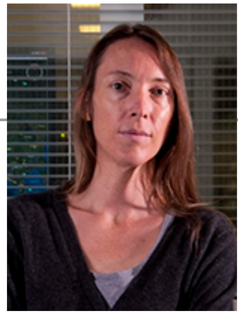
LHCb Liverpool Physics and M&O

Dr Paras Naik
Particle Physics Group Meeting
18 May 2023

The Friendly Faces of LHCb Liverpool

UNIVERSITY OF LIVERPOOL

(in Liverpool)


Tara


David


Themis


Eva

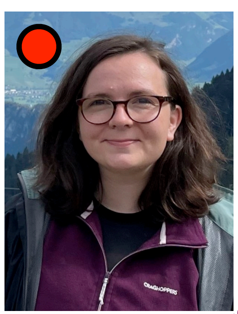

Paras New!


Ayushi


Ashley

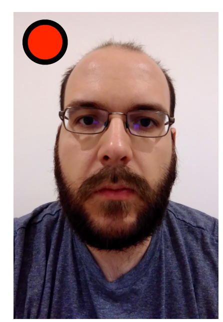

Kieran


John


Abbie Back from CERN!


Ned


Thomas

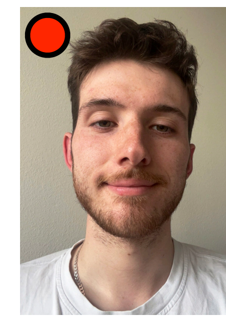

Jan

(at CERN)


Eduardo


Karol


Kurt


James

(at Karlsruhe)


Sigrid

● students

In October
New RA
+1 ● (!)

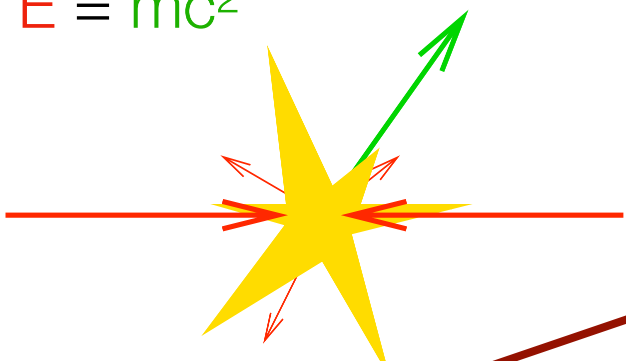
We are an active group, leading the field...
We've built/invented detectors, techniques, and tools used to collect/analyse LHCb data.

Two Roads to New Physics

Direct Observations

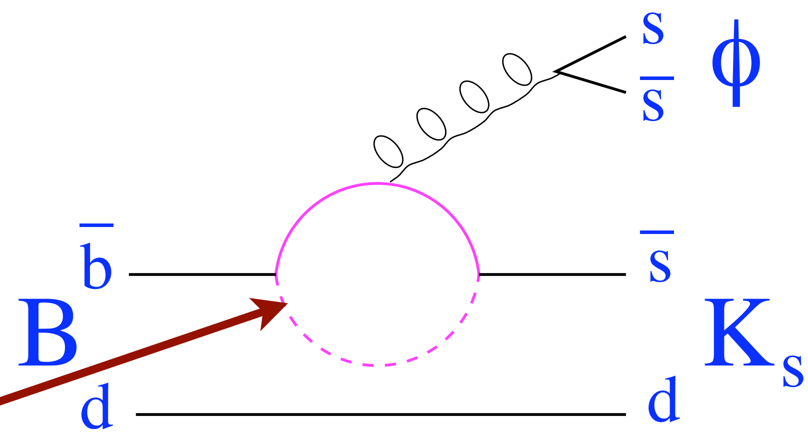
Particles with $mc^2 > E$ cannot be produced directly

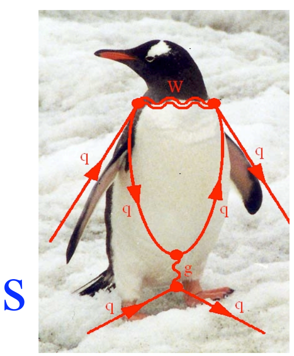
$E = mc^2$



Indirect Effects

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





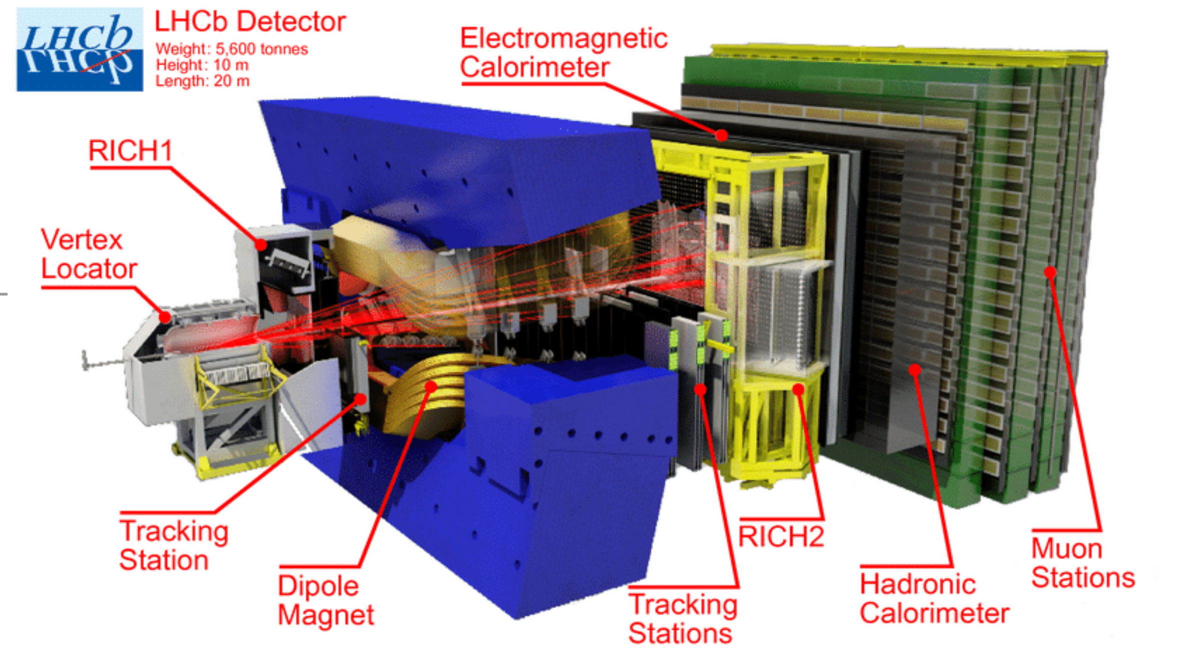
This kind of approach is sensitive to particles *far heavier* than those directly produced in a collider.

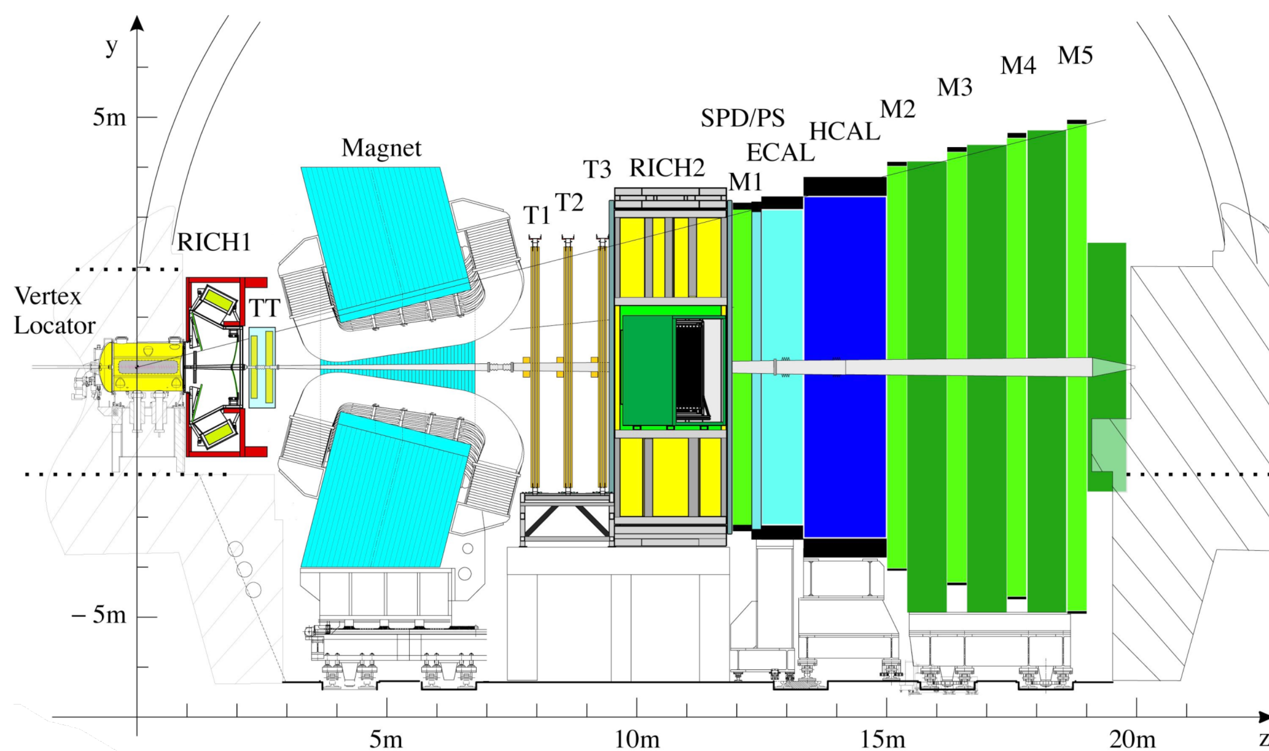
Flavour physics lets you *see beyond the energy frontier*...
LHCb is designed for this!

LHCb

1610 members
96 institutes
21 countries

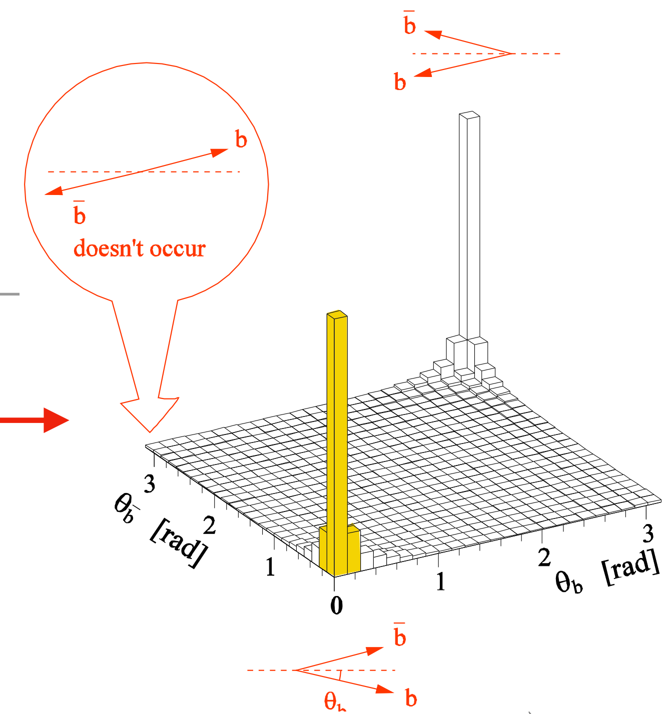
- **Optimised** for quark flavour physics, especially *the precision study of beauty quark and charm quark decays.*
- **100,000 b anti-b pairs per second** at the LHCb interaction point. (and 20 times as much charm!)
- Vast quantities of all b-hadron (B^0, B_s, ...) and c-hadron (D^0,D_s, ...) species





LHCb Experiment

Beauty (and Charm) quarks are produced in forward directions

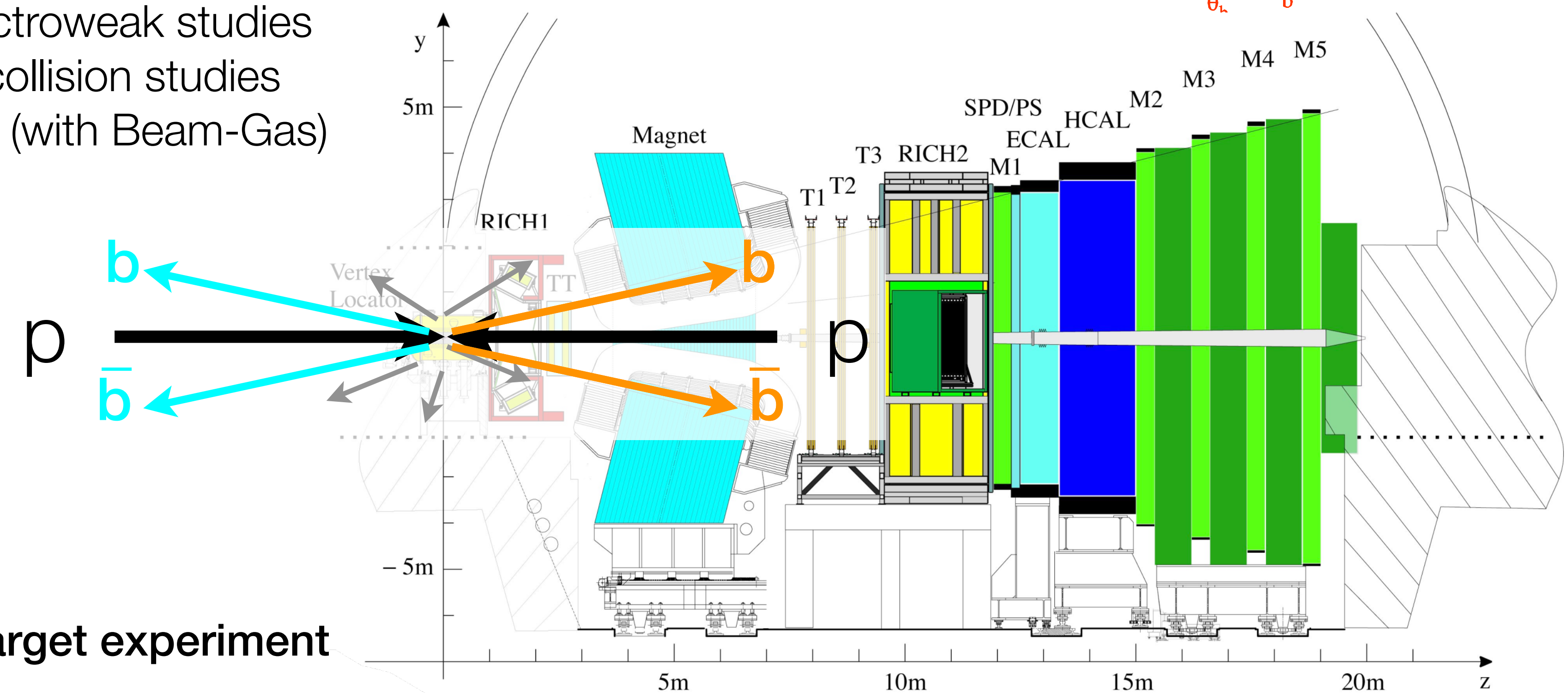


We built our detector to focus on finding these events, but we can do <u>much more</u>

Precision electroweak studies

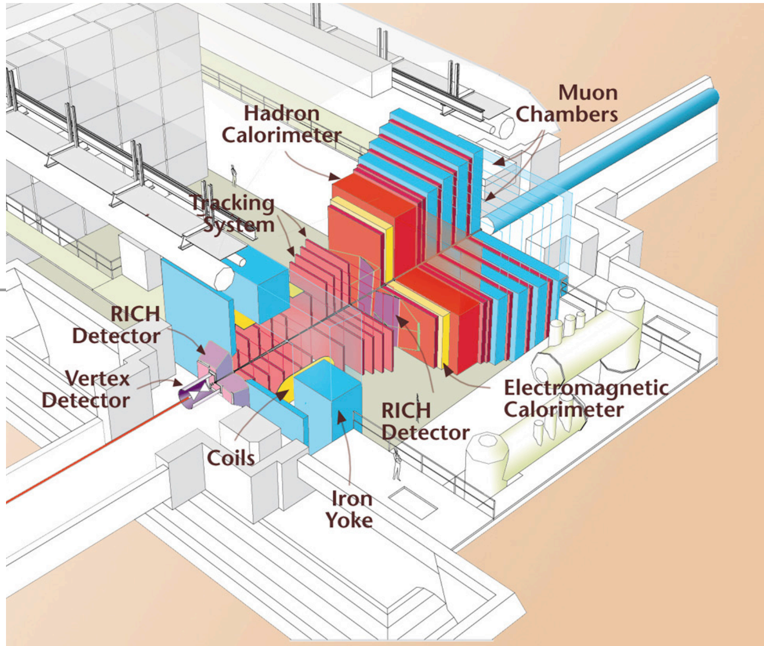
Heavy Ion collision studies

“Fixed Target” (with Beam-Gas)

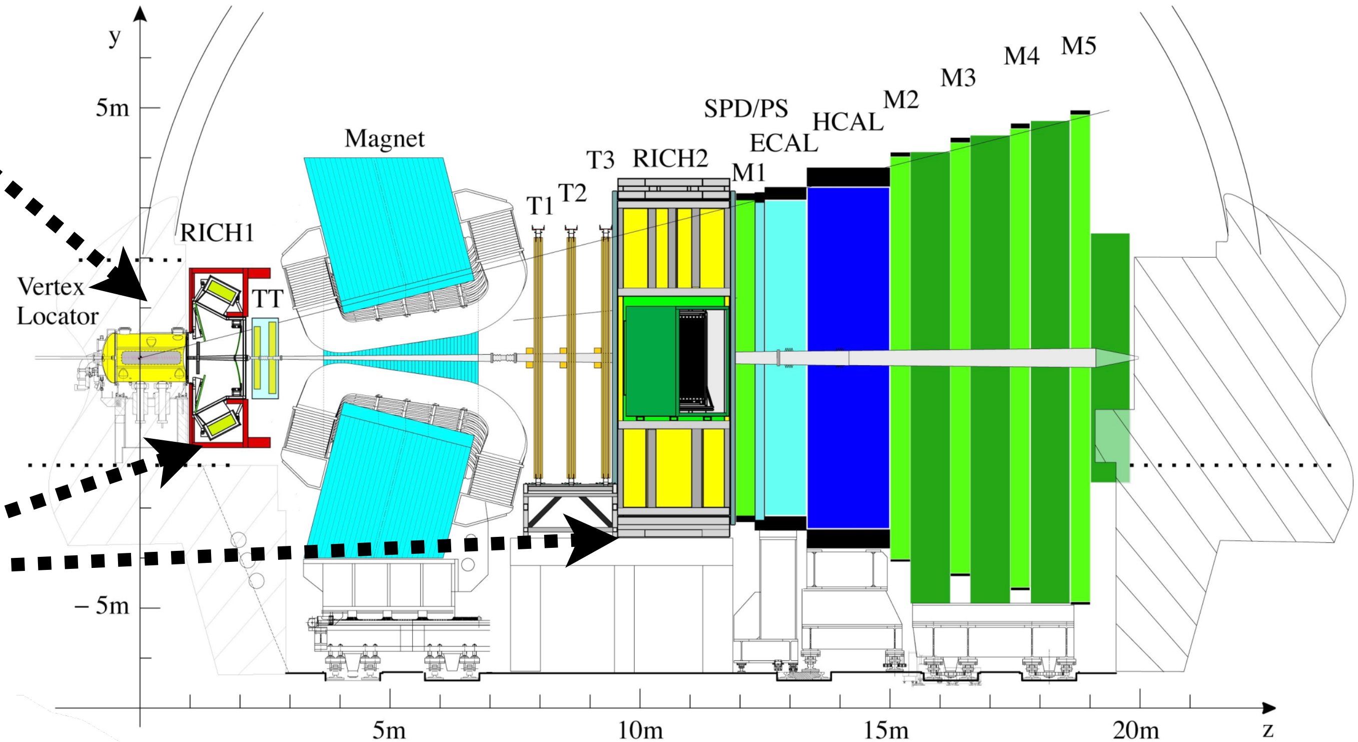


Not a fixed target experiment

LHCb Detector

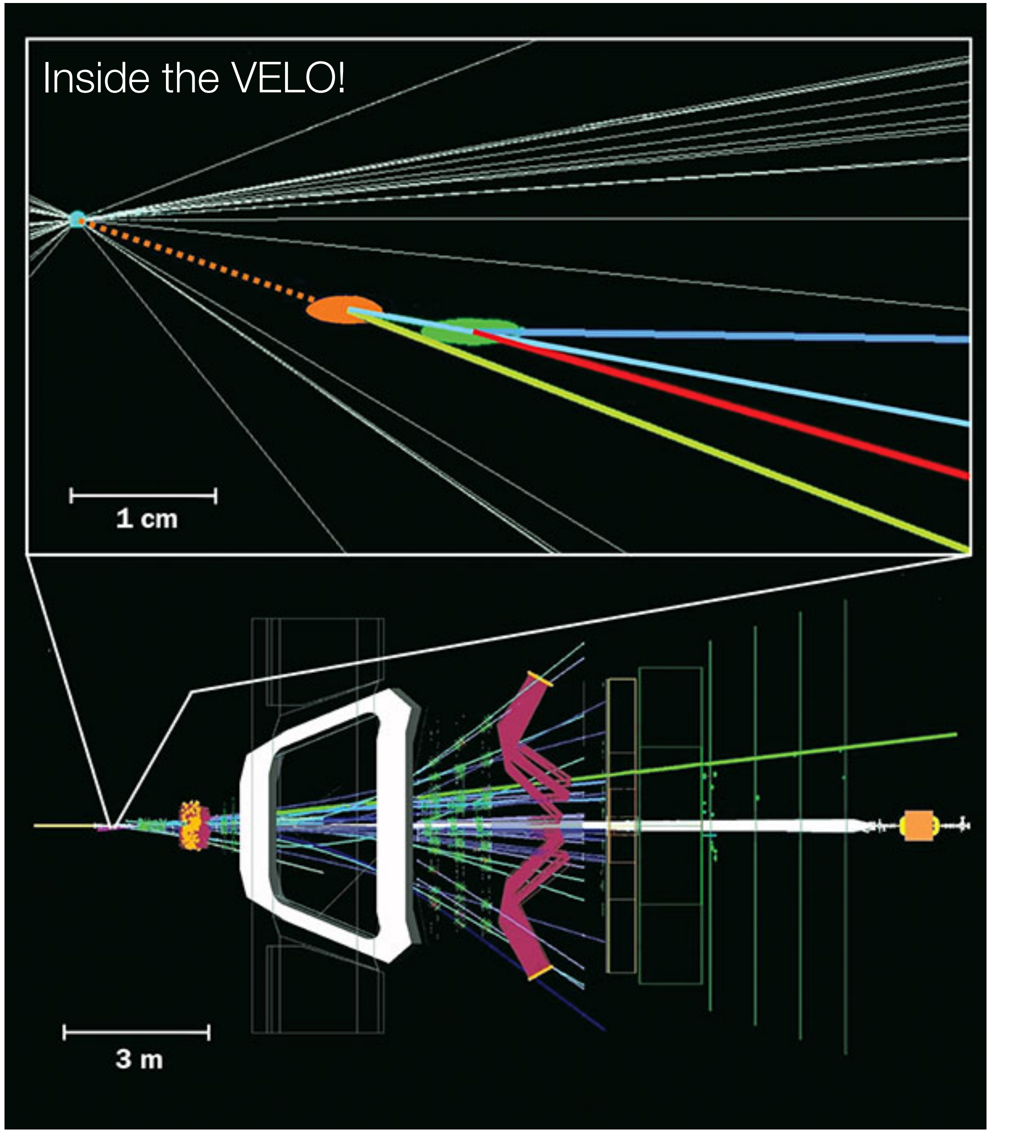


- Many detector elements not found elsewhere at the LHC
- The **VELO** - a vertex detector INSIDE the beam pipe, for excellent impact parameter and decay lengths resolution **Built at Liverpool**
- Two Ring Imaging Cherenkov (**RICH**) detectors provide particle identification.



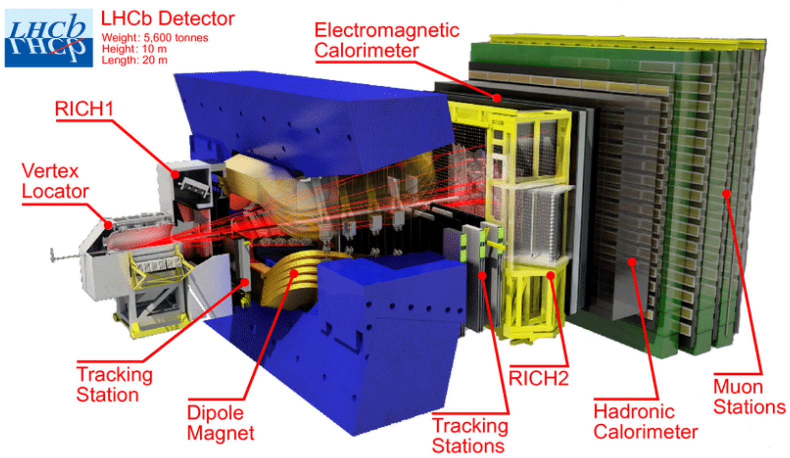
Inside the VELO

- 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



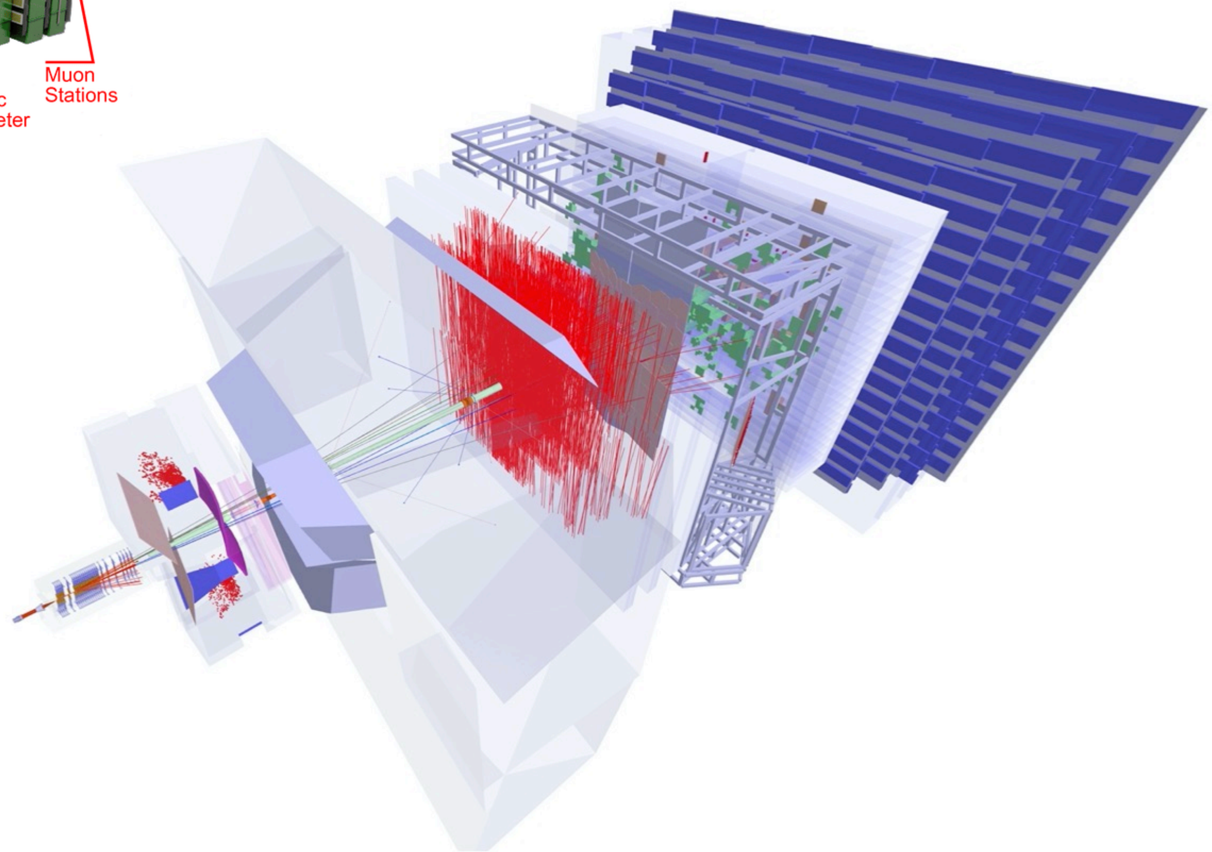
Run3 LHCb Event

9 fb^{-1} of pp collisions recorded so far during LHC Run 1 and 2

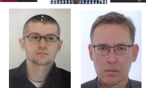
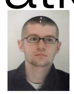
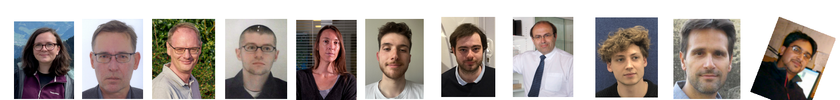


- Event display from **last week:** The first Run 3 LHCb data with all subdetectors included!

- First “long” (going through all tracking detectors) tracks



Liverpool LHCb (& related) Service Work

- 🔴 LHCb VELO Installation & Commisioning 
- 🔴 LHCb VELO & Alignment Operations 
- 🔴 LHCb Mighty Tracker 
- 🔴 LHCb VELO++ software 
- 🔴 LHCb Quantum Computing Activities 
- 🟠 LHCb VELO simulation lead 
- 🟠 LHCb VELO DAQ 
- 🟠 LHCb B to Open Charm convener 
- 🟠 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 RICH alignment leader  University of BRISTOL
- 🔴 Institutional review of LHCb papers 
- 🔴 Many LHCb paper committees, etc…

See Ashley's talk

🔴 responsibility
🟠 leadership

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And many former responsibilities / leadership roles!

See Eduardo's talk

Recent LHCb (& related) Publications

- LHCb $B^0_{(s)} \to p\ \text{anti-}p$ 
- LHCb $B^0_{(s)} \to p\ \text{anti-}p\ p\ \text{anti-}p$ 

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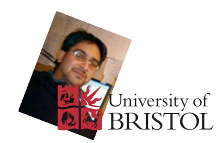
- LHCb $B_s \to \mu^+ \mu^-$ (and $B^0_{(s)} \to \mu^+ \mu^- (\gamma)$ search) Lauren Yeomans (Prior Student) 
- Quantum ML for b-jet charge ID  (As part of LHCb DPA)
- LHCb Measurement of the W boson mass Stephen Farry (left LHCb) 
- LHCb Run 2 RICH performance 

- Novel sources of quantum-correlated charm 

- Heavy Flavour Averaging Group paper 

And several more in review / leadership capacities

- published to conference/journal since ~2022

See Eduardo's talk for Computing & Software publications!

LHCb Conference / Workshop Participation

Liverpool LHCb Grants / Awards / Prizes / etc…

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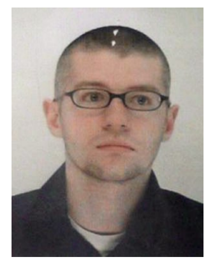
LHCb Upgrade II
(In process)




CERN Scientific Associateship
Oct. 2022 - Sep. 2023

Top-up award
Bell Burnell Graduate Scholarship Fund (IOP)

LHCb VELO

- Rocky start to the year 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)

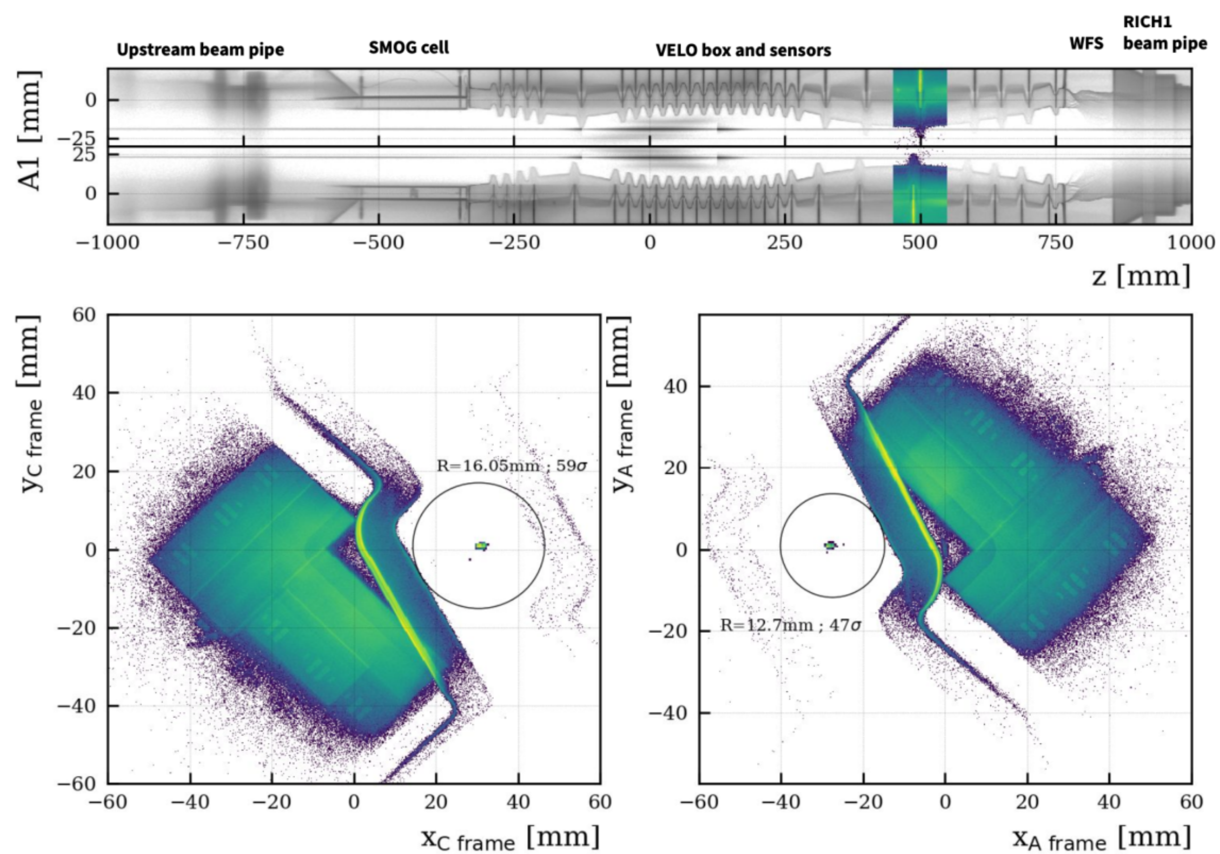
LHCb VELO

- 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

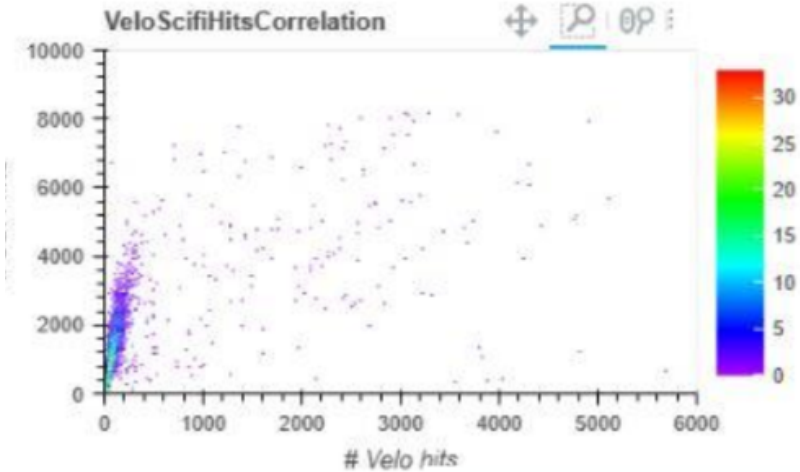
- Also, after helping to install the VELO, Kieran has been involved in inspections and repairs during the VELO commissioning

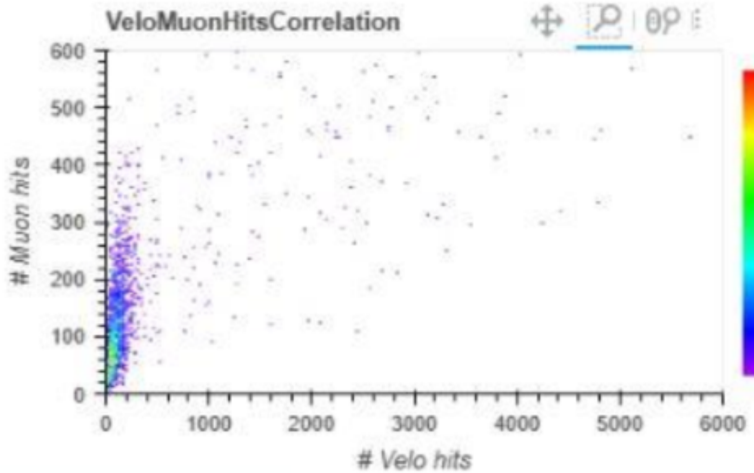
- Plan is to replace the RF foil at year-end — involves dismantling the entire VELO, support structure and upstream beam pipe

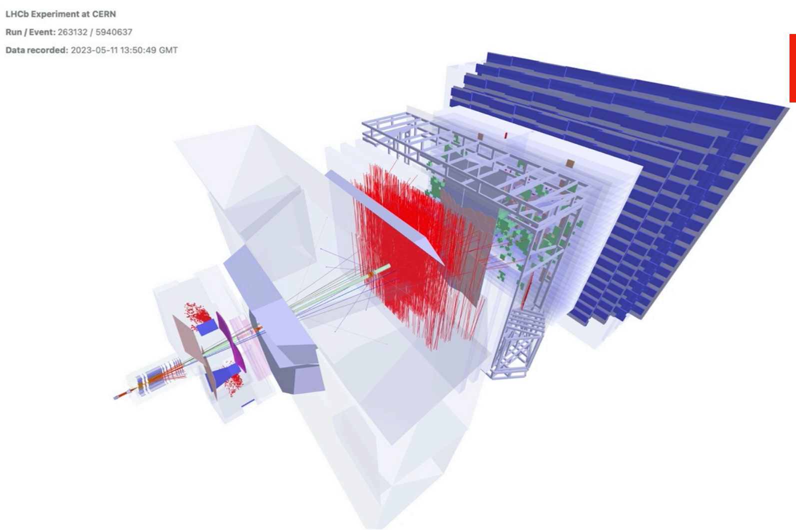
Precise Tomography of the VELO (using beam-gas)

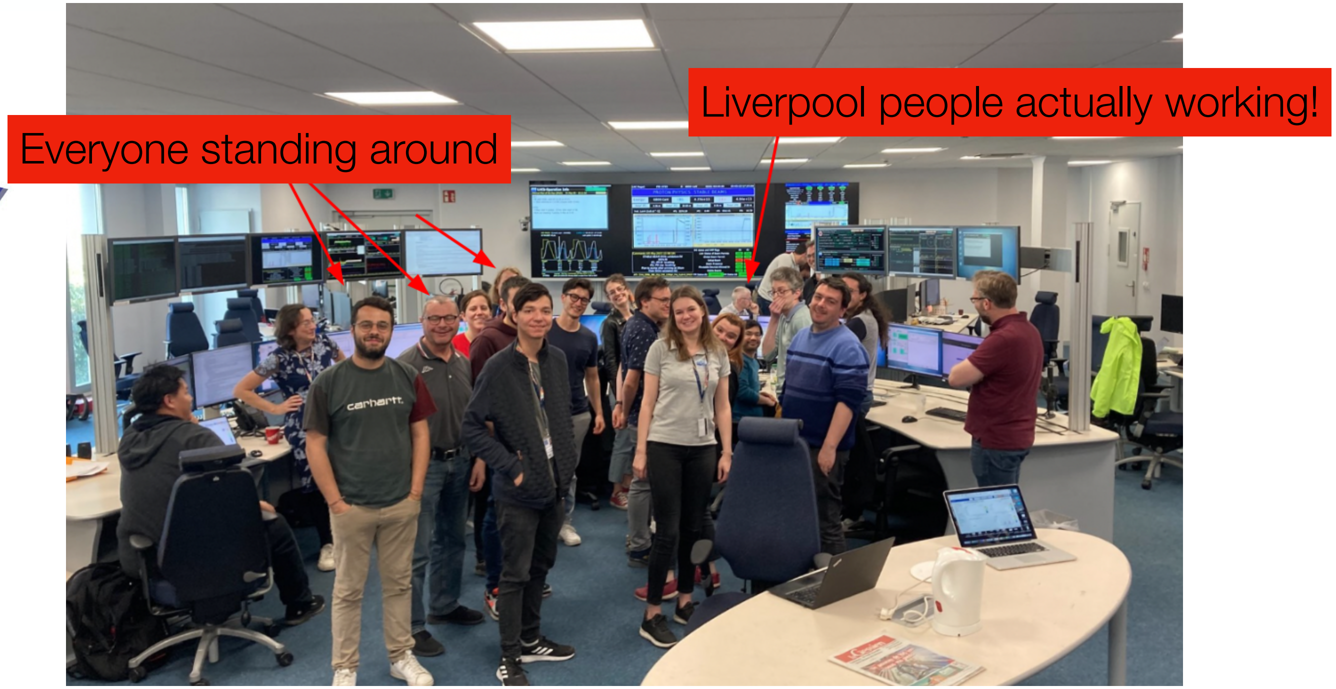


First Long Tracks of 2023!









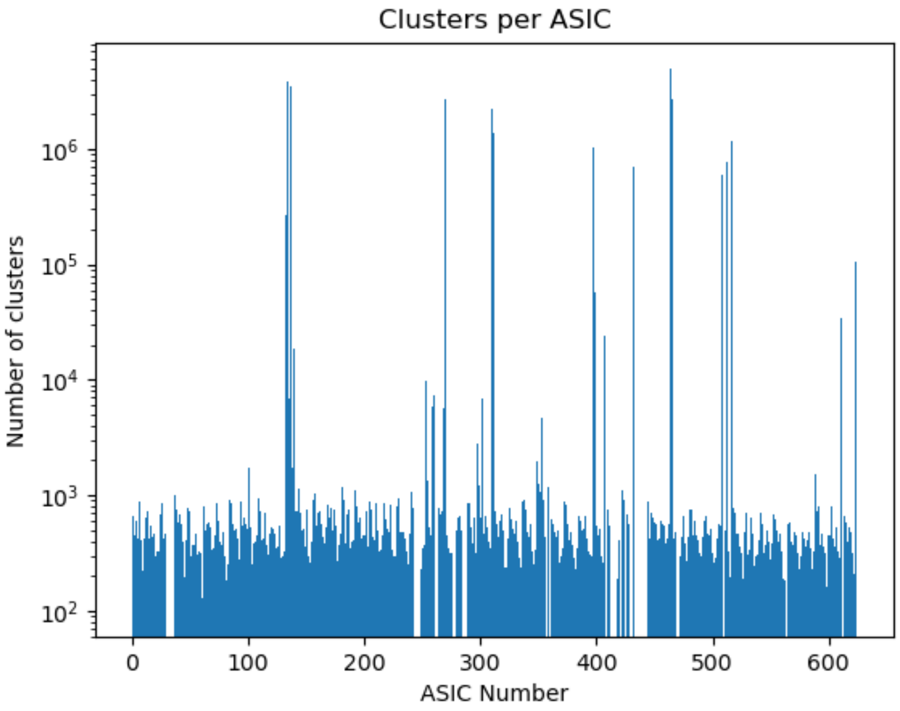
Noise of the VELO

- As seen this morning! (James)

- Producing masks that filter out noisy pixels present in the ASICs

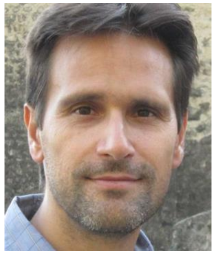
- This will be vital in reducing the noise and keeping the rate output from the ASICs manageable while controlling the quality of the data.

- Some chips (having larger than ~10^5 clusters) will need re-equalising, but the other big peaks likely have noisy pixels that will benefit from masking.



- A recent plot of the number of clusters (hits) in the ASICs for a sample of 100k events

LHCb Data Processing & Analysis (DPA)

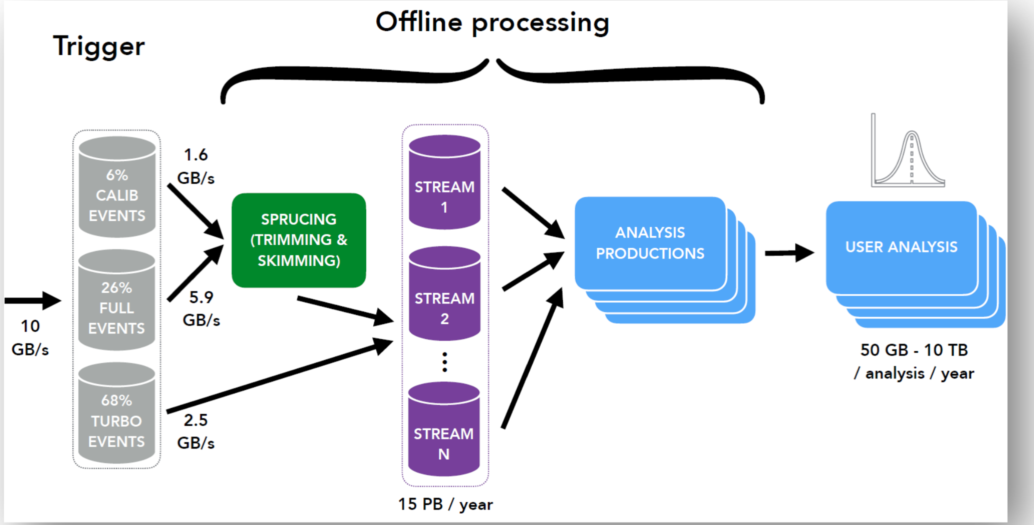


- The **DPA project** addresses the challenges due to the very large increase in data volume expected with respect to Run II.

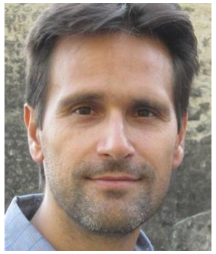
- Centralised skimming and trimming of a significant fraction of HLT2 outputs.

- Centralised analysis productions for physics analysts.

- Heavy contributions to the analysis software itself and innovative analysis techniques, including Quantum Machine Learning (generating great interest even outside LHCb!)



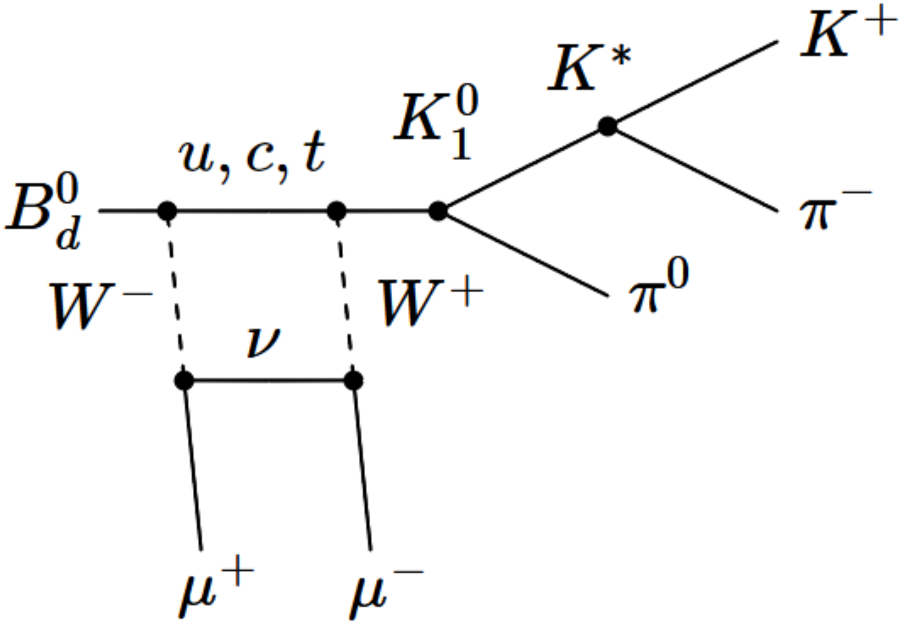
Purely Baryonic B decays



- As seen this morning! (Ned)
- **Unique at Liverpool!**
- Purely baryonic decays are a class of particle decay that is essentially unexplored
- First look at $\Lambda_b \rightarrow \Lambda_c$ anti-Λ_c n
- A nice means to measure a decay mode containing a neutron for the first time at a hadron collider experiment

Search for right-handed weak decays

- As seen this morning! (James)
- 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.
- Currently working on selections for Run3 and reprocessing the Run1/2 data in preparation to perform the analysis.

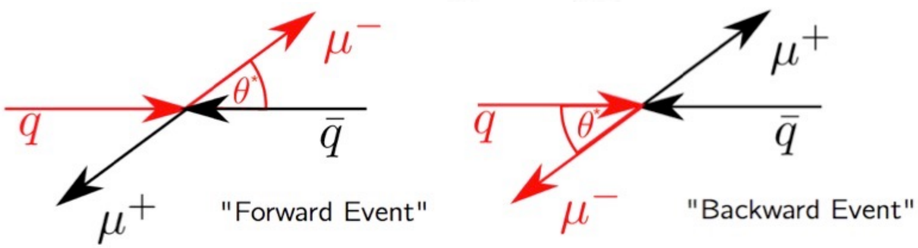


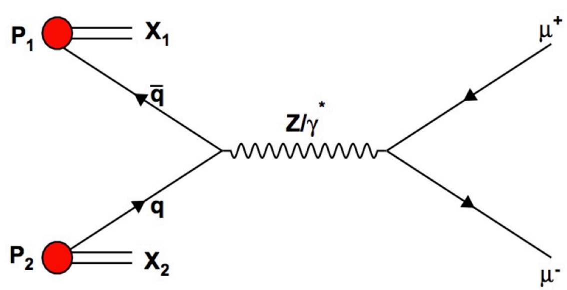
- The decay process $B^0 \to K_1^0 \mu^+\mu^-$

Z decay Forward-backward Asymmetry

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

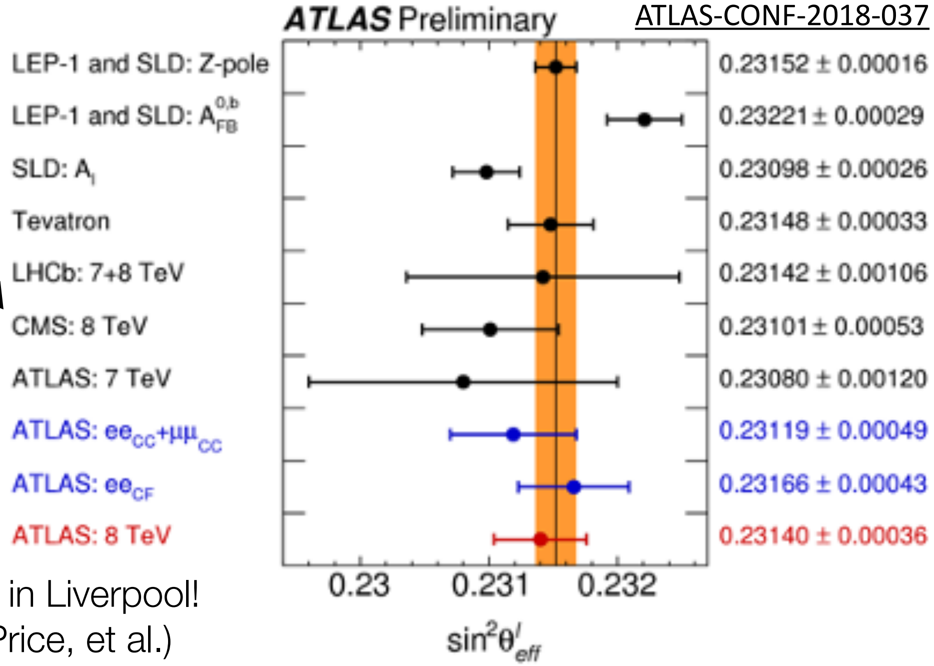
$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$





- Knowing A_{FB} allows us to measure key electroweak parameters, such as $\sin^2(\theta_W)$

ATLAS-CONF-2018-037



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

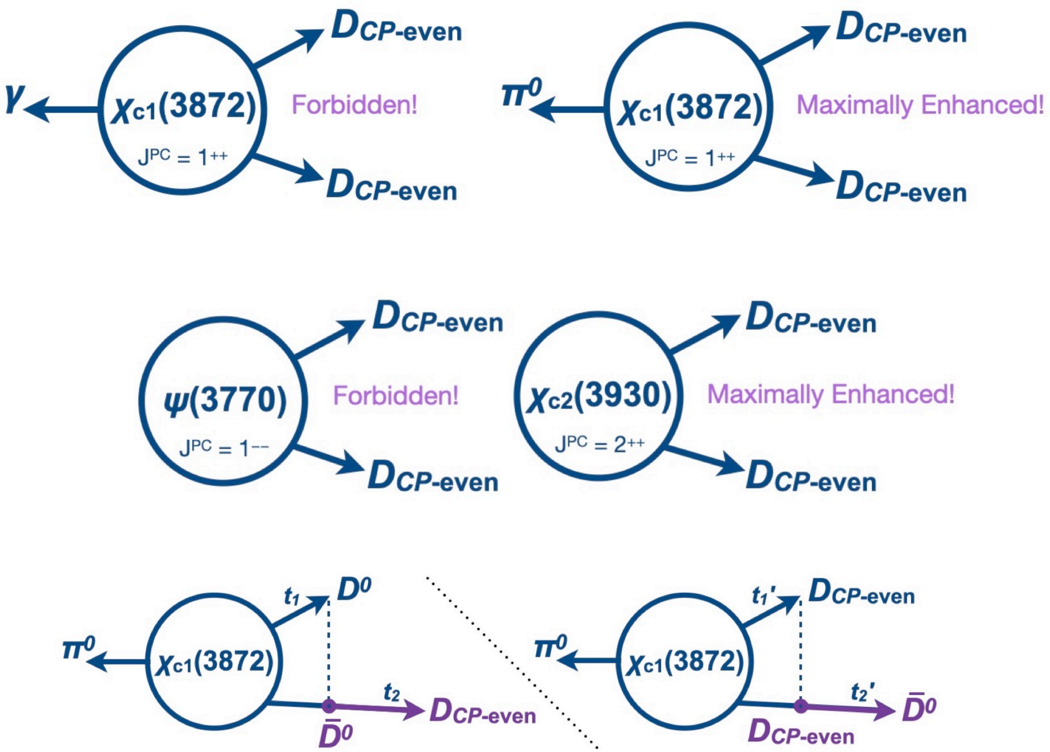
- Expect to enter LHCb review process in the later part of the year

Quantum Correlated Charm

- Quantum correlated $D^0 \bar{D}^0$ systems have been collected from $J^{PC} = 1^{--}$ sources produced at e^+e^- colliders

$$C_{D^0\bar{D}^0} = P_{D^0\bar{D}^0} = (-1)^{L_{D^0\bar{D}^0}}$$

- JHEP 03 (2023) 038:
    - These correlations exist in $J^{PC}=1^{++}$ sources as well, including $\chi_{c1}(3872) \rightarrow D^0 \bar{D}^0 \{\pi^0,\gamma\}$
    - By clever 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
        - Remove (enhance) $C = -1$ (+1) $D^0 \bar{D}^0$ resonances in $B \rightarrow D^0 \bar{D}^0 X$ amplitude analyses
    - $\chi_{c1}(3872)$ decays can be used to test time-reversal conservation



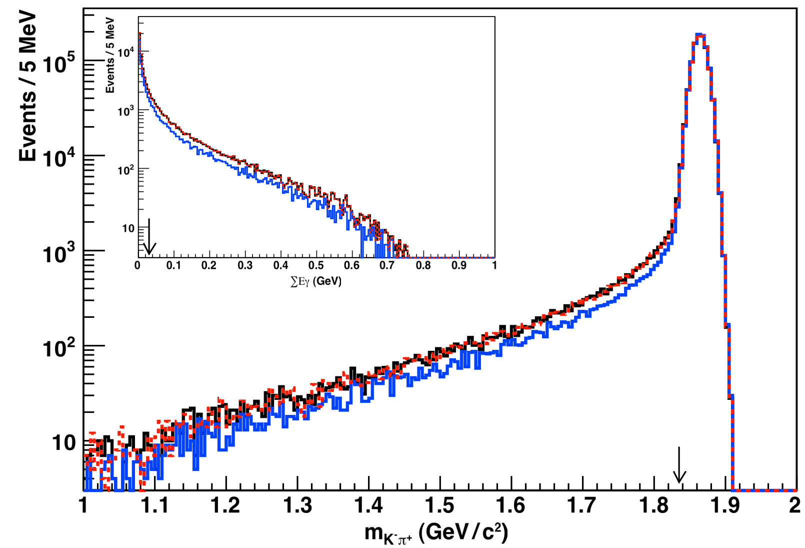
Two T-conjugate D transitions within $\chi_{c1}(3872)$ decays.

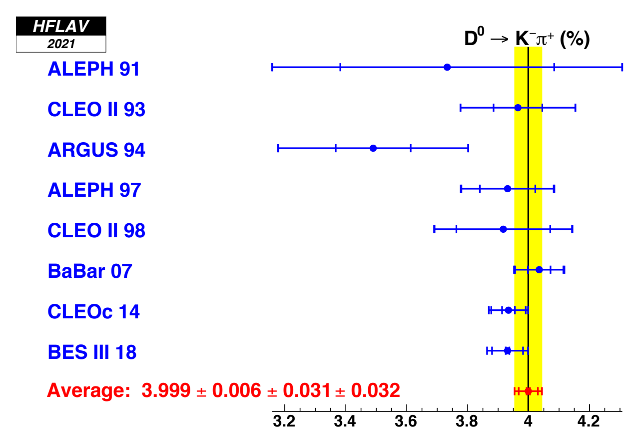
Discussion about studies at LHCb and other experiments at invitation-only charm workshop

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

average branching fractions accurately by correcting those with poorly modeled efficiency





Phys. Rev. D 107, 052008 (2023)

Summary

More in Ashley's & Eduardo's talks!

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

Expect plenty of excitement during Run 3!

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

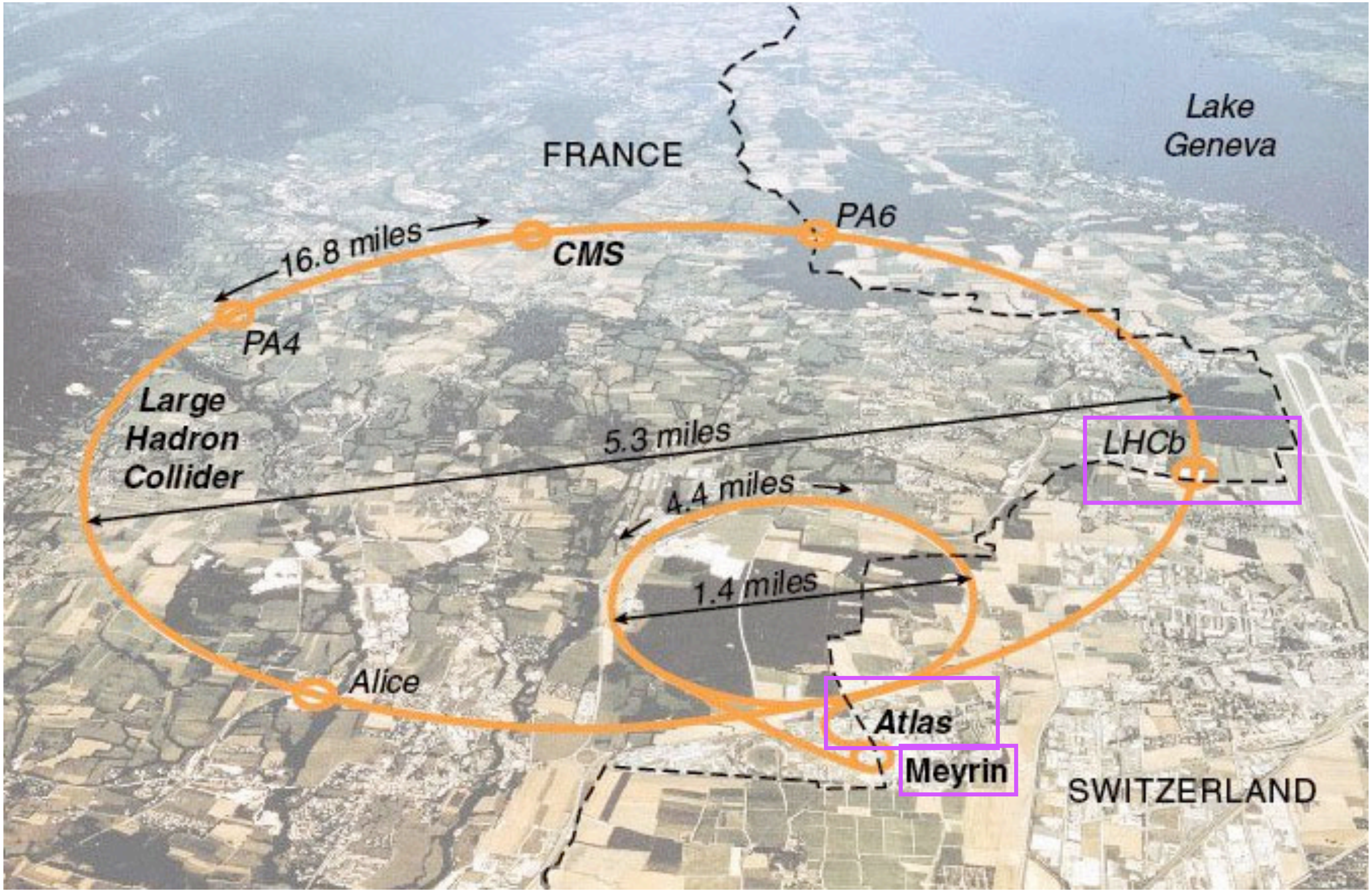
Team Leader: Tara Shears

Members: Abbie Jane Chadwick , Anthony Smith , Ashley Greenall , Ayushi Khatri , Carlos Alberto Chavez Barajas , David Hutchcroft , Eduardo Rodrigues [50] , Emlyn Jones , Eva Vilella Figueras , Gianluigi Casse , James David Brown , Jan Hammerich , John Carroll , Karol Hennessy , Kieran Bridges , Kurt Rinnert , Mark Whitley , Ned Francis Howarth , Paras Naik , Robert Fay , Sigrid Scherl , Tara Shears , Themistocles Bowcock , Thomas Ackernley

[50] *Also at European Organization for Nuclear Research (CERN), Geneva, Switzerland*

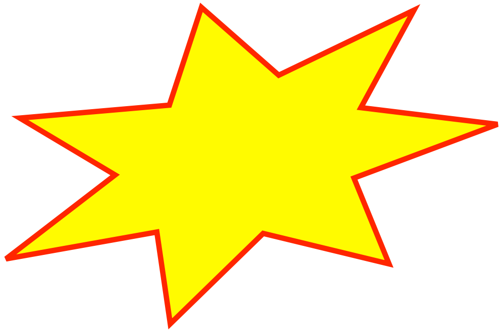
Backup

The LHC at CERN

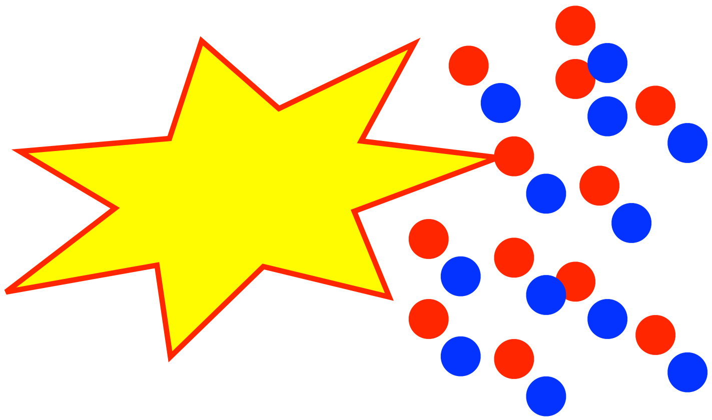


CP violation and the creation of the universe

CP violation and the creation of the universe

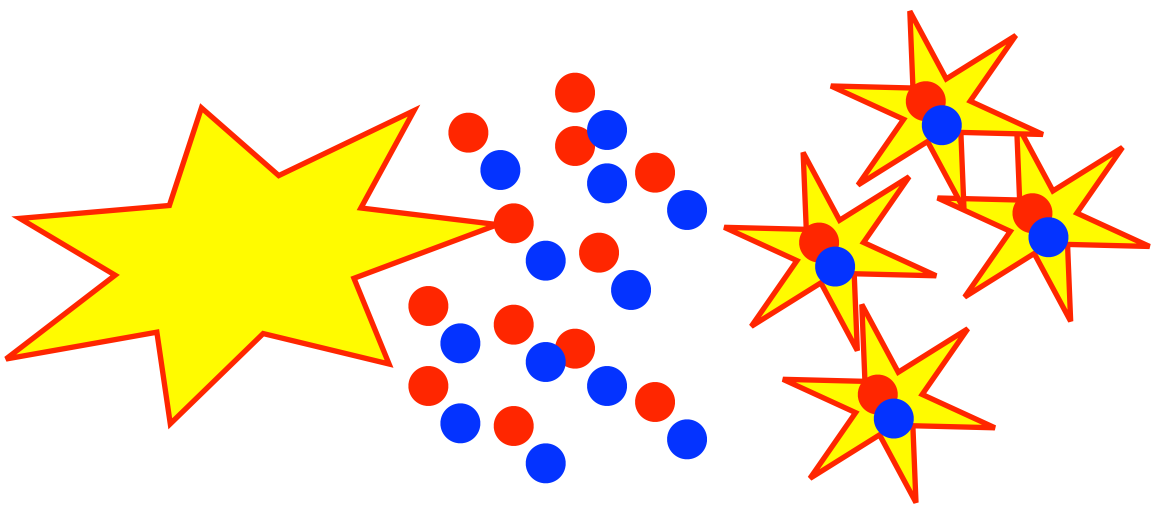


CP violation and the creation of the universe



equal amounts of
matter and
antimatter

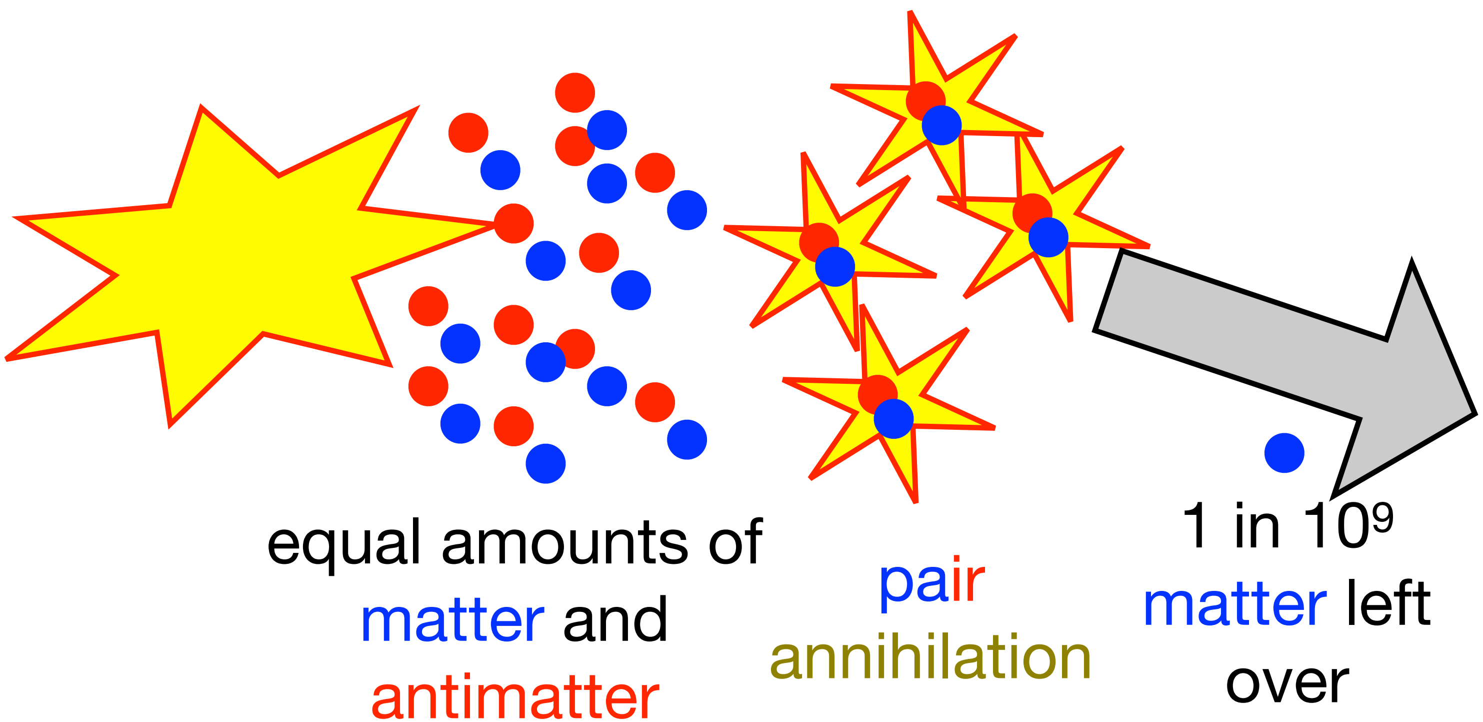
CP violation and the creation of the universe

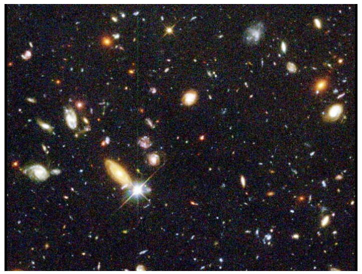


equal amounts of
matter and
antimatter

pair
annihilation

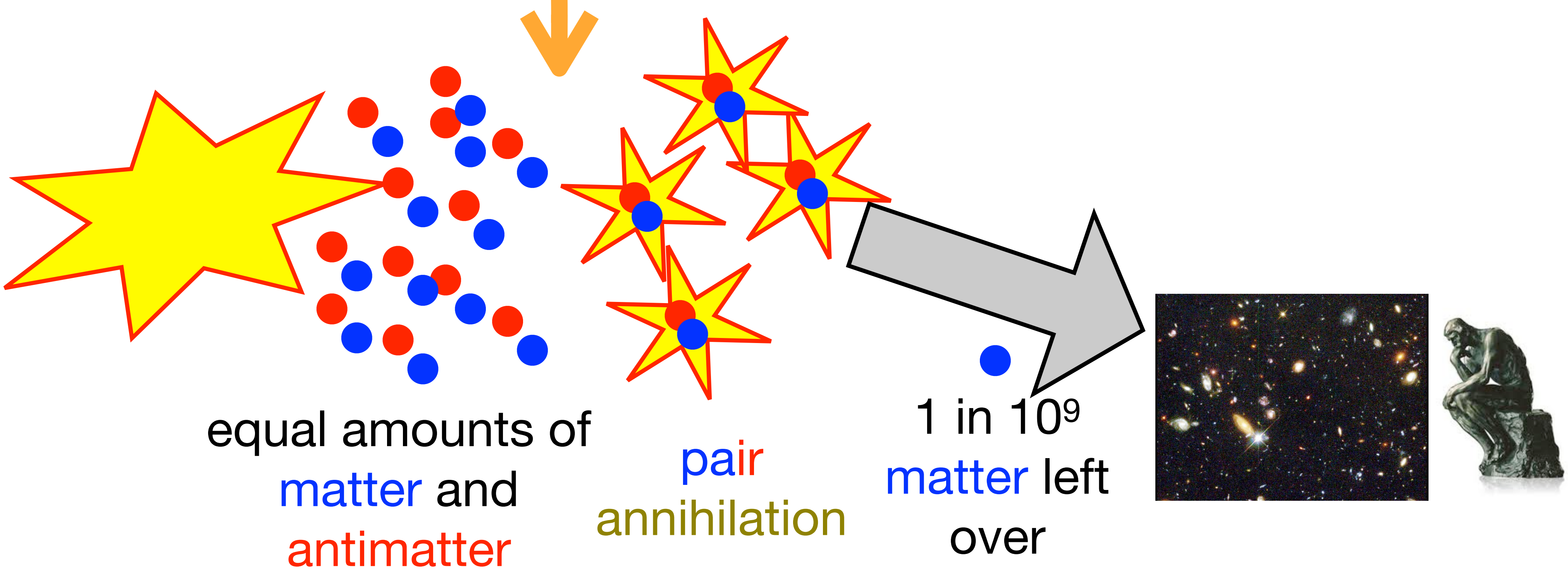
CP violation and the creation of the universe





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.



CP violation and the creation of the universe

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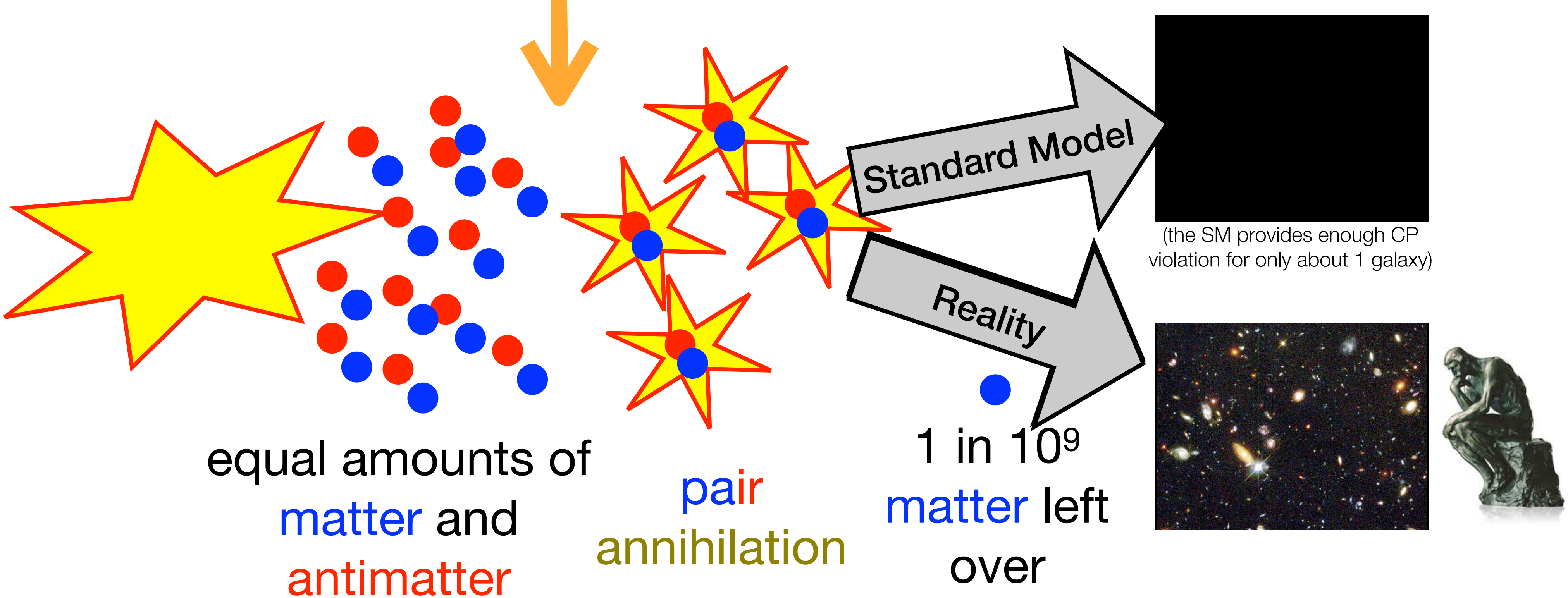
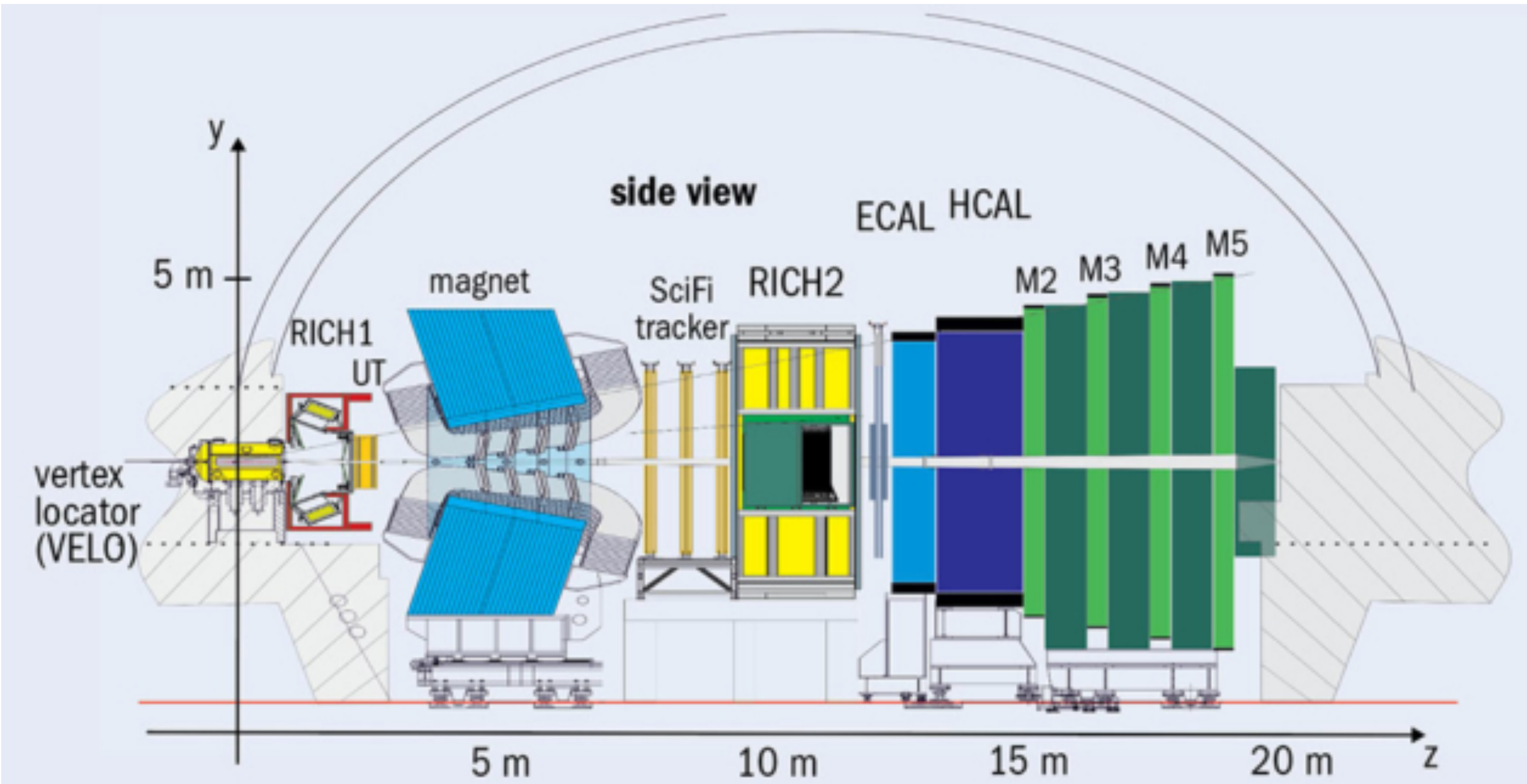


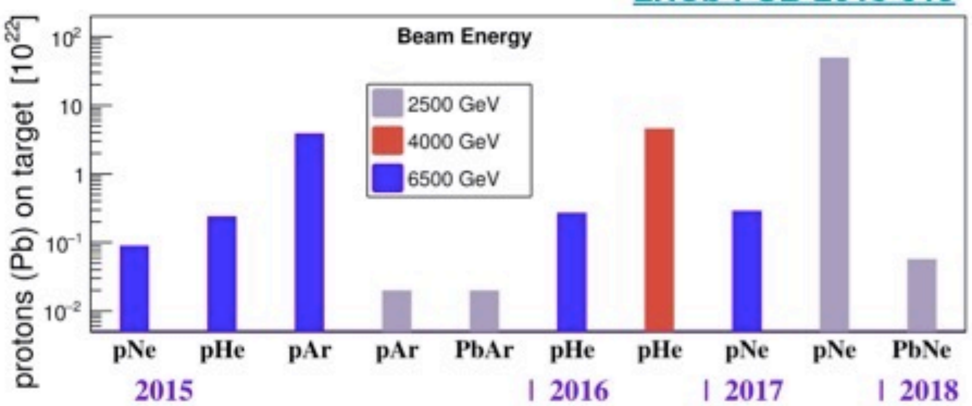
LHCb Upgrade



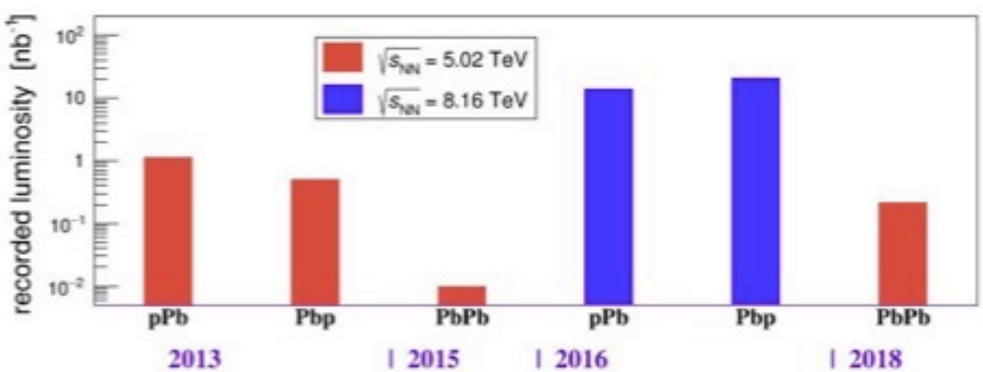
"Fixed Target" & Heavy Ions

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

Saverio Mariani   Heavy-ion and fixed-target physics at LHCb   3

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

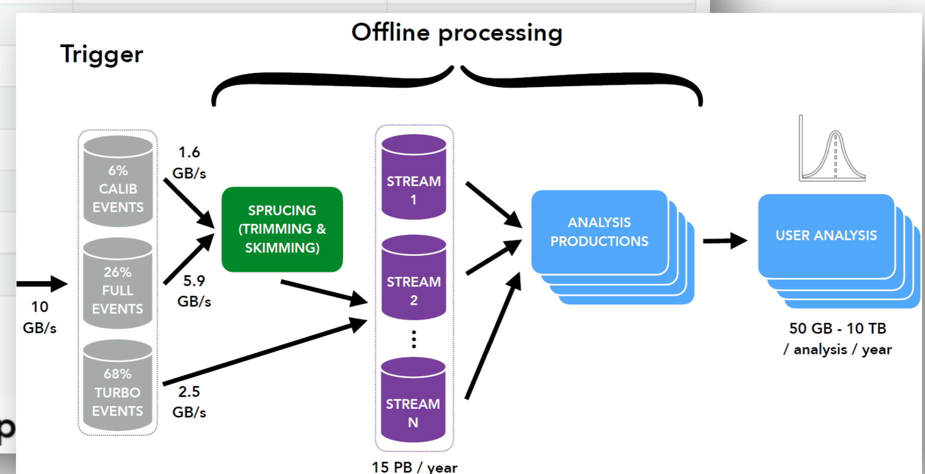
The **Data Processing & Analysis, DPA, project** addresses the challenges for offline data processing and analysis due to the very large increase in data volume with respect to Run II. DPA is built around 2 main ideas:

- 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



DPA – Liverpool involvement

- ❑ Expected involvement as project leader
- ❑ Personally more involved with the analysis software itself and the Innovative Analysis Techniques WP
- ❑ A lot of focus on commissioning activities in 2023, for obvious reasons. So far we had no real hiccups

- ❑ The first DPA project paper is a paper on Quantum Computing !
- ❑ First application of QML to the task of jet charge identification
- ❑ Paper published in JHEP over Summer 2022

- ❑ LHCb QC activities presented at several conferences and attracted interest, especially that we are the only ones to publish as "LHCb work" rather than as separate work

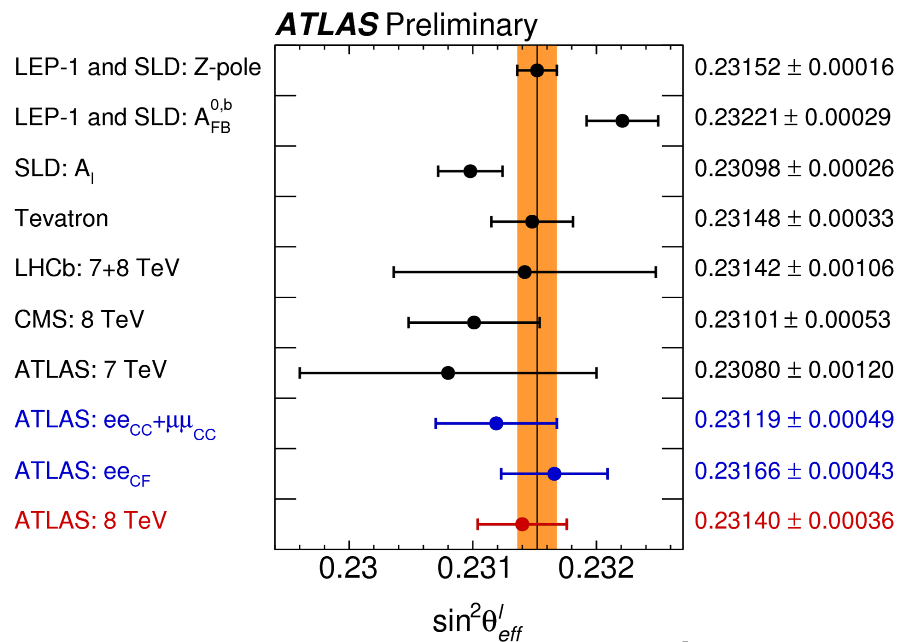
Quantum Machine Learning for *b*-jet identification

Abstract

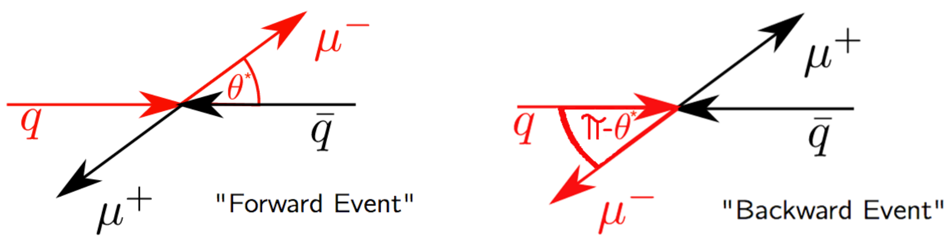
Machine Learning algorithms have played an important role in hadronic jet classification problems. The large variety of models applied to Large Hadron Collider data has demonstrated that there is still room for improvement. In this context Quantum Machine Learning is a new and almost unexplored methodology, where the intrinsic properties of quantum computation could be used to exploit particles correlations for improving the jet classification performance. In this paper, we present a brand new approach to identify if a jet contains a hadron formed by a b or $\bar{b}$ quark at the moment of production, based on a Variational Quantum Classifier applied to simulated data of the LHCb experiment. Quantum models are trained and evaluated using LHCb simulation. The jet identification performance is compared with a Deep Neural Network model to assess which method gives the better performance.

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 → $\mu^+\mu^-$ 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})



[ATLAS-CONF-2018-037]

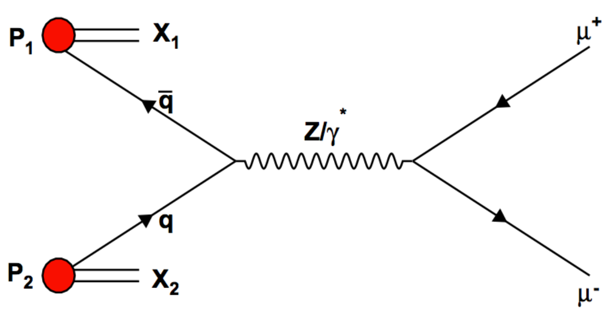


- Extracted via a comparison of MC templates and data
- Run 2 data, 6fb-1 via the forward backward asymmetry, A_{FB} in $Z/\gamma^* \rightarrow \mu^+ \mu^-$
- Previous LHCb result used 7 TeV and 8 TeV with 1 fb-1 and 2 fb-1 of data respectively

number of backward events

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

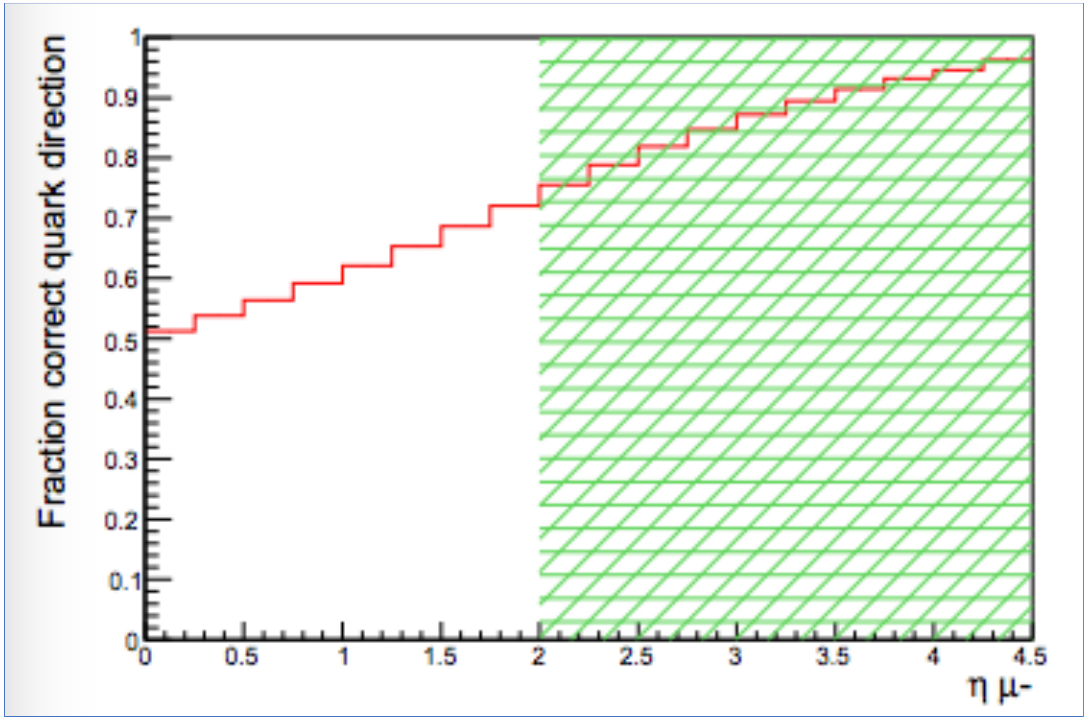
number of forward events



[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

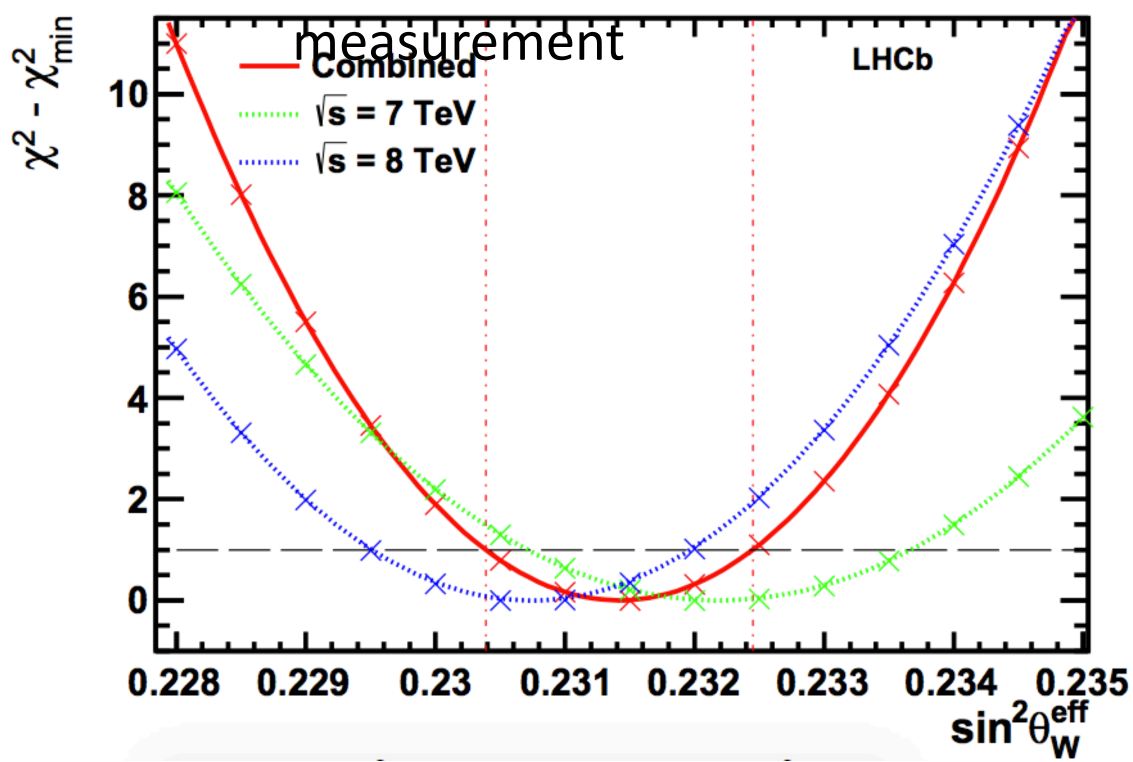


[LHCb-ANA-2015-002 28/09/2015]

$Sin^2\theta_W$ Calculation at LHCb

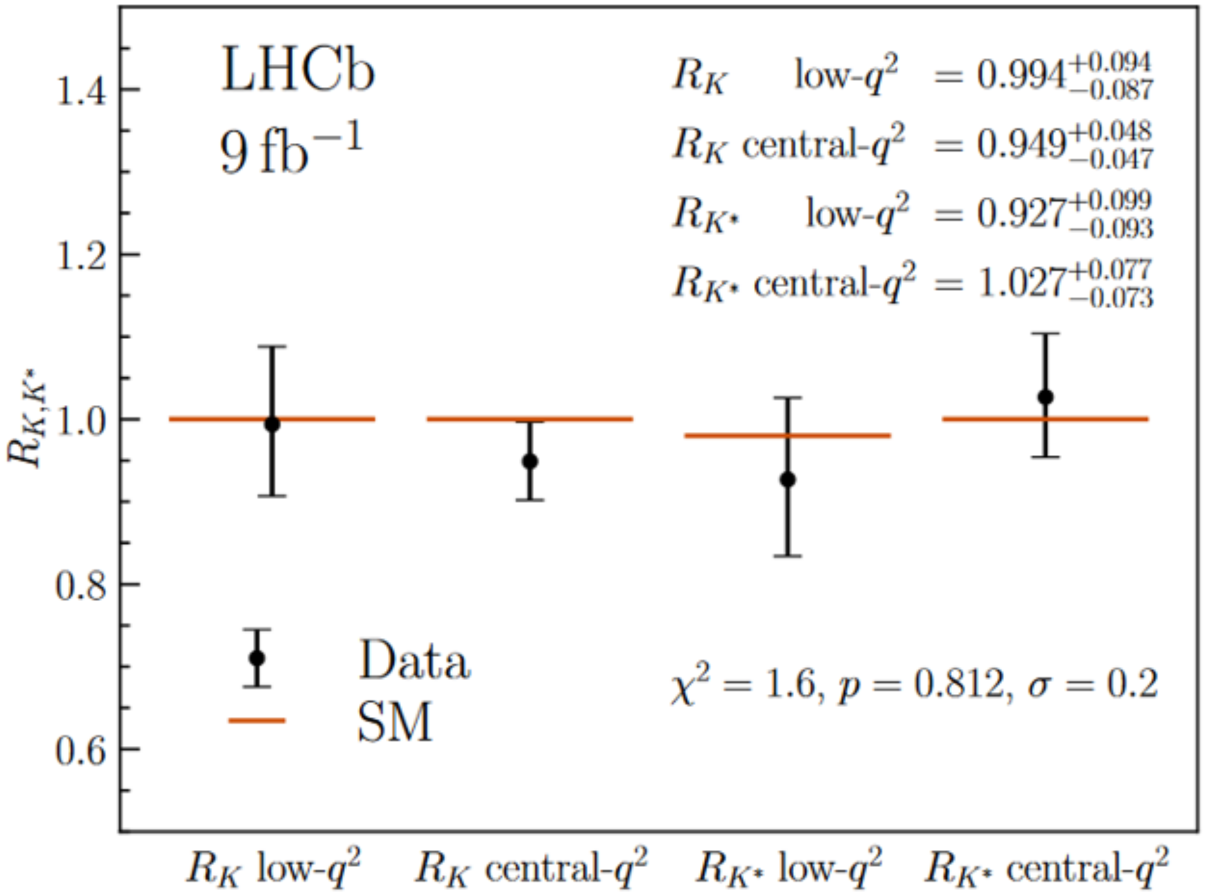
- Values for A_{FB}^{pred} are found via MC using a range of values for $sin^2(\theta_W^{eff})$
- χ^2 is calculated by comparing A_{FB}^{pred} to data values of A_{FB}
- Quadratic functions are fitted to the distributions
- The difference between χ^2 values and the minimum χ^2 value is plotted as a function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

From the 2015 3fb^{-1} measurement



[LHCb, 1509.07645]

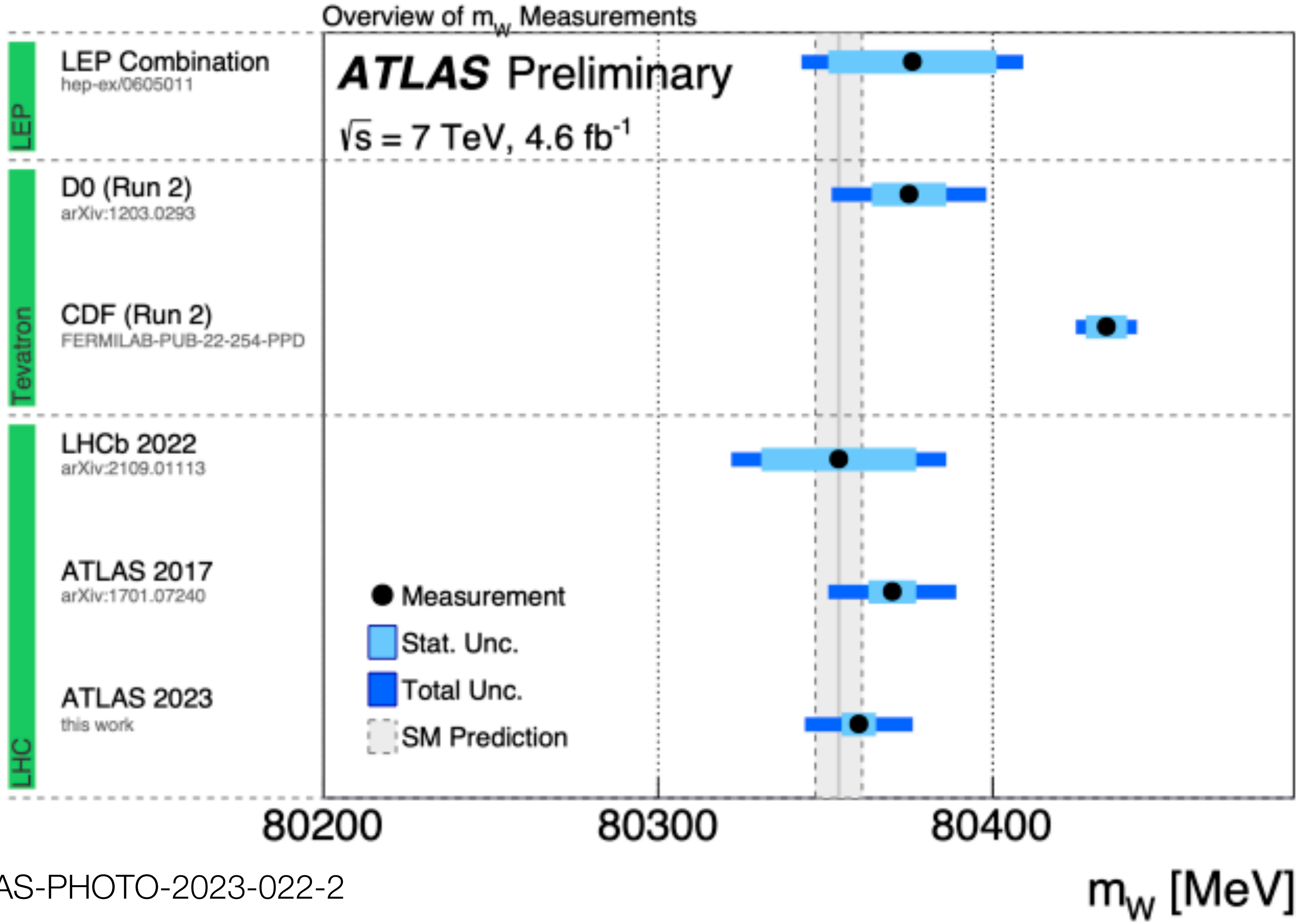
R_K



arXiv:2212.09152
arXiv:2212.09153

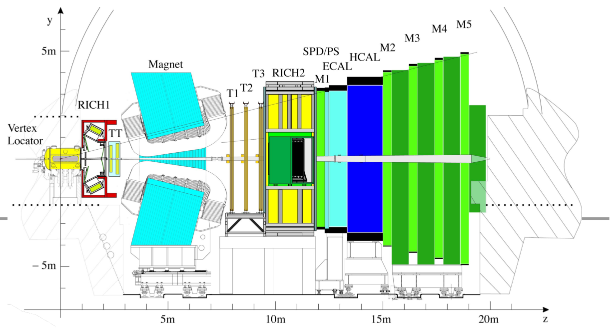
The results presented here differ from the previous LHCb measurements of R_K and R_{K^*}, which they supersede. The R_{K^*} analysis uses five times more B meson decays than the previous result. For R_K central-q^2, the difference is partly due to the use of tighter electron identification criteria and partly due to the modeling of the residual misidentified hadronic backgrounds; statistical fluctuations make a smaller contribution to the difference since the same data are used as in the previous publication. It is interesting to note that the statistical uncertainties remain significantly larger than the systematic uncertainties and therefore additional data will continue to challenge the SM.

W boson mass



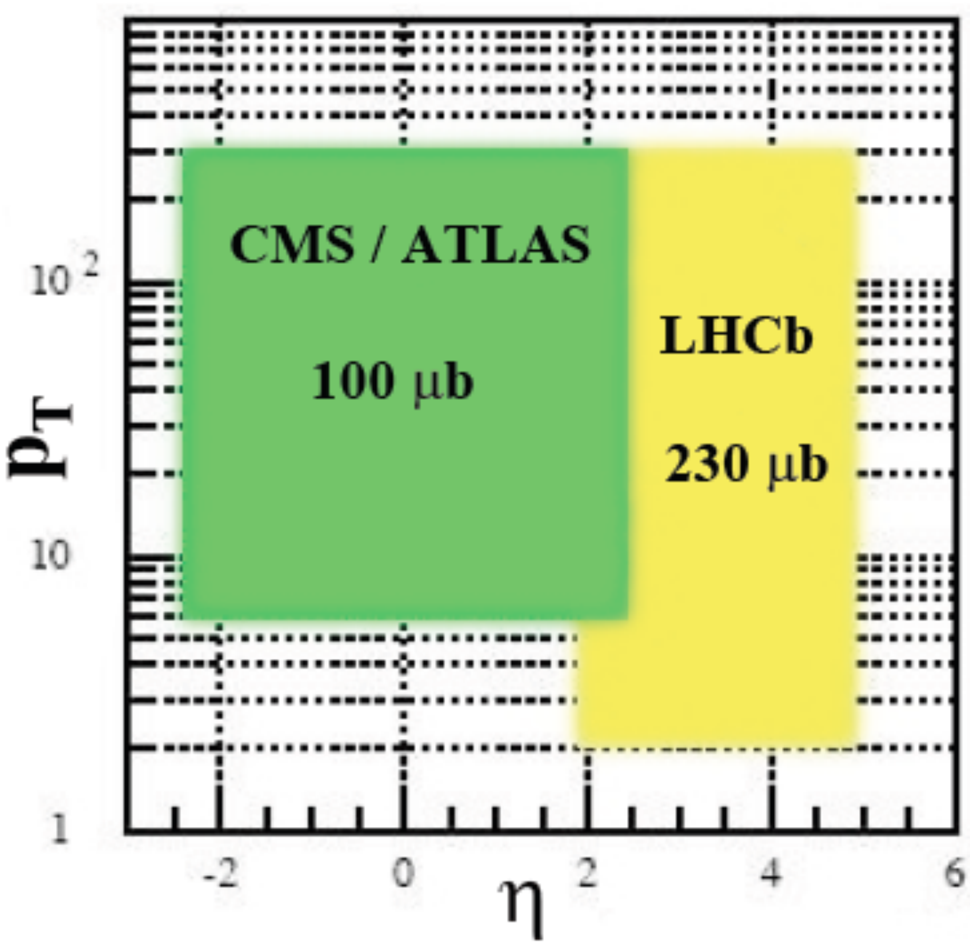
ATLAS-PHOTO-2023-022-2

Heavy flavour production



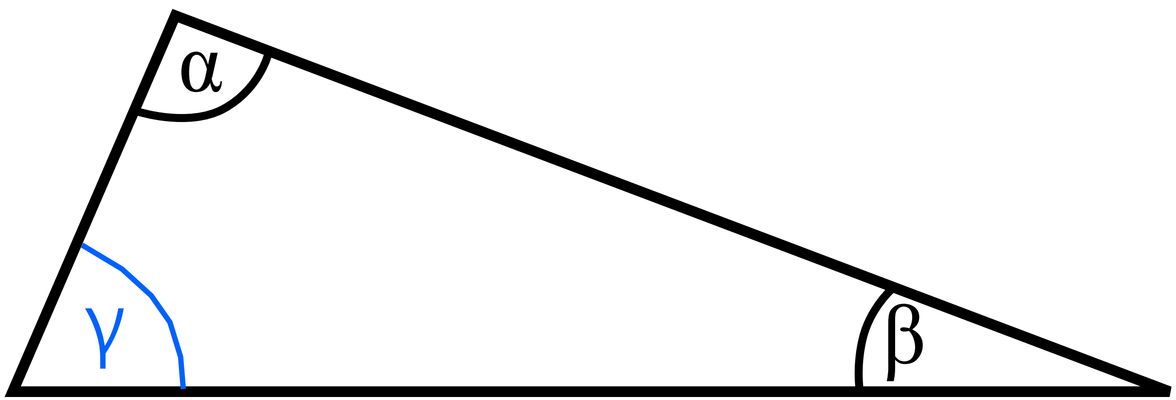
- Huge amounts of heavy quarks produced at LHC (that's why LHCb is there.)
- **Production mechanisms not well understood.**
- Great laboratory to **investigate and develop effective QCD models**.
- LHCb in a special position: Sees **more** than others, and in a **crucial kinematic range**, where other LHC experiments are virtually blind.

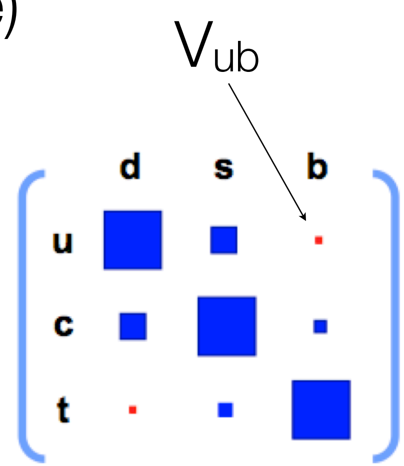
LHCb's unique coverage



The Unitarity Triangle and γ

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



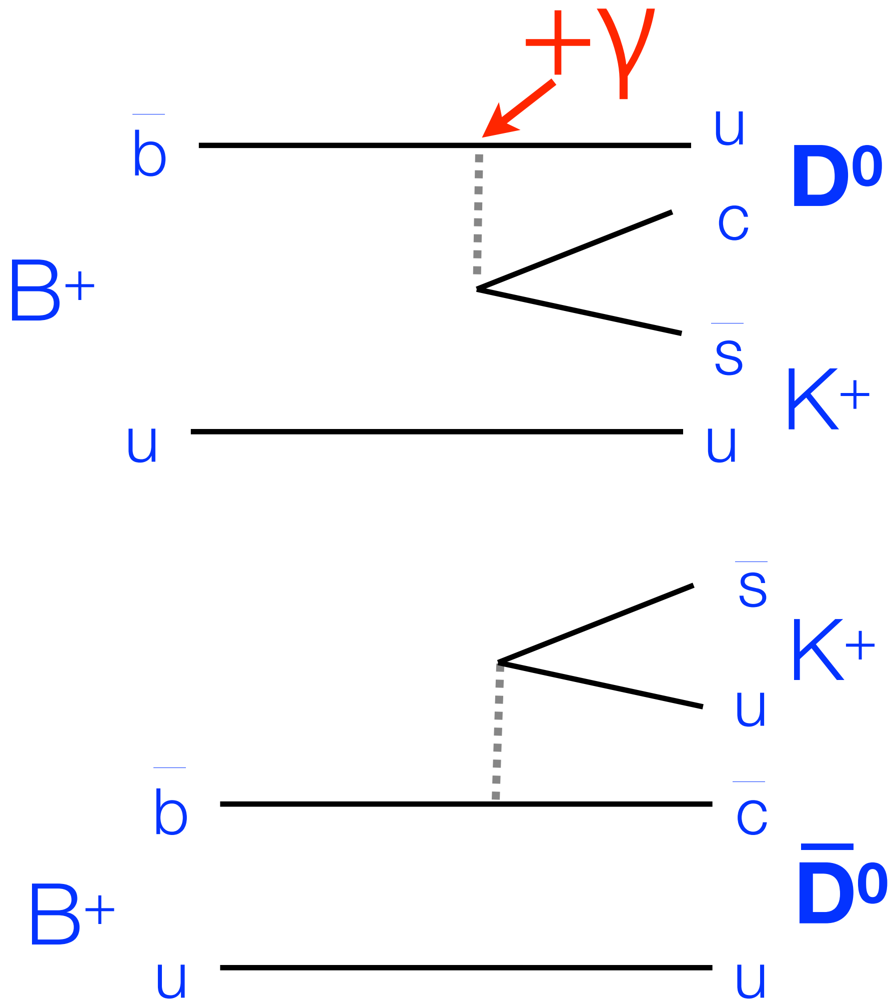


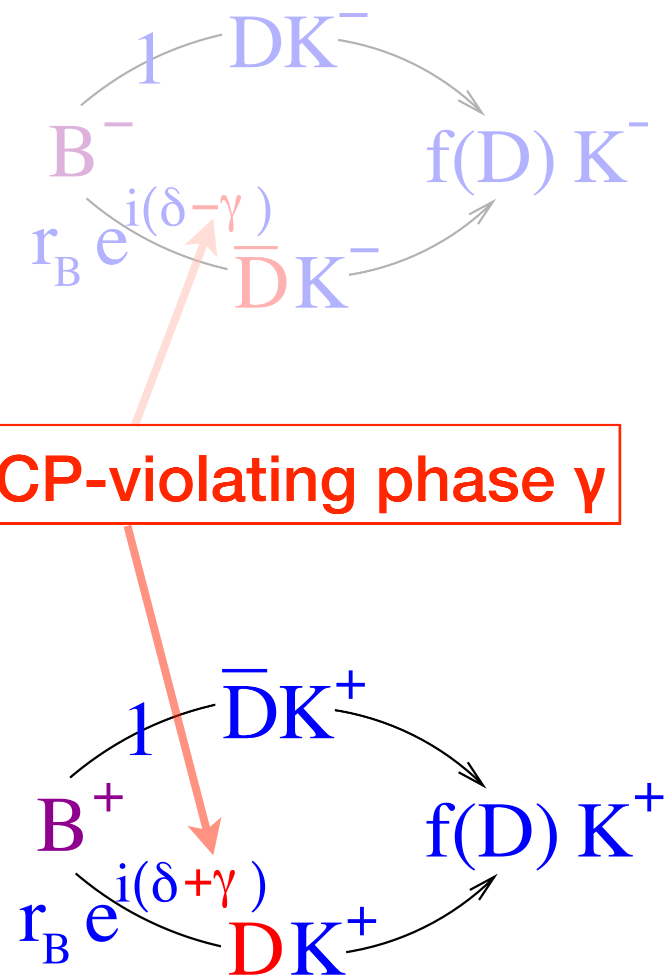
The angle γ is one of the phase angles responsible for **CP violation**...
...but it's poorly measured, and the least-well known of these angles

$\gamma = \arg(V_{ub}^{*}) = (63.8^{+3.5}_{-3.7})^{\circ}$ (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±





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