LHCb upgrades status and plan

Xuhao Yuan
IHEP
On behalf of the LHCb China group

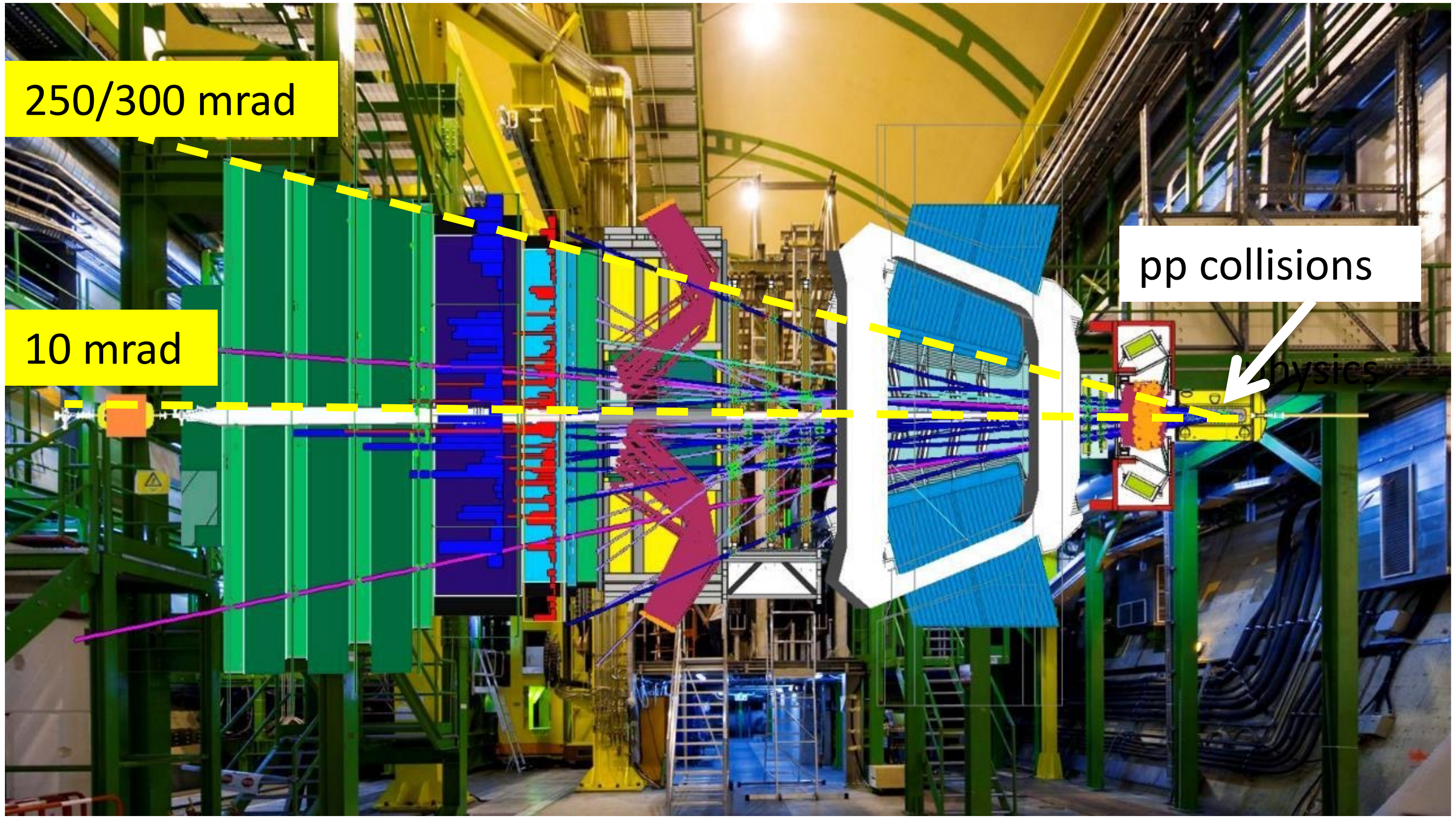
2023-04-15

Outline

- Introduction
- LHCb upgrades
  - Upgrade I (2019 - 2023)
    - ✓ Upgrade Ib (2026 – 2028)
  - Upgrade II (2032 -)
- LHCb physics in future
- Summary

LHCb: a forward spectrometer @ LHC

More details on Liupan's talk



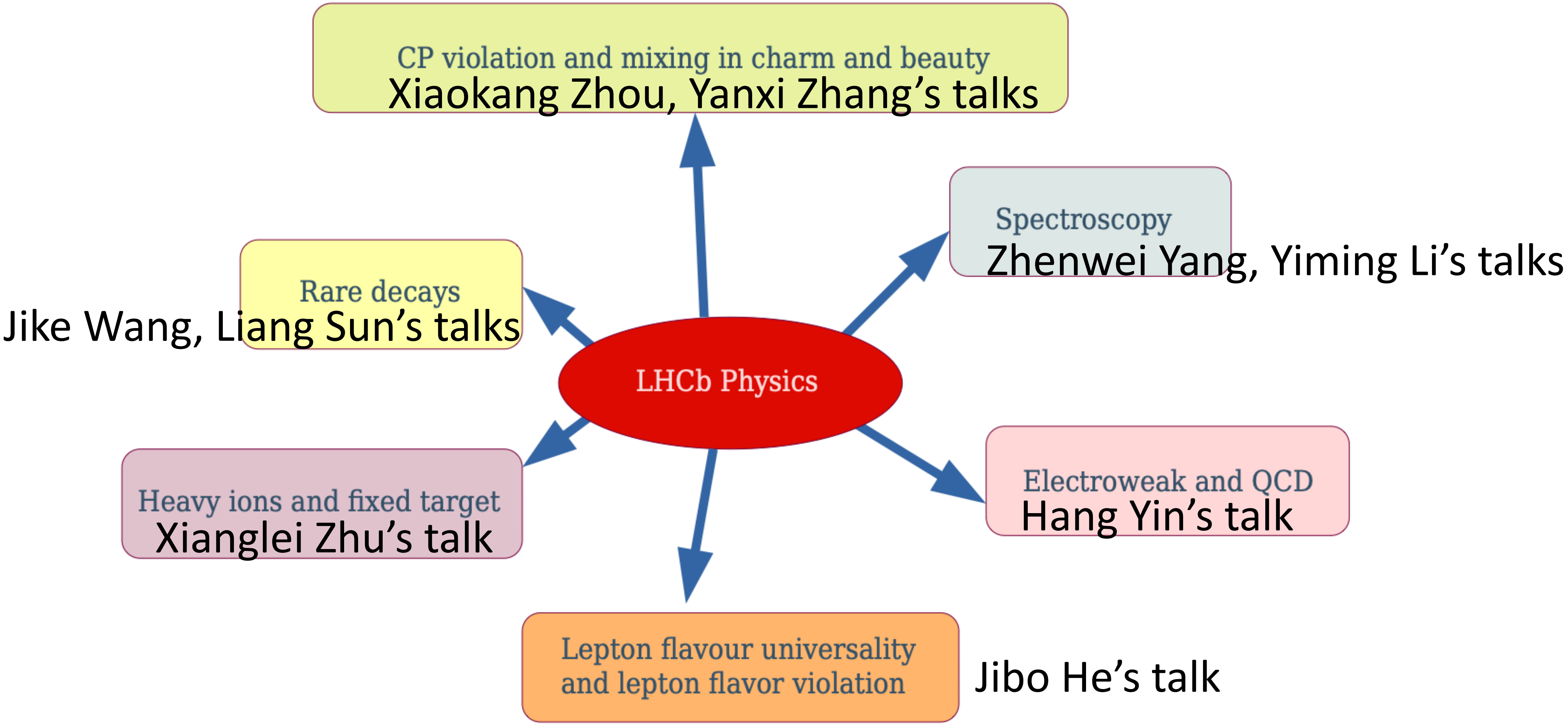
Main physics goal

- To study b & c sectors on CP-voilation, rare dedays, search for new physics...

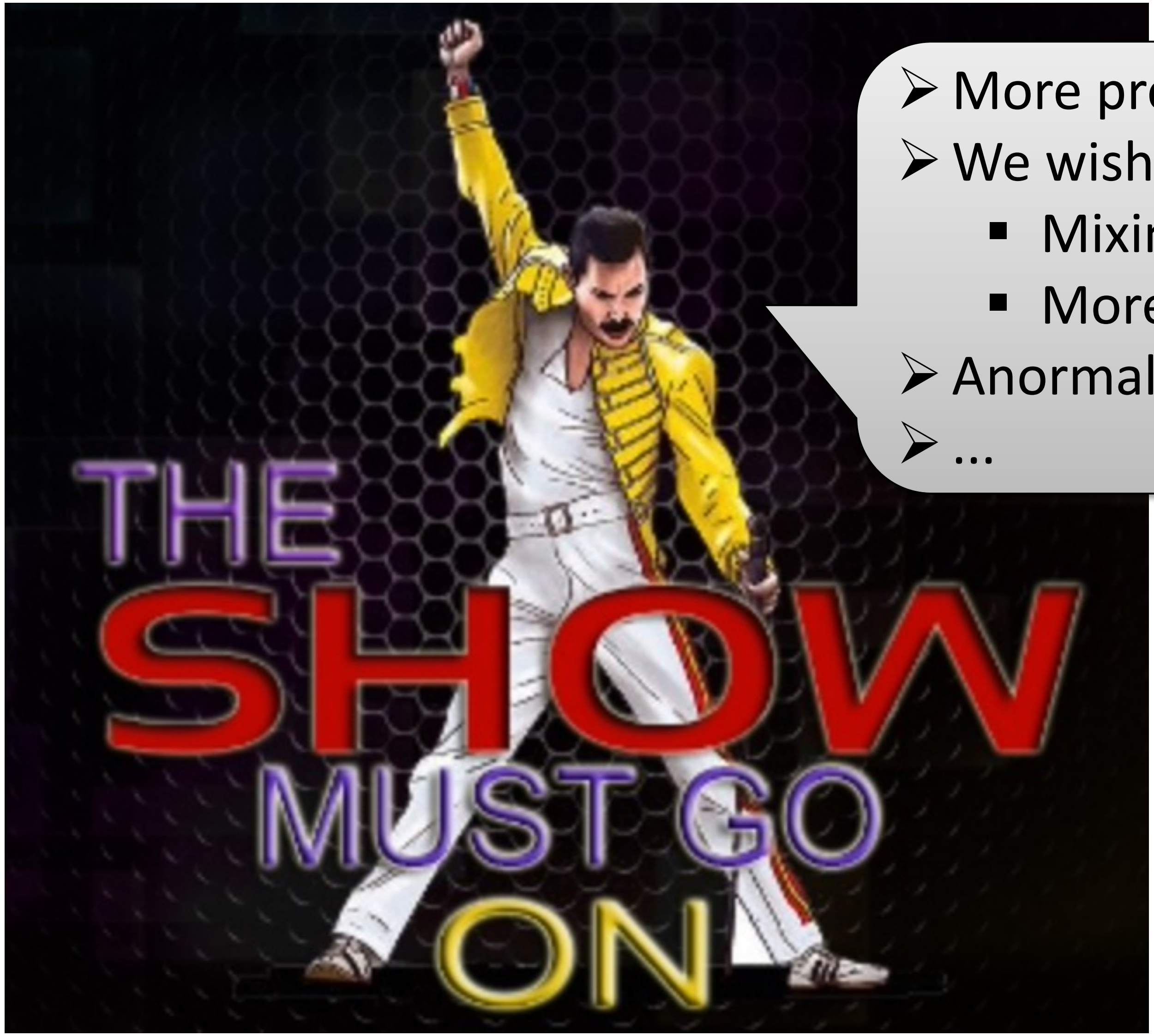
- $\Delta p/p = 0.5\%$ @ < 20 GeV/c, 1% @ < 200 GeV/c
- IP resolution ~ $15 + 29/p_T$ [GeV/c] μm
- Decay time resolution 45 fs ($B_s \to J/\psi \phi$)
- Kaon ID ~ 95% for 5% $\pi \to K$ mis-ID probability

LHCb physics performance in Run 1 & 2

A decade of important discoveries and precision measurements (9 fb^{-1} pp data)



LHCb beyonds



- More precision required in crucial observables
- We wish to observe:
  - Mixing CPV in Charm
  - More exotics ...
- Anormaly in P_5', Lepton flavor universality
- ...

LHCb Upgrades

Upgrade I (U1), started in LS2 and to be completed in weeks:

$\mathcal{L}_{max}$~2x10^{33} cm^{-2}s^{-1}

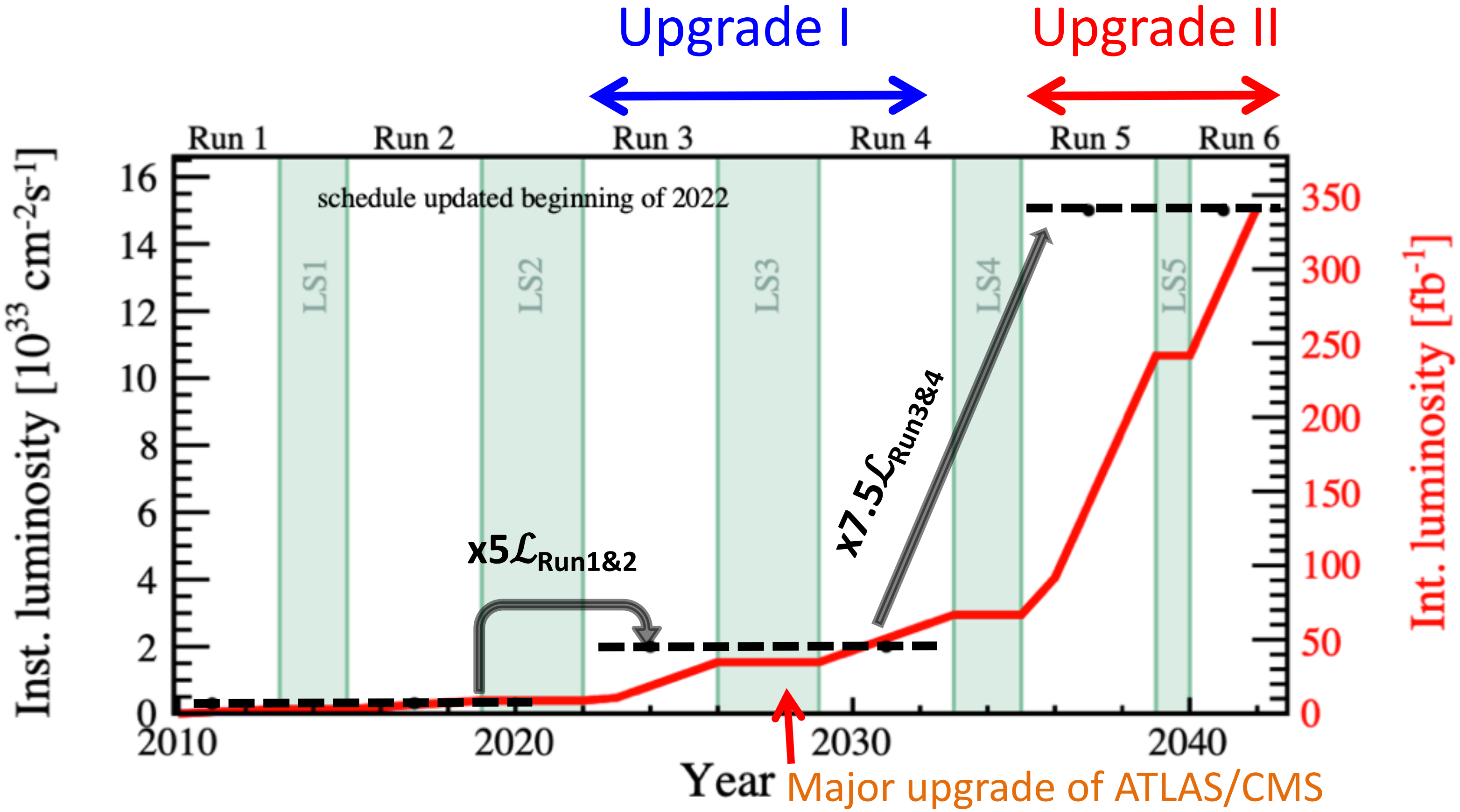
$\mathcal{L}_{int}$~50 fb^{-1}

Upgrade II (U2), starts after LS4

$\mathcal{L}_{max}$~1.5x10^{34} cm^{-2}s^{-1}

$\mathcal{L}_{int}$~300 fb^{-1}

Some smaller detector consolidation and enhancements in LS3 (2026) ⇦ U1b

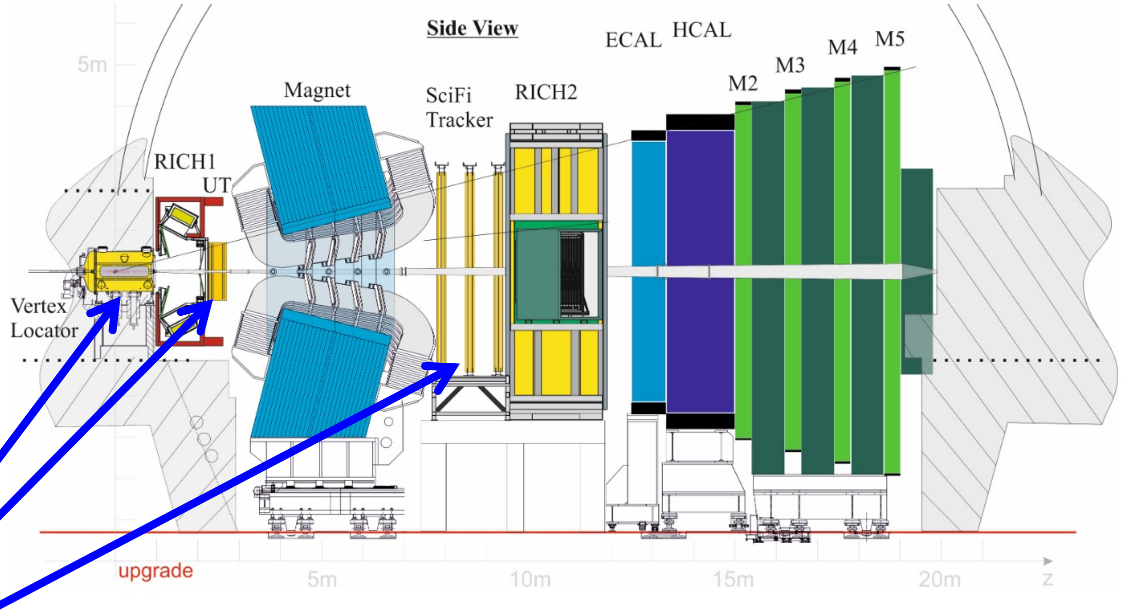


Major upgrade of ATLAS/CMS
LHCb also plan enhancements (U1b)

Upgrade I

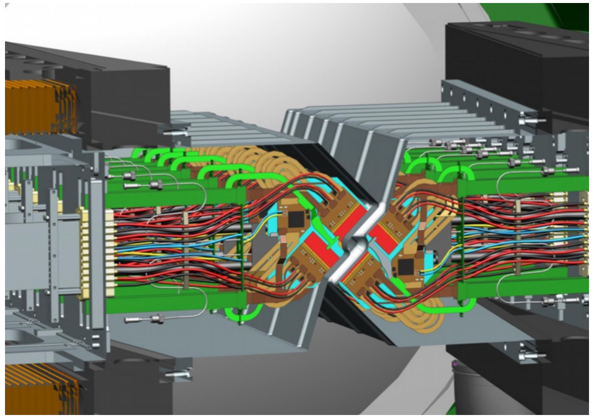
Higher luminosity (5x$\mathcal{L}_{Run1\&2}$) results in
- ➢ Higher pile up, occupancy, fluence

No hardware trigger
- ➢ GPU + CPU full software-based trigger
- ➢ Readout at the LHC bunch xing rate (40 MHz) for all subdetectors

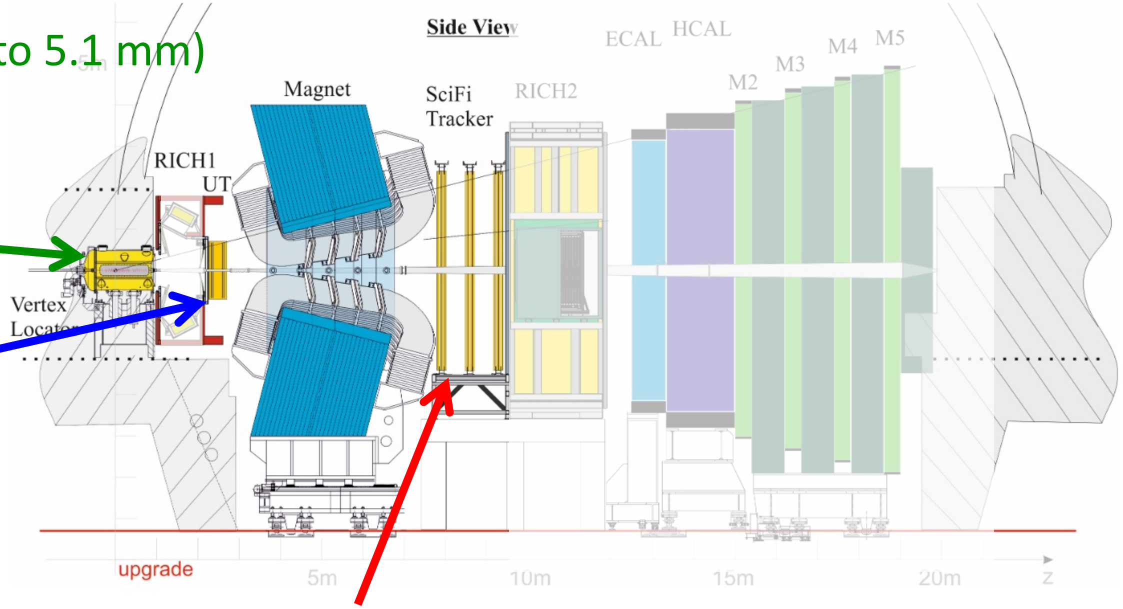


New tracking system
- ➢ **VE**rtex**LO**cator (VELO), **U**pstream **T**racker (UT) and **Sci**ntillating **Fi**ber Tracker (SciFi)

Upgraded trackers: VELO, UT and SciFi

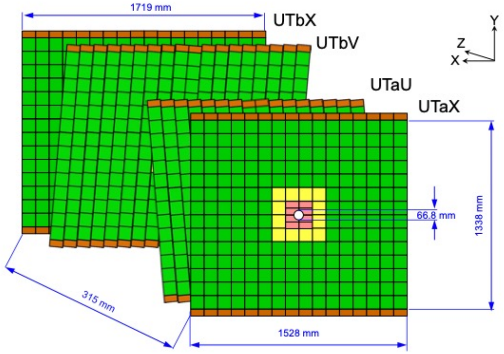


VELO: hybrid pixel detector
- Closer to the beam (from 8.2 mm to 5.1 mm)
- New RF box
- MAX fluence: 8×10^{15} $MeVn_{eq}cm^{-2}$



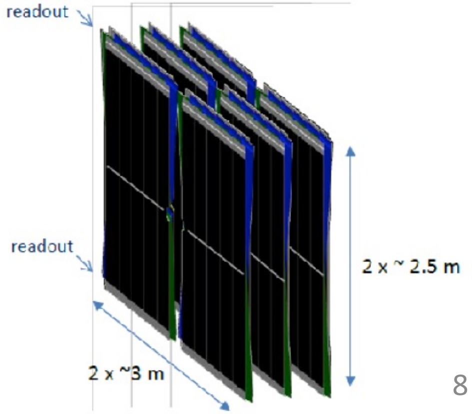
UT: Si Strip detector
- Higher coverage, segmentation, resolution
- Speed up tracks reconstruction & reduce $P_{GhostTrk}$

LHCb China group contributes from UT electronics, software to final installation



SciFi: Scintillating fibers detector
- 3 station with 4 detection layers
- 2x2.5 m long modules with Readout SiPMs at the outer edge

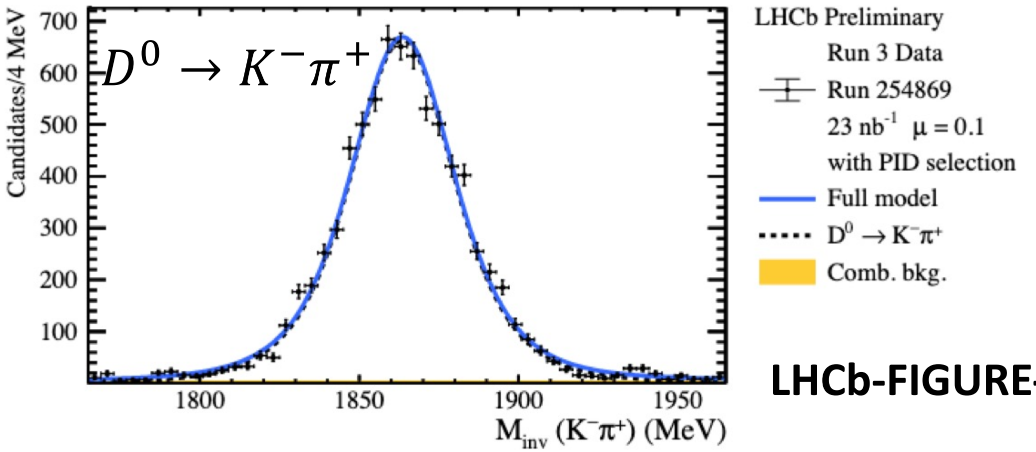
LHCb China group contributes PACIFIC R&D and production



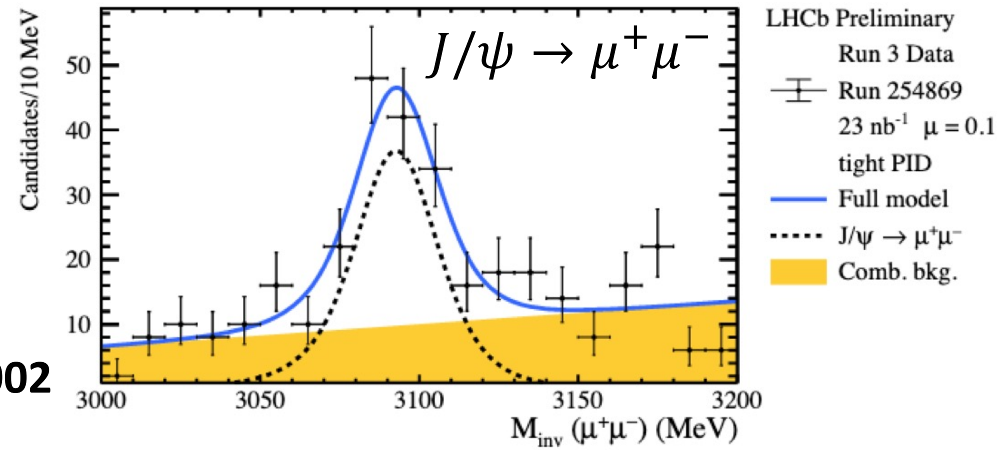
Upgrade I status

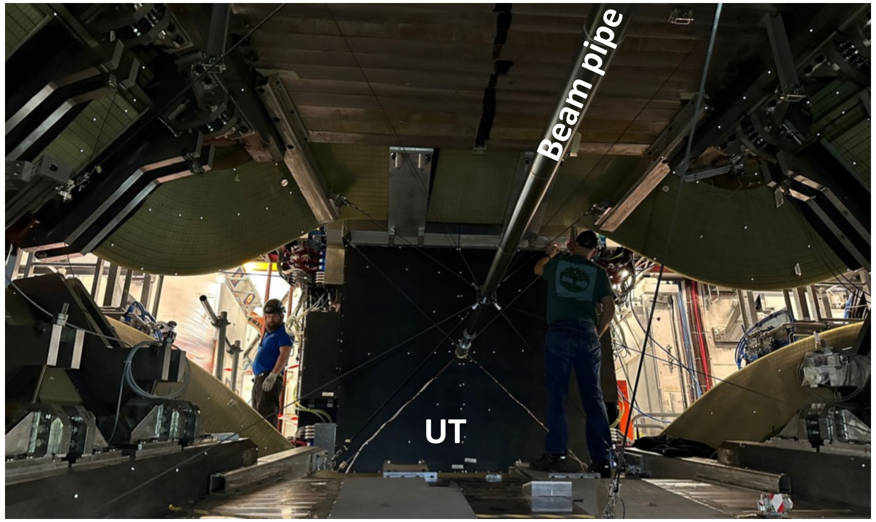
First collisions started from Jul 5, 2022

With GPU+CPU triggers and PID, the first mass peaks observed



LHCb-FIGURE-2023-002





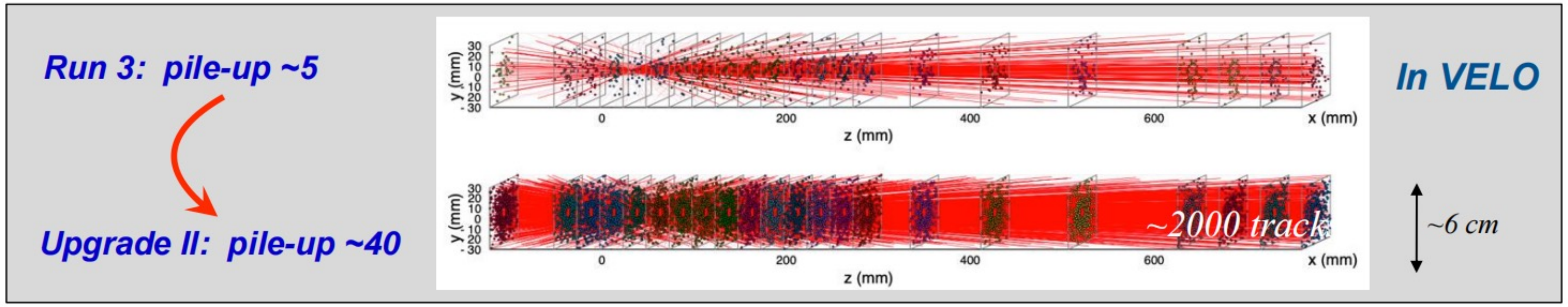
UT completed and closed around beam pipe by Mar 2023

- Commissioning now ongoing: ~96% channels are active

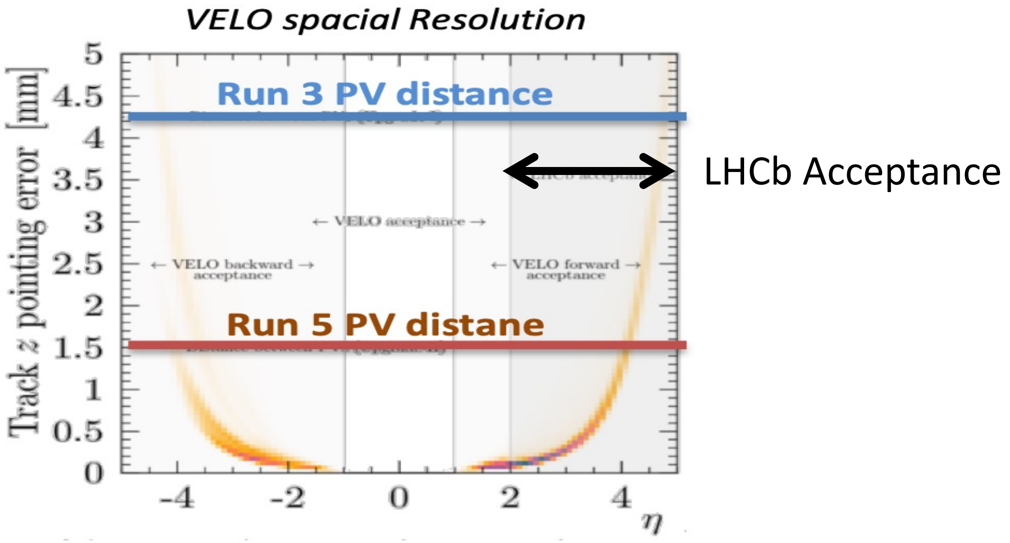
Stable beams @ 6.8 TeV by end of April

High pile-up in Upgrade II

In Upgrade II
$\mathcal{L}_{max}$~1.5x10^{34} $cm^{-2}s^{-1}$
$\mathcal{L}_{int}$~300 fb^{-1}
~ 40 visible interactions/Xing



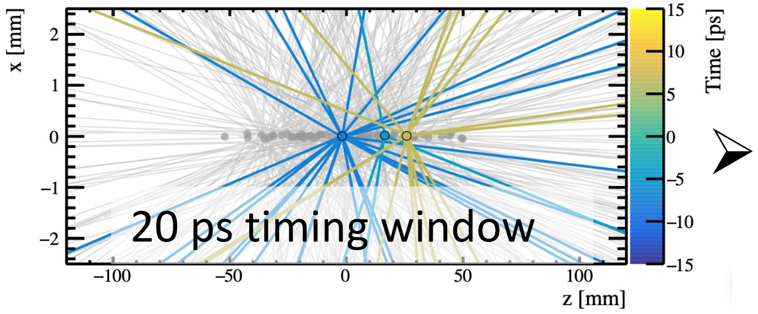
- High pile-up induces PV spacial separation of the same order as VELO resolution
  -> PV unresolvable
- Ensure $\varepsilon_{trigger}$ at high pileup condition



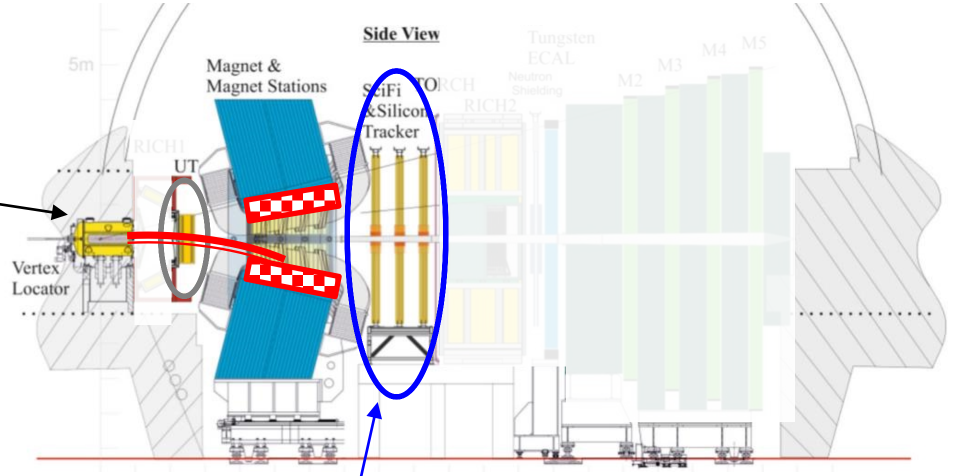
New detector with t information

New tracking detectors in U2

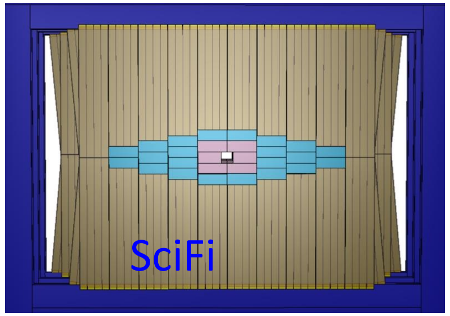
VELO: 4D detector with timing



- $\sigma_t(\text{Track}) = 20$ ps restores the performance to U1 level



UT: Pixel detector, more details on next slides



SciFi: Keep current design at outer region, while at most inner region CMOS sensors to be used

- New optical & cooling systems U1b @ 2026

Upgrade II UT (U2UT)

LHCb China group will lead this upgrade

Channel occupancy [%]

0.42	0.45	0.47	0.49	0.52	0.54	0.57	0.60	0.60
0.46	0.49	0.52	0.56	0.59	0.63	0.68	0.74	0.77
0.53	0.58	0.62	0.68	0.73	0.83	0.89	1.00	1.06
0.64	0.70	0.77	0.86	0.96	1.10	1.26	1.48	1.63
0.78	0.88	0.97	1.13	1.27	1.54	1.81	2.34	2.72
0.96	1.10	1.23	1.45	1.68	2.05	2.63	2.84	3.87
1.28	1.45	1.54	1.81	2.04	2.57	3.42	4.48	3.95 / 5.13

Beam pipe

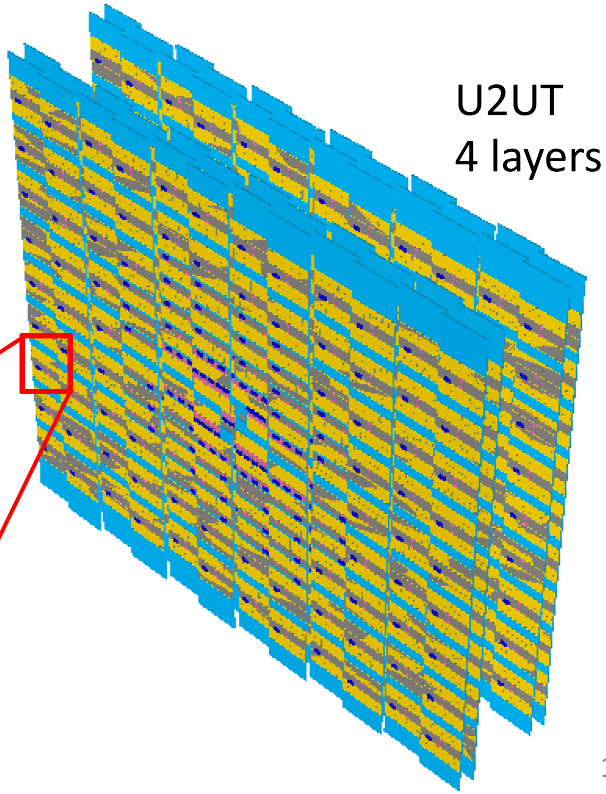
Current UT optimized for $\mathcal{L}_{\text{Run 3\&4}}$

Upgrade II luminosity $1.5\text{x}10^{34}\,\text{cm}^{-2}\text{s}^{-1}$ (x7.5 $\mathcal{L}_{\text{Run 3\&4}}$)

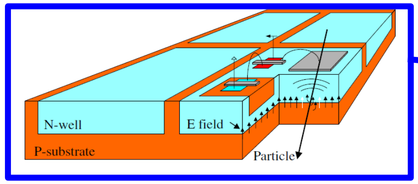
- The occupancy (max ~10%) will compromise the performance
- Radiation does too high for current sensor

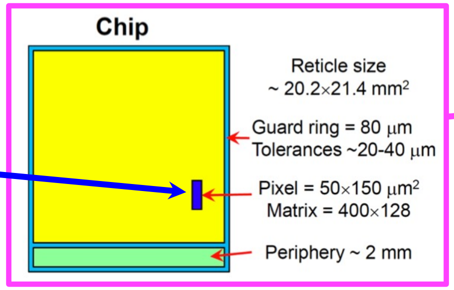
U2UT:

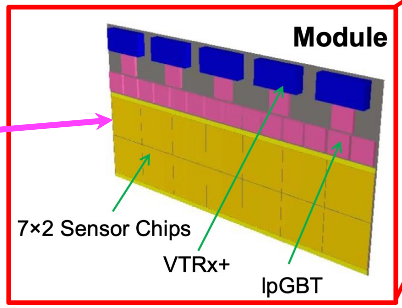
- CMOS MAPS technique applied
  Very promising and cost effective for large area pixel detectors.



Monolithic Active Pixel Sensor (MAPS)

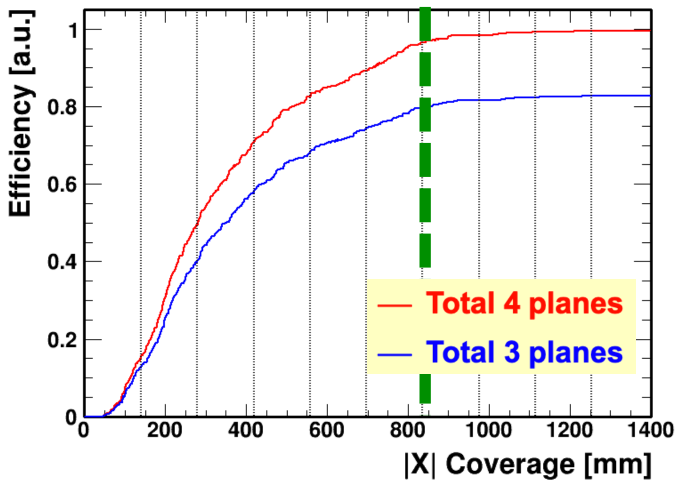




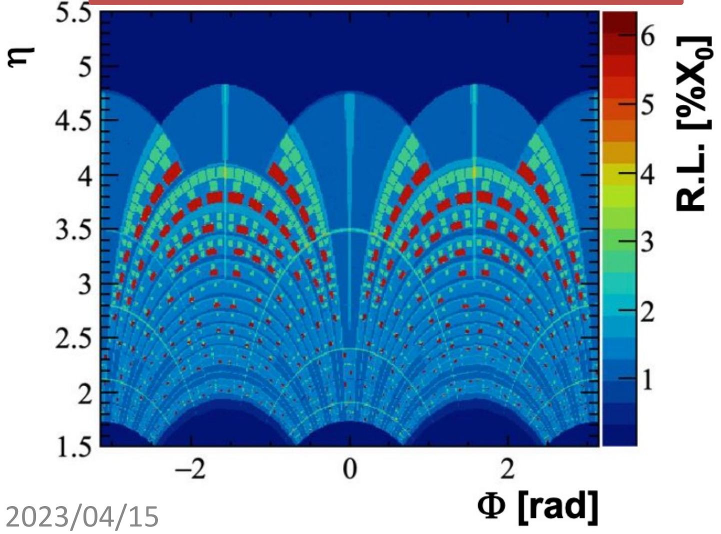


U2UT R&D status

Track efficiency vs X coverage



R.L. as functions of Φ and η

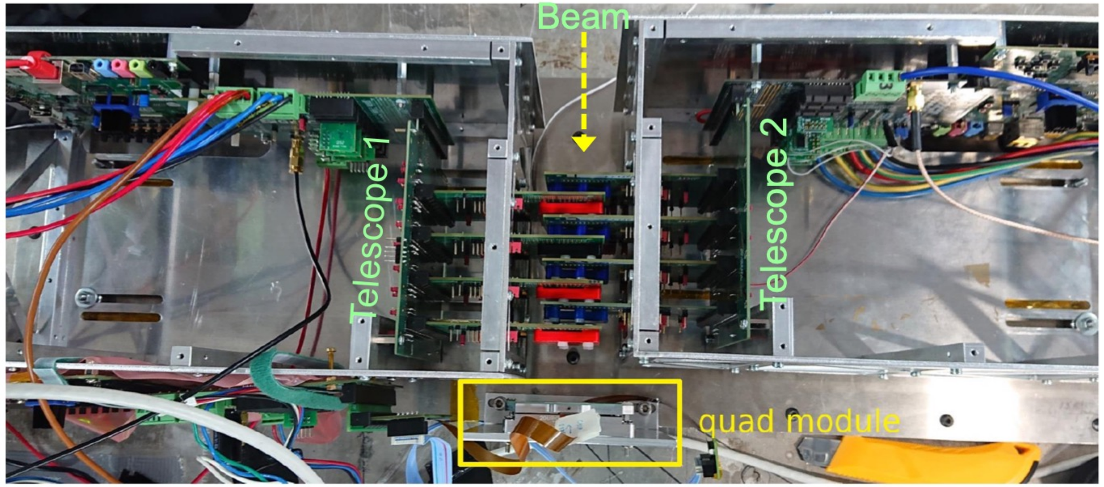


U2UT software ⇦ Lead by LHCb China group

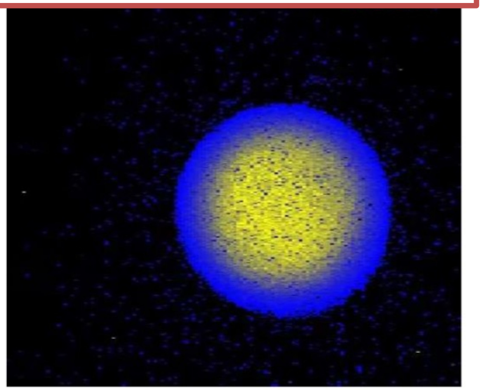
- Preliminary studies on
  - Track efficiency for $B^- \to D^0 K^-, D^0 \to K_S \pi^+ \pi^-, K_s \to \pi^+ \pi^-$ Optimizing U2UT coverage
  - Detector simulation mostly done and RL calculated

U2UT chips

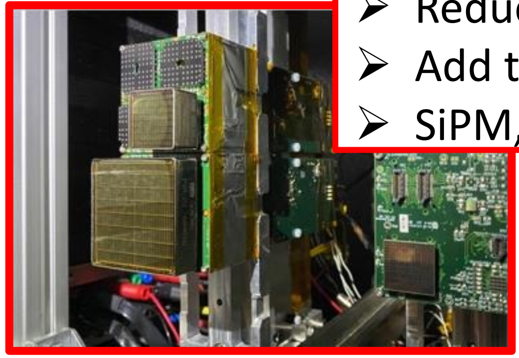
- Testbeam @ DESY in April 2022
- Tested in cosmic ray and various radioactive sources



Hitmap with Fe55 source

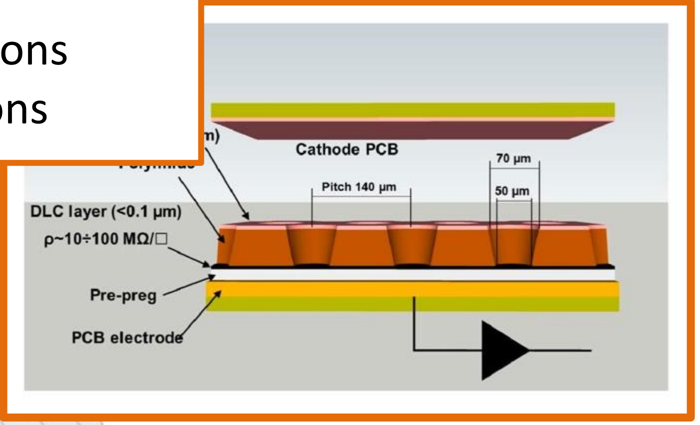


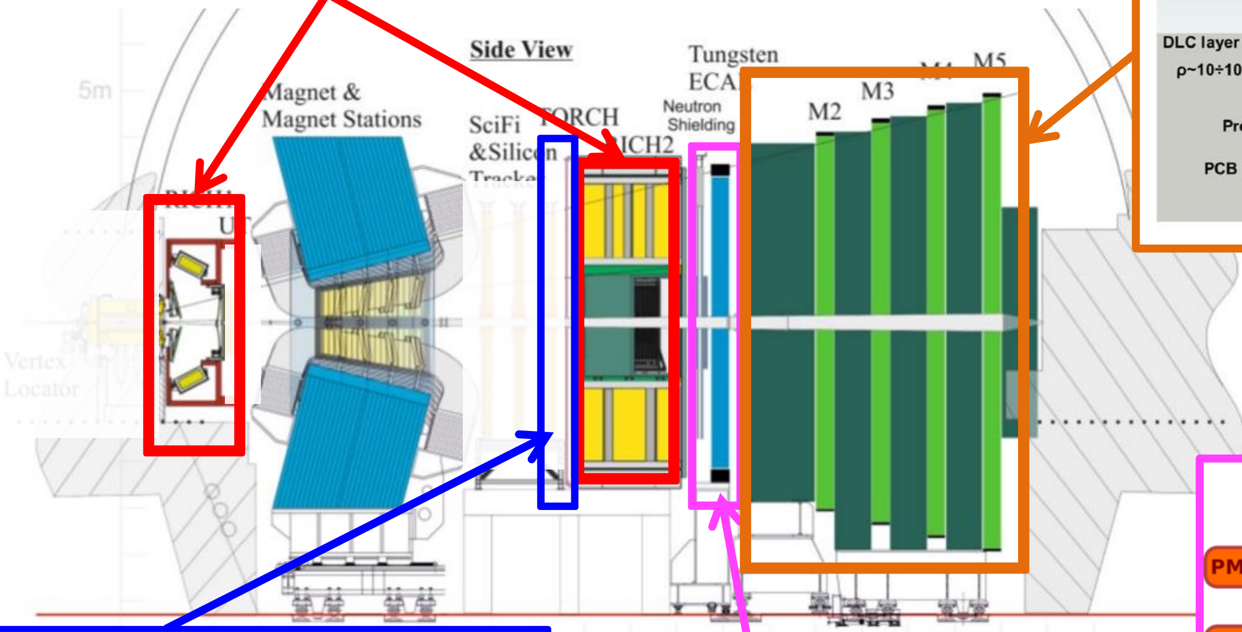
Particle Identification (PID) Detectors

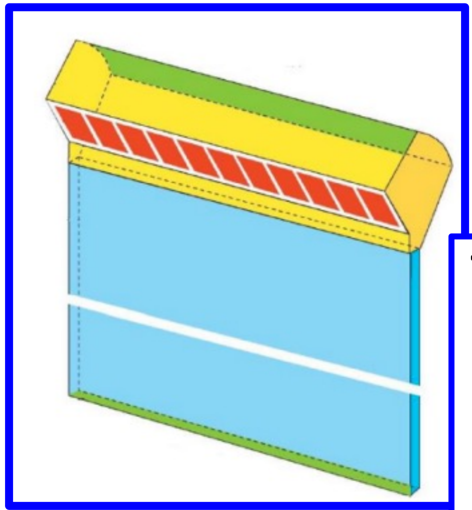


RICH1, RICH2
- Reduced pixel size
- Add timing information
- SiPM, MCP

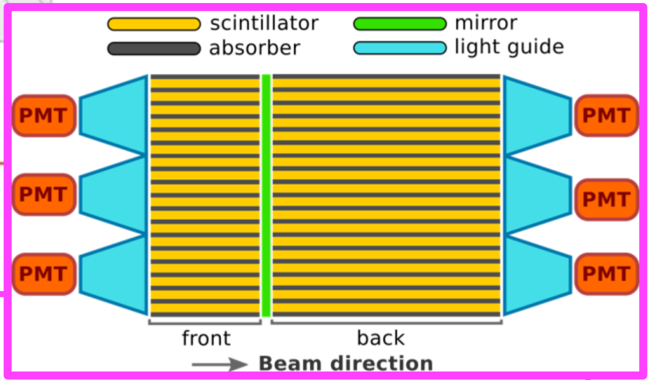
Muon
- µRWELL for inner regions
- MWPC for outer regions







TORCH
- To enhance PID capibilities for soft particles
- Measure light angle, path lenth and TOF



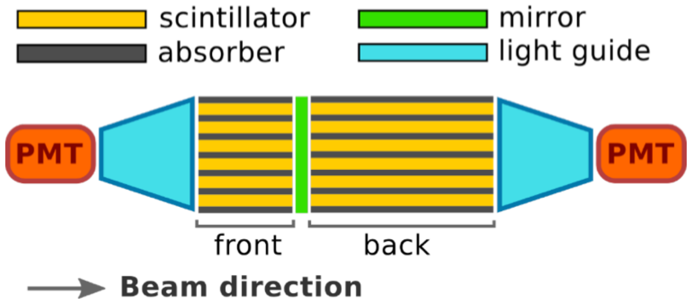
ECAL
- Space & time, longitudinal segmentation
- SPACAL with radiation hard crystals

5D calorimeter with precision timing

LHCb China groups are contributing

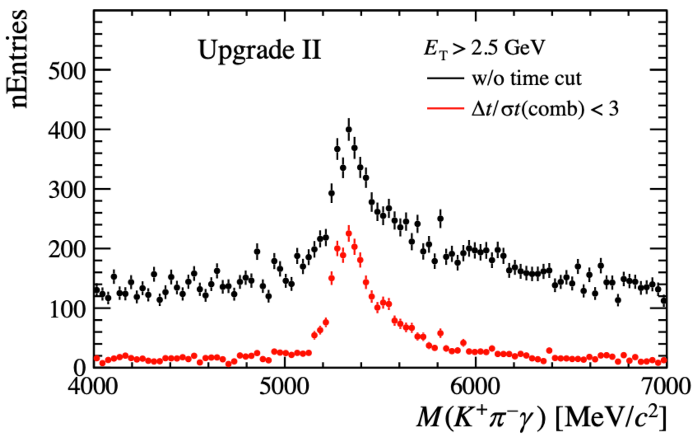
Key features: energy resolution $(10\%/\sqrt{E} \oplus 1\%)$, radiation hardness (up to 1 MGy), timing capability (tens of ps) and granularity.

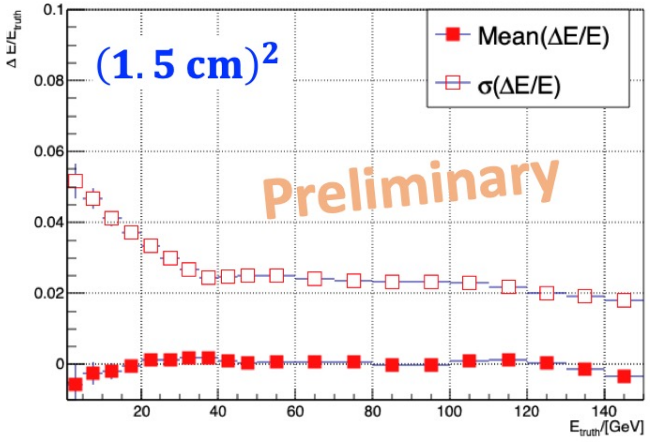
- Multiple technologies for different regions from inner to outer
- Possibility of adding timing layer: Si layers.
- Possibility of replacing the inner-most modules at LS3.

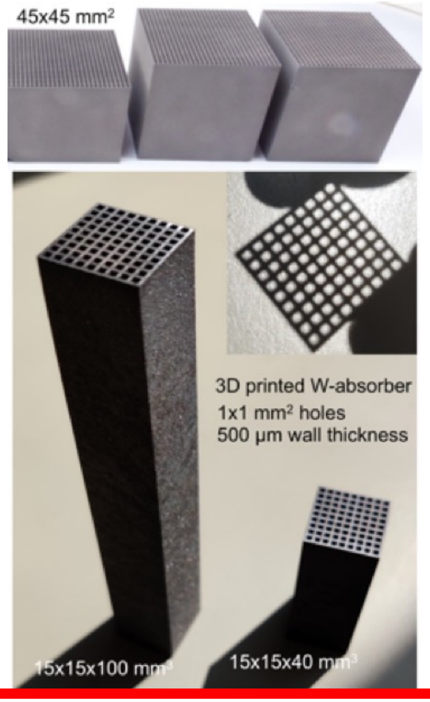


Significant contributions from LHCb China group

- Simulation studies
- Module production







Expected physics results @ LHCb Upgrade II

Key observables in flavor physics

Observable	Current LHCb (up to 9 fb^{-1})		Upgrade I (23 fb^{-1})	Upgrade I (50 fb^{-1})	Upgrade II (300 fb^{-1})
CKM tests					
γ ($B \to DK$, *etc.*)	4°	[9,10]	1.5°	1°	0.35°
ϕ_s ($B_s^0 \to J/\psi\phi$)	32 mrad	[8]	14 mrad	10 mrad	4 mrad
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$, *etc.*)	6%	[29,30]	3%	2%	1%
a_{sl}^d ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4}	[34]	8×10^{-4}	5×10^{-4}	2×10^{-4}
a_{sl}^s ($B_s^0 \to D_s^-\mu^+\nu_\mu$)	33×10^{-4}	[35]	10×10^{-4}	7×10^{-4}	3×10^{-4}
Charm					
ΔA_{CP} ($D^0 \to K^+K^-, \pi^+\pi^-$)	29×10^{-5}	[5]	13×10^{-5}	8×10^{-5}	3.3×10^{-5}
A_Γ ($D^0 \to K^+K^-, \pi^+\pi^-$)	11×10^{-5}	[38]	5×10^{-5}	3.2×10^{-5}	1.2×10^{-5}
Δx ($D^0 \to K_S^0\pi^+\pi^-$)	18×10^{-5}	[37]	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%	[40,41]	41%	27%	11%
$S_{\mu\mu}$ ($B_s^0 \to \mu^+\mu^-$)	—		—	—	0.2
$A_T^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
A_T^{Im} ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$\mathcal{A}_{\phi\gamma}^{\Delta\Gamma}(B_s^0 \to \phi\gamma)$	$^{+0.41}_{-0.44}$	[51]	0.124	0.083	0.033
$S_{\phi\gamma}(B_s^0 \to \phi\gamma)$	0.32	[51]	0.093	0.062	0.025
$\alpha_\gamma(\Lambda_b^0 \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$	[53]	0.148	0.097	0.038
Lepton Universality Tests					
R_K ($B^+ \to K^+\ell^+\ell^-$)	0.044	[12]	0.025	0.017	0.007
R_{K^*} ($B^0 \to K^{*0}\ell^+\ell^-$)	0.12	[61]	0.034	0.022	0.009
$R(D^*)$ ($B^0 \to D^{*-}\ell^+\nu_\ell$)	0.026	[62,64]	0.007	0.005	0.002

LHCC-2021-012

Upgrade II will fully realize the flavor physics potential of the HL-LHC

Further pursue a broad physics programme

- Spectroscopy
- High precision EW and Higgs
- Dark sector
- Exotic search
- Heavy ions and fixed target

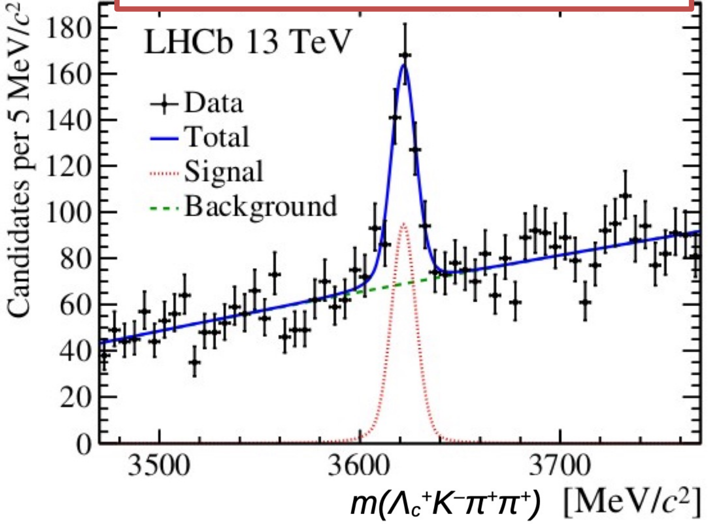
Success of the physics programme relies on

- HL-LHC providing LHCb ~ 50 fb^{-1}/year during Run 5&6
- A detector with similar or better performance as the present one for Run 3

Exotic hadrons

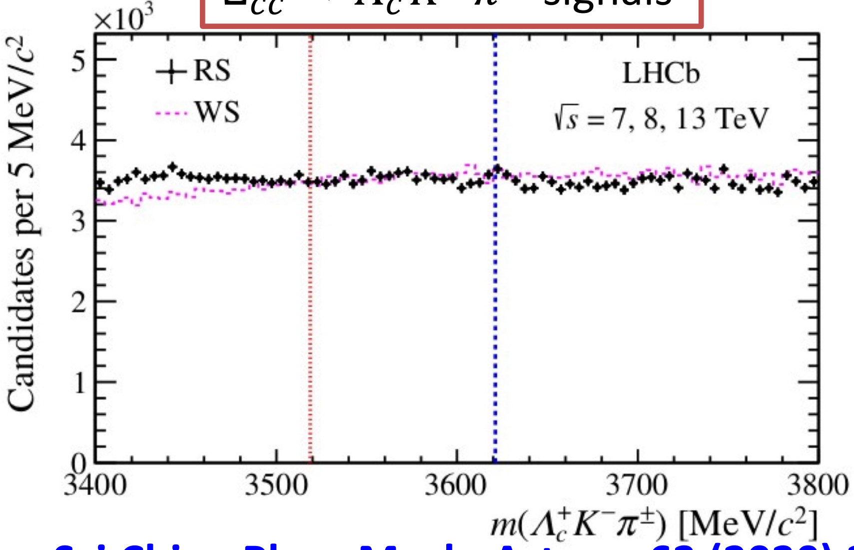
Q: Why do we observe the Ξ_{cc}^{++}, but not the Ξ_{cc}^{+}?

$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ signals



PRL119 (2017) 112001

$\Xi_{cc}^{\pm} \to \Lambda_c^+ K^- \pi^{\pm}$ signals



Sci.China Phys. Mech. Astron. 63 (2020) 221062

Likely explanation: $\tau(\Xi_{cc}^{++})\sim 250$ fs [PRL121 (2018) 052002], $\tau(\Xi_{cc}^{+})\sim 80$ fs [predicted]

Current VELO (Run 1+2) performance enough to separate Ξ_{cc}^{++}, but not Ξ_{cc}^{+} from PV background

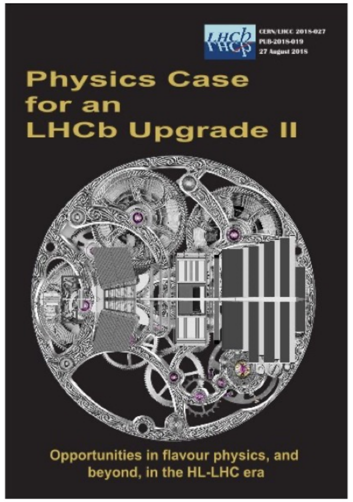
- Better performance expected in U1 & U2

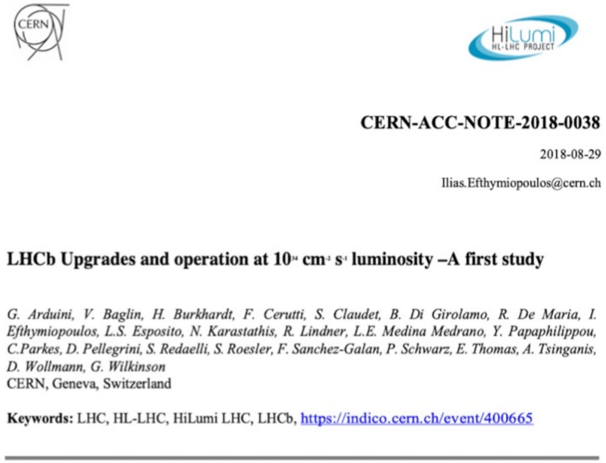
Summary

LHCb upgrades
- Upgrade I: to be completed in weeks
- Upgrade II: starts in LS4, with consolidation in LS3

LHCb Upgrade II to fully exploit HL-LHC for flavor physics and beyond
- FTDR approved and now in R&D phase
  Next: detector TDRs, construction, installation and eventually operation for physics
- LHCb China groups contribute more significantly, and you are welcome to join

More physical results can be expected from LHCb





CERN-ACC-NOTE-2018-0038
2018-08-29
Ilias.Efthymiopoulos@cern.ch

LHCb Upgrades and operation at 10^{34} cm^{-2} s^{-1} luminosity –A first study

G. Arduini, V. Baglin, H. Burkhardt, F. Cerutti, S. Claudet, B. Di Girolamo, R. De Maria, I. Efthymiopoulos, L.S. Esposito, N. Karastathis, R. Lindner, L.E. Medina Medrano, Y. Papaphilippou, C.Parkes, D. Pellegrini, S. Redaelli, S. Roesler, F. Sanchez-Galan, P. Schwarz, E. Thomas, A. Tsinganis, D. Wollmann, G. Wilkinson
CERN, Geneva, Switzerland

Keywords: LHC, HL-LHC, HiLumi LHC, LHCb, https://indico.cern.ch/event/400665

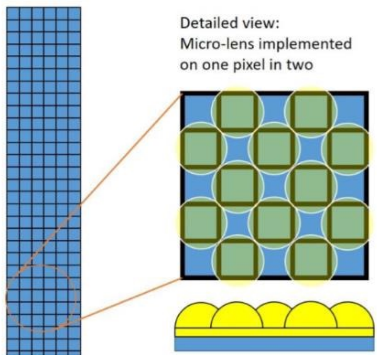
- Expression of Interest, LHCC-2017-003
- Physics case, LHCC-2018-027
- Accelerator study, CERN-ACC-2018-038

Thank you for your attentions

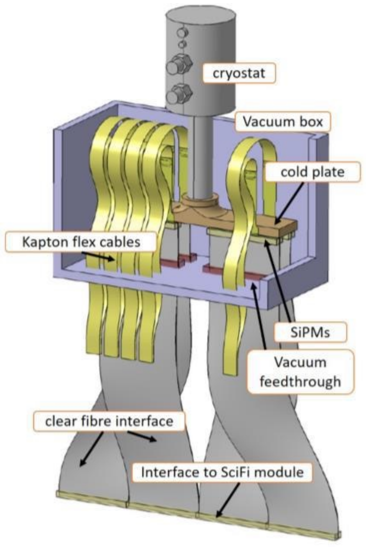
Backup

Mighty Tracker

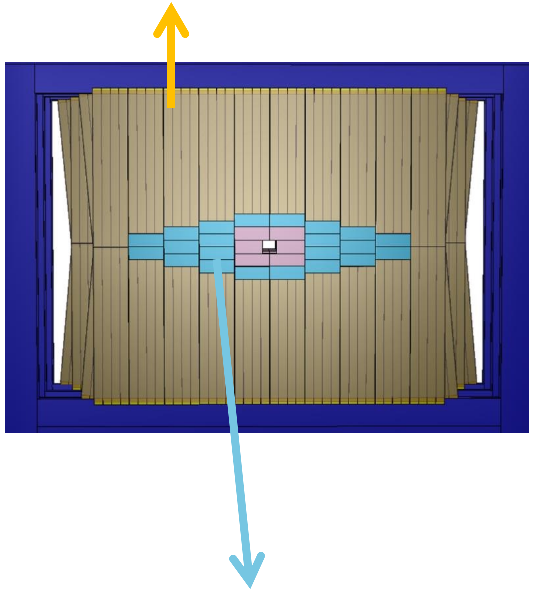
Micro-lens

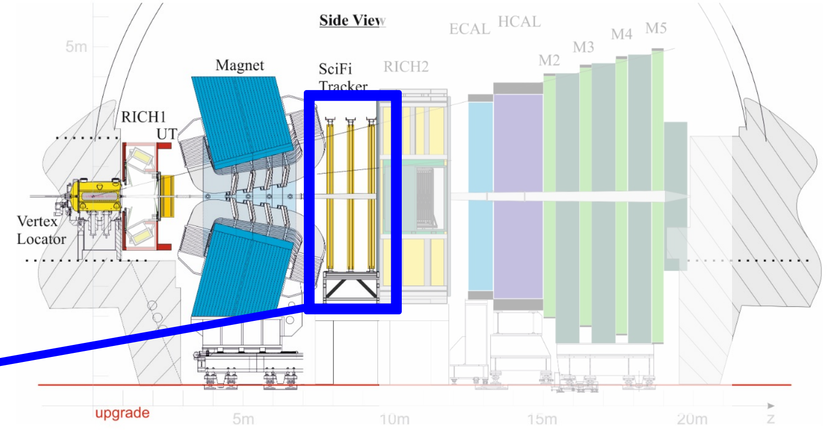


Cryogenic cooling

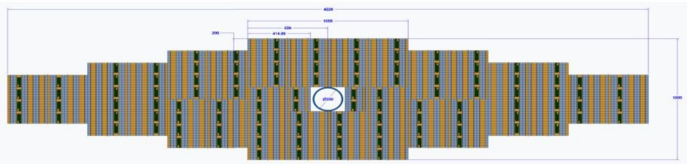


Keep SciFi design at outer region
- Further away from beam
- Micro-lens on SiPM to enhance light collection
- Crypgenic cooling for SiPM: -40°C ⇒ -120°C

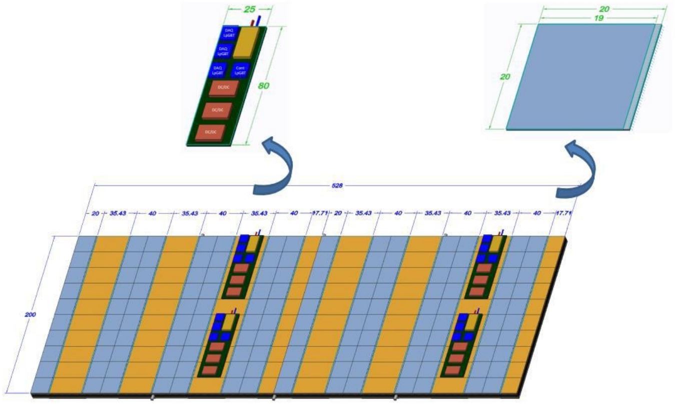




MT-CMOS Plane



HV-COMS MAPS detector (as U2UT)
- 6 layers, 18 m^2 in total
- Pixel size ~50x150 μm2
- Upgrade the inner-most at LS3

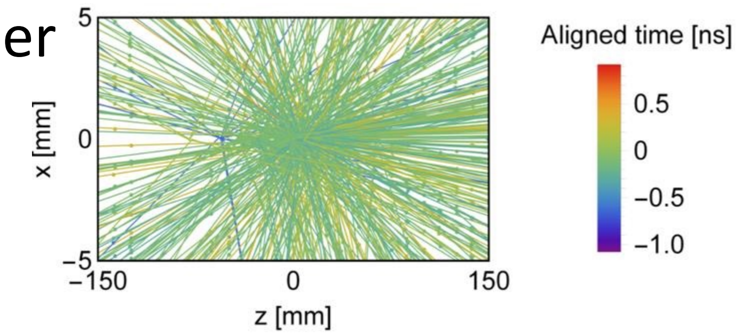


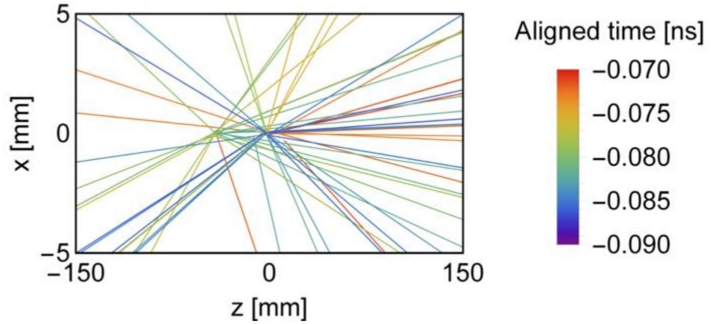
MT-CMOS Module

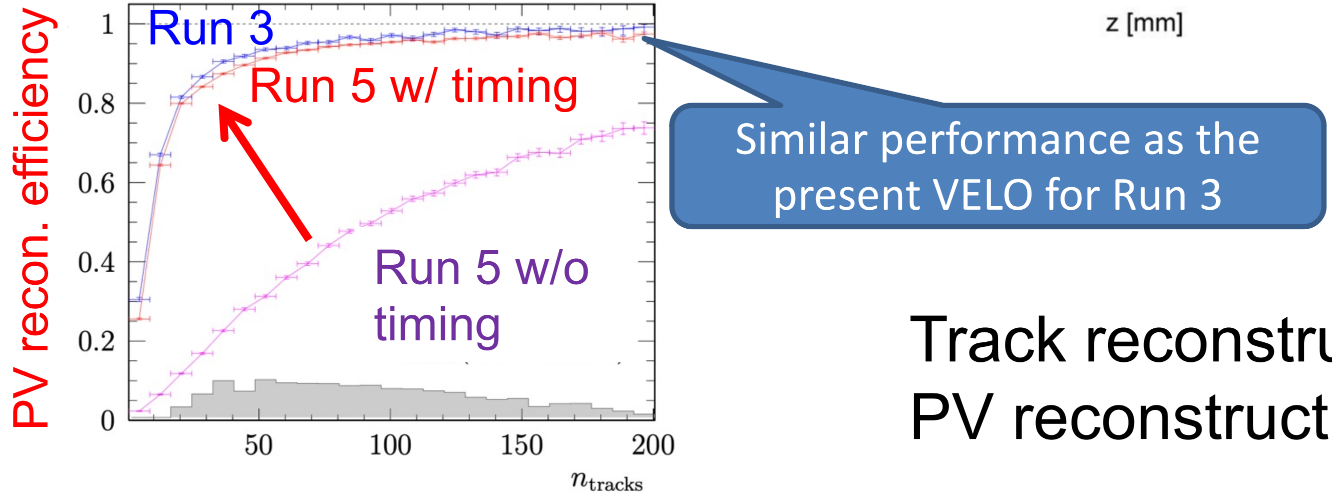
4D VELO with precision timing

PV RMS time distribution in the order of 186 ps (Gaussian)

- 20 ps track binning sufficient







Track reconstruction benefits from t

PV reconstruction efficiency recovered

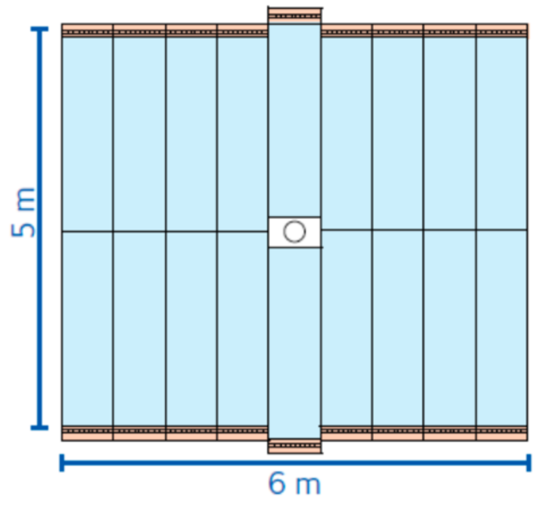
New techiques in R&D:

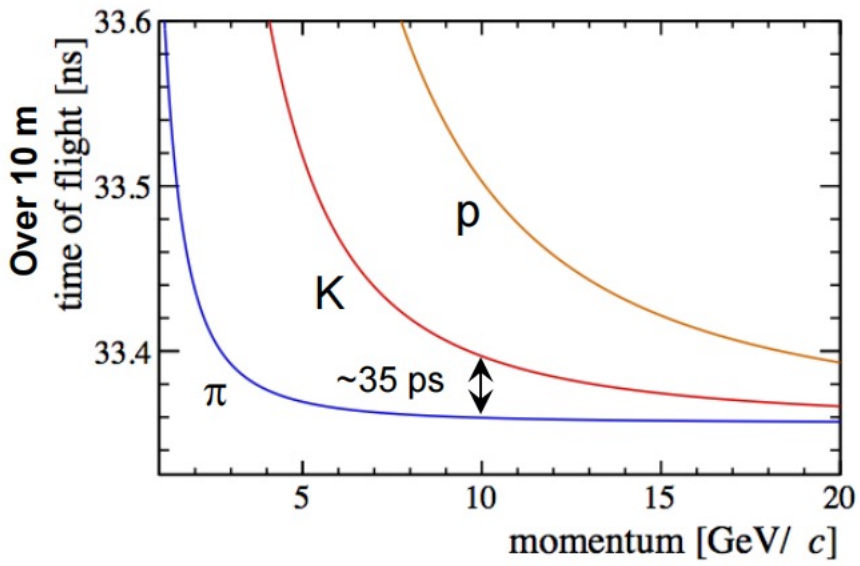
- Sensor: timing (~50 ps), radiation hardness (max ~$6\text{x}10^{16} n_{eq}/cm^2$)
  Candidates: Planar, LGAD, 3D pixel or new concepts
- Candidates of 28 nm tech. ASICs: VeloPix2, TimePix4 or PicpPix
- Replaceable modules, thinner or no RF foil, robust 3D printed Ti cooling substrate...

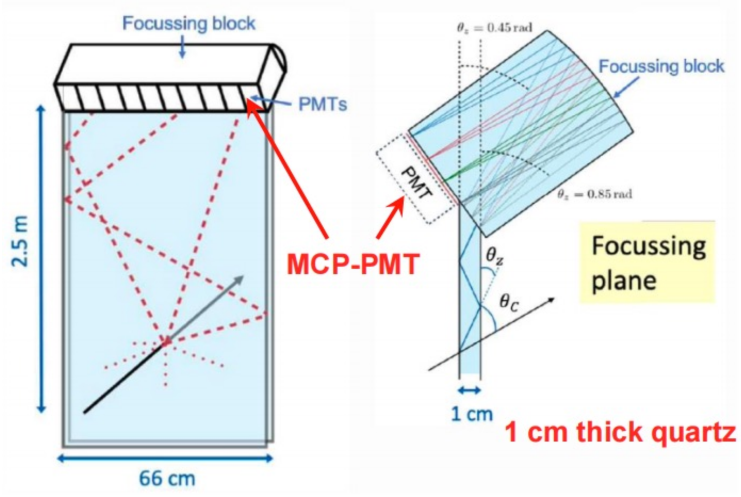
TORCH: Time of Flight Detector

Brand new detector to enhance low momentum PID capabilities, improve background suppression and flavour tagging.

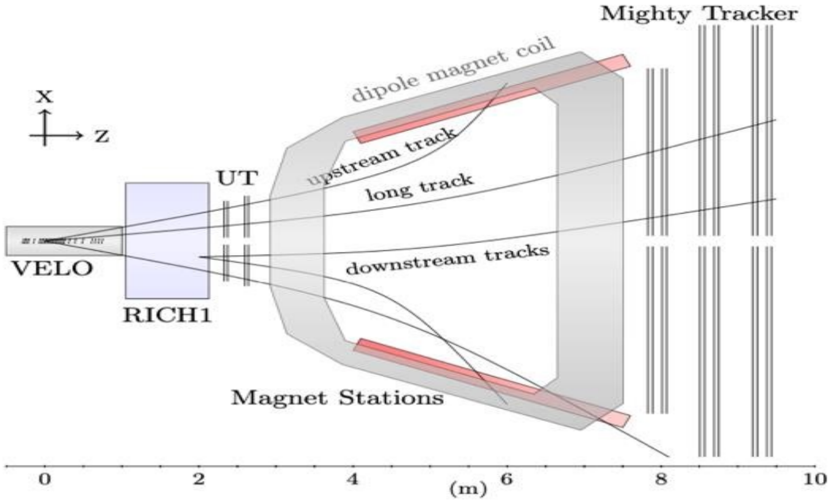
- Cherenkov photons produced by charged particles traversing quartz plane, then transported by total internal reflection to focusing block and detected with MCP-PMTs
- Measurement of Cherenkov angle, path length, and time of arrival.
- Aim for 10-15 ps resolution/track, needs ~30 photons, 70 ps/photon

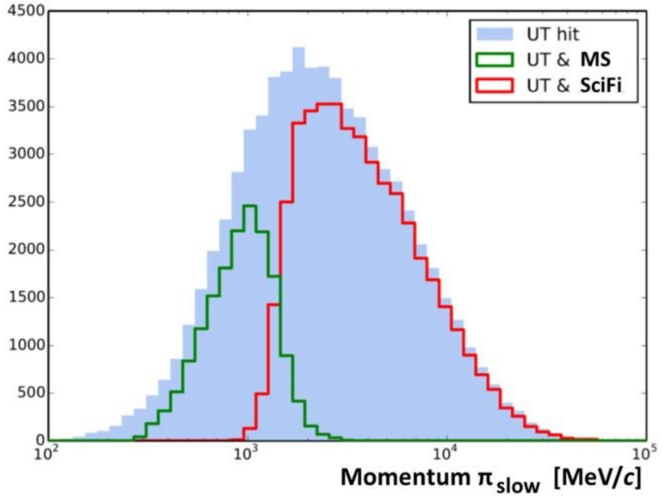


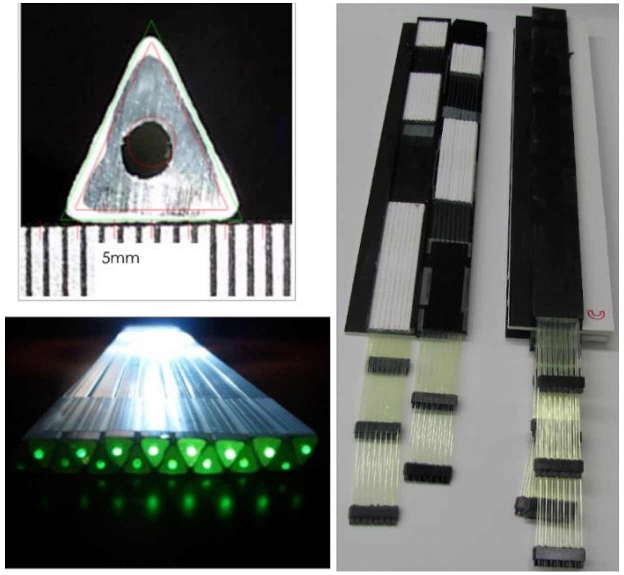




Magnet Stations (MS)







A new MS to be installed for reconstructing Upstream Tracks

- Tracking capability, reconstruction↗ for low momentum tracks.

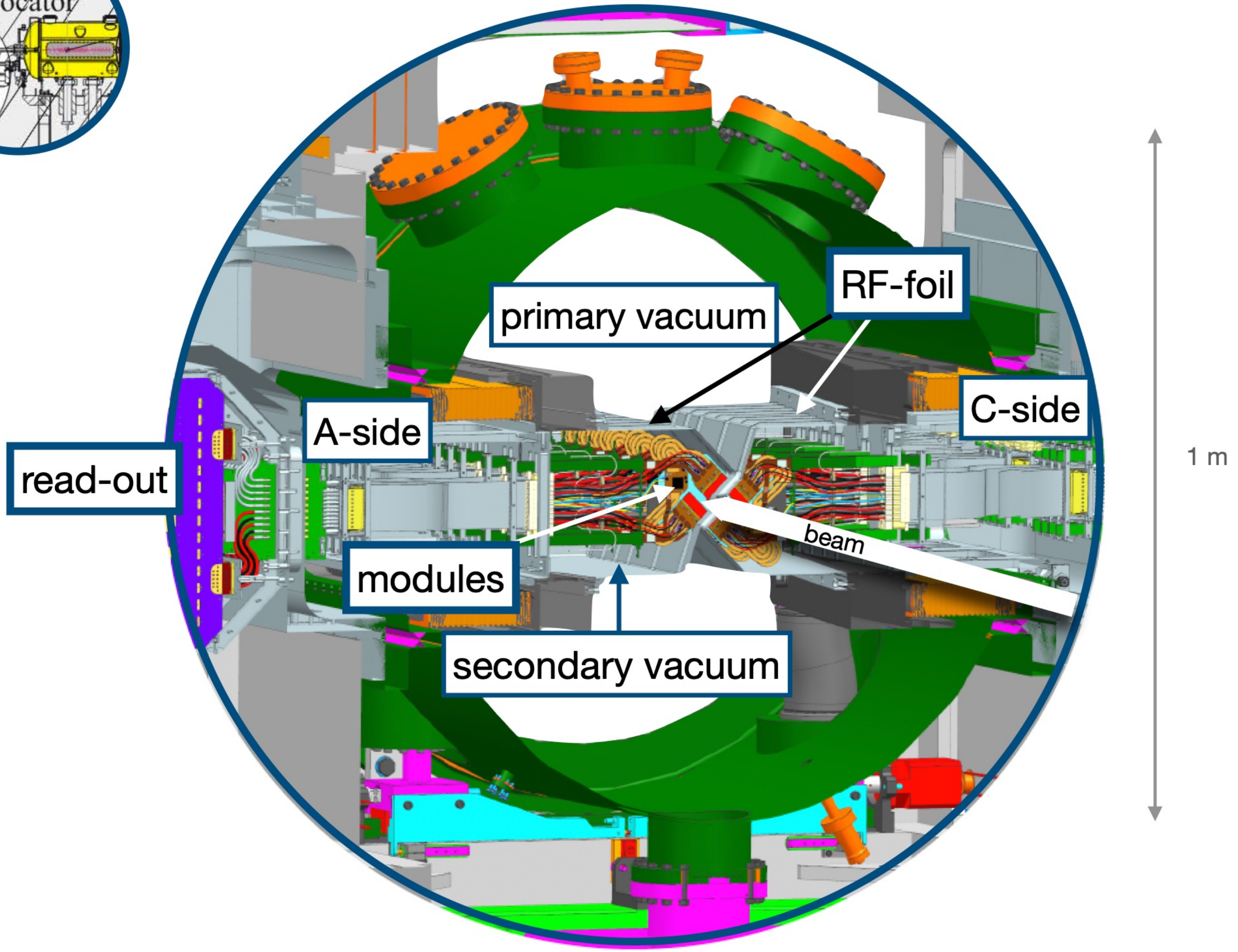
Instrument walls of magnet with extruded triangular scintillating bars.

- Light collected by WS, guided through clear fibers to SiPMs outside magnet.
- sub-% momentum measurement precision.

The Magnet Stations could be installed at LS3.

VELO


Vertex
Locator


primary vacuum
RF-foil
C-side
A-side
read-out
modules
beam
secondary vacuum
1 m

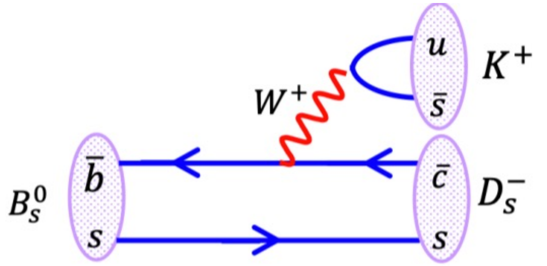
Prospect on CKM angle γ

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

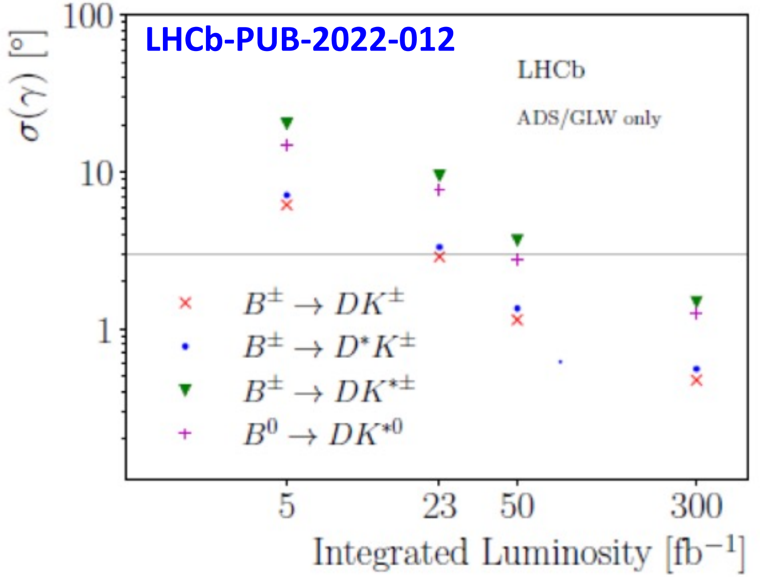
$$\gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^{*}}{V_{cd}V_{cb}^{*}}\right)$$

> Run 1-2:
> Some tension between direct and indirect methods
> need better precision from tress measurements

JHEP 12 (2021) 141

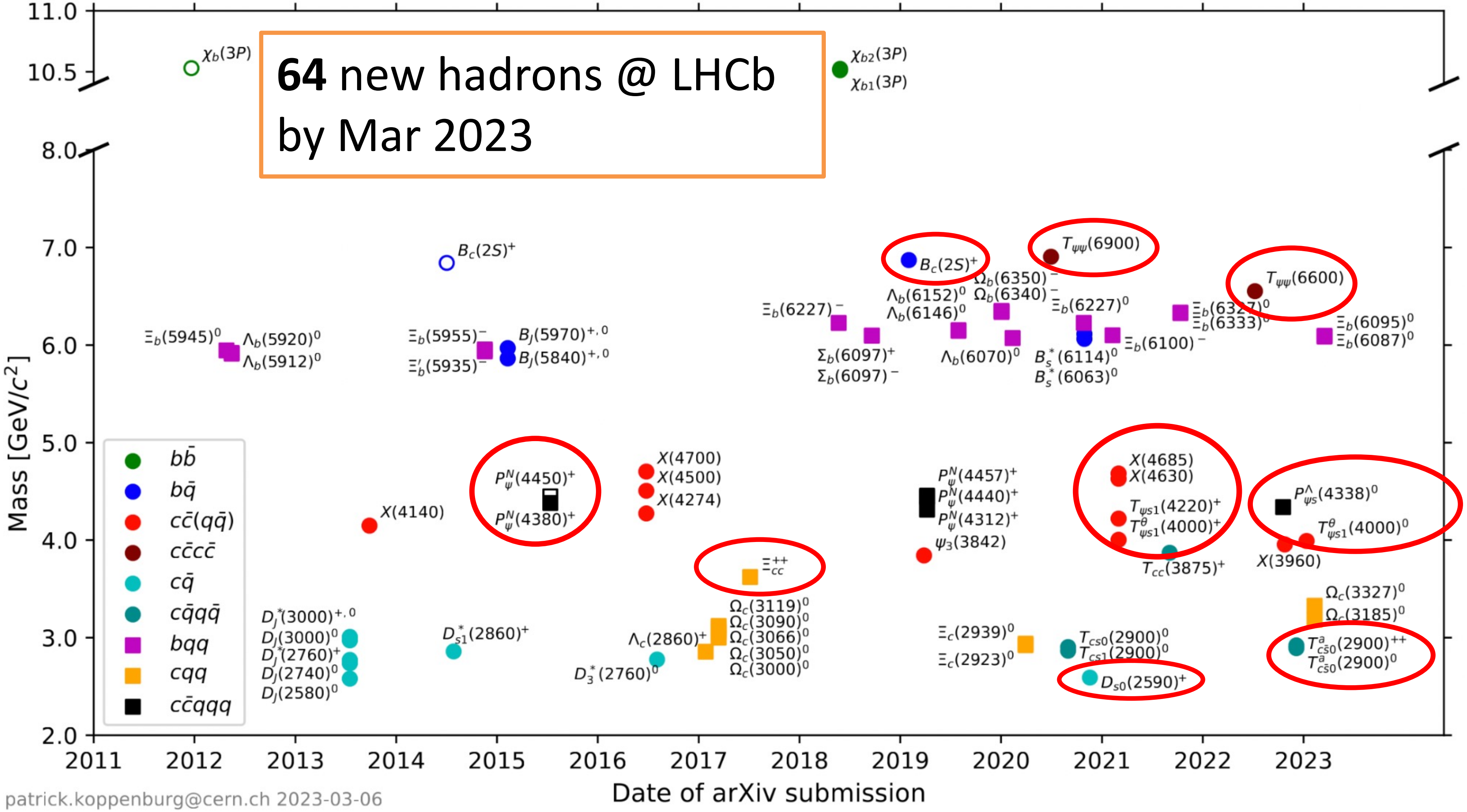


- Upgrade in sensitivity: combination of many decay channels in $B_{(s)} \to D_{(s)}^{(*)} h^{(*)}$
  - Charged and neutral (π^0, γ)
  - Two- and multi body D decays
  - Fully and partially reconstructed



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

New hadrons @ LHCb



LHCb China group contributions highlighted in **RED CIRCLEs**

Selected Topics for Prospects

With larger data sample (300 fb^{-1} for pp), we can expect from LHCb in

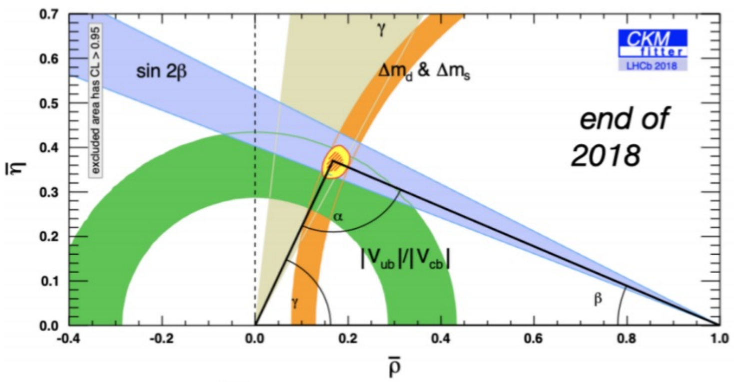
- CPV
- Rare decays
- New Physics searches
- Exotic hadrons
- Forward physics, QCD
- Dark matter
- Heavy ion physics

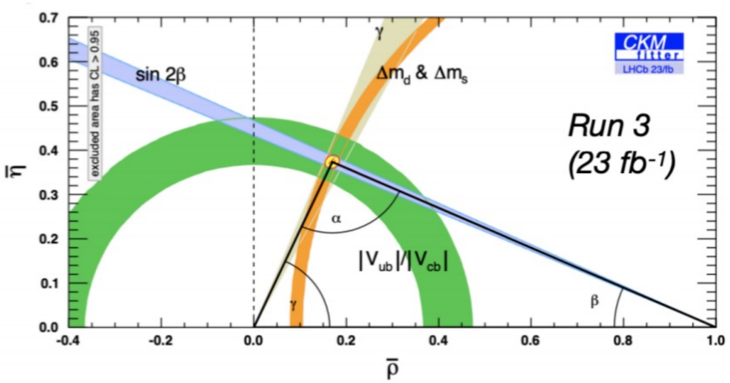
Constraining the Unitarity Triangle

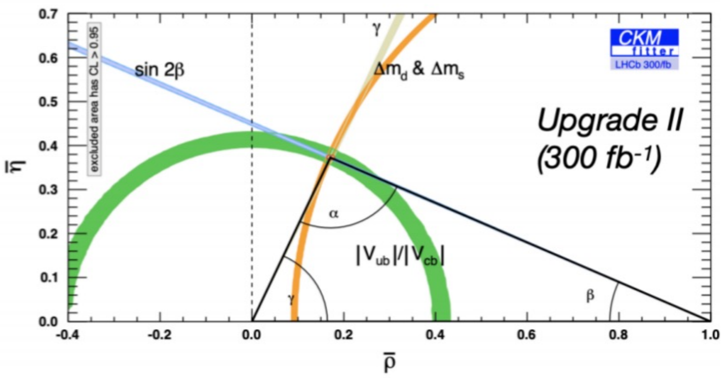
LHCb will test the CKM paradigm, searching for NP, with unprecedented accuracy

LHCb-only inputs for UT

LHCb U2 + LQCD improvement







- Two independent measurements: $(\Delta m_d/\Delta m_s, \sin 2\beta)_{\text{loop}}$ and $(V_{ub}, \gamma)_{\text{tree}}$
- Both pairs require Upgrade II for statistics ($\sin 2\beta$ and γ) and theory improvements for ($\Delta m_d/\Delta m_s$ and V_{ub})
  - ~Order of magnitude improvement in LQCD is assumed for Upgrade II

Possibility for clean picture of the flavor physics

CP Violation in Charm

Charm CP violation in decay discovered in 2019

$$\Delta A_{CP} = [-15.4 \pm 2.9] \times 10^{-4}$$

Phys.Rev.Lett. 122 (2019) 21, 211803

- SM or BSM?: Open question

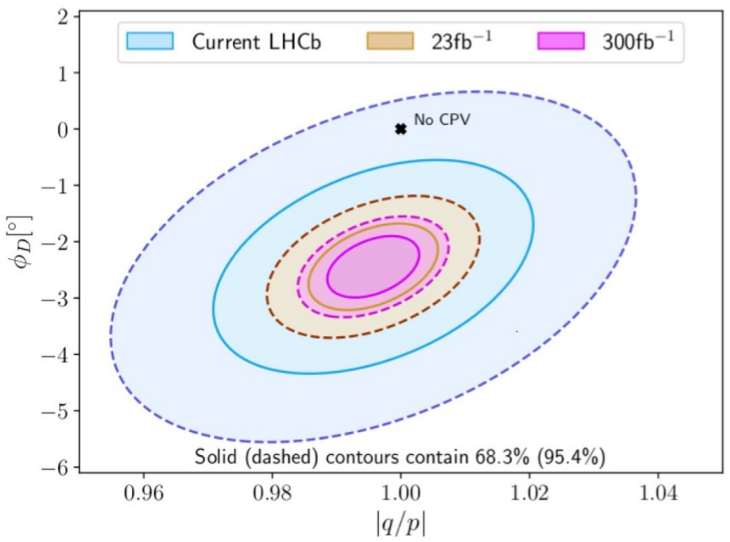
Upgrade II will allow for an order-of-magnitude improvement in precision

Sample ($\mathcal{L}$)	Tag	Yield $D^0 \to K^- K^+$	Yield $D^0 \to \pi^- \pi^+$	$\sigma(\Delta A_{CP})$ [%]	$\sigma(A_{CP}(hh))$ [%]
Run 1–2 (9 fb^{-1})	Prompt	52M	17M	0.03	0.07
Run 1–3 (23 fb^{-1})	Prompt	280M	94M	0.013	0.03
Run 1–4 (50 fb^{-1})	Prompt	1G	305M	0.01	0.03
Run 1–5 (300 fb^{-1})	Prompt	4.9G	1.6G	0.003	0.007

LHCC-2021-012

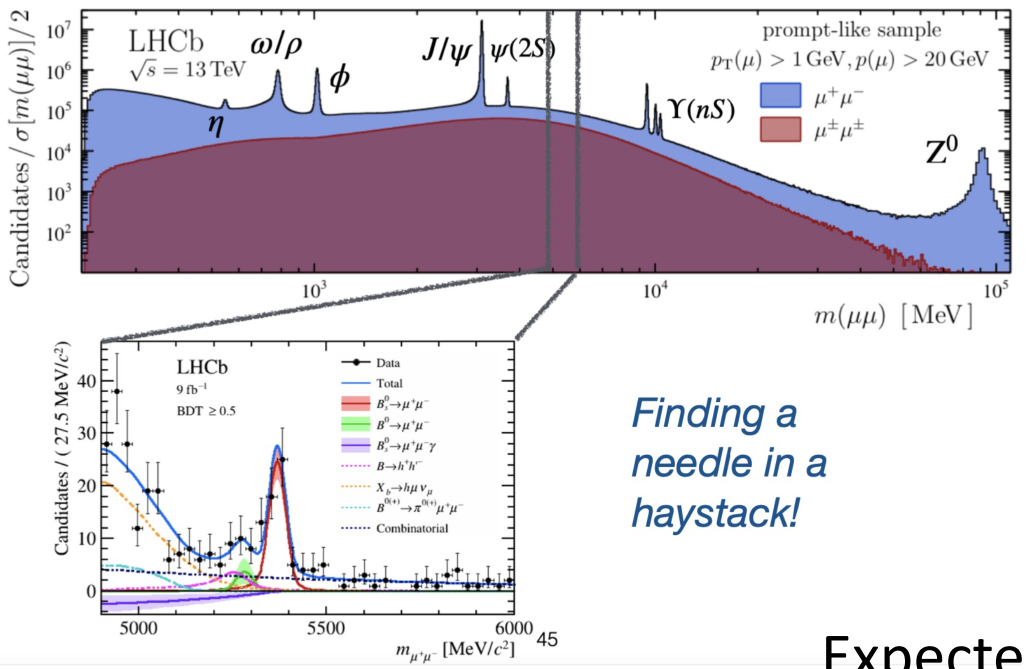
No sign of indirect CPV yet ($\sim\mathcal{O}(10^{-5})$)

- LHCb Upgrade II is the only planned experiment with possibility to observe CPV in charm mixing
- Searches of NP more efficient



Measurement of $B_s^0 \to \mu^+\mu^-$

PRL 120 (2018) 061801



Finding a needle in a haystack!

LHCb 9 fb^{-1} data result:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.09^{+0.46+0.15}_{-0.43-0.11})\times 10^{-9}$$
$\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.6\times 10^{-10}$ @ 95% C.L.

15% accuracy on B_s^0, compatible with SM

Phys.Rev.Lett. 128 (2022) 4, 041801

In upgrade II, we expect

- Large cross section
- Efficient muon trigger
- Excellent vertex and IP resolutions, and PID against $h \to \mu$ misID

Expected future statistical precisions on $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$

- ~7% after Run3, ~2% @ Upgrade II
- Systematics dominated by f_s/f_d, now @ 3%
- Effective lifetime $\tau_{\mu\mu}$ will be measured to 3%

Prospects in $b \to sl^+l^-$

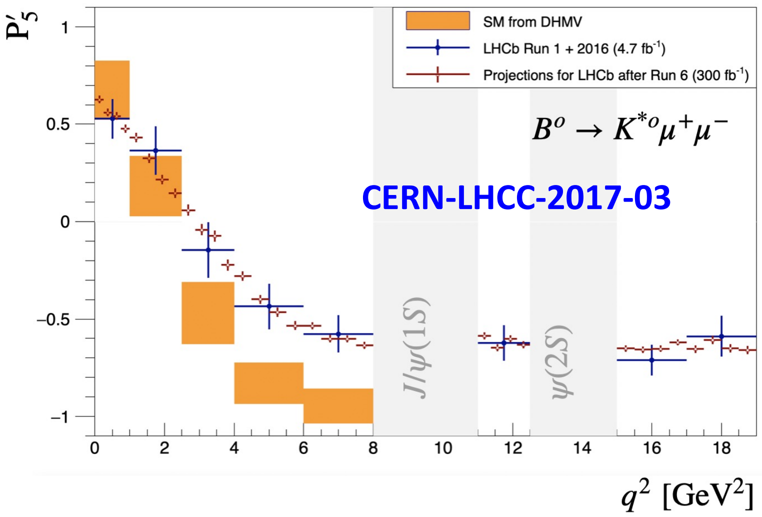
$b \to sl^+l^-$: Rare, SM suppressed, sensitive to $m_{\text{Heavy}}^{\text{NP}}$

Present P'_5result (Run 1+2016 data) ~ 3σ above SM

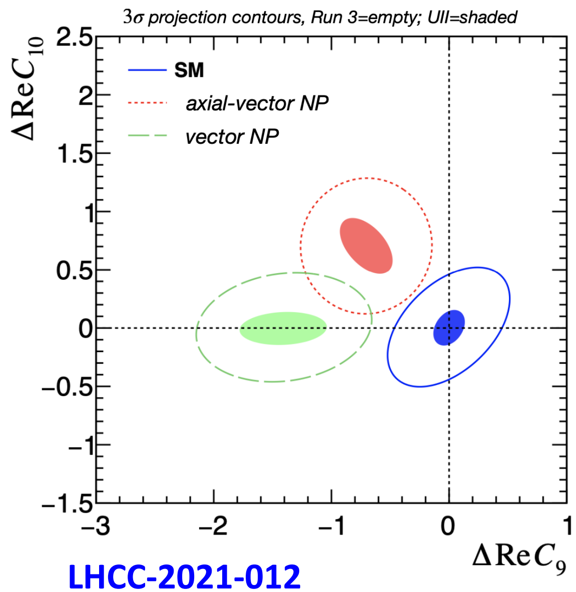
- Based on BR & angular analyses on $B^+ \to K^+\mu^+\mu^-$, $B^0 \to K^{(*)0}\mu^+\mu^-$, $B \to \phi\mu^+\mu^-$
- Upgrade II will clarify the situation

LFU in $R_K = \mathcal{B}(B \to K^+\mu^+\mu^-)/\mathcal{B}(B \to K^+e^+e^-)$

- Intriguing deviations in a range of channels ← need more data



CERN-LHCC-2017-03



LHCC-2021-012