第二届桂子山粒子物理前沿论坛

LHCb upgrades

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IHEP

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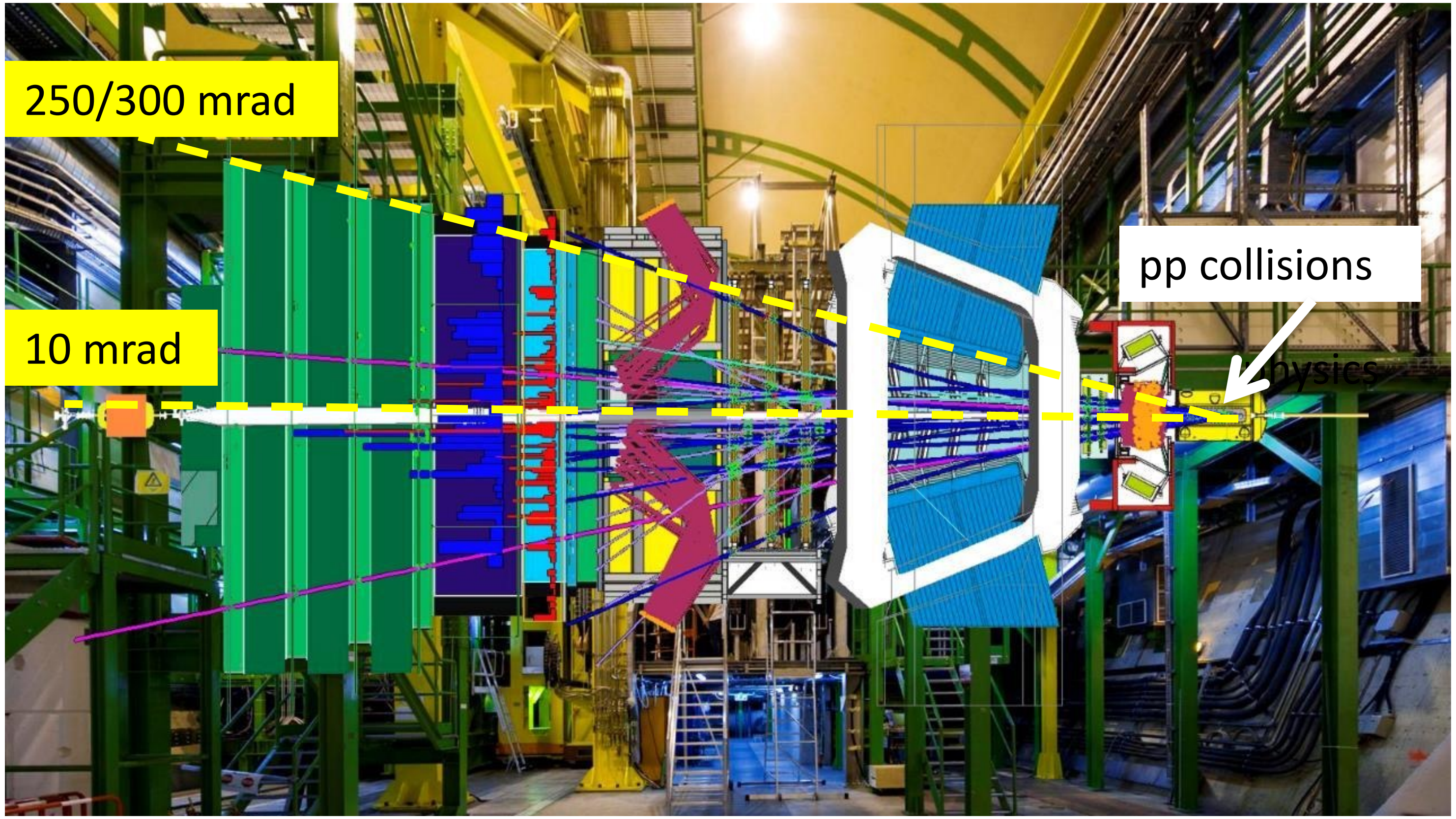
Outline

- Introduction
- Experiment sensitivity
- LHCb upgrades
  - Upgrade I (2019 - 2023)
    - ✓ Upgrade Ib (2026 – 2028)
  - Upgrade II (2032 -)
- Summary

LHCb: a forward spectrometer @ LHC

Detector before 2019



Main physics goal

- To study b & c sectors on CPV, rare decays, new physics...

$\Delta p/p = 0.5\% \ @ < 20\ \mathrm{GeV}/c,\ 1\% \ @ < 200\ \mathrm{GeV}/c$

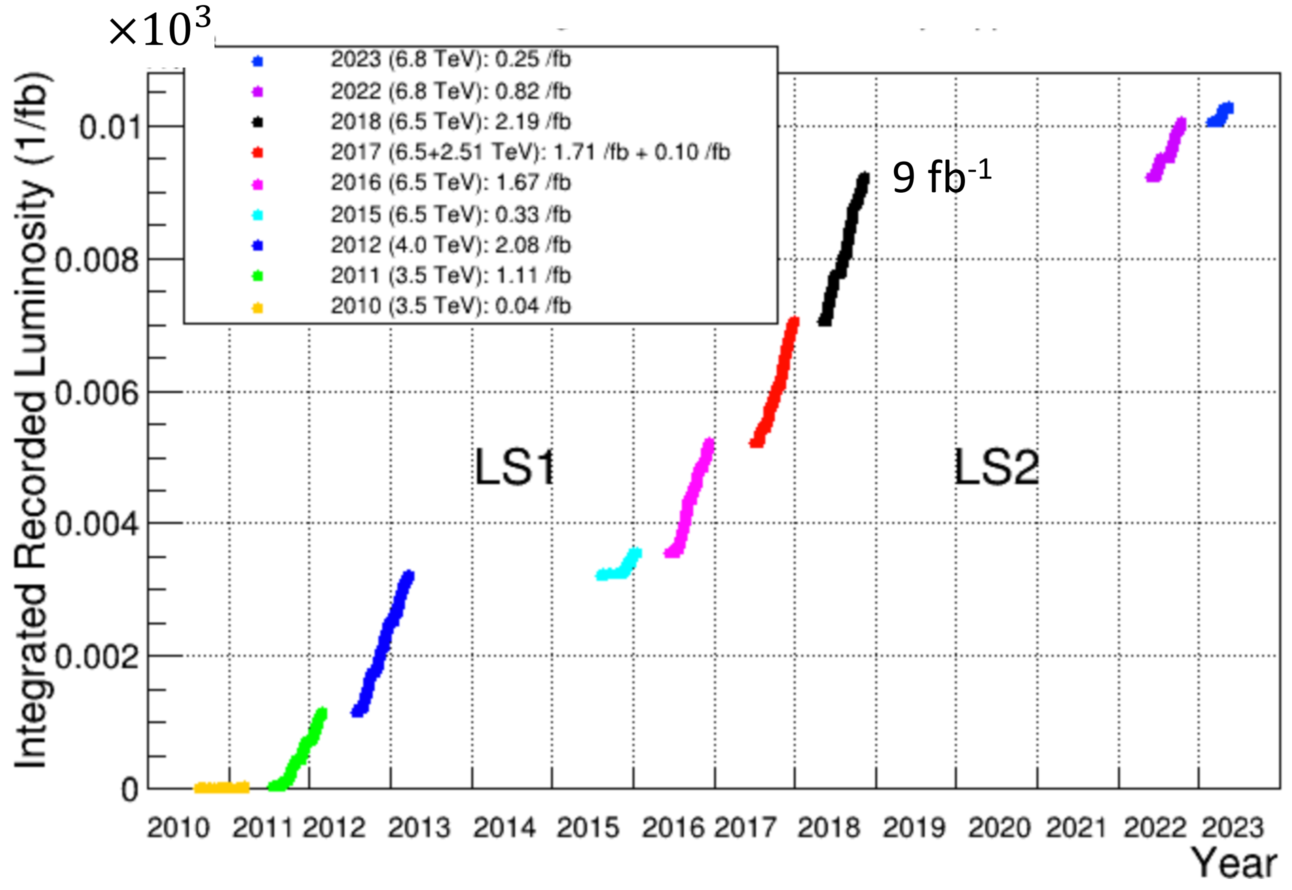
IP resolution ~ $15 + 29/p_T\ [\mathrm{GeV}/c]\ \mu m$

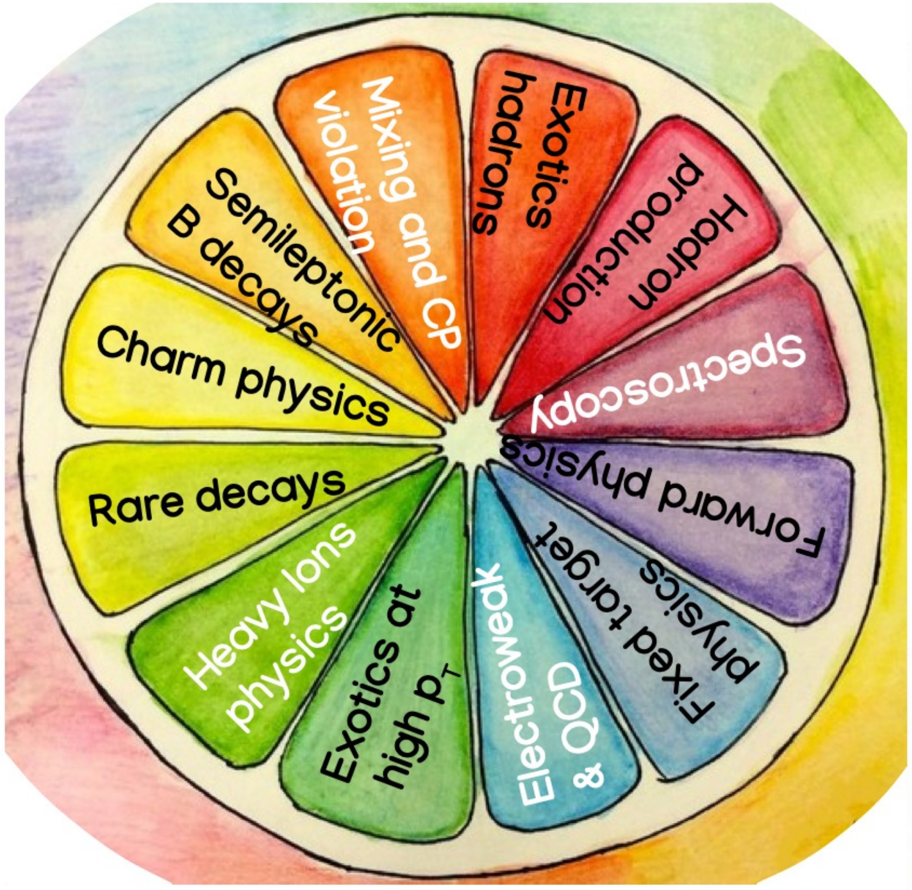
Decay time resolution 45 fs ($B_s \to J/\psi\phi$)

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 Upgrades

Upgrade I (U1), started in LS2 and installation completed in this March

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

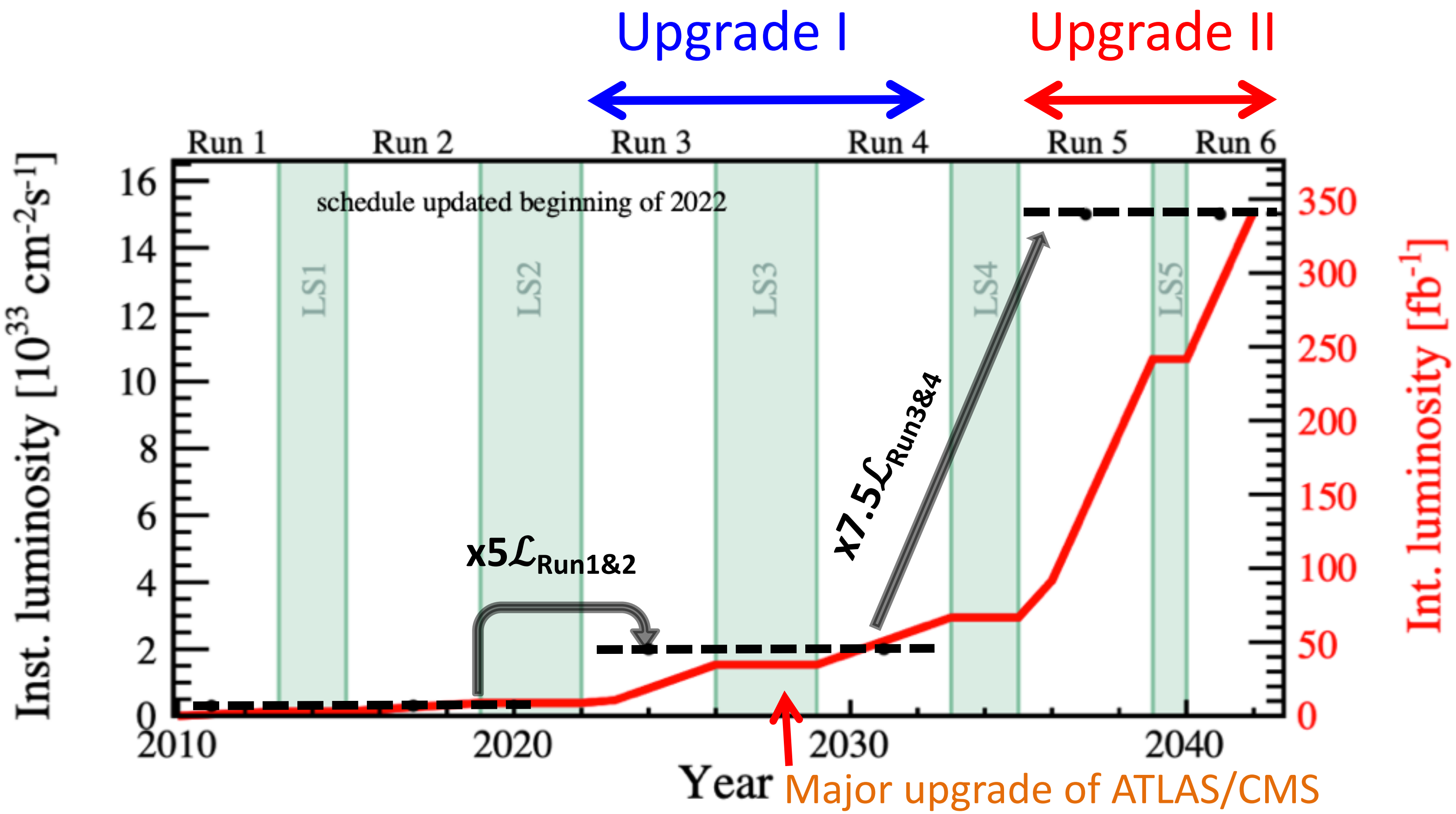
$\mathcal{L}_{int}$~**50** fb^{-1}

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)

- Introduction
- **Experiment sensitivity**
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$B_s \to \mu^+\mu^-$

LHCb 9 fb^{-1} data result:

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

$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.09^{+0.46+0.15}_{-0.43-0.11})\times10^{-9}$

$\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.6\times10^{-10}$ @ 95% C.L.

15% accuracy on B_s^0, compatible with SM

SM: $(3.66 \pm 0.14)\times10^{-9}$

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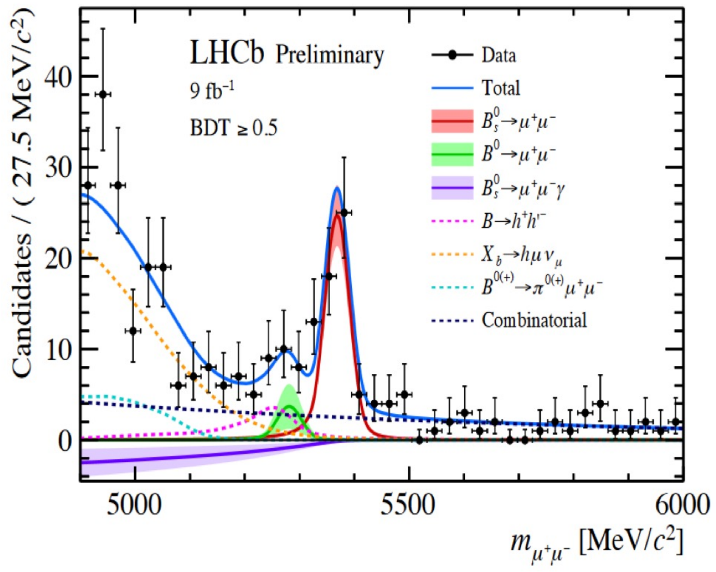


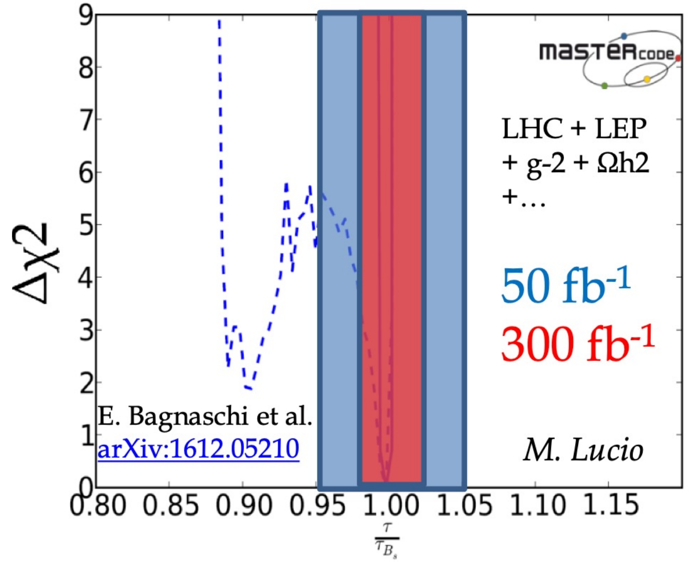
Expected precision

- ~7% @ UI, ~2% @ U II
  Systematics dominated by f_s/f_d ~3%

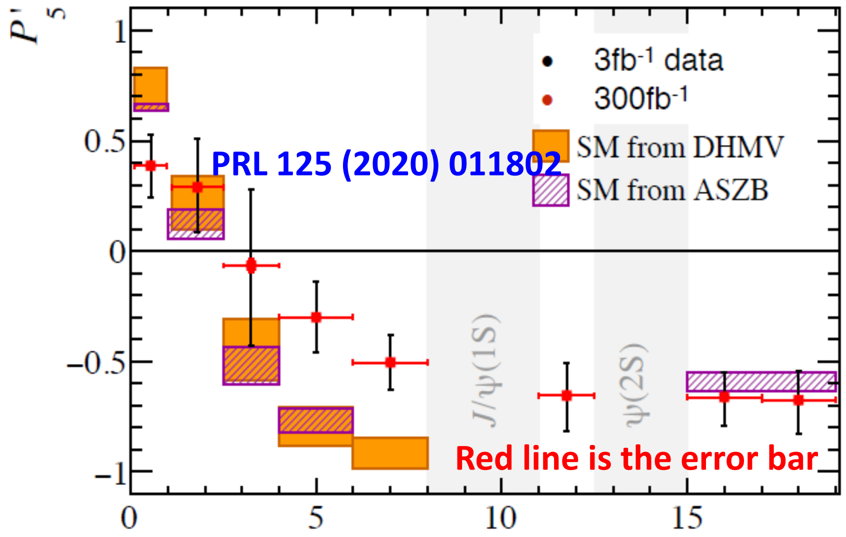
- Large cross section
- Efficient muon trigger
- Excellent σ_{VTX} & PID

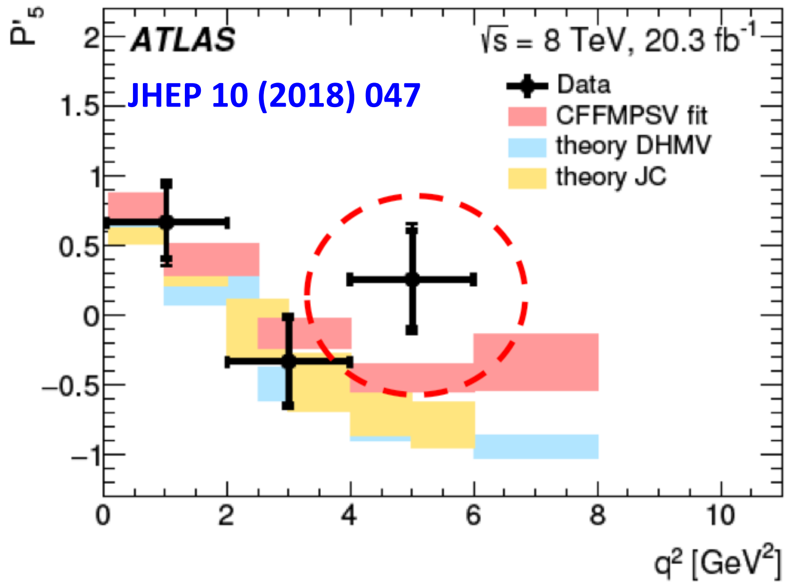
The effective B_s^0 lifetime in $B_s^0 \to \mu^+\mu^-$ also sensitive to NP for precisions of percent

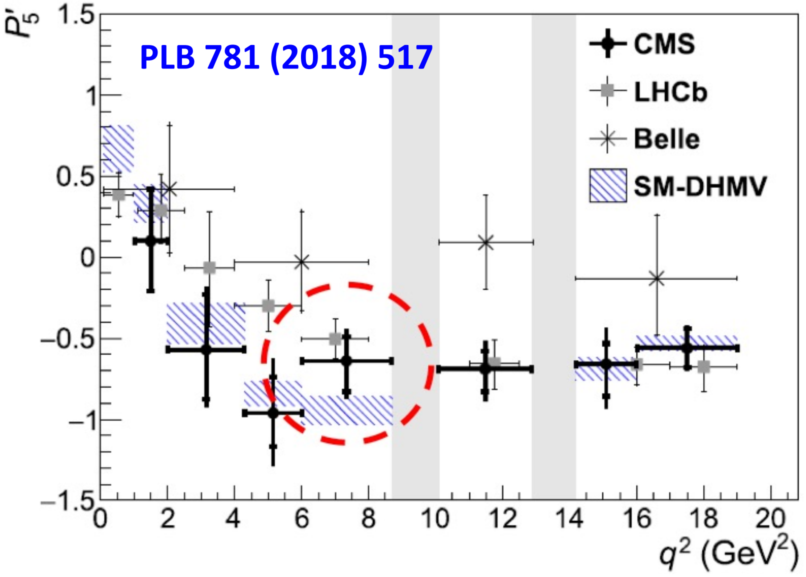
- $\sigma(\tau)$, 50 fb^{-1} ~ 5%
- $\sigma(\tau)$, 300 fb^{-1} ~ 2%

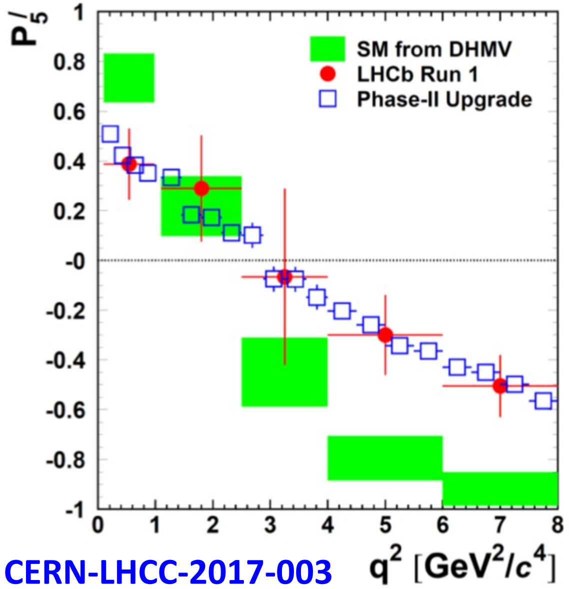


$B^0 \to K^* \mu^+ \mu^-$









CERN-LHCC-2017-003

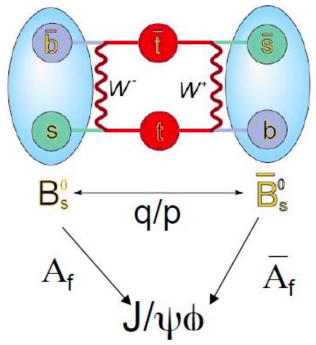
Possible discrepancies at low q^2

- Observed from LHCb+CMS+ATLAS

The q^2 dependence will be known with high precision

- Very valuable input to discussion on NP vs hadronic power corrections to SM
- Larger datasets would allow finer q^2 binning

B_s^0 mixing phase, ϕ_s



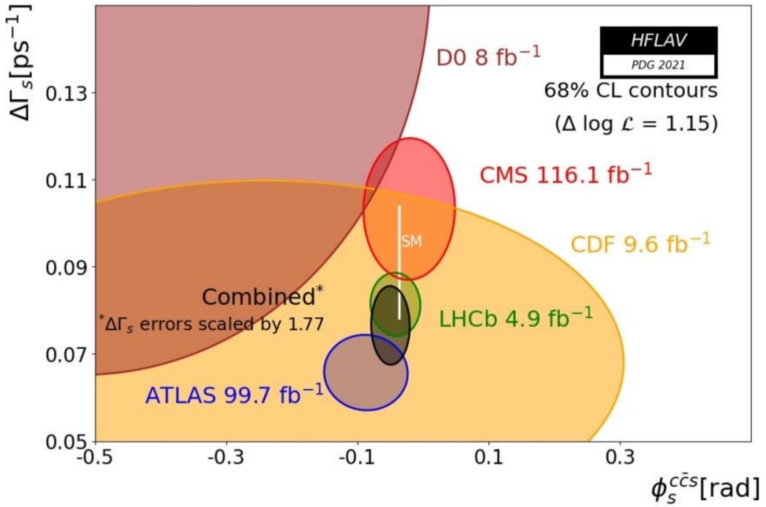
CPV in interference mixing-decay

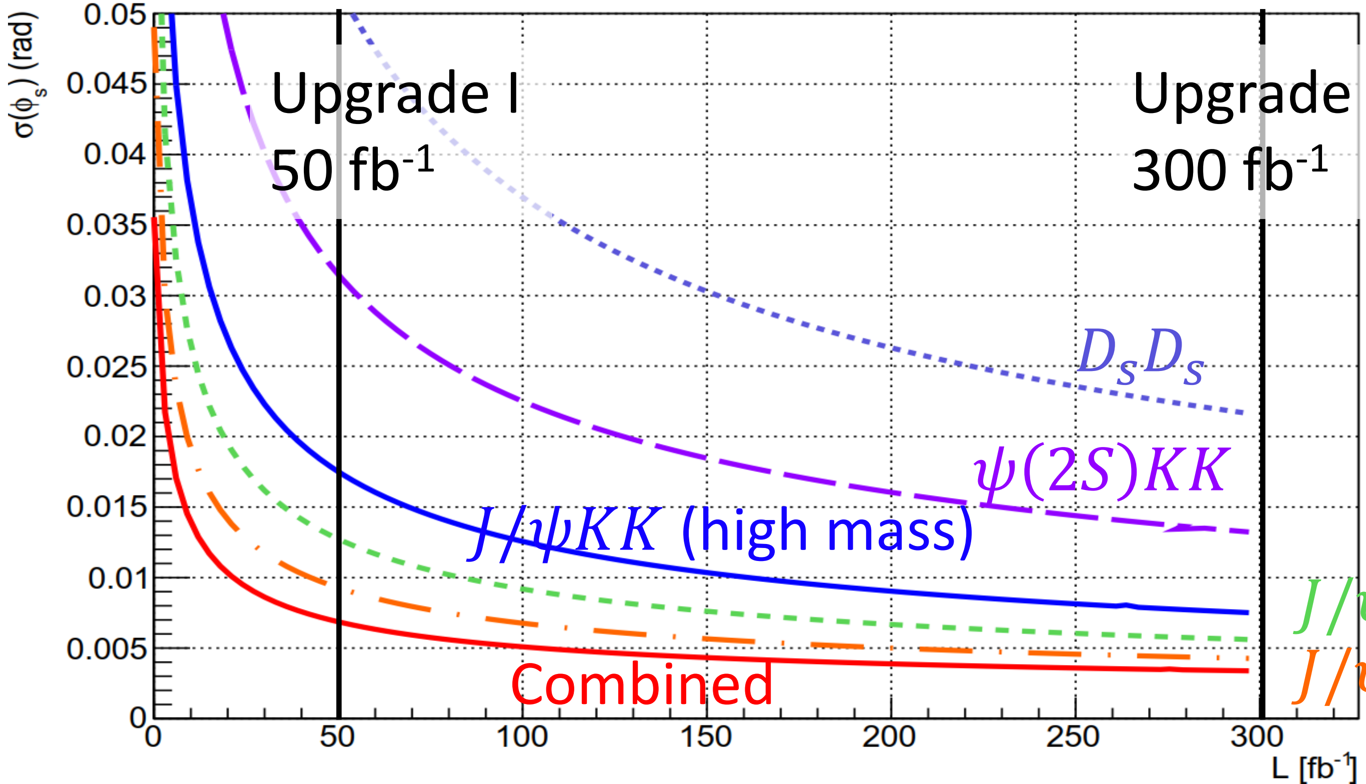
$$\phi_s^{\mathrm{SM}} = -2\arg\left(\frac{V_{tb}V_{ts}^*}{V_{cb}V_{cs}^*}\right) \equiv -2\beta_s = -0.0376 \pm 0.0008\ \mathrm{rad}$$

$$\phi_s^{\mathrm{LHCb}} = -0.042 \pm 0.025\ \mathrm{rad}$$

$$\phi_s^{\mathrm{W/A}} = -0.050 \pm 0.019\ \mathrm{rad}$$

HFLAV 4 PDG 2021





To expect

- $\sigma(\phi_s) \sim 7$ mrad @ 50 fb^{-1}
- $\sigma(\phi_s) < 5$ mrad @ 300 fb^{-1}

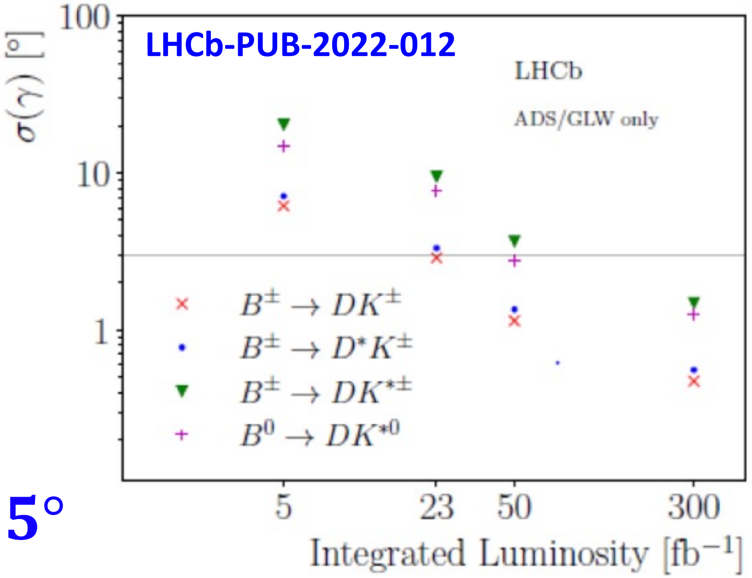
Based on the same performance @ Run2

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 NP searches
- The most recent LHCb result (15 decay modes): $\gamma = (65.4^{+4.2}_{-3.8})^\circ$ JHEP 12 (2021) 141

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

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



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

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
$A_{\mathrm{T}}^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$A_{\mathrm{T}}^{\mathrm{Im}}$ ($B^0 \to K^{*0}e^+e^-$)	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

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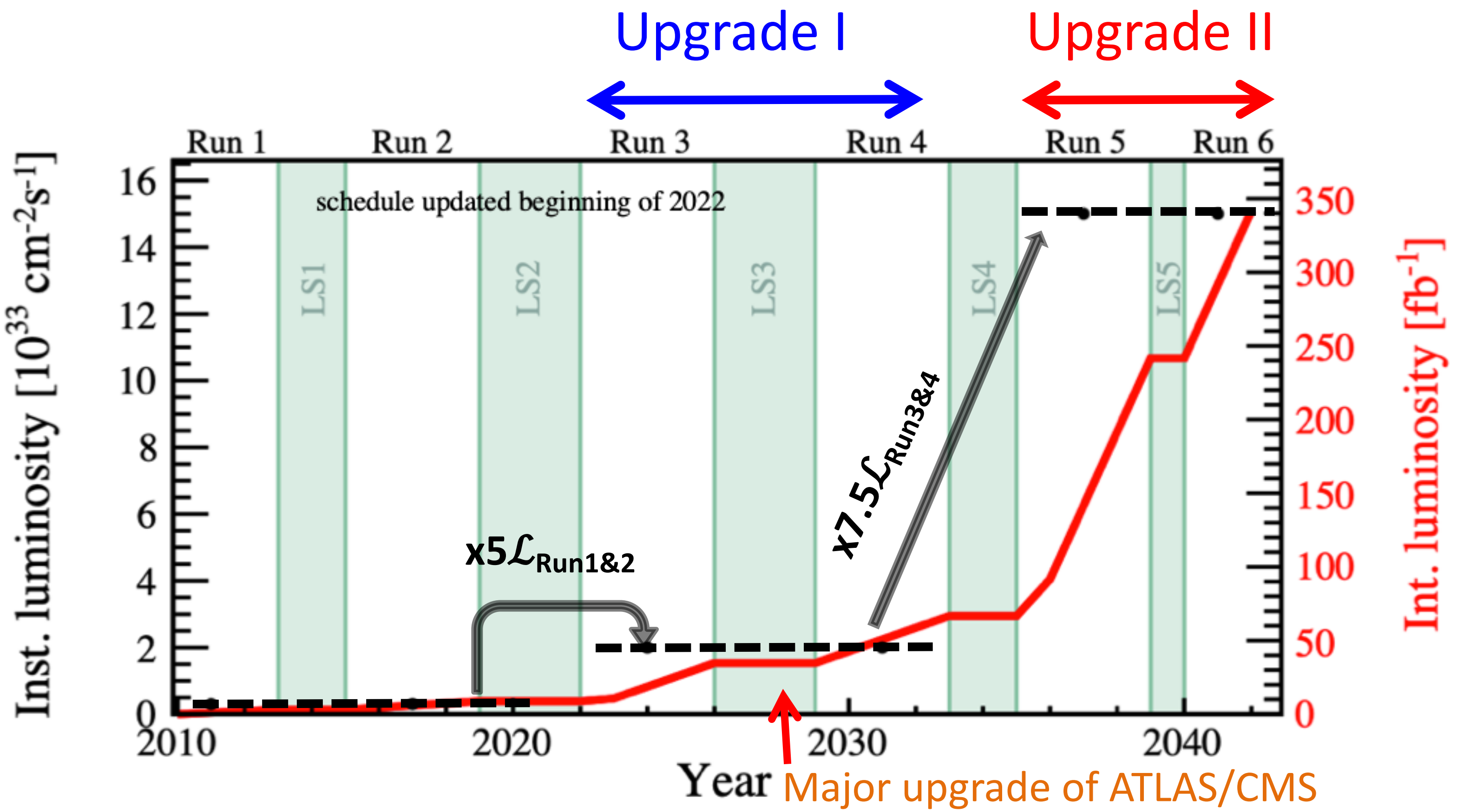


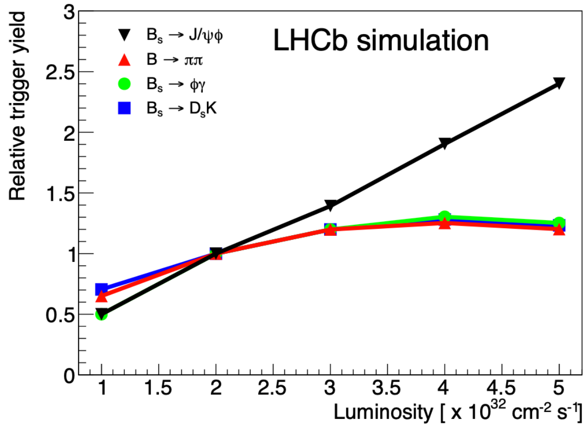
Major upgrade of ATLAS/CMS
LHCb also plan enhancements (U1b)

Upgrade I: a brand new detector

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

Particle ID: New optics + photon detectors
Calos: Reduce PMT gain + new electronics

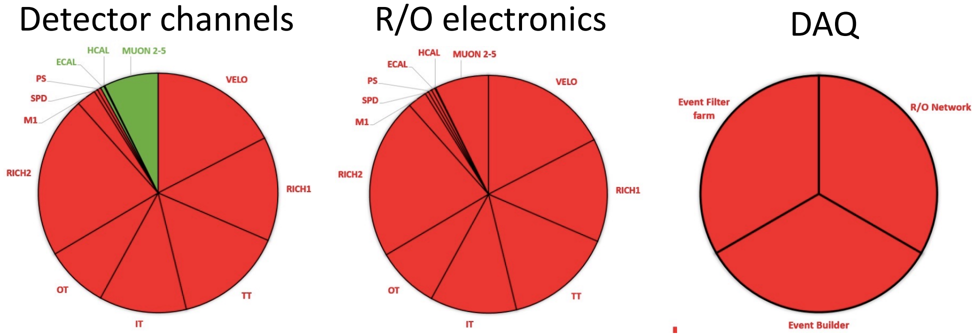
No hardware trigger
- ➢ 1st GPU trigger in a HEP experiment

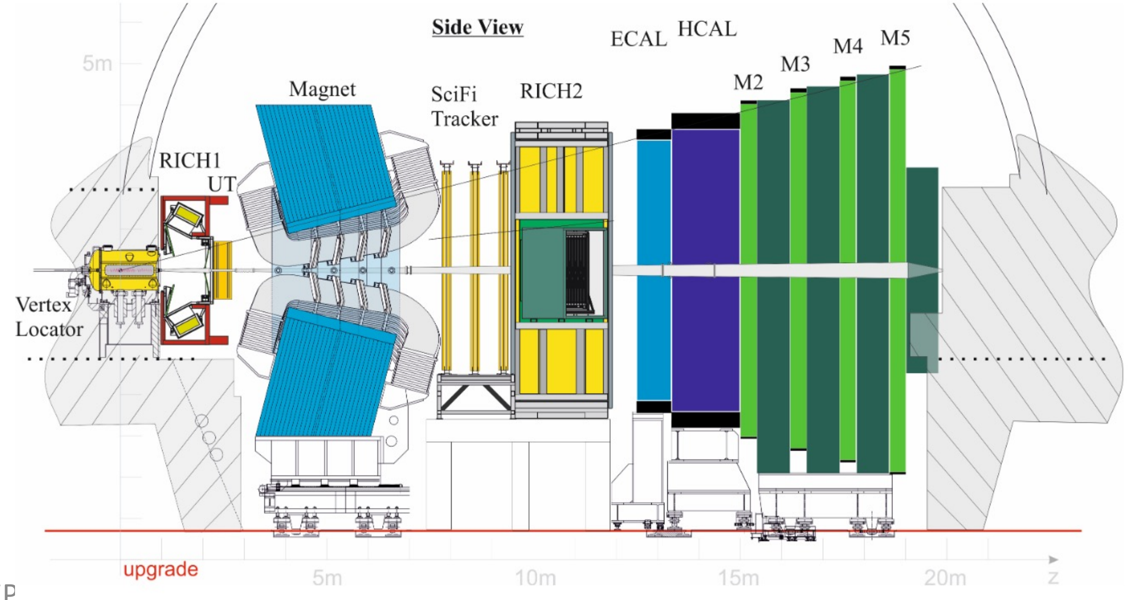


Already saturated @ Run 1&2

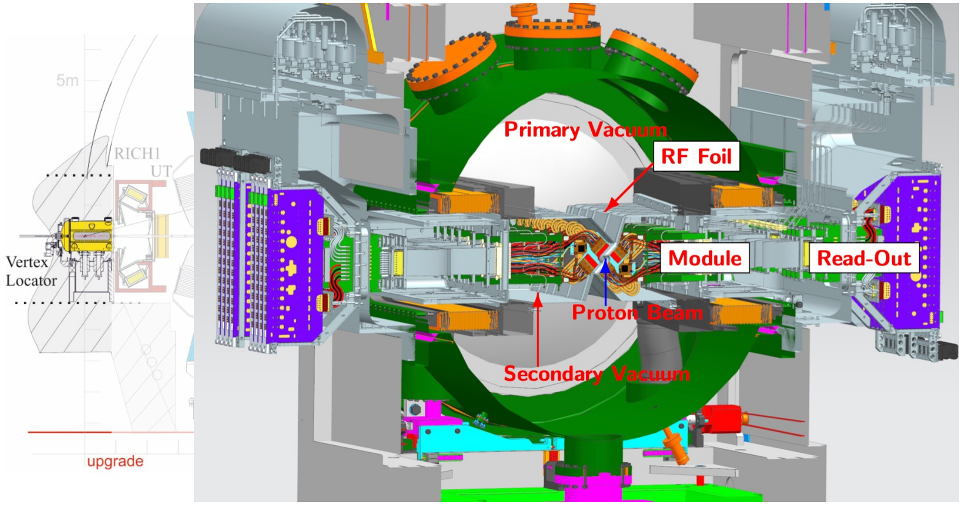
Readout at the LHC bunch xing rate (40 MHz)

To be upgraded
To be kept



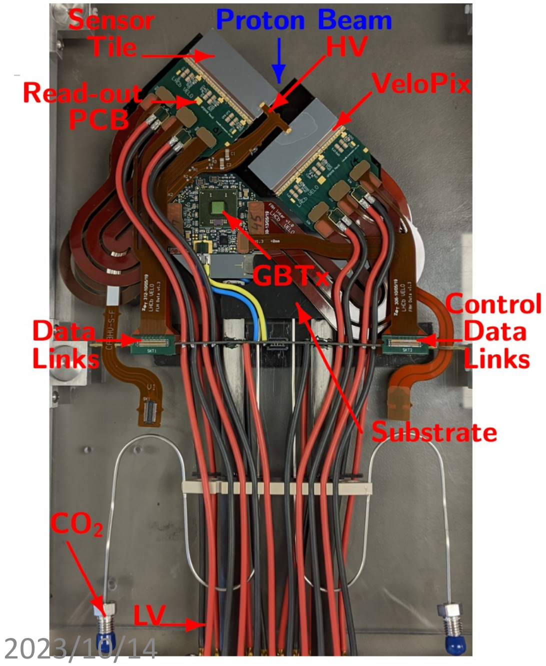


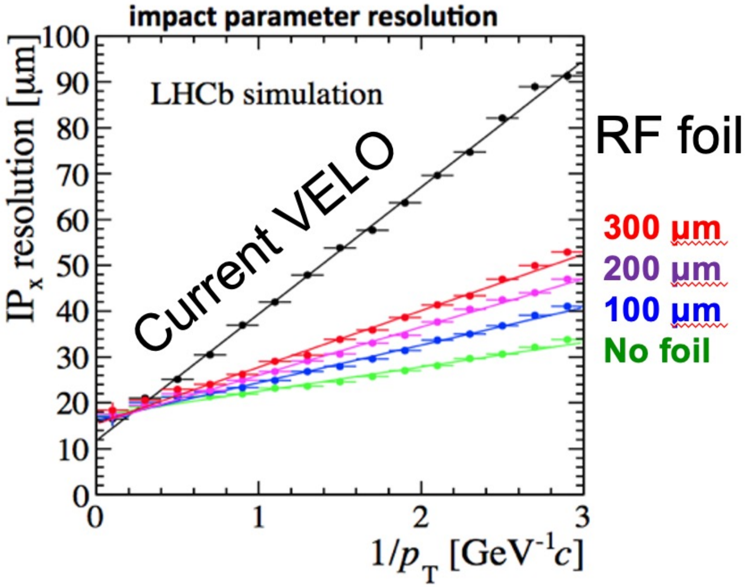
Velo pixel (VP)



New hybrid pixel detector

- ➢ c/b hadrons: flight ~mm before decay – distinctive feature to select them
- ➢ Silicon pixels (55x55 um)
  single hit resolution 12-15 um
- ➢ Closer to beam (5 mm -> 3 mm) => better σ_{IP}

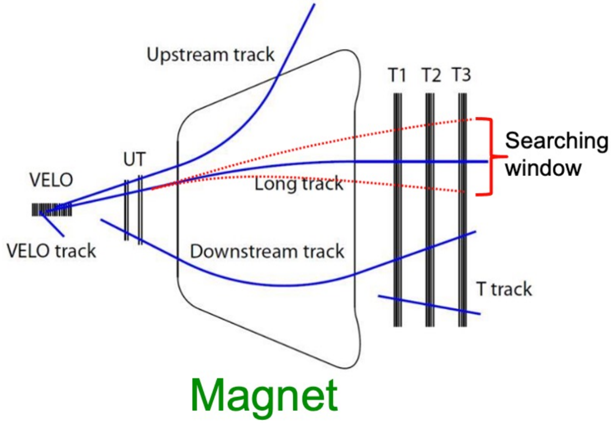


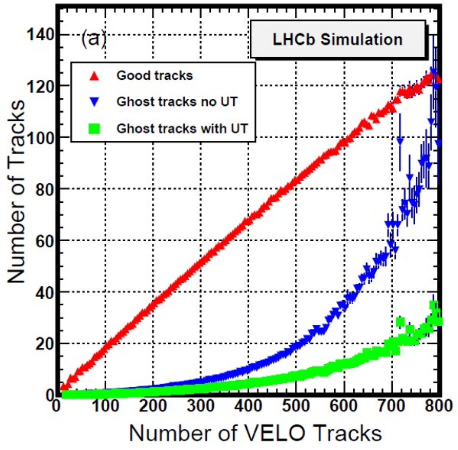


RF foil (250 um thickness)

- ➢ Separate VELO from primary vacuum
- ➢ An vacuum incident on 2023 Jan 10
  - ❑ RF foils deformed
  - ❑ No damage on sensors
  - ❑ Cant fully close (3 mm -> 24.5 mm x2)
  - ❑ Replace during YETS 2023

Upstream Tracker (UT)



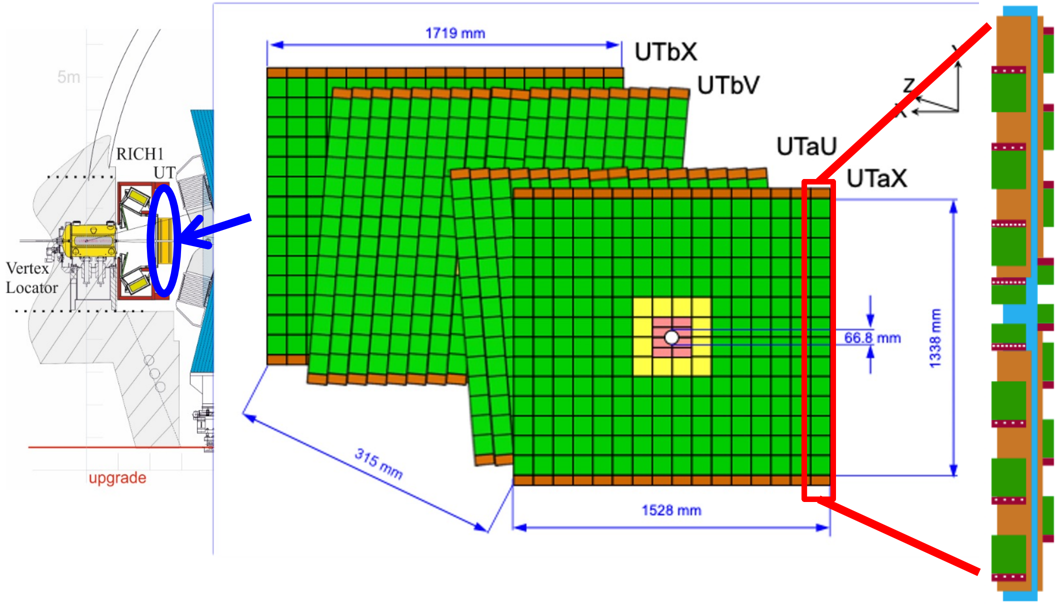


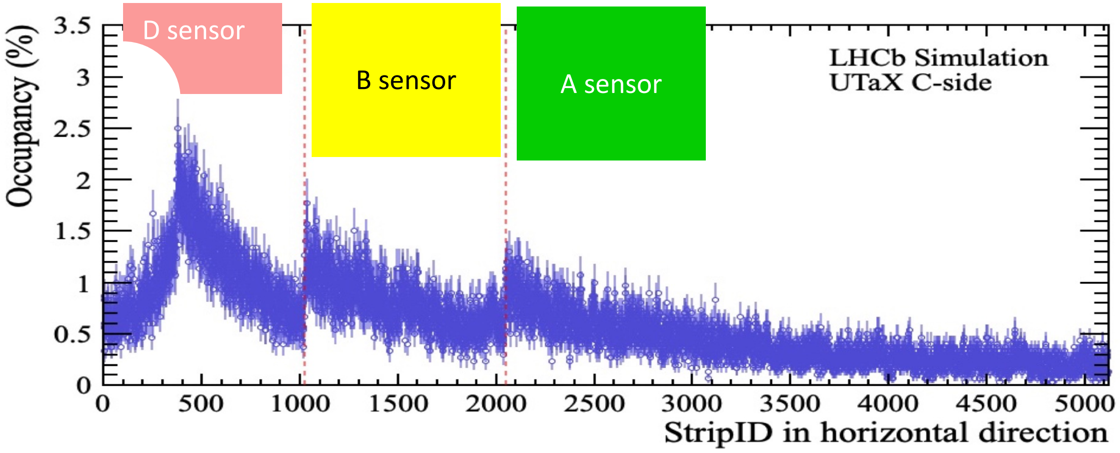
UT: Si Strip detector

- ➢ High coverage, segmentation, resolution
- ➢ Speed up tracks reconstruction & reduce $P_{GhostTrk}$

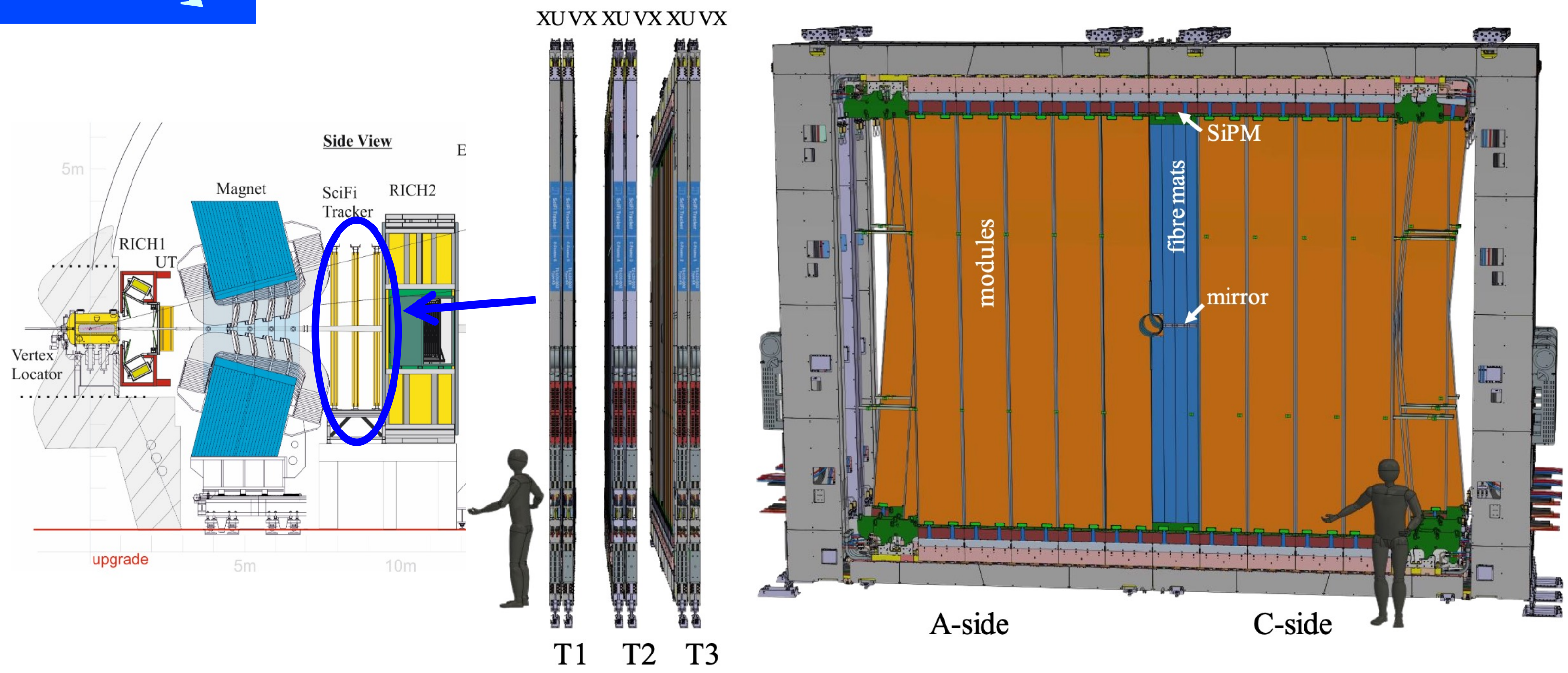
Different sensors for different regions

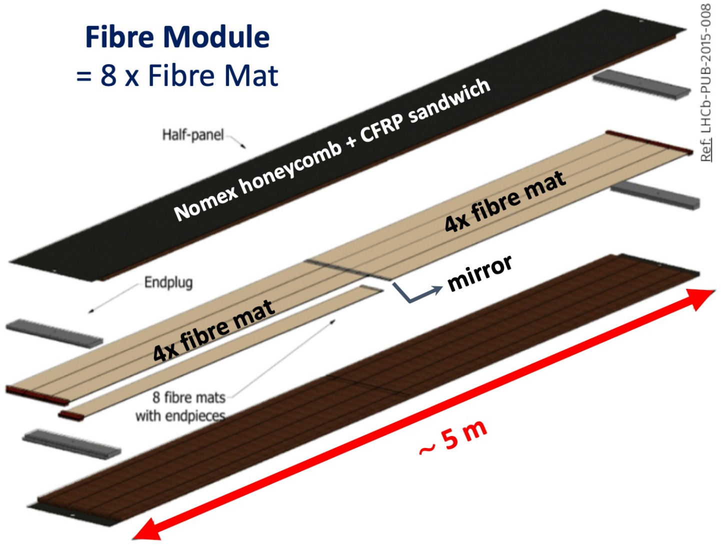
- ➢ Maximum occupancy ~ 1%





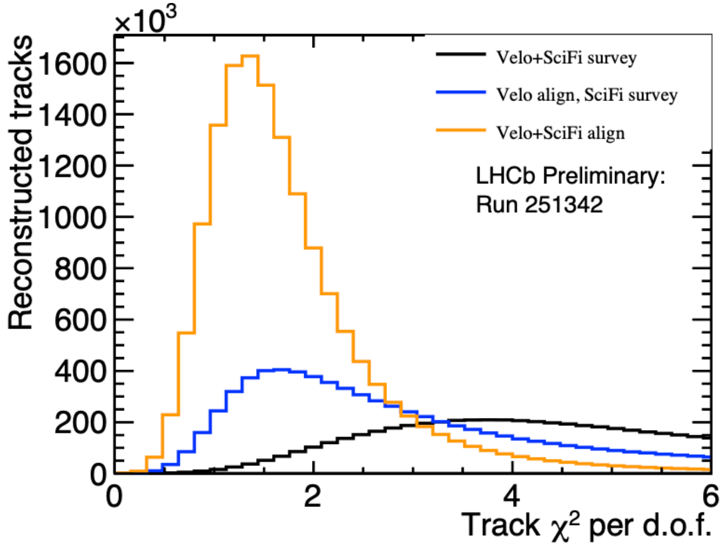
Scintillating fibers tracker (SciFi)



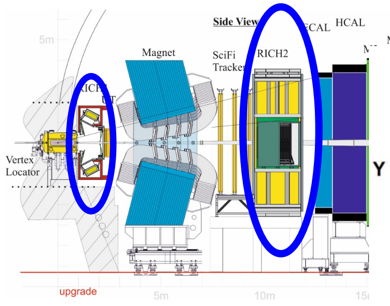


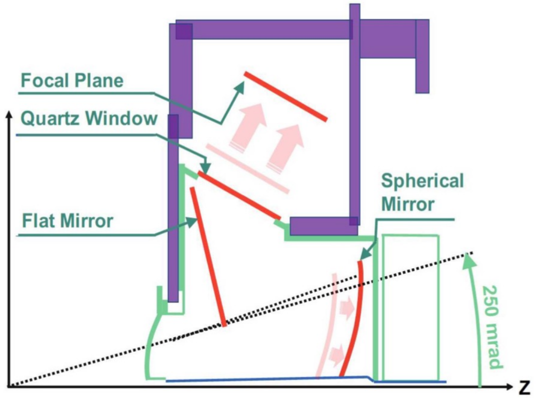
SciFi: Scintillating fibers detector

- 3 station with 4 detection layers
- >10 km scintillating fiber, covering 340m^2 area
- 2x2.5 m long modules with Readout SiPMs at the outer edge
- ϵ_{Hit}~99%, σ_{Hit}~100 μm, X/X$_0$~1% per layer



Ring imaging Cherenkov detector (RICHs)





New optics+photon detectors (HPDs -> MaPMTs)

- ➢ PID for $p \in (2.6, 100)$ GeV

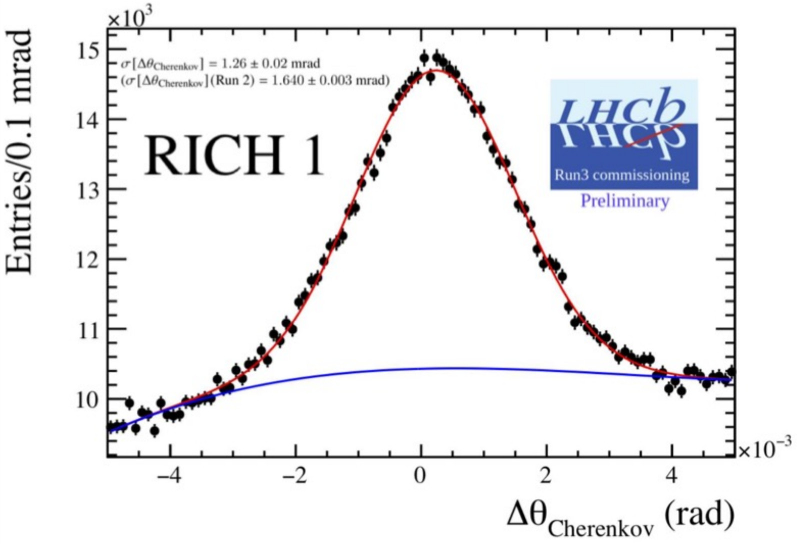
Performance already better than Run2

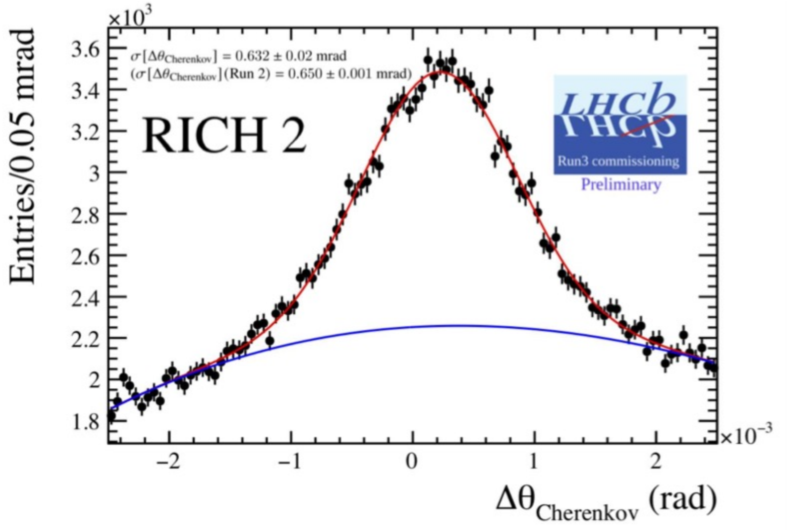
RICH1

1888 1-inch MaPMTs

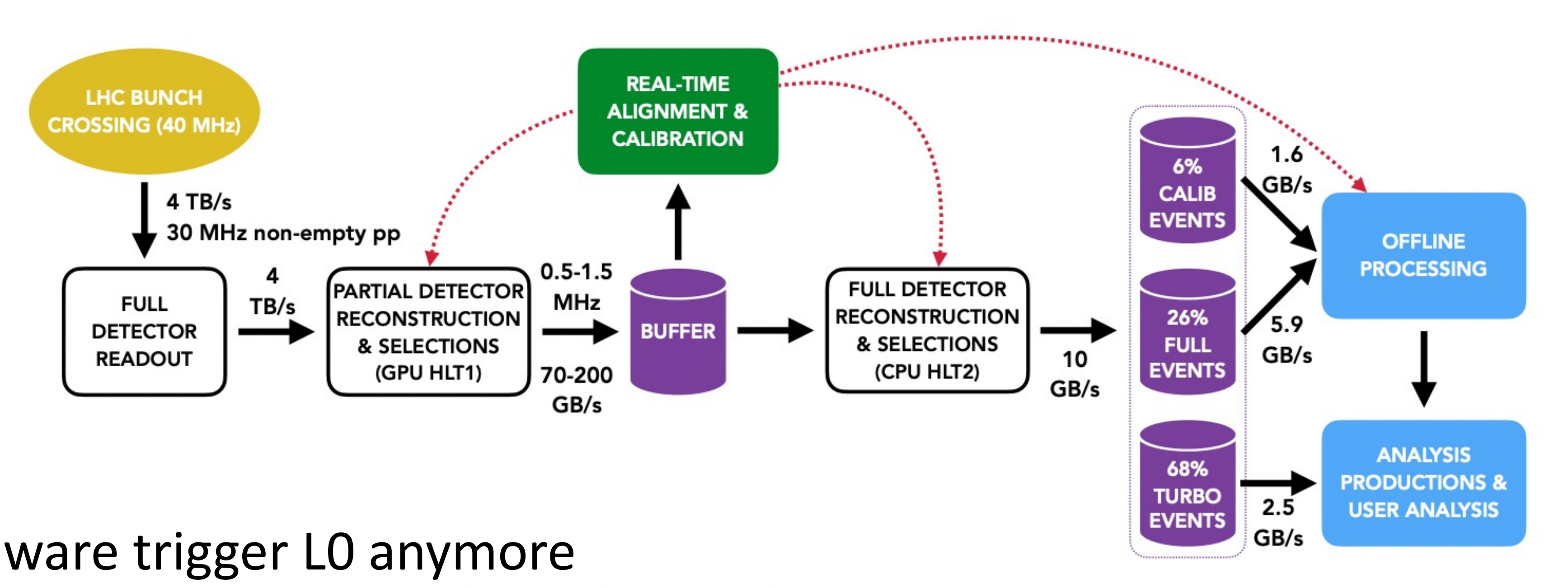
RICH2

768 1inch MaPMTs in the inner region 384 in the outer region





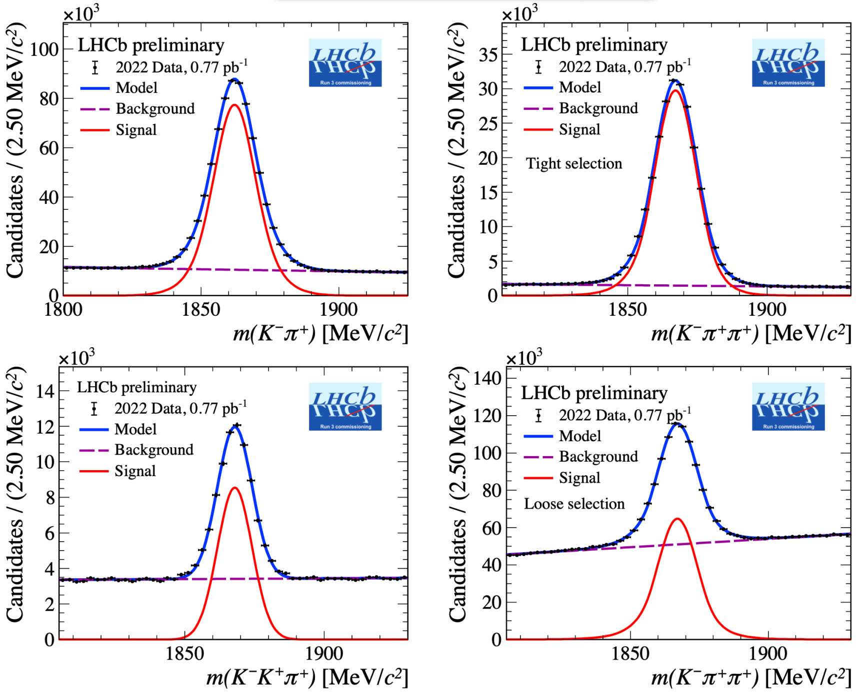
Trigger & Real Time Analysis



- No hardware trigger L0 anymore
- Data stored @ 30 MHz by FPGAs
- HLT1 running on GPUs – track reconstruction
- HLT2 running on CPUs – reconstruction and selection for each decay
- Alignment (VELO, RICH mirrors, UT, SciFi, Muon) and calibration (RICH, ECAL, HCAL) in real time

Physics performance

Charmed meson

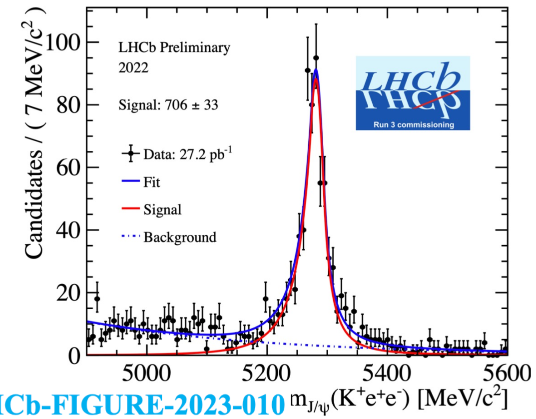


LHCb upgrade I detectors functions well

- W/ full triggers/"sub-detectors" signals return since 2019

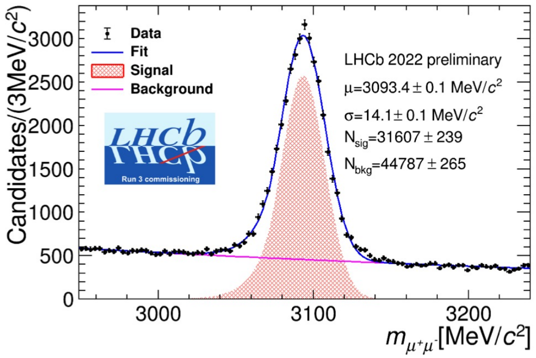
- D^0 and K_S^0 candidates reconstructed directly @ 1st level trigger
- Trigger efficiency can be improved w.r.t. Run2

Beauty mesons



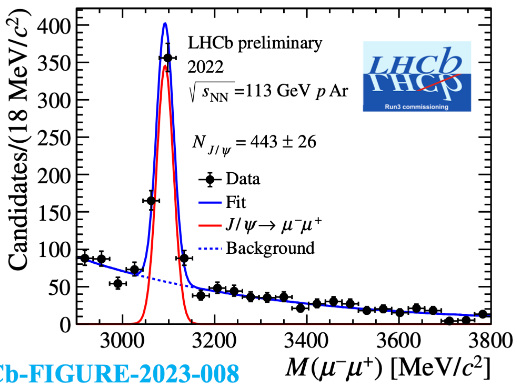
LHCb-FIGURE-2023-010

$J/\psi \to \mu^+\mu^-$



LHCb-FIGURE-2023-015

J/ψ in pAr collisions



LHCb-FIGURE-2023-008

Mass resolution compatible with MC expectations within 1 MeV

- Introduction
- Experiment sensitivity
- **LHCb upgrades**
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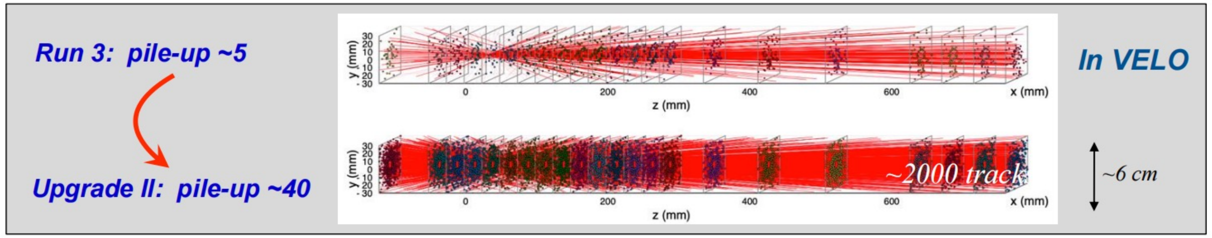
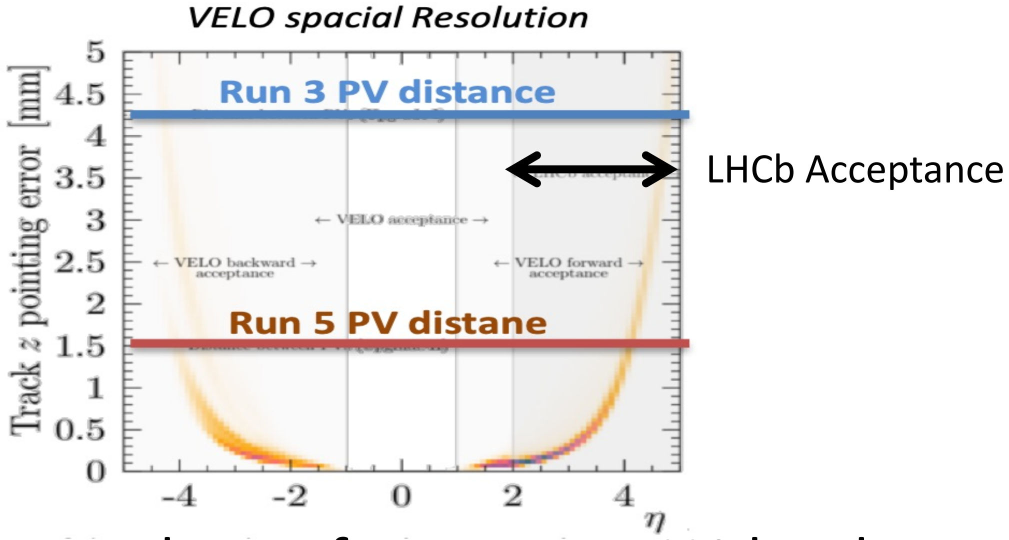
  - **Upgrade II (2032 -)**
- Summary

High pile-up in Upgrade II

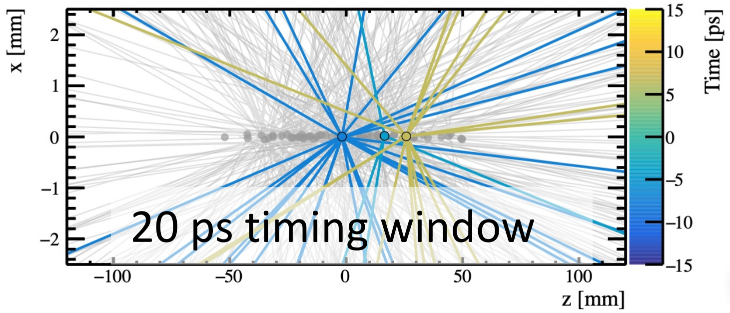
In Upgrade II
$\mathcal{L}_{max}$~1.5x10^{34} cm^{-2}s^{-1}
$\mathcal{L}_{int}$~300 fb^{-1}
~ 40 visible interactions/Xing



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



VELO: 4D detector with timing



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

New techiques in R&D:

- Sensor: timing (~50 ps), radiation hardness (max ~6x10^{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...

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 $\mathcal{L}_{\text{Run 3\&4}}$

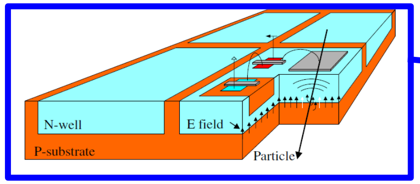
Upgrade II luminosity $1.5\text{x}10^{34}\,cm^{-2}s^{-1}$ (x7.5 $\mathcal{L}_{\text{Run 3\&4}}$)

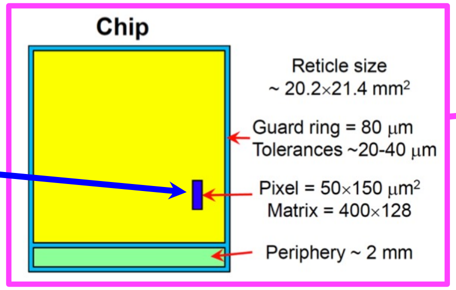
- The occupancy (max ~10%) will compromise the performance
- Radiation does too high for current sensor

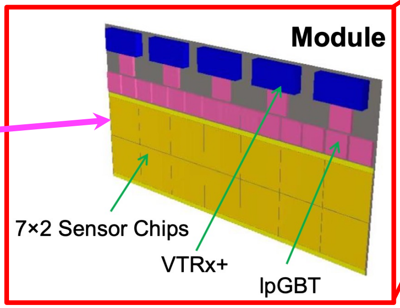
U2UT:

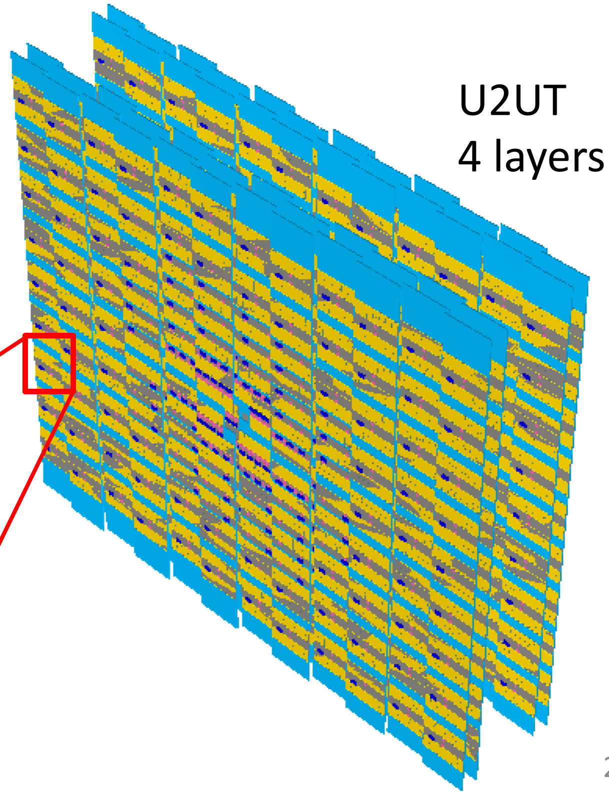
- CMOS MAPS technique applied
  Very promising and cost effective for large area pixel detectors.

Monolithic Active Pixel Sensor (MAPS)





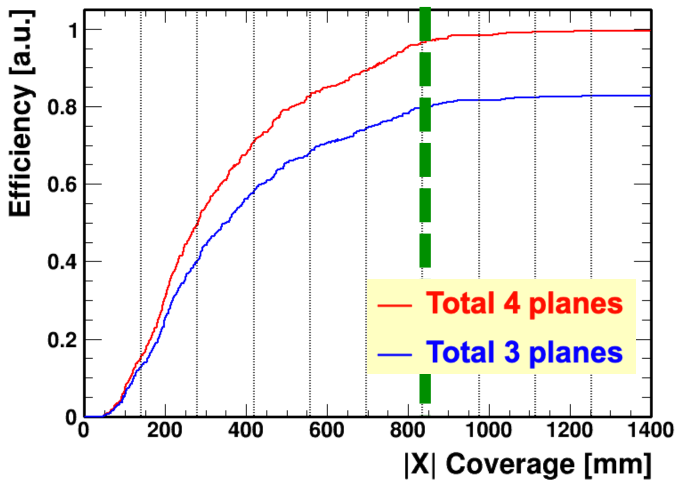




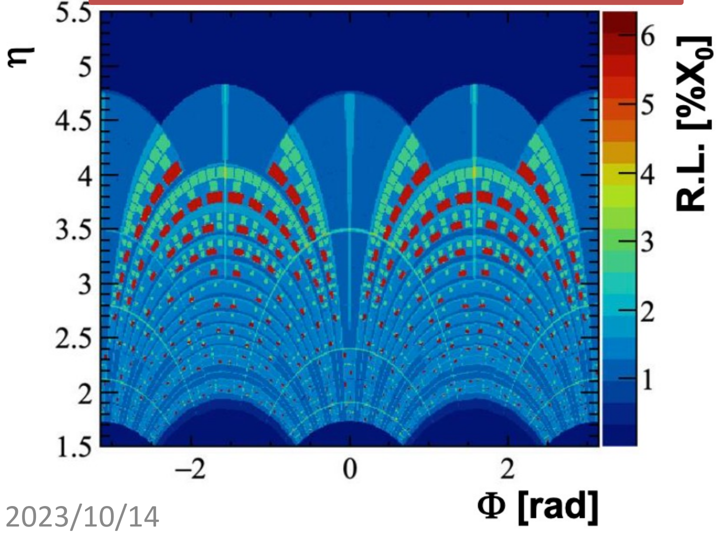
U2UT
4 layers

U2UT R&D status

Track efficiency vs X coverage



R.L. as functions of Φ and η

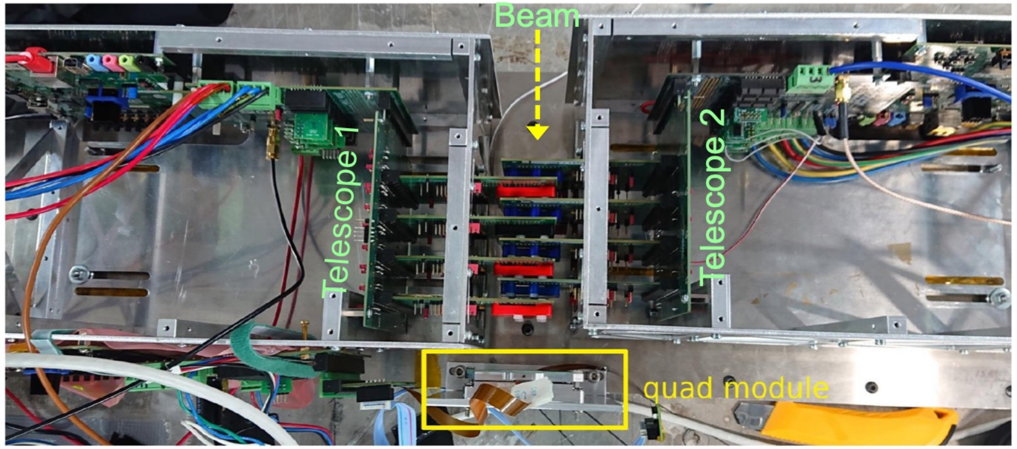


U2UT software ⇦ Lead by LHCb China group

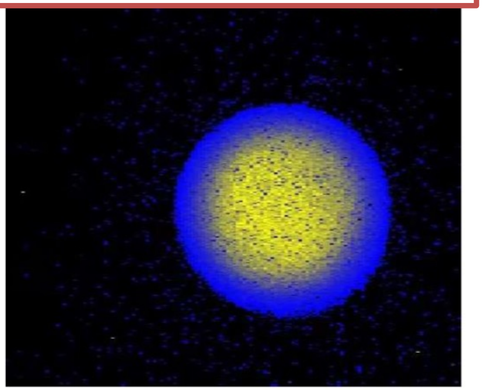
- Preliminary studies on
  - Track efficiency for $B^- \to D^0K^-, D^0 \to K_S\pi^+\pi^-, K_s \to \pi^+\pi^-$ Optimizing U2UT coverage
  - Detector simulation mostly done and R.L. calculated

LHCb China group lead HVCMOS-based development

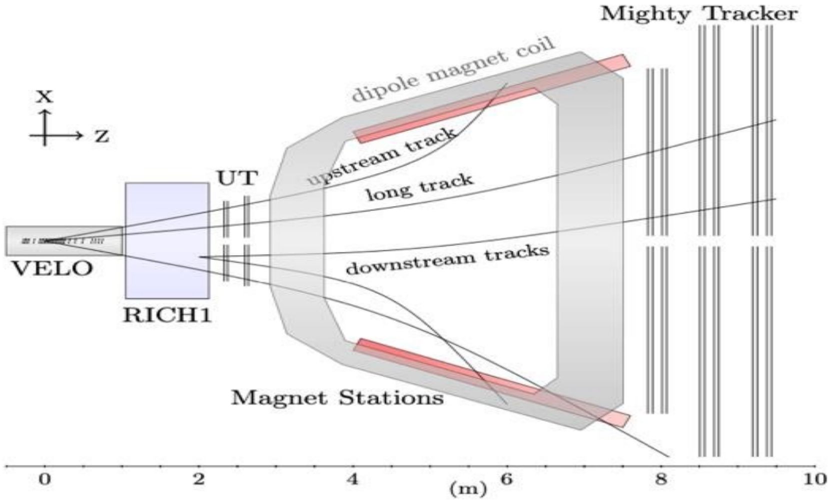
- Extensive tests using ATLASPix: lab test with cosmic ray and radioactive sources, testeam at DESY in April 2022
- Search for domestic foundry ongoing

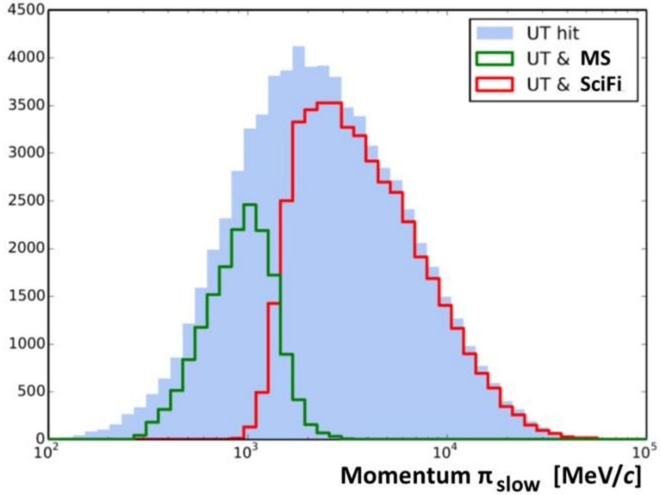


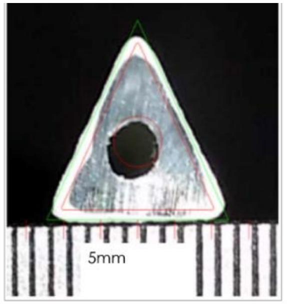
Hitmap with Fe55 source



Magnet Stations (MS)







A new MS to be installed for reconstructing Upstream Tracks

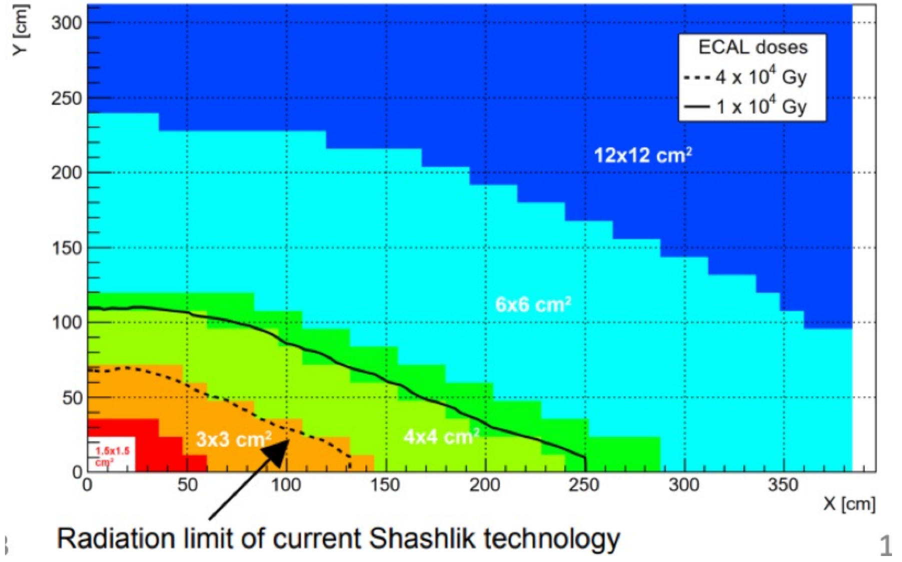
- ➢ Tracking capability, reconstruction ↗ for low momentum tracks.

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.

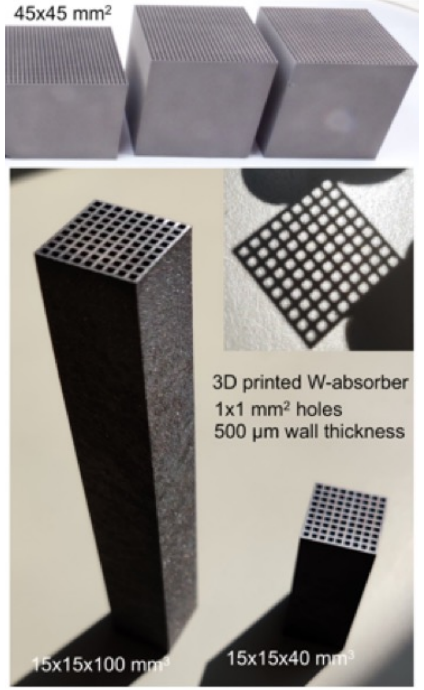
The Magnet Stations could be installed at LS3.

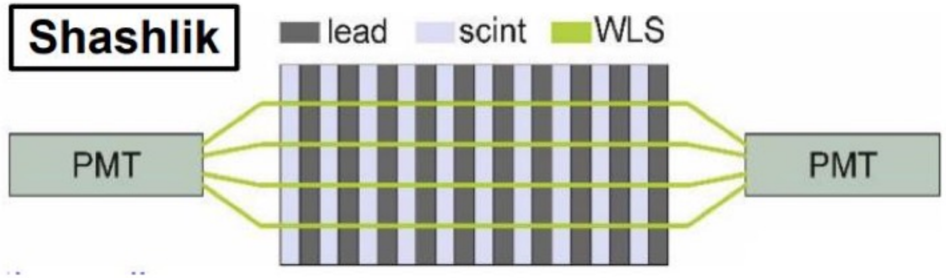
5D calorimeter with precision timing

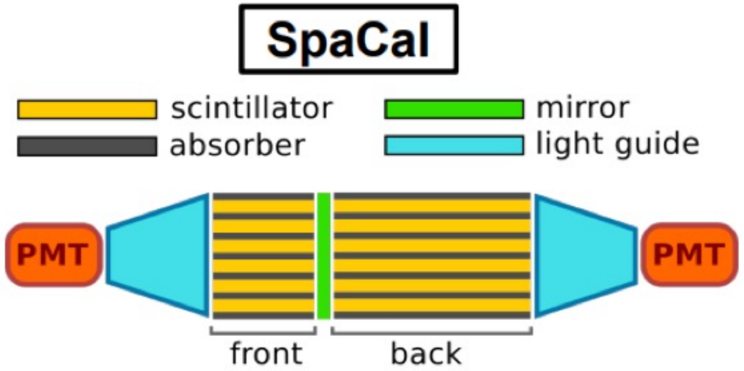


Key features: energy resolution ($10\%/\sqrt{E} \oplus 1\%$) , radiation hardness (up to 1 MGy), timing capability (tens of ps) and granularity.

- 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.

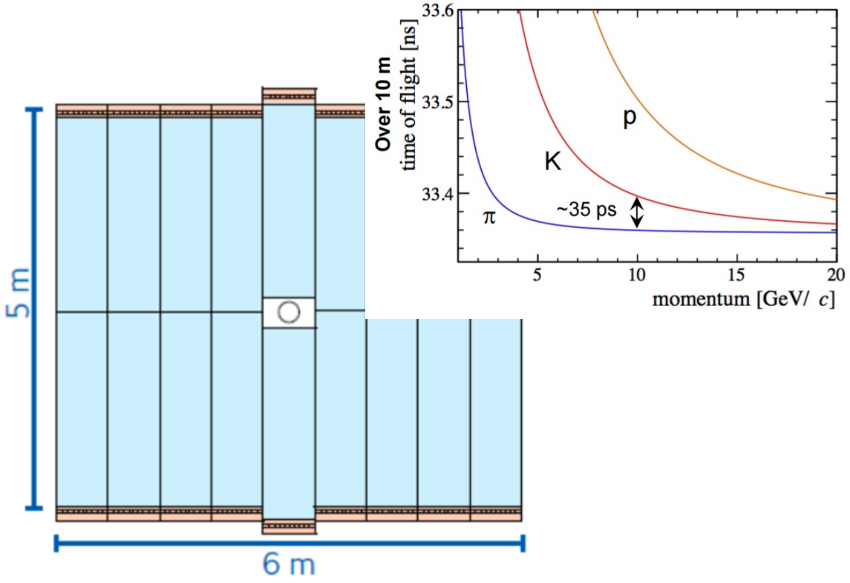




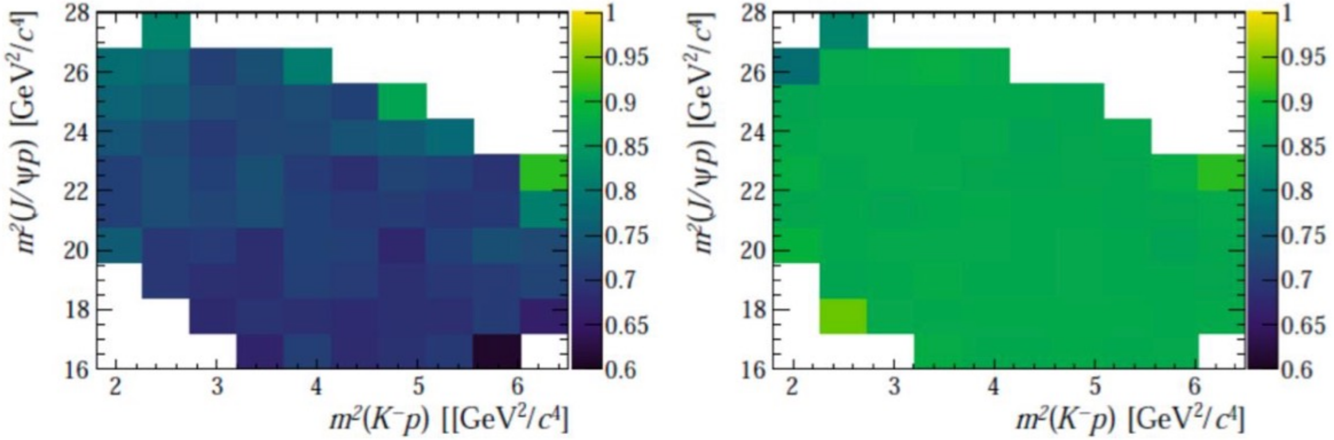


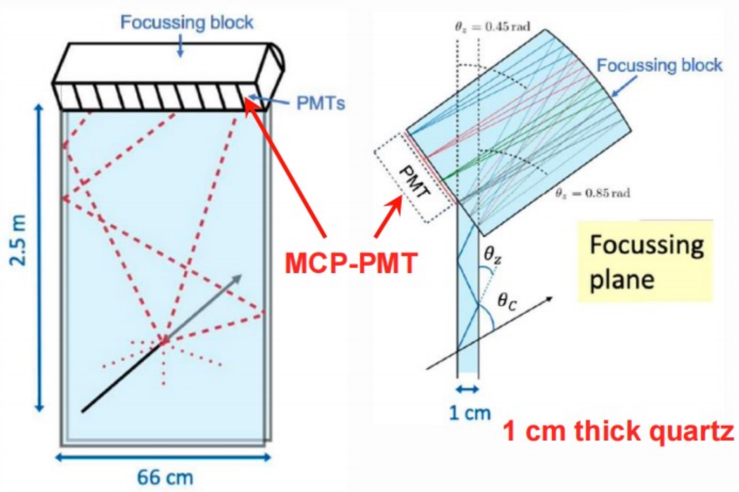
TORCH: Time of Flight Detector

Low-momentum PID (2-10 GeV)
- Improve background suppression and flavor tagging
- To measure θ_γ, L_γ, and time of arrival
- Aim: $\sigma_{\mathrm{ToF}} \sim 10-15$ ps per track
  a single-photon timing resolution: 70 ps (30 photon/track)



Dalitz plot efficiency for $\Lambda_b \to J/\psi p K^-$ w/o and with TORCH





Summary

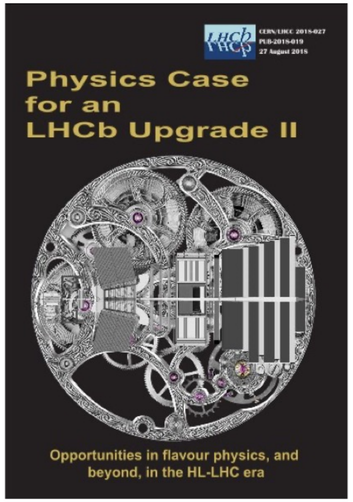
LHCb upgrades

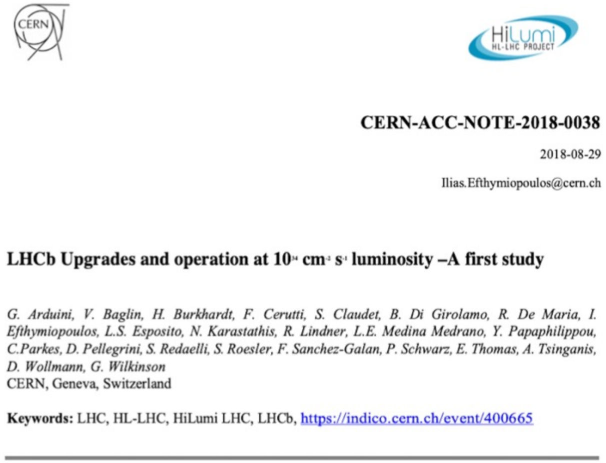
- Upgrade I: installation completed
- Upgrade II: starts in LS4, with consolidation in LS3

LHCb Upgrade II to fully exploit HL-LHC for flavor physics and beyond

- FTDR approved and now in R&D phase
  Next: TDR @2026, 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





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

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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
- Framework TDR, CERN-LHCC-2021-012

Thank you for your attentions