LHCb 实验现状和展望
LHCb Status and Upgrade Plan

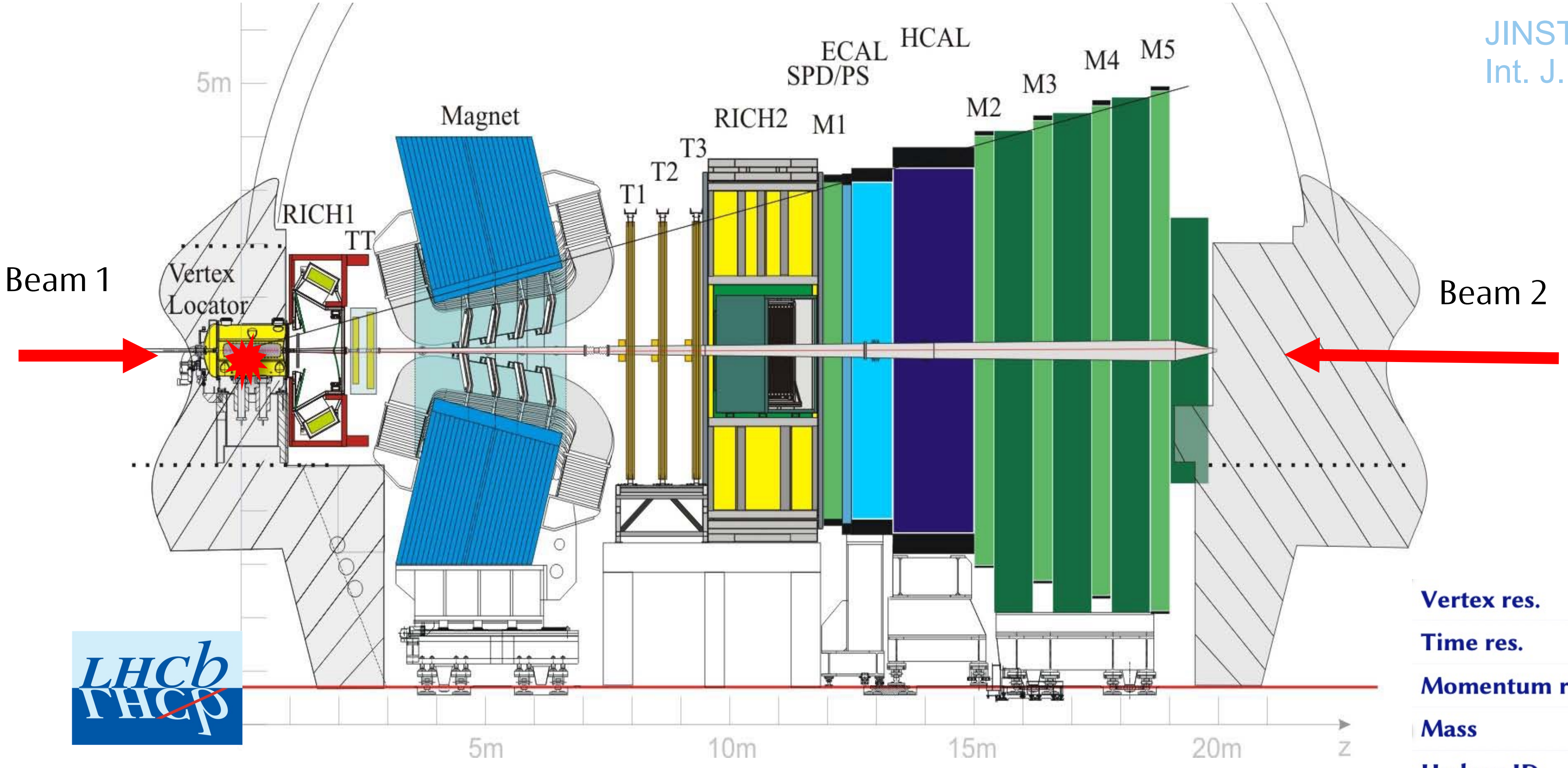
李一鸣 LI Yiming
中国科学院高能物理研究所
(liyiming@ihep.ac.cn)
Institute of High Energy Physics, CAS

第三届BESIII-BelleII-LHCb粲强子物理联合讨论会 @ 长沙
The 3rd BESIII-BelleII-LHCb Charm Physics Workshop, Jun 2025

Content

- Upgrade I … or the status of upgraded LHCb detector
- Future plan: Upgrade II
- Conclusion

LHCb as we knew



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

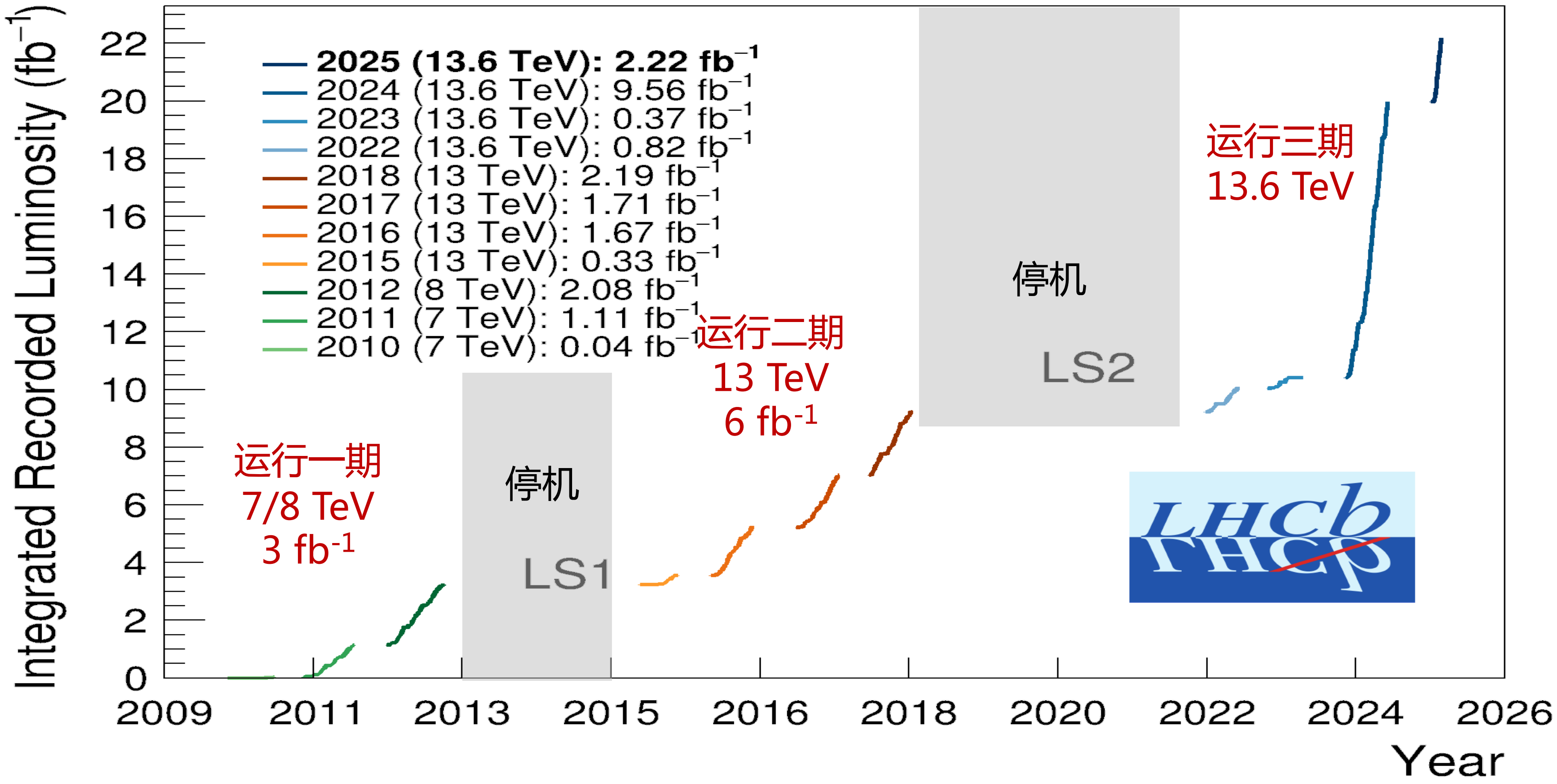
Ideal for charm physics:

- $\sigma(c\bar{c}X) = 2369 \pm 192\ \mu\mathrm{b}$
- All charm hadrons can be produced
- Excellent performance
    - Mass resolution
    - Time resolution
    - PID

Vertex res.	$\sigma_{\mathrm{IP}} = 20\ \mu\mathrm{m}$
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.	$\Delta E/E = 1\% \oplus 10\%/\sqrt{E\ (\mathrm{GeV})}$

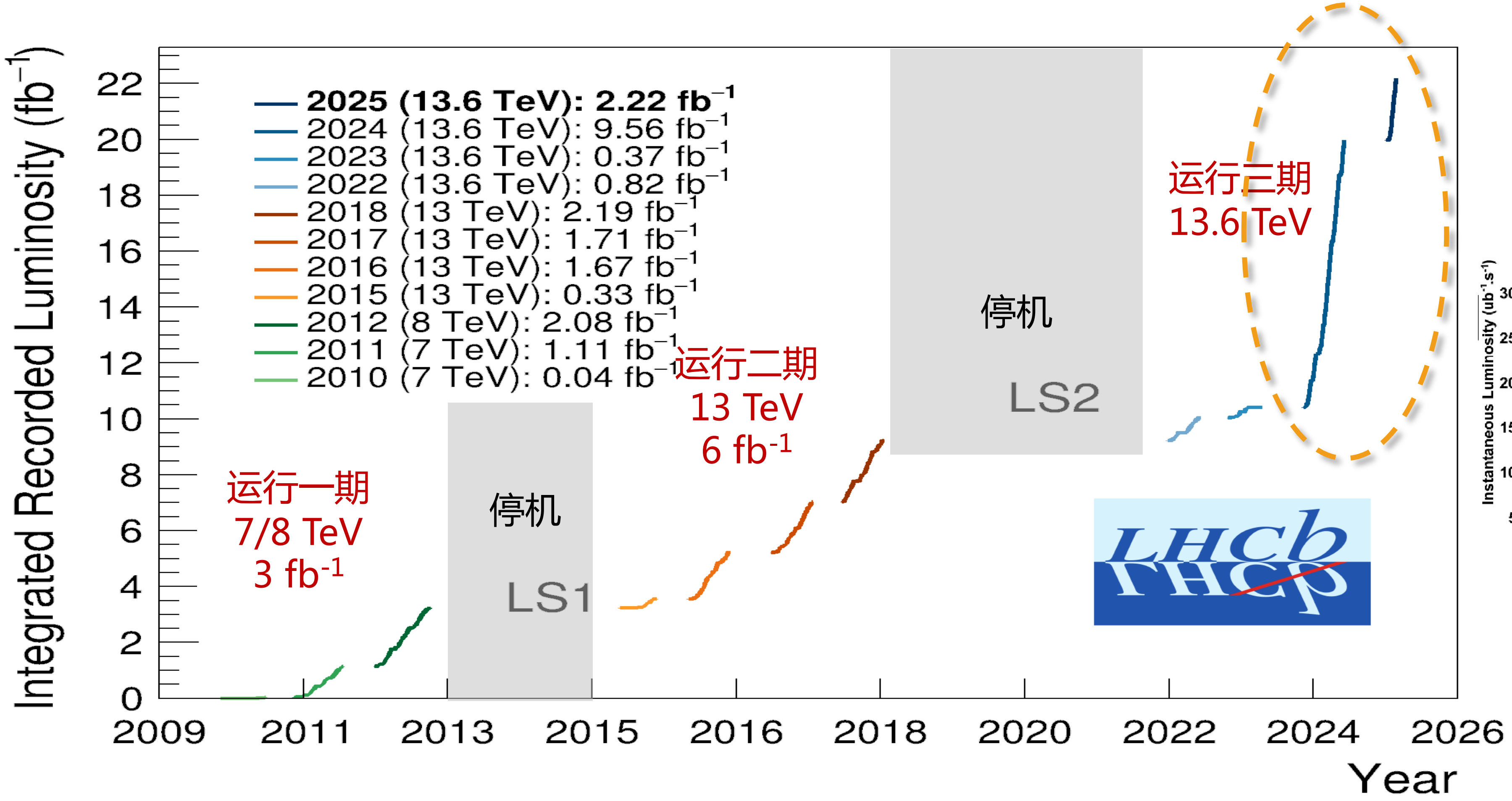
Data taking

- Most physics output using data before 2019

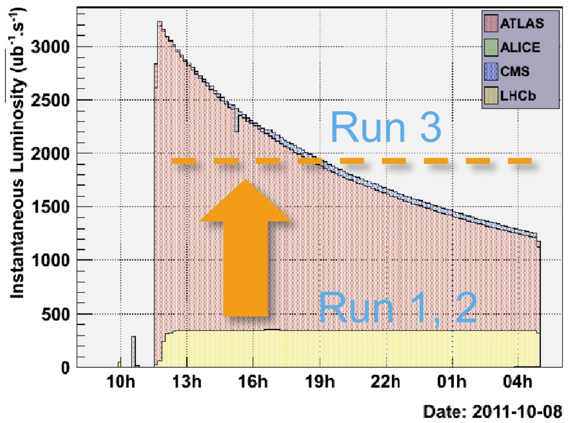


Data taking

- Most physics output using data before 2019

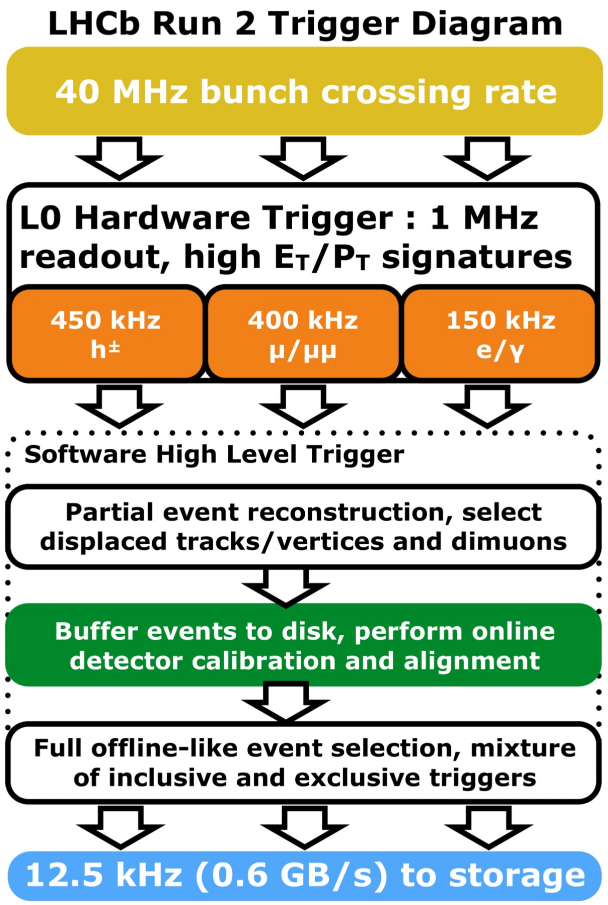


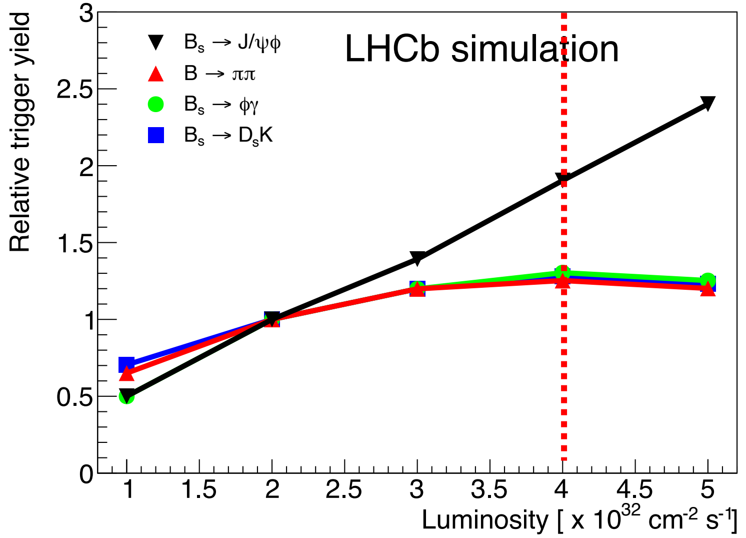
Instantaneous lumi:
A typical fill at LHC
before Upgrade I



Limitation due to trigger saturation

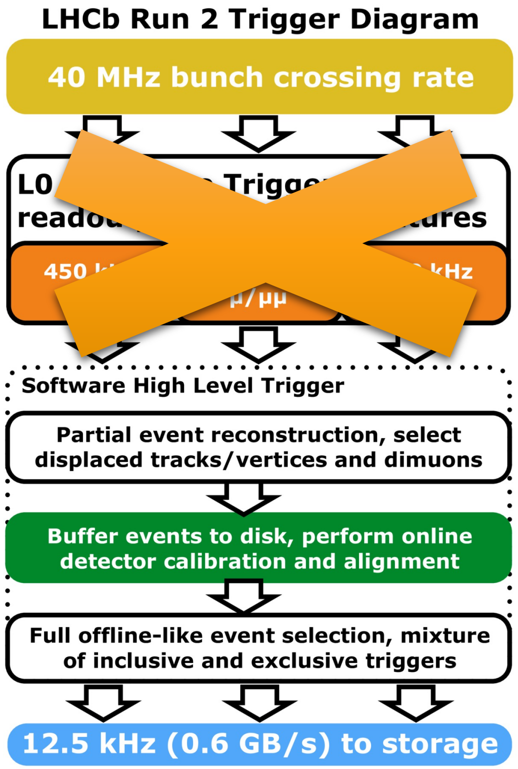
- Previous luminosity of $4\times10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ limited by detector capability!

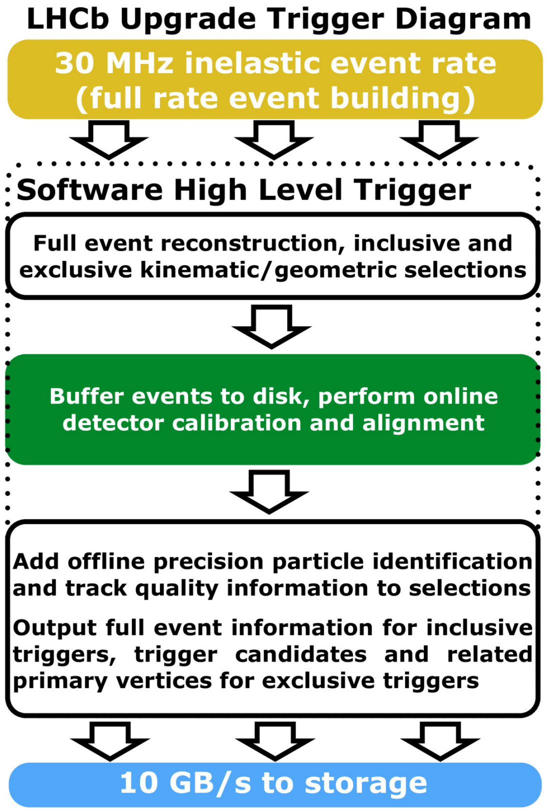




Goal of LHCb Upgrade I

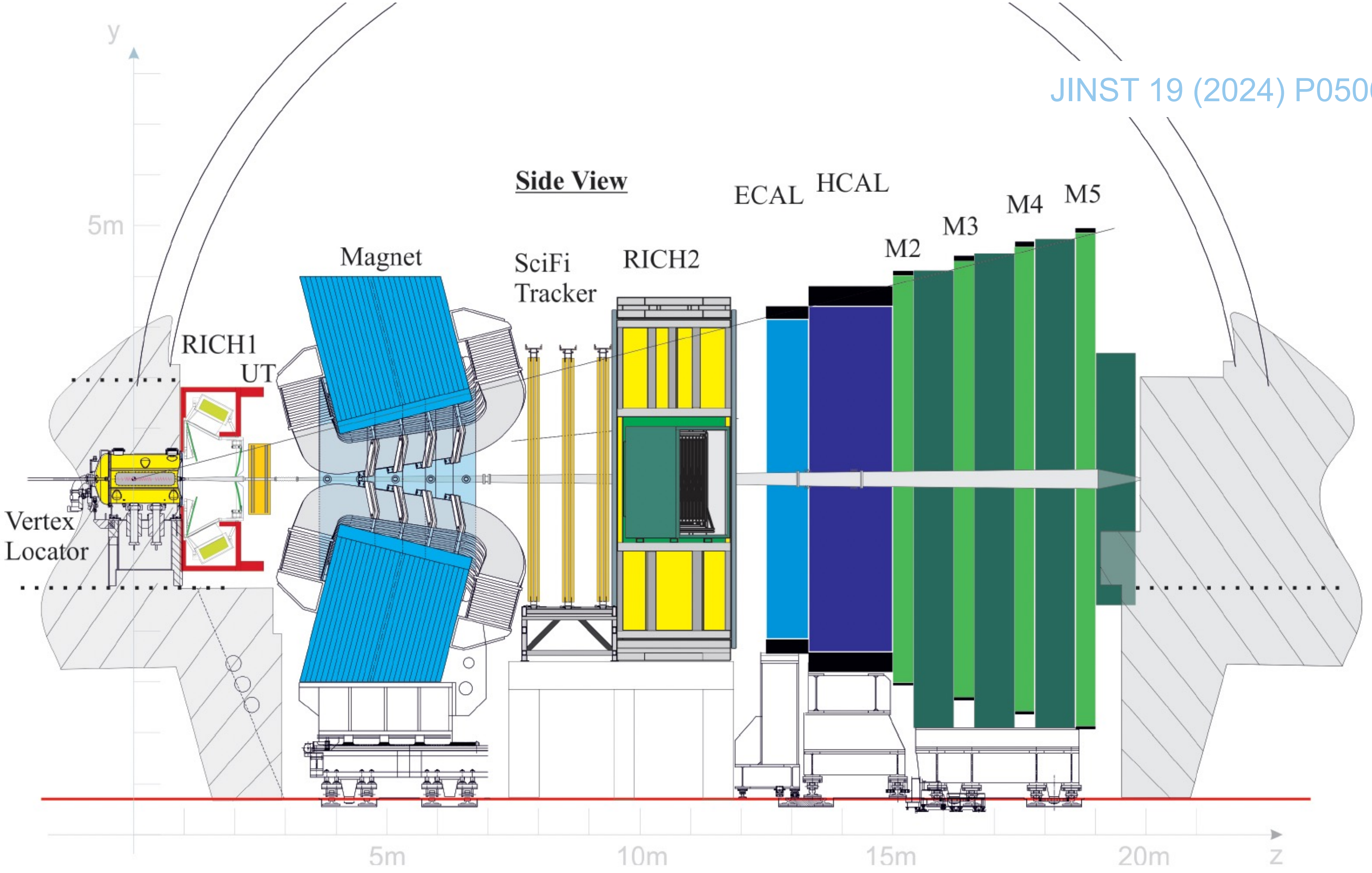
- Removing the hardware trigger
- Increase lumi by a factor of 5: $4\times10^{32}\text{cm}^{-2}\text{s}^{-1} \rightarrow \mathbf{2\times10^{33}cm^{-2}s^{-1}}$



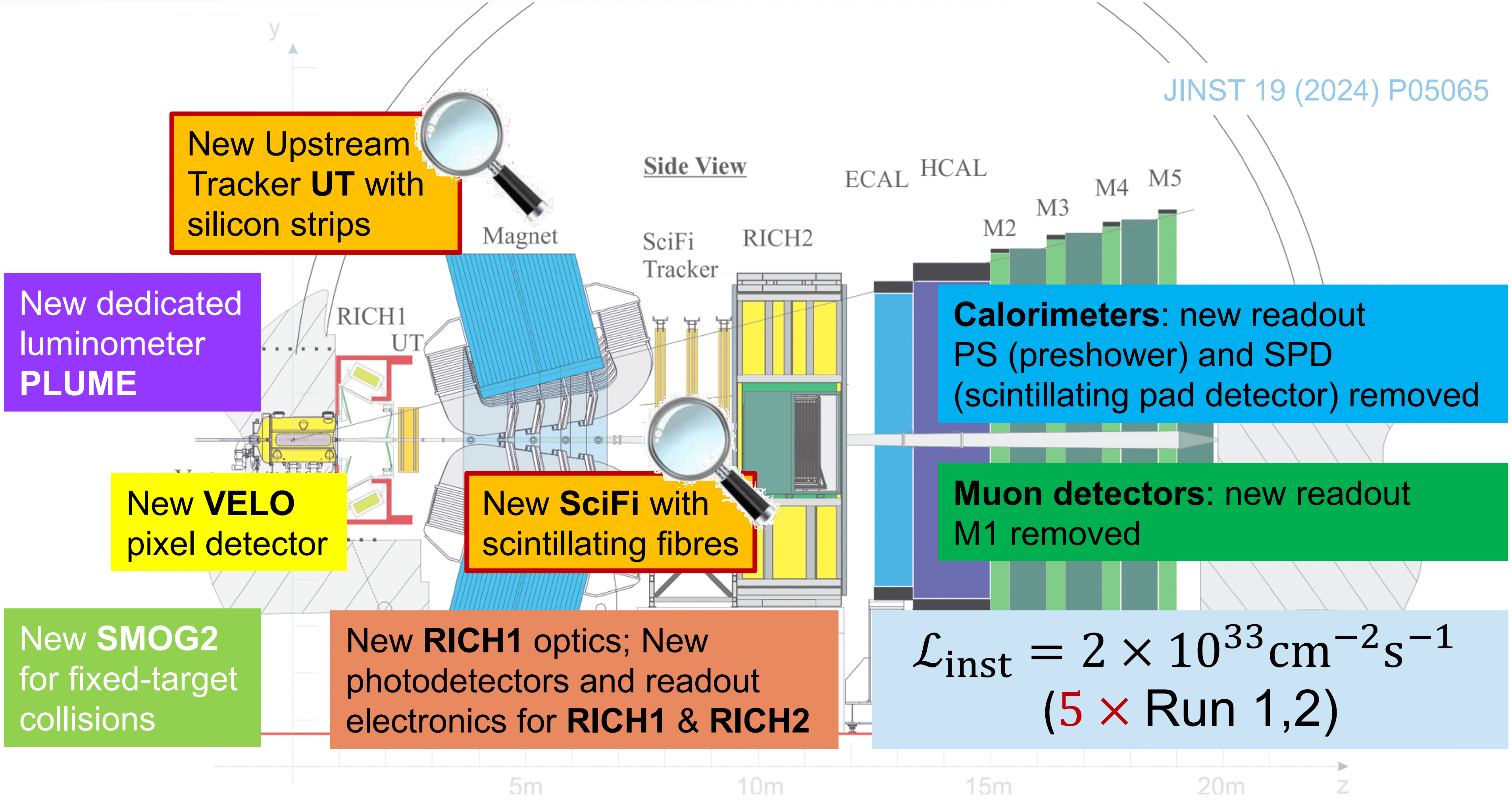


Upgraded LHCb: what it looks like now

JINST 19 (2024) P05065

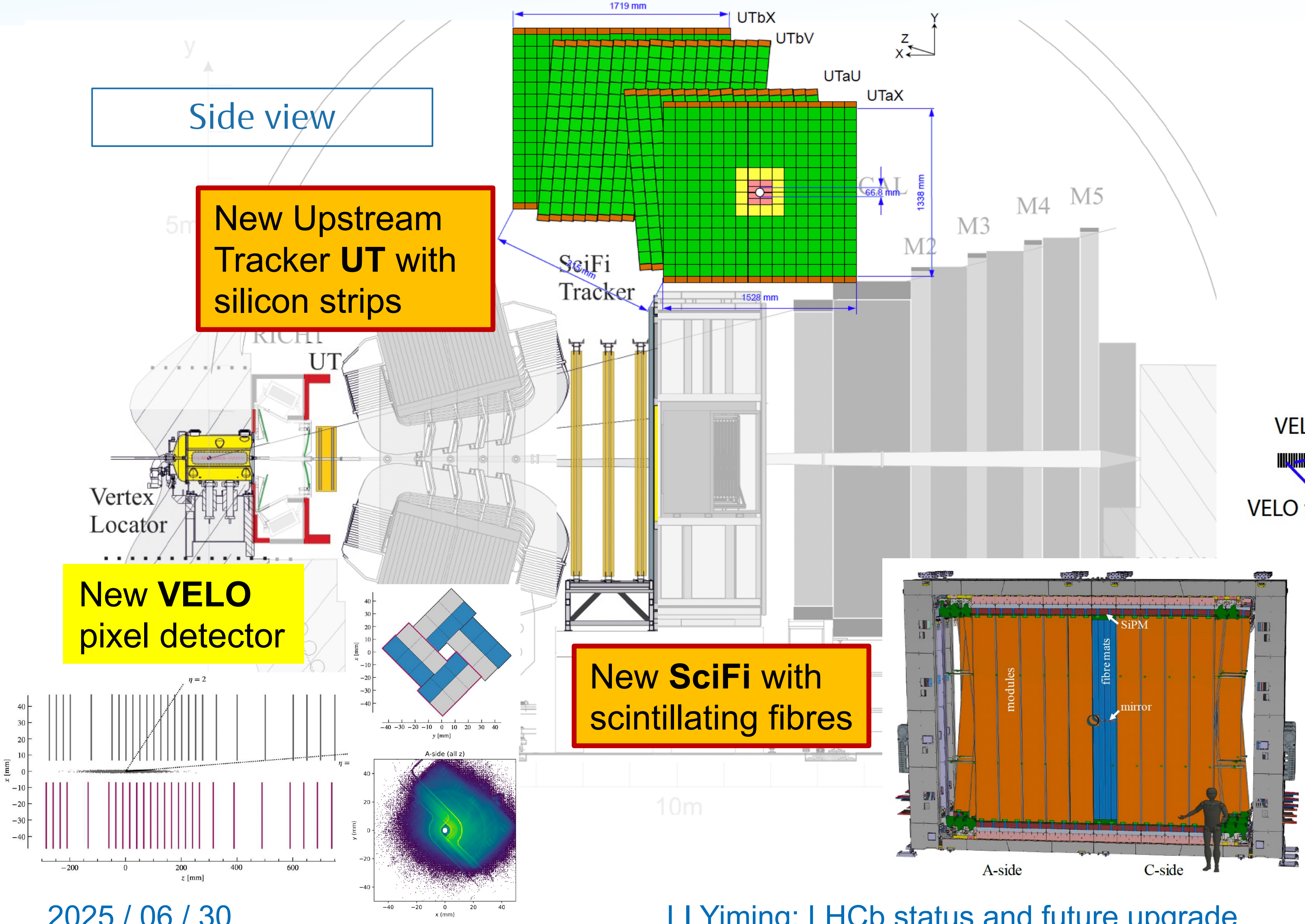


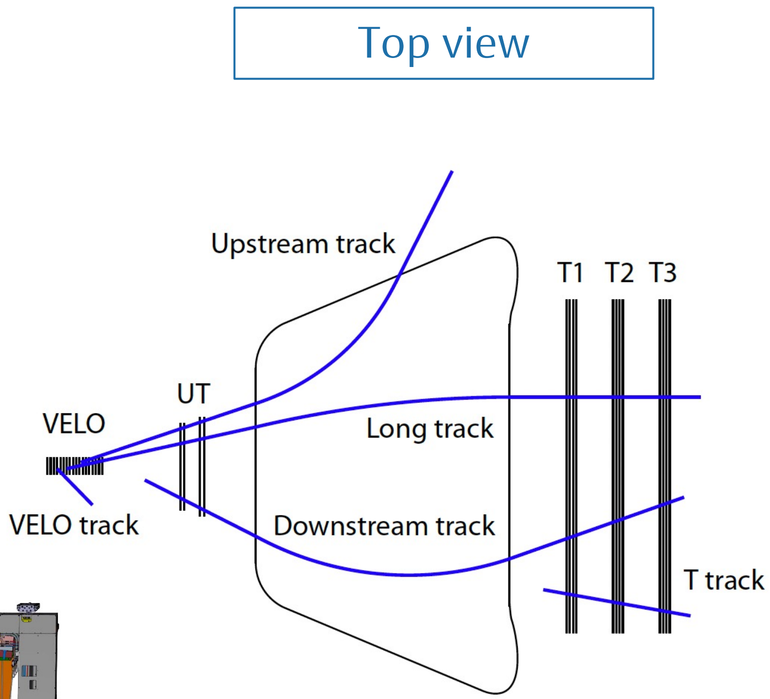
A brand new detector!



$$\mathcal{L}_{\text{inst}} = 2 \times 10^{33} \text{cm}^{-2} \text{s}^{-1}$$
($5 \times$ Run 1,2)

Tracking system

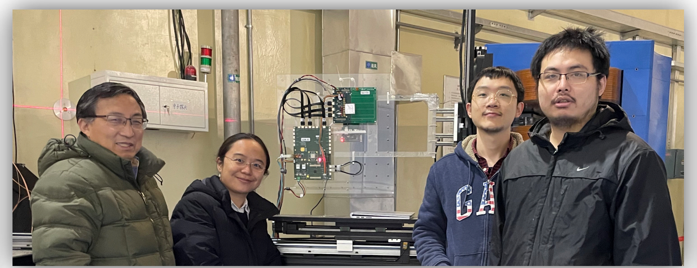




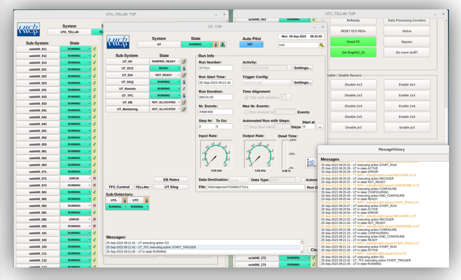
Chinese contribution in UT

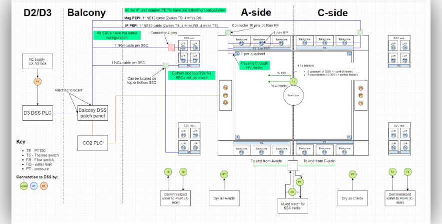
- Played a key role in UT installation, FE verification and commissioning
  - Verifying irradiation performance of SALT Frontend chip using Chinese facilities
  - Control software (ECS) and detector safety software
  - Installation of UT from the very first stave to completion despite pandemic

Completion of UT A-/C-side



Irradiation test at CIAE and CSNS

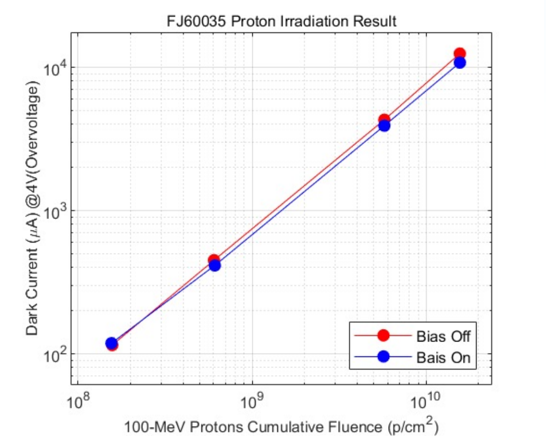


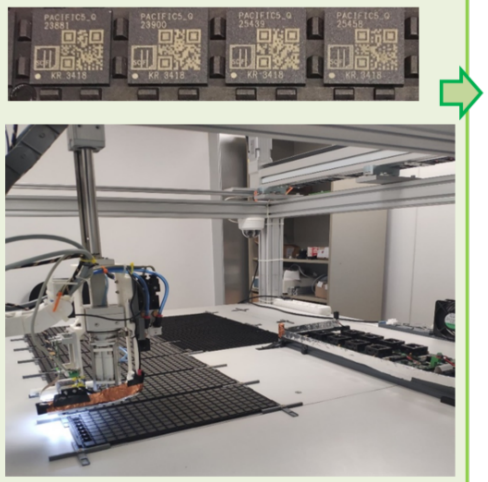


ECS and DSS panels designed by IHEP

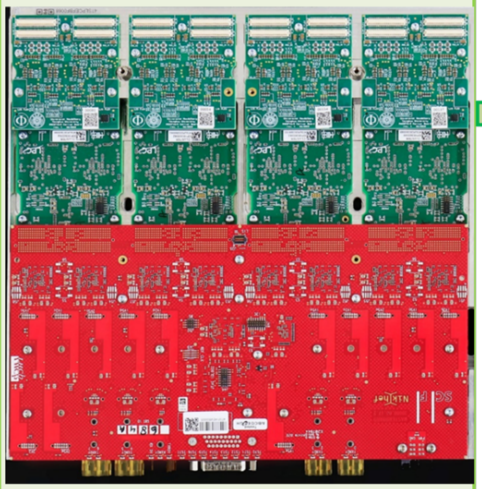
Chinese contribution to SciFi

- 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

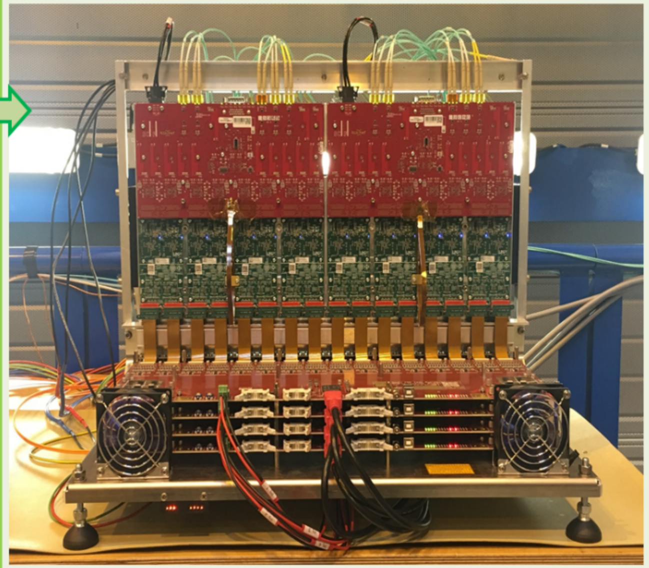




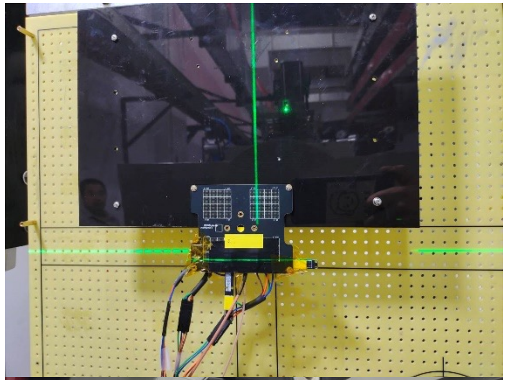
~12k ASICs tested :
✓Heidelberg (DE)
✓**Tsinghua (CN)**
✓ Barcelona (ES)
scan all critical parameters
with a custom design system.
Best ones selected for SciFi

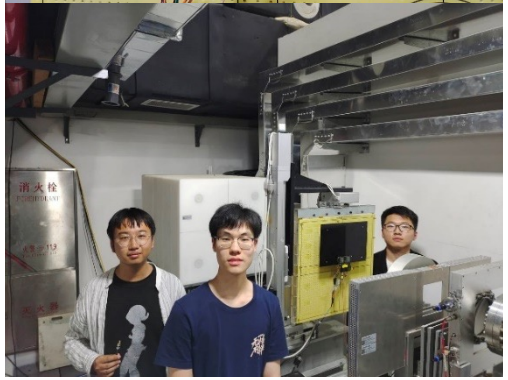


sub-component boards
tested individually
✓ Heidelberg (DE)
✓ **Tsinghua (CN)**
✓ Valencia (ES)
✓ Clermont-Ferrand (FR)
✓ Nikhef (NL)
Before assembled into a FEB



every FEB tested by a custom test
system for quality assurance

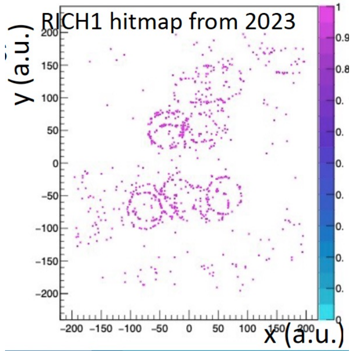


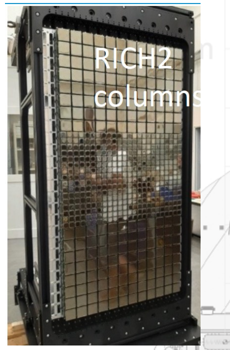


Upgraded PID systems

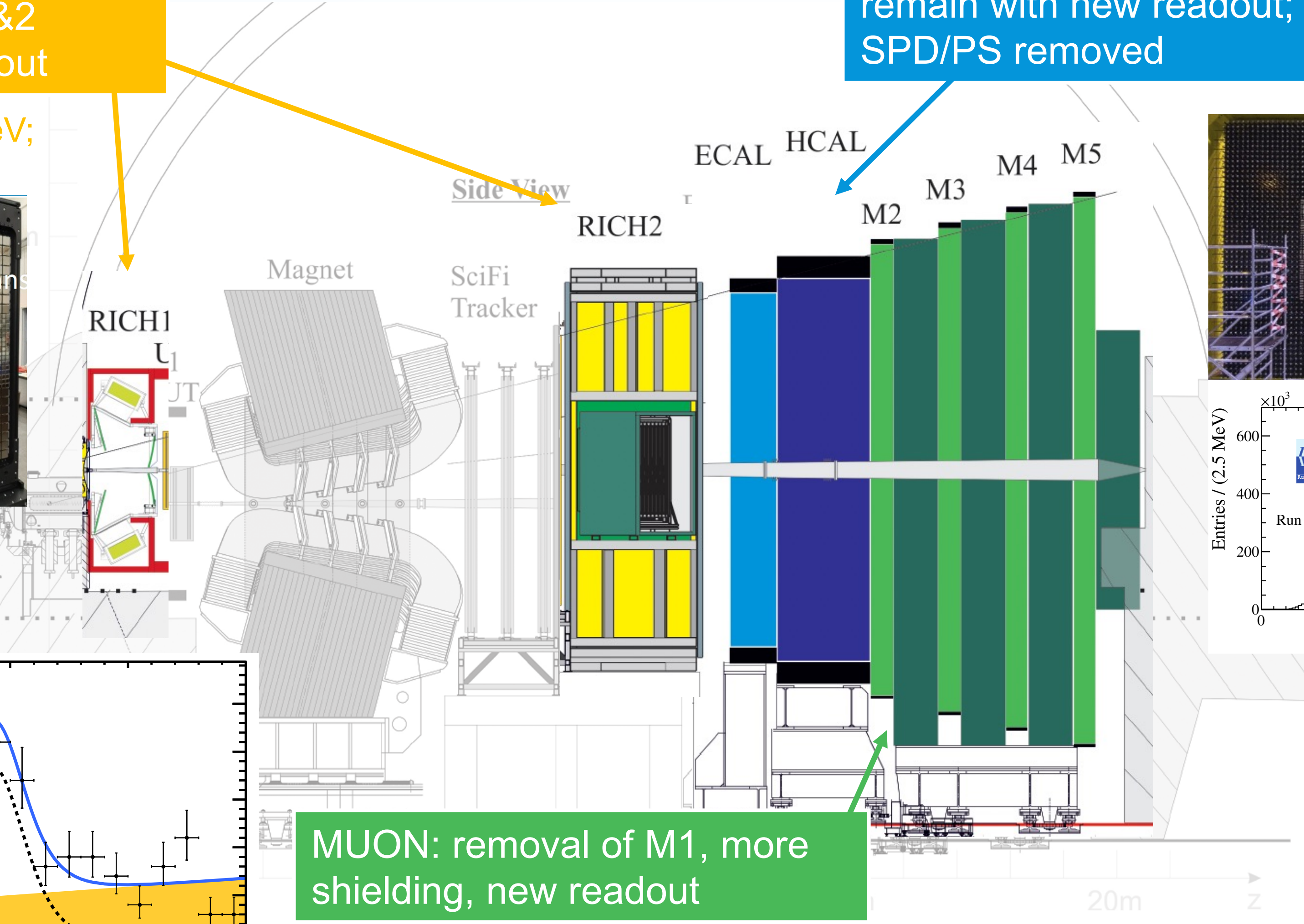
New RICH1 optics to reduce occupancy; RICH 1&2 MaPMT + new readout

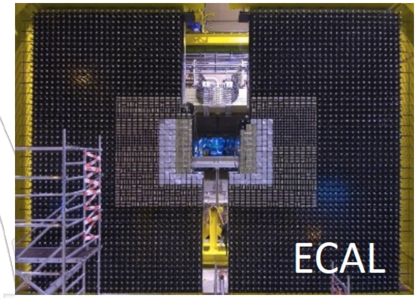
RICH1: C_4F_{10}, 2.6~60 GeV;
RICH2: CF_4, 15~100 GeV

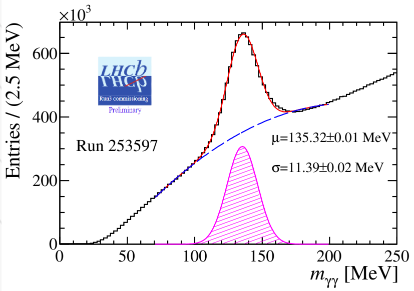


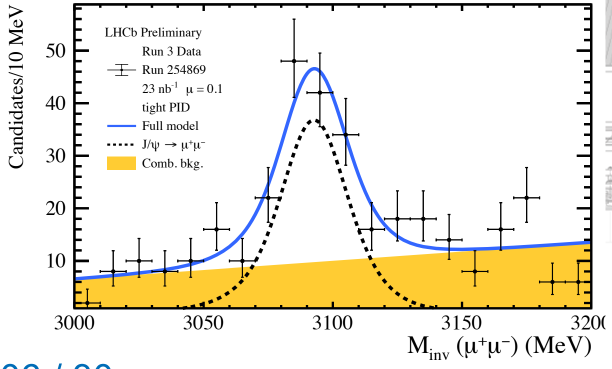


ECAL / HCAL detector remain with new readout; SPD/PS removed





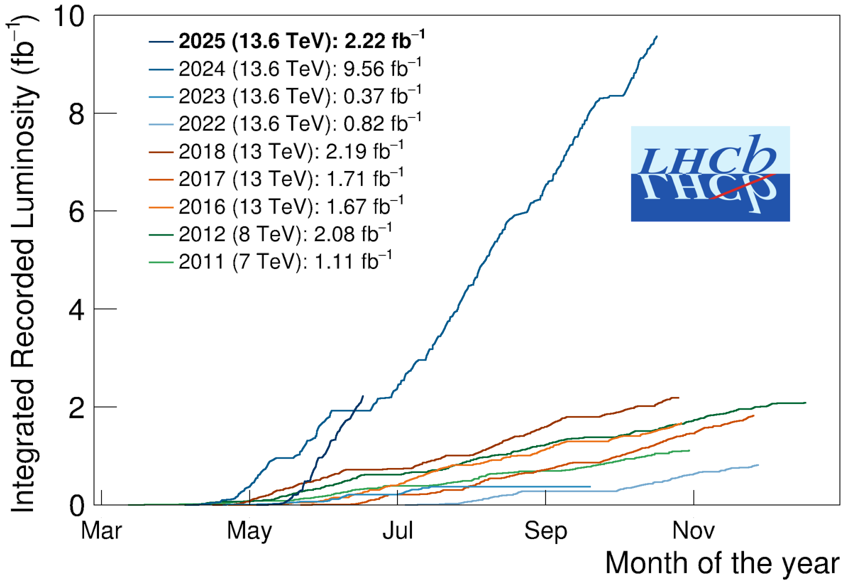




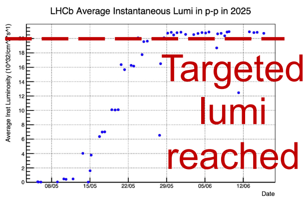
MUON: removal of M1, more shielding, new readout

Run 3 ongoing!

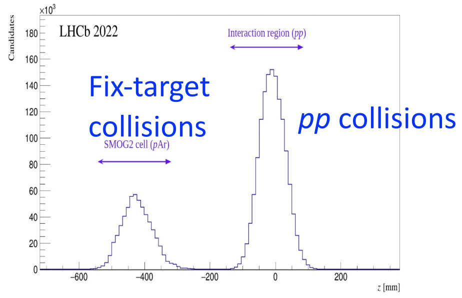
- Completion of installation in Mar 2023, commissioning since 2022, physics production since 2024
- 2025 data-taking smooth
  - DAQ stability improved wrt 2024; All subdetectors working as designed!
  - Record lumi (> $2\times10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$) ➔Design goal achieved
- $50\ \mathrm{fb}^{-1}$ by end of Run 4: > 5 times of data now



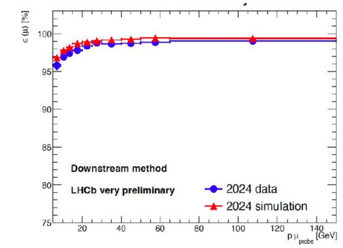
$\mathcal{L}(2024) > \mathcal{L}(\text{Run } 1+2)$



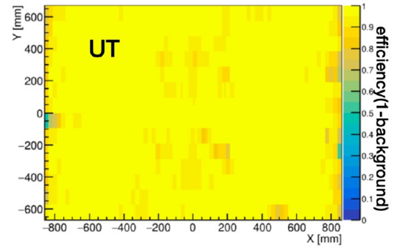
SMOG2



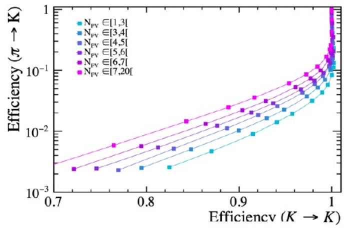
VELO efficiency



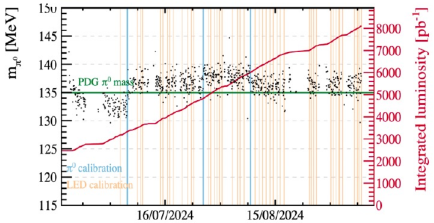
UT efficiency



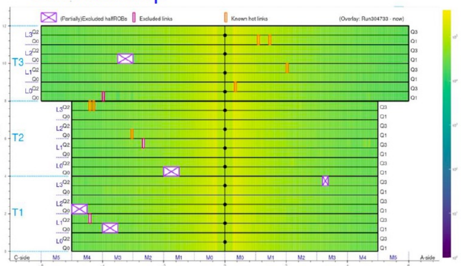
RICH PID



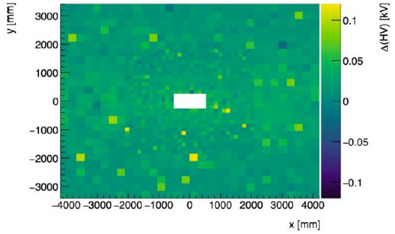
ECAL calibration



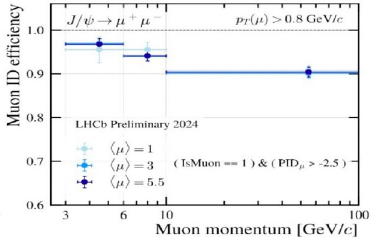
SciFi hitmap



HCAL calibration



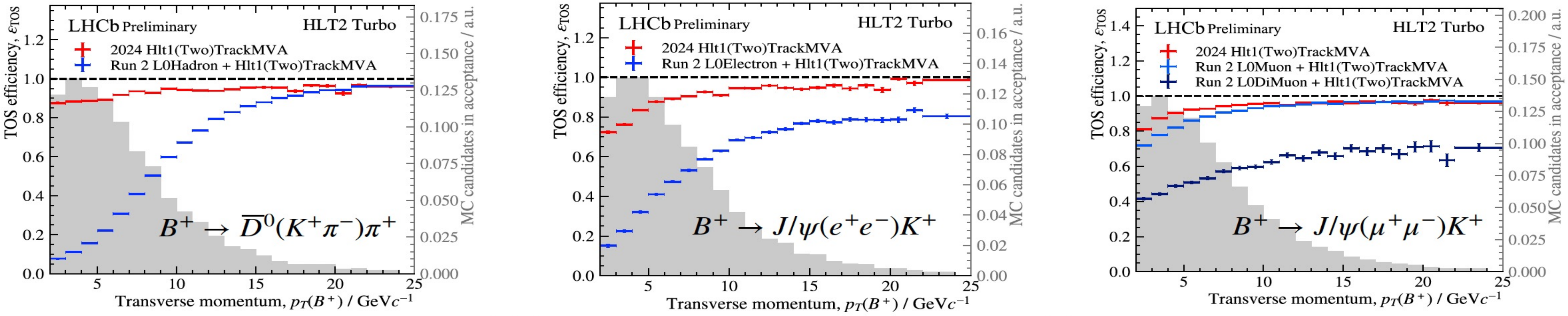
MUON ID



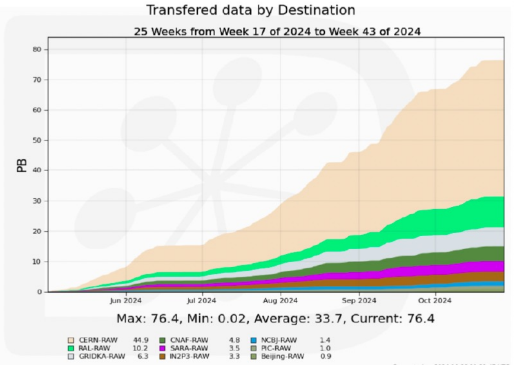
Performance

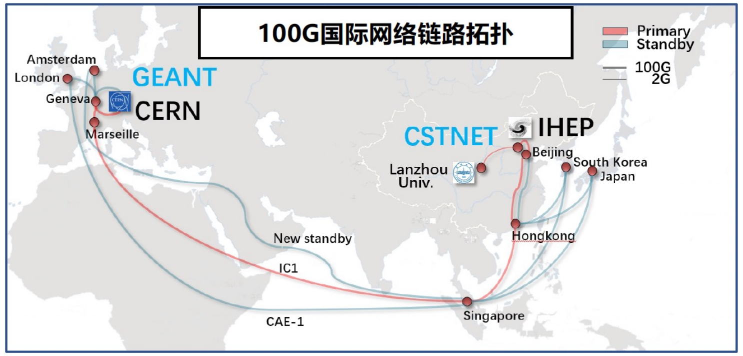
- Trigger efficiency significantly improved – removal of L0 working
  - For hadron and electron as intended, and also for muons

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

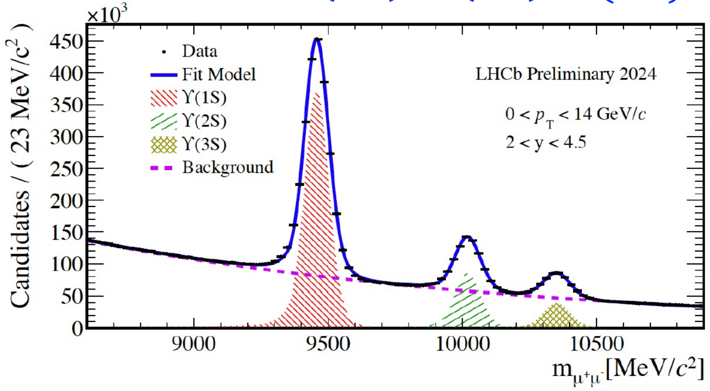




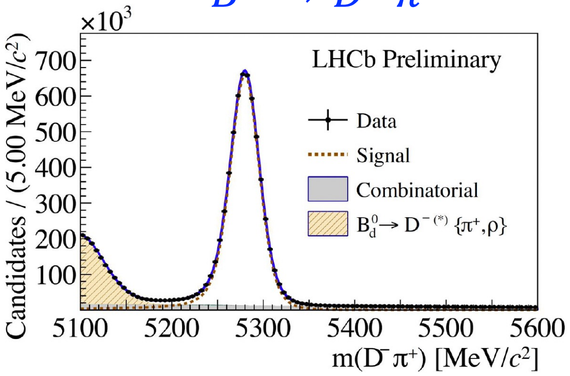
Performance

- First glimpse at the mass peaks …

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

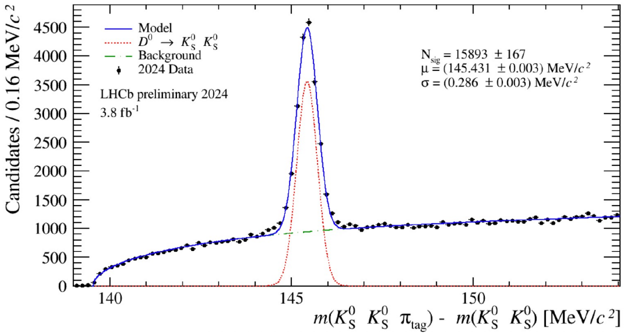


$B^0 \to D^-\pi^+$



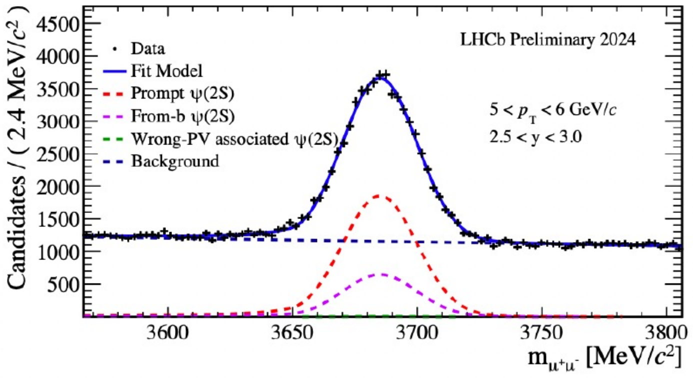
1.1e6 per fb^-1, 3× Run2

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

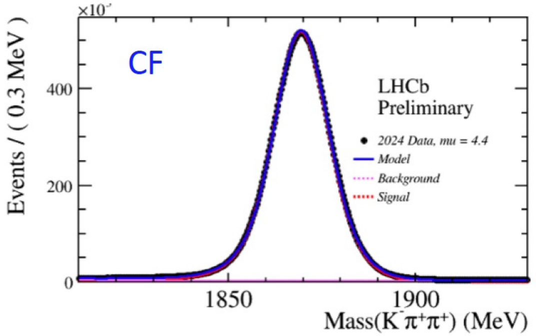


3.6× Run2

$\psi(2S)$

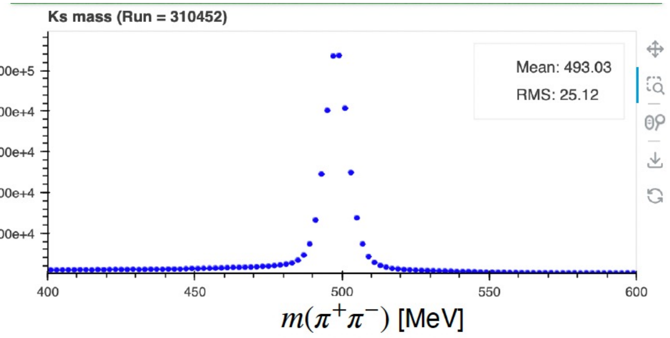


$D^+ \to K^-\pi^+\pi^+$.

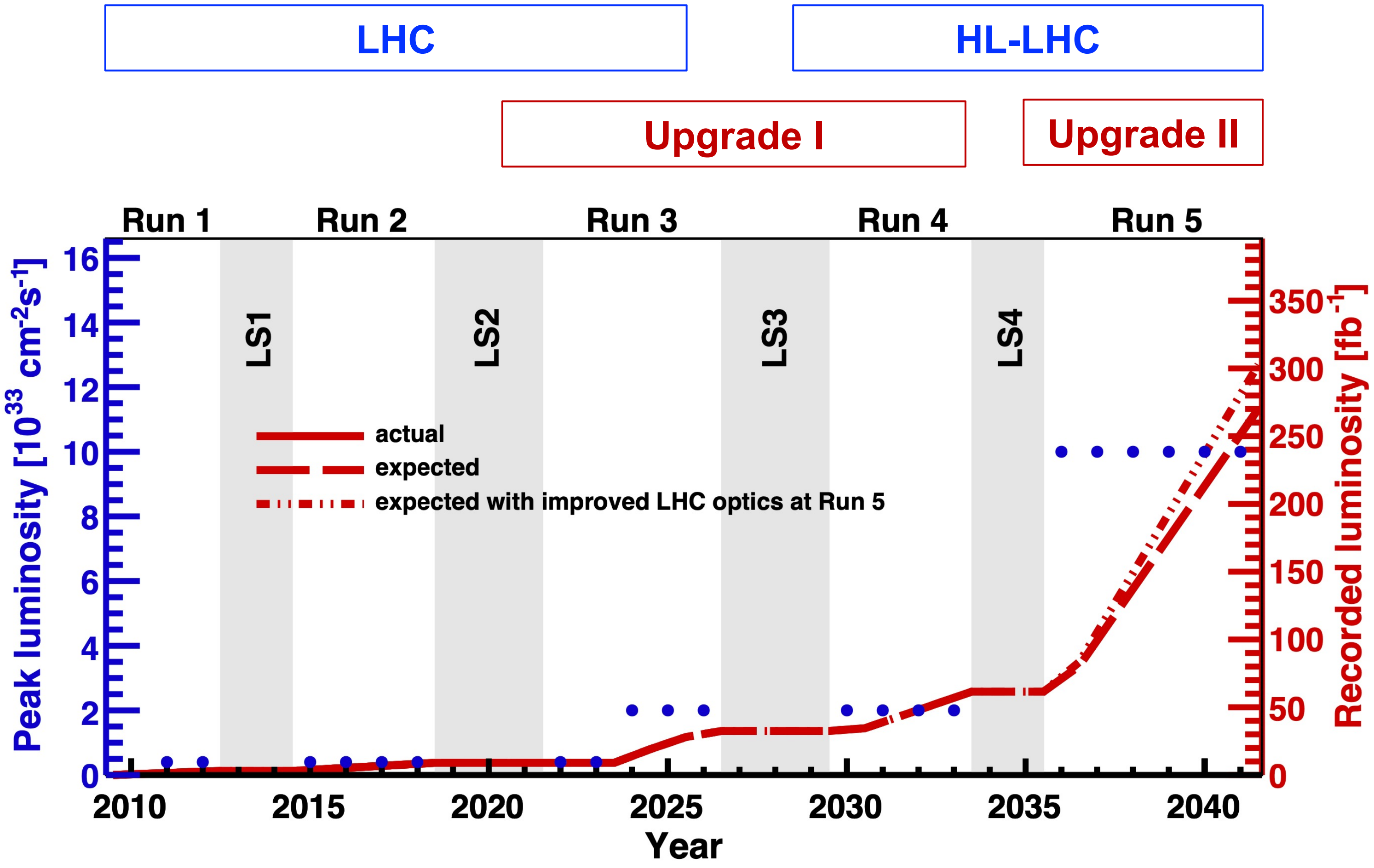


1.8e6 per pb^-1, 2.8× Run2

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

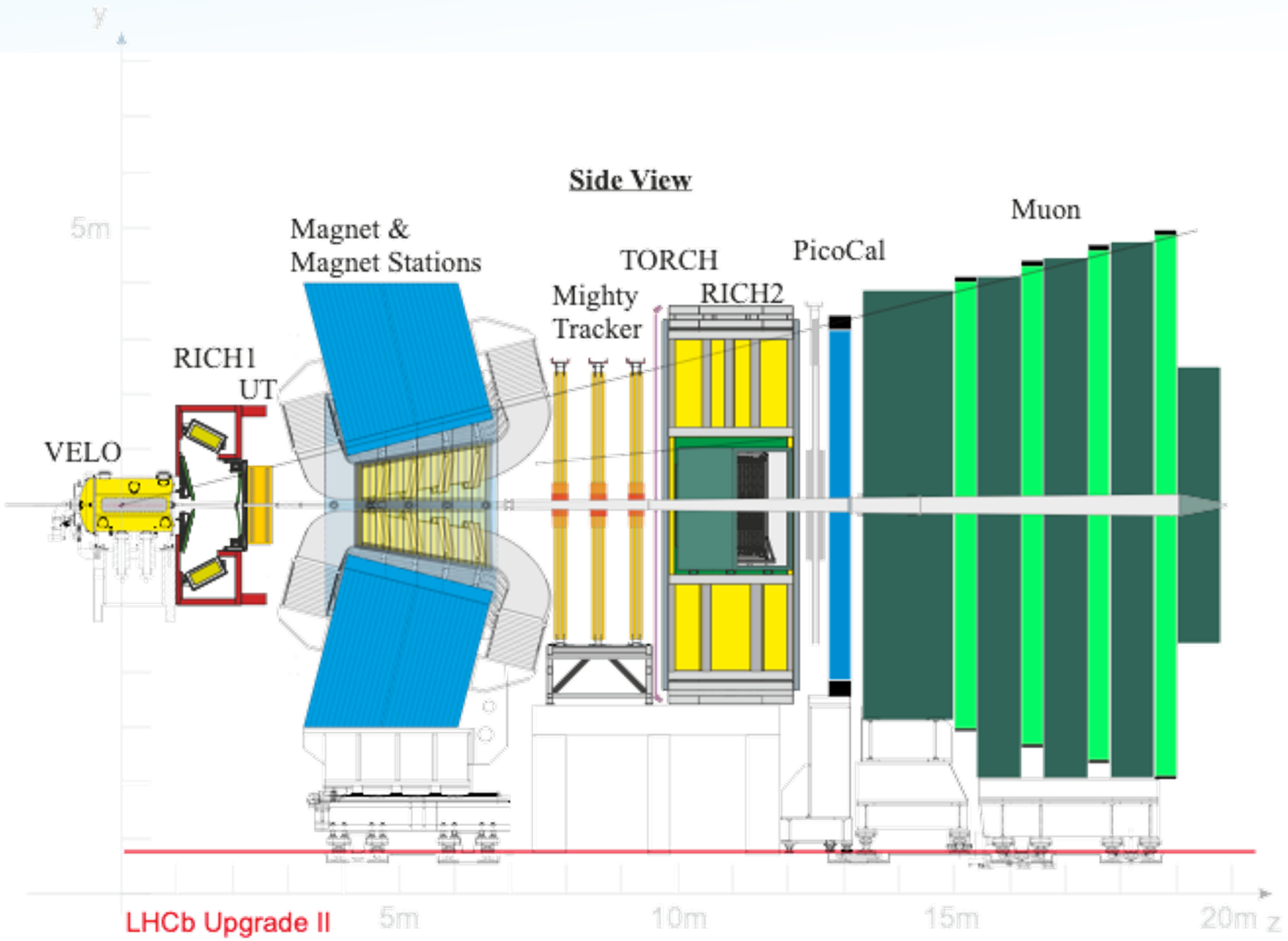


Future plan



- In LS3: consolidation work (Upgrade Ib)
  - ECAL, RICH, DAQ, …
- Upgrade II to fully exploit flavour physics potential in HL-LHC
- Target luminosity:
  - $1.0{\sim}1.5 \times 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - $300{\sim}350\ \mathrm{fb}^{-1}$
- High-lumi operation challenges:
  - Pile-up: $\mu \sim 1 \rightarrow 5\ (\mathrm{UI}) \rightarrow 40\ (\mathrm{UII})$,
  - 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

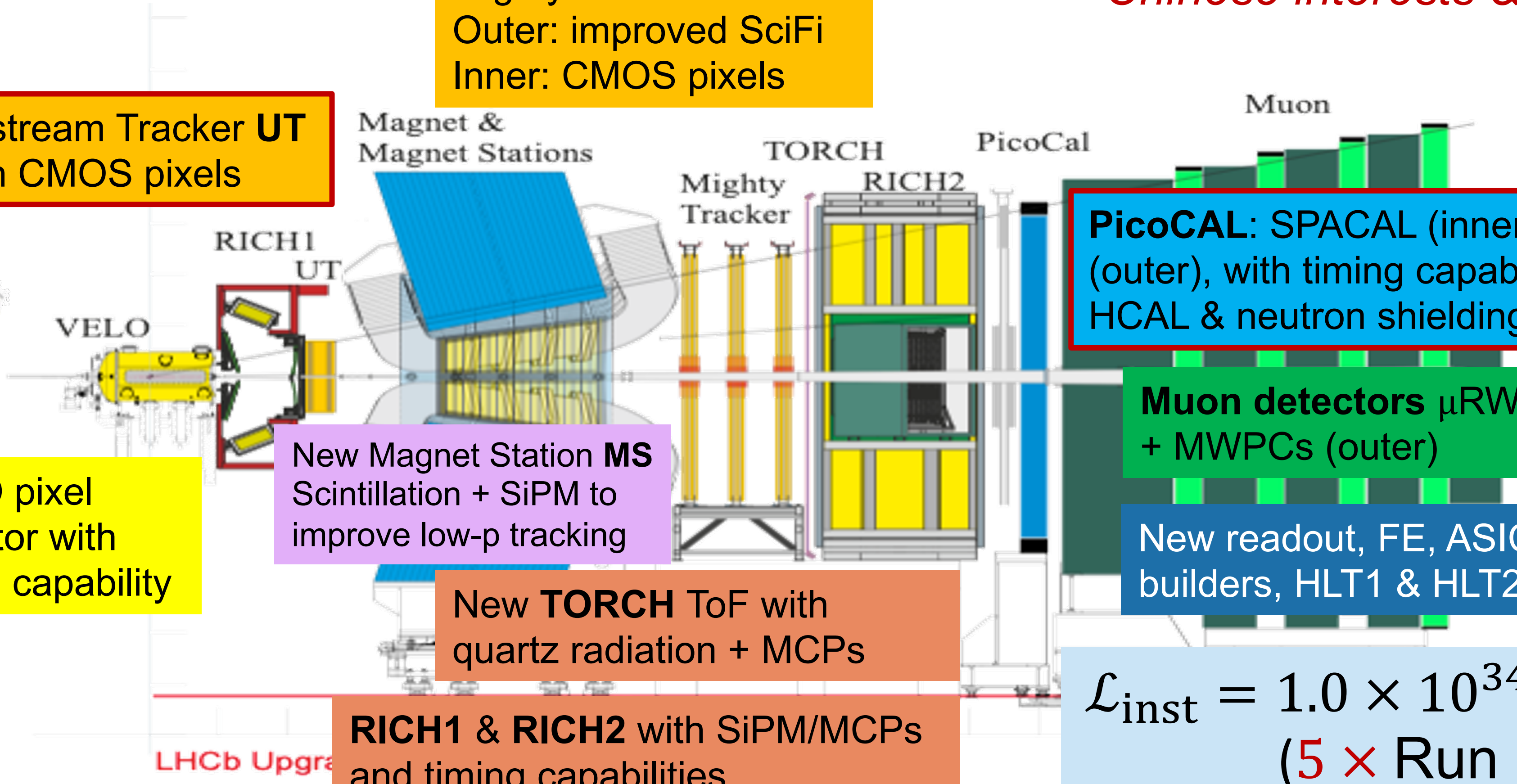
Scoping Document
CERN-LHCC-2024-010

- *Baseline*, $1.5 \times 10^{34} cm^{-2} s^{-1}$
- ***Middle-descoping***, $\mathbf{1.0 \times 10^{34} cm^{-2} s^{-1}}$
- *Low-descoping*, $1.0 \times 10^{34} \mathrm{cm}^{-2} \mathrm{s}^{-1}$

Recommended by LHCC to proceed with 'middle-scenario' ($1.0 \times 10^{34} \mathrm{cm}^{-2} \mathrm{s}^{-1}$)

… an ultimate flavour experiment at HL-LHC

Chinese interests & activities



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

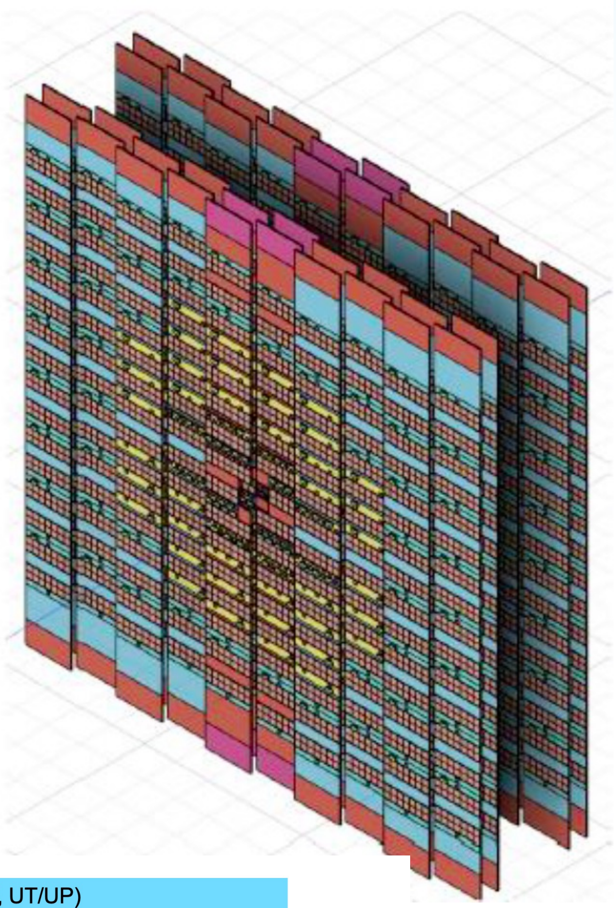
New readout, FE, ASICs, event builders, HLT1 & HLT2 farms …

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



- Challenges for UT due to higher luminosity
  - Increased track density (hit rate ~160 MHz/cm^2) → higher granularity
  - Higher bandwidth (up to 9 Gb/s on innermost chip)
  - Increased radiation level:
    NIEL up to 3×10^{15} n_{eq}/cm^2, TID up to 240 MRad
- A MAPS based pixel detector proposed
  - Sensor options: HVCMOS / small electrode CMOS
- R&D collaboration formed mainly by Chinese and French institutes

The 1st UP mini-workshop @ Beijing, 22nd Jan 2025

PL: Jianchun Wang (IHEP, UT/UP)
DPL: Tomasz Skwarnicki (Syracuse, UT), Stefano Panebianco (IRFU, UP)

UT Management Structure

Yiming Li / IHEP
Fabrice Guilloux / IRFU
Franck Gastaldi / LLR
Sensor chip design and characterization

Charlotte Riccio / IRFU
Jiesheng Yu / HNU
Module stave and mechanical structure

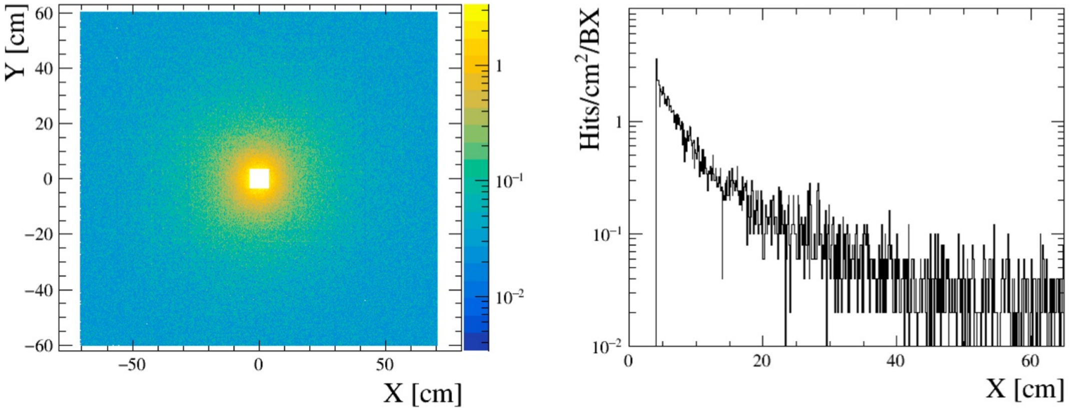
Benjamin Audurier / IRFU
Xuhao Yuan / IHEP
Simulation, reconstruction & performance

Manuel Guittiere / Subatech
Overall mechanics, integration & services

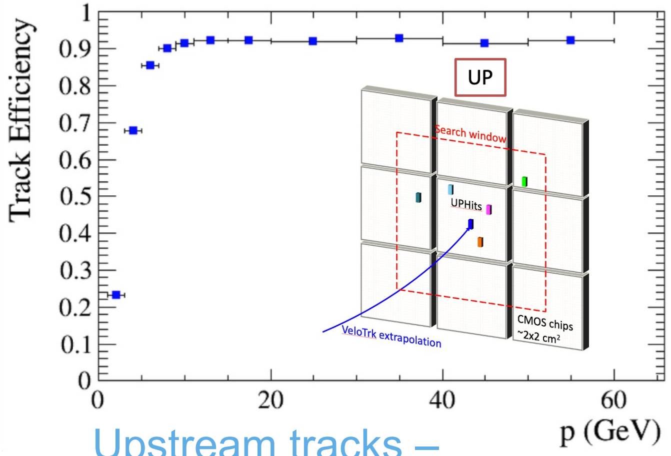
Kai Chen / CCNU
Readout scheme, DAQ firmware & software

UP simulation and performance

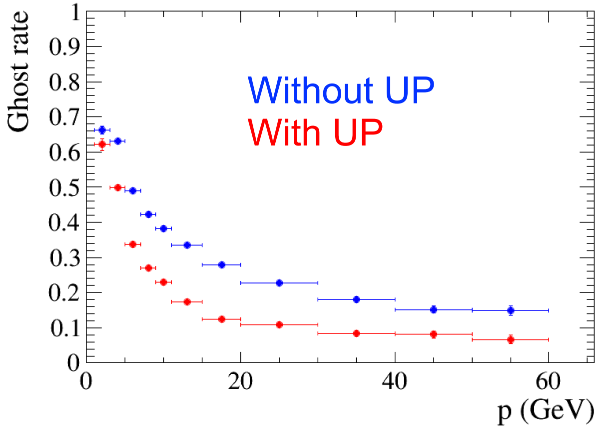
- UP geometry implemented in scoping document
- Upstream and downstream tracks UP is crucial
  - Ensure tracking efficiency
  - Reduce ghost rate
  - Momentum resolution



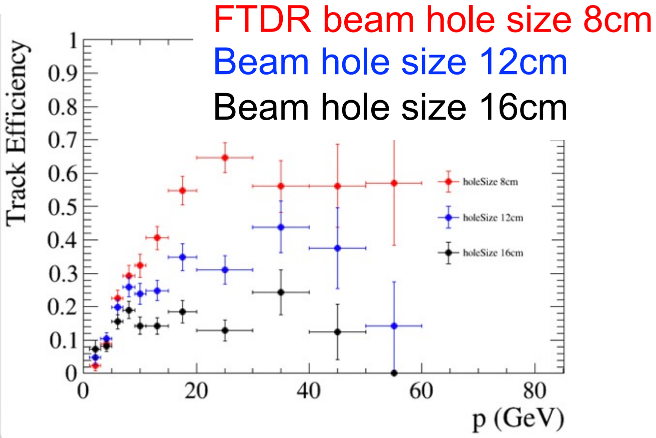
Hit density

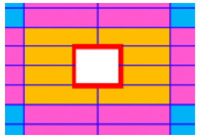


Upstream tracks – Tracking efficiency



Long tracks – ghost rate





Downstream tracks – Tracking efficiency

UP sensor development

COFFEE
CMOS SENSOR IN FIFTY-FIVE NM PROCESS

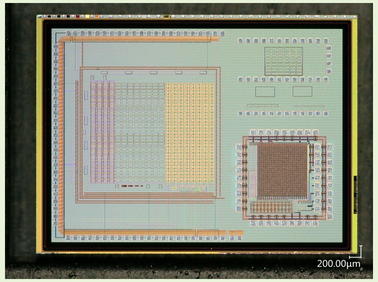
Parameter	UP Specification
Pixel size, square rectangular	$\leq 85 \times 85\ \mu m^2$ $\leq 50 \times 200\ \mu m^2$
Substrate thickness	$< 200\ \mu m$
Pixel orientation	x
Max. Particle Rate (R_{Part})	74(34) MHz/cm^2
Max. Hit Rate	150 Mhit s^-1cm^{-2}
Max. length of data word	32
Overall efficiency	>96%
In-time efficiency	>99% within 25 ns
Noise rate (End of life)	$\leq$ 400kHz/ cm^2
Transmission rate	$N \times 1.28$ Gbit/s
NIEL	$3 \times 10^{15} n_{eq}/cm^2$
TID	240 MRad
Power Consumption	$\leq$ 200 mW/ cm^2

- Development of High Voltage CMOS sensor with advanced process from domestic foundry
- Synergies with Mighty Tracker pixel part with other sensor candidates

COFFEE 2

First HVCMOS 55nm prototype chip

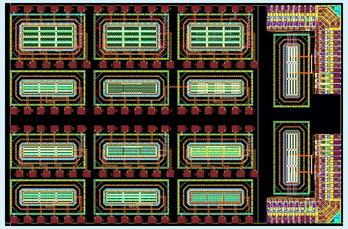
- Breakdown at -70V
- Responsive to laser, X-ray and beta-ray sources



… → 2022 → 2023 → 2024 → 2025 → …

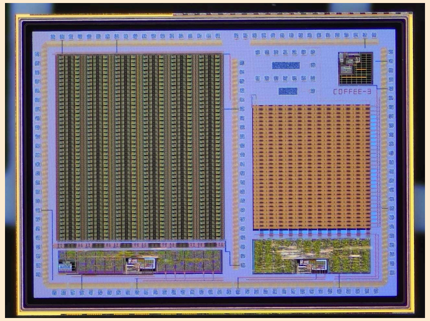
COFFEE1

- Prototype in LL process
- Validation of deep N-well structure
- Breakdown at -9V



COFFEE3

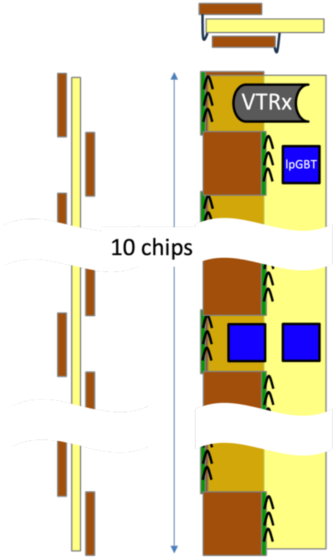
- Two pixel arrays with data-driven readout
- Designed for good timing resolution and moderate power consumption



Large prototype planned around 2027

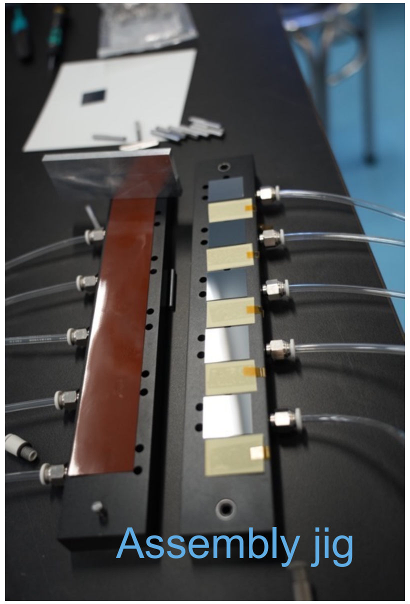
UP module and mechanics

- Module design updated to reduce dead area
- Prototyping starting with dummy components
  - Dummy silicon sensors produced with similar thermal mechanical properties
  - Tools designed for assembly procedure
  - Thermal simulation + market survey for realistic mechanical design

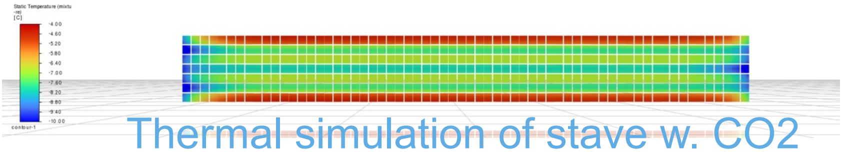


1st dummy sensor

1st dummy hybrid



Assembly jig



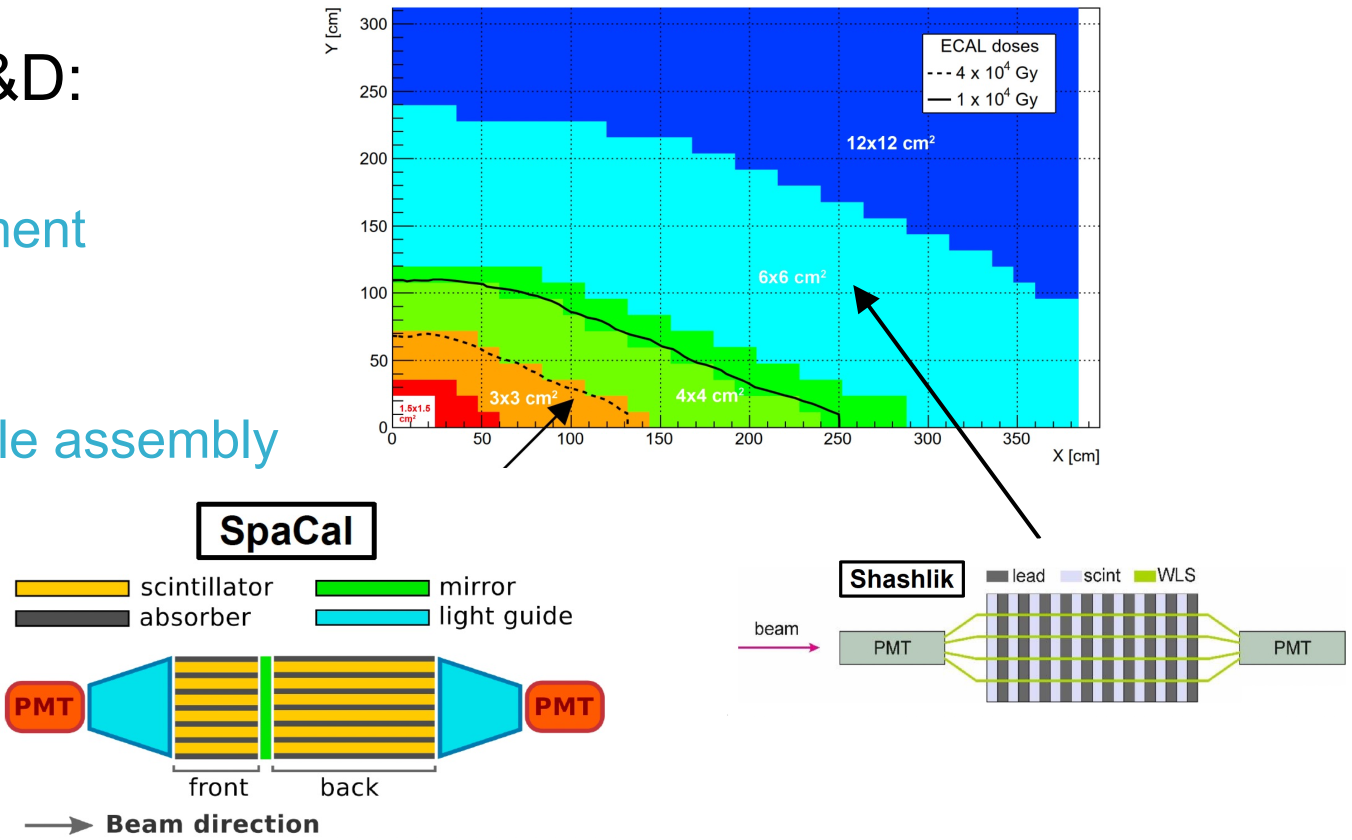
Thermal simulation of stave w. CO_2

1st dummy module assembled
Apr 2025

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:
  - Software and simulation
  - Fast GAGG crystal fibre development
  - 3D printed tungsten absorbers
  - Light-guide system development
  - LS3 SpaCal-W-Polystyrene module assembly
  - (just started) PMT R&D



PicoCAL: progress

- Software and simulation
  - Performance studies for LHCb Upgrade II (U2) Scoping Document
  - Software development & optimization of reconstruction algorithm in full swing towards U2 TDR
- Fast GAGG crystal fibre development
  - Collaborating with SiPAT (电科芯片)+CERN starting from end of 2021
  - Gradually reducing effective decay time τ_{eff}: 50 ns (2022) → 20 ns (2024) → 8 ns (2025)
  - SpaCal-W-GAGG prototype with GAGG with $\tau_{\mathrm{eff}} \approx 20\ \mathrm{ns}$, testbeam at SPS+DESY in 2024
- 3D printed tungsten absorbers
  - Finalising details for PRR (Production Readiness Review) in June
- Light-guide system development
  - Light-guide design for LS4 and market investigation for material candidates in China
- LS3 SpaCal-W-Polystyrene module assembly
  - Module assembly starting from 1 cell, to 4 cells, and finally full-size (36 cells)
    - Many inputs for optimising the design and the assembly process
    - Beam-test planned at SPS end of May, results for EDR review in June
- PMT R&D started, collaborating with NNVT(北方夜视)+IHEP

To conclude …

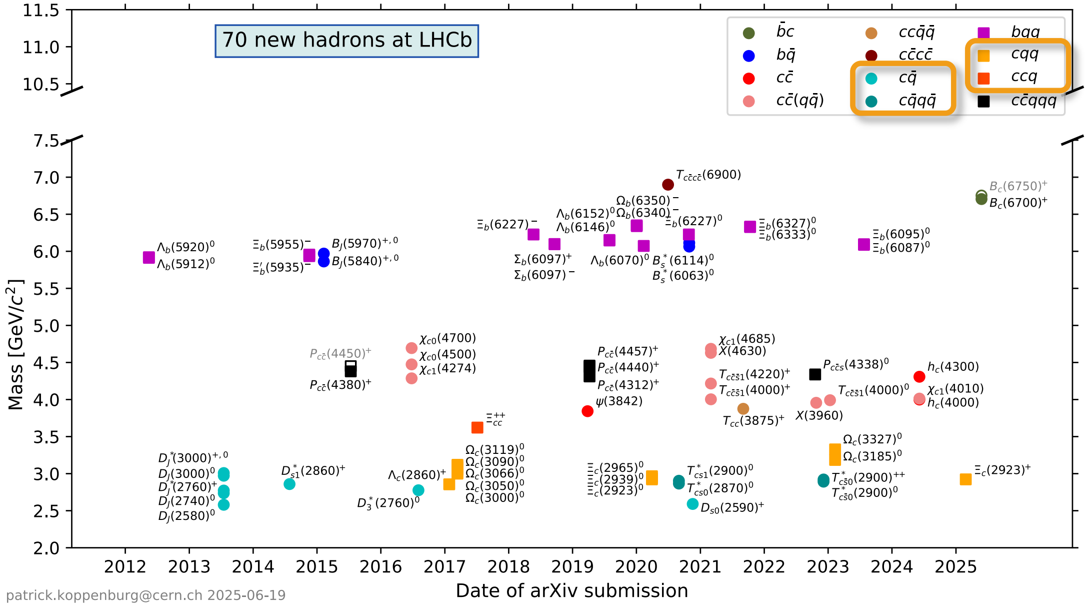
Physics Prospects

Experiment Assumed data sample	ATLAS 20.3-99.7 fb^{-1}	CMS 116-140 fb^{-1}	LHCb 2-9 fb^{-1}	Belle II 364-1075 fb^{-1}
CKM angles				
β	—	—	0.57° [15]	1.2° [16]
α	—	—	—	6.6° [17]
γ	—	—	2.8° [18]	13° [17]
ϕ_s [mrad]	42 [19]	23 [20]	20 [21]	—
***CP* violation in loop-dominated decays**				
$S(B^0 \to \eta' K^0_S)$	—	—	—	0.087 [17]
$\phi_s(B^0_s \to \phi\phi)$ [mrad]	—	—	69 [22]	—
$\phi_s(B^0_s \to K^{*0}\overline{K}^{*0})$ [mrad]	—	—	130 [23]	—
***CP* violation in $B^0_{(s)}$–$\overline{B}^0_{(s)}$ mixing**				
a^s_{sl} $[10^{-4}]$	—	—	33 [24]	—
a^d_{sl} $[10^{-4}]$	—	—	26 [25]	40 [26]
***CP* violation in the charm sector**				
ΔA_{CP} $[10^{-5}]$	—	—	29 [27]	630 [16]
$A_{CP}(D^{+,0} \to \pi^{+,0}\pi^0)$ $[10^{-5}]$	—	—	900 [28], —	870, 750
$A_\Gamma(KK, \pi\pi)$ $[10^{-5}]$	—	—	11 [29]	—
$\Delta x(D^0 \to K^0_S\pi^+\pi^-)$ $[10^{-5}]$	—	—	18 [30]	140 [31]
Semileptonic *B* decays				
$\lvert V_{ub}\rvert$	—	—	6% [32]	6.3% [33]
$\lvert V_{cb}\rvert$	—	—	—	1.7% [34]
$R(D)$, $R(D^*)$	—	—	14% [35], 6% [36]	12%, 7% [17]
Leptonic *B* decays				
$\mathcal{B}(B^0_s \to \mu^+\mu^-)$ $[10^{-9}]$	$^{+0.8}_{-0.7}$ [37]	0.45 [38]	0.48 [39]	—
$\mathcal{B}(B^0 \to \mu^+\mu^-)$ $[10^{-10}]$	$< 2.1^*$ [37]	< 1.5 [38]	0.79 [39]	—
$\tau_{\text{eff}}(B^0_s \to \mu^+\mu^-)$ [ps]	$^{+0.45}_{-0.18}$ [40]	0.23 [38]	0.29 [39]	—
$S(B^0_s \to \mu^+\mu^-)$	—	—	—	—
$\mathcal{B}(B^+ \to \tau^+\nu_\tau)$	—	—	—	34% [17]
$\mathcal{B}(B^+ \to \mu^+\nu_\mu)$	—	—	—	41% [17]
Flavour-changing neutral current $b \to s\ell\ell$ decays				
$P'_5(B^0 \to K^{*0}\mu^+\mu^-)$ $[10^{-3}]$ †	390 [41]	100 [42]	111 [43]	—
$\mathcal{B}(B^{+,0} \to K^{+,*0}\nu\overline{\nu})$	—	—	—	57%, 110% [17]
$\mathcal{B}(B^{+,0} \to K^{+,*0}\tau^+\tau^-)$ $[10^{-4}]$	—	—	—	< 10, < 18 [44]
Flavour-changing neutral current $b \to s\gamma$ decays				
$\mathcal{B}(B \to X_s\gamma; E_\gamma > 1.6\,\text{GeV})$	—	—	—	(16 – 18)% [17]
$S(B^0 \to K^0_S\pi^0\gamma)$	—	—	—	0.27 [45]
$S(B^0_s \to \phi\gamma)$	—	—	0.32 [46]	—
$A^{(2)}_T(B^0 \to K^{*0}e^+e^-;$ very low $q^2)$	—	—	0.10 [47]	0.76 [48]
$\alpha_\gamma(\Lambda^0_b \to \Lambda^0\gamma)$	—	—	0.26 [49]	—
Lepton flavour violation in τ decays				
$\mathcal{B}(\tau^+ \to \mu^+\gamma)$ $[10^{-8}]$	—	—	—	< 7.5 [16]
$\mathcal{B}(\tau^+ \to \mu^+\mu^+\mu^-)$ $[10^{-8}]$	< 37.6 [50]	< 2.9 [51]	< 4.6 [52]	< 1.8 [53]

† The sensitivity for the P'_5 variable is quoted for the range $q^2 \in [4.0, 6.0]\,\text{GeV}^2$ for ATLAS and LHCb and $q^2 \in [4.3, 6.0]\,\text{GeV}^2$ for CMS.

Input to ESPPU 2024-2026: Projections for Key Measurements in Heavy Flavour Physics, arXiv: 2503.24346

- Statistics is powerful
  - No exception for charm hadron related studies
- Some gain can be expected
- 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
  - LHCb-China are key players in UP and PicoCAL
  - Subsystem TDR expected by end 2026

- A lot more data and potential for physics output, interplay with theory community more important than ever

Thank you for your time!

Reference

- Inputs for European Strategy in Particle Physics Update:
  - Discovery potential of LHCb Upgrade II
  - Technology developments for LHCb Upgrade II
  - Heavy ion physics at LHCb Upgrade II
  - Computing and software for LHCb Upgrade II
  - Projections for Key Measurements in Heavy Flavour Physics[Joint effort with ATLAS, CMS and Belle II]
- 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