LHCb Status and Plans: The View from the US

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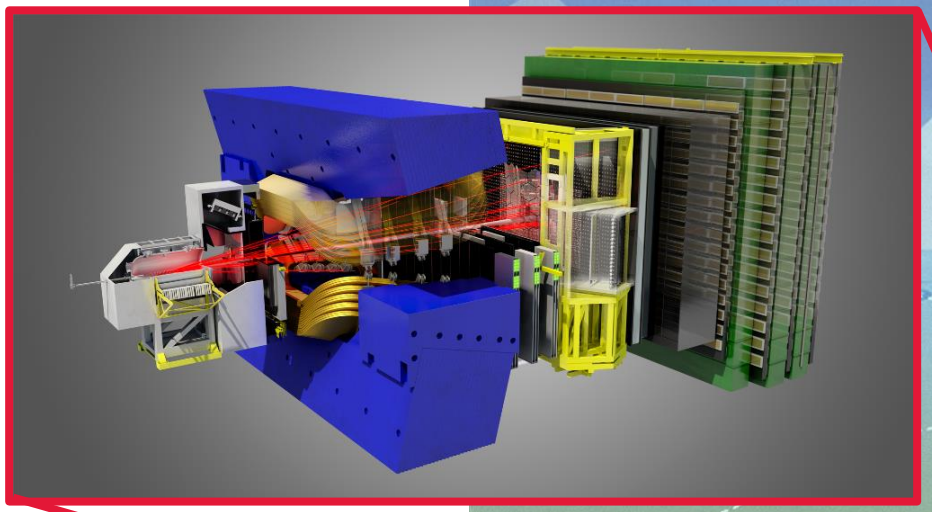
of the University of Cincinnati
for the US-based LHCb community

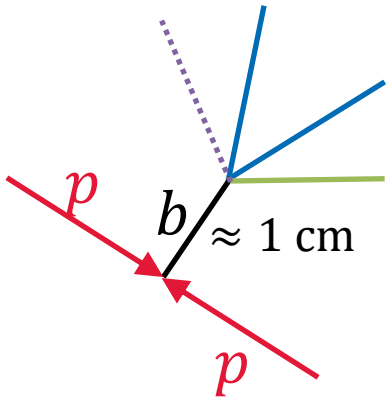
US LUA annual meeting
17 December 2024

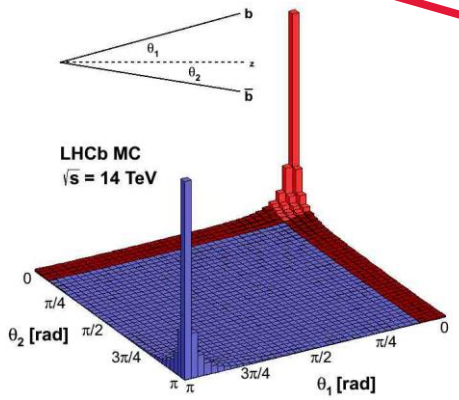
LHCb overview

https://lhcb-public.web.cern.ch/en/LHCb-outreach/multimedia/LHCbDetectorpnglight1.png

LHCb is a general-purpose forward detector, exploiting boost to separate b-decays from background







https://lhcb.web.cern.ch/speakersbureau/html/bb_ProductionAngles.html

AC Team. *The four main LHC experiments*. 1999. CDS.

LHCb sub-detectors (LHC Runs 1 & 2)

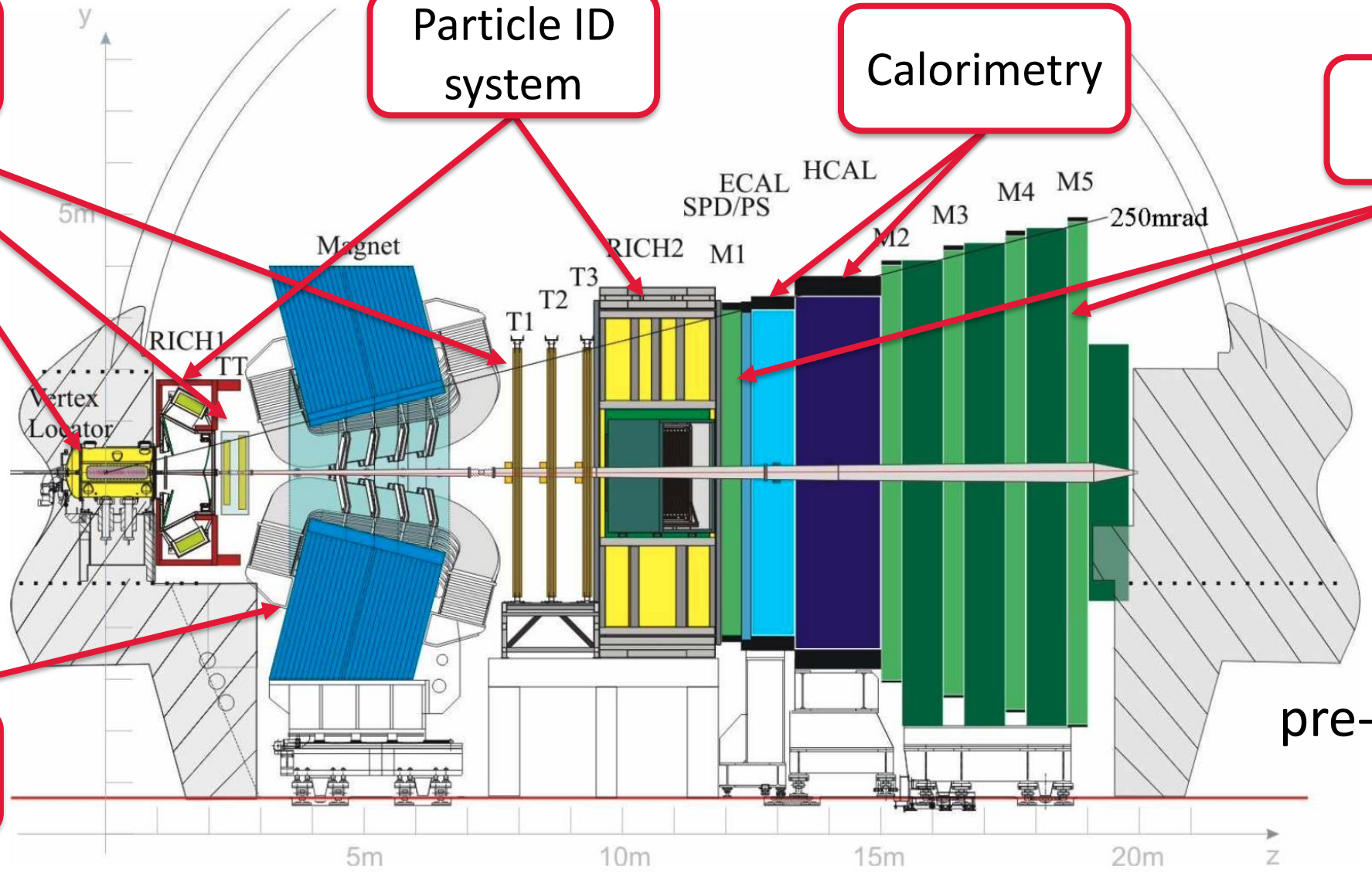
Tracking system

Particle ID system

Calorimetry

Muon ID

Magnet



pre-upgrade!

A. A. Alves, Jr. and others. *The LHCb Detector at the LHC*. JINST, 3:S08005, 2008.

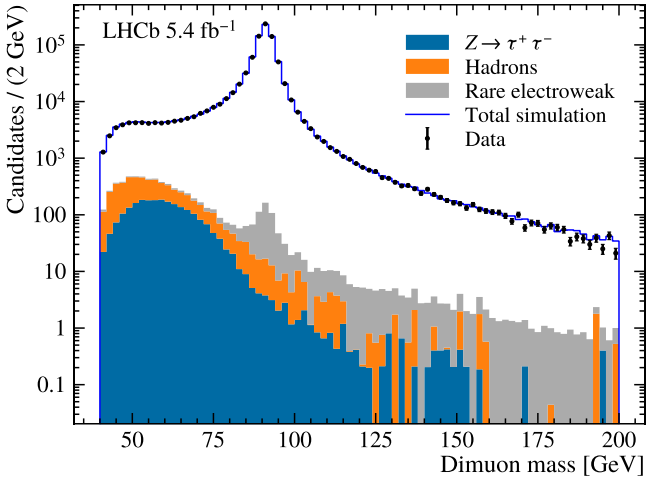
LHCb physics analysis program

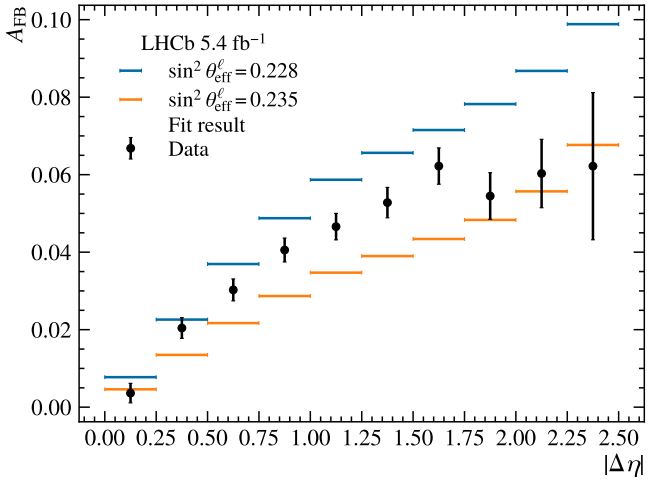
Physics analysis working group	Description
QCD, Electroweak and Exotica	$Z, W, \chi_{c1}(3872)$ …
B hadrons and Quarkonia	$\tau \to J/\psi \to \mu\mu\mu\mu$
Charm physics	
Rare decays	
Charmless b-hadron decays and B decays to Charmonia	$B \to J/\psi X$ …
B decays to Open Charm	$B \to DX$ …
Semileptonic decays	
Ions and Fixed Target	-lead, lead-lead, proton helium, …

Papers with direct US-involvement released in 2024!

…or late 2023!

QCD, Electroweak and Exotica

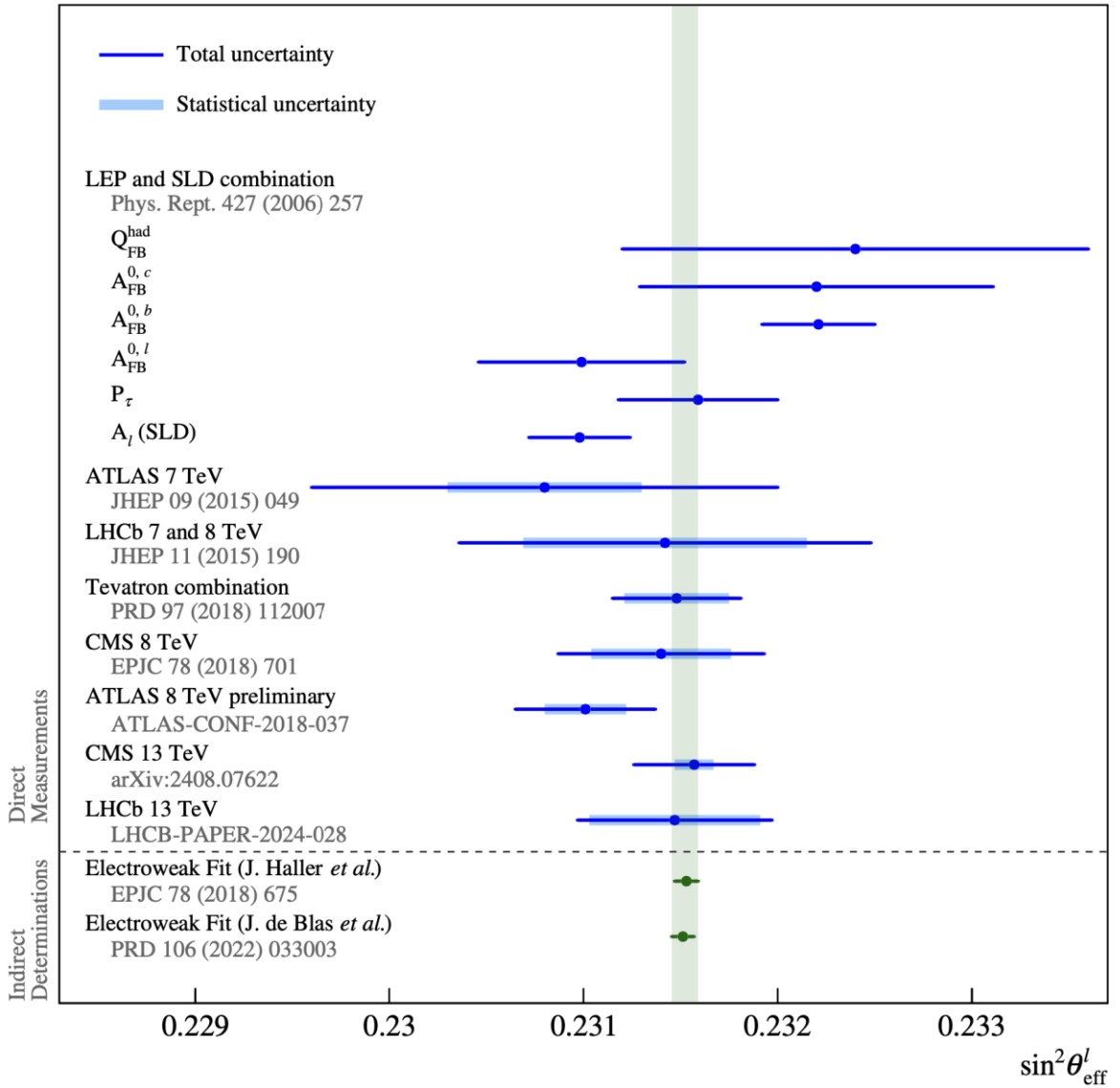




Measured forward-backward asymmetry in $pp \to Z/\gamma^* \to \mu^+\mu^-$, finding $\sin^2\theta^\ell_{\rm eff} = 0.23147 \pm 0.00044 \pm 0.00005 \pm 0.00023$, consistent with predictions and previous measurements

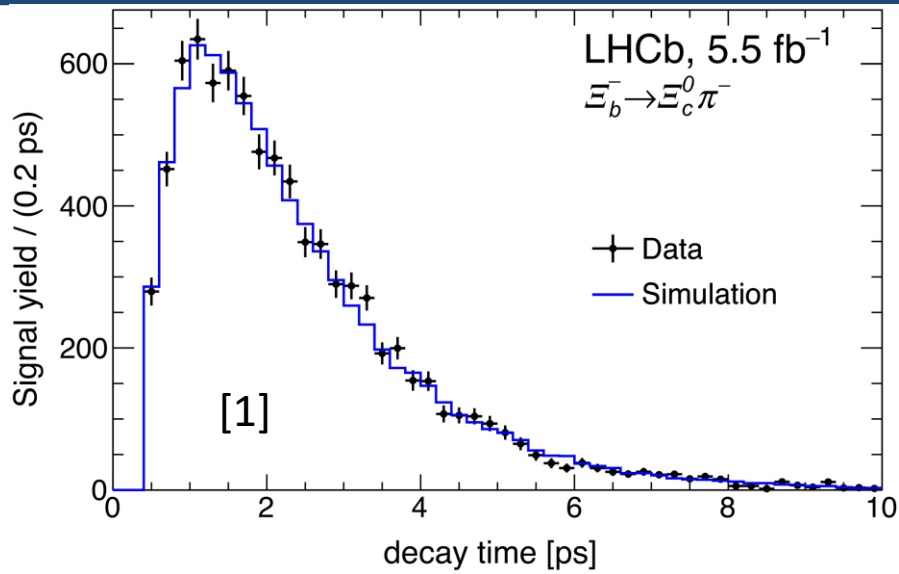
Two papers with direct US-involvement in 2024:

- **R. Aaij and others. *Measurement of the effective leptonic weak mixing angle*. JHEP, 12:026, 2024. arXiv:2410.02502.**
- R. Aaij and others. *Measurements of $\psi(2S)$ and $\chi_{c1}(3872)$ production within fully reconstructed jets*. 2024. arXiv:2410.18018.



B hadrons and Quarkonia

- Measured ratio of Ξ_b^- to Λ_b^0 lifetimes ($r_\tau^{\mathrm{HQE}} = 1.078 \pm 0.021$ predicted) [1]:
$$r_\tau^{\mathrm{Run\ 2}} = 1.076 \pm 0.013 \pm 0.006$$
- …and extracted Ξ_b^- lifetime with $\approx 2\times$ better precision than world-average [1]:
$$\tau_{\Xi_b^-}^{\mathrm{Run\ 1,2}} = 1.578 \pm 0.018 \pm 0.010 \pm 0.011\ \mathrm{ps}$$
- Also observed first b-baryon decay where s-quark decays first and measured [2]:
$$\mathcal{B}\left(\Xi_b^- \to \Lambda_b^0 \pi^-\right) = (0.89 \pm 0.10 \pm 0.07 \pm 0.29)\%$$

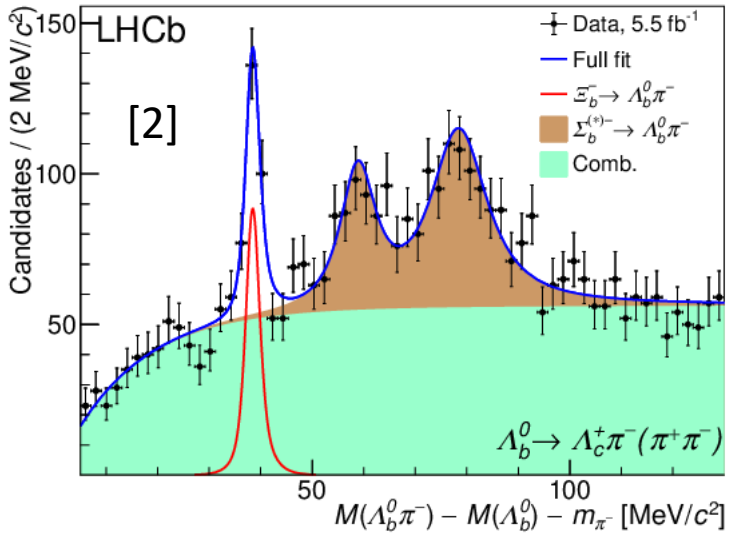


One paper with direct US-involvement in 2024:

1. R. Aaij and others. *Precision measurement of the Ξ_b^- baryon lifetime*. Phys. Rev. D, 110(7):072002, 2024. arXiv:2406.12111.

…and a selected one from late 2023:

2. R. Aaij and others. *Observation and branching fraction measurement of the decay $\Xi_b^- \to \Lambda_b^0 \pi^-$*. Phys. Rev. D, 108(7):072002, 2023. arXiv:2307.09427

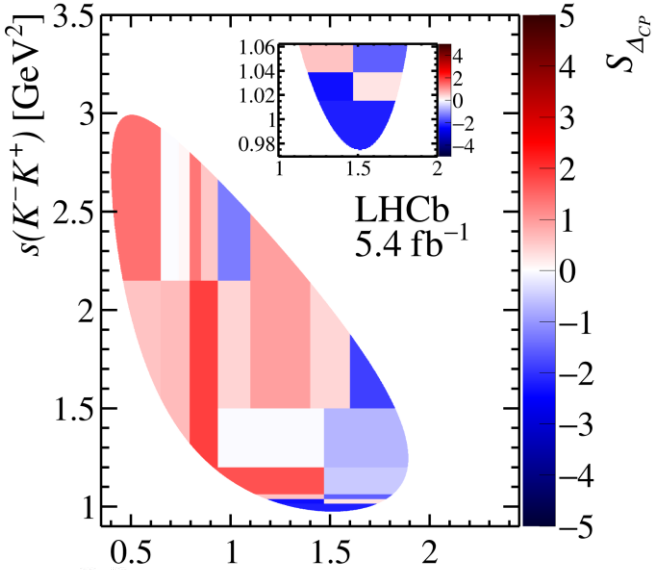


Charm physics

- Search for CP violation in $D^+ \to K^-K^+\pi^+$ using Run 2 data using a model-independent comparison between D^+ and D^- phase-space distributions
- Most precise search for localized CP violation ever; no evidence
- Measured

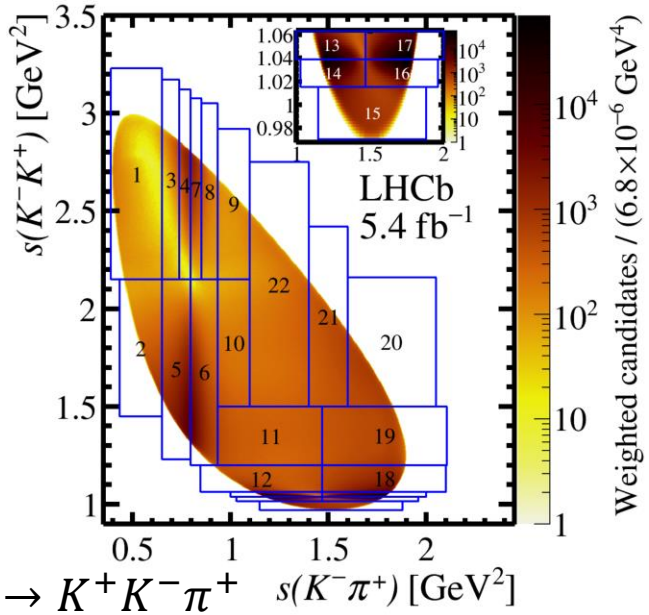
$A_{CP|S}^{\phi\pi^+} = (0.95 \pm 0.43 \pm 0.26) \times 10^{-3}$ (most precise)

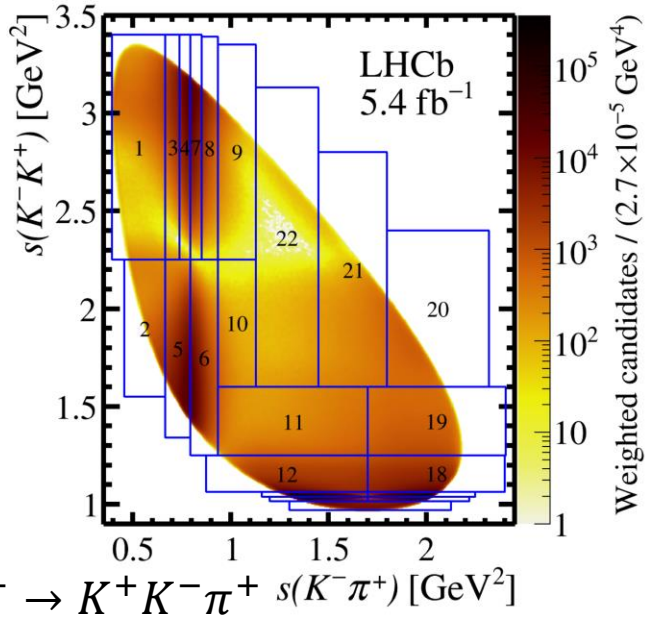
$A_{CP|S}^{K^{*0}K^+} = (-0.26 \pm 0.56 \pm 0.18) \times 10^{-3}$ (first time)



One paper with direct US-involvement in 2024:

- R. Aaij and others. *Measurement of CP violation observables in $D^+ \to K^-K^+\pi^+$ decays*. 2024. arXiv:2409.01414.



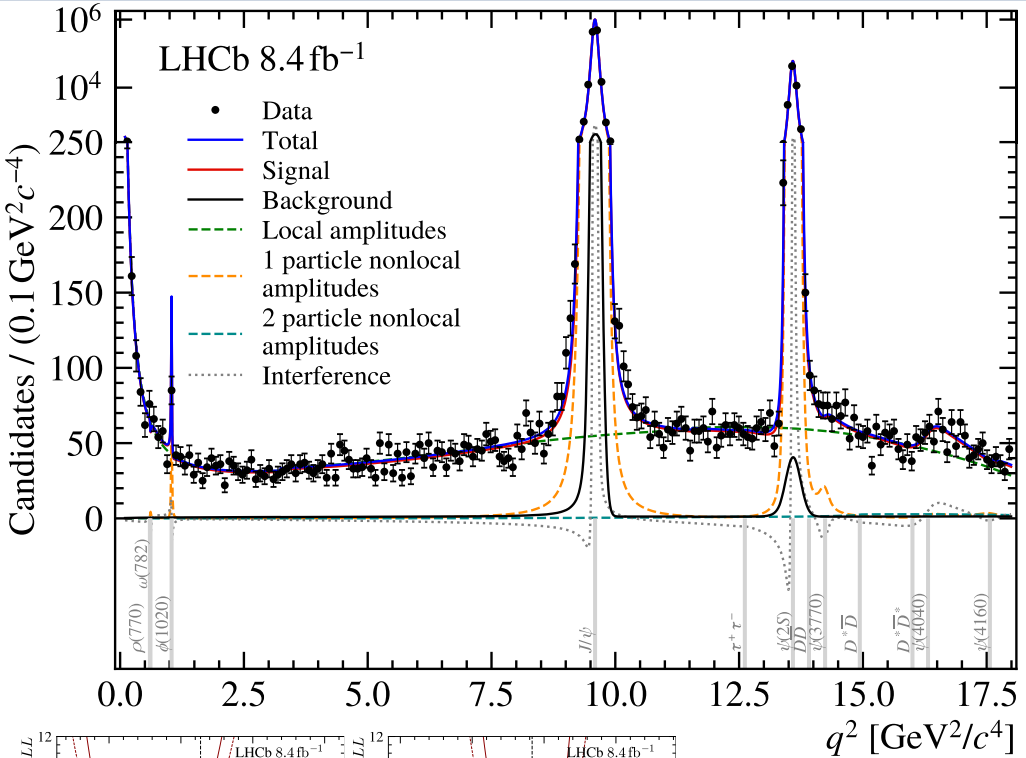


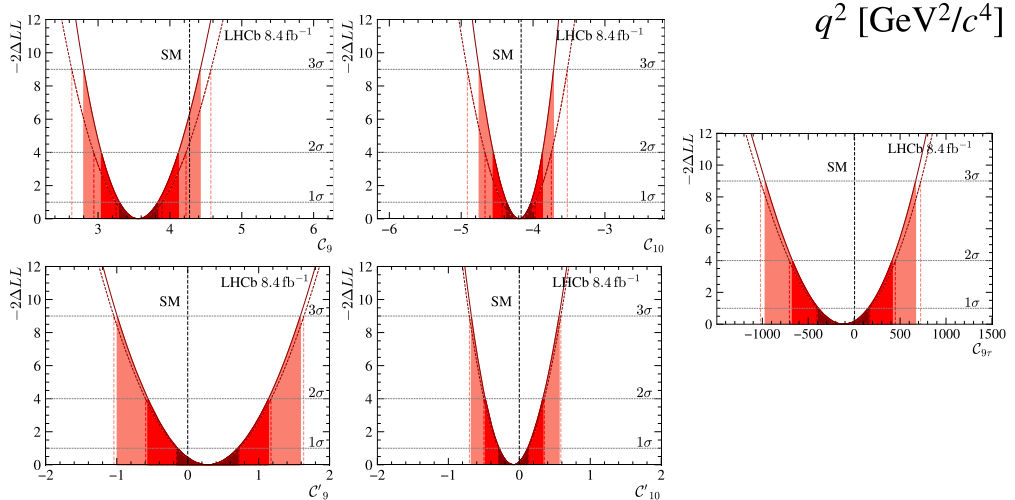
Rare decays

- First time $K^{*0}\mu^+\mu^-$ has been measured across full q^2 spectrum and most precise measurement of $K^{*0}\tau^+\tau^-$
- Measures long-distance charmonium contributions to $K^{*0}\mu^+\mu^-$
- Confirms that flavor anomalies cannot be trivially explained by long-distance contributions

Eight papers with with direct US-involvement in 2024:

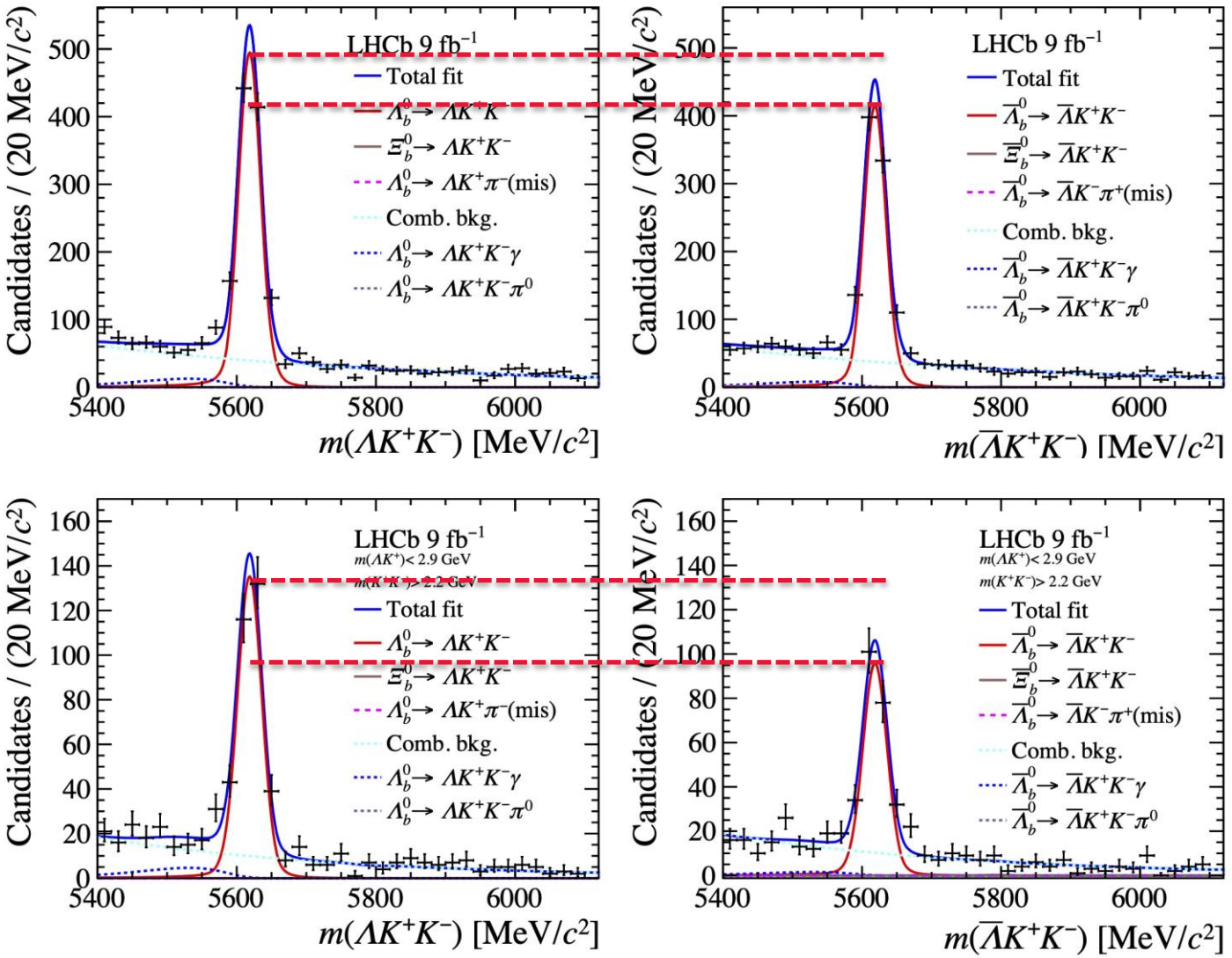
- R. Aaij and others. *Determination of short- and long-distance contributions in* $B^0 \to K^{*0}\,\mu^+\,\mu^-$ *decays*. Phys. Rev. D, 109(5):052009, 2024. arXiv:2312.09102.
- R. Aaij and others. Amplitude Analysis of the $B^0 \to K^{*0}\,\mu^+\,\mu^-$ Decay. Phys. Rev. Lett., 132(13):131801, 2024. arXiv:2312.09115.
- **R. Aaij and others. *Comprehensive analysis of local and nonlocal amplitudes in the* $B^0 \to K^{*0}\mu^+\mu^-$ *decay*. JHEP, 09:026, 2024. arXiv:2405.17347.**
- R. Aaij and others. *Amplitude analysis of the* $\Lambda_b^0 \to pK^-\gamma$ *decay*. JHEP, 06:098, 2024. arXiv:2403.03710.
- R. Aaij and others. *Test of lepton flavour universality with* $B_s^0 \to \phi\,\ell^+\ell^-$ *decays*. 2024. arXiv:2410.13748.
- R. Aaij and others. *Search for the lepton-flavor violating decay* $B_s^0 \to \phi\,\mu^\pm\tau^\mp$. Phys. Rev. D, 110(7):072014, 2024. arXiv:2405.13103.
- R. Aaij and others. *Analysis of* $\Lambda_b^0 \to pK^-\mu^+\mu^-$ *decays*. 2024. arXiv:2409.12629.
- R. Aaij and others. Test of lepton flavour universality with $B^+ \to K^+\pi^+\pi^-\ell^+\ell^-$ decays. 2024. arXiv:2412.11645.





Charmless b-hadron decays

- Measured branching fractions for $\Lambda_b^0/\Xi_b^0 \to \Lambda h^+ h'^-$ $(h^{(\prime)} = \pi, K)$
- Evidence for CP violation in $\Lambda_b^0 \to \Lambda K^+ K^-$ (only evidence in b-baryon decay!)
- First observation of $\Lambda_b^0 \to \Lambda \pi^+ \pi^-$ and $\Xi_b^0 \to \Lambda K^- \pi^+$

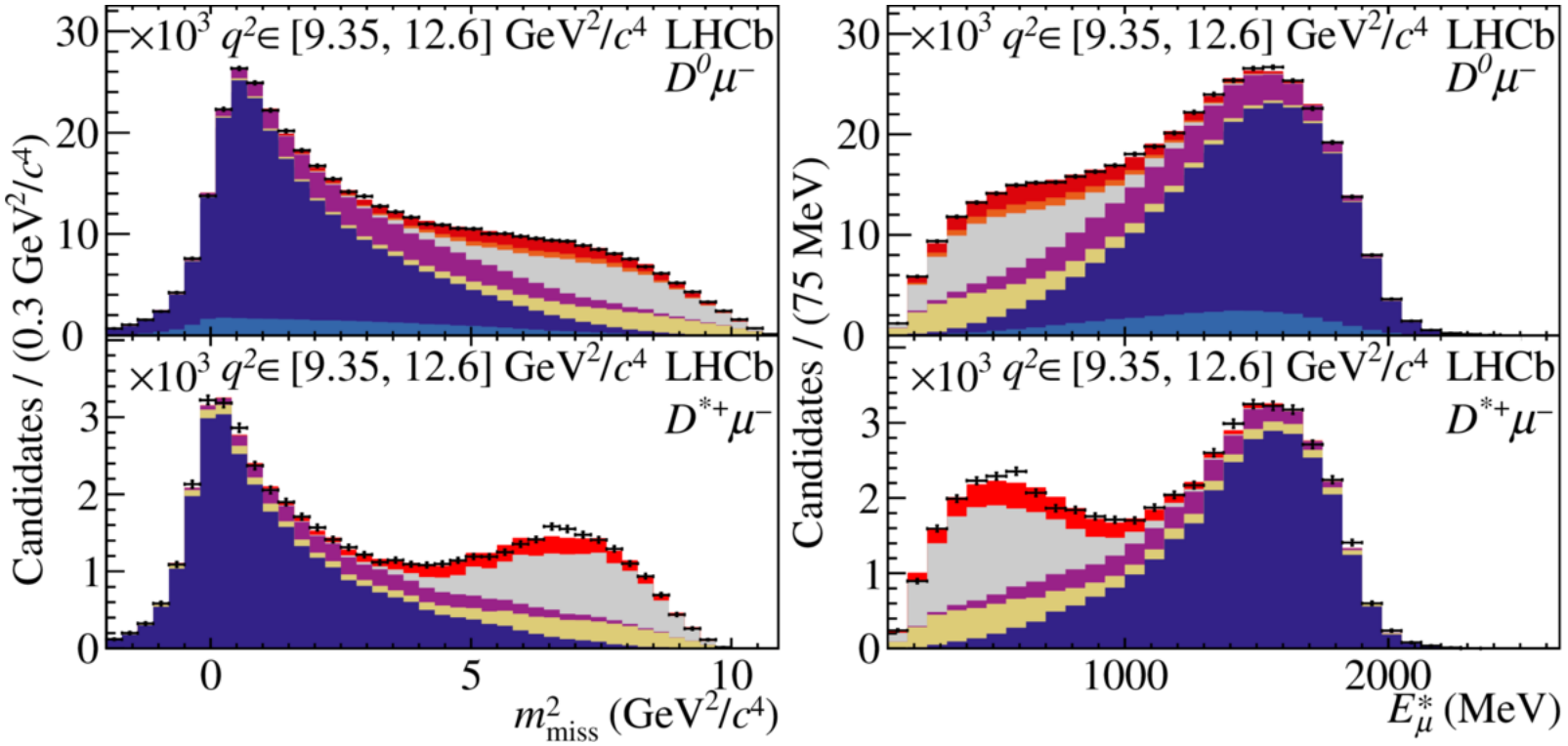


One paper with direct US-involvement in 2024:

- R. Aaij and others. *Study of Λ_b^0 and Ξ_b^0 decays to $\Lambda\, h^+ h'^-$ and evidence for CP violation in $\Lambda_b^0 \to \Lambda\, K^+ K^-$ decays*. 2024. arXiv:2411.15441.

Semileptonic decays

- Uses samples of $\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell$ to measure
  $R(D^*)$
  $= 0.281 \pm 0.018 \pm 0.024$
  $R(D^0)$
  $= 0.441 \pm 0.060 \pm 0.066$
- Consistent with Lepton Flavor Universality, reducing Standard Model tension of HFLAV average by 0.1σ



A selected paper with direct US-involvement in late 2023:

- R. Aaij and others. *Measurement of the ratios of branching fractions $R(D^*)$ and $R(D^0)$*. Phys. Rev. Lett., 131:111802, 2023. arXiv:2302.02886. Also see last year's report.

$$R(D^*) \equiv \frac{\mathcal{B}(\bar{B} \to D^*\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^*\mu^-\bar{\nu}_\mu)}$$

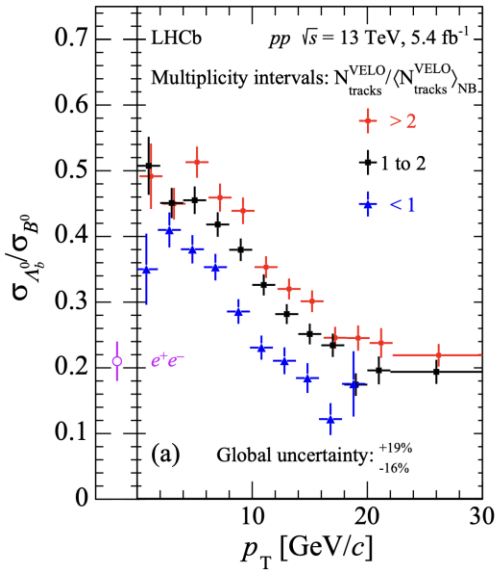
$$R(D^0) \equiv \frac{\mathcal{B}(\bar{B} \to D^0\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^0\mu^-\bar{\nu}_\mu)}$$

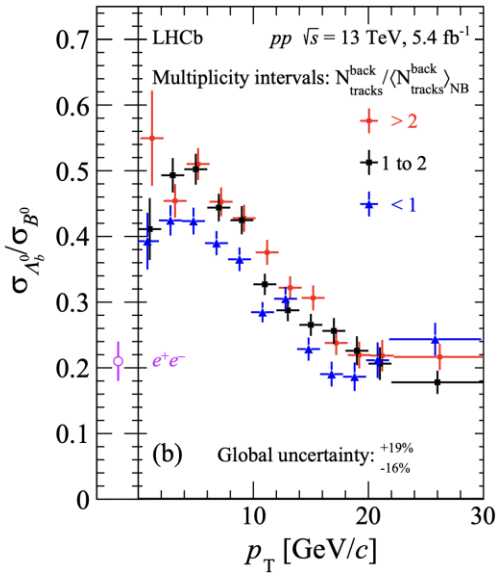
Ions and Fixed Target

Six papers with direct US-involvement in 2024:

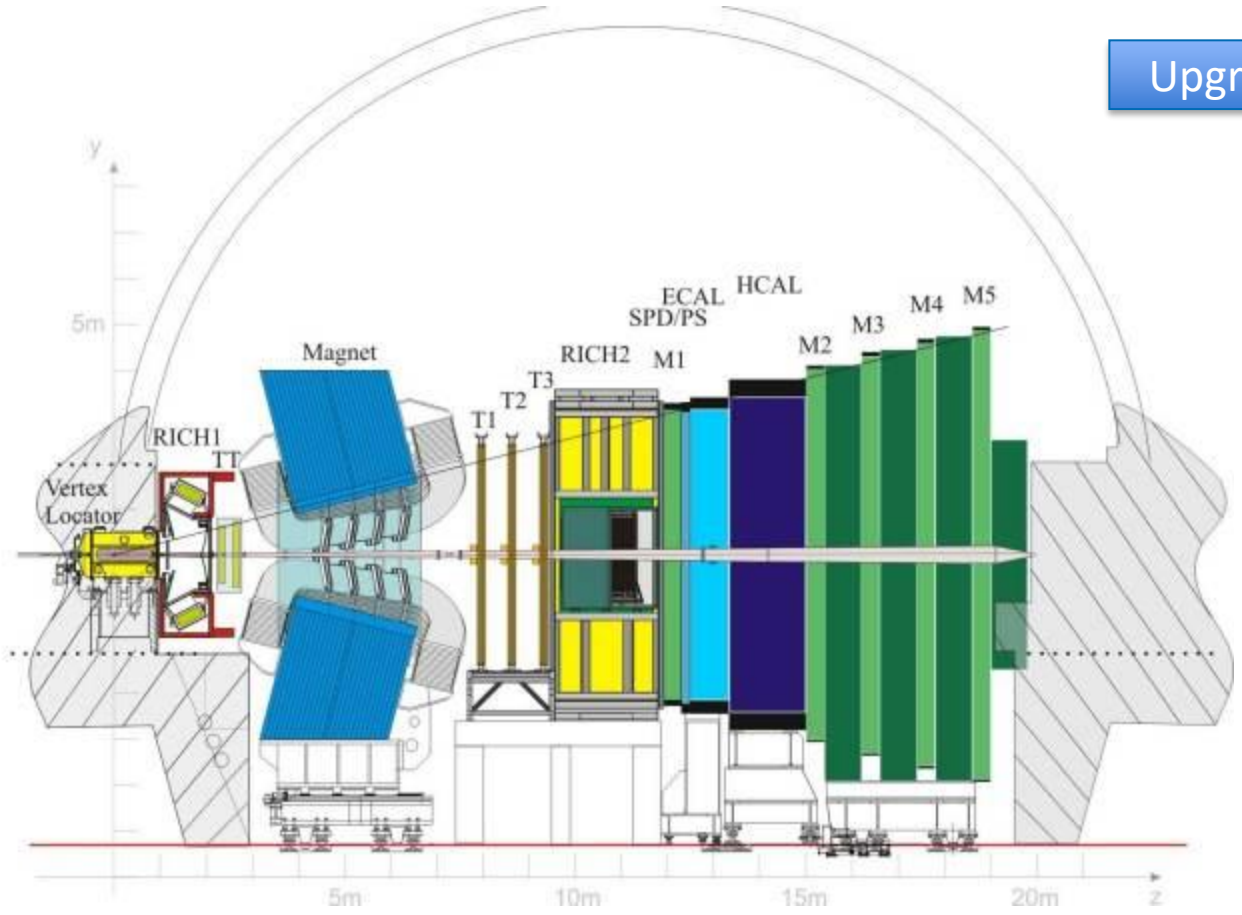
- **R. Aaij and others. *Enhanced Production of Λ_b^0 Baryons in High-Multiplicity pp collisions at $\sqrt{s} = 13$ TeV.* Phys. Rev. Lett., 132(8):081901, 2024. arXiv:2310.12278.**
- R. Aaij and others. *Modification of $\chi_{c1}(3872)$ and $\psi(2S)$ Production in pPb Collisions at $\sqrt{s_{NN}} = 8.16$ TeV.* Phys. Rev. Lett., 132(24):242301, 2024. arXiv:2402.14975
- R. Aaij and others. *Fraction of χ_c Decays in Prompt J/ψ Production Measured in pPb Collisions at $\sqrt{s_{NN}} = 8.16$ TeV.* Phys. Rev. Lett., 132(10):102302, 2024. arXiv: 2311.01562.
- R. Aaij and others. *Production of η and η' mesons in pp and pPb collisions*. Phys. Rev. C, 109(2):024907, 2024. arXiv:2310.17326.
- R. Aaij and others. *Measurement of forward charged hadron flow harmonics in peripheral $PbPb$ collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the LHCb detector*. Phys. Rev. C, 109(5):054908, 2024. arXiv:2311.09985.
- R. Aaij and others. *Measurement of the $\psi(2S)$ to J/ψ cross-section ratio as a function of centrality in $PbPb$ collisions at $\sqrt{s_{NN}} = 5.02$ TeV.* 2024. arXiv:2411.05669.

- Measured production rate of Λ_b^0 to B^0 in pp using Run 2 data
- Ratio depends on p_T and charge multiplicity, implying evolution of heavy hadrons is dependent on the density of the produced hadronic environment

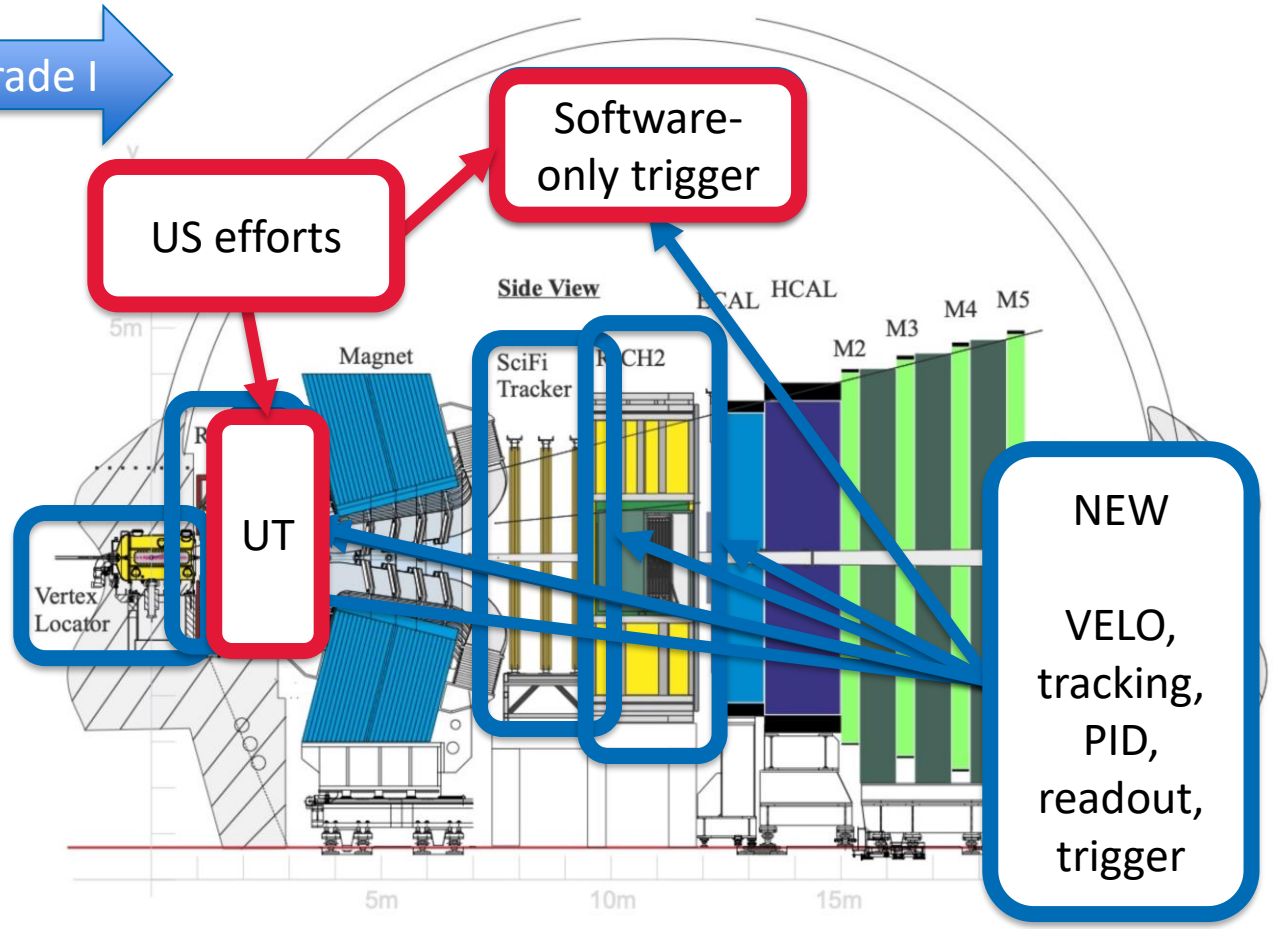




LHCb upgrade I



Upgrade I



LHCb (2011-2018)

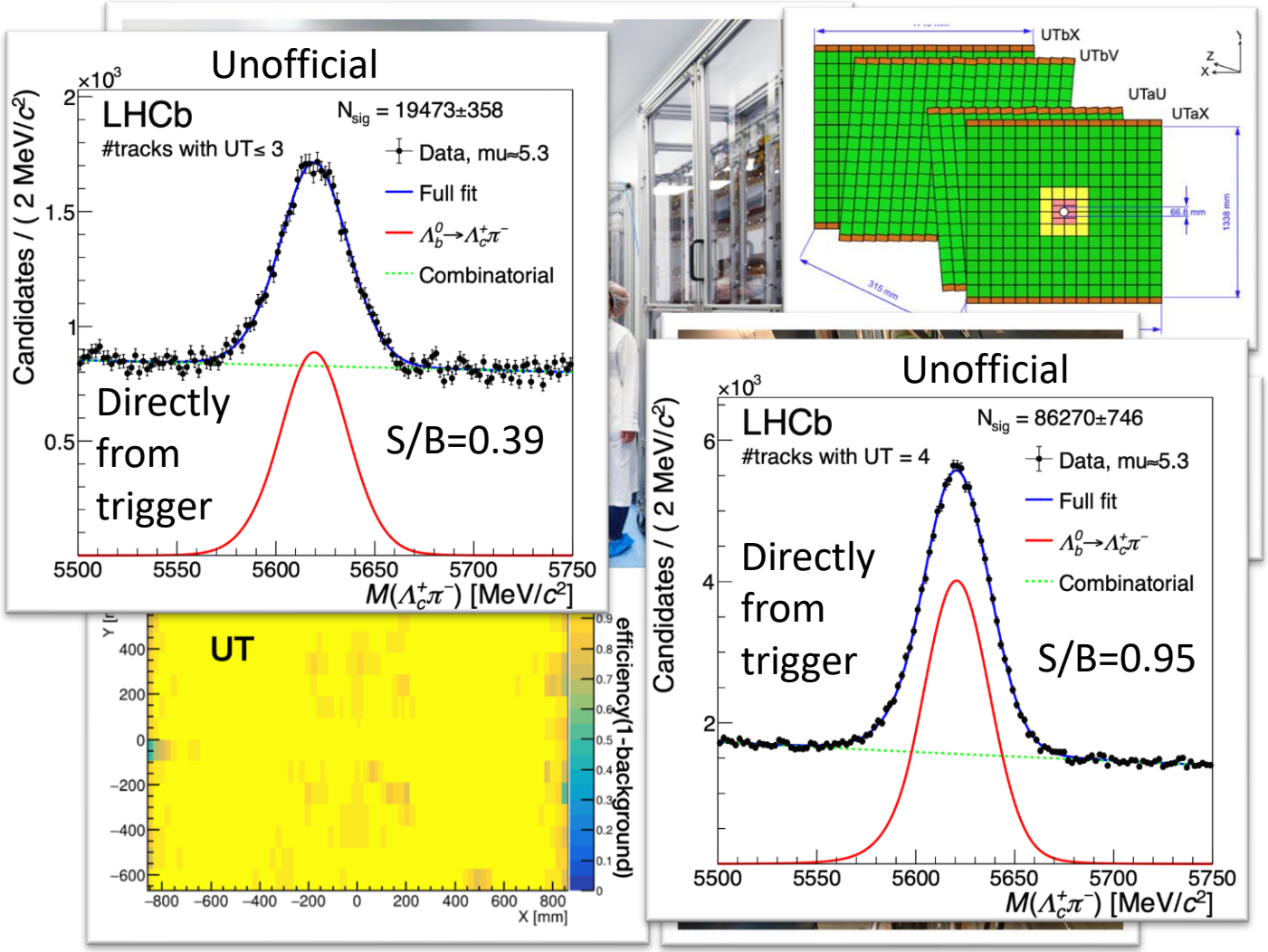
- R. Lindner. *LHCb layout_2. LHCb schema_2*. LHCb Collection., 2008. CDS.
- R. Aaij and others. *The LHCb Upgrade I*. JINST, 19(05):P05065, 2024.

LHCb (2022-2033)

- I. Bediaga and others. *Framework TDR for the LHCb Upgrade: Technical Design Report*. 2012.
- *LHCb Tracker Upgrade Technical Design Report*. 2014.
- *LHCb Trigger and Online Upgrade Technical Design Report*. 2014.

Upstream Tracker (UT)

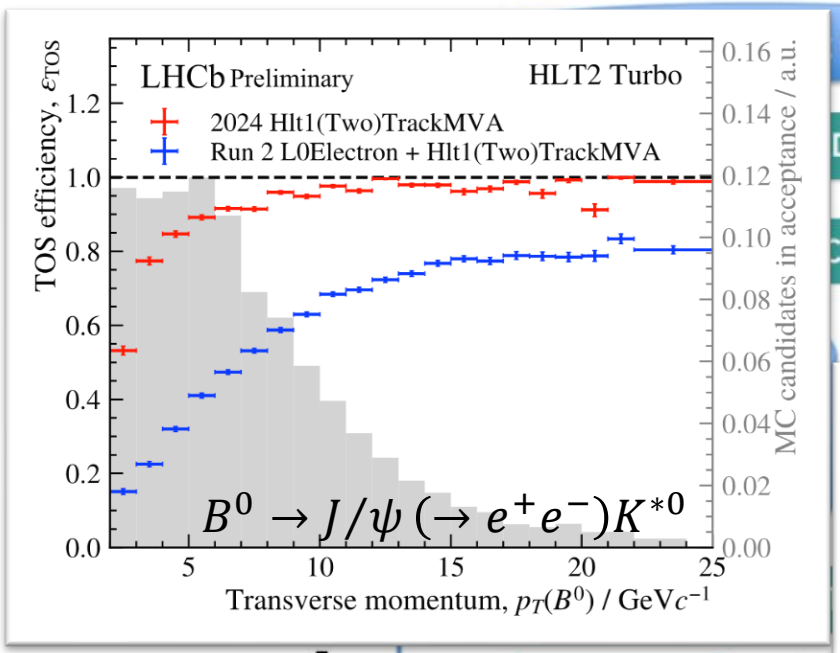
- Upgrade of the old Tracker Turicensis (TT)
- Needed to withstand higher radiation environment, handle higher occupancy, and provide 40 MHz read-out
- Improves momentum resolution and ghost suppression, reducing trigger bandwidth
- Enables reconstruction of downstream decays
- Installation completed in 2023

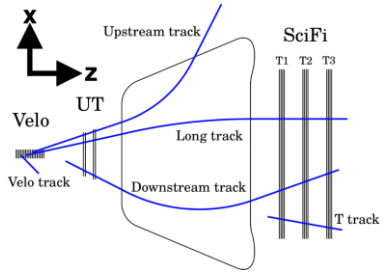


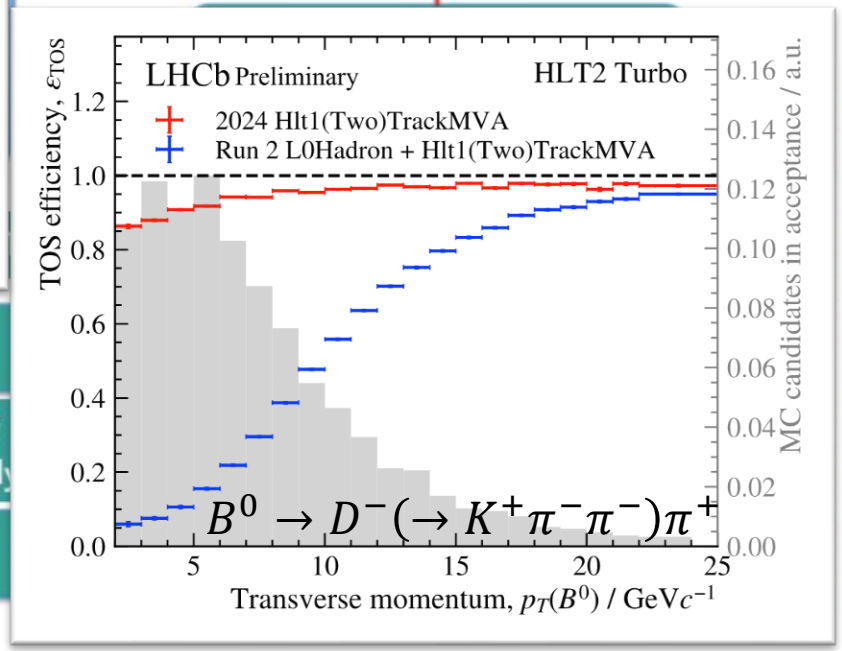
- *LHCb Tracker Upgrade Technical Design Report*. 2014
- M. Brice. *LHCb Upstream Tracker (UT) in clean room*. 2022. CDS.
- *Upstream Tracker closing completes installation of the LHCb Upgrade 1 detector*. link.
- T. Mombächer. *Status of the LHCb Experiment*. 2024. link.

Software-only trigger (Allen)

- LHCb moved to software-only trigger in Run 3
- Allen is the 1st-level trigger, implemented on GPUs, to perform partial track-reconstruction and reduce data-rate by ≈ 30 ×
- Improves efficiencies compared to hardware trigger across particle species

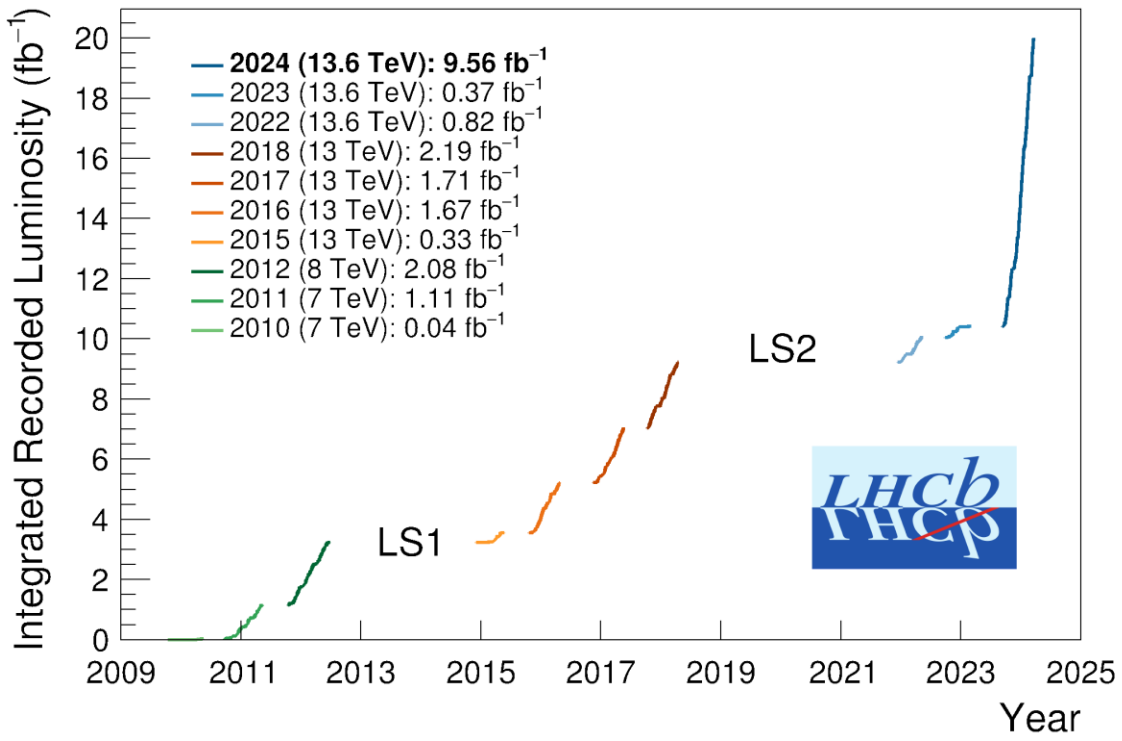


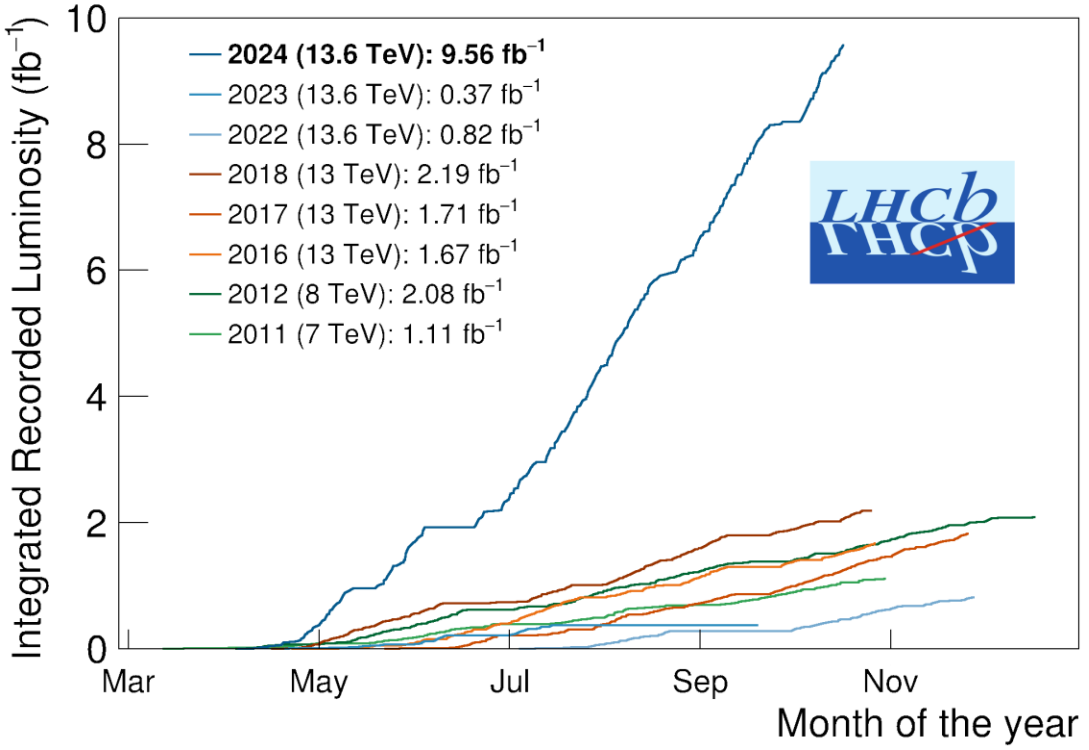




- I. Bediaga and others. *Framework TDR for the LHCb Upgrade: Technical Design Report*. 2012.
- *LHCb Trigger and Online Upgrade Technical Design Report*. 2014.
- *LHCb Upgrade GPU High Level Trigger Technical Design Report*. 2020. DOI.
- *HLT1 trigger efficiencies in 2024 data*. 2024. CDS.
- *HLT1 trigger efficiencies in 2024 data.* 2024. CDS.

LHCb data-taking post-upgrade I



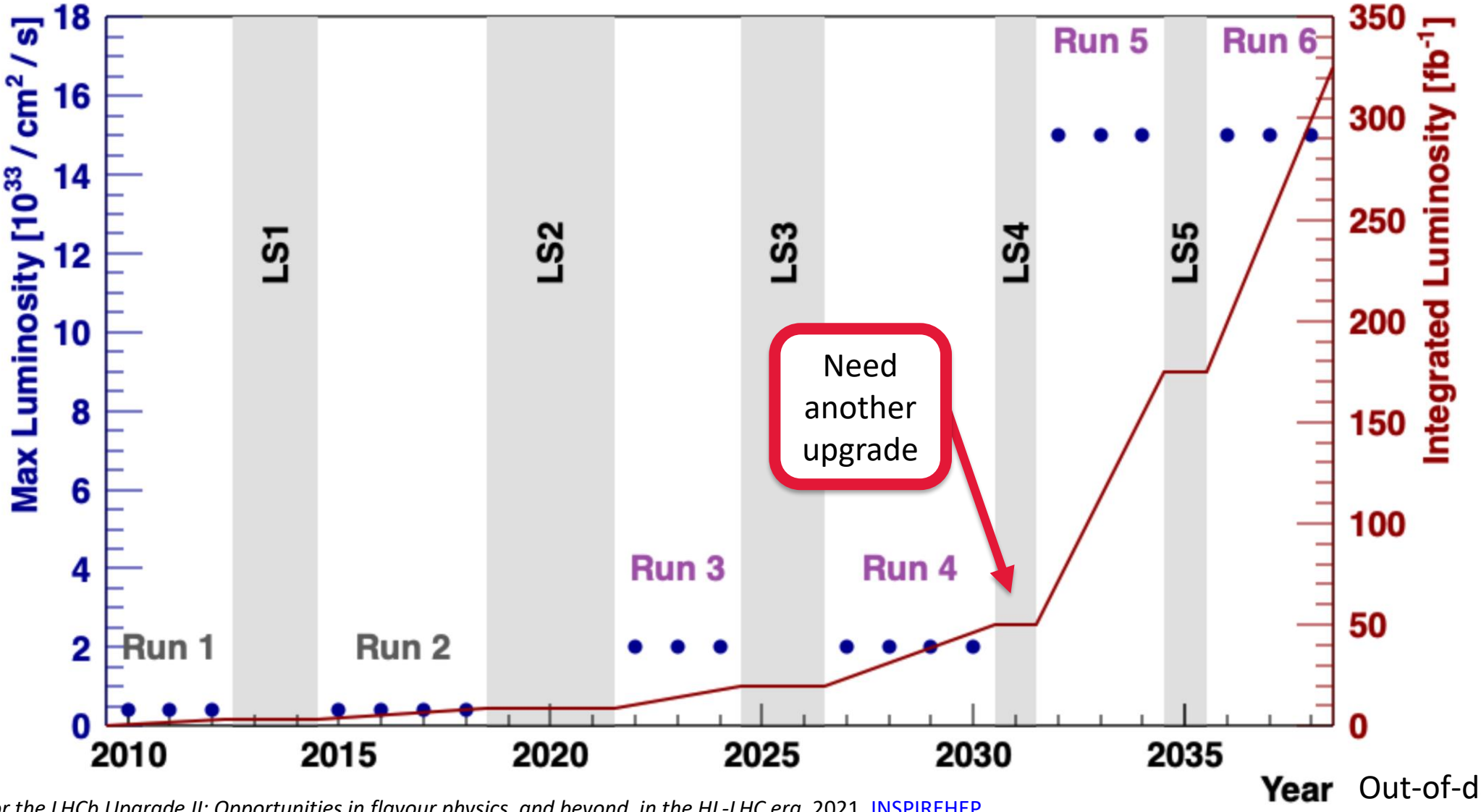


- Installation completed in 2023
- Commissioning in 2023 continued into 2024
- Problem with RF foil in 2023, resolved in 2024
- All detectors in global since late June 2024

https://lbgroups.cern.ch/online/OperationsPlots/index.htm

- Run 3 pp sample ($9.6\ \mathrm{fb}^{-1}$ from just 2024) already larger than Runs 1 & 2 combined ($8.7\ \mathrm{fb}^{-1}$)
- Similarly for Run 3 PbPb and fixed-target samples, plus new gases (H, D, …)
- Performance papers, early results, etc., expected in 2025

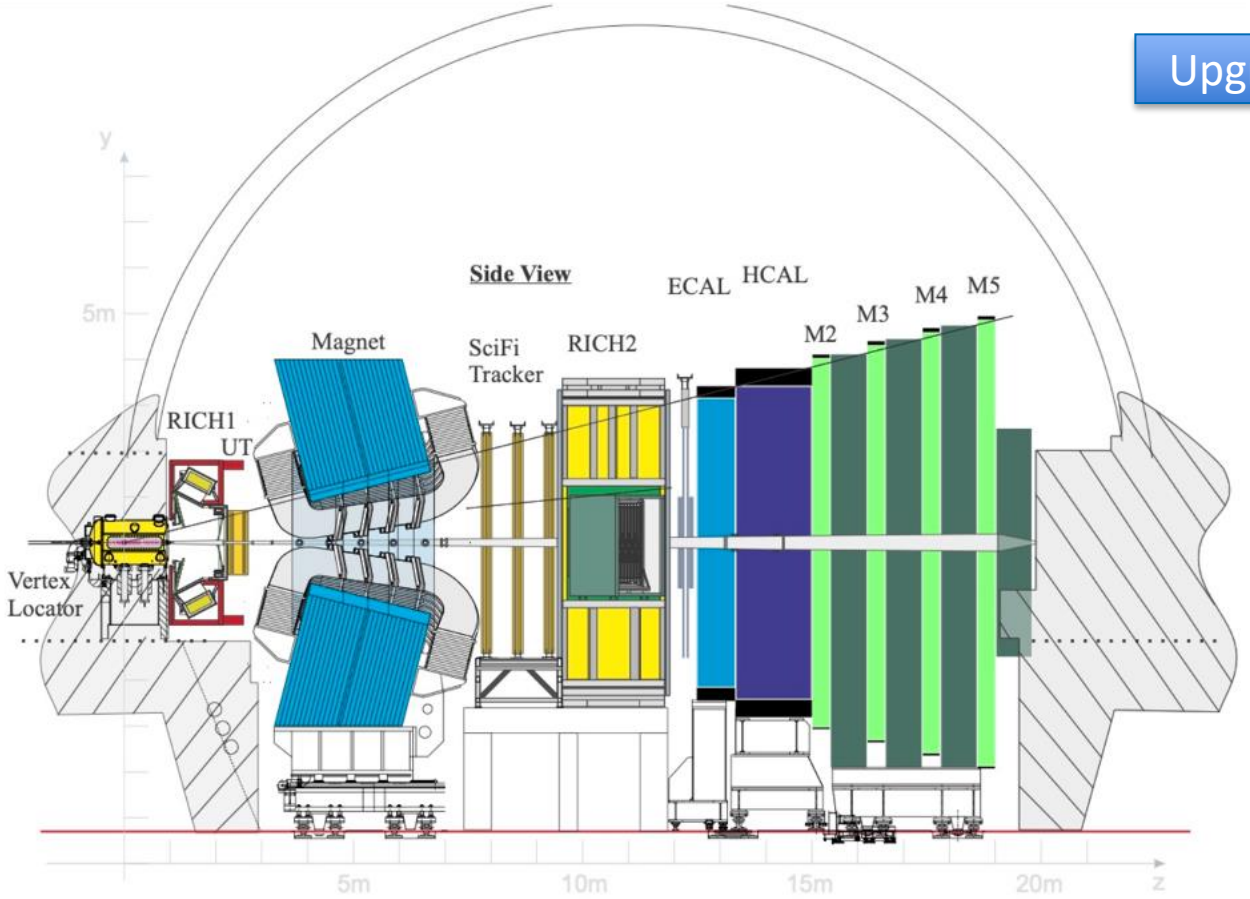
LHC luminosity schedule



Framework TDR for the LHCb Upgrade II: Opportunities in flavour physics, and beyond, in the HL-LHC era. 2021. INSPIREHEP

Out-of-date timeline; see backup

LHCb upgrade II

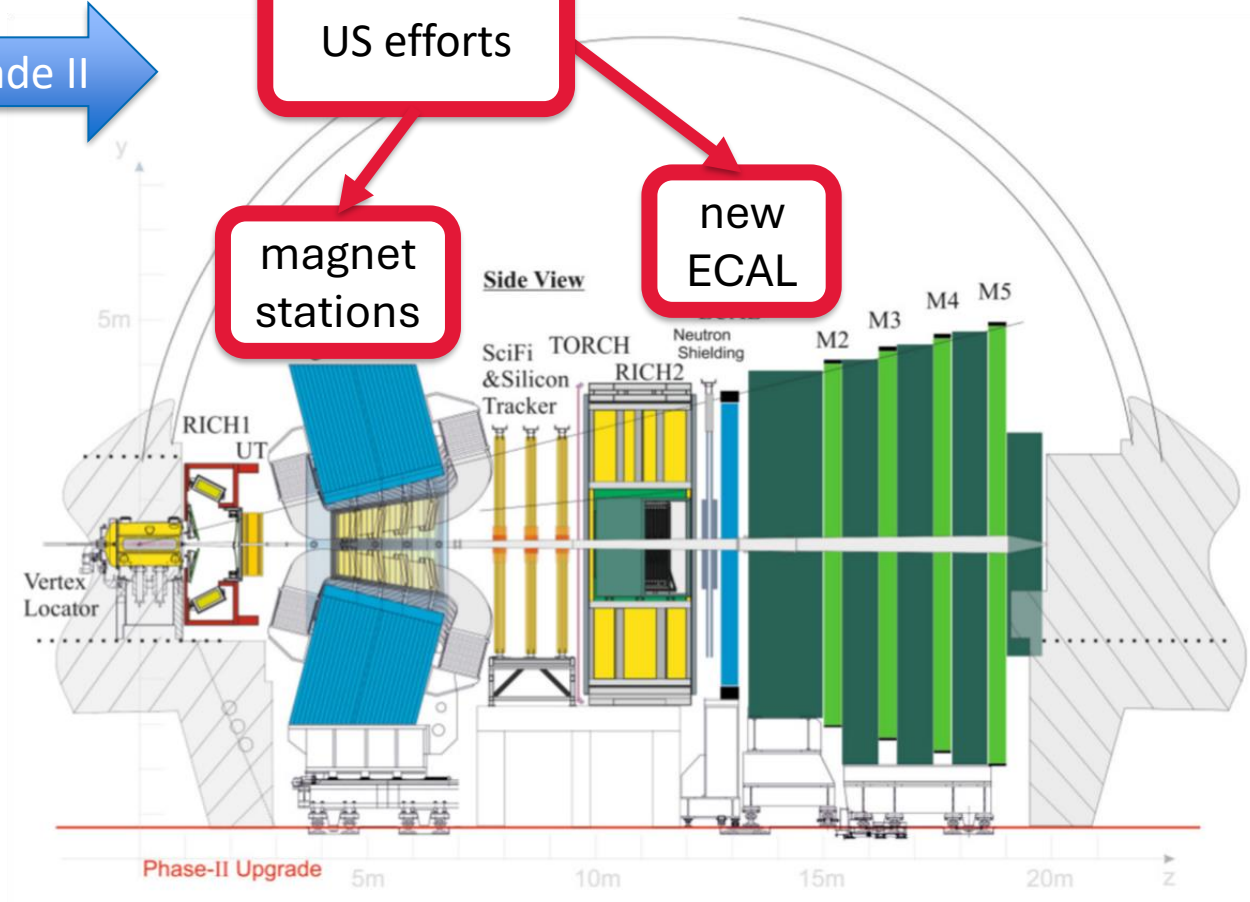


Upgrade II

US efforts

magnet stations

new ECAL



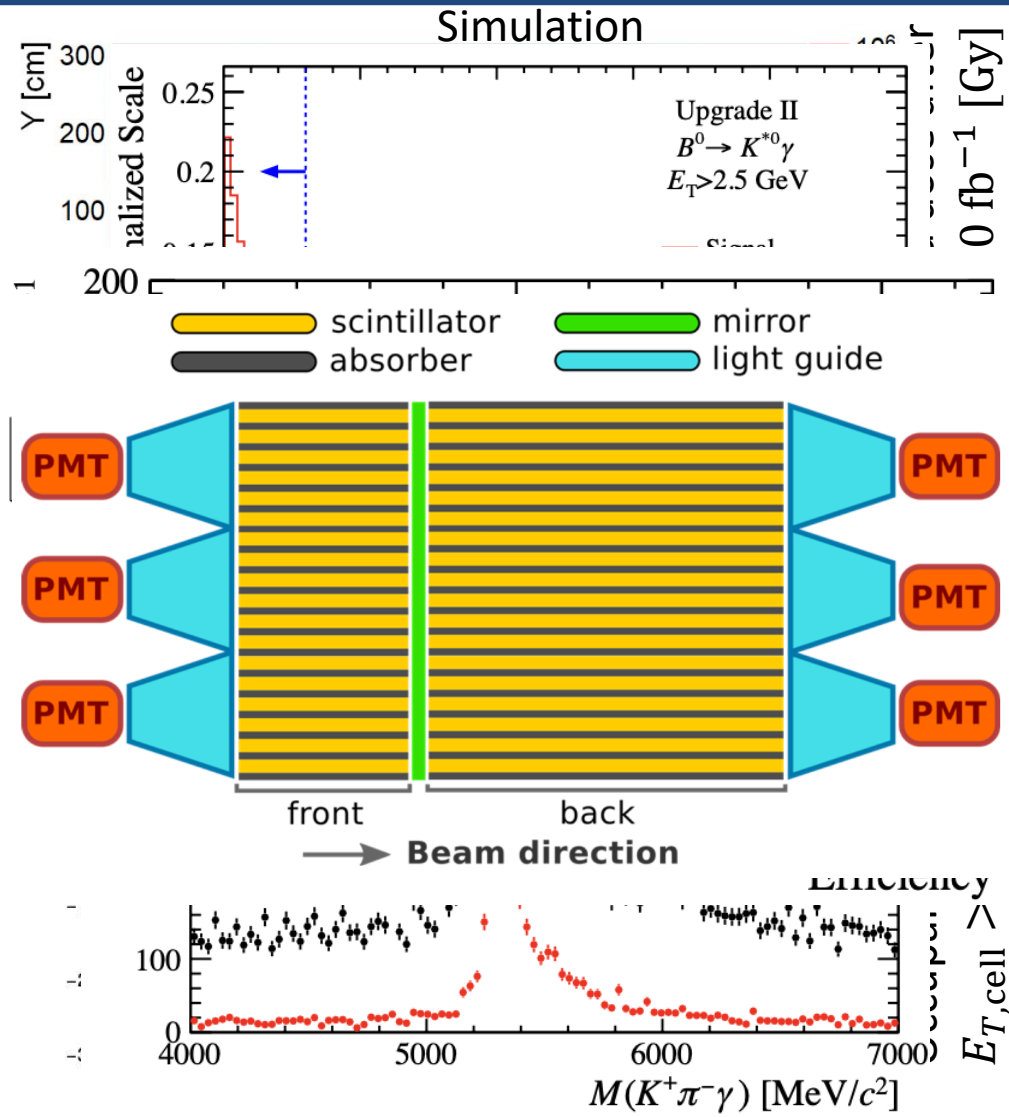
LHCb (2022-2033)

LHCb (2036-)

- *Framework TDR for the LHCb Upgrade II: Opportunities in flavour physics, and beyond, in the HL-LHC era*. 2021. CDS.
- LHCb collaboration. *LHCb Upgrade II Scoping Document*. 2024. CDS (forthcoming).

Electromagnetic calorimeter (ECAL)

- ECAL essential to studies with neutrals / electrons [1, 2, 3, 4]
- Upgrade needed to handle very high luminosity (increased radiation and pile-up)
- Timing information ($\mathcal{O}(10)$ ps) needed to resolve pile-up
- Use Shashlik technology in outer region, as current ECAL
- Use new Spaghetti Calorimeter (SpaCal) technology in central region
  - Absorber with longitudinal fibers for scintillation and light-transport, split into front and back regions to improve timing and cluster resolutions and to resist radiation damage
  - Tungsten absorber in innermost region, lead elsewhere
- May include dedicated timing layer, technology TBD
- R&D ongoing

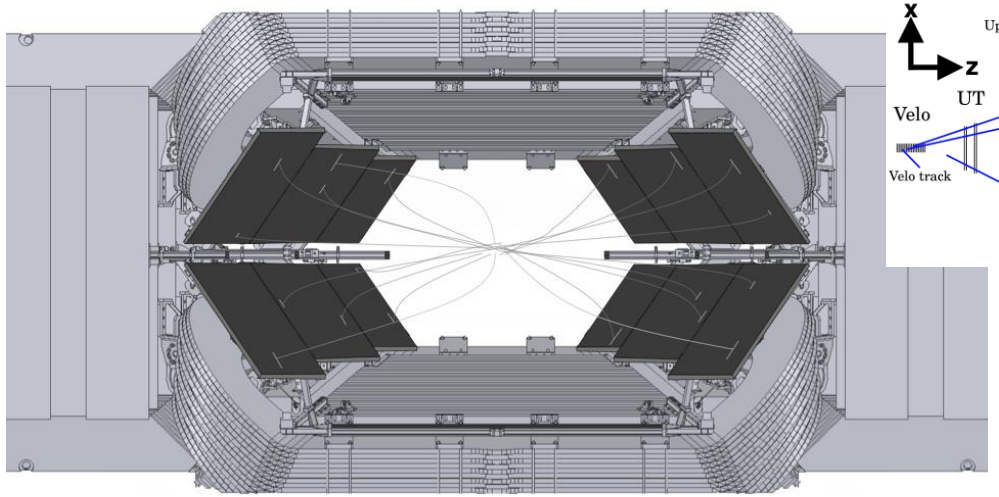


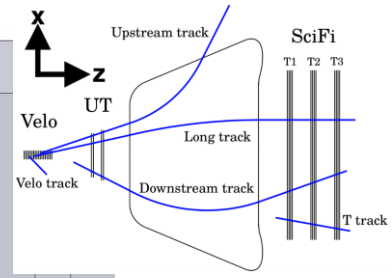
1. R. Aaij and others, *Test of lepton universality in beauty-quark decays*, arXiv:2103.11769.
2. R. Aaij and others, *Observation of photon polarization in the $b \to s\gamma$ transition*, Phys. Rev. Lett. 112 (2014) 161801, arXiv:1402.6852.
3. R. Aaij and others, *Measurement of CP Violation in the decay $B^+ \to K^+\pi^0$*, Phys. Rev. Lett. 126 (2021) 091802, arXiv:2012.12789.
4. R. Aaij and others, *Test of lepton universality with $B^0 \to K^{*0}\ell^+\ell^-$ decays*, JHEP 08 (2017) 055, arXiv:1705.05802.

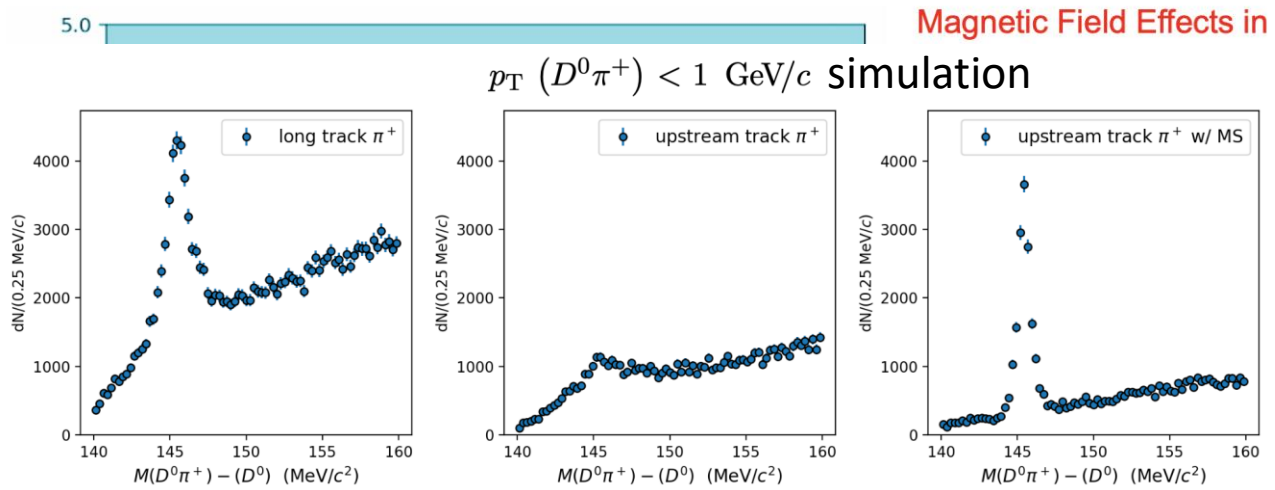
- *Framework TDR for the LHCb Upgrade II: Opportunities in flavour physics, and beyond, in the HL-LHC era*. 2021. CDS.
- LHCb collaboration. *LHCb Upgrade II Scoping Document*. 2024. CDS (forthcoming).

Magnet Stations (MS)

- LHCb (original and upgrade I) has only partial tracking information for particles deflected by the magnet ($p_T \lesssim 5$ GeV/c), giving $\frac{\delta p}{p} = 12.3\%$
- A scintillating-based tracker inside the magnet would give $\frac{\delta p}{p} < 1\%$
- Would enable all new measurements and improvements to previous measurements
- R&D ongoing







π^+ hits all 3 tracking systems

π^+ hits only 2 tracking systems

π^+ hits 2 + magnet stations

- *Framework TDR for the LHCb Upgrade II: Opportunities in flavour physics, and beyond, in the HL-LHC era*. 2021. CDS.
- LHCb collaboration. *LHCb Upgrade II Scoping Document*. 2024. CDS (forthcoming).

Conclusions

- LHCb continues to make important measurements using 2011-2018 data
- LHCb entering new era of data-taking with exciting new possibilities
- US institutions significant contributors to LHCb physics analysis, detector performance, and ongoing upgrade efforts

- *M. Brice. LHCb detector*. 2024. CDS.

LHCb Lighting Round talks:

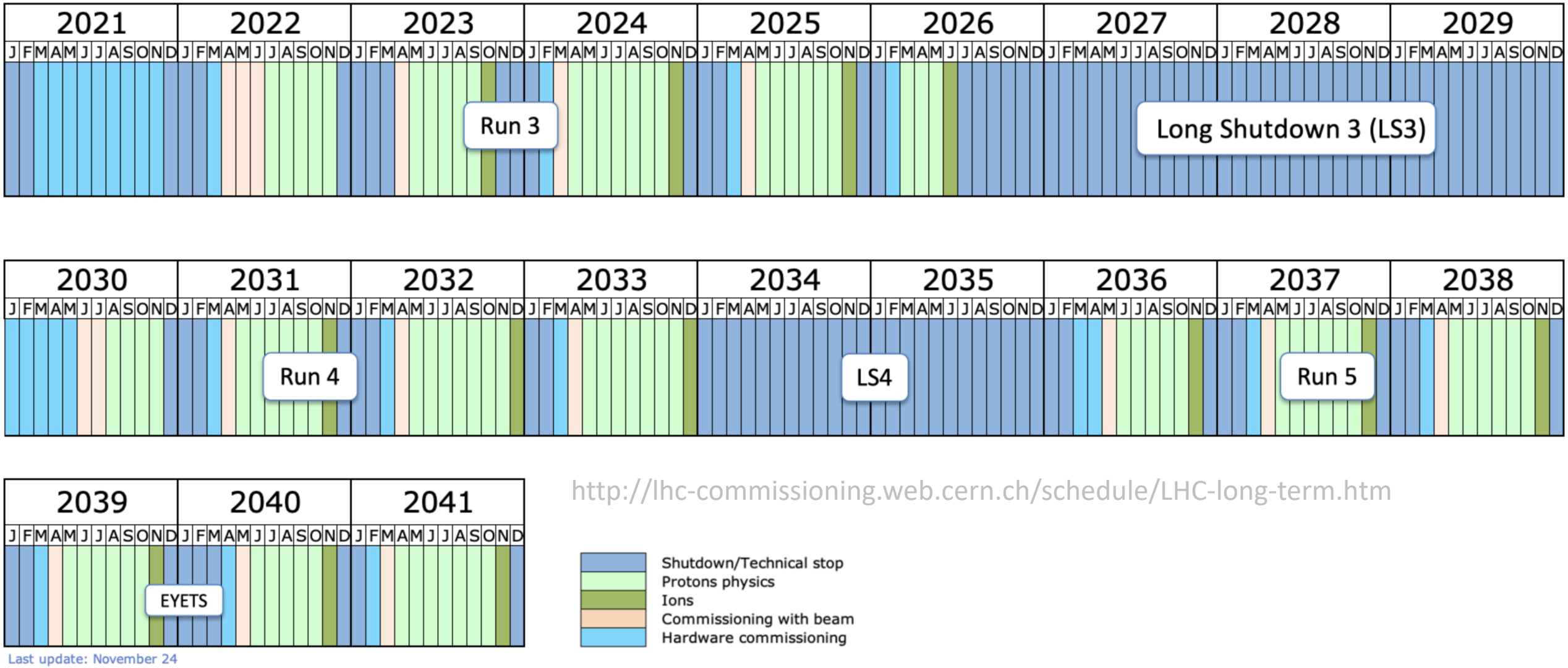
- “Real-time analysis in HLT1 at LHCb in Run 3” by Kate Richardson: link
- “Heavy-Flavour Jet Tagging Using Graph Neural Networks at LHCb” by Gabriella Pesticci: link
- “Waveform Sampling for Future Detector Timing Layers” by Andrew Dowling: link

Questions?

FIN

BACKUP

LHC long-term schedule



http://lhc-commissioning.web.cern.ch/schedule/LHC-long-term.htm