LHCb Run 3 operational challenges and first results

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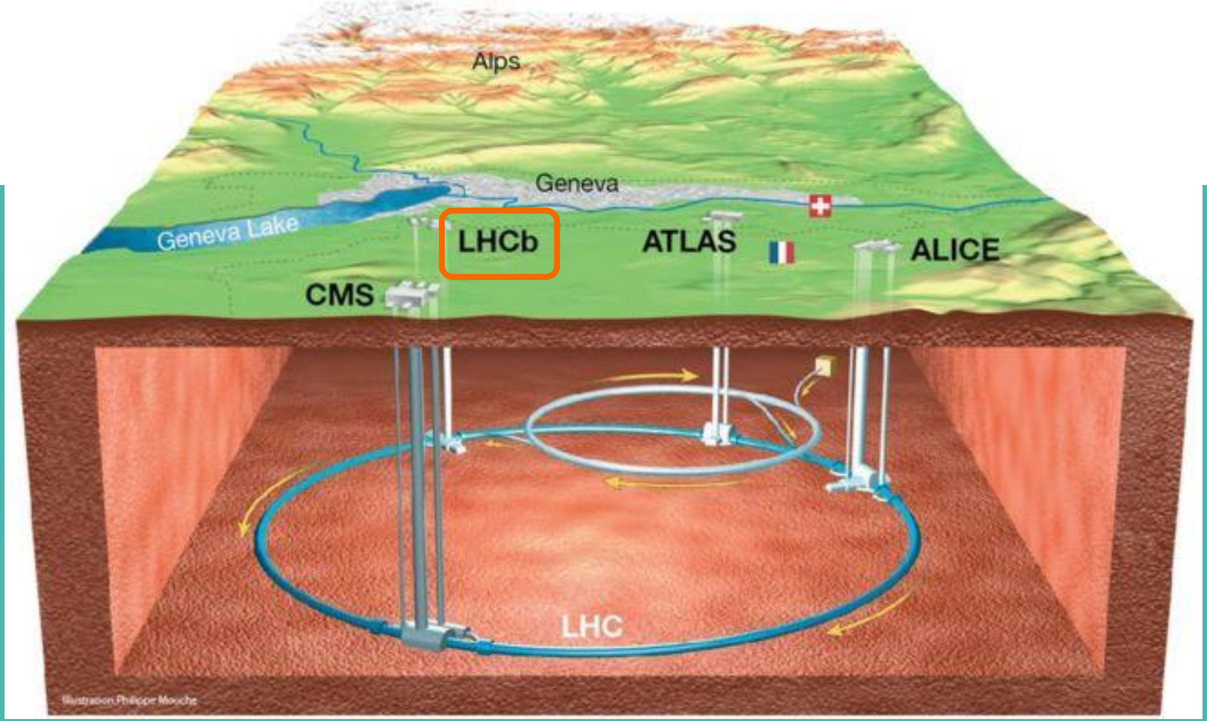
Outline

- The LHCb experiment and Run 2 highlights

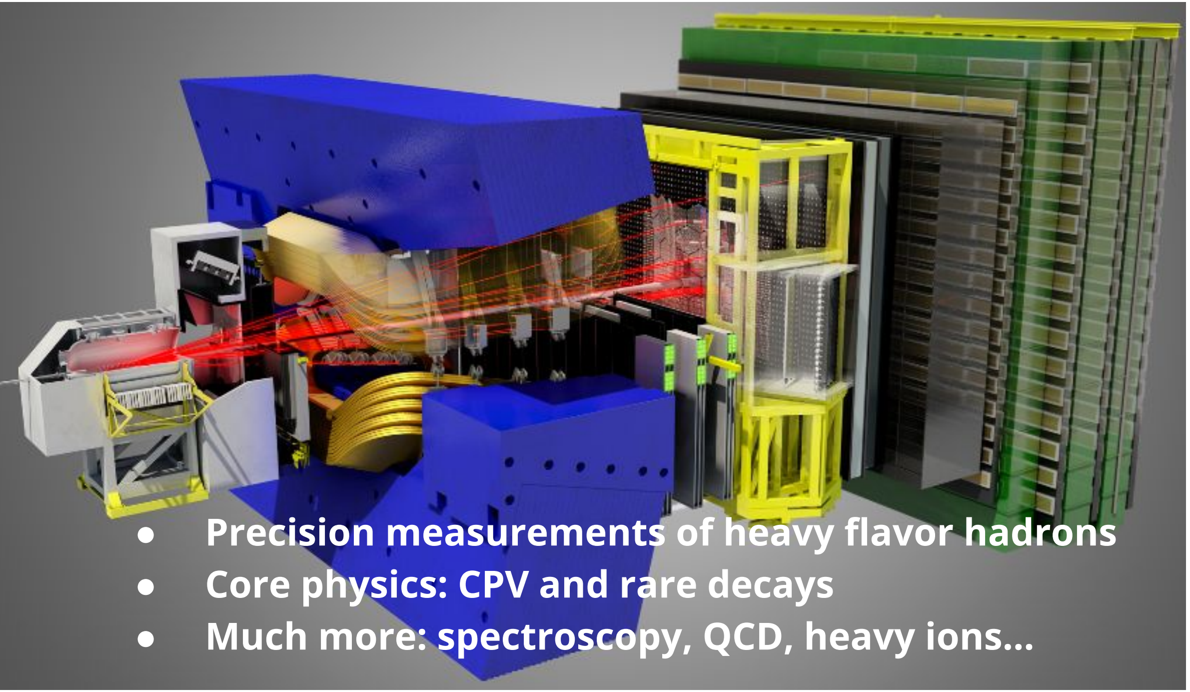
- The LHCb upgrade:
    - Detector
    - DAQ & Trigger

- First data and physics prospects

The LHCb experiment at the LHC

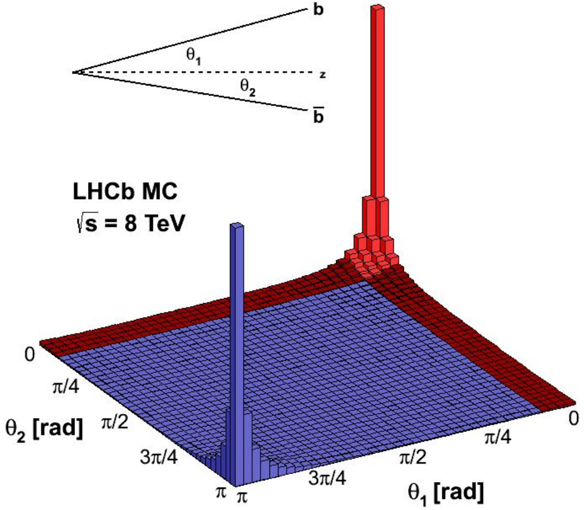


LHCb: Large Hadron Collider Beauty experiment



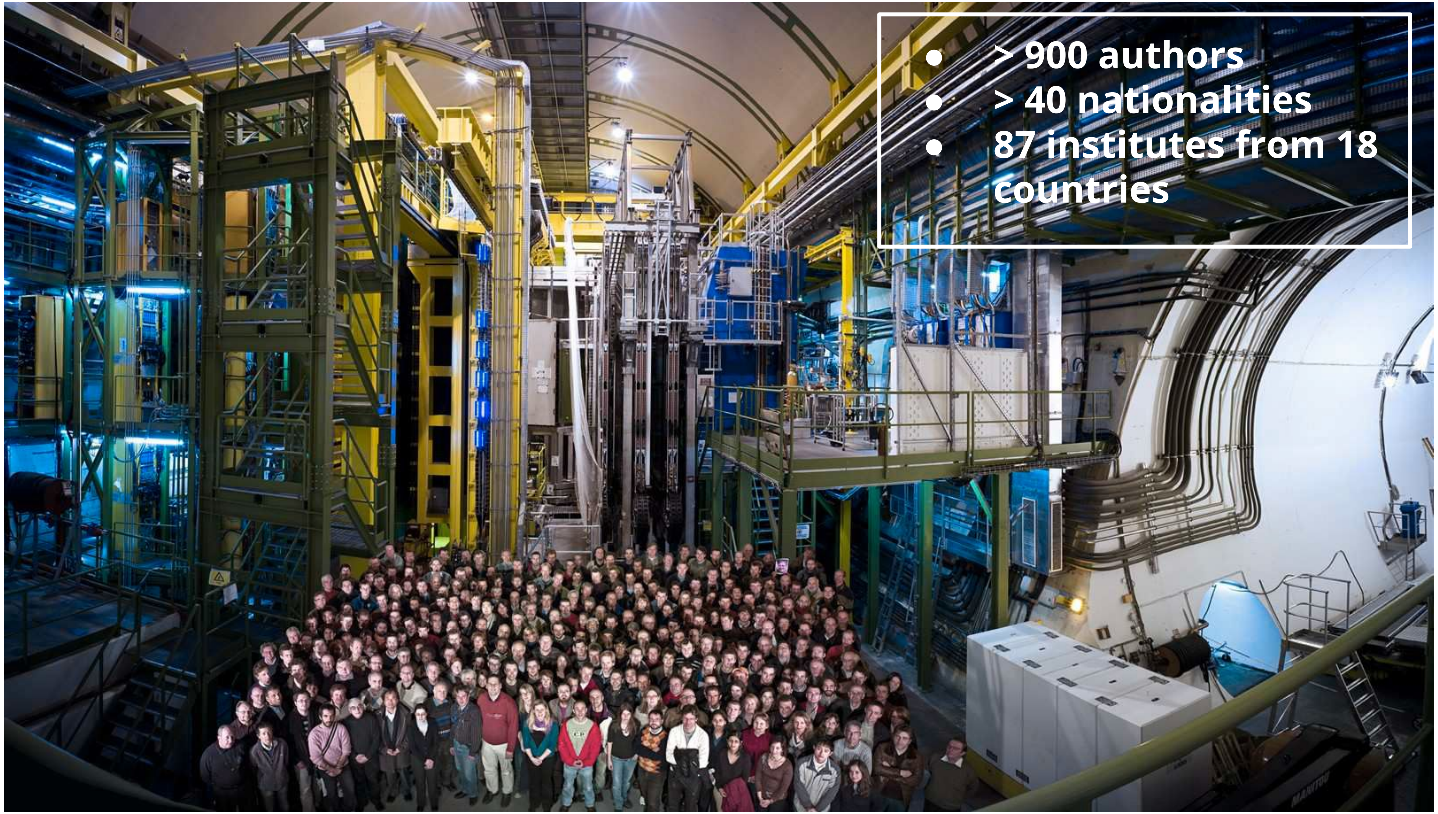
- Precision measurements of heavy flavor hadrons
- Core physics: CPV and rare decays
- Much more: spectroscopy, QCD, heavy ions…

Distribution of produced b-quarks



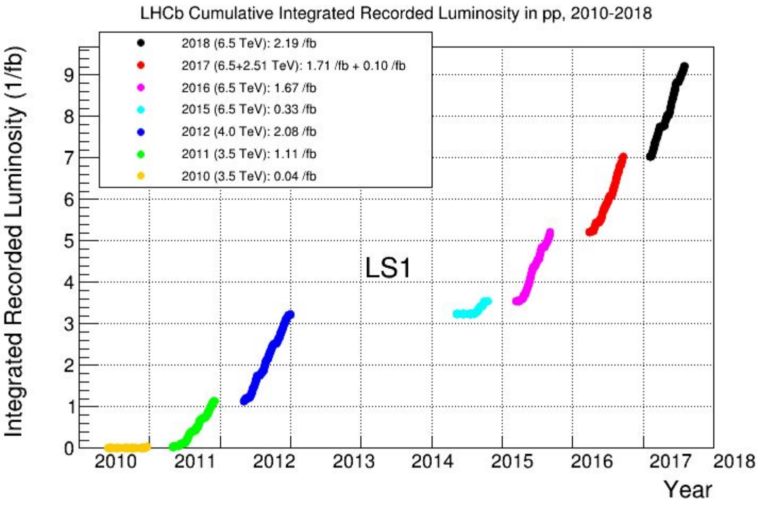
JINST 3 (2008) S08005

LHCb: Large Hadron Collider Beauty experiment



- > 900 authors
- > 40 nationalities
- 87 institutes from 18 countries

LHCb dataset



All b-hadron species! [PRD100(2019)031102]

- B_s: $\frac{f_s}{f_d+f_u} = 0.122 \pm 0.006$
- Λ_b: $\frac{f_{\Lambda_b}}{f_d+f_u} = 0.259 \pm 0.018$

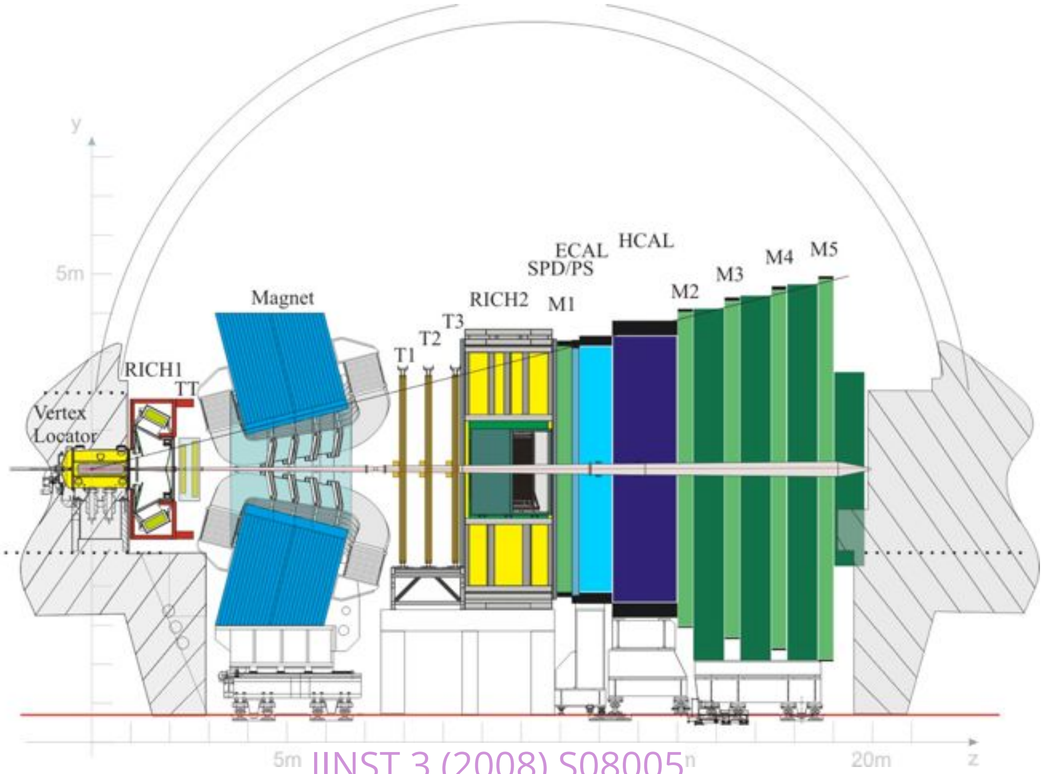
and more: Ξ_b, Ω_b, B_c, B^* …

Total recorded luminosity ~9 fb^{-1}:

- Run 1 (2010-2012) ~ 3 fb^{-1}
- Run 2 (2015-2018) ~ 6 fb^{-1}

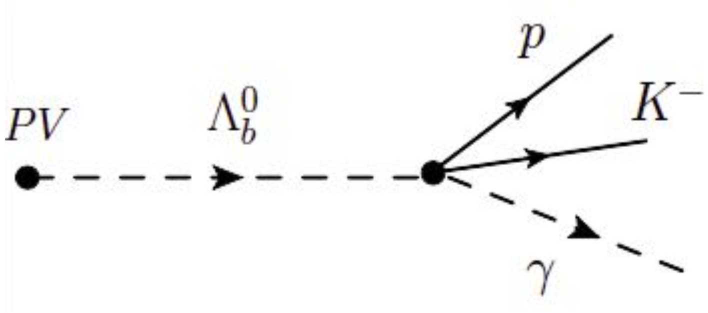
x2 b-quark production from 7 to 13 TeV pp collisions
→ around x4 b-hadrons in Run 2

Experimental setup



JINST 3 (2008) S08005

Typical decay signature

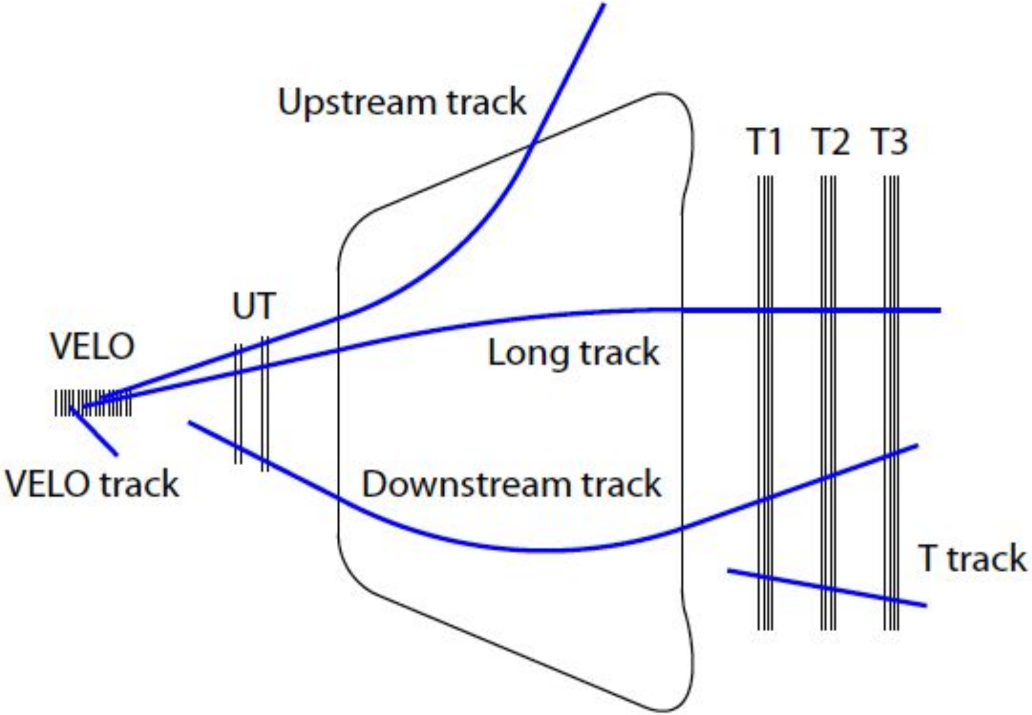


Tracking system

Reconstruct trajectories of charged particles

Identify pp and b-decay vertex

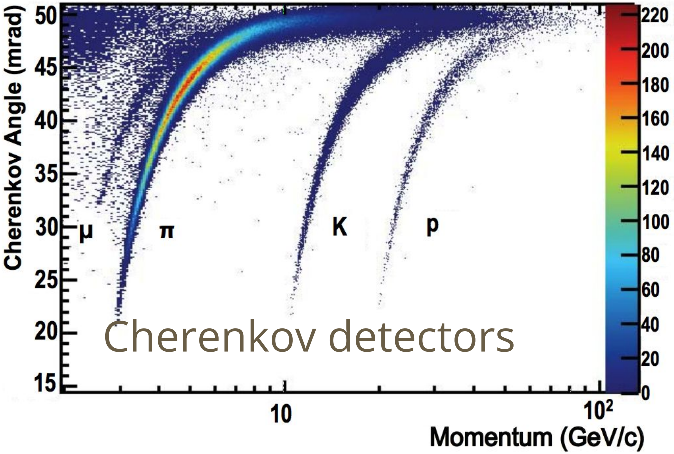
Measure particle momentum from bending in magnetic field



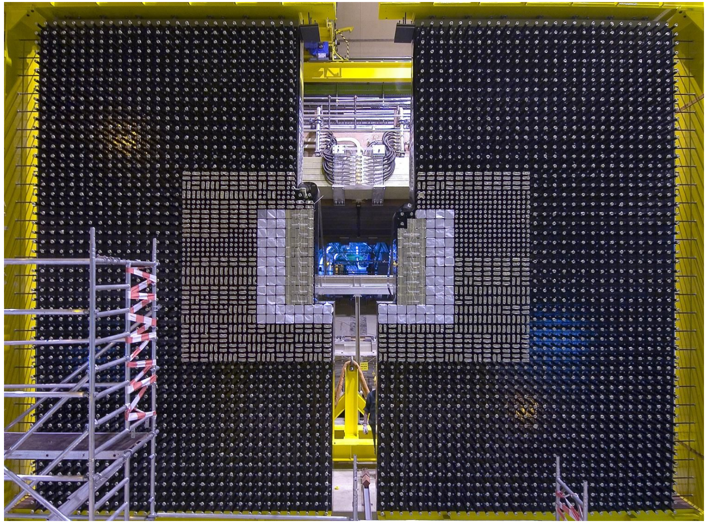
Run 2 performance:
$\Delta p / p = 0.5 - 1.0\%$
$\Delta IP = (15 + 29/p_T[\text{GeV}])\ \mu m$

Particle identification system

- Cherenkov detectors: identify $\pi^\pm$, $K^\pm$, p
- Calorimeters: identify γ, π^0, $e^\pm$
- Muon chambers: identify $\mu^\pm$



Cherenkov detectors



Electromagnetic calorimeter

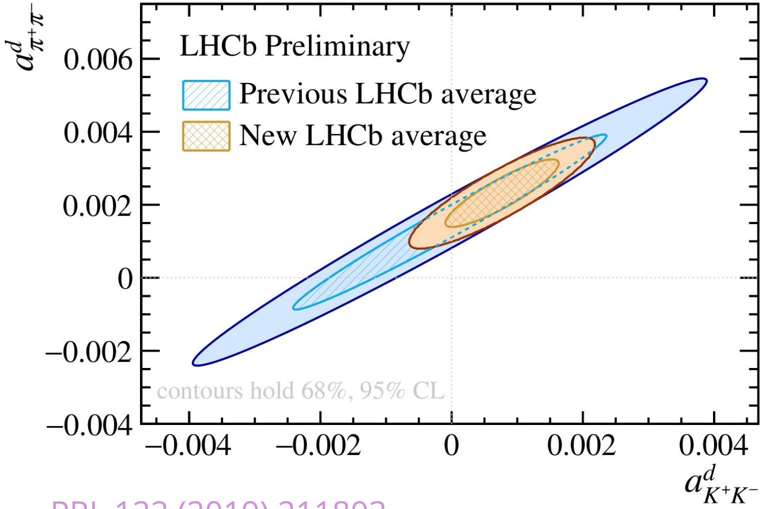
Muon chambers

LHCb highlights

CPV

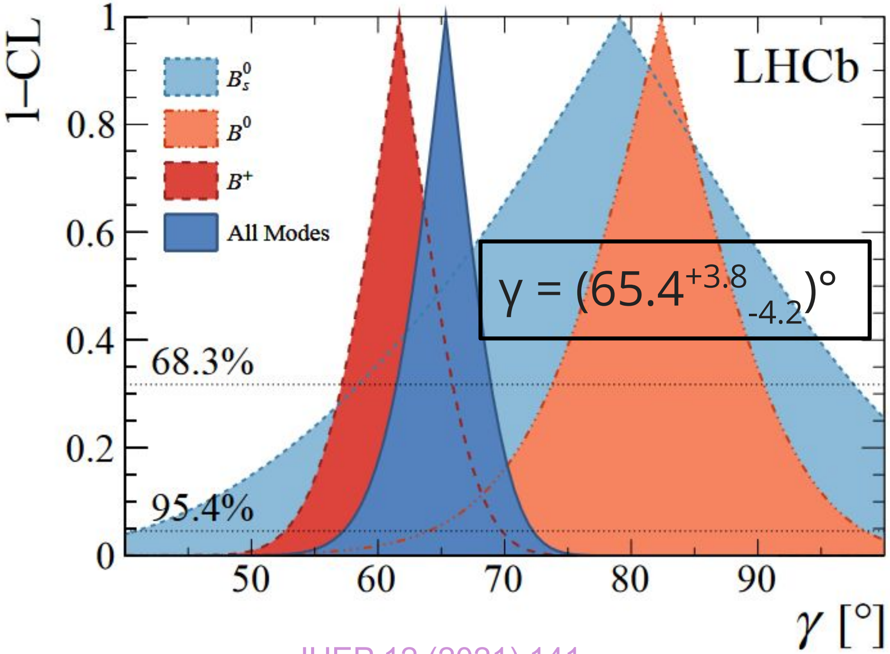
CPV in Charm decays
$D^0 \to h^+h^-$

$\Delta A_{CP} = (-0.154 \pm 0.029)\%$



PRL 122 (2019) 211803,
LHCB-PAPER-2022-024 (in preparation)

CKM angle γ

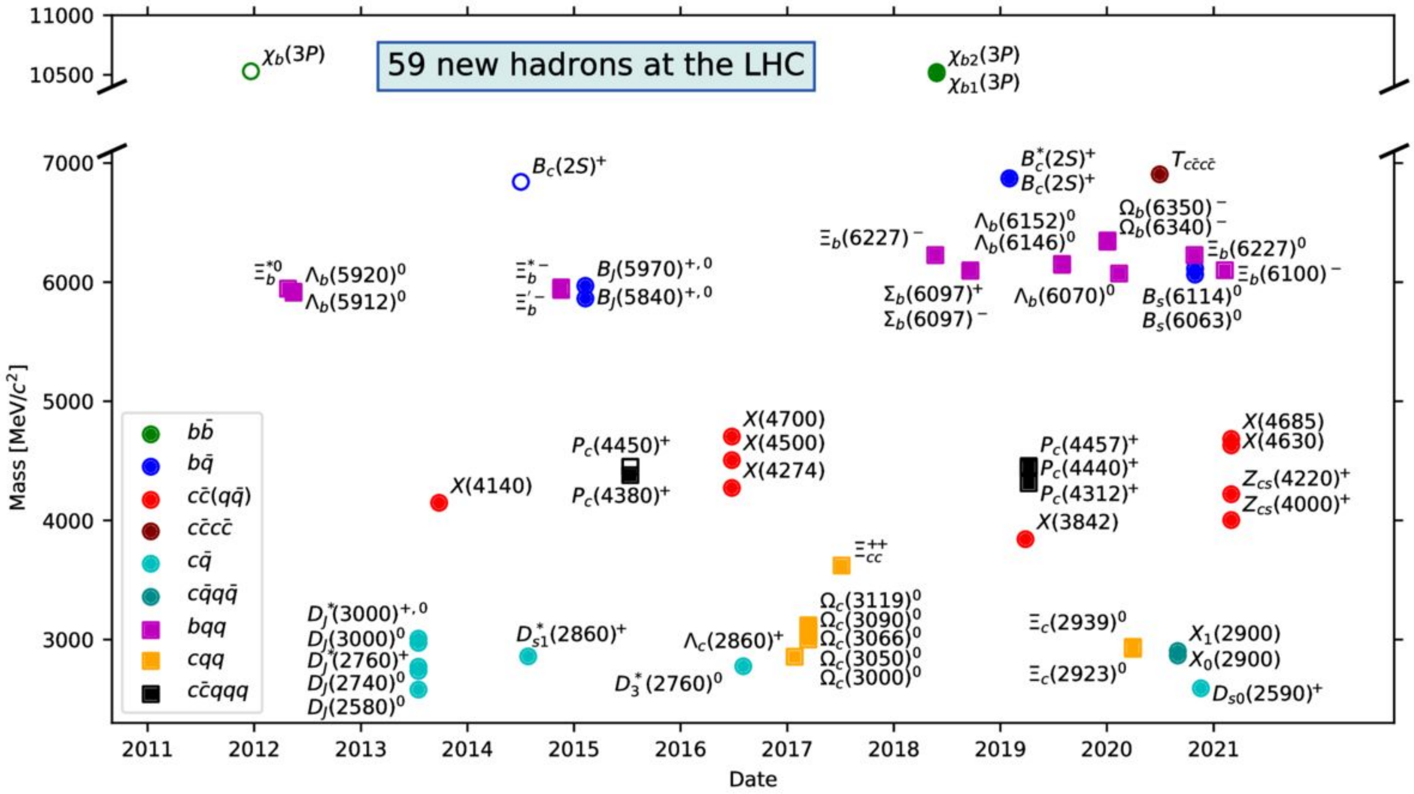


$\gamma = (65.4^{+3.8}_{-4.2})°$

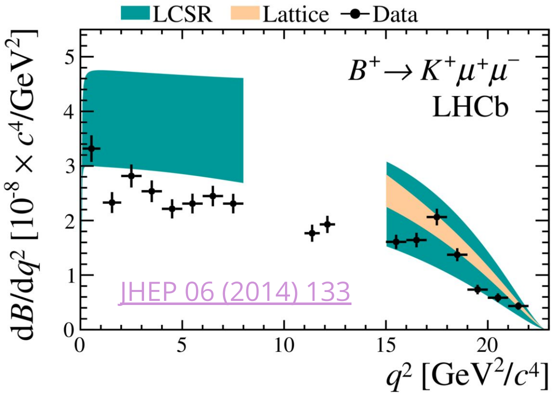
JHEP 12 (2021) 141

LHCb-FIG-2021-001

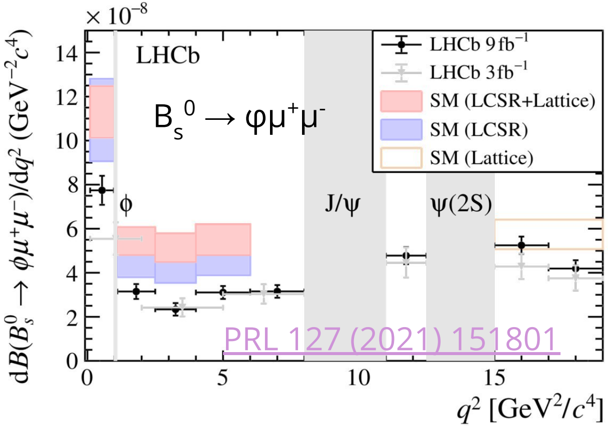
Spectroscopy



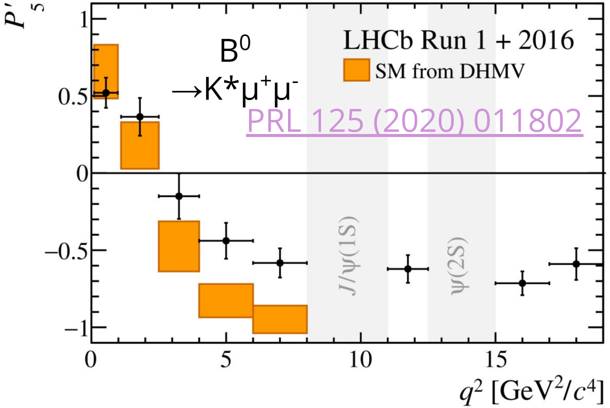
Intriguing deviations in rare B decays



JHEP 06 (2014) 133



PRL 127 (2021) 151801



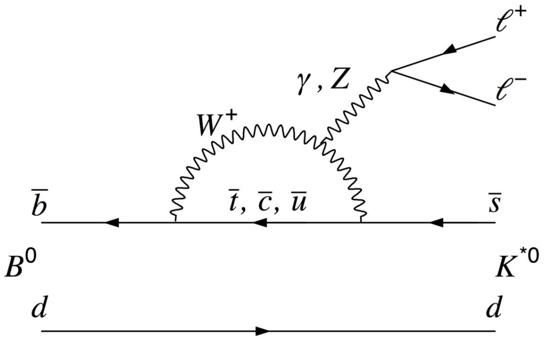
PRL 125 (2020) 011802

Lepton Universality tests

Leptons of different species couple identically to electroweak bosons in SM
→ Lepton Universality (LU)

Measure ratio of same b → sll process with muons and electrons in final state:

$$\boxed{R_H \equiv \frac{\int \frac{d\Gamma(B \to H\mu^+\mu^-)}{dq^2}\, dq^2}{\int \frac{d\Gamma(B \to He^+e^-)}{dq^2}\, dq^2}}$$



FCNC

Hadronic uncertainties cancel in ratio → very clean theory prediction

How do we measure LU?

Observable:

$$R_H \equiv \frac{\int \frac{d\Gamma(B\to H\mu^+\mu^-)}{dq^2}\, dq^2}{\int \frac{d\Gamma(B\to He^+e^-)}{dq^2}\, dq^2}$$

Experimentally:

$$R_H \propto \underset{\text{count in experiment}}{\overset{\text{events}}{\boxed{\frac{N(B\to H\mu^+\mu^-)}{N(B\to He^+e^-)}}}} \times \underset{\text{from simulation and calibration samples}}{\overset{\text{efficiency}}{\boxed{\frac{\epsilon(B\to He^+e^-)}{\epsilon(B\to H\mu^+\mu^-)}}}} \longrightarrow$$

Challenge:

- e and μ efficiencies are very different
- hard to estimate absolute efficiencies

Challenges: hardware trigger

ECAL occupancy > Muon one

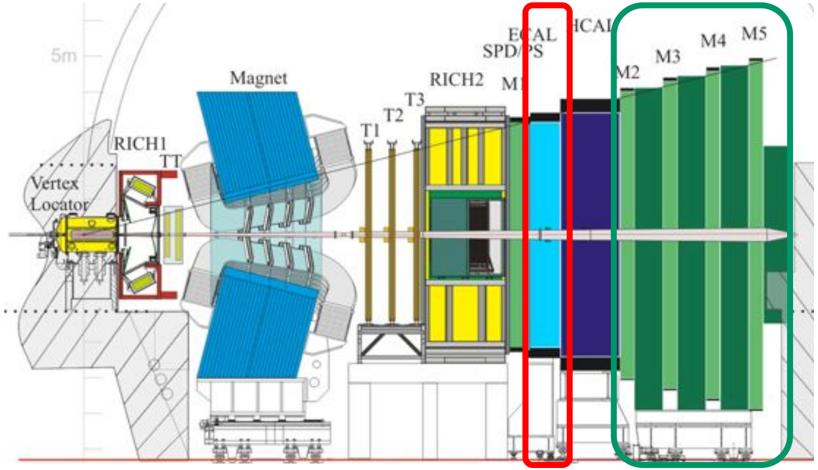
⇒ tighter thresholds for electrons:

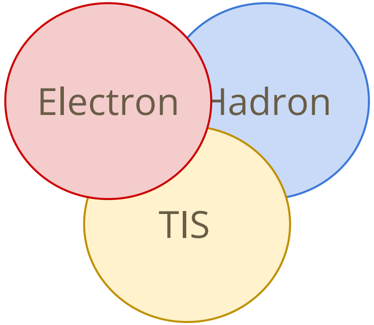
- **e p_T** > 2700/2400 MeV in 2012/2016
- **μ p_T** > 1700/1800 MeV in 2012/2016

[LHCb-PUB-2014-046, 2019 JINST 14 P04013]

Mitigation:

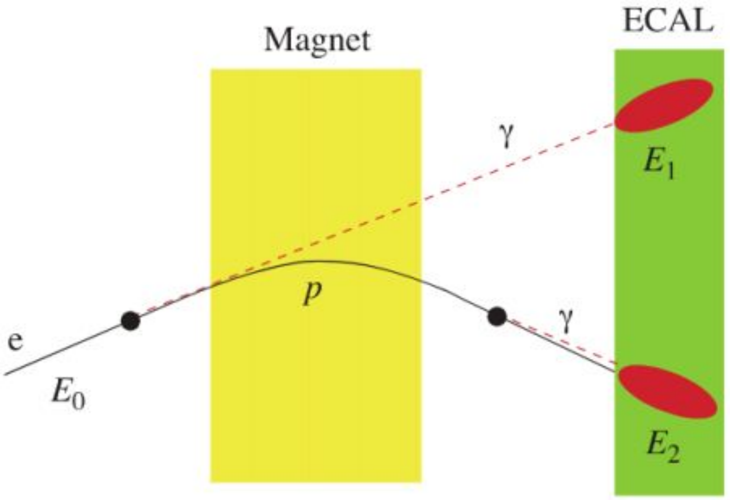
- events triggered independently of the signal (TIS)
- (hadron trigger)





Challenges: material interaction

Electrons radiate much more
Bremsstrahlung → recovery procedure:



Limitations:

- miss some photons and add fake ones
- ECAL resolution worse than tracking

→ worse mass resolution for electron modes
→ larger backgrounds
→ more complicated mass fit

How do we control the efficiencies?

Exploit J/ψ modes to build double ratio to cancel systematic effects

$$R_H = \frac{\dfrac{N(B\to H\mu^+\mu^-)}{N(B\to HJ/\psi(\mu^+\mu^-))}}{\dfrac{N(B\to He^+e^-)}{N(B\to HJ/\psi(e^+e^-))}} \times \frac{\dfrac{\epsilon(B\to He^+e^-)}{\epsilon(B\to HJ/\psi(e^+e^-))}}{\dfrac{\epsilon(B\to H\mu^+\mu^-)}{\epsilon(B\to HJ/\psi(\mu^+\mu^-))}}$$

LU well tested in J/ψ modes → stringent cross-check

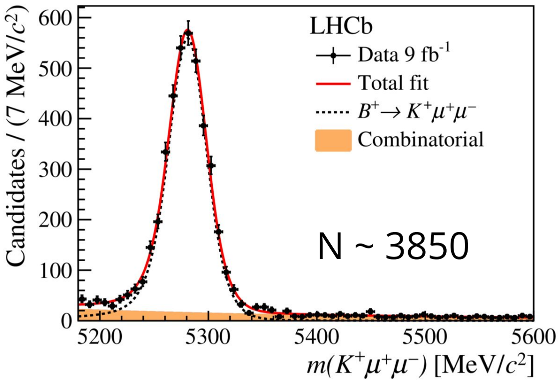
$$r_{J/\psi} = \frac{N(B\to HJ/\psi(\mu^+\mu^-))}{N(B\to HJ/\psi(e^+e^-))} \times \frac{\epsilon(B\to HJ/\psi(e^+e^-))}{\epsilon(B\to HJ/\psi(\mu^+\mu^-))}$$

Nature Physics 18, (2022) 277-282

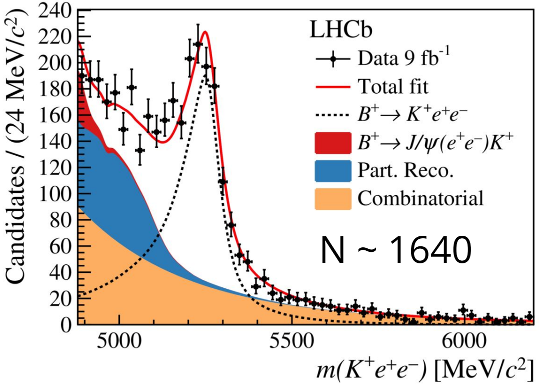
R_K with full LHCb data

Measurement in $1.1 < q^2 < 6.0\ \mathrm{GeV}^2$ with Run 1+2 datasets

R_K from simultaneous fit to $B^+ \rightarrow K^+\mu^+\mu^-$ and $B^+ \rightarrow K^+e^+e^-$ candidates



N ~ 3850



N ~ 1640

$$\boxed{R_K(1.1 < q^2 < 6.0\,\mathrm{GeV}^2/c^4) = 0.846\,^{+0.042}_{-0.039}\,^{+0.013}_{-0.012}}$$

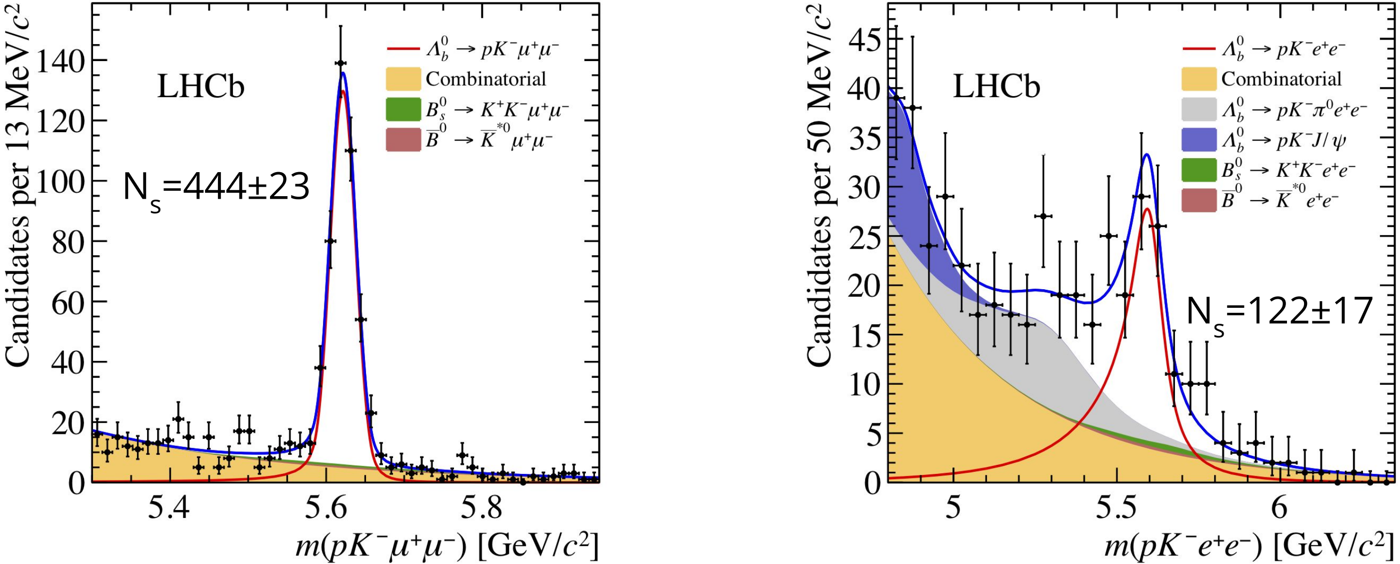
most precise LFU measurement in $b \rightarrow s\ell\ell$!

Tension with SM at 0.10% (3.1σ)

LFU in $\Lambda_b \to pKll$ (R_{pK})

JHEP05(2020)040

Mass degradation for electrons → larger backgrounds



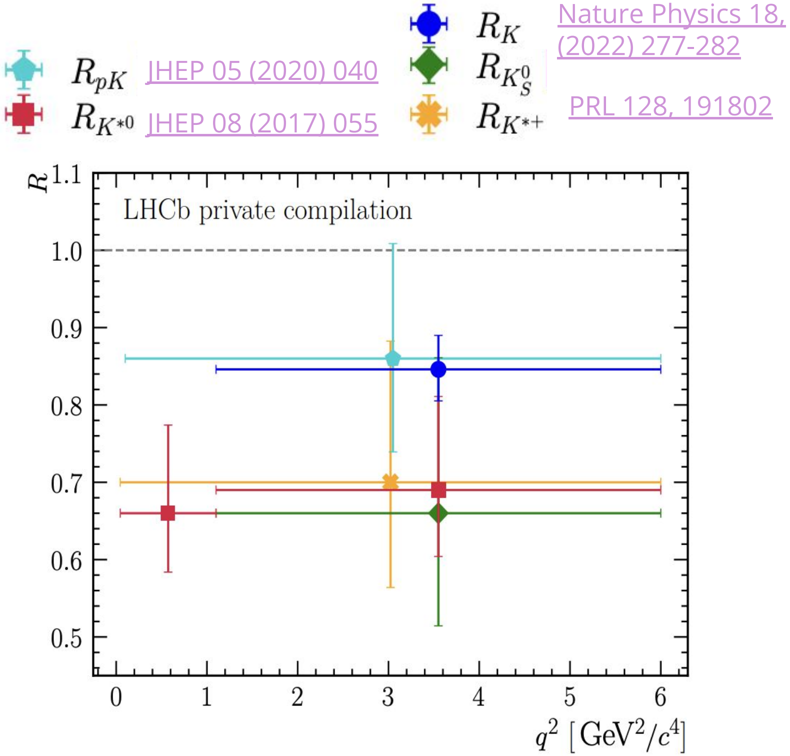
$$\boxed{R_{pK}\big|_{0.1<q^2<6\,\mathrm{GeV}^2/c^4} = 0.86^{+0.14}_{-0.11} \pm 0.05}$$

Overview of LHCb LFU measurements

Working on final results with full Run 2 data

Unified analysis of R_K and R_{K*} ongoing
- Final Run 1 + 2 results
- Deeper understanding LFU
- High priority for collaboration

Updates and new measurements:
- R_{pK} full Run 1+2 (UB)
- R_φ, $R_{K\pi\pi}$, etc.



JHEP 05 (2020) 040

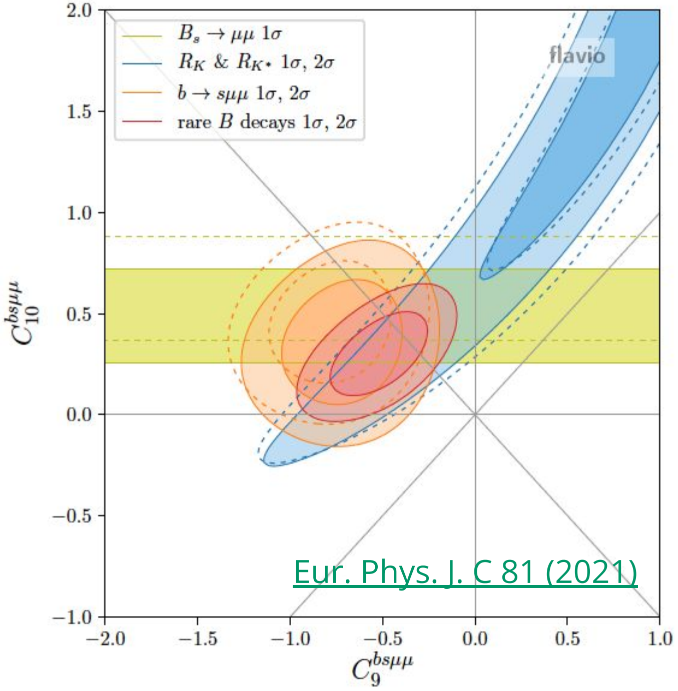
JHEP 08 (2017) 055

Nature Physics 18, (2022) 277-282

PRL 128, 191802

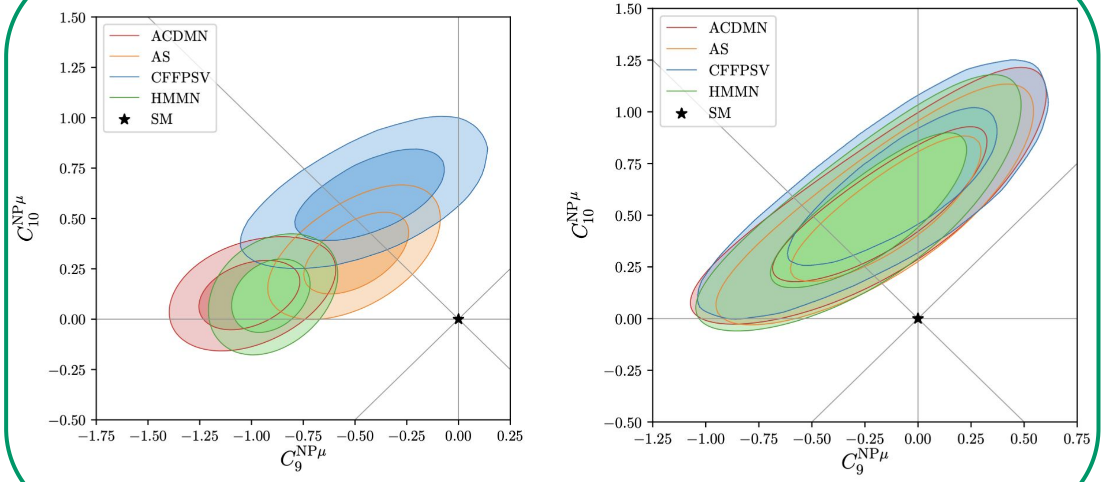
Coherent set of anomalies

Among measurements

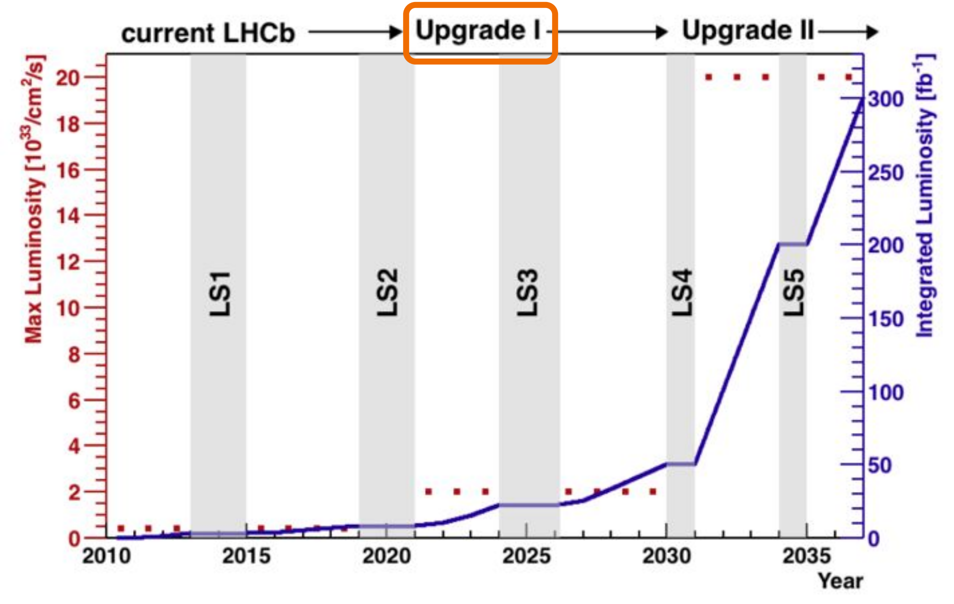


Eur. Phys. J. C 81 (2021)

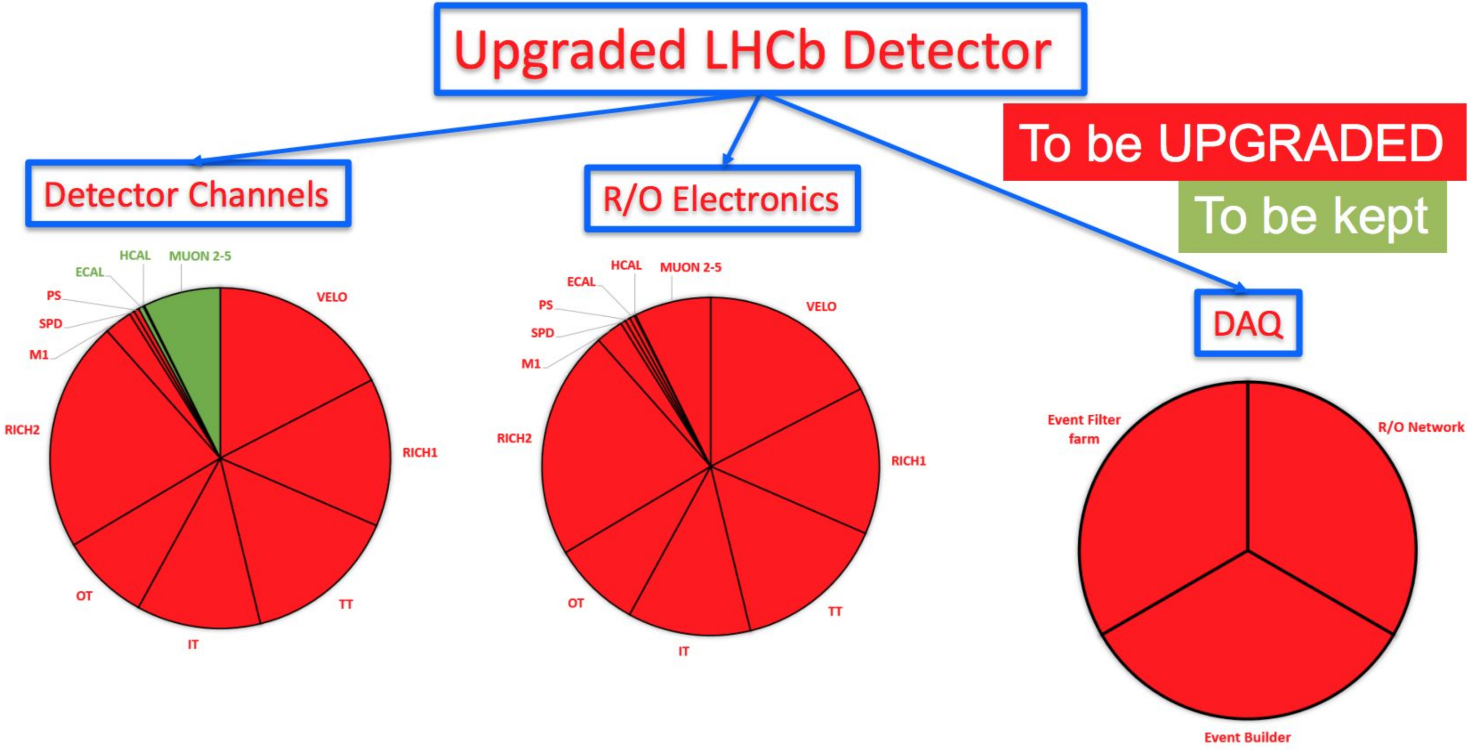
Among pheno groups



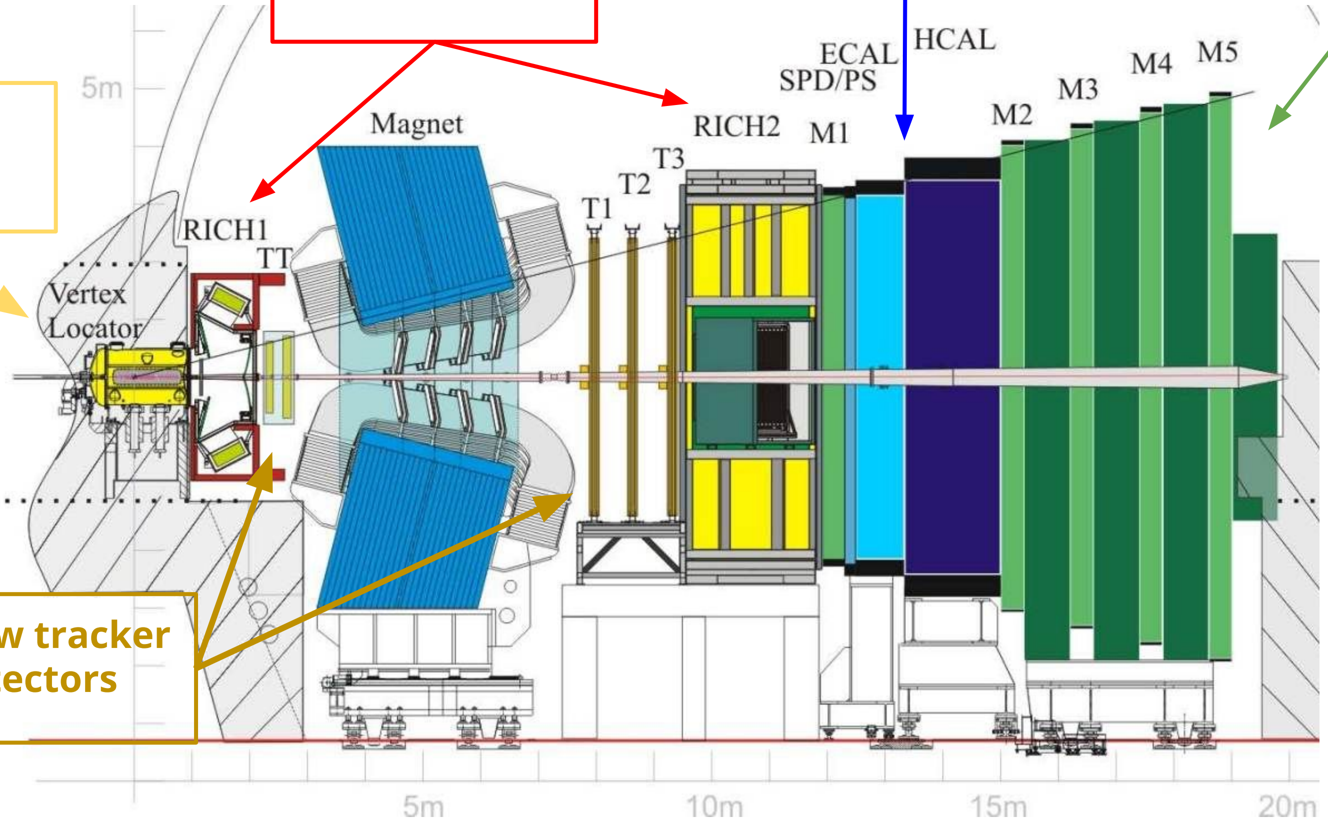
The LHCb upgrade



LHCb Upgrade: a quasi-new detector



LHCb Upgrade



New RICH detectors

Removal of SPD/PS, new electronics

Removal of M1, new electronics

New VeloPix detector

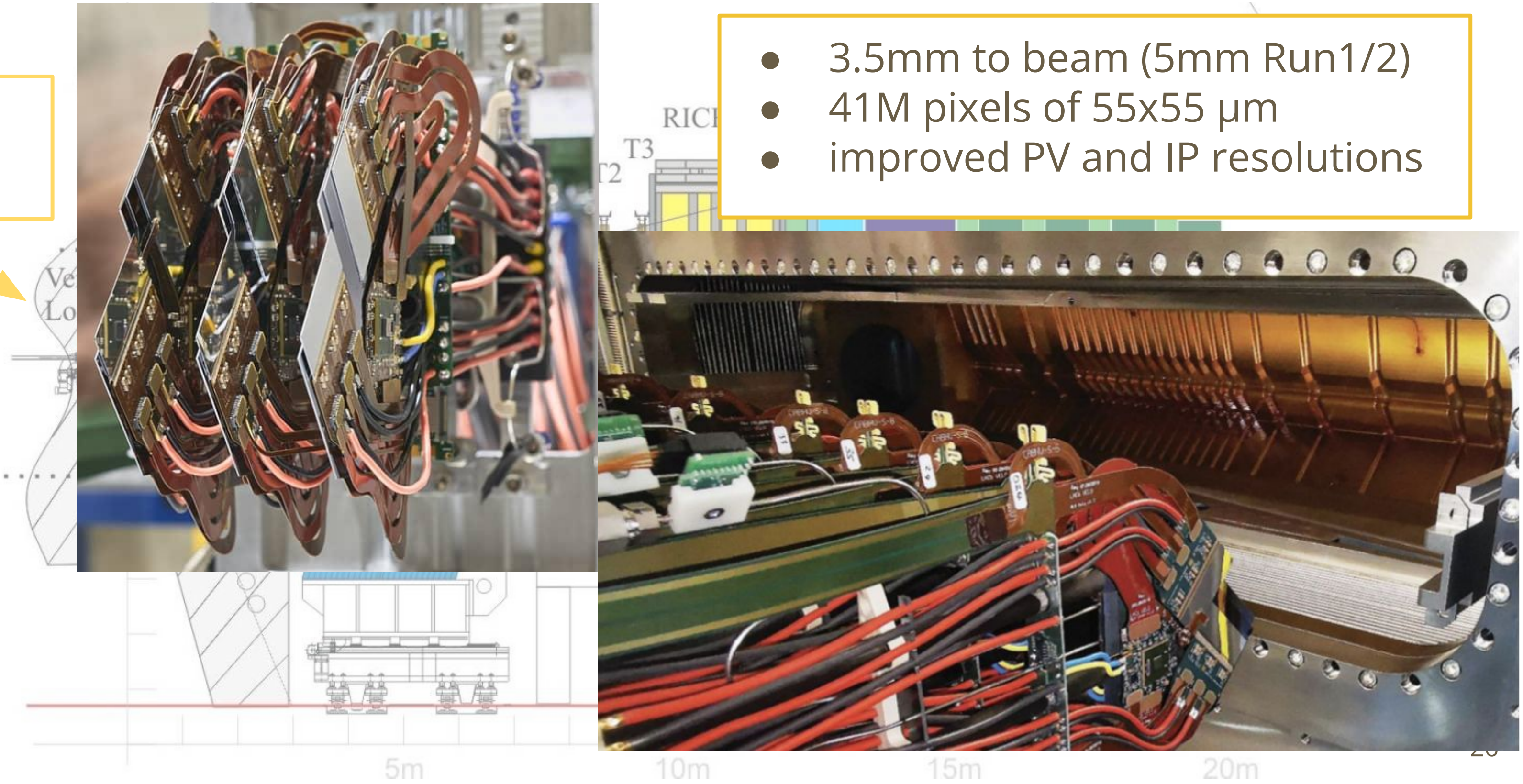
New tracker detectors

LHCb Upgrade

CERN-LHCC-2013-021

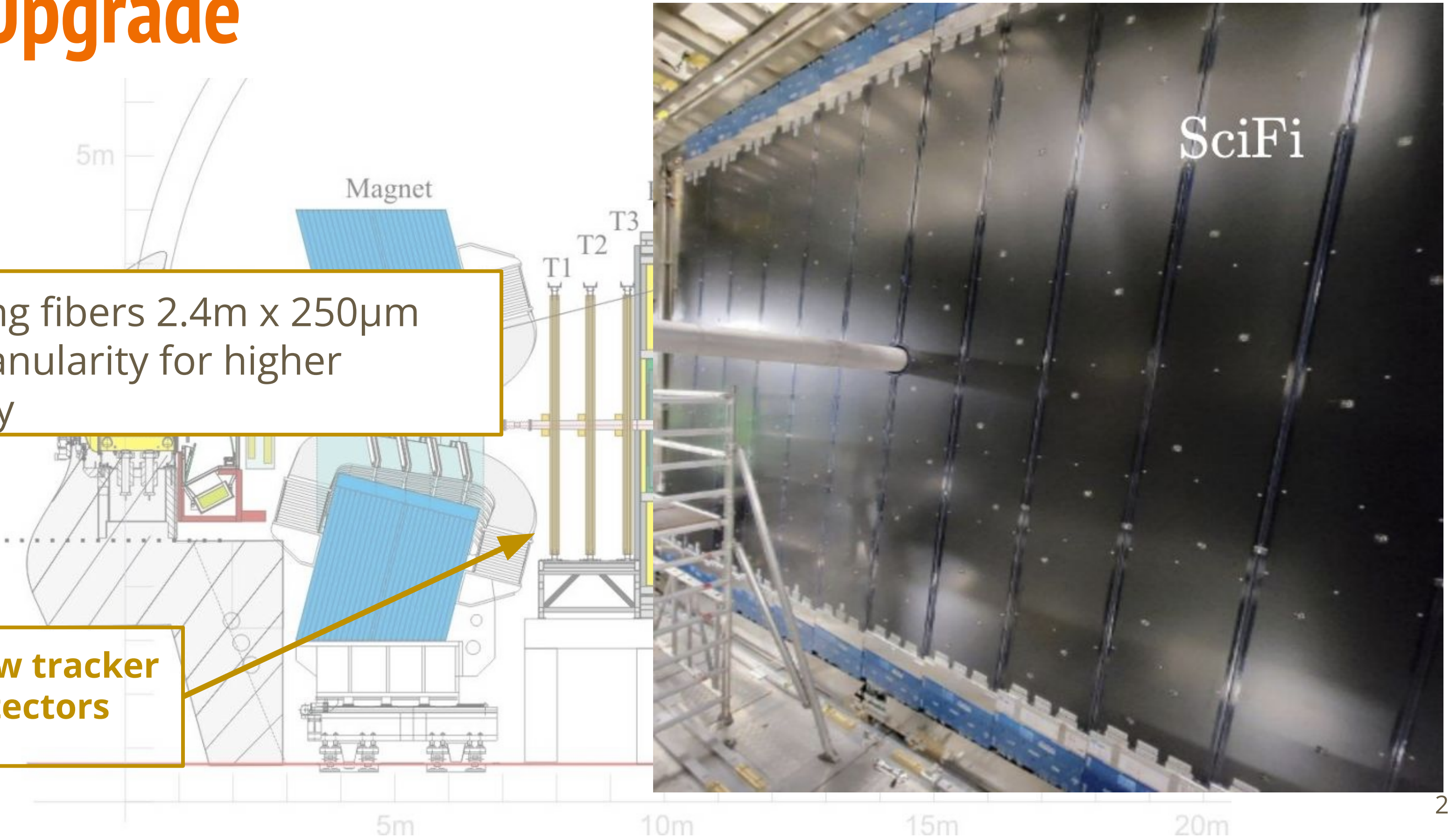
New VeloPix detector

- 3.5mm to beam (5mm Run1/2)
- 41M pixels of 55x55 μm
- improved PV and IP resolutions



CERN-LHCC-2014-001

LHCb Upgrade

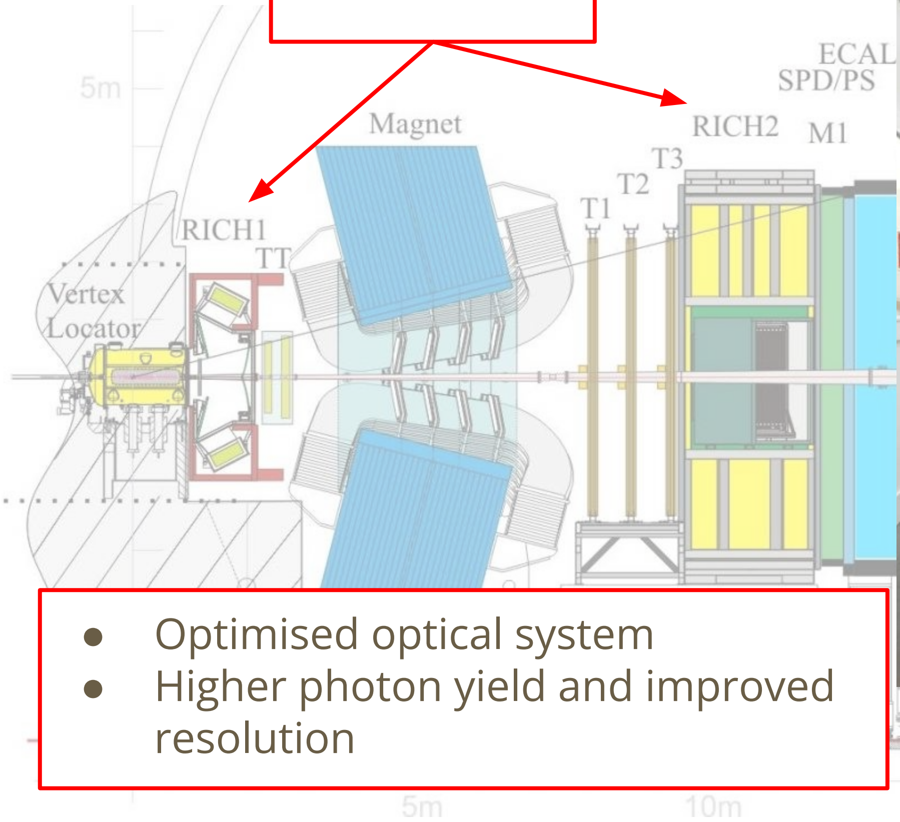


- Scintillating fibers 2.4m x 250μm
- higher granularity for higher occupancy

New tracker detectors

CERN-LHCC-2013-022

LHCb Upgrade



New RICH detectors

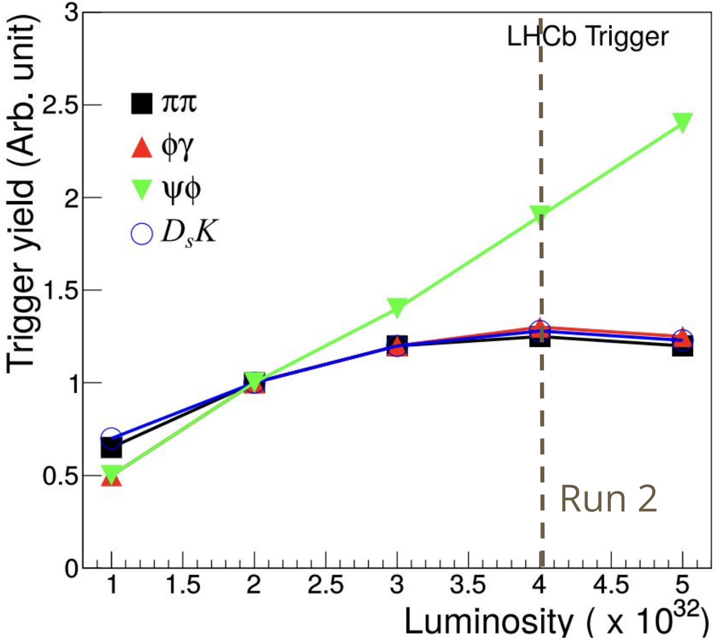
- Optimised optical system
- Higher photon yield and improved resolution

A trigger-less readout

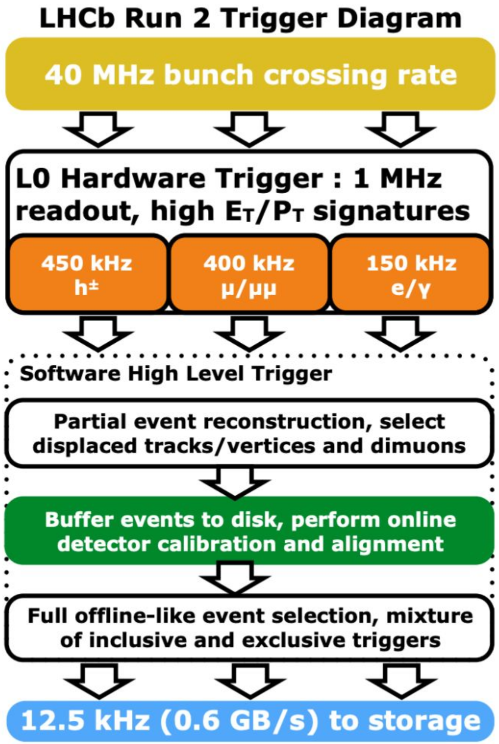
- Instantaneous Lumi: 2×10^{33} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - was 4×10^{32} in Run 2
- Hardware trigger rate limit (1 MHz) saturates fully hadronic modes

⇒ read full detector at 30 MHz and apply selections in software

J. Phys.: Conf. Ser. 878 012012



A trigger-less readout



LHCb Run 2 Trigger Diagram

40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures

450 kHz $h^{\pm}$	400 kHz $\mu/\mu\mu$	150 kHz e/γ

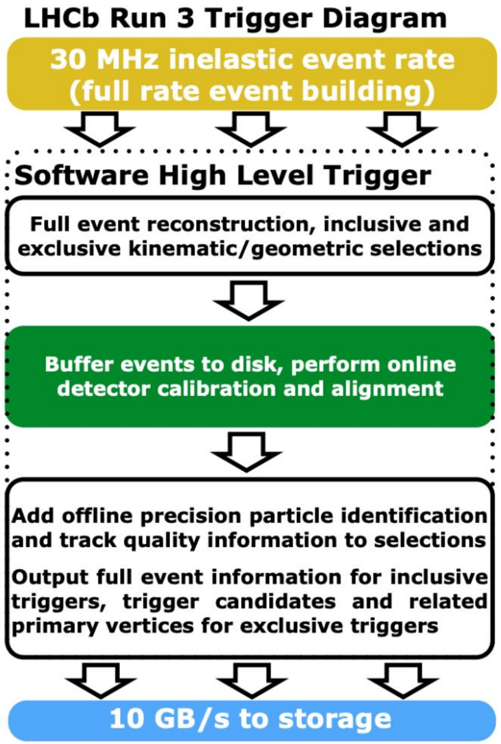
Software High Level Trigger

Partial event reconstruction, select displaced tracks/vertices and dimuons

Buffer events to disk, perform online detector calibration and alignment

Full offline-like event selection, mixture of inclusive and exclusive triggers

12.5 kHz (0.6 GB/s) to storage



LHCb Run 3 Trigger Diagram

30 MHz inelastic event rate (full rate event building)

Software High Level Trigger

Full event reconstruction, inclusive and exclusive kinematic/geometric selections

Buffer events to disk, perform online detector calibration and alignment

Add offline precision particle identification and track quality information to selections

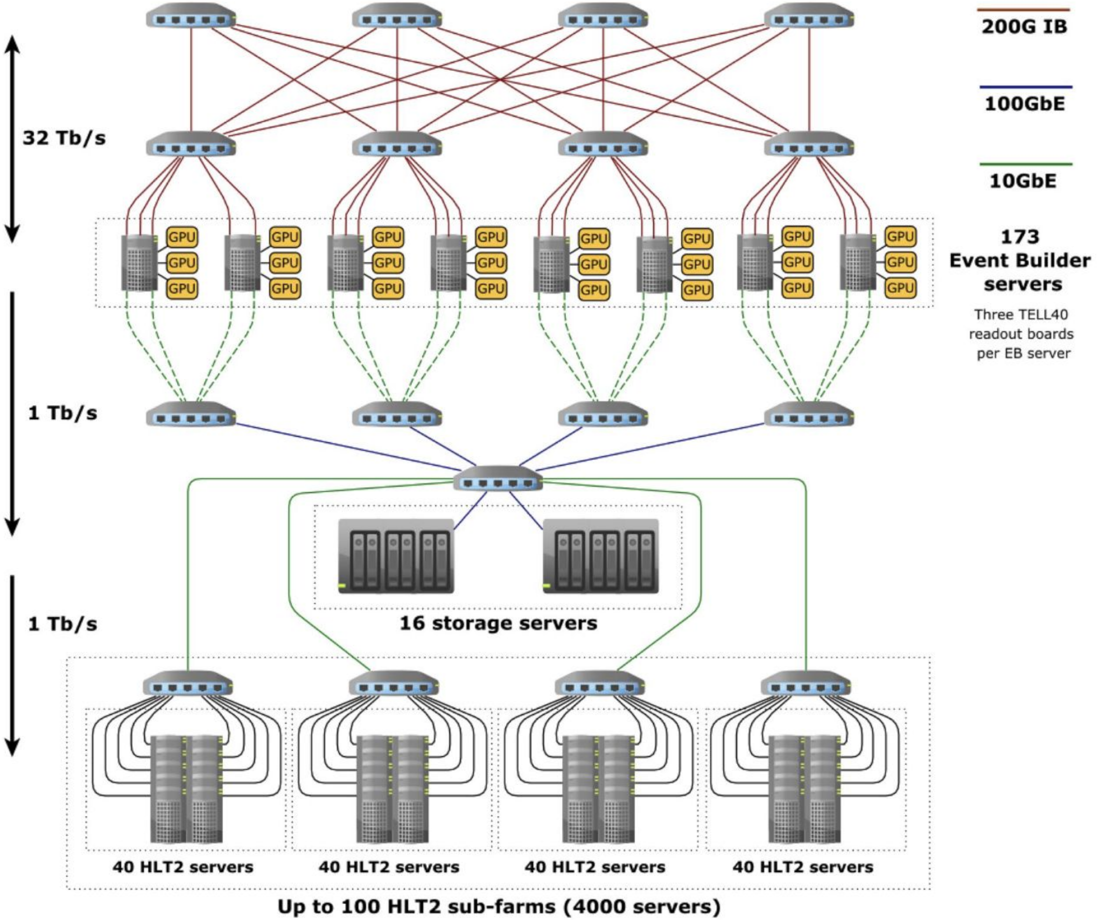
Output full event information for inclusive triggers, trigger candidates and related primary vertices for exclusive triggers

10 GB/s to storage

DAQ architecture

Hybrid architecture:

- HLT1: **GPUs** installed in EB servers
- HLT2: **CPUs** in Event Filter Farm



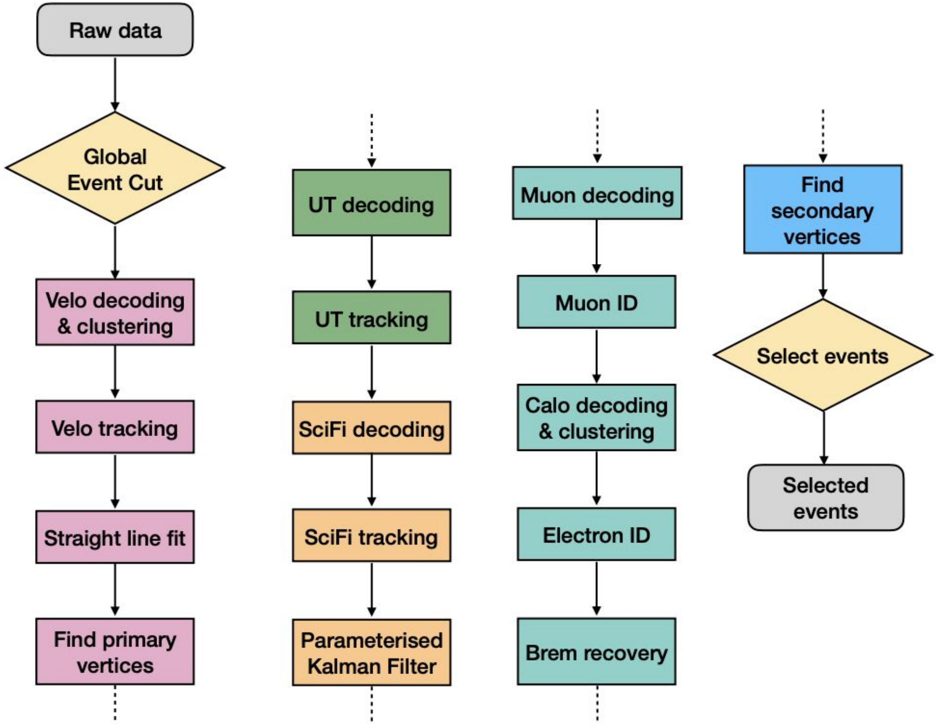
HLT1

Core based on tracking:

- VELO: tracking, vertex reconstruction
- UT: tracking, p estimate, fake rejection
- SciFi: track reconstruction, momentum measurement

PID from muon stations & **Calo** (new!)

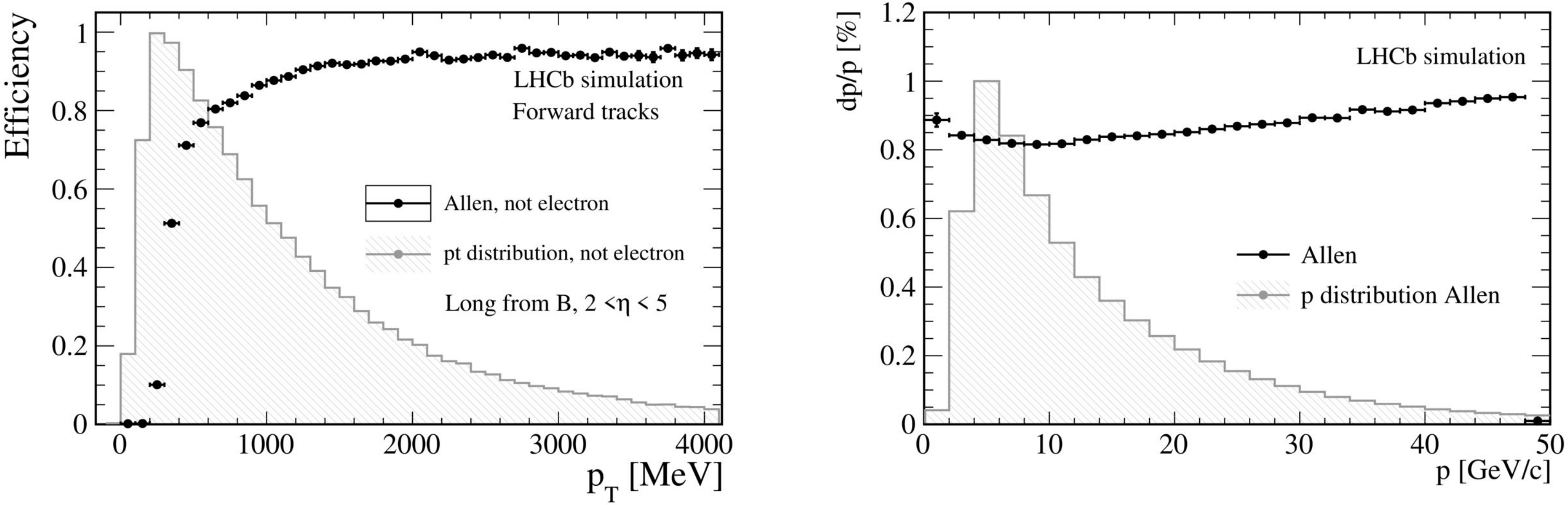
Highly parallel tasks → exploit GPUs: Nvidia RTX A5000



HLT1 performance: tracking

LHCB-FIGURE-2020-014

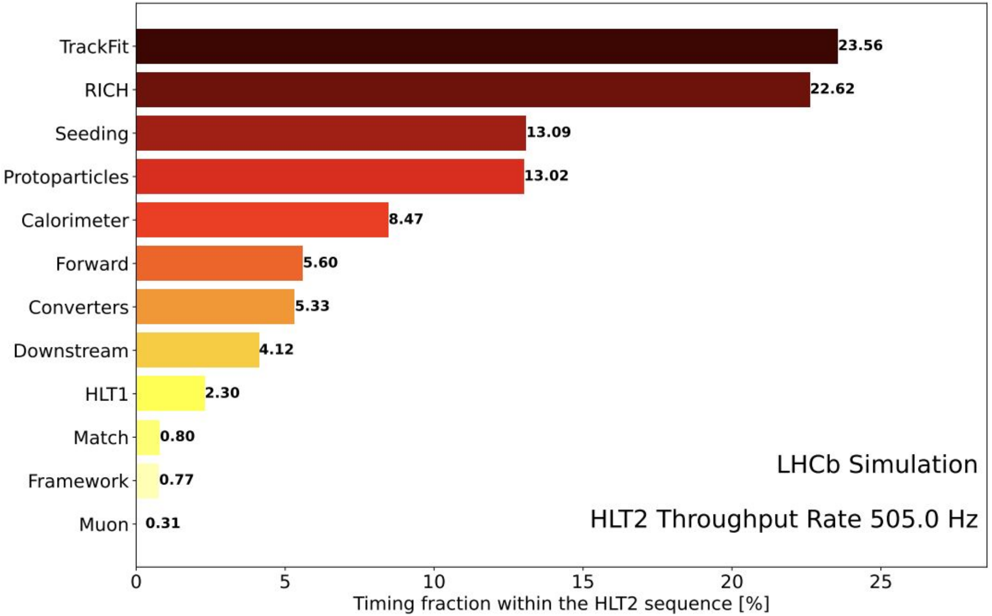
Same performance at x5 luminosity: high efficiency, good δp, low fake rate



HLT2

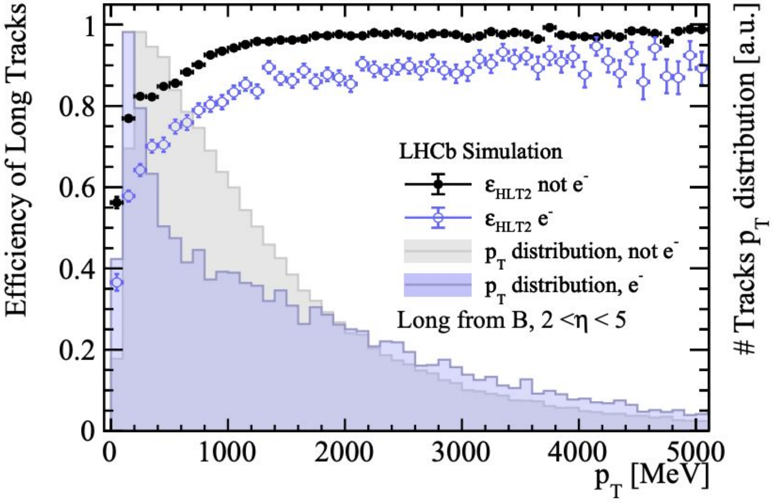
LHCB-FIGURE-2022-005

Full reconstruction of tracks and neutrals, and PID with offline-quality

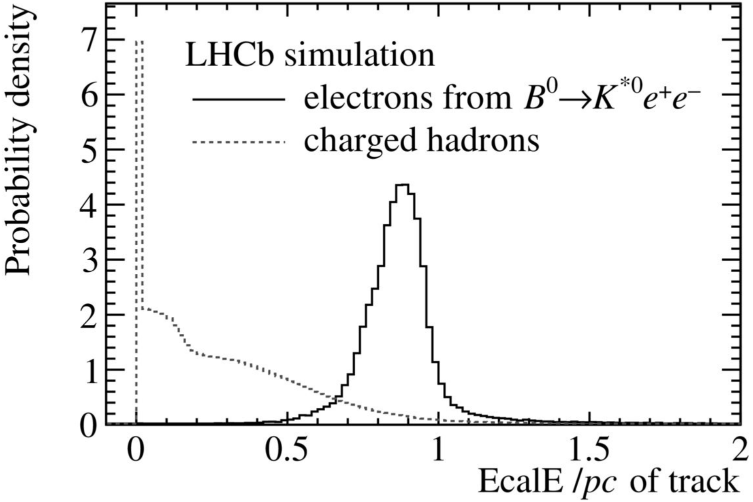


HLT2

Full reconstruction of tracks and neutrals, and PID with offline-quality



LHCB-FIGURE-2022-005



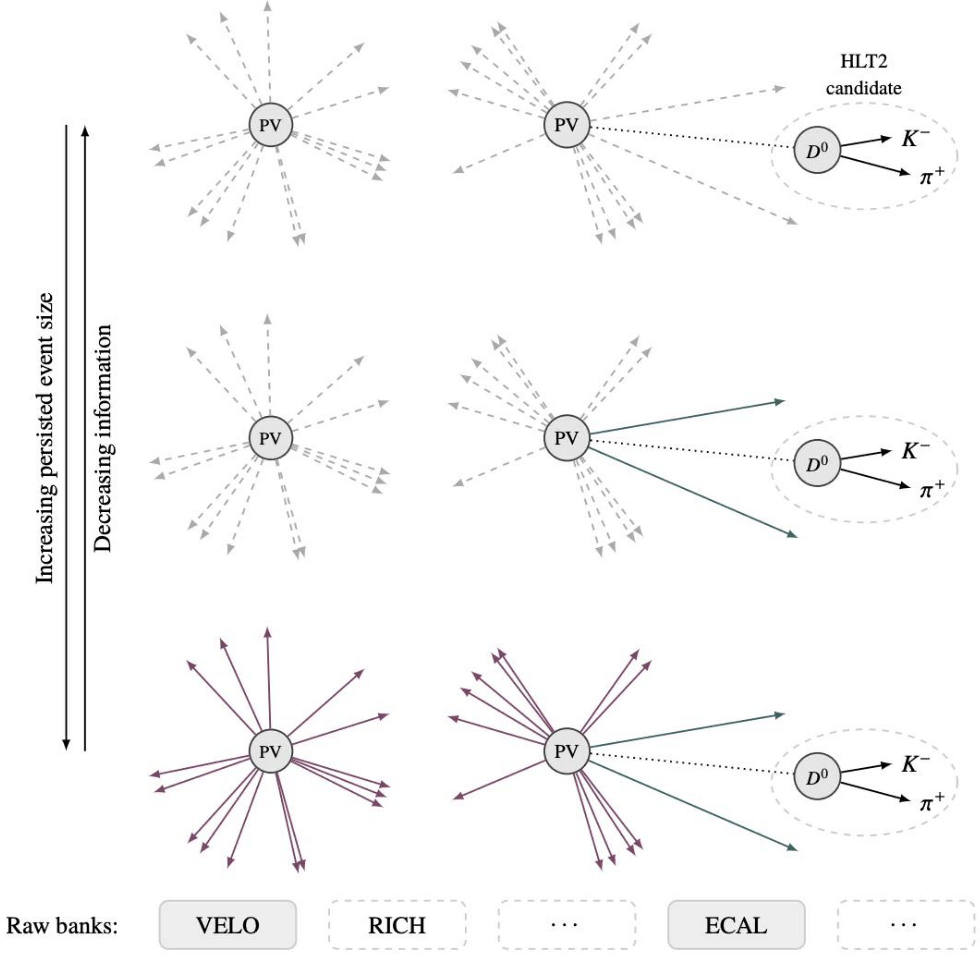
LHCB-FIGURE-2021-003

HLT2: turbo model

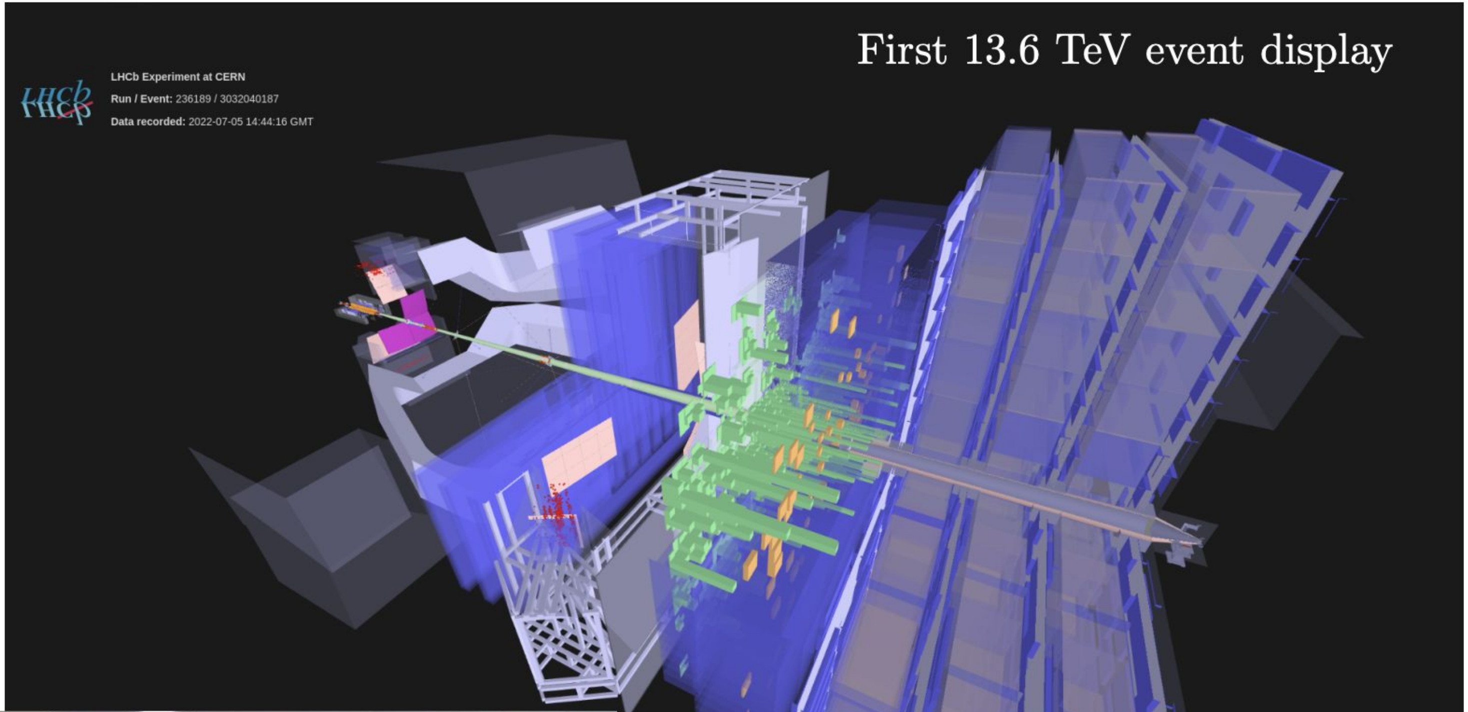
Flexible persistence model:

- **Turbo** (35 kB): signal only
- **Full** (70 kB): all reco’ed objects
- **Selective**: signal + selection of reconstructed objects and raw banks

JINST 14 P04006

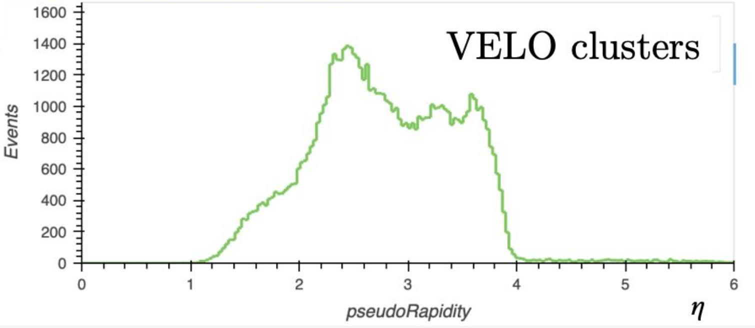


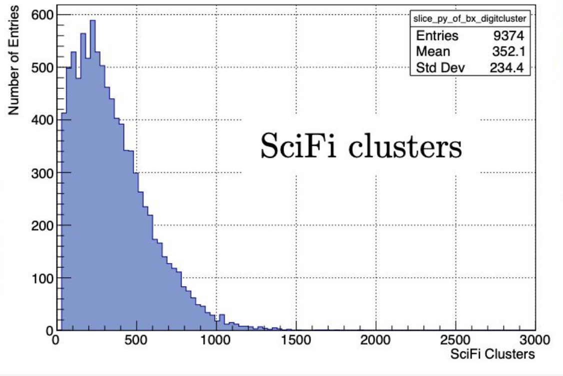
Commissioning and first data

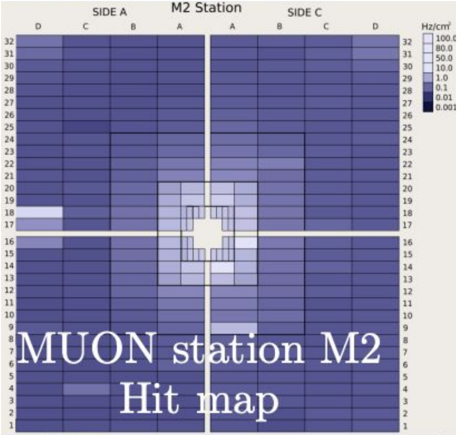


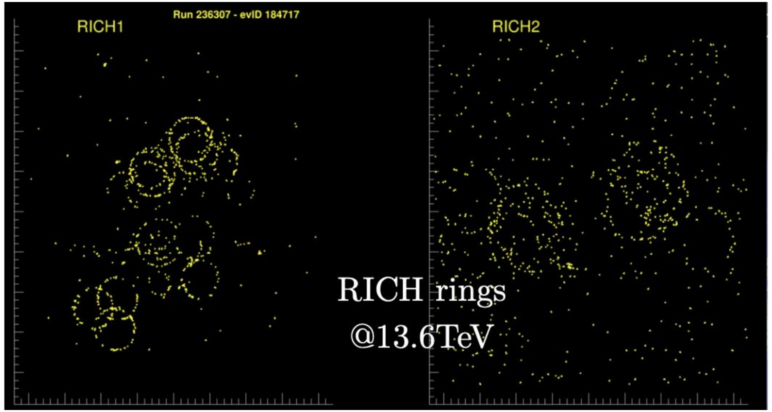
F. Blanc @ICHEP22

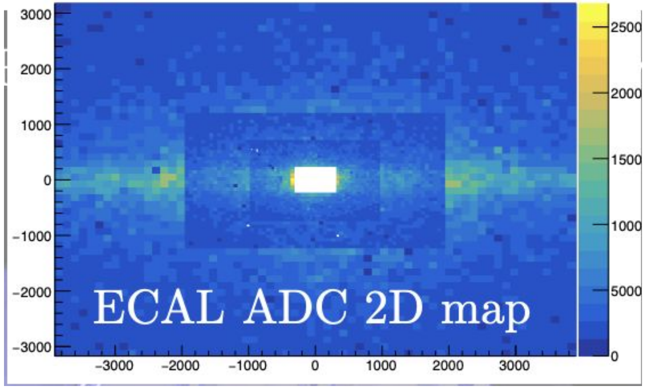
First Run 3 data



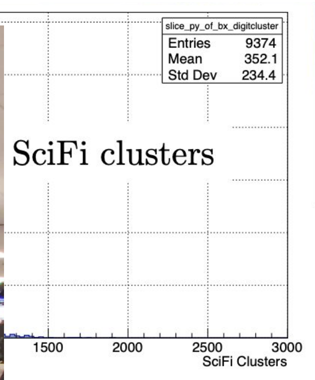




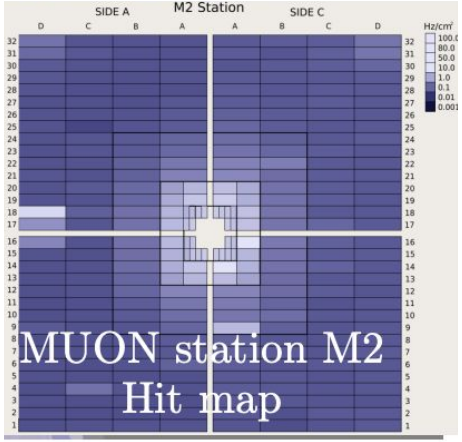




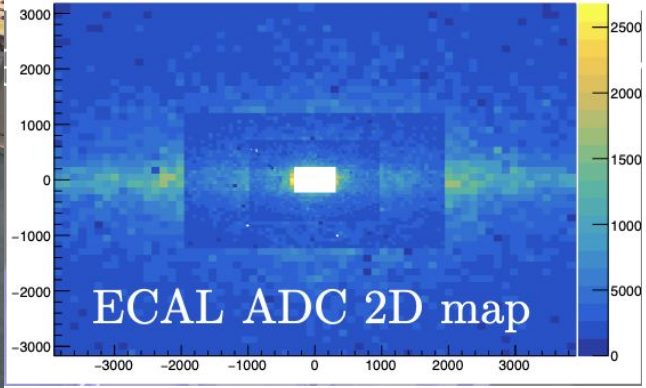
First Run 3 data



SciFi clusters



MUON station M2 Hit map



ECAL ADC 2D map

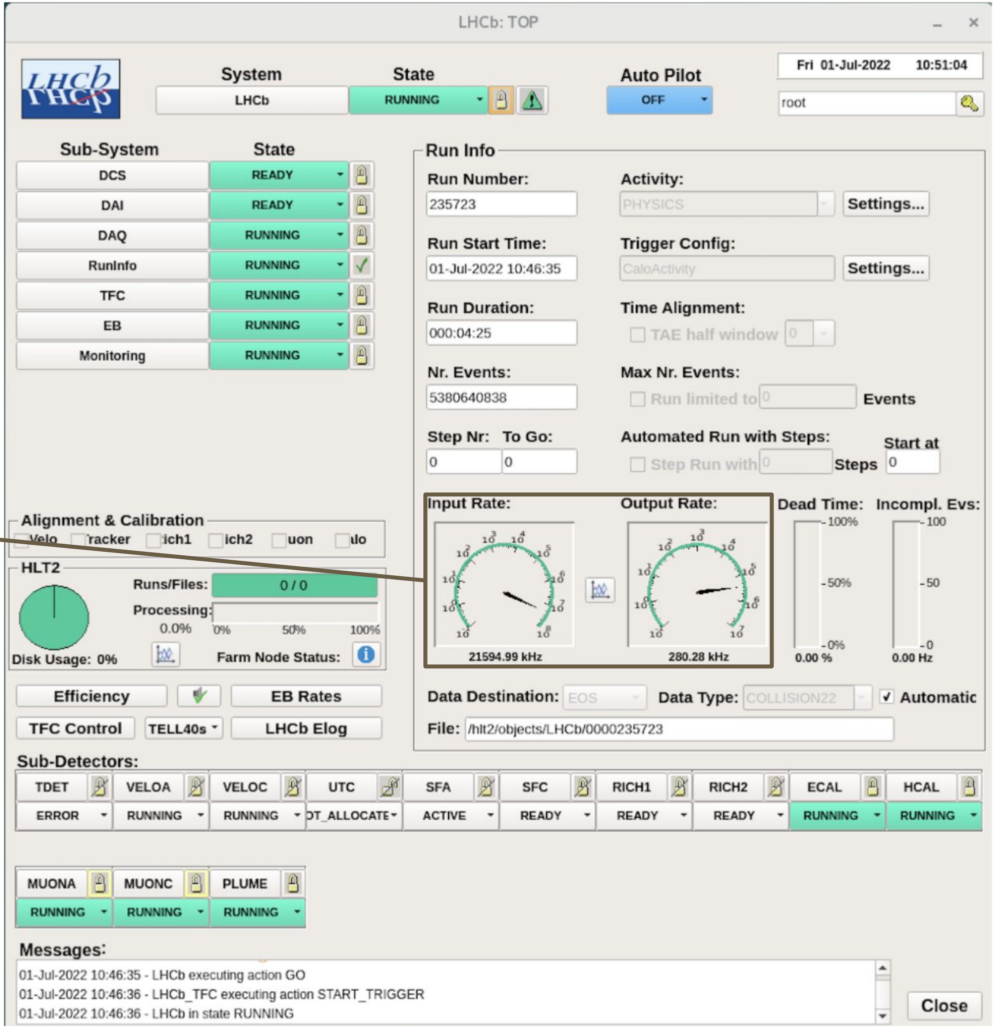
C. Agapopoulou @ICHEP

HLT1 commissioning

- LHCb DAQ running in parallel to detector commissioning since July
- ~200 GPUs installed and HLT1 running in global partition

- Triggering on ECAL clusters @20 MHz!

- Next: include trackers when ready



Fri 01-Jul-2022 10:51:04

System	State	Auto Pilot
LHCb	RUNNING	OFF

root

Sub-System	State
DCS	READY
DAI	READY
DAQ	RUNNING
RunInfo	RUNNING
TFC	RUNNING
EB	RUNNING
Monitoring	RUNNING

Run Info

Run Number: 235723

Activity: PHYSICS

Run Start Time: 01-Jul-2022 10:46:35

Trigger Config: CaloActivity

Run Duration: 000:04:25

Time Alignment: ☐ TAE half window 0

Nr. Events: 5380640838

Max Nr. Events: ☐ Run limited to 0 Events

Step Nr: 0 To Go: 0

Automated Run with Steps: ☐ Step Run with 0 Steps Start at 0

Input Rate: 21594.99 kHz

Output Rate: 280.28 kHz

Dead Time: 0.00 %

Incompl. Evs: 0.00 Hz

Runs/Files: 0 / 0

Processing: 0.0%

Disk Usage: 0%

Farm Node Status:

Data Destination: EOS

Data Type: COLLISION22 ☑ Automatic

File: /hlt2/objects/LHCb/0000235723

Sub-Detectors:

TDET	VELOA	VELOC	UTC	SFA	SFC	RICH1	RICH2	ECAL	HCAL
ERROR	RUNNING	RUNNING	OT_ALLOCATE	ACTIVE	READY	READY	READY	RUNNING	RUNNING

MUONA	MUONC	PLUME
RUNNING	RUNNING	RUNNING

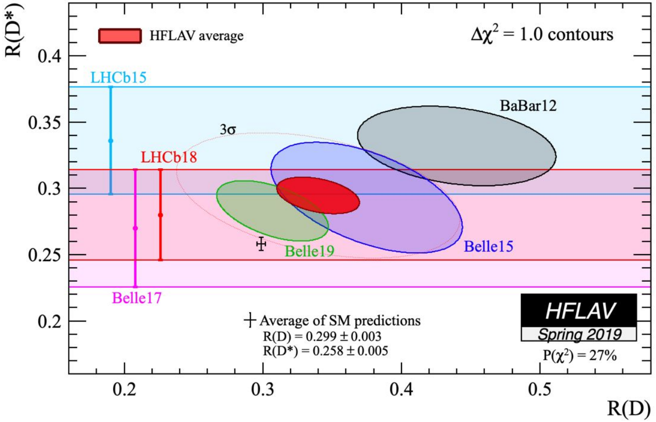
Messages:

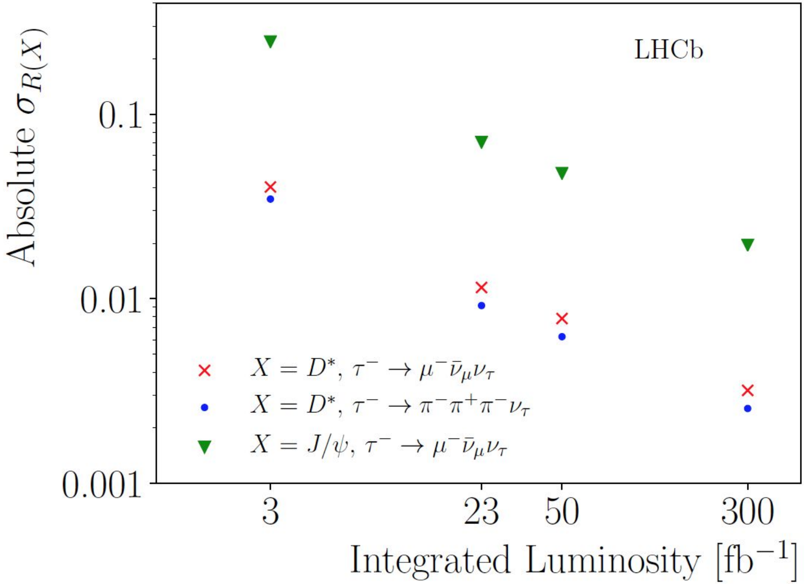
```
01-Jul-2022 10:46:35 - LHCb executing action GO
01-Jul-2022 10:46:36 - LHCb_TFC executing action START_TRIGGER
01-Jul-2022 10:46:36 - LHCb in state RUNNING
```

Physics prospects

arXiv:1808.08865

Prospects for LU tests in b → clν decays





R(D)-R(D*) ongoing with current dataset

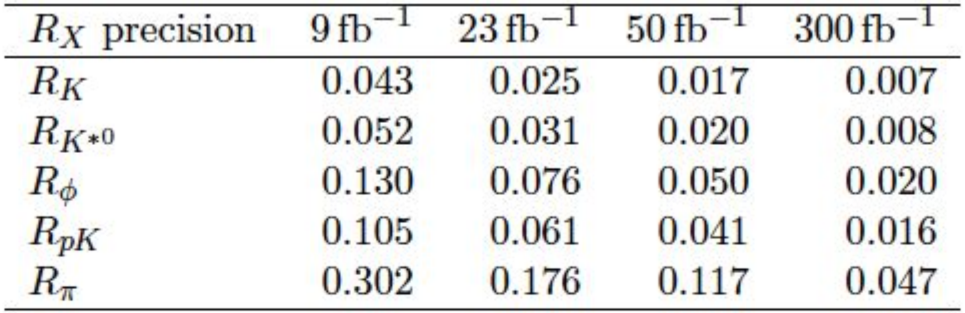
Also measurements with other b hadrons:

- $\sigma_{R(D_s)}$ < 6% (2.5%) and R(D$^{*(*)}_s$)
- $\sigma_{R(\Lambda_c)}$ < 4% (2.5%) and R(pp) (b → ulν)

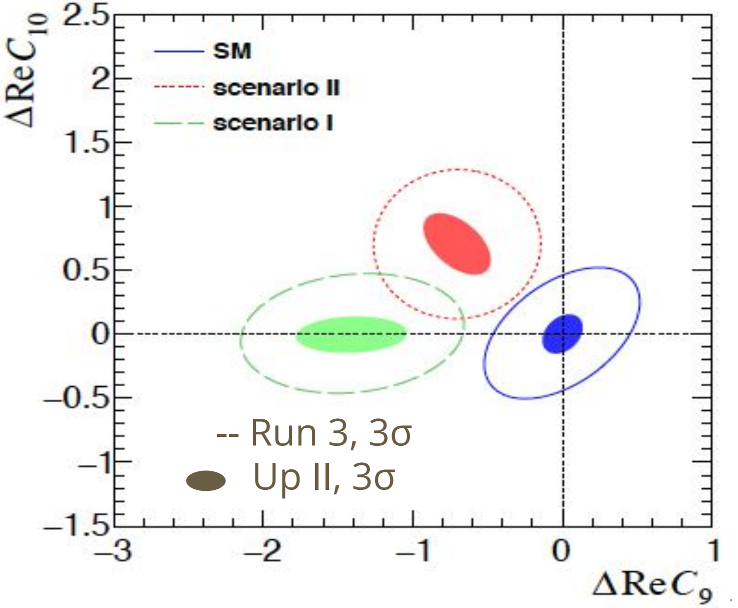
arXiv:1808.08865

Prospects for Rare Decays

- updated and completely new LFU and angular observables
  - access electron modes in several b → sll decays
  - access b → dll decays too!

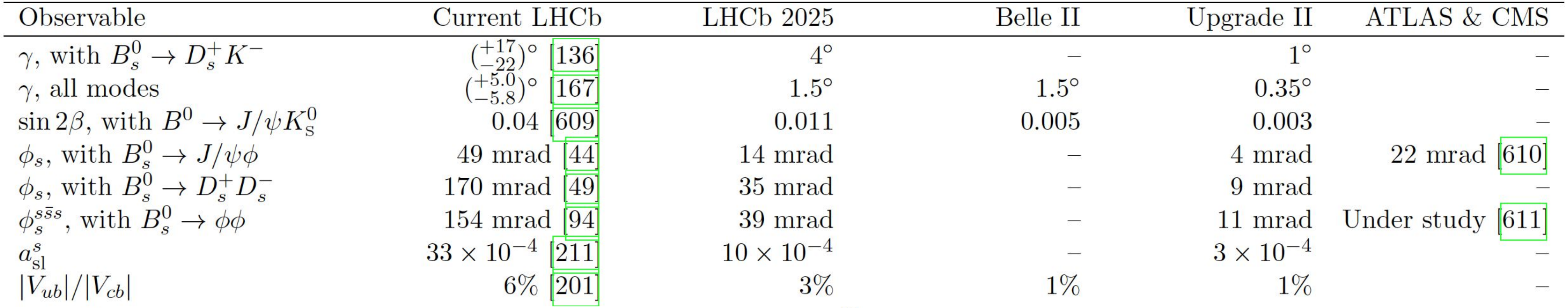


		Run 3	Run 4	Upgrade II
R_X precision	$9\,\mathrm{fb}^{-1}$	$23\,\mathrm{fb}^{-1}$	$50\,\mathrm{fb}^{-1}$	$300\,\mathrm{fb}^{-1}$
R_K	0.043	0.025	0.017	0.007
$R_{K^{*0}}$	0.052	0.031	0.020	0.008
R_ϕ	0.130	0.076	0.050	0.020
R_{pK}	0.105	0.061	0.041	0.016
R_π	0.302	0.176	0.117	0.047

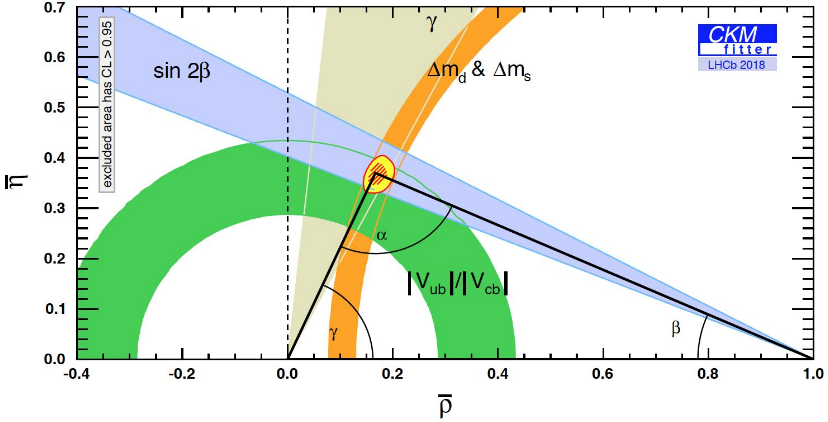


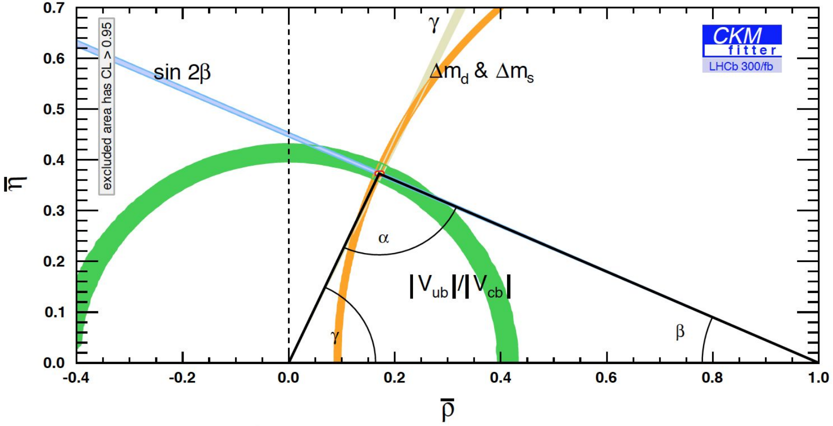
arXiv:1808.08865

Prospects for CKM measurements



Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [609]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [610]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	–	11 mrad	Under study [611]
$a_{\rm sl}^s$	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–





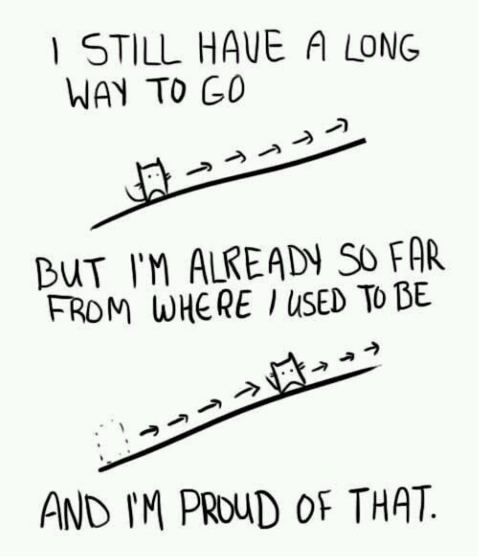
Conclusions

Wide range of physics at LHCb, with intriguing anomalies in rare b-decays

Upgraded detector and trigger-less readout open doors to even more physics:

- hadronic final states
- electron final states
- long-lived particles

Strong progress with commissioning but it is a new detector so it takes time!

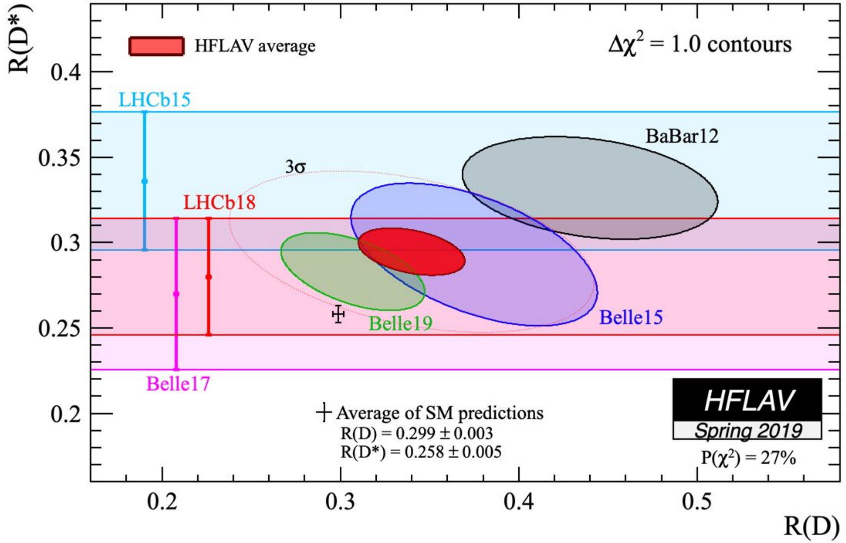


Stayed tuned!

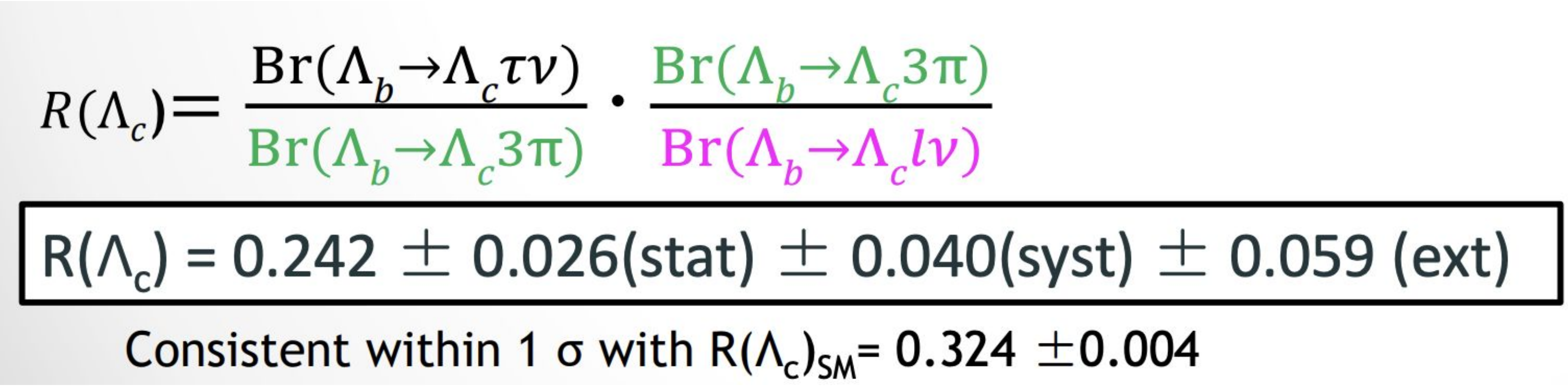
Thanks for the attention

BACK-UP

LFU in b ⟶ clv decays



PRL 128, 191803 (2022)



$$R(\Lambda_c) = \frac{Br(\Lambda_b \to \Lambda_c \tau\nu)}{Br(\Lambda_b \to \Lambda_c 3\pi)} \cdot \frac{Br(\Lambda_b \to \Lambda_c 3\pi)}{Br(\Lambda_b \to \Lambda_c l\nu)}$$

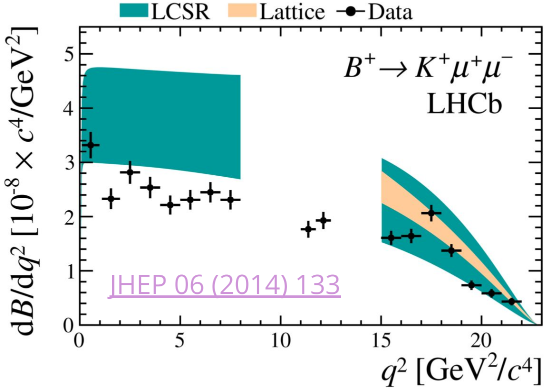
$$\boxed{R(\Lambda_c) = 0.242 \pm 0.026(\text{stat}) \pm 0.040(\text{syst}) \pm 0.059\ (\text{ext})}$$

Consistent within 1 σ with $R(\Lambda_c)_{SM} = 0.324 \pm 0.004$

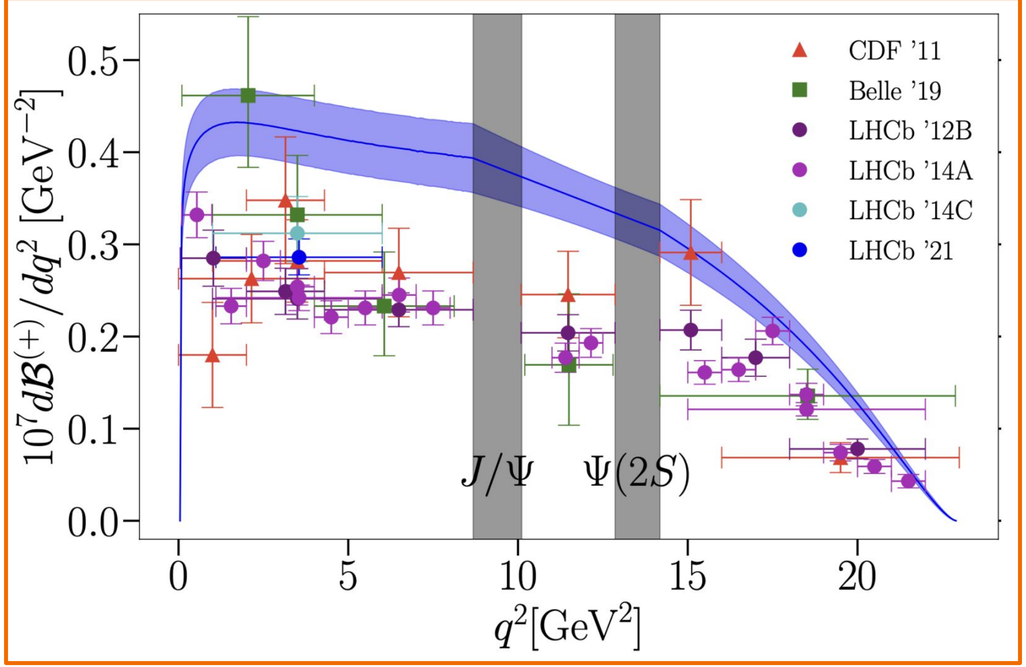
Branching ratios

Trend: b → s$\mu^+\mu^-$ BR systematically
than SM predictions

NEW LQCD FF for B → K: better precision, increased tension! See talk by C. Bouchard

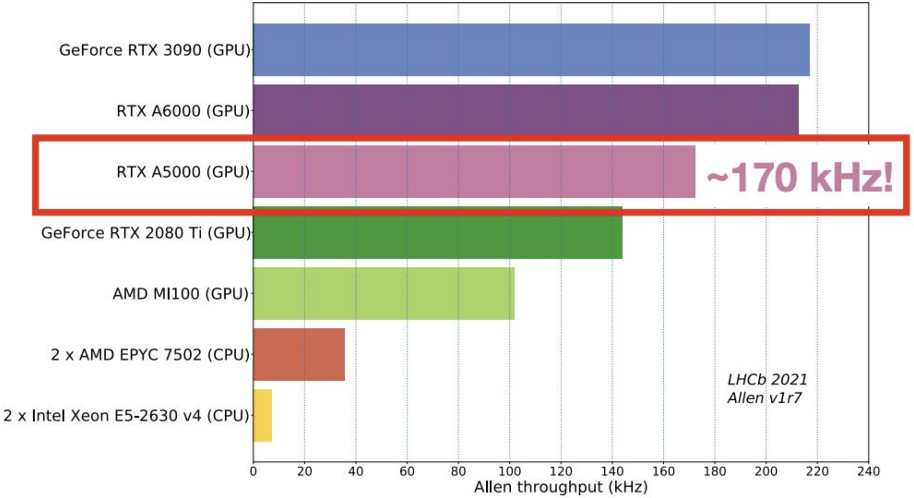


JHEP 06 (2014) 133

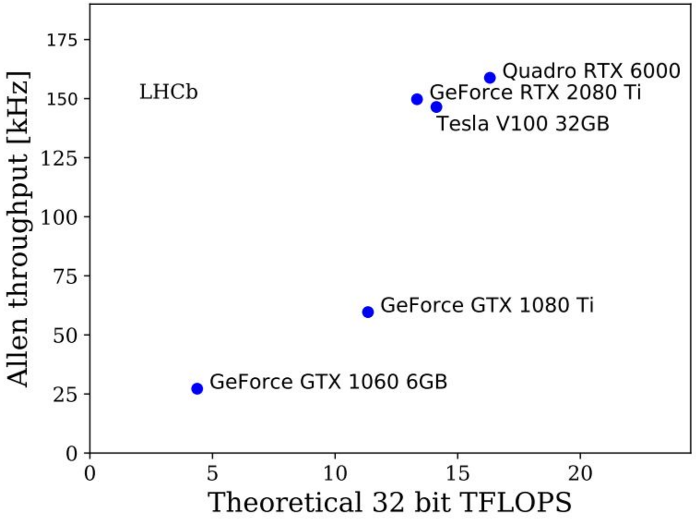


GPU choice

C. Agapopoulou @ICHEP 22



~170 kHz!

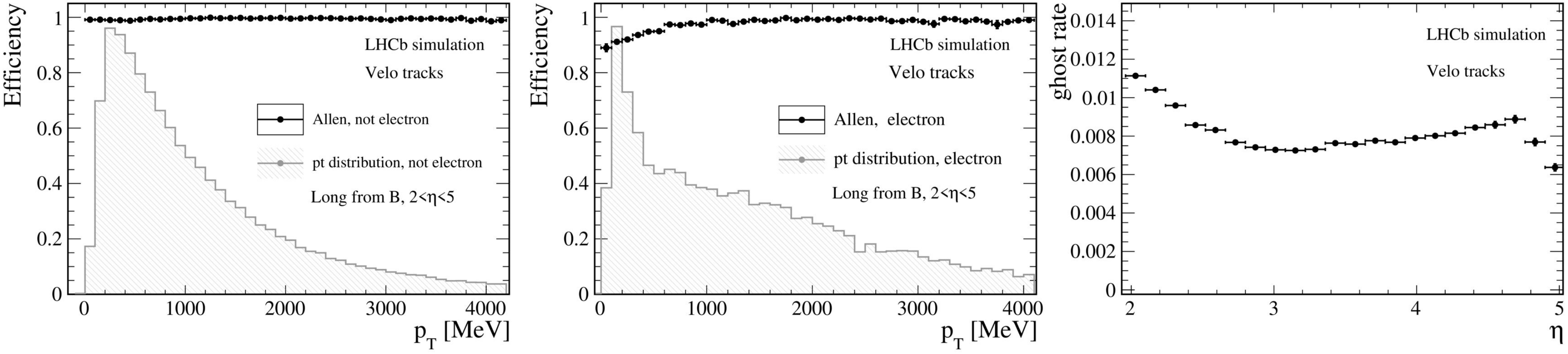


LHCb-FIGURE-2020-014

HLT1 performance: Velo

LHCB-FIGURE-2020-014

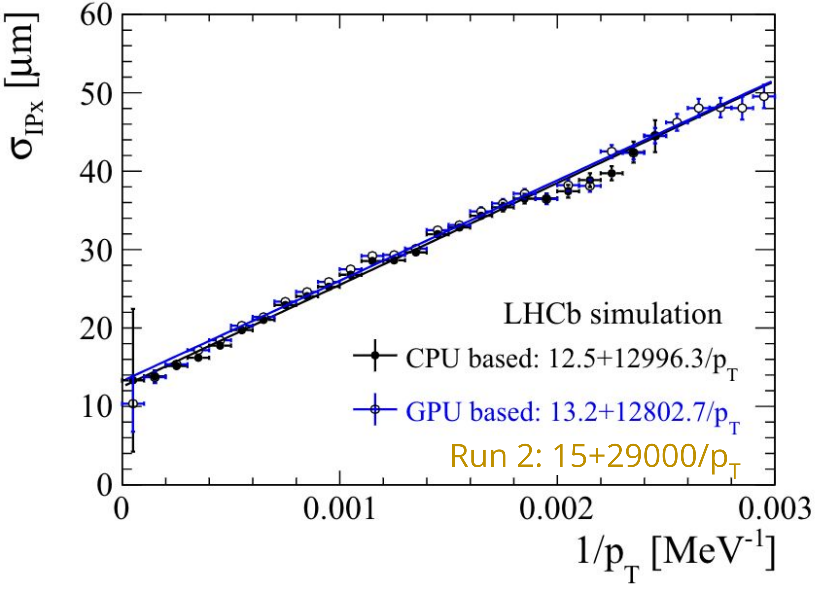
Same performance at x5 luminosity: high efficiency, good δp, low fake rate



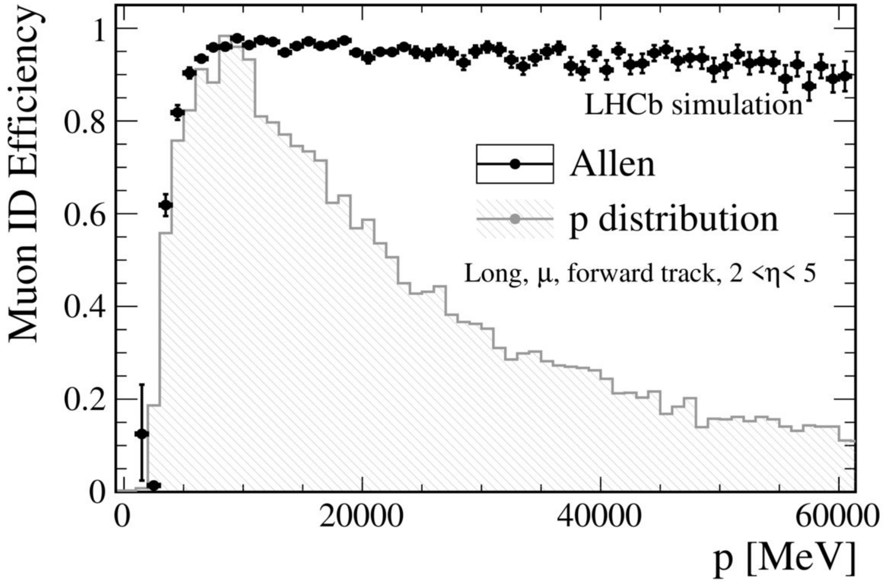
HLT1 performance

LHCB-FIGURE-2020-014

Same performance at x5 luminosity: high efficiency, good δp, low fake rate



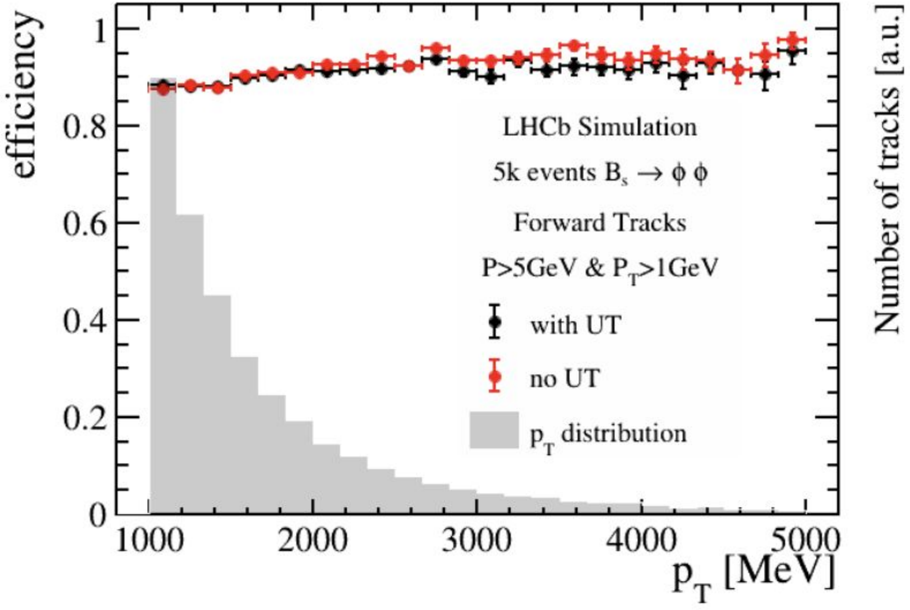
Run 2: $15+29000/p_T$

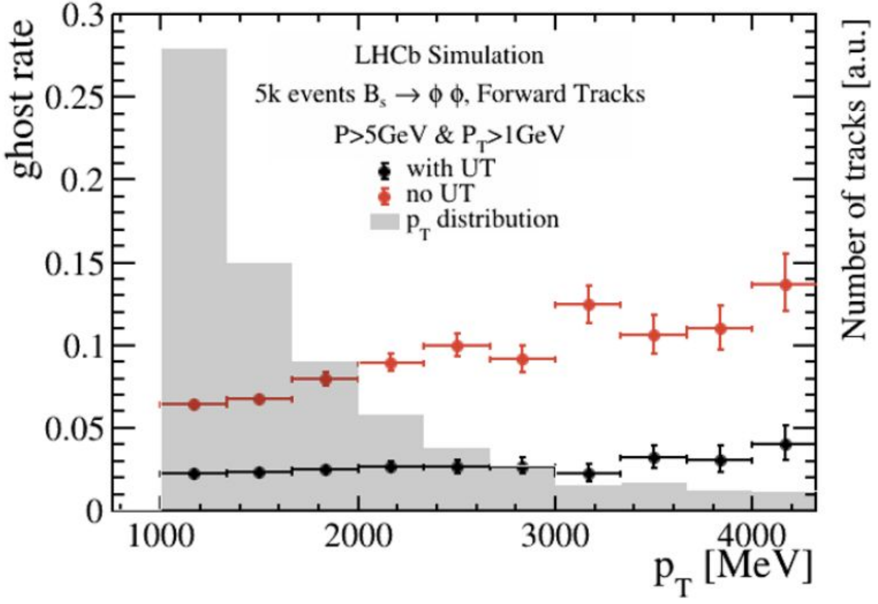


HLT1 without UT

LHCB-FIGURE-2022-007

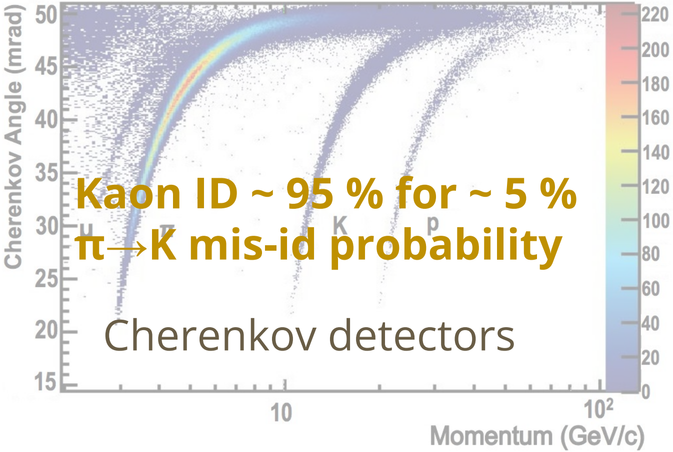
Same signal efficiency but larger fake rate





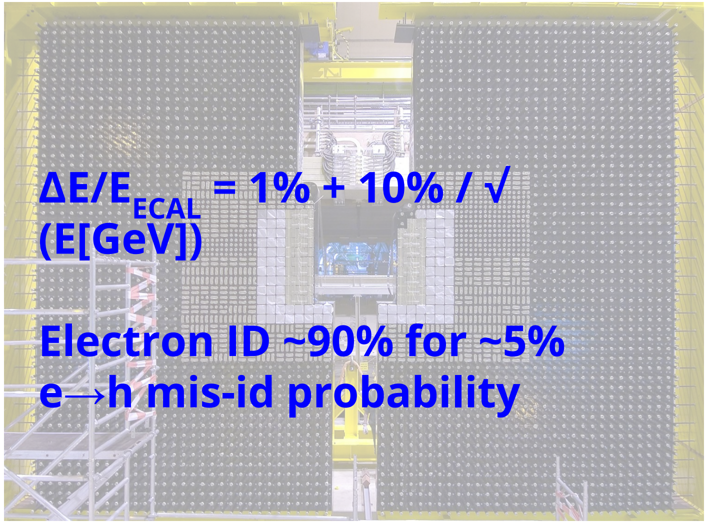
Particle identification system

- Cherenkov detectors: identify $\pi^\pm$, $K^\pm$, p
- Calorimeters: identify γ, π^0, $e^\pm$
- Muon chambers: identify $\mu^\pm$



Kaon ID ~ 95 % for ~ 5 % π→K mis-id probability

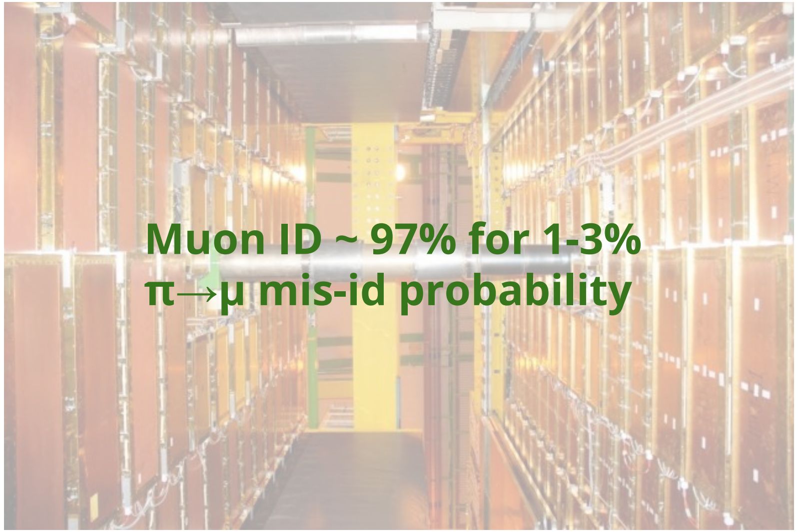
Cherenkov detectors



$\Delta E/E_{ECAL} = 1\% + 10\% / \sqrt{(E[\mathrm{GeV}])}$

Electron ID ~90% for ~5% e→h mis-id probability

Electromagnetic calorimeter



Muon ID ~ 97% for 1-3% π→μ mis-id probability

Muon chambers

The Kπ puzzle in B → Kπ decays

Direct CPV measured in whole family of B → Kπ decays, with amplitudes related by isospin symmetry in SM: $B^0 \to K^+\pi^-$, $B^+ \to K^+\pi^0$, $B^0 \to K^0\pi^0$ and $B^+ \to K^0\pi^+$

However:

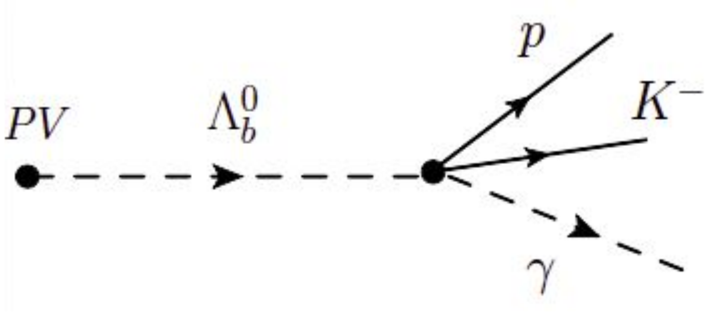
$$\left.\begin{aligned} A_{CP}(B^0 \to K^+\pi^-) &= -0.084 \pm 0.004 \\ A_{CP}(B^+ \to K^+\pi^0) &= -0.044 \pm 0.021 \end{aligned}\right\} \text{not equal at } 5.5\sigma$$

Limited by precision on $B^+ \to K^+\pi^0$ → measure it at LHCb

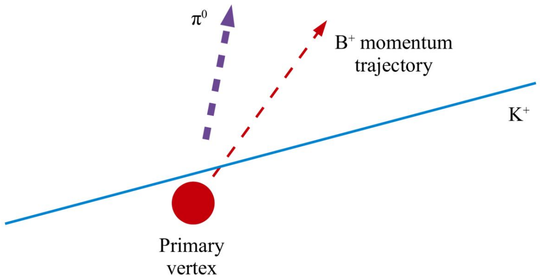
The Kπ puzzle in B ⟶ Kπ decays

Limited by precision on $B^+ \to K^+\pi^0$ → measure it at LHCb

Challenge: B^+ decay vertex cannot be reconstructed in this decay



≠

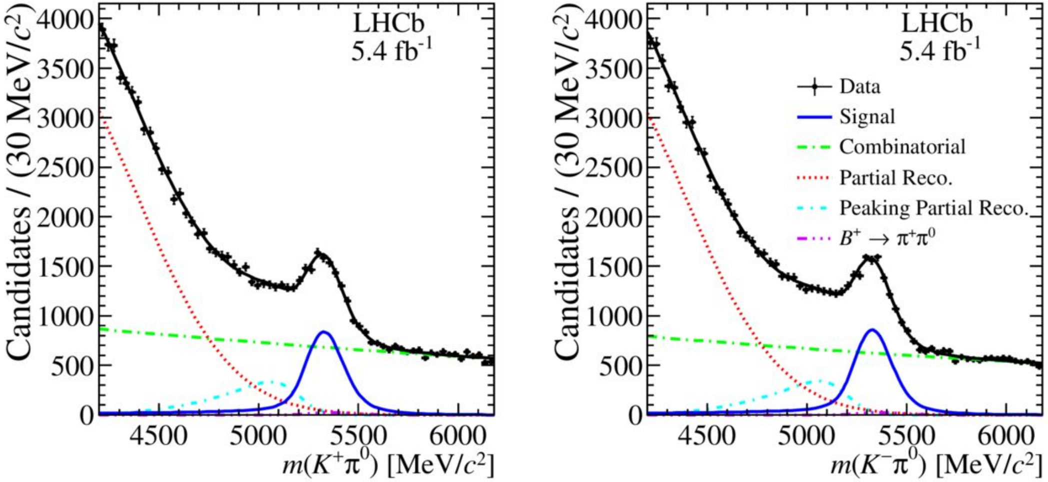


Only 1 charged particle in the decay → cannot find B decay vertex (no direction from π^0)

CPV in $B^+ \rightarrow K^+\pi^0$

arXiv:2012.05319

Use 2016 - 2018 LHCb sample and highly optimised selection (multivariate algorithms) to fight large backgrounds



Using new word average:

ΔCP(Kπ) ≠ 0 at >8σ

$$A_{CP}(B^+ \rightarrow K^+\pi^0) = 0.025 \pm 0.015 \pm 0.006 \pm 0.003,$$

More precise than word average!