Liverpool LHCb Physics + M&O

Dr Paras Naik

Liverpool Particle Physics Group Meeting

22 May 2025

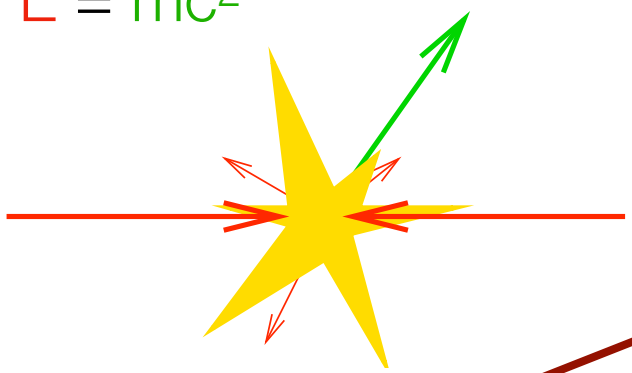
UNIVERSITY OF LIVERPOOL

Two Roads to New Physics

Direct Observations

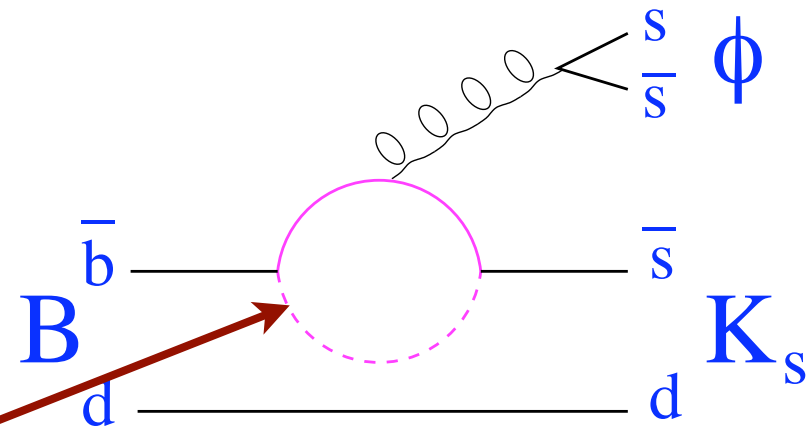
Particles with $mc^2 > E$ cannot be produced directly

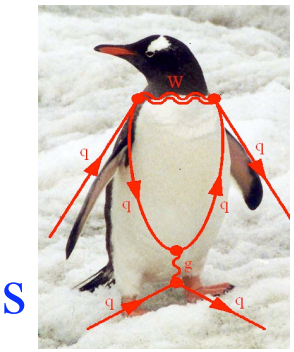
$E = mc^2$



Indirect Effects

… but they can have an effect as virtual particles, especially in loops





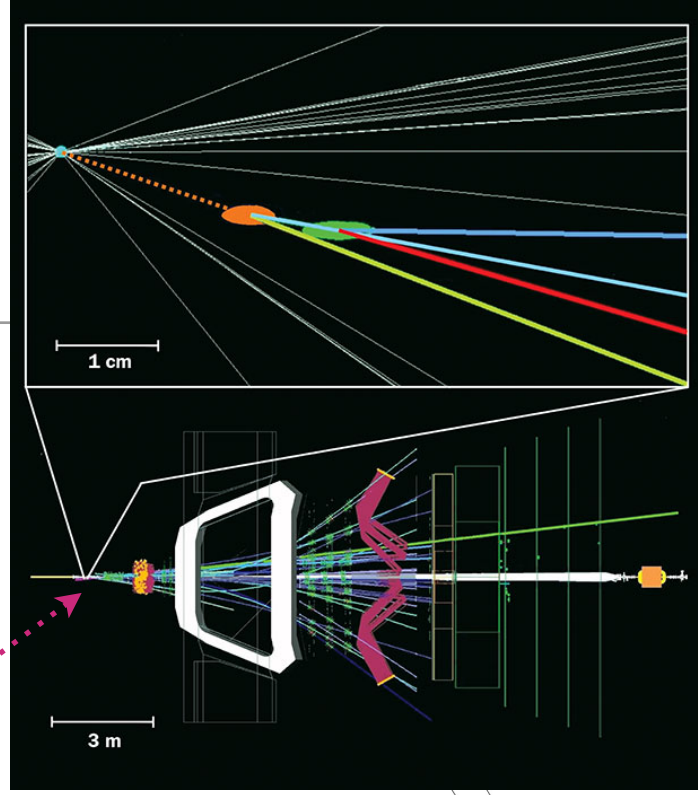
This kind of approach is sensitive to particles *far heavier* than those directly produced in a collider.

Flavour physics lets you *see beyond the energy frontier*…
LHCb is designed for this!

2025 Breakthrough Prize in Fundamental Physics

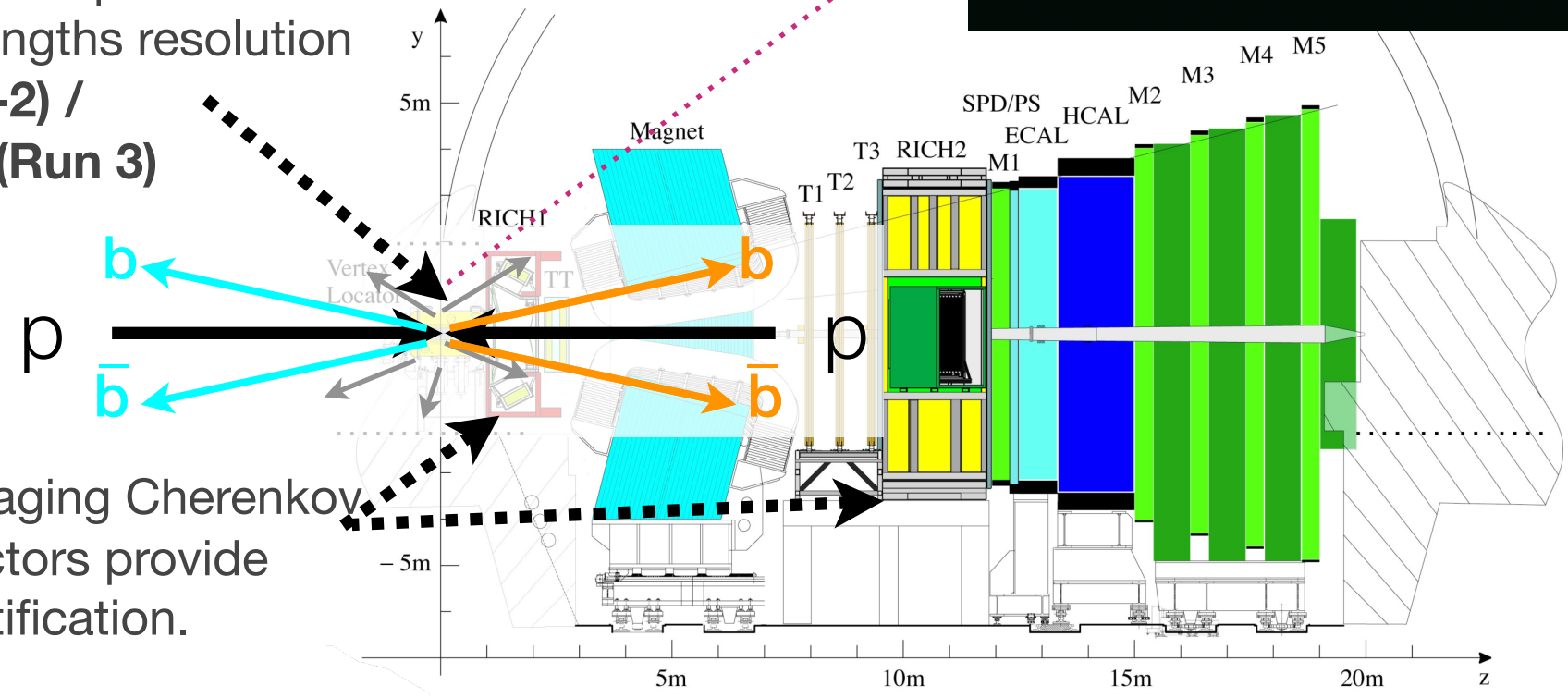
LHCb

1787 members
103 institutes
24 countries



- Vast quantities of all b-hadron and c-hadron species

- The **VELO** - a vertex detector INSIDE the beam pipe, for excellent impact parameter and decay lengths resolution **Built (Run 1-2) / Assembled (Run 3) at Liverpool**

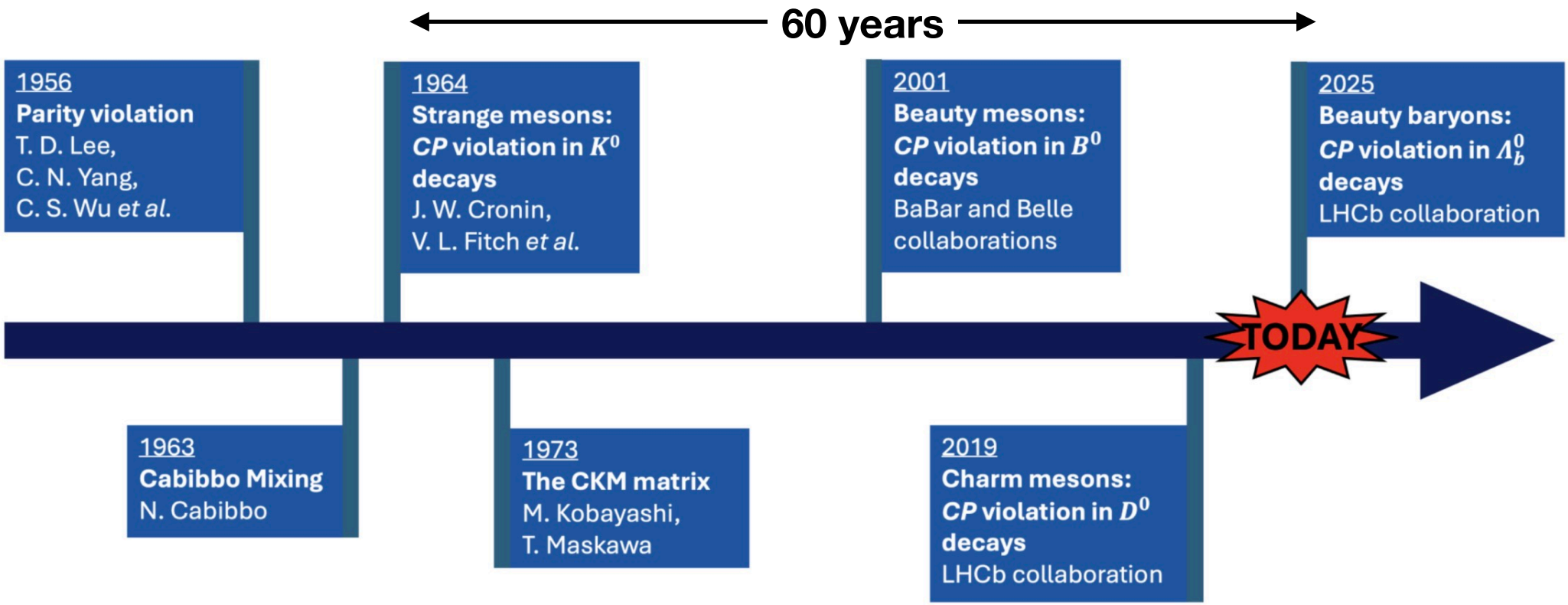


- Two Ring Imaging Cherenkov (**RICH**) detectors provide particle identification.

CP violation in baryon decay

arXiv:2503.16954

- LHCb recent result: **CP violation seen for the first time in baryon decay!**



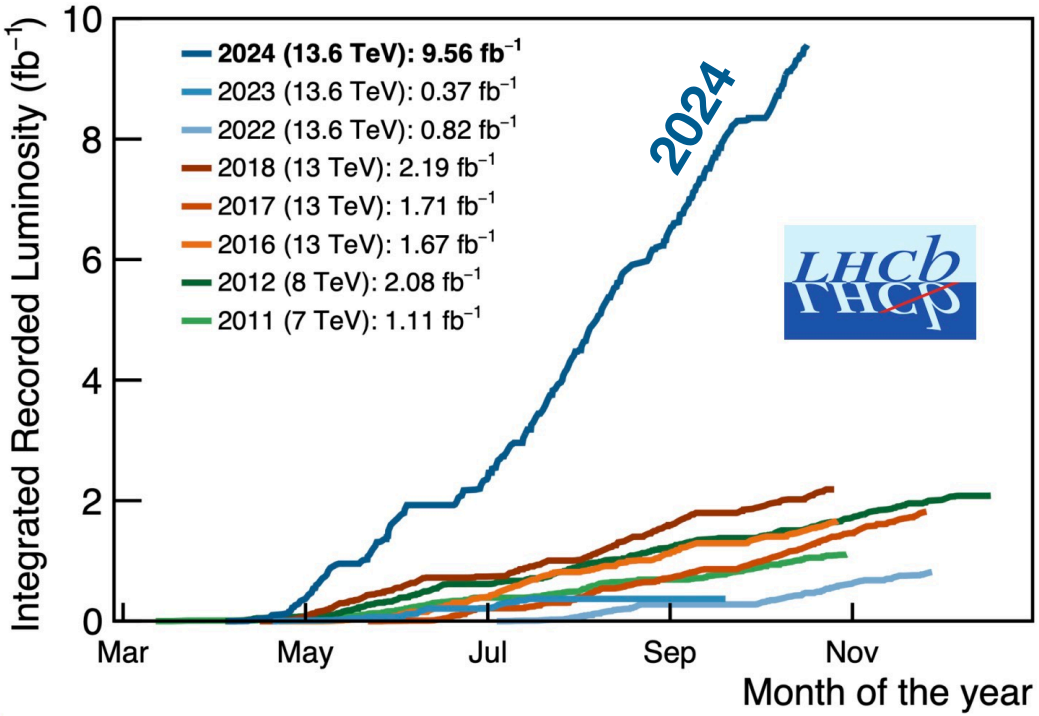
- **CPV from interference between tree and loop processes in** $\Lambda_b^0 \to pK^-\pi^+\pi^-$

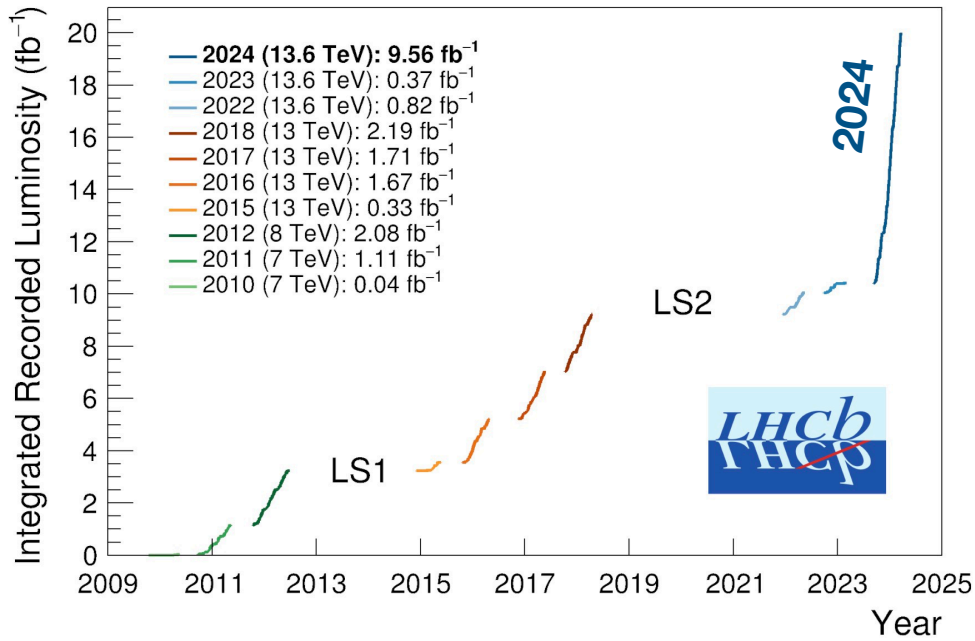
$$\mathcal{A}_{CP} = (2.45 \pm 0.46 \pm 0.10)\% \qquad 9\,\text{fb}^{-1}$$

LHCb Run 3 Data Taking

- **More data in 2024 than all previous years combined!**

- **Trigger efficiency for hadronic beauty and charm decays two/three times larger**





The Friendly Faces of LHCb Liverpool

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Tara

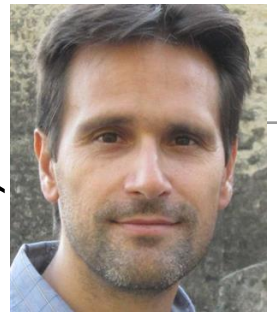

David

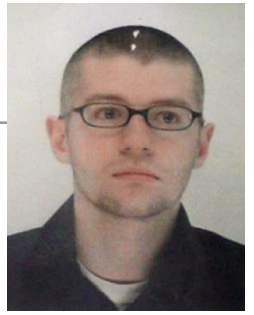

Themis


Eva


Paras

(at CERN)


Eduardo


Karol


Ayushi

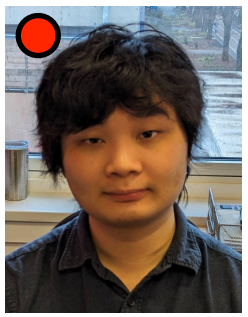

left for Brazil (permanent!)
Juan

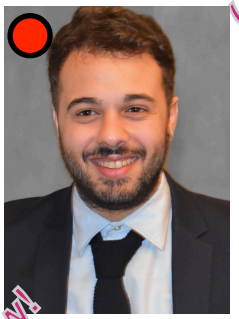

Ashley

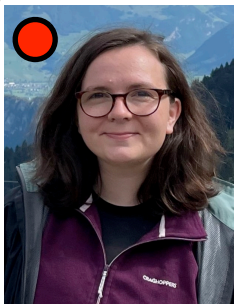

Kieran

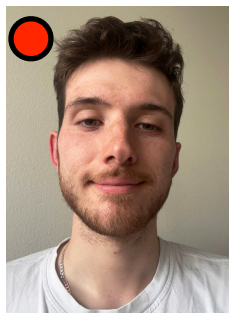

John


Kurt


Ho Sang


New!
Giuseppe


Abbie


James


Dr.!
Sigrid


Back from CERN!
Ned


Had viva! (doing corrections)
Thomas

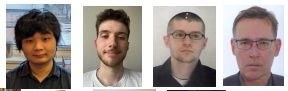
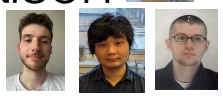
students!

We are an active group, leading the field...

We've built/invented detectors, techniques, and tools used to collect/analyse LHCb data.

28 shifts taken by Liverpool in 2025 already! (52 in 2024)
Ho Sang took 15 (10 night shifts)!

Liverpool LHCb (& related) Service Work

- **LHCb-UK PI/Spokesperson** 
- LHCb VELO Installation & Commisioning 
- **LHCb VELO Operations** 
- LHCb Mighty Tracker 
  - **New role!**  **See Eva's talk!**
- LHCb VELO++ software 
- LHCb Quantum Computing Activities 
- LHCb VELO simulation lead 
- LHCb VELO DAQ 
- WLCG management board software liaison 
- **LHCb Shift Leader / Data Manager** 
- LHCb Data Processing & Analysis Project Leader 
- HSF coordination team & HSF PyHEP WG co-convener 
- SWIFT-HEP WP5 (Data Analysis) co-convener 
- HFLAV Charm Decays convener 
- LHCb Speakers' Bureau 
- LHCb Quarkonia WG double charm trigger liaison 
- Outreach **(LHCb featured in 2025 Liverpool Masterclass!**    **)**

- responsibility
- leadership

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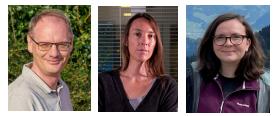
See Eduardo's talk

And many former responsibilities / leadership roles!

Recent LHCb (& related) Publications

- Weak mixing angle 
- LHCb Open Data Ntupling Service 
- LHCb Stripping Project and Legacy Data 
- Heavy Flavour Averaging Group paper 
- Contributions to European Strategy 

Several more in review / leadership capacities

- submitted to arXiv/journal since ~2024

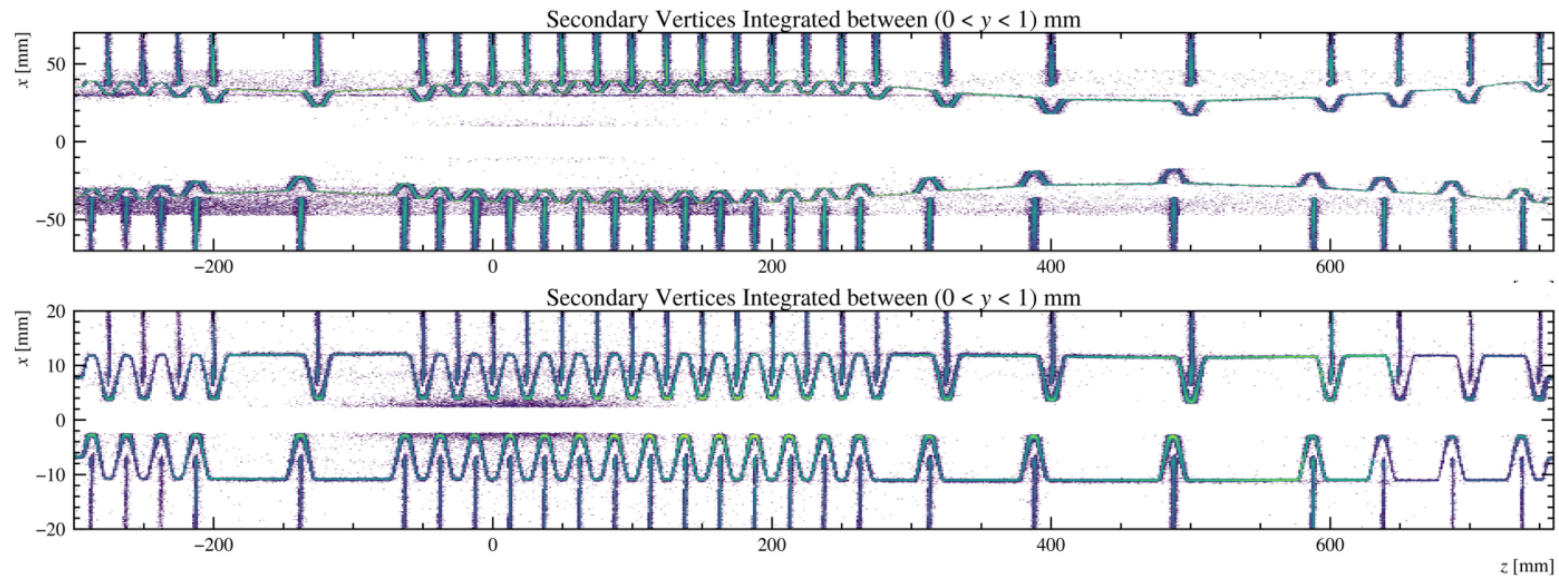
See Eduardo's talk for Computing & Software publications!

LHCb VELO

Post LHC incident on the VELO, 2024 became first year running in the design configuration with VELO fully closed

2023

2024



Reconstructed vertices excluding the luminous region and in a limited y-range around the beam (at other y values the VELO halves overlap in this x-z projection)

LHCb VELO

Shims removal in March 2025

- Added shims to VELO halves to move them 0.5mm away from the beam, until the foil was imaged (see previous slide).

- **Kieran** removed the shims during the winter shutdown

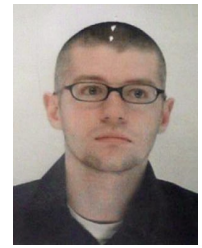
- In 2025, **expecting an improvement in IP resolution of 10%**

- A suspected leak into the vacuum was addressed

- Screws tightened to address a slight drift affecting the alignment

LHCb VELO



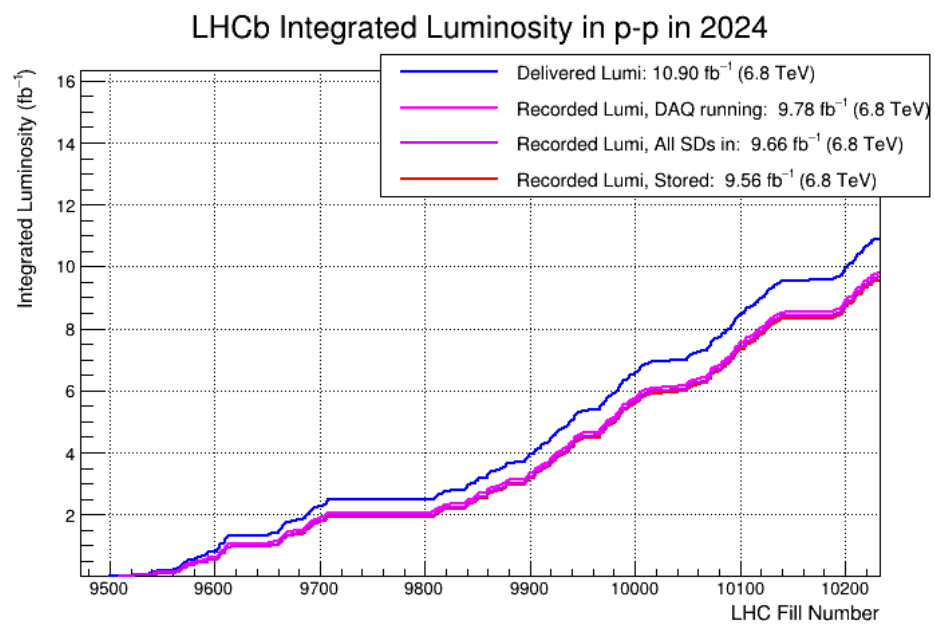



VELO Operations work

- Most work is now **automation, optimisation, and monitoring**
- VELO bad pixels map and online monitoring (James)
  - Online version to mask bad pixels “live” in development (James/Kurt)
- Improvements to VELO recipes, backend WinCC libraries and generator (Kurt)
- Improvements to VELO firmware error handling and rate optimisation (Karol)
- Improvements to VELO control and DAQ software and operational monitoring (Karol/Kurt)
- Update the VELO simulation to match the new detector (David, Karol, James)

Despite the VELO incident,
LHCb has reached peak efficiency.

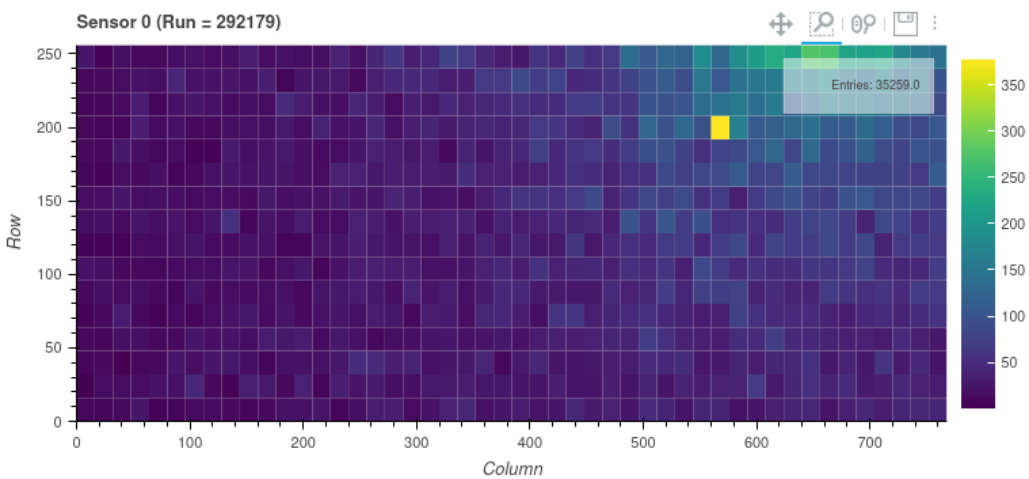
Target of **50 fb^{-1}** (Run 1-4) in the LHCb Upgrade I era is achievable!

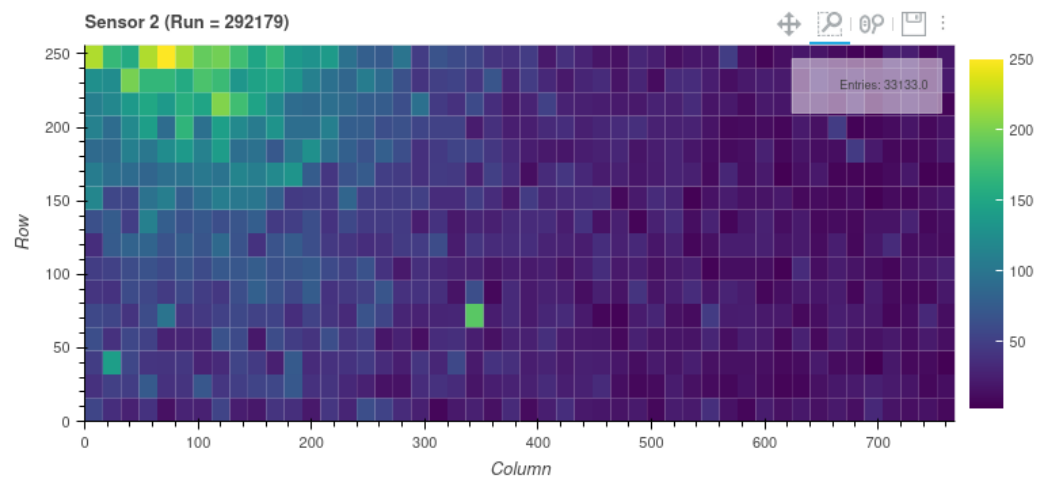


Noise of the VELO

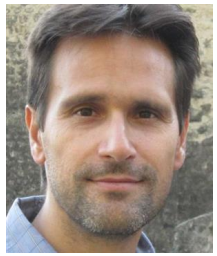
- Developed a **decoder** for the firmware scan data that will allow us to **trial different pixel threshold cuts**, and see how they vary with other parameters (e.g. HV current).

- Developed a **monitor** to **catch Single Event Upsets** (disruptions to the electronics) that cause noise in pixels until the module is reconfigured.





LHCb Data Processing & Analysis (DPA)

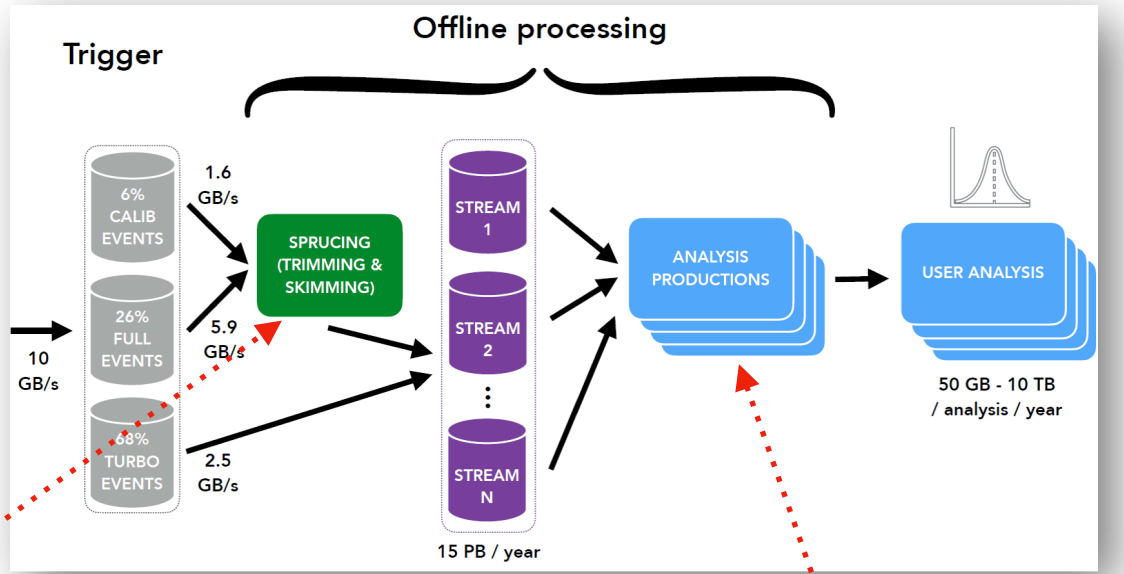


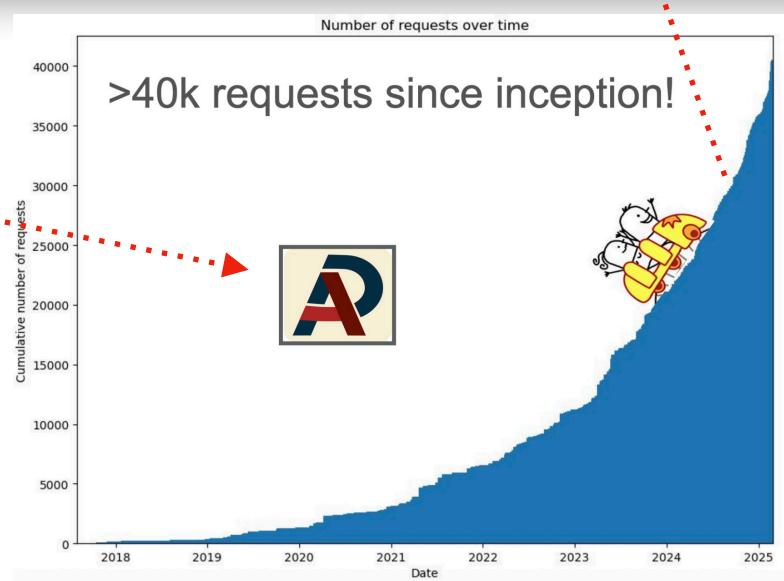
- Eduardo's DPA project leader role ended in June 2024

- The **DPA project addresses the challenges due to the very large increase in data volume** expected in Run 3 and beyond.

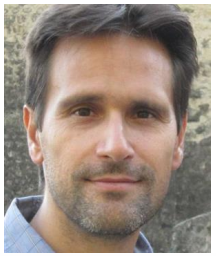
- Centralised **skimming and trimming** of a significant fraction of trigger outputs & **analysis productions** for physics analysts.

- R&D, preparations and commissioning went well – **delivered working software and infrastructure on time, successfully!**





LHCb Analysis Facilities



- Idea: **Leverage CPU and GPU resources** used for data-taking and online farms **for physics analysis** in off-peak times.
- Discussions started in Nov. 2024 with several CERN IT people to understand the best strategy
- Converged in the **proposal of a pilot project in collaboration with CERN IT** towards the set-up of a prototype **Analysis Facility**
- Steering committee **approval** of project and allocation of assistance (2 x 0.1 FTE) **expected tomorrow!**

CERN

RCS-ICT PSO

DRAFT

Utilizing LHCb Farms as Analysis Facilities through SWAN

Authors:

Pilot-Propos.

Ed *R* *rio* *s* (University of Liverpool) and *Francesco Sborzacchi* (CERN)

dreas-Joachim *&* *inal* - CERN RCS-ICT Engagement Manager,

Simone Campana C RI T Bu ess Engagement Lead

Responsibles:

Se tic Pa power

Su mi ic Date: 27.2.2025

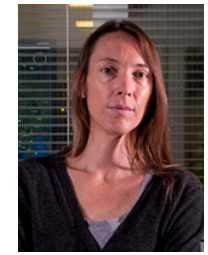
See Eduardo's talk for details!

The ultimate objective is to **develop a production-ready Analysis Facility** (AF) **for LHCb** through a three-phase approach. The pilot project focuses on the first two phases, prioritizing prototyping and technical validation before moving toward full production, which will necessitate additional planning for maintenance and support.

This initiative **serves as a potential model for other communities** seeking to repurpose existing computing resources for advanced analysis and machine learning applications.

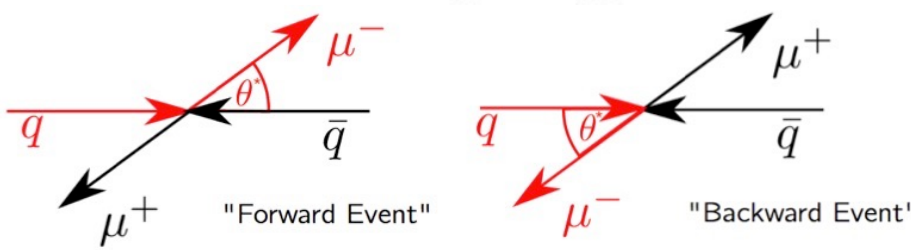
Z Forward-backward Asymmetry

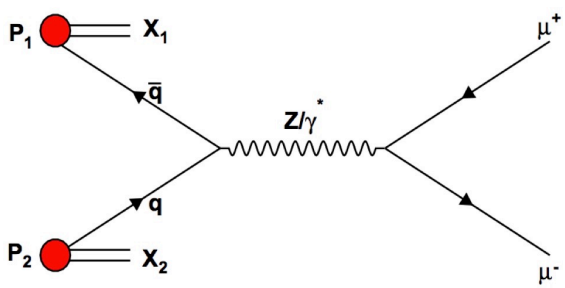


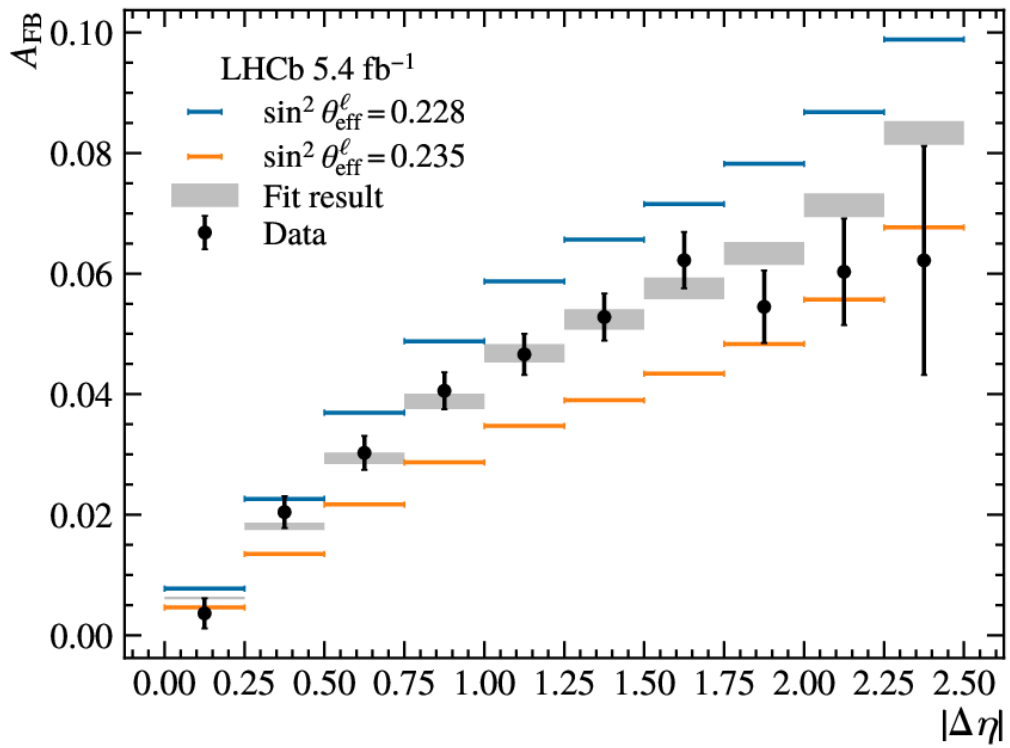


- Study of the asymmetry **A_{FB}** in ***Z* → *μ*⁺*μ*⁻** decays, with Run 2 (13 TeV) data. The interference between *Z* boson and virtual photon gives rise to a non-zero A_{FB} value.

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$



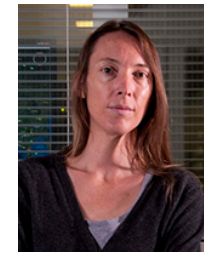




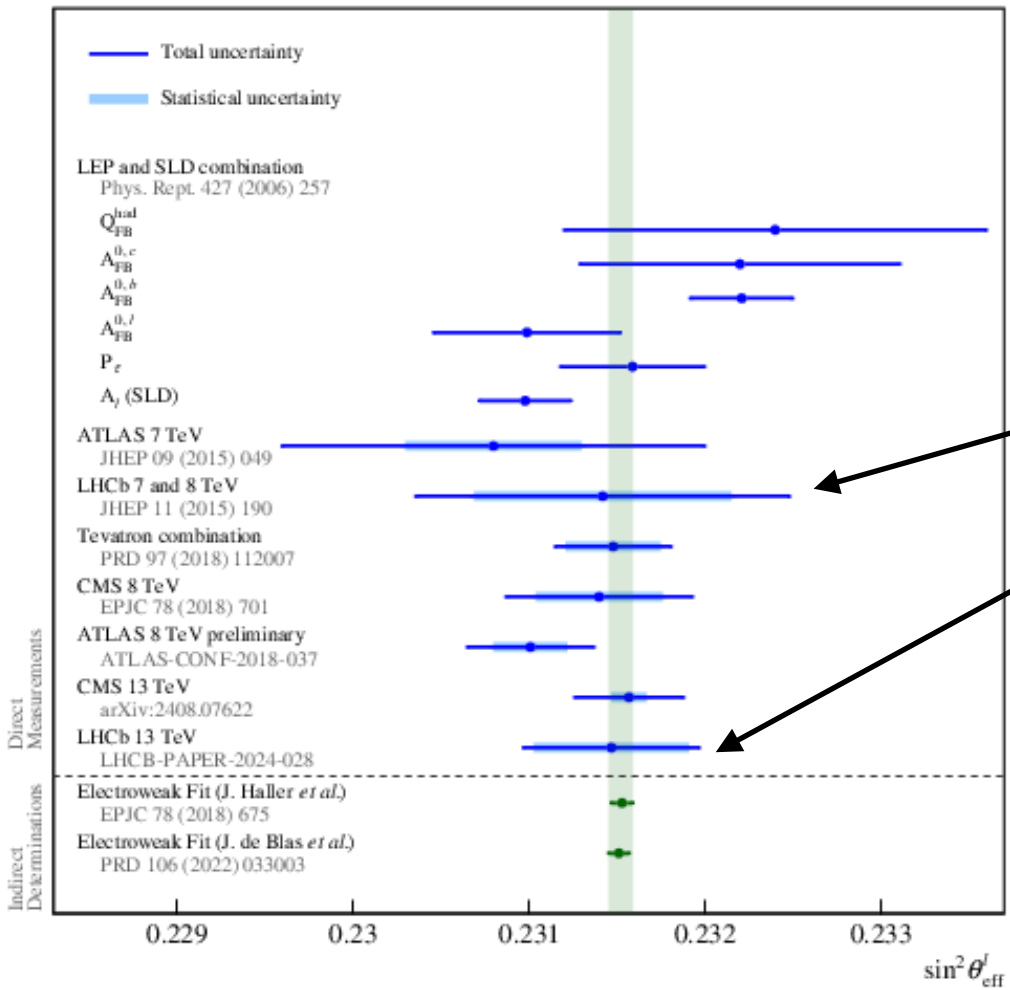
- **Published in JHEP 12 (2024) 026**

Effective leptonic weak mixing angle





- Knowing **A_{FB} allows us to measure** key electroweak parameters, such as **the effective leptonic weak mixing angle $\sin^2(\theta^l_{eff})$**



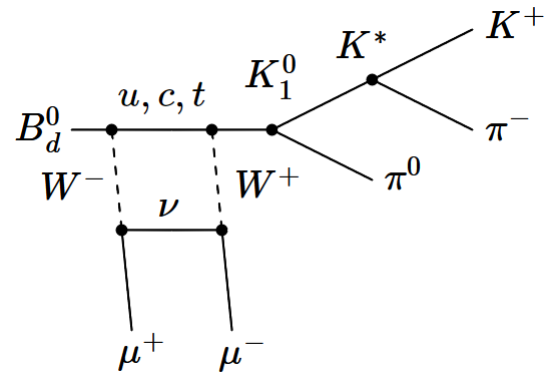
Performed in Liverpool!
(by Joe Price, et al.)
JHEP 11 (2015) 190

- **Published in JHEP 12 (2024) 026**

This 13 TeV LHCb result is consistent with other direct measurements and with the prediction from global electroweak fits.

Search for right-handed weak decays

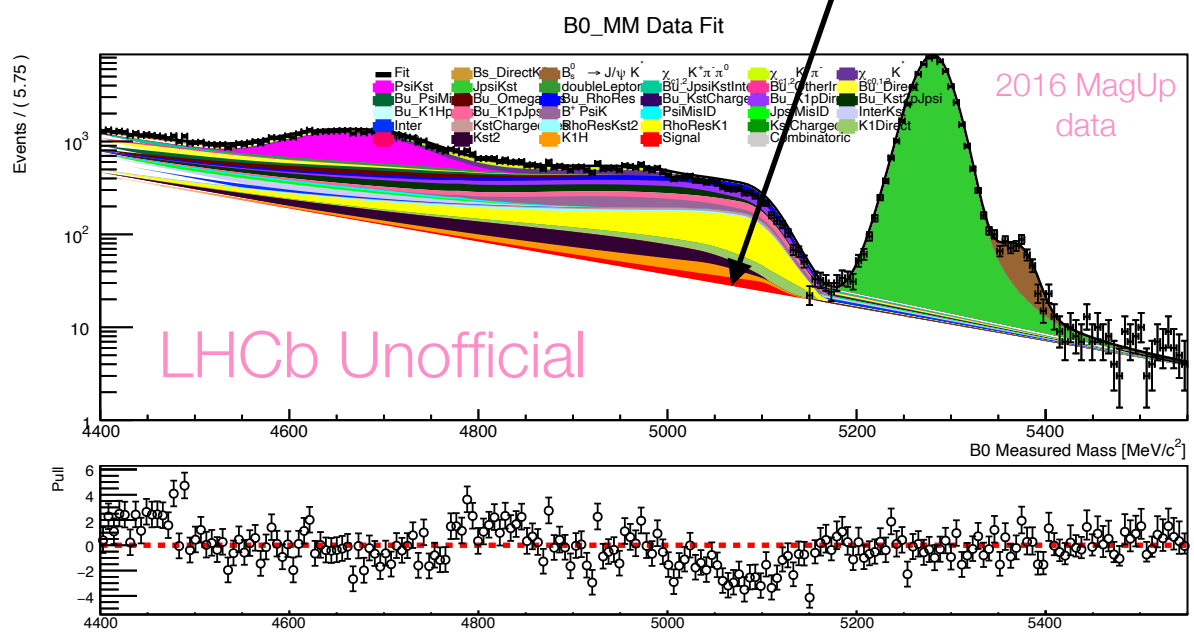

- To **search for right handed weak decays** by using parity doubling, we compare two channels with opposite parity products (in this case $B^0 \to K_1^0 \mu^+ \mu^-$ and $B^0 \to K^{*0} \mu^+ \mu^-$) where there is a cancellation of SM interactions that would otherwise dilute any **BSM** contributions.



- Analysis work in progress with Run 1/2 data.

- Selections for Run 3 in place.

- The decay process $B^0 \to K_1^0 \mu^+ \mu^-$

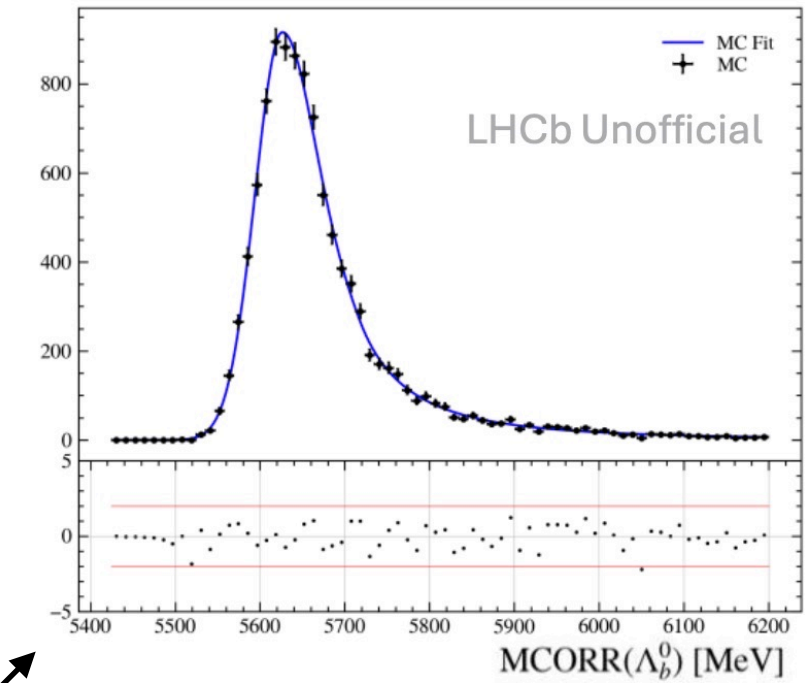


Purely Baryonic B decays





- **Purely baryonic decays** are a class of particle decay that is essentially unexplored. **Unique at Liverpool!**
- First investigation of $\Lambda_b \rightarrow \Lambda_c$ *anti-*Λ_c ***n***
- A nice means to measure a decay mode containing a **neutron** for the first time at a hadron collider experiment
- Neutron not reconstructed, thus understanding of the many **peaking backgrounds** is crucial and underway.



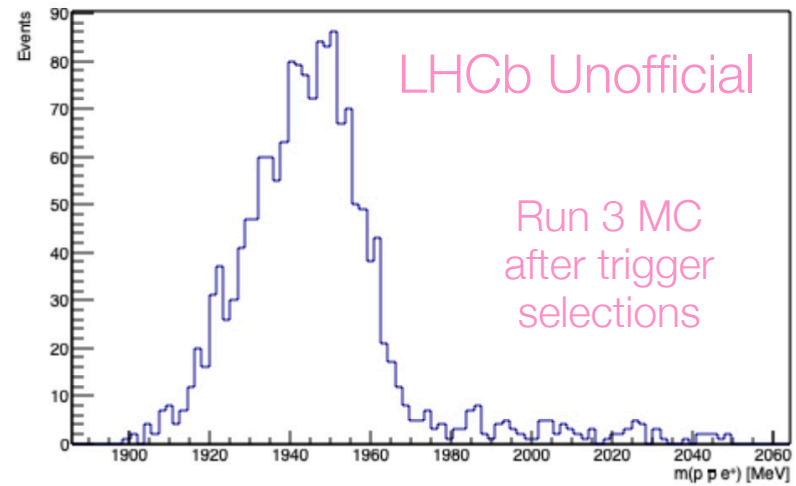
- Study of $B \rightarrow \Lambda_c$ *anti-*Λ_c K MC lineshape in M_{CORR} spectrum

$$M_{CORR} = \sqrt{P_{vis}^{T\ 2} + m_{vis}^2} + \sqrt{P_{vis}^{T\ 2} + m_{invis}^2}$$

- For Run 3: Started the studies on control channels for an analysis of $B^0 \rightarrow p\ p$ **anti-***p* **anti-***p* using 2024 data.

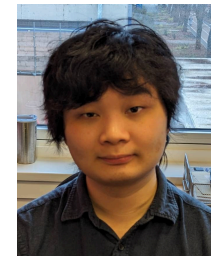
Very Rare D_s decay


- **Search for** the very rare ***D_s -> p anti-p e v*** in **Run 3** (The only semi-leptonic baryonic decay in the charm sector)
- Development of a new trigger aiming at a first search using Run 3 data
- BF expected in the range 10^{-9} – 10^{-8} (BESIII tried before did not observed – well off relevant sensitivity).
- We think that **LHCb can observe it for the first time**

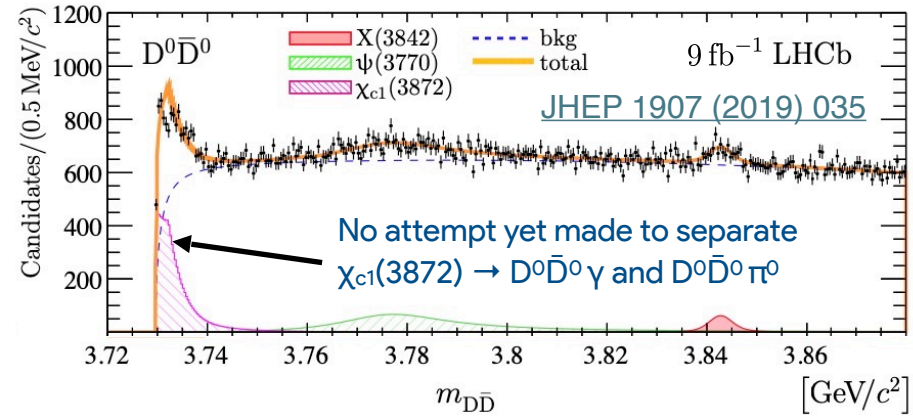


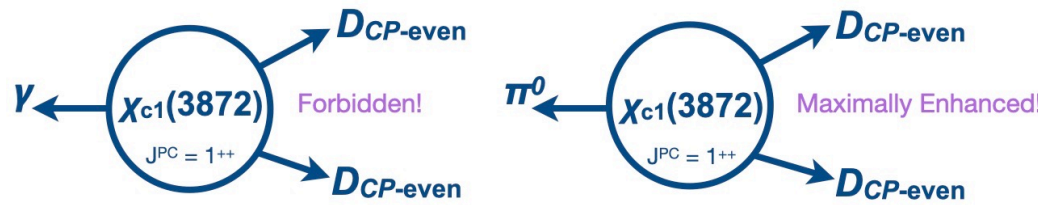
- ***p anti-p e*** invariant mass spectrum

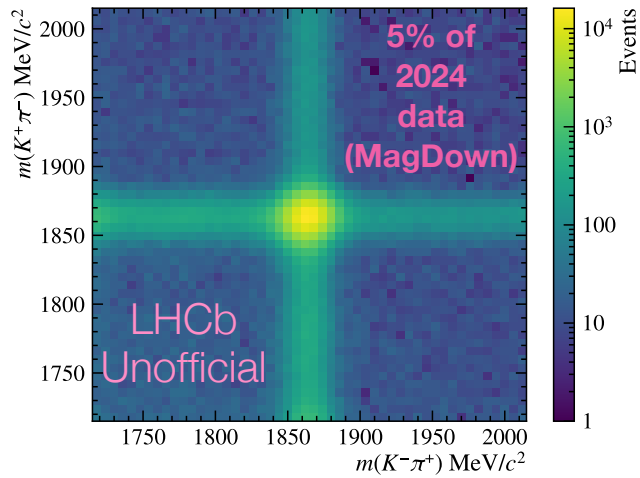
Quantum Correlated Charm




- **Quantum correlated $D^0\bar{D}^0$ systems** can be collected from $\chi_{c1}(3872) \rightarrow D^0\bar{D}^0\{\pi^0,\gamma\}$ decays. (JHEP 03 (2023) 038)
  - By clever "**CP-tagged**" reconstruction
    - ***$\chi_{c1}(3872) \rightarrow D^0\bar{D}^0\gamma$*** is forbidden; ***$\chi_{c1}(3872) \rightarrow D^0\bar{D}^0\pi^0$*** doubled
  - Leverage this to **empirically determine the line shapes of both decays**. Additional goals include **near-threshold spectroscopy, input to CKM gamma, test of time-reversal violation in charm**.
  - (As seen earlier today!) Considerable work done to **trigger effectively within bandwidth constraints**. Run 3 data samples becoming available now.







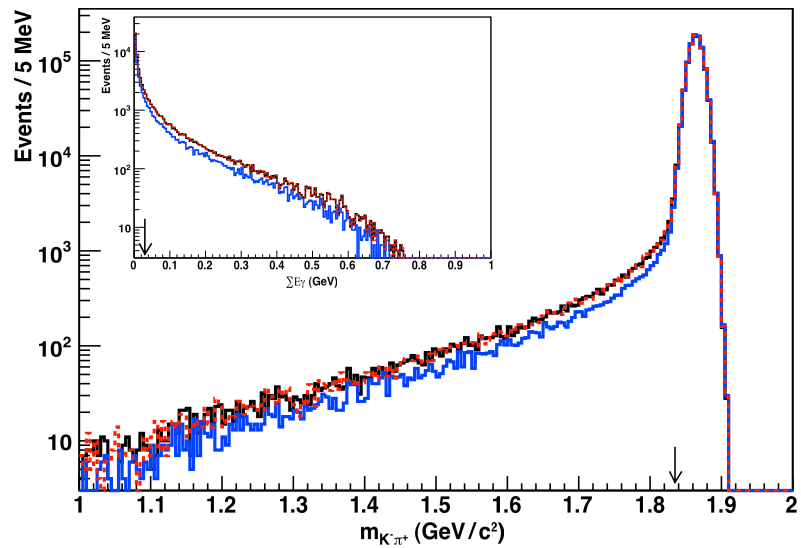
invariant mass of one D meson candidate vs. invariant mass of the other D (both reconstructed Cabibbo-favoured)

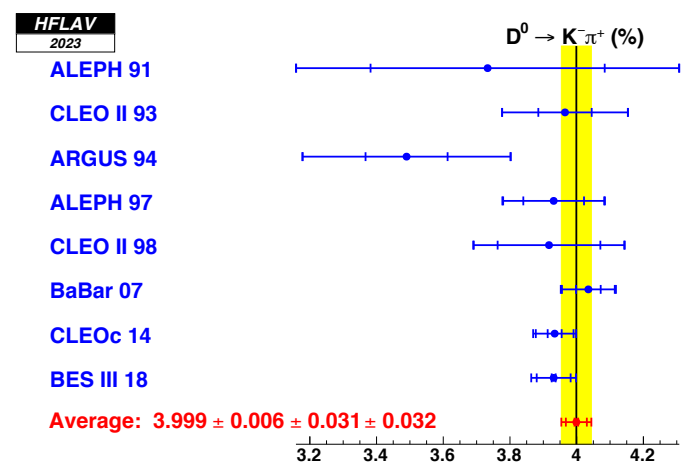
with pre-selections (all sub-detectors in)

Heavy Flavour Averaging Group (HFLAV)

- **Informed averages** of quantities relevant to flavour physics experiments
- Final state radiation (FSR) modeling improved significantly over last 30+ years
- **Must account for FSR consistently so the accuracy of the average matches experimental precision**
- Discussions ongoing to incorporate these results into the PDG.

average branching fractions accurately by correcting those with poorly modeled efficiency





arXiv:2411.18639

Summary

More in Eva's & Eduardo's talks!

9 fb^{-1} of data already recorded in Run 1 & 2

+ >9 fb^{-1} in Run 3 so far!

and more!

[60] **Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom**

Team Leader: Tara Shears

Members: Abbie Jane Chadwick , Andrea Loreti , Anthony Smith , Ashley Greenall , Ayushi Khatri , Ce Zhang , Clement Loic Devanne , David Hutchcroft , Dominika Vasilkova , Eduardo Rodrigues , Elia Bottalico , Eva Vilella Figueras , Fedor Ignatov , Gianluigi Casse , Giorgia Cacciola , Ho Sang Lee , James David Brown , Jan Hammerich , John Carroll , Joseph David Price , Juan Baptista de Souza Leite , Karol Hennessy , Katherine Ferraby , Kieran Bridges , Kurt Rinnert , Mark Whitley , Ned Francis Howarth , Paras Naik , Riccardo Nunzio Pilato , Robert Fay , Samuel Powell , Saskia Charity , Sigrid Scherl , Tara Shears , Themistocles Bowcock , Thomas Ackernley

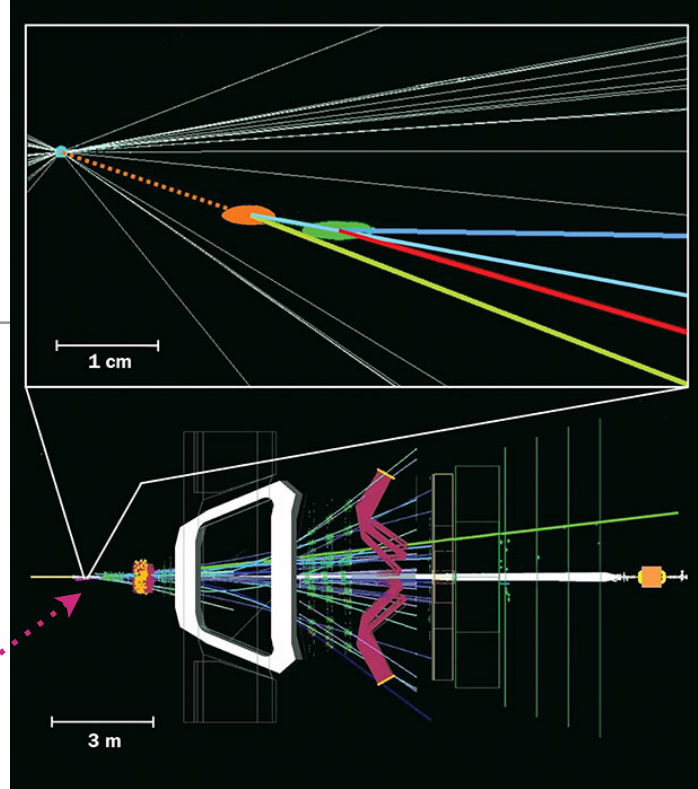
Backup (slides I would have liked to put in this talk)

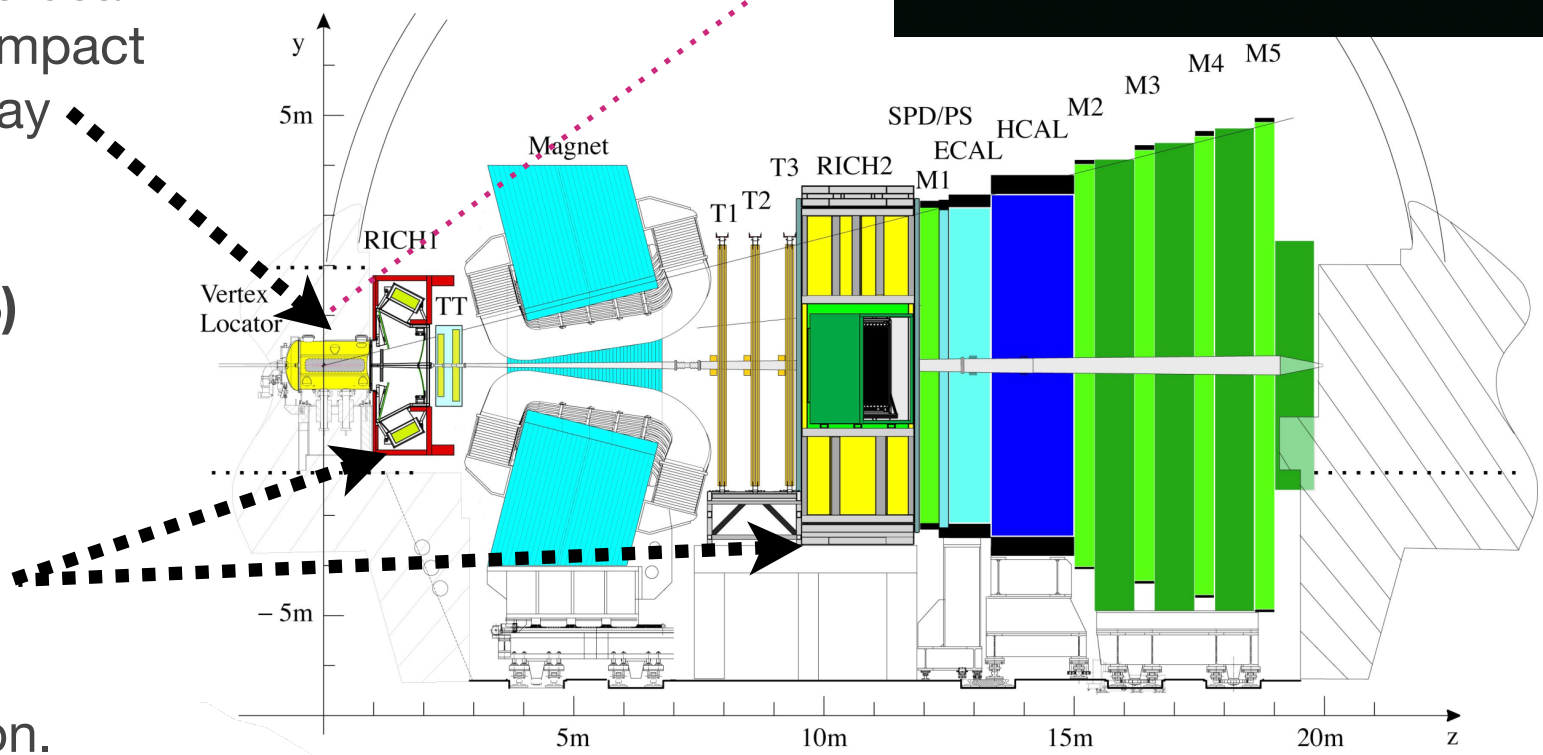
LHCb Detector

- Many detector elements not found elsewhere at the LHC

- The **VELO** - a vertex detector INSIDE the beam pipe, for excellent impact parameter and decay lengths resolution **Built (Run 1-2) / Assembled (Run 3) at Liverpool**

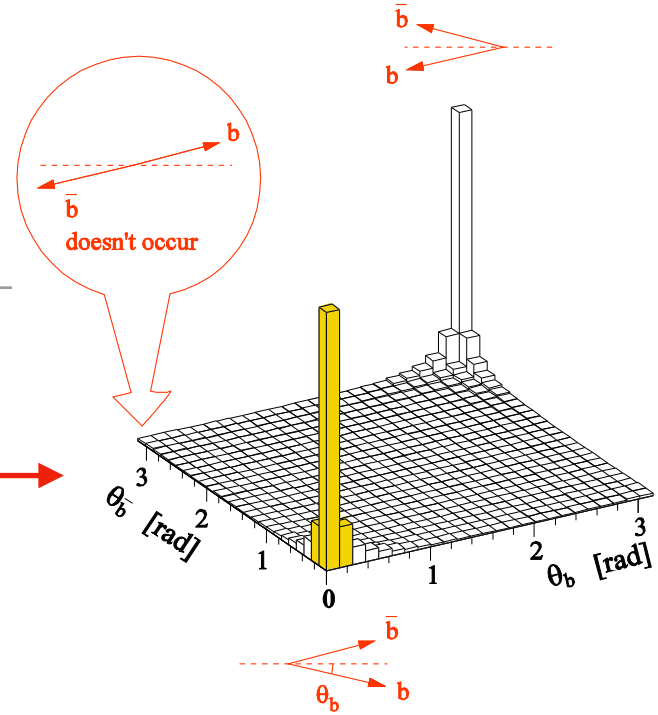
- Two Ring Imaging Cherenkov (**RICH**) detectors provide particle identification.





LHCb Experiment

Beauty (and Charm) quarks are produced in forward directions

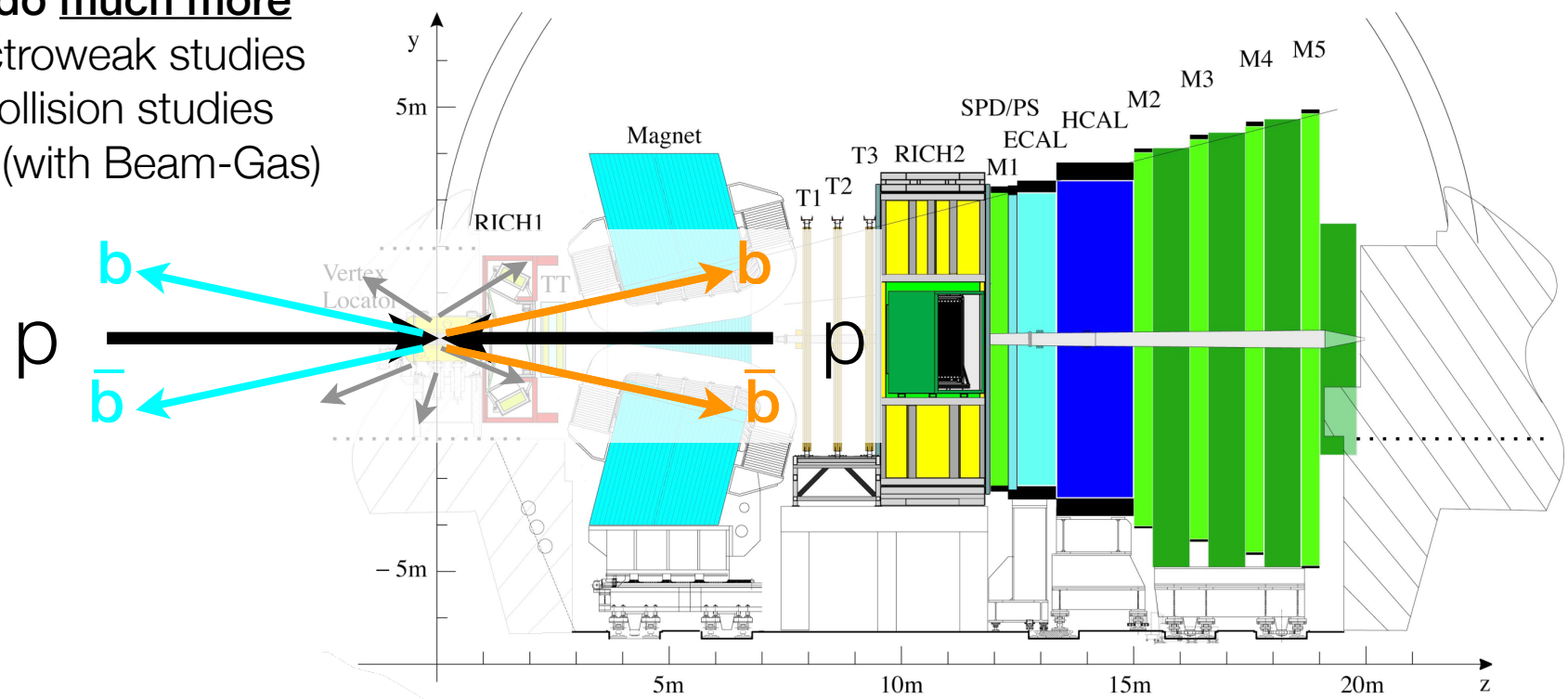


We built our detector to focus on finding these events, but we can do <u>much more</u>

Precision electroweak studies

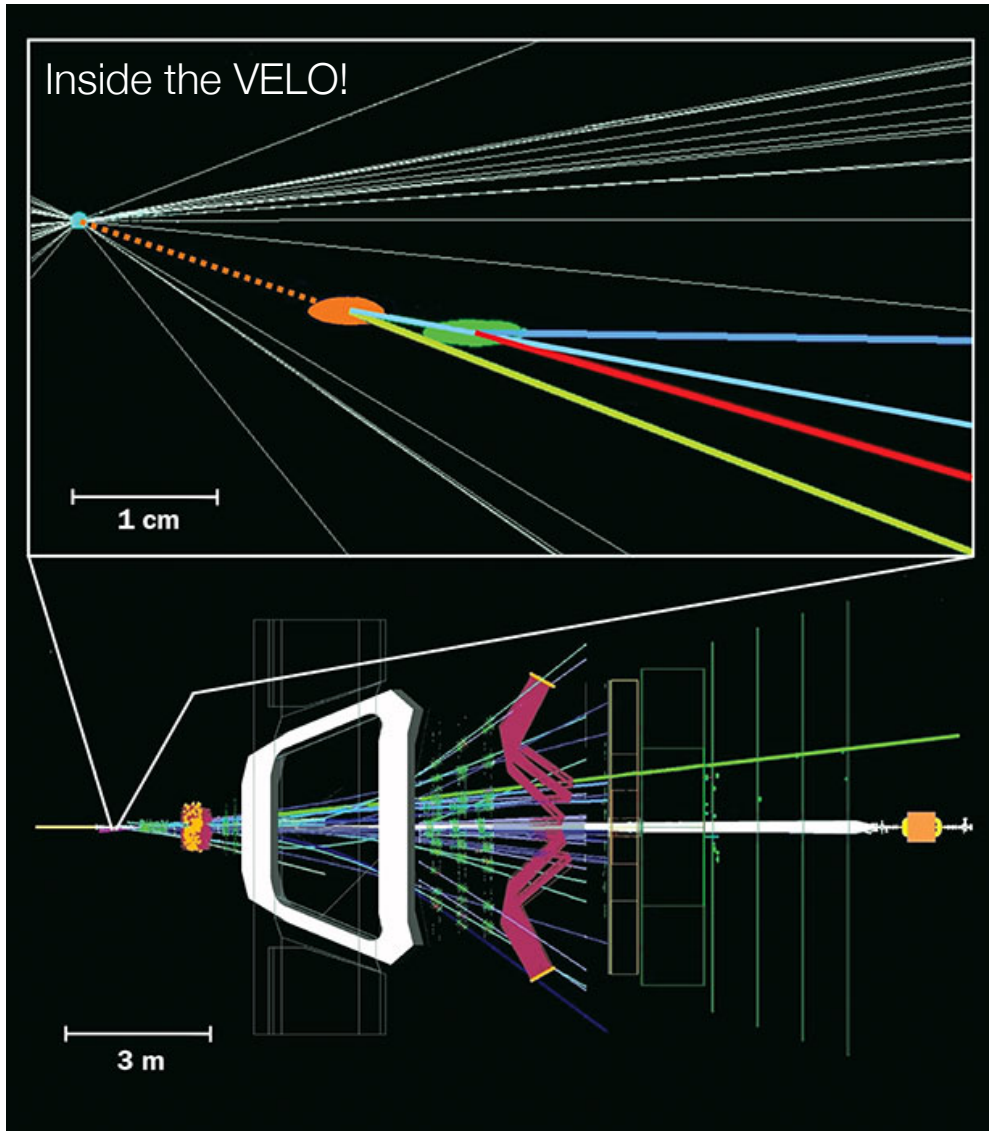
Heavy Ion collision studies

“Fixed Target” (with Beam-Gas)



Inside the VELO

- Charged particles produced in one proton-proton collision
- Here, one neutral particle containing a b-quark travels along the dotted path
- It then decays into another particle containing a c-quark and one other charged particle
- The c-quark containing particle then travels further and decays into three charged tracks



LHCb Conference / Workshop Participation

since 2024
imminent
organised

Expect more as Run 3 data is analyzed!

UNIVERSITY OF LIVERPOOL

Liverpool LHCb Grants / Awards / Prizes / etc…

LHCb Collaboration

2025 Breakthrough Prize in Fundamental Physics

For detailed measurements of Higgs boson properties confirming the symmetry-breaking mechanism of mass generation, the discovery of new strongly interacting particles, the study of rare processes and matter-antimatter asymmetry, and the exploration of nature at the shortest distances and most extreme conditions at CERN's Large Hadron Collider.

Vincenzo Vagnoni (INFN, Bologna, spokesperson 2023 to 2026) accepted the prize on behalf of the collaboration. The $500,000 (of the $3 million prize) allocated to LHCb was donated to the CERN & Society Foundation for grants to doctoral students from member institutes to spend research time at CERN.

Backup (other)

LHCb

1787 members
103 institutes
24 countries

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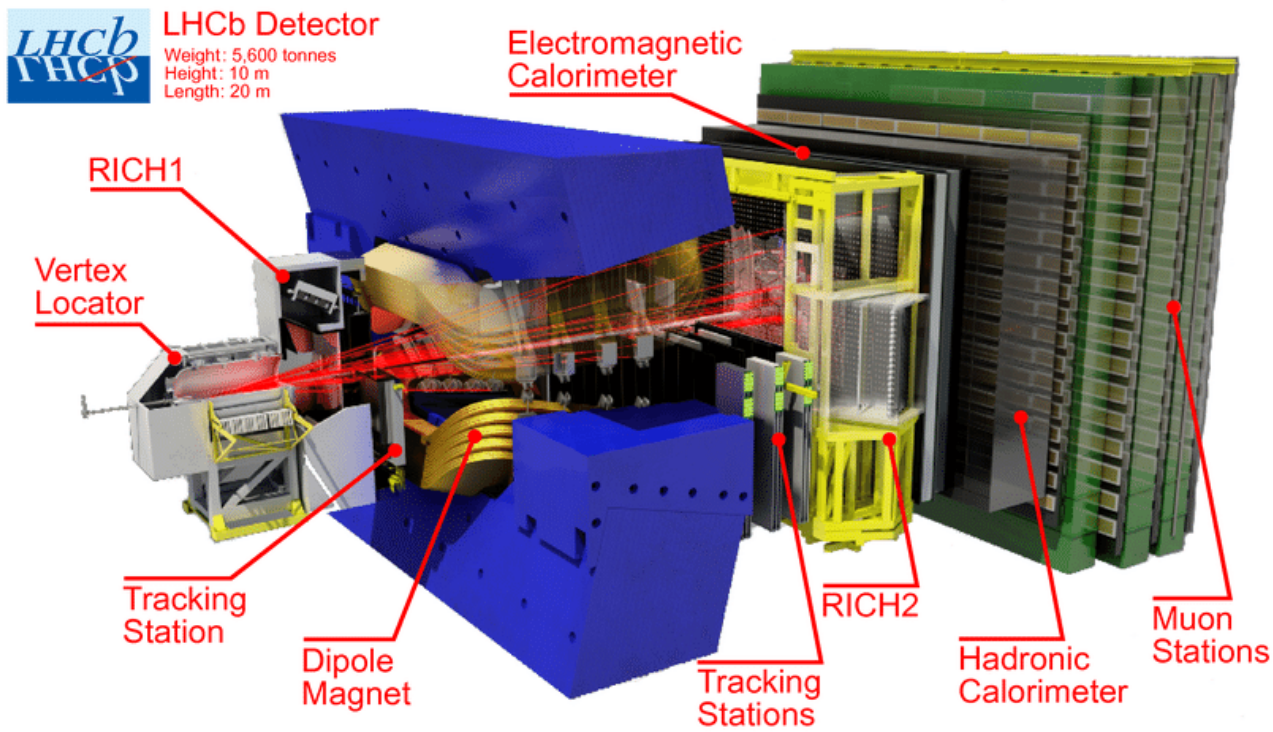
For detailed measurements of Higgs boson properties confirming the symmetry-breaking mechanism of mass generation, the discovery of new strongly interacting particles, the study of rare processes and matter-antimatter asymmetry, and the exploration of nature at the shortest distances and most extreme conditions at CERN's Large Hadron Collider.

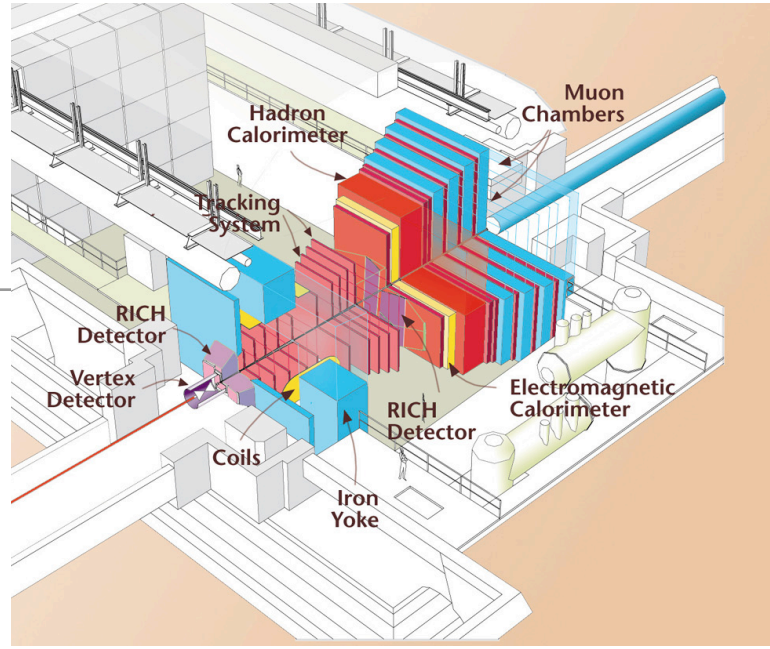
- **Optimised** for quark flavour physics, especially *the precision study of beauty quark and charm quark decays.*

- Over **100,000 b anti-b pairs per second** at the LHCb interaction point. (and 20 times as much charm!)

- Vast quantities of all b-hadron (B^0, B_s, ...) and c-hadron (D^0,D_s, ...) species



LHCb Detector



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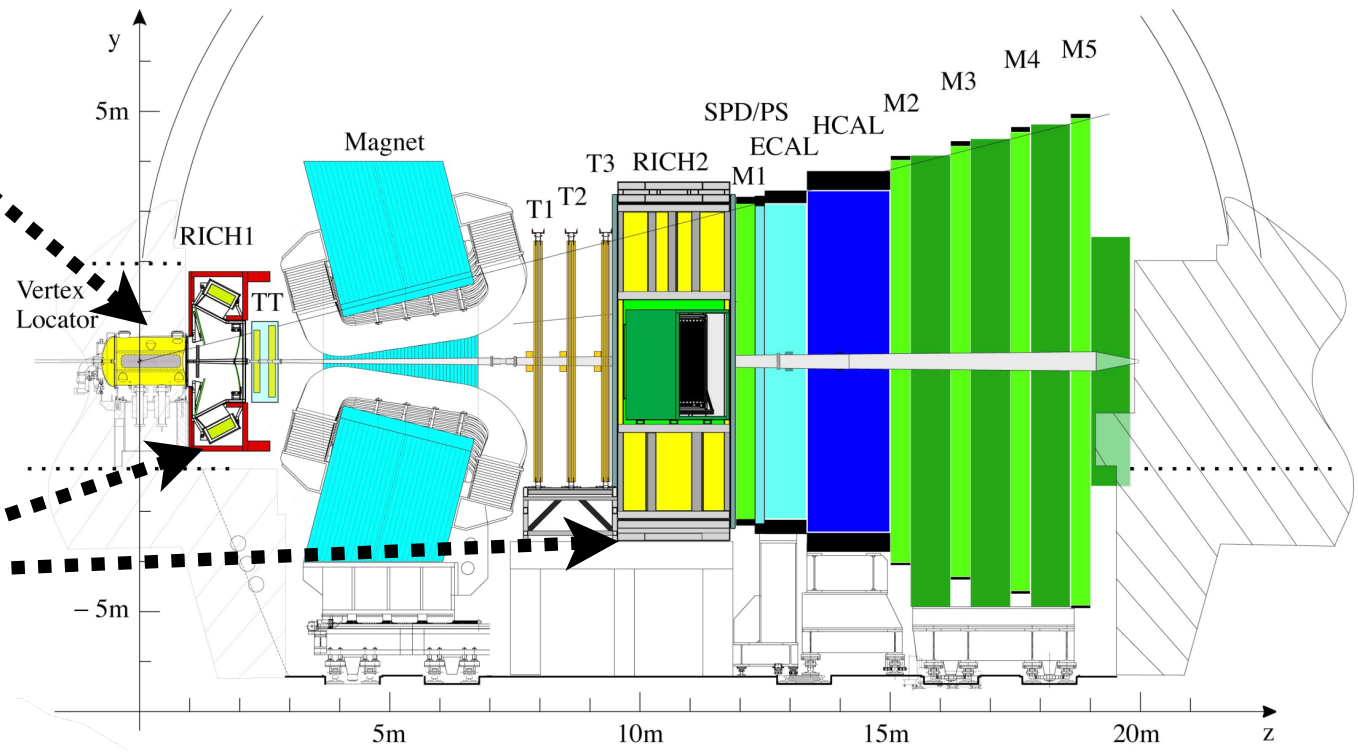
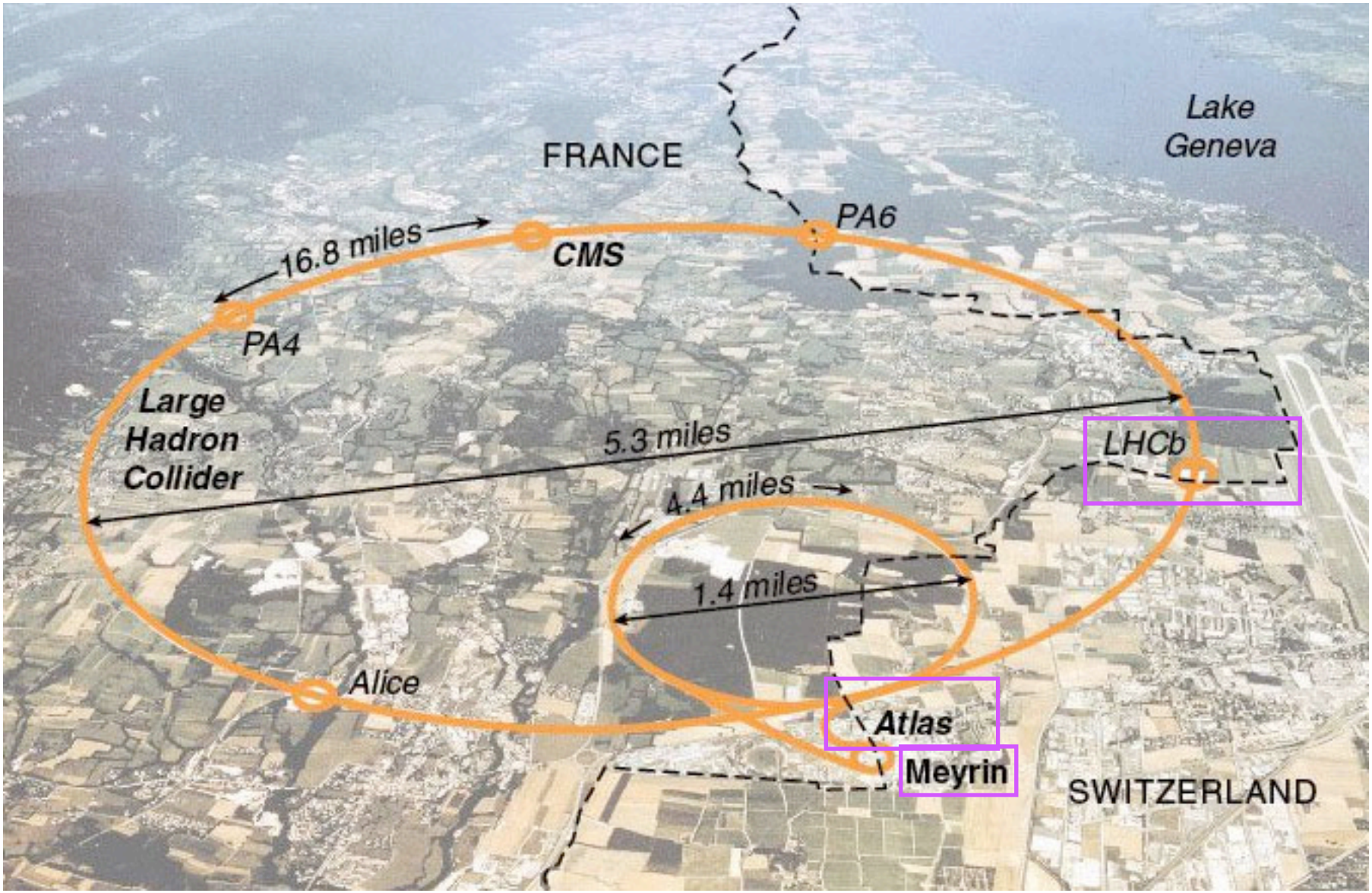
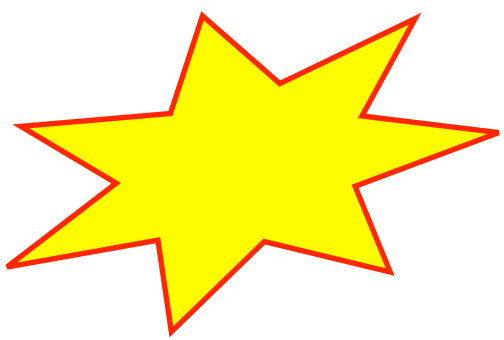


The LHC at CERN

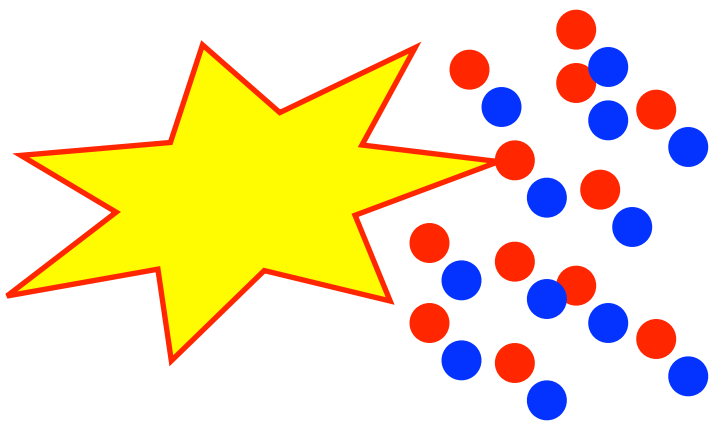


CP violation and the creation of the universe

CP violation and the creation of the universe

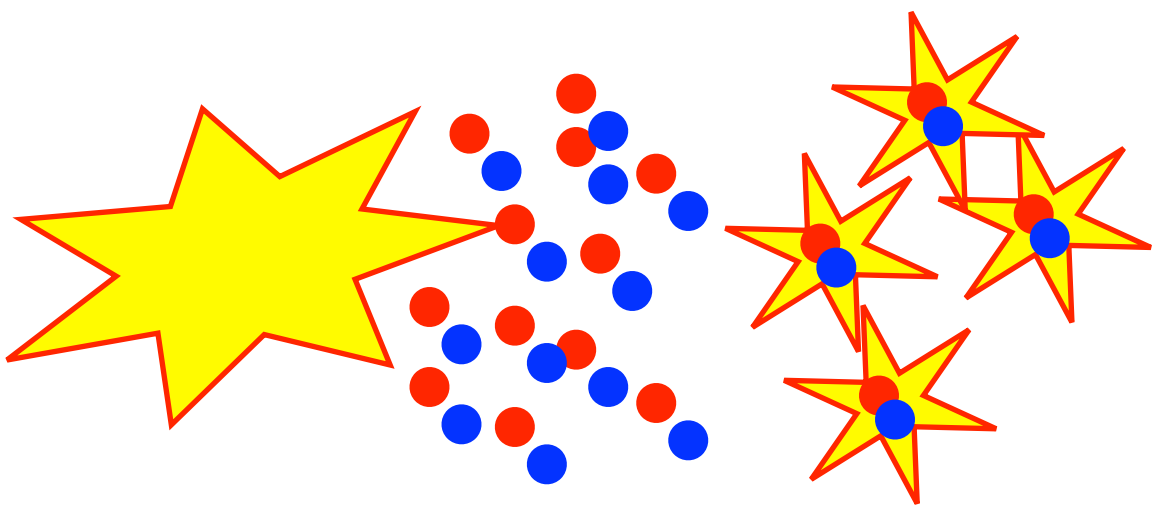


CP violation and the creation of the universe



equal amounts of
matter and
antimatter

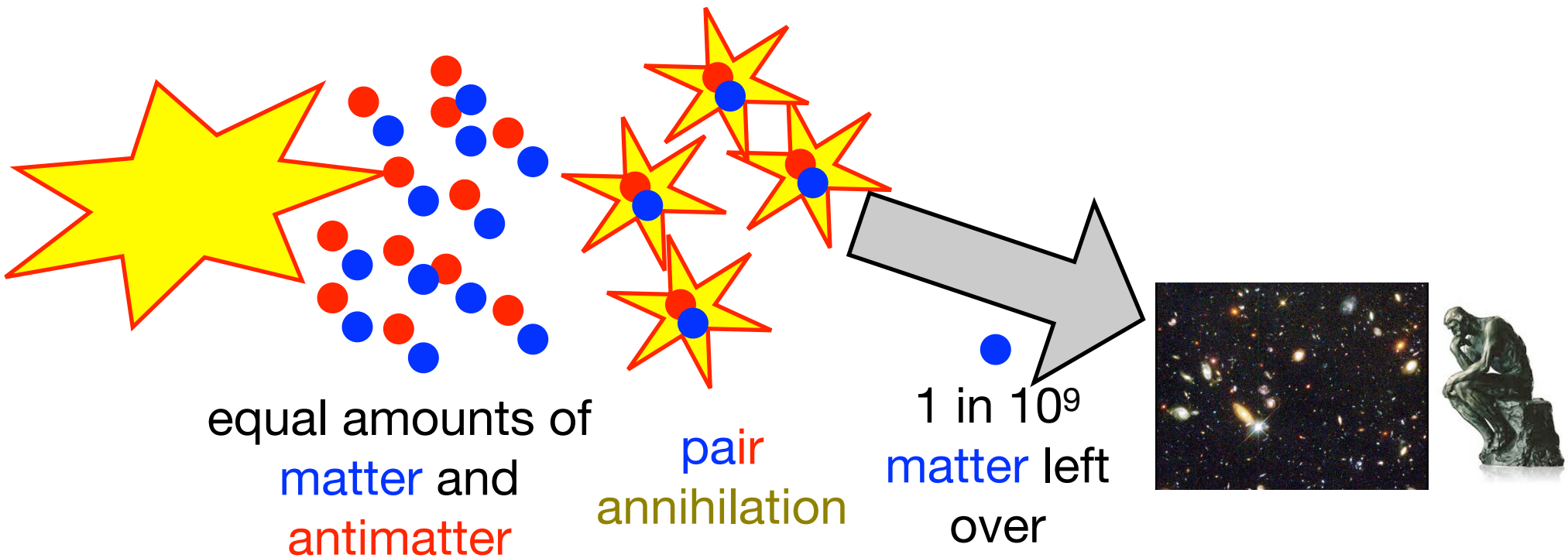
CP violation and the creation of the universe



equal amounts of
matter and
antimatter

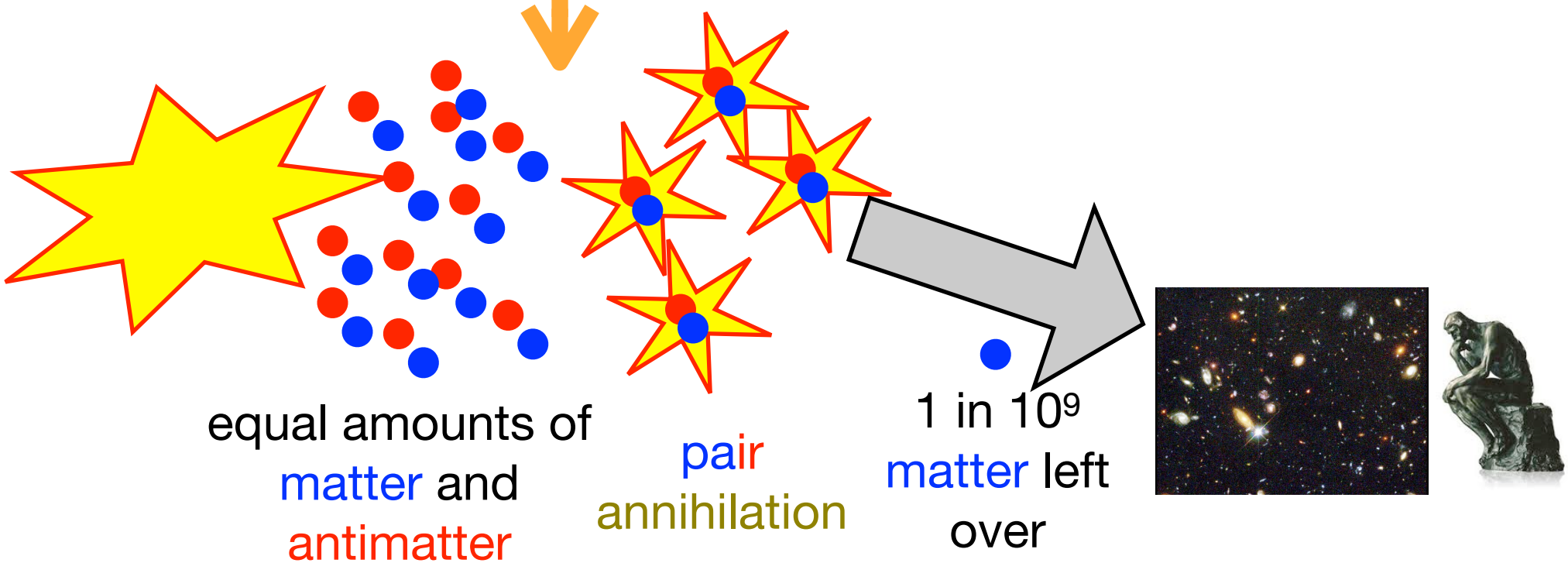
pair
annihilation

CP violation and the creation of the universe



CP violation and the creation of the universe

Somewhere here, matter & antimatter must have behaved fundamentally different - this, in essence, is what CP violation is about. The Standard Model has CP violation, but not enough of it.



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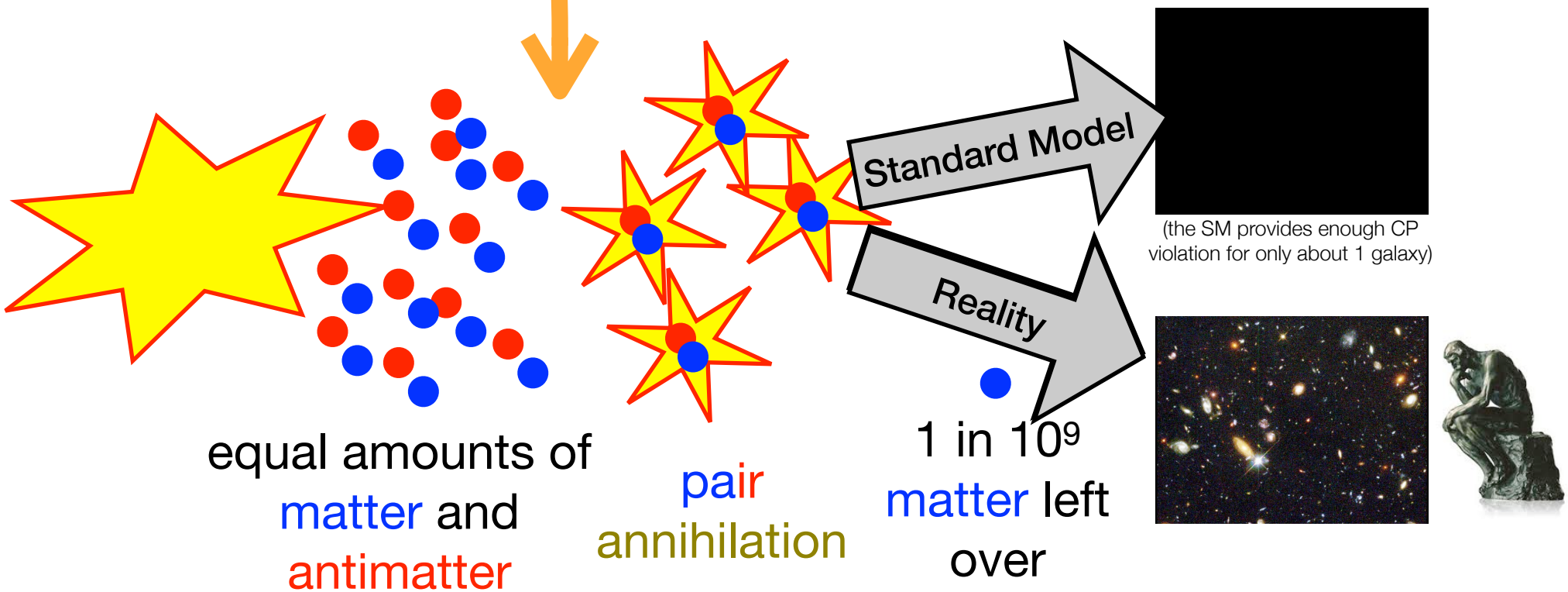
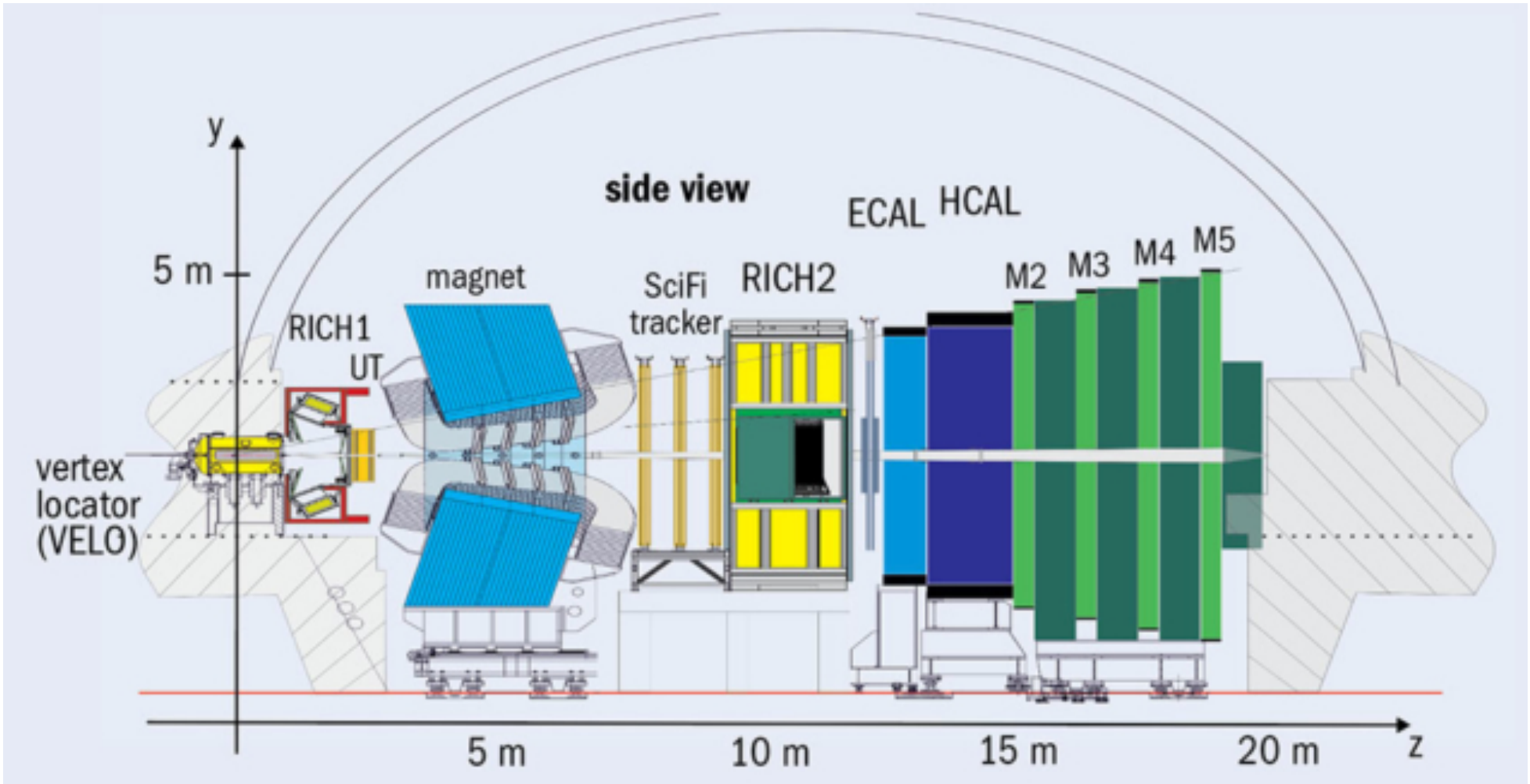


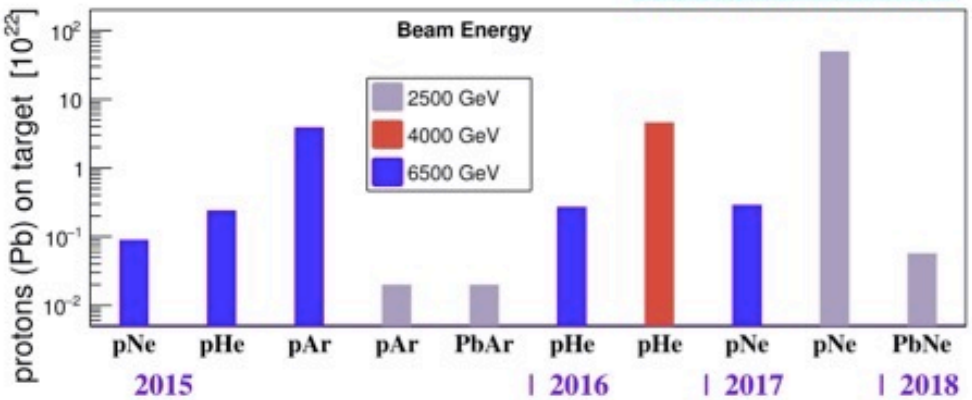
LHCb Upgrade



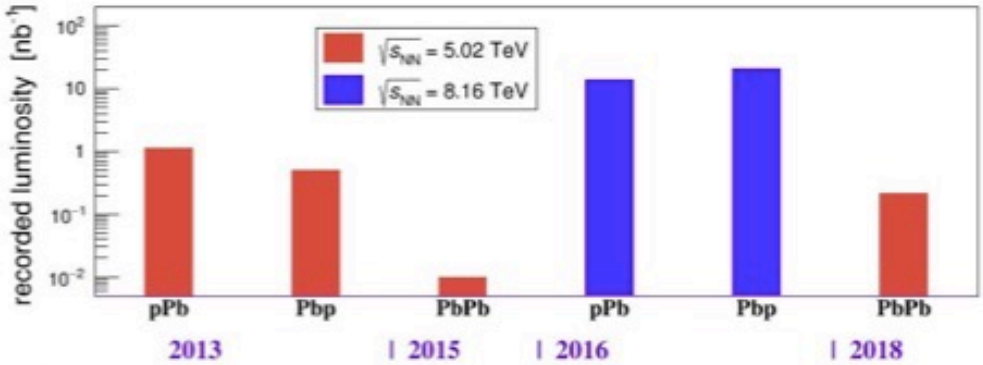
“Fixed Target” & Heavy Ions

A broad and growing physics programme

LHCb-PUB-2018-015



- **Gas injection in the LHC beam-pipe** allows LHCb to also operate in fixed-target mode
- The poorly explored **high-*x* and moderate Q^2** region can be precisely probed in **different collision systems**



- In collider mode, unique pseudorapidity range to study both **forward and backward pPb collisions down to x $O(10^{-6})$**
- PbPb acquisition **limited to 60-100% centrality** due to detector saturation

DPA in a nutshell

https://lhcb-dpa.web.cern.ch/

DPA

Search docs

WORK PACKAGES
- WP1 - Sprucing
- WP2 - Analysis Productions
- WP3 - Offline Analysis Tools
- WP4 - Innovative Analysis Techniques
- WP5 - Legacy Software & Data
- WP6 - Analysis Preservation & Open Data

DOCUMENTATION
- Contributing
- Conferences
- Joint RTA/DPA liaisons
- Publications

MISCELLANEOUS
- Storage group area
- Useful links

» Welcome to the Data Processing & Analysis (DPA) project — Edit on GitLab

Welcome to the Data Processing & Analysis (DPA) project

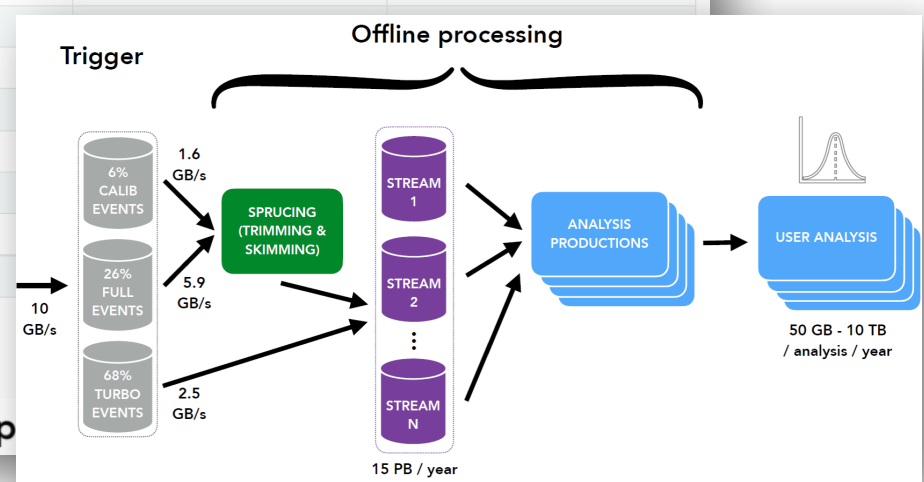
The **Data Processing & Analysis, DPA, project** addresses the challenges for offline data processing and analysis due to the very large increase in data volume with respect to Run II. DPA is built around 2 main ideas:

- Centralised skimming and trimming (aka Sprucing) of a significant fraction of HLT2 outputs.
- Centralised analysis productions for physics WGs and users.

Overviews of the project Work Packages and offline processing flow are given below. The general project mailing list is lhcb-dpa-general.

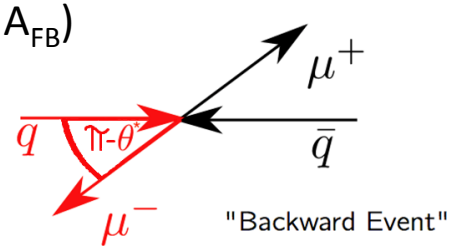
Work package	Coordinator(s)	Mailing list	Mattermost
Overall coordination	Eduardo Rodrigues		
WP1 - Sprucing	Nicole Skidmore		
WP2 - Analysis Productions	Chris Burr		
WP3 - Offline Analysis Tools	Patrick Koppenburg		
WP4 - Innovative Analysis Techniques	Donatella Lucchesi		
WP5 - Legacy Software & Data	Federico Leo Redi		
WP6 - Analysis Preservation & Open Data	Sebastian Neubert		

Overview of DPA's data processing flow



Weak Mixing Angle $Sin^2\theta_W$

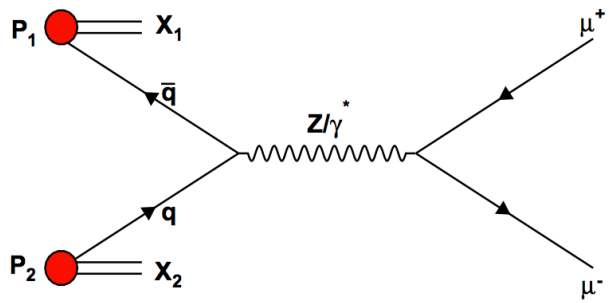
- The two most precise measurements (LEP and SLD) measured different processes at similar precision, have a 3.2σ variation
- Overall LEP and SLD average shown by the vertical band
- Currently measuring $Sin^2\theta_W$ via the forward backward asymmetry (A_{FB}) in $Z \rightarrow \mu^+\mu^-$ decays.
- The interference between Z boson and virtual photon gives rise to a non-zero AFB value
- $Sin^2\theta_W$ cannot be measured directly, it is extracted from the measurement of variables sensitive to it (eg A_{FB})
-



number of backward events

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

number of forward events



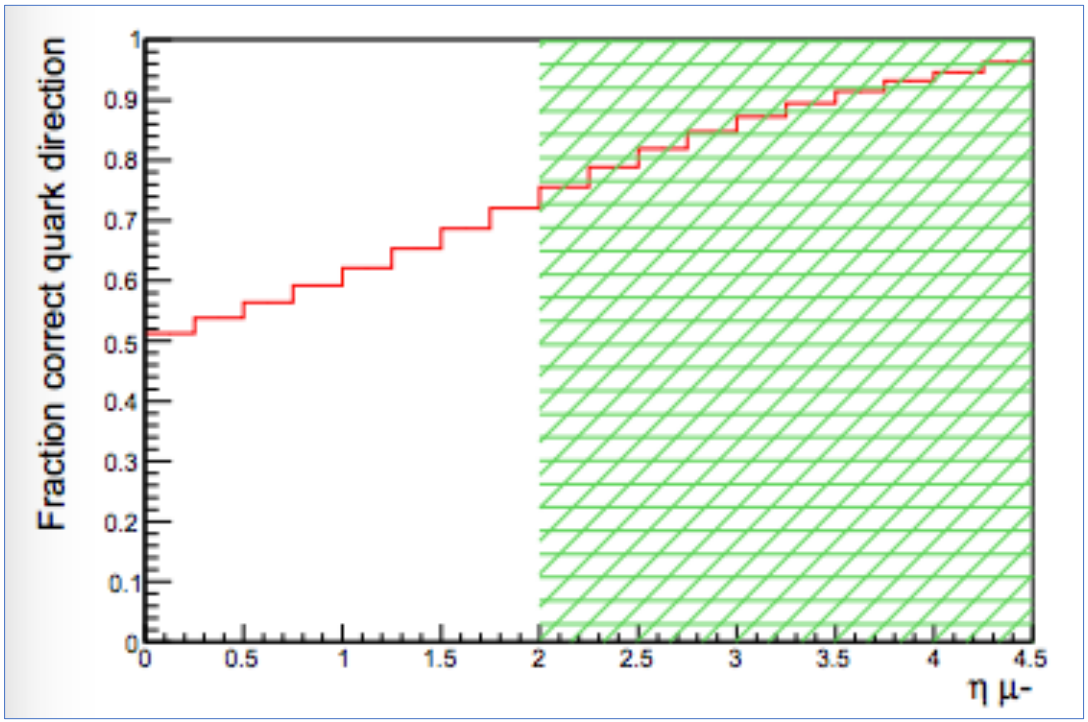
[ATLAS-CONF-2018-037]

- Extracted via a comparison of MC templates and data
- Run 2 data, 6fb^{-1} via the forward backward asymmetry, A_{FB} in $Z/\gamma^* \rightarrow \mu^+\mu^-$
- Previous LHCb result used 7 TeV and 8 TeV with 1 fb^{-1} and 2 fb^{-1} of data respectively

[CERN-THESIS-2011-202]

LHCb and Weak Mixing Angle $Sin^2\theta_W$

- LHCb focuses on higher rapidity range, $2 < \eta < 5$, which has high sensitivity to A_{FB} and therefore $Sin^2\theta_W^{eff}$
- Asymmetry most pronounced when the Z boson direction is correctly known
- The further forward the more likely that the Z boson follows the direction of the quark
- LHCb focuses on the forward region and the further forward in rapidity, the more likely the Z forward direction is determined correctly



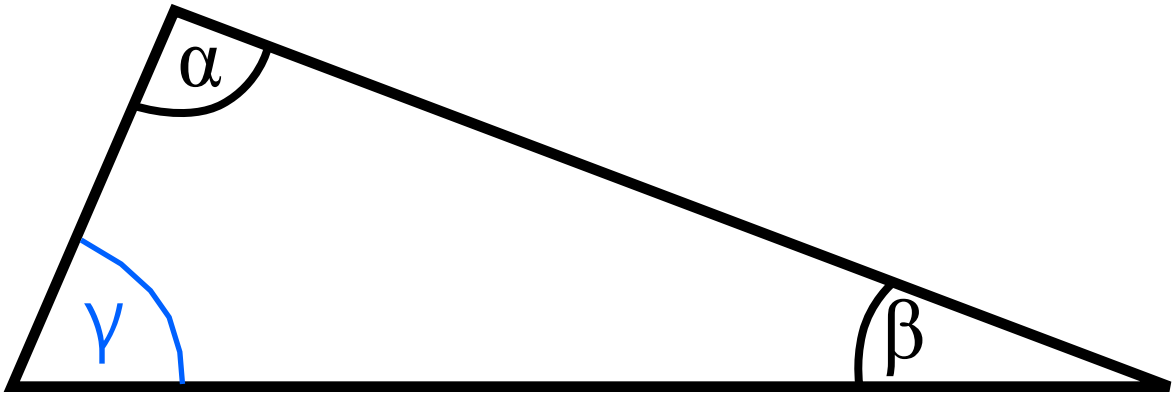
[LHCb-ANA-2015-002 28/09/2015]

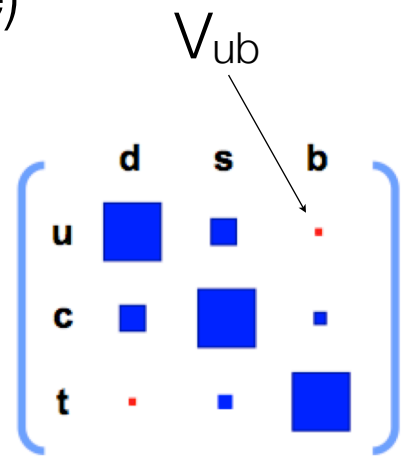
$\mathrm{Sin}^2\theta_W$ Calculation at LHCb

- Values for A_{FB}^{pred} are found via MC using a range of values for $sin^2(\theta_W^{eff})$
- χ^2 is calculated by comparing A_{FB}^{pred} to data values of A_{FB}
- Quadratic functions are fitted to the distributions
- The difference between χ^2 values and the minimum χ^2 value is plotted as a function of the $sin^2(\theta_W^{eff})$ values used in MC
- The minimum of the plotted χ^2 distribution is the final value of $sin^2(\theta_W^{eff})$

The Unitarity Triangle and γ

Geometrical representation of the relationships of (some) parameters of Kobayashi and Maskawa's theory





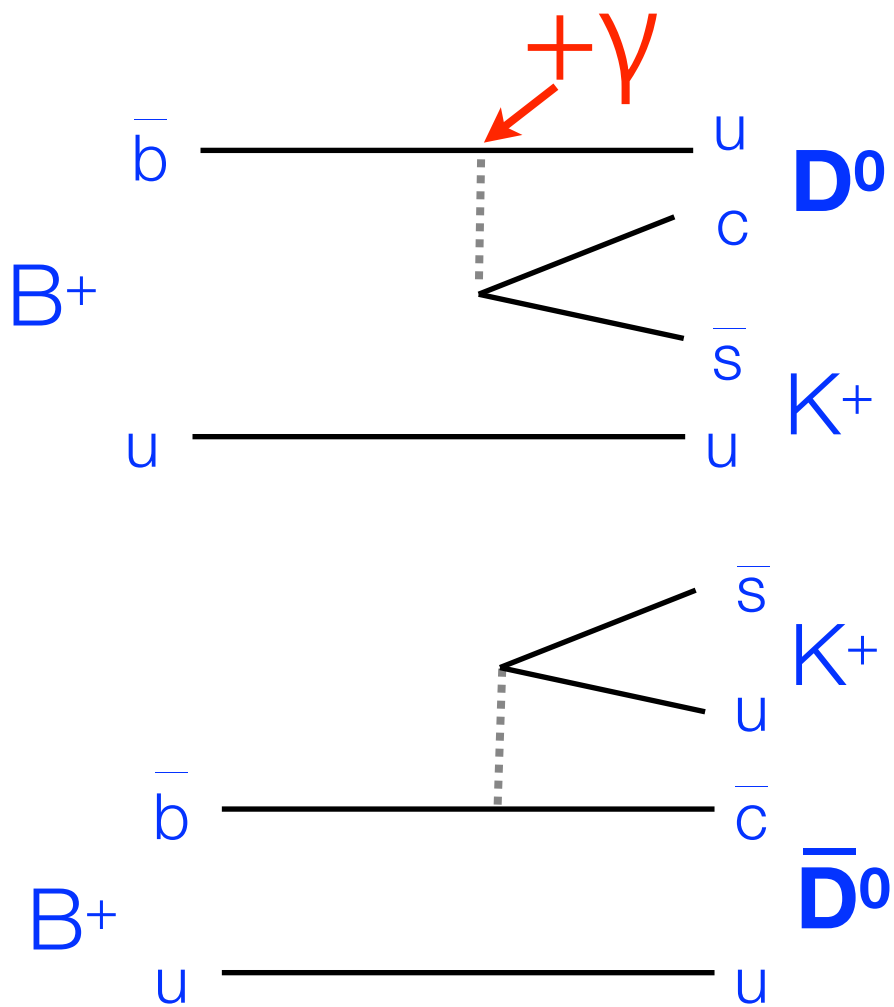
The angle γ is one of the phase angles responsible for **CP violation**...
...but it's poorly measured, and the least-well known of these angles

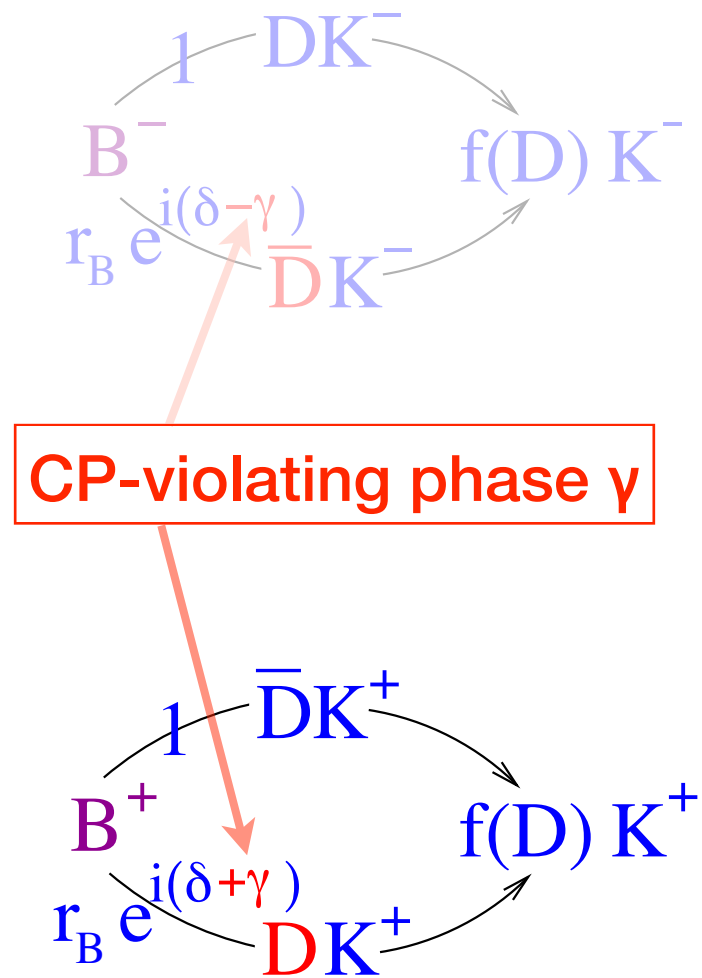
$\gamma = \arg(V_{ub}^{*}) = (63.8\,^{+3.5}_{-3.7})^{\circ}$ (from LHCb direct measurements)
LHCb-CONF-2022-002

LHCb will increase the precision of this measurement in Run 3!

CP Violating phase γ from B±→DK±

+1 ● in October!





Gronau, Wyler Phys.Lett.B265:172-176,1991, (GLW), Gronau, London Phys.Lett.B253:483-488,1991 (GLW) Atwood, Dunietz and Soni Phys.Rev.Lett. 78 (1997) 3257-3260 (ADS) Giri, Grossman, Soffer and Zupan Phys.Rev. D68 (2003) 054018 Belle Collaboration Phys.Rev. D70 (2004) 072003

LHCb VELO

- Rocky start to the 2023 where the VELO RF Foil got deformed when the automated balancing system failed , resulting in build up of pressure beyond spec
  - Note: this system is not the responsibility of the VELO group
- We have been doing a tomography of the foil using secondary interactions to determine the extent of the damage. Very impressive imaging power! (next slide)
- We continue all the other commissioning work on the VELO
  - First long tracks of 2023 on 5th May!
  - DAQ and Control firmware running smoothly (Karol)
    - New versions being tested to accommodate large events for Pb-Pb running at the end of the year
    - Improvements for time alignment, resource usage
  - Testing new scanning routines with fast firmware techniques
  - New Front-end control and configuration framework (Kurt)
    - Major rewrite to calibration and configuration chain
  - End-to-end determination of fibre mapping (Abbie)
  - Work on Noise and bad channel mapping (James)
  - Update the VELO simulation to match the new detector (David, Karol, James)

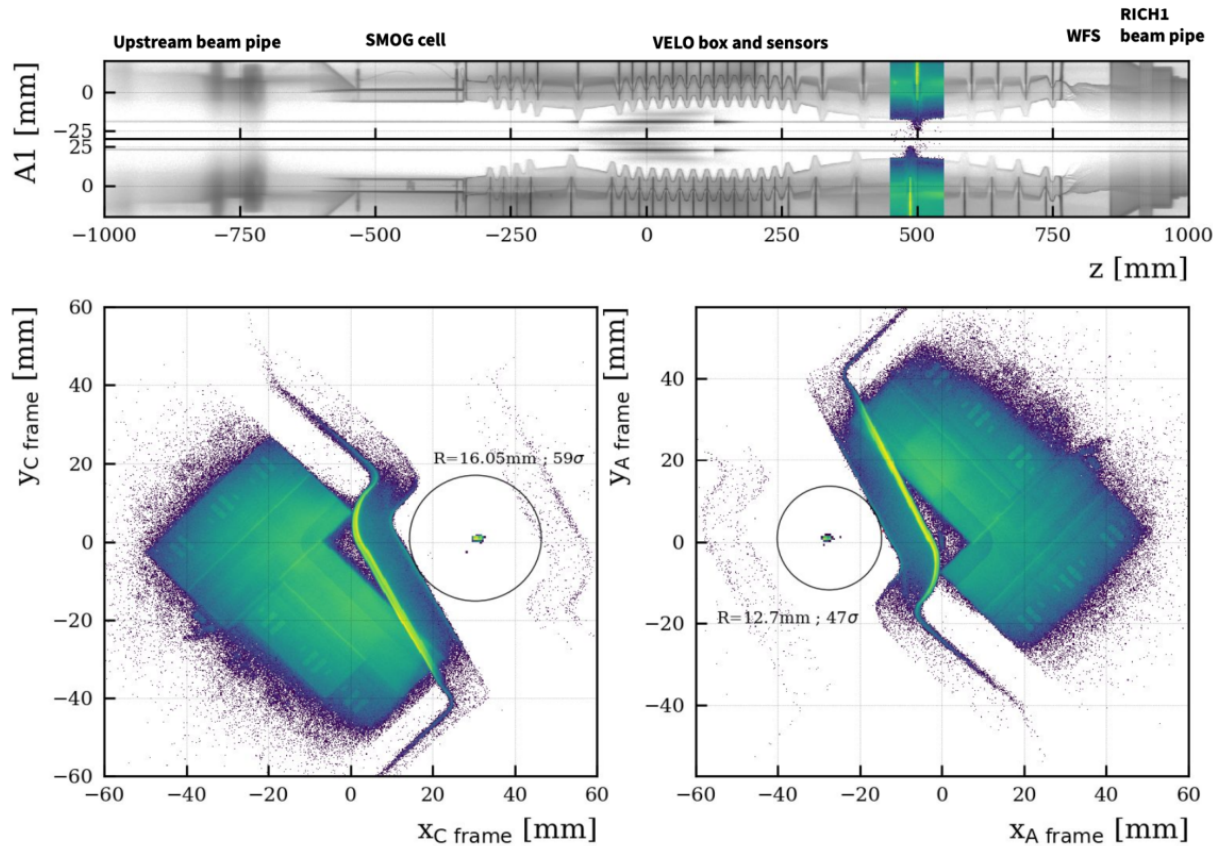
LHCb VELO

- multiple equipment failures resulted in a build up of pressure beyond specification between VELO and beam volumes
- RF foils have been deformed. VELO modules do not show damage
- Physics programme significantly affected in 2023

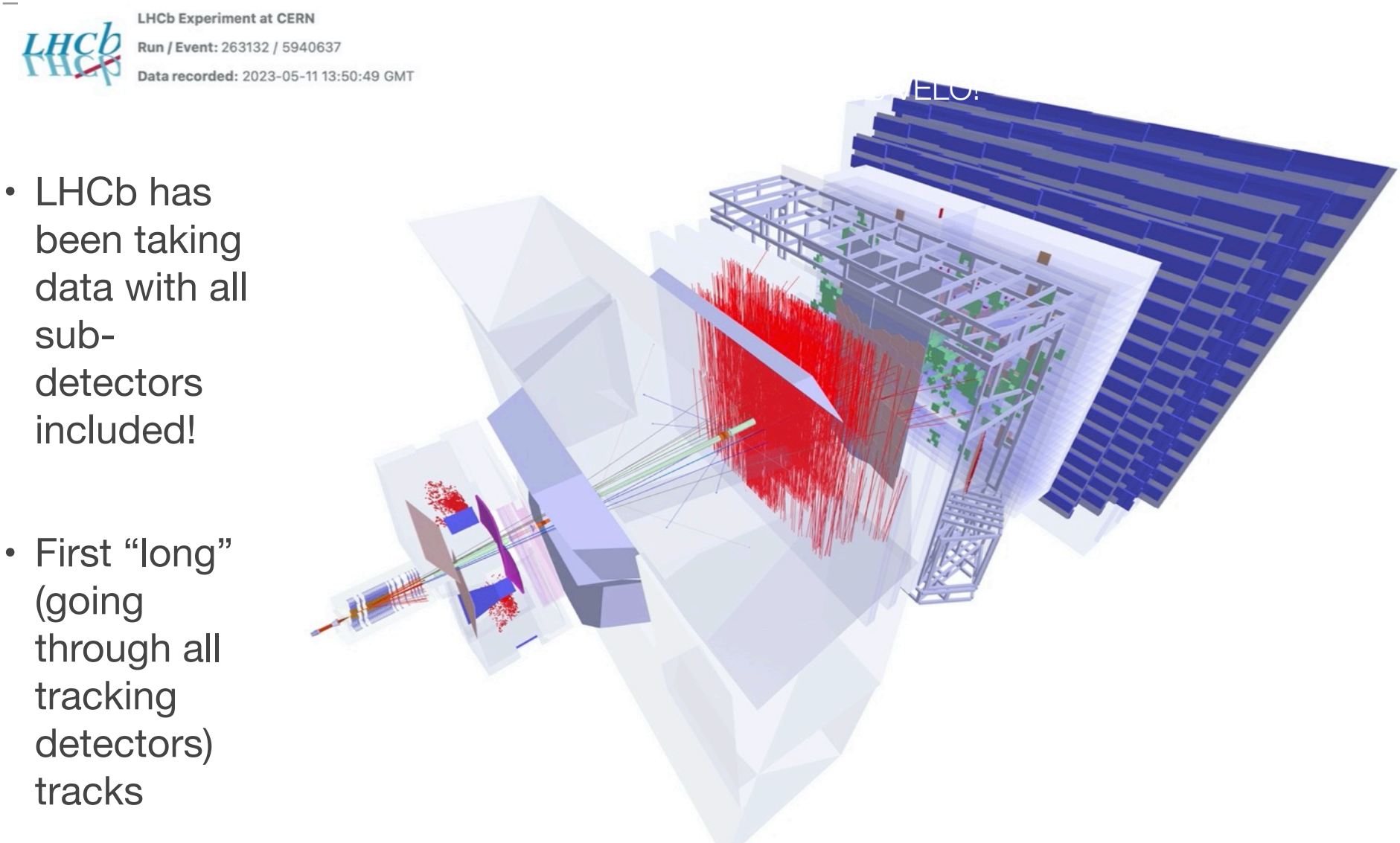
- Also, after helping to install the VELO, Kieran has been involved in inspections and repairs during the VELO commissioning

- Plan is to replace the RF foil at year-end — involves dismantling the entire VELO, support structure and upstream beam pipe

Precise Tomography of the VELO (using beam-gas)



Run3 LHCb Event



- LHCb has been taking data with all sub-detectors included!
- First “long” (going through all tracking detectors) tracks