sl}^s	33×10^{-4}	10×10^{-4}	–	3×10^{-4}
$\|\|V_{ub}\|\|/\|\|V_{cb}\|\|$	6%	3%	1%	1%
$\boldsymbol{B_s^0, B^0 \to \mu^+\mu^-}$				
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90%	34%	–	10%
$\tau_{B_s^0 \to \mu^+\mu^-}$	22%	8%	–	2%
$S_{\mu\mu}$	–	–	–	0.2
$\boldsymbol{b \to c\ell^-\bar{\nu}_l}$ **LUV studies**				
$R(D^*)$	0.026	0.0072	0.005	0.002
$R(J/\psi)$	0.24	0.071	–	0.02
Charm				
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4}	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4}	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4}	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}
$x \sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}

Upgrade document milestones

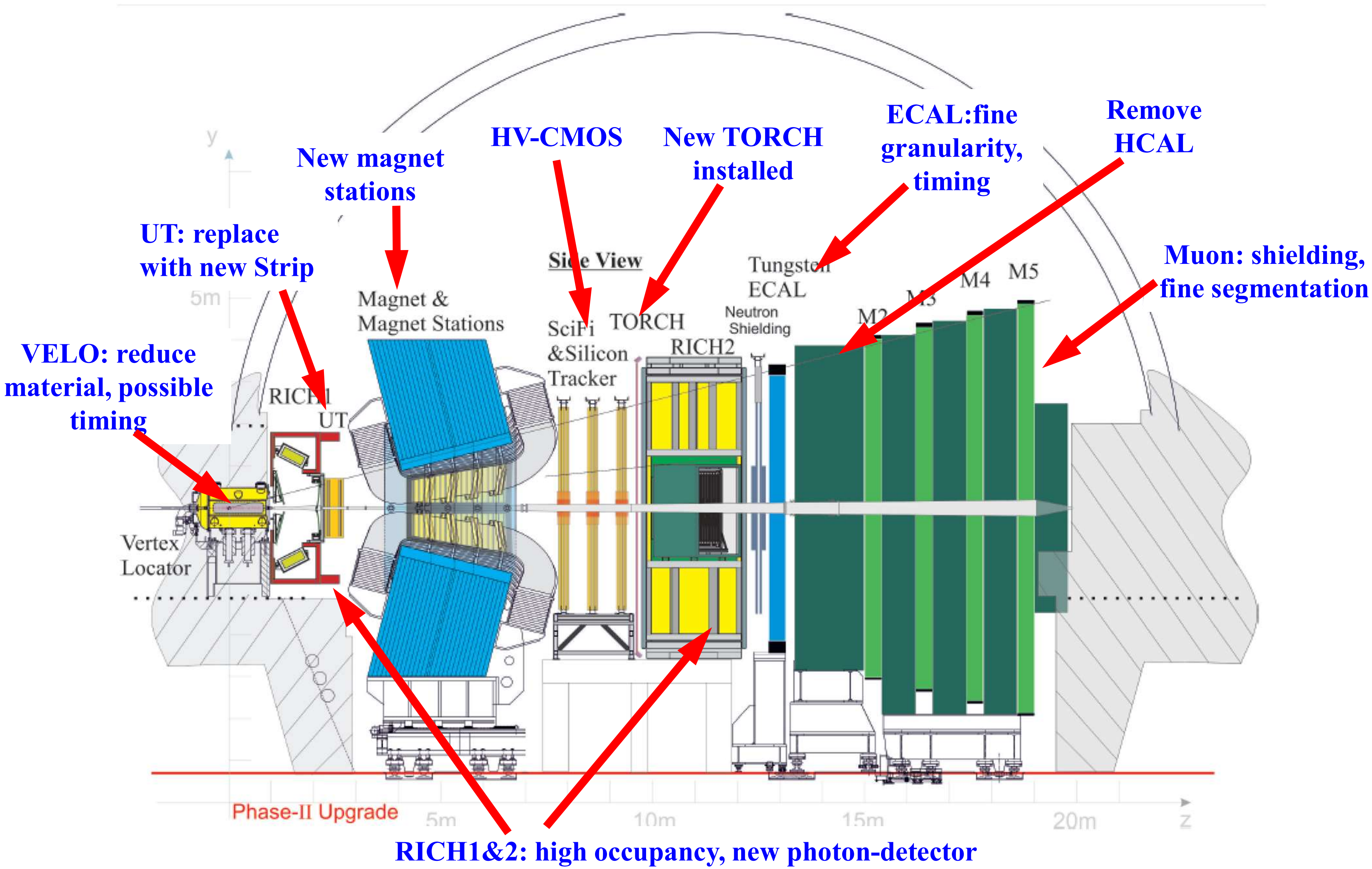


Upgrade-I Detectors

- VELO: strips ⇒ hybird pixels, closer, finer
- UT ⇒ TT (Strips); IT + OT ⇒ SciFiber Tracker
- New electronics/trigger-system, 40MHz

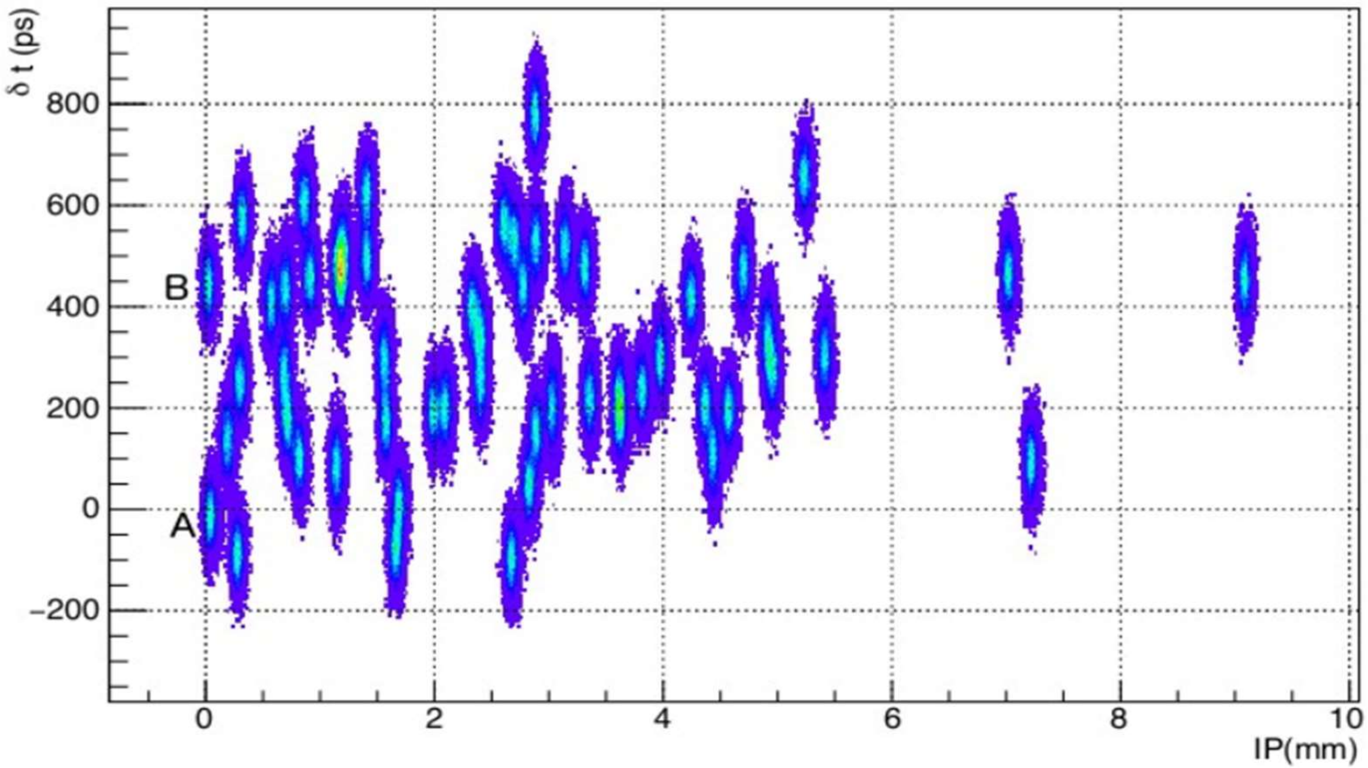


Upgrade-II Detectors



Timing@ HL-LHC

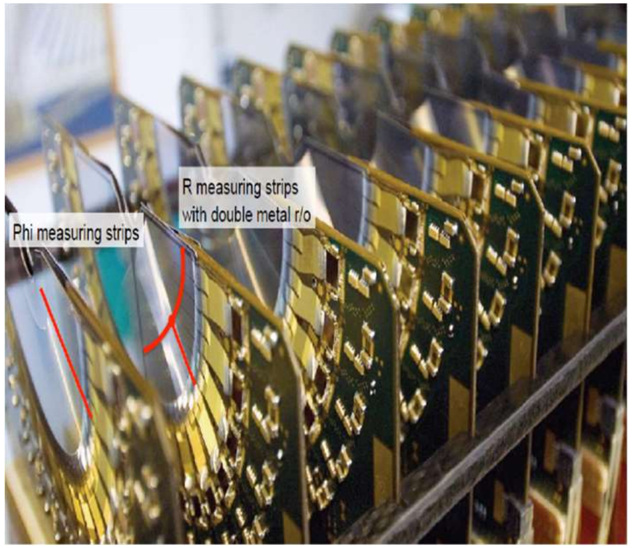
- HL-LHC: pile-up is the biggest issue
- Generally, exploring timing is being considered for all detectors to suppress pile-up



Distribution of tracks in space and time

VELO Upgrade I

- Upgrade I:
  rows of silicon micro-strip modules
  ⇒ rows of silicon hybrid pixel modules



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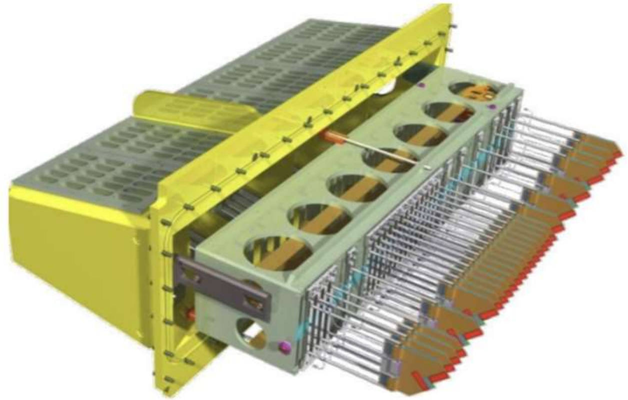
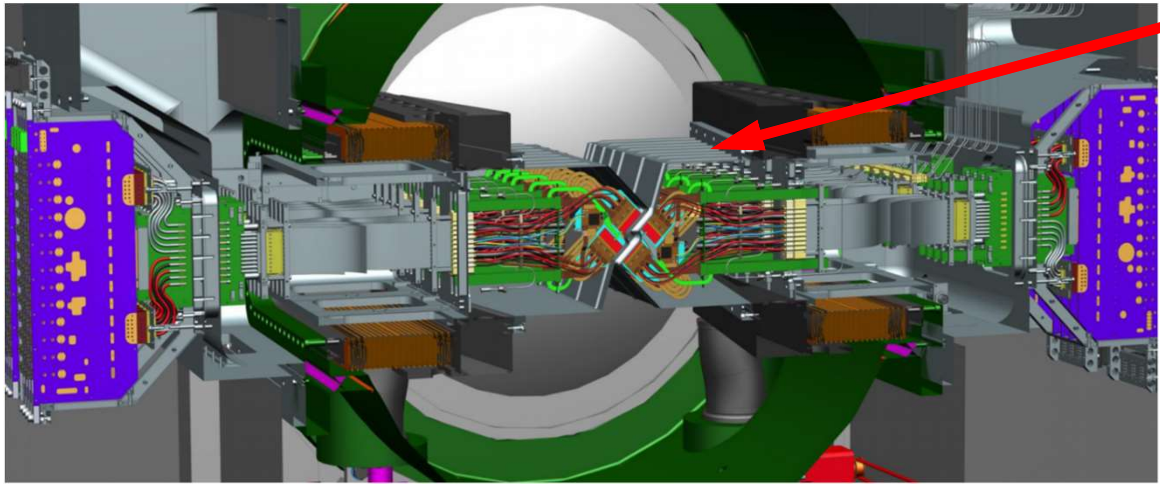


- Upgrade I assembly:

The RF foil

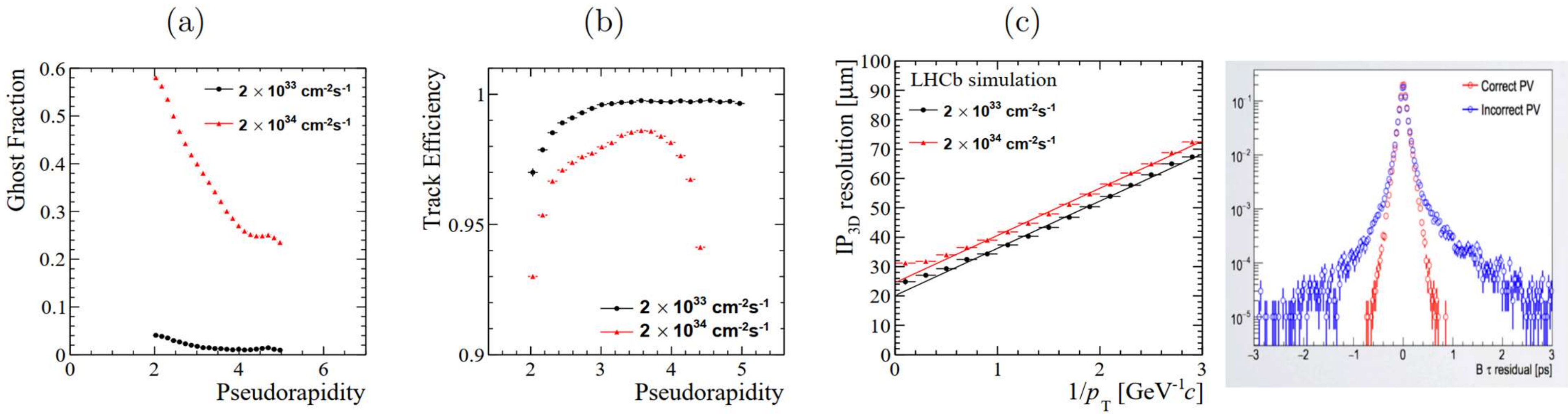


VELO needs Upgrade for high Lumi

The machine parameters for high-lumi: pileup ~ 42, Upgrade II must deliver at least the same performance as Upgrade I, with:

- 10 x higher particle multiplicity
- 10 x higher radiation damage
- 10 x higher data-out rates
- 10 x denser primary vertex environment

Very challenging!

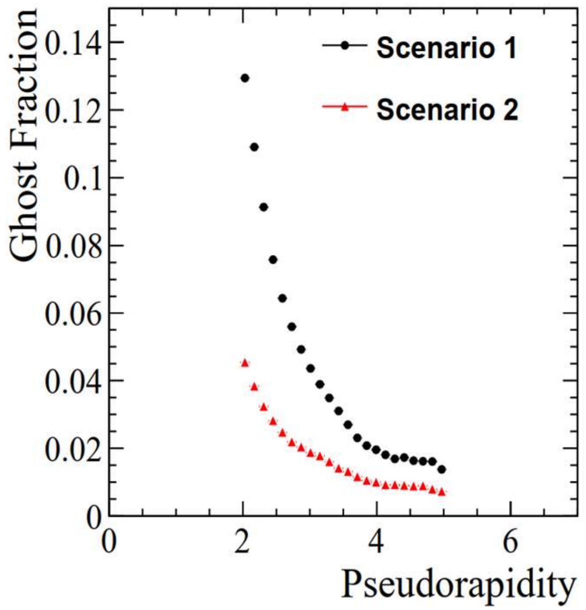


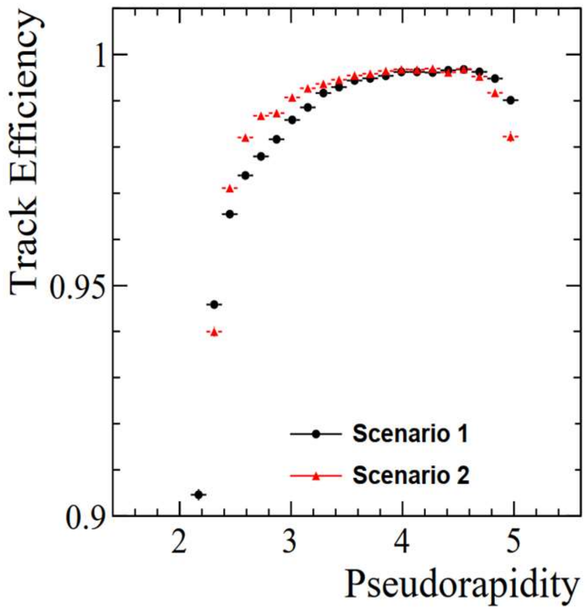
Simulated of the Upgrade I VELO design, with no further improvements

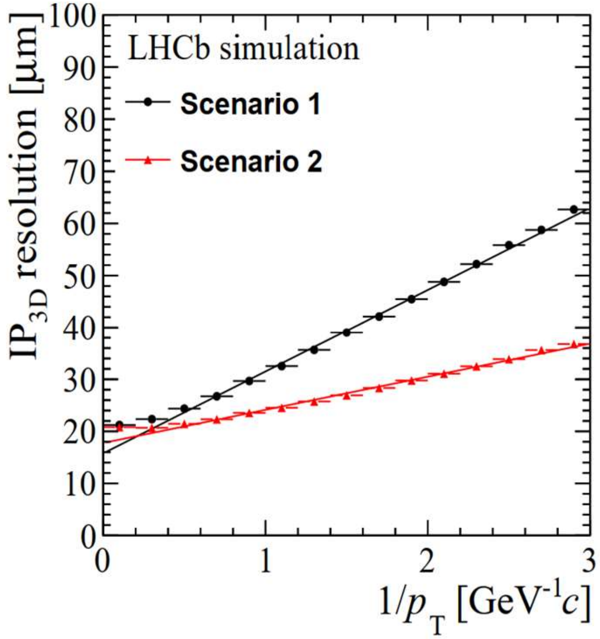
VELO Upgrade II --- Part1

Remove the RF foil :

- gives the largest material budget
- alternative designs can be considered, such as a system of wires



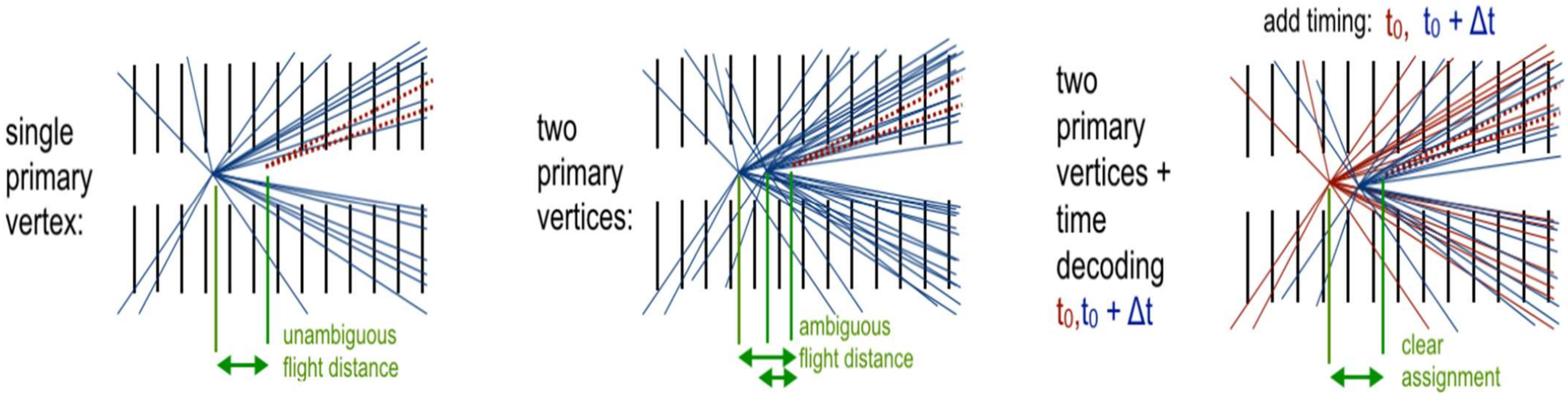




- Scenario 1 includes pixels with one quarter of the area of the Phase-I pixels, and a reduced sensor thickness
- Scenario 2 also includes removal of the RF foil separating the VELO and beam vacuum

VELO Upgrade II --- Part2

Moving towards 4D tracker concept with addition of timing:



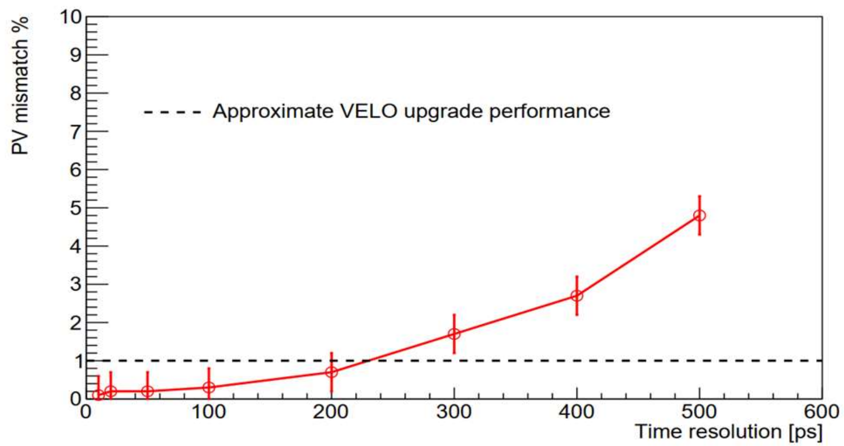
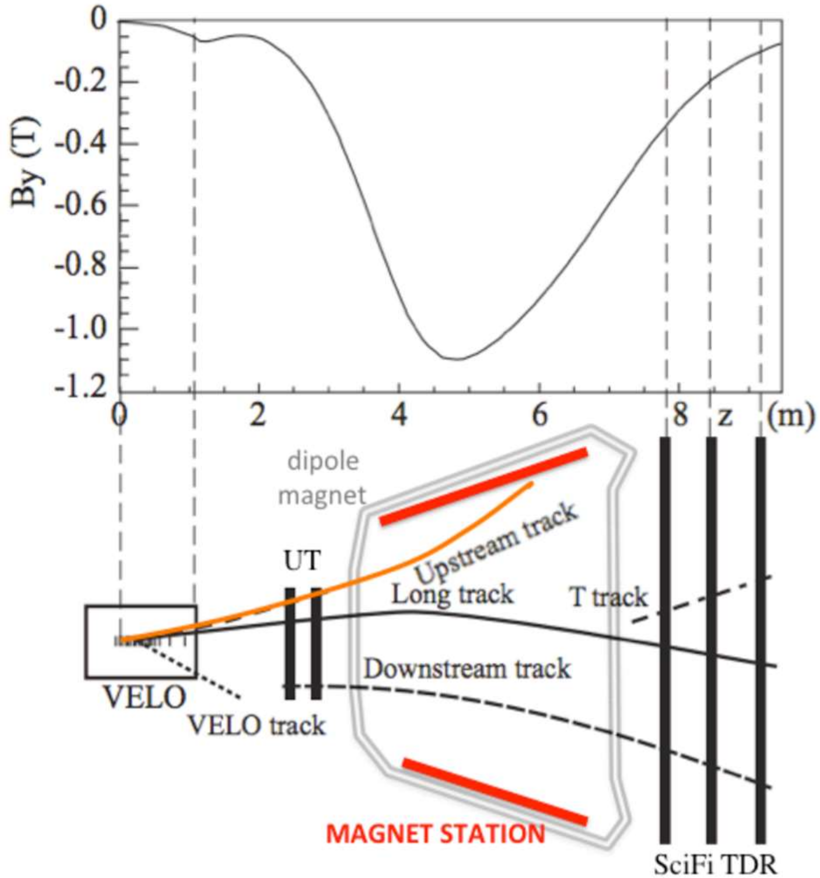
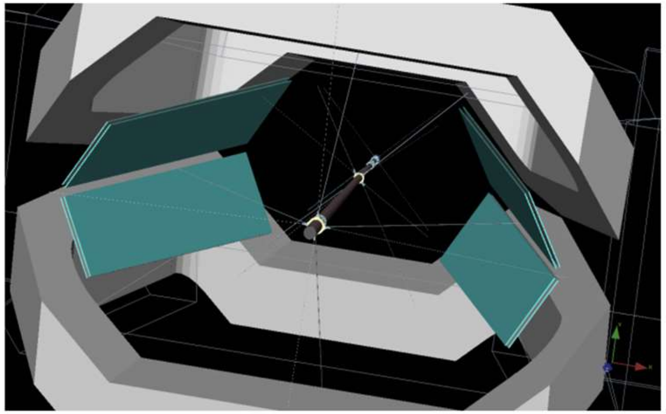
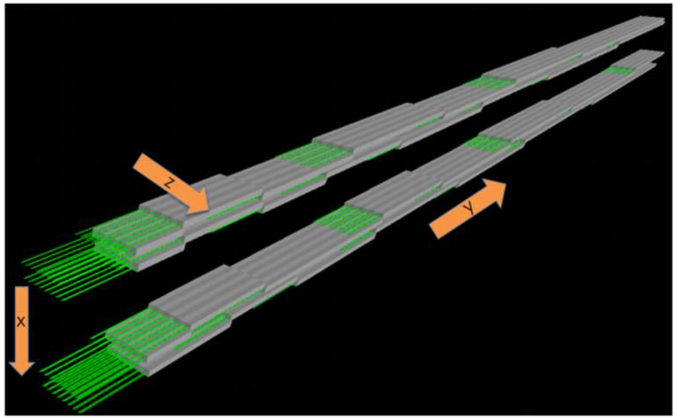


Figure 4.4: Fraction of b-hadron decays mismatched to the wrong PV as a function of the time resolution per hit at a luminosity of $2 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The horizontal dashed line shows the approximate performance of the Phase-I Upgrade VELO at $2 \times 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The hit information used as input to the study is obtained from a sample of simulated events assuming the layout of the Phase-I Upgrade VELO.

Magnet Stations





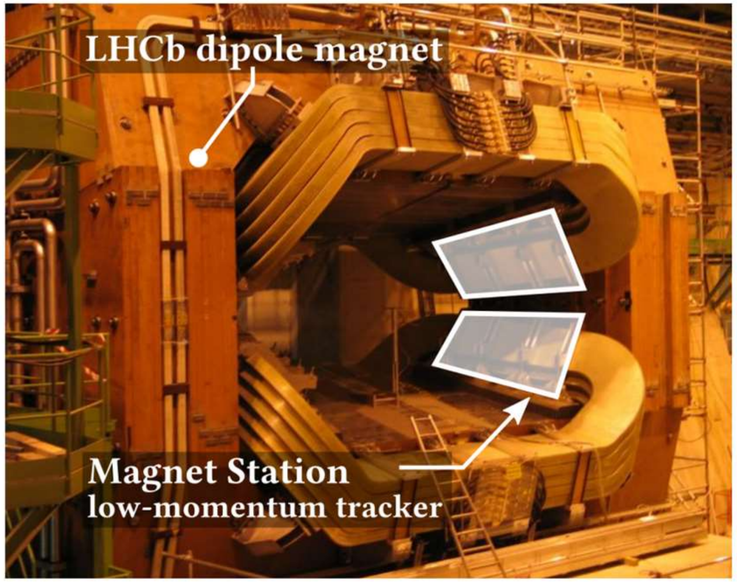


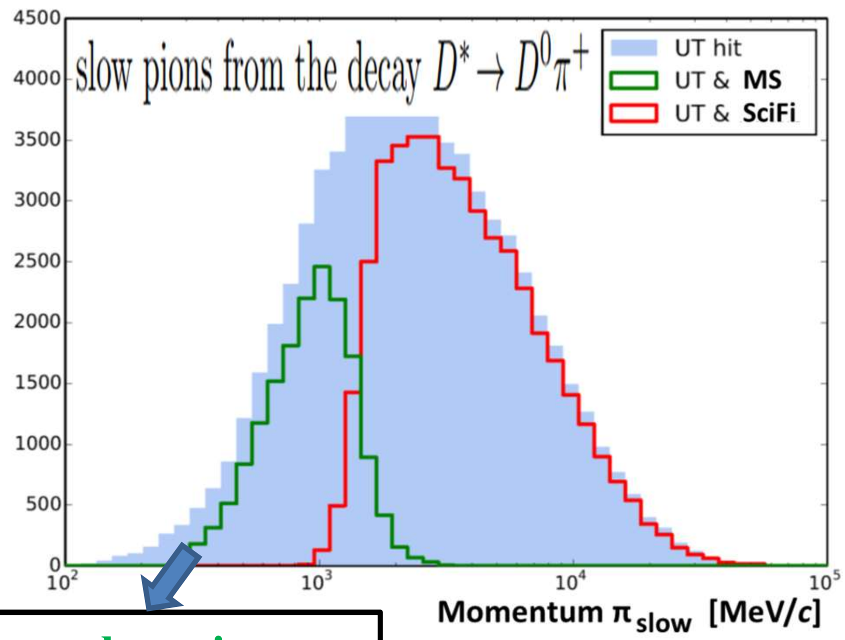
- Improve tracking for soft particles which cannot cross the magnet
- Scintillator-based tracker on the internal side walls of the magnet

Magnet Stations

Physics cases:

- Many body final states in beauty/charm decays commonly contain one or more low-momentum
- strange mesons/baryons would benefit due to the low momentum of the products originating from the decays of these lower mass particles.
- improve for decays where a final-state particle is produced at/near threshold

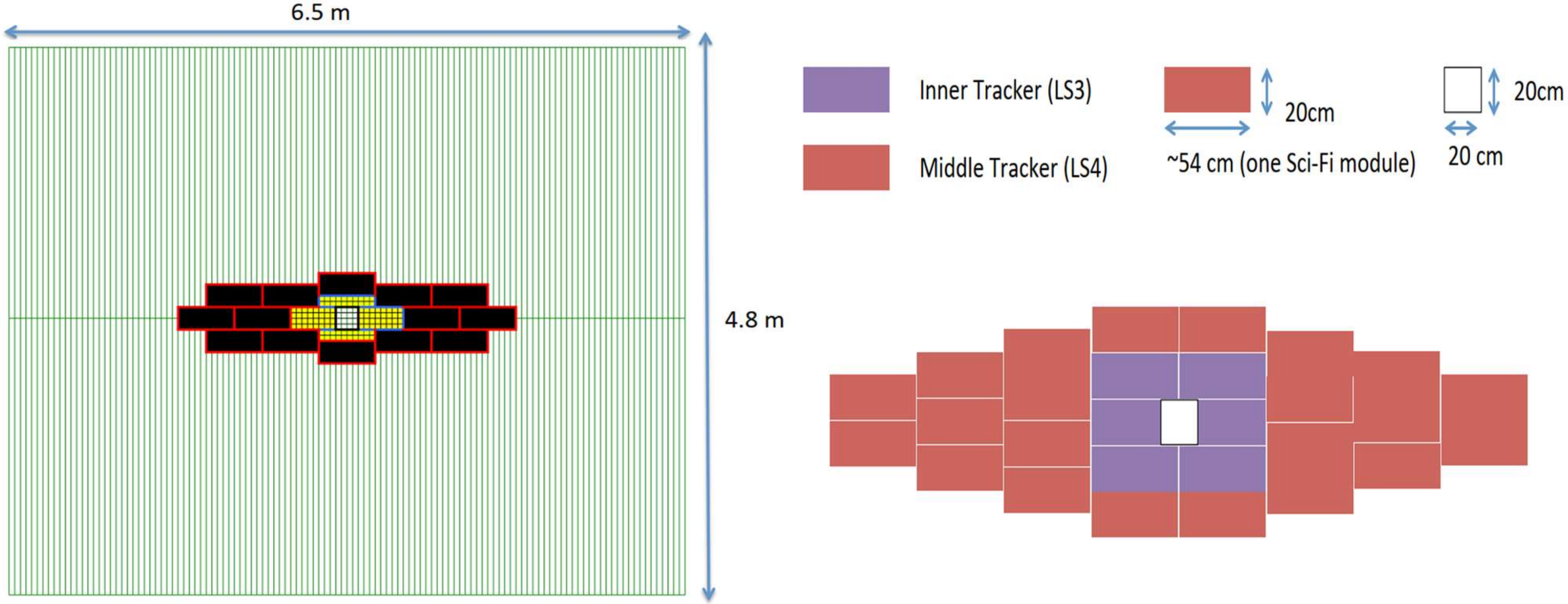




Recovery 40% more slow pion

Mighty Tracker

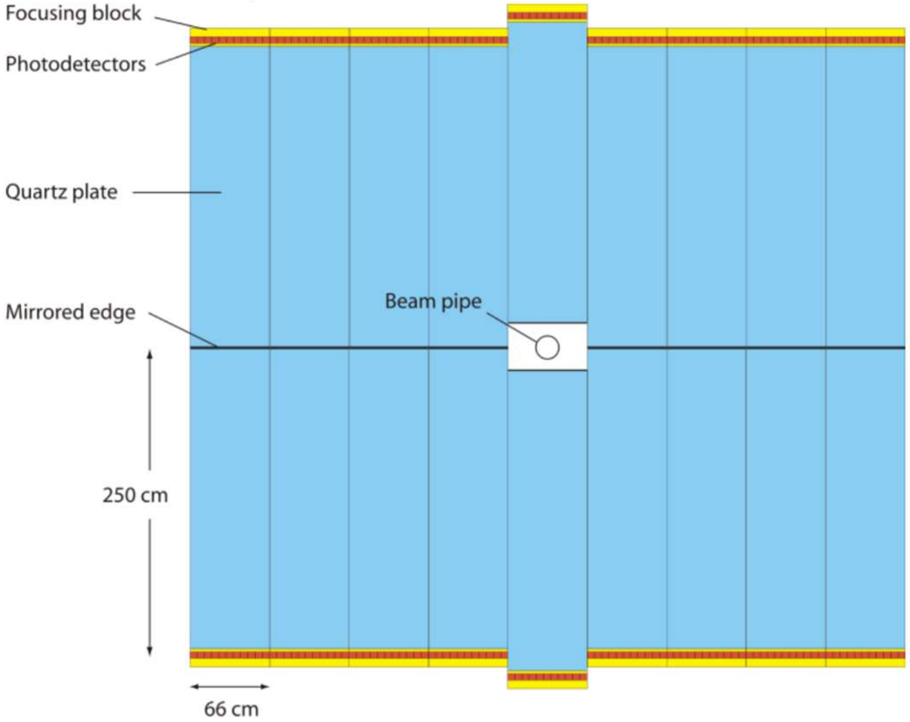
Primary tracking device that provides momentum resolution for the tracks, in conjunction with the VELO and UT.

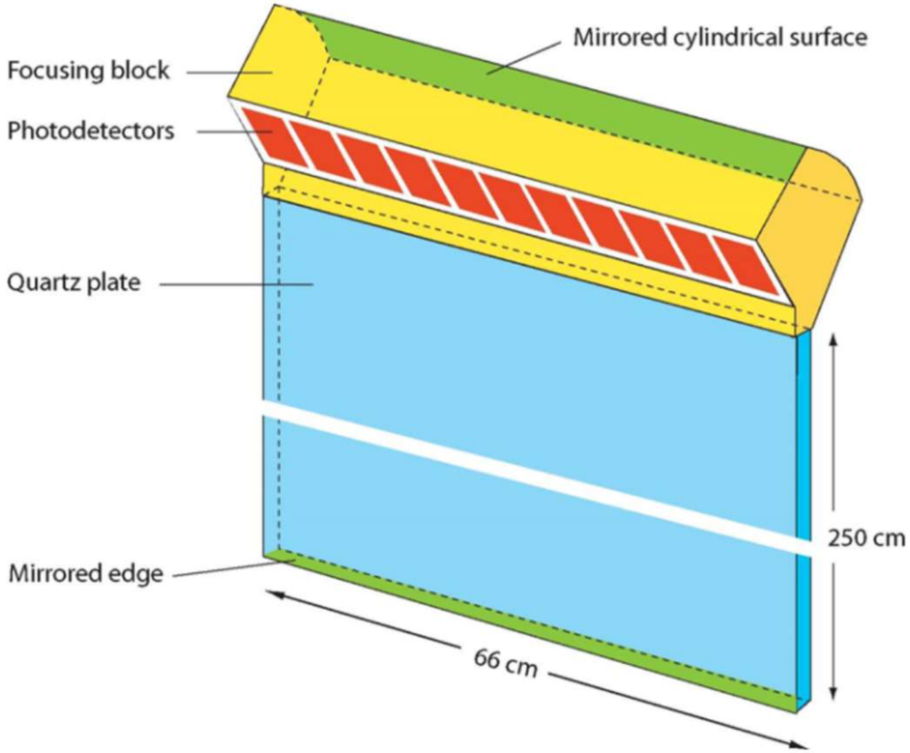


- Two stage approach: Inner tracker in LS3, middle tracker in LS4
  - HVCMOS (borrowed from ATLAS, mu3e)
- The Outer region: vertical scintillating fibres

TORCH

Time Of interally Reflected CHerenkov light：
measure the arrival time of charged particles with a precision of a few tens of ps



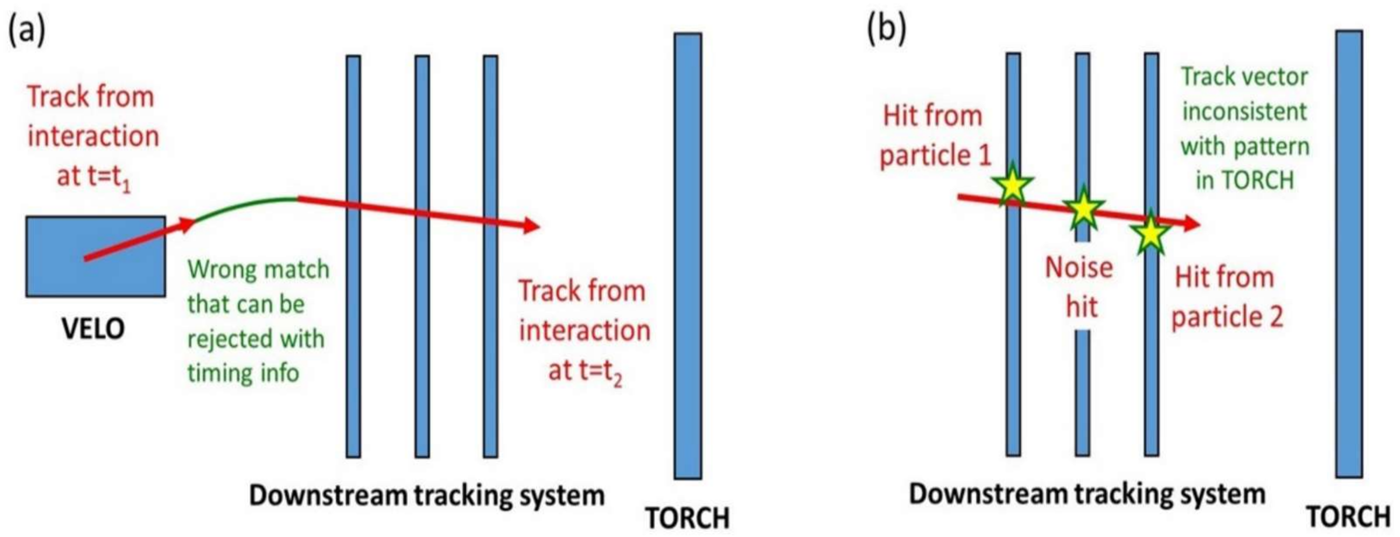


- New multi-channel photontube technology, aiming to provide ~15 ps timing resolution

TORCH

Physics cases:

- suppress the rate of ghost tracks (compare TORCH timestamp with the timestamp from the VELO)
- sensitive to the direction of the incident particles, suppress T-track ghosts arising from the incorrect association of hits in the DT

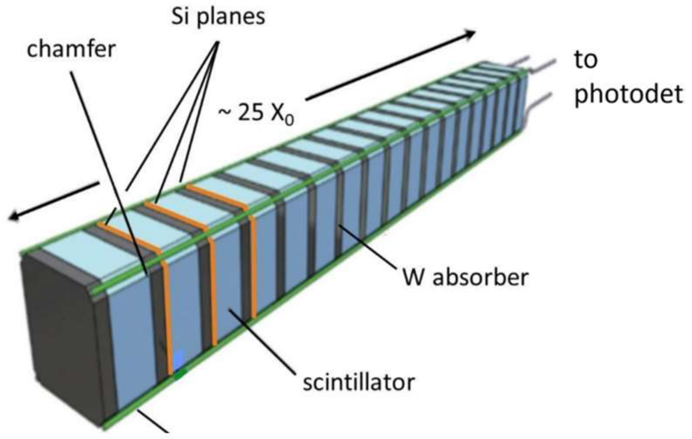


- 2/3 of *K*s0 mesons (a higher proportion of *Λ)*, decay after the VELO and so could only be time-stamped by the TORCH. Allow these long-lived particles to be assigned to the correct interaction
- Time-of-flight PID detector for $p < 10$ GeV/c

ECAL

ECAL requirements for Upgrade II:

- Innermost modules must sustain doses up to ~1MGy
- Better spatial resolution in inner, middle region; Keep good energy resolution
- Add timing info to mitigate pile-up effects



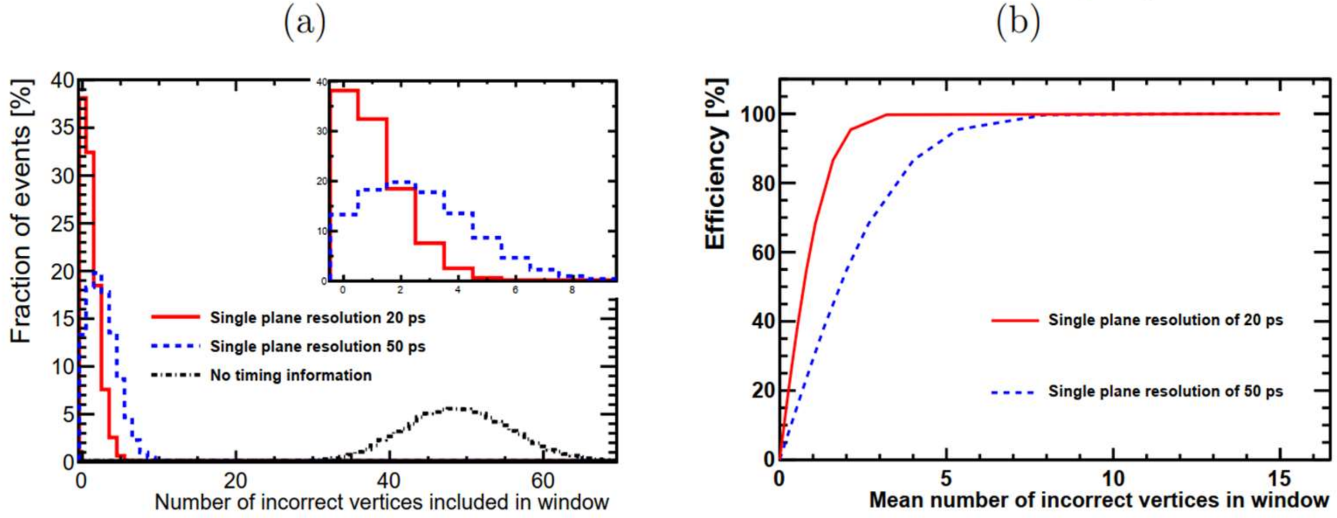
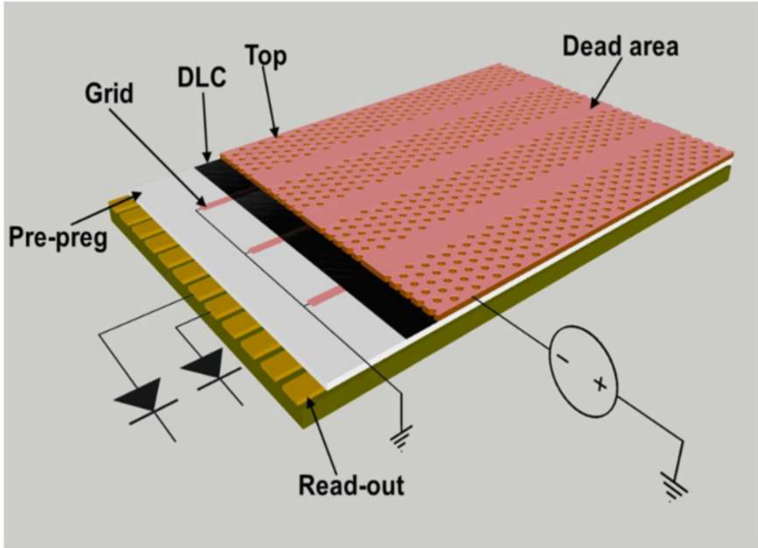


Figure 4.13: Impact of timing information on assigning ECAL clusters to PVs: (a) number of incorrect vertices passing selection; (b) efficiency of selection vs. number of incorrect vertices.

Muon

μ-RWELL



- Additional iron shielding instead of HCAL
  - HCAL was for hardware trigger
- New chamber technology with their own customised frontend electronics in the hottest region

Summary

- LHCb currently ongoing a major upgrade for Run-3 and Run-4.

- Preparations underway for a new era of discoveries taking maximum advantage of the High-Luminosity LHC
  - timing information may be key to coping with pile-up