Measurement of CP asymmetry in $B^0 - \bar{B}^0$ mixing at LHCb

57. Herbstschule HEP

Bad Honnef, September 2026

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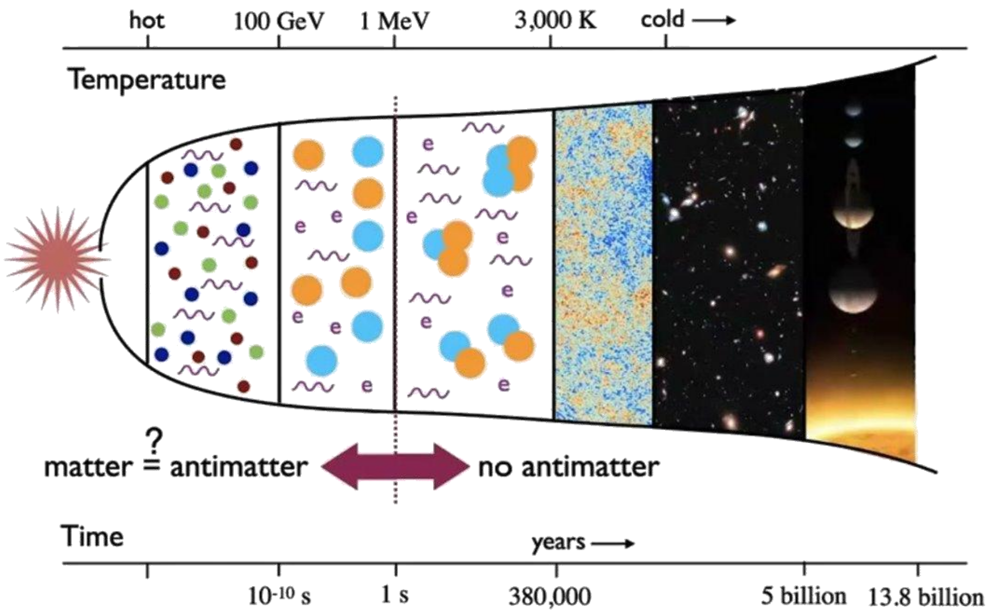
Matter over antimatter

- At Big Bang creation of equal amounts of matter and antimatter, yet we observe a Universe made mostly of matter.
- Baryogenesis in the early Universe: production of matter is favoured, CP symmetry must be broken.
- Standard Model accounts for some CP violation, but still not enough!



LHCb goal: search for new manifestation of CP violation.

CP symmetry

Charge conjugation + Parity

Laws of physics should be unchanged if we exchange particle with antiparticle and invert the spatial coordinates.

Image: Ipek, S. "Why Are We Here? Matter-Antimatter Asymmetry of the Universe." Harvey Mudd College Physics Colloquium.

LHCb experiment

- Located at Large Hadron Collider, *pp* collider at 13.6 TeV (during Run 3 from 2022 to 2026).
- Focus: search for new physics through studies of CP-violation and decays of heavy-flavour hadrons.
- Single-arm forward spectrometer, designed to capture a large fraction of *b* and *c* hadrons.

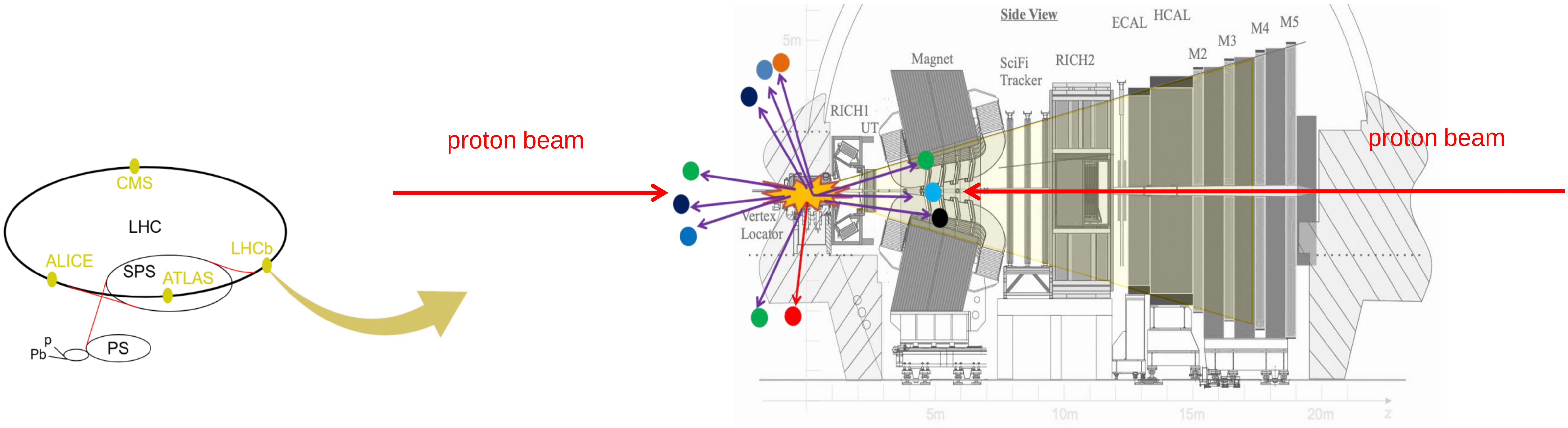
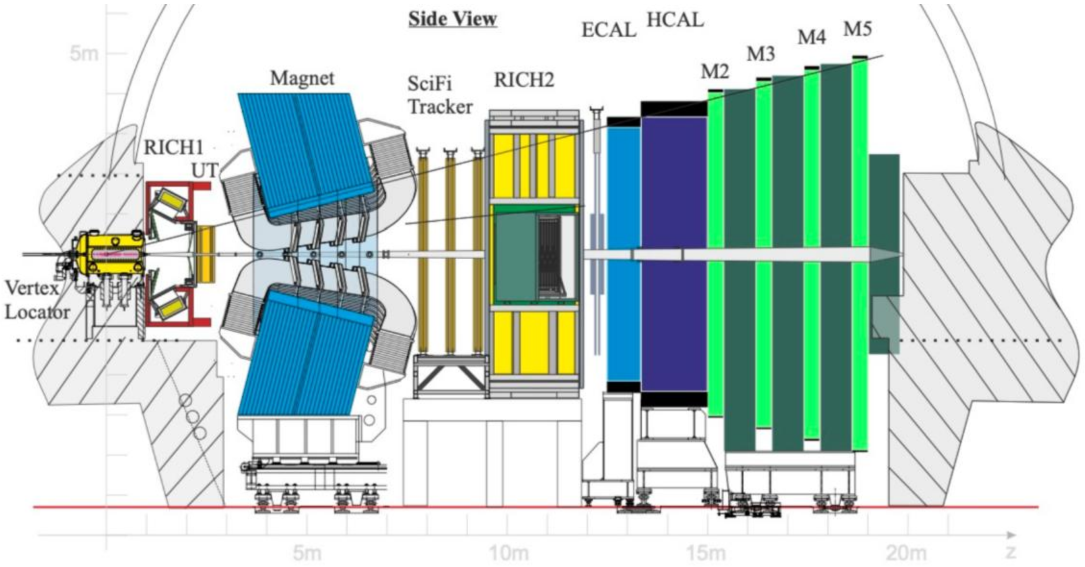


Image LHC: Di Arpad Horvath https://commons.wikimedia.org/w/index.php?curid=679693
Image LHCb detector: CERN

LHCb detector in Run 3 (2022-2026)

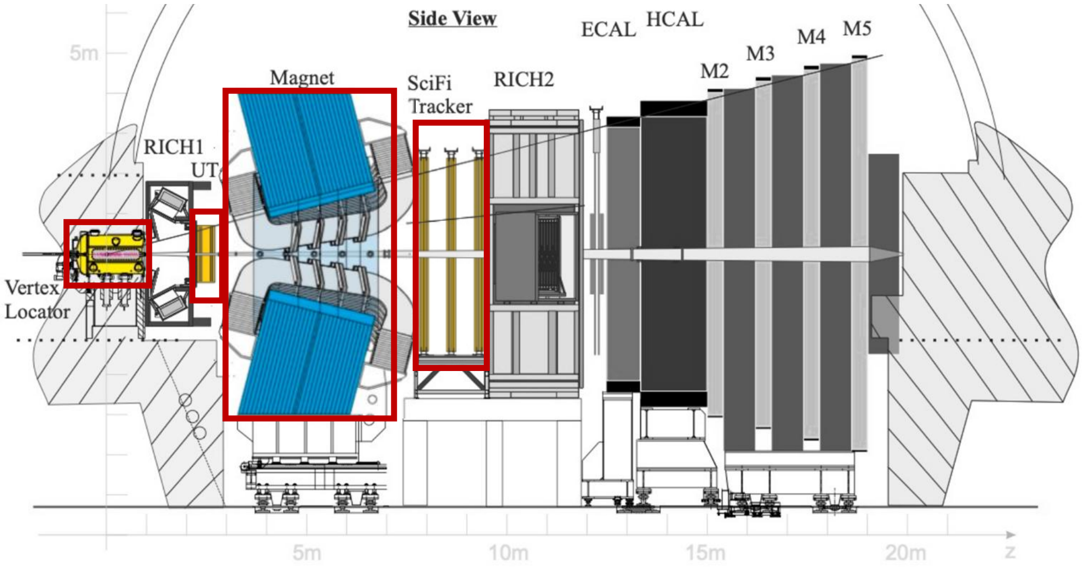


LHCb detector in Run 3 (2022-2026)

Tracking system

Vertex Locator
Collision point and vertex reconstruction

Upstream Tracker, Magnet, Scintillating Fiber Tracker
Charged particle track and momentum reconstruction



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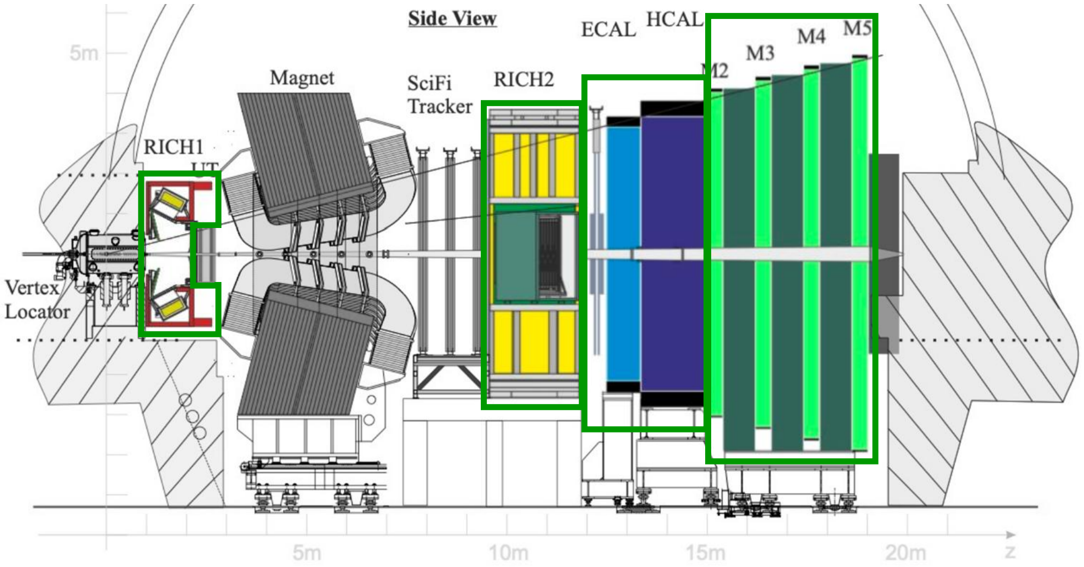
PID system

Two Ring Imaging Cherenkov detectors
Particle ID, π/K/p separation

Electromagnetic calorimeter
Electron and photon energy

Hadronic calorimeter
Hadron energy

Four muon chambers
Muon ID



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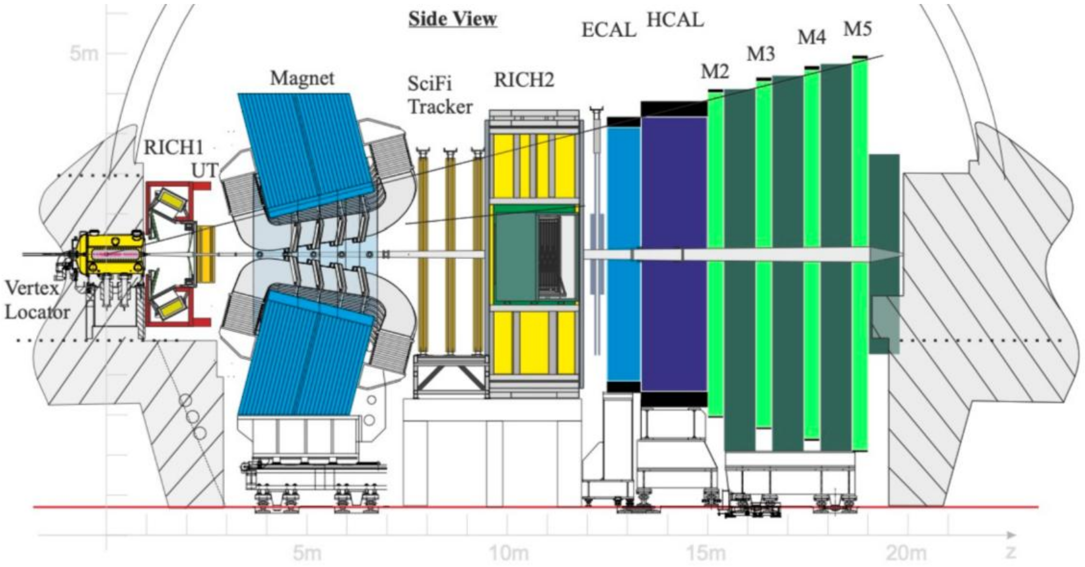
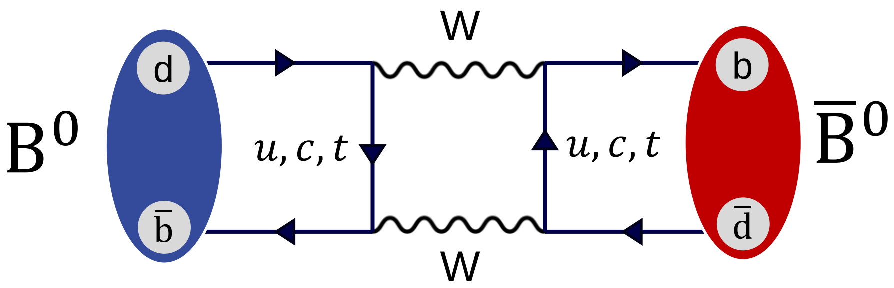


+ Data acquisition system, fully software-based trigger, real-time analysis, …

Neutral B meson mixing

- Spontaneous oscillation $\mathrm{B}^0 \leftrightarrows \overline{\mathrm{B}}^0$ through weak interaction.

Interaction in the flavour eigenstates		**Time evolution in the mass eigenstates**
$\lvert B^0\rangle = \lvert d\bar{b}\rangle$ $\lvert \bar{B}^0\rangle = \lvert b\bar{d}\rangle$	$\neq$	$\lvert B^0_L\rangle \quad M_L, \Gamma_L$ $\lvert B^0_H\rangle \quad M_H, \Gamma_H$



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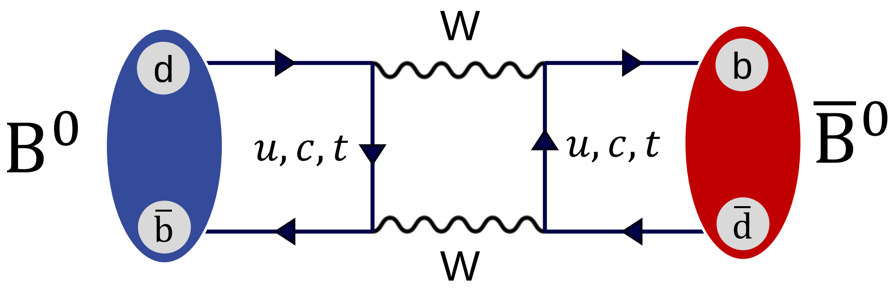

- Schrödinger equation for coupled system:

$$\mathrm{i}\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}|B(t)\rangle\\|\bar{B}(t)\rangle\end{pmatrix} = \mathcal{H}\begin{pmatrix}|B(t)\rangle\\|\bar{B}(t)\rangle\end{pmatrix} \qquad \mathcal{H} = \begin{pmatrix}M & M_{12}\\M_{12}^* & M\end{pmatrix} - \frac{\mathrm{i}}{2}\begin{pmatrix}\Gamma & \Gamma_{12}\\\Gamma_{12}^* & \Gamma\end{pmatrix}$$

with **eigenvalues *q* and *p*** such as: $|p|^2 + |q|^2 = 1$ and $\frac{q}{p} = \pm\sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}}$

and **eigenvectors $|B_L\rangle$ and $|B_H\rangle$** : $|B_L\rangle = p|B^0\rangle + q|\bar{B}^0\rangle$ and $|B_H\rangle = p|B^0\rangle - q|\bar{B}^0\rangle$.

Neutral B meson mixing

Oscillation rates:

$$\Gamma\left(B^0 \to \bar{B}^0(t)\right) = \frac{e^{-\Gamma t}}{2}\left|\frac{q}{p}\right|^2\left[\cosh\left(\frac{\Delta\Gamma t}{2}\right) - \cos(\Delta m\, t)\right]$$

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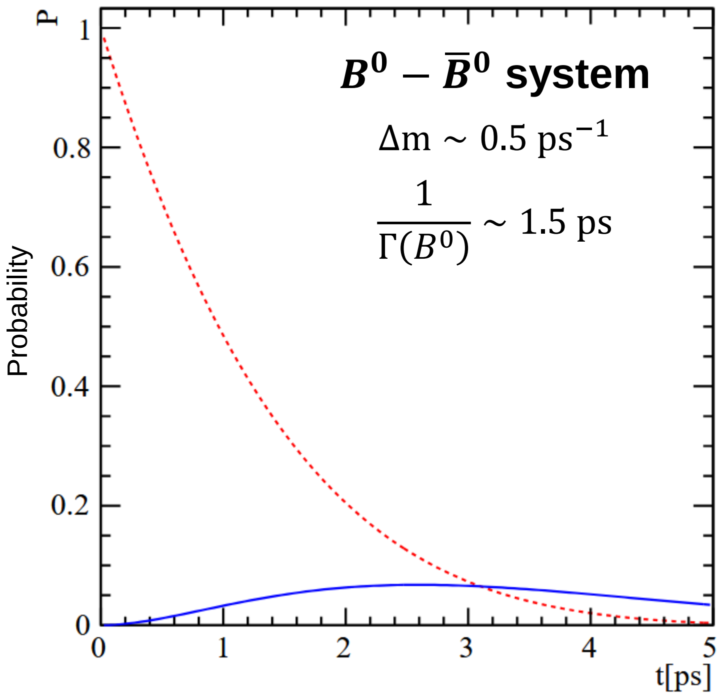
$$\Delta\Gamma = \Gamma_L - \Gamma_H$$

$$\Delta m = M_H - M_L$$

$$B^0 = B^0(t=0)$$

Oscillations determined by Δm: a higher value indicates faster oscillations.

Focus of this project



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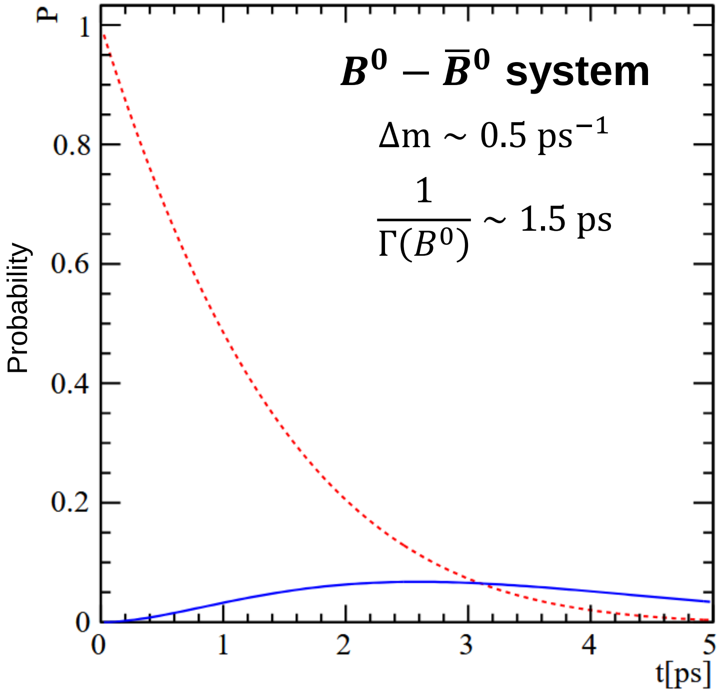

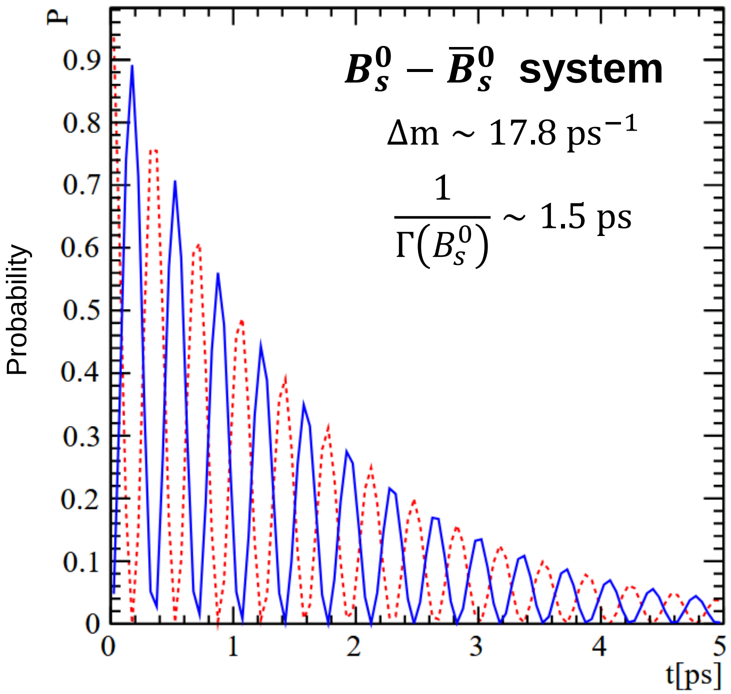

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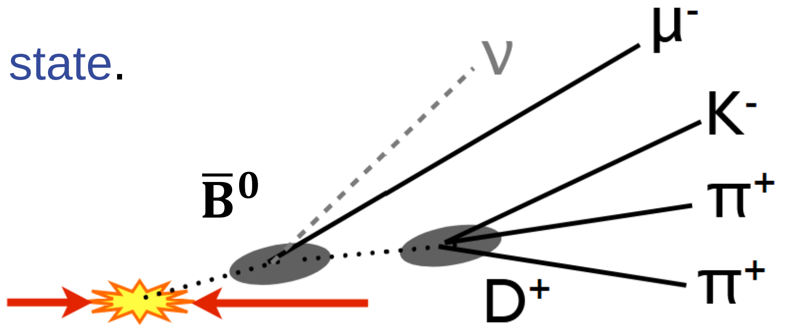
- $\left|\frac{q}{p}\right| \neq 1$ → CP is violated! ⟶ ***CP violation in mixing*** $\boldsymbol{\Gamma\left(B^0 \to \bar{B}^0(t)\right) \neq \Gamma\left(\bar{B}^0 \to B^0(t)\right)}$

- How to measure: define a CP violating parameter $1 - \left|\frac{q}{p}\right|^2 \sim O\left(10^{-3}\right)^*$ from SM

* https://pdg.lbl.gov/2026/reviews/rpp2026-rev-b-bar-mixing.pdf

How to measure CP violation in mixing

- Need to reconstruct the flavour at decay, through a flavour-specific final state.
- Common choice: semileptonic final state $f = Xl\nu_l$.



$B^0 \to D^- \mu^+ \nu_\mu$, with $D^- \to K^+\pi^-\pi^-$; f

$\bar{B}^0 \to D^+ \mu^- \bar{\nu}_\mu$, with $D^+ \to K^-\pi^+\pi^+$; $\bar{f}$

What we see in the detector

- From lepton sign, flavour of B meson at decay is identified.
- If flavour at production is reconstructed, then the CP asymmetry follows as:

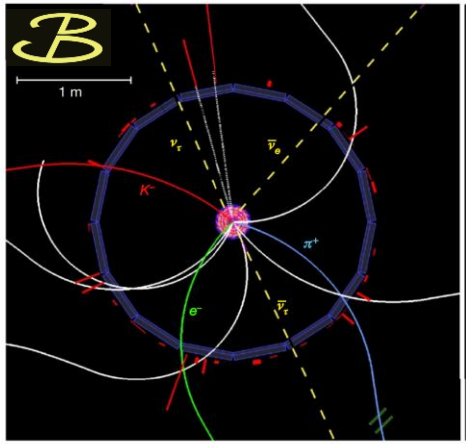
$$a_{sl}^d = \frac{\Gamma(\bar{B}^0 \to B^0 \to f) - \Gamma(B^0 \to \bar{B}^0 \to \bar{f})}{\Gamma(\bar{B}^0 \to B^0 \to f) + \Gamma(B^0 \to \bar{B}^0 \to \bar{f})} \simeq 1 - \left|\frac{q}{p}\right|^2$$

- SM prediction: $a_{sl}^d(SM) = (-4.73 \pm 0.42) \times 10^{-4}$ *

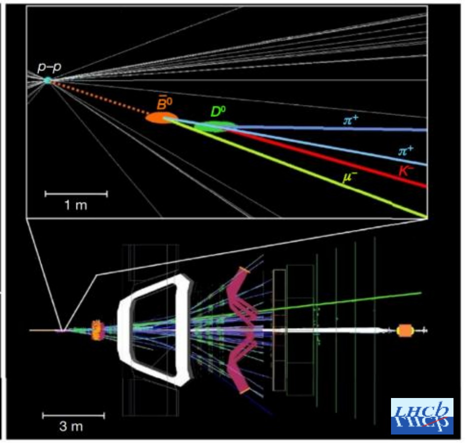
Image: Vesterinen, M. "Measurement of semileptonic asymmetries at LHCb." CERN LHC seminar (2014).
* https://pdg.lbl.gov/2026/reviews/rpp2026-rev-b-bar-mixing.pdf

Measurement strategy

B-factories
Belle II



Hadron factories
LHCb



- At hadron colliders reconstruction of flavour at production is quite inefficient.
- Alternative method: measurement of untagged decay rates.

- Count number of decays to f and $\bar{f}$ respectively as a function of B decay time *t*:

$$\mathrm{N}(f,t) = \mathrm{N}\left(\bar{B}^0(t) \to f\right) + \mathrm{N}\left(B^0(t) \to f\right),$$

$$\mathrm{N}\left(\bar{f},t\right) = \mathrm{N}\left(\bar{B}^0(t) \to \bar{f}\right) + \mathrm{N}\left(B^0(t) \to \bar{f}\right).$$

- From these, the untagged asymmetry is obtained: $$\mathrm{A}_{\mathrm{untagged}}(\mathrm{t}) = \frac{\mathrm{N}(f,t) - \mathrm{N}\left(\bar{f},t\right)}{\mathrm{N}(f,t) + \mathrm{N}\left(\bar{f},t\right)}.$$

Image: Ciezarek, Gregory, et al. (2017). A Challenge to Lepton Universality in B Meson Decays. Nature. 546. 10.1038/nature22346.

Measurement strategy

Other sources of asymmetries

- Untagged asymmetry depends on different contributions:

$$A_{\text{untagged}}(\mathrm{t}) = \frac{N(f,t) - N(\bar{f},t)}{N(f,t) + N(\bar{f},t)} \approx A_D + \frac{a_{sl}^d}{2} - \left(A_P + \frac{a_{sl}^d}{2}\right)\frac{\cos(\Delta m\, t)}{\cosh\left(\frac{\Delta\Gamma}{2}\mathrm{t}\right)}$$

Detection asymmetries A_D

Due to different particle-antiparticle interaction *(nuclear interaction with the detector material, detector inefficiencies and misalignments, PID, trigger).*

$$A_D = \frac{\varepsilon(f) - \varepsilon(\bar{f})}{\varepsilon(f) + \varepsilon(\bar{f})}$$

Can be split in two contributions:

$$A_D(\mu^+\pi^-K^+\pi^-) = A(\mu^+\pi^-) + A(\mathrm{K}^+\pi^-)$$

$$= A_{PID,trigger}(\mu^+) + A_{PID}(\pi^-) + A_{track}(\mu^+\pi^-) + A_{nuclear}(\pi^-)$$

$J/\psi \rightarrow \mu^+\mu^-$

$$= A\left(D^- \rightarrow K^+\pi^-\pi^-\right) - A\left(D^- \rightarrow \mathrm{K}_S^0\pi^-\right) - A_{nuclear}(\bar{K}^0)$$

For [dashed box] calibration samples are used.

Measurement strategy

Other sources of asymmetries

Production asymmetries A_P

Due to CP asymmetric initial state *pp*. Value obtained from fit on $N(f,t)$ distribution together with a_{sl}^d.

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Outlook: A_{sl}^{d} measurements at LHCb

Previous measurements

- Run 1 ($3.0\ \text{fb}^{-1}$), systematics dominate the uncertainties:

  $$a_{sl}^{d} = \left(-0.02 \pm 0.19\ (\text{stat}) \pm 0.30\ (\text{syst})\right)\%\ .$$

- **Run 3 ($\sim 27\ fb^{-1}$): expected precision $O(10^{-4})$.** Still higher than SM prediction (value of $a_{sl}^{d}(SM) = (-4.73 \pm 0.42) \times 10^{-4}$), but sufficient to place constraint on BSM theories.

- (Run 2 ($5.1\ \text{fb}^{-1}$): ongoing, close to completion)

Project status

✓ Processing data and preparing data + MC samples.

→ Main steps ahead:

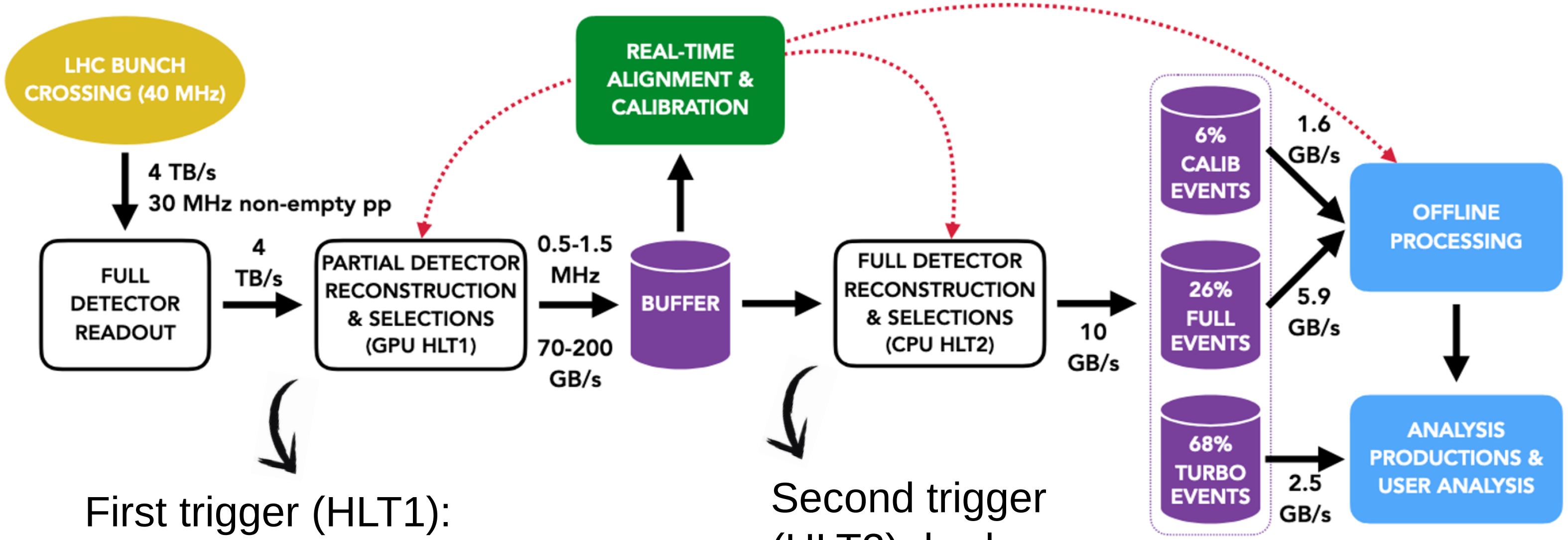
- Finalise event selection;
- Define background contributions;
- Study detection asymmetries;
- Fit on decay time distributions to extract CP asymmetry;
- Estimate systematic uncertainties.

Thank you!

Backup

Data processing in Run 3

- With upgraded detector: Information processed in real time by a fully-software based trigger.



First trigger (HLT1): decide if the event is worth storing, to reduce the data rate.

Second trigger (HLT2): hadron identification.

https://lhcb-starterkit-run3.docs.cern.ch/first-analysis-steps/dataflow/

Measurement strategy

Other sources of asymmetries

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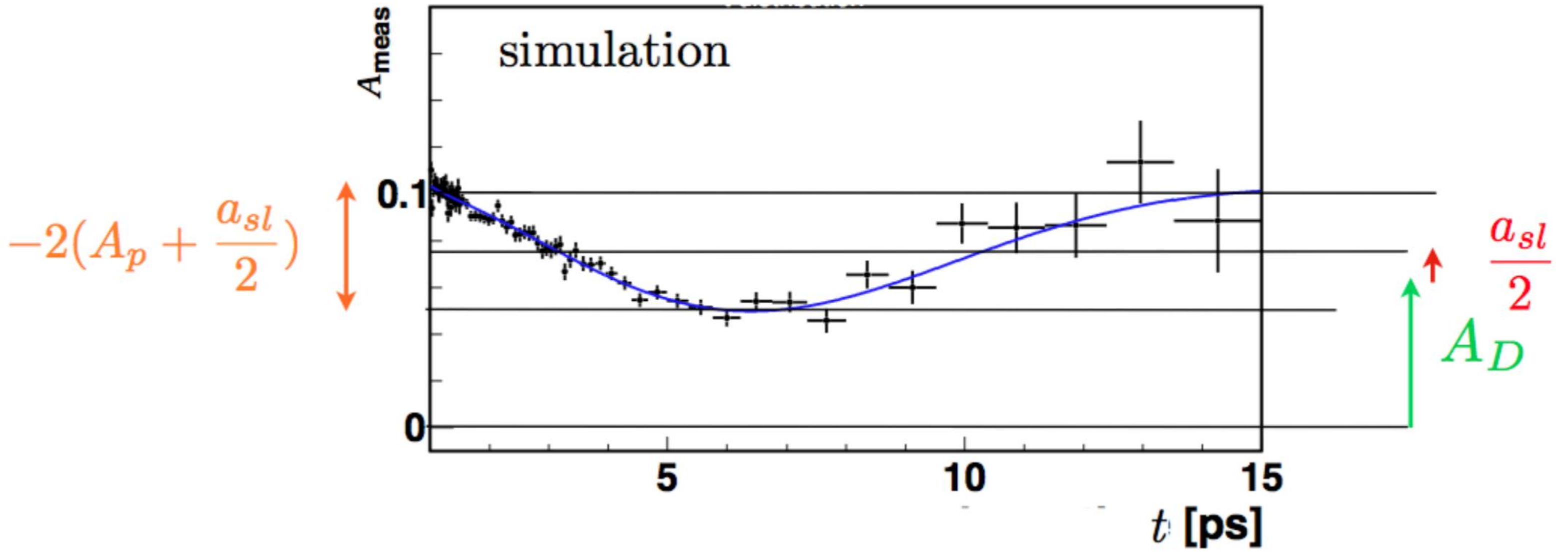

Image: Grillo, L. (2015). Measurement of CP violation in $B^0 - \bar{B}^0$ mixing using semileptonic decays at LHCb. PhD thesis. Ruperto-Carola-University of Heidelberg. https://archiv.ub.uni-heidelberg.de/volltextserver/19555/

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Production asymmetries A_P

Due to different interaction probability between $\mathrm{b}, \bar{\mathrm{b}}$ quarks and proton valence quarks u and d (initial state *pp* is not CP symmetric):

$$A_P(B^0) = \frac{\sigma(\bar{B}^0) - \sigma(B^0)}{\sigma(\bar{B}^0) + \sigma(B^0)} \sim O(1\%).$$

Value obtained from fit on $N(f,t)$ distribution together with a_{sl}^d.

Measurement strategy

Missing energy due to neutrino

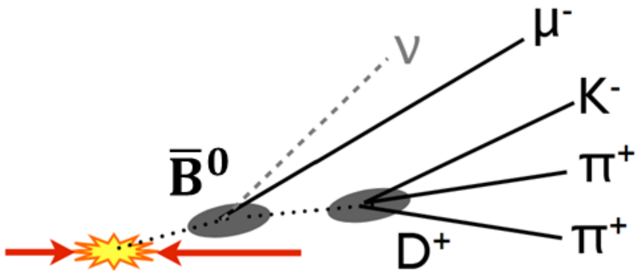
- B decay time calculated from reconstructed flight distance and momentum:

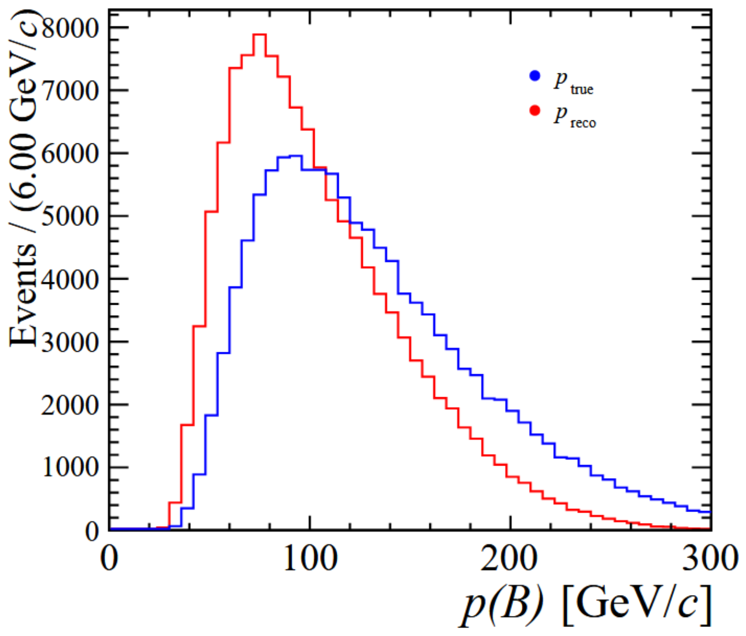
$$t = \frac{L \cdot M}{|p|} \; .$$

- Total B momentum can't be reconstructed due to the missing momentum of the neutrino: $\boldsymbol{p_{rec} < p_{true}}$.
- How to account for missing energy: **k-factor method.**
- From simulation, estimate a correction factor k such us:

$$\mathrm{k} = \frac{p_{MC,rec}}{p_{MC,true}}$$

- Momentum correction: $p_{data,corr} = \frac{p_{data,rec}}{k}$





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Systematic uncertainties on Run 1

Table 1: Systematic uncertainties (in %) on a_{sl}^{d} and A_{P} for 7 and 8 TeV pp centre-of-mass energies. Entries marked with – are found to be negligible.

Source of uncertainty	a_{sl}^{d}	A_{P}(7 TeV)	A_{P}(8 TeV)
Detection asymmetry	0.26	0.20	0.14
B^+ background	0.13	0.06	0.06
Λ_b^0 background	0.07	0.03	0.03
B_s^0 background	0.03	0.01	0.01
Combinatorial D background	0.03	–	–
k-factor distribution	0.03	0.01	0.01
Decay-time acceptance	0.03	0.07	0.07
Knowledge of Δm_d	0.02	0.01	0.01
Quadratic sum	0.30	0.22	0.17

Table: LHCb Collaboration, Measurement of the semileptonic CP asymmetry in B0 mixing (2014), https://arxiv.org/abs/1409.8586