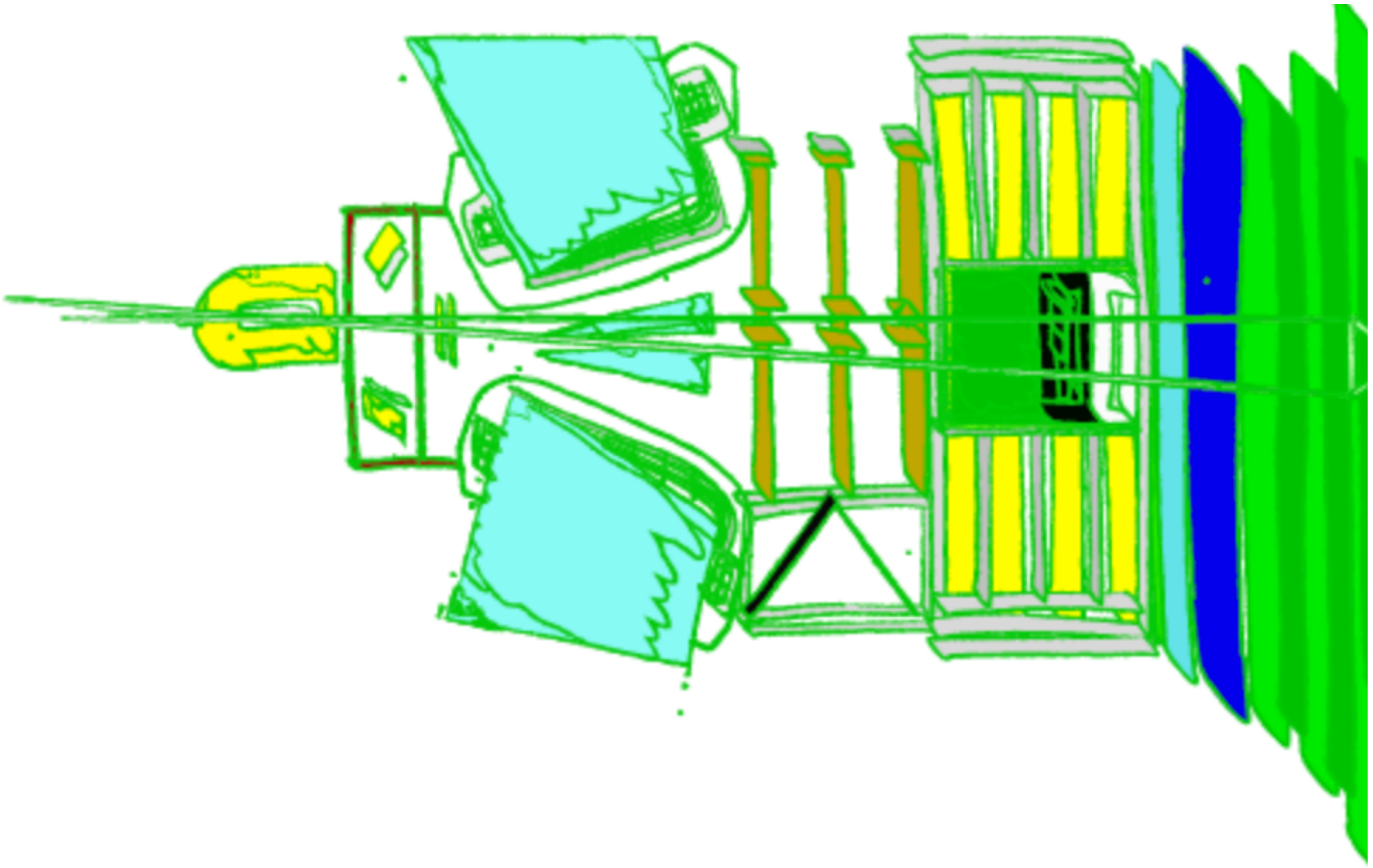


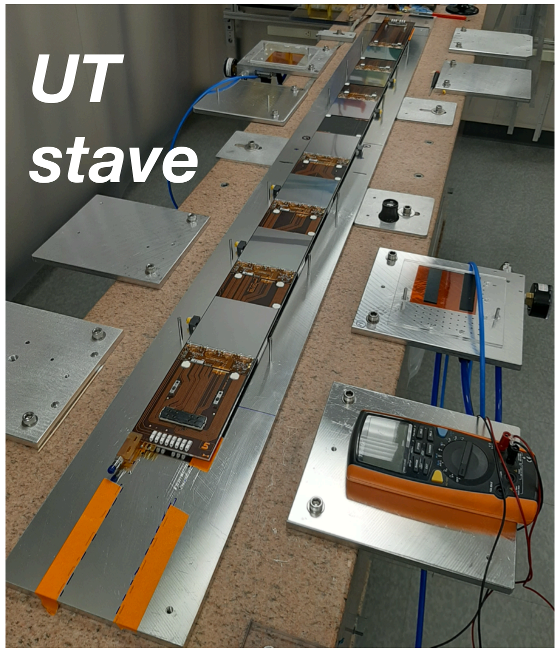
The LHCb upgrades

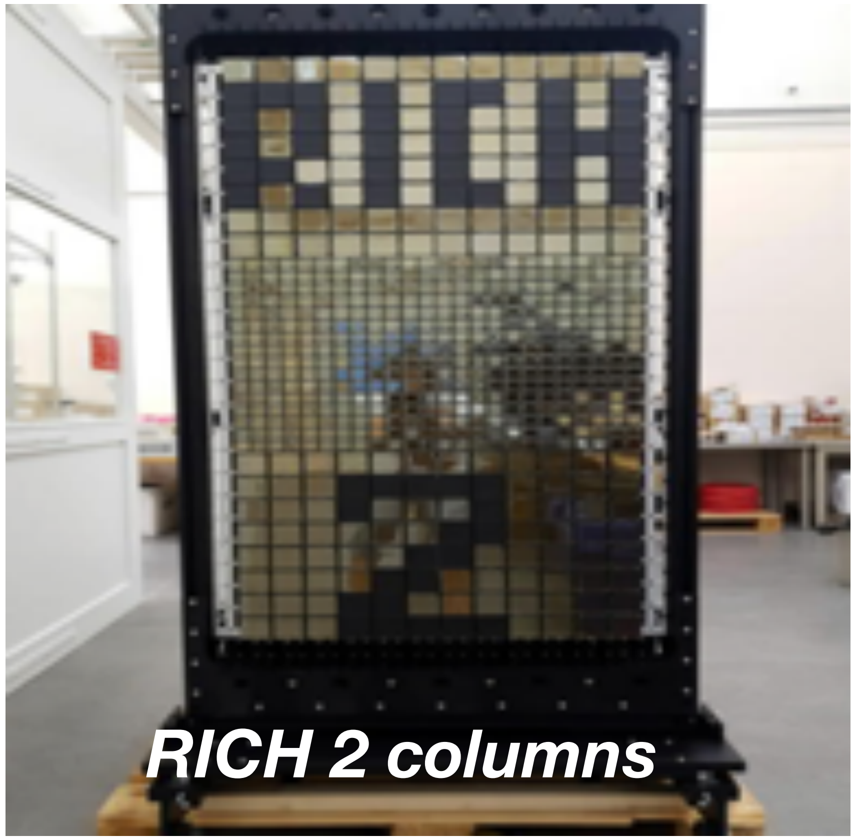
Matteo Palutan
(INFN Frascati)

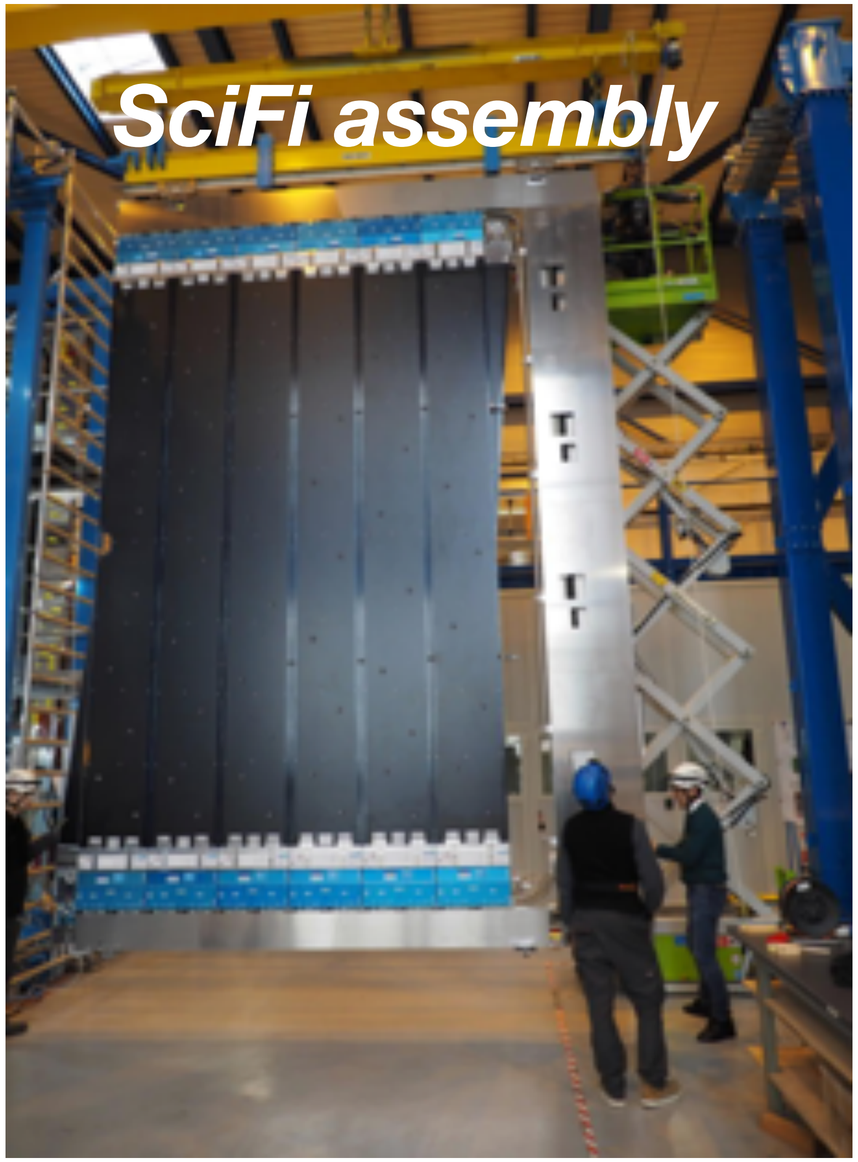
Jahrestreffen der deutschen LHCb-gruppen, Bonn October 5-6 2020

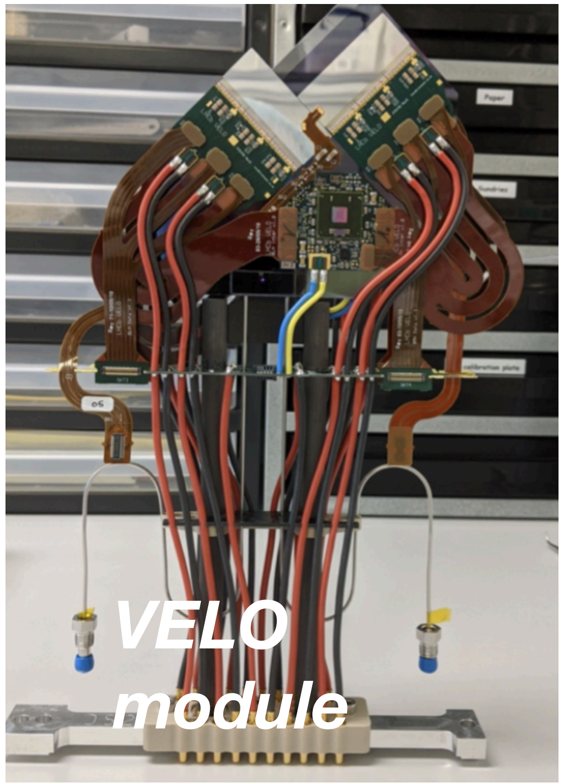
LHCb Upgrade I is happening now!

Ready to start in Run 3 to raise the instantaneous luminosity to 2×10^{33} cm^{-2} s^{-1} during Run 3 and Run 4 with the goal of accumulating 50 fb^{-1}





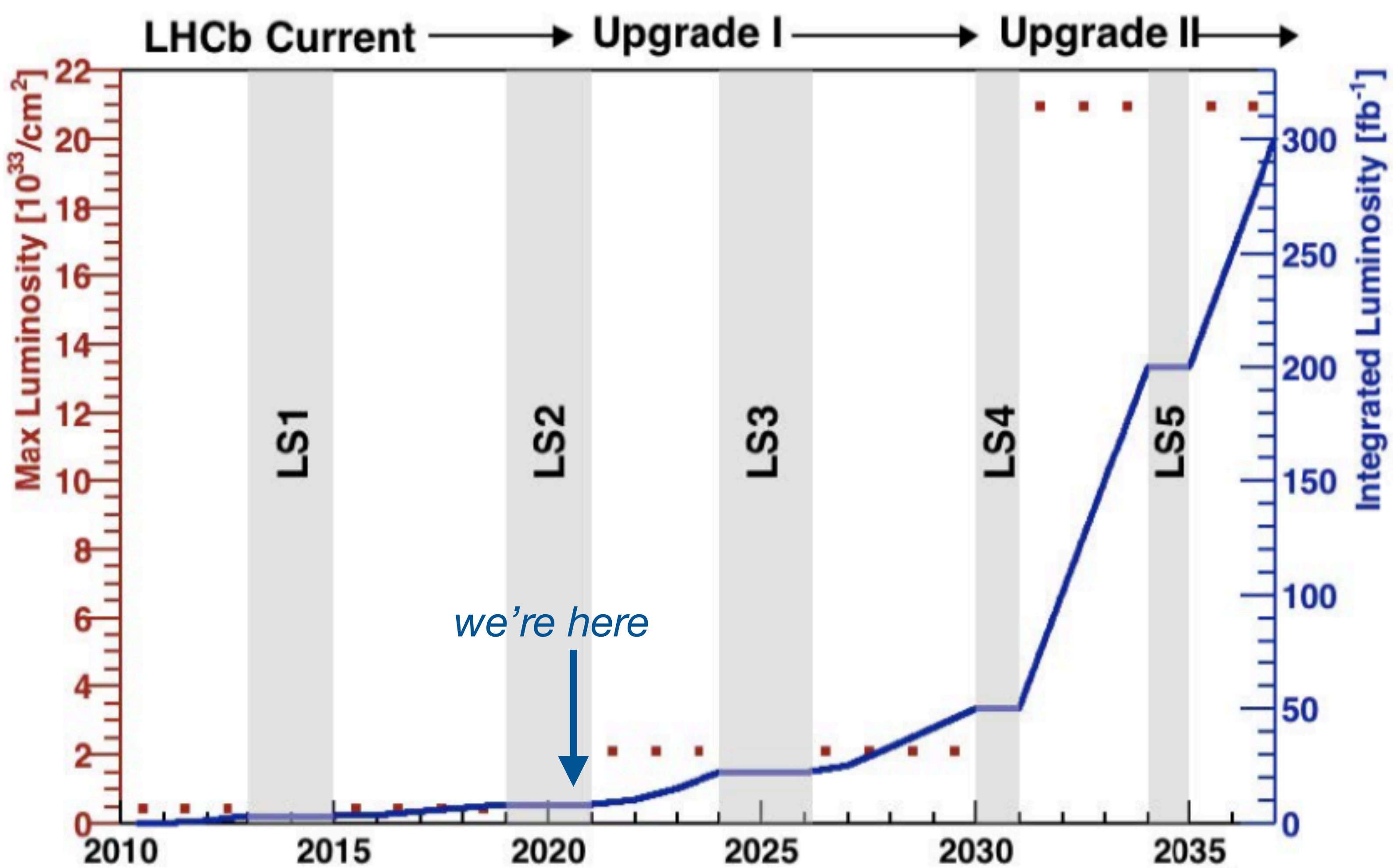




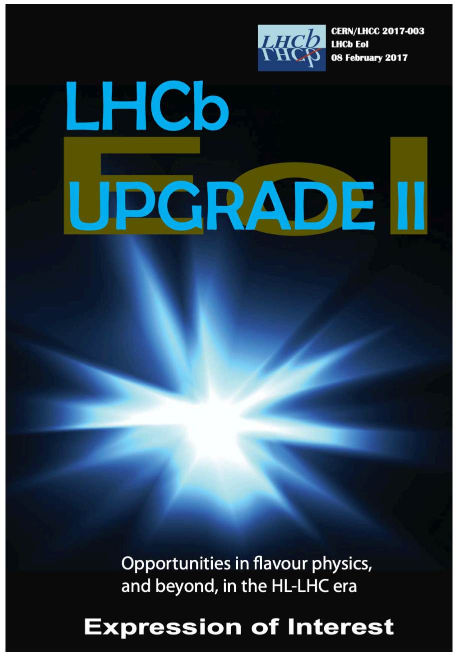
It will be a great success, despite Covid!

LHCb upgrades

A first LHCb upgrade will be ready to start in Run 3 to raise the instantaneous luminosity to $2\text{x}10^{33}$ cm^{-2} s^{-1} during Run 3 and Run 4 with the goal of accumulating 50 fb^{-1}.
Selected improvements and consolidations will be also proposed for installation at LS3



*LHCb has also submitted an Expression of Interest for a further upgrade at Run 5 to reach **$2\text{x}10^{34}$ cm^{-2} s^{-1} and accumulate 300 fb^{-1} throughout the HL-LHC era;** a Framework TDR is due to the LHCC in September 2021*

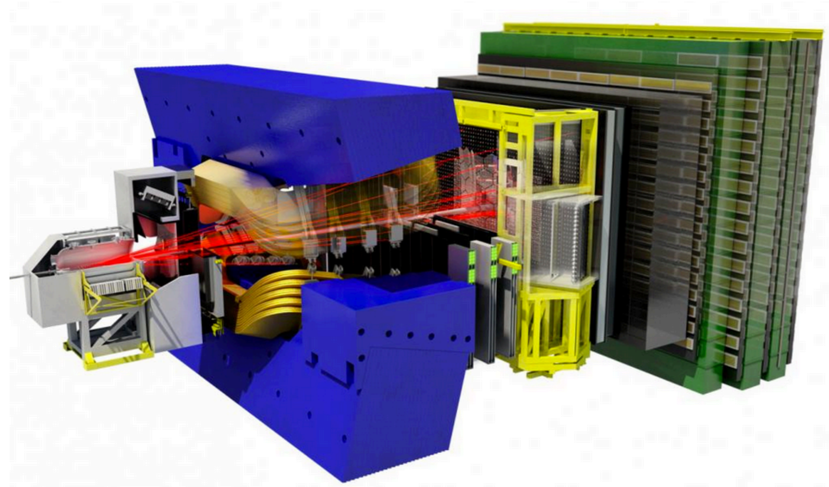


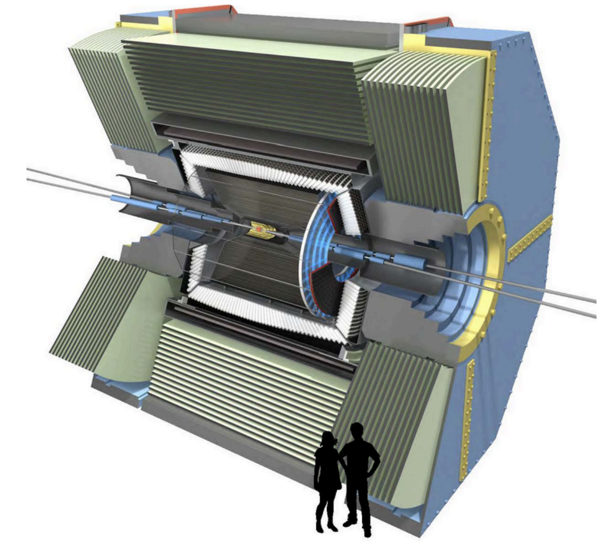
LHCC-2017-003

The main players in quark-flavour physics

LHCb and Belle II

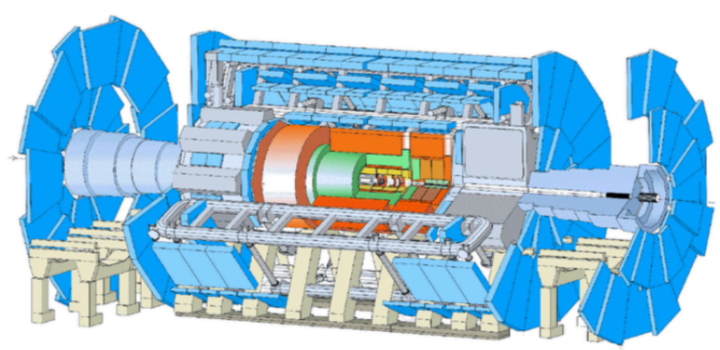
dedicated flavour experiments with wide range of measurements

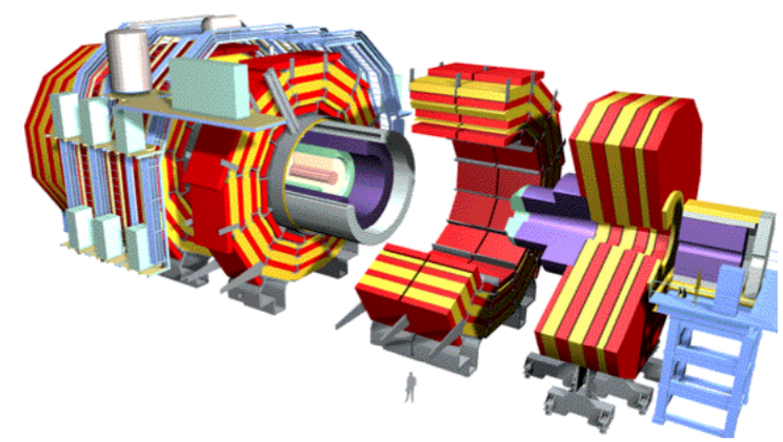




ATLAS and CMS

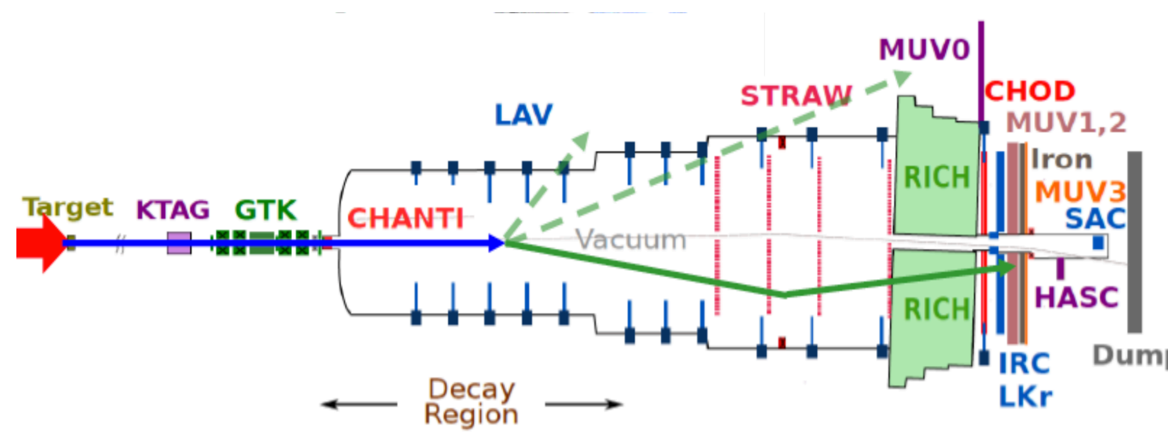
measure some relevant B-physics channels, mainly with muons in the final state





NA62

measure the branching ratio of $K \to \pi\nu\nu$ with 10% precision



Complementarity btw the different experiments is the key for success!

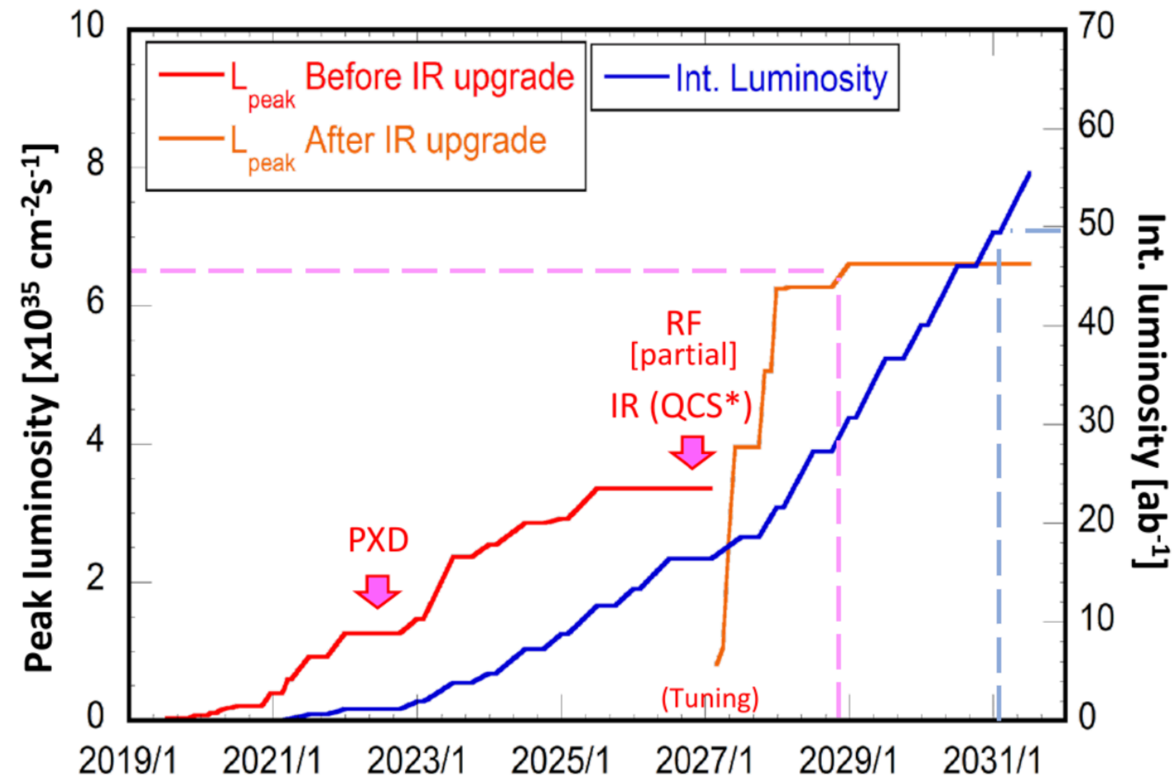
Belle II taking first data

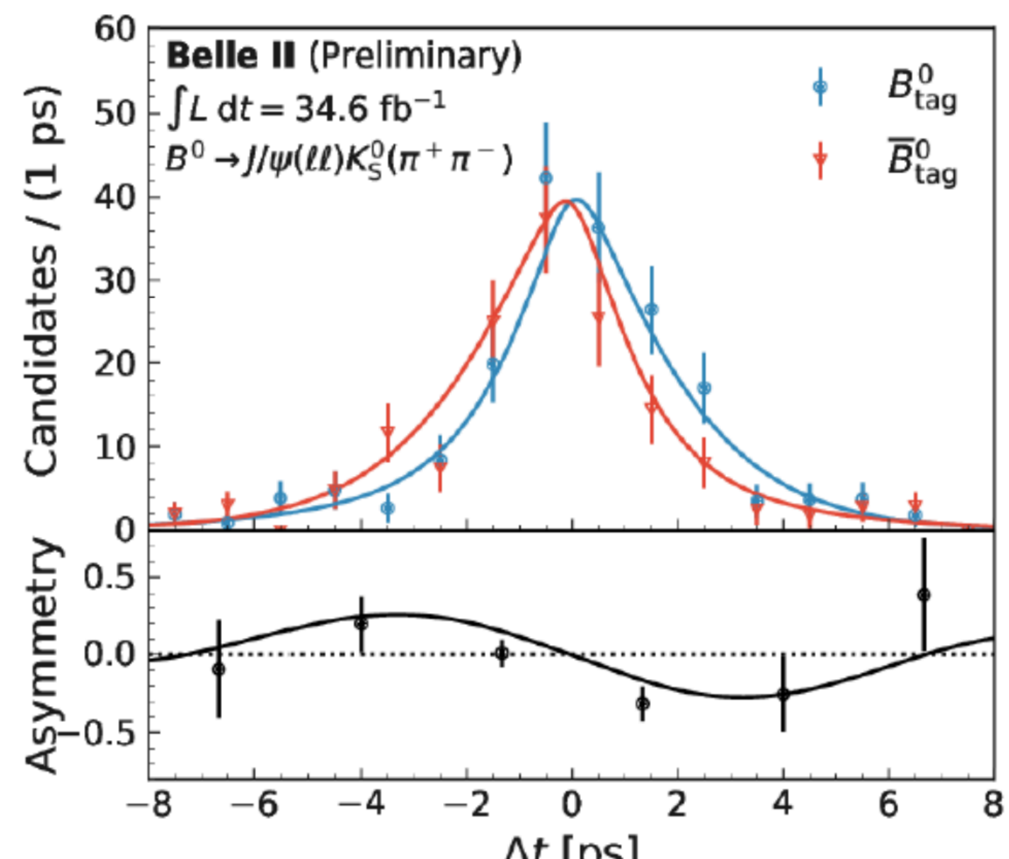
Exciting prospects from the SuperKEKB machine and new Belle II detector, L_{peak} = 2.4x10^{34} $cm^{-1}s^{-1}$, L_{int} ~ 75 fb^{-1}

The goal is to collect an integrated luminosity of 50 ab^{-1} by the end of the decade

Luminosity is still very limited, but the experiment is showing to be ready and chase the data vey quickly

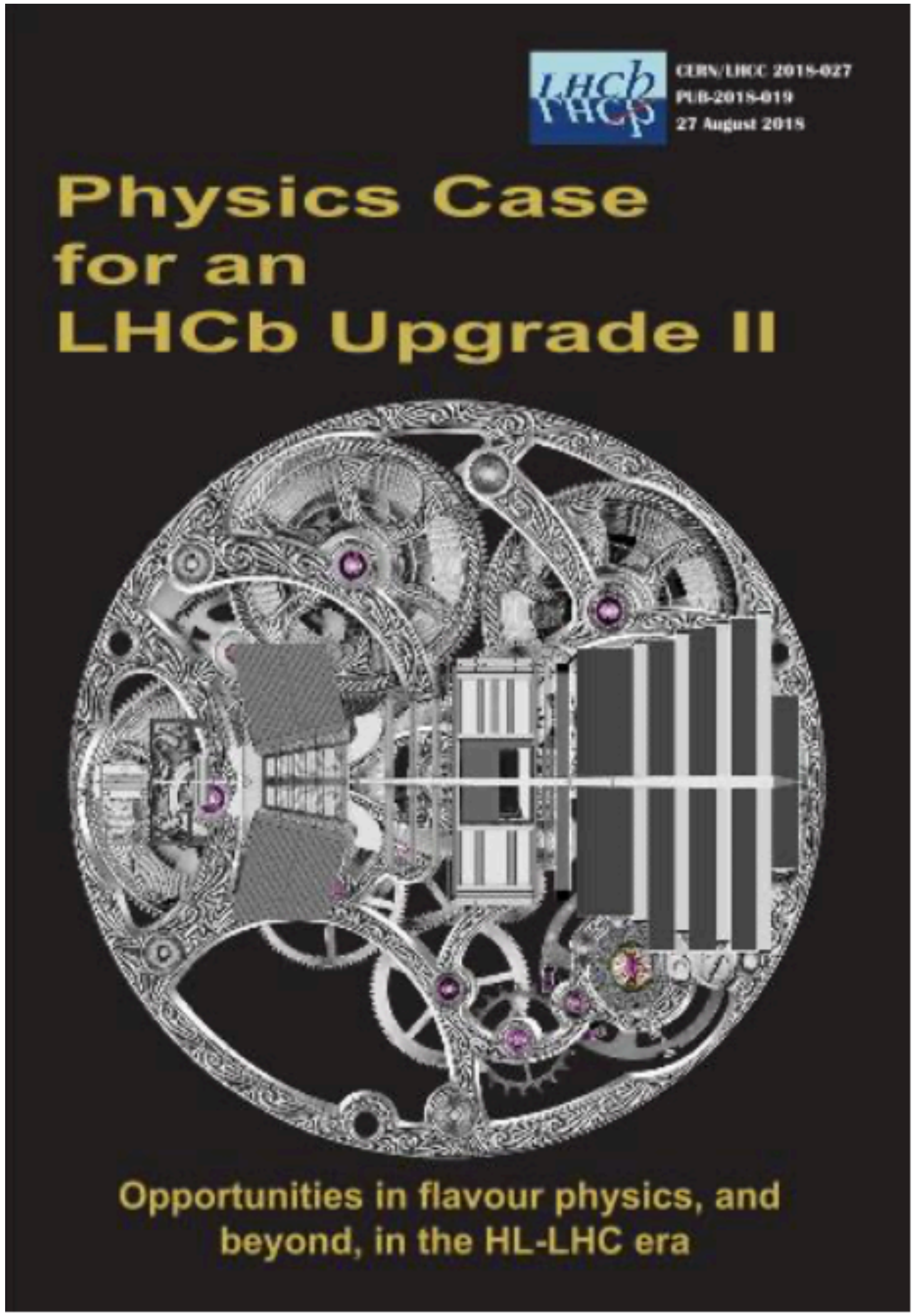
The critical path is on the machine





The physics case of LHCb Upgrade II

- *CP-violating phases will be measured with precisions unattainable at any other envisaged facility.*
- *The experiment will probe $b \to s\, \ell^+\ell^-$ and $b \to d\, \ell^+\ell^-$ transitions in both muon and electron decays in modes not accessible at Upgrade I.*
- *Minimal flavour violation will be tested with a precision measurement of the ratio of $B(B^0 \to \mu^+\mu^-)/B(B_s^0 \to \mu^+\mu^-)$.*
- *Mixing and CP violation in charm at the 10^{-5} level.*
- *Major advances in hadron spectroscopy*
- *Potentially highest sensitivity of all the LHC experiments on the Higgs to charm-quark couplings.*



LHCC-2018-027

NP searches in the flavour sector

Instead of searching for new particles directly produced, look for their indirect effects to low energy processes (e.g. *b*-hadron decays)

General amplitude decomposition in terms of couplings and scales

$$A = A_0 \left[c_{SM} \frac{1}{M_W^2} + c_{NP} \frac{1}{\Lambda^2} \right]$$

Enhanced NP sensitivity due to smallness of c_{SM} (loop + CKM suppression)

Increase of precision allows to probe mass scales not accessible directly at a collider like LHC

Need huge statistics: energy scale scales as ~$L_{int}^{1/4}$ ⇒ LHCb running throughout the full HL-LHC phase will represent a factor ~1.9 in energy reach

*Need precise SM predictions: clean observables (LFU ratios, leptonic decays, CKM angle **γ**…), calculable hadronic contributions at sub-precent level (non-perturbative techniques, lattice QCD…), null tests (LFV, CP violation in D mixing..)*

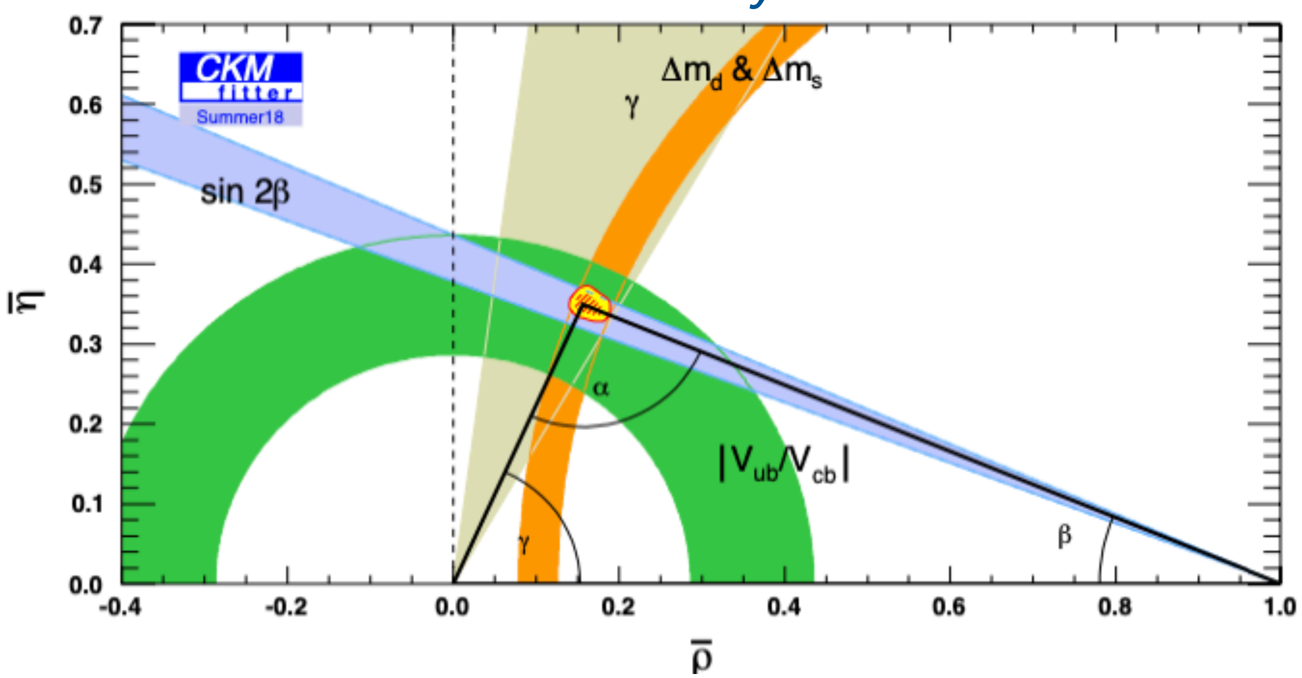
Low systematic uncertainties: excellent detector design and performances, large statistics can help

Constraining the unitarity triangle

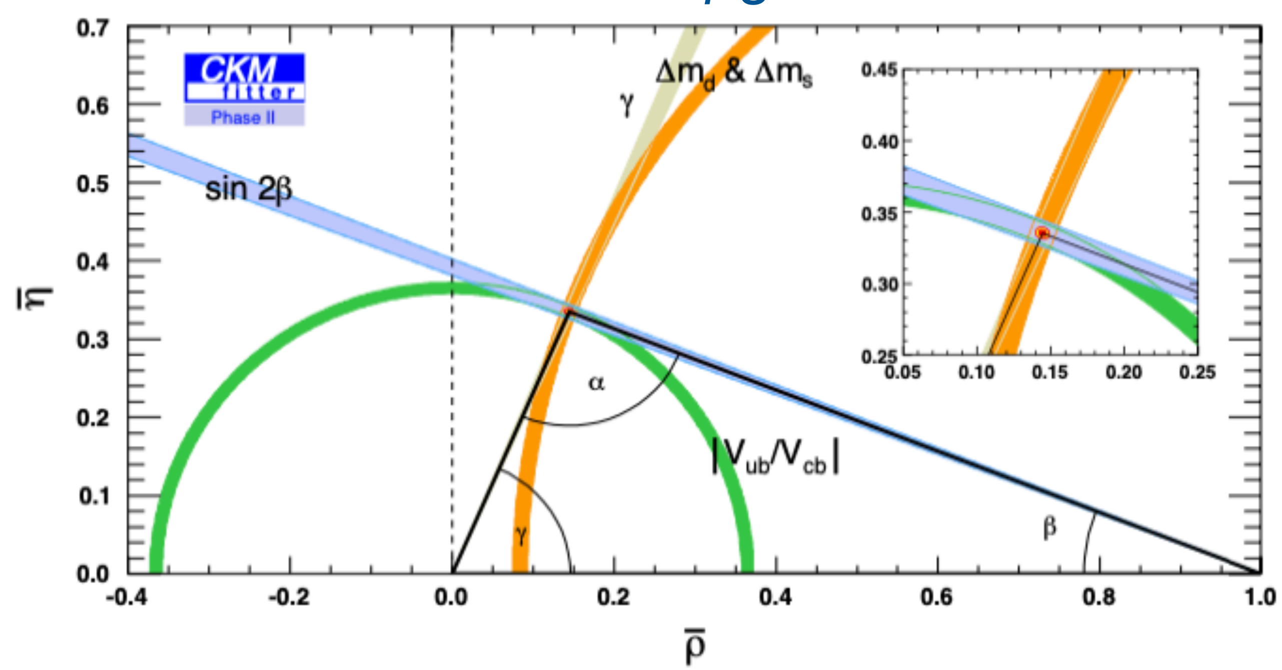
Current data show no significant deviations from the SM on $\Delta F=2$ observables and many other flavour-changing processes: either NP is very heavy of it has a highly non trivial structure.

LHCb Upgrade 2 will test the CKM paradigm with unprecedented accuracy

Today



LHCb Upgrade 2



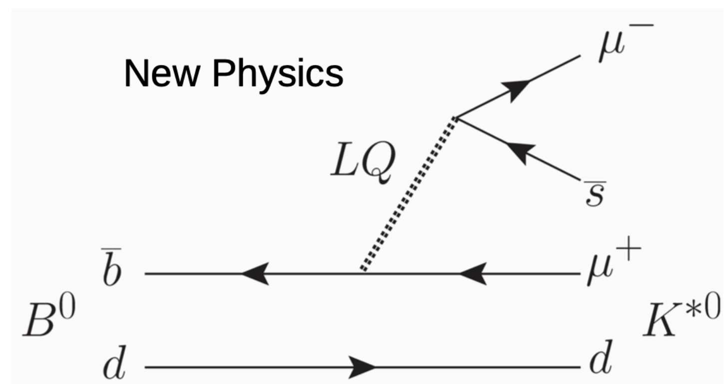
Two independent measurements of triangle apex: ($\Delta m_d/\Delta m_s$, sin 2β) and (V_{ub}, γ)

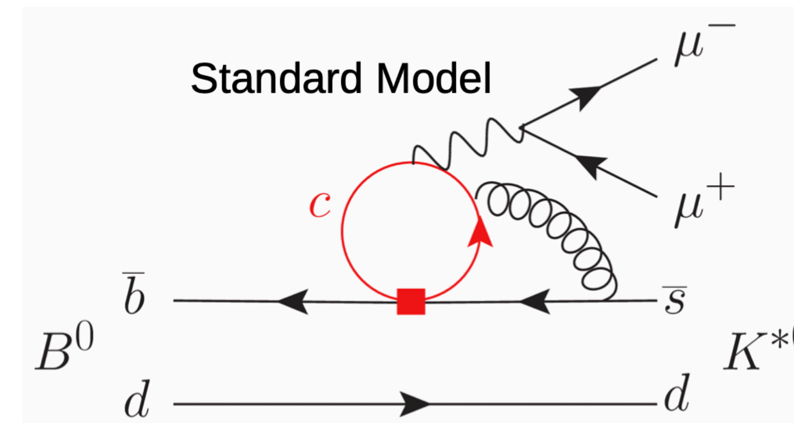
Both pairs require Upgrade 2 for statistics (sin 2β and γ) and time for theory improvements ($\Delta m_d/\Delta m_s$ and V_{ub})

Complementary measurements from Belle II

Rare decays b → s $\ell^+\ell^-$

Current rare decay anomalies can’t tell us if we have new physics or if there are charm loop effects that we do not understand

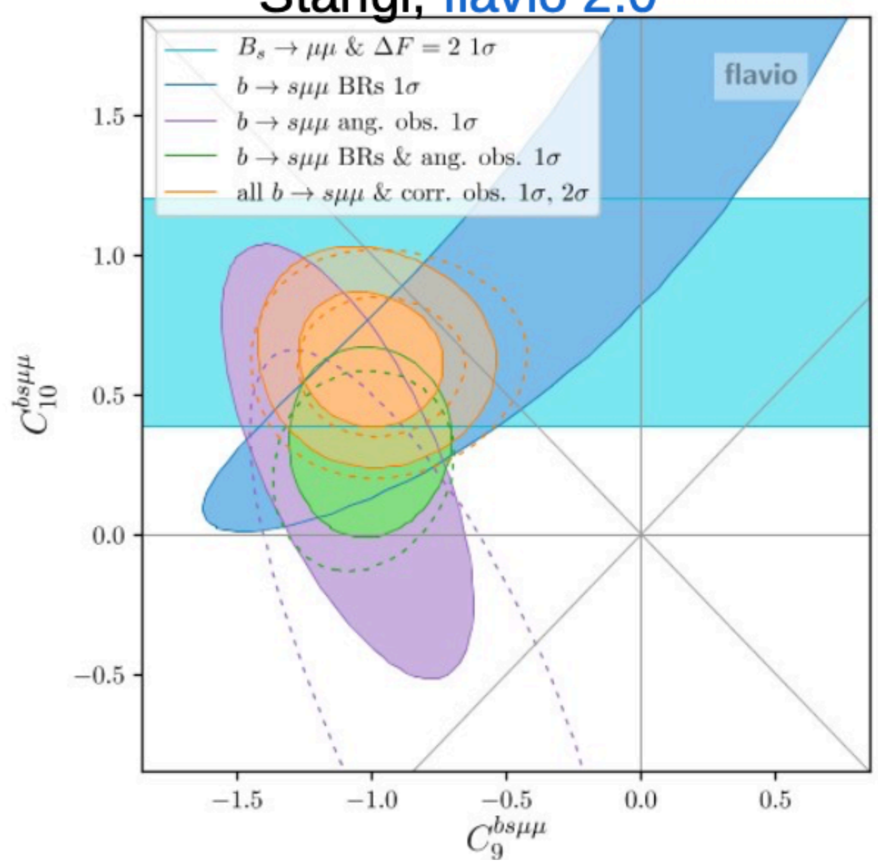




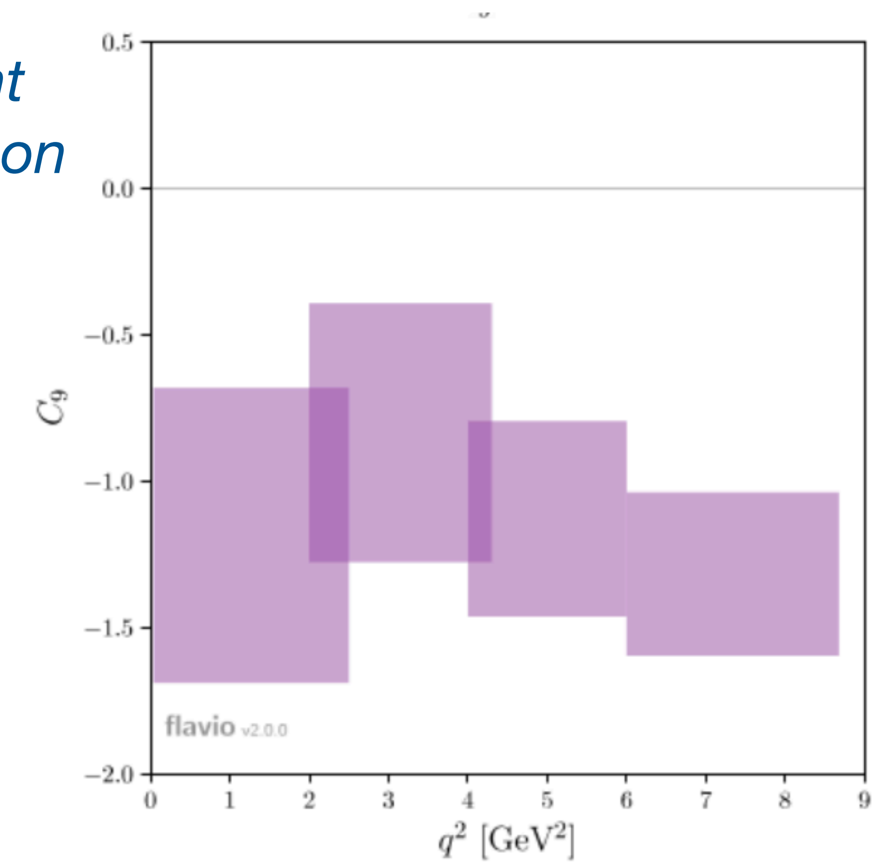
But “same" NP has to fit all measurements

Different decays and observables to same Wilson coefficients

Stangl, flavio 2.0



Measurement of same Wilson coefficient in different kinematic regions



The above will become strong constraints with Upgrade 2, when uncertainties will go down by factor ~5

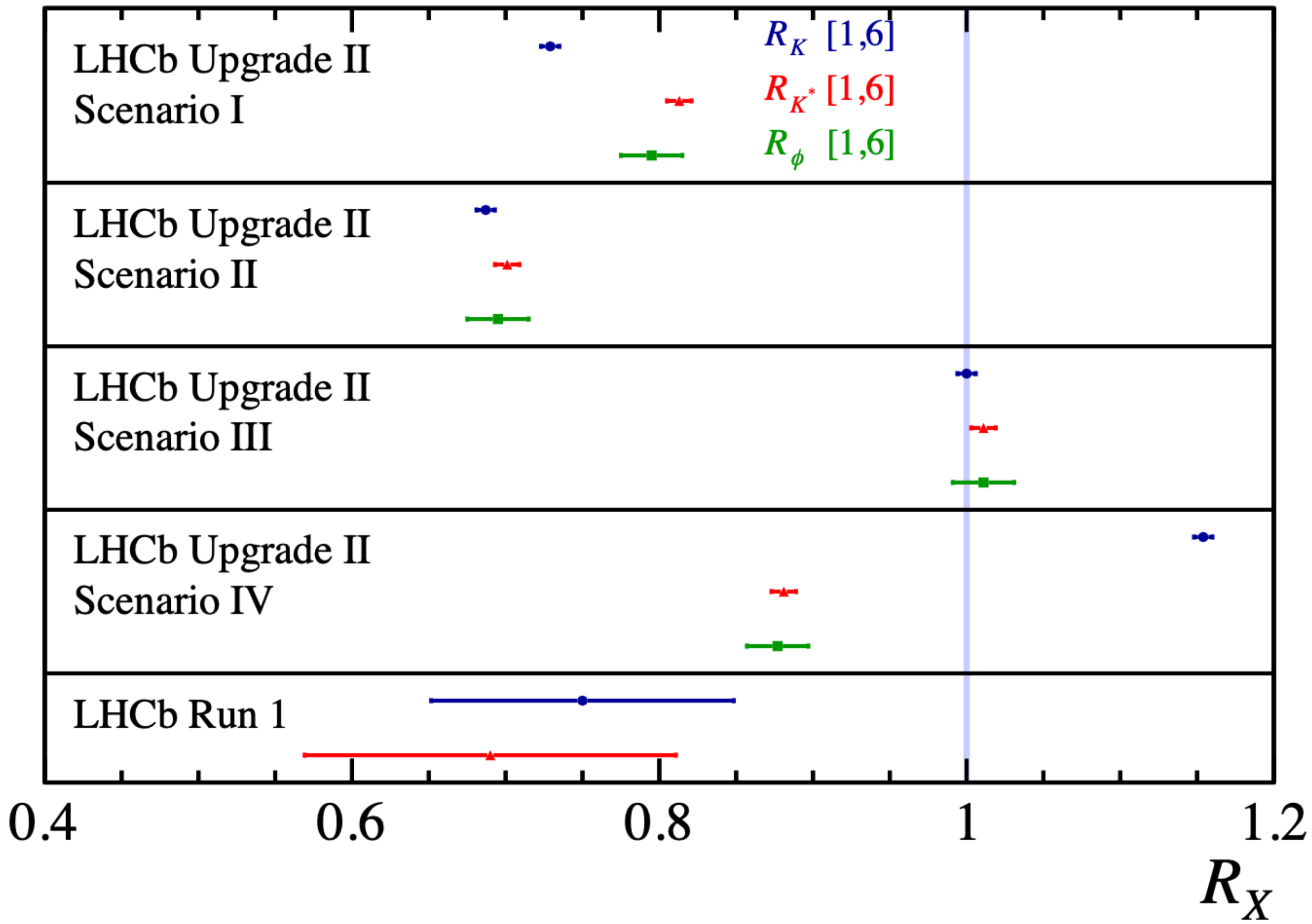
Lepton flavour universality

Looking for NP by comparing decays with muons and electrons, a huge challenge

$$R_K = \frac{\mathcal{B}(B \to K\mu^+\mu^-)}{\mathcal{B}(B \to K e^+ e^-)}$$ *= 1 in SM*

Benefit is in terms of measurements with almost no theoretical uncertainty

Projected sensitivities for R_X meas. in different NP scenarios

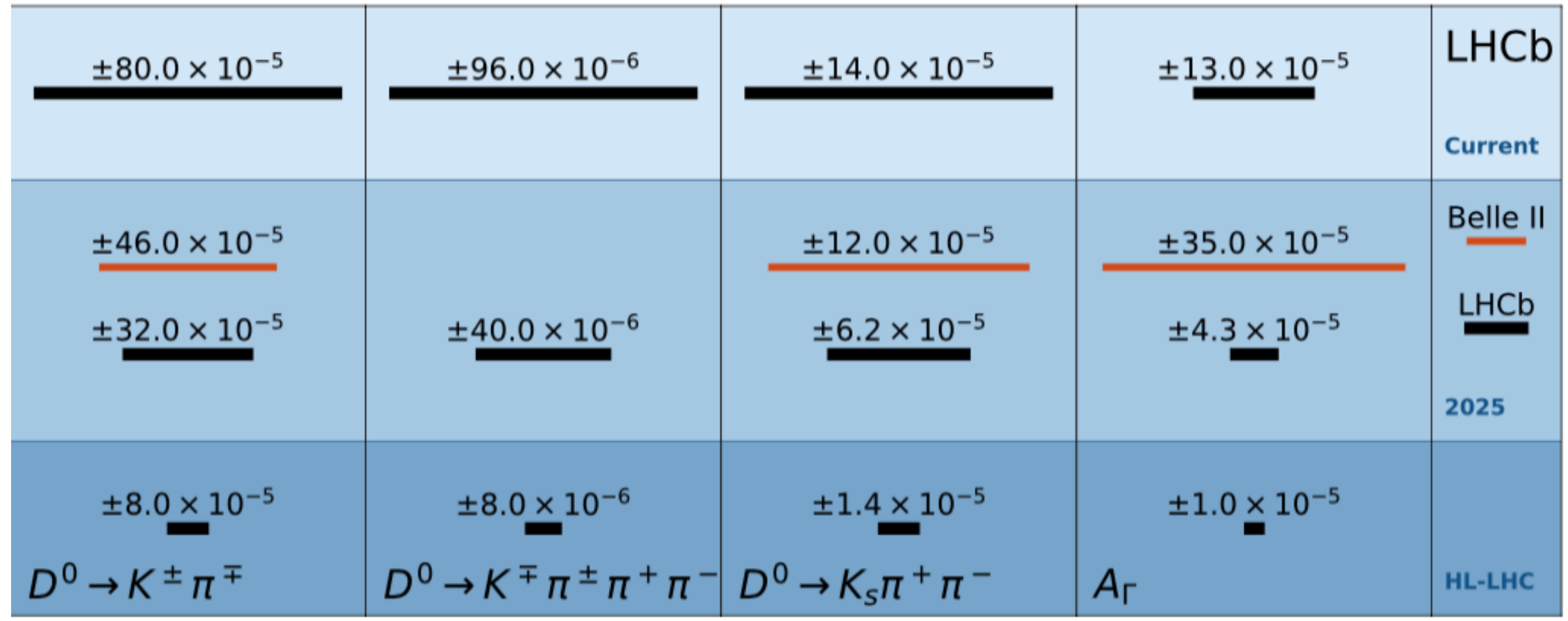


Additional informations from differences in angular observables between $B \to X\mu^+\mu^-$ and $B \to Xe^+e^-$

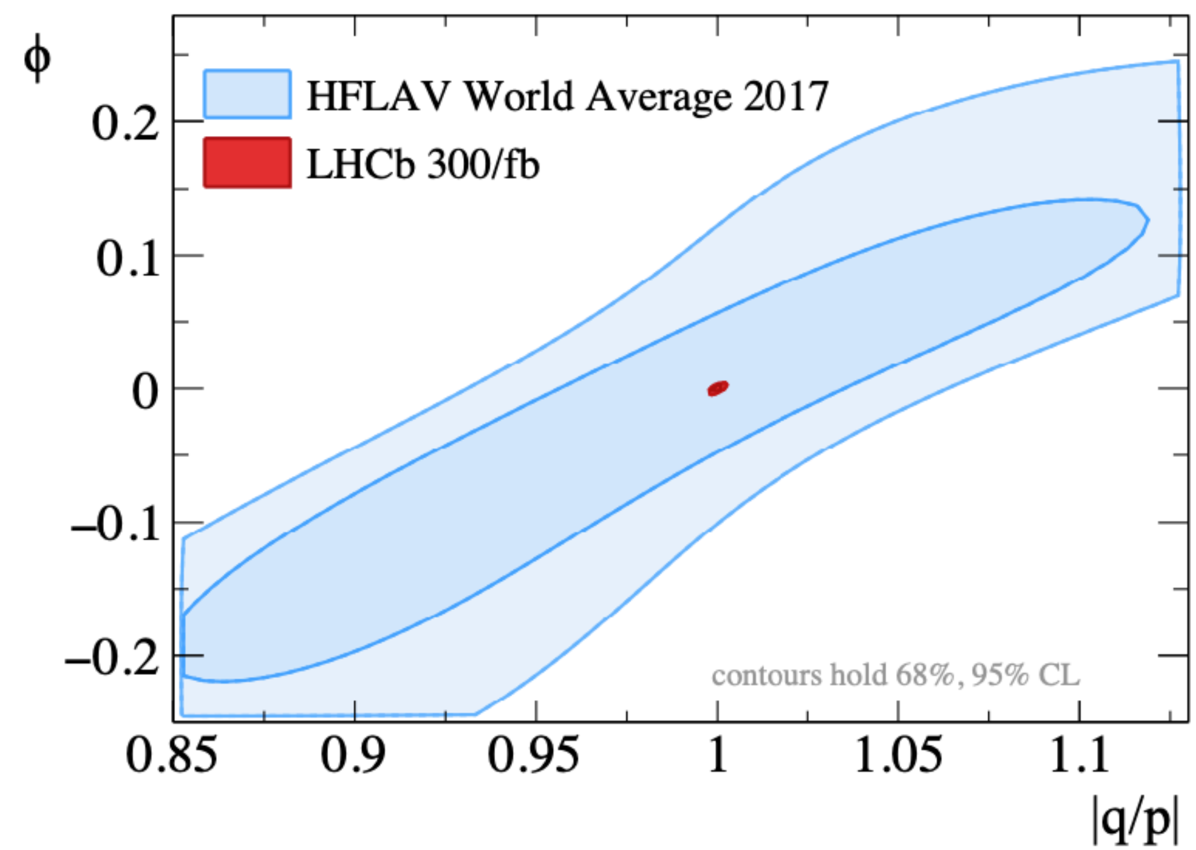
With Upgrade 2 statistics capability to discriminate between different NP scenarios

Charm CP violation

Time dependent CP violation in charm serves as an excellent null test for the SM: mixing amplitudes are approximately real ad are GIM or CKM suppressed



CP violation in mixing $|q/p| \neq 1$, $\phi \neq 0$ would represent a signature for NP



Impressive sensitivity to characterise NP contributions to CP violation

LHCb upgrade 2: the full table

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [275]	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 $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [606]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [607]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	150 mrad [94]	60 mrad	–	17 mrad	Under study [608]
a_{sl}^s	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–
$B_s^0, B^0 \to \mu^+\mu^-$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [609]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$b \to c\ell^-\bar{\nu}_l$ LUV studies					
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002	–
$R(J/\psi)$	0.24 [220]	0.071	–	0.02	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [610]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	–
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	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}	–

LHCC-2018-027

External approvals

Briefing book for the 2020 European Strategy Particle Physics

“The LHCb Upgrade II... will enable a wide range of flavour observables to be determined at HL-LHC with unprecedented precision which will give the experiment sensitivity to NP scales several orders of magnitude above those accessible to direct searches. "

arXiv:1910.11775

CERN Research Board, September 2019

"The recommendation to prepare a framework TDR for the LHCb Upgrade-II was endorsed, noting that LHCb is expected to run throughout the HL-LHC era.”

European Strategy Update, June 2020

"The flavour physics programme made possible with the proton collisions delivered by the LHC is very rich, and will be enhanced with the ongoing and proposed future upgrade of the LHCb detector."

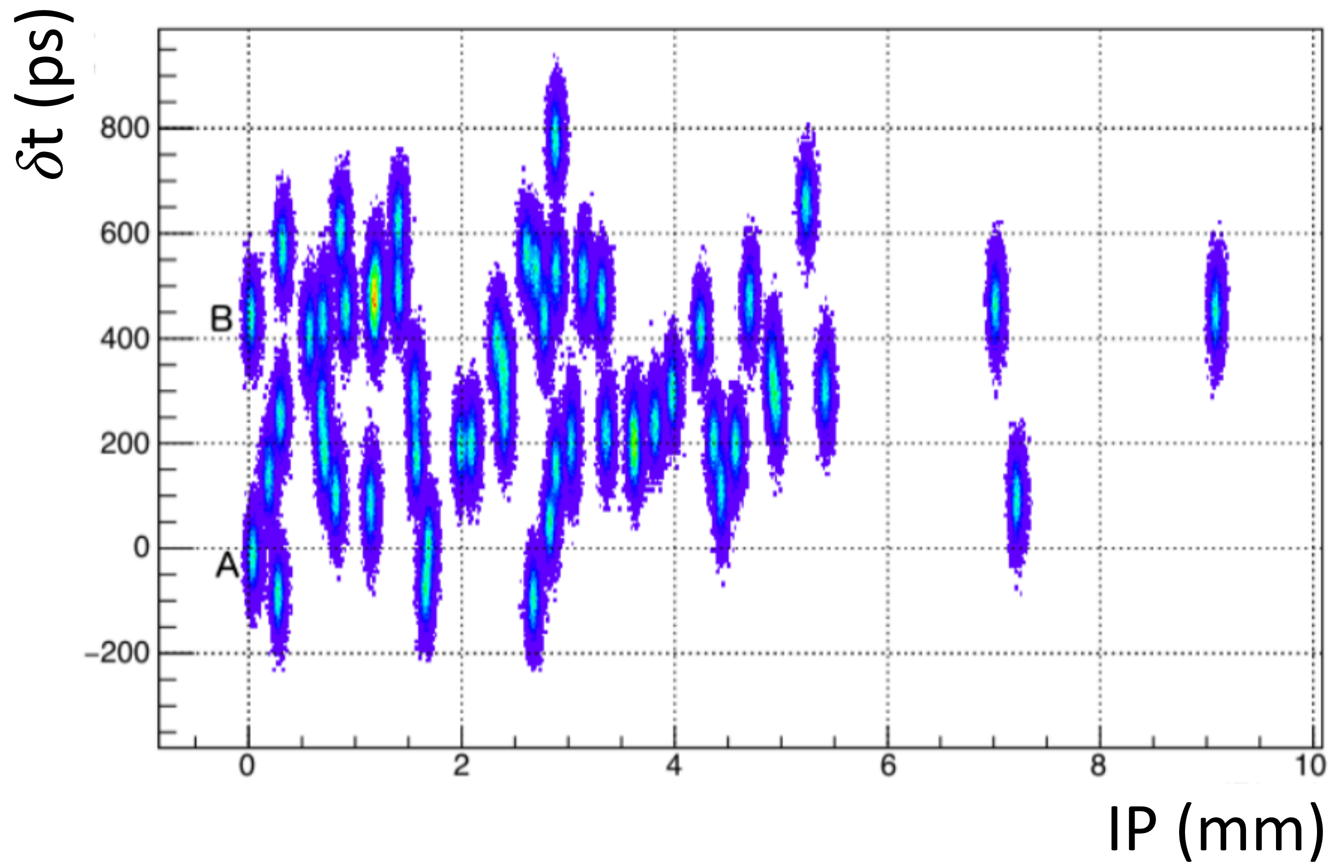
"The full potential of the LHC and the HL-LHC, including the study of flavour physics, should be exploited”

Upgrade II: the detector challenge

Instantaneous luminosity: 1.5×10^{34} cm^{-2}s^{-1}
⇒ ~40 visible interactions / crossing

Need timing to correctly associate the primary vertices to the decay particles

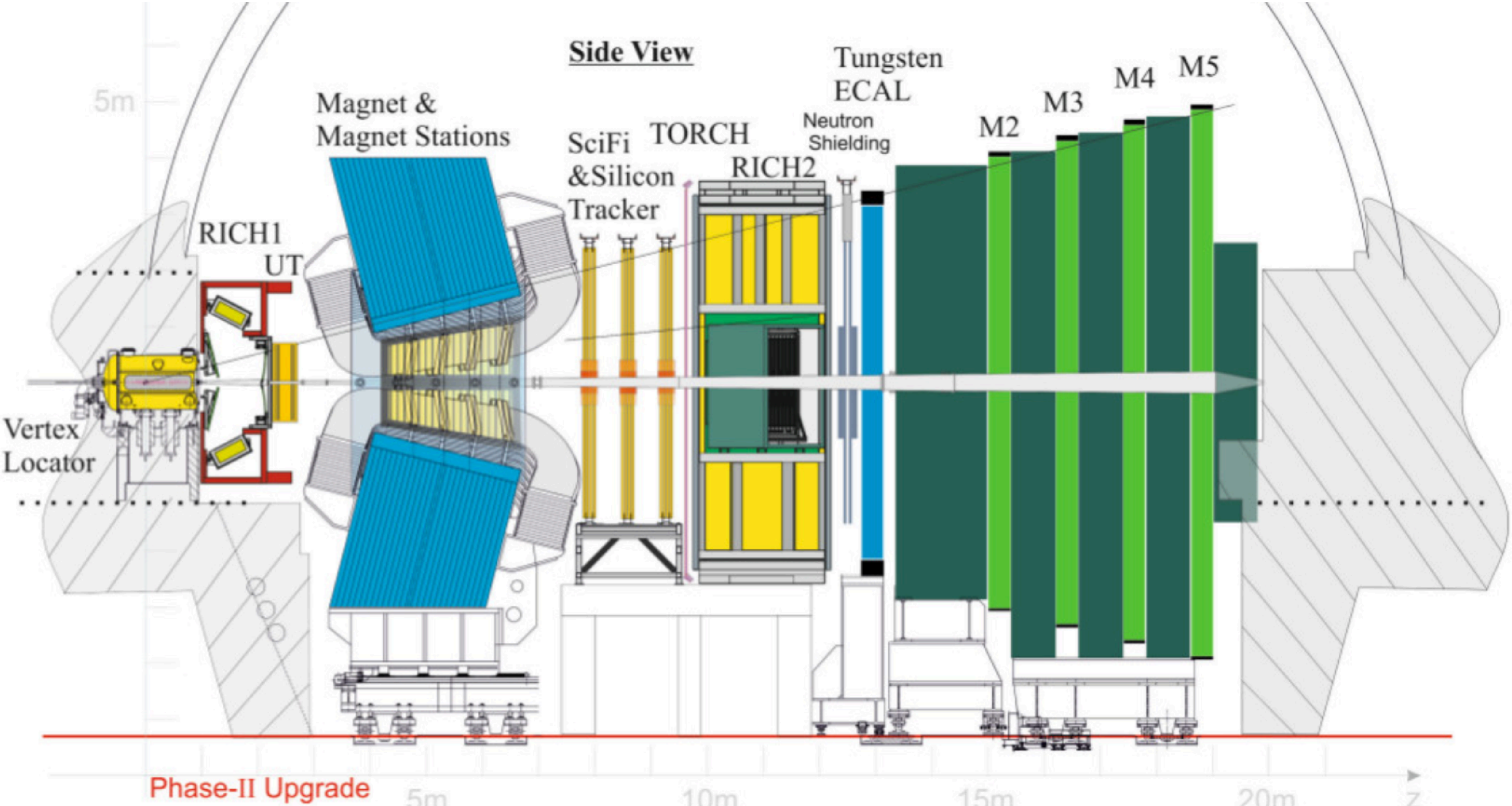
~2000 charged particles within the LHCb acceptance, extremely severe radiation environment, very large occupancies and combinatoric background



Tracking: modify the existing spectrometer components to increase the granularity, reduce the amount of material in the detector and to exploit the use of precision timing to achieve an **efficient real-time track reconstruction**; increase acceptance for low momentum tracks

Particle Identification: common theme will be again improved granularity and fast timing to associate the signals with a small number of *pp* interactions; **keeping present performances in K/π separation** (RICH) and **improve on electrons** (ECAL) will be crucial for precision flavour measurements

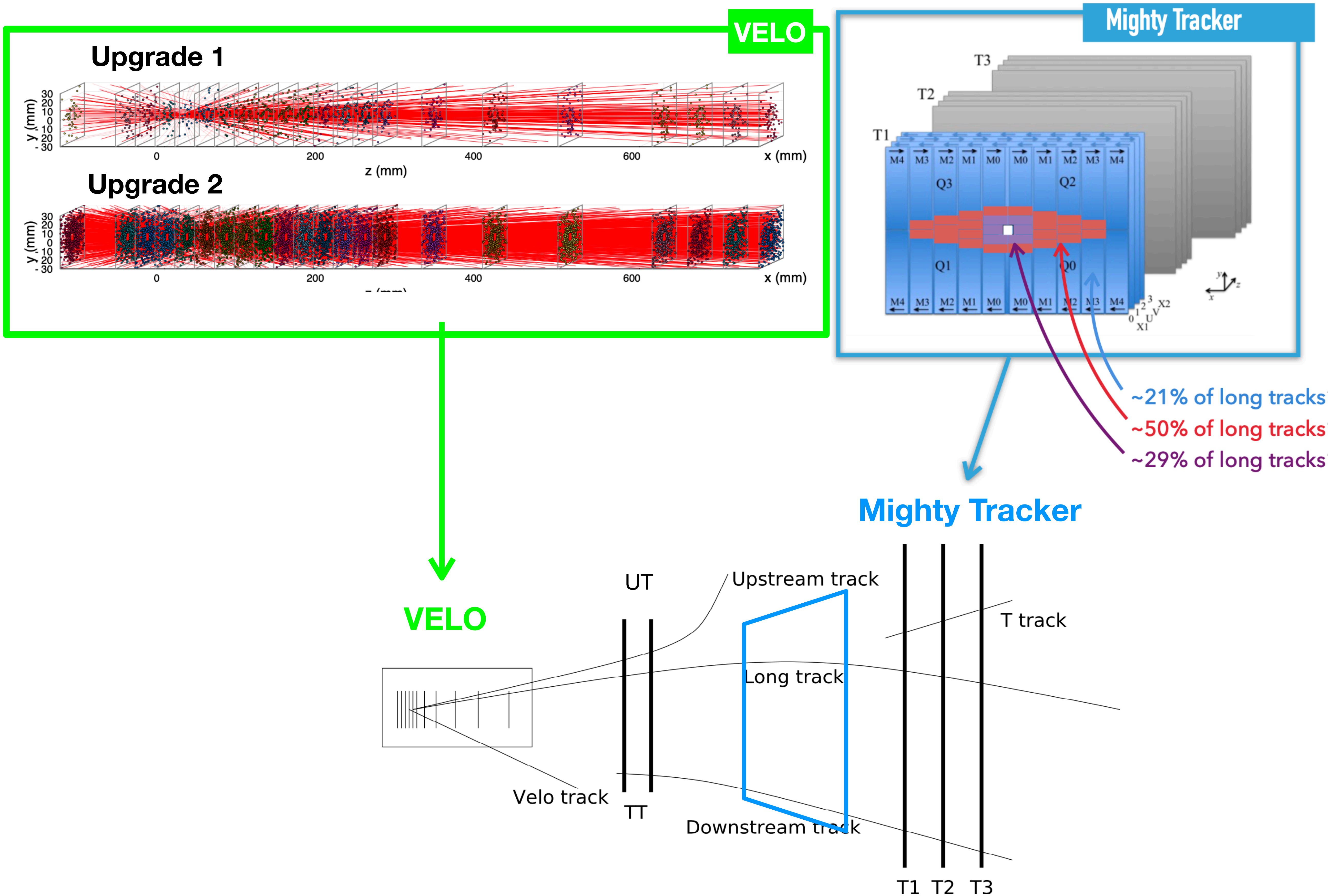
The LHCb 2 detector



Same spectrometer footprint, brand new sub-detectors

A huge technological challenge

Tracking detectors

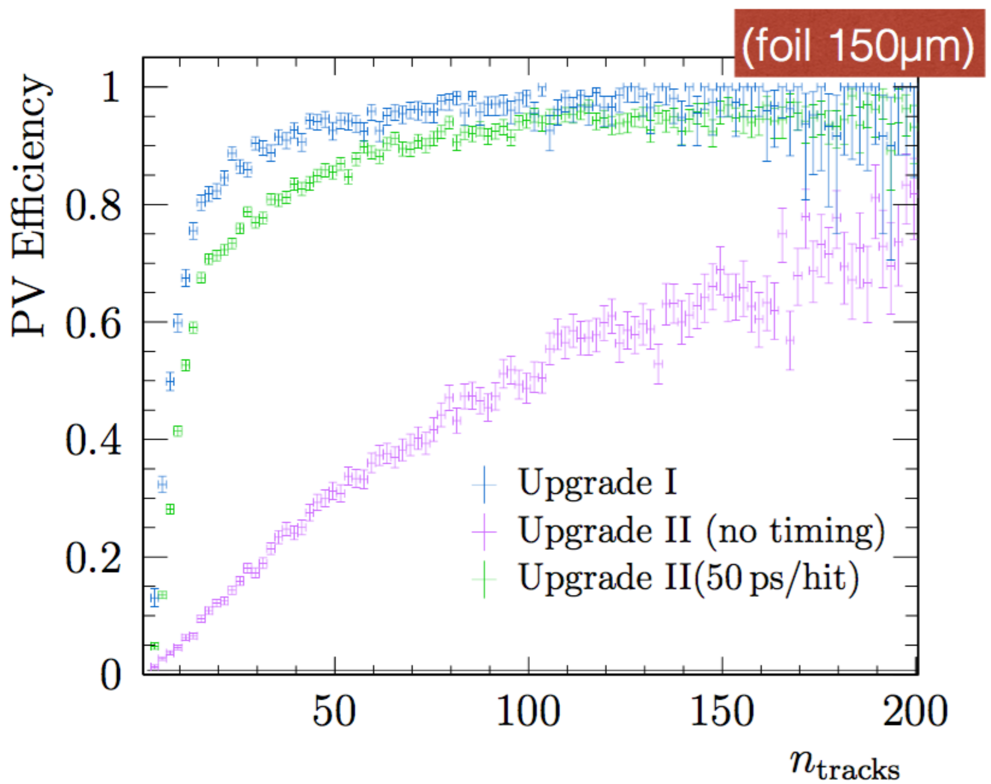


Performance evaluation of VELO options

The vast increase of luminosity with the upgrade II is particularly challenging for the vertex detector, which has the highest track density. Several options for the detector have been identified from first principles and toys: foil, timing, pitch, barrel.

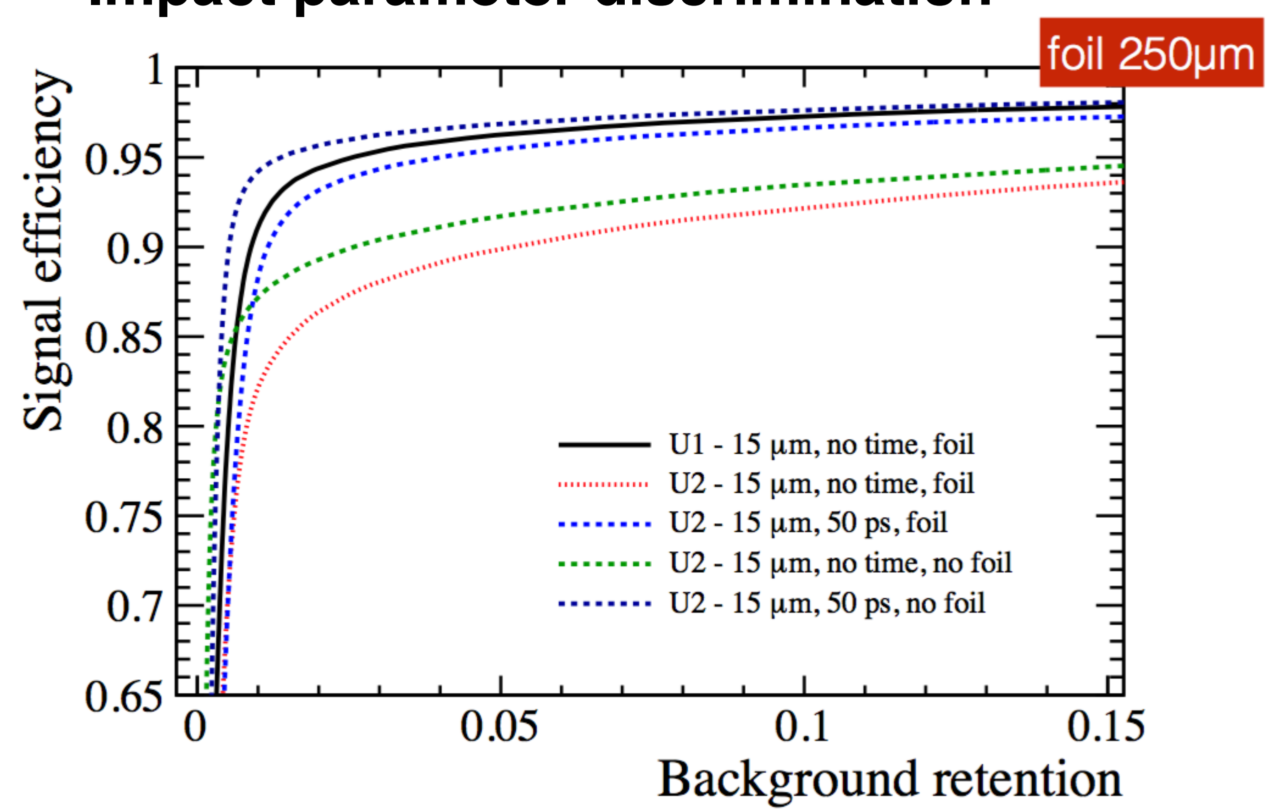
Using full simulation, the impact of a 50 ps time resolution per hit and/or removing the RF foil has been evaluated at different stages of reconstruction: pattern recognition, PV reconstruction, IP discrimination (HLT1) and multibody selection.

PV reconstruction



Impact of timing in PV reconstruction is dramatic

Impact parameter discrimination



Both foil removal and timing contribute

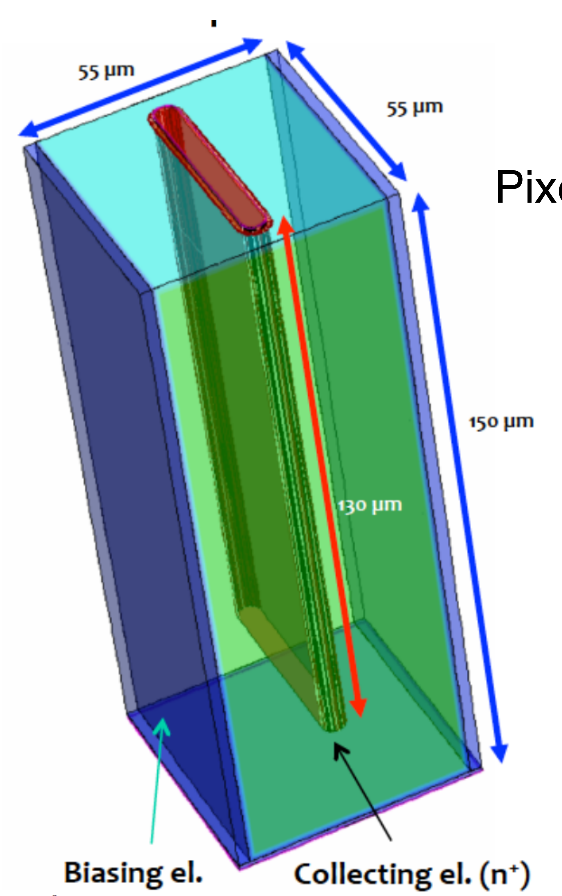
R&D on VELO sensors

Requirements: pixel size < 55μm, hit time resolution < 50 ps, operation up to 5×10[16] *neq*

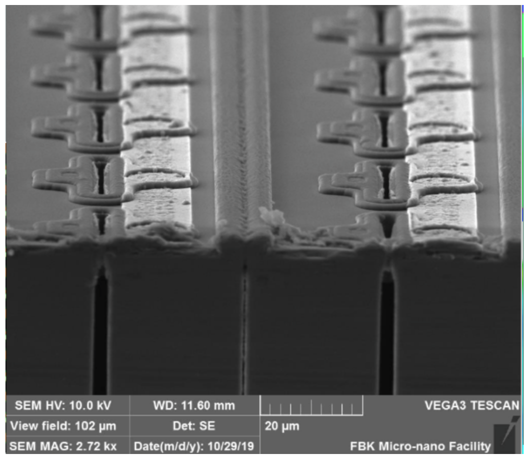
The VELO upgrade is targeting Run 5 (no intermediate steps): time to develop innovative solutions

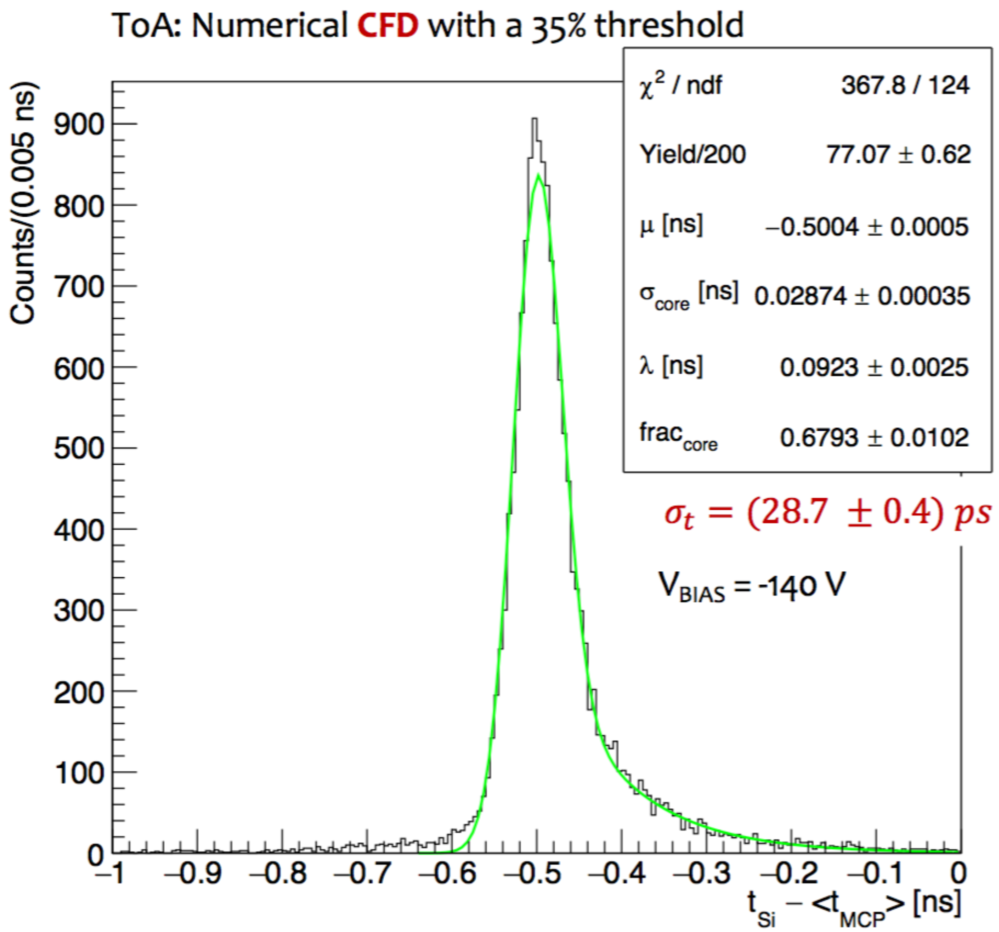
- Several candidate technologies for sensors: LGAD, 3D, MAPS, planar
- Future ASIC (28 nm): Timepix4 ⇒Velopix2, TimeSpot

Example: 3D sensor technology under development (TimeSpot)



Pixel size 55 μm

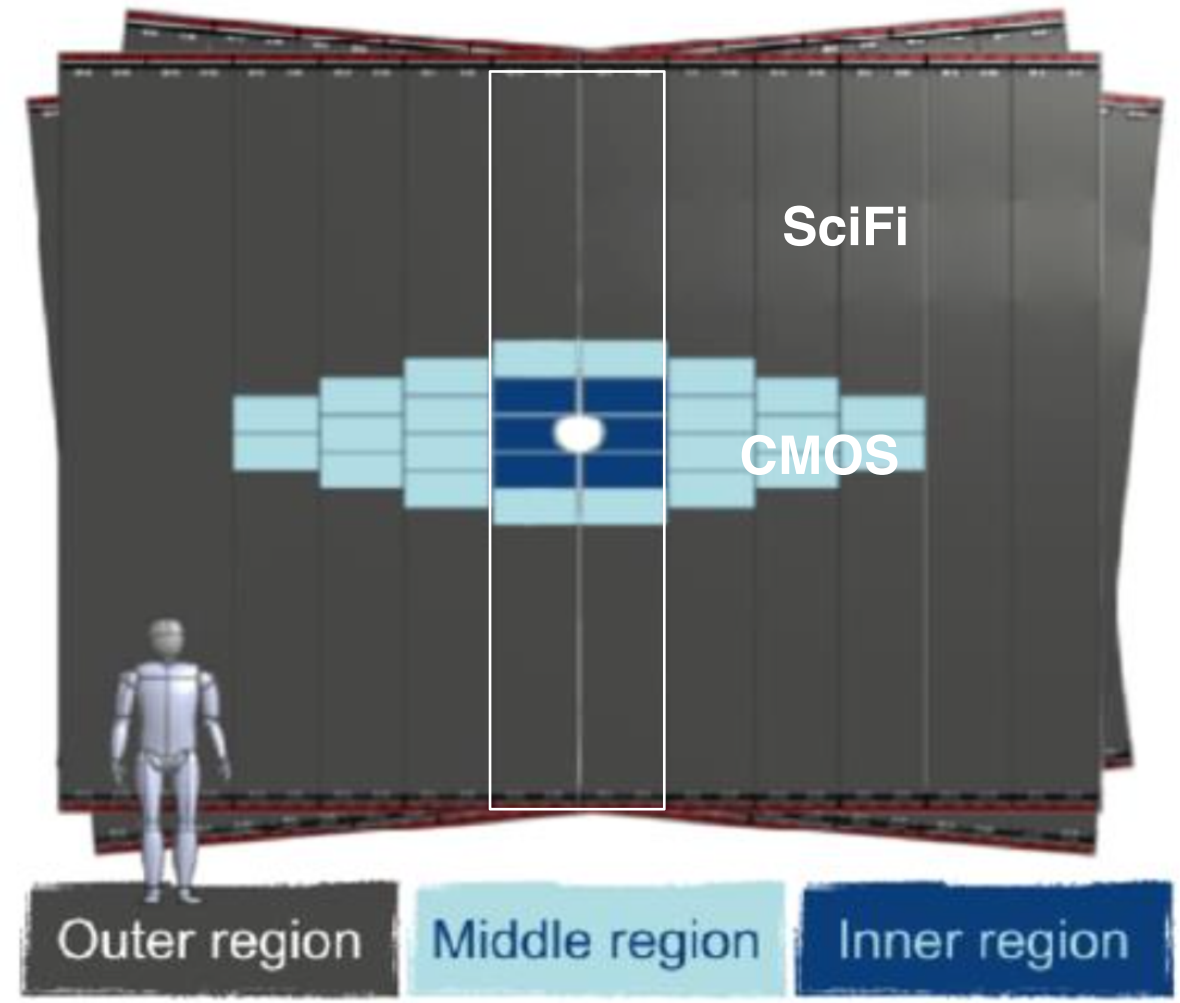




Radiation hardness to be measured

Measured time resolution better than 30 ps

Mighty Tracker: overview



Combined project

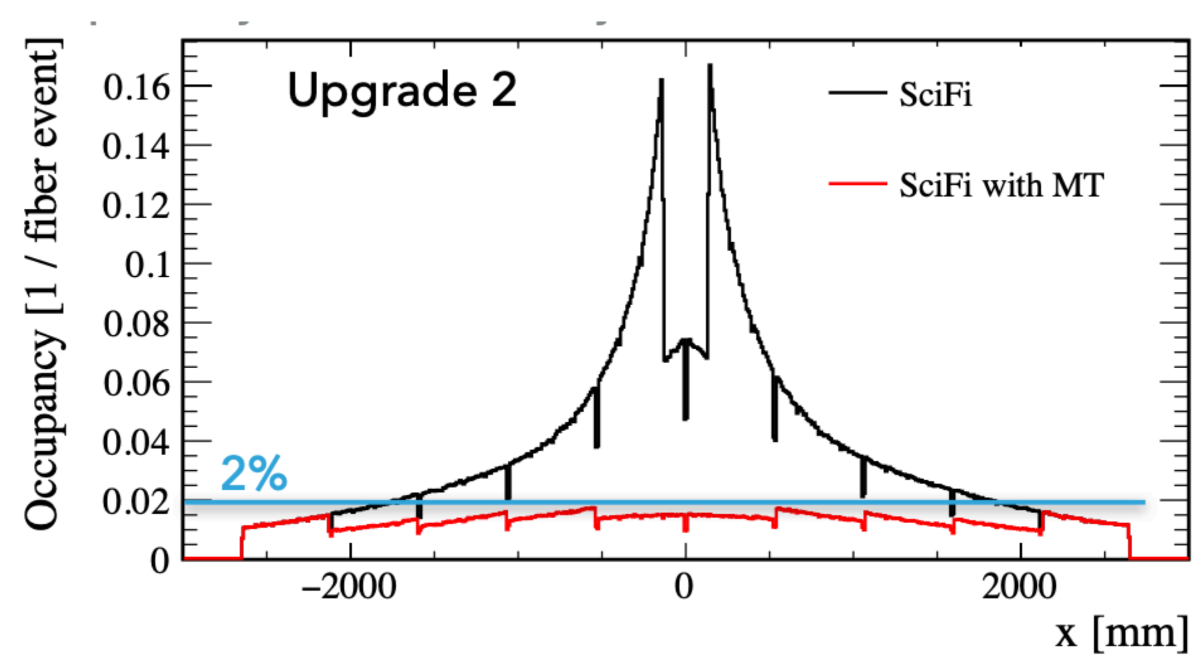
- CMOS silicon pixel for the inner/middle region
- Scintillating fibres for the outer region

Inner region (LS3)

- Motivated by SciFi radiation damage before the end of Run 4: need to rebuild the two SciFi innermost modules at LS3, 12 layers

- Add in correspondence silicon pixels in the inner part: 6 planes are sufficient, ~ 4 m^2

- Physics gains: improvement in ghost rejection and momentum resolution at high p (~30% long tracks), increased capability for downstream tracking (K_S) and heavy ions at centrality zero



Middle/Outer regions (LS4)

- Add CMOS silicon pixels for middle region ~ 14 m^2

- Smaller silicon rely on improvement in SciFi radiation hardness

- Entirely new SciFi

Mighty Tracker: overview

Combined project

- CMOS silicon pixel for the inner/middle region
- Scintillating fibres for the outer region

Inner region (LS3)

- Motivated by SciFi radiation damage before the end of Run 4: need to rebuild the two SciFi innermost modules at LS3, 12 layers

- Add in correspondence silicon pixels in the inner part: **4** planes are sufficient, ~ 4 m²

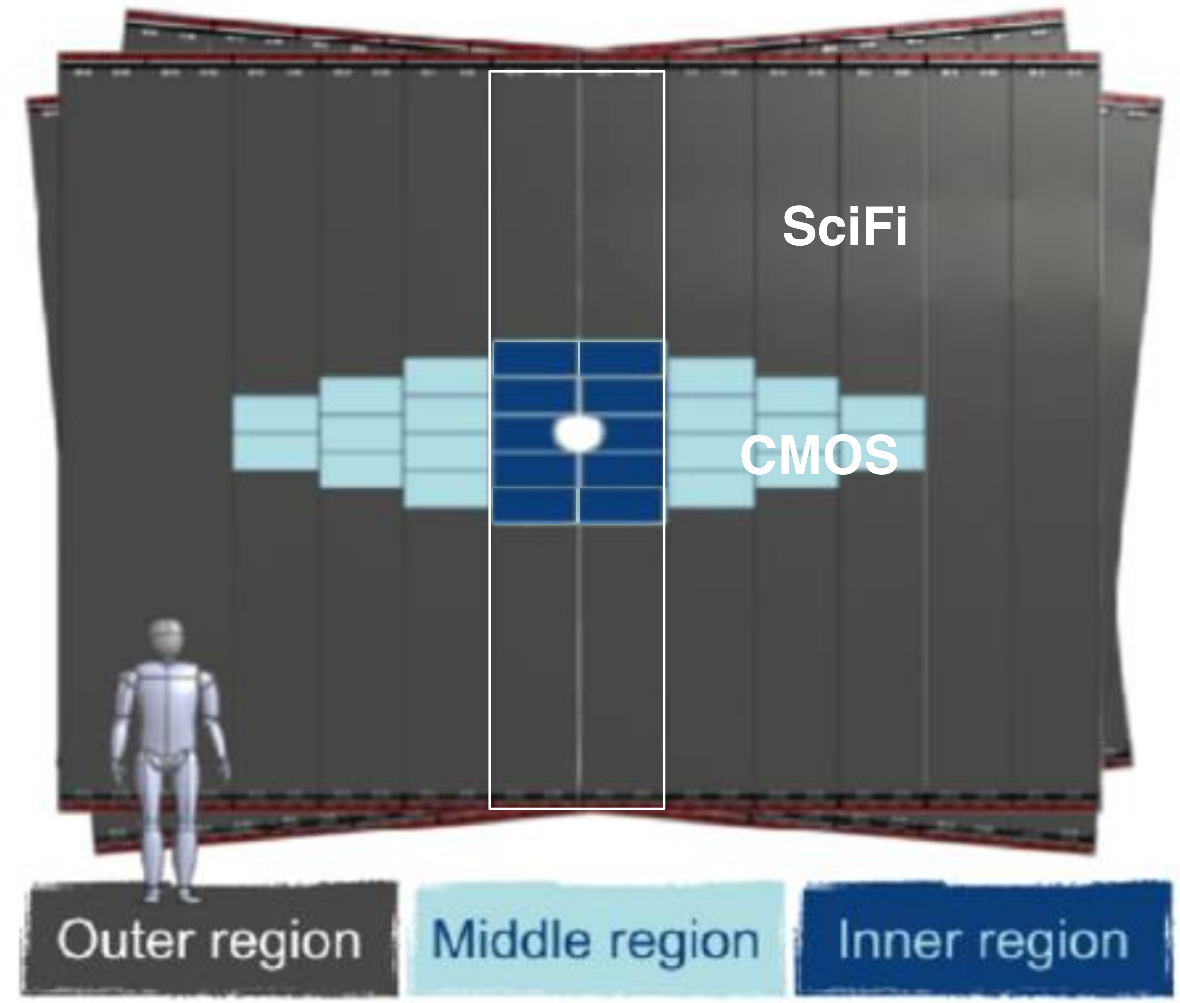
- Physics gains: improvement in ghost rejection and momentum resolution at high p (~30% long tracks), increased capability for downstream tracking (K_S) and heavy ions at centrality zero

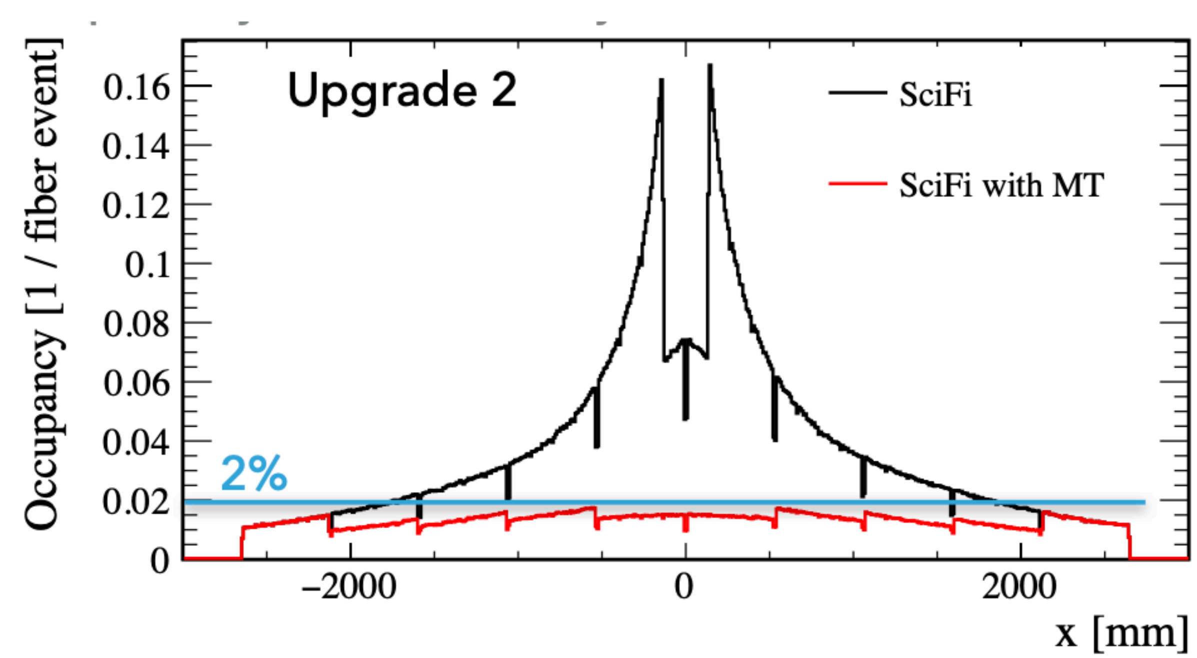
Middle/Outer regions (LS4)

- Add CMOS silicon pixels for middle region ~ 14 m²

- Smaller silicon rely on improvement in SciFi radiation hardness

- Entirely new SciFi

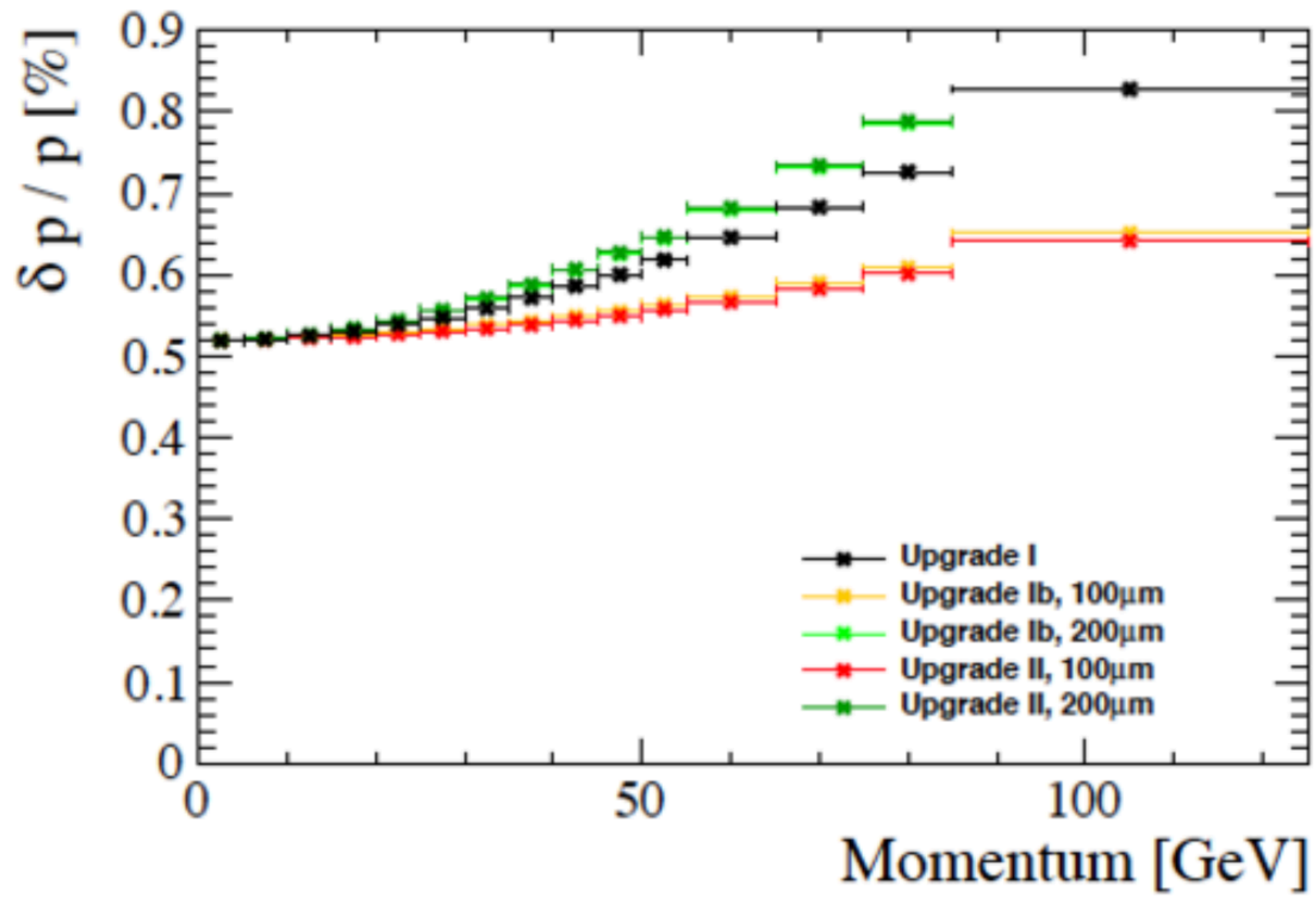




Mighty tracker: simulation studies

Detector design based on simplified simulation studies of tracking

- Choice of pixel size
- Momentum resolution
- Track matching with VELO



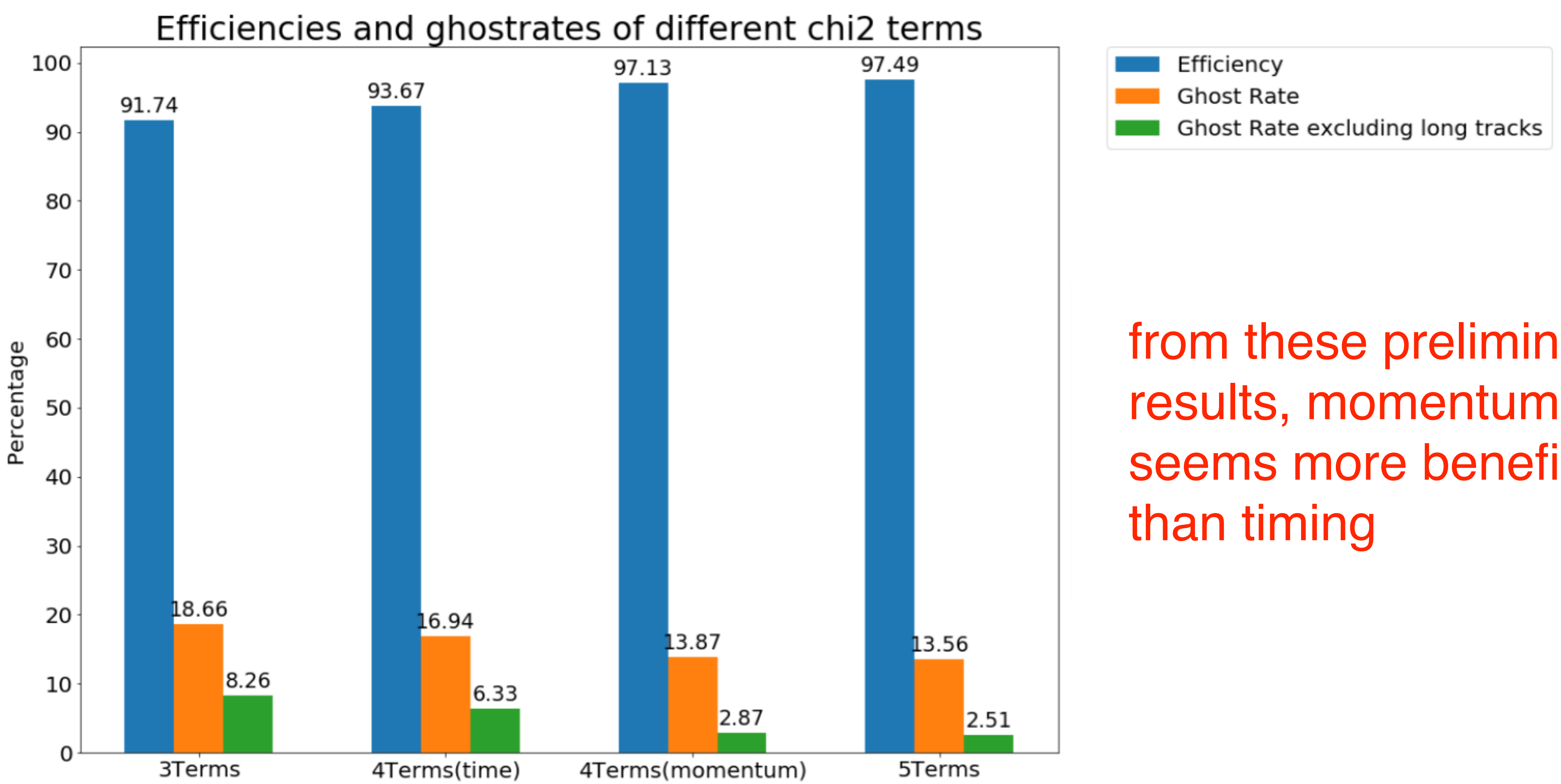
A lot still to be done but already clear first impression

- Ghost rejection and momentum resolution at high p gains
- Small pixels help in track finding
- From preliminary results on upstream/downstream matching (UT design critical also) ⇒ do not anticipate need for timing

Mighty tracker: track matching

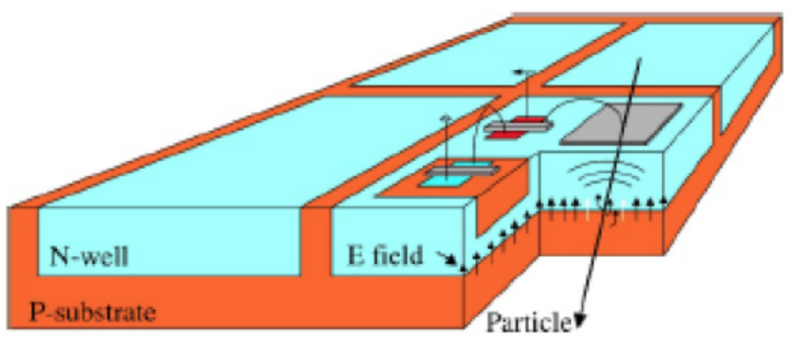
Track matching efficiency and ghost probability with space only (3 terms), or adding time and/or momentum information (4/5 terms)

$$\chi^2_{\text{match}} = \frac{(x_{pred} - x_{meas})^2}{\sigma_x^2} + \frac{(y_{pred} - y_{meas})^2}{\sigma_y^2} + \frac{(t_{y\,pred} - t_{y\,meas})^2}{\sigma_{t_y}^2} + \frac{(p_{VeloUT} - p_{Tstat})^2}{\sigma^2_{p,VeloUT} + \sigma^2_{p,Tstat}} + \frac{(t^{PV}_{Velo} - t^{PV}_{Tstat})^2}{\sigma^2_{t,Velo} + \sigma^2_{t,Tstat}}$$

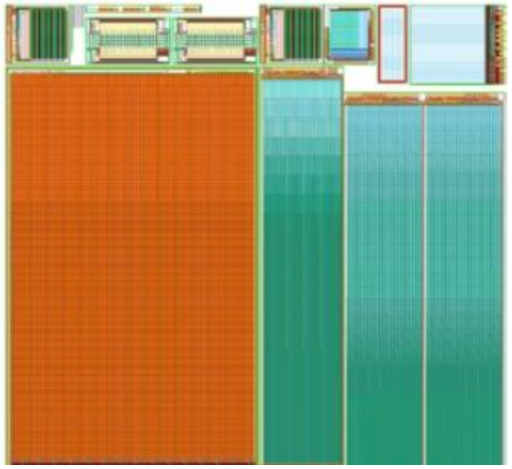


from these preliminary results, momentum seems more beneficial than timing

CMOS technology for Mighty tracker



- Monolithic Active Pixel Sensor (MAPS)
- Integrated pixel sensor & chip on **single** piece of silicon
  - Low-cost commercial process
  - e.g. used for mobile phone cameras
- First radiation hard CMOS tracker at LHC



- Chip based on existing MuPix/ATLASPix
- https://arxiv.org/abs/2002.07253
  - "MightyPix" Specification document in preparation

Parameter	Depleted CMOS Sensors for LHCb
Chip Size	$\sim 2\,\text{cm} \times 2\,\text{cm}$
Sensor Thickness (μm)	200 (ATLASPix3)
Pixel Size (μm)	100×300 (with smaller sizes to be explored)
Time Resolution (ns)	Must be within 25 ns window
Inactive area	$< 5\%$
Power Consumption (W/cm^2)	0.15
Data transmission (Gbps)	4 links of 1.28 Gb/s each, multiplexed to 2 and 1 links
NIEL (TBC)	3×10^{14} (6×10^{14} with safety factor)

from performance studies do not anticipate need for timing

LHCb-INT-2020-016

Radiation dose well within demonstrated capability of HV-CMOS

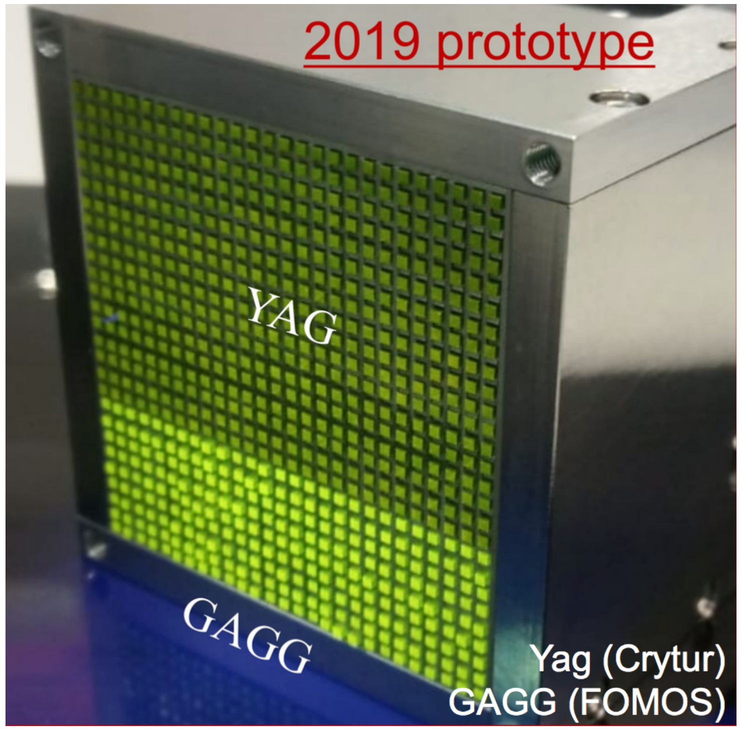
Particle identification detectors

ECAL

Proposed solutions are being validated with simulation

Radiation-hardness, timing capability (few tens of picosecond required) and granularity are key parameters under study

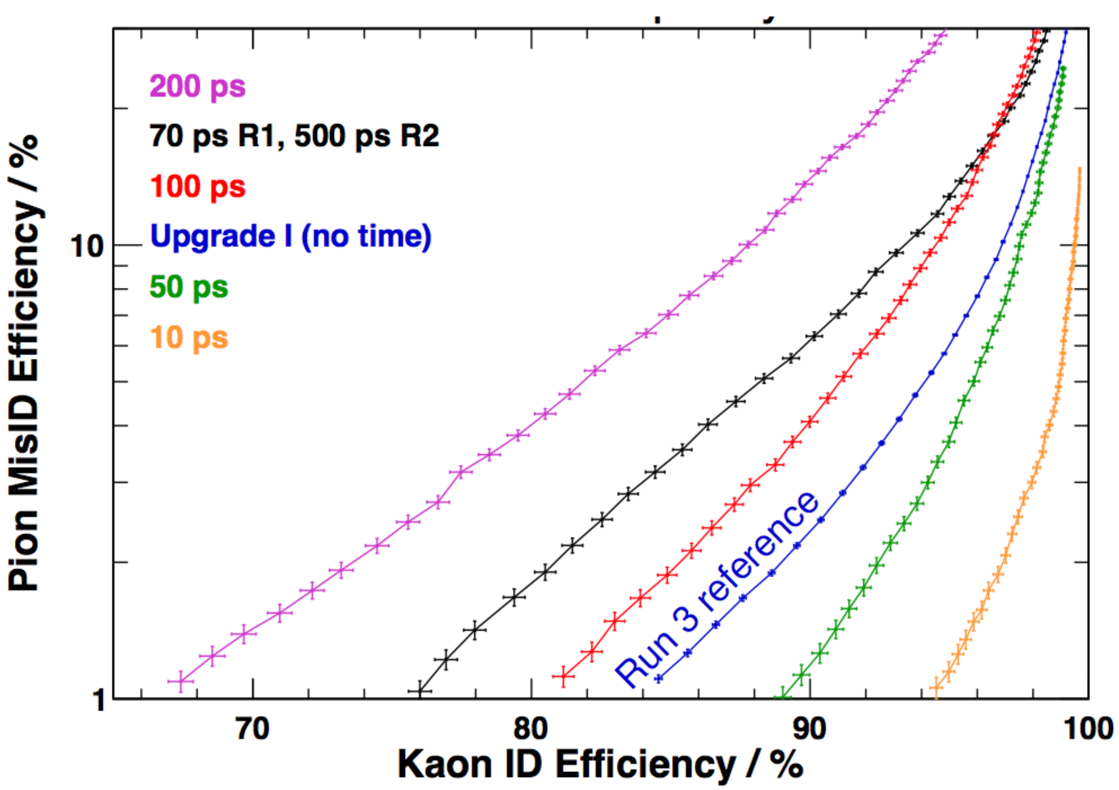
R&D ongoing with: SPACAL with crystal fibres (very rad. hard) with timing readout and timing layer with MCPs



RICH

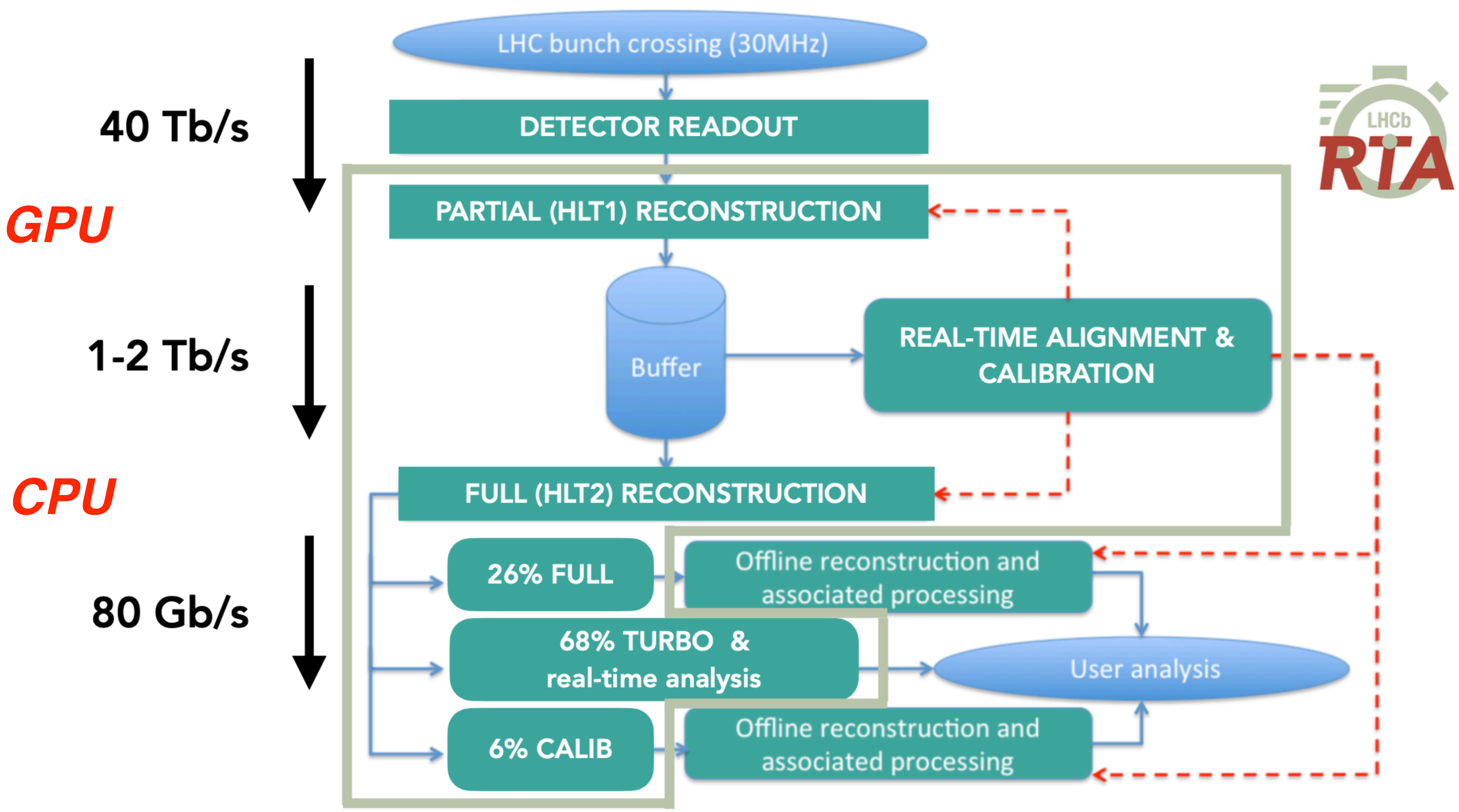
Redesign of the detector (including new photodetectors) aiming for a time resolution below 100 ps.

Expected to recover Run 3 performances



Real time analysis: where we stand

Tremendous effort to implement for the fist time at an hadron collider a full software trigger



On the way to get this done:

- *impressive improvement achieved in HLT1, now vastly exceeding the needed throughput ⇒ resource optimisation*

- *HLT2 under optimisation to maximise the physics throughput*

LHCb choice towards an heterogenous trigger is setting the path for future applications, there's an increasing synergy with the other LHC experiments

Real time analysis: the future challenge

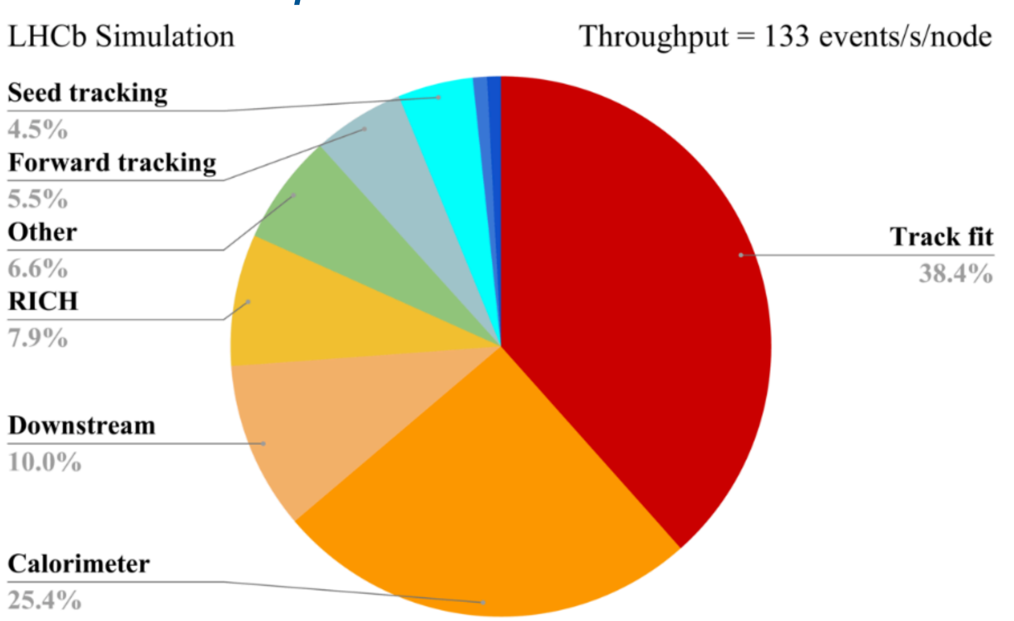
RUN 3	RUN 4	RUN 5
40 Tb/s from detector	40 Tb/s from detector (after L0)	400 Tb/s from detector
80 Gb/s to storage	480 Gb/s to storage	800 Gb/s to storage

Bottom line: process x10 more data from the detector than GPDs at Run 4, and write out a similar (~x2) amount of data: LHCb pioneering the challenge in HEP technology!!

Scenario presently discussed in the RTA

- *HLT1 on GPU, HLT2 reconstruction on GPU, selections on CPU*
- *2.6 improvement assumed in cost/performance (1.1 per year), get GPU at consumer prices*

present HLT2



Numbers are evolving rapidly, but clearly DAQ & trigger will represent a substantial cost (and will affect the physics output)

Some thoughts on track reconstruction

Track reconstruction sequence for Run 3 is modular in the sub-detectors, perfect for parallel processing ⇒ Run 5 layout also optimal for parallelisation

Detector occupancy similar as in Run 3 (detectors are being designed for that)

Roughly even distribution of tracks among different detector nicely map to occupancy in processors on a GPU (modularity concept)

Pre-processing: clusters (and tracklets ?) from FPGAs

VELO: split event based on time information, process time slices of hits to handle combinatorics ⇒ very similar problem to VELO reconstruction nowadays

Mighty Tracker: pixels in the high occupancy region ⇒ problem will become simpler than with SciFi, as x- and y-information are available

Optimization is needed including detector readout, event building and software trigger which will require a joint effort between the sub-detectors and the Online & RTA projects

R&D on future implementations

Summaries on CPU and GPU technologies indicate a promising R&D path: exploitation of heterogeneity advances in CPU/GPU/coprocessor technologies just started

Progress of technology in this field is not at all in our hands, but we need to get ready and understand on how to make best use of it

Inside RTA a coprocessor testbed is being developed to determine a common means to integrate the various technologies into the experiment framework, access test data and interact with the online environment (already during Run 3)

Ongoing activities include:

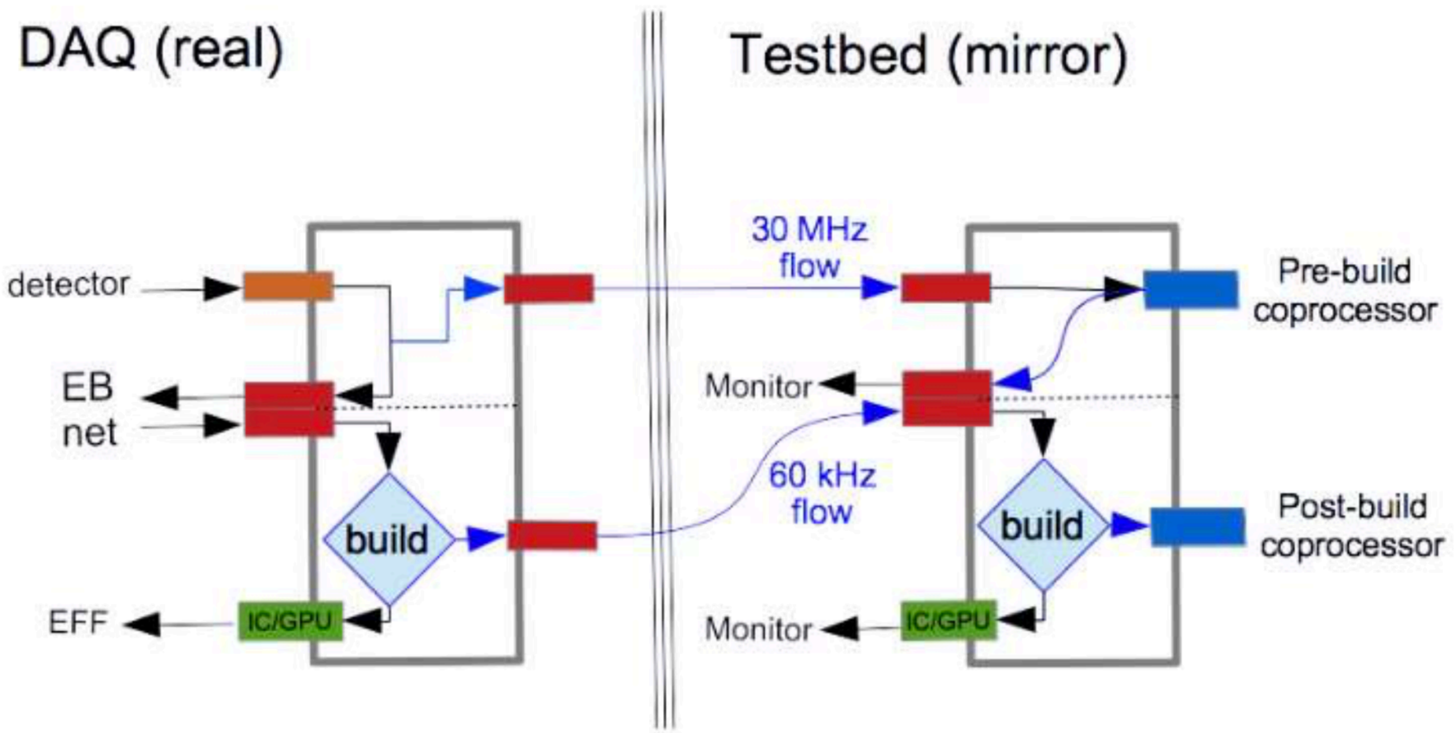
The TimeSPOT project for 4D real-time tracking in FPGAs

The RETINA project for downstream tracking

Using 'Intelligence Processing Units' (IPUs) as a drop-in GPU replacement

Microsoft-supported FPGAs for Ml-based VELO pattern recognition

Using the CMS 'Serenity' readout boards as a PCIe40 replacement



Conclusions

LHCb upgrade II is taking shape!!

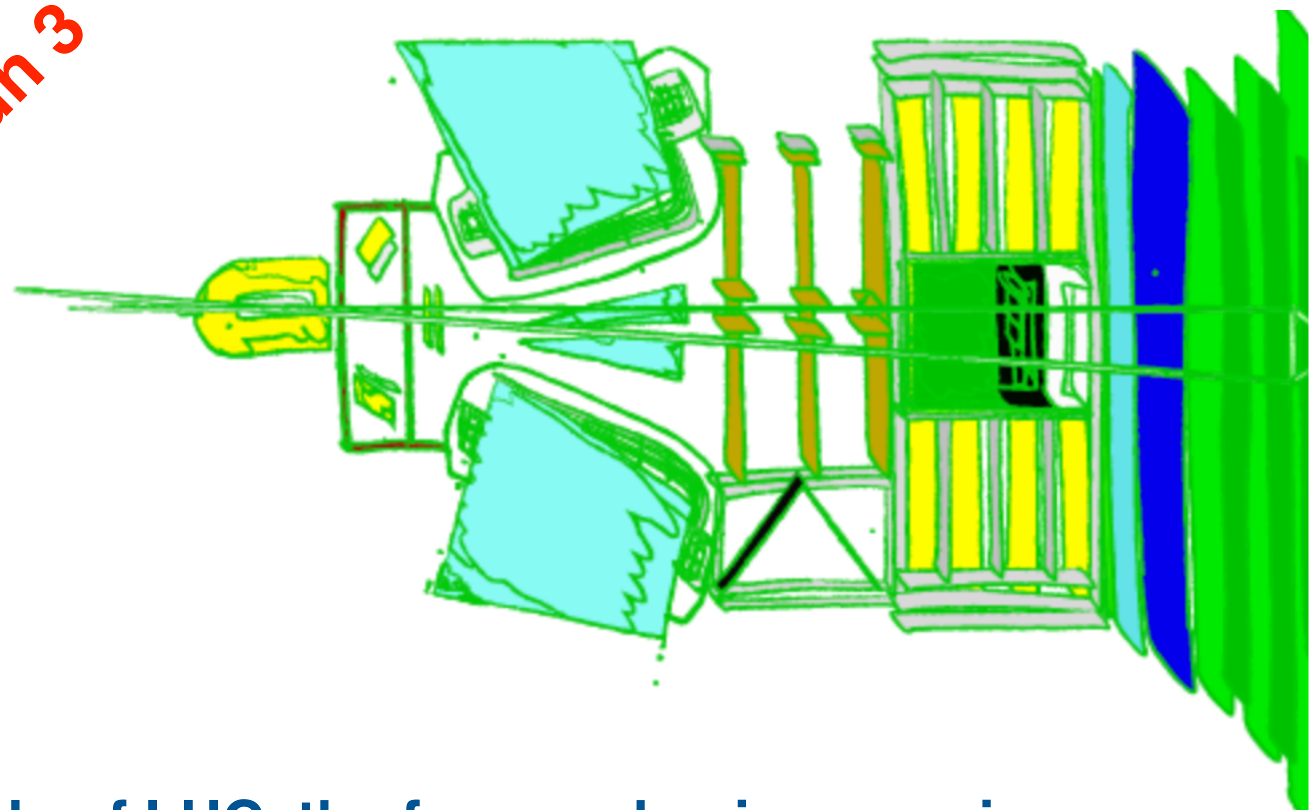
- Subdetectors are developing baseline scenarios for upgrade 2
- Simulation of physics performances is giving indications on key detector parameters: timing, granularity, radiation hardness
- For upgrade 2, we have time and we need to develop innovative solutions
- **A FTDR is expected in september 2021 by the LHCC, discussing detector options which can deliver our physics case, with approximate cost matrix**

A brilliant (and long) future is ahead of us

Exploitation of Run 2 data

Start of Run 3

Preparation of upgrade II



After a decade of LHC, the favour physics case is now more solid than ever: “The LHCb Upgrade II … will enable a wide range of flavour observables to be determined at HL-LHC with unprecedented precision"

The next challenges will require very good ideas and excellent technology solutions, which are the best ingredients for a successful scientific enterprise

Thank you for contributing!

A brilliant (and long) future is ahead of us

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Thank you for contributing!

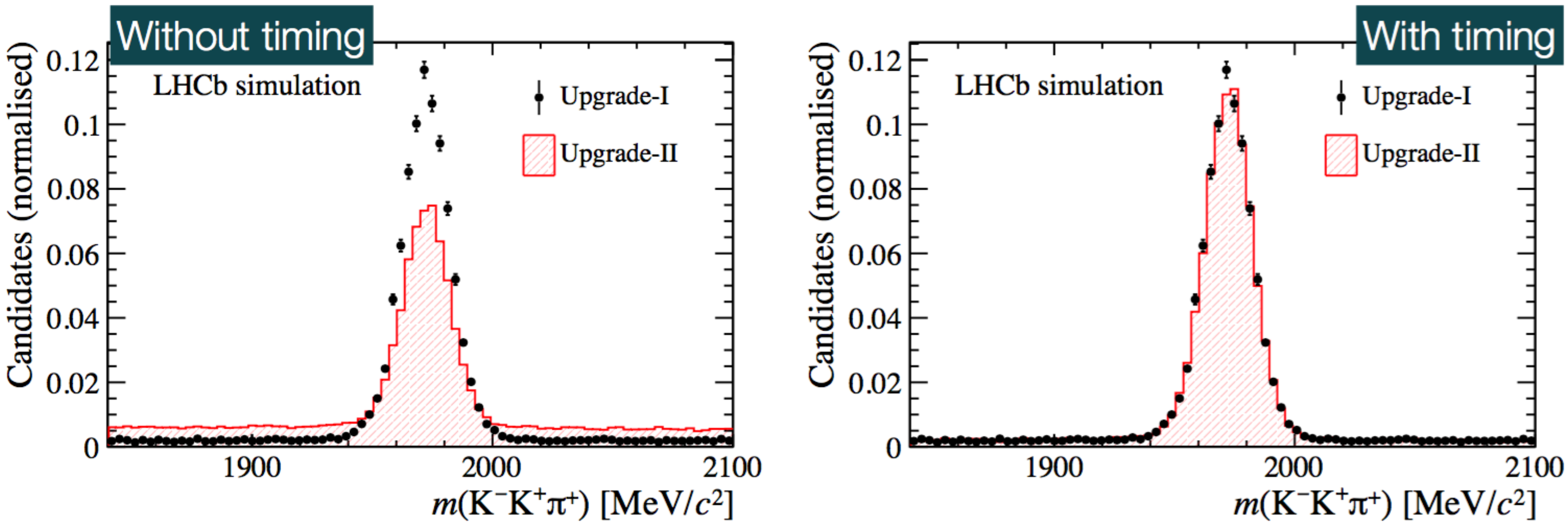
SPARES

Performance evaluation of VELO options

After selecting displaced tracks with a reasonable pT, combine then to find a signal candidate

With the increased track density, more combinatorial background is expected

Generated signal $B_s \to D_s^+ \pi^+$ Monte Carlo, samples artificially pure (*every event* contains signal!). Try and reconstruct the D_s^+.



Timing greatly helps in rejecting the combinatorial background: useful for trigger!

SciFi

Major challenge is radiation damage for fibres and SiPMs

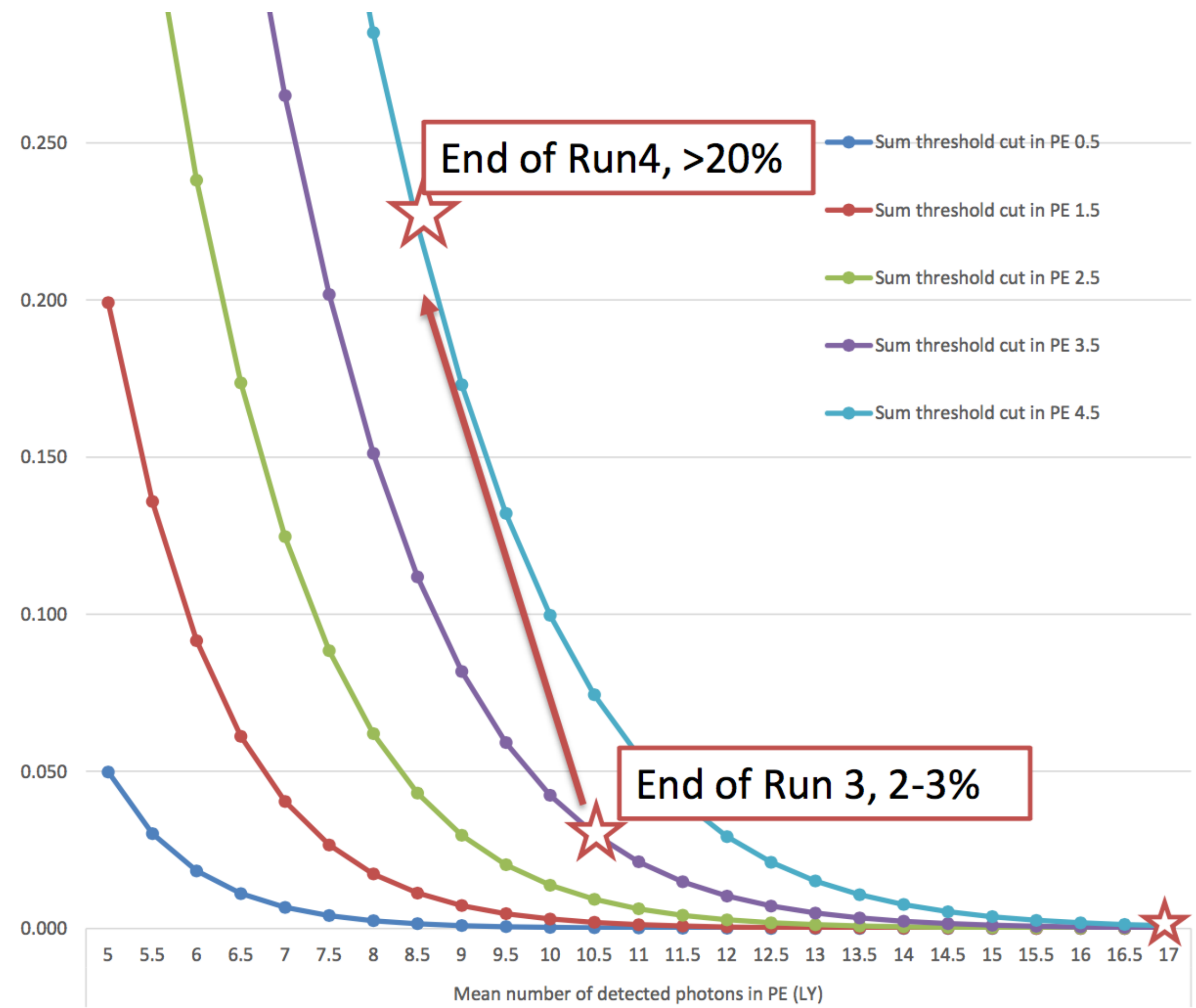
Fibres: ionising dose leads to loss of transparency: reduction of Light Yield

SiPMs: neutron fluence leads to increased dark count rate: the threshold has to be increased and the efficiency drops rapidly

Fluka simulation used for the neutron fluency estimate has a factor of 2 uncertainty (not included in the plot shown)

This also could be a problem in view of possibly accumulating >50 fb^{-1} during Run 3 + Run 4

Inefficiency as a function of noise cut and LY



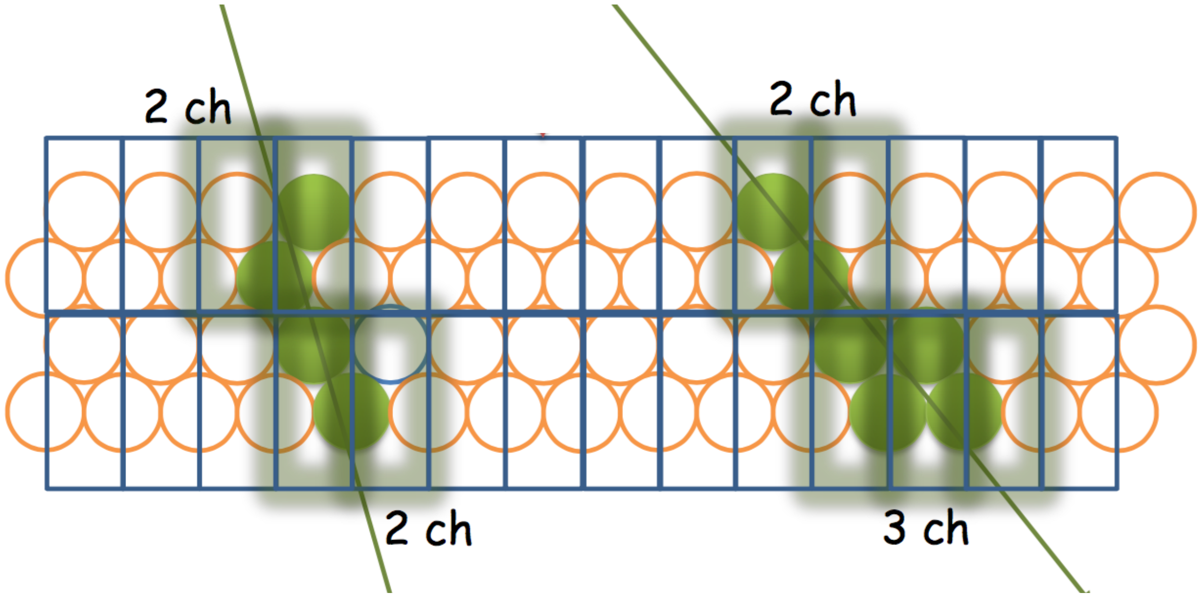
For Upgrade II, reduce SiPM noise dramatically (>10^4) with cryogenic cooling (LN2) in a vacuum chamber, and developing a clear fibre interface

SciFi: R&D for Upgrade II

Reducing occupancy

Thinner SciFi mats and/or segmenting channels in height

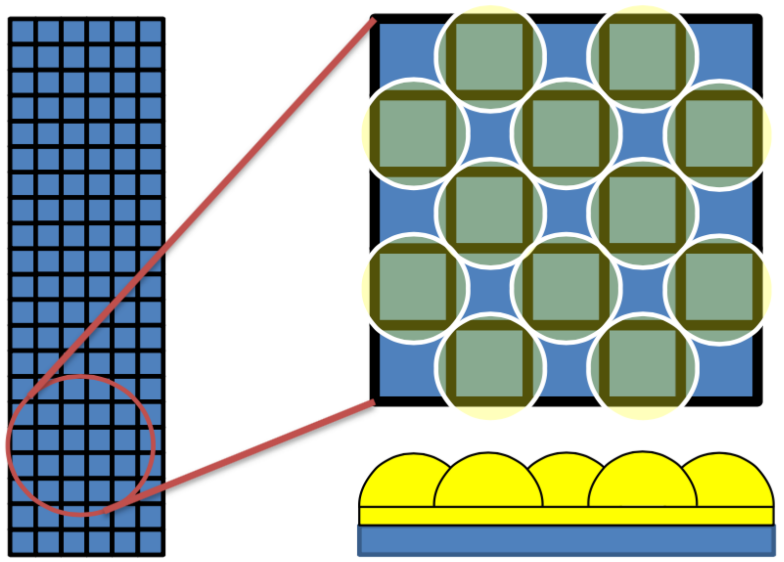
Less light, can work with cryogenic cooling



Micro-lens enhanced SiPMs

Reduce pixel size without loosing light to reduce optical x-talk, gain and therefore bias current, dead time, and dark count rate for irradiated devices

Improve Photon Detection Efficiency by focussing light in the center of the pixel



Improving SiPM Geometrical Field Factor

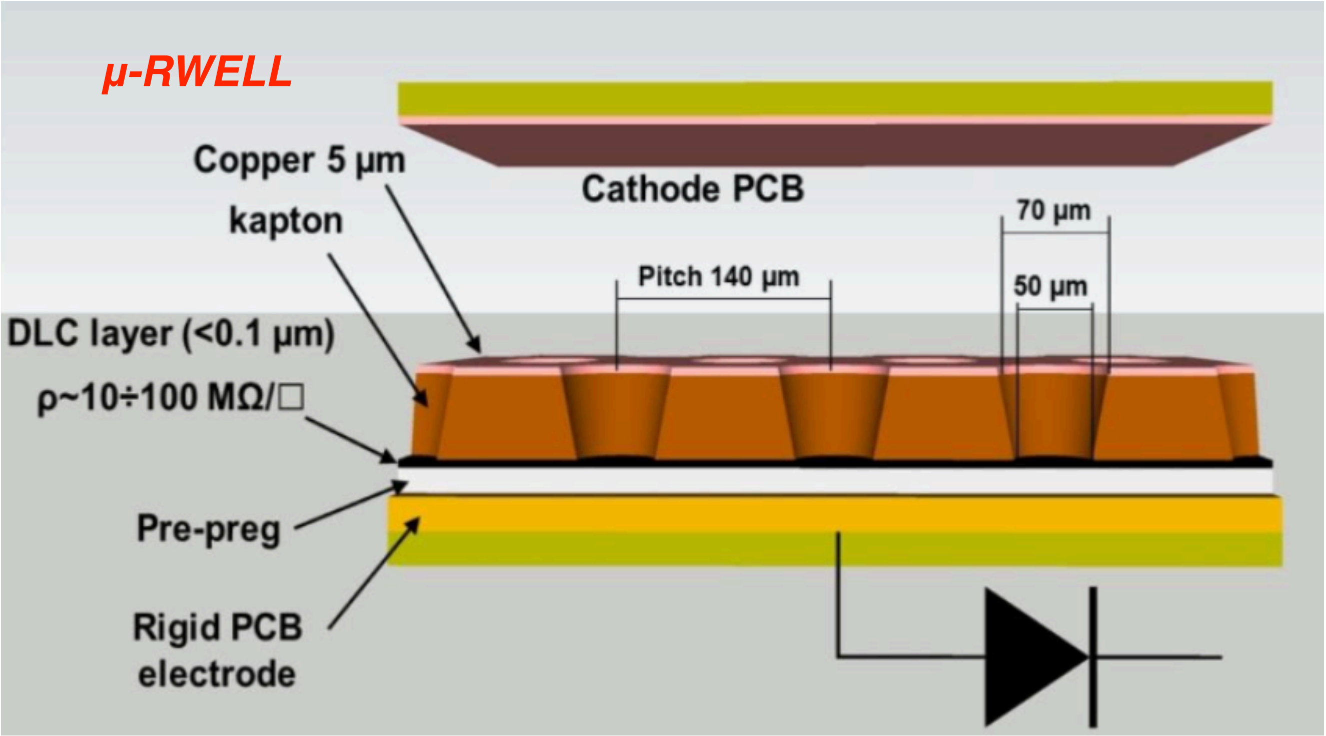
GFF=70% for H2017 62x57.5μm^2 vs GFF>80% for FBK 40x40μm^2

MUON

R&D on MPGD detectors of new generation (μ-RWELL) for the high rate region

Several solutions are being explored for the low rate region: reuse of present MWPC, new RPC chambers, SciTiles

Additional shielding is being designed



TORCH

Quartz modules read by MCPs, time resolution 70-100 ps

Expected to recover PID performances at low momentum, p < 10 GeV/c