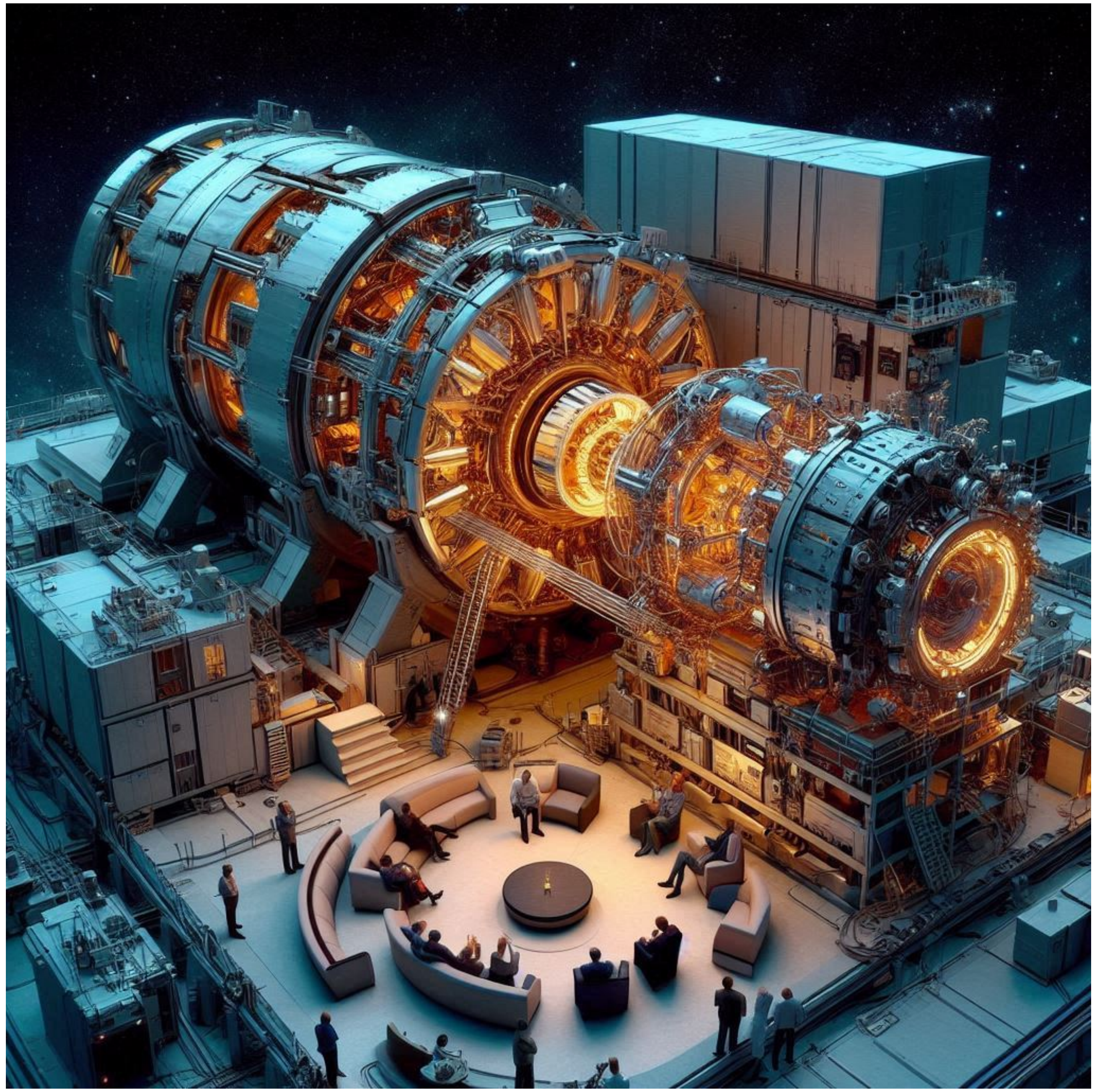
LHCb upgrades and plans



Vladimir V. Gligorov, CNRS/LPNHE/CERN
115th plenary ECFA meeting, CERN, 15.11.2024

LHCb – past, present, and future

Run 1				LS1		Run 2				LS2			Run 3					LS3			Run 4				LS4		Run 5					
2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041
3 fb^{-1}						9 fb^{-1}							23 fb^{-1}								50 fb^{-1}						>300 fb^{-1}					

LHCb – past, present, and future

Run 1	LS1	Run 2	LS2	Run 3	LS3	Run 4	LS4	Run 5
2009 2010 2011 2012	2013 2014	2015 2016 2017 2018	2019 2020 2021	2022 2023 2024 2025 2026	2027 2028 2029	2030 2031 2032 2033	2034 2035	2036 2037 2038 2039 2040 2041
3 fb^{-1}		9 fb^{-1}		23 fb^{-1}		50 fb^{-1}		>300 fb^{-1}

It works! Concept of forward flavour detector validated, many world-best measurements

LHCb – past, present, and future

Align and calibrate detector in quasi-real time, full detector reconstruction and pileup suppression in trigger

Run 1				LS1		Run 2				LS2			Run 3					LS3			Run 4				LS4		Run 5					
2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041
3 fb^{-1}						9 fb^{-1}							23 fb^{-1}								50 fb^{-1}						>300 fb^{-1}					

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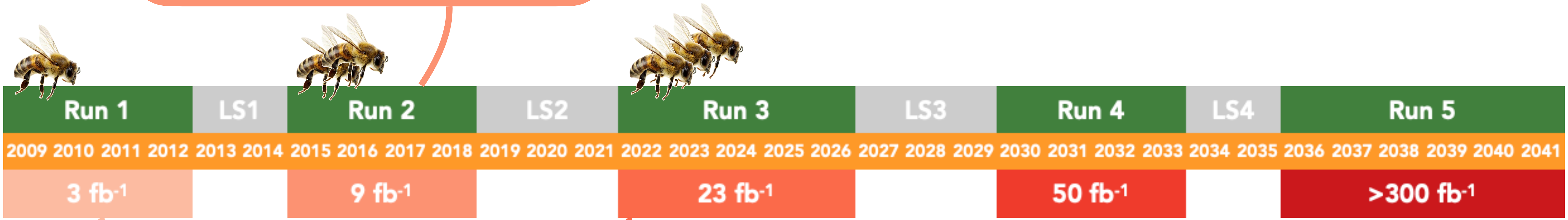

Run 1	LS1	Run 2	LS2	Run 3	LS3	Run 4	LS4	Run 5
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Greatly improved tracker & PID granularity, 30 MHz detector readout & GPU tracking trigger

LHCb – past, present, and future

Align and calibrate detector in quasi-real time, full detector reconstruction and pileup suppression in trigger

Enhance PID with precise timing and improved granularity, explore enhanced readout boards with fast tracking

Run 1	LS1	Run 2	LS2	Run 3	LS3	Run 4	LS4	Run 5
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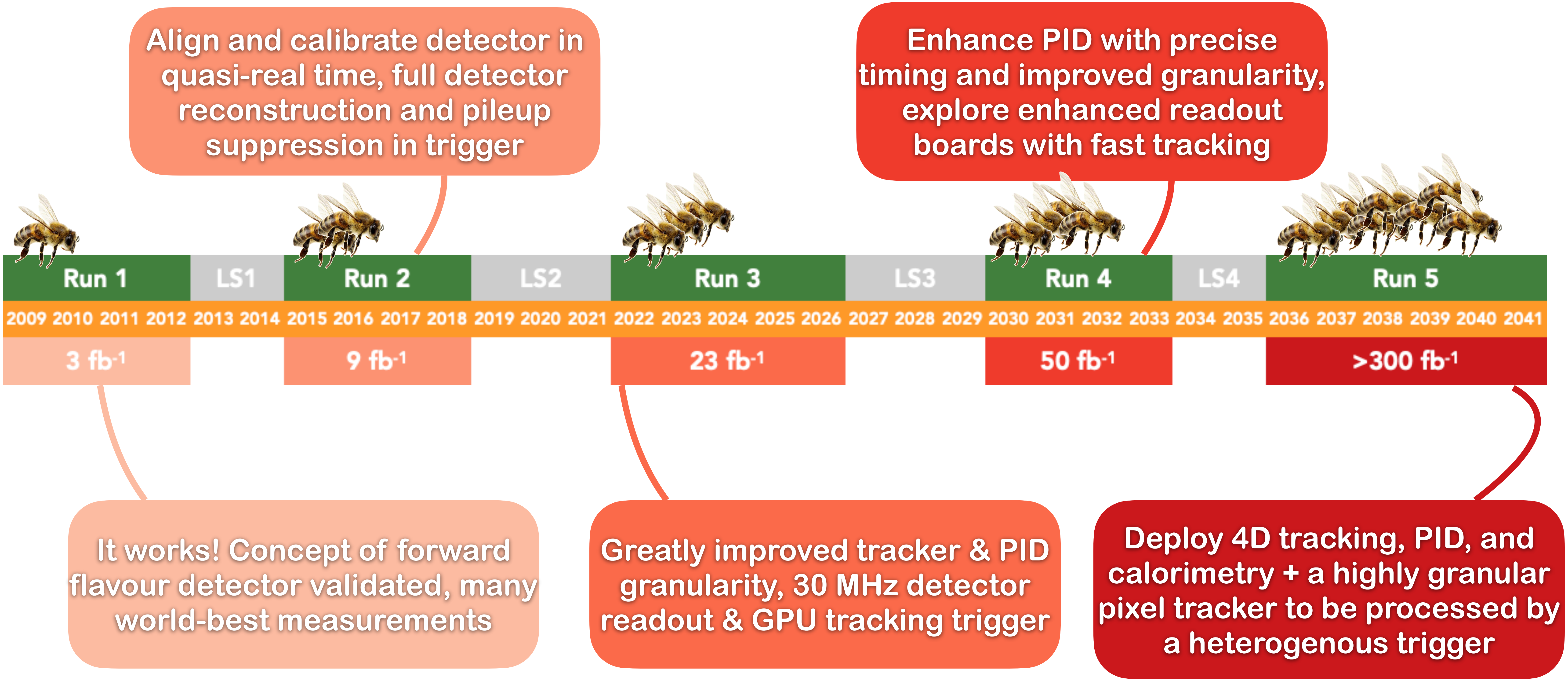
LHCb – past, present, and future



Align and calibrate detector in quasi-real time, full detector reconstruction and pileup suppression in trigger

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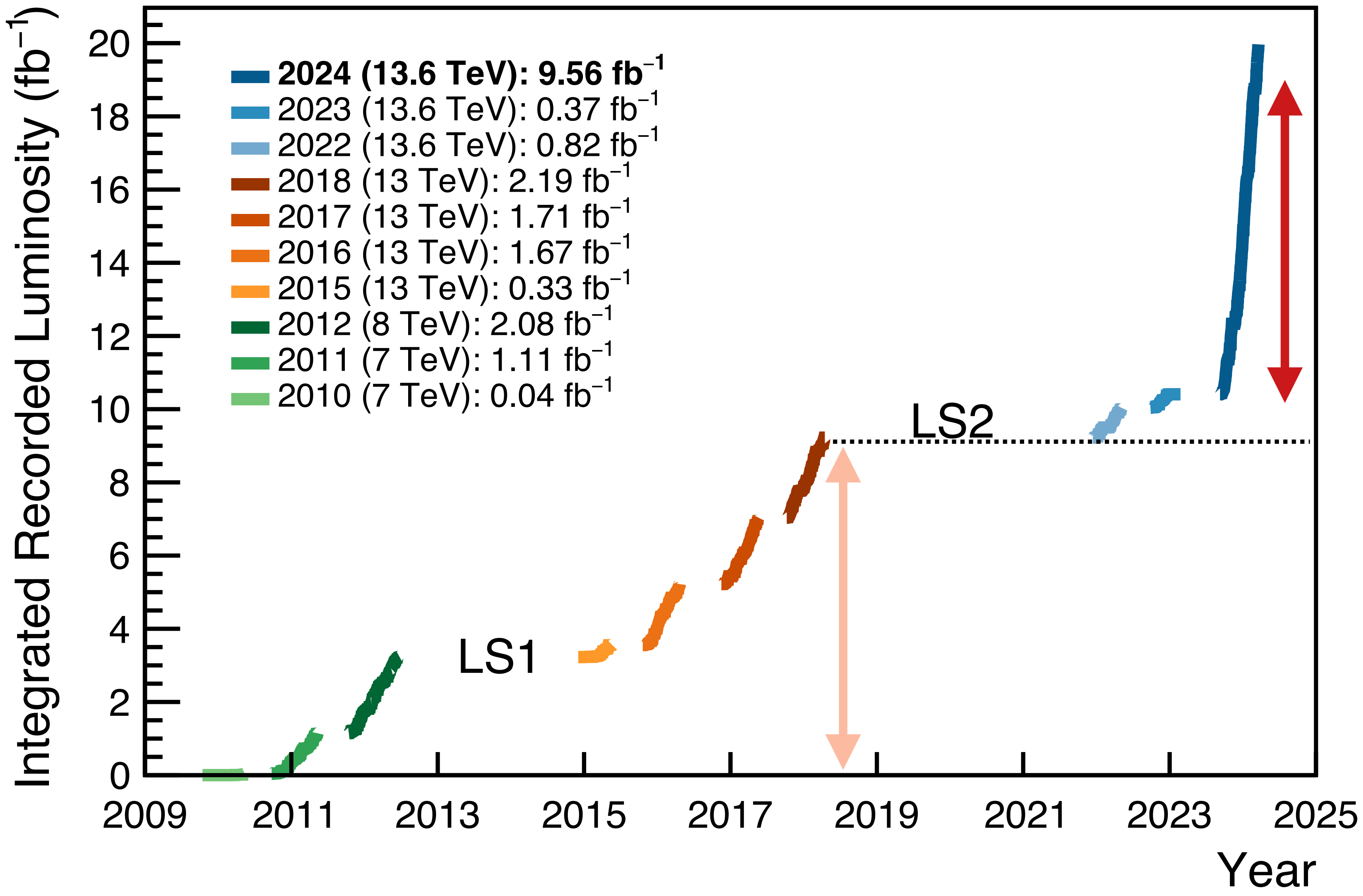
It works! Concept of forward flavour detector validated, many world-best measurements

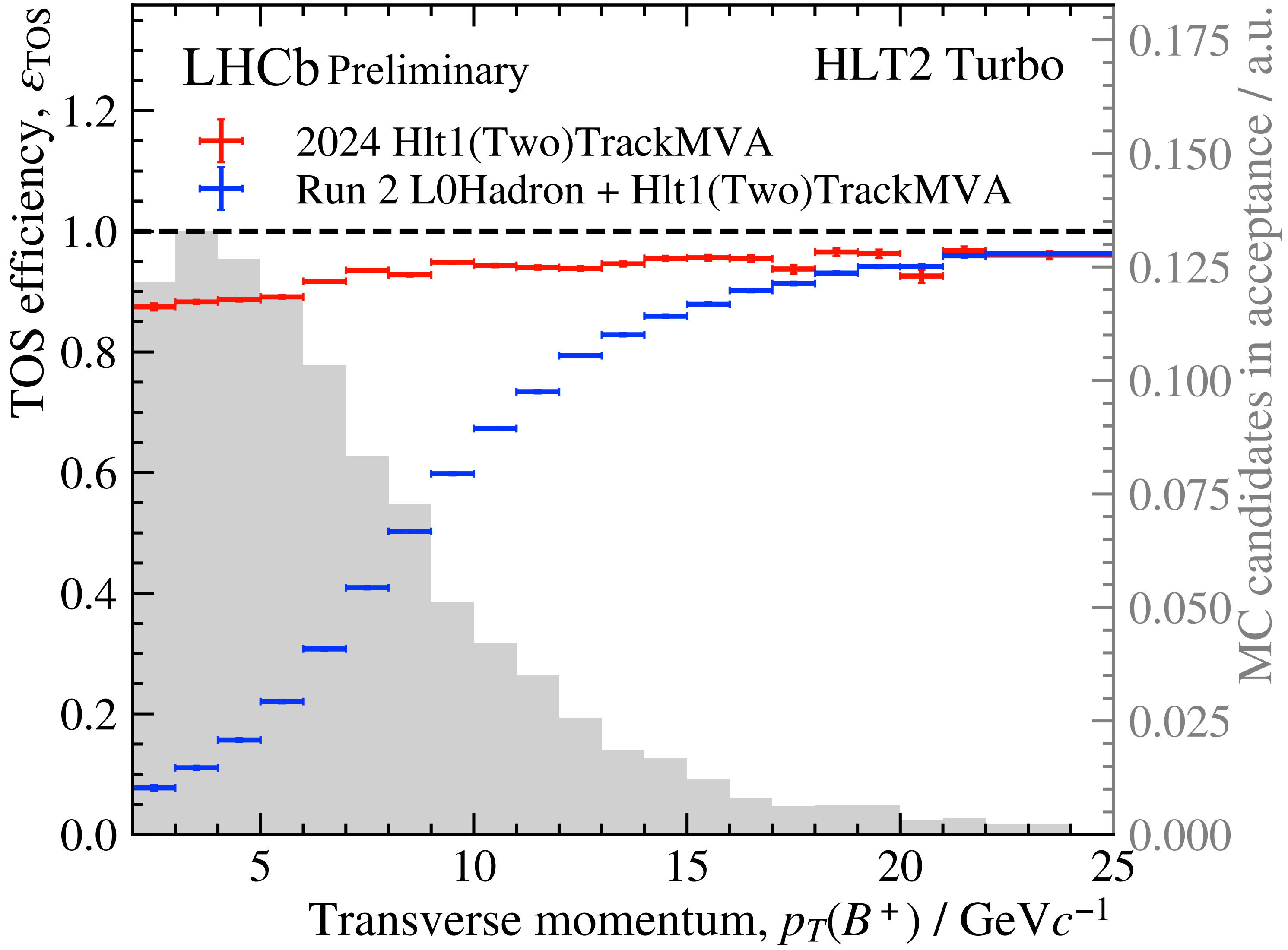
Greatly improved tracker & PID granularity, 30 MHz detector readout & GPU tracking trigger

Deploy 4D tracking, PID, and calorimetry + a highly granular pixel tracker to be processed by a heterogenous trigger

LHCb in 2024: twice doubled data



LHCb-FIGURE-2024-030



Doubled the recorded integrated luminosity thanks to excellent detector&LHC performance

More than doubled the efficiency for hadronic signals thanks to 30 MHz GPU tracking trigger

LHCb prospects for Run 3

Observable	**Old LHCb** (up to $9\,\text{fb}^{-1}$)		**LHCb U1** ($23\,\text{fb}^{-1}$)
<u>CKM tests</u>			
γ ($B \to DK$, *etc.*)	2.8°	[18, 19]	1.3°
ϕ_s ($B_s^0 \to J/\psi\phi$)	20 mrad	[22]	12 mrad
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$, *etc.*)	6%	[55, 56]	3%
<u>Charm</u>			
ΔA_{CP} ($D^0 \to K^+K^-, \pi^+\pi^-$)	29×10^{-5}	[25]	13×10^{-5}
A_Γ ($D^0 \to K^+K^-, \pi^+\pi^-$)	11×10^{-5}	[29]	5×10^{-5}
Δx ($D^0 \to K_S^0\pi^+\pi^-$)	18×10^{-5}	[57]	6.3×10^{-5}
<u>Rare decays</u>			
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	69%	[30, 31]	41%
$S_{\mu\mu}$ ($B_s^0 \to \mu^+\mu^-$)	—		—
$A_{\mathrm{T}}^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[58]	0.060
$S_{\phi\gamma}(B_s^0 \to \phi\gamma)$	0.32	[59]	0.093
$\alpha_\gamma(\Lambda_b^0 \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$	[60]	0.148

Beyond-luminosity-scaling improvements in sensitivity expected in many observables due to the full detector readout and 30 MHz tracking trigger

Thanks to a new automated analysis production system terabytes of physics-ready ntuples are already being analysed across the working groups – prepare your spoons!

LHCb prospects for Run 3

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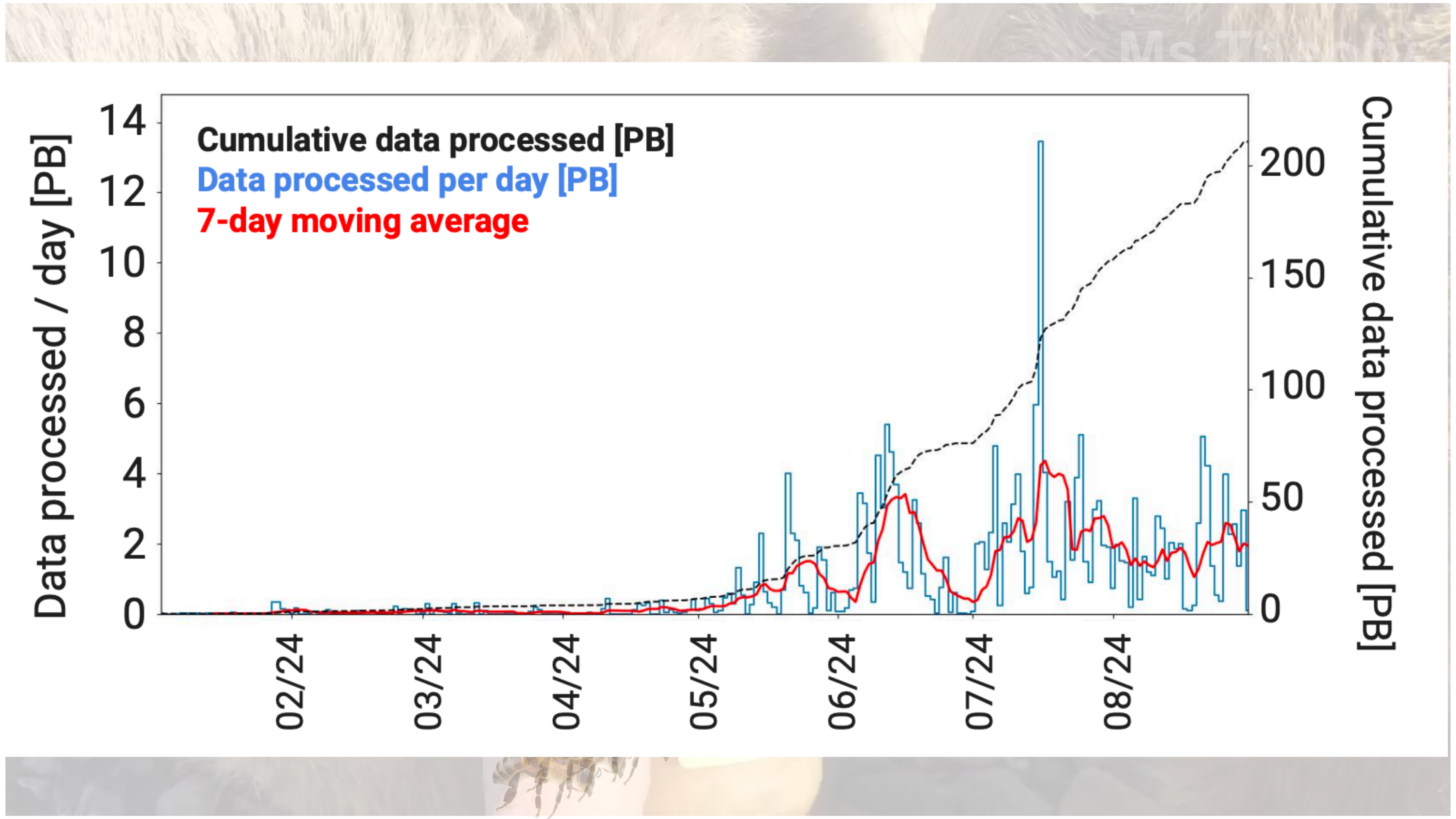

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LHCb prospects for Run 3

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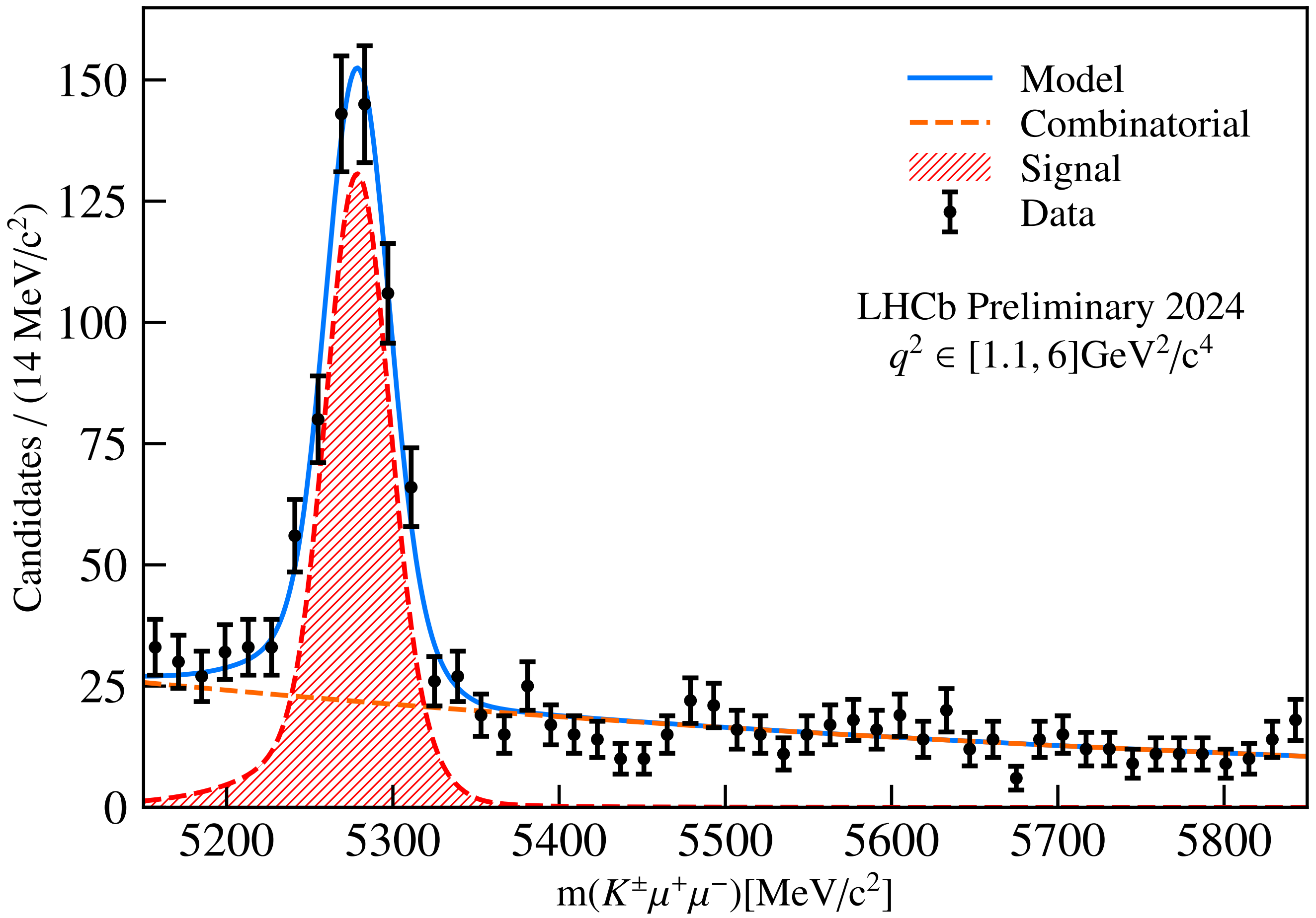

Beyond-luminosity-scaling improvements in sensitivity expected in many observables due to the full detector readout and 30 MHz tracking trigger

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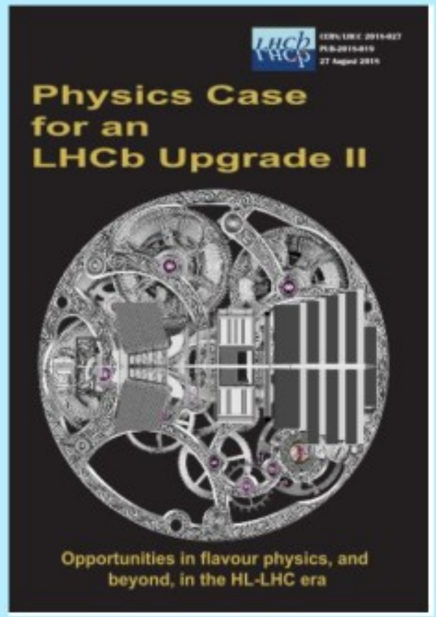
Why another LHCb upgrade?

EoI

LHCC-2017-003

Physics case



LHCC-2018-027

Accelerator study CERN-ACC-2018-038

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 2020

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

Framework TDR

LHCC-2021-012

Detector design and technology options

R&D program and schedule

Cost for baseline, options for descoping

National interests

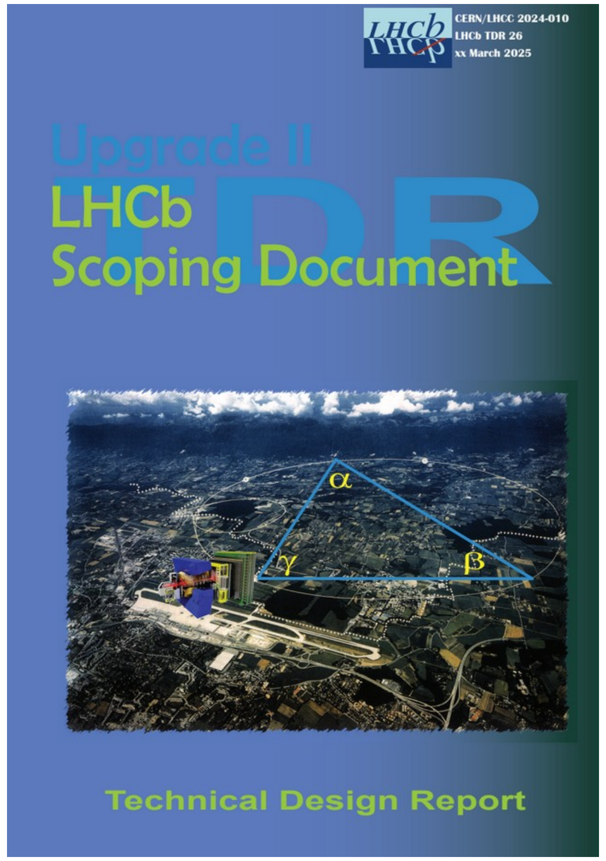
Approved by LHCC March 2022

"The **LHCC recommends** that LHCb continue the R&D necessary to complete technical design reports on the proposed schedule, …"

"The **LHCC recommends** the continued investigation of descoping and other cost-saving possibilities. …"

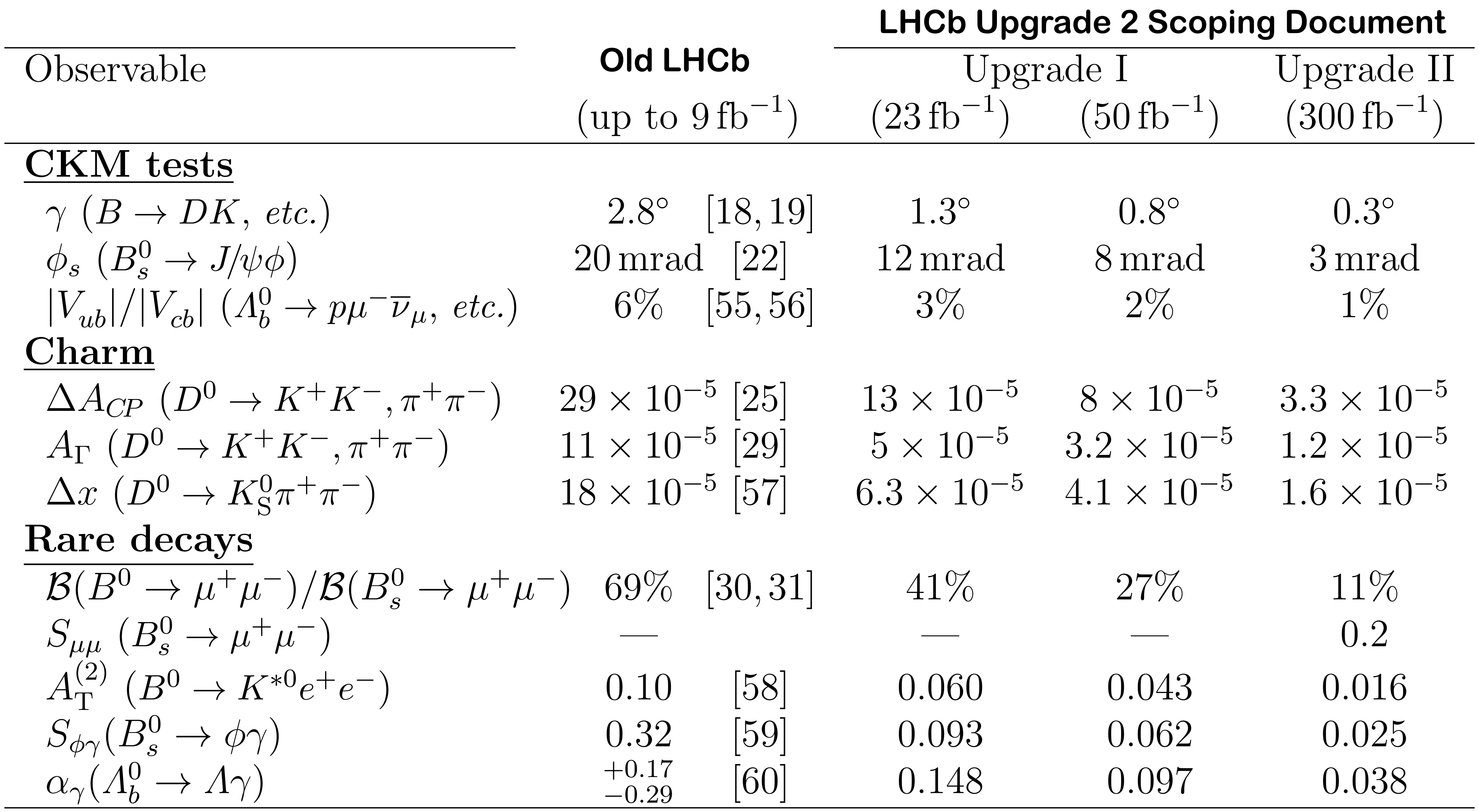
"The **LHCC recommends** that a well-defined process to establish the financial envelope prior to the preparation of TDRs be set up and notes that close coordination with funding agencies will likely be required in this process.

Scoping document



Submitted to LHCC
(Sept 2024)
Under review

Why another LHCb upgrade?



Observable	**Old LHCb**		**LHCb Upgrade 2 Scoping Document**		
			Upgrade I		Upgrade II
	(up to $9\,\mathrm{fb}^{-1}$)		($23\,\mathrm{fb}^{-1}$)	($50\,\mathrm{fb}^{-1}$)	($300\,\mathrm{fb}^{-1}$)
CKM tests					
γ ($B \to DK$, *etc.*)	2.8°	[18, 19]	1.3°	0.8°	0.3°
ϕ_s ($B_s^0 \to J/\psi\phi$)	20 mrad	[22]	12 mrad	8 mrad	3 mrad
$\vert V_{ub}\vert/\vert V_{cb}\vert$ ($\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$, *etc.*)	6%	[55, 56]	3%	2%	1%
Charm					
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A_Γ ($D^0 \to K^+K^-, \pi^+\pi^-$)	11×10^{-5}	[29]	5×10^{-5}	3.2×10^{-5}	1.2×10^{-5}
Δx ($D^0 \to K_S^0\pi^+\pi^-$)	18×10^{-5}	[57]	6.3×10^{-5}	4.1×10^{-5}	1.6×10^{-5}
Rare decays					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	69%	[30, 31]	41%	27%	11%
$S_{\mu\mu}$ ($B_s^0 \to \mu^+\mu^-$)	—		—	—	0.2
$A_{\mathrm{T}}^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[58]	0.060	0.043	0.016
$S_{\phi\gamma}(B_s^0 \to \phi\gamma)$	0.32	[59]	0.093	0.062	0.025
$\alpha_\gamma(\Lambda_b^0 \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$	[60]	0.148	0.097	0.038

Key precision observables remain statistically limited + unique reach for ions, baryons & exotic hadrons

After showing that systematics scale with luminosity in Run 3 – aim to build the best quality U2 detector!

Why another LHCb upgrade?

Observable	Current LHCb (up to 9 fb^{-1})		Upgrade I (23 fb^{-1})	(50 fb^{-1})	Upgrade II (300 fb^{-1})
CKM tests					
$A_T(B^0 \to K^{*0}e^+e^-)$	0.10	[58]	0.060	0.043	0.016
$S_{\phi\gamma}(B_s^0 \to \phi\gamma)$	0.32	[59]	0.093	0.062	0.025
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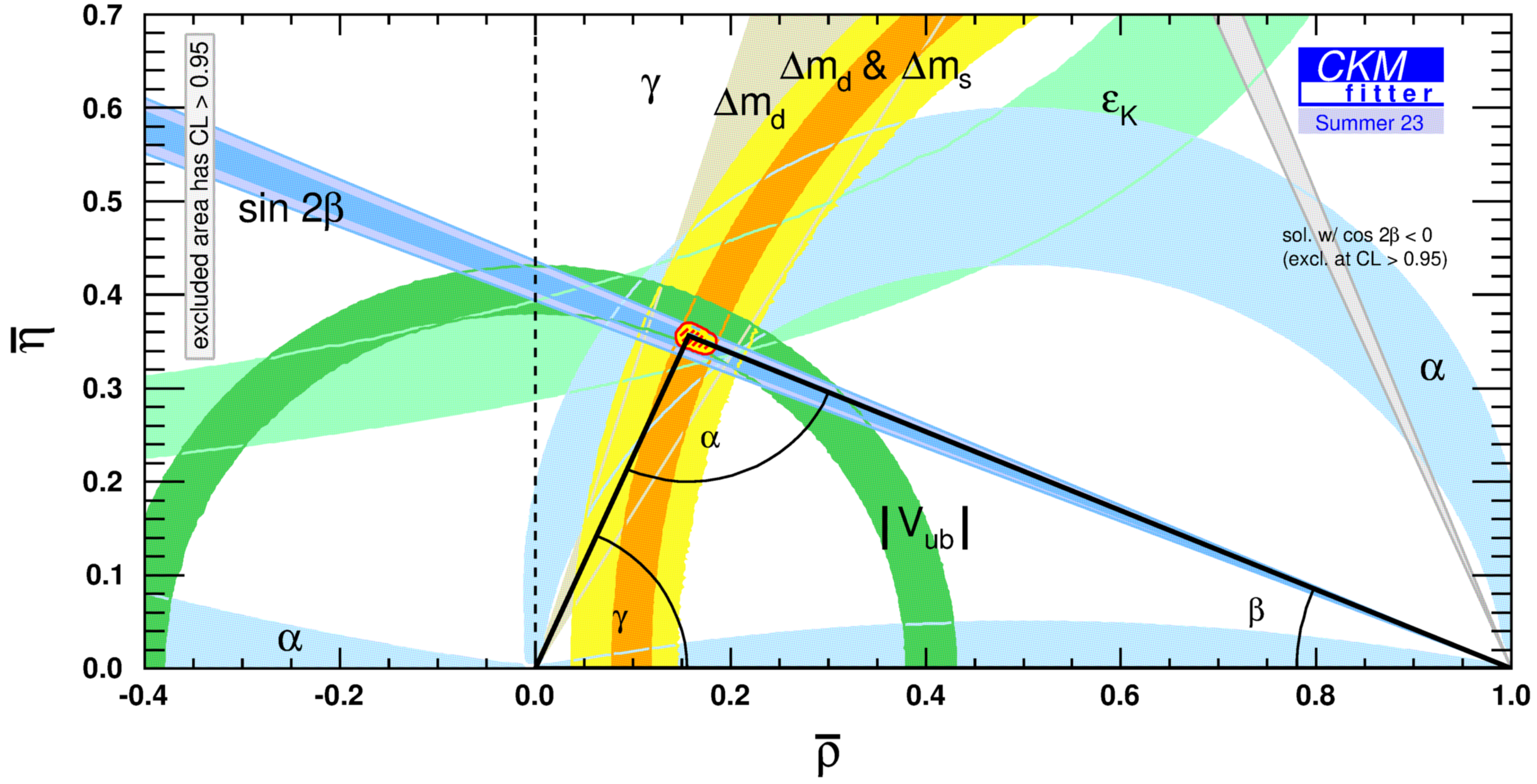
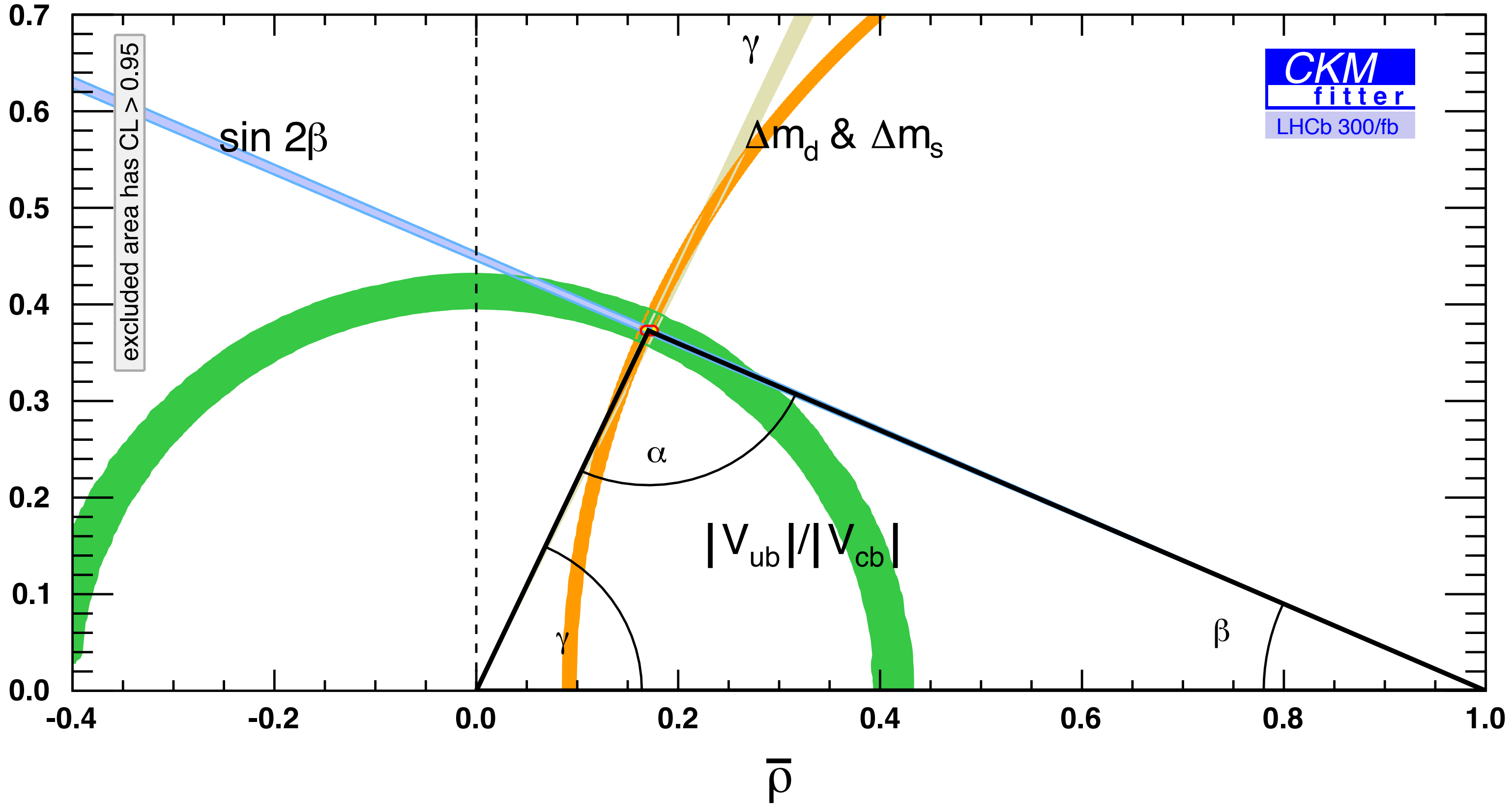
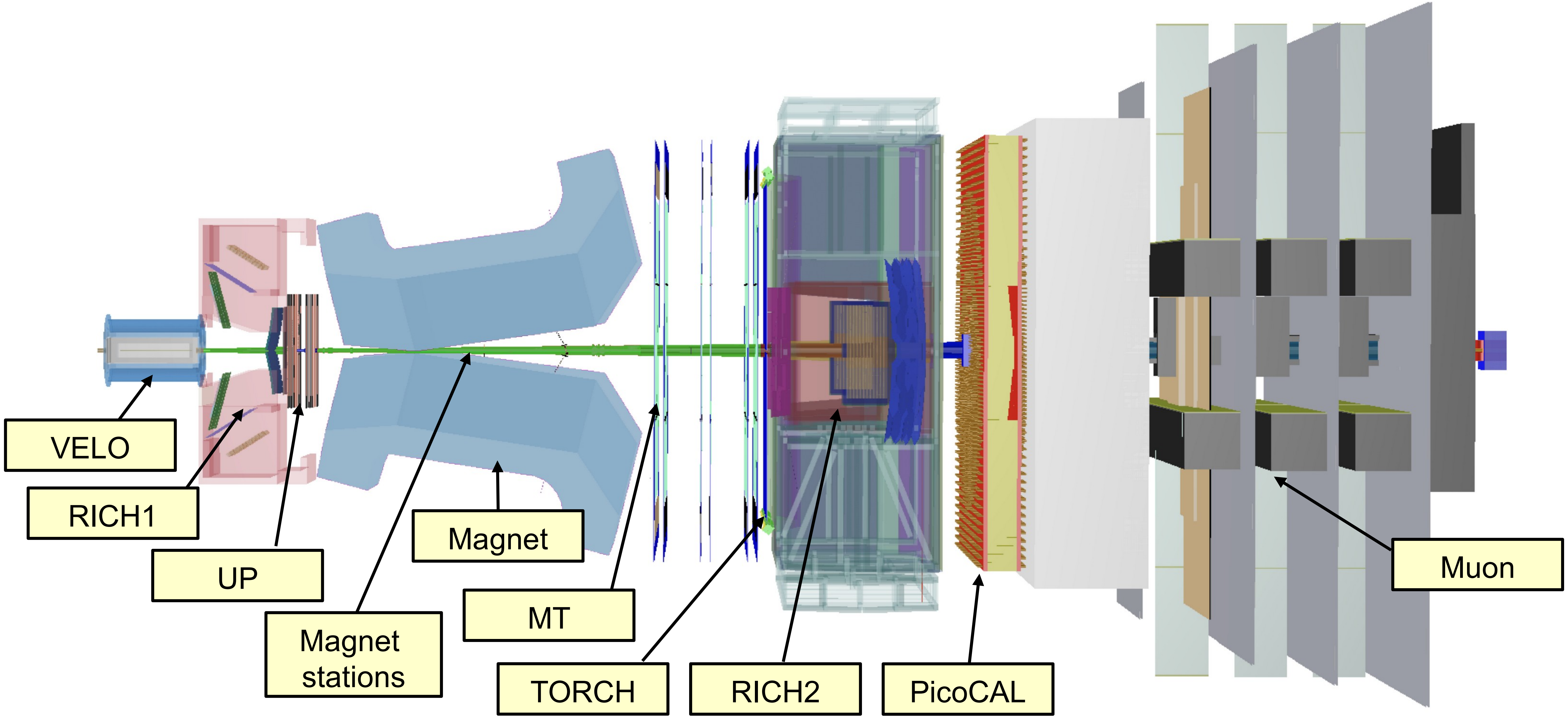


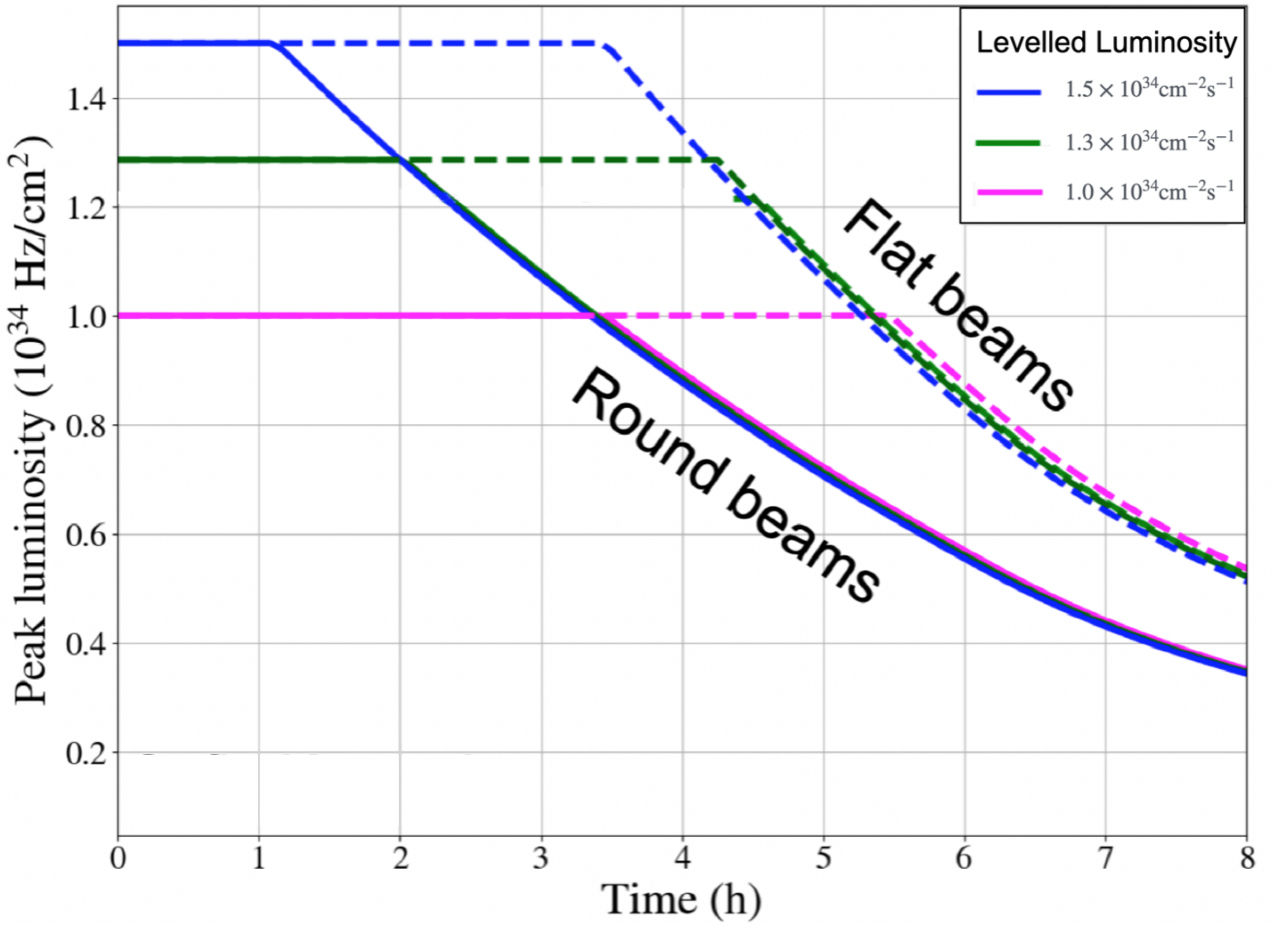


LHCb Upgrade 2 detector layout



LHCb Upgrade 2 luminosity scenarios

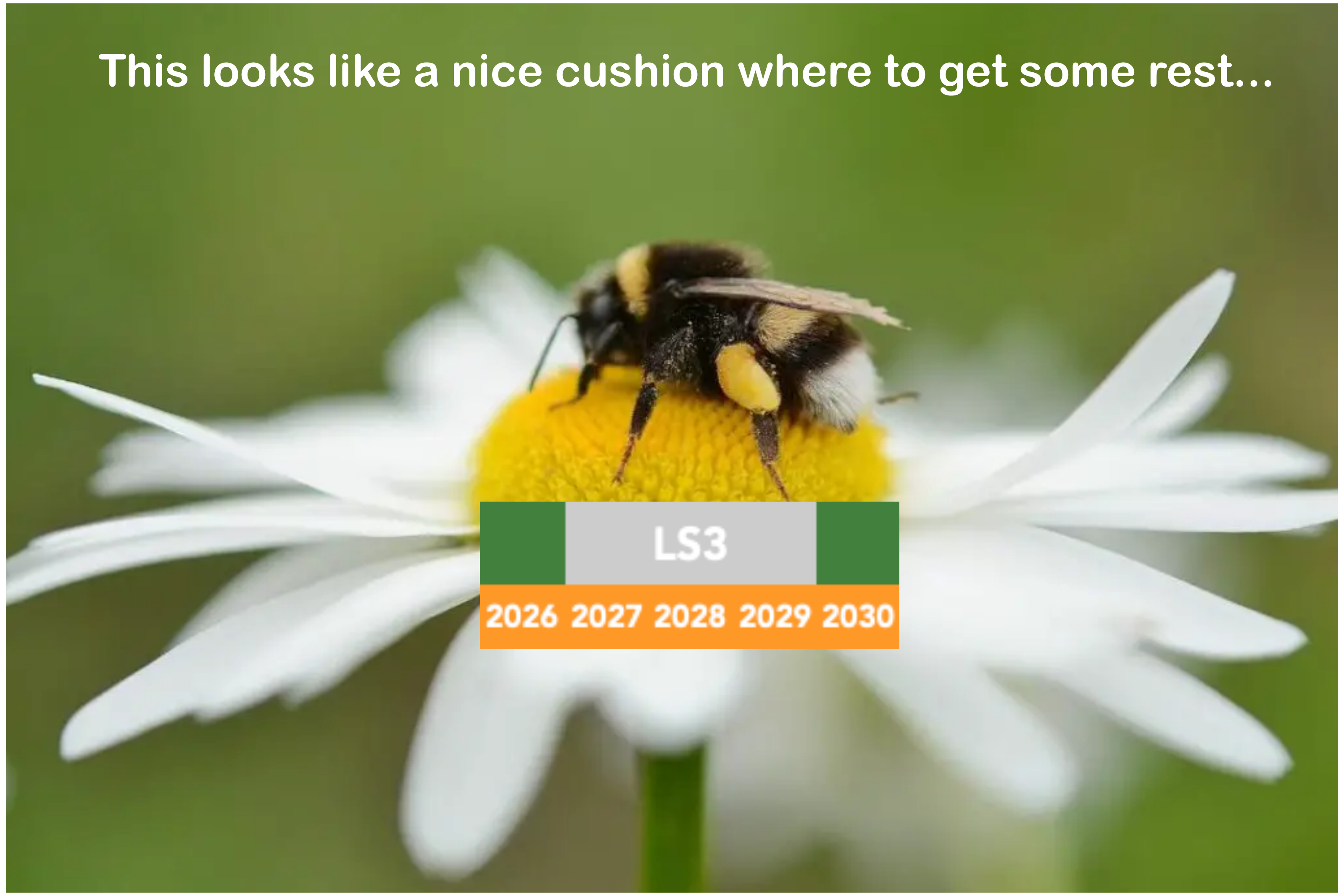
	Round optics			Flat optics		
Levelled $\mathcal{L}_{\text{peak}}$ $(10^{34}\,\text{cm}^{-2}\,\text{s}^{-1})$	1.0	1.3	1.5	1.0	1.3	1.5
β_x^*/β_y^* (m)	1.5/1.5			0.5/1.5		
N_{bunch} total/colliding in LHCb	2760/2574			2760/2574		
Levelled pile-up	28	36	42	28	36	42
Delivered $\mathcal{L}_{\text{int}}$ per year (fb^{-1})	42.16	47.25	49.34	48.73	57.89	63.36
Levelling time t_{lev} (h)	3.42	2.00	1.08	5.42	4.25	3.42
Optimal fill length t_{opt} (h)	7.67	7.58	7.58	7.58	7.50	7.42
$t_{\text{lev}}/t_{\text{opt}}$	0.45	0.26	0.14	0.72	0.57	0.46
RMS luminous region (z) at $t = 0$ (mm)	43.30	43.31	43.31	38.41	38.44	38.45
Peak pile-up density at $t = 0$ (mm^{-1})	0.29	0.35	0.40	0.41	0.49	0.54



Many thanks to our LHC machine colleagues for their hard work and support!
Looking forward to the results of machine tests to understand if flat optics are feasible.

Why enhance LHCb during LS3?

1. Calorimeter radiation damage must be addressed – use this opportunity to improve instead of standing still
2. We know precision timing is mandatory for U2 physics performance: exercise as much of this as possible in LS3 so we can learn any lessons long before Run 5
3. We must nurture and develop a team with the right mixture of skills to master heterogeneous computing architectures of the 2030s. This is best done through concrete incremental work.


This looks like a nice cushion where to get some rest...

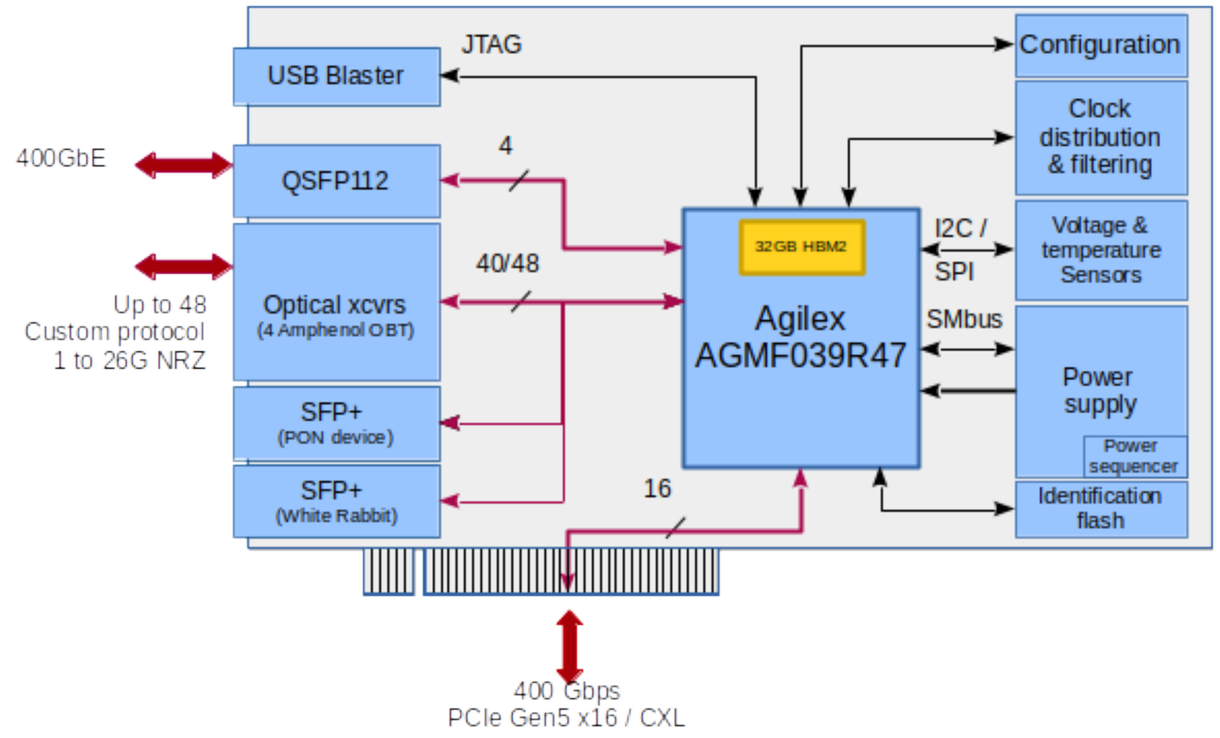
And of course seize any opportunity to improve the physics sensitivity of Run 4!

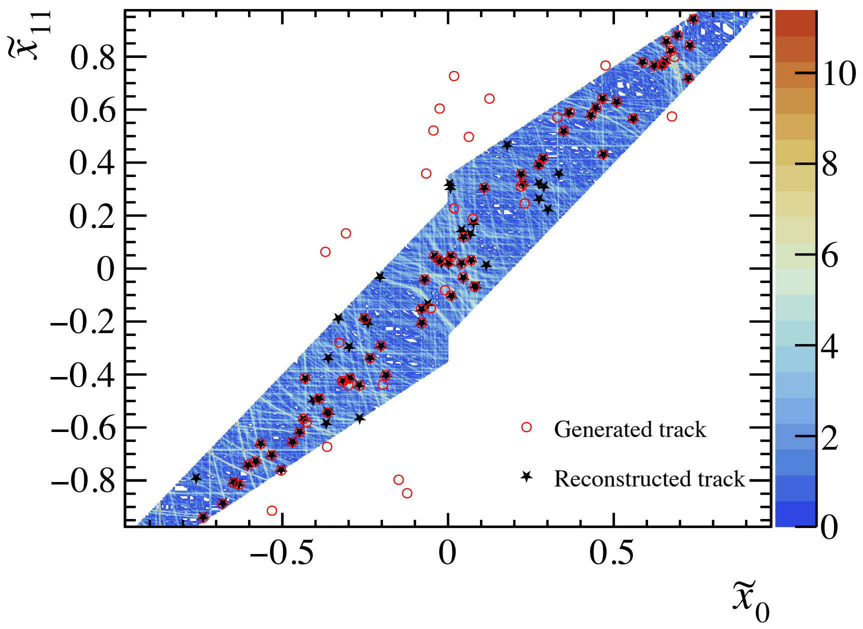
LS3 enhancements: data acquisition

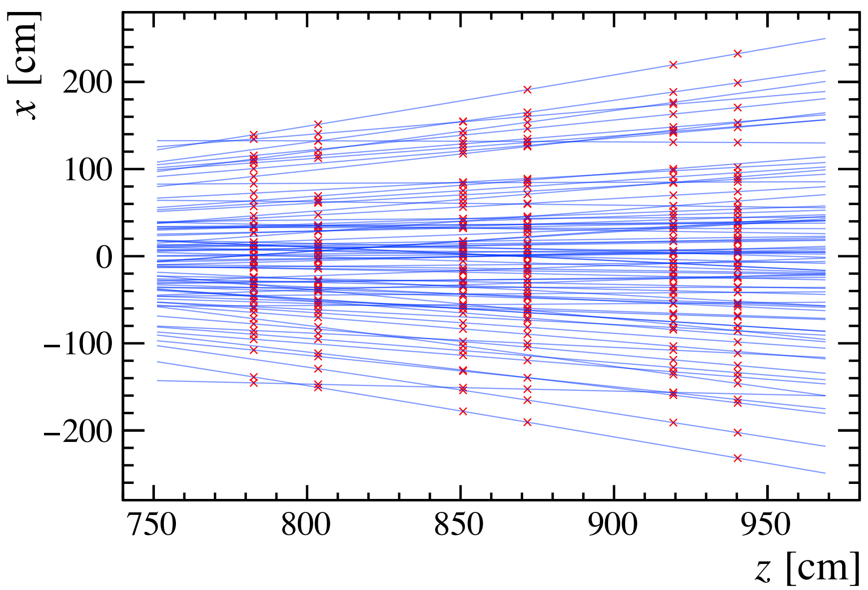
The aim is to exercise the following features ahead of Run 5

1. **Clock distribution with jitter and deterministic phase of O(10) ps**
2. **The usage of lpGBT links**
3. **The usage of very high speed links running at 100Gbit/s using data-centre protocols like Ethernet 400 or PCIe Gen5**
4. **Creation and use of reconstruction primitives embedded within the readout, with potential gains for triggering already in Run 4.**

LHCb data acquisition enhancements TDR

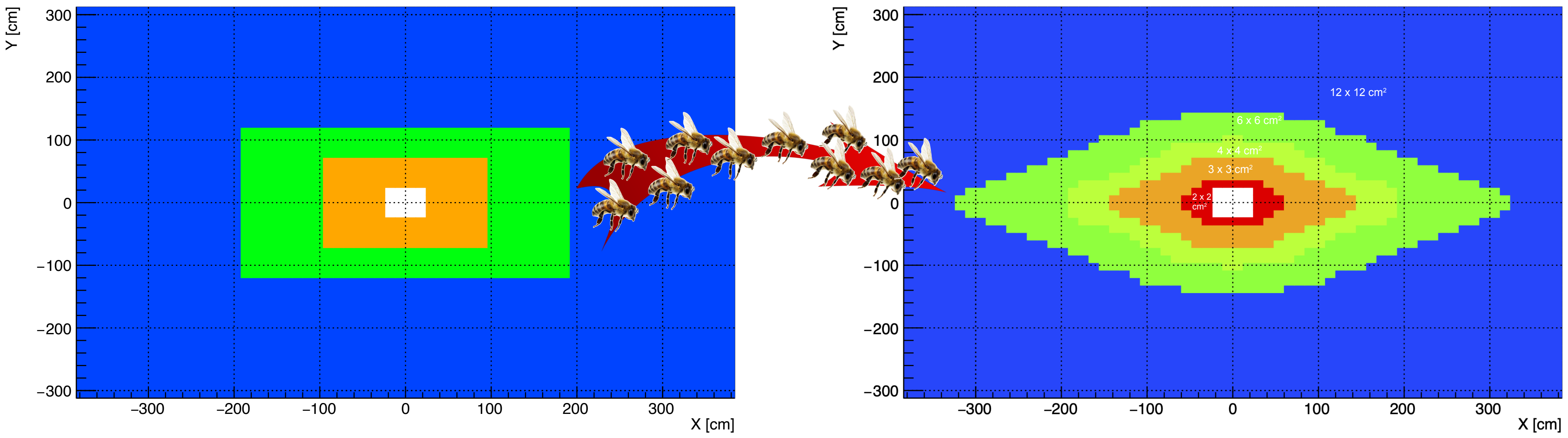


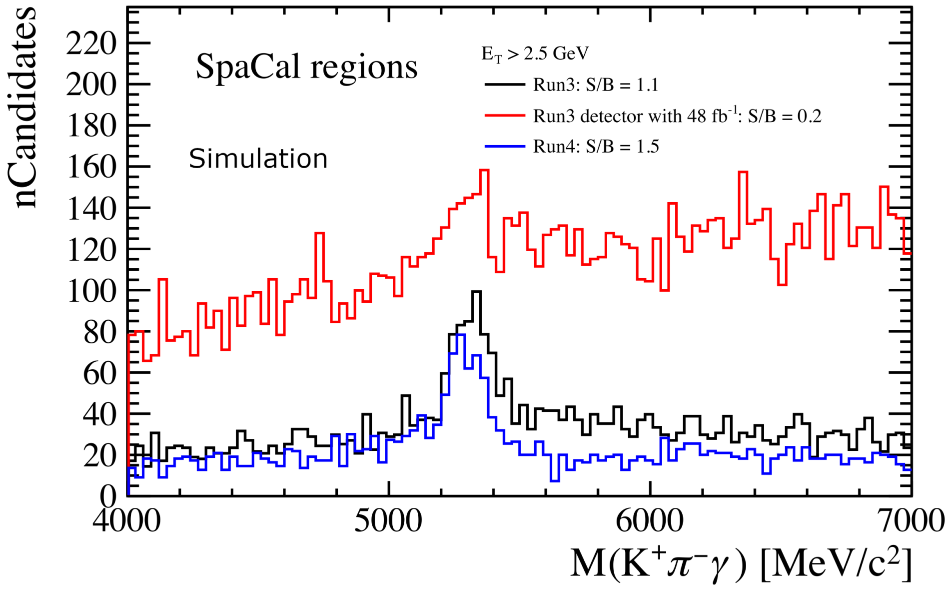


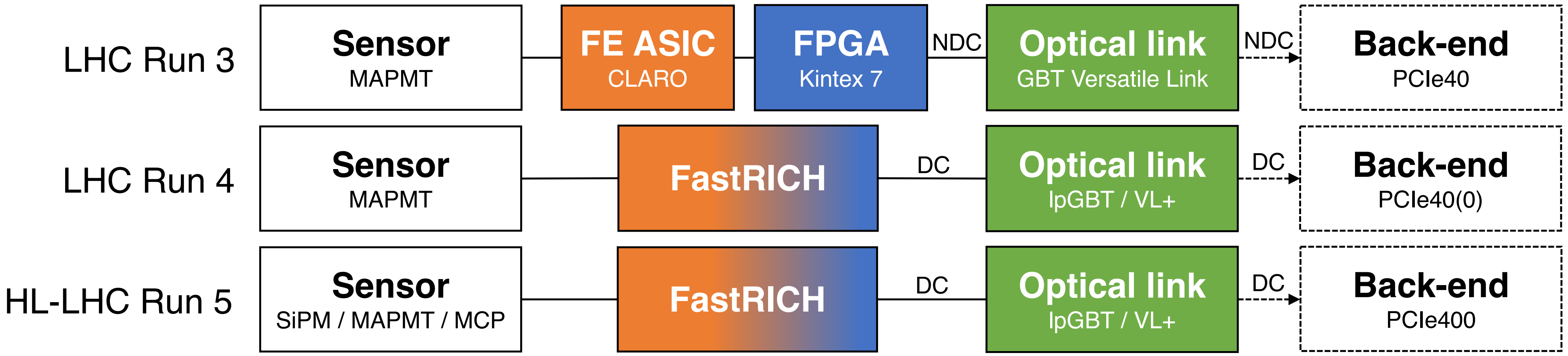


General architecture of online + DAQ system remains unchanged for Run 4

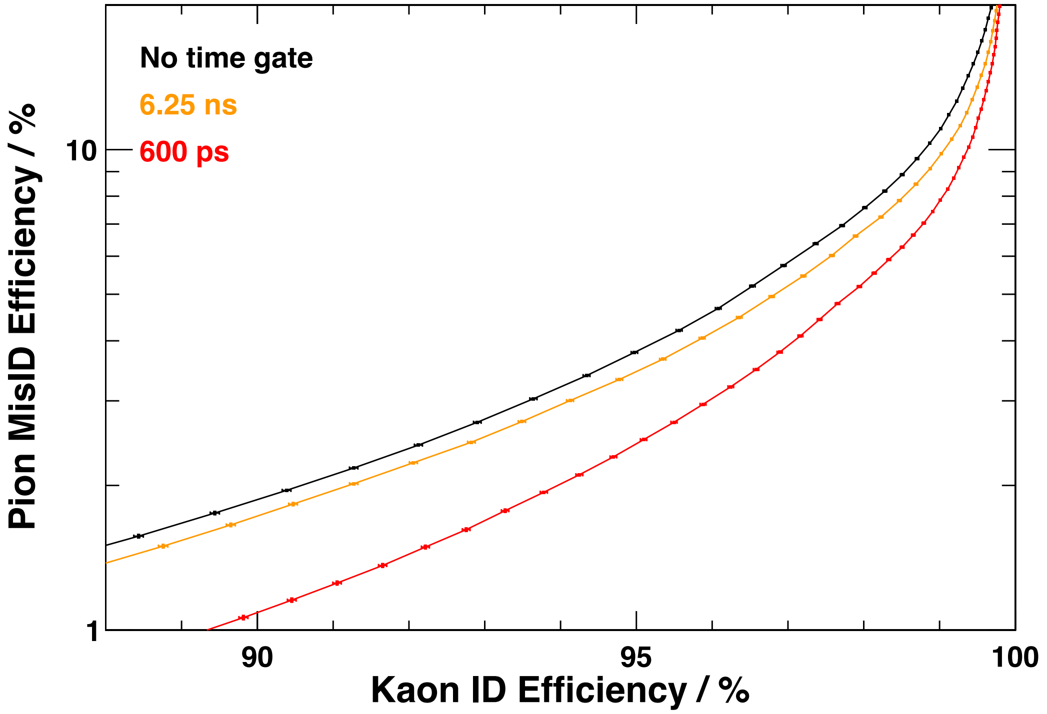
LS3 enhancements: particle identification







LHC Run 3	**Sensor** MAPMT	**FE ASIC** CLARO	**FPGA** Kintex 7	NDC **Optical link** GBT Versatile Link	NDC **Back-end** PCIe40
LHC Run 4	**Sensor** MAPMT	**FastRICH**		DC **Optical link** lpGBT / VL+	DC **Back-end** PCIe40(0)
HL-LHC Run 5	**Sensor** SiPM / MAPMT / MCP	**FastRICH**		DC **Optical link** lpGBT / VL+	DC **Back-end** PCIe400



LHCb particle identification enhancements TDR

Enhanced calorimeter granularity & SpaCal modules: maintain performance despite radiation damage

Fast timing information in the RICH: improved hadron identification and gain experience for Run 5

LHCb U2: detector scenarios

Three detector scenarios considered

Baseline: ultimate acceptance, granularity, and material budget leading to maximal instantaneous luminosity headroom.

Middle: keeps all subsystems but in some cases reduces their acceptance. Lower instantaneous luminosity leads to significant savings in data processing cost.

Low: worse acceptance, granularity, and material budget depending on the detector. Two detectors fully removed. Highest risk and least robust option.

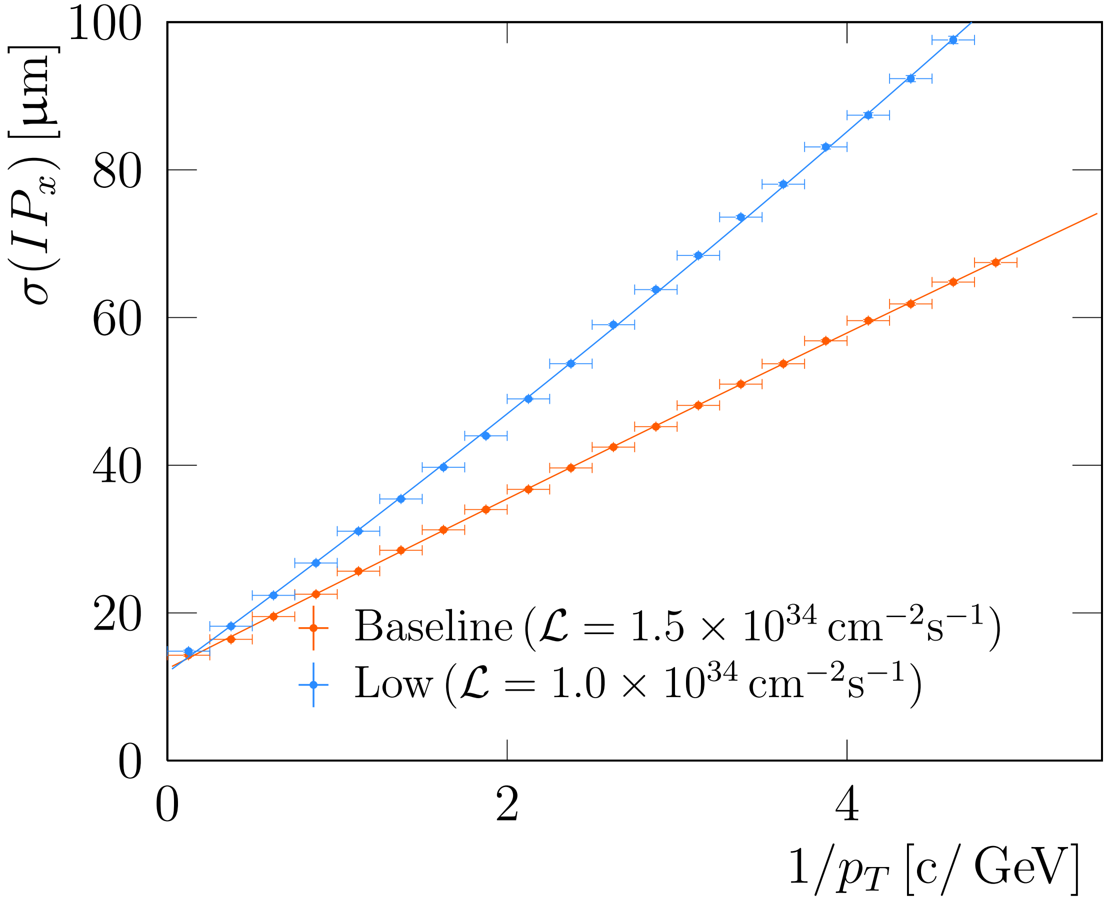
LHCb Upgrade 2 Scoping Document

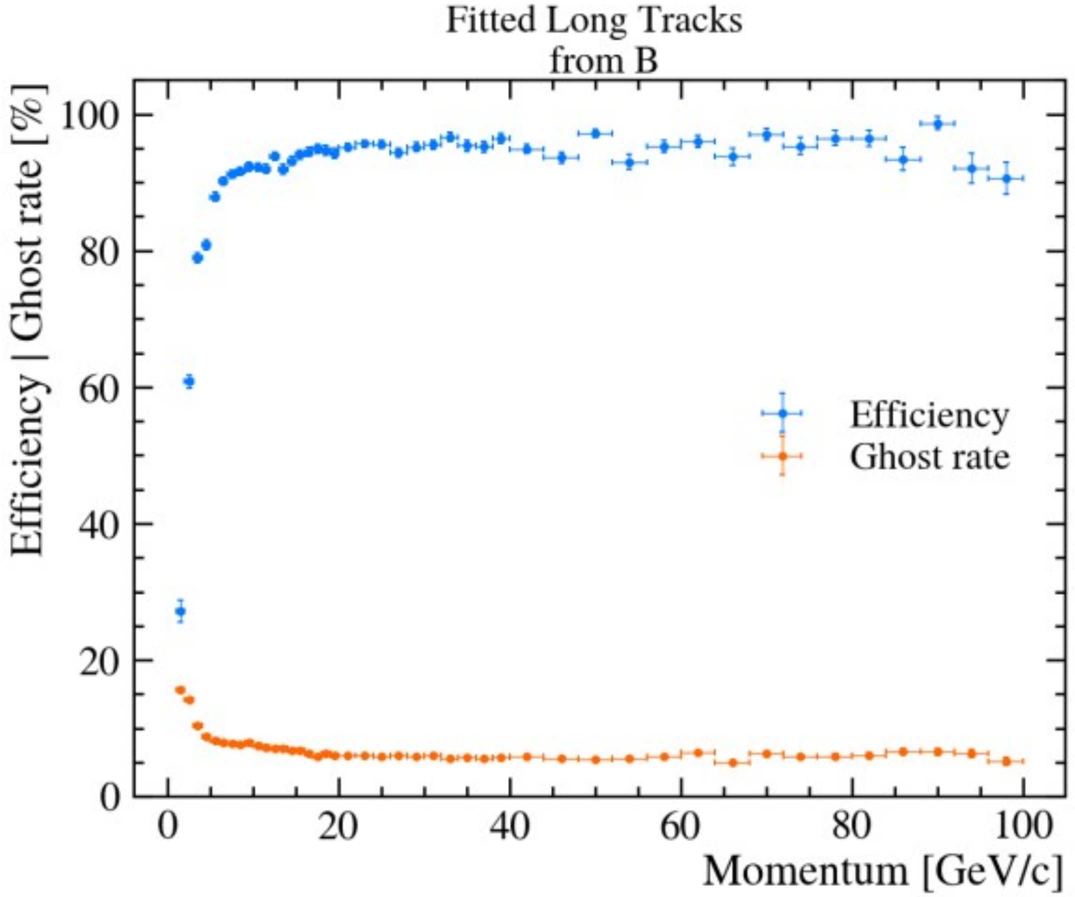
	Baseline	Middle	Low
$\mathcal{L}_{\text{peak}}$ ($10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$)	1.5	1.0	1.0
	(kCHF)	(kCHF)	(kCHF)
VELO	16672	15906	13753
UP	8077	7719	6887
Magnet Stations	2592	2234	0
Mighty-SciFi	21767	21273	17388
Mighty-Pixel	15994	11641	11061
RICH	21450	18415	14794
TORCH	12508	8756	0
PicoCal	27607	27607	21584
Muon	9785	8266	8266
RTA	18800	11700	9500
Online	11800	9467	8993
Infrastructure	14463	13284	12430
Total	181515	156268	124656

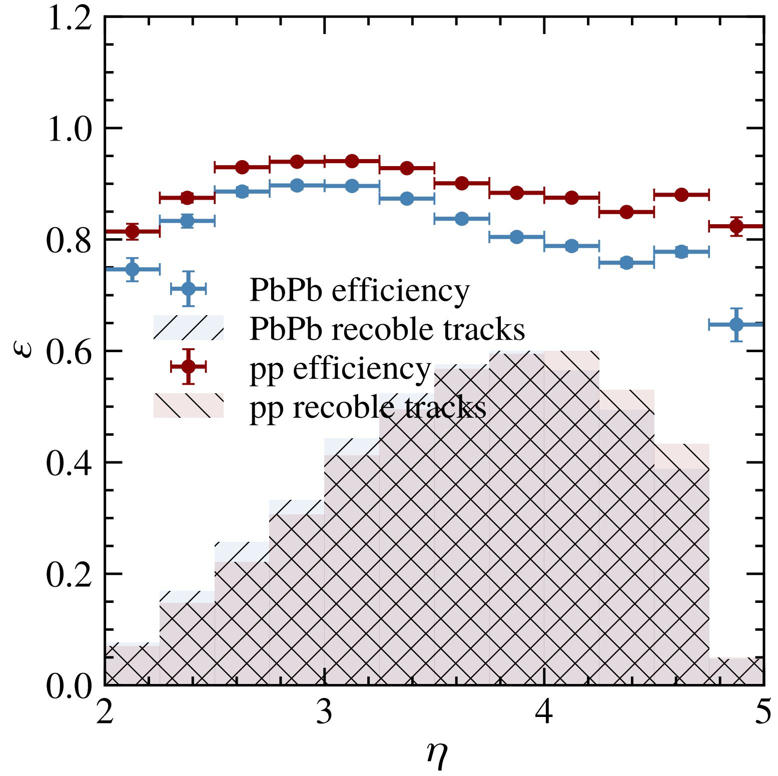
All scenarios meet the core physics goals of Upgrade 2, but low has the least versatility and robustness

LHCb U2: tracking

LHCb Upgrade 2 Scoping Document







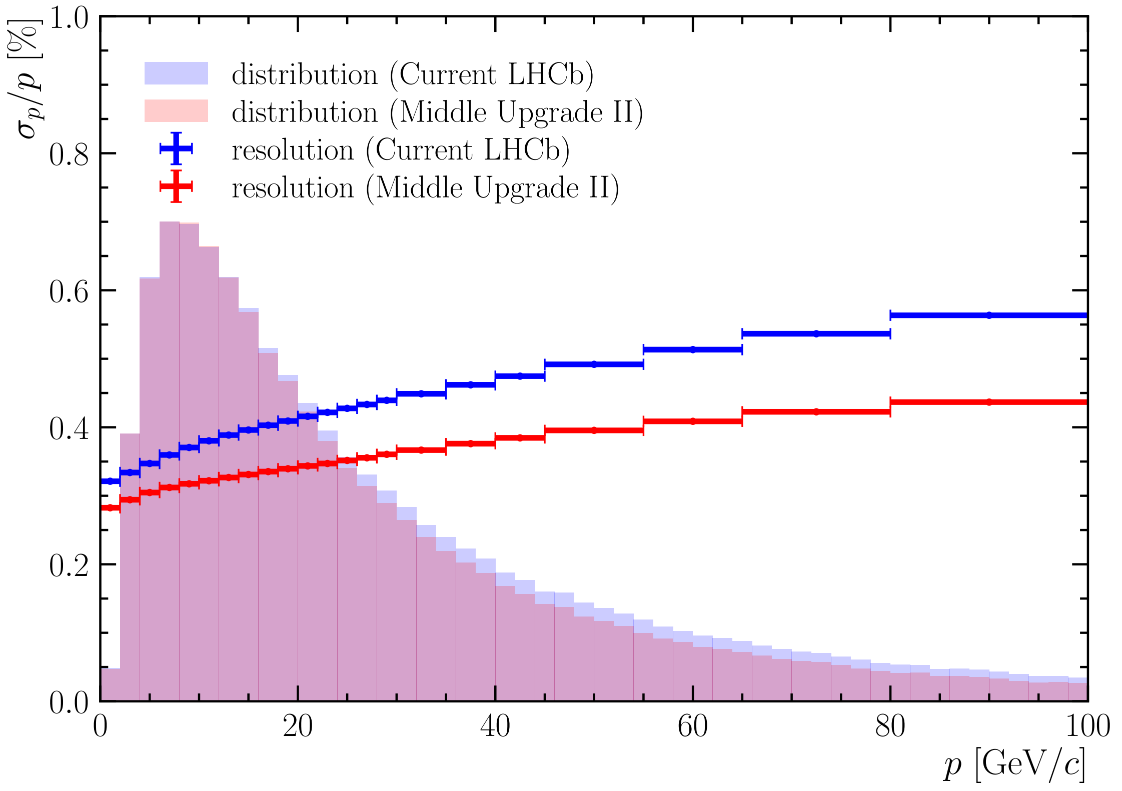
The baseline design ensures high efficiencies with acceptable fake rates!

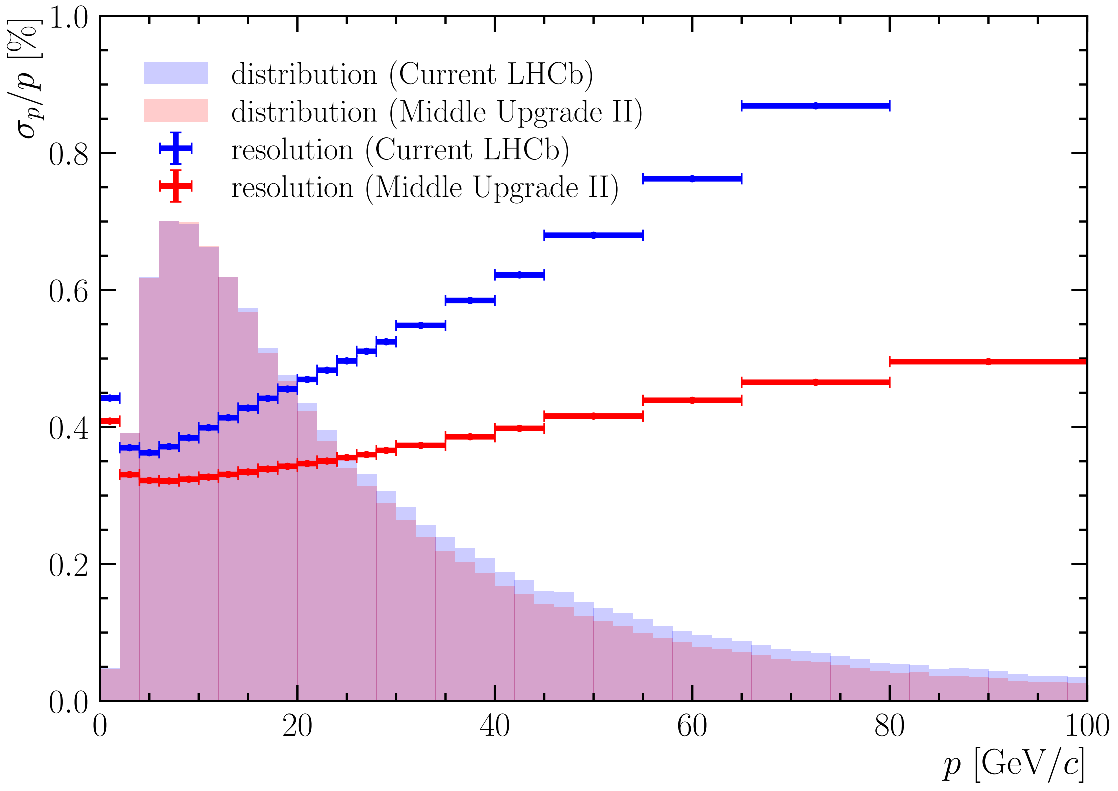
Similar tracking efficiencies for pp and PbPb will allow reconstruction of the most central collisions.

Channel	Relative acceptance %	
	Middle	Low
$B_s^0 \to \mu^+\mu^-$	99.3 ± 0.1	95.3 ± 0.1
$B_s^0 \to \phi(\to K^+K^-)\phi(\to K^+K^-)$	99.4 ± 0.1	90.6 ± 0.2
$D^0 \to K_S^0(\to \pi^+\pi^-)\pi^+\pi^-$	99.7 ± 0.1	84.8 ± 0.8

Reduced acceptance and increased material in the low scenario will have a clear impact on physics.

LHCb U2: tracking (2)

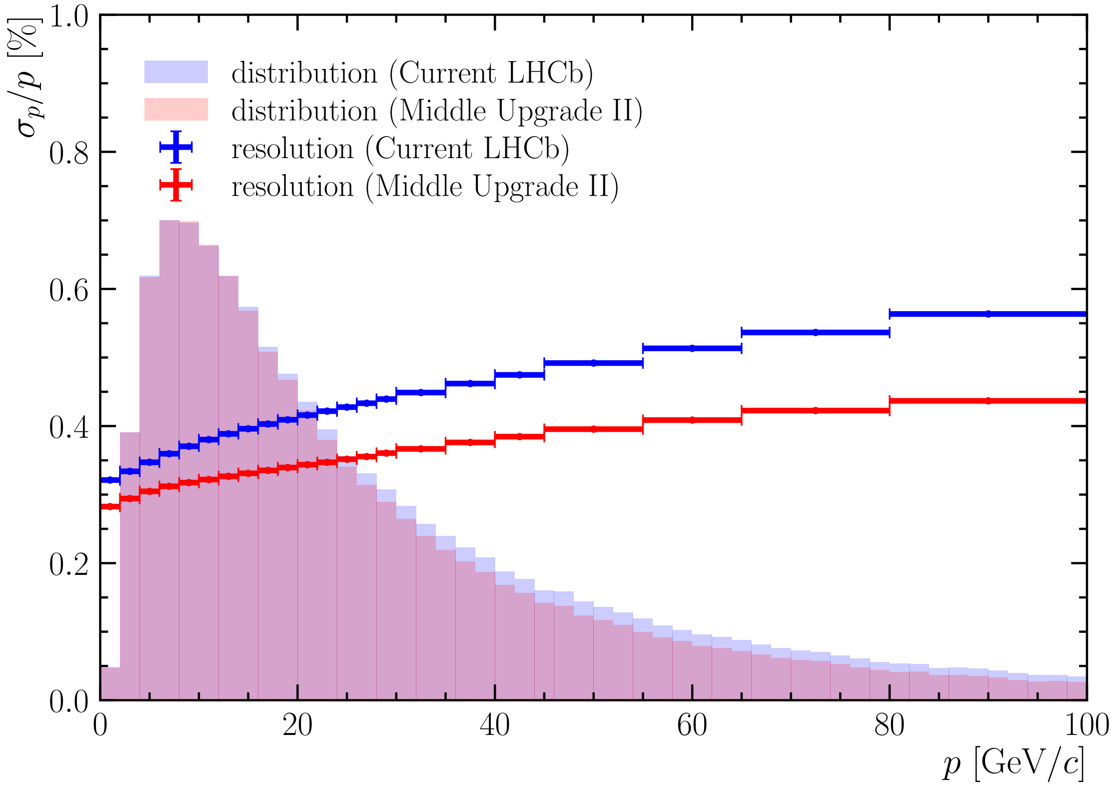


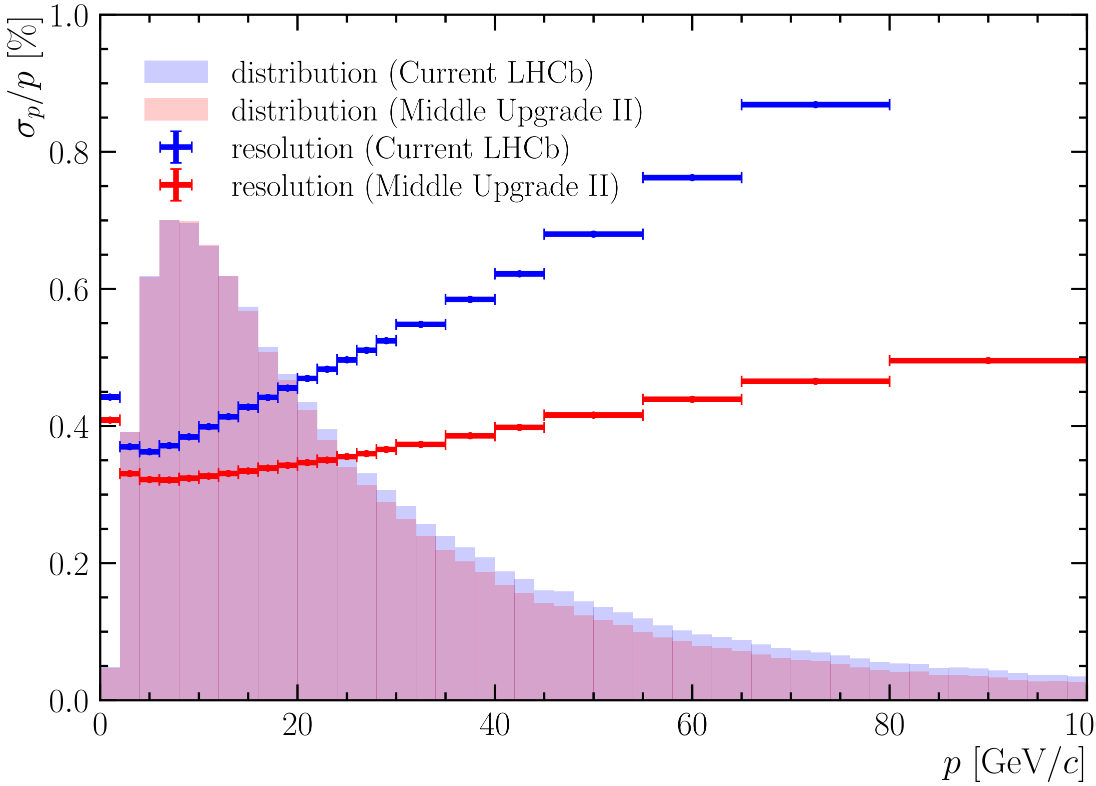


LHCb Upgrade 2 Scoping Document

UP + MT (pixels) significantly improves momentum resolution compared to U1 LHCb!

LHCb U2: tracking (3)





LHCb Upgrade 2 Scoping Document

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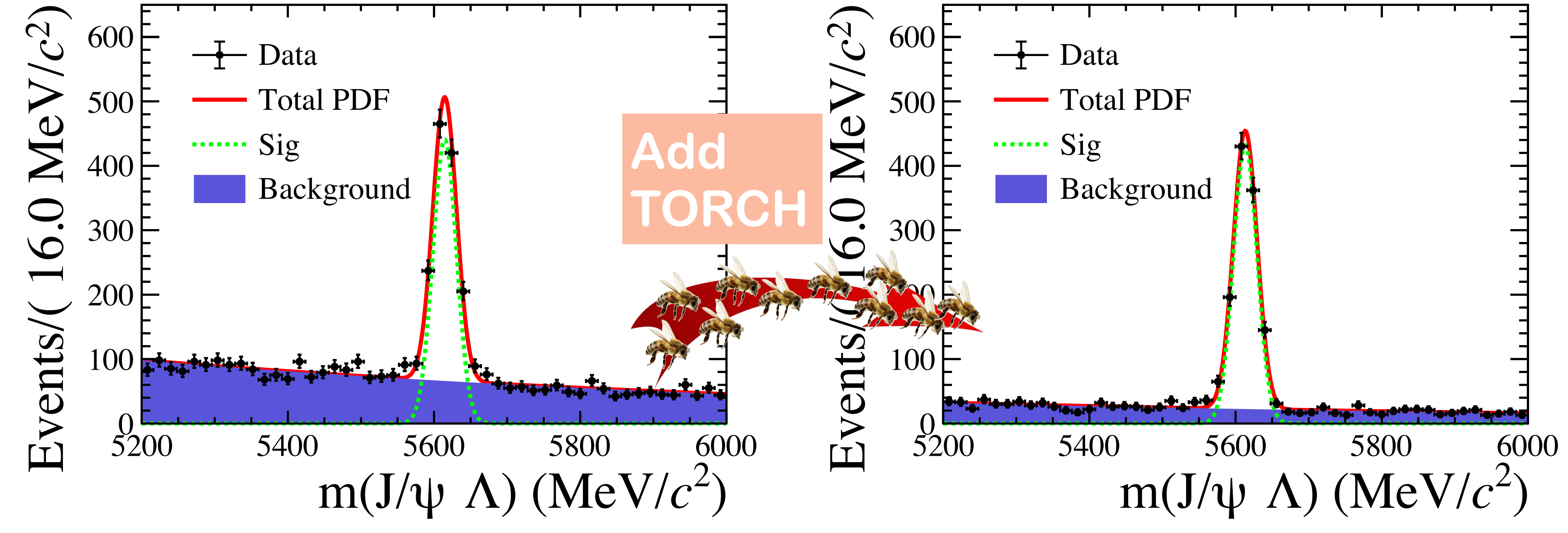
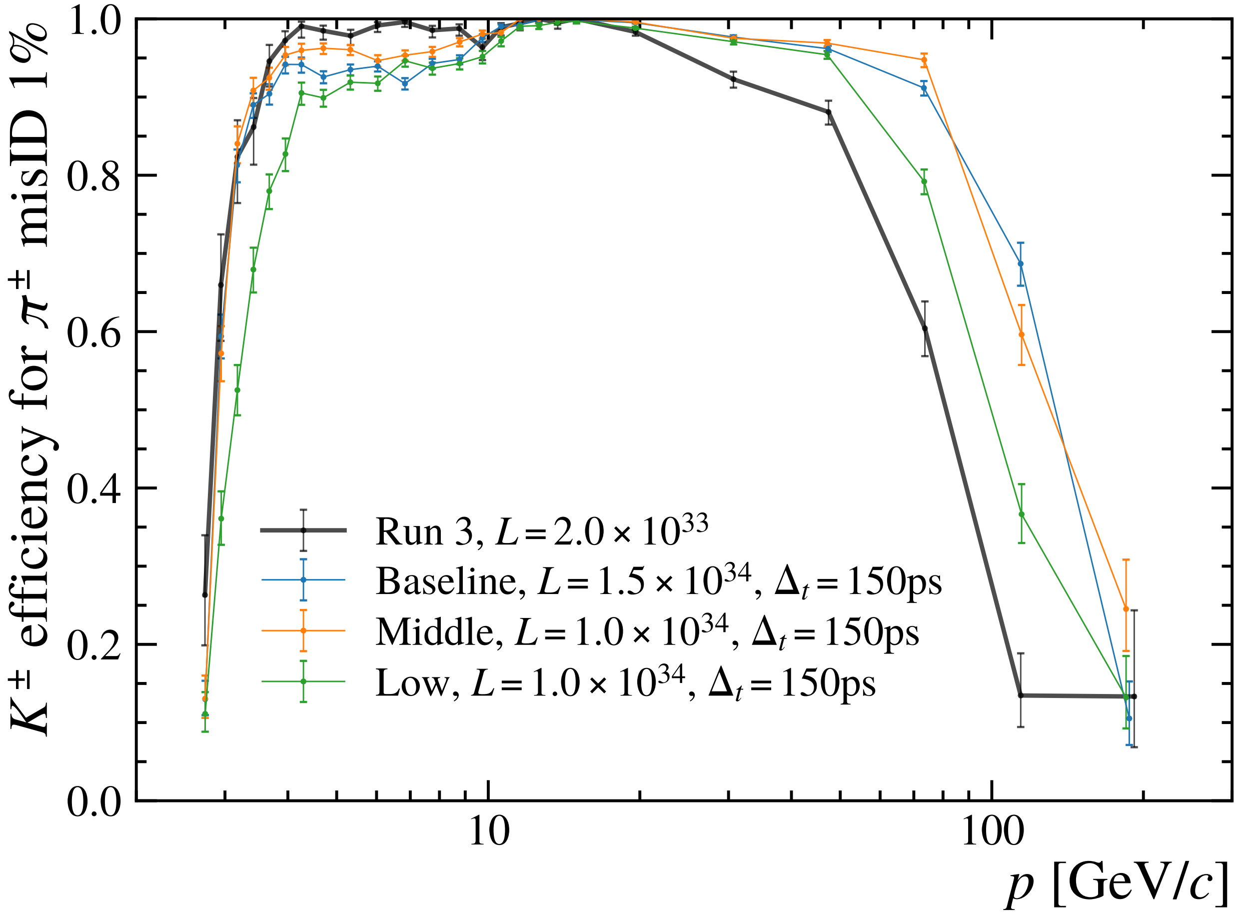
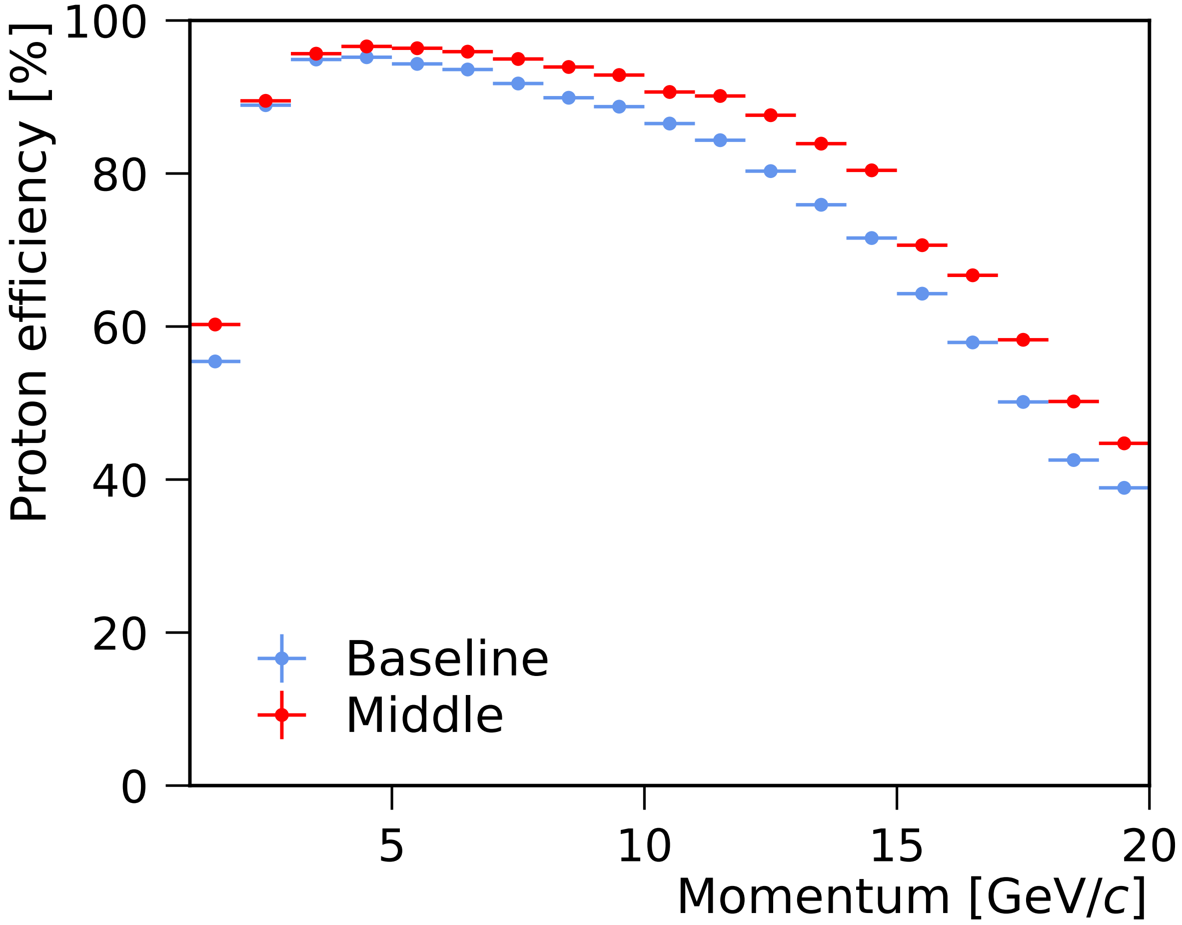


TORCH timing can help suppress backgrounds in tracks without a VELO segment.

LHCb U2: particle identification

LHCb Upgrade 2 Scoping Document





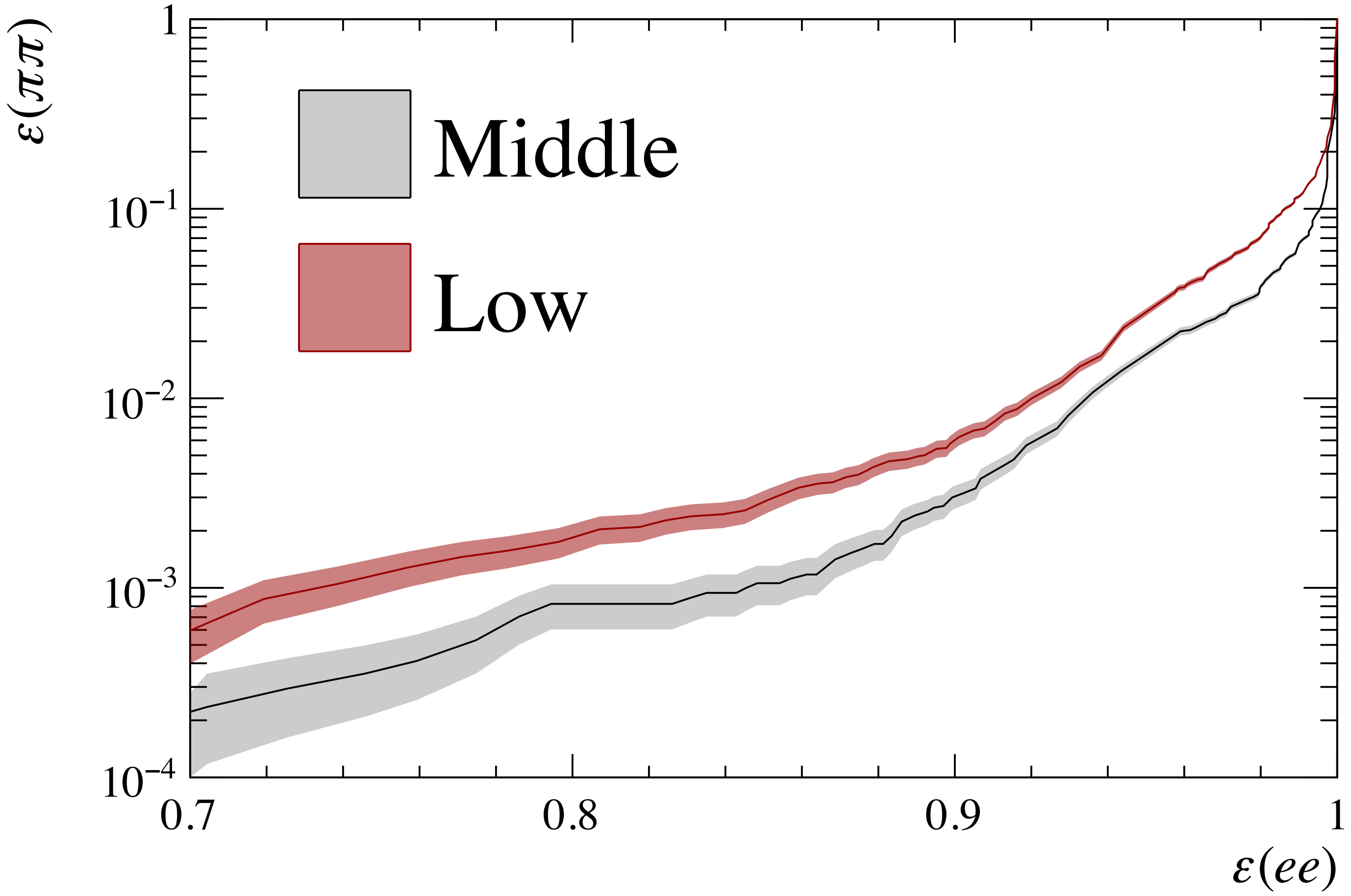
Potential to improve pion-kaon separation at high momenta

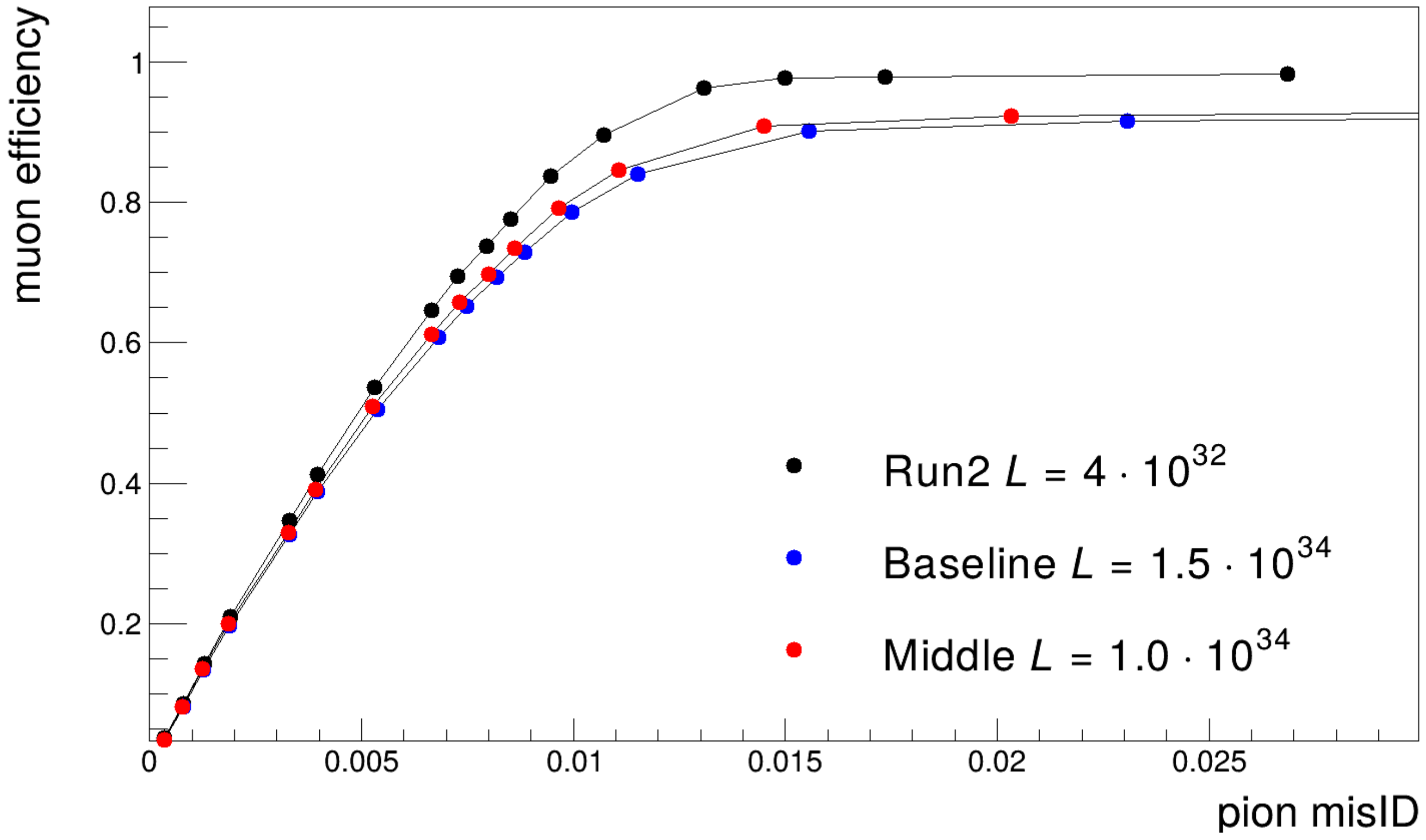
Strong impact of reduced RICH photoelectron yield at low momentum, especially for the Low detector scenario

TORCH provides additional capabilities at low momenta

LHCb U2: particle identification (2)

LHCb Upgrade 2 Scoping Document

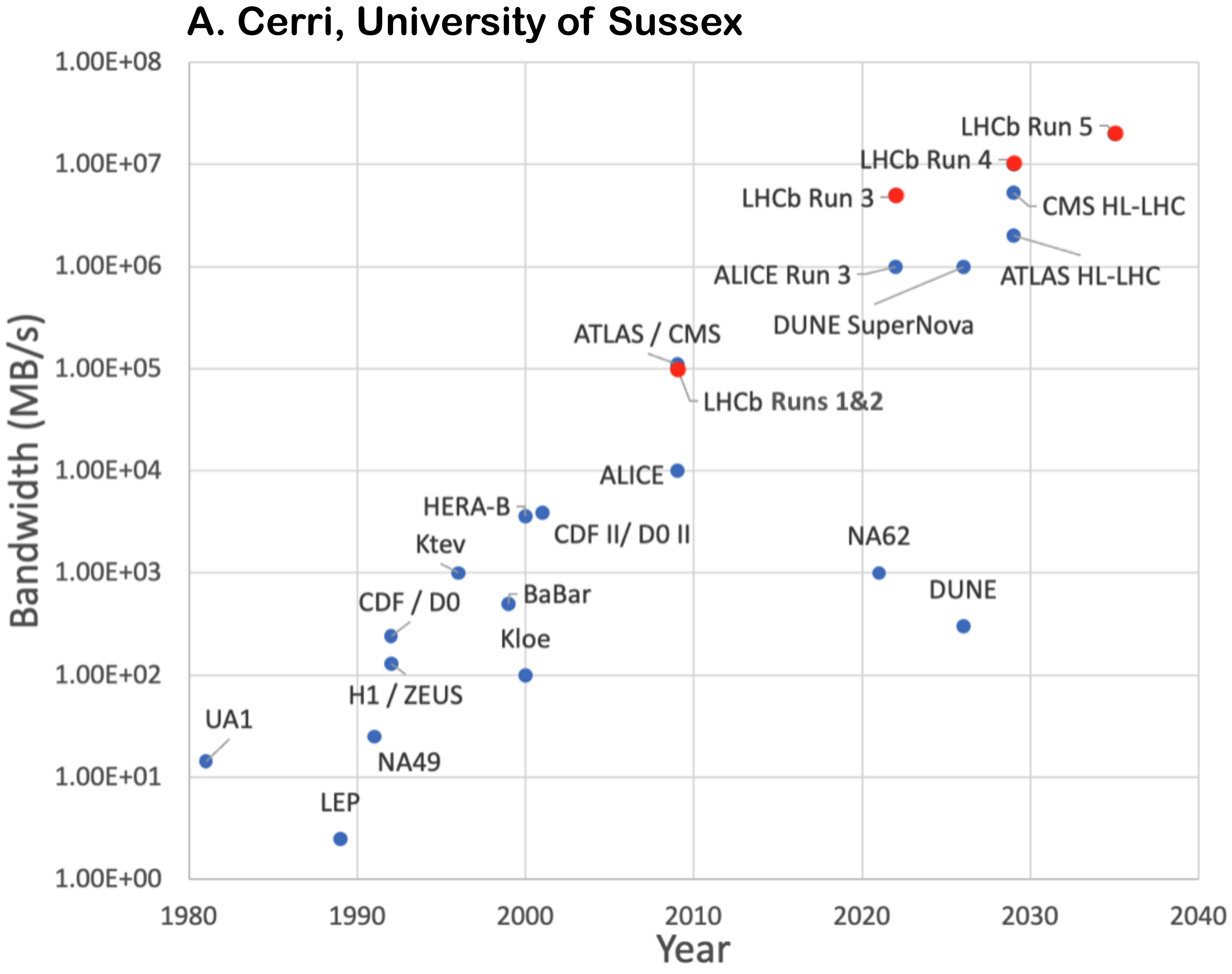




Electron-pion separation is significantly degraded in the low scenario

The muon ID performance good, but not yet at the excellent levels we are used to. Studies to improve it are ongoing.

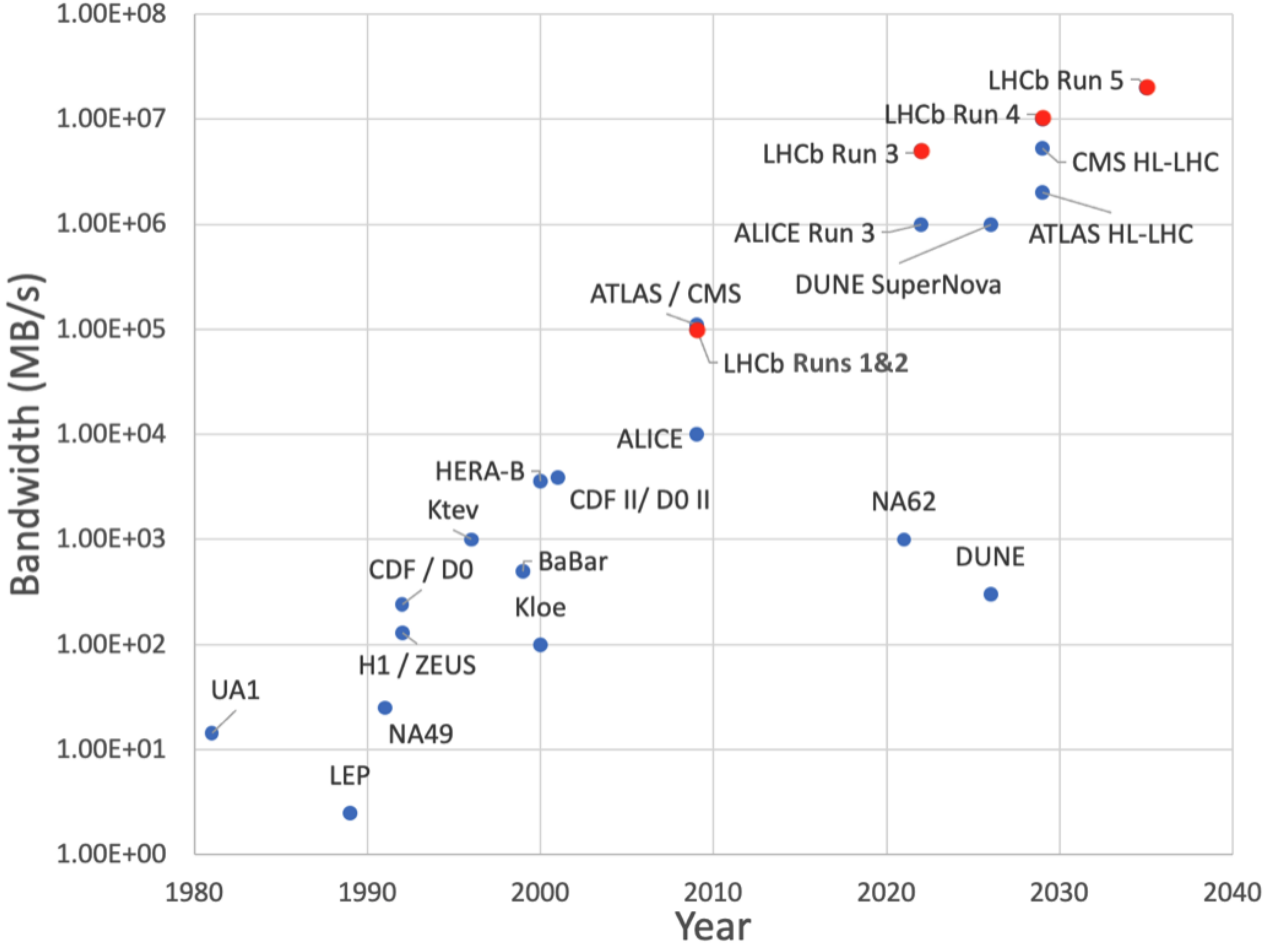
LHCb U2: DAQ & real-time analysis



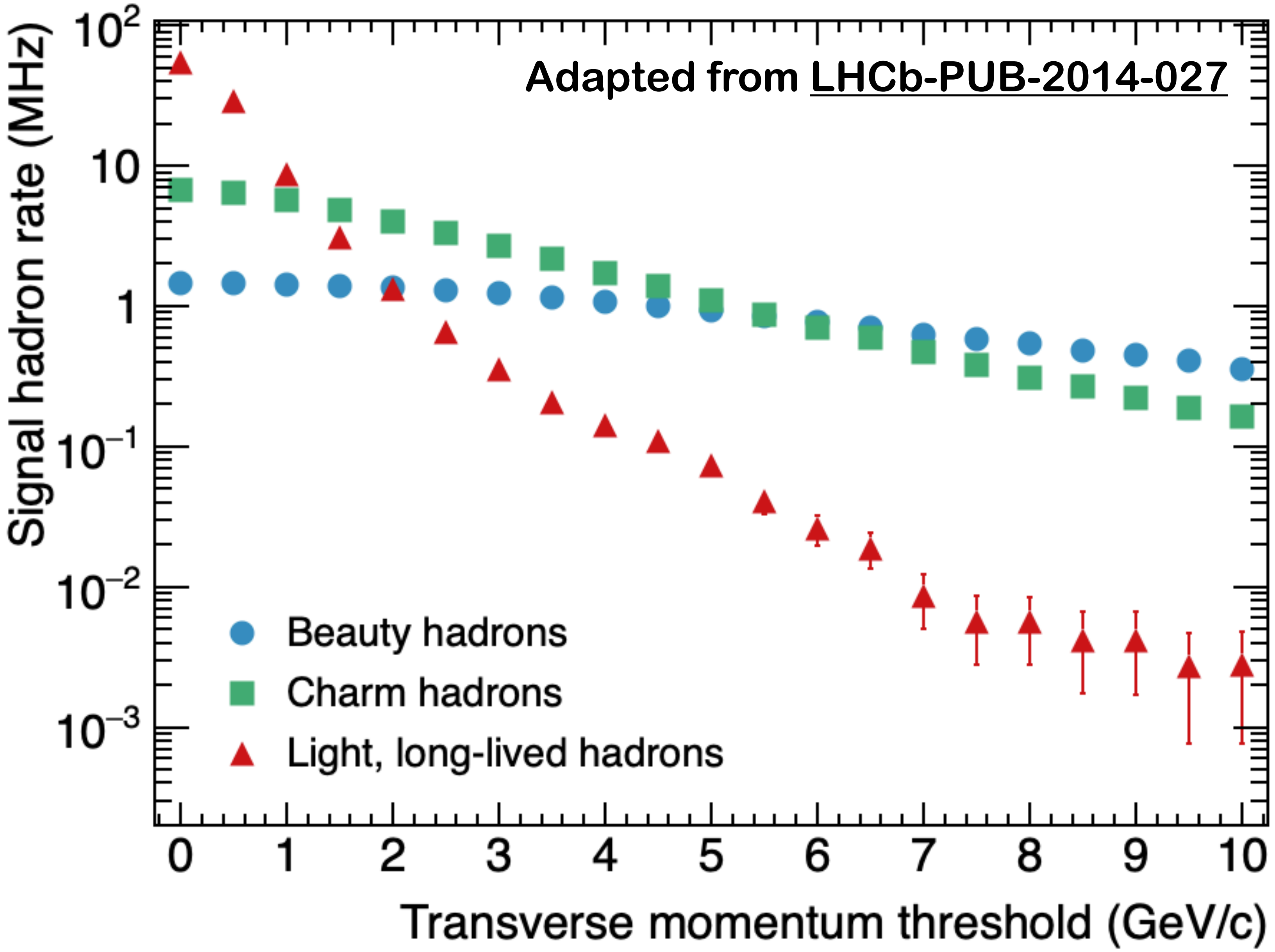
LHCb Upgrade 2 will be the biggest data processing challenge attempted in HEP

LHCb U2: DAQ & real-time analysis

A. Cerri, University of Sussex



LHCb @ 1e34: partially reconstructed signal rate



Trigger saturated by signal – must perform real-time analysis! See slide 36 for details.

Impact of U2 scenarios on sensitivity

Baseline	Middle	Low	
$B^0_{(s)} \to \mu^+\mu^-$			
Improved background rejection from VELO with timing		Worse background rejection	**Precise impact under study**
Improved mass resolution to separate B^0 and B^0_s peaks			
Loss of muon identification	Loss of muon identification	Loss of muon identification	
Acceptance comparable to current detector		Reduced acceptance	**~5% per track**
γ from $B^+ \to DK^+, D \to K^0_S\pi^+\pi^-$			
Improved high momentum kaon/pion separation		Less or no improvement	**~10% PID efficiency loss**
Background rejection for downstream tracks with RICH2 & TORCH timing	Reduced TORCH acceptance	RICH2 timing only	**3x higher background**
Acceptance comparable to current detector		Reduced acceptance also for downstream tracks	**~10-15% per track**
$D^{*+} \to D\pi^+, D \to K^+K^-$			
Acceptance for long tracks comparable to current detector		Reduced acceptance	**Up to 40% total tracking efficiency loss**
Improved slow pion acceptance from Magnet Stations		No improvement	
Trigger throughput comparable to current detector		Reduced online farm capacity	**Impact on trigger to be evaluated**
ϕ_s from $B^0_s \to J/\psi\phi$			
Loss of muon identification	Loss of muon identification	Loss of muon identification	
Improved high momentum kaon/pion separation		Less or no improvement	
Improved decay time resolution		Worse performance	**~10% sensitivity dilution**
Improved flavour tagging		No improvement	**~5% flavour tagging loss**

LHCb Upgrade 2 Scoping Document

U2 schedule, risks, mitigation

LHCb Upgrade 2 Scoping Document

Run 3					LS3			Run 4				LS4		Run 5					
2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041
		TDR phase			Construction phase							Installation		Exploitation					

We are making sure lessons from Upgrade 1 are being learned

- ASIC developments will minimise the number of different chips
        - RICH + TORCH | UP + MT(pixel) | MS + MT (SciFi)
    - Ensure continuous communication with designers in system test stage
- DAQ and firmware will establish the design early & benefit from LS3 enhancements
    - Key so that we can start commissioning early with final DAQ system

Further details for individual subdetectors can be found in the scoping document

Conclusion

LHCb Upgrade 1 is moving at full speed and will dramatically improve knowledge of heavy flavour physics during Run 3, often by >2x in sensitivity

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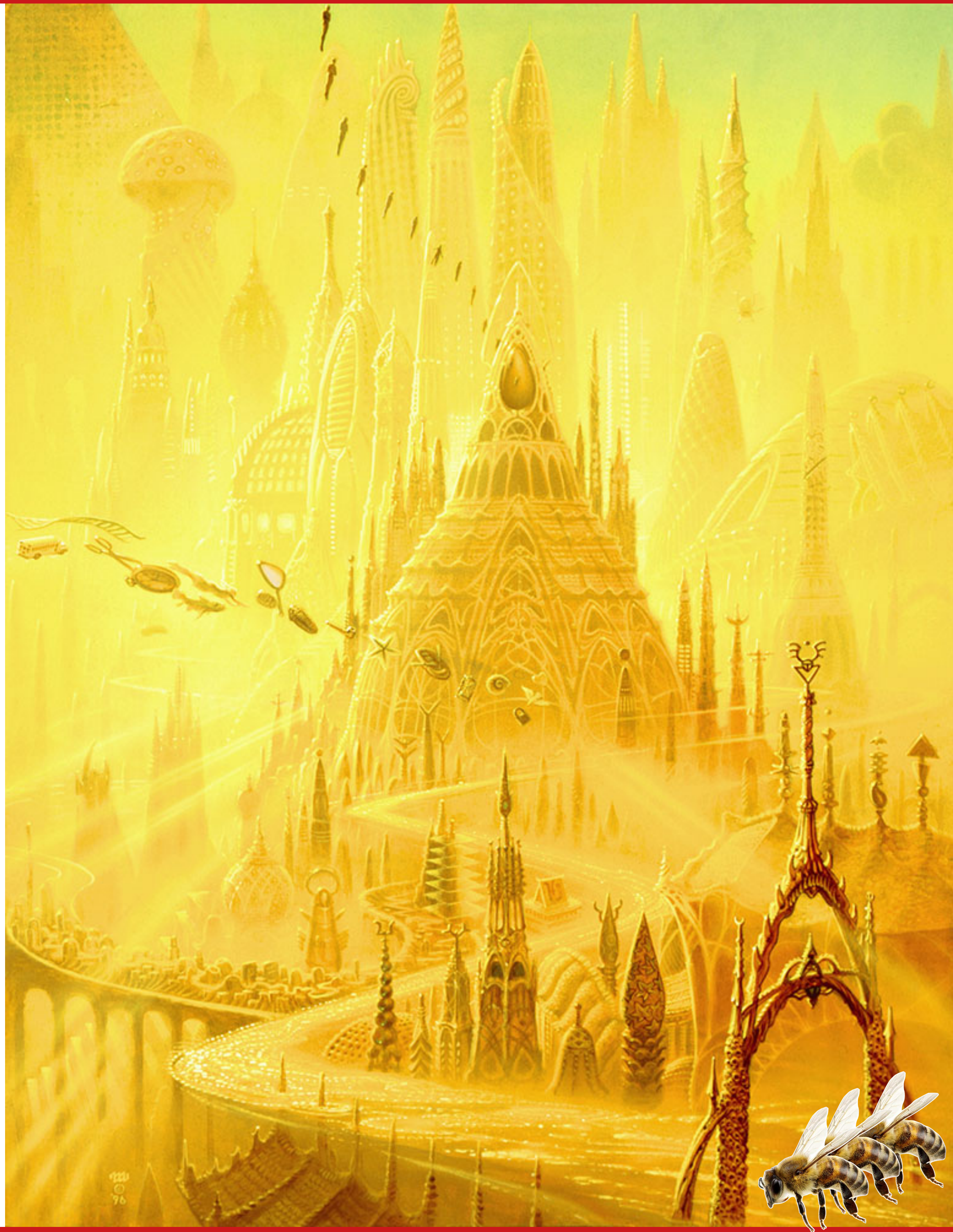

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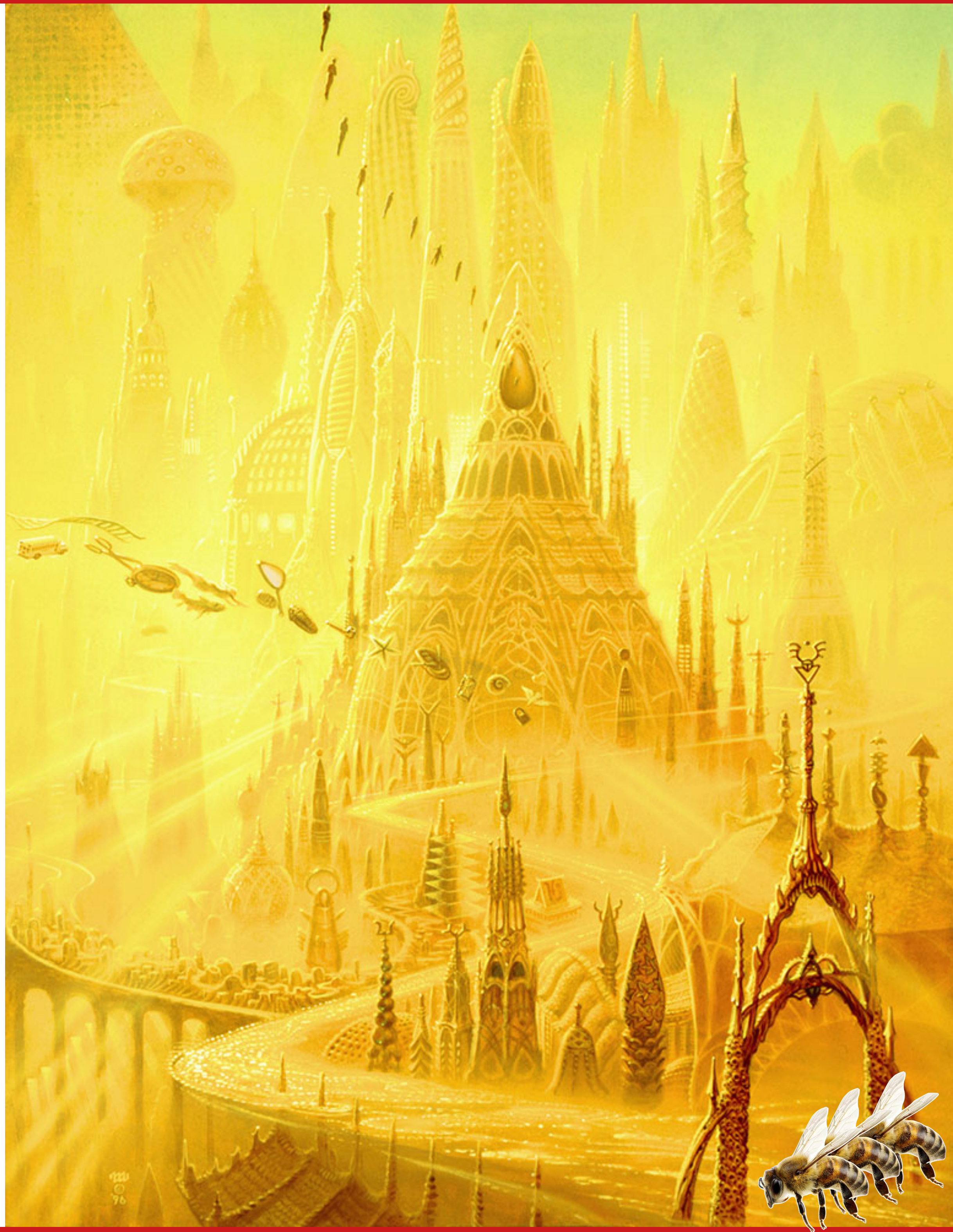
LHCb Upgrade 2 is also a tangible project with which to drive technology developments for future experiments and facilities



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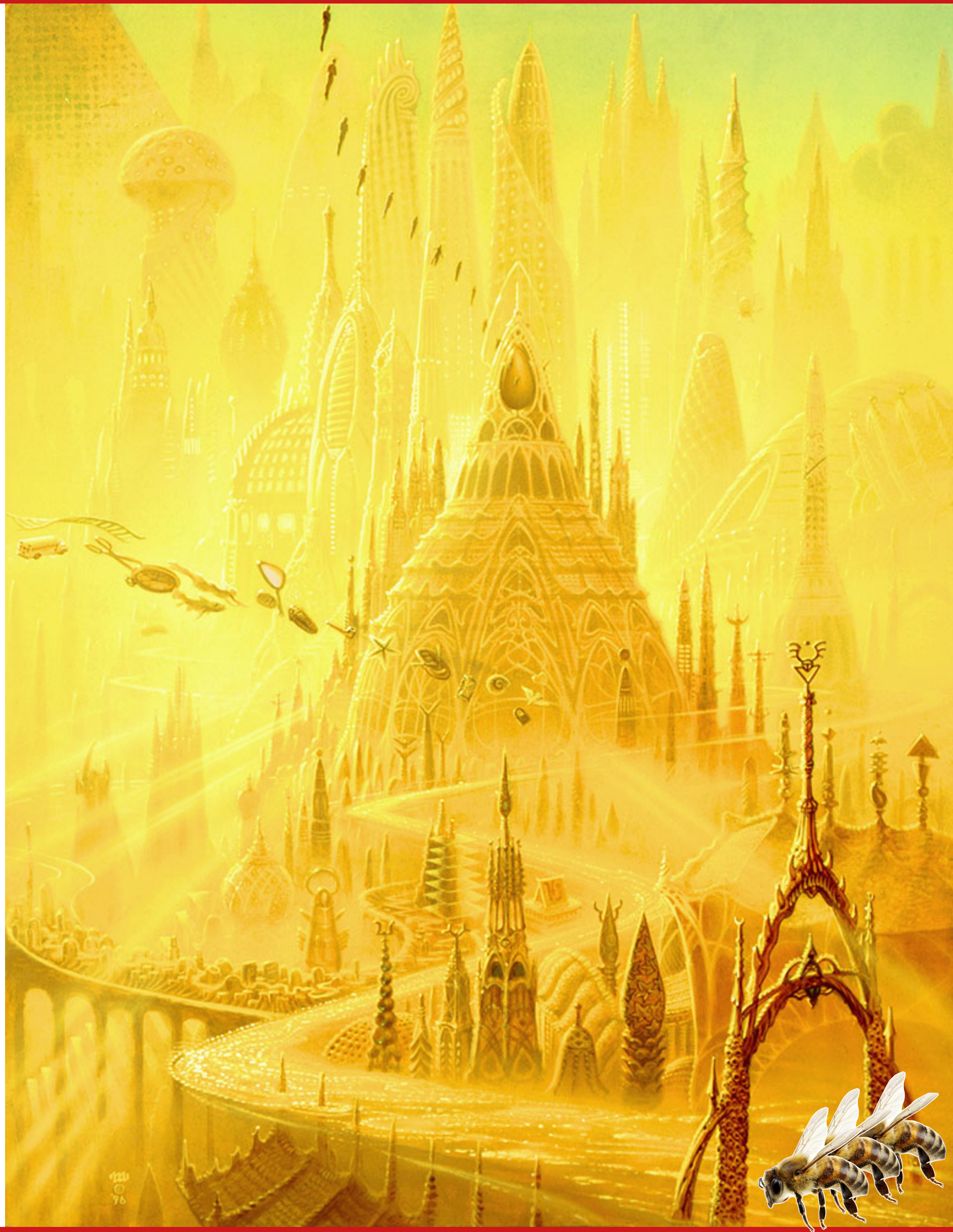
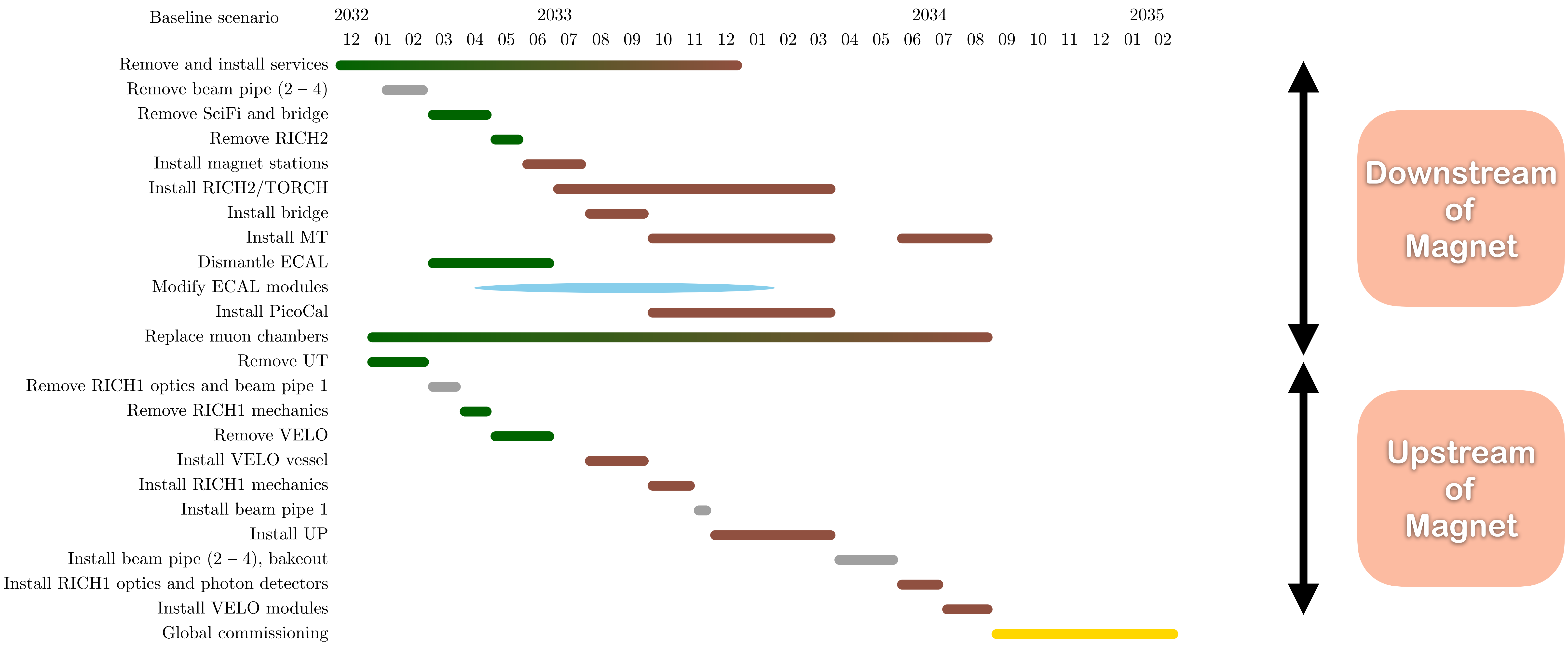
Join us!



BACKUP

U2 installation schedule

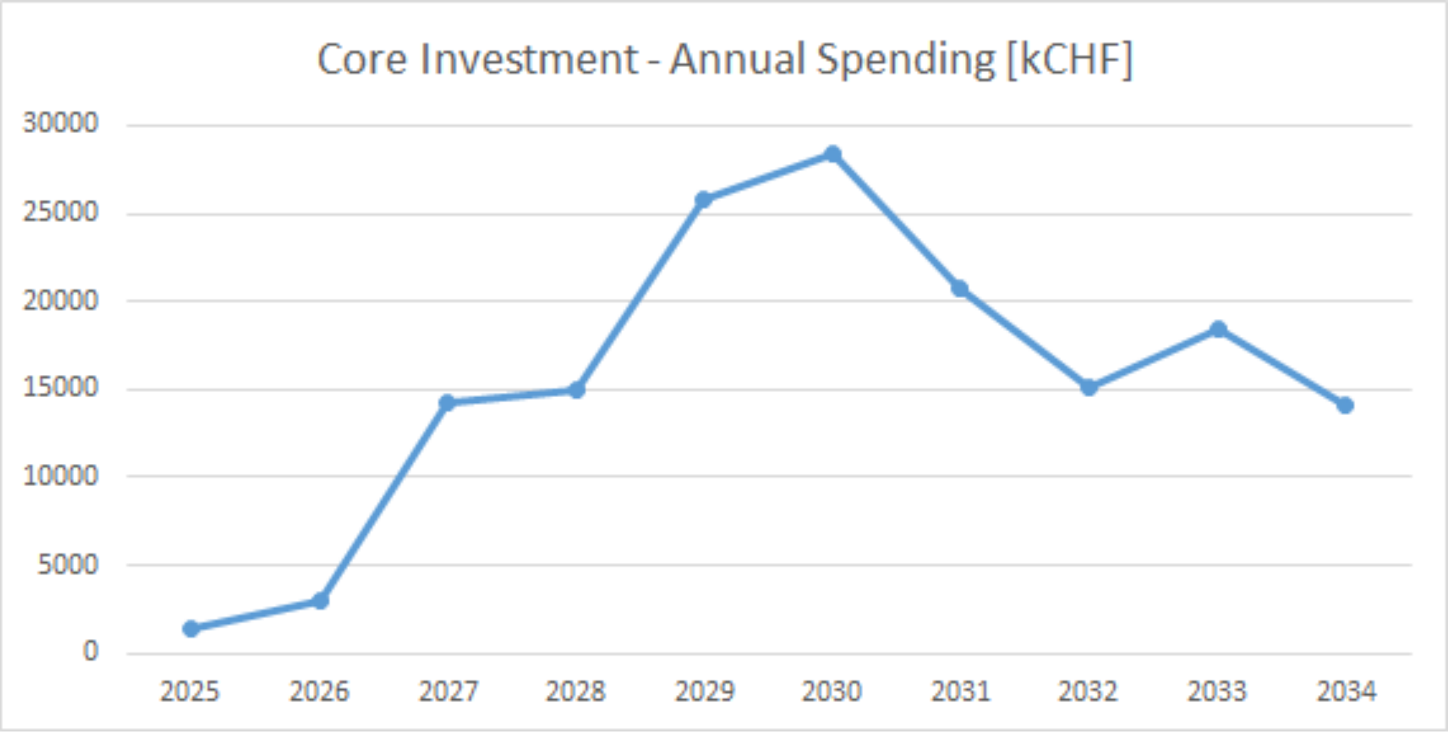
LHCb Upgrade 2 Scoping Document

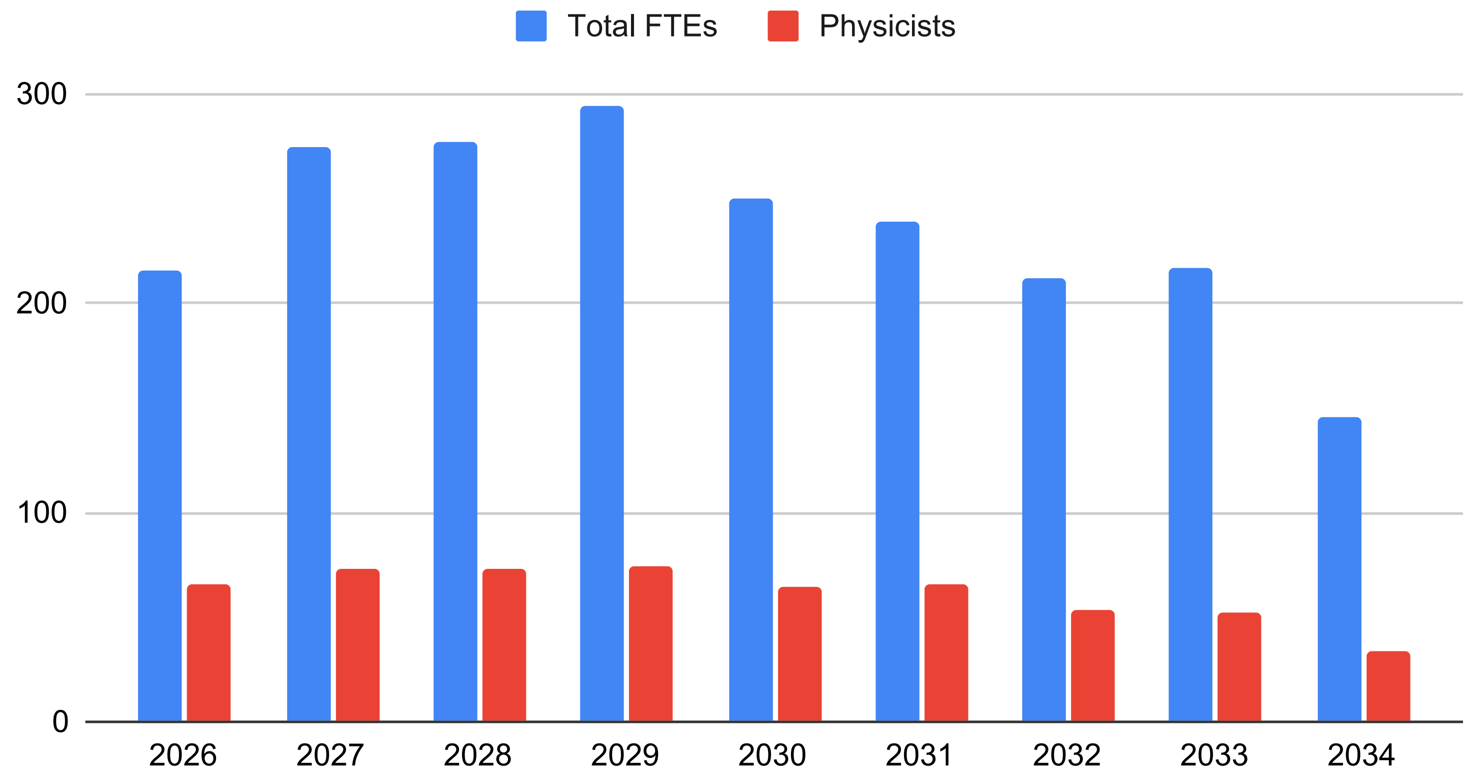


Completing all work in 2 years is challenging but achievable

U2 resource requirements and profile

LHCb Upgrade 2 Scoping Document





These are aggregated from inputs provided by subdetectors, comparisons ongoing to calibrate

LHCb U2: DAQ & real-time analysis

The LHCb trigger architecture is designed to be fully efficient for hadronic decays of charm hadrons

At 1.5e34 ~every bunch crossing produces a ccbar pair! You can't inclusively select interesting bunch crossings.

This is why LHCb performs "real-time analysis": full analysis-quality reconstruction, alignment, calibration, and selection (including pileup suppression) in the trigger.

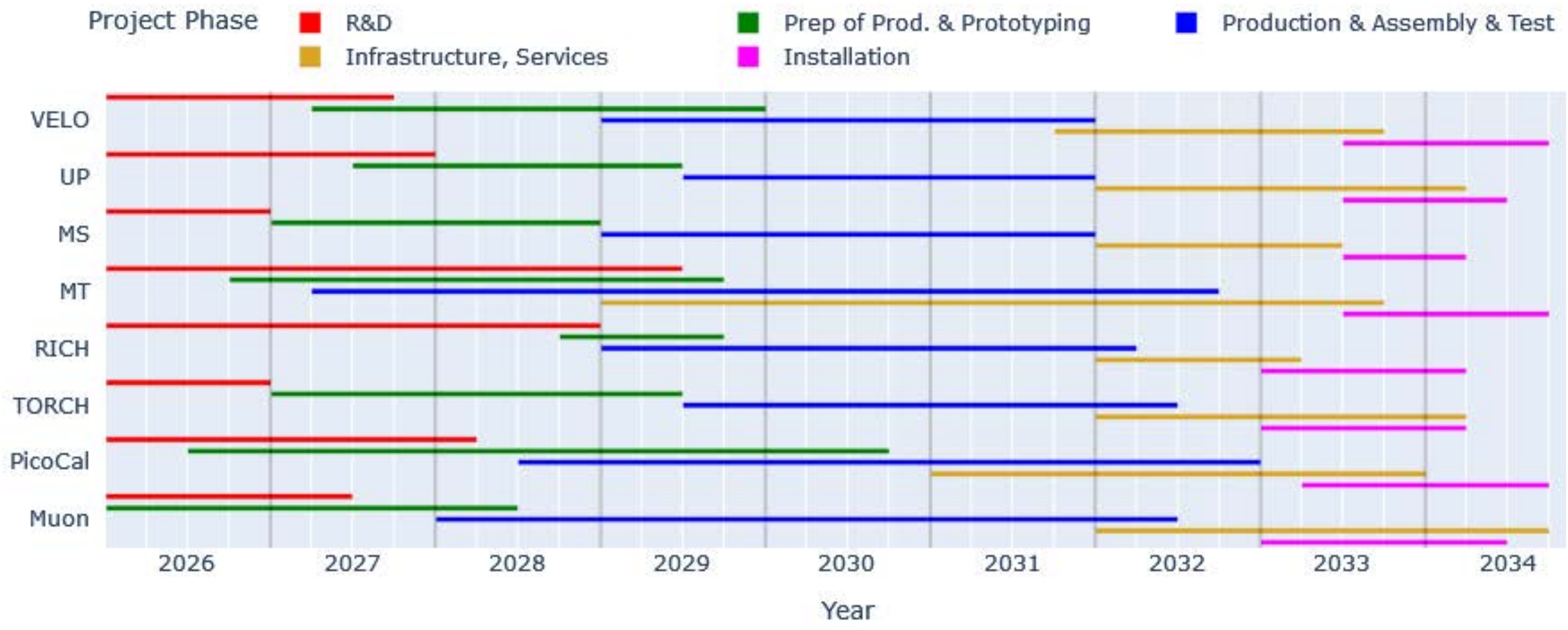
Increasing the instantaneous luminosity simultaneously increases the fraction of events containing signal to be analysed and event complexity.

So the bulk of the system cost varies with the integrated luminosity squared even if the reconstruction and selection algorithms vary linearly with event complexity.

The key challenge of the next decade will be to maintain and further develop a team with the skills to exploit heterogeneous parallel computing architectures in the mid-2030s, alongside languages and frameworks specialising for high-throughput scientific computing.

U2 detailed schedule

LHCb Upgrade 2 Scoping Document



Upgrade 2 risks & lessons from U1

LHCb Upgrade 2 Scoping Document

- Procurement delays
  - Start early, include time for tendering in planning
- ASIC developments
  - Minimise number of different chips
    - RICH + TORCH
    - UP + MT(pixel)
    - MS + MT (SciFi)
  - Communication with designers in system test stage
  - Contingency for additional submissions
- DAQ and firmware
  - Establish design early & benefit from LS3 enhancements
  - Monitor availability of experts and broaden base of expertise
  - Start commissioning early with final DAQ system

LHCb open geometry makes a staged installation possible, but careful planning is needed

Re-use of significant existing infrastructure (Magnet, mechanical support structures, certain subdetector elements)

Exceptional circumstances (like Covid) can only be handled through contingency and the ability to inject additional person-power, especially at CERN