LHCb 实验升级展望
LHCb Upgrades and physics prospects

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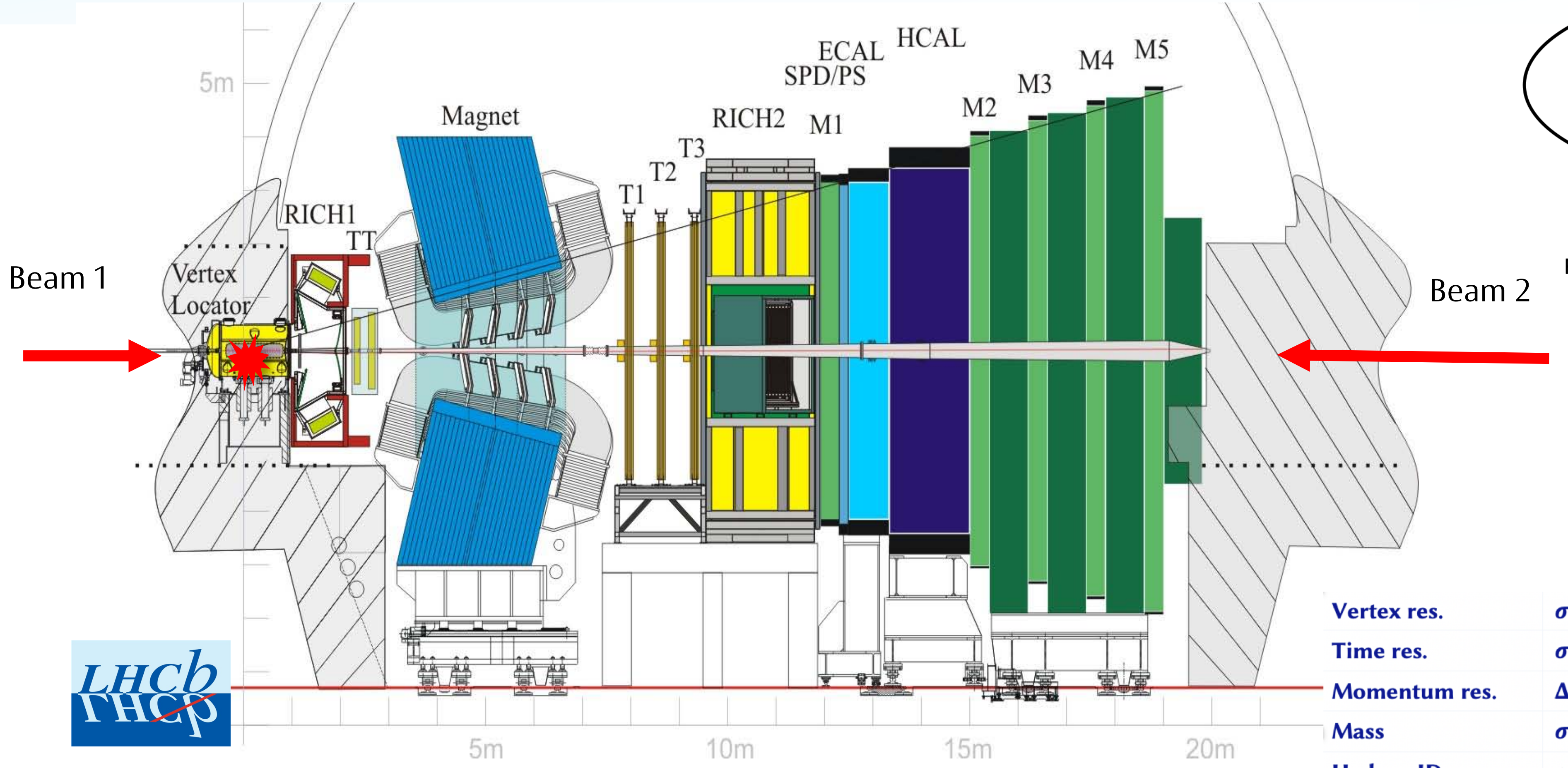
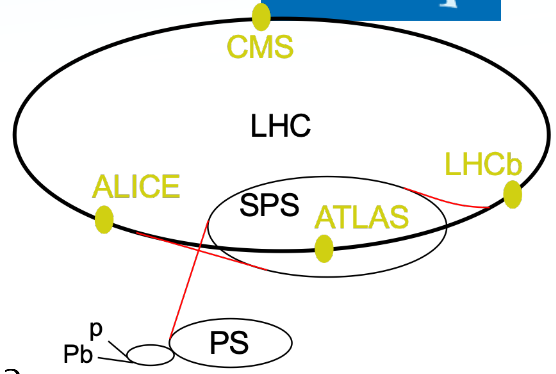
第七届重味物理与量子色动力学研讨会 @ 南京
The 7th HFQCD @ Nanjing, 19 Apr 2024

LHCb as we knew



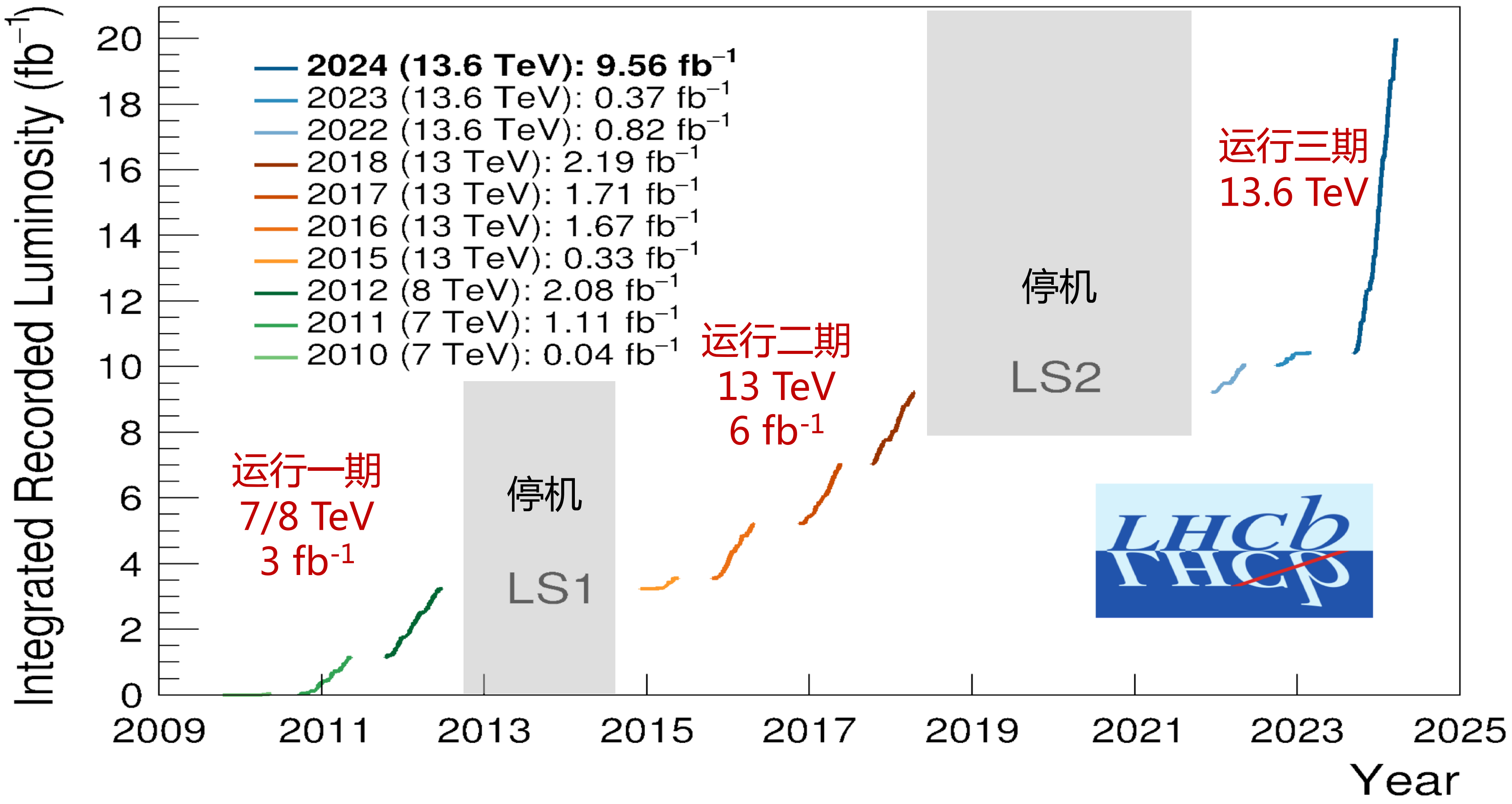


Vertex res.	$\sigma_{IP} = 20\ \mu m$
Time res.	$\sigma_\tau = 45$ fs for $B_s^0 \to J/\psi\phi$ or $D_s^+\pi^-$
Momentum res.	$\Delta p/p = 0.4 \sim 0.6\%$ $(5 - 100\ \mathrm{GeV}/c)$
Mass	$\sigma_m = 8\ \mathrm{MeV}/c^2$ for $B \to J/\psi X$
Hadron ID	$\varepsilon(K \to K) \sim 95\%$ mis-ID $\varepsilon(\pi \to K) \sim 5\%$
Muon ID	$\varepsilon(\mu \to \mu) \sim 97\%$ mis-ID $\varepsilon(\pi \to \mu) \sim 1 - 3\%$
ECAL res.	$\Delta E/E = 1\% \oplus 10\%/\sqrt{E\ (\mathrm{GeV})}$

JINST 3 (2008) S08005
Int. J. Mod. Phys. A 30 (2015) 1530022

Data samples

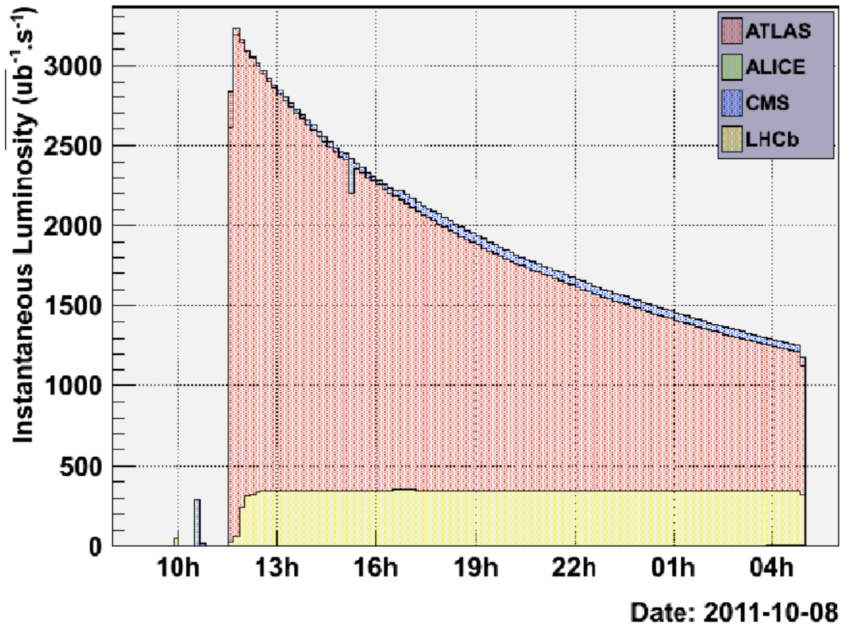
- Most physics output using data before 2019



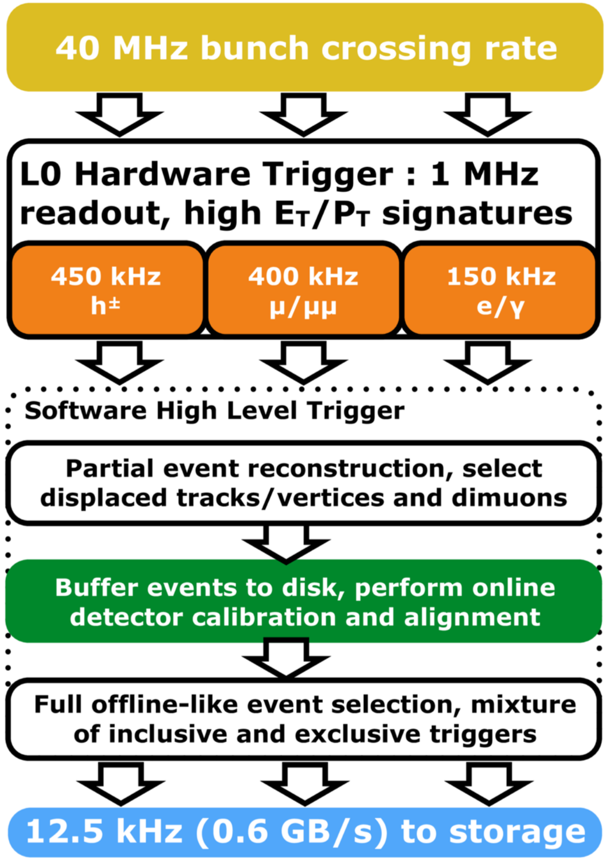
Limitation due to trigger saturation

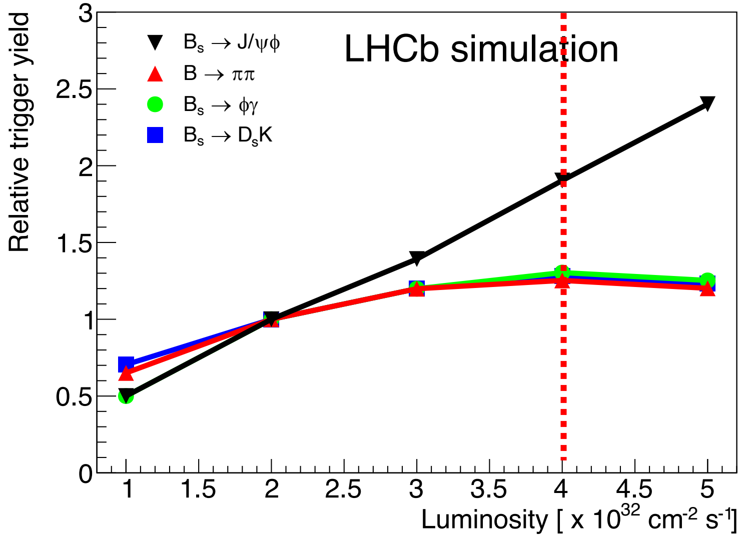
- Previous luminosity of $4{\times}10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ limited by detector capability!

A typical fill at LHC



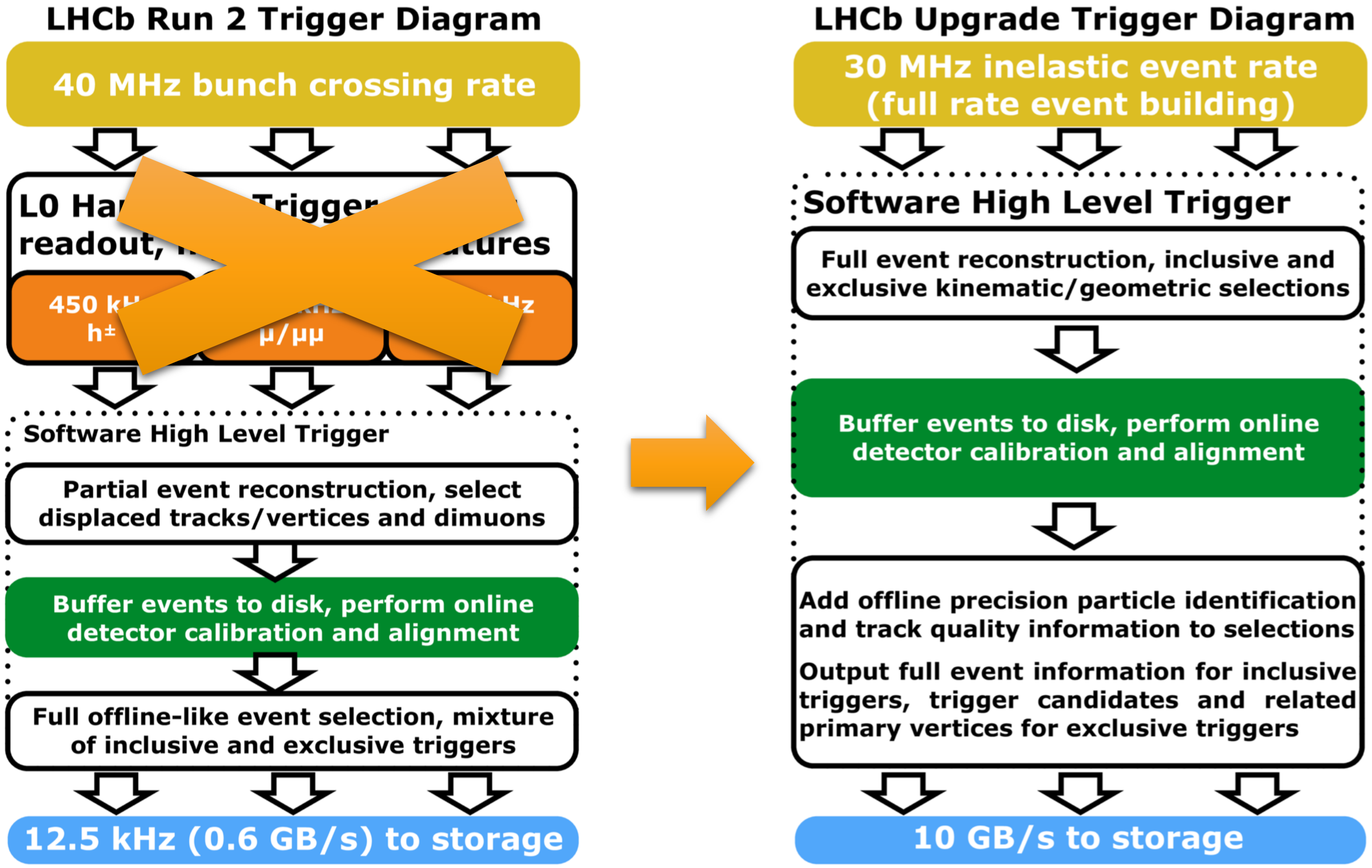
LHCb Run 2 Trigger Diagram



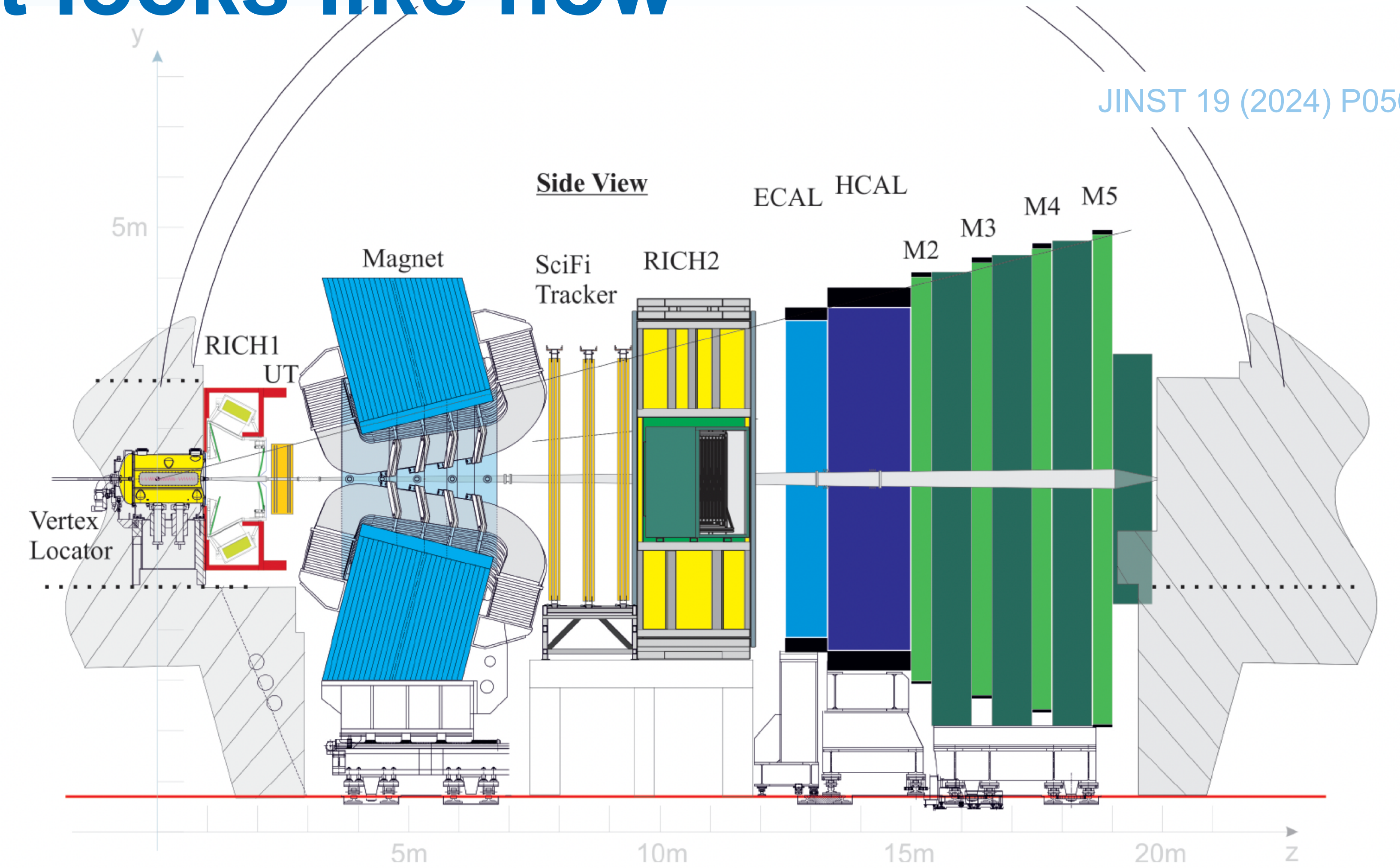


Goal of LHCb Upgrade I

- Removing the hardware trigger
- Increase lumi by a factor of 5
  - $4\times10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1} \rightarrow \mathbf{2\times10^{33}cm^{-2}s^{-1}}$

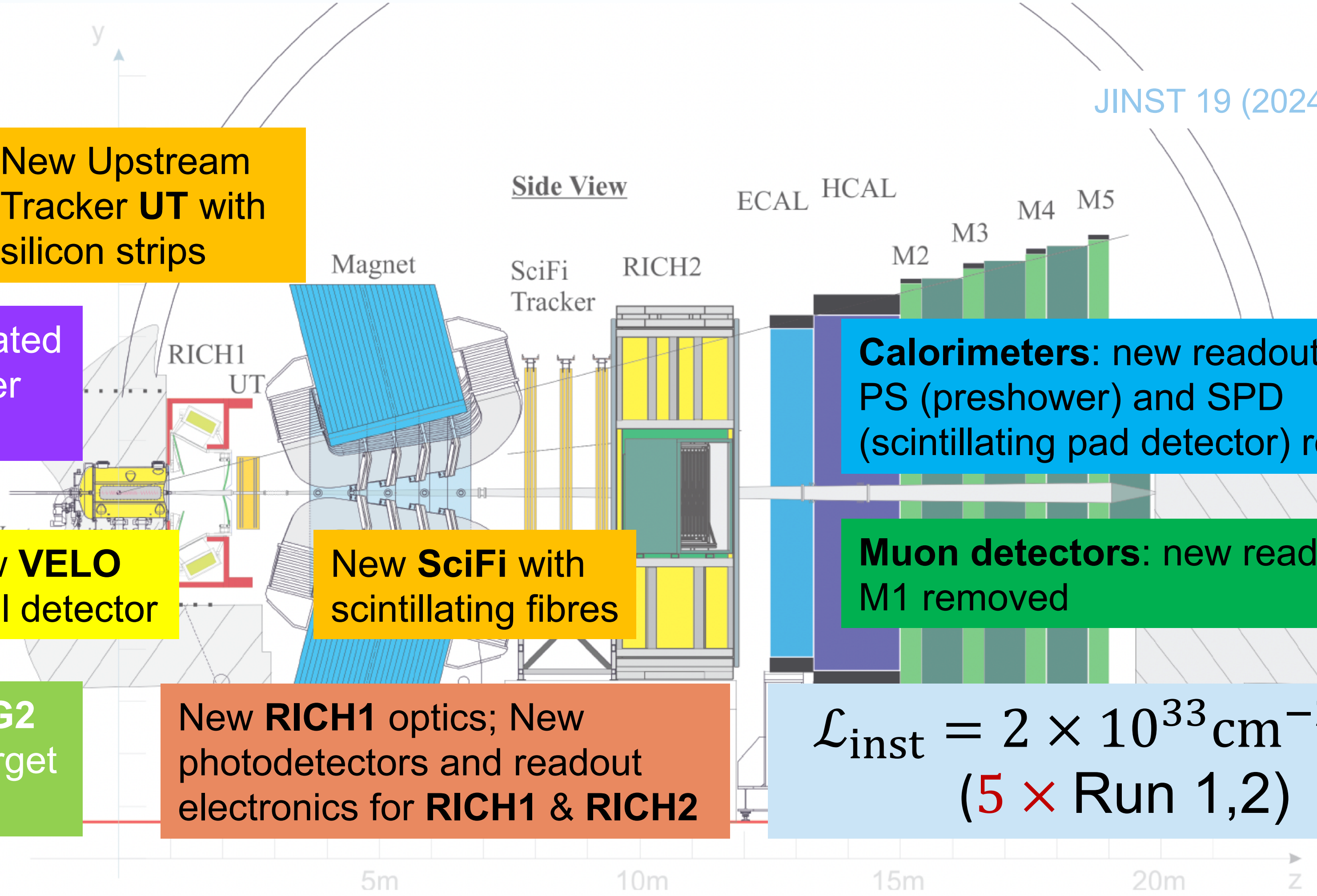


Upgraded LHCb: what it looks like now



A brand new detector!

JINST 19 (2024) P05065



New Upstream Tracker **UT** with silicon strips

New dedicated luminometer **PLUME**

New **VELO** pixel detector

New **SciFi** with scintillating fibres

New **SMOG2** for fixed-target collisions

New **RICH1** optics; New photodetectors and readout electronics for **RICH1** & **RICH2**

Calorimeters: new readout
PS (preshower) and SPD (scintillating pad detector) removed

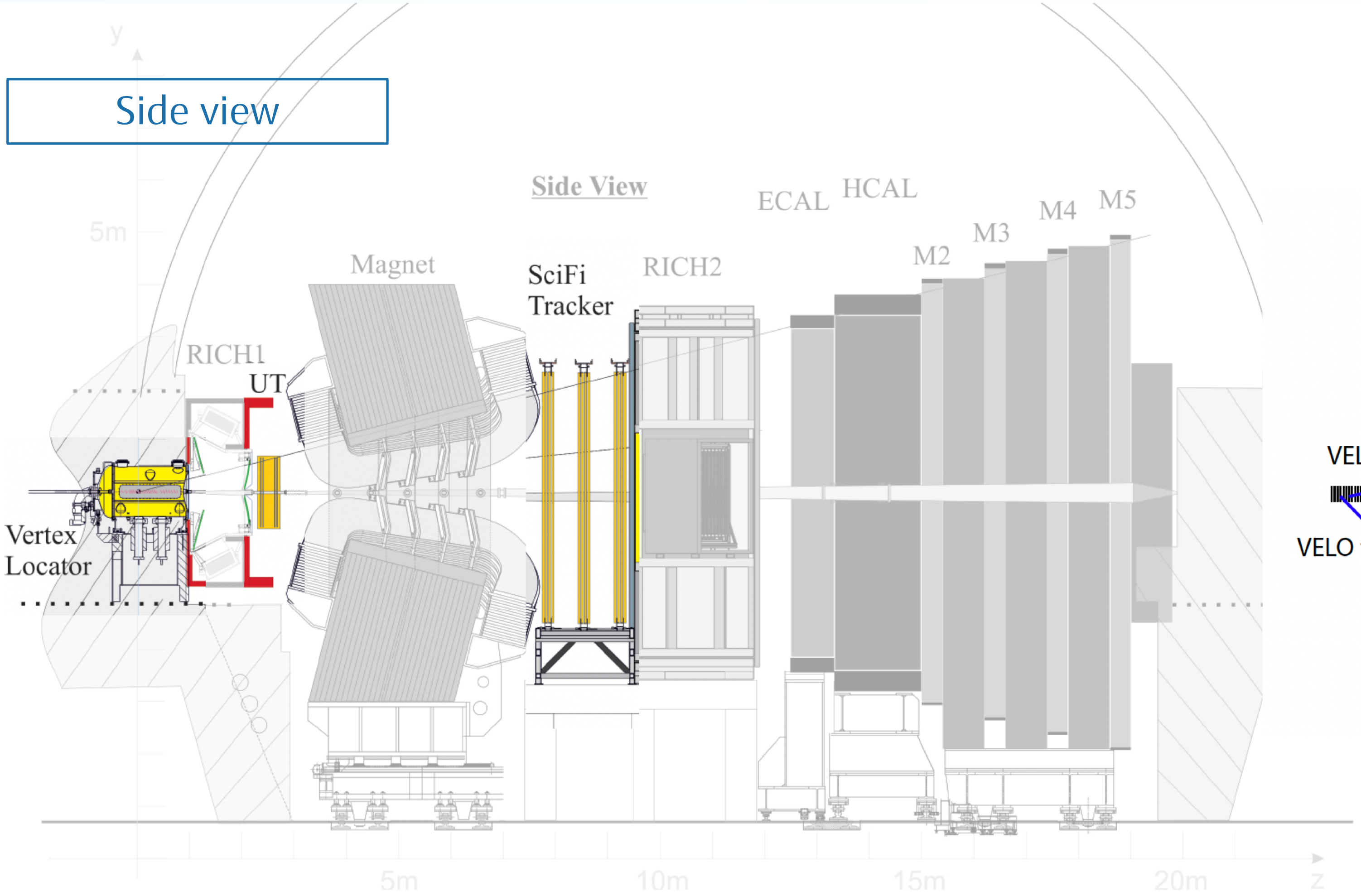
Muon detectors: new readout
M1 removed

$$\mathcal{L}_{\text{inst}} = 2 \times 10^{33} \text{cm}^{-2} \text{s}^{-1}$$

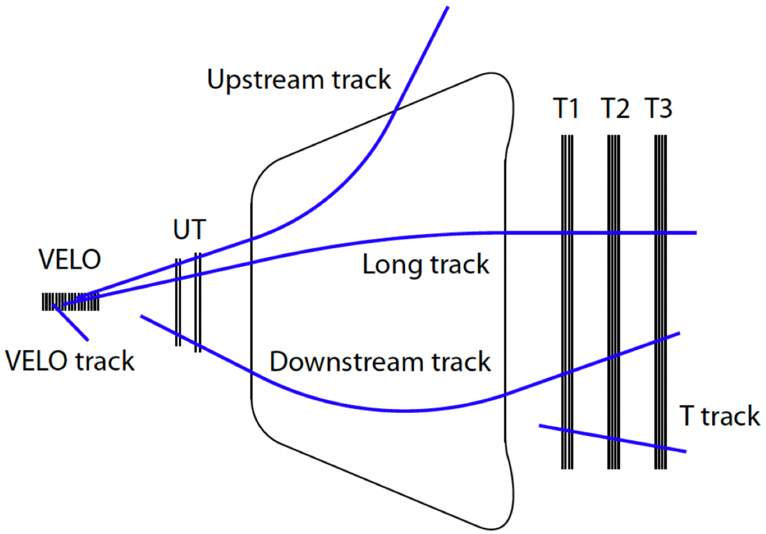
($5 \times$ Run 1,2)

Tracking system

Side view

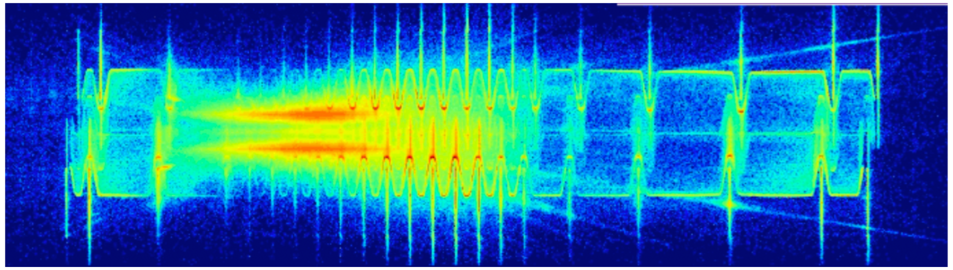


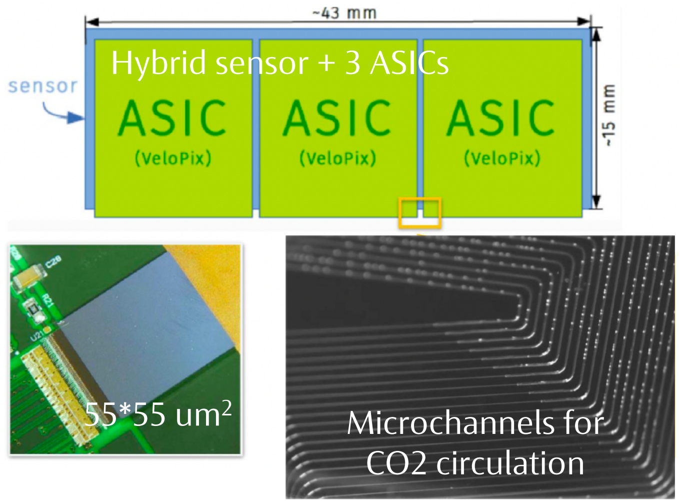
Top view

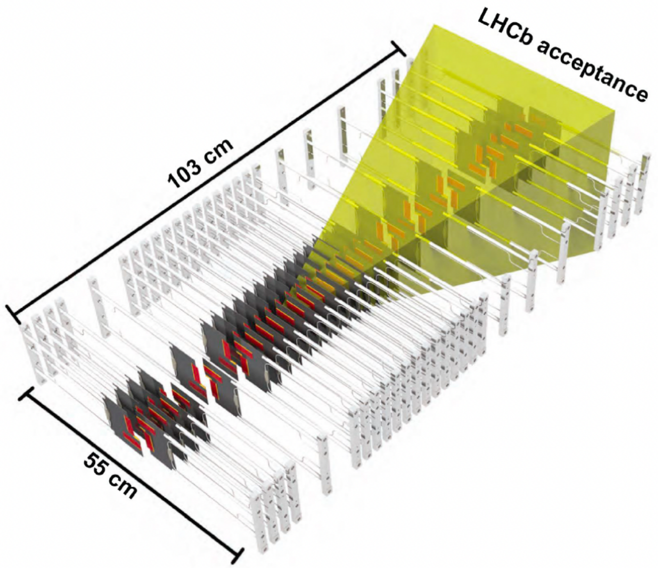


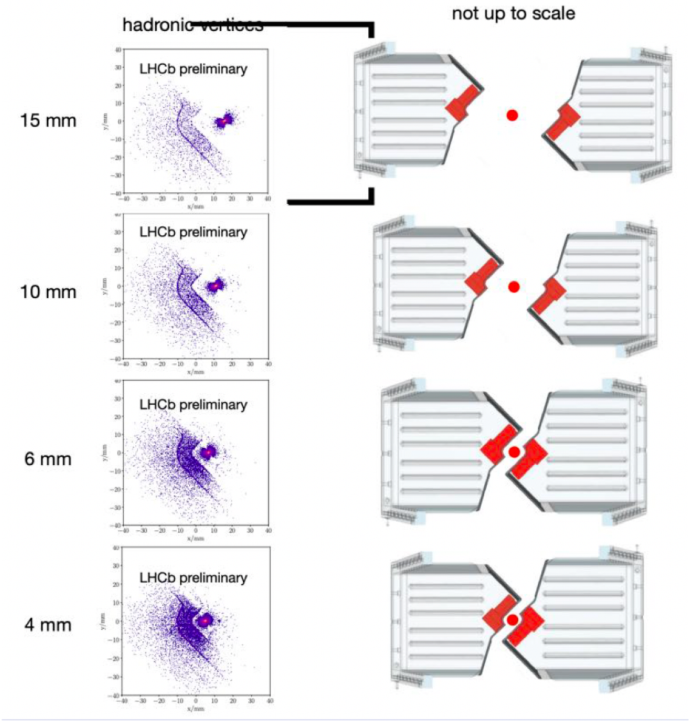
VELO

- Silicon pixel to replace strips
  - 55um * 55um pixel with microchannel cooling
  - 26 pair of modules
  - $\Phi_{max} \sim 7\times10^{14} \rightarrow 8\times10^{15}\ n_{eq}\ \mathrm{cm}^{-2}$
  - 150um thick RF foil
  - Only 5.1mm away from the beam



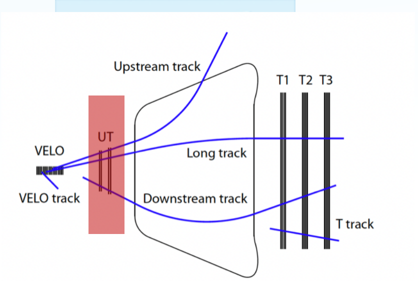


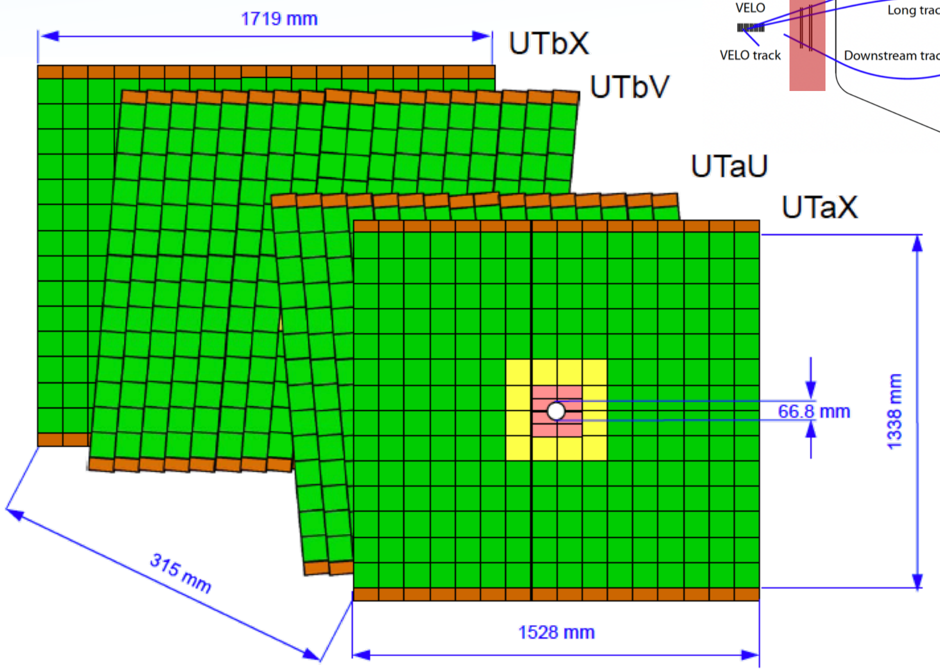


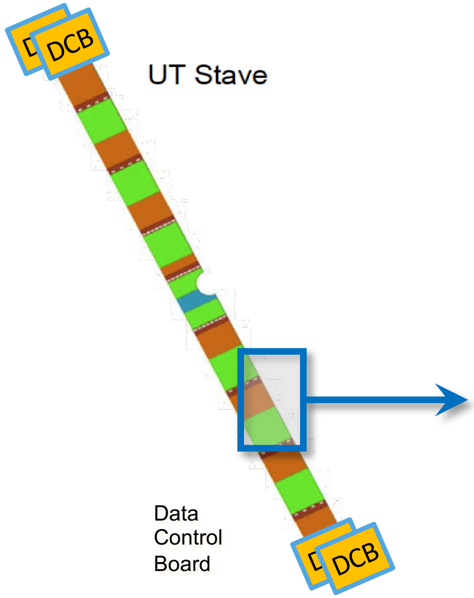


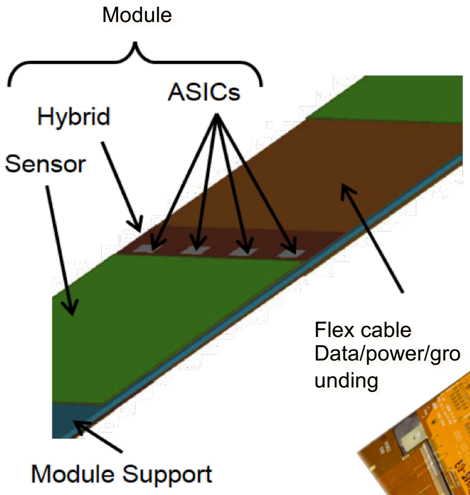
Upstream Tracker (UT)

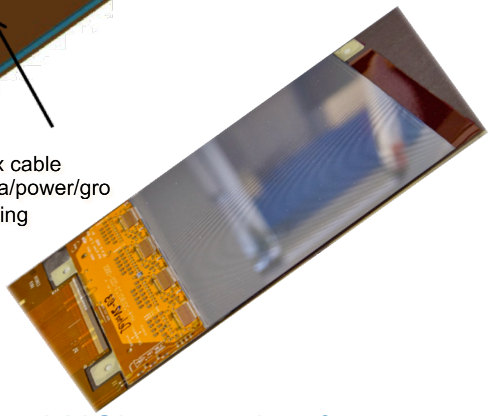
- Key component in tracking
  - Reducing ghost rate, speeding up tracking, crucial for long-lived particles like K_S, Λ
- Silicon strip detectors
  - 4 layers $(0°, +5°, -5°, 0°)$
  - 4 different sensor types depending on region









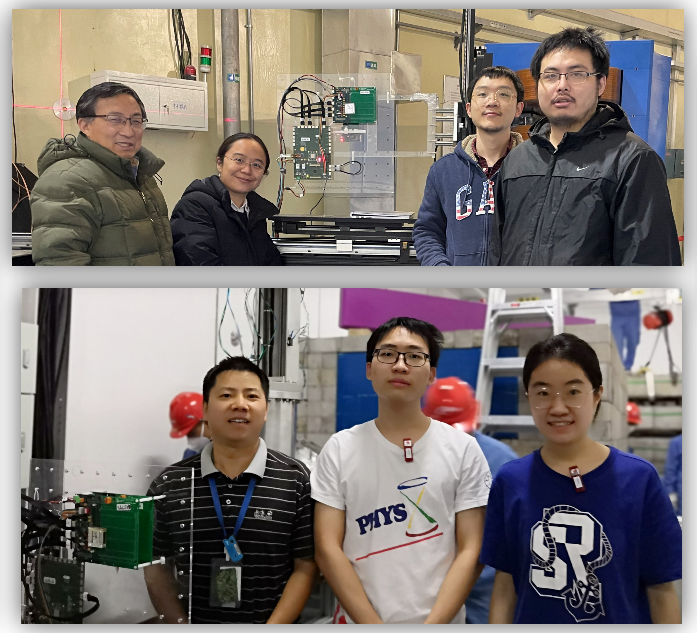


Sensor	Type	Pitch, µm	Length, mm	Strips	Sensor #
A	p-in-n	187.5	98	512	888
B	n-in-p	93.5	98	1024	48
C	n-in-p	93.5	49	1024	16
D	n-in-p	93.5	49	1024	16

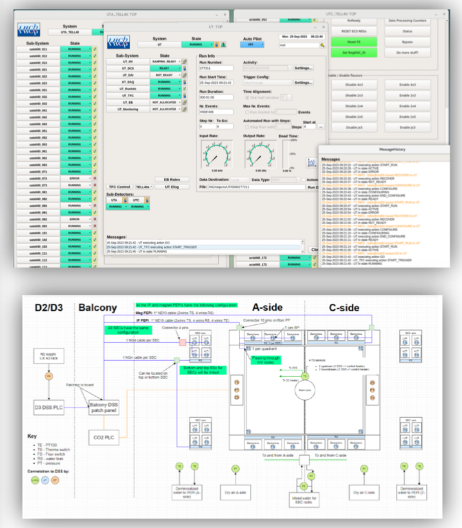
Chinese contribution in UT

- Played a key role in UT installation, FE verification and commissioning
  - Verifying irradiation performance of SALT Frontend chip using Chinese facilities
  - Control software (ECS) and detector safety software
  - Installation of UT from the very first stave to completion despite pandemic

Completion of UT A-/C-side



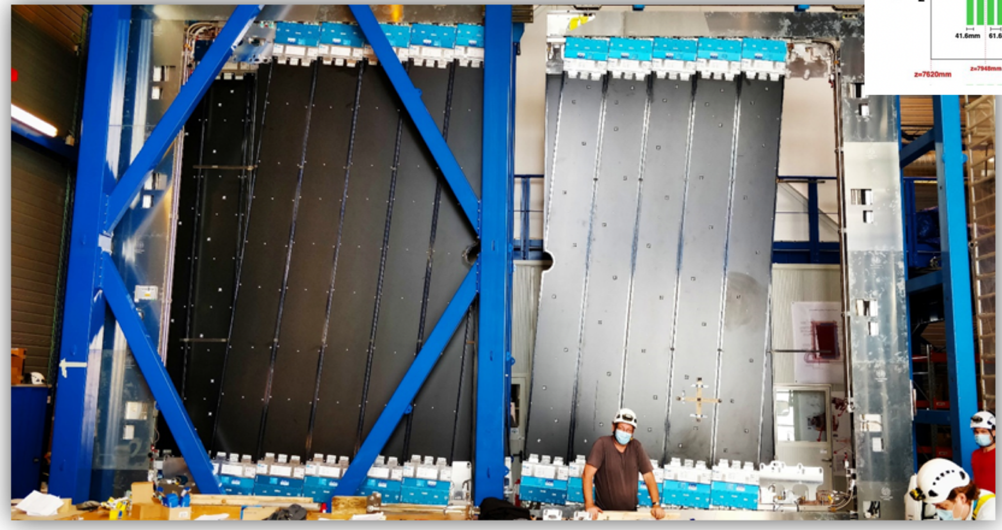
Irradiation test at CIAE and CSNS

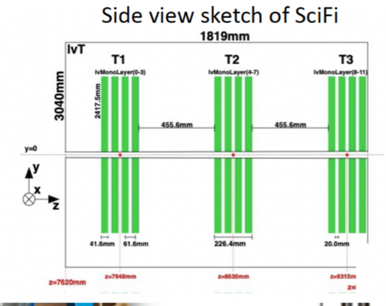


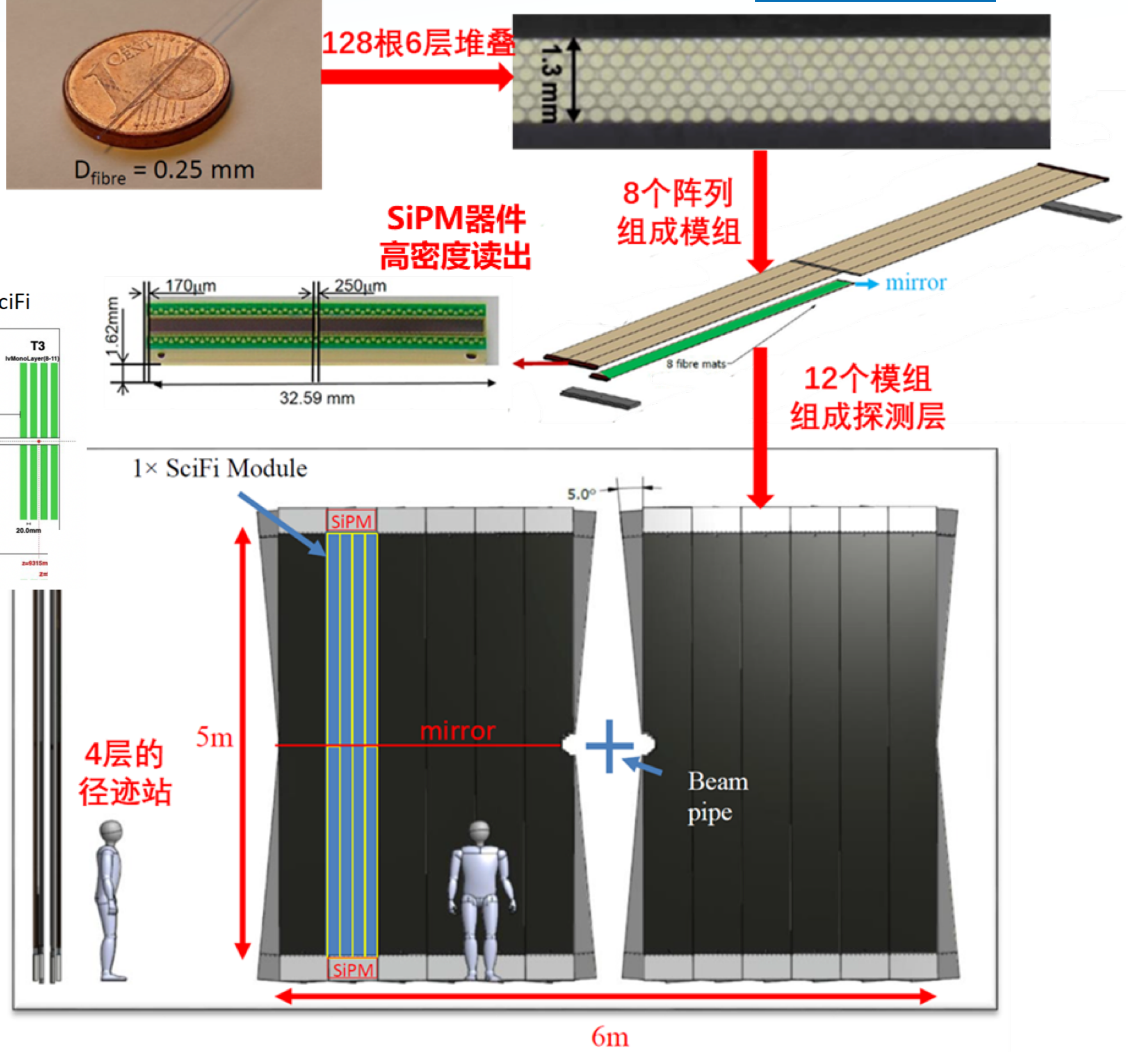
ECS and DSS panels designed by IHEP

SciFi

- Scintillator fibre read out by SiPM readout
  - 12 layers with area $6 \times 5\ \mathrm{m}^2$
  - Fibres 2.5 m in length, 250 um in diameter
  - Spatial resolution < 80 um
  - Hit efficiency > 99%
  - 524,000 readout channels!

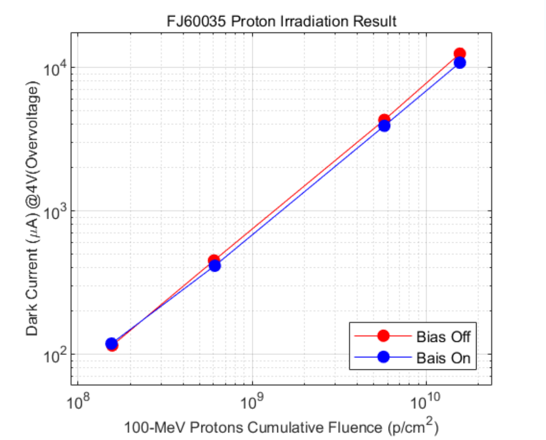


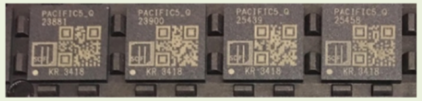


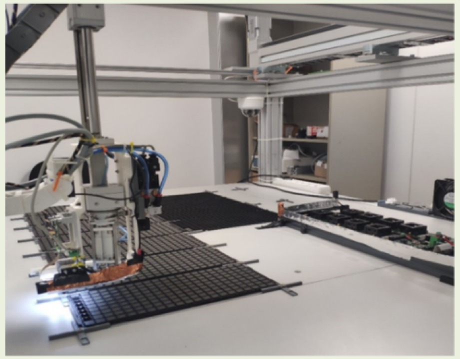


Chinese contribution to SciFi

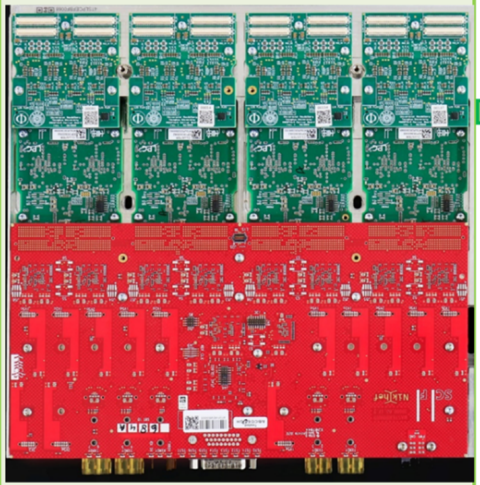
- Development and production of FE electronics boards (> 2,500 PCB)
  - Installed and working in SciFi
- Development of quality assurance system used in all SciFi assembly sites
- Study of radiation damage on SiPM



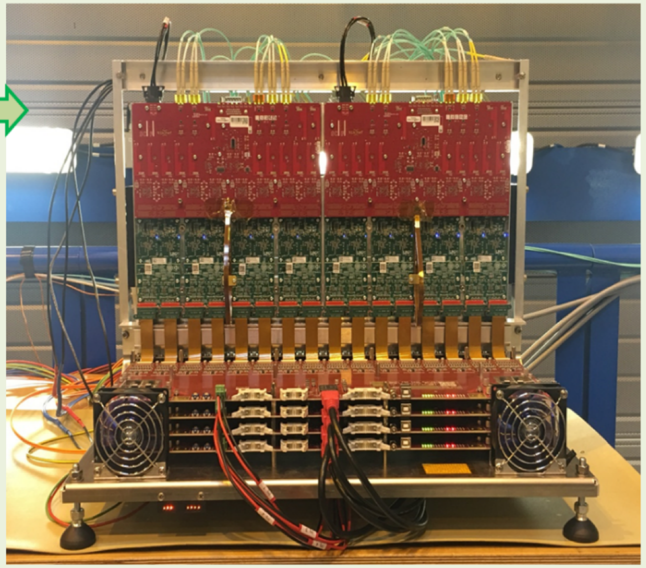




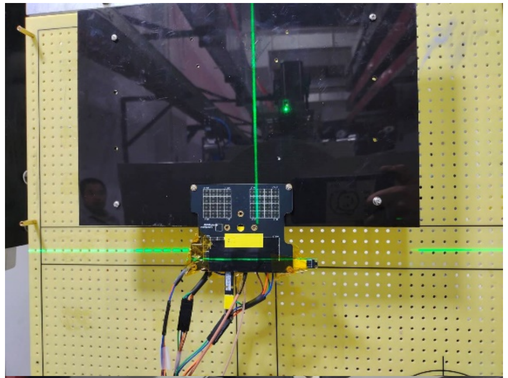
~12k ASICs tested :
✓Heidelberg (DE)
✓**Tsinghua (CN)**
✓ Barcelona (ES)
scan all critical parameters
with a custom design system.
Best ones selected for SciFi

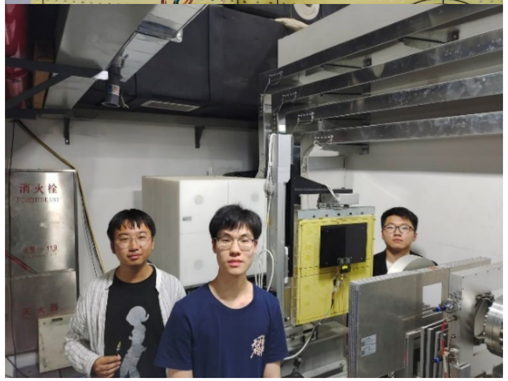


sub-component boards
tested individually
✓ Heidelberg (DE)
✓ **Tsinghua (CN)**
✓ Valencia (ES)
✓ Clermont-Ferrand (FR)
✓ Nikhef (NL)
Before assembled into a FEB



every FEB tested by a custom test
system for quality assurance

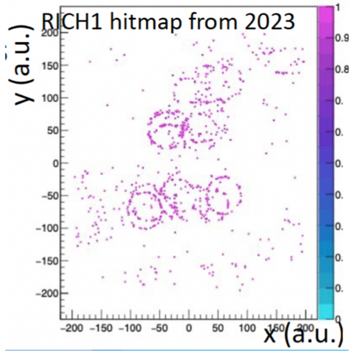




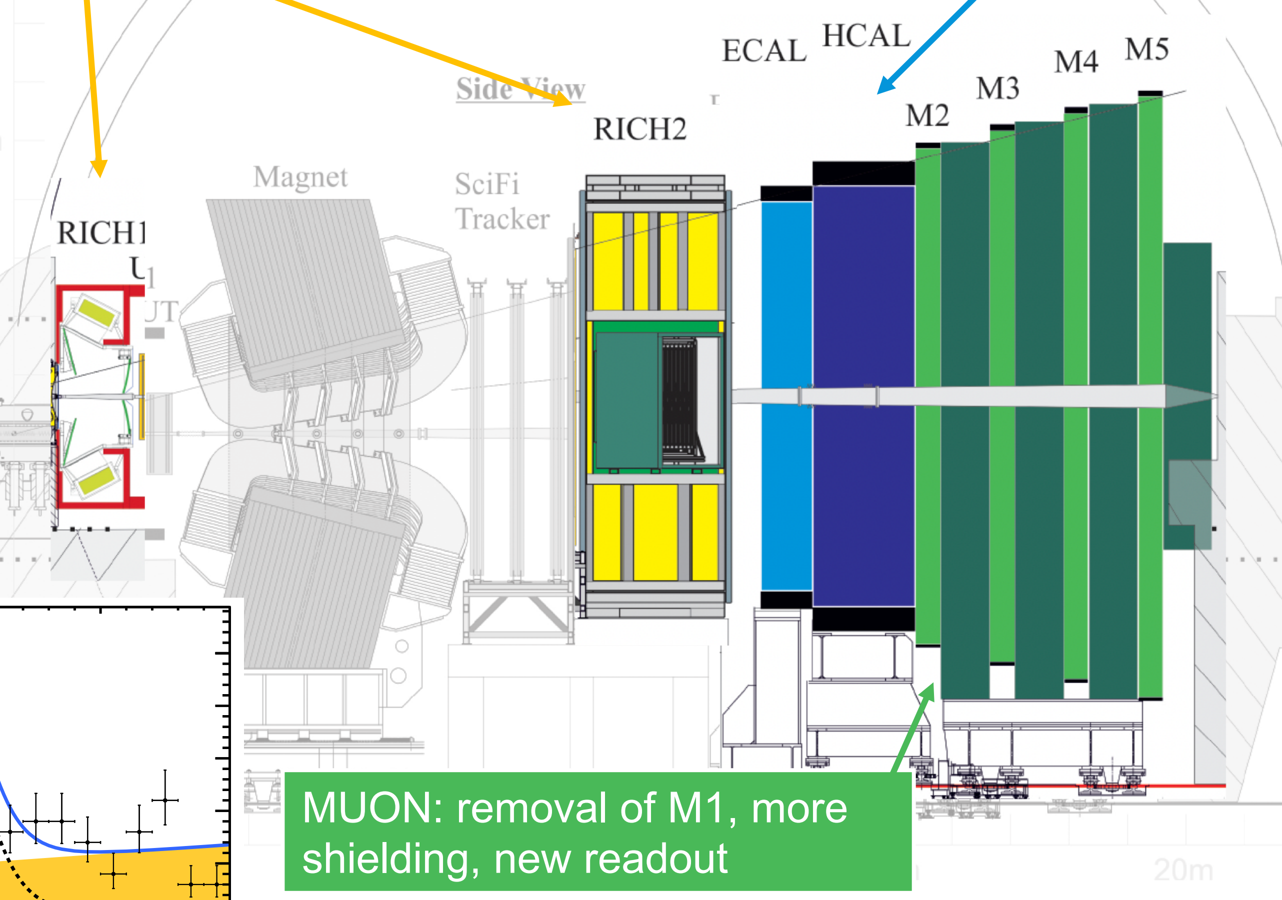
Upgraded PID systems

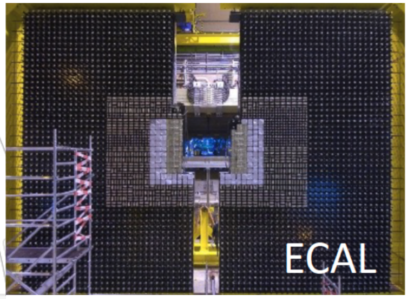
New RICH1 optics to reduce occupancy; RICH 1&2 MaPMT + new readout

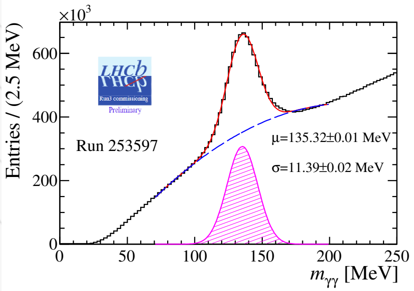
RICH1: C_4F_{10}, 2.6~60 GeV;
RICH2: CF_4, 15~100 GeV

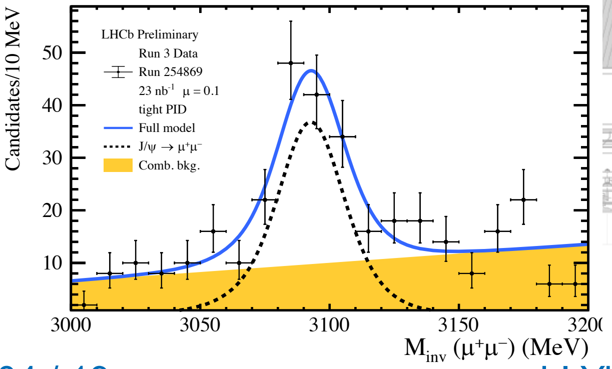


ECAL / HCAL detector remain with new readout; SPD/PS removed





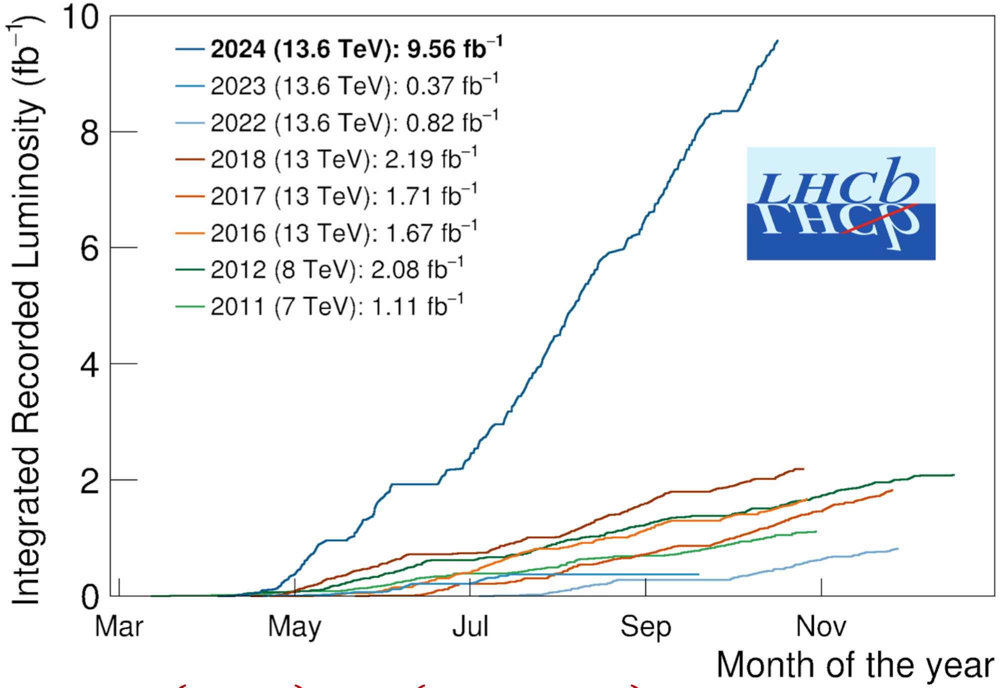




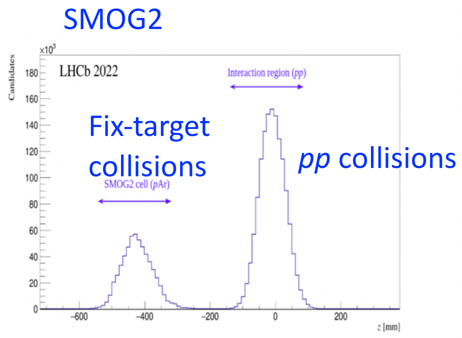
MUON: removal of M1, more shielding, new readout

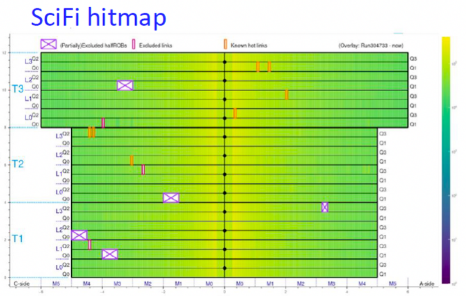
Run 3 ongoing!

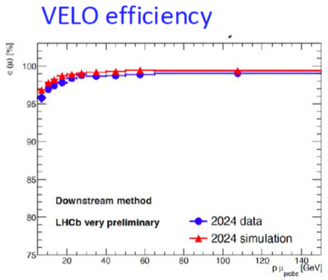
- Completion of installation in Mar 2023, commissioning since 2022
- All subdetectors working as designed!
- $50\ \mathrm{fb}^{-1}$ by end of Run 4: > 5 times of data now

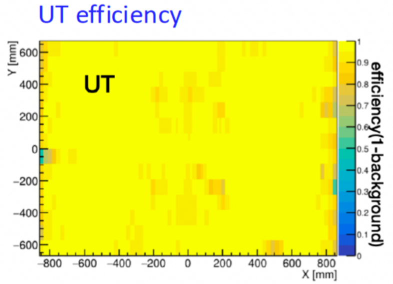


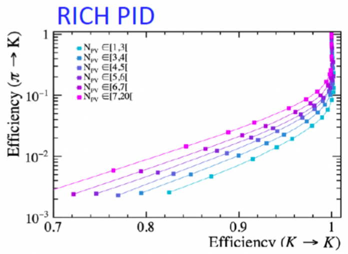
$\mathcal{L}(2024) > \mathcal{L}(\mathrm{Run}\ 1+2)$

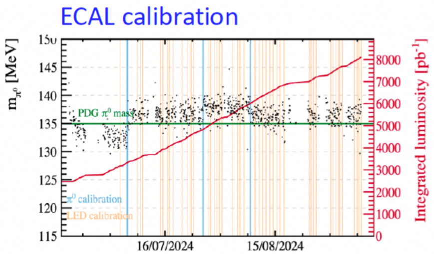


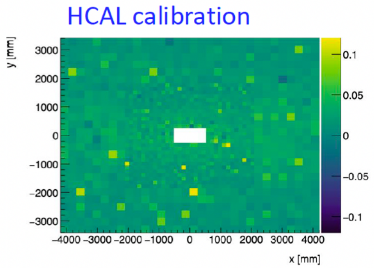


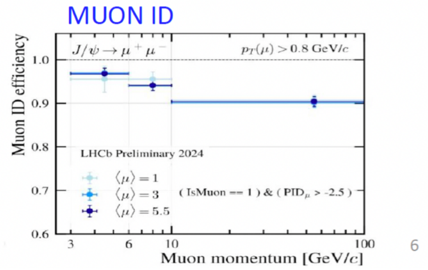








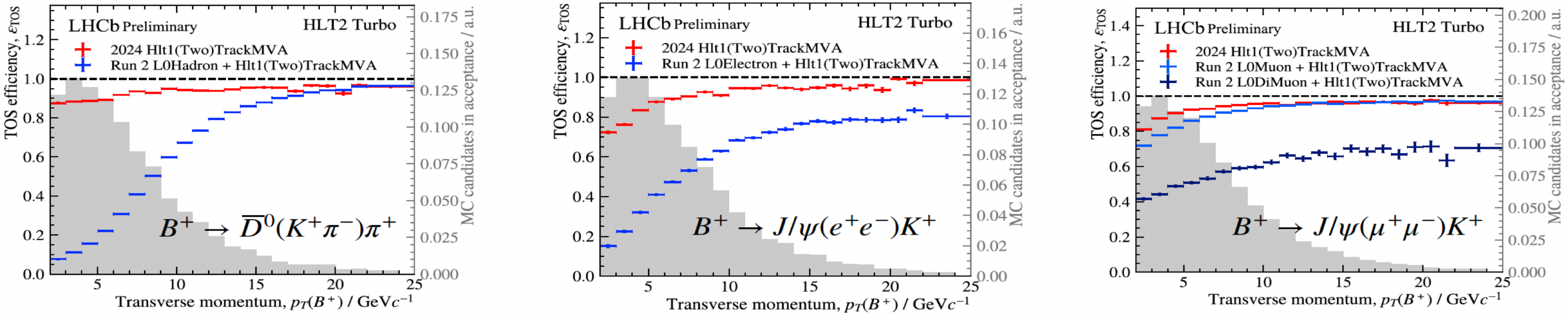




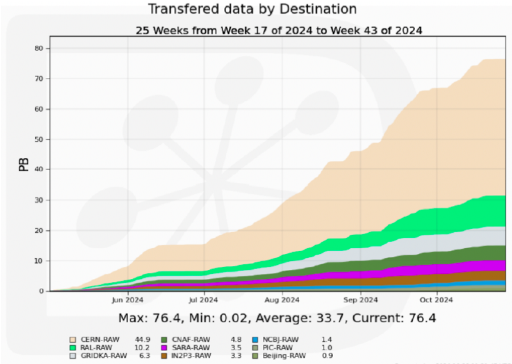
Performance

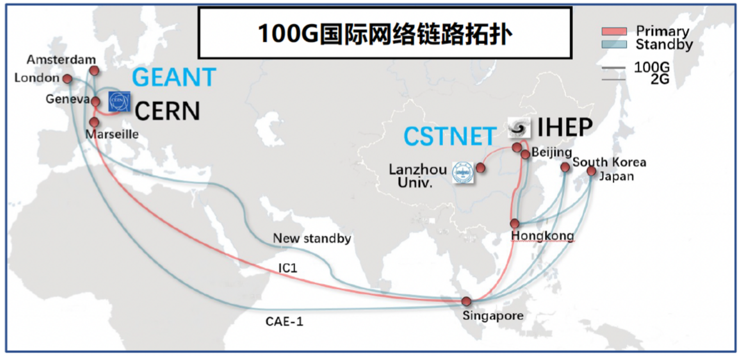
- Trigger efficiency significantly improved – removal of L0 working
  - For hadron and electron as intended, and also for muons

LHCb-Figure-2024-030



- Efficient use of CPU on WLCG grid to process huge amount of data
  - > 75 PB transferred from online farm
  - Contribution from Beijing Tier-1, Lanzhou Tier-2 operating since 2024

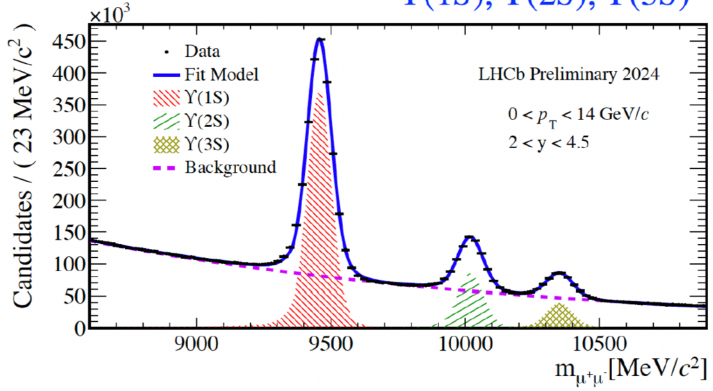




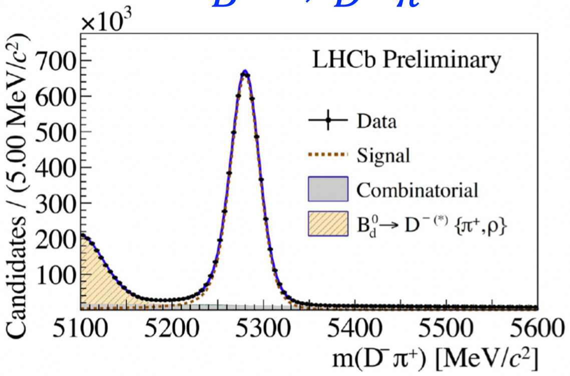
Performance

- First glimpse at the mass peaks …

$\Upsilon(1S), \Upsilon(2S), \Upsilon(3S)$

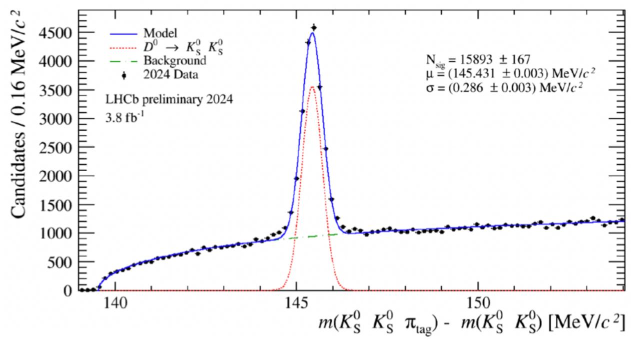


$B^0 \rightarrow D^- \pi^+$



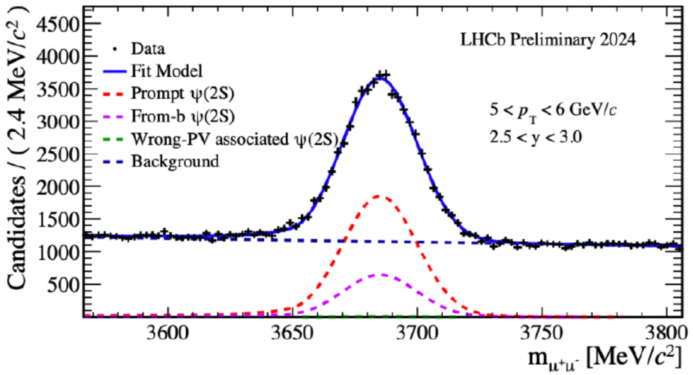
1.1e6 per fb^{-1}, 3× Run2

$D^* \rightarrow D^0(K_S K_S)\,\pi$

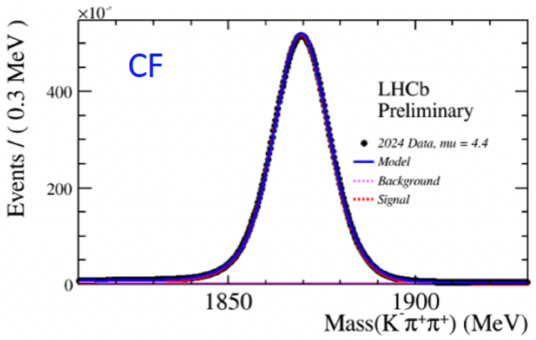


3.6× Run2

$\psi(2S)$

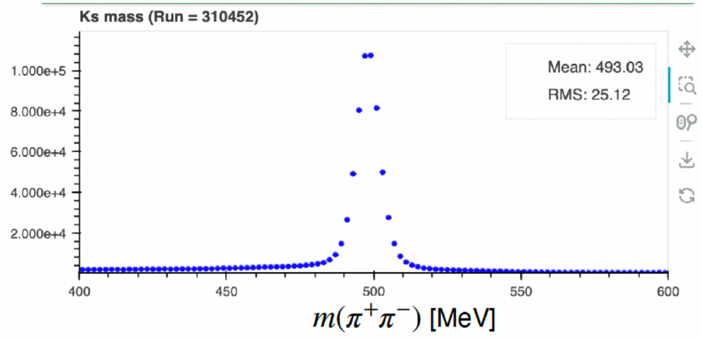


$D^+ \rightarrow K^- \pi^+ \pi^+$

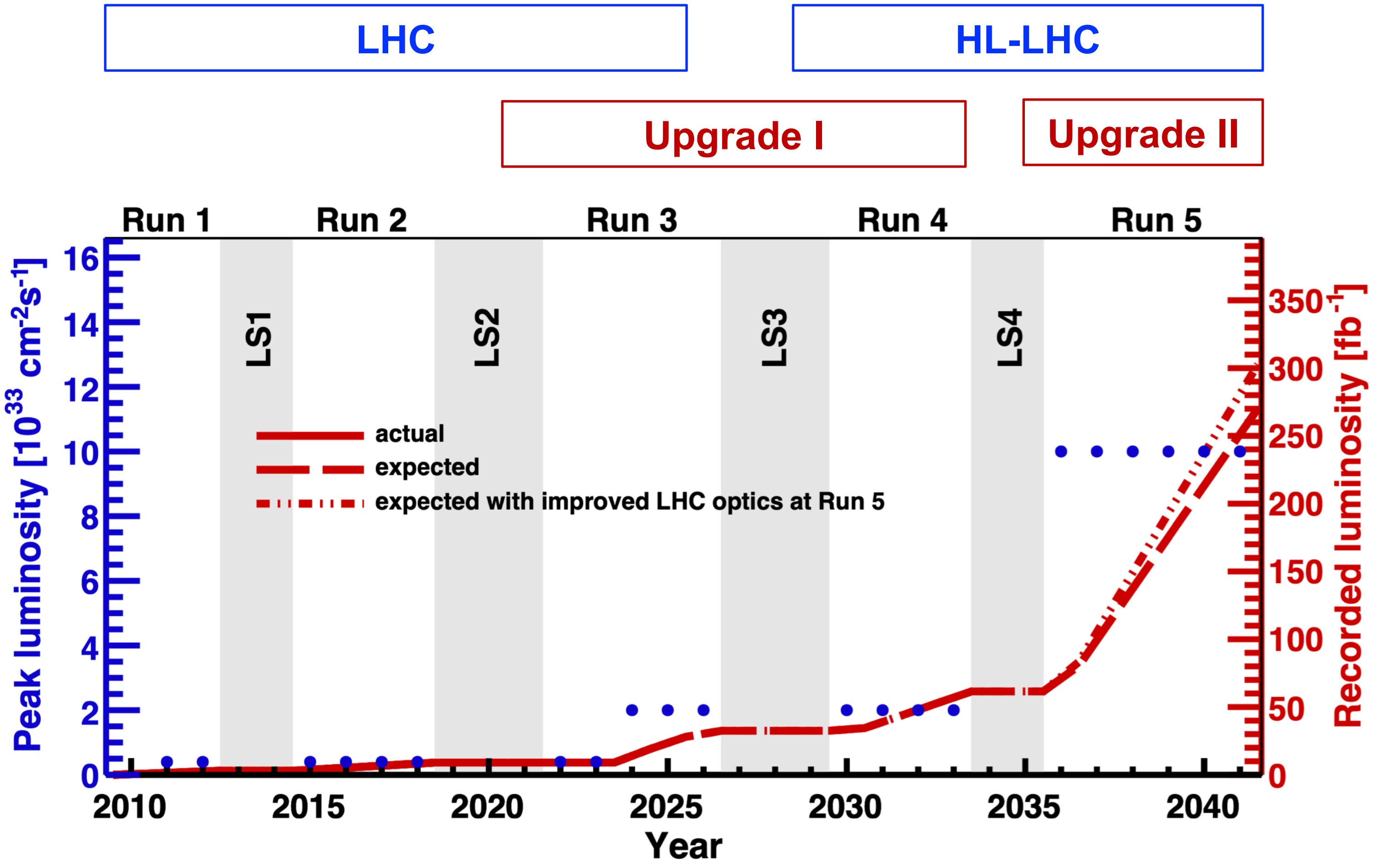


1.8e6 per pb^{-1}, 2.8× Run2

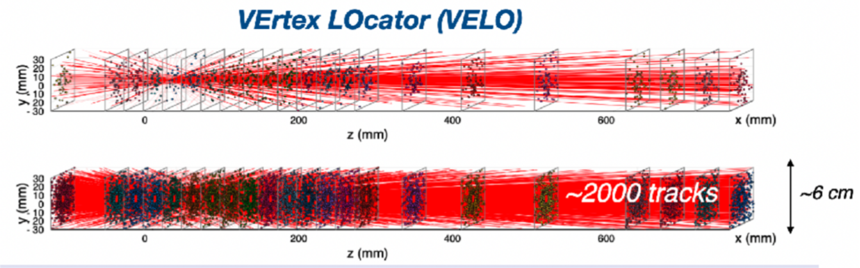
$K_S \rightarrow \pi^+\pi^-$ at PbPb run



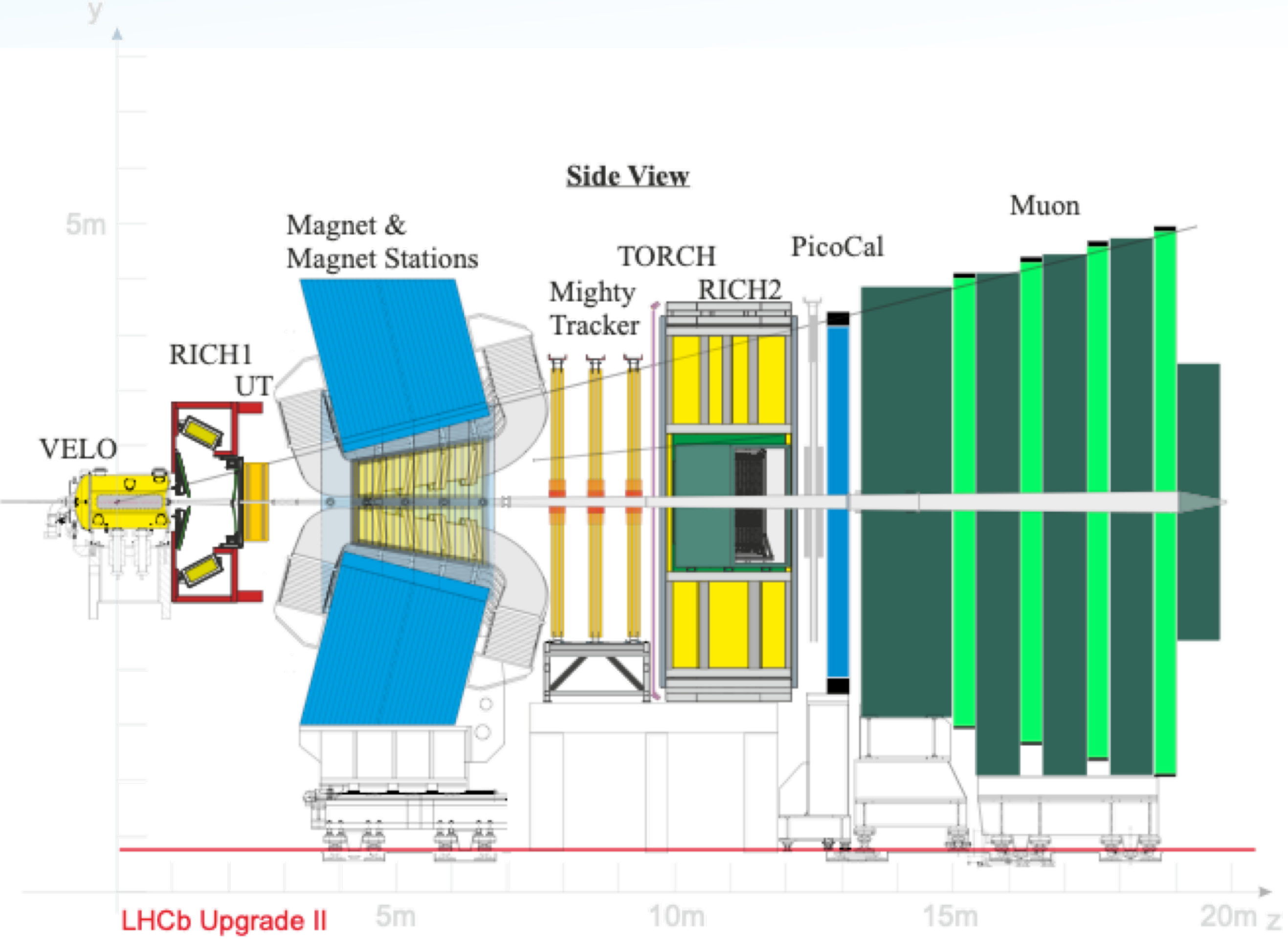
Upgrade II



- Upgrade II to fully exploit flavour physics potential in HL-LHC
- Target luminosity:
  - $1.0{\sim}1.5 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$
  - $300{\sim}350\ \text{fb}^{-1}$
- High-lumi operation challenges:
  - Pile-up: $\mu \sim 1 \rightarrow 5\ (\text{UI}) \rightarrow 40\ (\text{UII})$,
  - High multiplicity (→ occupancy)
  - Severe radiation damage
  - High data rates (200 Tb/s)



LHCb in Upgrade II



Expression of interest
CERN-LHCC-2017-003

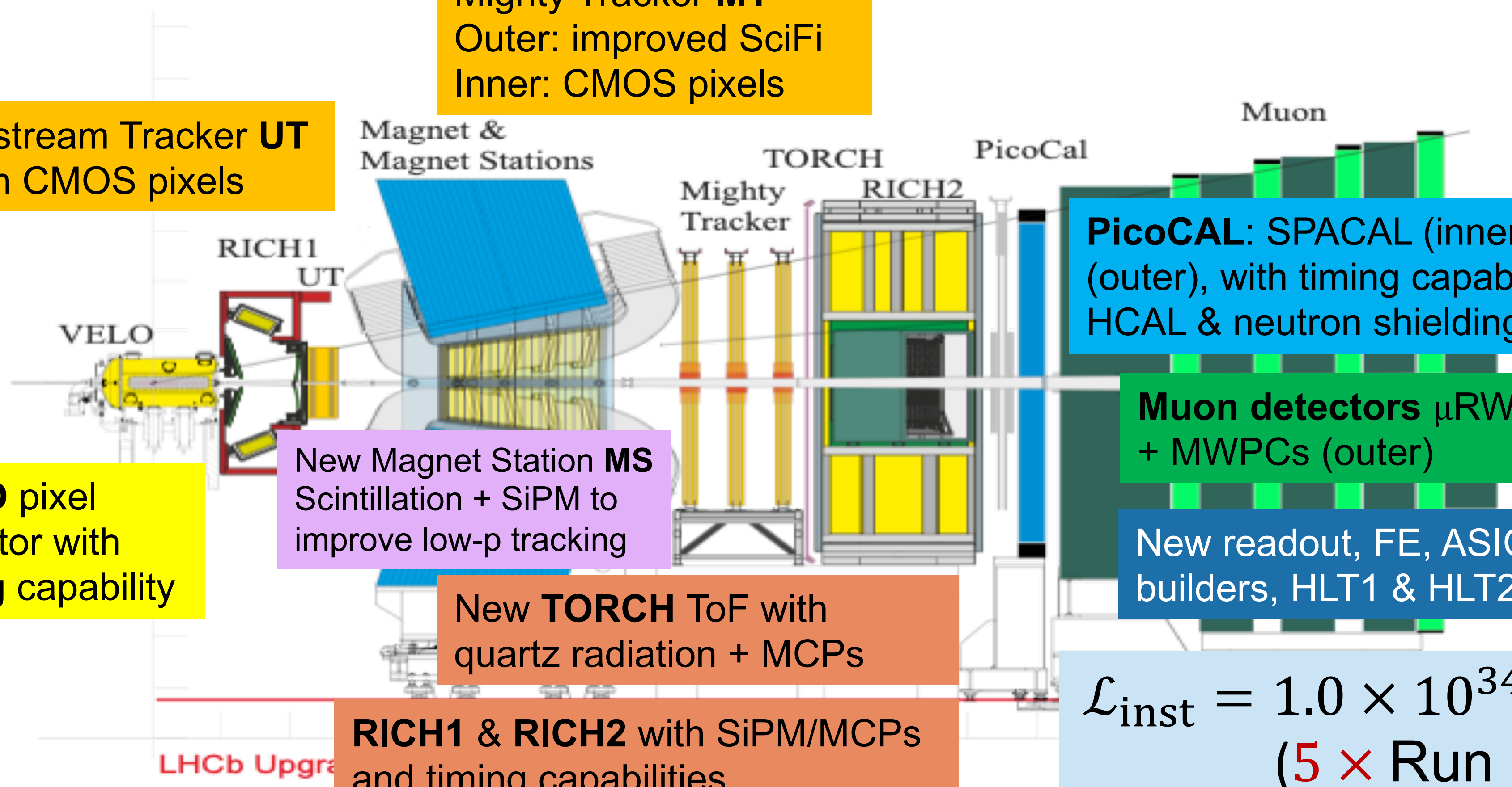
Physics case
CERN-LHCC-2018-027

Framework TDR
CERN-LHCC-2021-012

Scoping Document
CERN-LHCC-2024-010

- Review by LHCC concluded & endorsed; recommended to proceed with ‘middle-scenario’ $(1.0 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1})$

… an ultimate flavour experiment at HL-LHC



Mighty Tracker **MT**
Outer: improved SciFi
Inner: CMOS pixels

Upstream Tracker **UT** with CMOS pixels

PicoCAL: SPACAL (inner) + Shashlik (outer), with timing capabilities
HCAL & neutron shielding removed

Muon detectors μRWELL (inner) + MWPCs (outer)

VELO pixel detector with timing capability

New Magnet Station **MS** Scintillation + SiPM to improve low-p tracking

New readout, FE, ASICs, event builders, HLT1 & HLT2 farms …

New **TORCH** ToF with quartz radiation + MCPs

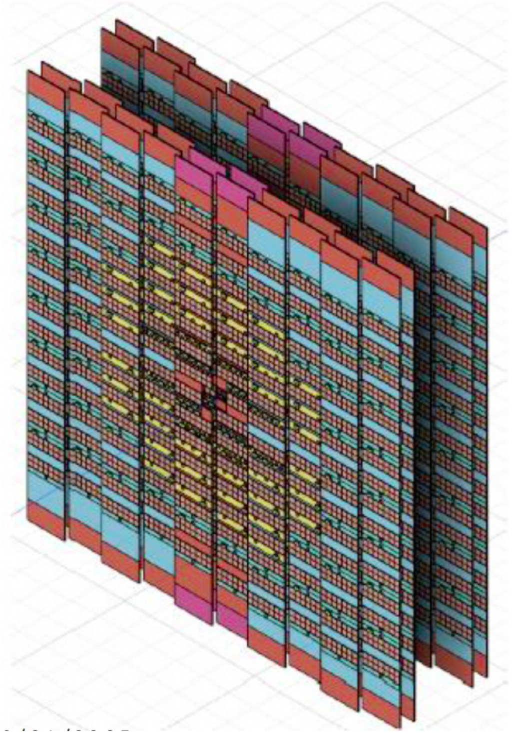
RICH1 & **RICH2** with SiPM/MCPs and timing capabilities

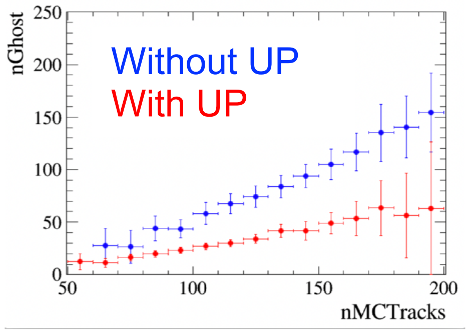
$$\mathcal{L}_{\text{inst}} = 1.0 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$$
(5 × Run 3)

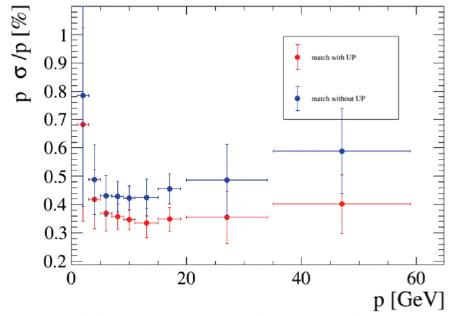
Upstream Pixel detector

NIM A 1032 (2022) 166629

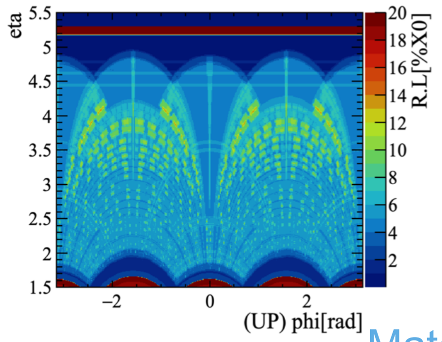
- Proposal for a new UT using CMOS MAPS technology
  - Higher granularity for high multiplicity
  - Better radiation tolerance
- R&D collaboration formed mainly by Chinese and French institutes
  - Leading development in simulation, CMOS sensor R&D and prototyping

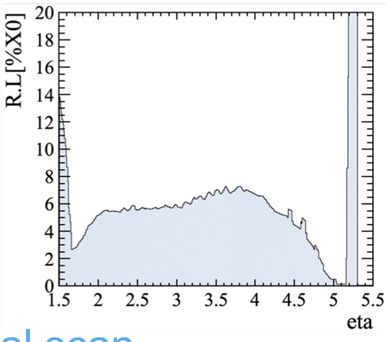




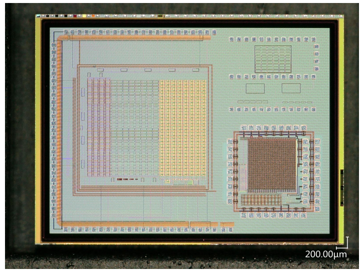


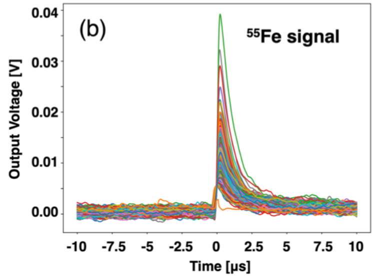
Simulation shows UP improves ghost rate and momentum resolution





Material scan



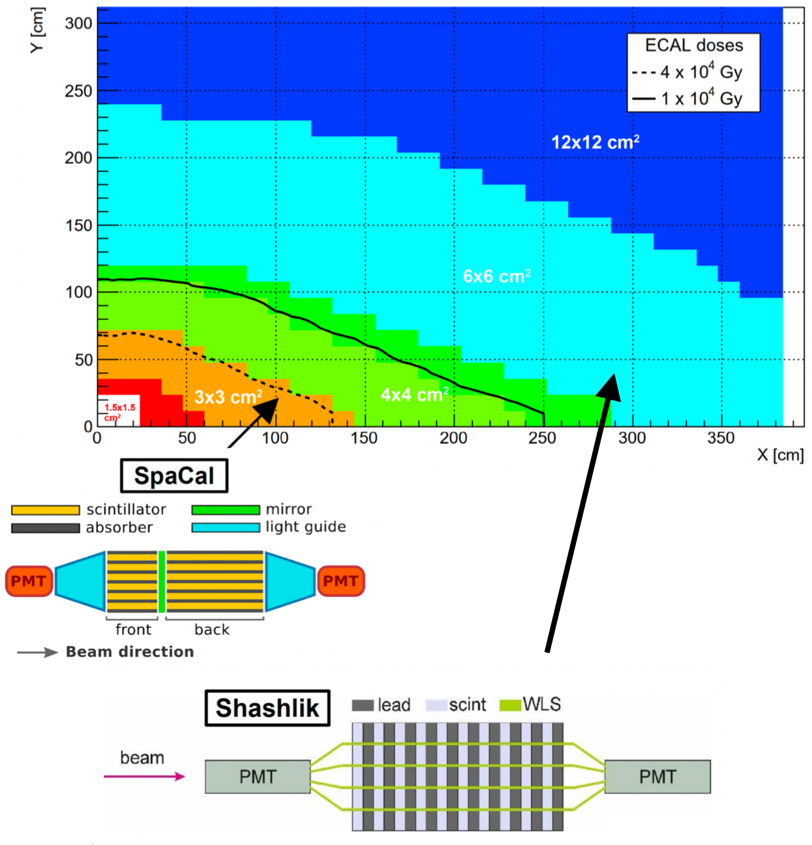


R&D of SMIC 55nm HVCMOS (COFFEE)

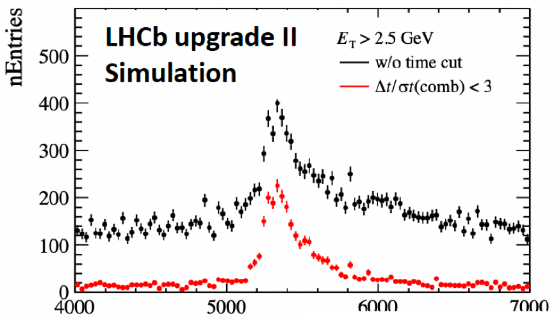
PicoCAL

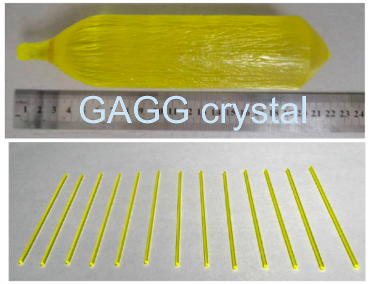
CERN-LHCC-2023-005

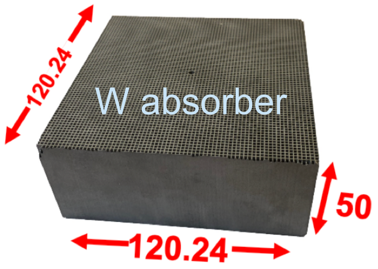
- Maintaining ECAL performance
- Inner part using SpaCal and outer keeps Shashlik technology
- Timing of O(10) ps expected



- Chinese groups active in the R&D:
  - Simulation and optimization
  - 3D-printed tungsten absorber
  - GAGG crystal fibre development





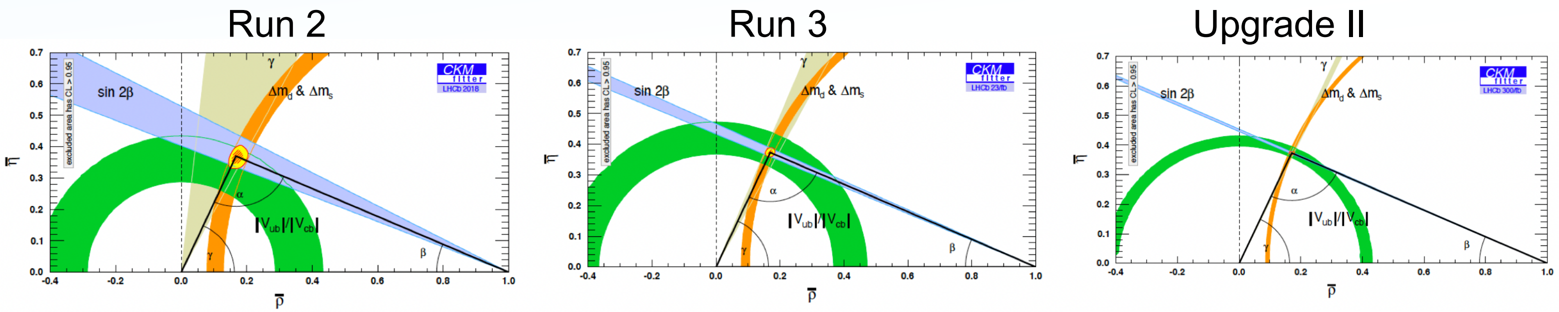


Physics Prospects

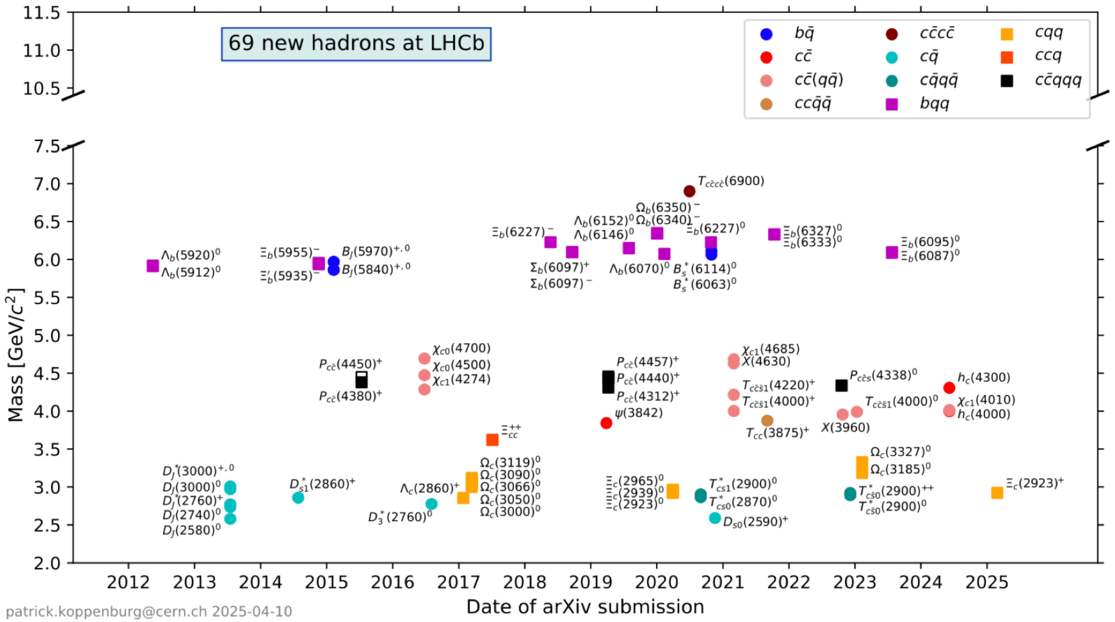
- Statistics is powerful
- Some gain can be expected

Observable	LHCb current	LHCb (23 fb^{-1})	LHCb (300 fb^{-1})
CKM tests			
γ (all modes)	4° [784, 931]	1.5°	0.35°
γ ($B_s^0 \to D_s^+ K^-$)	$(^{+17}_{-22})°$	4°	1°
$\sin 2\beta$	0.04 [932]	0.011	0.003
ϕ_s ($B_s^0 \to J/\psi\phi$)	49 mrad [933]	14 mrad	4 mrad
ϕ_s ($B_s^0 \to D_s^+ D_s^-$)	170 mrad [825]	35 mrad	9 mrad
$\phi_s^{s\bar{s}s}$ ($B_s^0 \to \phi\phi$)	154 mrad [936]	39 mrad	11 mrad
a_{sl}^s	33×10^{-4} [938]	10×10^{-4}	3×10^{-4}
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [847]	3%	1%
Charm			
$\Delta\mathcal{A}^{CP}$	2.9×10^{-4} [790]	1.7×10^{-4}	3.0×10^{-5}
A_Γ	1.3×10^{-4} [877]	4.2×10^{-5}	1.0×10^{-5}
$B^0_{(s)} \to \mu^+\mu^-$			
$\frac{\mathcal{B}(B^0 \to \mu^+\mu^-)}{\mathcal{B}(B_s^0 \to \mu^+\mu^-)}$	71% [661, 662]	34%	10%
$\tau_{B_s^0 \to \mu^+\mu^-}$	14% [661, 662]	8%	2%
EW penguins			
R_K ($B^+ \to K^+\ell^+\ell^-$)	0.044 [703]	0.025	0.007
R_{K^*} ($B^0 \to K^{*0}\ell^+\ell^-$)	0.10 [709]	0.031	0.008
LFU tests			
R_{D^*} ($B^0 \to D^{*-}\ell^+\nu$)	0.026 [941, 942]	0.007	0.002
$R_{J/\psi}$ ($B_c^+ \to J/\psi\ell^+\nu$)	0.24 [943]	0.07	0.02

Physics case for Upgrade II, CERN-LHCC-2018-027, arXiv:1808.08865
Chen et al, Frontiers of Physics 18 (2023) 44601



- Some not



https://www.nikhef.nl/%7Epkoppenb/particles.html

??

Baryons?
(bqq, ccq, bcq, bbq,…)

Tetraquark?

Pentaquarks?

Summary

- LHCb upgrade I is completed and continues to take high-quality physics data
- R&D ongoing for Upgrade II, Chinese groups are key players in UT and ECAL
- A lot more data and potential for physics output, interplay with theory community more important than ever

Thank you for your time!

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Reference

- LHCb探测器及升级计划，科学通报 2024,69（31）：4529
- The LHCb Upgrade I, JINST 19 (2024) P05065
- LHCb Upgrade II Scoping Document, CERN-LHCC-2024-010
- LHCb Framework TDR for the LHCb Upgrade II, CERN-LHCC-2021-012
- Physics case for an LHCb Upgrade II – Opportunities in flavour physics, and beyond, in the HL-LHC era, arXiv:1808.08865