40 Years of CHARM: Part 2 Focus on mixing and CP violation

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Mixing

The story starts in 1954

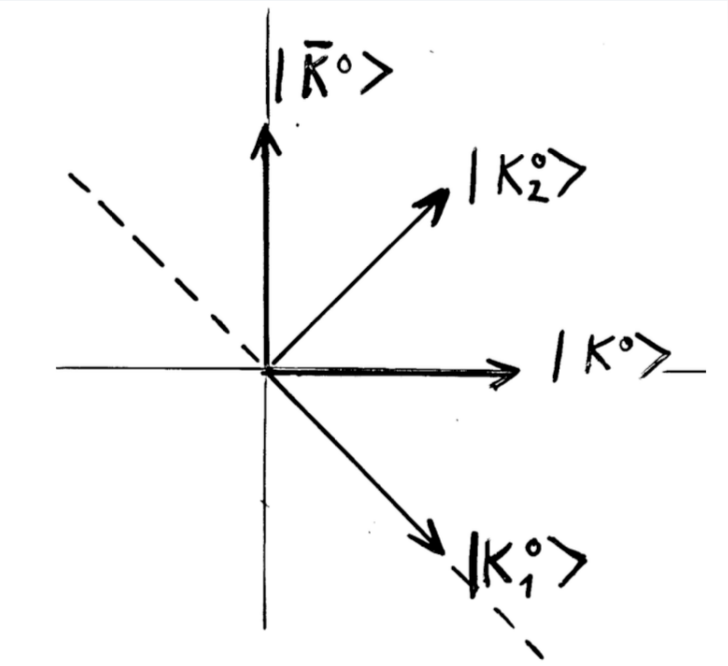
What is particle mixing?

- In 1954, Guell-Mann was giving a lecture about K^0 and $\bar{K}^0$ (θ^0 and $\bar{\theta}^0$) and described that these two « strange » particles had the same decay mode.
- One difference: opposite strangeness
- Fermi asked him: « If K^0 and $\bar{K}^0$ decay to the same final states, what's the difference between them ? »
- Guell-Mann did not have an answer but though a lot about it.

$$\bar{K}^0 \rightarrow \begin{cases} \pi^+\pi^- \\ \pi^0\pi^0 \\ \pi^+\pi^-\pi^0 \\ \pi^0\pi^0\pi^0 \end{cases} \qquad K^0 \rightarrow \begin{cases} \pi^+\pi^- \\ \pi^0\pi^0 \\ \pi^+\pi^-\pi^0 \\ \pi^0\pi^0\pi^0 \end{cases}$$

Superposition

- Guell-Mann teemed up with Pais to realise we have to look at K^0 and $\bar{K}^0$ at two pendulums on a common string (being their common final states).
- In quantum mechanics, we see this a superposition of quantum states → mixing!
- $|K^0\rangle$ and $|\bar{K}^0\rangle$ = Eigenstates of the strong interaction hamiltonian, defining the quark content
- $|K_1^0\rangle$ and $|K_2^0\rangle$ = Eigenstates of the the weak interaction hamiltonian, defining the particles lifetimes.
- In the next slide, I will show you how this situation leads to matter-antimatter oscillations



$$|K_1^0\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle + |\bar{K}^0\rangle\right)$$

$$|K_2^0\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle - |\bar{K}^0\rangle\right)$$

Neutral meson mixing: a bit of history

Read this beautiful article by James Cronin

- Murray Gell-Mann and Abraham Pais wrote this paper in 1955. They concluded that the best way to describe the behavior of $\theta^0(K^0)$ and $\bar{\theta}^0(\bar{K}^0)$ mesons was to see the two particles not as independent entities but as a two-state system.

PHYSICAL REVIEW VOLUME 97, NUMBER 5 MARCH 1, 1955

Behavior of Neutral Particles under Charge Conjugation

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AND

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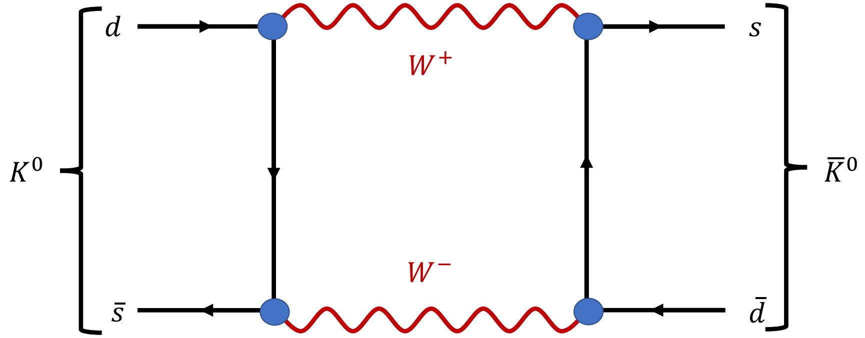
(Received November 1, 1954)

Some properties are discussed of the θ^0, a heavy boson that is known to decay by the process $\theta^0 \to \pi^+ + \pi^-$. According to certain schemes proposed for the interpretation of hyperons and K particles, the θ^0 possesses an antiparticle $\bar{\theta}^0$ distinct from itself. Some theoretical implications of this situation are discussed with special reference to charge conjugation invariance. The application of such invariance in familiar instances is surveyed in Sec. I. It is then shown in Sec. II that, within the framework of the tentative schemes under consideration, the θ^0 must be considered as a "particle mixture" exhibiting two distinct lifetimes, that each lifetime is associated with a different set of decay modes, and that no more than half of all θ^0's undergo the familiar decay into two pions. Some experimental consequences of this picture are mentioned.

"If there is any place where we have a chance to test the main principles of quantum mechanics in the purest way — does the superposition of amplitudes work or doesn't it? — this is it"

Richard Feynman, The Feynman Lectures on Physics, Volume III, Chapter 11.

- Their framework describes the quantum phenomenon of $K^0 - \bar{K}^0$ mixing, leading to *matter-antimatter* oscillations over time.



Flavour and mass eigenstates

- Mesons have defined flavour eigenstates $|M^0\rangle$ and $|\bar{M}^0\rangle$, defining the quark content:

$$F\begin{pmatrix}|M^0\rangle\\0\end{pmatrix} = +\begin{pmatrix}|M^0\rangle\\0\end{pmatrix}, \qquad F\begin{pmatrix}0\\|\bar{M}^0\rangle\end{pmatrix} = -\begin{pmatrix}0\\|\bar{M}^0\rangle\end{pmatrix}$$

For instance:
$|K^0\rangle = \bar{s}d$
$|\bar{K}^0\rangle = s\bar{d}$

- But, they also have weak Hamiltonian ($\mathcal{H}$, defining the time evolution of the system) eigenstates, with a defined mass m_i and width Γ_i (lifetime), and with eigenvalues λ_1 and λ_2:

$$\mathcal{H}\begin{pmatrix}|M_1\rangle\\0\end{pmatrix} = \lambda_1\begin{pmatrix}|M_1\rangle\\0\end{pmatrix}, \qquad \mathcal{H}\begin{pmatrix}0\\|M_2\rangle\end{pmatrix} = \lambda_2\begin{pmatrix}0\\|M_2\rangle\end{pmatrix}$$

$$\lambda_1 = m_1 - i\Gamma_1/2$$
$$\lambda_2 = m_2 - i\Gamma_2/2$$

- Each set is a linear combination of the others:

$$\begin{pmatrix}|M_1\rangle\\|M_2\rangle\end{pmatrix} = \mathcal{Q}\begin{pmatrix}|M^0\rangle\\|\bar{M}^0\rangle\end{pmatrix}, \qquad \text{with } \mathcal{Q} = \begin{pmatrix}p & q\\p & -q\end{pmatrix} \text{ and } |p|^2 + |q|^2 = 1$$

Where is mixing from?

- The evolution of a quantum state $|\xi(t)\rangle$ can be described by the Schrödinger equation:

$$i\frac{\mathrm{d}}{\mathrm{d}t}|\xi(t)\rangle = \mathcal{H}|\xi(t)\rangle \qquad \Longrightarrow \qquad |\xi(t)\rangle = e^{-i\mathcal{H}t}|\xi(0)\rangle$$

- Since $|M_1\rangle$ and $|M_2\rangle$ are eigenvectors of $\mathcal{H}$:

$$|M_{1,2}(t)\rangle = e^{-i\lambda_{1,2}t}|M_{1,2}(0)\rangle$$

- We can change the flavour basis and see the flavour evolution of the system:

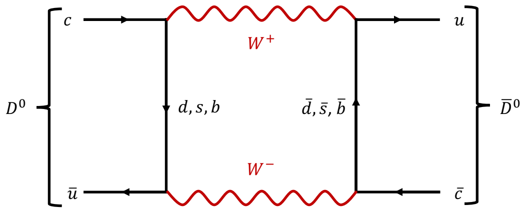
$$\begin{pmatrix}|M^0(t)\rangle \\ |\bar{M}^0(t)\rangle\end{pmatrix} = \mathcal{Q}^{-1}\begin{pmatrix}e^{-i\lambda_1 t} & 0 \\ 0 & e^{-i\lambda_2 t}\end{pmatrix}\mathcal{Q}\begin{pmatrix}|M^0(0)\rangle \\ |\bar{M}^0(0)\rangle\end{pmatrix} = \begin{pmatrix}g_+(t) & \frac{q}{p}g_-(t) \\ \frac{p}{q}g_-(t) & g_+(t)\end{pmatrix}\begin{pmatrix}|M^0(0)\rangle \\ |\bar{M}^0(0)\rangle\end{pmatrix}$$

$$g_\pm(t) = \frac{e^{-i\lambda_1 t} \pm e^{-i\lambda_2 t}}{2}$$

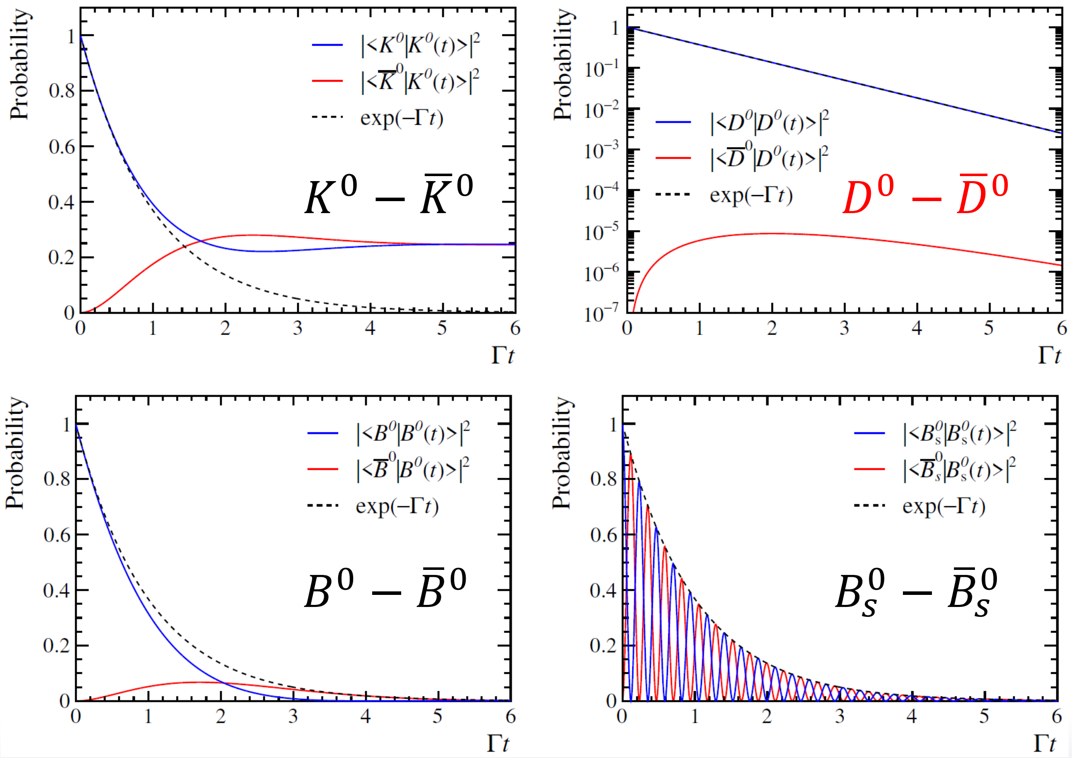
Mixing of different systems

- This allows us to get the probability of a initial flavour evolving to another one (particle *oscillation* or *mixing*!):

$$\text{Prob}(M^0 \to \bar{M}^0, t) = |\langle M^0(t)|\bar{M}^0\rangle|^2 = \left|\frac{q}{p}\right|^2 |g_-(t)|^2 = \left|\frac{q}{p}\right|^2 \frac{e^{-\Gamma t}}{2}(\cosh(y\Gamma t) - \cos(x\Gamma t))$$



where $x = \frac{m_1 - m_2}{\Gamma}$ and $y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$, and with $\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$.



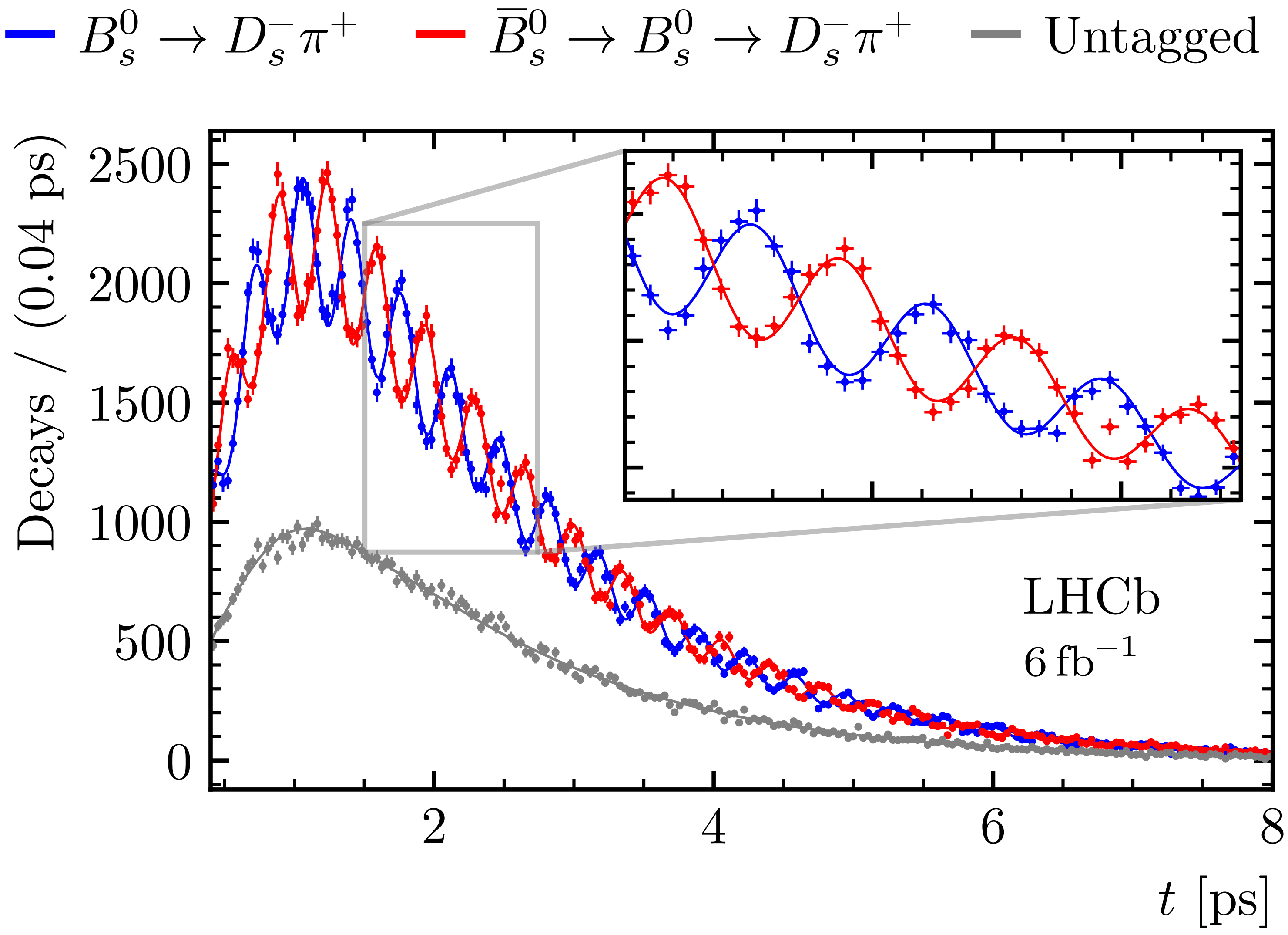
Experimental knowledge of x and y [HFLAV and PDG]

System	x	y
$K^0 - \bar{K}^0$	-0.946 ± 0.004	0.99650 ± 0.00001
$D^0 - \bar{D}^0$	$(4.09^{+0.48}_{-0.49})\times10^{-3}$	$(6.15^{+0.56}_{-0.55})\times10^{-3}$
$B^0 - \bar{B}^0$	-0.769 ± 0.004	$(0.1 \pm 0.1)\times10^{-2}$
$B_s^0 - \bar{B}_s^0$	26.89 ± 0.07	$(12.9 \pm 0.6)\times10^{-2}$

$D^0 - \bar{D}^0$ system

$B_s^0 - \bar{B}_s^0$ system

B_s^0 mixing: One or the most beautiful LHCb plot

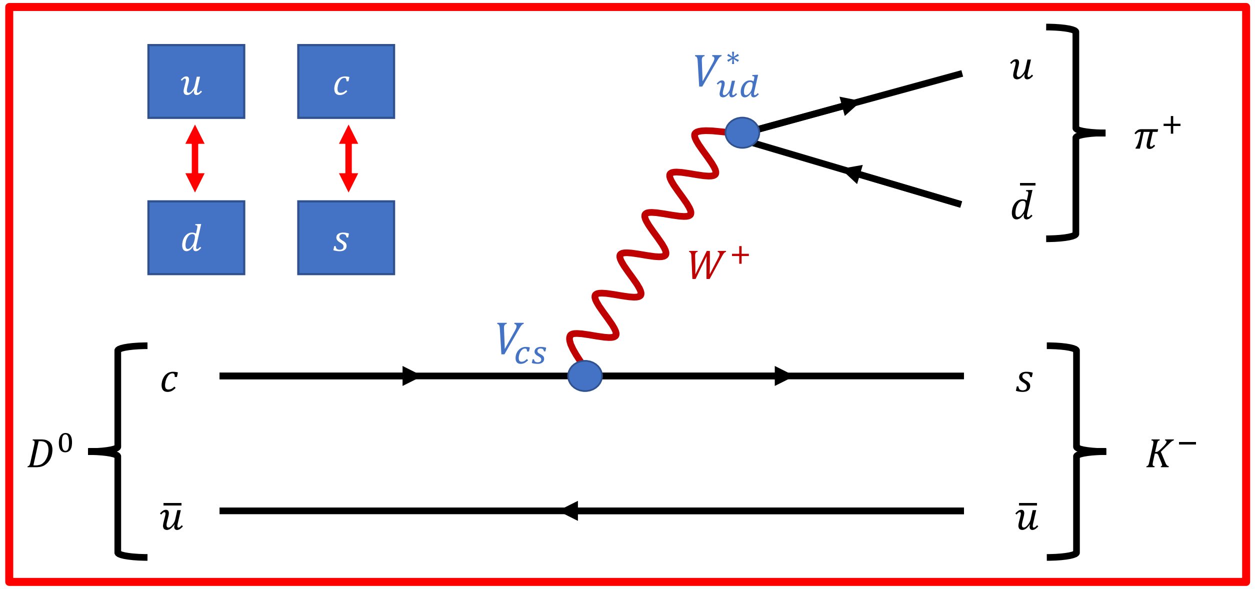


How to see charm mixing?

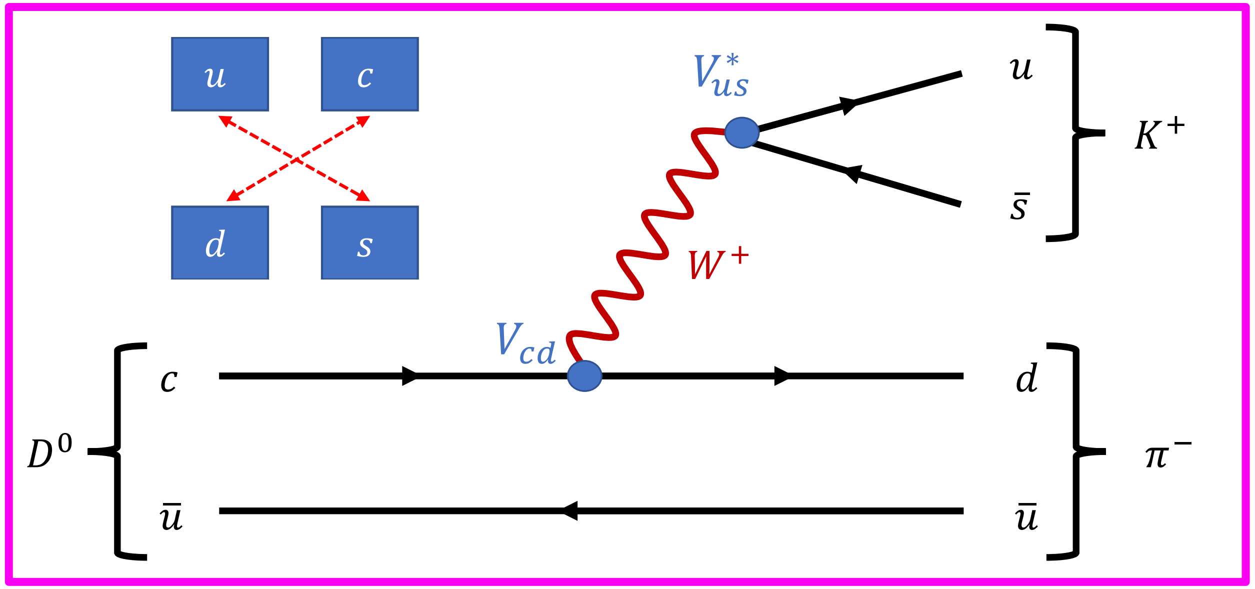
- Idea: Look at two important decays: $D^0 \to K^-\pi^+$ and $D^0 \to K^+\pi^-$
- These decays have very different probabilities, because of the CKM mechanism:

$$R_D = \frac{\mathcal{B}(D^0 \to K^+\pi^-)}{\mathcal{B}(D^0 \to K^-\pi^+)} = (0.344 \pm 0.002)\%$$

$D^0 \to K^-\pi^+$: Cabibbo favoured

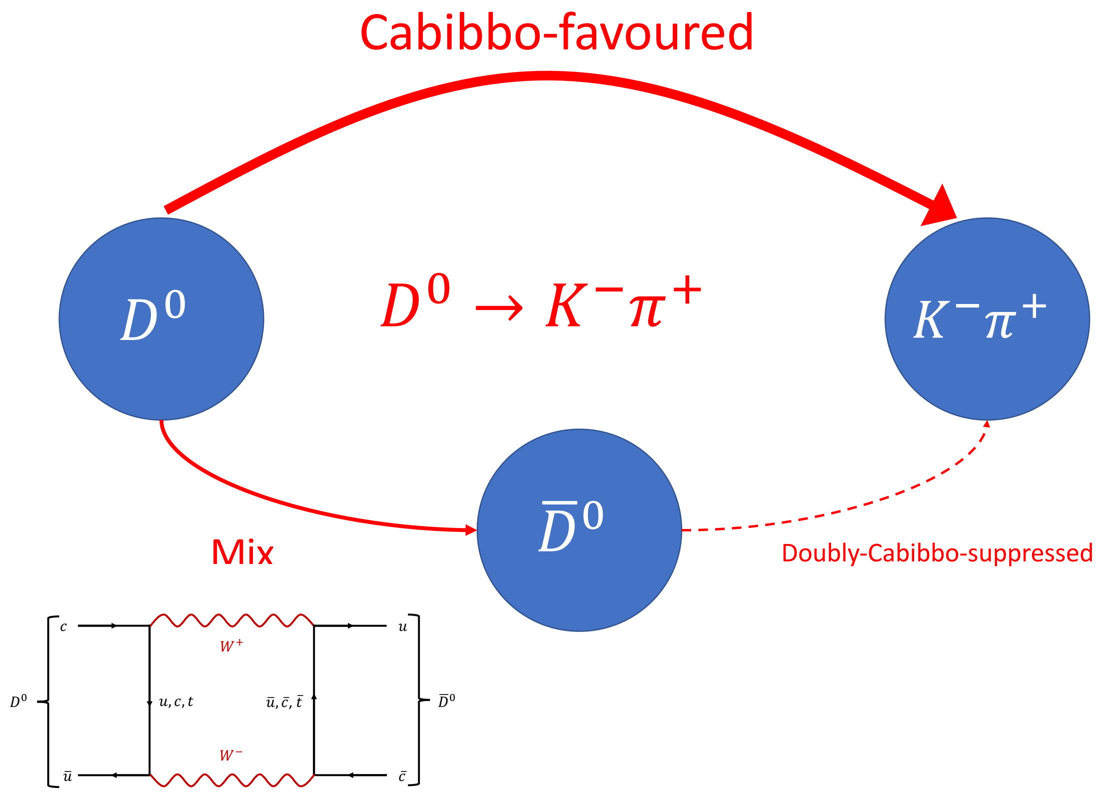


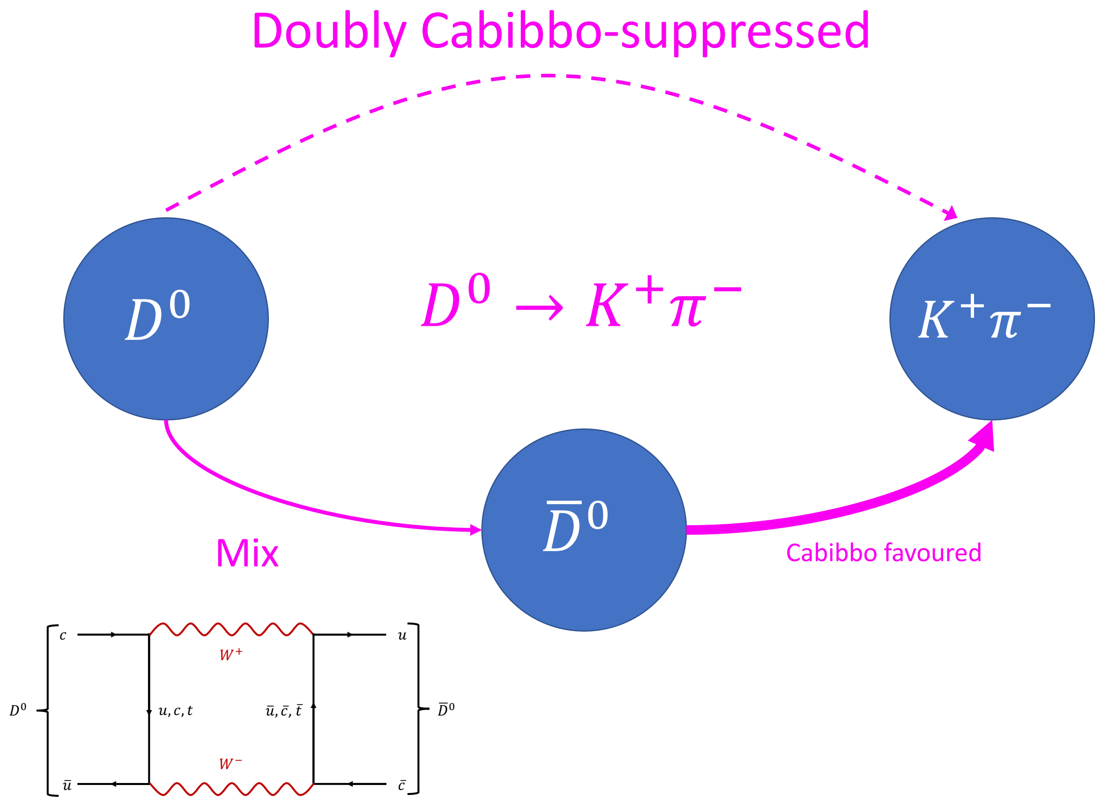
$D^0 \to K^+\pi^-$: Doubly Cabibbo-suppressed



First evidence of charm mixing

- <u>However:</u> I just showed you that D^0 can also mix to a $\overline{D}^0$ before decaying. Therefore, the possibilities will look like this:





- The presence of this mixing path implies that $D^0 \to K^-\pi^+$ and $D^0 \to K^+\pi^-$ will have slightly different lifetimes!

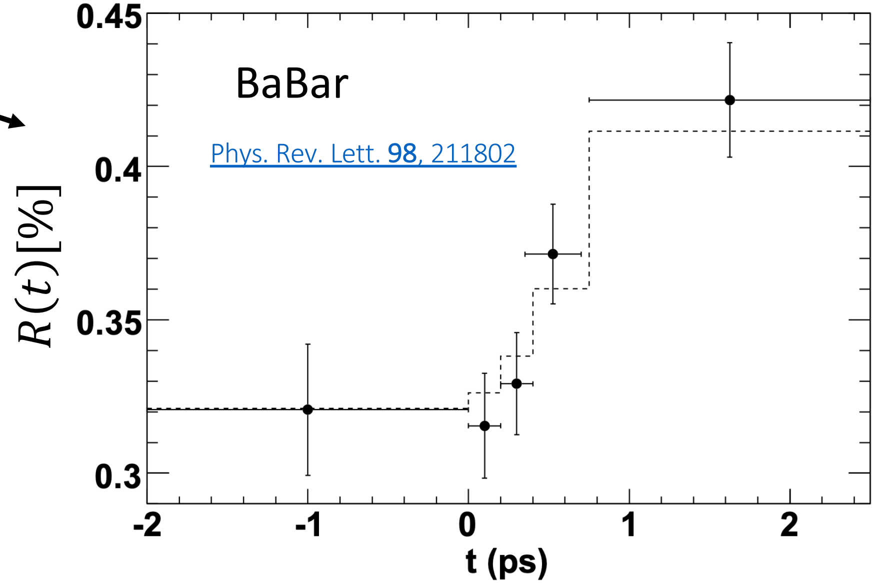
First evidence of charm mixing

- Strategy: Measure the ratio of decay time distributions

$$R(t) = \frac{\Gamma(D^0(t) \to K^+\pi^-)}{\Gamma(D^0(t) \to K^-\pi^+)} = R_D + \sqrt{R_D}\,y\,\frac{t}{\tau_D} + \mathcal{O}\left(\left(\frac{t}{\tau_D}\right)^2\right)$$

- Hence, with no mixing $R(t)$ is compatible with a straight line $R(t) = R_D$. However, the presence of mixing through y makes this ratio depart from a straight line!

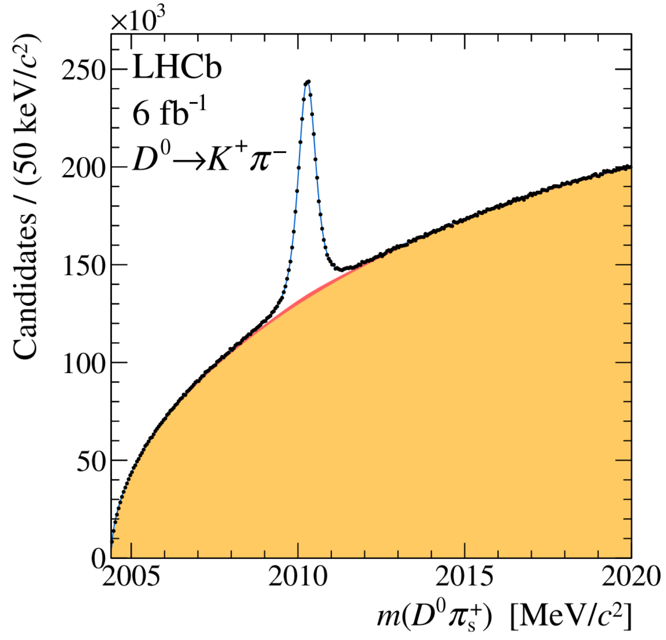
- This is what BaBar (SLAC, California) did in 2007, leading to the first evidence of charm mixing!

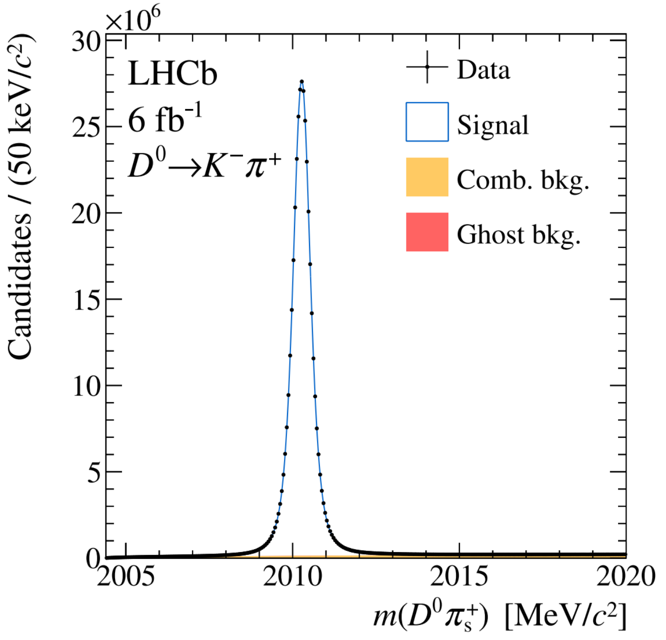


* It is not exactly y but $y' = y\cos\delta - x\sin\delta$, but I do not want to swarm you with such things

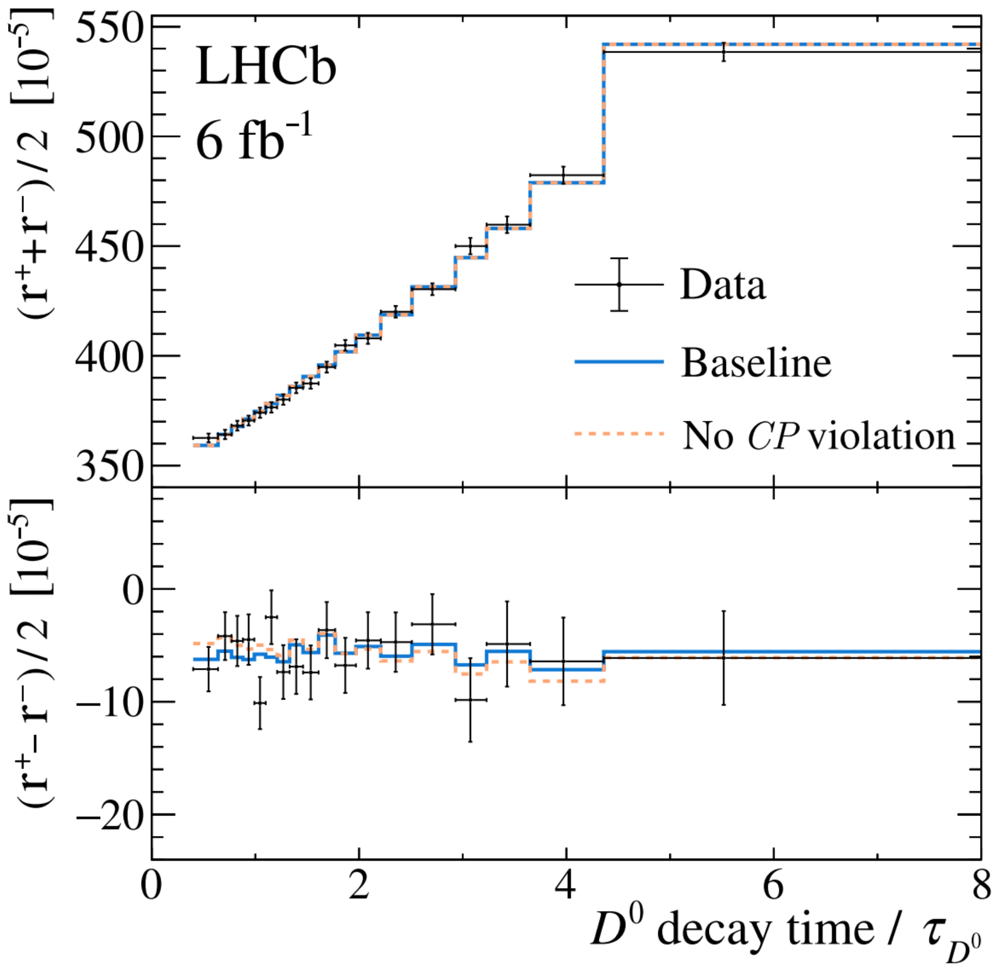
New results by LHCb

- LHCb is now a leader in this way of measuring charm mixing, we can resolve $R(t)$ 15 times more precisely!
- We can also separate matter and antimatter $R(t)$ distributions. Their subtraction is a measurement of CP violation!





[See a presentation of this new result](#)



CP Violation

A few words on CP violation

- CP violation (CPV) is one of the three Sakharov conditions needed to explain the asymmetry between matter and antimatter in the Universe.
- CPV was first observed in 1964 in the decays of neutral K mesons by James Cronin and Val Fitch.
- In 1973, Makoto Kobayashi and Toshihide Maskawa postulated a third generation of quarks to incorporate CPV within the Standard Model.

→ They introduced a unitary matrix, now called the CKM matrix, which has 4 free parameters : 3 mixing angles and one CP-violating phase δ.

$$V_{\mathrm{CKM}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$

A few words on CP violation in the charm sector

- The CKM matrix is unitary matrix that can be visualised as a unitary triangle, described (especially in B physics) that the following relation:

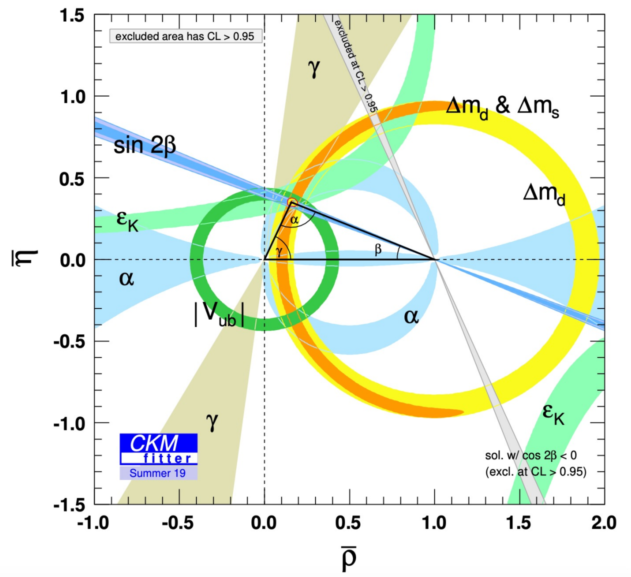
$$V_{ud}^* V_{ub} + V_{cd}^* V_{cb} + V_{td}^* V_{tb} = 0$$

- The area of the triangle is proportional to the amount of CP violation in the Standard Model!

- In charm systems, another relation is used

$$V_{cd}^* V_{ud} + V_{cs}^* V_{us} + V_{cb}^* V_{ub} = 0$$

- This relation leads to an extremely squashed unitary triangle, inducing reduced CP violation w.r..t the B system!



$\Lambda_s \sim \lambda$

$\Lambda_b \sim \lambda^5$

$\Lambda_d \sim \lambda$

Not to scale!

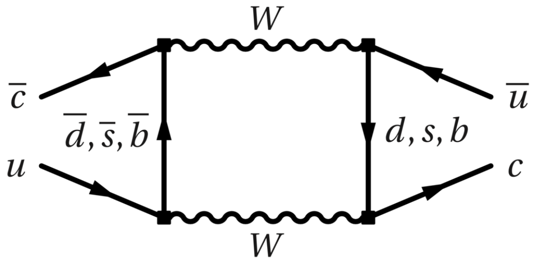
$$\lambda = |V_{us}| \sim 0.23$$

CP-violation in the charm sector

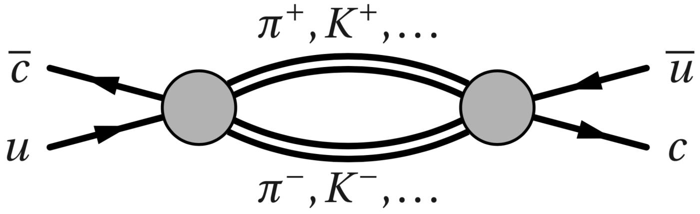
	d	s	b
$\bar{d}$	-	K^0	B_0
$\bar{s}$	$\bar{K}^0$	-	B_s^0
$\bar{b}$	$\bar{B}^0$	$\bar{B}_s^0$	-

	u	c	t
$\bar{u}$	-	D^0	-
$\bar{c}$	$\bar{D}^0$	-	-
$\bar{t}$	-	-	-

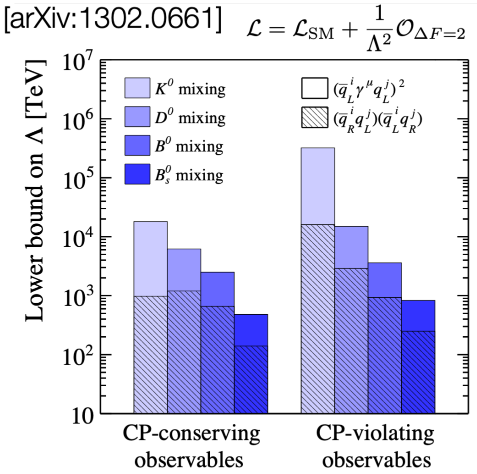
- The charm sector encompasses the only up-type quark decays of neutral mesons in which CP-violation (CPV) can be probed.
- CPV in SM is predicted to be (very) small $(\sim 10^{-3} - 10^{-4})$.
  - → Room for new physics enhancements.
- These predictions are dominated by long distance contributions.
  - → Experimental measurements are crucial to improve theoretical predictions.



Short Distance Contributions:
Heavily suppressed!



Long Distance Contributions:
Large theoretical uncertainties!



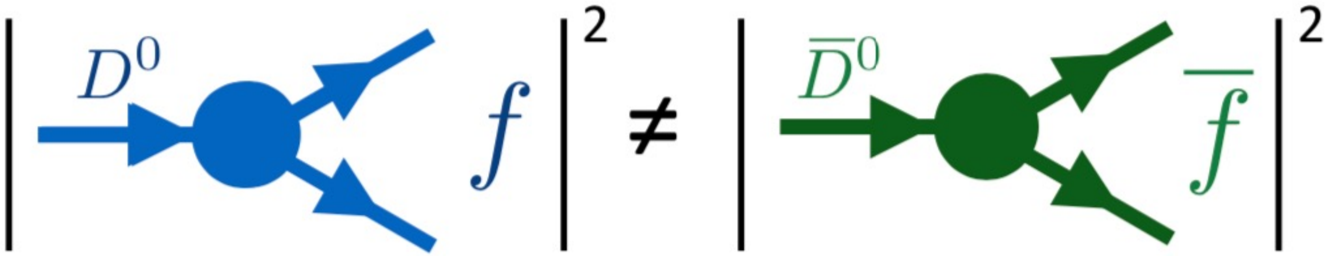
- Charm data samples are huge: ~ a few billion D^0 decays to be analysed at LHCb with Run 1 + Run 2 data.

CP-violation in the charm sector

DIRECT

Decay

$|A_f| \neq |\bar{A}_{\bar{f}}|$

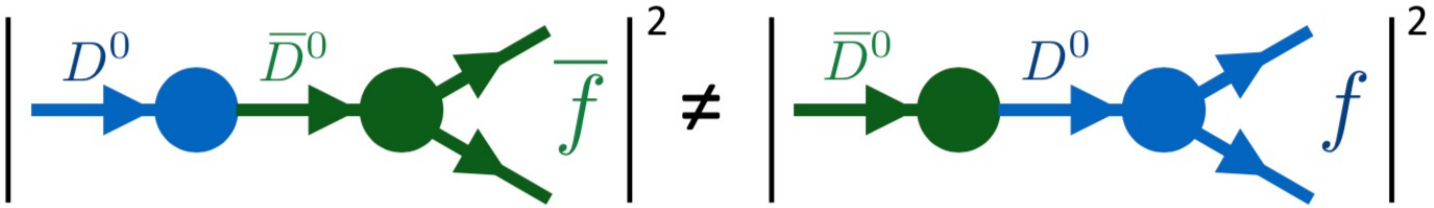


CPV in the decay observed at 5.3σ by the LHCb collaboration in March 2019! 🍾
[PhysRevLett.122.211803]

INDIRECT

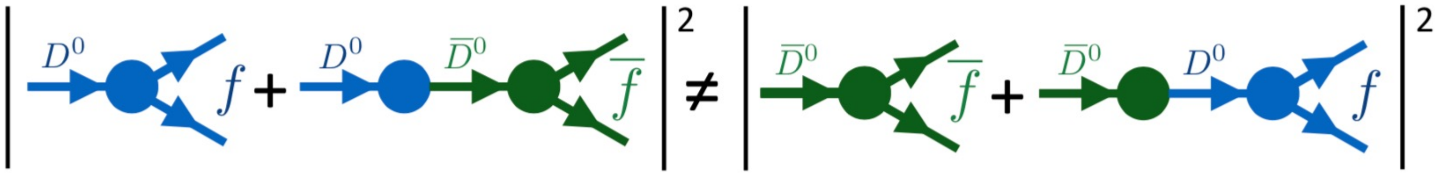
Mixing

$|q| \neq |p|$



Interference mixing-decay

$\phi_{\lambda_f} = \arg\left(\frac{q\bar{A}_f}{pA_f}\right) \neq 0$

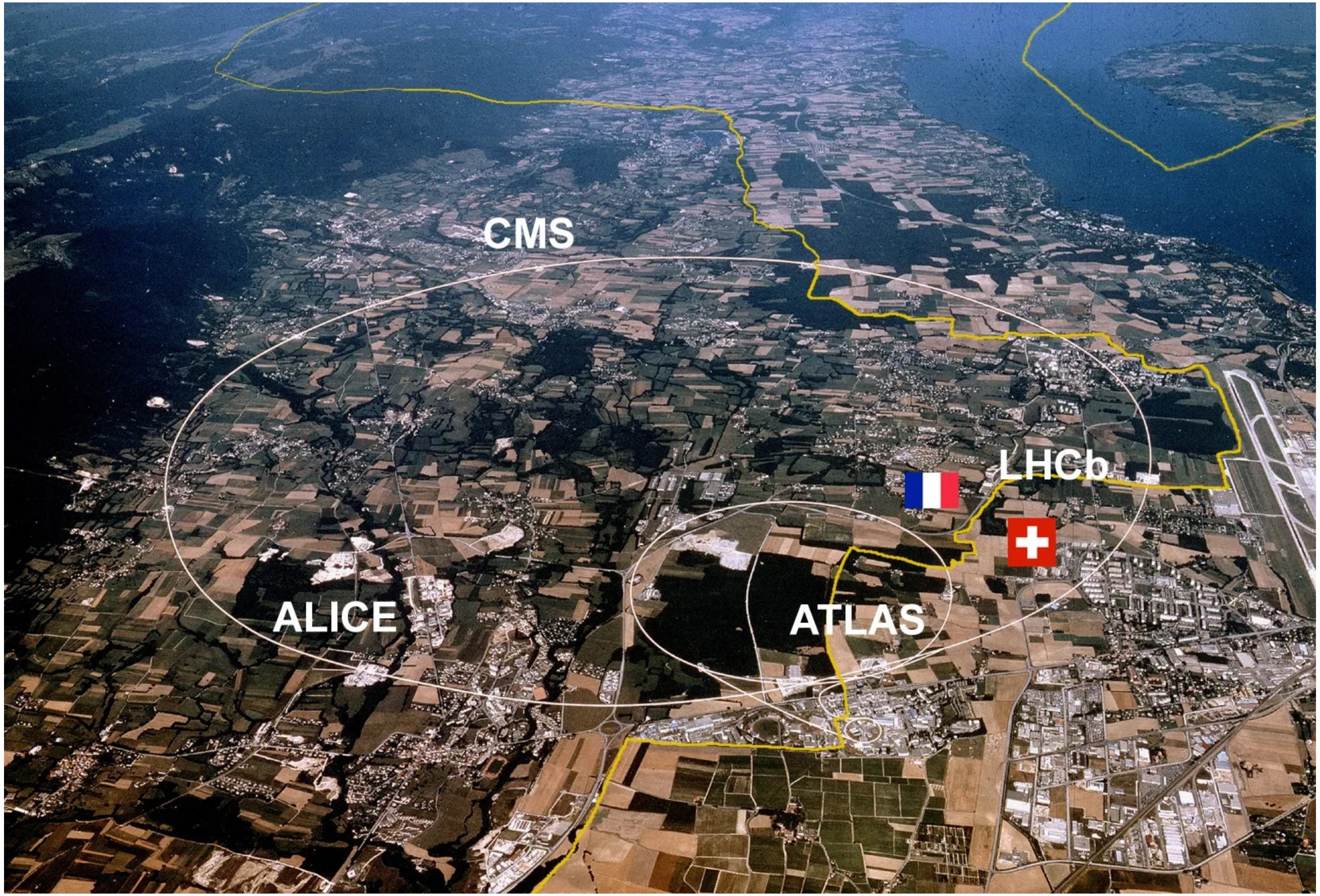


Still no evidence of CPV

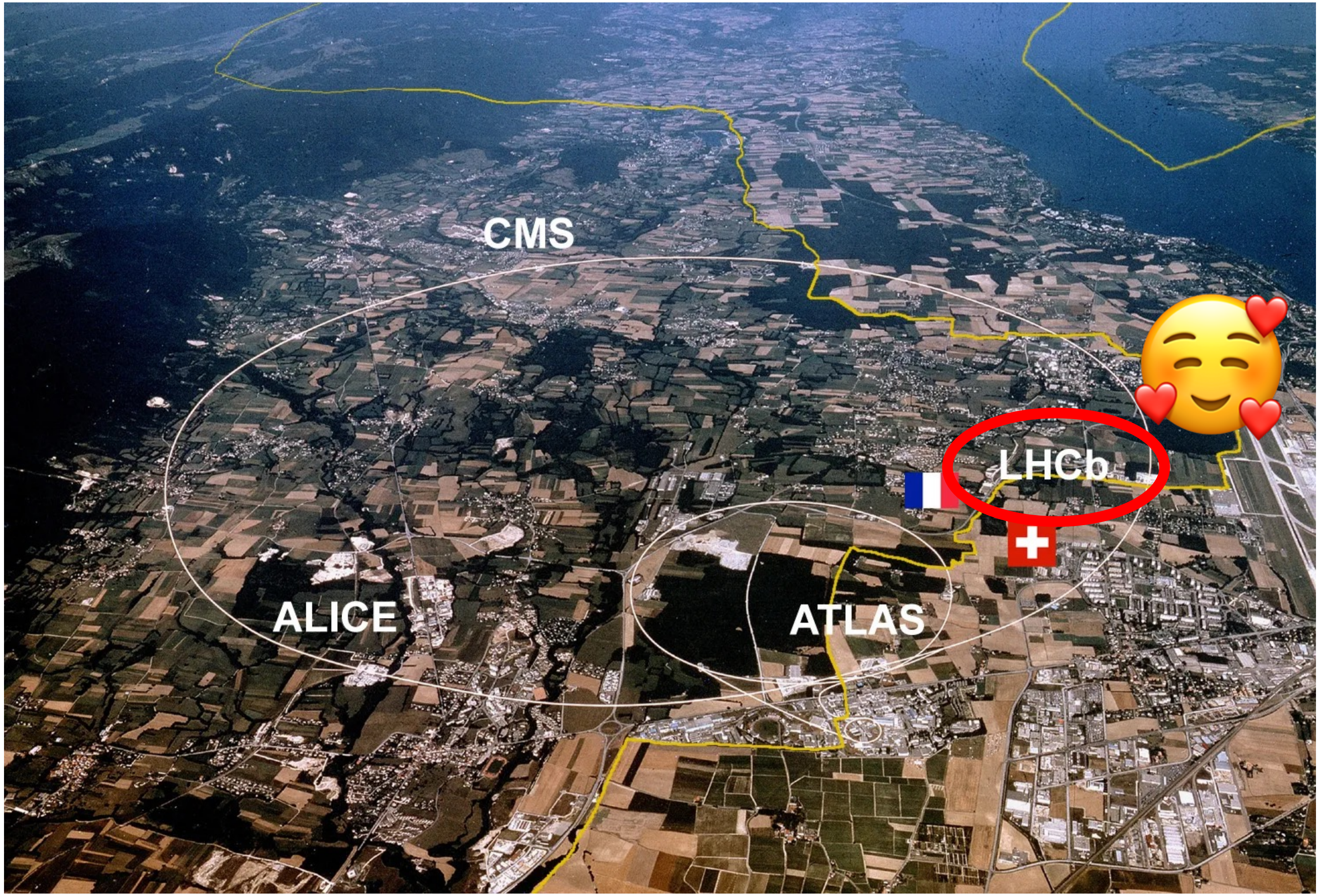
The Large Hadron Collider

- Collider with a circumference of 27km
- Can collide protons and heavy ions.
- Biggest machine ever built!
- Collisions up to 13.6 TeV
- Four interaction points = Four big experiments

The LHC experiments



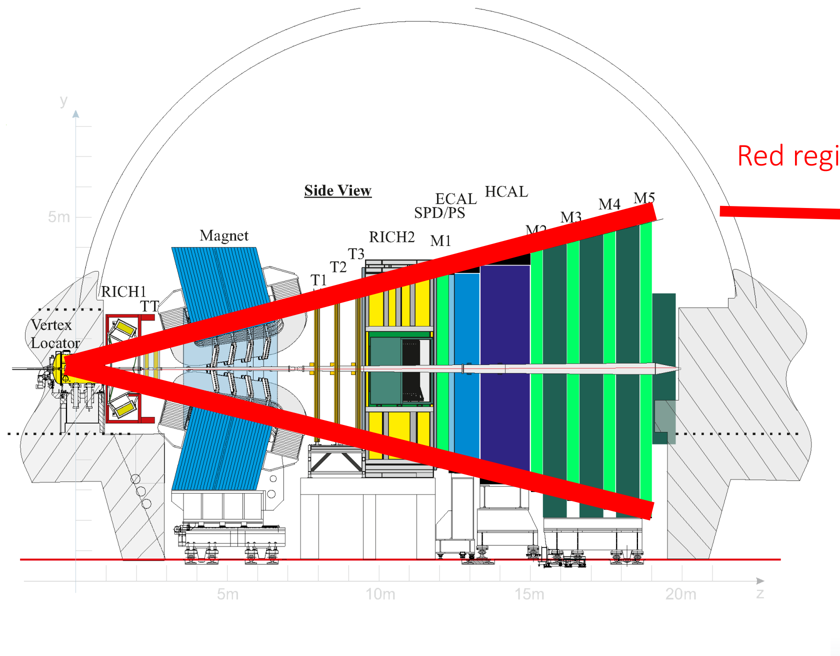
The LHC experiments



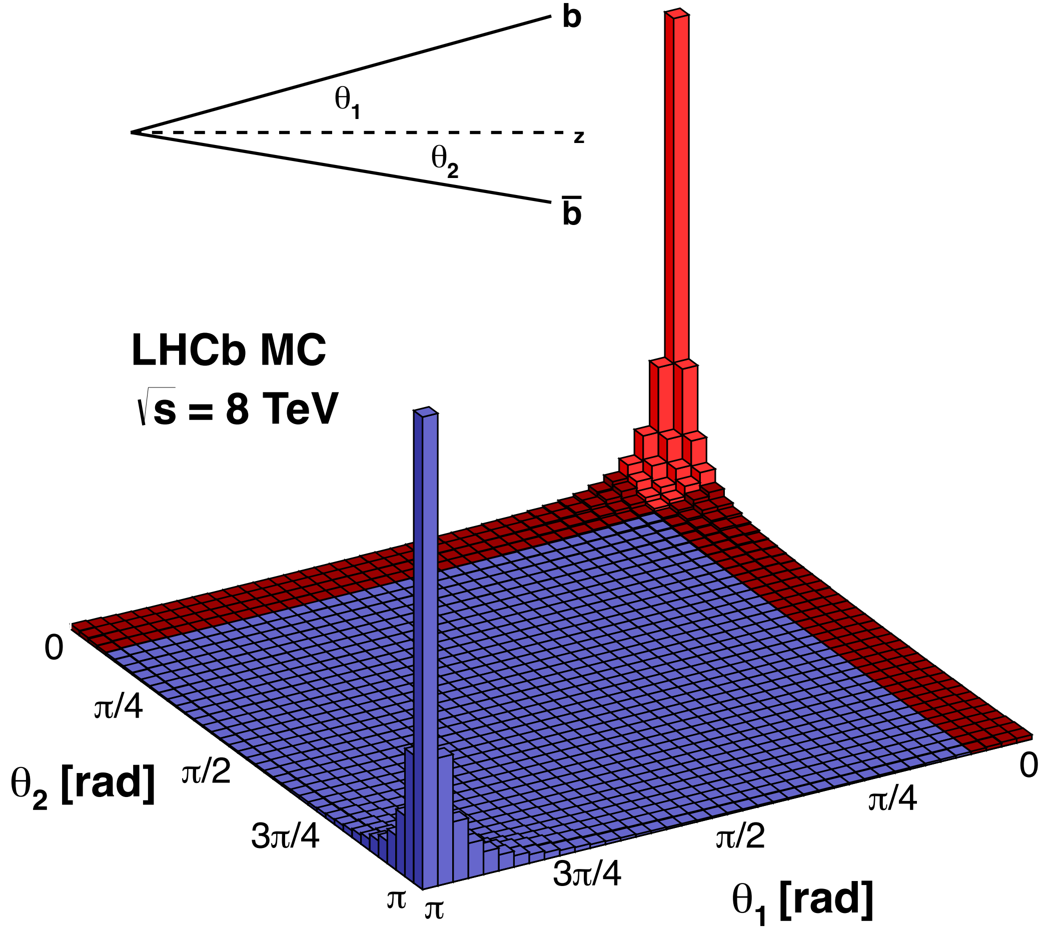
The LHCb detector

The LHCb geometry

- Most $b\bar{b}$ and $c\bar{c}$ pairs are produced from gluon fusion in the forward (and backward) region
- Since LHCb specialises in the study of B (beauty) and D (charm) hadrons, its detector elements are placed in the forward region!



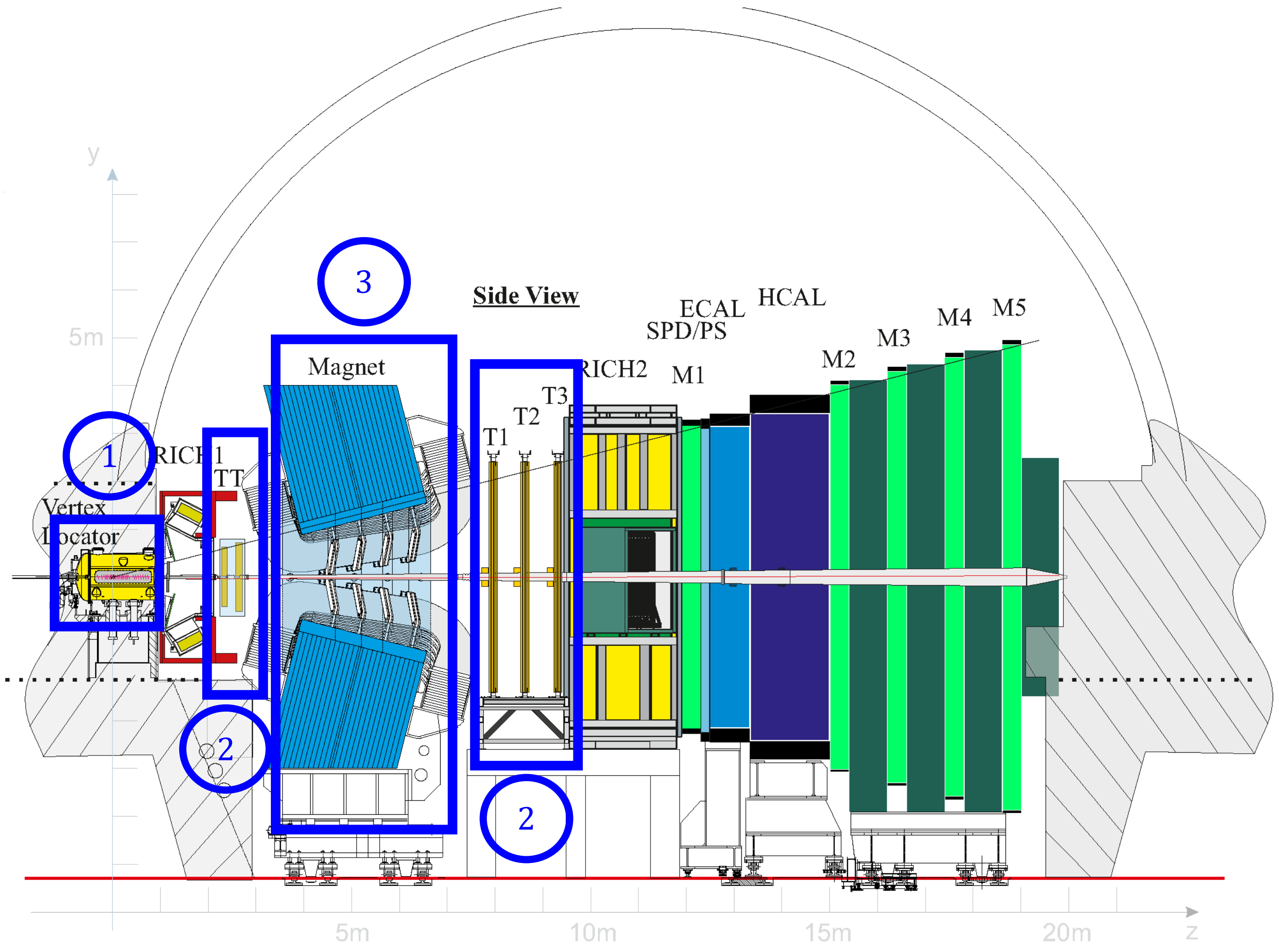
Red region is LHCb acceptance



Charm numbers

Experiment	$\sqrt{s}$	$\sigma_{acc}(D^0)$	L	$N(D^0)$
BESIII	3.77 GeV	8 nb	3 fb^{-1}	2.4×10^{7}
Belle II	10.6 GeV	1.45 nb	50 ab^{-1}	7.5×10^{10}
LHCb Run 1	7-8 TeV	1.5 mb	3 fb^{-1}	4.5×10^{12}
LHCb Run 2	13 TeV	3 mb	6 fb^{-1}	1.8×10^{13}
LHCb Run 3+4	14 TeV	~3mb	50 fb^{-1}	1.5×10^{14}
LHCb Run 5+	14 TeV	~3mb	300 fb^{-1}	6.0×10^{14}

The LHCb detector: Tracking system



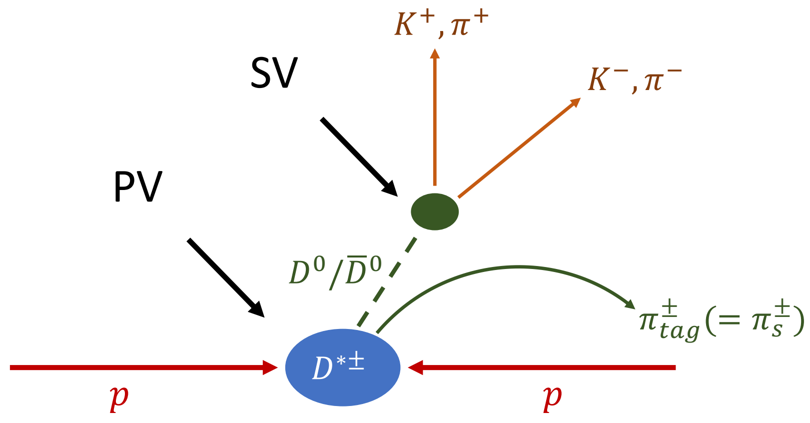
- The LHCb tracking system consists of:

1. The Vertex Locator (VELO)
2. The Trackers (TT + T1-3)
3. A **4 Tm** dipole magnet

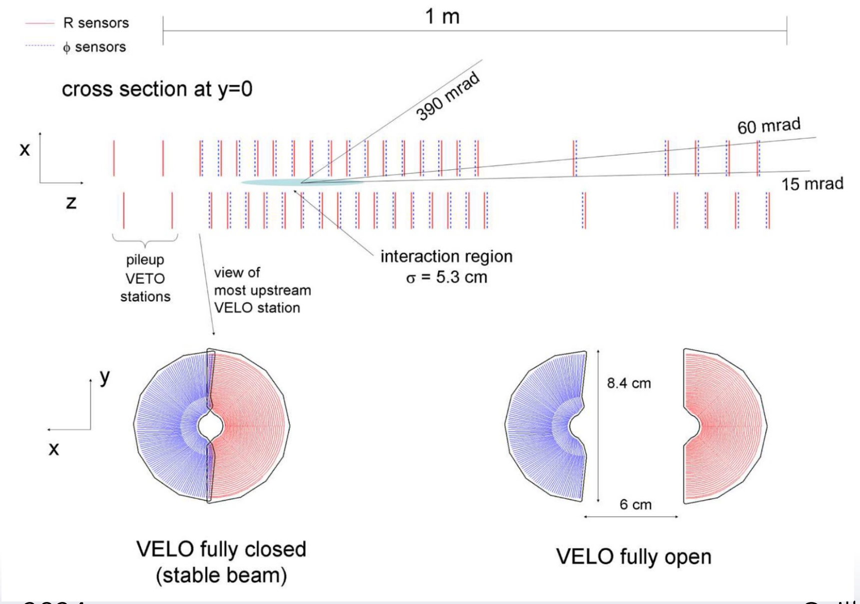
- Basic idea: Charged particles leave hits in the VELO and the tracking stations, allowing to determine the particles' trajectory with dedicated reconstruction algorithms.
- Excellent performances:
  - $\sigma(t) \approx 45\text{fs}$
  - $\sigma(p)/p \approx 0.5\%$

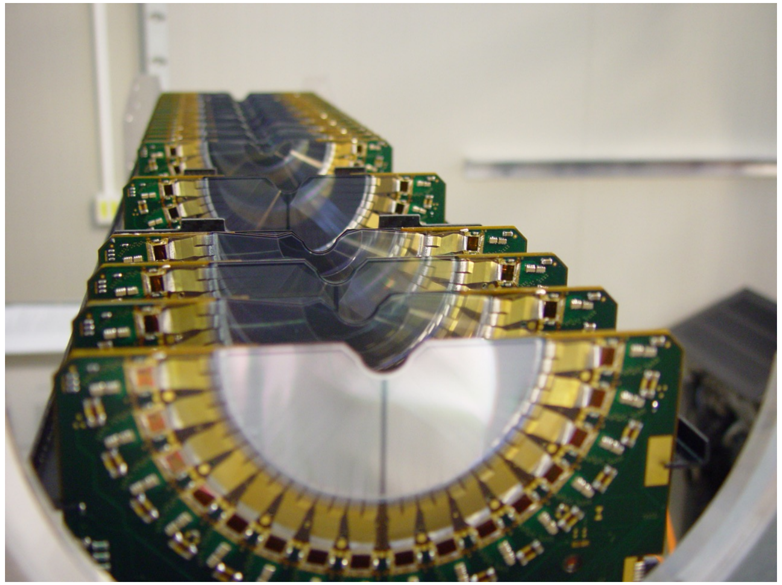
The VELO detector

$D^{*+} \to D^0\pi^+$



- Silicon micro-strip detector placed at the pp interaction point
- <u>**Main task:**</u> Locate the Primary Vertex (PV, the collision point) and the Secondary Vertex (SV) with high precision
- 21 circular modules which can measure either the r or φ position of charged particle hits.
- $\sigma(IP) = 12 + 24/p_T$ [μm] (p_T in GeV)

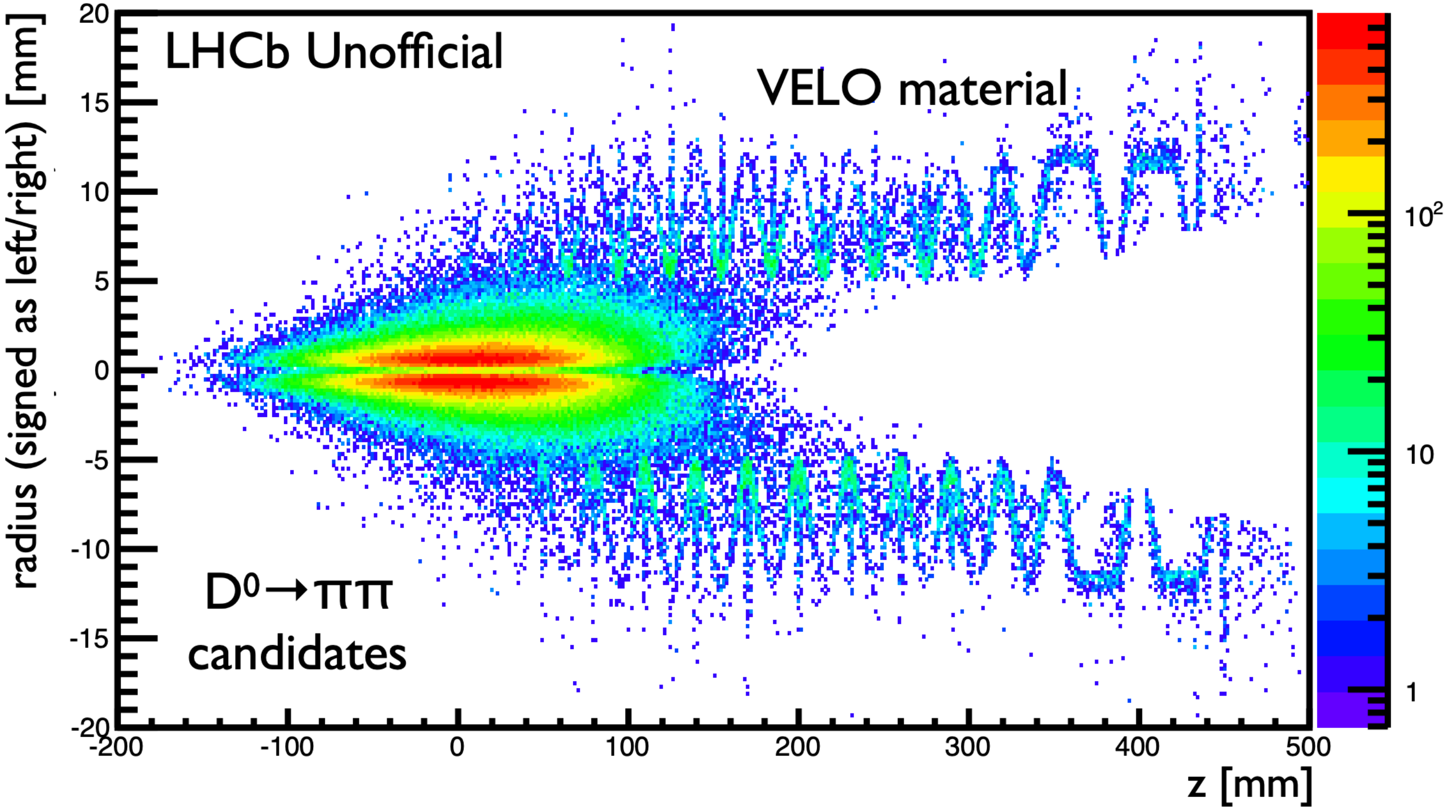




Boost

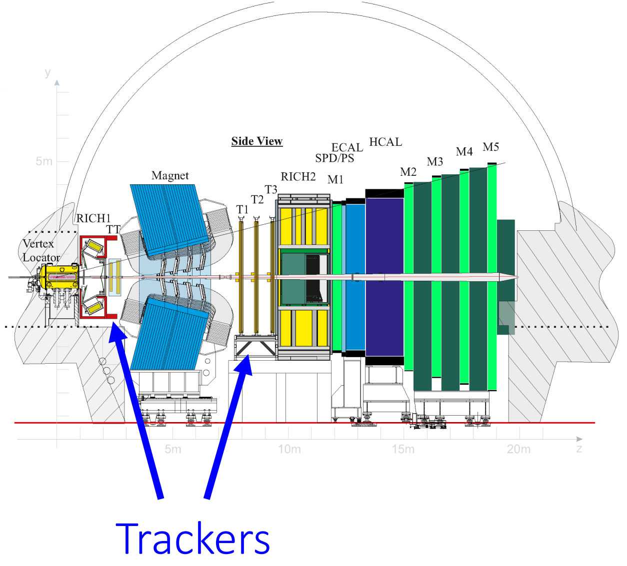
Average $\beta\gamma$:
- LHCb: $\mathcal{O}(10)$
- Belle: $\mathcal{O}(1)$

- Charm particles fly a few mm before decaying
- First material at $\sim 5mm$ perpendicular to z-direction
- Charm time resolution $\sim 0.1\tau_{\mathrm{D}}$

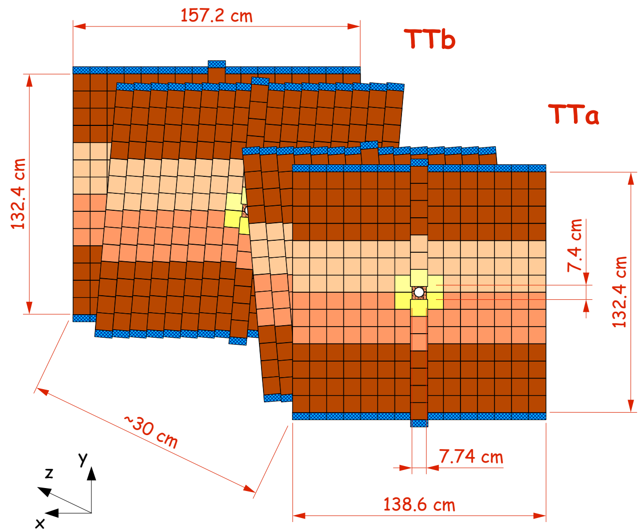


The Trackers

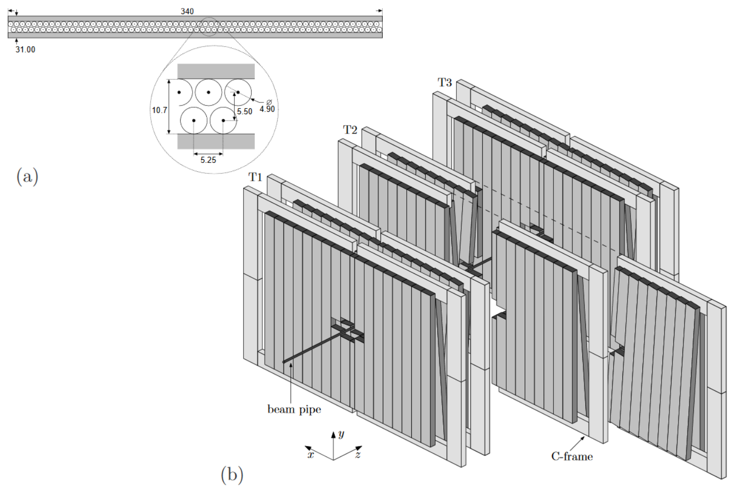
- Positioned before and after the 4Tm dipole magnet
- TT: Silicon detector placed before the magnet → important to remove *ghost tracks*: fake tracks obtained by connecting particle hits not coming from the same particle.
- T1-T3: Gaseous straw tube detector.

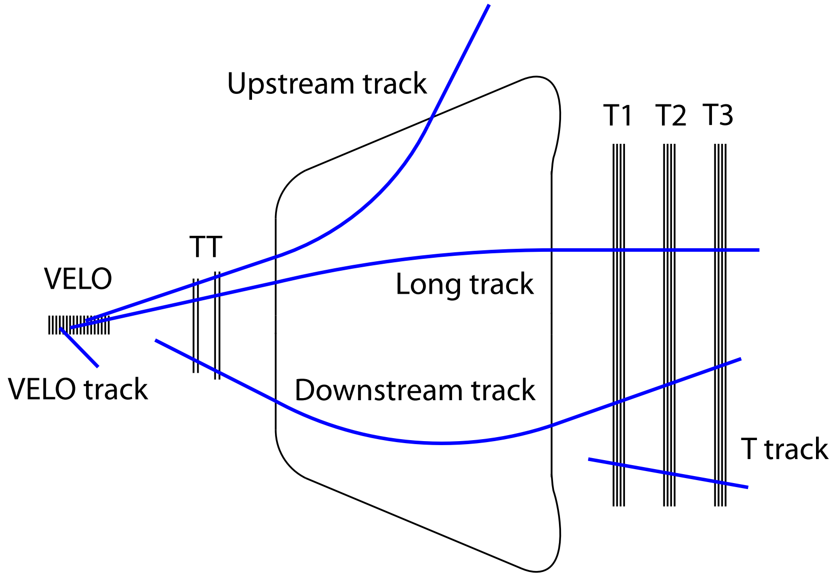


TT

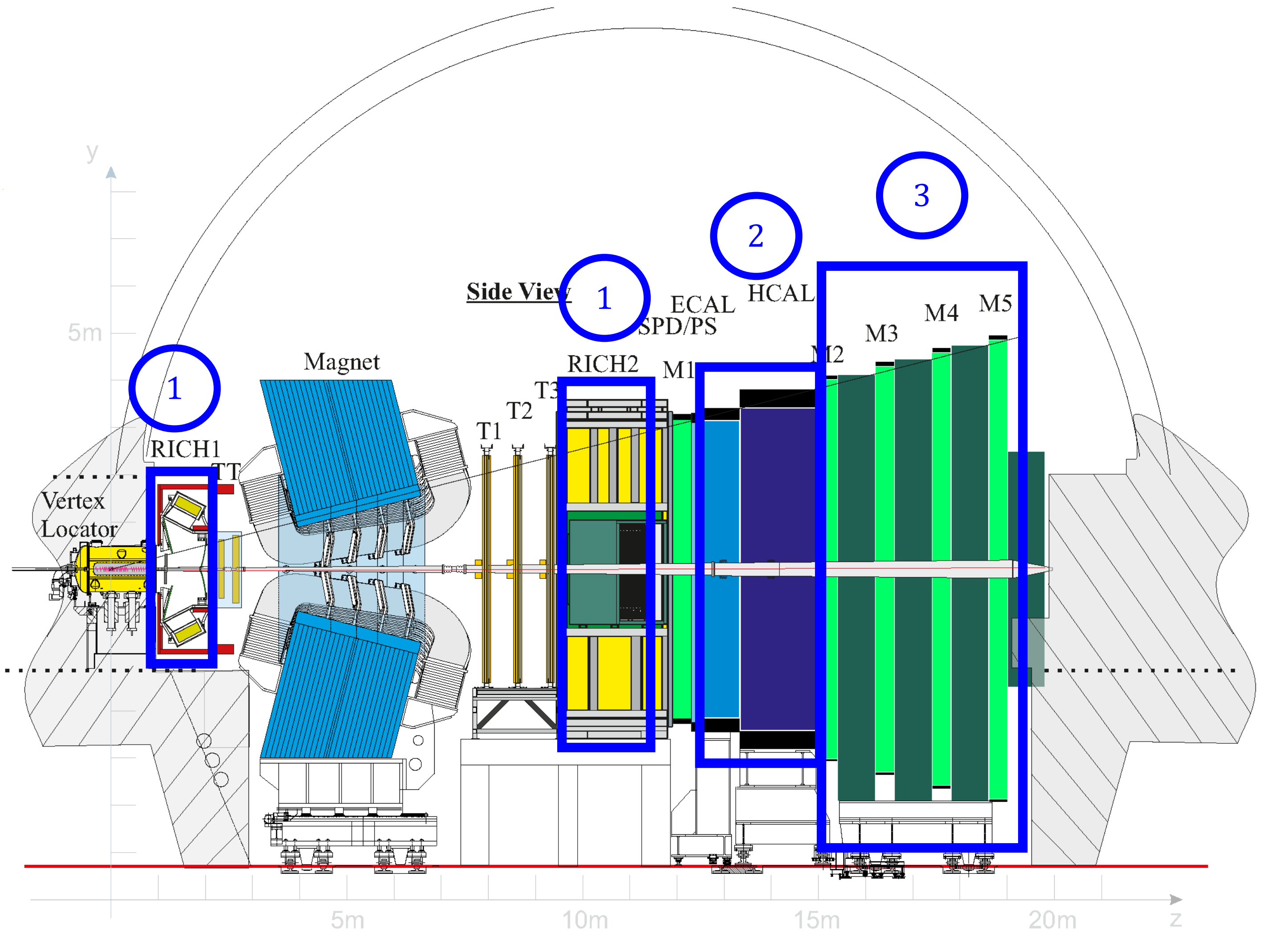


T1-T3





The LHCb detector: Particle identification system



- The LHCb particle identification system consists of:
1. The Ring Imaging Cherenkov (RICH) detectors
2. The Calorimeter system
3. The Muon system
- The tracking system only gives info on the momentum of particles, but not on their mass (defining their identity)
- For instance, crucial to know if we see in our detector $D^0 \to K^- K^+, D^0 \to K^- \pi^+$ or $D^0 \to \pi^- \pi^+$

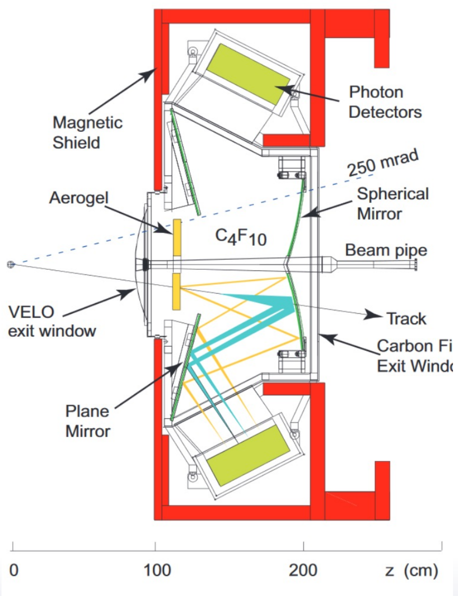
The RICH system

- Cherenkov effect: when a charged particle of velocity v goes through a medium (of refraction index n) faster than the speed of light in this medium, it emits a cone of light with angle θ:

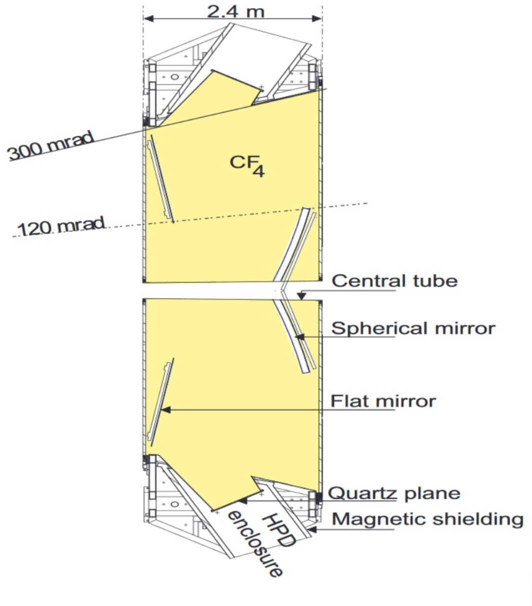
$$\cos\theta = \frac{c}{nv}$$

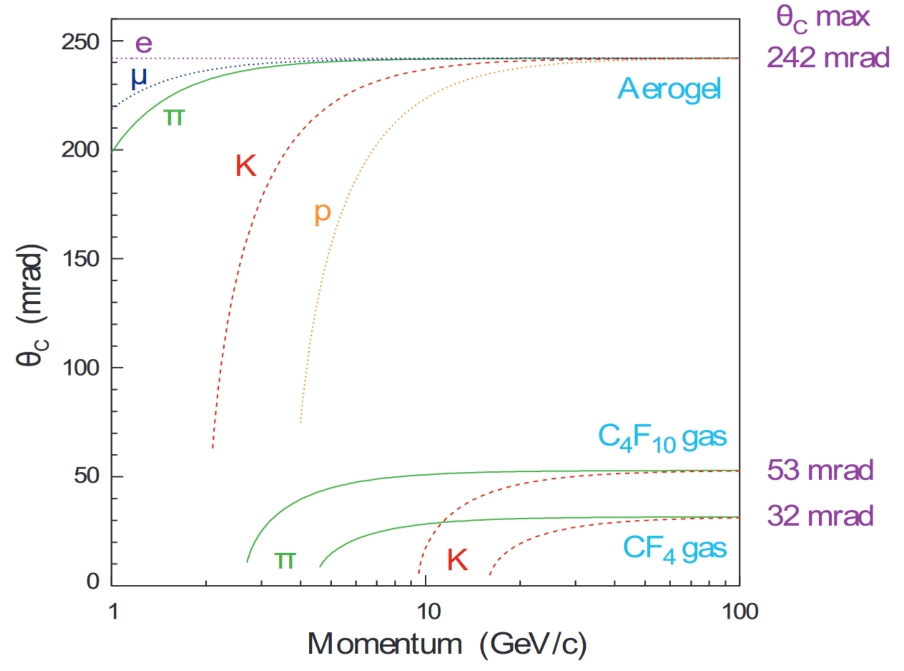
- We got p from the tracking system → we now get m (the particle identity)
- e and μ are not suited for the RICH system: they need their own system (CALO + muon chambers)

RICH 1: $p \in [1, 60]\text{GeV}/c$



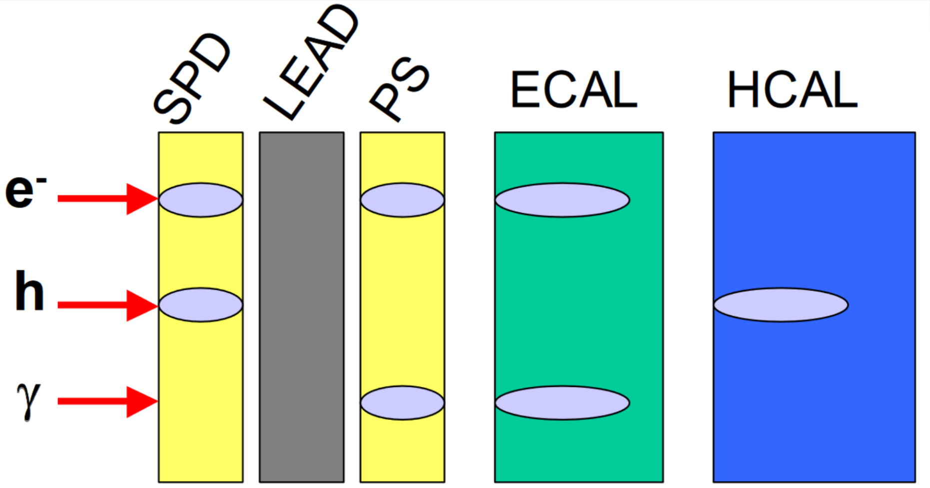
RICH 2: $p \in [50, 100]\text{GeV}/c$

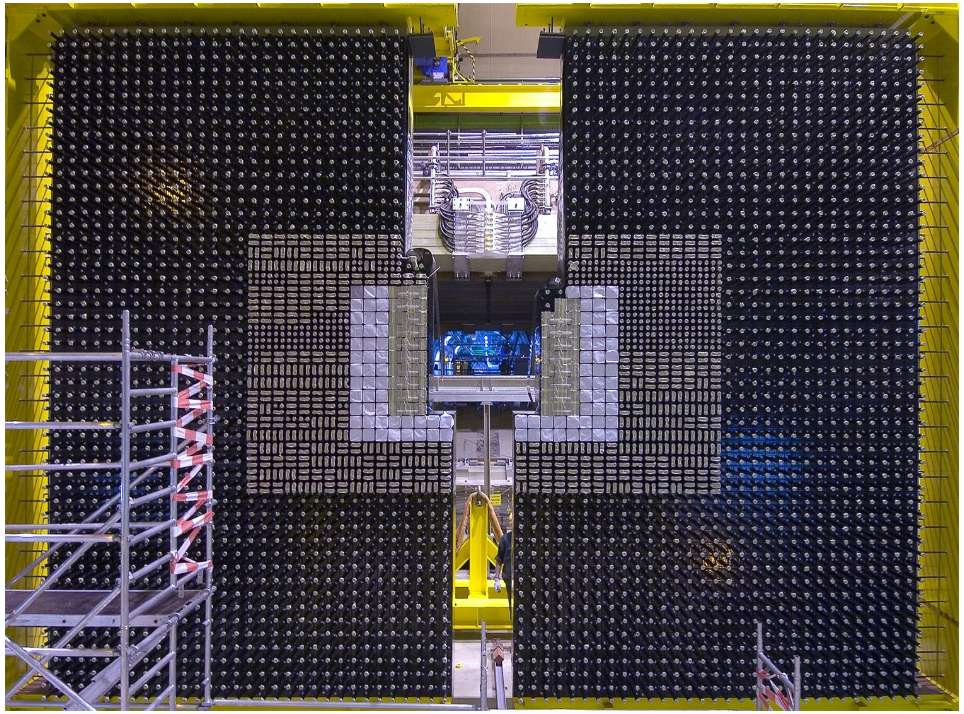




The calorimeter system

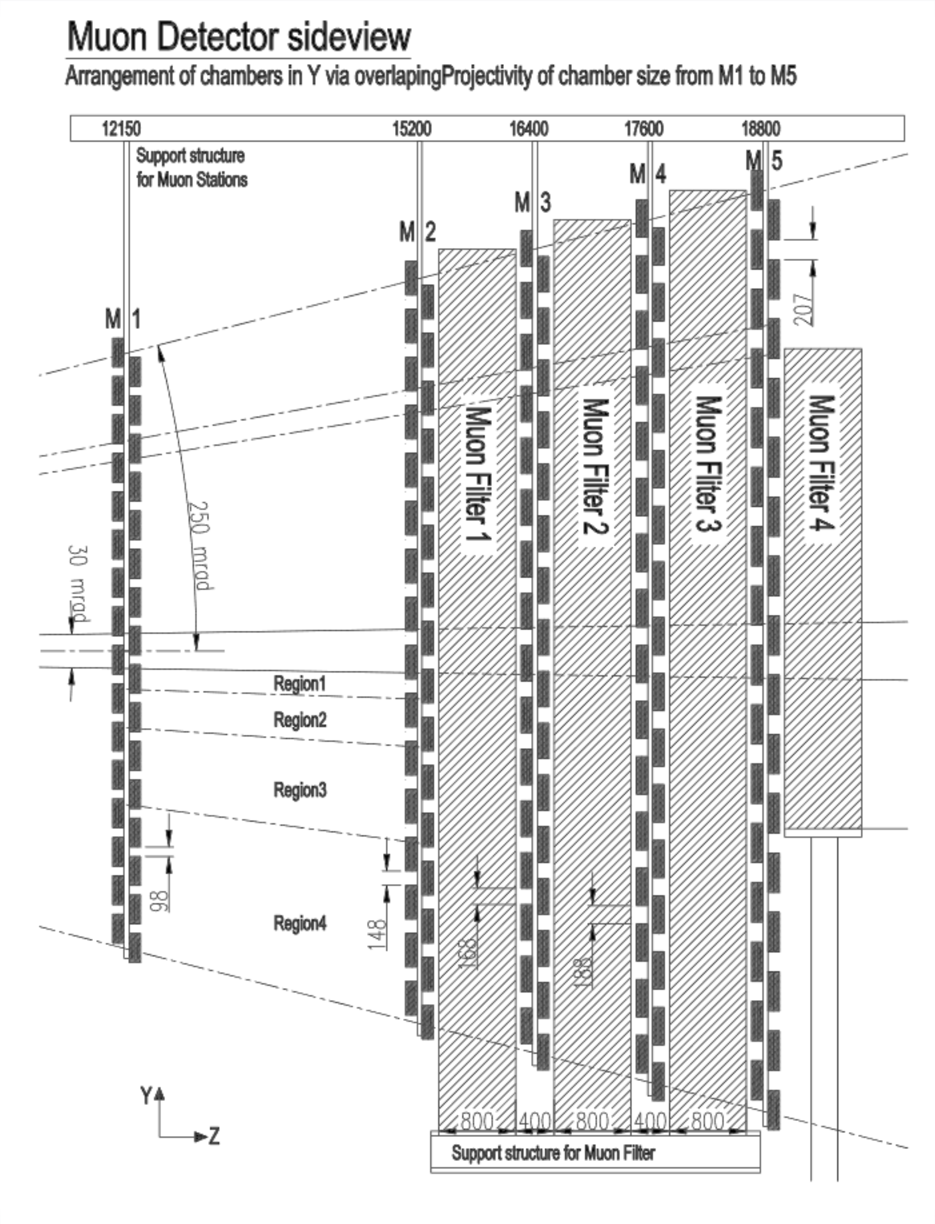
- Calorimeters are heavy detectors whose job is to completely stop incoming particles to measure their energy.
- It has 5 components:
  - Scintillating Pad Detector (SPD): discrimate charged from neutral particles (and give a estimation on number of tracks)
  - A Lead converter
  - Preshower detetector (PS): to separate hadronic from electromagnetic showers
  - Electromagnetic Calorimeter (ECAL): measures energy and position of hits of light particles (electrons, gammas)
  - Hadronic Calorimeter (ECAL): measures energy and position of hits of heavier particles (kaons, protons, pions)





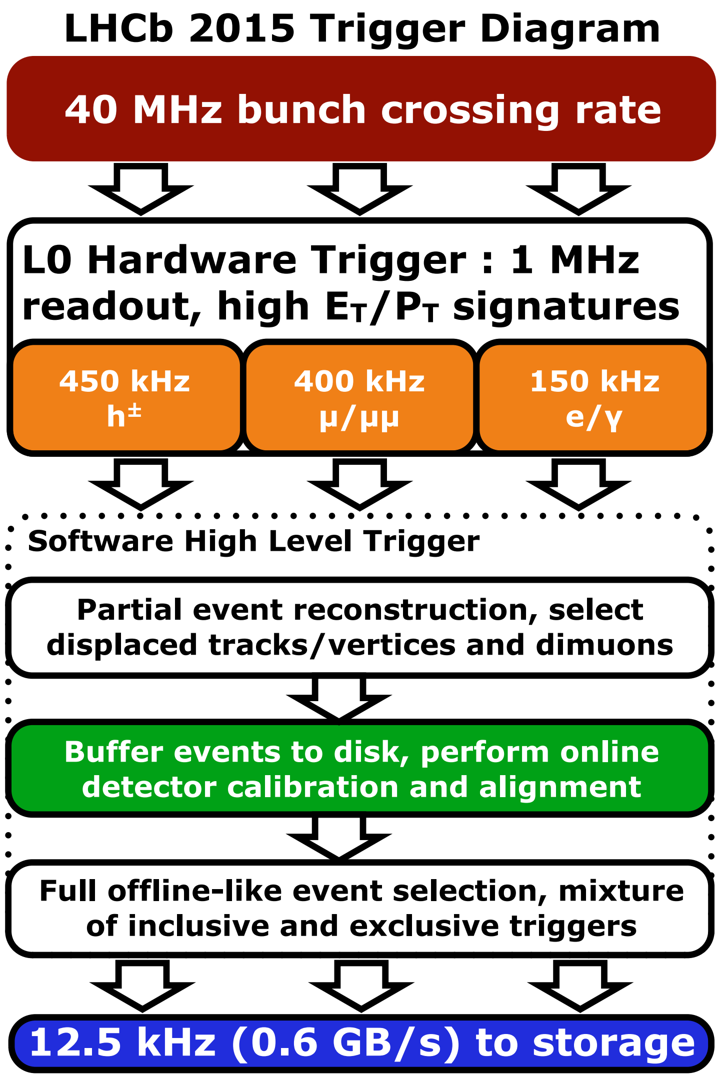
The muon system

- Gaseous detector which contain 80 cm thick iron absorbers to select incoming muons.
- 5 big detectors:
  - M1: positioned before the calorimeters, used primarily for triggering purposes.
  - M2-M5: The most distant LHCb detectors
- Muons have a large lifetime ($c\tau = 700m$) and have a low cross-section with matter → they're the only charged particles (in good number) that can reach the end of LHCb without being absorbed or decaying.



The LHCb trigger system (2011-2018) [EASY VERSION]

- LHCb: $40\text{M}\ pp$ collisions per second → $1\text{TB}/s$ (impossible!)
- Solution: Have a trigger system to select only the physics processes of interest for analysts!
- Stages of the trigger system:
  - $L0$: hardware trigger → fast system that takes direct electronic information from detectors → keep only events with highly energetic signals in the calorimeter and muon systems.
  - HLT system: use computing farms to perform a track reconstruction and a selection of interesting events for physics.
- Hence, out of the 40×10^6 collisions per second we kept only 12×10^3!



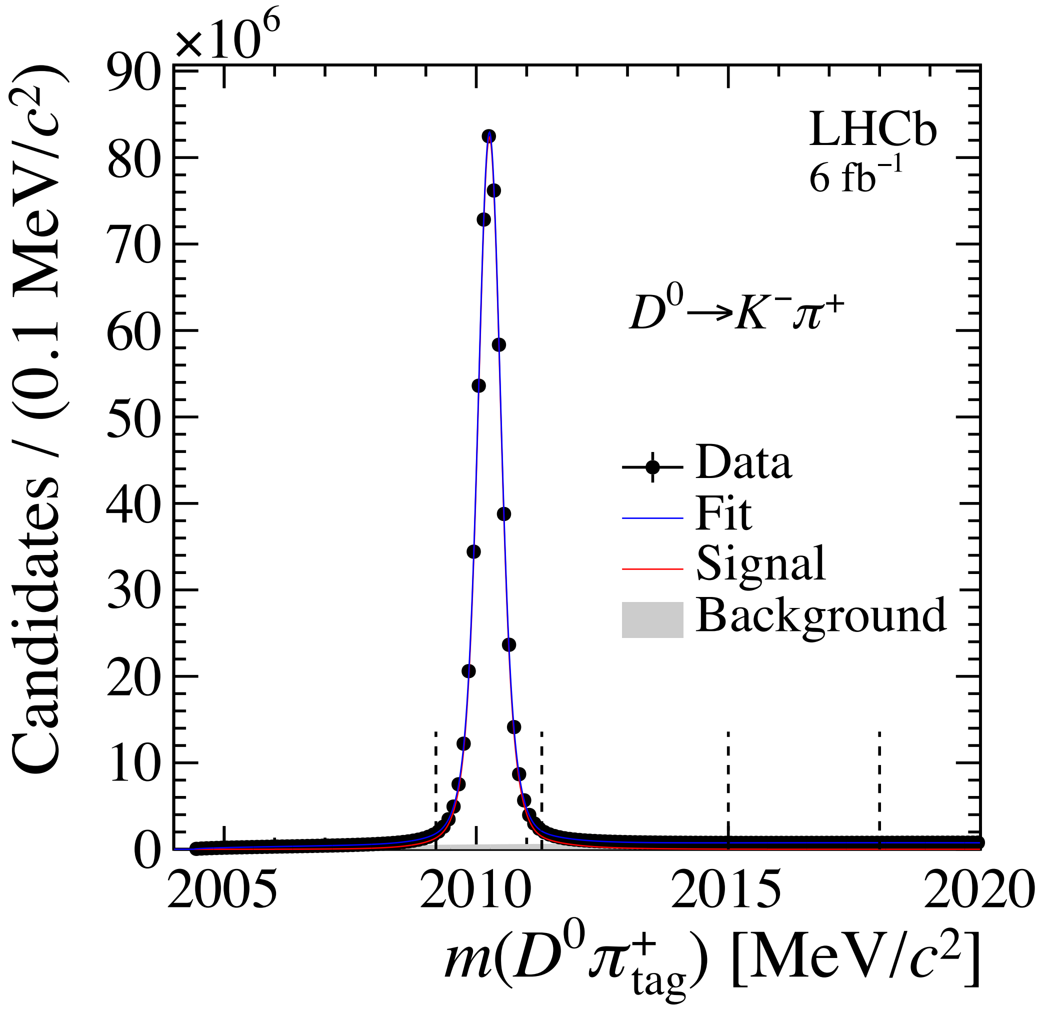
Small Masterclass work

- Let us learn how we select D^0 mesons at LHCb!

https://lhcb-d0.web.cern.ch/

Challenges of charm at LHCb

- At LHCb, we have collected HUGE data samples!
- This plot shows you 519M $D^{*+} \to D^0(\to K^- \pi^+)\pi^+$ decays fully selected and reconstructed between 2015 and 2018!
- Question: what challenges do you see with this?



Personal selected choice of cool charm analyses

1. Observation of CP violation in charm decays [LHCb-PAPER-2019-006]
2. Observation of the mass difference between neutral charm-meson eigeinstates [LHCb-PAPER-2021-009]

Observation of CP violation in charm decays [LHCb-PAPER-2019-006]

Direct CP violation

- One can write a decay amplitude A_f and as $\bar{A}_f$ as:

$$A_f = \sum_k |A_f^k| e^{i\delta_f^k} e^{i\phi_f^k}, \qquad \bar{A}_f = \sum_k |\bar{A}_f^k| e^{i\delta_f^k} e^{-i\phi_f^k}$$

f: final state. In this talk $f = K^+K^-$ and $\pi^+\pi^-$

k: amplitude order

δ_f^i: strong phase (does not change sign under CP)

ϕ_f^i: weak phase (changes sign under CP)

- The most straightforward way of measuring direct CPV is to see differences between the amplitudes $A_f = \langle f|\mathcal{H}|D^0\rangle$ and $\bar{A}_f = \langle f|\mathcal{H}|\bar{D}^0\rangle$:

$$|A_f|^2 - |\bar{A}_f|^2 \propto \sin(\delta_f^1 - \delta_f^2)\cos(\phi_f^1 - \phi_f^2)$$

- Hence, to observe direct CPV, you need both weak and strong phases to differ!

- We generally access direct CPV through the the time-integrated asymmetry:

$$A_{CP}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)} = \frac{|A_f|^2 - |\bar{A}_f|^2}{|A_f|^2 + |\bar{A}_f|^2}$$

If $A_{CP}(f) \neq 0 \to$ CPV!

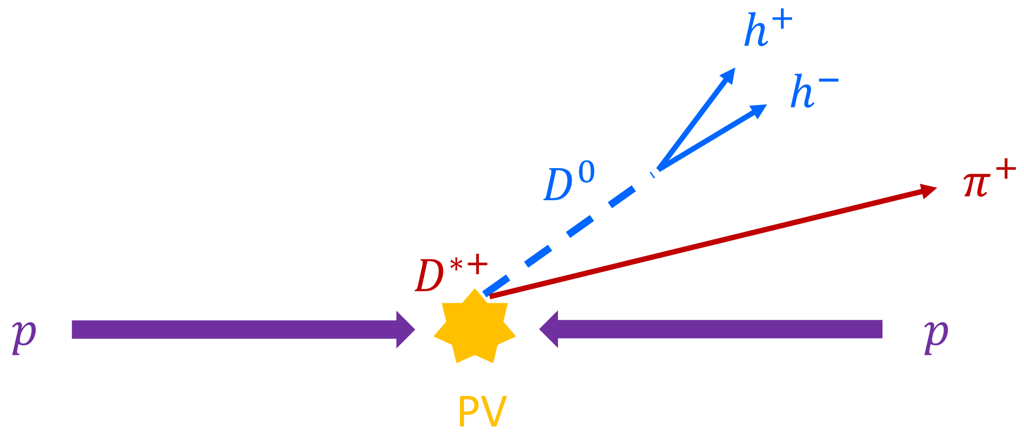
Measurement of CPV in charm decays – Data samples

- Comparison of the two Cabibbo-suppressed (CS) decays $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ (referred to as $D^0 \to h^+h^-$).

Prompt decays:

$D^{*+} \to (D^0 \to h^+h^-)\,\pi^+$

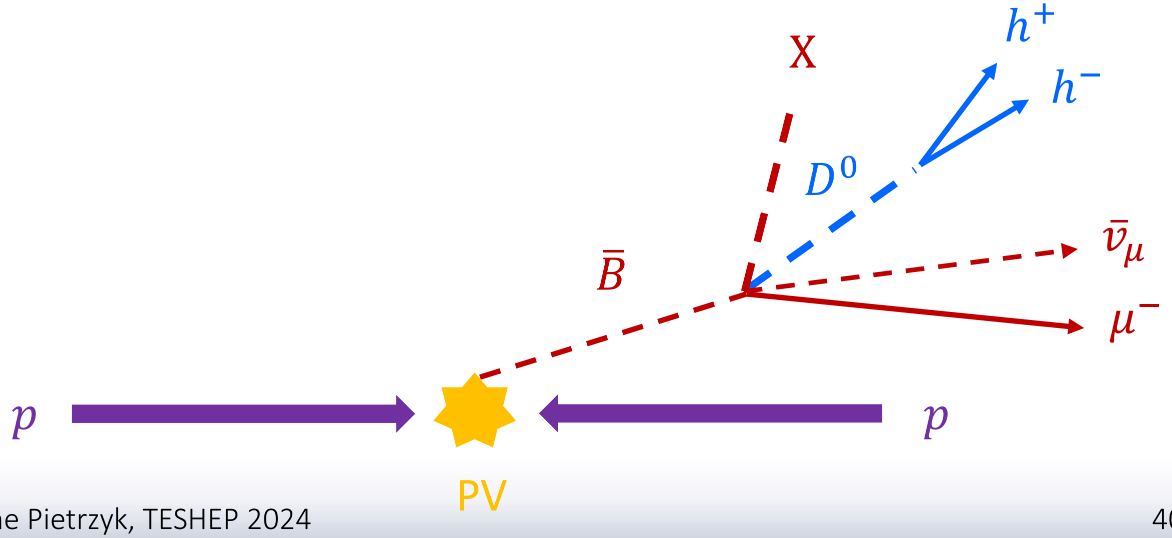
π^+ is used for flavour tagging



Semileptonic B decays:

$\bar{B} \to (D^0 \to h^+h^-)\,X\,\bar{\nu}_\mu\,\mu^-$

μ^- is used for flavour tagging



The charm ΔA_{CP} measurement – Asymmetries

- Without additional correction, we observe $A_{raw}(f)$ instead of the wanted $A_{CP}(f)$:

$$A_{raw}(f) = \frac{\mathrm{N}(D^0 \to f) - \mathrm{N}(\overline{D}^0 \to f)}{\mathrm{N}(D^0 \to f) + \mathrm{N}(\overline{D}^0 \to f)} = A_{CP}(f) + A_D(f) + \underbrace{A_D(\mathrm{tag}) + A_P}_{\text{Experimental asymmetries}} + \mathcal{O}(A^3)$$

- $A_D(f)$ is the detection asymmetry of the K^+K^- or $\pi^+\pi^-$ final state. $A_D(f) = 0$ since f is equal for D^0 and $\overline{D}^0$
- $A_D(\mathrm{tag})$ is the detection asymmetry of the tagging tracks ($\pi^+(\mu^-)$ versus $\pi^-(\mu^+)$) $A_D(\mathrm{tag}) \neq 0$ since π^+ and π^- interact differently with the detector.
- A_P is the asymmetry between the production of $D^{*+}(\overline{B})$ and $D^{*-}(B)$ mesons. $A_P \neq 0$ since $D^*(B)$ are produced through pp collisions that are not CP-symmetric.

Experimental strategy

- $A_D(\pi)$ and $A_p(D^*)$ are challenging to access experimentally.
- Solution: By equalising the kinematic distributions of $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$, $A_D(\pi)$ and $A_p(D^*)$ becomes equal for both final states. One can then measure:

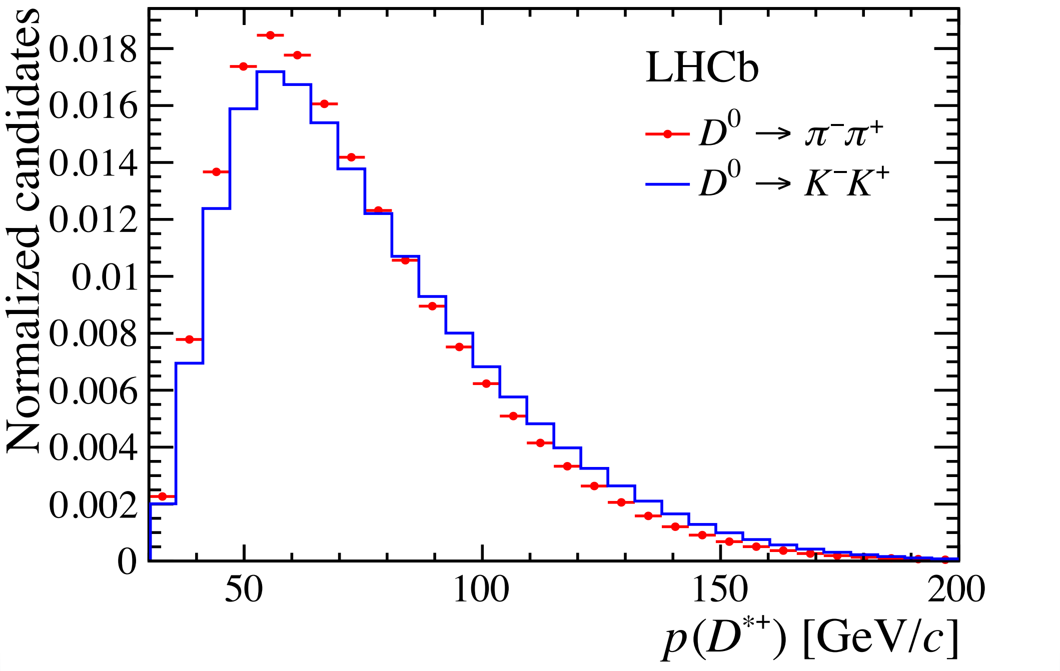
$$\begin{aligned}\Delta A_{CP} &= A_{raw}(K^+K^-) - A_{raw}(\pi^+\pi^-) \\ &= A_{CP}(K^+K^-) + A_D(\pi) + A_p(D^*) - A_{CP}(\pi^+\pi^-) - A_D(\pi) - A_p(D^*) \\ &= A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)\end{aligned}$$

- The strong interaction U-spin symmetry imposes that $A_{CP}(K^+K^-) = -A_{CP}(\pi^+\pi^-)$, implying that observing $\Delta A_{CP} \neq 0$ is a direct sign of CP violation in charm!

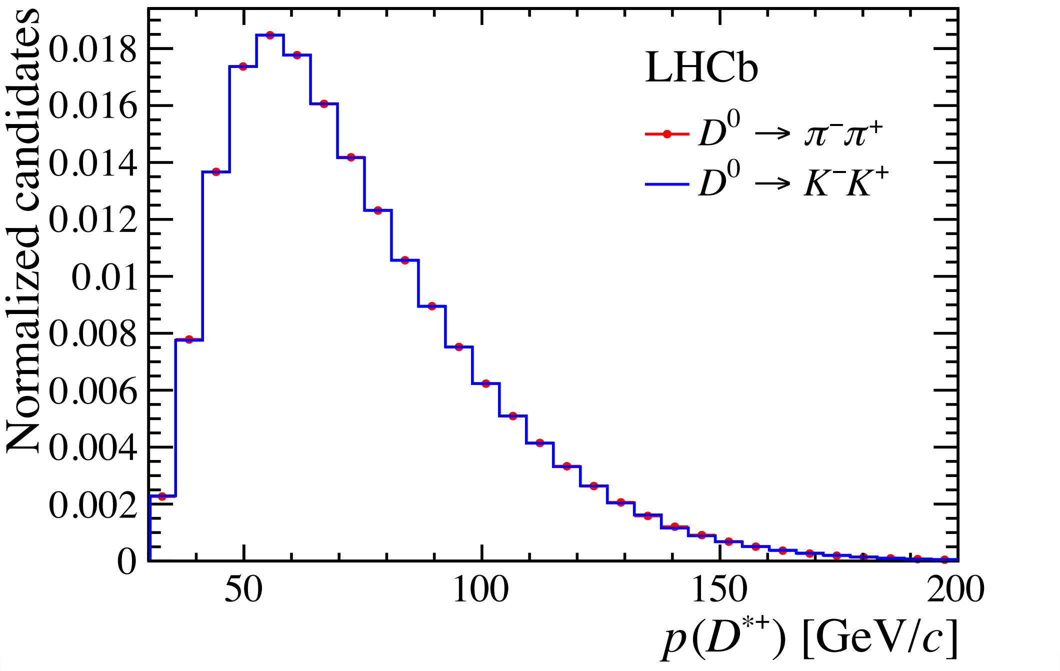
Equalising the kinematic distributions of $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$

- The kinematics of both decays are equalised through by weighting the kinematics of $D^0 \to K^+K^-$ to the ones of $D^0 \to \pi^+\pi^-$.
- Reweighting of 3 variables: $p_T(D^*), p(D^*)$ and $\phi(D^*)$ (use D^0 for B decays)

Before reweighting

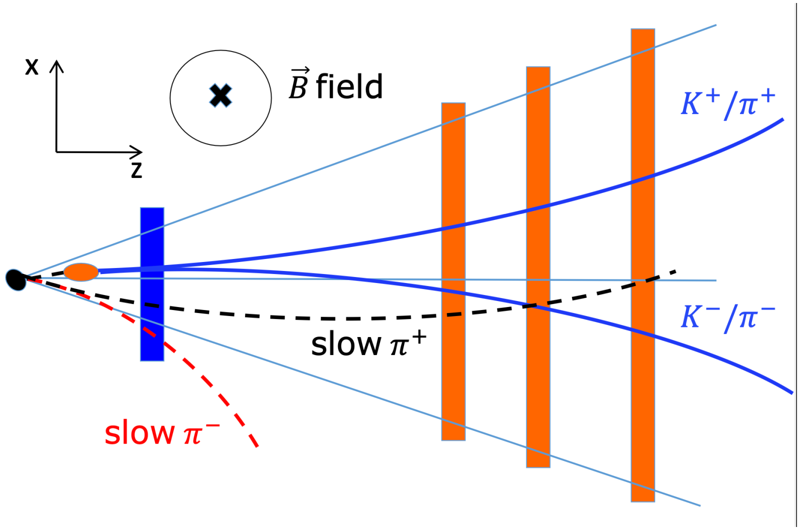


After reweighting

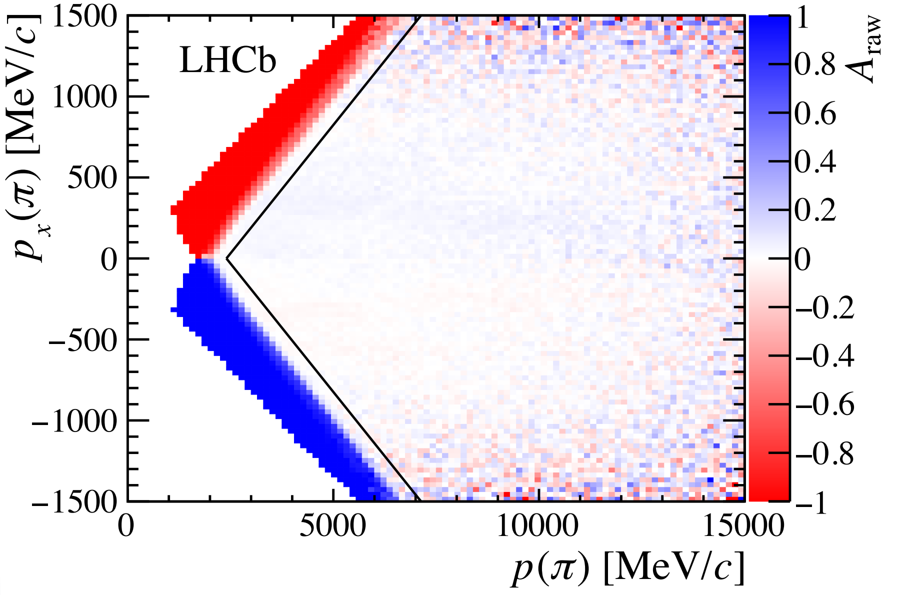


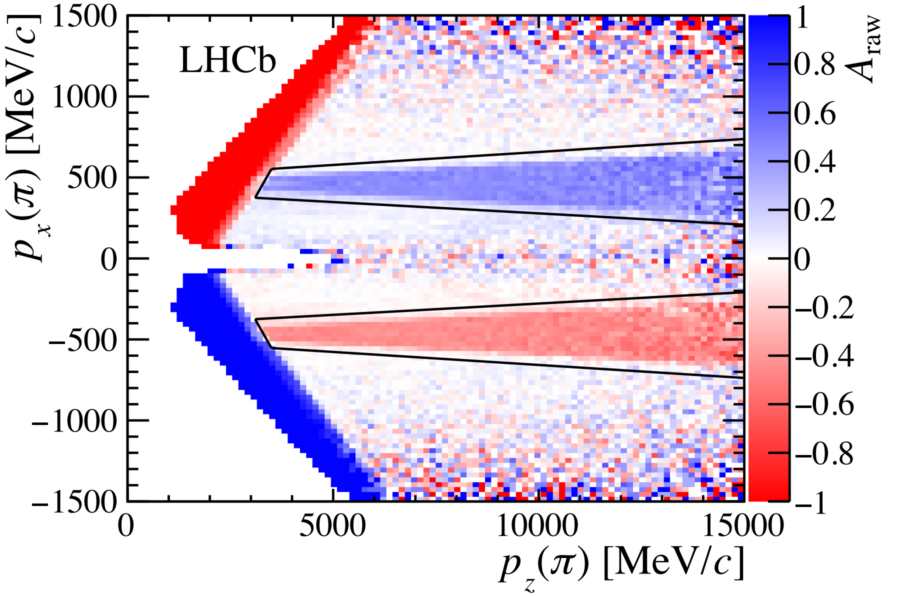
Fiducial selection

LHCb « from above »



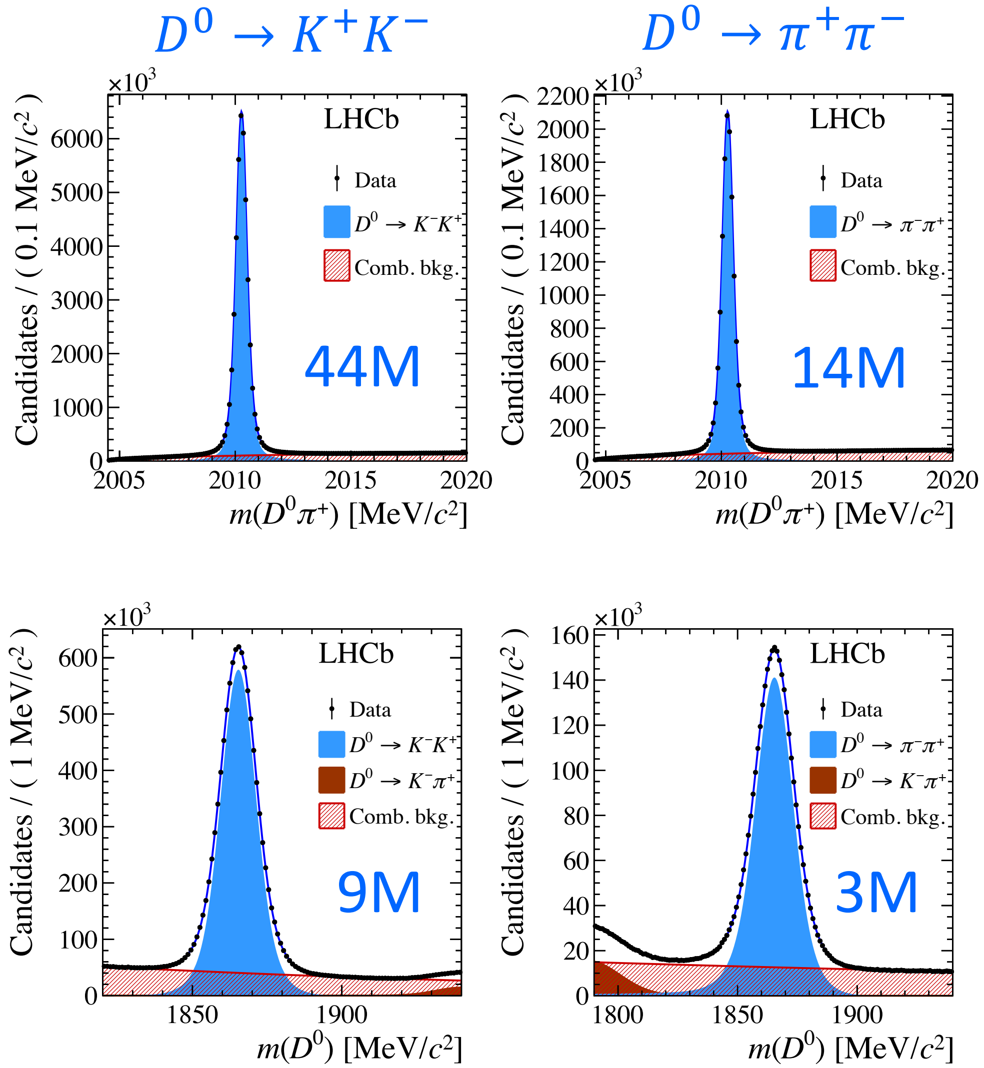
- For some regions of phasespace, the soft pion of a specific charge gets kicked out of the detector by the $\vec{B}$ field.
- These regions exhibit very high values of A_{raw} → we remove them!





Obtaining values of $A_{raw}(K^+K^-)$ and $A_{raw}(\pi^+\pi^-)$

- Separate D^0 and $\overline{D}^0$ fits to get the corresponding signal yields to measure A_{raw}
- <u>Prompt:</u> Fit $m(D^0\pi^+)$ distribution. Background expected to be random association of particle tracks: « combinatorial background »
- <u>Semileptonic:</u> Fit $m(D^0)$ distribution.



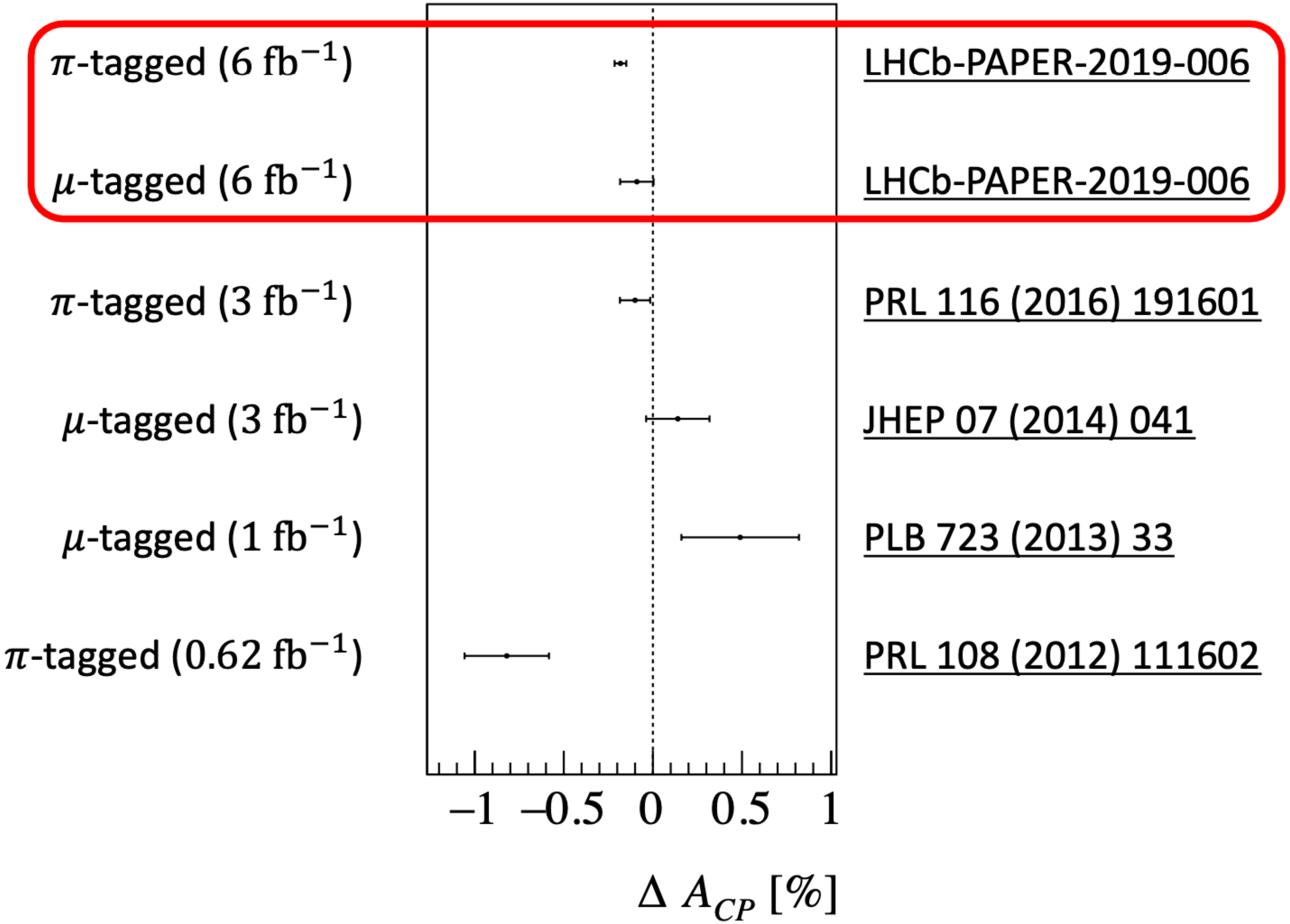
Question: What is the background that is not « combinatorial background » ?

The charm ΔA_{CP} measurement – Systematic uncertainties

TABLE I. Systematic uncertainties on ΔA_{CP} for π- and μ-tagged decays (in 10^{-4}). The total uncertainties are obtained as the sums in quadrature of the individual contributions.

Source	π tagged	μ tagged
Fit model	0.6	2
Mistag	···	4
Weighting	0.2	1
Secondary decays	0.3	···
Peaking background	0.5	···
B fractions	···	1
B reco. efficiency	···	2
Total	0.9	5

Evolution of the measurements of ΔA_{CP}



The charm ΔA_{CP} measurement – Results

- Run 2 (2015-2018) results:

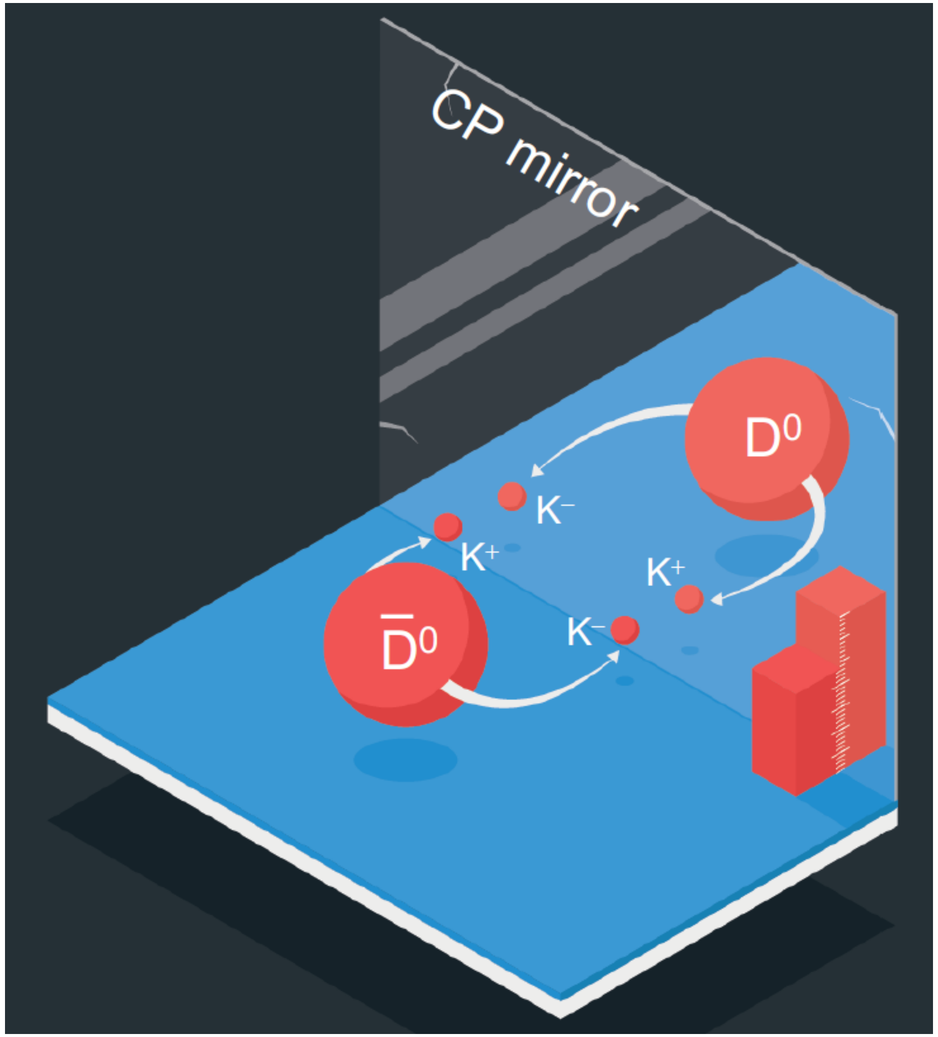
$$\Delta A_{CP}(\text{prompt}) = (-18.2 \pm 3.2 \pm 0.9) \times 10^{-4}$$

$$\Delta A_{CP}(\text{semileptonic}) = (-9 \pm 8 \pm 5) \times 10^{-4}$$

- Combination of both production modes + Run 1 (2011-2012) results [JHEP 07 (2014) 041] [PRL 116 (2016) 191601]:

$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$

→ CPV in charm decays observed for the first time at a significance of 5.3σ!



[PhysRevLett.122.211803]

Search for time-dependent CPV in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays [LHCB-PAPER-2020-045]

Observation of the mass difference between neutral charm-meson eigeinstates [LHCb-PAPER-2021-009]

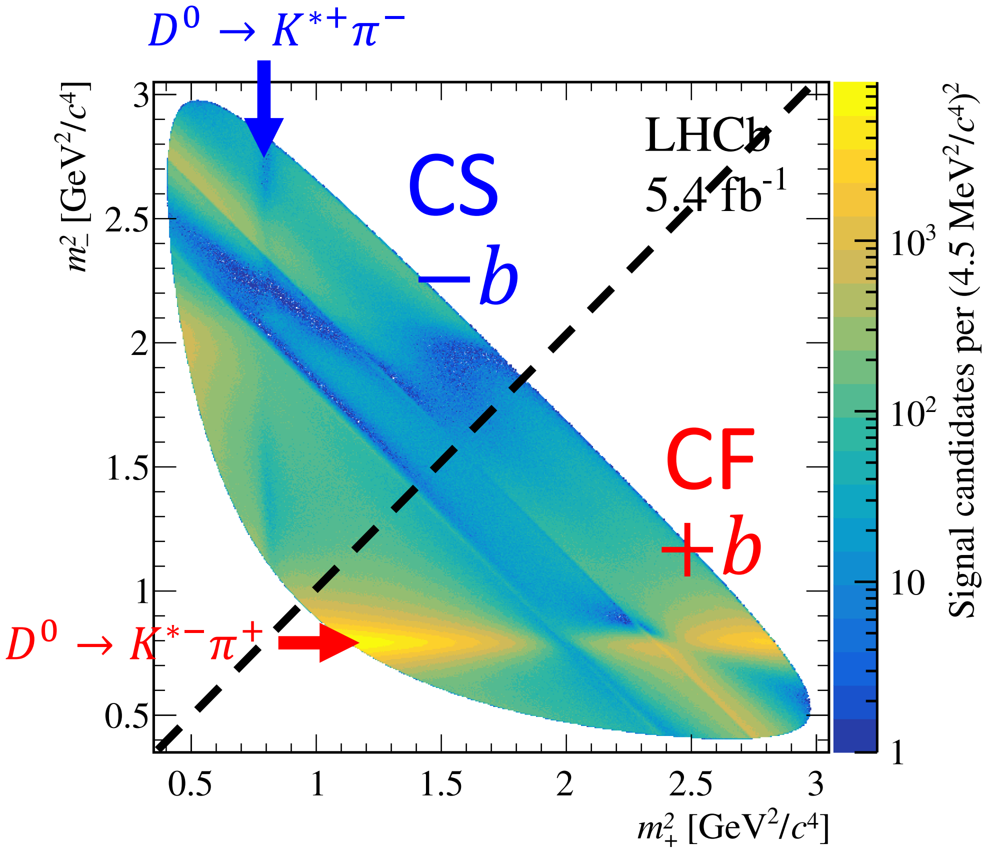
(a.k.a « Observation of $x \neq 0$ »)

Use the magic $D^0 \to K_S^0(\to \pi^+\pi^-)\pi^+\pi^-$

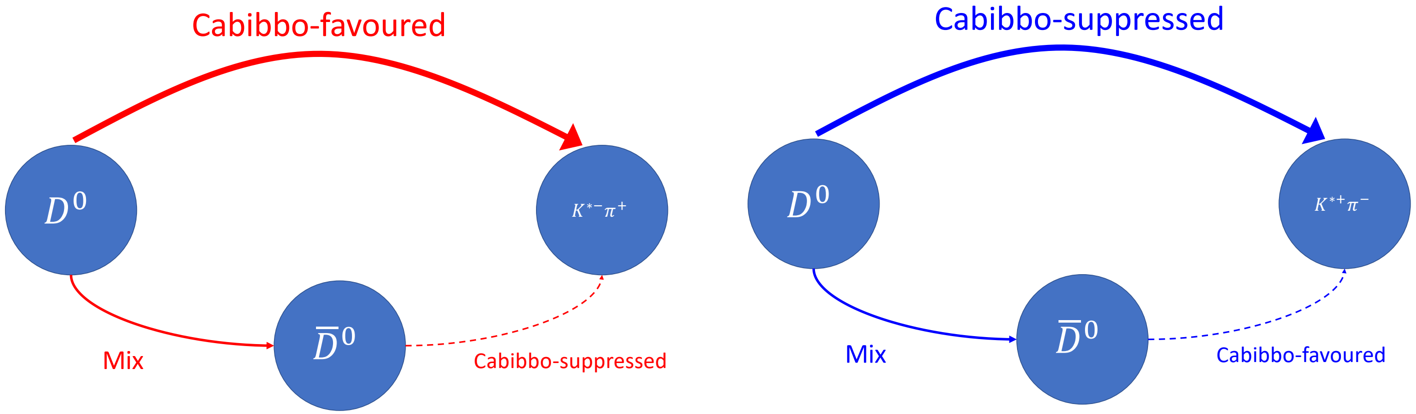
- $D^0 \to K_S^0\pi^+\pi^-$ has a rich resonant structure. For instance:
  - $D^0 \to K^{*-}(\to K_S^0\pi^-)\pi^+$: Cabibbo favoured (CF)
  - $D^0 \to K^{*+}(\to K_S^0\pi^+)\pi^-$: Cabibbo suppressed (CS)
- We study the decay in *Dalitz coordinates*:

For D^0: $\begin{cases} m_+^2 = m^2(K_S^0\pi^+) \\ m_-^2 = m^2(K_S^0\pi^-) \end{cases}$

- $+b$ region: decays dominated by CF decays
- $-b$ region: decays dominated by CS decays
- Can we use this to study charm mixing?



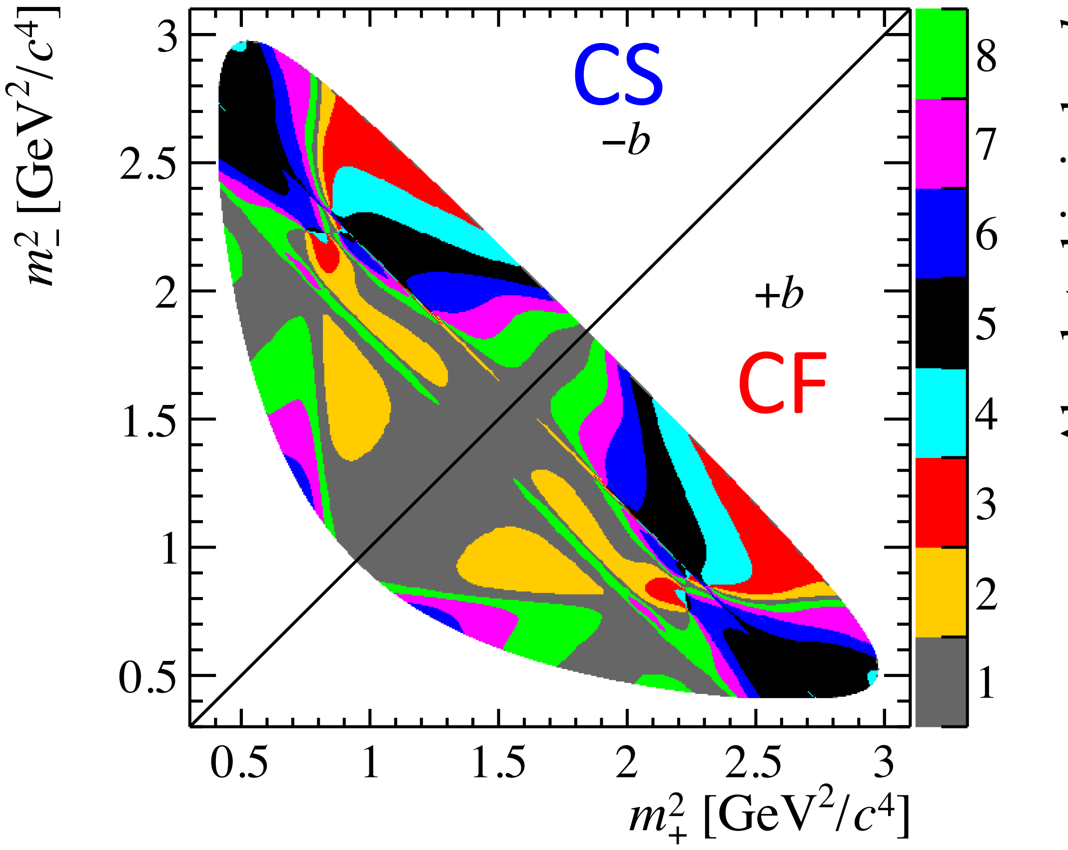
Use the magic $D^0 \to K_S^0(\to \pi^+\pi^-)\pi^+\pi^-$



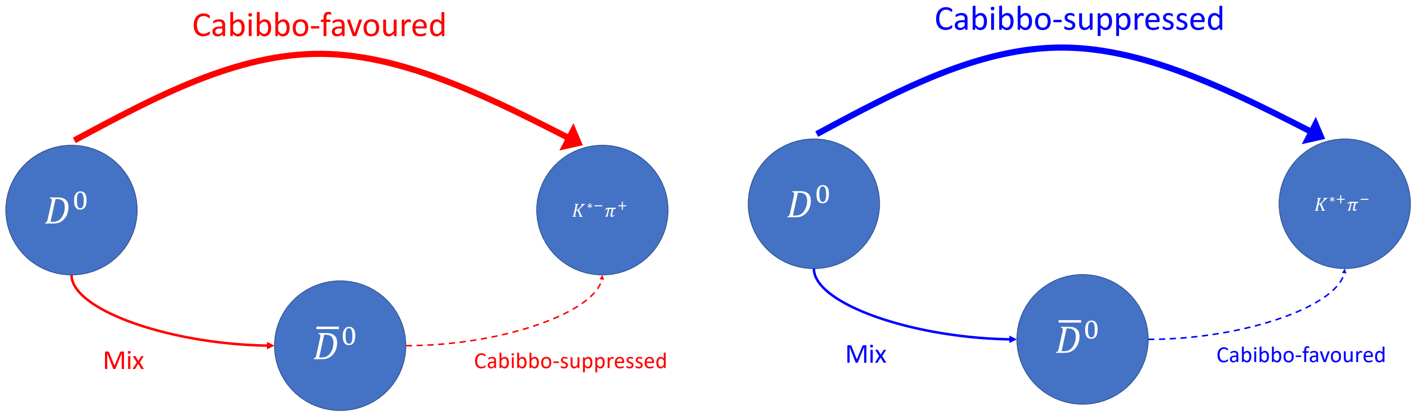
- Remember, I showed you how you use $R(t)$ to measure mixing:

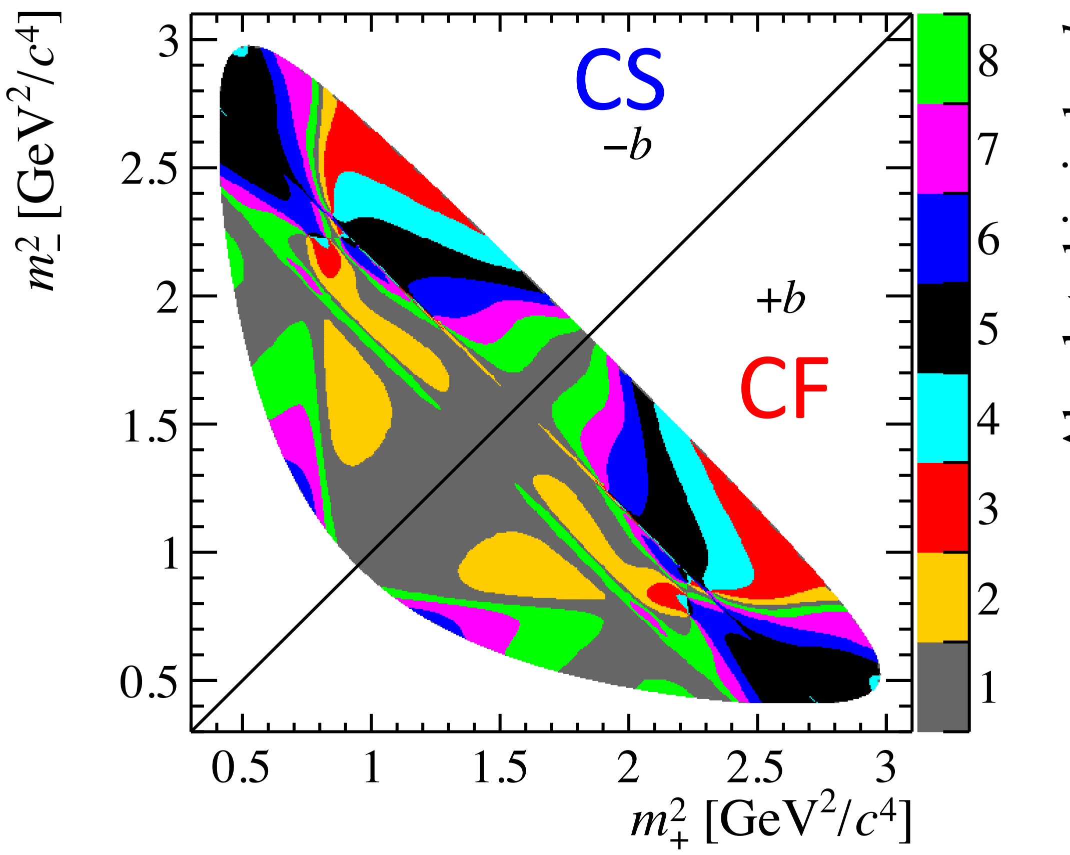
$$R(t) = \frac{\Gamma(D^0(t) \to K^+\pi^-)}{\Gamma(D^0(t) \to K^-\pi^+)} = \frac{N(CS, t)}{N(CF, t)}$$

- Here, we're doing the same but in the Dalitz plane!
- Slight subtlety: data is binned in Dalitz coordinates where the binning scheme is chosen to have approximately constant strong-phase differences (8 different regions).



Use the magic $D^0 \to K^0_S(\to \pi^+\pi^-)\pi^+\pi^-$





- We measure, as a function of t, the number of decays occuring at the bottom right over the ones at the top left:

$$R_b^{\pm}(t) \approx r_b - \sqrt{r_b}[(1 - r_b)c_b y - (1 + r_b)s_b x]t/\tau_D$$

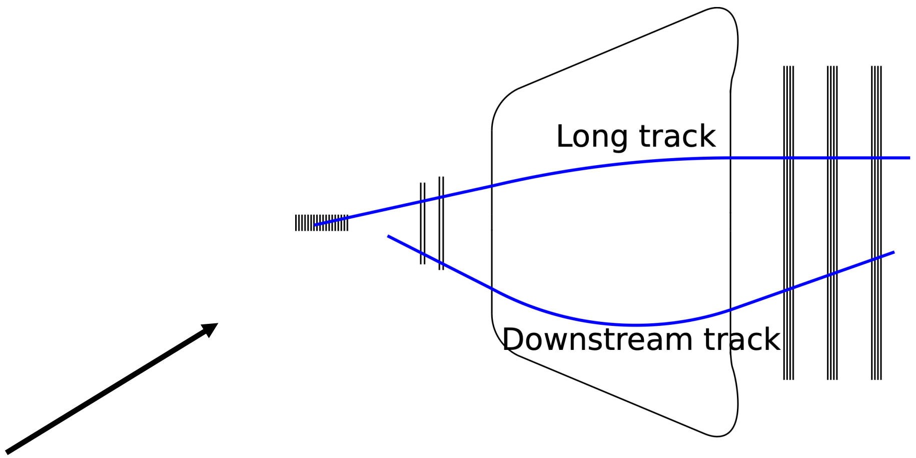
- We can access both mixing parameters x and y!!
- $r_b \equiv R_b(t = 0)$ and c_b and s_b are related to the strong phase differences between opposing regions (based on external inputs).

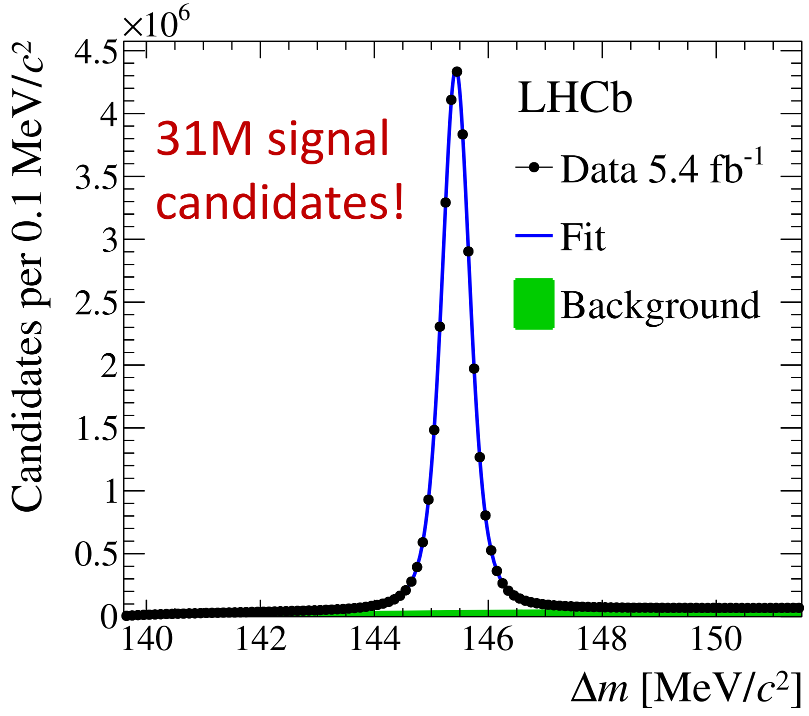
Samples selection of $D^0 \to \pi^+\pi^-$ decays

- Run 2 data from 2015-2018
- $K_S^0 \to \pi^+\pi^-$ reconstructed in two ways:
  - Long tracks: K_S^0 decays inside the VELO
  - Downstreak tracks: K_S^0 decays outside of the VELO
- Signal yields determined by fitting

$$\Delta\text{m} = \text{m}(D^{*+}) - \text{m}(D^0)$$

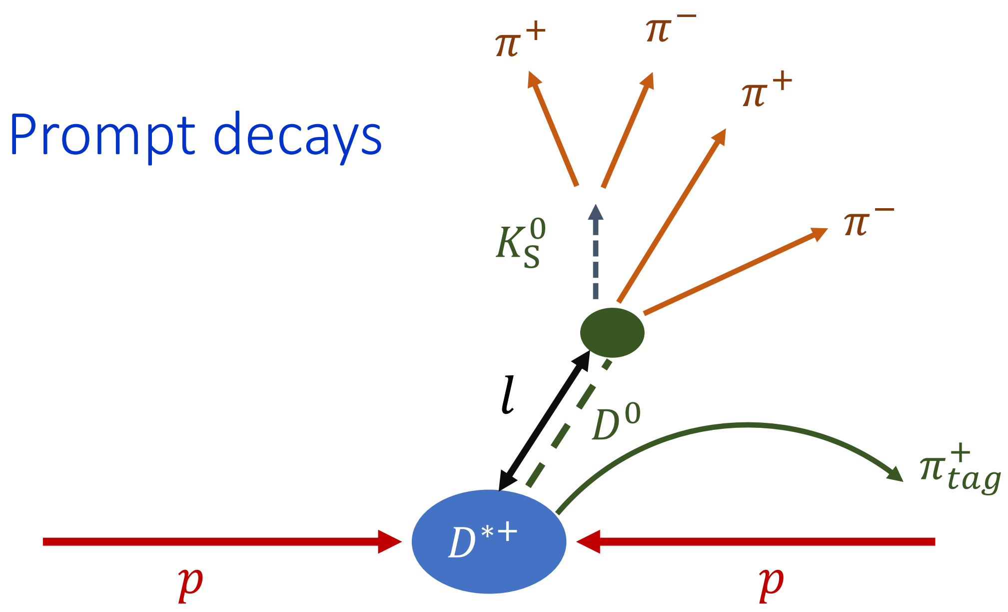
- Very pure sample!

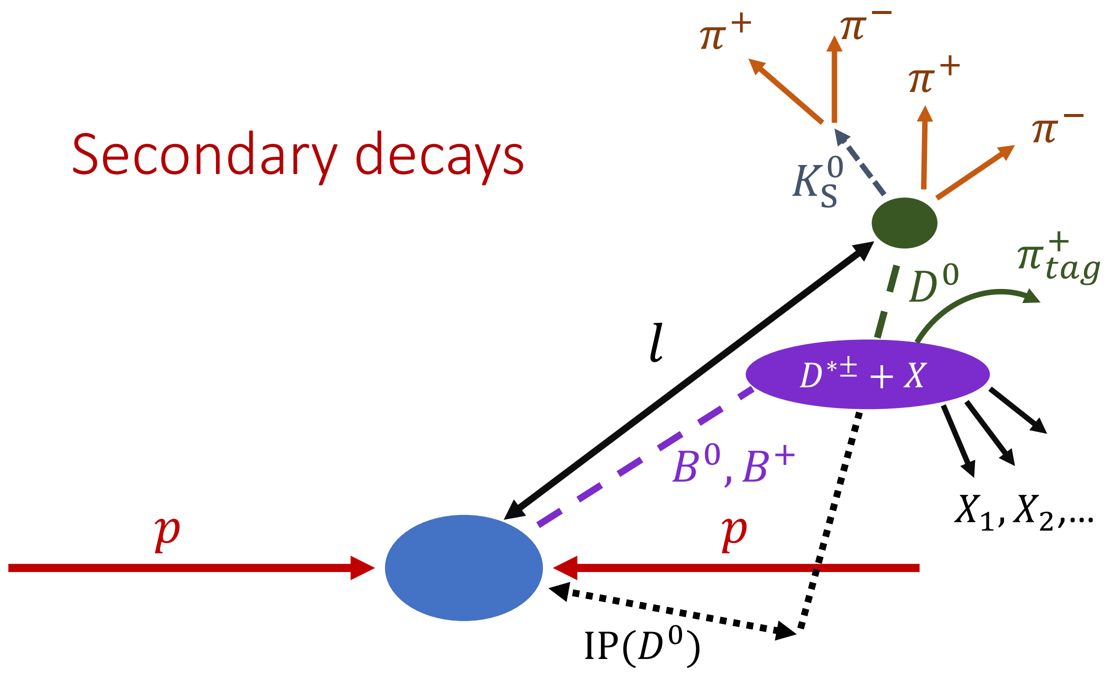




Treatment of secondary decays

- The samples are contaminated by the presence of secondary D^0 decays coming from B meson decays.
- Decay times are measured as: $t = l\frac{m_D}{p_D}$ where the decay length l is measured w.r.t the PV. For secondary decays, t will be estimated as significantly larger than the proper D^0 decay time ($\tau_B \approx 4\tau_{D^0}$).
- Prompt decays have IP$(D^0) \approx 0$µm whereas secondary decays can have non-zero IP(D^0) → the requirement IP$(D^0) < 50$µm is applied to remove a large fraction of secondary decays.





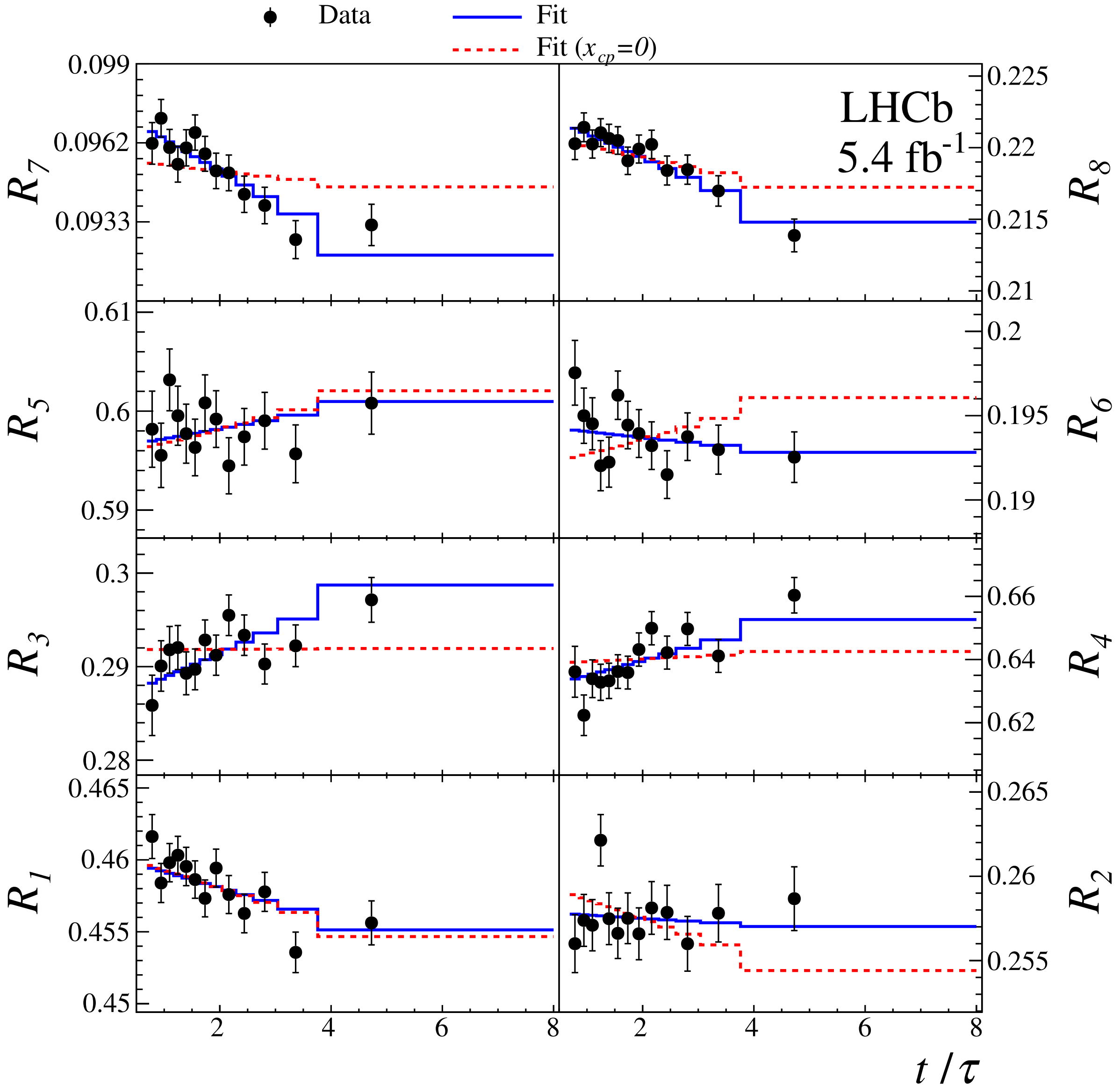
Results

- Show the ratio $R_b(\mathrm{t})$ for each region b.
- Compare to predictions of $x = 0$
- We can clearly see that the data fit is not compatible with $x = 0$!
- The fit gives

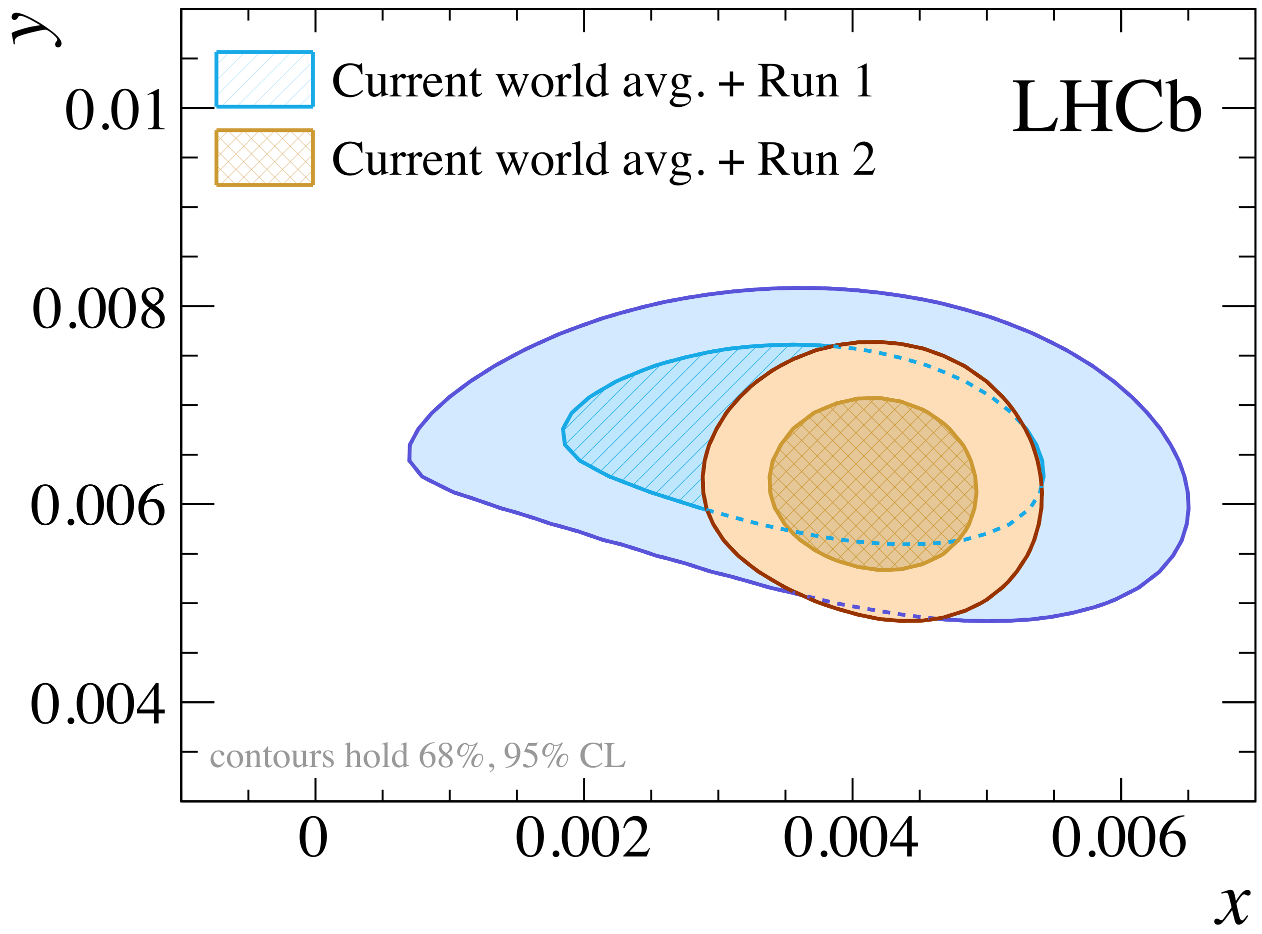
$$x = 3.98^{+0.56}_{-0.54} \times 10^{-3}$$

that is more than 5σ away from zero!

- This is an observation of $x \neq 0$, showing that in our data D^0 oscillated to $\overline{D}^0$, and vice-versa!



Effect of this measurement on the knowledge of charm mixing

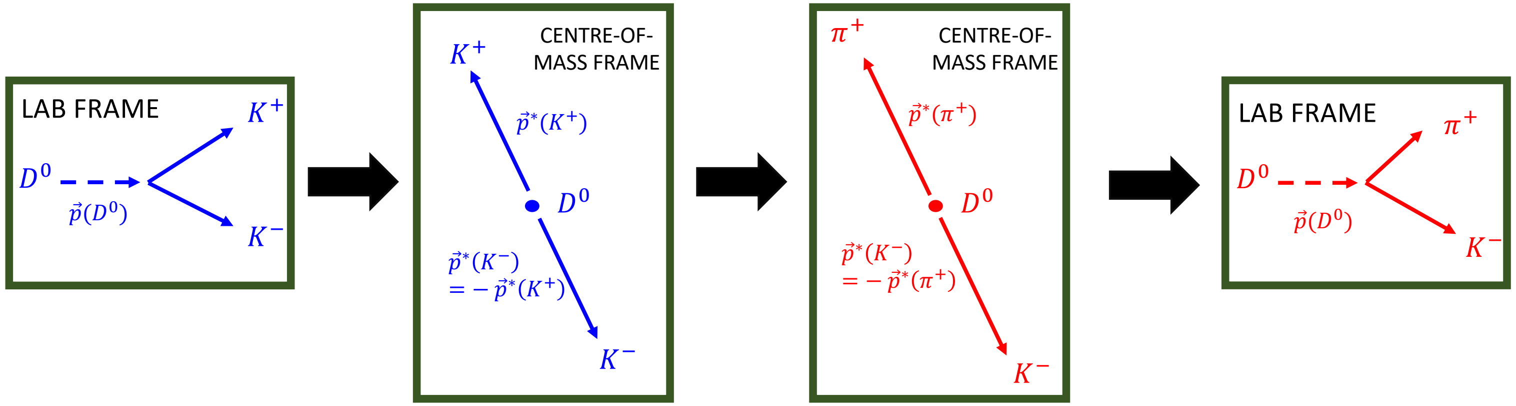


Other cool measurements: High precision measurement of y

- Challenging measurement: Fit decay-time ratio of $D^0 \to f\ (f = K^-K^+$ and $\pi^-\pi^+)$ over $D^0 \to K^-\pi^+$ to obtain y:

$$R^f(t) = \frac{N(D^0 \to f, t)}{N(D^0 \to K^-\pi^+, t)} \overset{\approx}{\propto} e^{-yt/\tau_{D^0}} \frac{\varepsilon(f, t)}{\varepsilon(K^-\pi^+, t)}$$

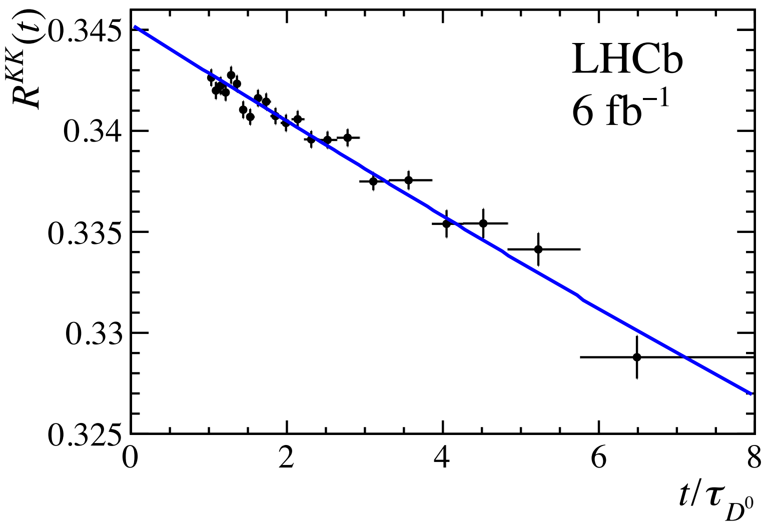
- Complicated measurement: need to carefully *equalise* the efficiencies $\varepsilon(h^-h'^+, t)$ to make them cancel out.
- Many methods tried and abandoned. Best solution was to develop a kinematic matching procedure to place both decays in the same kinematic phasespace.

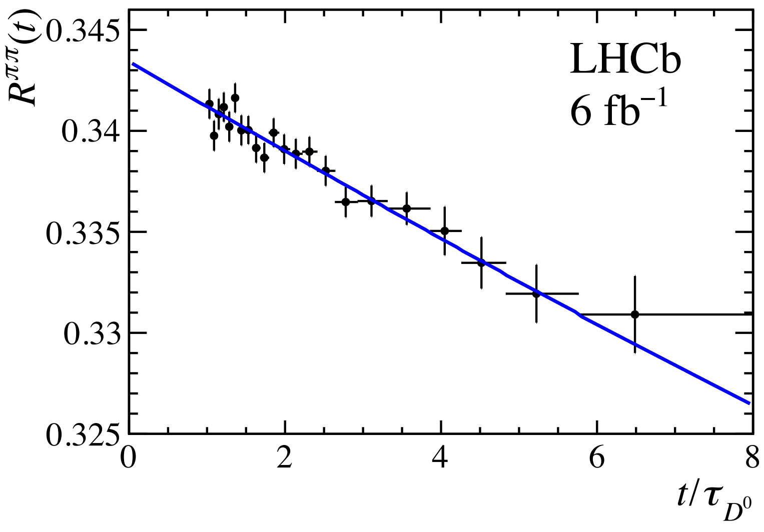


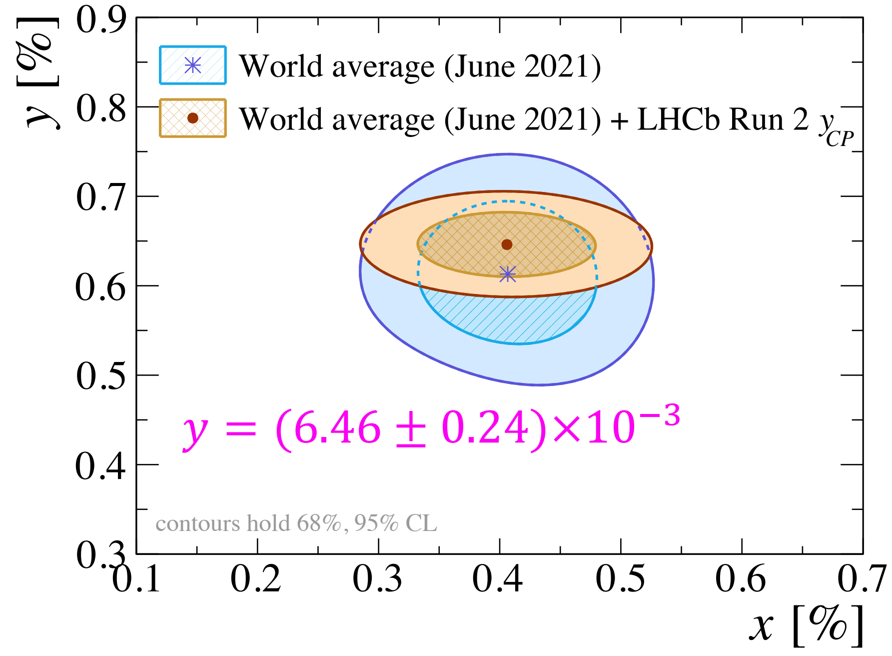
Other cool measurements: High precision measurement of y

$$R^f(t) = \frac{N(D^0 \to f, t)}{N(D^0 \to K^-\pi^+, t)} \overset{\approx}{\propto} e^{-yt/\tau_{D^0}}$$

- Improvement of y by a factor of 2!
- Question: What would the two bottom slopes look like with no mixing?





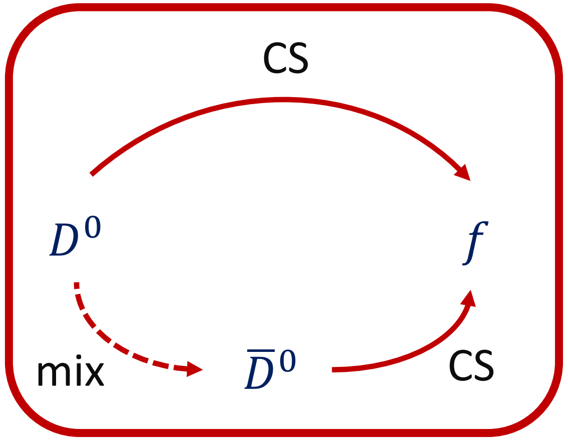


Phys. Rev. D 105, 092013

Other cool measurements: Search for time-dependent CPV

- Search for indirect CPV using the slope of the time-dependent $D^0 - \bar{D}^0$ asymmetry ΔY_f:

$f = K^+K^-, \pi^+\pi^-$



$$A_{raw}(f,t) = \frac{N(D^0 \to f,t) - N(\bar{D}^0 \to f,t)}{N(D^0 \to f,t) + N(\bar{D}^0 \to f,t)}$$

$$= A_{CP}^{\text{decay}}(f) + \Delta Y_f \frac{t}{\tau_{D^0}} + A_D(f,t) + A_P(f,t)$$

Time-dependent nuisance asymmetries: Removed by reweighting D^0 to $\bar{D}^0$ kinematics

$$\Delta Y_f \approx x\phi_{\lambda_f} - y\left(\left|\frac{q}{p}\right| - 1\right)$$

CPV in the mixing-decay interference

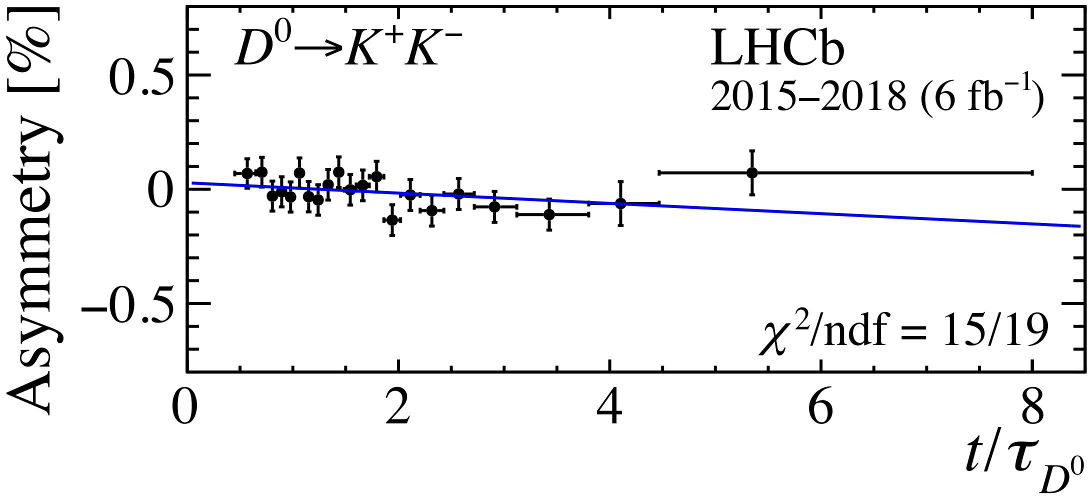
CPV in the mixing

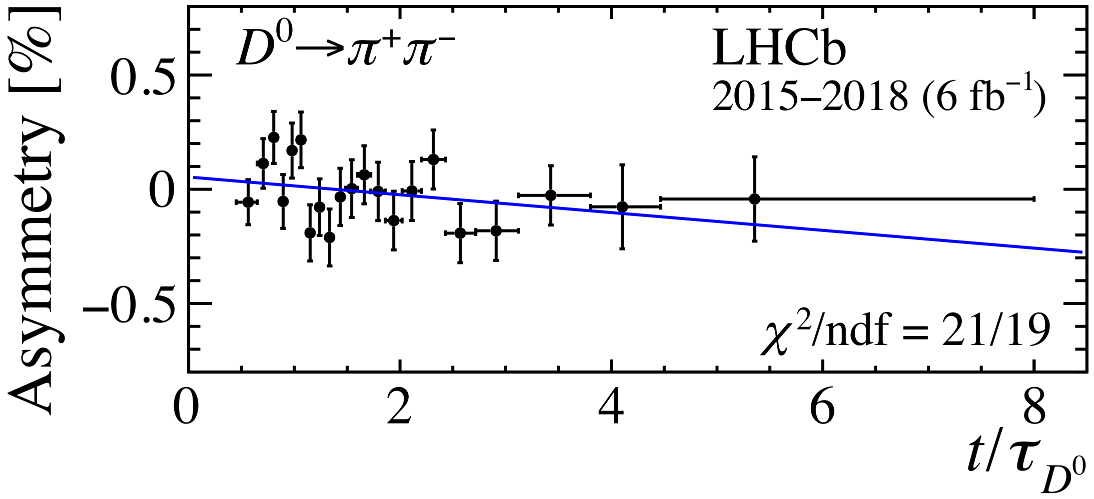
- If $\Delta Y_f \neq 0 \to$ CP violation in charm decays!
- SM expectation: $\mathcal{O}(2\times10^{-5})$ Kagan, Silvestrini (2020), Li, Umeeda, Xu, Yu (2020)
- Current best experimental precision: $\sim 2\times10^{-4}$ HFLAV

Other cool measurements: Search for time-dependent CPV

$\Delta Y_{K^+K^-} = (-2.3 \pm 1.5 \pm 0.3)\times 10^{-4}$

$\Delta Y_{\pi^+\pi^-} = (-4.0 \pm 2.8 \pm 0.4)\times 10^{-4}$



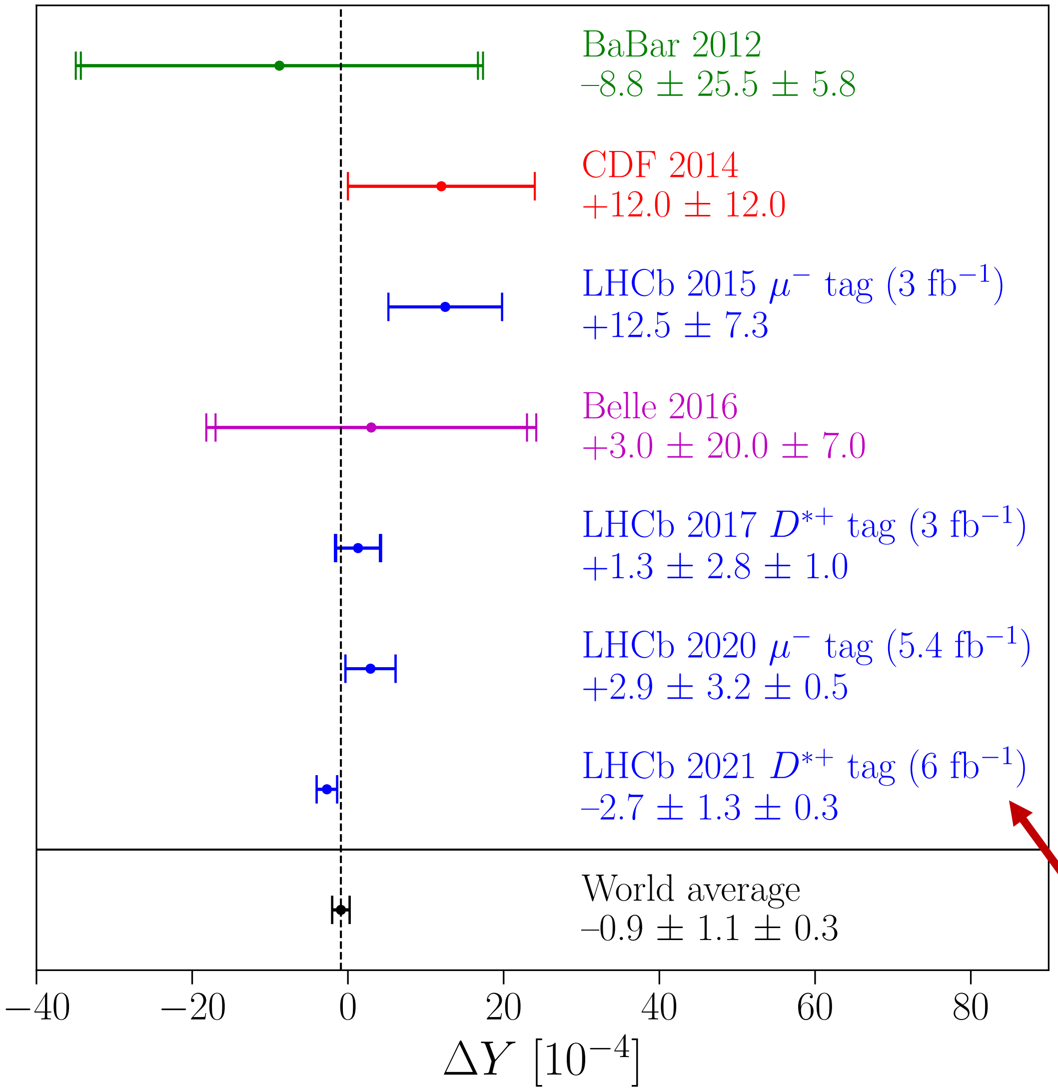


Systematic uncertainties (units of 10^{-4})

Source	$\Delta Y_{K^+K^-}$	$\Delta Y_{\pi^+\pi^-}$
Subtraction of the $m(D^0\pi^+_{\text{tag}})$ background	0.2	0.3
Flavour-dependent shift of $m(D^{*+})$ peak	0.1	0.1
D^{*+} from B-meson decays	0.1	0.1
$m(h^+h^-)$ background	0.1	< 0.1
Kinematic weighting	0.1	0.1
Total systematic	0.3	0.4
Statistical	1.5	2.8

- $\Delta Y_{K^+K^-}$ and $\Delta Y_{\pi^+\pi^-}$ agree with each other within 0.5σ and are compatible with zero within 2σ.
- Systematic uncertainties are at the level of a few 10^{-5}: less than 20% of the statistical uncertainty. Very promising for future LHCb measurements!

Other cool measurements: Search for time-dependent CPV



This measurement!

Previous world average value: $\Delta Y = (+3.1 \pm 2.0 \pm 0.5) \times 10^{-4}$

Our estimated new world average value:

$$\Delta Y = (-0.9 \pm 1.1 \pm 0.3) \times 10^{-4}$$

Compatible with CP conservation hypothesis

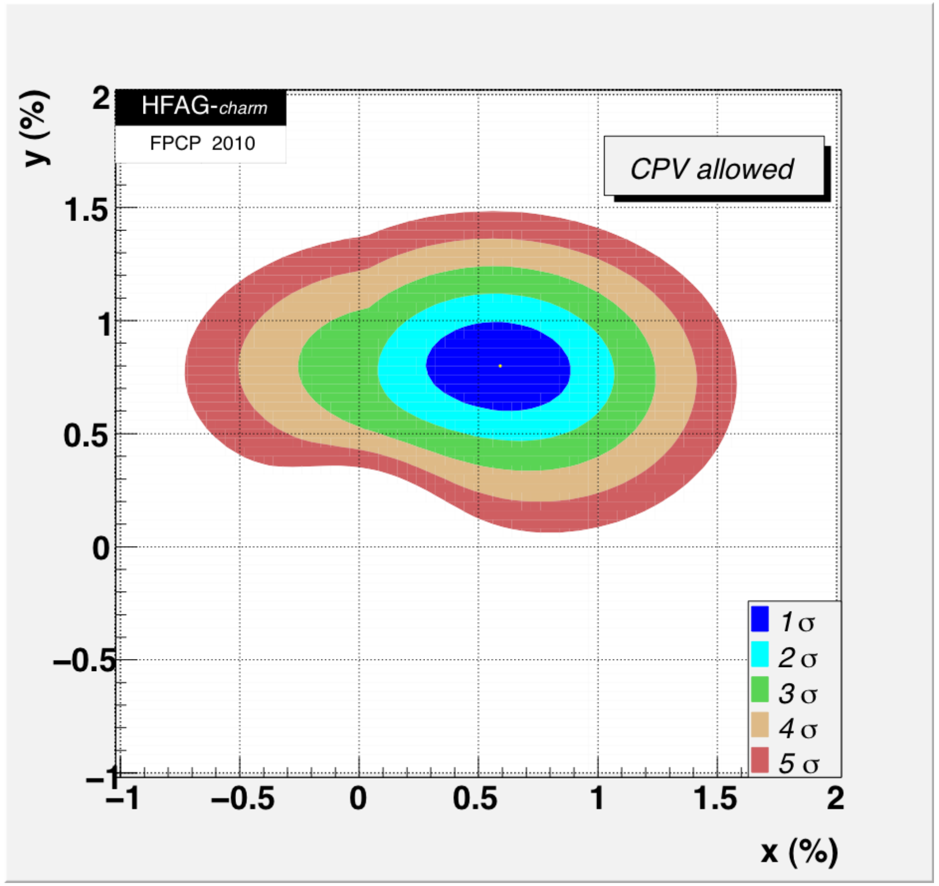
Standard Model prediction:

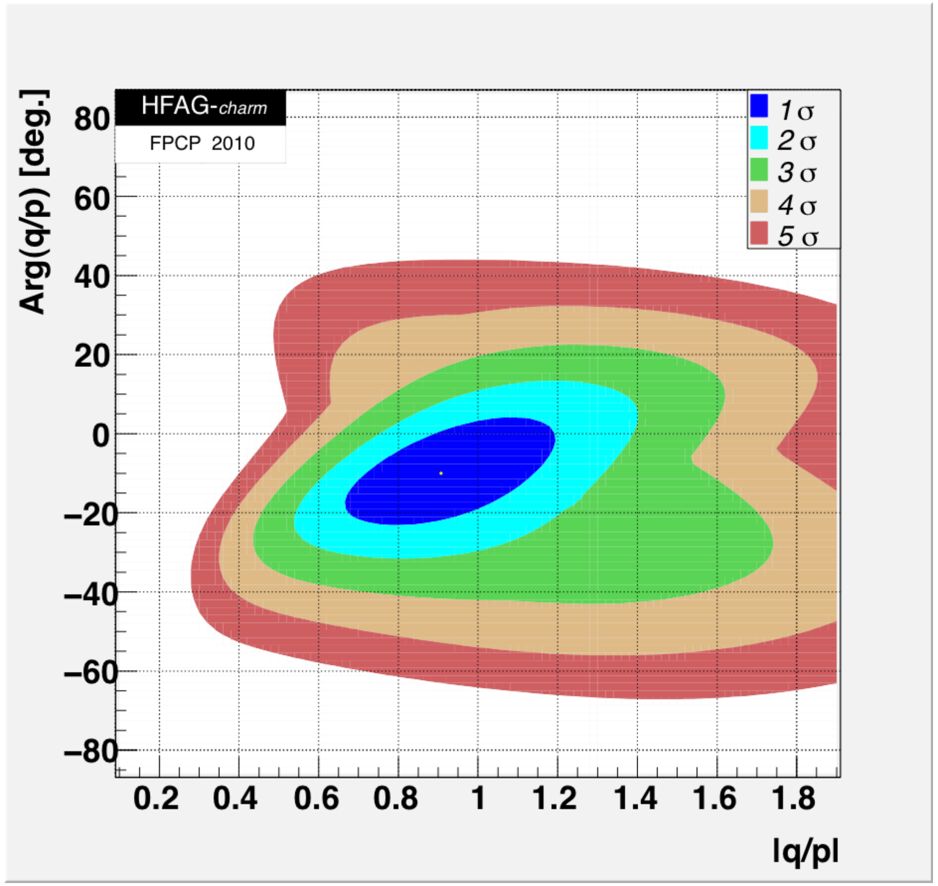
$$\Delta Y \approx \mathcal{O}(2 \times 10^{-5})$$

Kagan & Silvestrini 2020

Li, Umeeda, Xu, Yu 2020

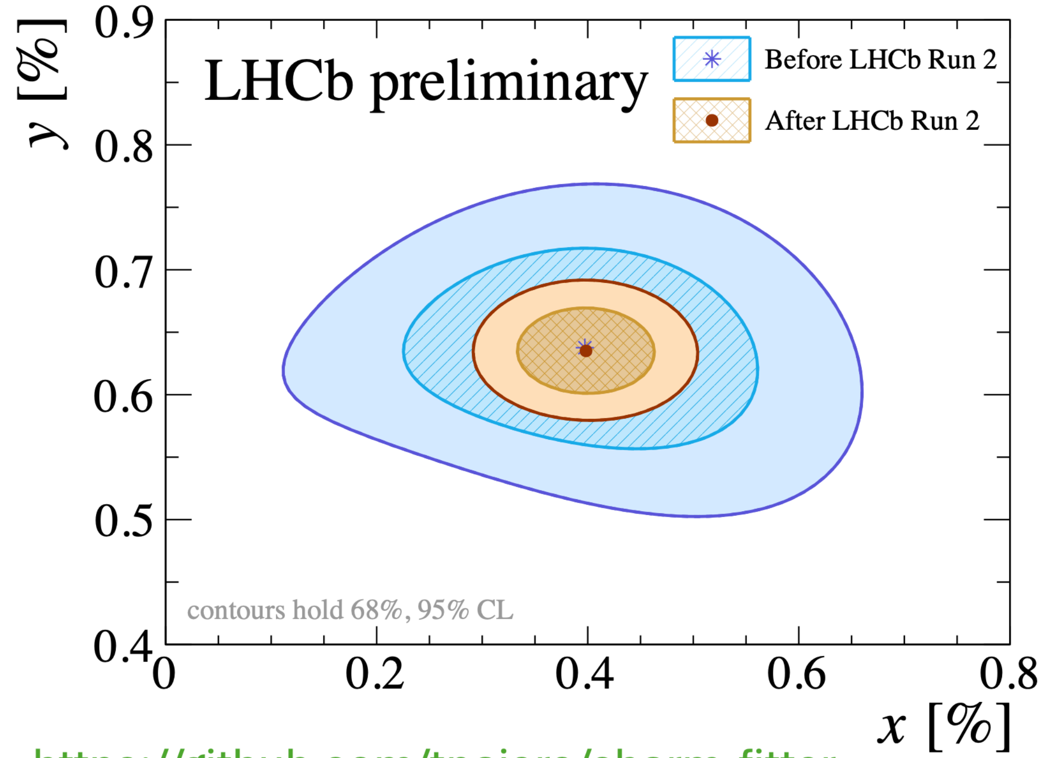
Evolution of our knowledge of indirect CPV and mixing (2010)



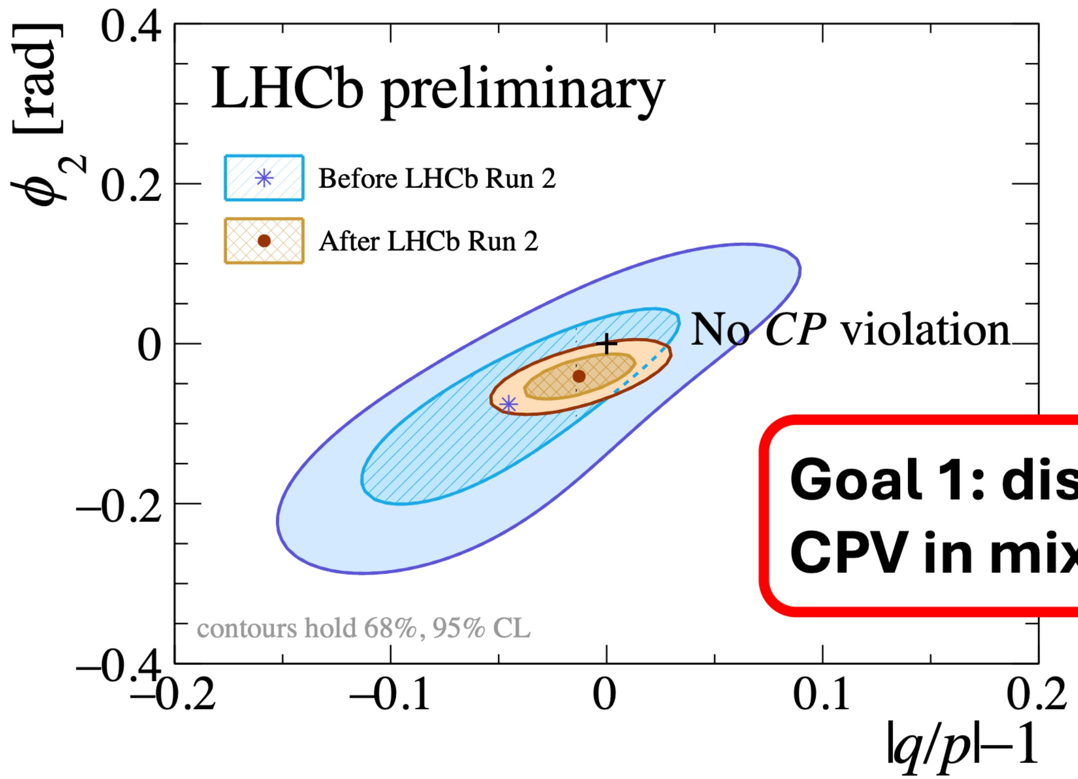


Evolution of our knowledge of indirect CPV and mixing

- The LHCb Run 2 data has allowed to make amazing improvement in the charm sector
- x and y and now far away from zero by more than 5σ → charm mixing very well established
- However, we still do not have a clear evidence of indirect CPV → need more data!



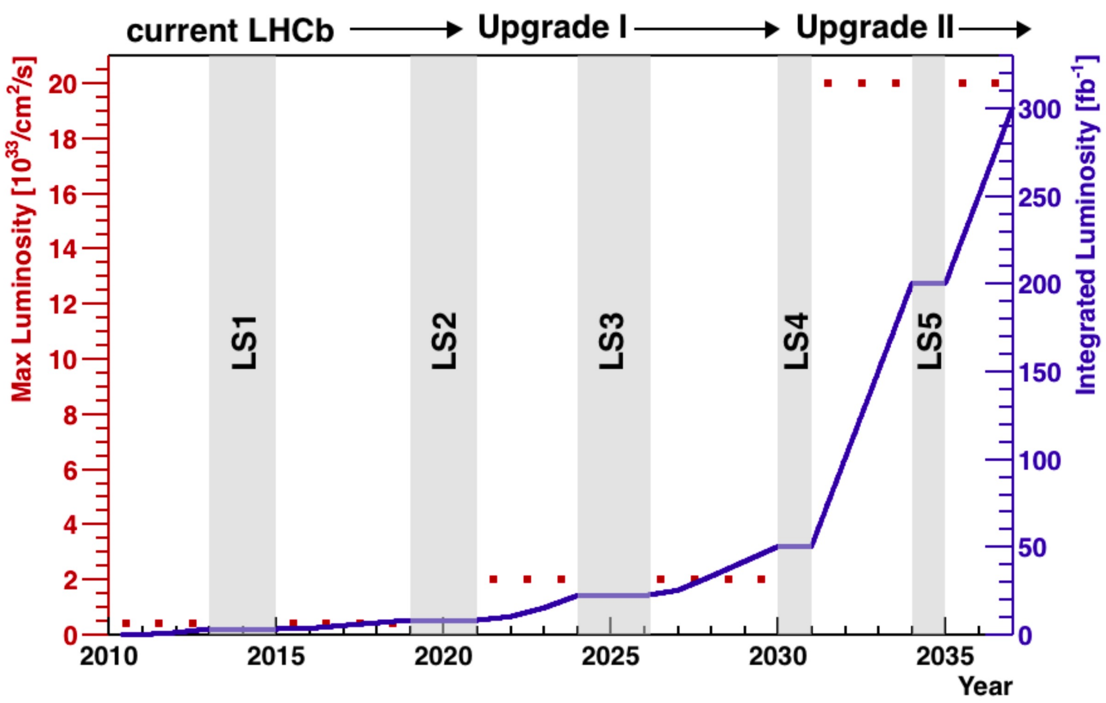
https://github.com/tpajero/charm-fitter



Goal 1: discover CPV in mixing

Charm mixing and indirect CPV: prospects for future LHCb measurements

arXiv:1808.08865



*Current plan shifted by a year due to Covid-19

Prospects for Run 4 and Run 5 at LHCb

Sample ($\mathcal{L}$)	Tag	Yield K^+K^-	$\sigma(A_\Gamma)$	Yield $\pi^+\pi^-$	$\sigma(A_\Gamma)$
Run 1–2 (9 fb^{-1})	Prompt	60M	0.013%	18M	0.024%
Run 1–3 (23 fb^{-1})	Prompt	310M	0.0056%	92M	0.0104 %
Run 1–4 (50 fb^{-1})	Prompt	793M	0.0035%	236M	0.0065 %
Run 1–5 (300 fb^{-1})	Prompt	5.3G	0.0014%	1.6G	0.0025 %

300fb^{-1} predictions reach the SM expectations of $A_\Gamma \approx \mathcal{O}(2 \times 10^{-5})$

Charm mixing parameters

Sample (lumi $\mathcal{L}$)	Tag	Yield	$\sigma(x)$	$\sigma(y)$	$\sigma(\lvert q/p\rvert)$	$\sigma(\phi)$
Run 1–2 (9 fb^{-1})	SL	10M	0.07%	0.05%	0.07	4.6°
	Prompt	36M	0.05%	0.05%	0.04	1.8°
Run 1–3 (23 fb^{-1})	SL	33M	0.036%	0.030%	0.036	2.5°
	Prompt	200M	0.020%	0.020%	0.017	0.77°
Run 1–4 (50 fb^{-1})	SL	78M	0.024%	0.019%	0.024	1.7°
	Prompt	520M	0.012%	0.013%	0.011	0.48°
Run 1–5 (300 fb^{-1})	SL	490M	0.009%	0.008%	0.009	0.69°
	Prompt	3500M	0.005%	0.005%	0.004	0.18°

Recap: $\Delta Y \approx -A_\Gamma$

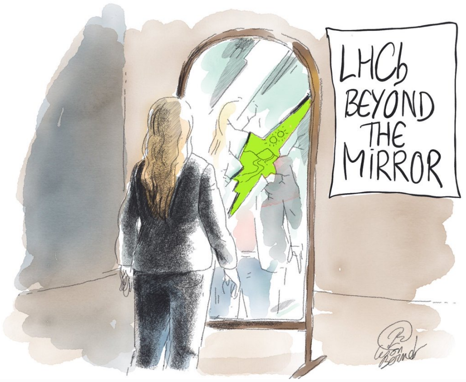
BACKUP

Measurement of the time-integrated CP asymmetry in $D^0 \rightarrow K^-K^+$ decays [LHCb-PAPER-2022-024]

Measurement of the time-integrated CP asymmetry in $D^0 \to K^- K^+$ decays [LHCb-PAPER-2022-024]

$$A_{CP}(KK) = \frac{\int \varepsilon(t)[\Gamma(D^0 \to K^- K^+)(t) - \Gamma(\bar{D}^0 \to K^+ K^-)(t)]\mathrm{d}t}{\int \varepsilon(t)[\Gamma(D^0 \to K^- K^+)(t) + \Gamma(\bar{D}^0 \to K^+ K^-)(t)]\mathrm{d}t} = a^d_{KK} + \frac{\langle t \rangle_{KK}}{\tau_D} \Delta Y_{KK}$$

- $a^d_{KK} \approx 1 - \left|\frac{\bar{A}_{KK}}{A_{KK}}\right|$ probes CPV in the decay.
- $\Delta Y_{KK} \approx x\phi - y\left(\left|\frac{q}{p}\right| - 1\right)$ probes CPV in the mixing + interference between mixing and decay.
- CPV has been observed in $\Delta A_{CP} = A_{CP}(KK) - A_{CP}(\pi\pi) = (-15.4 \pm 2.9)\times 10^{-4}$. Phys. Rev. Lett. 122 (2019) 211803
- Strategy: Measure $A_{CP}(KK)$ and then retrieve a^d_{KK} and $a^d_{\pi\pi}$ using ΔA_{CP} and ΔY [Phys. Rev. D 104, 072010] results.
- Dataset: Run 2 (2015-2018, 6 fb^{-1}).



Credit: Lison Bernet

Prompt = produced at pp interaction point

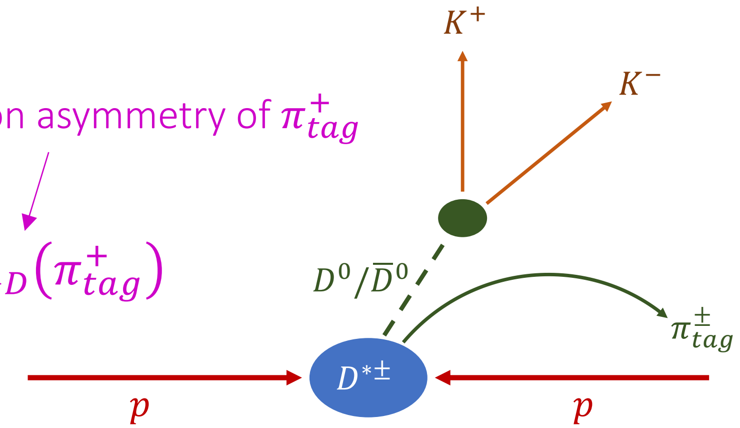
$A_{CP}(KK)$: Experimental challenges

- $\overset{(-)}{D}{}^0 \to K^- K^+$ obtained from prompt $D^{*\pm} \to \overset{(-)}{D}{}^0 \pi^{\pm}_{tag}$. Charge of $\pi^{\pm}_{tag}$ tags D^0 flavour.
- We experimentally measure:

Production asymmetry of D^{*+} — Detection asymmetry of π^{+}_{tag}

$$A(KK) = \frac{N\left(D^{*+} \to D^0 \pi^{\pm}_{tag}\right) - N\left(D^{*-} \to \bar{D}^0 \pi^{-}_{tag}\right)}{N\left(D^{*+} \to D^0 \pi^{\pm}_{tag}\right) + N\left(D^{*-} \to \bar{D}^0 \pi^{-}_{tag}\right)} = A_{CP}(KK) + A_P(D^{*+}) + A_D\left(\pi^{+}_{tag}\right)$$

what we want



- Strategy to treat nuisance asymmetries: use Cabibbo-favoured $D^0/D^+_{(s)}$ decays (where CPV≈ 0):
  - D^+ method (C_{D^+}):

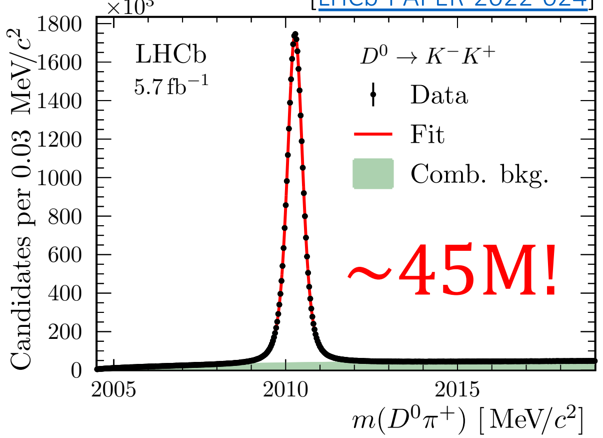
$$A_{CP}(KK) = +A\left(D^{*\pm} \to (D^0 \to K^- K^+)\pi^{\pm}_{tag}\right) - A\left(D^{*\pm} \to (D^0 \to K^- \pi^+)\pi^{\pm}_{tag}\right)$$
$$+A(D^+ \to K^- \pi^+ \pi^+) - [A(D^+ \to \bar{K}^0 \pi^+) - A(\bar{K}^0)]$$

Neutral Kaon asymmetry: detection + mixing + CPV

  - D_s^+ method ($C_{D_s^+}$, gain of $\sim 40\%$ precision on final result):

$$A_{CP}(KK) = +A\left(D^{*\pm} \to (D^0 \to K^- K^+)\pi^{\pm}_{tag}\right) - A\left(D^{*\pm} \to (D^0 \to K^- \pi^+)\pi^{\pm}_{tag}\right)$$
$$+A(D_s^+ \to \phi \pi^+) - [A(D_s^+ \to \bar{K}^0 K^+) - A(\bar{K}^0)]$$

[LHCb-PAPER-2022-024]



* Particles with same colour are weighted to have identical kinematic distributions

A new precise measurement of CPV in the decay!

Final results:

$$C_{D^+}: \ A_{CP}(KK) = [13.6 \pm 8.8(\text{stat}) \pm 1.6(\text{sys})] \times 10^{-4},$$
$$C_{D_s^+}: \ A_{CP}(KK) = [\ 2.8 \pm 6.7(\text{stat}) \pm 2.0(\text{sys})] \times 10^{-4}.$$

$\rho = 0.06$

Combination:

$$A_{CP}(KK) = [6.8 \pm 5.4(\text{stat}) \pm 1.6(\text{sys})] \times 10^{-4}.$$

Using ΔA_{CP} result, we get:

$$a^d_{KK} = (\ 7.7 \pm 5.7) \times 10^{-4}$$
$$a^d_{\pi\pi} = (23.2 \pm 6.1) \times 10^{-4}$$

$\rho(a^d_{KK}, a^d_{\pi\pi}) = 0.88$

First evidence of CP violation in $D^0 \to \pi^-\pi^+$ decays at 3.8σ!

LHCb prospects [arXiv:1808.08865] (stat uncertainties only)

Sample ($\mathcal{L}$)	Tag	Yield $D^0 \to K^-K^+$	Yield $D^0 \to \pi^-\pi^+$	$\sigma(\Delta A_{CP})$ [%]	$\sigma(A_{CP}(hh))$ [%]
Run 1–2 (9 fb^{-1})	Prompt	52M	17M	0.03	0.07
Run 1–3 (23 fb^{-1})	Prompt	280M	94M	0.013	0.03
Run 1–4 (50 fb^{-1})	Prompt	1G	305M	0.007	0.015
Run 1–5 (300 fb^{-1})	Prompt	4.9G	1.6G	0.003	0.007

We do better than our own propects for Run1-2!