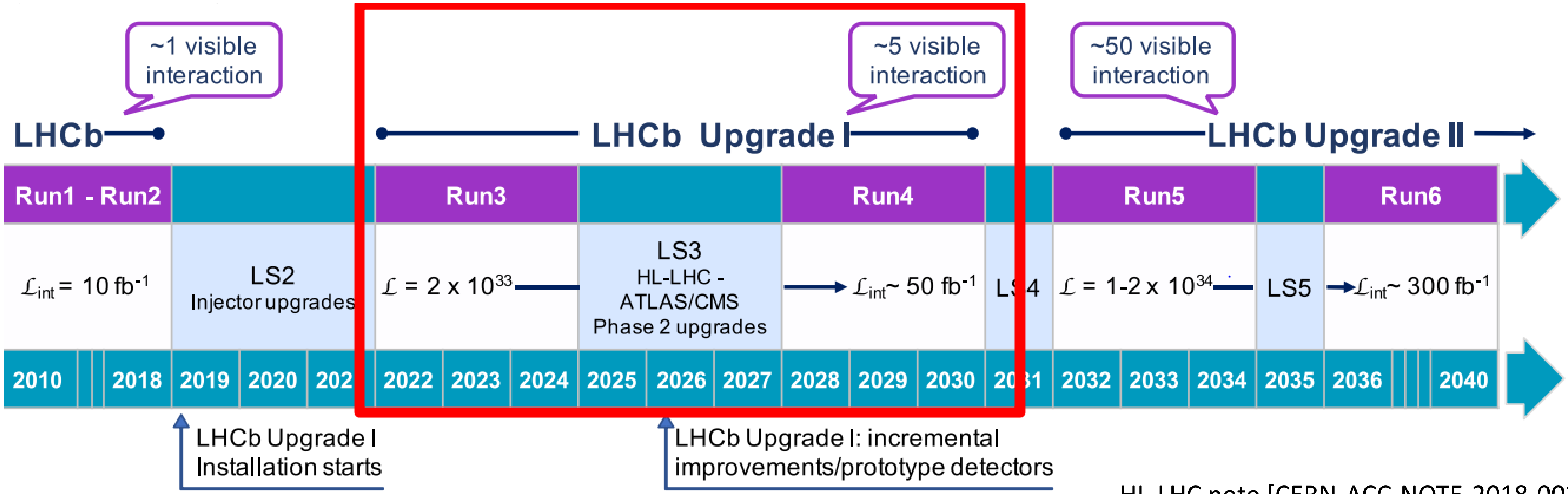
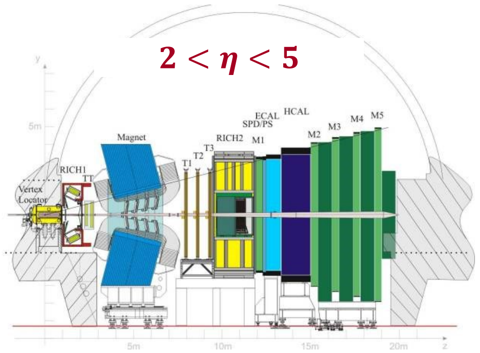
Physics prospects, experimental challenges - LHCb Upgrade II

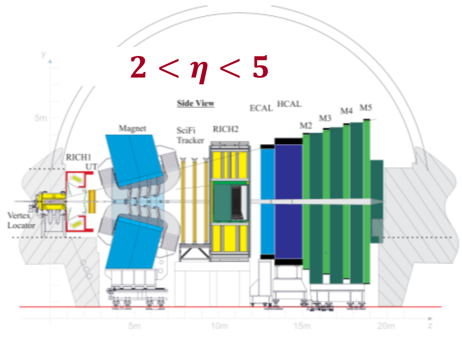
XIV International Conference on Beauty, Charm and Hyperon Hadrons
5-11.06.2022 Kraków

Agnieszka Obłąkowska-Mucha
AGH-UST Kraków
on behalf of LHCb Collaboration

Timeline for the LHCb Upgrades







HL-LHC note [CERN-ACC-NOTE-2018-0038]

Feasibility of running of LHCb Upgrade II

LHCb response [LHCb-PUB-2019-001]

Considerations for the VELO detector at the LHCb Upgrade II
CERN-LHCb-PUB-2022-001

LHCb Upgrades

- LHCb physics programme in Run 1 – Run 3 and 4 is limited exclusively by the detector.
- LHCb **Upgrade I** has been completed this year, Run 3 starts next month!

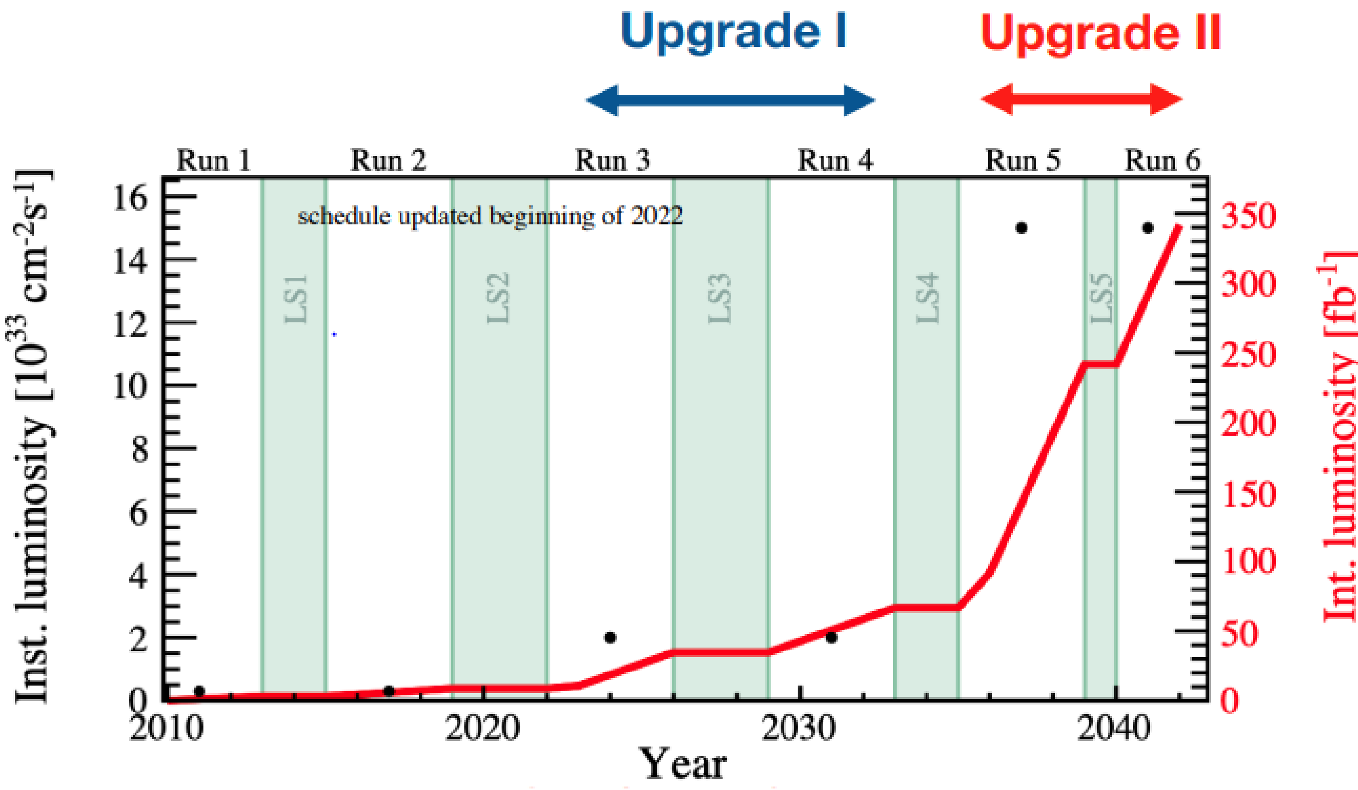
Upgrade I:

- $\mathcal{L}_{max} = 2 \times 10^{33}$ cm^{-2}s^{-1}
- $\mathcal{L}_{int} = 50$ fb^{-1} (Run 3+4)

- LHCb Upgrade II starts after LS4 (major upgrade of ATLAS/CMS)

Upgrade II:

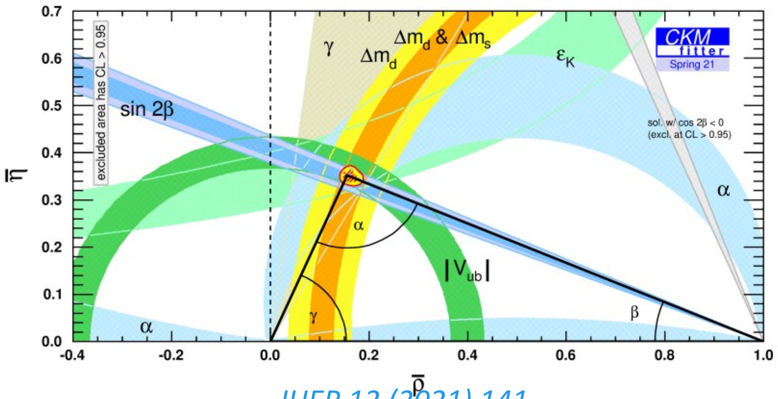
- $\mathcal{L}_{max} = 1.5 \times 10^{34}$ cm^{-2}s^{-1}
- $\mathcal{L}_{int} = 250\text{-}300$ fb^{-1} (Run 5+6)



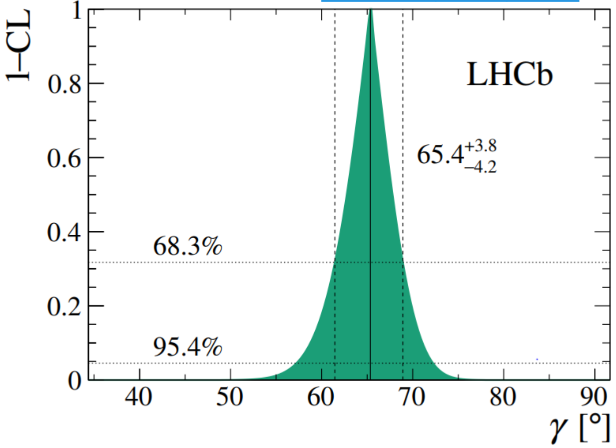
Physics programme for Upgrade I

Run 1 -2 and 3-4

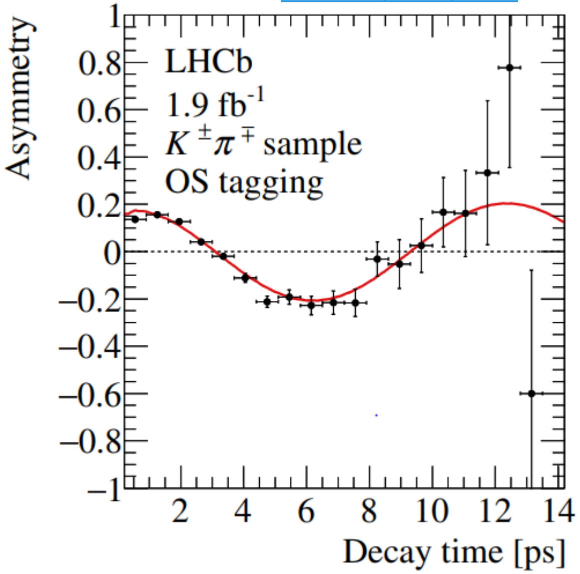
- Time-dependent and time-integrated CPV measurements
- Measurement of unitarity triangle sides
- Mixing and CPV in charm
- Rare decays, exotic hadrons
- Forward physics, QCD
- Dark matter
- Heavy ion physics

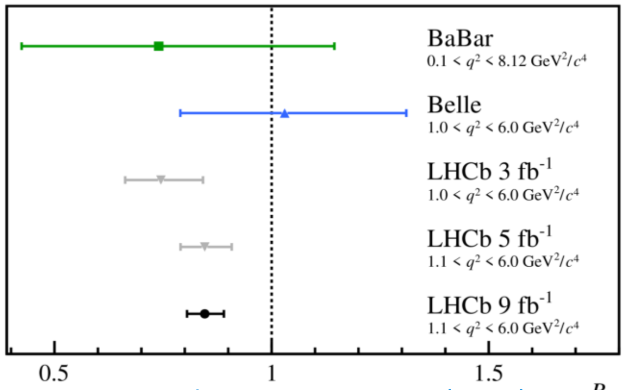


JHEP 12 (2021) 141



JHEP 03 (2021) 075

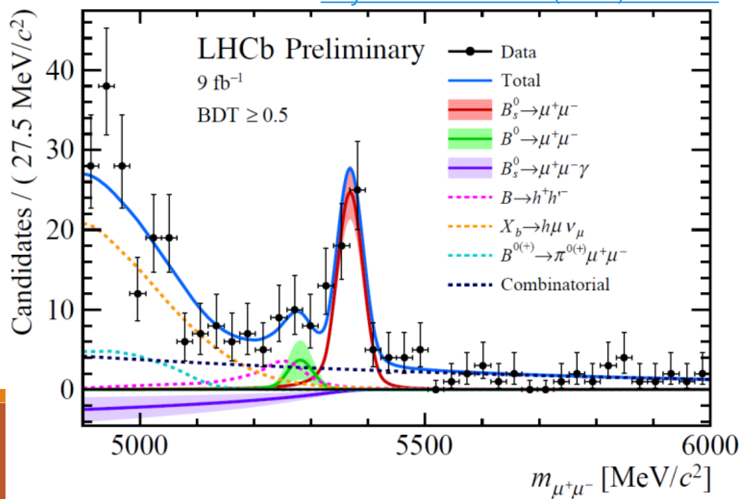




Nature Physics **18**, 277–282 (2022)

see Monday's talk for details

Phys. Rev. Lett. 128 (2022) 041801



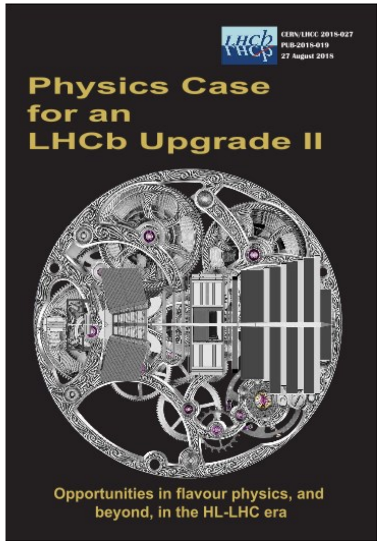
Physics prospects

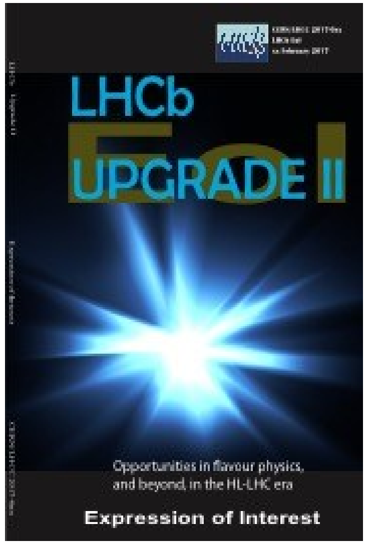
Run 5-6

- Time-dependent and time-integrated CPV measurements
- Measurement of unitarity triangle sides
- **Mixing and CPV in charm**
- Rare decays, **exotic hadrons**
- Forward physics, QCD
- **Dark matter**
- **New Physics Searches**
- Heavy ion physics

AIM: increase the precision (larger data sample)
with the same performance as in Run 2,3-4 but with **pile-up ~ 42!**

Expresion of Interest LHCC-2017-003
Physics case LHCC-2018-027
Accelerator study CERN-ACC-2018-038

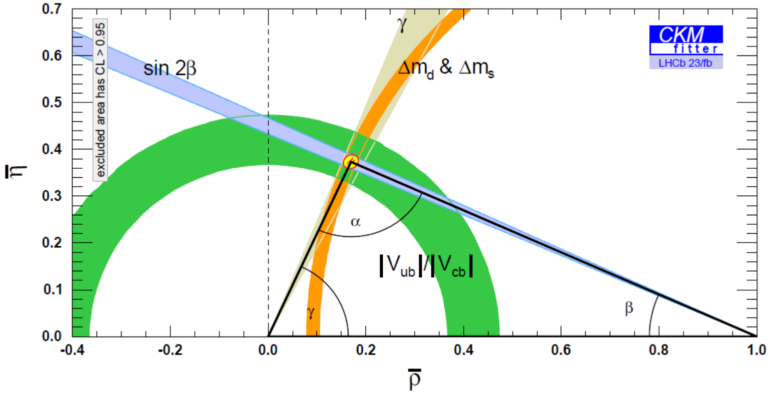




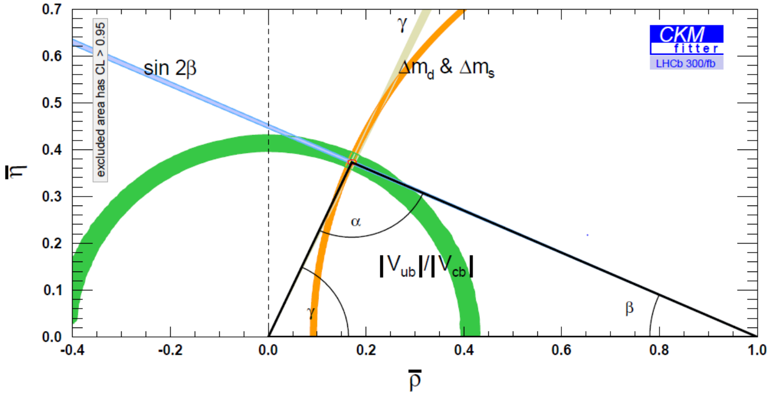
Measurement of UT

- CP observables measured in Run 1, 2 and 3 may not exclude NP!
- More and more precise results may reveal possible inconsistencies
- HL-LHC era: possibility for clean picture of the physics of flavour

Run 1 - 3



HL-LHC



Two independent measurements of triangle apex:

$(\Delta m_d/\Delta m_s, sin2\beta)$ and (V_{ub}, γ)

Both require Upgrade II: $(\Delta m_d/\Delta m_s, sin2\beta, \gamma)$ for statistics, and theory improvements ($\Delta m_d/\Delta m_s$ and V_{ub})

CKM elements $|V_{ub}|$ and $|V_{cb}|$ affect the UT apex and interpretation of rare $B_{(s)} \to \mu^+\mu^-$

LHCb-PUB-2022-012

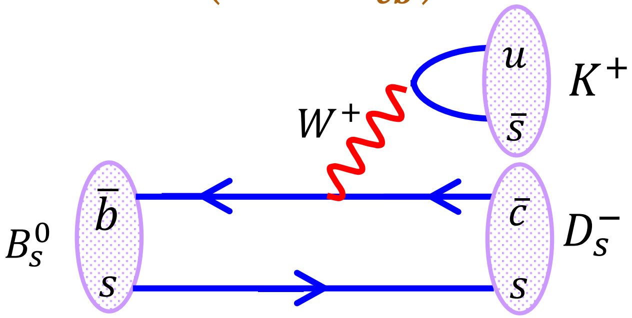
CKM angle γ

CKM angle γ

see also Wojtek Krupa's talk

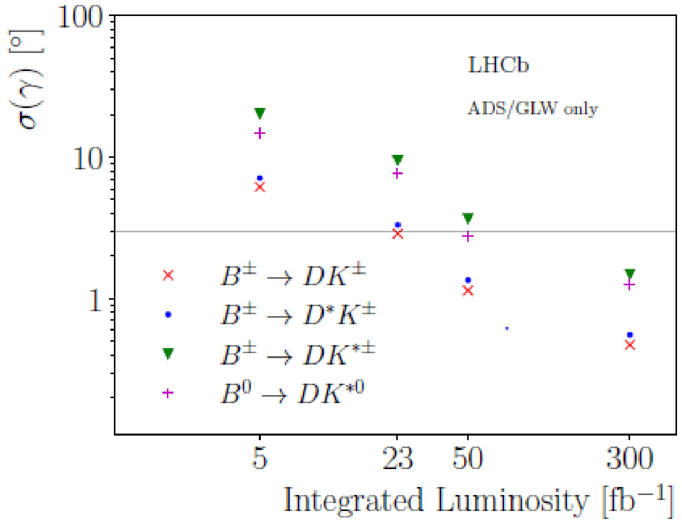
$$\gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

1. The only angle that can be determined exclusively from tree processes
2. Theoretically clean: $\delta\gamma/\gamma \leq \mathcal{O}(10^{-7})$
3. SM benchmark for New Physics searches
4. The most recent LHCb result (15 decay modes): $\gamma = \left(65.4^{+4.2}_{-3.8}\right)^\circ$



Run 1-2:
some tension between direct and indirect methods-
need better precision from trees measurements

LHCb-PUB-2022-012



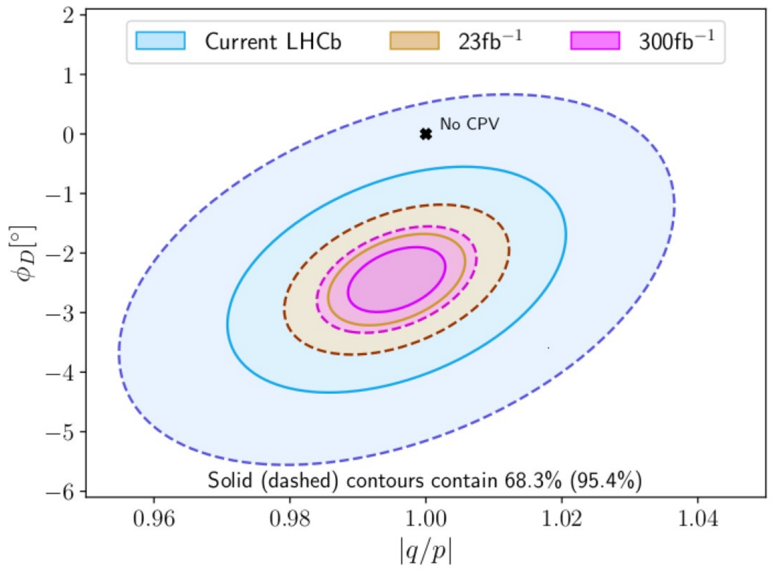
5. Upgrade in sensitivity: combination of many final states in $B_{(s)} \to D_{(s)}^{(*)} h^{(*)}$:
   - charged and neutral (π^0, γ),
   - two- and multi body D decays
   - fully and partially reconstructed

LHCb Upgrade II anticipates a precision on γ of about 0.35°.

Exclusively @LHCb U2

CP Violation in charm

- SM – CPV in charm at level of 10^{-4}
- Fully software LHCb trigger – more charm hadrons than B-factories.
- Tracking stations inside magnet – more flavour-tagged decays
- LHCb Upgrade II is the only planned experiment with possibility to observe **CPV in charm mixing at the level of 10^{-5}**
- Strighten CP violation in decay:
  - ✓ Higher rate of two-body D^0 decays
  - ✓ Interfering structure of three(four-)body decays of charm mesons
- Searches of NP more efficient.



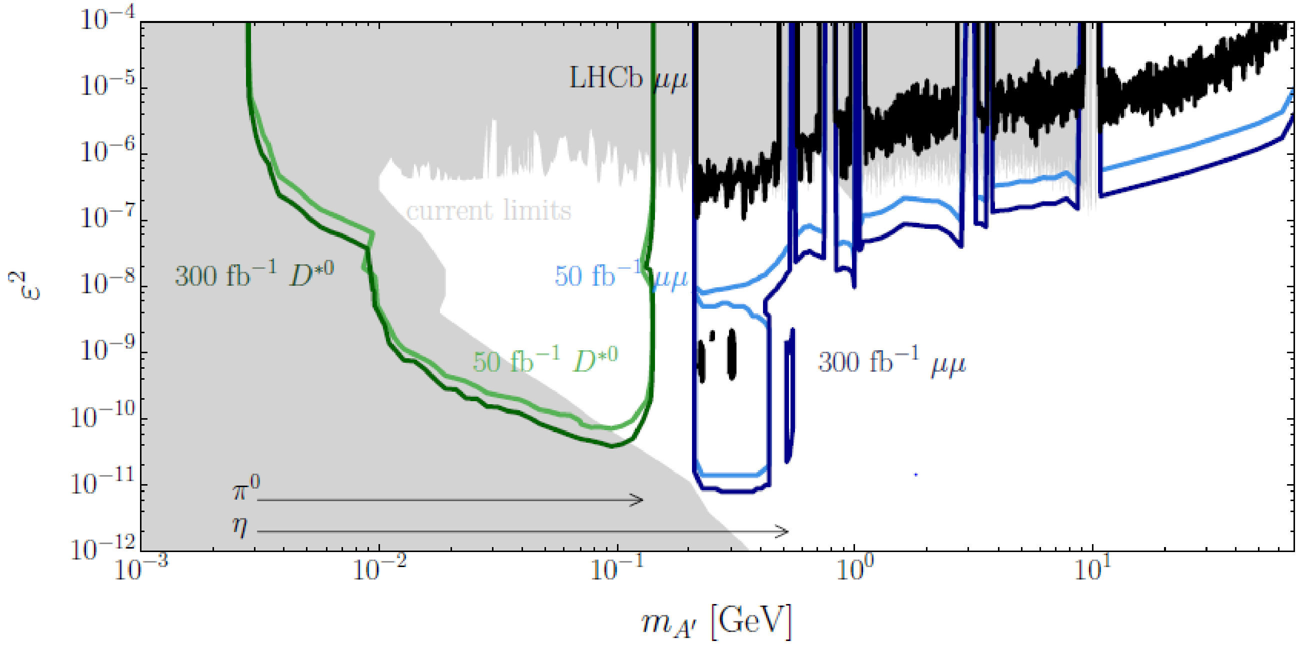
see also A.Ukleja's and E.Shields' talk

LHCb-PUB-2022-012

Dark Matter

LHCC-2018-027

Search for prompt and detached **dark photons**



Model of A':

- dark force in SM with dark mediator,
- A' can mix kinematically with SM photon with:
  mixing term $\epsilon^2, m_{A'}$
  ϵ^2 is the ratio DM to EM force strength

In Run 2:

- small luminosity
- hardware trigger removed most of possible $A' \rightarrow \mu^+\mu^-$ events
- world best upper limits in $(\epsilon^2 - m_{A'})$ space

Upgrade II:
LHCb can explore significant ranges of unconstrained A' parameter space for prompt and detached dark photon

HL runs at LHCb - precisions

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.044 [6]	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.12 [19]	0.031	0.034	0.009	–
CKM tests					
γ	4° [5]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K^0_S$	0.04 [20]	0.011	0.005	0.003	–
ϕ_s, with $B^0_s \to J/\psi\phi$	32 mrad [21]	14 mrad	–	4 mrad	22 mrad [22]
ϕ_s, with $B^0_s \to D^+_s D^-_s$	170 mrad [23]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B^0_s \to \phi\phi$	154 mrad [24]	39 mrad	–	11 mrad	Under study [25]
a^s_{sl}	33×10^{-4} [26]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [27]	3%	1%	1%	–
$B^0_s, B^0 \to \mu^+\mu^-$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$	69% [4, 28]	41%	–	11%	21% [29]
$\tau_{B^0_s \to \mu^+\mu^-}$	14% [4, 28]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$b \to c\ell^-\bar{\nu}_l$ LUV studies					
$R(D^*)$	0.026 [30, 31]	0.007	0.005	0.002	–
$R(J/\psi)$	0.24 [32]	0.07	–	0.02	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	29×10^{-5} [7]	13×10^{-5}	5.4×10^{-4}	3.3×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	11×10^{-5} [33]	5×10^{-5}	3.5×10^{-4}	1.2×10^{-5}	–
Δx $(D^0 \to K^0_S\pi^+\pi^-)$	18×10^{-5} [34]	6.3×10^{-5}	–	1.6×10^{-5}	–

LHCC-2018-027

LHCb-PUB-2022-012

Detector requirements for LHCb Upgrade II

AIM: the same performance as in Run 2 but with pile-up ~ 42!

LHCb Run 2 performance breaks down at Upgrade II luminosity:

- tracking efficiency is reduced 😐
- ghost rate has increased ☹
- PV reconstruction has low efficiency ☹

New tracker concept

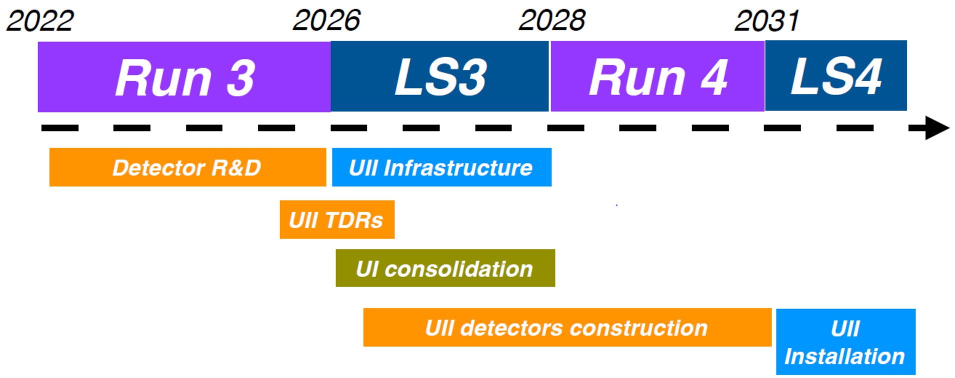
- radiation hardness $\Phi_{eq} > n \times 10^{16}$(sensors) and > 1 Grad (electronics)
- space resolution: $\sigma(10\ \mu m)$
- time resolution < 100 ps per pixel
- data rates > n ×Tb/s must be handled

New PID system

- TORCH for low momentum hadrons

New ECAL

- requires granularity and timing



LHCb Upgrade II

LHCb is moving to luminosity 1.5×10^{34} cm^{-2}s^{-1} with the same performance as for 2×10^{33} cm^{-2}s^{-1}

Scintillating Fibre (SciFi) will be replaced for Upgrade II

New tracking system:

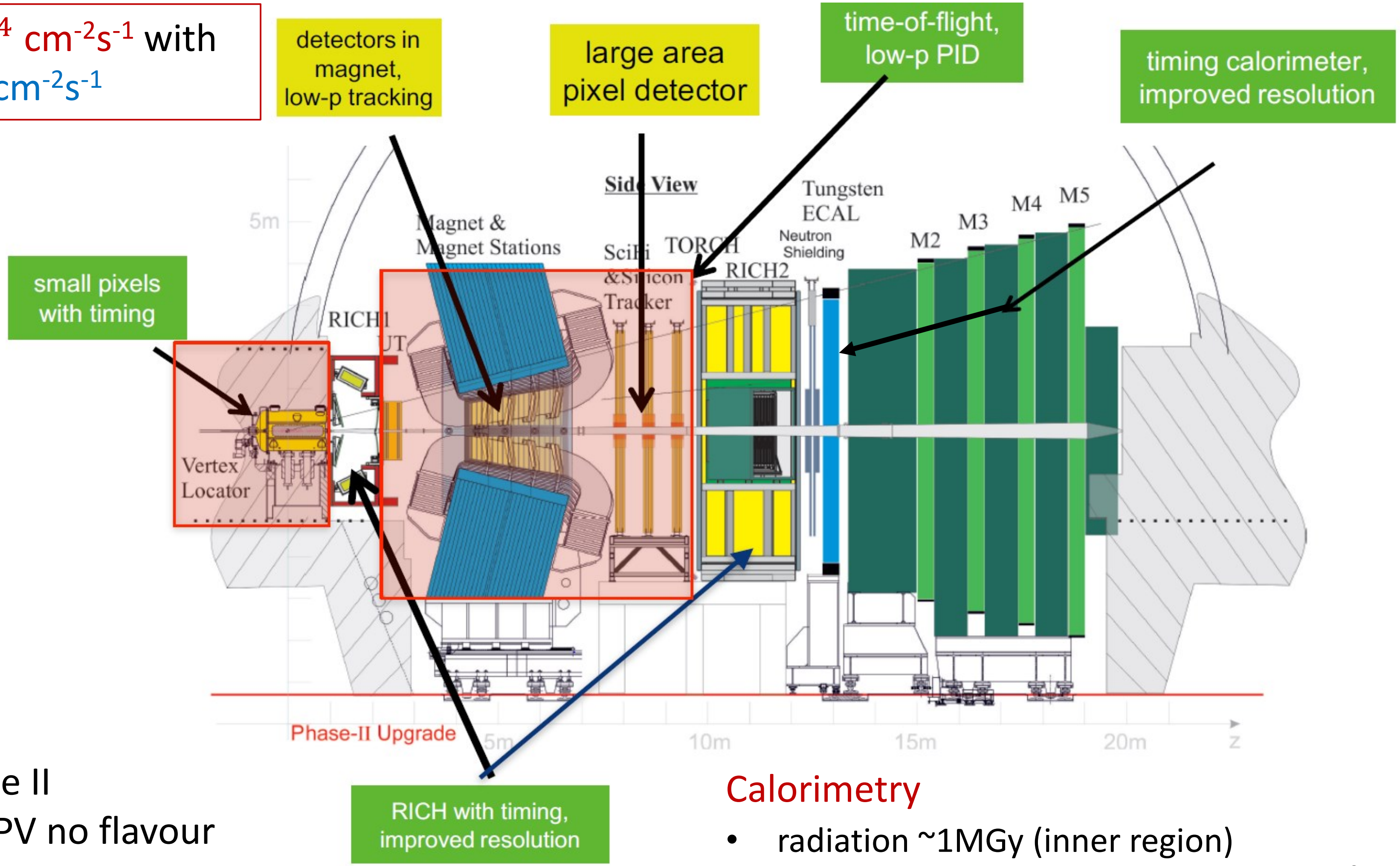
- MightyTracker
- Magnet stations

New PID:

- New RICH
- TORCH

Redesigned Vertex Locator:

- crucial to the success of Upgrade II
- without the precision in IP and PV no flavour physics



Calorimetry

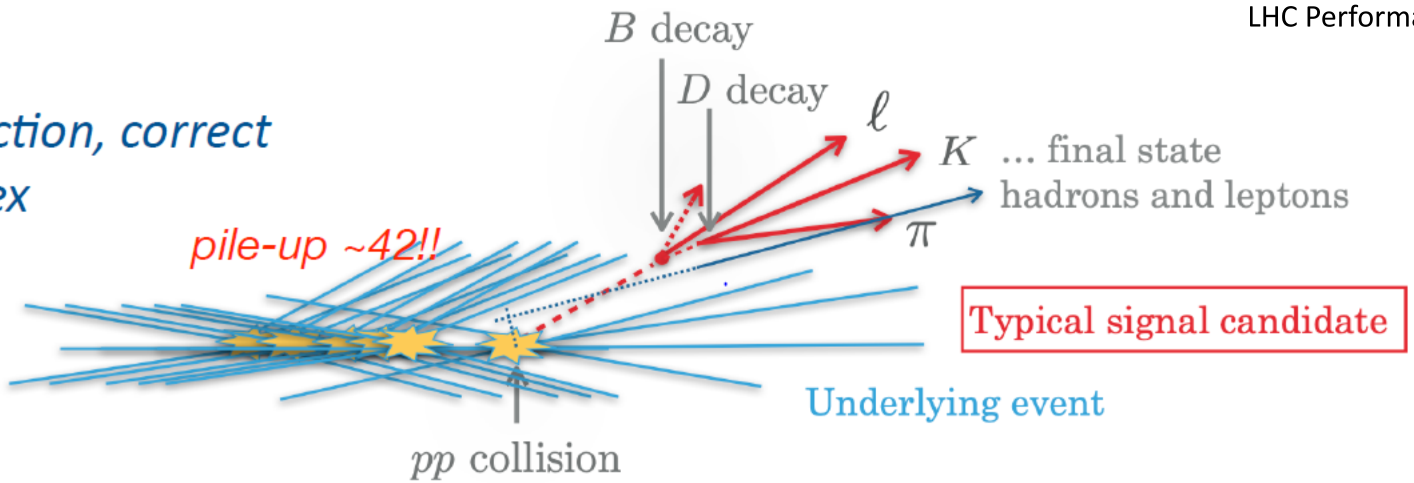
- radiation ~1MGy (inner region)
- large combinatoric background from π^0

Vertex reconstruction for LHCb Upgrade II

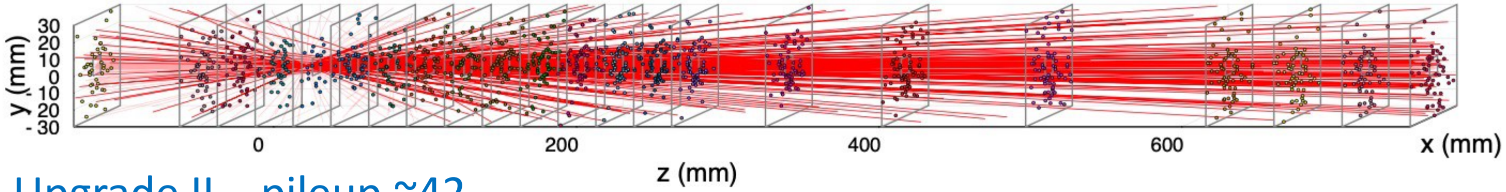
LHC Performance Workshop 2022

Essential for flavour physics

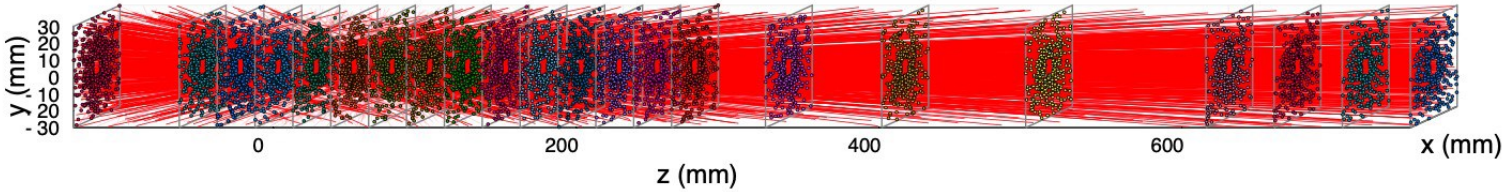
- *primary vertex (PV) reconstruction, correct association with B decay vertex*
- *decay time and impact parameter resolutions*



Upgrade I – pileup ~6



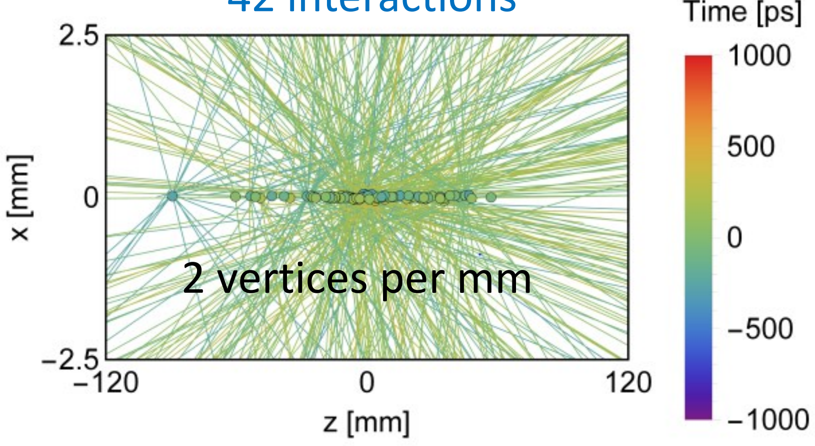
Upgrade II – pileup ~42



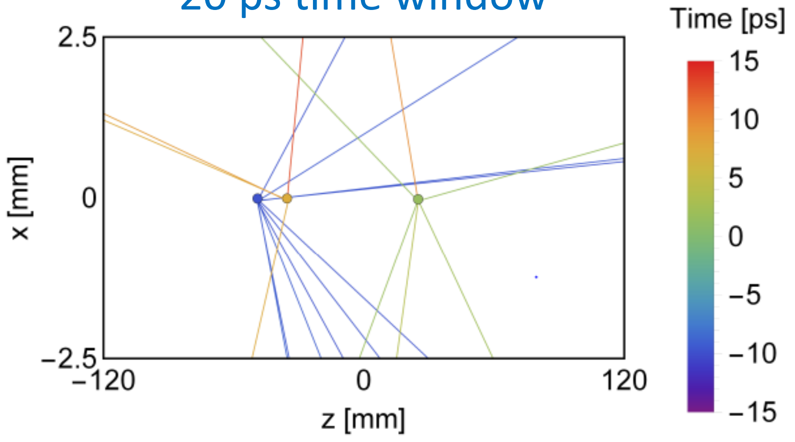
Vertex reconstruction for LHCb Upgrade II

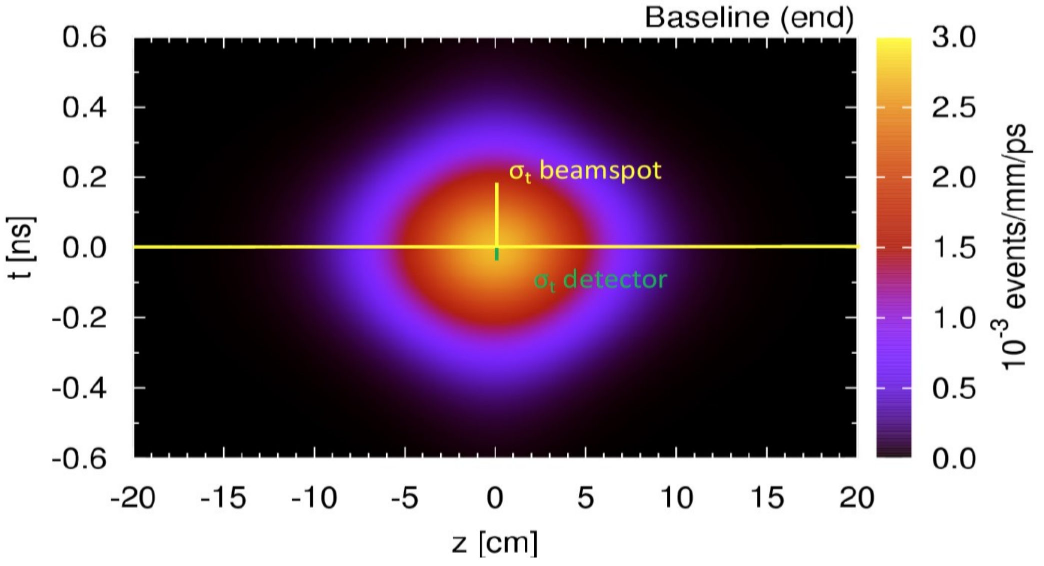
PV will have a spread in time of about 180 ps.
In slices of 20-30 ps, only a few collisions and corresponding tracks

42 interactions



20 ps time window





R. Bates http://indico.hep.manchester.ac.uk/ event/NewDimensions2017

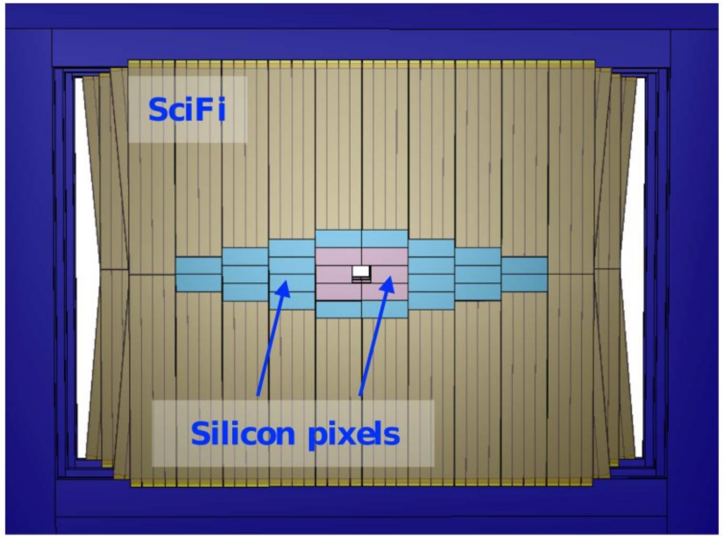
A new dimension will be added to the LHCb experiment.
Tracking detectors must be fast with common time information.

Innovative technology for detector and data processing.
Develop a novel tracking devices both for tracking and timing

LHCb Upgrade II: tracking

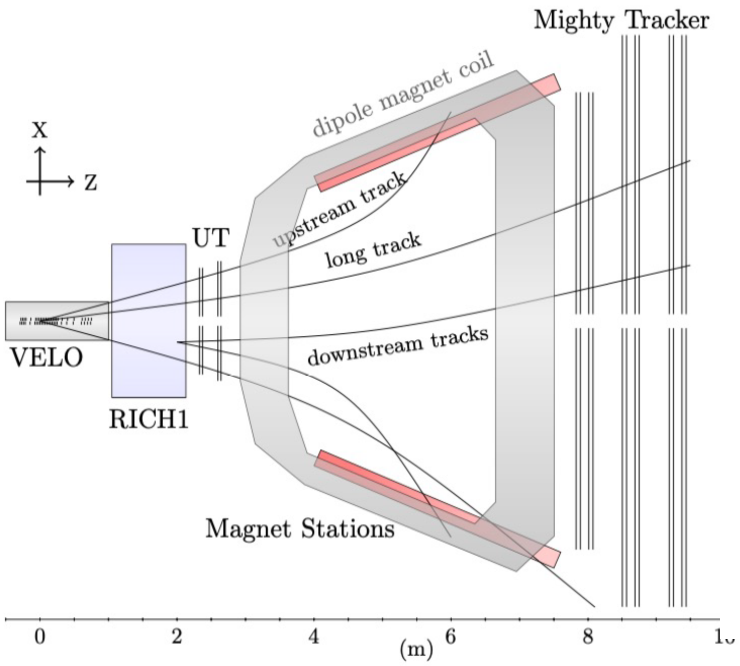
Mighty Tracker

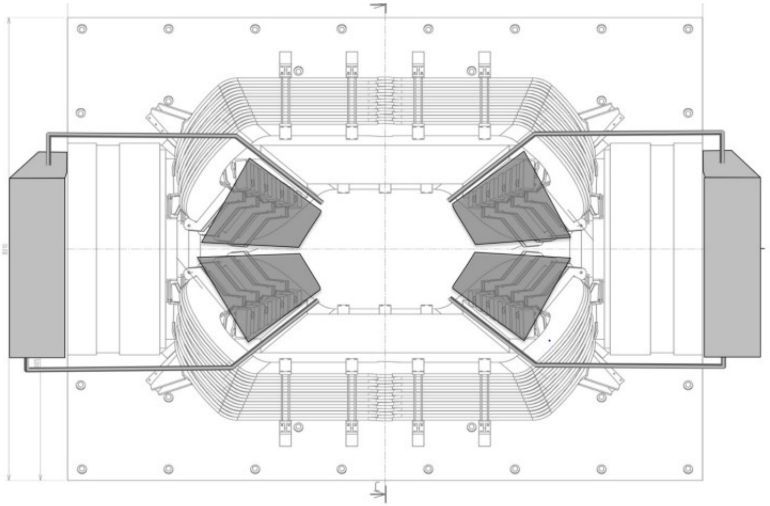
- Silicon inner and middle tracker regions:
  - Monolithic Active Pixel Sensors $\phi = 3 \times 10^{15}\ n_{eq}/cm^2$
- Scintillating fibers in the outer region



Magnet stations

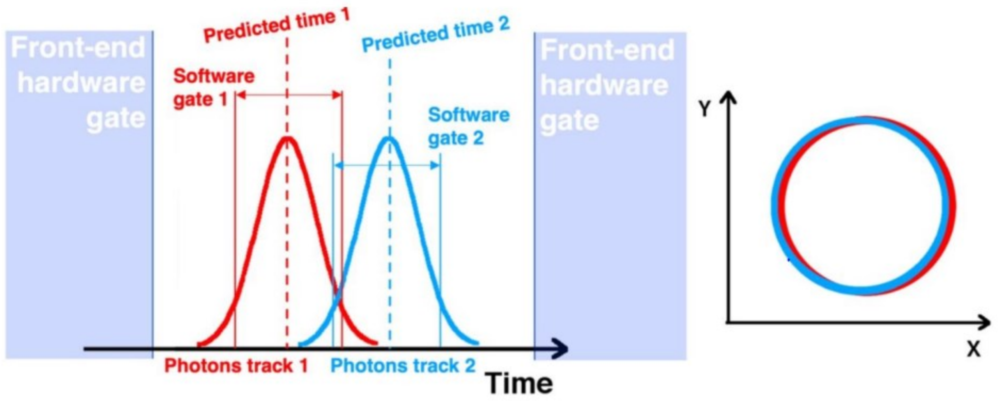
- low momentum tracker (down to 150 MeV)
- increase in charm events with slow pion





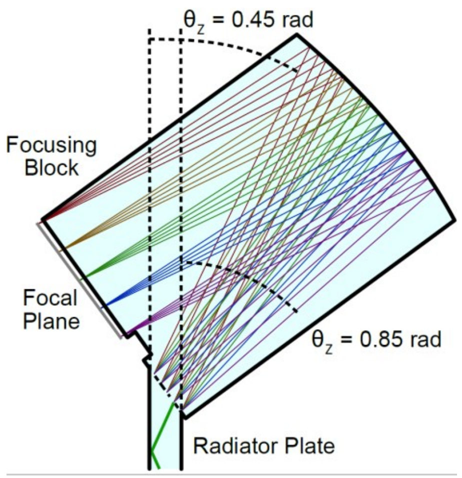
RICH

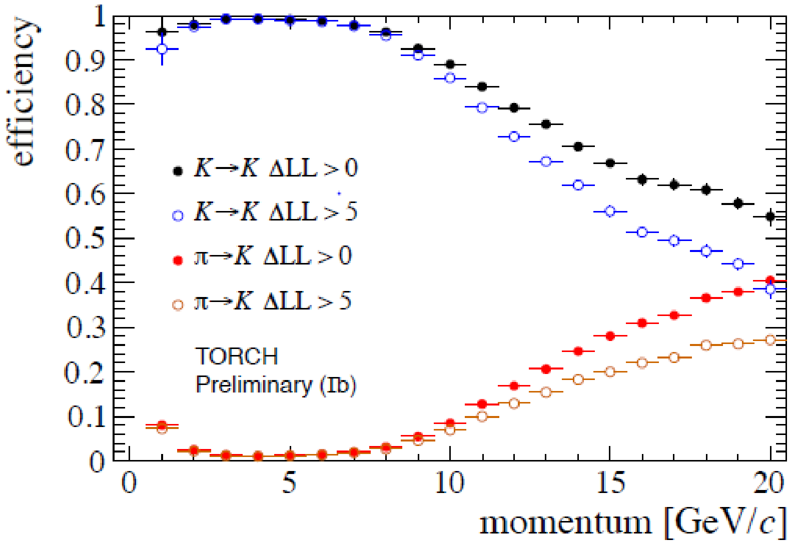
Photon arrival can be predicted to better than 10 ps
need of time estimate from tracking
- reduction of background
- improving Cherenkov angle resolution to 0.1-0.2 mrad



TORCH

Time of internally Reflected Cherenkov light:
- 1 cm crystal and large area time-of-flight detector
- measurement of Cherenkov angle, path length and time of arrival
- provide PID in low momentum range 1-10 GeV/c



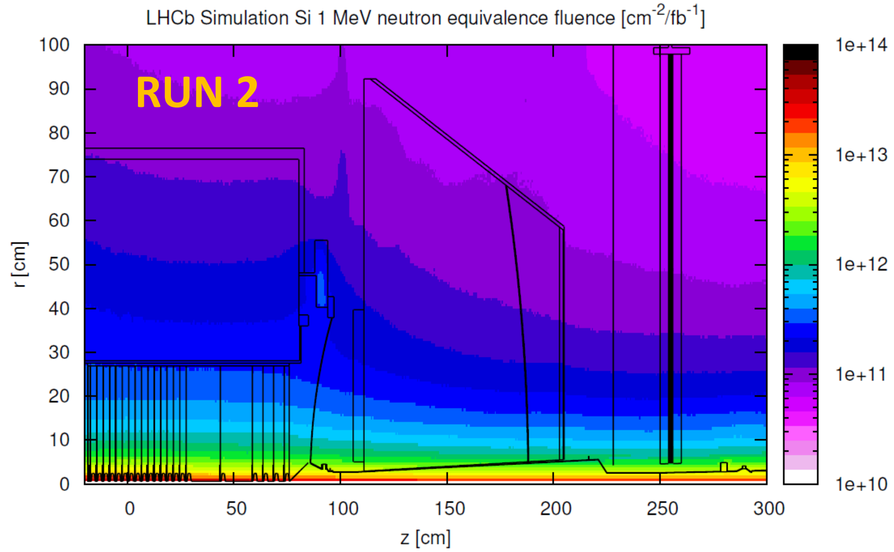


Challenge: radiation

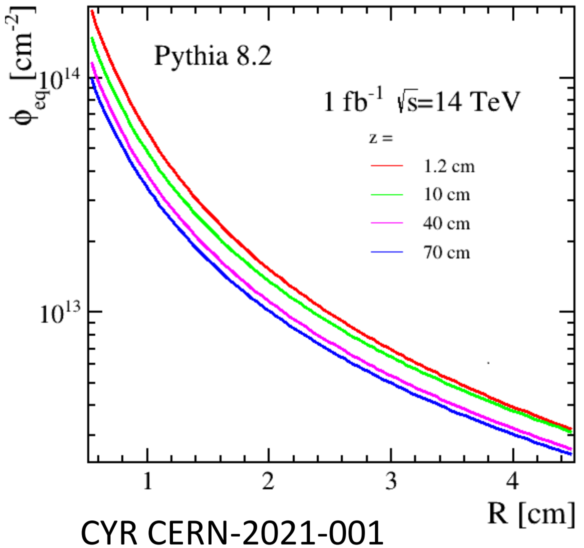
LHCb Run 3: $\Phi_{eq} \approx 1 \times 10^{16}$ cm^{-1} neq

Hi-Lumi LHC: $\Phi_{eq} \approx n \times 10^{16} - 10^{17}$ cm^{-1} neq, 300 fb^{-1},

FCC-hh $\Phi_{eq} \approx 1 \times 10^{18}$ cm^{-1} neq, TID 300 MGy,



LHCb VELO Upgrade II:
$\Phi_{max,eq} \approx 5 \times 10^{16}$ cm^{-1} with huge fluence spread over the sensor, full 4D tracking desired.



CYR CERN-2021-001

IP measurement is the best if the first station is close to the IP.
Problem of material budget:

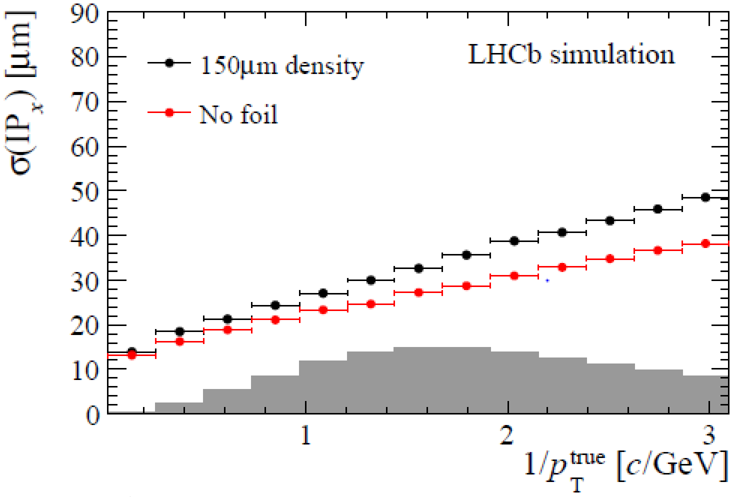
current VELO is separated from primary vacuum by a thin foil, can a thin tube be used instead?

LHCb VELO Upgrade II

CERN-LHCb-PUB-2022-001

VELO: maintain performance at ~7.5 times occupancy and 6 x radiation damage

- Sensors can be retreated to 12.5 mm from the beam (but we do not want to do that),
  - pixel pitch should be reduced from 55 to 41 μm,
  - material in RF foil and first detection layer is drastically reduced
- to date no single sensor technology has been shown to survive the required life time fluence
- bi- or annual replacement could be an option



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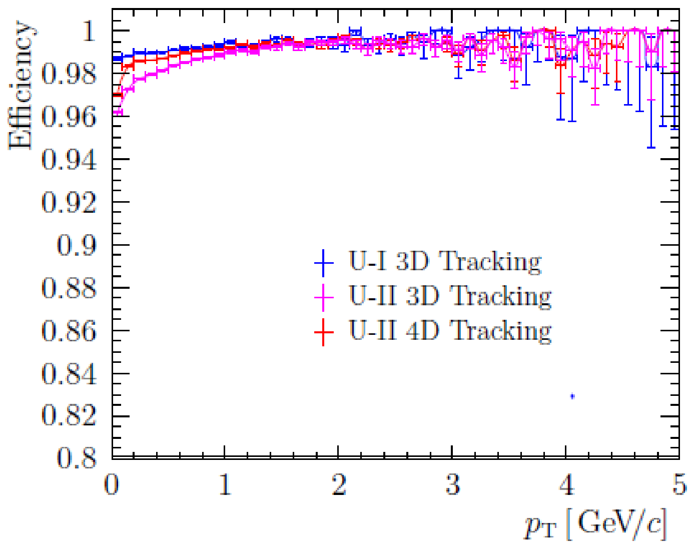
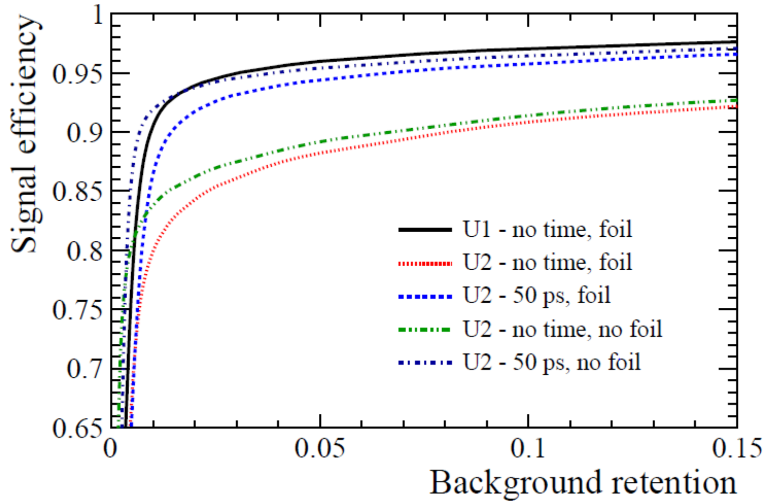
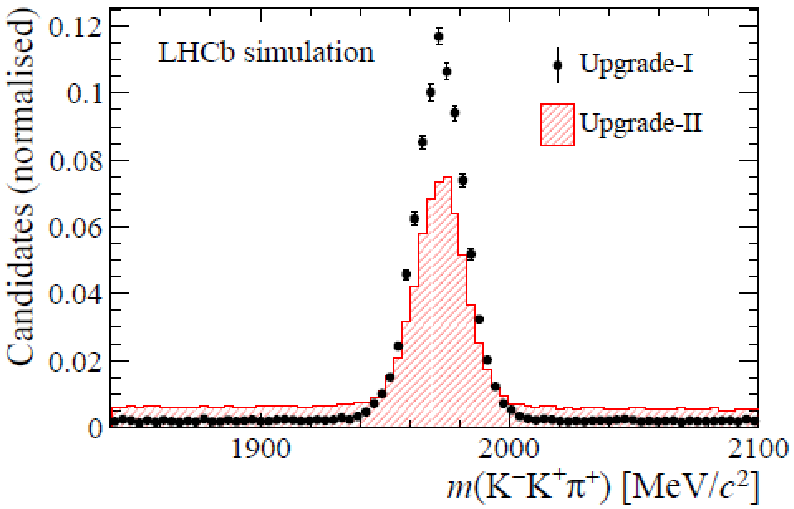




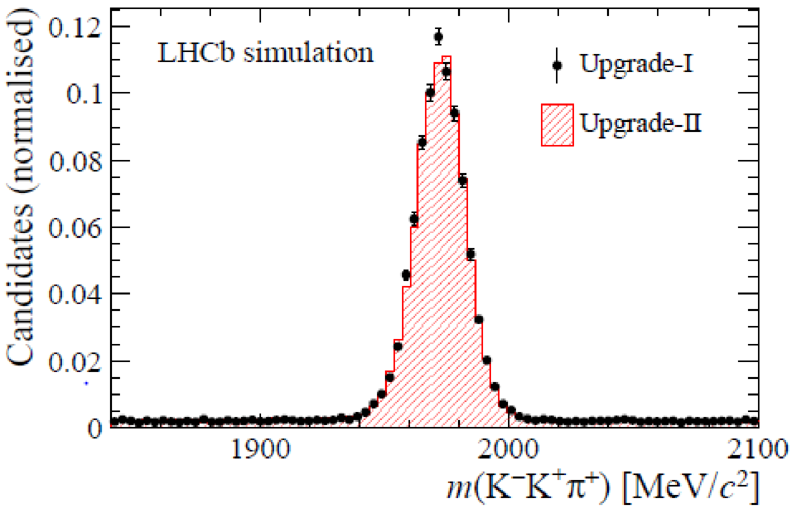
LHCb VELO Upgrade II – physics @ 4D

VELO: maintain performance at ~7.5 times occupancy and 6 x radiation damage

no time information



20 ps timing



CERN-LHCb-PUB-2022-001

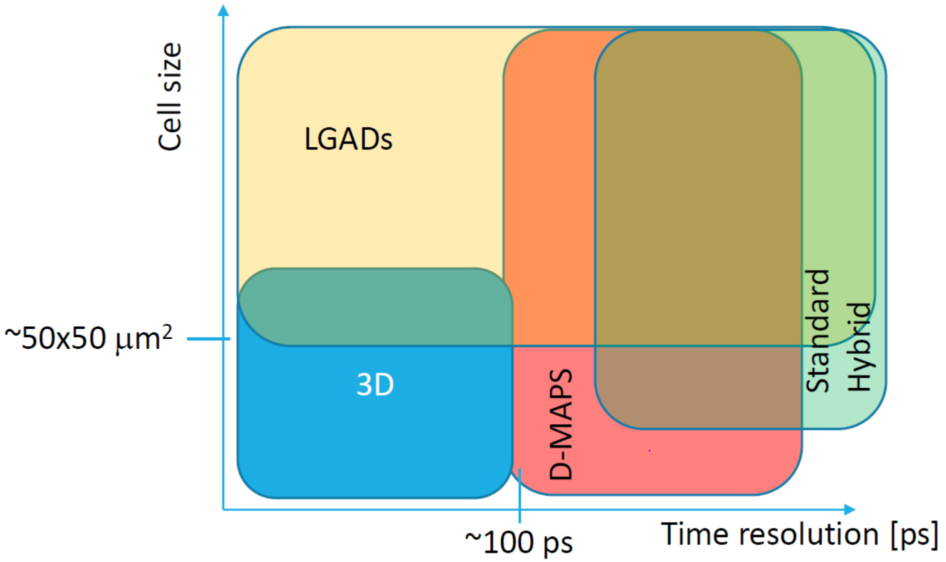
4D tracking detectors

Redesigning of the trackers:

- additional timing layers
- 4D structures (LHCb)

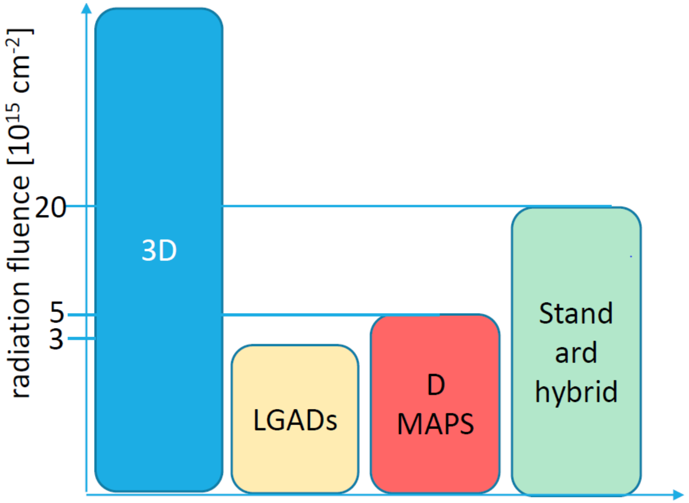
Interexperiment projects within RD50:

- LGADS
- 3D sensors



time resolution depends on:

- noise (jitter)
- time walk (fluctuation in amount of deposit charge, electric field, Landau fluctuations in signal shape – hit position



G. KRAMBERGER, ECFA DETECTOR R&D ROADMAP SYMPOSIUM

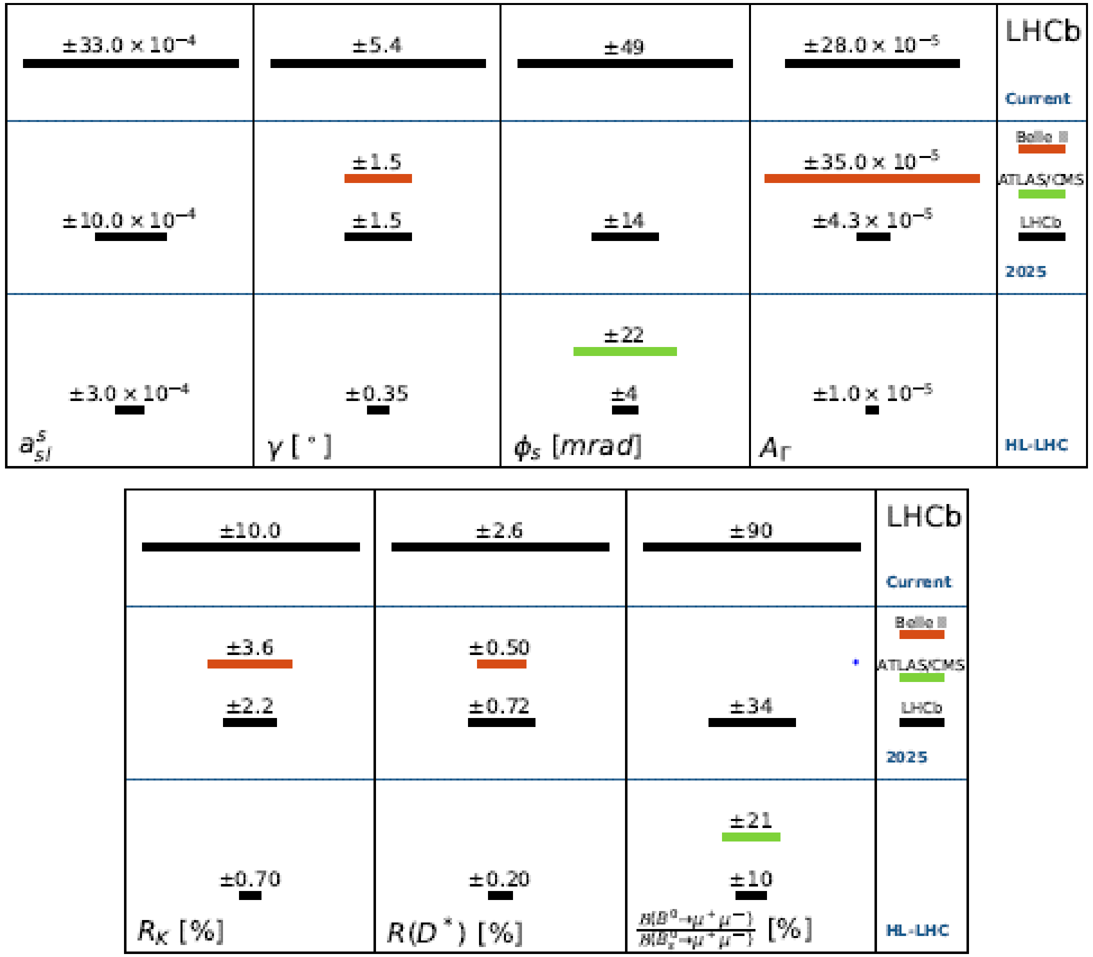
VELO Upgrade II options: 3D, LGADS, mix in inner and outer areas

Conclusions

1. The Run 3 LHCb physic program will be reinforced by higher statistic and modernisation of the detector.
2. LHCb shows potential for flavour measurements with high-luminosity LHC runs with unique results on:
   - CKM matrix parameters (expected precision of γ 0.35°),
   - LFV and rare decays in muon, electron modes and full range of b hadrons,
   - CP violation in charm with 10^{-5} precision,
   - dark matter and effects of physics beyond the Standard Model,
   - prospects for heavy-ion and fixed-targed physics.
3. New tracking and vertexing system with radiation-hard with timing possibility is a reasonable option.
4. Two technologies: 3D pixels or LGADs are proposed for a new VELO.

Backup

Sensitivity to key observables in flavour physics

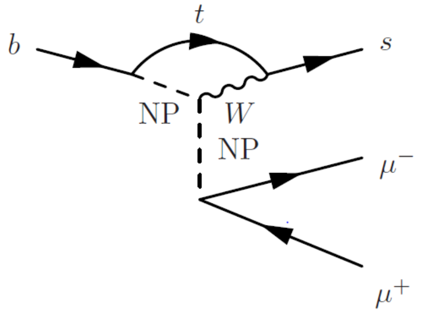


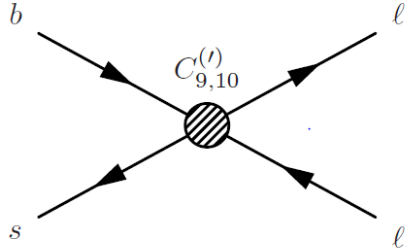
Exclusively @LHCb U2

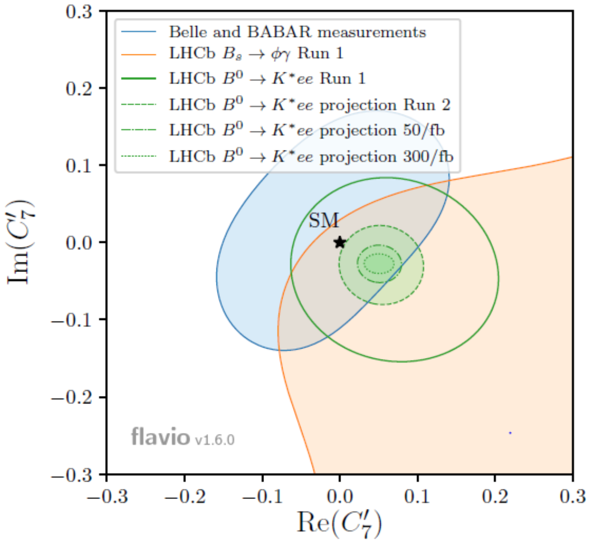
LHCC-2018-027

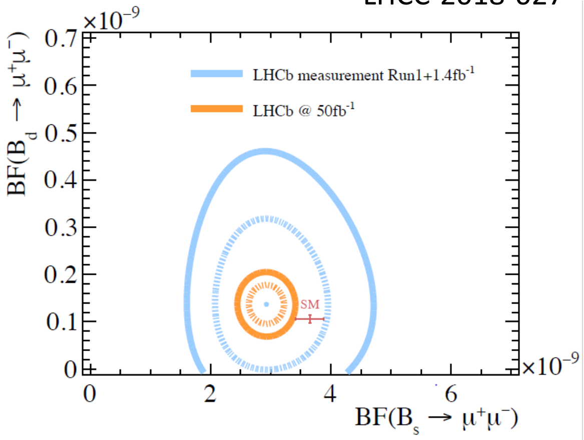
Rare decays: $B_{(s)} \to \mu^+\mu^-, B_{(s)} \to e^+e^-, B_{(s)} \to \tau^+\tau^-$

- main systematics of Run 1-2 due to f_s/f_d , improved after Run 3
- at 300 fb^{-1}: $\sigma_{\mathcal{B}}(B_s \to \mu^+\mu^-) \sim 1.8$ %,
- key measurement to understand NP contribution to C_{10}







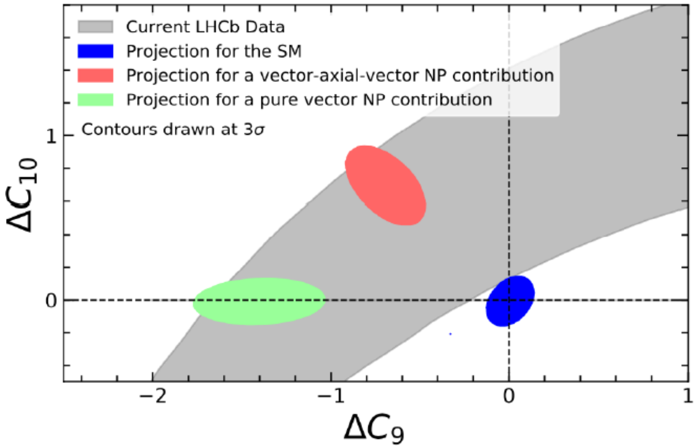


Lepton Flavour Universality: $B^0 \to K^{*0}\tau^+\mu^-, B^+ \to K^+l^+l^-, B^+ \to K^+e^+\mu^-$

Difference between $b \to s\mu^+\mu^-$ and $b \to se^+e^-$ is a sign of NP

- new modes in LHCB Upgrade II
- 1%-level uncertainties expected, enough to establish or reject LFV

Sensitivity to the difference between muon and electron mode contributions to the vector, C_9, and axial-vector, C_{10}, Wilson coeff.

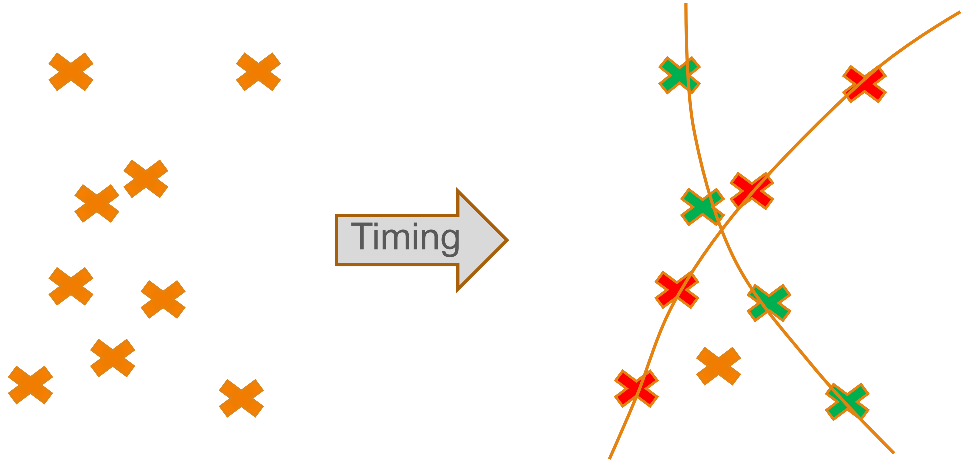


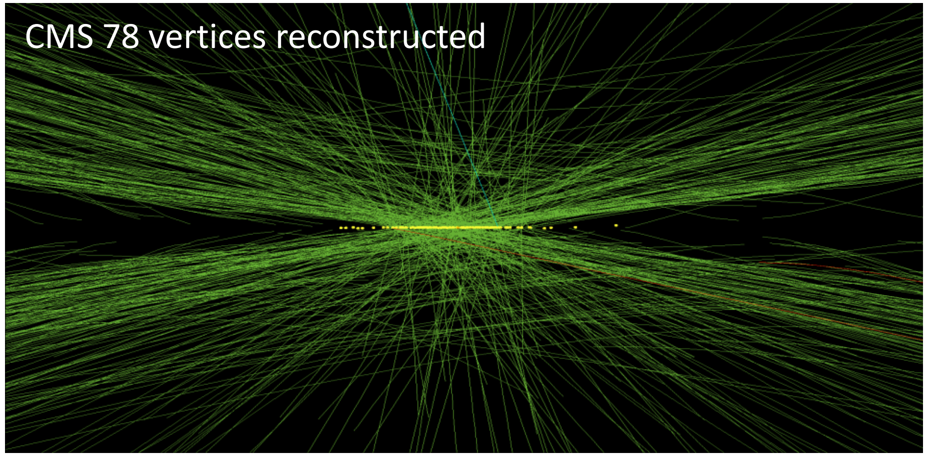
see also Marcin Chrząszcz’s talk

Methods of 4D tracking

Timing at each point along the track

- use only points with time stamps
- algorithms may be faster even in very dense environments

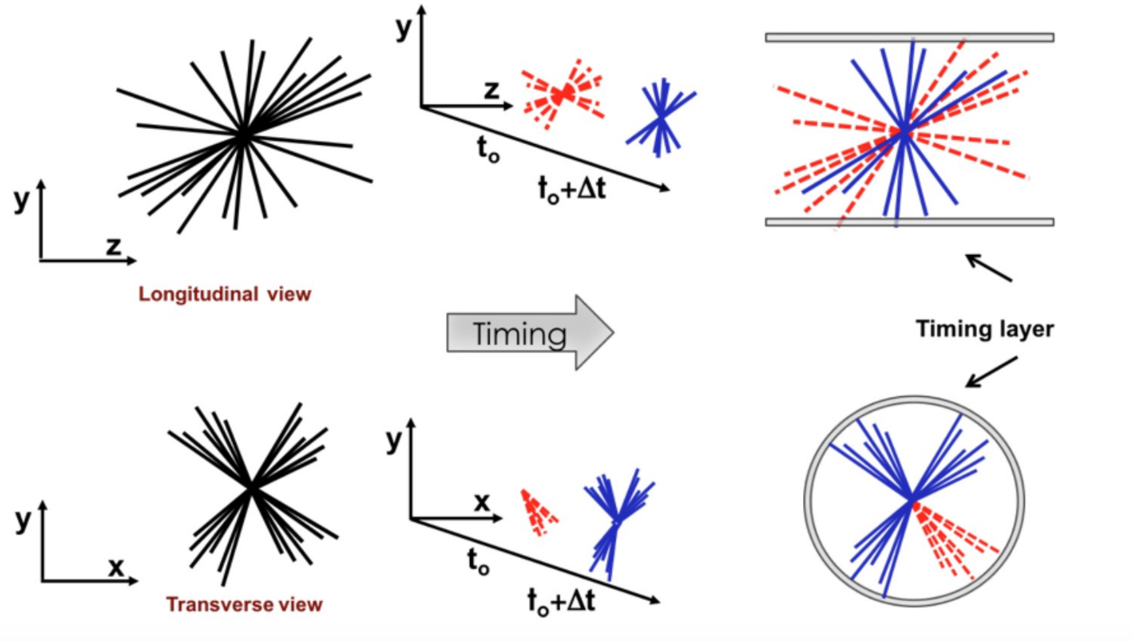




Methods of 4D reconstruction

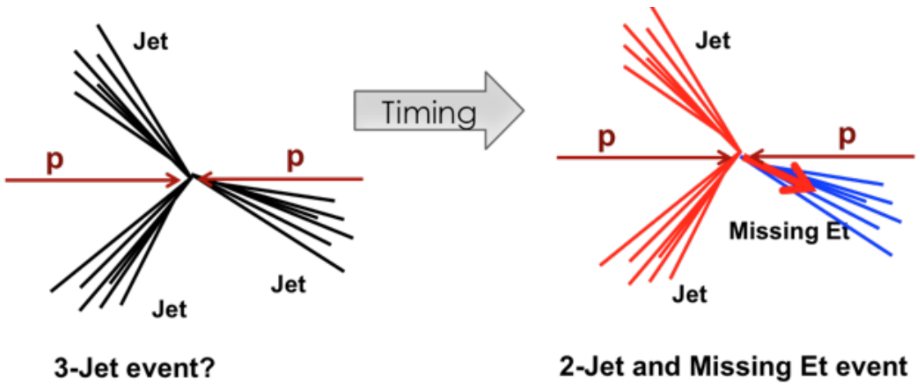
Timing in the event reconstruction:

- disentanglement of overlapping events by means of an extra dimension



Timing at the trigger level:

- disentanglement of topologies that look similar but actually are different



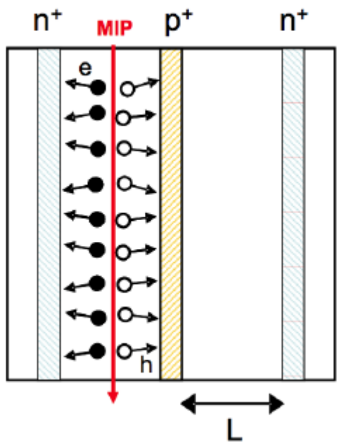
Adding time information to the event changes radically the design of experiments

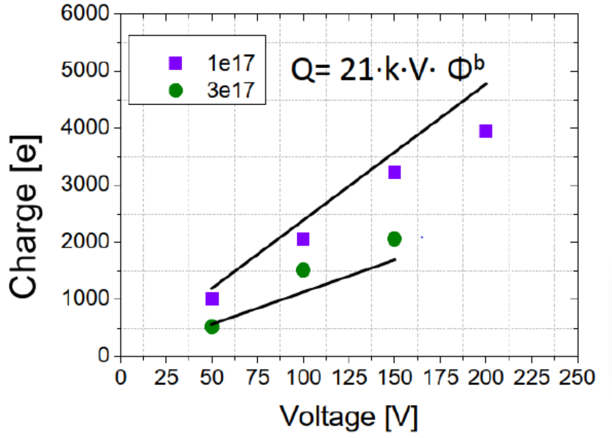
Sensors designes

3D detectors for timing applications:

- sensor sustain $\Phi_{eq} > 10^{17}$ cm^{-2},
- short collection times
- rather thin sensor, otherwise of large noise and jitter
- small fill factor - very complicated production, limited efficiency and position resolution
- novel materials?

From: S. Fenandez-Perez, TWEPP 2015





LGADs (planar sensors with gain):

- seem to be ideal solution to reach excellent resolution,
- main limitation – radiation hardness up to $\Phi_{eq} < 3 \times 10^{15}$ cm^{-2}
- many attempts to design a more radiation hard gain layer
- small fill factor