New horizons in flavour physics: the discovery of CP violation in charm

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PSI colloquium
7/11/19

Colloquium outline

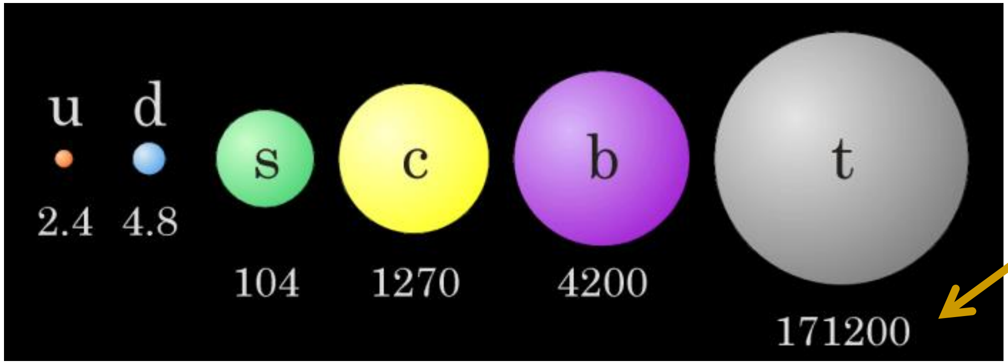
- What is flavour physics and why should we care ?
- CP violation – a closer look
- The LHCb experiment
- The singular history of charm physics
- Discovery of CP violation in charm
- The future of charm physics

What is flavour physics and why should we care ?

What is flavour physics?

The concept of ‘flavour’ in particle physics relates to the existence of different families of quarks*, and how they couple to each other

i.e. 6 known flavours of quark, grouped into 3 generations



Not to linear scale !

mass in MeV/c^2

Open questions:

- why 3 generations ?
- why do the quarks exhibit this striking hierarchy in mass ?

No answer yet !
These values (i.e. ‘3’ & the masses) are free parameters of the SM

These mysteries make the ‘flavour sector’ of the Standard Model of great interest.

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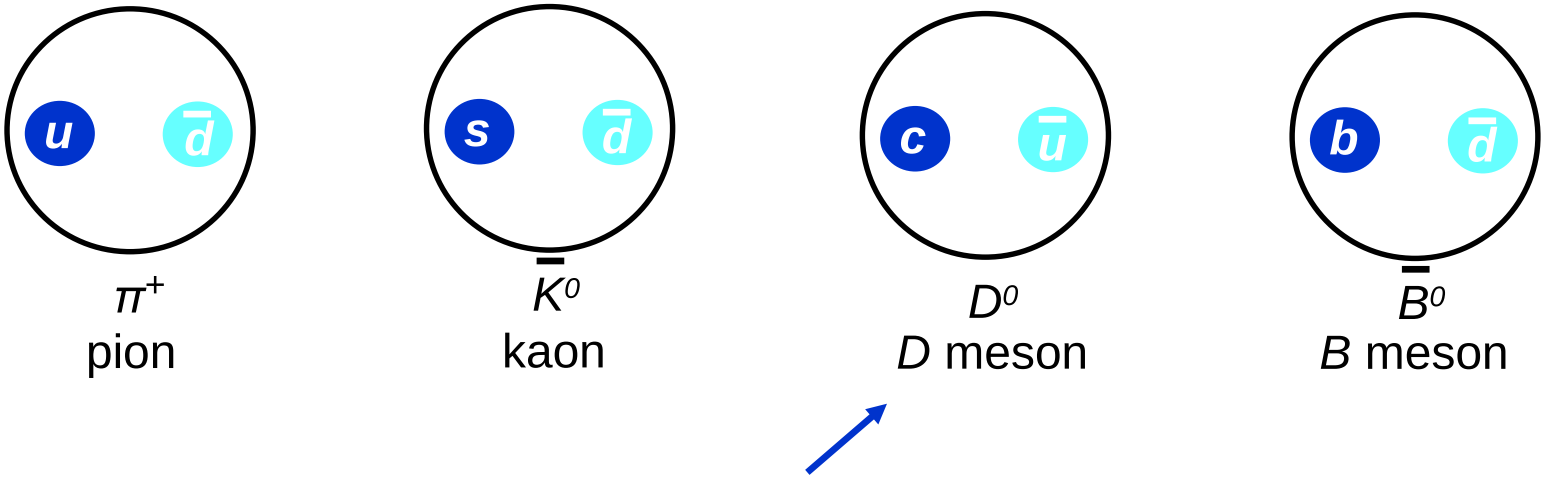
* the concept of flavour extends to the lepton sector too

By the way, we must study hadrons, not quarks

The nature of the strong force does not allow quarks to exist in isolation. Rather they must be bound together in hadrons, *e.g.* baryons ($q_1q_2q_3$) or mesons ($q_1\bar{q}_2$).



π^+
pion

$\bar{K}^0$
kaon

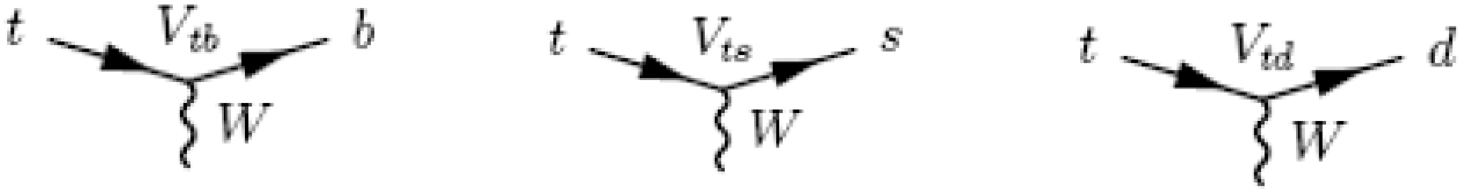
D^0
D meson

$\bar{B}^0$
B meson

irritating, but important
notation for today's discussion,
i.e. that *D* mesons contain *c* (charm) quarks

Flavour and the CKM matrix

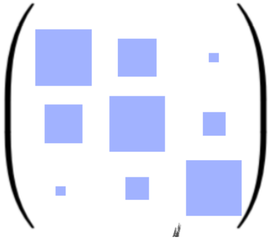
In the Standard Model quarks can only change flavour through emission of a W boson (*i.e.* weak force). For example a t quark can decay into a b, s or d quark:



But these decays are not equally likely. At the amplitude level they are weighted by factors that are elements of the Cabibbo-Kobyashi-Maskawa (CKM) matrix, and these factors vary dramatically – here is another hierarchy we don't understand !

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 0.9705-0.9770 & 0.21-0.24 & 0-0.014 \\ 0.21-0.24 & 0.971-0.973 & 0.036-0.070 \\ 0-0.014 & 0.036-0.070 & 0.997-0.999 \end{pmatrix}$$

These elements of the CKM matrix are also fundamental parameters of the Standard Model. Why they have these values is another great mystery.



Parameters of the Standard Model

- 3 gauge couplings
- 2 Higgs parameters
- strong CP parameter θ
- 6 quark masses
- 3 quark mixing angles + 1 phase [*i.e.* CKM matrix]
- 3 (+3) lepton masses
- (3 lepton mixing angles + 1 phase [*i.e.* PMNS matrix])

() = with Dirac neutrino masses

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These are all flavour parameters !

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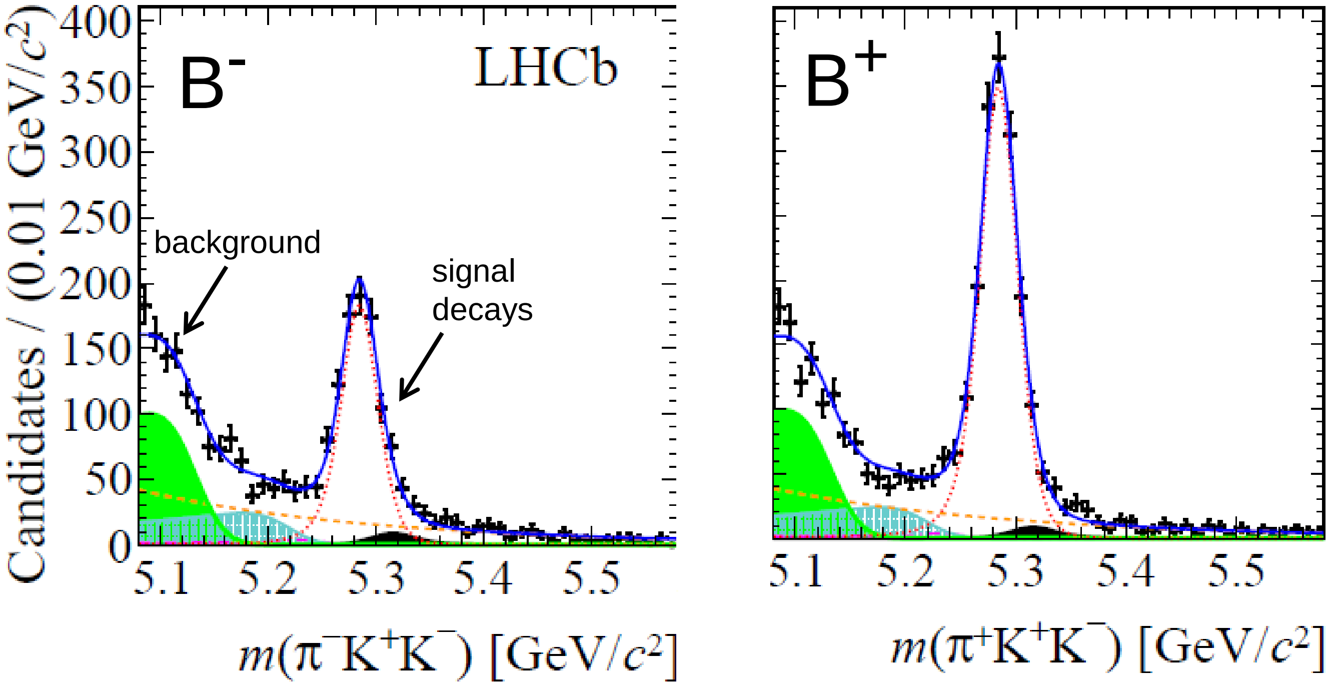
This is of particular relevance…

() = with Dirac neutrino masses

CP violation

CP violation (CPV) → difference in behaviour between matter and anti-matter.

A recent example from LHCb - look at B meson decaying into a pion & two kaons…

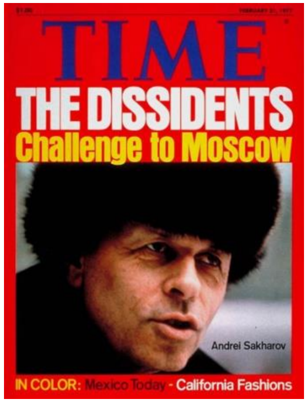


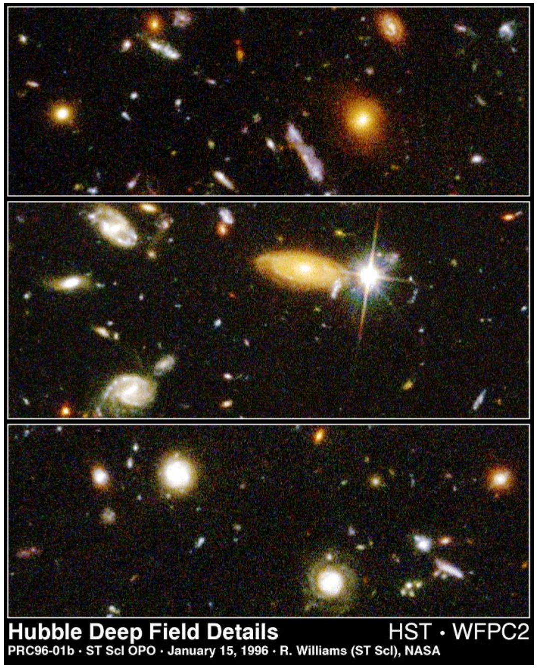
[LHCb, PRD 90 (2014) 112004]

…the decay probabilities are manifestly different for B^- & B^+ ! In the Standard Model CPV is accommodated, *but not explained*, by an imaginary phase in the CKM matrix.

Cosmological connections ?

As first pointed out by Andrei Sakharov, CP-violation is one requirement for explaining *baryogenesis* – the process that took us from the equal amounts of matter and anti-matter produced in the Big Bang, to the matter dominated universe of today





The problem is that the CP-violation that appears in the Standard Model, is woefully inadequate to explain the matter-antimatter asymmetry we have today.

This is a big problem with the Standard Model !

More & better measurements
may point a way forward.

Problems with the Standard Model

The Standard Model (SM) cannot be a final theory

We have already encountered the following shortcomings:

- No explanation for baryogenesis
- No explanation for the quark or CKM hierarchy
- No real explanation for CP violation, and why it is only found in the weak interaction.

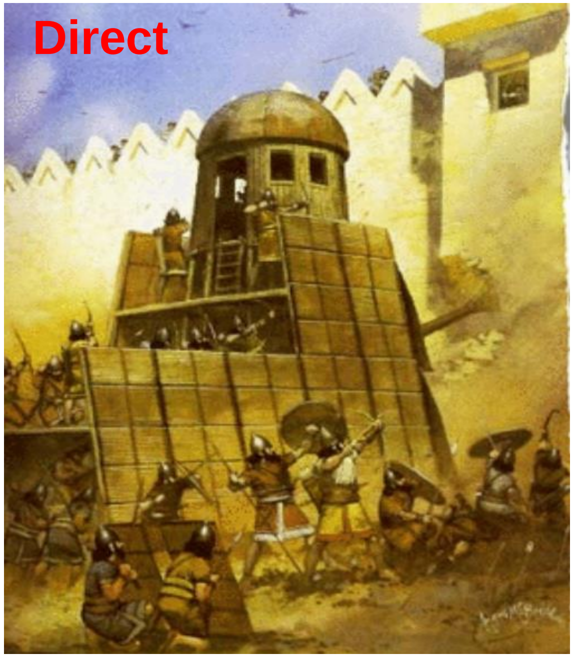
And there are plenty of others, for example:

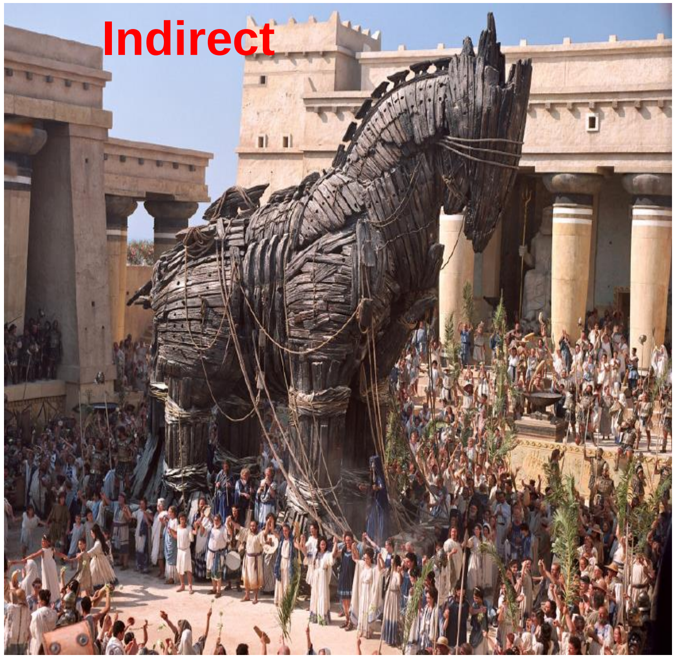
- No explanation for dark matter or dark energy
- No explanation for neutrino masses
- Gravity not included
- No explanation for why the Higgs boson has the mass it does (left to itself the theory would make it much, much heavier)

More ambitious theories (*e.g.* supersymmetry or SUSY) can solve at least some of these problems. They generally predict new particles or effects outside the SM. Finding these effects is the goal of the LHC & many other present/planned facilities !

Breaching the walls of the Standard Model

The HEP community is searching for ‘New Physics’ - to find this we need to penetrate the walls of the Standard Model fortress. There are two strategies used in this search.





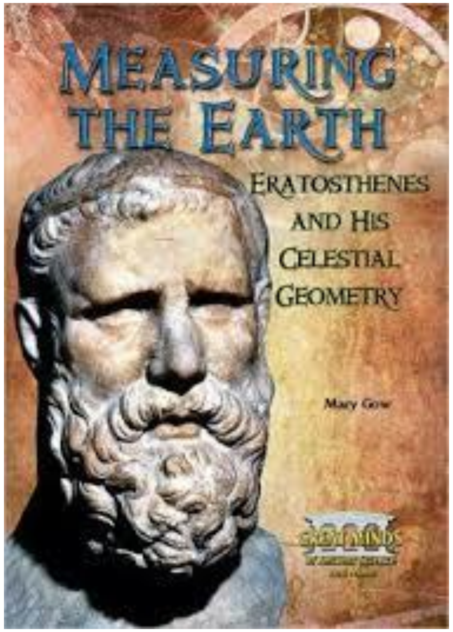
Use the high energy of, *e.g.* the LHC to produce the New Physics particles, which we then detect

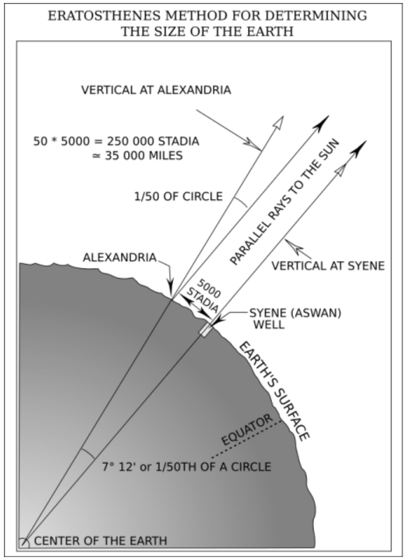
Make precise measurements of processes in which New Physics particles enter through ‘virtual loops’

Both methods are powerful. Flavour physics follows the ‘indirect’ approach.

Indirect measurements – an established tradition in science

Eratosthenes was able to determine
the circumference of the earth
using indirect means…





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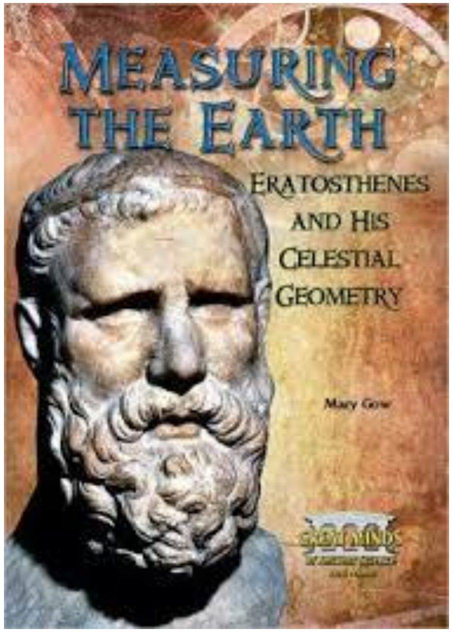
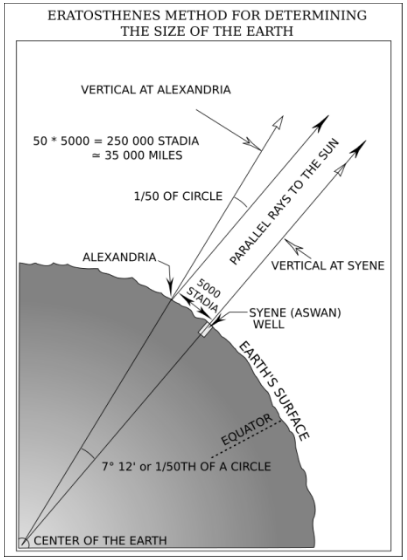
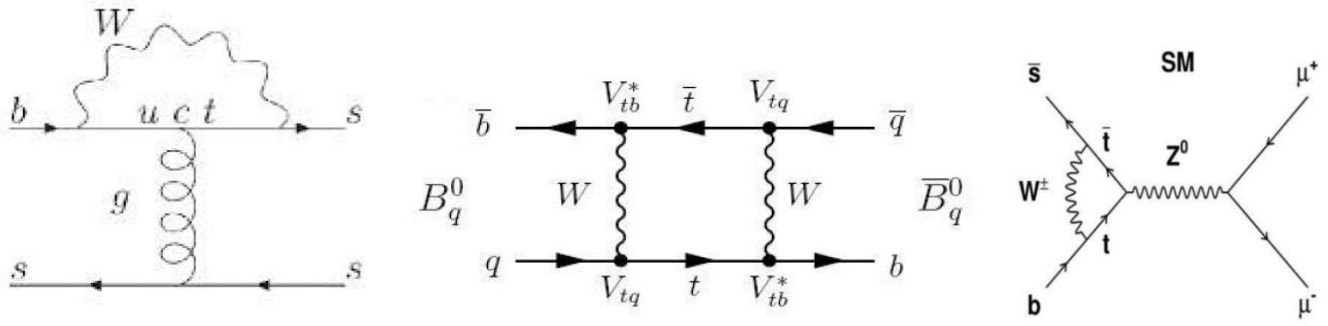




…around 2.2 thousand years prior to the direct observation.

Indirect measurements – an established tradition in science

In flavour physics the guiding principle is to probe processes where loop diagrams are important, as here non-SM particles may contribute



(but as we will see, tree-mediated decays also have their role to play)

Indirect search principle ➡ Precise measurements of low energy phenomena tells us about unknown physics at energies *far* beyond direct searches (~10^4 TeV in some cases)

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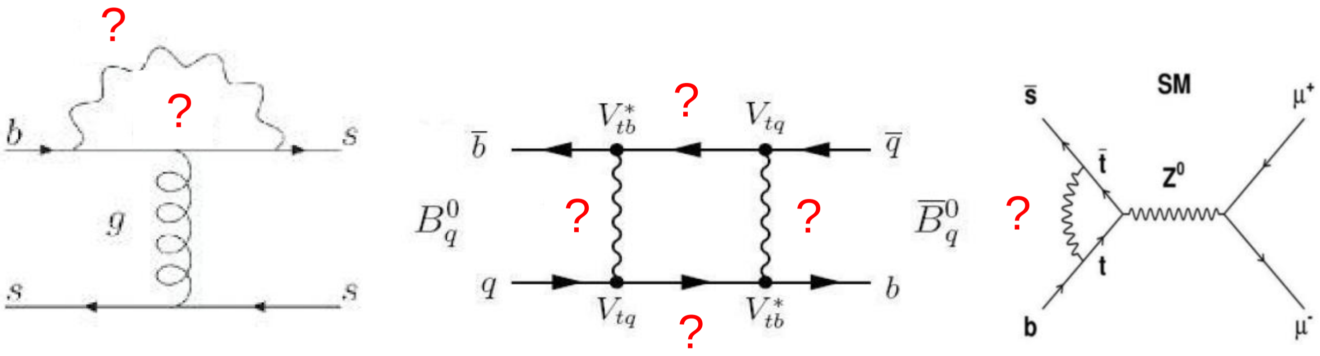

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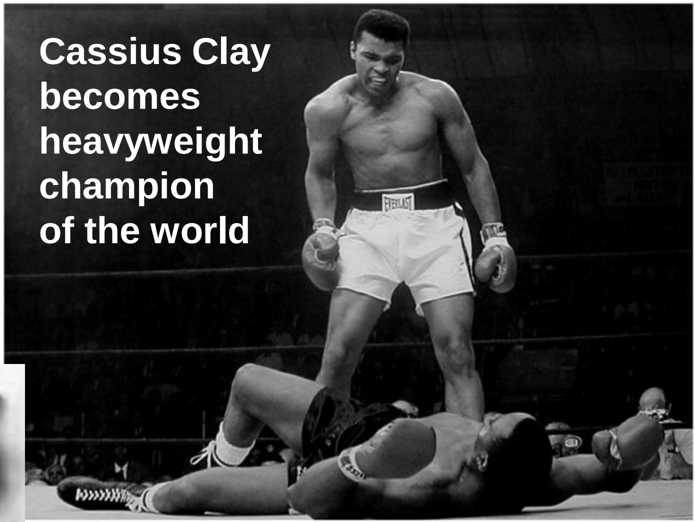
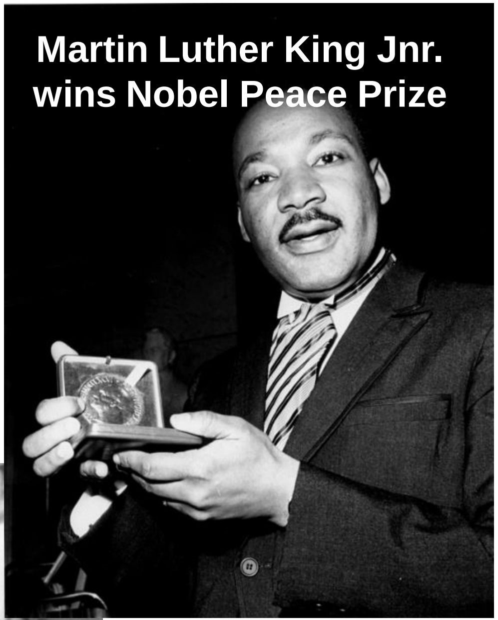
CP violation – a closer look

Events of 1964

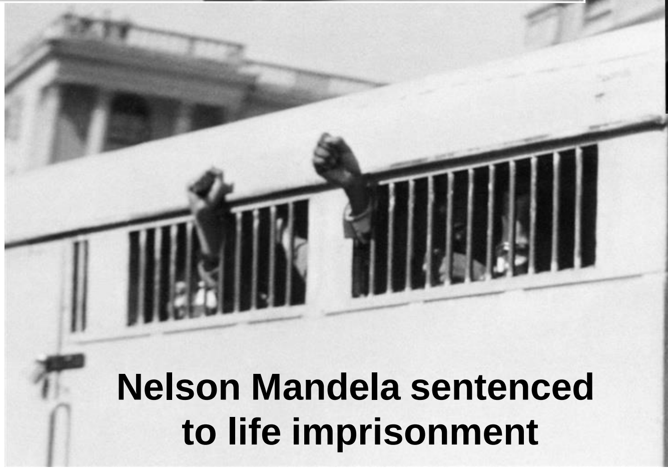
Change of face in the Kremlin



Cassius Clay becomes heavyweight champion of the world

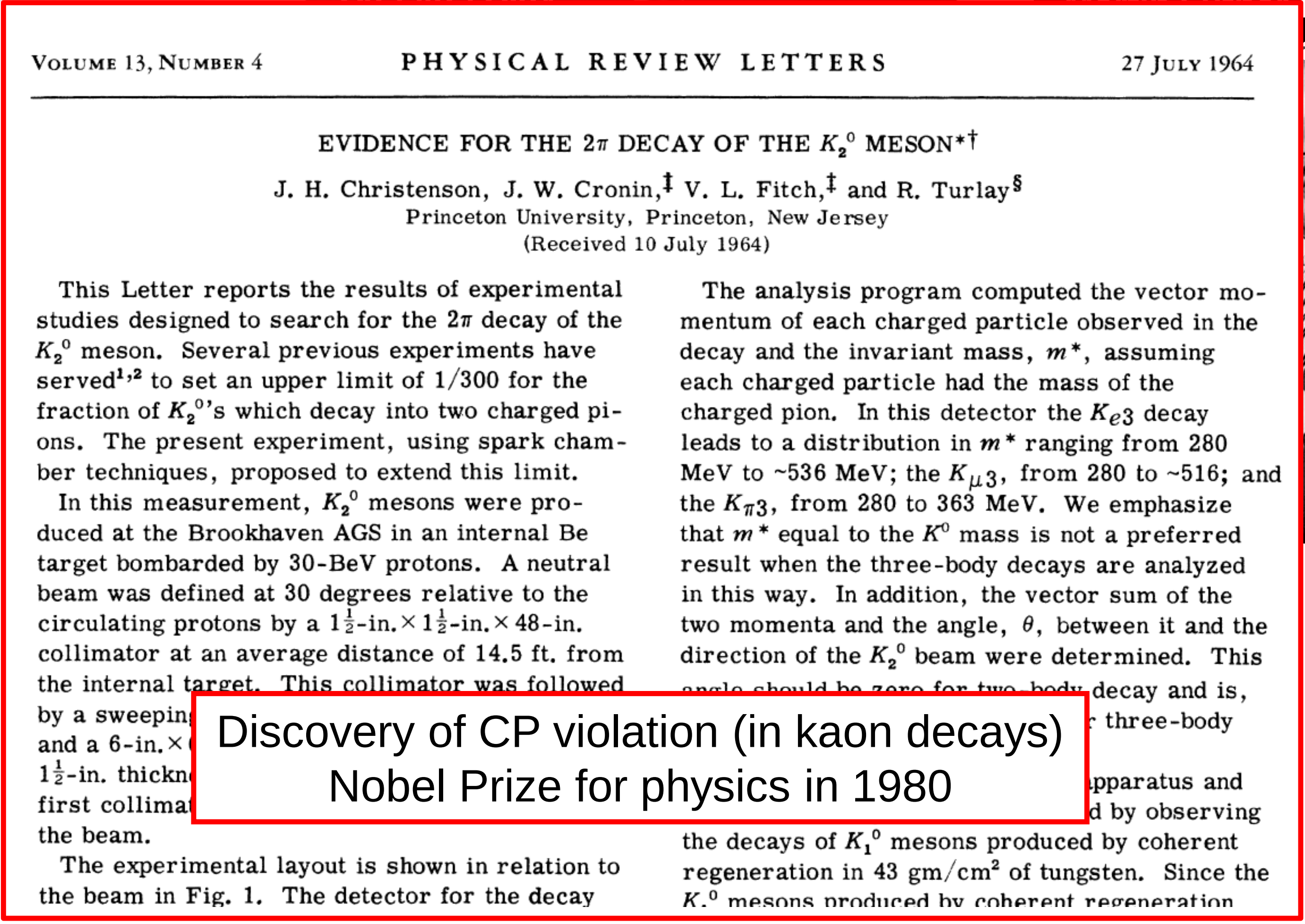


Martin Luther King Jnr. wins Nobel Peace Prize



Nelson Mandela sentenced to life imprisonment

Events of 1964



Volume 13, Number 4 PHYSICAL REVIEW LETTERS 27 July 1964

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey

(Received 10 July 1964)

This Letter reports the results of experimental studies designed to search for the 2π decay of the K_2^0 meson. Several previous experiments have served[1,2] to set an upper limit of 1/300 for the fraction of K_2^0's which decay into two charged pions. The present experiment, using spark chamber techniques, proposed to extend this limit.

In this measurement, K_2^0 mesons were produced at the Brookhaven AGS in an internal Be target bombarded by 30-BeV protons. A neutral beam was defined at 30 degrees relative to the circulating protons by a $1\frac{1}{2}$-in.×$1\frac{1}{2}$-in.×48-in. collimator at an average distance of 14.5 ft. from the internal target. This collimator was followed by a sweepin

and a 6-in.×

$1\frac{1}{2}$-in. thickn

first collimat

the beam.

The experimental layout is shown in relation to the beam in Fig. 1. The detector for the decay

The analysis program computed the vector momentum of each charged particle observed in the decay and the invariant mass, m^*, assuming each charged particle had the mass of the charged pion. In this detector the K_{e3} decay leads to a distribution in m^* ranging from 280 MeV to ~536 MeV; the $K_{\mu 3}$, from 280 to ~516; and the $K_{\pi 3}$, from 280 to 363 MeV. We emphasize that m^* equal to the K^0 mass is not a preferred result when the three-body decays are analyzed in this way. In addition, the vector sum of the two momenta and the angle, θ, between it and the direction of the K_2^0 beam were determined. This angle should be zero for two-body decay and is,

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pparatus and

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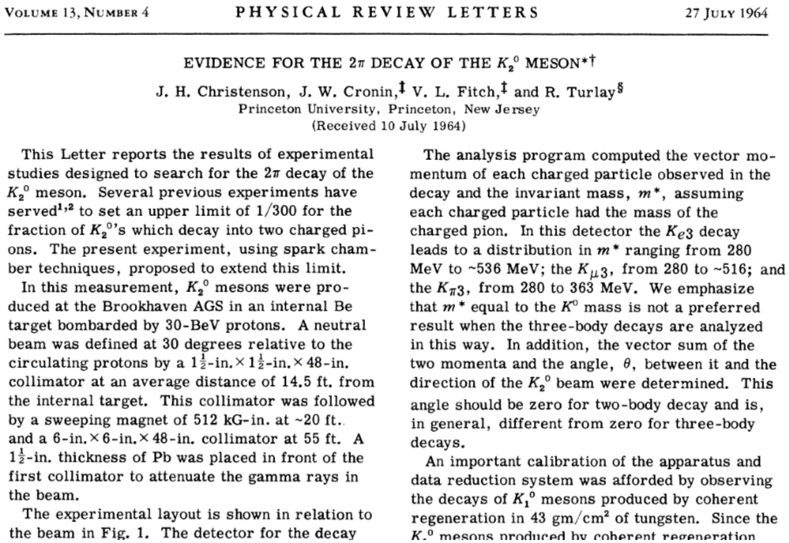
Discovery of CP violation (in kaon decays)
Nobel Prize for physics in 1980

Discovery of CP violation

Observation of 45 ± 10 $\pi^+\pi^-$ decays in a K^0_L beam [Christenson *et al.*, PRL 13 (1964) 138].



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The experimental layout is shown in relation to the beam in Fig. 1. The detector for the decay

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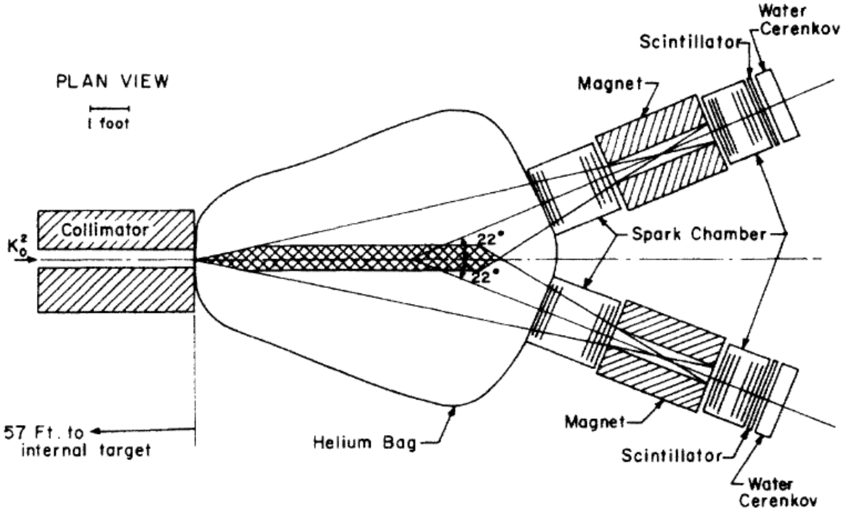
An important calibration of the apparatus and data reduction system was afforded by observing the decays of K_1^0 mesons produced by coherent regeneration in 43 gm/cm² of tungsten. Since the K_1^0 mesons produced by coherent regeneration



Final state is CP even, whereas initial state (one of two neutral-kaon mass eigenstates) had been assumed to be purely CP odd. A great surprise, following discovery of parity violation which had only taken place 8 years previously.

CP violation and the CKM matrix

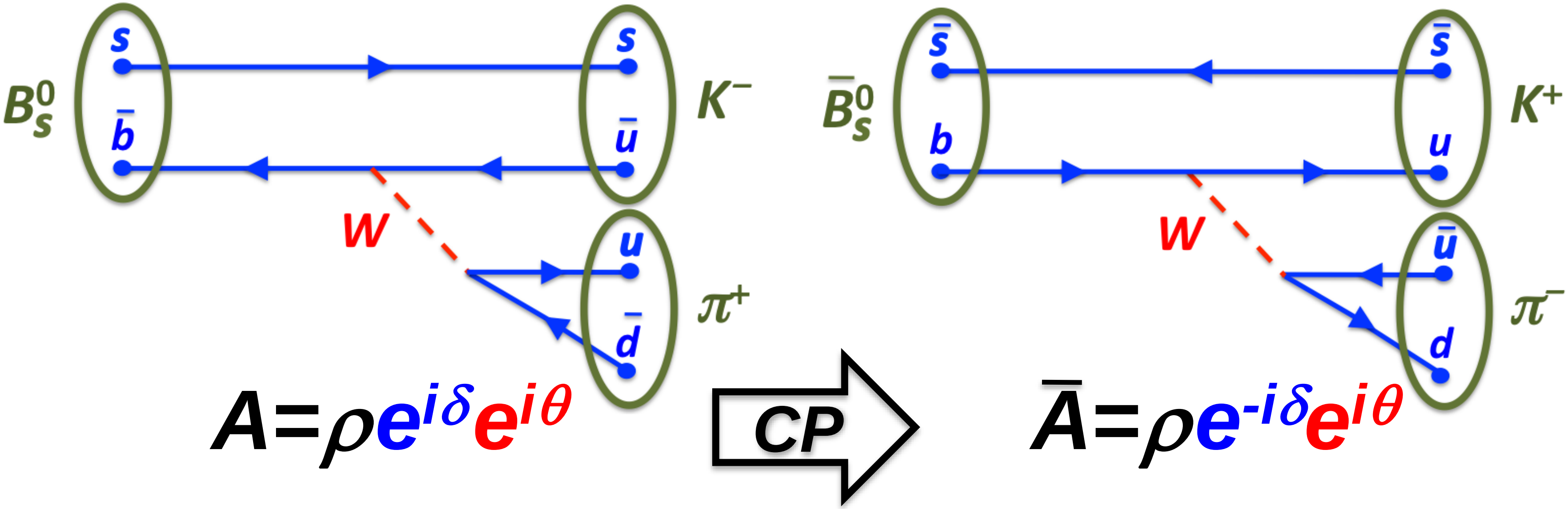
As stated, within the SM, CPV is accommodated, but not really explained, by a single imaginary phase in the quark mixing (Cabibbo-Kobayashi-Maskawa) matrix.

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Four independent parameters in total, one of which enters as imaginary part of certain elements (here shown in the so-called Wolfenstein representation [PRL 51 (1983) 1945]).

$$V_{CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho-\boxed{i\eta}) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-\boxed{i\eta}) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

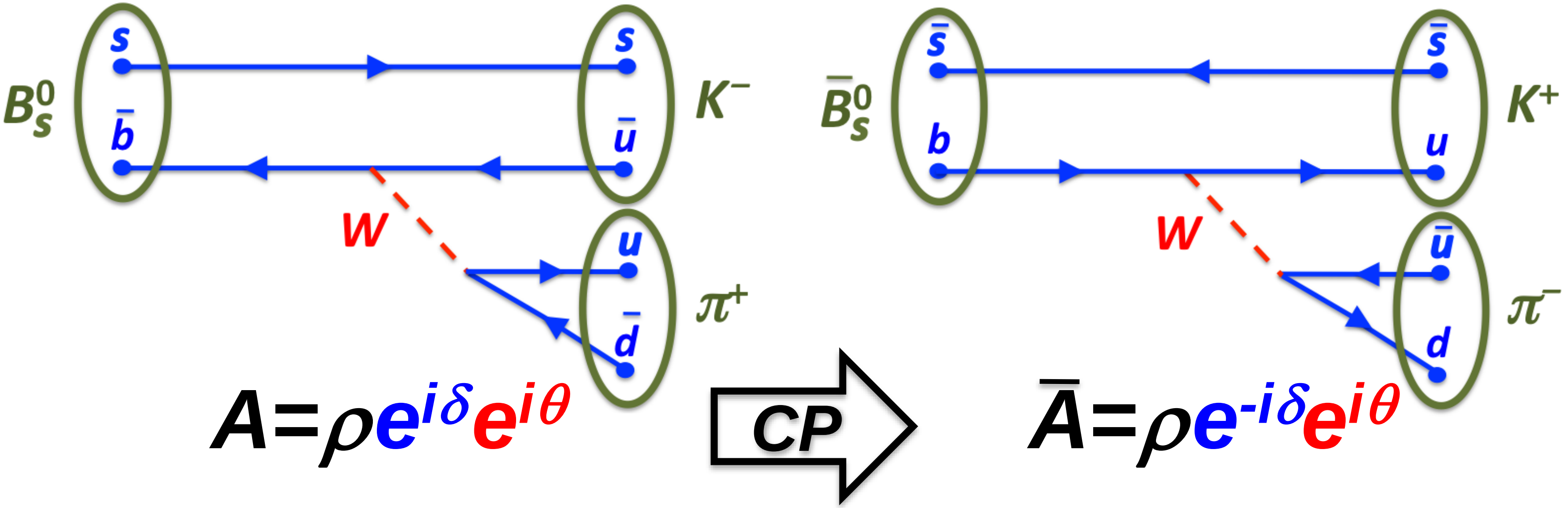
How to see the imaginary phase



$$A=\rho e^{i\delta}e^{i\theta} \qquad \bar{A}=\rho e^{-i\delta}e^{i\theta}$$

On the amplitude of a given process (here a $B_s \rightarrow K^+\pi^-$ decay) a CP transformation changes the sign of the phase due to weak interactions (related to the CKM phase), leaving the strong-interaction phase unchanged.

How to see the imaginary phase

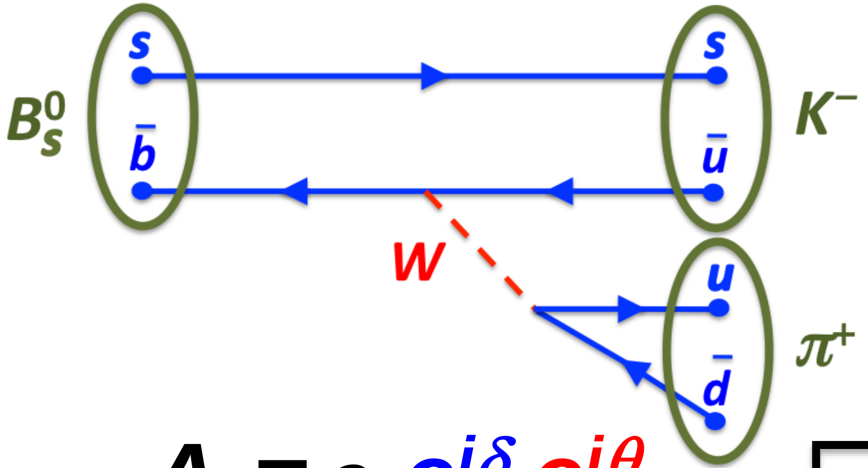


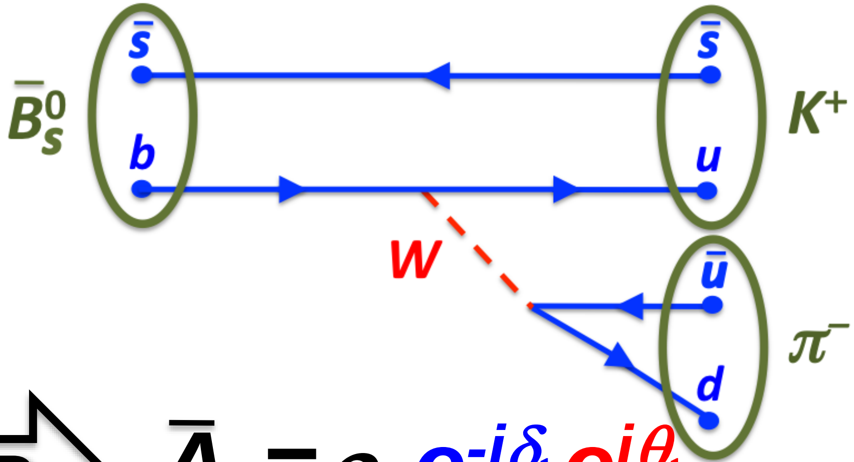
$$A=\rho e^{i\delta}e^{i\theta} \quad \xrightarrow{CP} \quad \bar{A}=\rho e^{-i\delta}e^{i\theta}$$

As the rate of the two processes is obtained by taking the absolute square of the amplitudes, since $|A|^2 - |\bar{A}|^2 = 0$ the number of decays to $K^+\pi^-$, considering these amplitudes alone, is identical to that of those to $K^-\pi^+$.

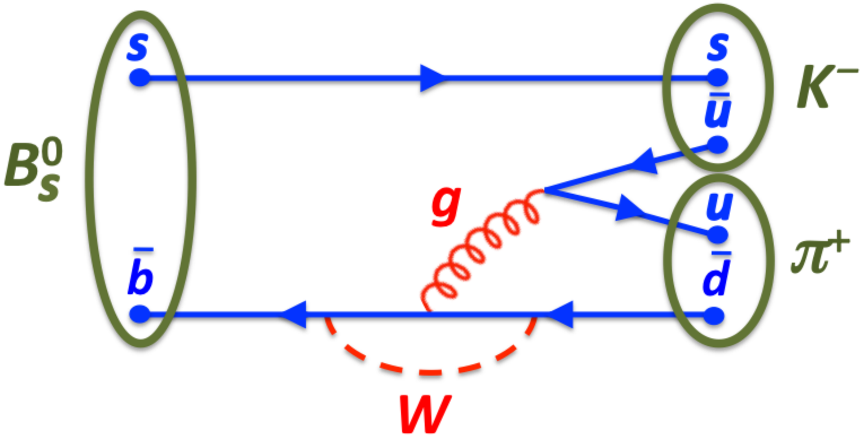
→ no rate asymmetry is observable.

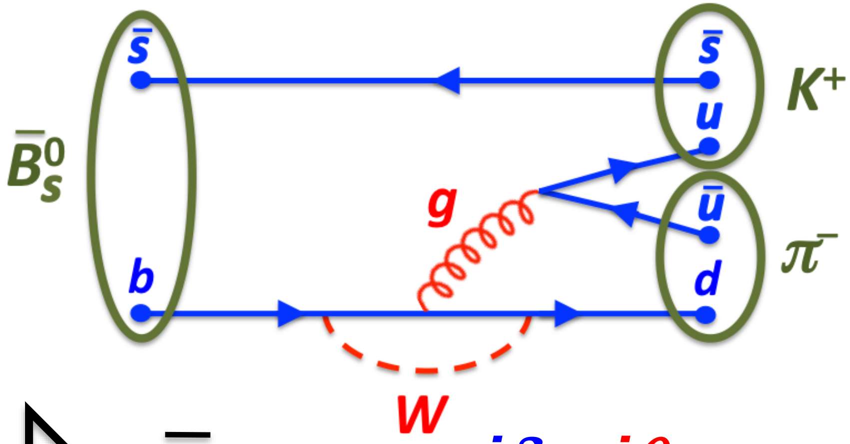
How to see the imaginary phase





$$A_1=\rho_1 e^{i\delta_1} e^{i\theta_1} \xrightarrow{CP} \bar{A}_1=\rho_1 e^{-i\delta_1} e^{i\theta_1}$$





$$A_2=\rho_2 e^{i\delta_2} e^{i\theta_2} \xrightarrow{CP} \bar{A}_2=\rho_2 e^{-i\delta_2} e^{i\theta_2}$$

How to see the imaginary phase

Now the situation looks different

$$|\bar{A}_1+\bar{A}_2|^2 - |A_1+A_2|^2 = 4\rho_1\rho_2 \sin(\delta_1 - \delta_2) \sin(\theta_1 - \theta_2)$$

This differs from zero if weak phase differ $\delta_1 \neq \delta_2$ and the strong phases differ $\theta_1 \neq \theta_2$

→ the rate asymmetry becomes observable!

This is a typical effect of quantum interference, where one has two paths with amplitudes of different phases and it is impossible to know which of the two paths the system has been following to reach the final state.

→ CPV requires a process involving (at least) two amplitudes.

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It is possible that for certain processes there are additional amplitudes, involving New Physics particles, with their own CP-violating phases. This will bring further interference & change effect w.r.t. SM expectation !

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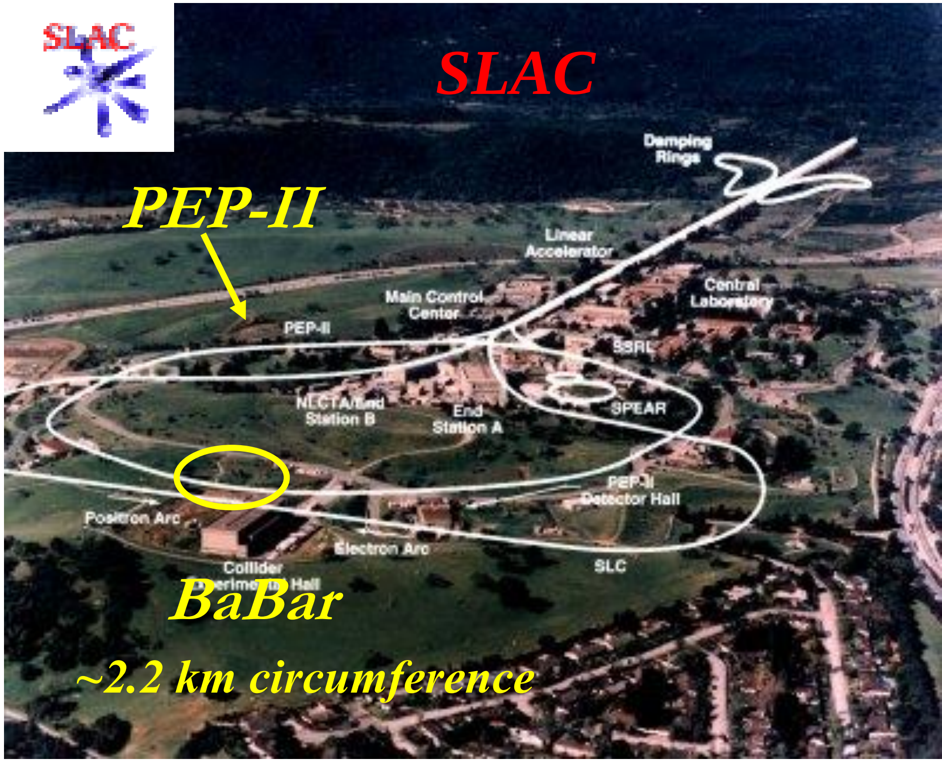
Further experimental progress to check this paradigm was difficult in the kaon system. Effects are small, & theoretical predictions are complicated by hadronic corrections. These problems, in general, do not exist with beauty hadrons. Precise studies of CPV in beauty hadrons became feasible early this century.

e^+e^- asymmetric B-factories



8 GeV e^- x 3.5 GeV e^+

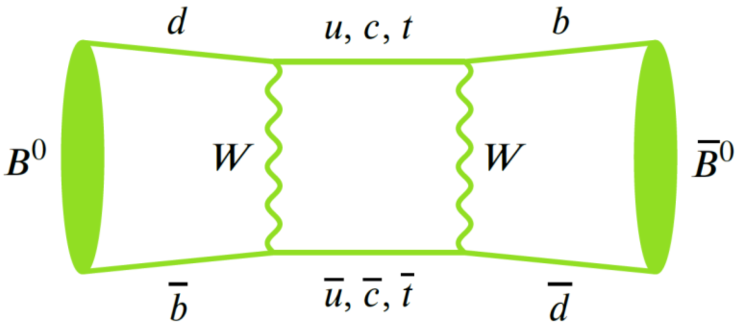
9 GeV e^- x 3.1 GeV e^+

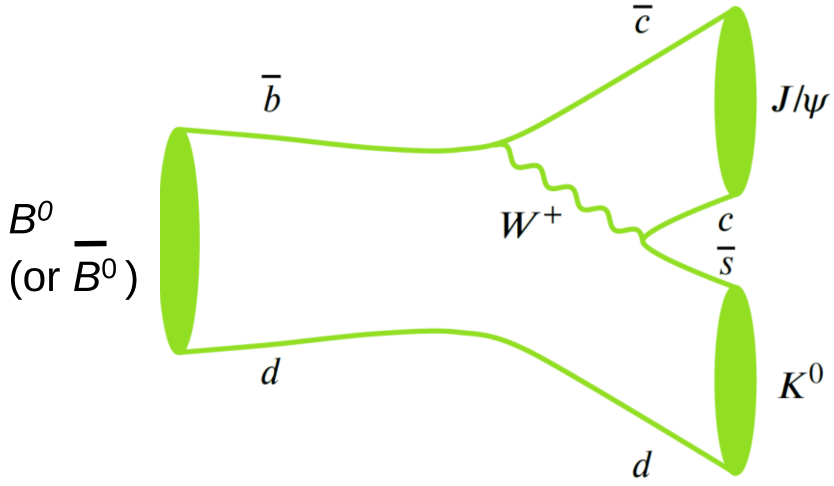
Previous generation of e^+e^- accelerators could produce ~tens of $b\bar{b}$ pairs / day, KEKB & PEP-II were capable of producing ~one million $b\bar{b}$ pairs / day.

2001 - dawn of modern flavour physics

We can date the start of modern CPV studies to the 2001 measurements of the CP-violating asymmetry in $B^0 \to J/\psi K^0$ decays by the BaBar and Belle experiments.

The interfering amplitudes:





(Here the left diagram allows for so-called flavour oscillations, which gives a CP asymmetry that varies with decay time, not just an overall difference in decay rates.)

2001 - dawn of modern flavour physics

2008
Nobel
Prize

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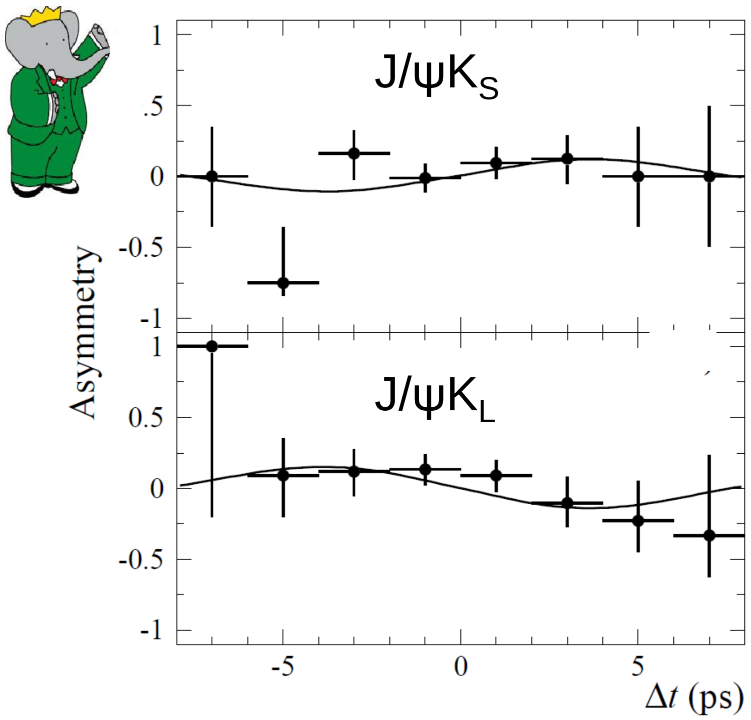
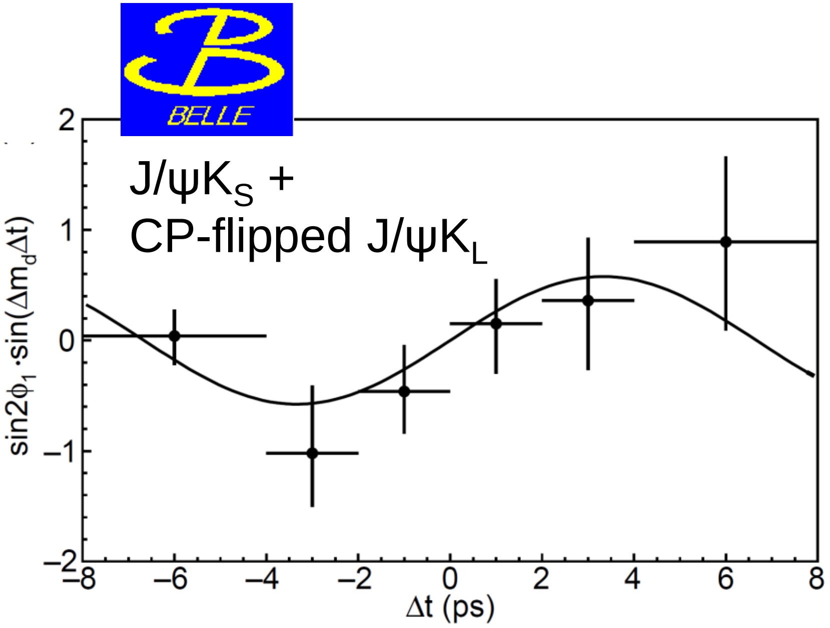


[BaBar, PRL 86 (2001) 2515]



[Belle, PRL 86 (2001) 2509]

These studies, when improved with larger samples, confirmed the CKM paradigm as the dominant mechanism of CP violation in nature (→ 2008 Nobel Prize), and also opened up a rich and wide spectrum of complementary measurements.

CP violation: the first 50 years

1956
Parity violation
T. D. Lee,
C. N. Yang and
C. S. Wu *et al.*

1963
Cabibbo Mixing
N. Cabibbo

1964
Strange particles:
***CP* violation in K**
meson decays
J. W. Cronin,
V. L. Fitch *et al.*

1973
The CKM matrix
M. Kobayashi and
T. Maskawa

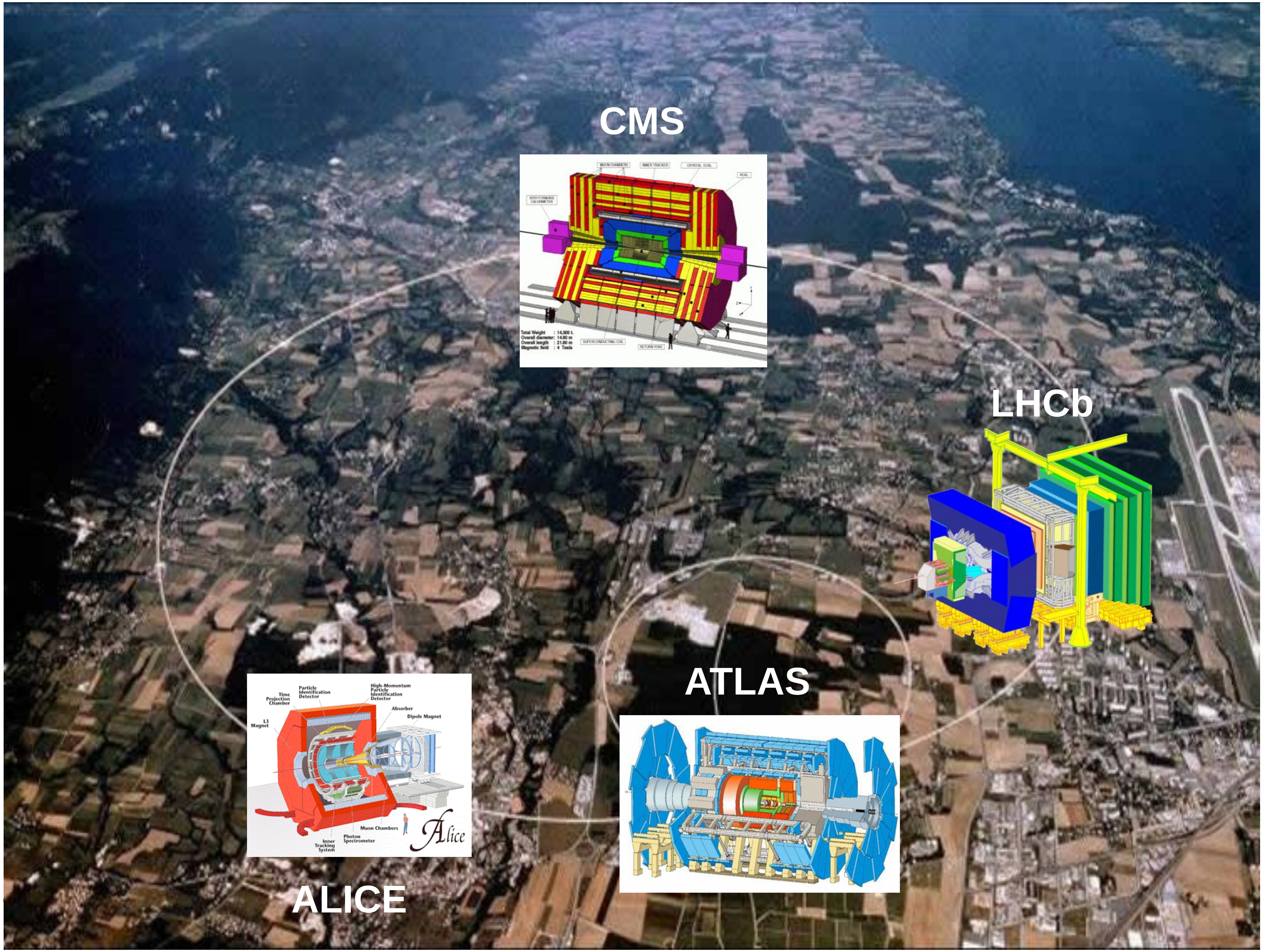
2001
Beauty particles:
***CP* violation in B^0**
meson decays
BaBar and Belle
collaborations

LHCb: a dedicated experiment for flavour physics at the LHC

LHCb – a flavour physics experiment at the LHC

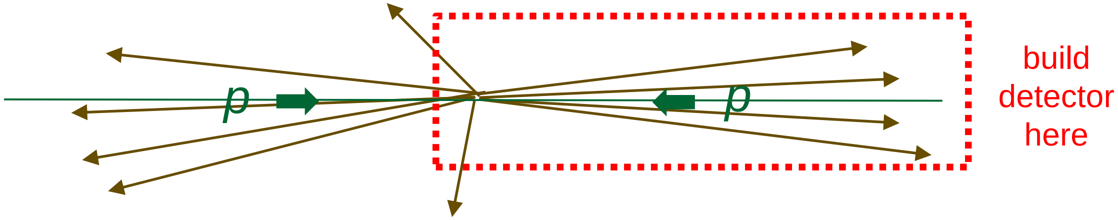
A collaboration of ~1400 members from 81 institutes in 19 countries

An experiment to search for physics beyond the **Standard Model**, through **flavour** studies of particles containing **beauty** (**b**) and **charm** (**c**) quarks.


CMS
MUON CHAMBERS
INNER TRACKER
CRYSTAL ECAL
HCAL
VERY FORWARD CALORIMETER
Total Weight : 14,500 t.
Overall diameter : 14.60 m
Overall length : 21.60 m
Magnetic field : 4 Tesla
SUPERCONDUCTING COIL
RETURN YOKE
LHCb
ATLAS
Time Projection Chamber
Particle Identification Detector
High-Momentum Particle Identification Detector
Absorber
Dipole Magnet
L3 Magnet
Muon Chambers
Photon Spectrometer
Inner Tracking System
Alice
ALICE

Three requirements for an LHC flavour experiment

Optimal geometry

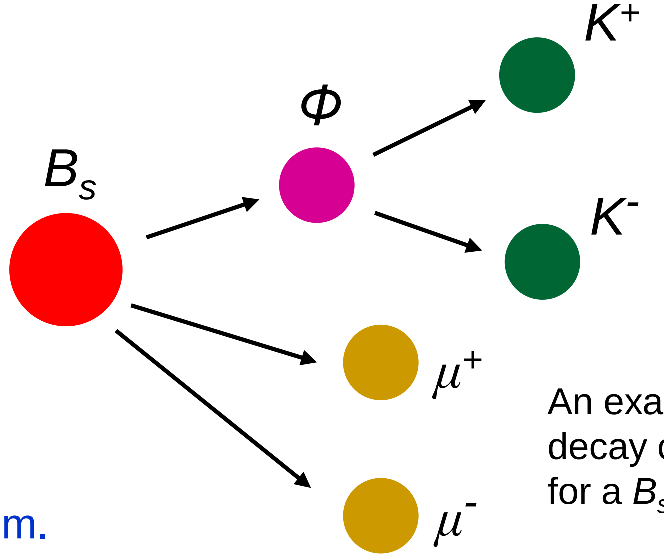


At LHC b *and* c-hadrons are produced predominantly at low angles to beamline.

Hence a ‘forward’, rather than, ‘central’ detector geometry is desirable.

It must be able to reconstruct the ‘decay chain’ of the beauty/charm hadron.

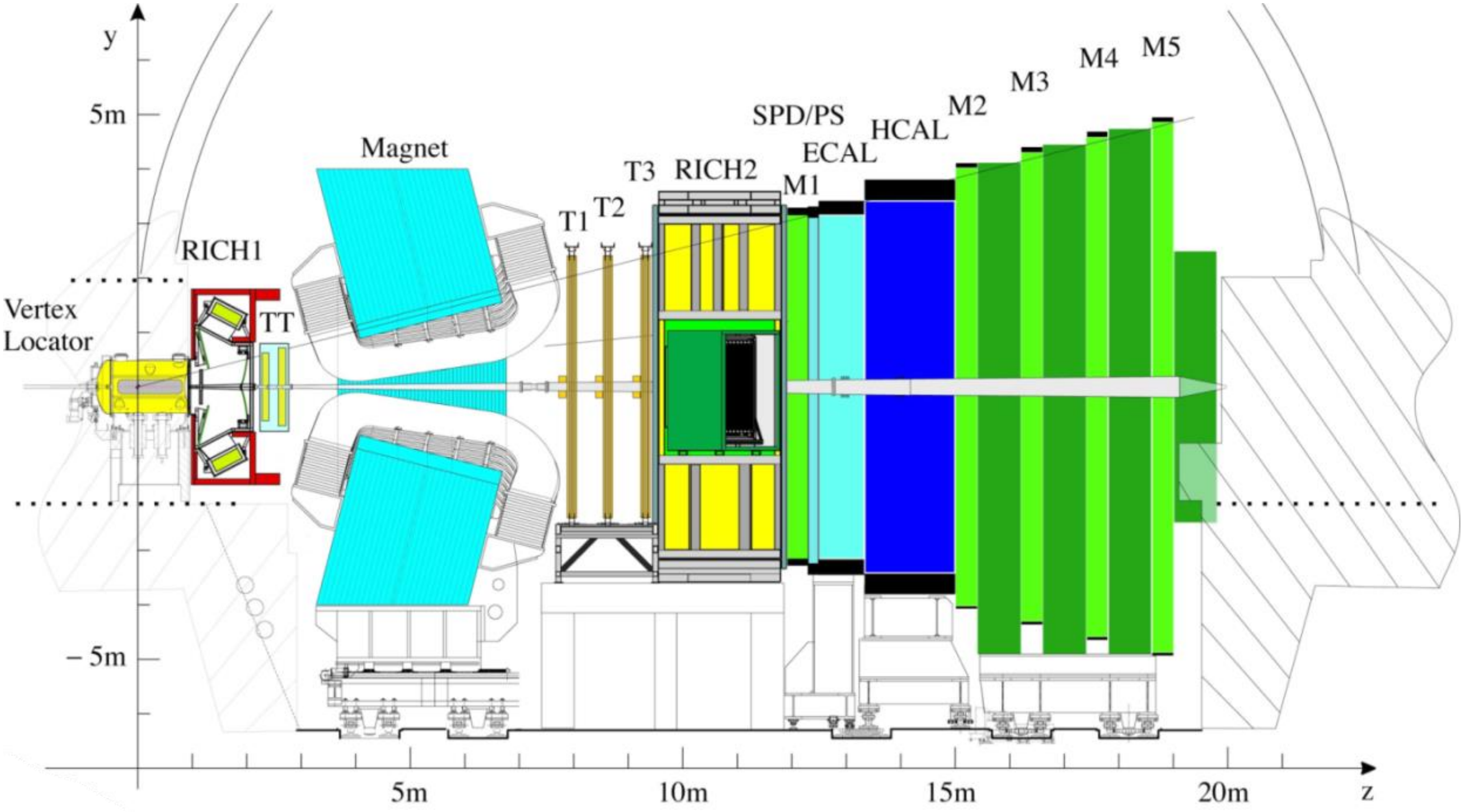
We don’t see the b/c-hadron, which travels for only a few mm before decaying. But we can detect the daughter particles from the decay, and from these ‘re-build’ the parent hadron. We need to know *what* these daughter particles are, and *where* they come from.



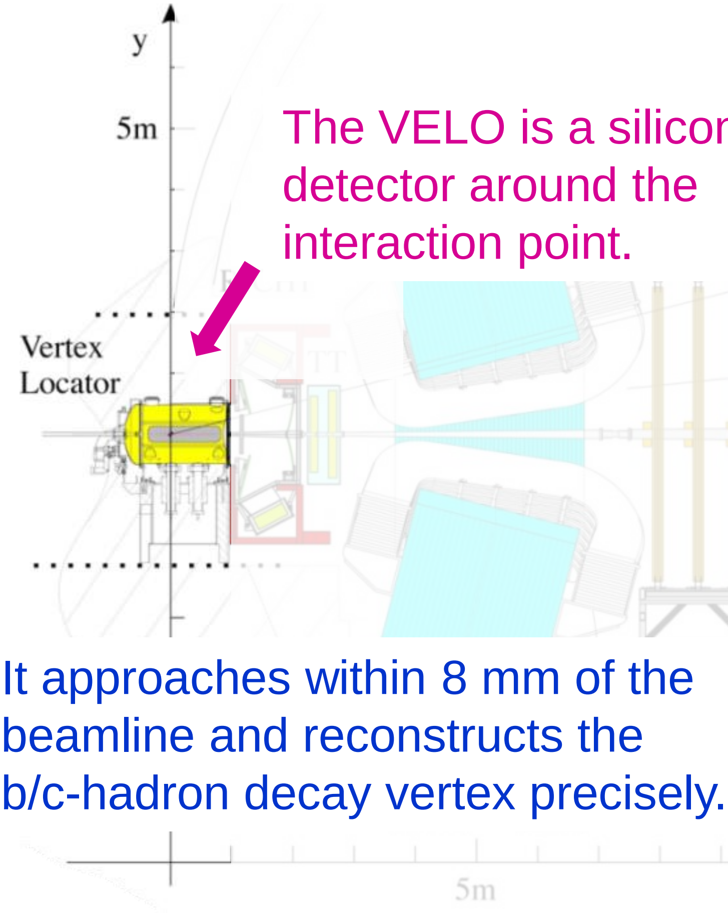
An example decay chain for a B_s meson

Not every collision contains a b/c-hadron, & not all b/c-hadron decays are of interest. We need to ‘trigger’ quickly on the collisions we care about & record them.

LHCb – a forward spectrometer for flavour physics



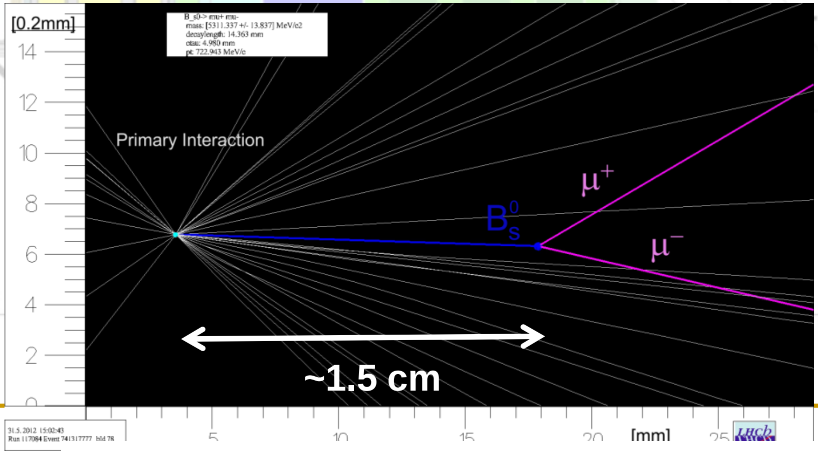
LHCb – a forward spectrometer for flavour physics



The VELO is a silicon detector around the interaction point.

It approaches within 8 mm of the beamline and reconstructs the b/c-hadron decay vertex precisely.

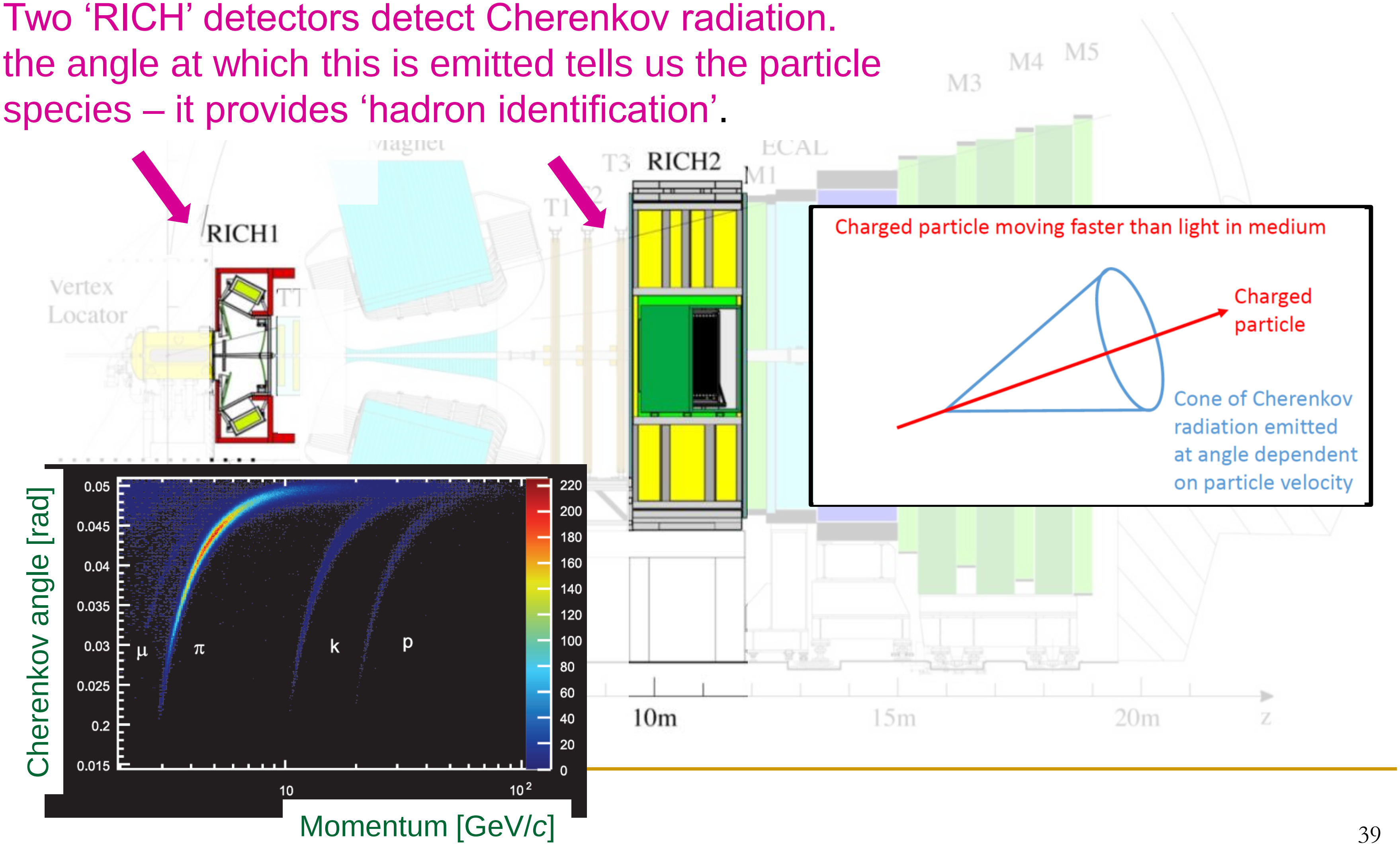
One-half of the VELO under construction



A reconstructed *b*-hadron decay vertex

LHCb – a forward spectrometer for flavour physics

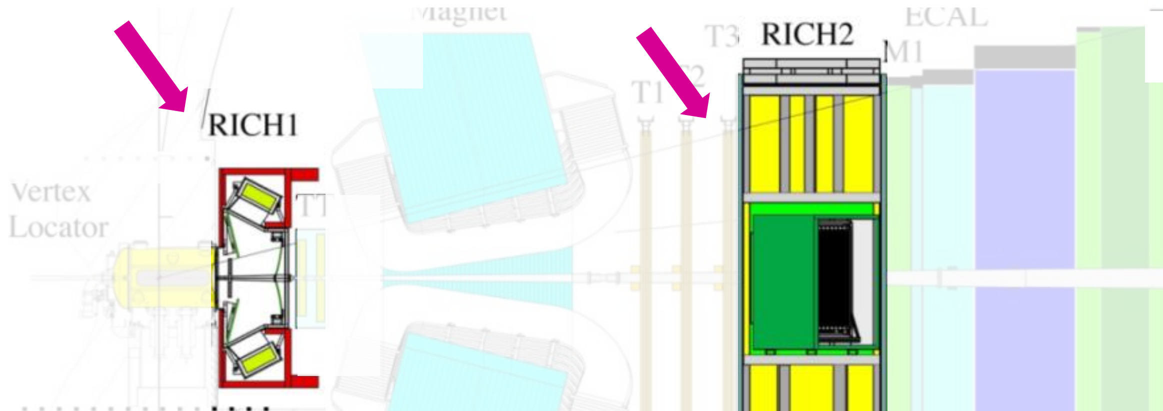
Two ‘RICH’ detectors detect Cherenkov radiation. the angle at which this is emitted tells us the particle species – it provides ‘hadron identification’.

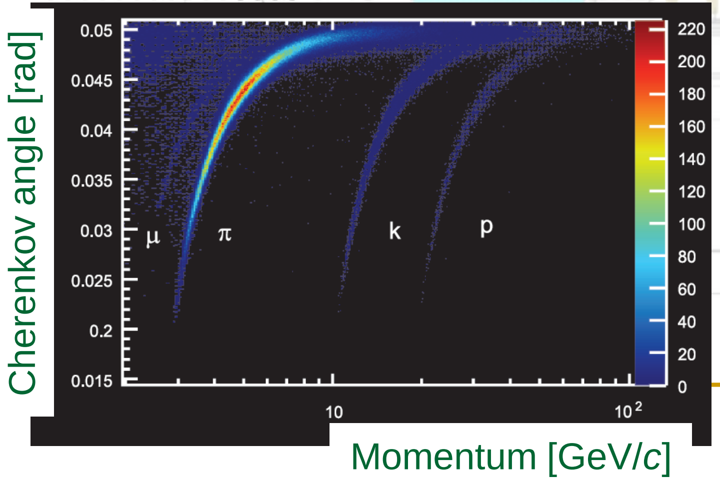


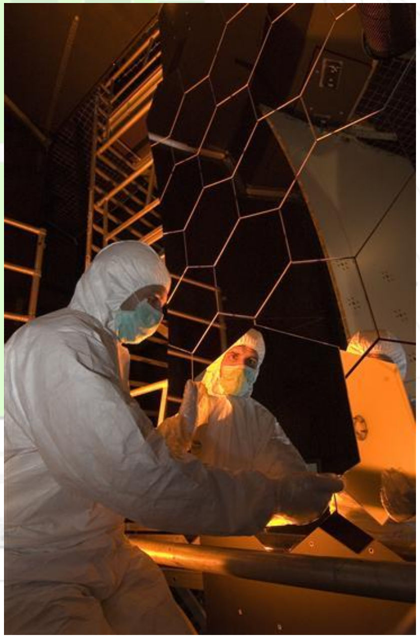
LHCb – a forward spectrometer for flavour physics

Two ‘RICH’ detectors detect Cherenkov radiation. the angle at which this is emitted tells us the particle species – it provides ‘hadron identification’.

Array of RICH photodetectors



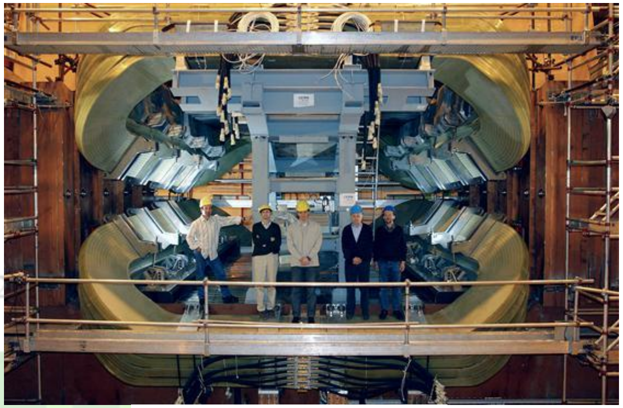




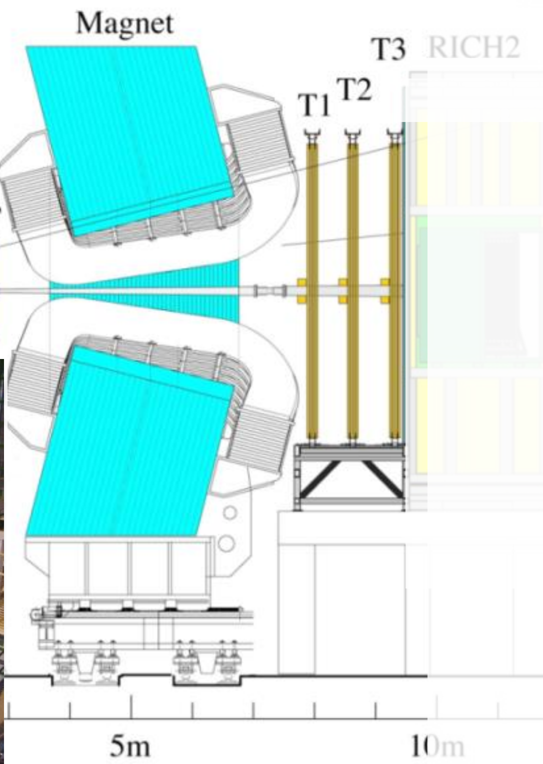
Assembling RICH 2; note the mirrors

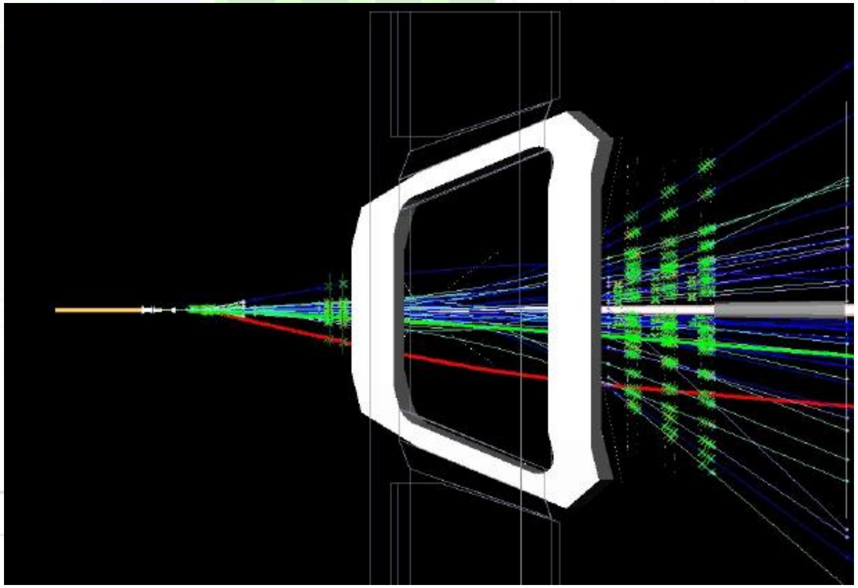
LHCb – a forward spectrometer for flavour physics

A 4 Tm dipole, and the tracking detectors reconstruct the trajectory of charged particles, and allows their momentum to be determined.



Dipole magnet

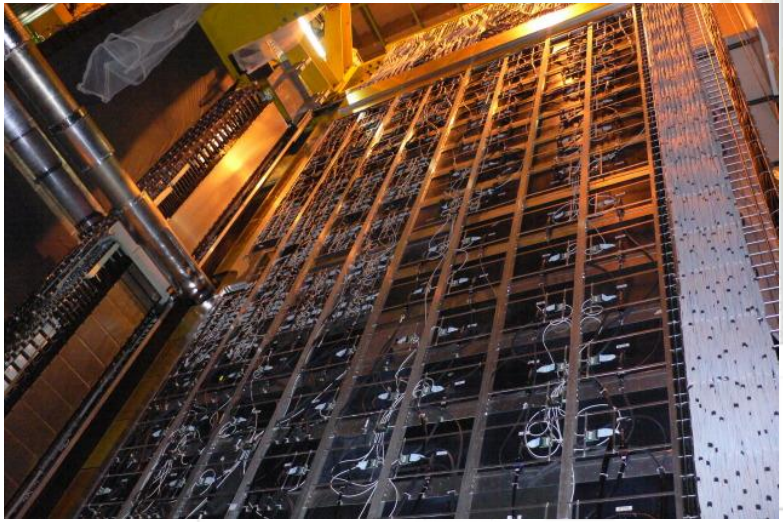




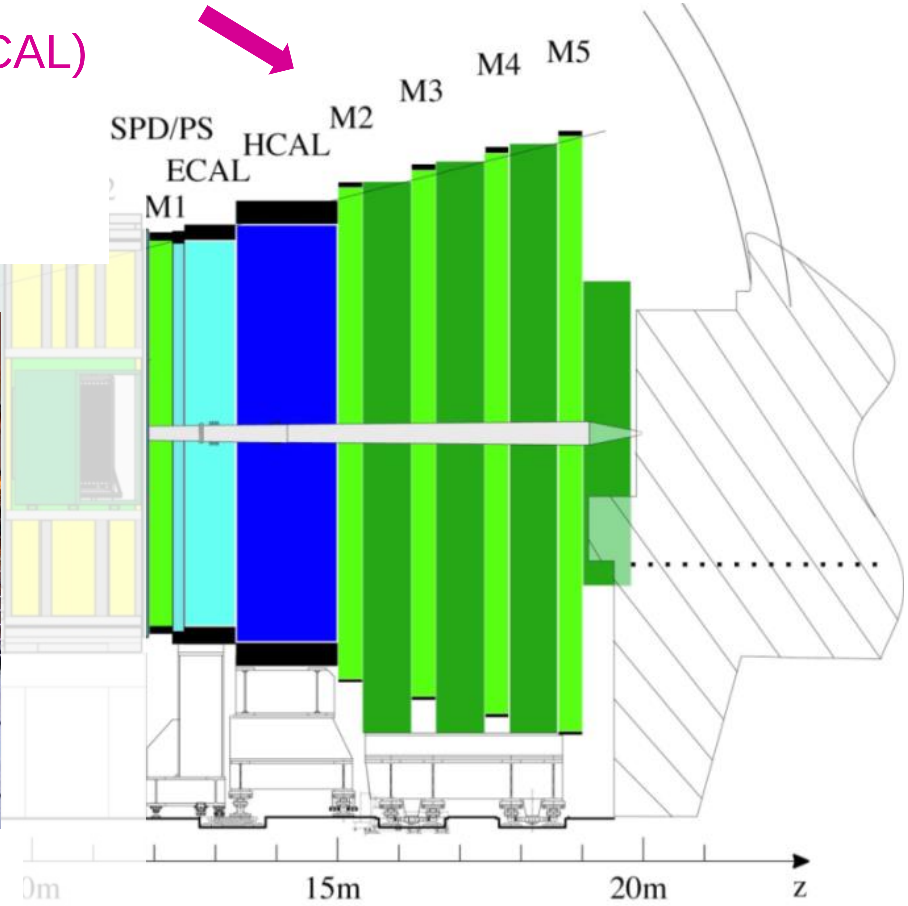
Reconstructed tracks

LHCb – a forward spectrometer for flavour physics

The calorimeter system (ECAL & HCAL) reconstructs the energy of photons, electrons and hadrons. The muon system (M1-M5) identifies muons.



Part of calorimeter system (preshower)

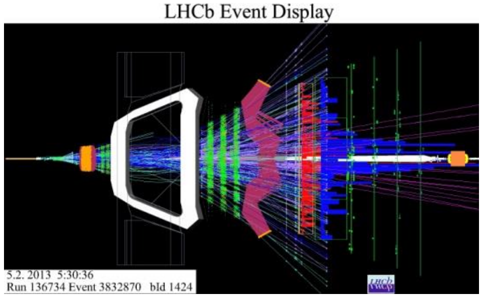


These detectors are particularly important for the role they play in the LHCb trigger

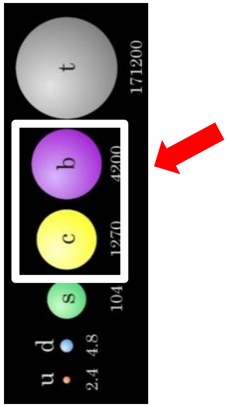
Not all collisions are equally interesting

Core business of LHCb is flavour physics, and here we can be selective

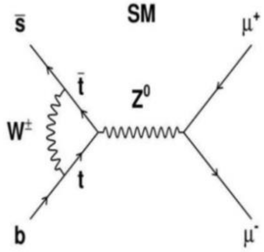
Collision rate 40 MHz
(currently a little less,
but this sets the ballpark)



b(c)-hadrons produced about once every ~150(~10) *pp* collisions



And most b/c-hadrons decays don't interest us.



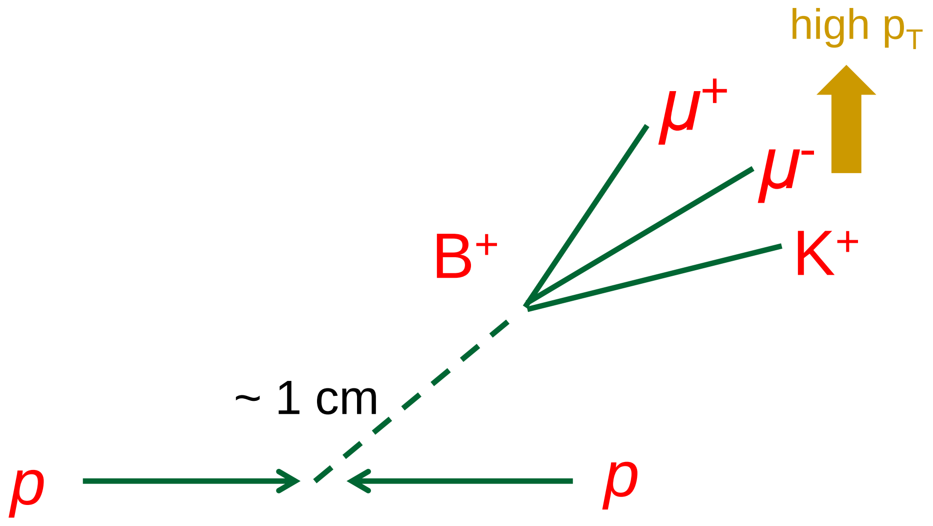
$B_s \to \mu\mu$ occurs every 4×10^{-9} B_s decays

The ones that do, occur every 10^{-3} -10^{-10} of time.

So we only save to disk the potentially interesting collisions – task of the trigger.

Triggering on charm and beauty

There exist characteristics of increasing complexity than can be searched for to determine if the collision is of interest and should be preserved for offline analysis.



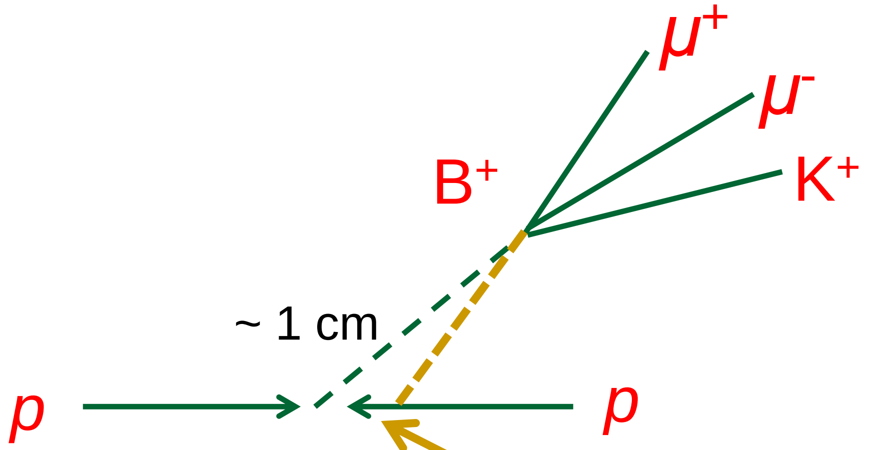
Interaction point
or ‘primary vertex’
(many other particles
produced, not shown)

1. Look for high transverse energy (E_T) or momentum (p_T) in calorimeters or muon system from decay products.

   That’s because the *b*-hadron is relatively heavy and so gives a significant ‘kick’ when it decays.

Triggering on charm and beauty

There exist characteristics of increasing complexity than can be searched for to determine if the collision is of interest and should be preserved for offline analysis.



Interaction point
or 'primary vertex'
(many other particles
produced, not shown)

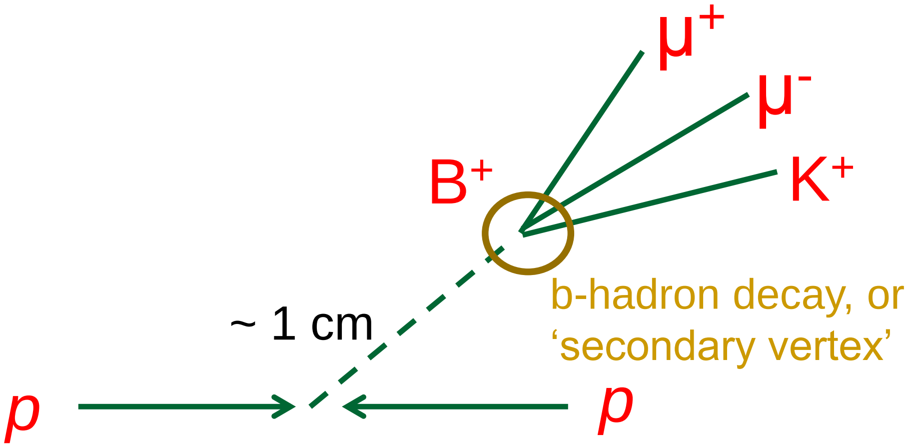
finite
impact
parameter

1. Look for high transverse energy (E_T) or momentum (p_T) in calorimeters or muon system from decay products.

2. Look for tracks with significant 'impact parameter' with respect to primary vertex.

Triggering on charm and beauty

There exist characteristics of increasing complexity than can be searched for to determine if the collision is of interest and should be preserved for offline analysis.

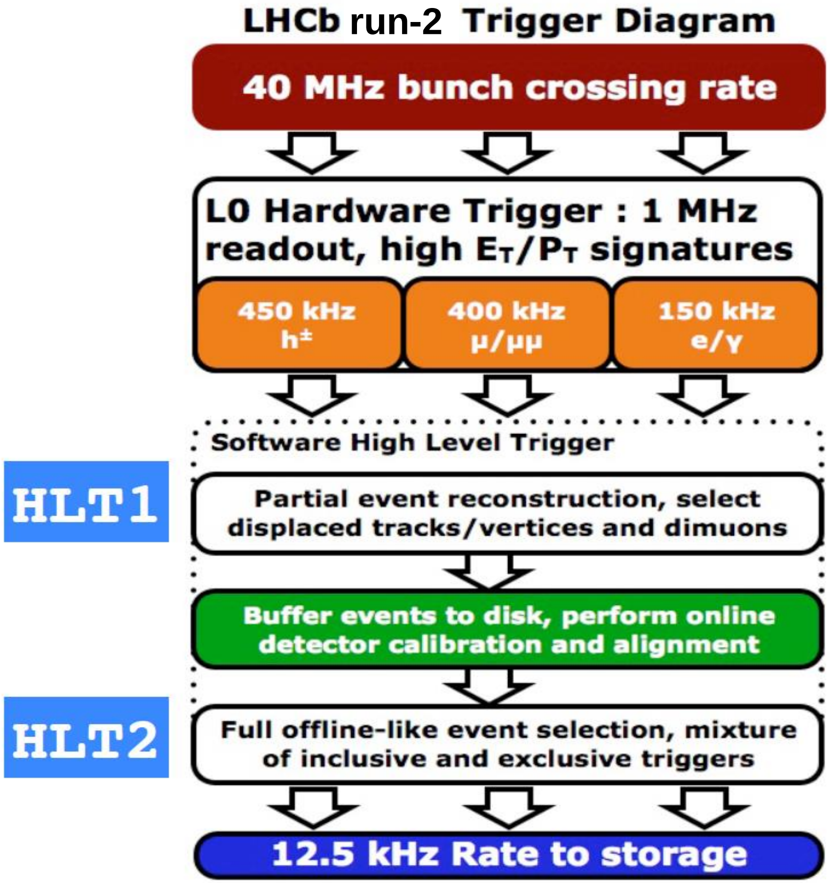


Interaction point
or 'primary vertex'
(many other particles
produced, not shown)

1. Look for high transverse energy (E_T) or momentum (p_T) in calorimeters or muon system from decay products.
2. Look for tracks with significant 'impact parameter' with respect to primary vertex.
3. Reconstruct secondary vertex and full b/c-hadron decay products.

Each successive step provides improved discrimination, but requires more information and time to execute.

The LHCb trigger



LHCb run-2 Trigger Diagram

40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures

450 kHz $h^\pm$	400 kHz $\mu/\mu\mu$	150 kHz e/γ

Software High Level Trigger

HLT1

Partial event reconstruction, select displaced tracks/vertices and dimuons

Buffer events to disk, perform online detector calibration and alignment

HLT2

Full offline-like event selection, mixture of inclusive and exclusive triggers

12.5 kHz Rate to storage

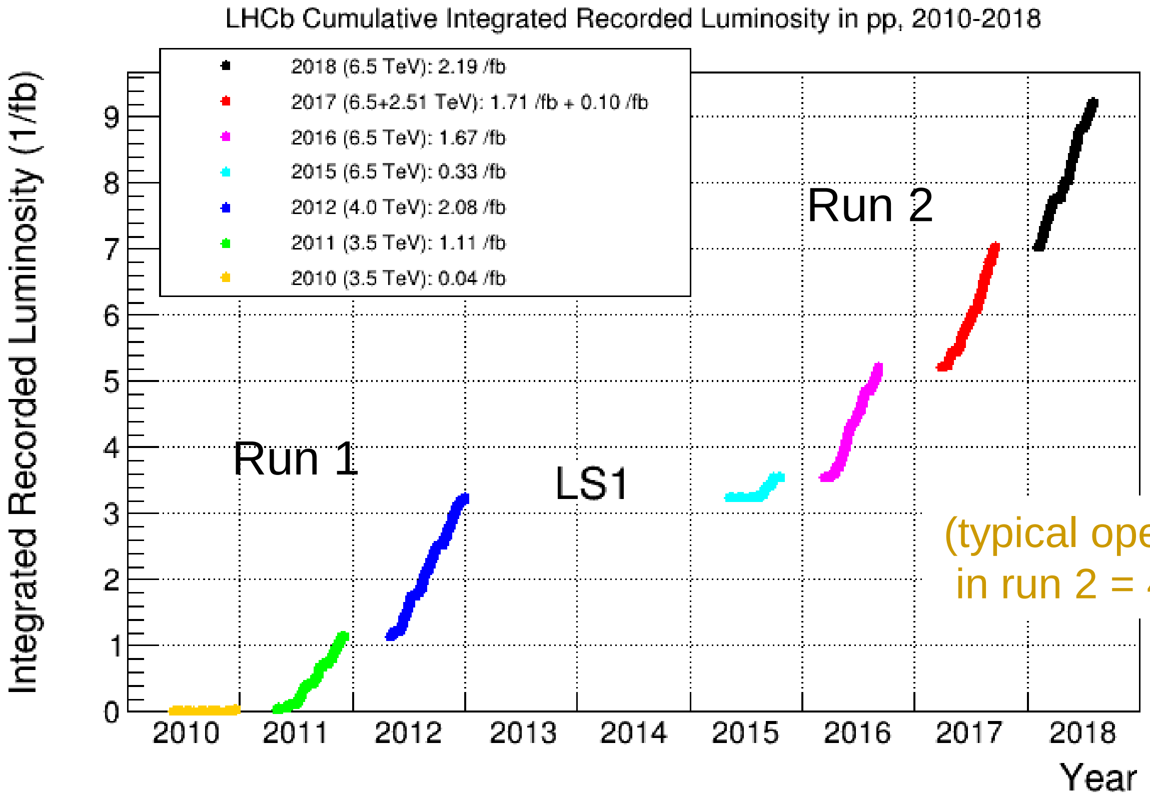
Key point

Trigger is *fully* optimised for flavour physics, with (almost) all bandwidth devoted to b and c decays.

This means that lower thresholds can be set than in other experiments, and *very* large samples collected.

LHCb – the story so far

LHCb collected ~9 fb^{-1} of data throughout runs 1 and 2 of the LHC.
(This corresponds to ~2 x 10^{13} c anti-c pairs being produced within LHCb.)



(typical operational luminosity in run 2 = 4 x 10^{32} cm^{-2} s^{-1})

Main result I shall show today derives from this full data set.

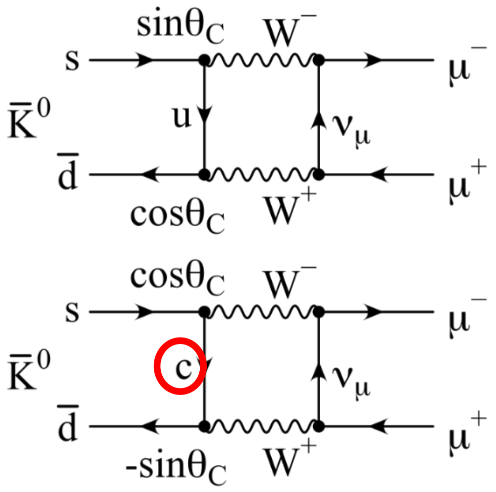
The singular history of charm physics: from fame to neglect and back again

Charm – a glorious history

Charm played a key role in the foundation of the Standard Model of particle physics.

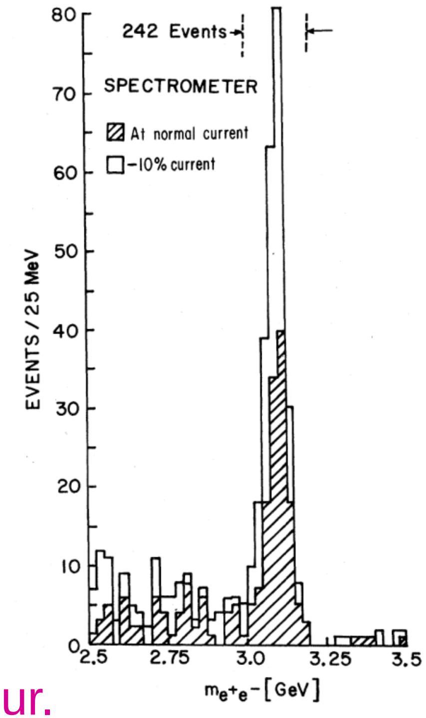
[Glashow, Iliopoulos & Maiani, PRD 2 (1970)1285]

Its existence was predicted to explain the suppression of $K_L \to \mu\mu$



This 'GIM mechanism' is central to the flavour structure of the SM.

The discovery of the J/ψ, in 1974, brought immediate acceptance of the existence of quarks.



[J.J. Aubert *et al.*, PRL 33 (1974) 1404]

[J.-E. Augustin et al., PRL 33 (1974) 1406]

But since then charm has largely fallen out of favour.

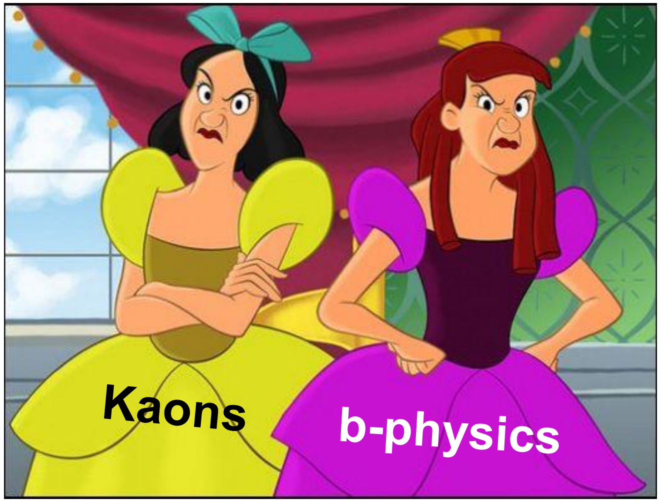
"I know she invented fire, but what has she done recently?" [I. Bigi, arXiv:0808.1773]

Charm – the years of neglect

In flavour studies, charm has certain disadvantages compared to strange & beauty:

1. Neutral meson mixing effects (see later) expected to be very small;
2. CPV effects also expected to be very small;
3. Theoretical predictions somewhat imprecise, because of hadronic effects, which are resistant to techniques developed for handling the 'light' kaon system and the 'heavy' beauty system.

Due to these reasons, and due to ~30 years of experiment confirming 1 & 2, charm became the 'Cinderella' of flavour studies, being eclipsed by her step-sisters.



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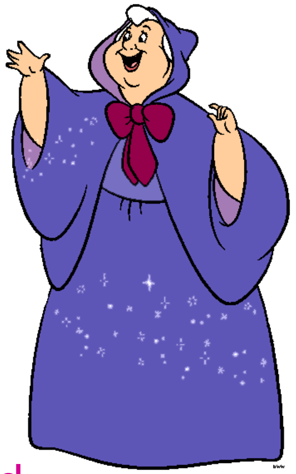
Due to these reasons, and due to ~30 years of experiment confirming 1 & 2, charm became the ‘Cinderella’ of flavour studies, being eclipsed by her step-sisters.

Yet, this neglect was always unjustified:

- Points 1 & 2 can be seen positively, as very small expectations in the Standard Model provides a low ‘background’ above which larger New Physics effects may manifest themselves.
- In contrast to strange and beauty, charm is an up-type quark, which gives it unique access to potential New Physics effects.



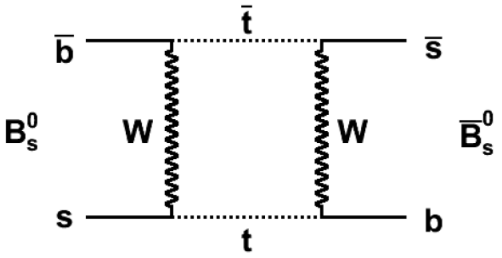
And indeed, early this century, charm’s fairy-godmother moment arrived.

Neutral meson mixing

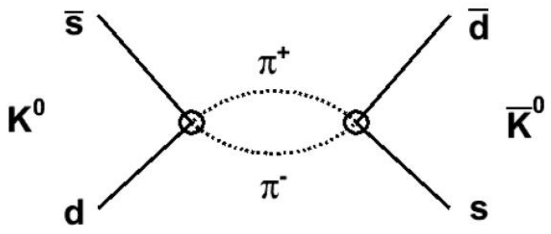
Flavour oscillations, or mixing, are an important phenomenon in neutral meson physics, and for have been established for many years in K^0, B^0 and B^0_s systems.

Caused by either:

Virtual,
short-range
(box diagrams)

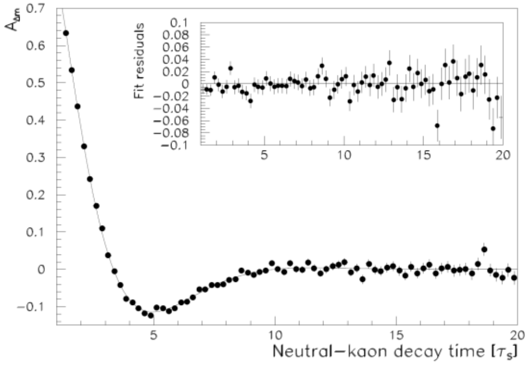


or:



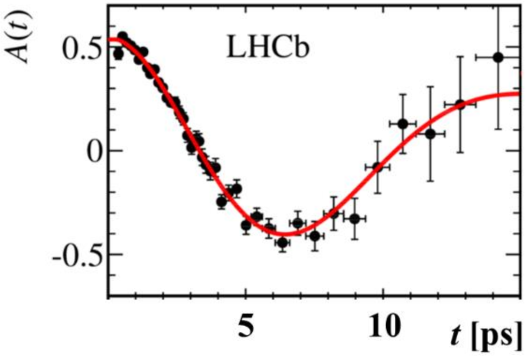
On-shell,
long-range
(common
intermediate
states)

Slow for K^0 mesons …



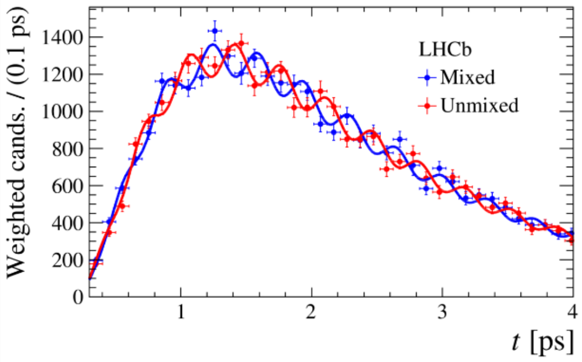
[CPLEAR, PLB 444 (1998) 38]

quicker for B^0 mesons…



[LHCb, EPJC 76 (2016) 412]

even quicker for B^0_s mesons.



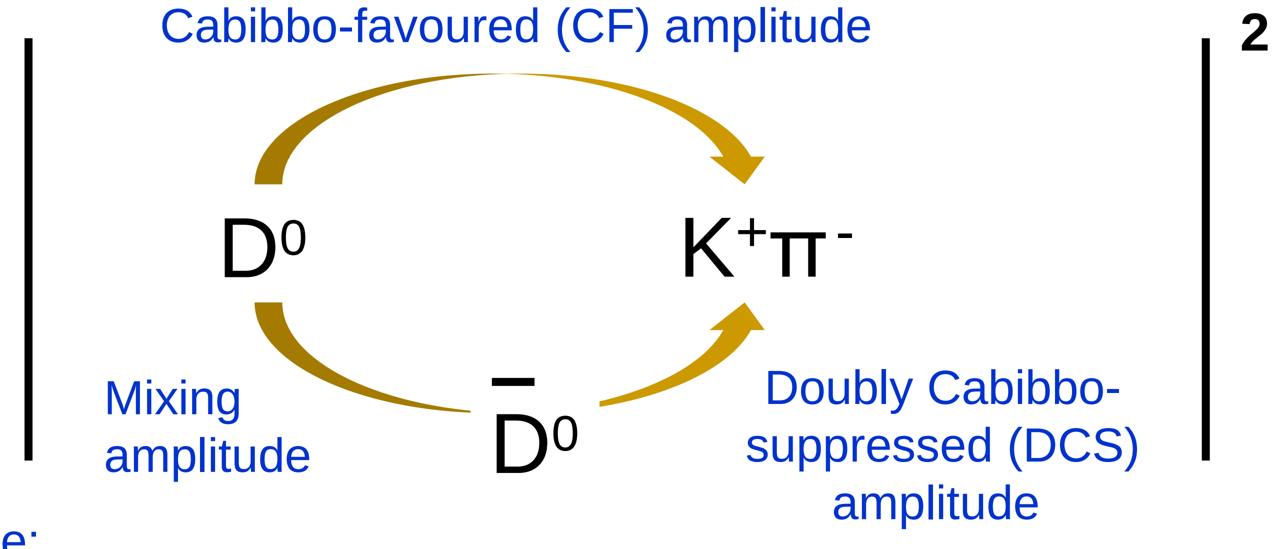
[LHCb, EPJC 79 (2019) 706]

Of great interest, because box diagrams are sensitive to possible New Physics effects, modifying the oscillation frequency, and also because the process provides several ways for CP violation to manifest itself (‘indirect CPV’).

Charm mixing with ‘wrong-sign’ $D^0 \to K^+\pi^-$

As charm mixing is small, look for mixing-decay interference effects that are linear in the amplitude, rather than pure mixing effects that are quadratic. Compare time-dep. rate of suppressed $D^0 \to K^+\pi^-$ ‘wrong sign’ decay with favoured $D^0 \to K^-\pi^+$ ‘right sign’.

Decay-time dependent rate ≈



Cabibbo-favoured (CF) amplitude

D^0

$K^+\pi^-$

Mixing amplitude

$\bar{D}^0$

Doubly Cabibbo-suppressed (DCS) amplitude

2

Normalise by right-sign decay rate:

$$R(t) \approx R_D + \sqrt{R_D}\, y' \frac{t}{\tau} + \frac{x'^2 + y'^2}{4}\left(\frac{t}{\tau}\right)^2$$

$\left|\frac{\text{DCS amp}}{\text{CF amp}}\right|^2 \sim 1/300$

Mixing–decay interference

Mixing

x’ and y’ are mixing parameters…

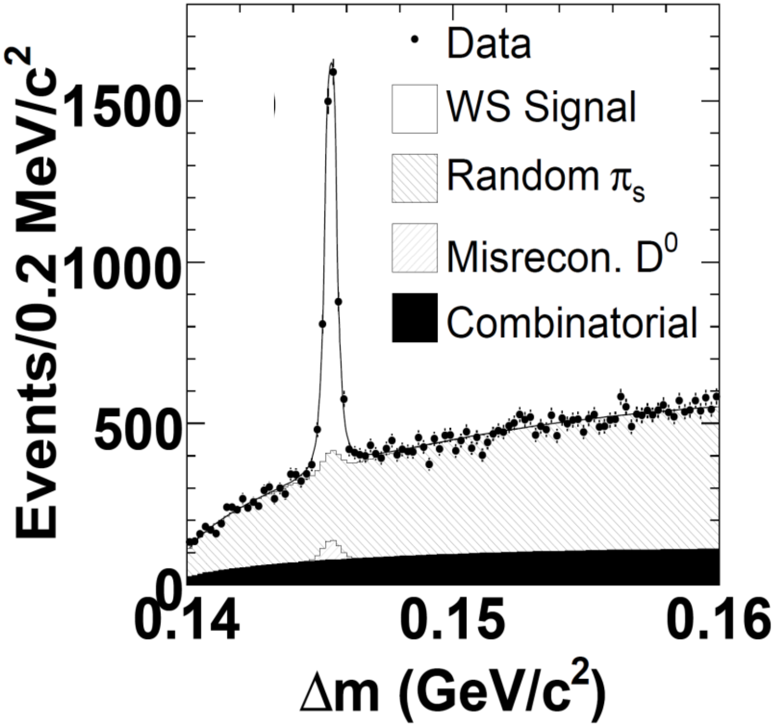
…these small, so mixing signature is a linear, not oscillatory effect.

Nothing seen in this analysis (or others) for many, many years.

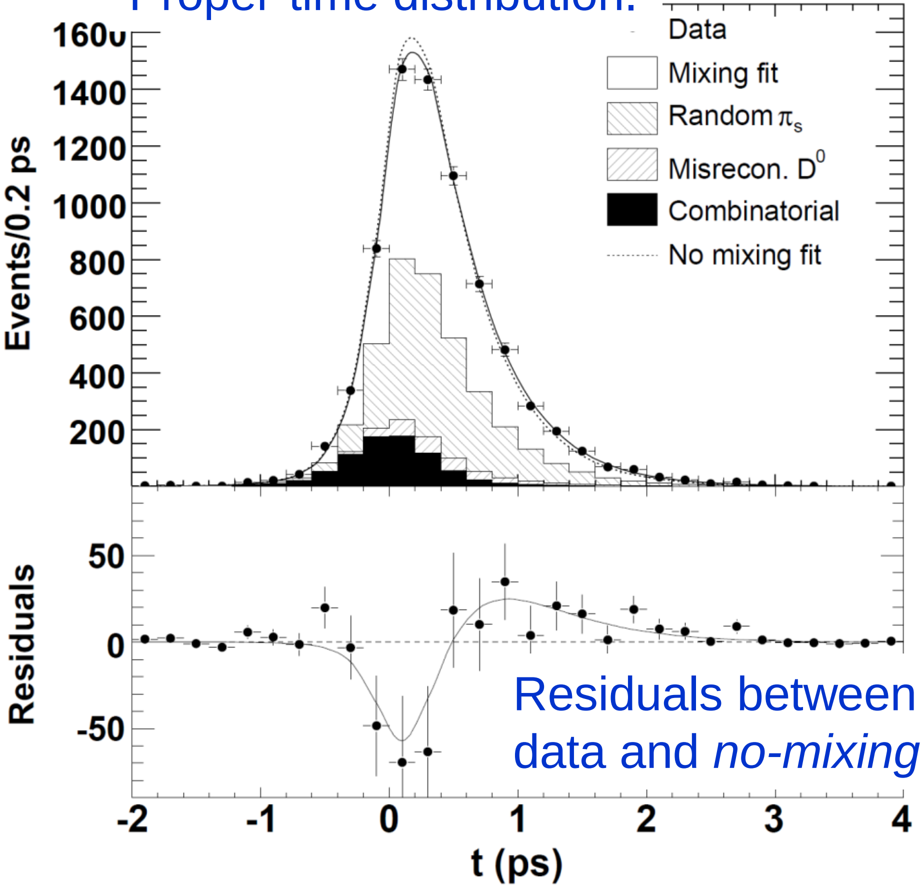
First evidence from the B-factories !

B factories produced enormous amounts of charm as well as beauty hadrons.
As data accumulated at the B-factories, a non-zero mixing signal began to emerge.

BaBar: 4k WS Kπ signal decays with 384 fb^{-1}.



Proper-time distribution.



Residuals between data and *no-mixing* fit.

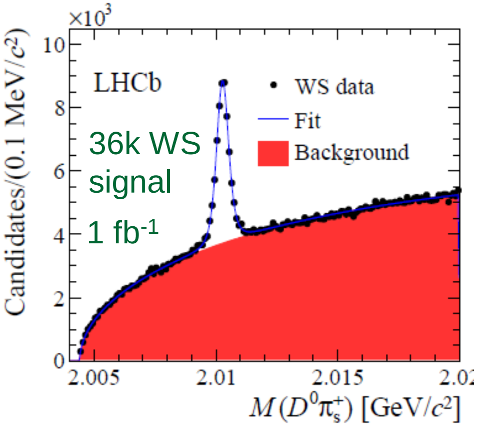
[BaBar, PRL 98 (2007) 211802]

Rise of the hadron machines

First observation of signal in single measurement required statistical muscle of hadron machines. In 2013 LHCb & CDF published first (>)>5σ measurements.

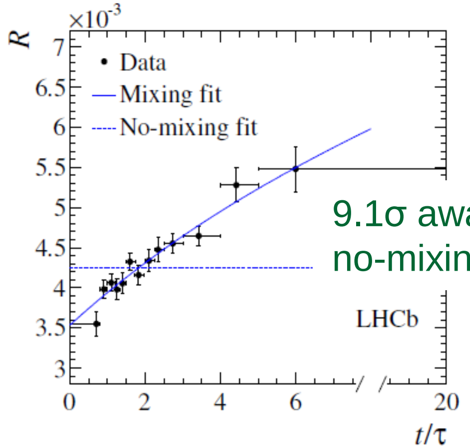
This is the WS/RS ratio vs. proper time.

Linear slope comes from mixing-decay interference.



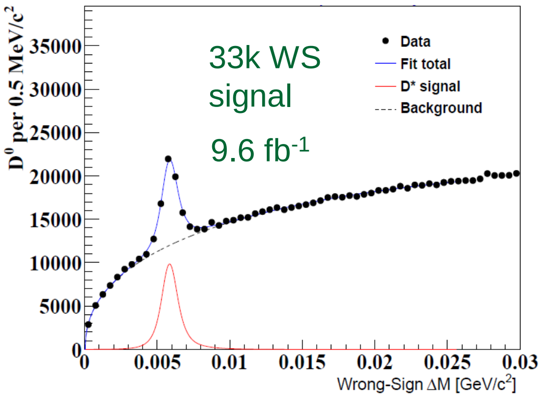
36k WS signal

1 fb^{-1}



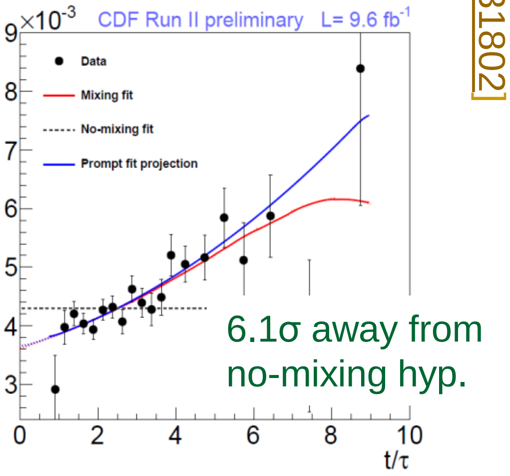
9.1σ away from no-mixing hyp.

[LHCb, PRL 110 (2013) 101802]



33k WS signal

9.6 fb^{-1}



6.1σ away from no-mixing hyp.

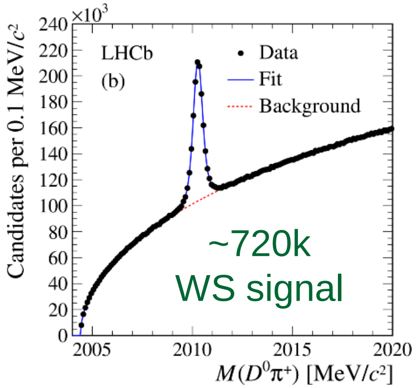
[CDF, PRL 111 (2013) 231802]

LHCb sample is a just small fraction of Run 1, but is order of magnitude larger than that of BaBar. These measurements also benefit from better time resolution.

Search for CPV in charm-mixing effects

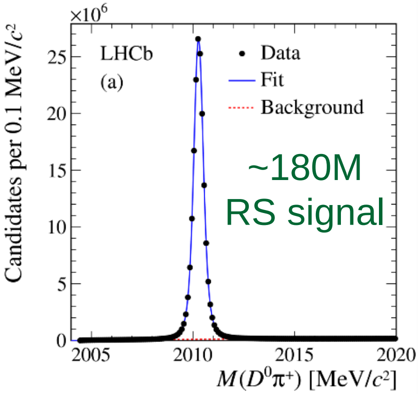
Emboldened by this discovery, physicists fell in love with charm once again. Precise searches initiated for CPV in mixing-related phenomenon ('indirect CPV'). *e.g.* perform WS/RS analysis for D^0 & D^0bar separately with Run 1 & early Run 2 data.

Study ratio of WS (*i.e.* $D^0 \to K^+\pi^-$)…

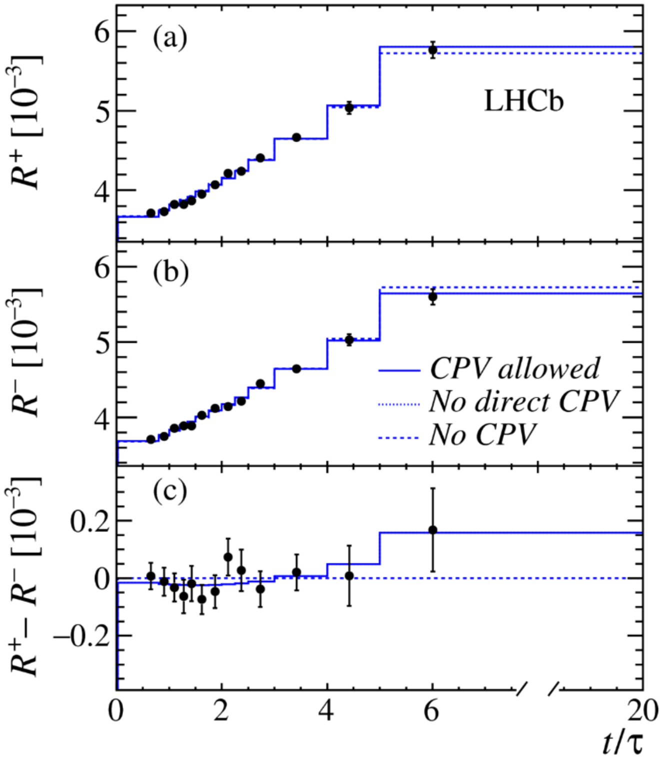


~720k WS signal

…to RS (*i.e.* $D^0 \to K^-\pi^+$), vs. proper decay time



~180M RS signal



For D^0…

…and D^0bar…

…and difference of both.

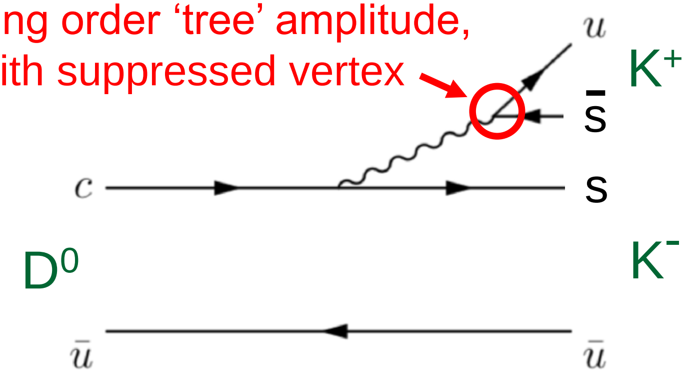
[PRD 97 (2018) 031101]

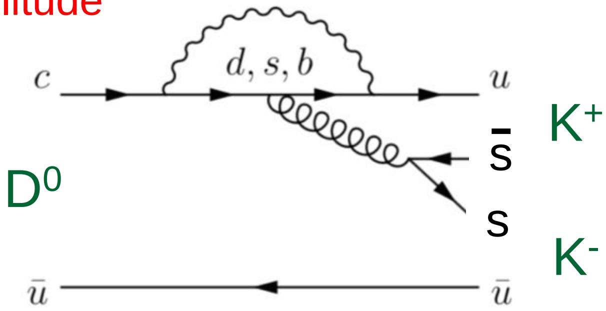
Difference flat → no sign of indirect CPV (yet). But charm again an exciting field of study !

Discovery of CP violation in charm

Searches for direct CPV in charm

Recall that to be sensitive to CPV we need (at least) two interfering diagrams, so we should pick a decays where leading tree diagram is not overwhelmingly dominant → singly Cabibbo-suppressed (SCS) decays, *e.g.* $D^0 \to K^+K^-$, $D^0 \to \pi^+\pi^-$.


Leading order 'tree' amplitude, but with suppressed vertex


Suppressed 'loop' amplitude

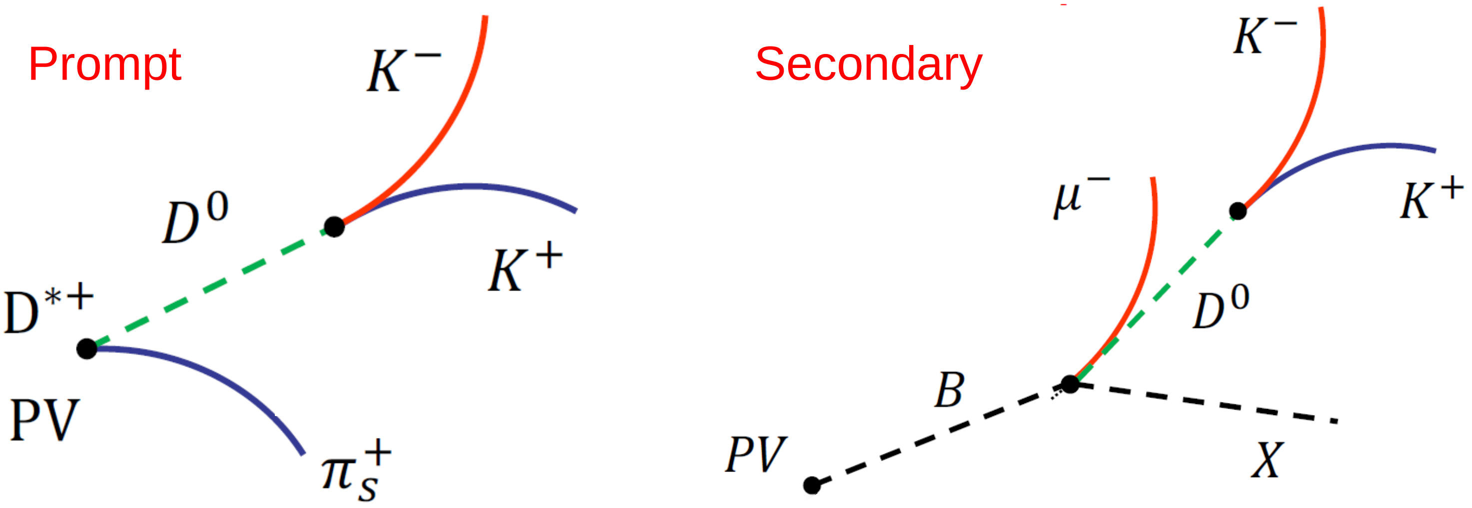
We measure an asymmetry

$$\mathcal{A}_{CP} = \frac{D^0 \to K^+K^- - \overline{D}^0 \to K^+K^-}{D^0 \to K^+K^- - \overline{D}^0 \to K^+K^-}$$

The meson is neutral, but we are interested in so-called 'direct' CPV, so measure the asymmetry integrated over all decay times (still, possible residual 'indirect' CPV coming from mixing effects must be accounted for in interpretation).

CPV measurements – practical considerations

At the LHC can exploit two production modes, prompt (*i.e.* from primary interaction / vertex (PV)), or secondary (from B decay). Prompt is more abundant.



Furthermore, in prompt case, choose to reconstruct $D^{*+} \rightarrow D^0\pi_S^+$ decays, as the charge of the 'slow pion' tags flavour (D^0 or D^0bar) - needed to construct A_{CP}.
In secondary case the tag comes from charge of muon in a semileptonic B decay.

CPV measurements – practical considerations

When probing a sub-% A_{CP}, one must worry about sources of fake asymmetry that will contribute to raw value. So for D* tagged events* & final state *f*:

$$\mathcal{A}_{\mathrm{raw}}(f) = \mathcal{A}_{CP}(f) + \mathcal{A}_{D}(f) + \mathcal{A}_{D}(\pi_{s}) + \mathcal{A}_{P}(D^{*+})$$

what we
are after

detection
asymmetry
for final state

must be zero for
decays of D^0 into
two pseudoscalars !

detection
asymmetry
for slow pion

production asymmetry:
there can be different
numbers of D^{*+} and D^{*-}
produced in acceptance

- Analogous expression for semileptonic tags

CPV measurements – practical considerations

When probing a sub-% A_{CP}, one must worry about sources of fake asymmetry that will contribute to raw value. So for D* tagged events* & final state *f*:

$$\mathcal{A}_{\mathrm{raw}}(f) = \mathcal{A}_{CP}(f) + \cancel{\mathcal{A}_D(f)} + \mathcal{A}_D(\pi_s) + \mathcal{A}_P(D^{*+})$$

what we are after

detection asymmetry for slow pion

production asymmetry: there can be different numbers of D^{*+} and D^{*-} produced in acceptance

Consider A_{raw} for two final states: K^+K^- and $\pi^+\pi^-$:

- A_{CP} is not expected to be the same, as direct CP violation is final-state specific (indeed the naïve expectation if hadronic physics works just the same for both is that $A_{CP}(KK) = - A_{CP}(\pi\pi)$);
- But $A_D(\pi_S)$ & $A_P(D^{*+})$ is independent of final state, in given phase space region.

So measure ΔA_{CP} , the *difference* between the two raw asymmetries:

$$\Delta\mathcal{A}_{CP} \equiv \mathcal{A}_{raw}(KK) - \mathcal{A}_{raw}(\pi\pi) = \mathcal{A}_{CP}(KK) - \mathcal{A}_{CP}(\pi\pi)$$

Event selection

Reconstruction performed online [Comput. Phys. Commun. 208 (2016) 35]

- ❑ Using the so-called Turbo stream

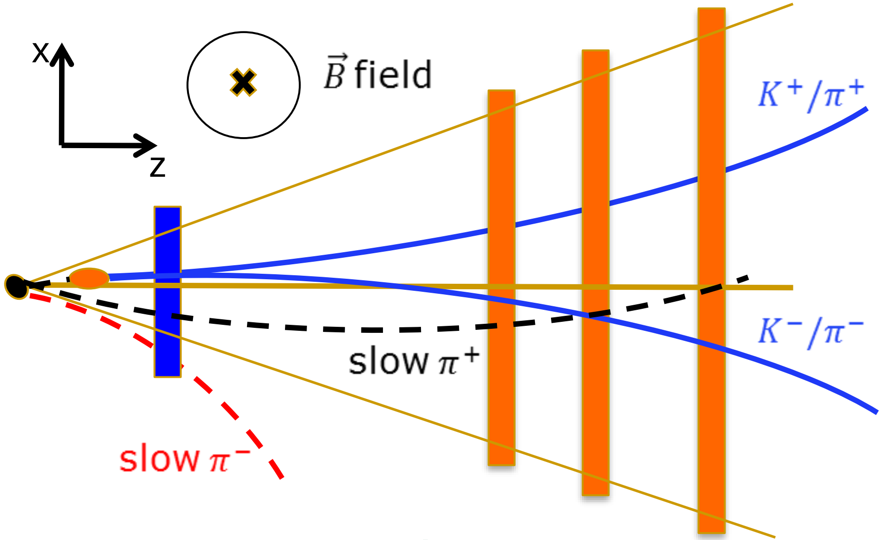
Requirements placed on:

- ○ Quality and particle identification information of tracks
- ○ p_{T} of tracks and D^0
- ○ D^0 vertex quality
- ○ Impact parameter of the D^0
- ○ $m_{corr} = \sqrt{m(D^0\mu) + p_T'(D^0\mu)}$+ $p_T'(D^0\mu)$ for the μ-tagged analysis
- ○ $m(D^0)$ for prompt and $m(D^0\mu)$ for the μ-tagged analysis

μ-tagged candidates are further filtered with a multivariate classifier using as inputs vertex quality, D^0 flight distance, impact parameter and p_{T} of D^0 decay products.

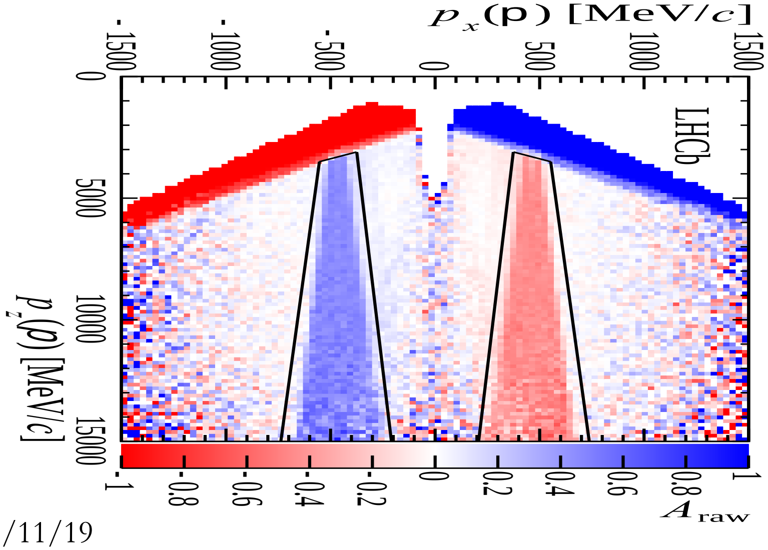
Fiducial selection

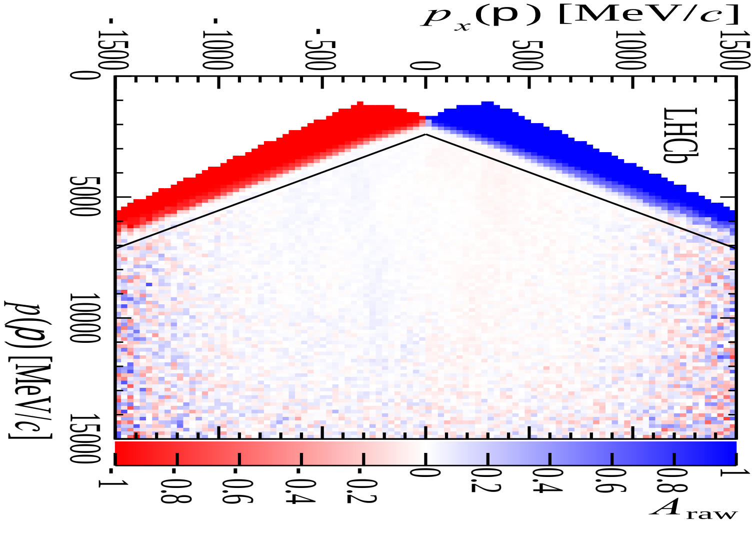
For specific regions of phase space, the tagging pion or muon of a specific charge is kicked out from the detector acceptance by the magnetic field.



In such regions very large values of the raw asymmetries are found

→ remove kinematic regions where the raw asymmetry is large.

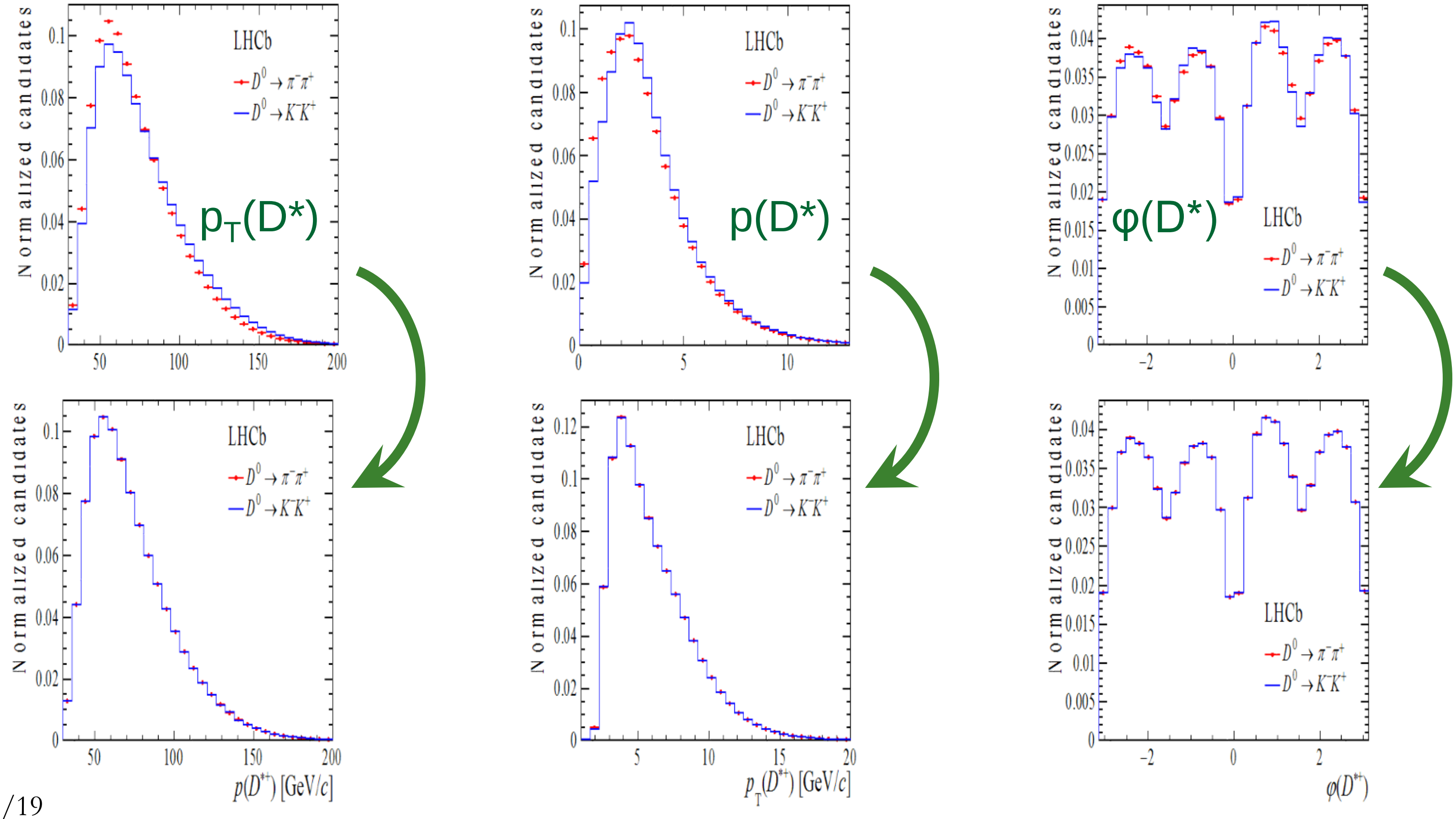




Kinematic re-weighting

Event selection induces small differences in kinematics between $D^0 \to KK$ & $D^0 \to \pi\pi$.

To achieve perfect cancellation of detection & production asymmetries in ΔA_{CP} it is necessary to re-weight KK sample to $\pi\pi$ kinematics. *e.g.* for π tagged sample:

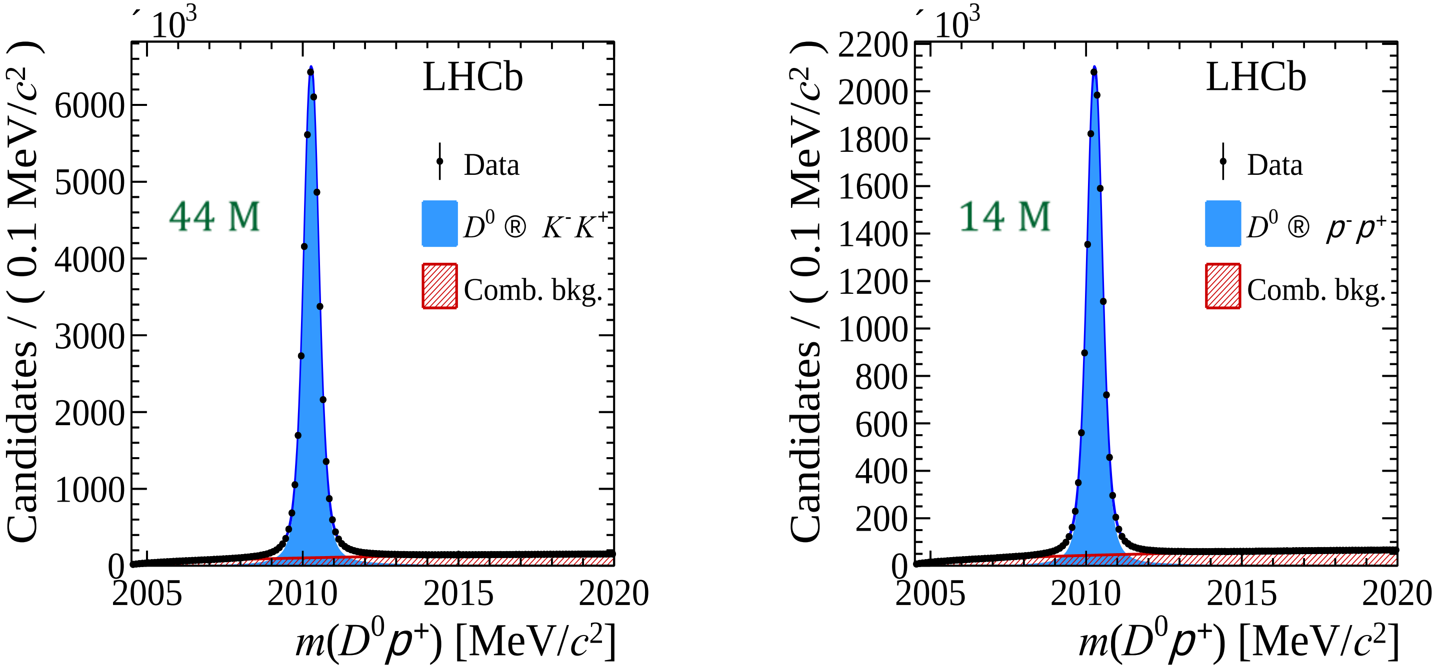


Determination of A_{raw}

In the π-tagged analysis fit the $m(D^0\pi)$ distributions corresponding to the two flavour tags.

$$A_{\mathrm{raw}}(f) = \frac{N(D^0 \to f) - N(\overline{D}^0 \to f)}{N(D^0 \to f) + N(\overline{D}^0 \to f)}$$

About 44 million signal decays for K^-K^+ and 14 million for $\pi^-\pi^+$ are used.

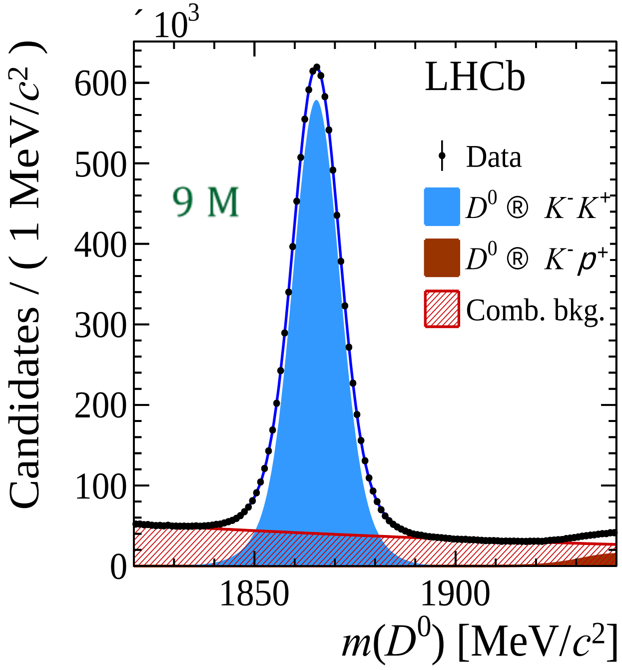


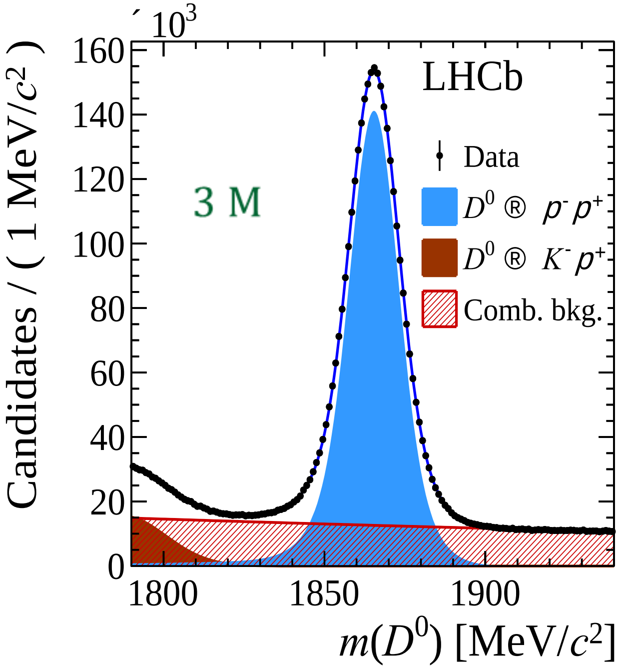
Determination of A_{raw}

In the μ-tagged analysis fit the $m(D^0)$ distributions corresponding to the two flavour tags.

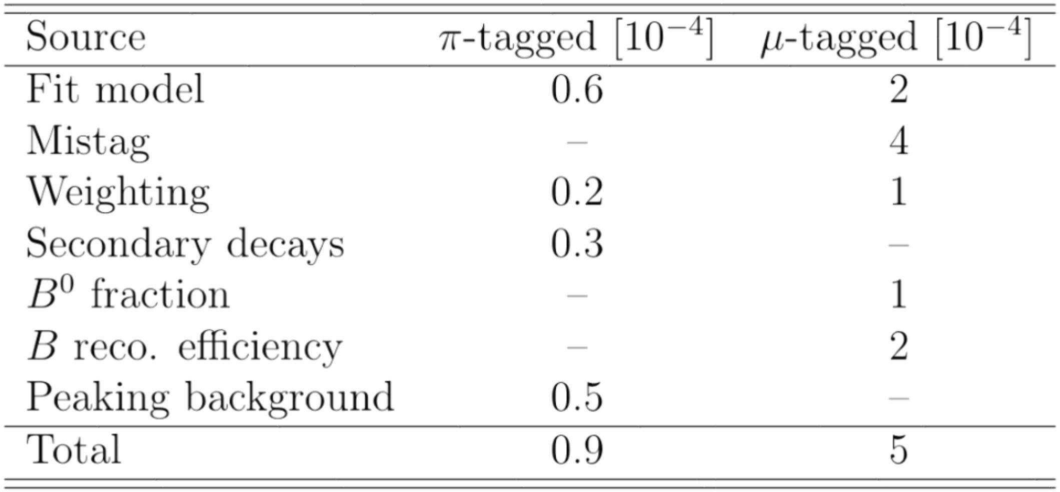
$$A_{\text{raw}}(f) = \frac{N(D^0 \to f) - N(\overline{D}^0 \to f)}{N(D^0 \to f) + N(\overline{D}^0 \to f)}$$

About 9 million signal decays for K^-K^+ and 3 million for $\pi^-\pi^+$ are used





Systematic uncertainties



Source	π-tagged $[10^{-4}]$	μ-tagged $[10^{-4}]$
Fit model	0.6	2
Mistag	–	4
Weighting	0.2	1
Secondary decays	0.3	–
B^0 fraction	–	1
B reco. efficiency	–	2
Peaking background	0.5	–
Total	0.9	5

π-tagged dominated by:

Fit model

Evaluated by generating pseudo-experiments and fitting alternative models;

Physics backgrounds

e,g. $D^0 \to K^-\pi^+\pi^0$, $D^0 \to \pi^- l^+ \nu_l$ peaking in $m(D^0\pi)$

Potential bias estimated by measuring the yields and asymmetries of backgrounds from the $m(D^0)$ distributions.

μ-tagged dominated by

Mistag (wrong muon)

Evaluated on the $B \to D^0(\to K^-\pi^+)\mu X$ control sample.

Systematic uncertainties

Source	π-tagged $[10^{-4}]$	μ-tagged $[10^{-4}]$
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Potential bias estimated by measuring the yields and asymmetries of backgrounds from the $m(D^0)$ distributions.

μ-tagged dominated by

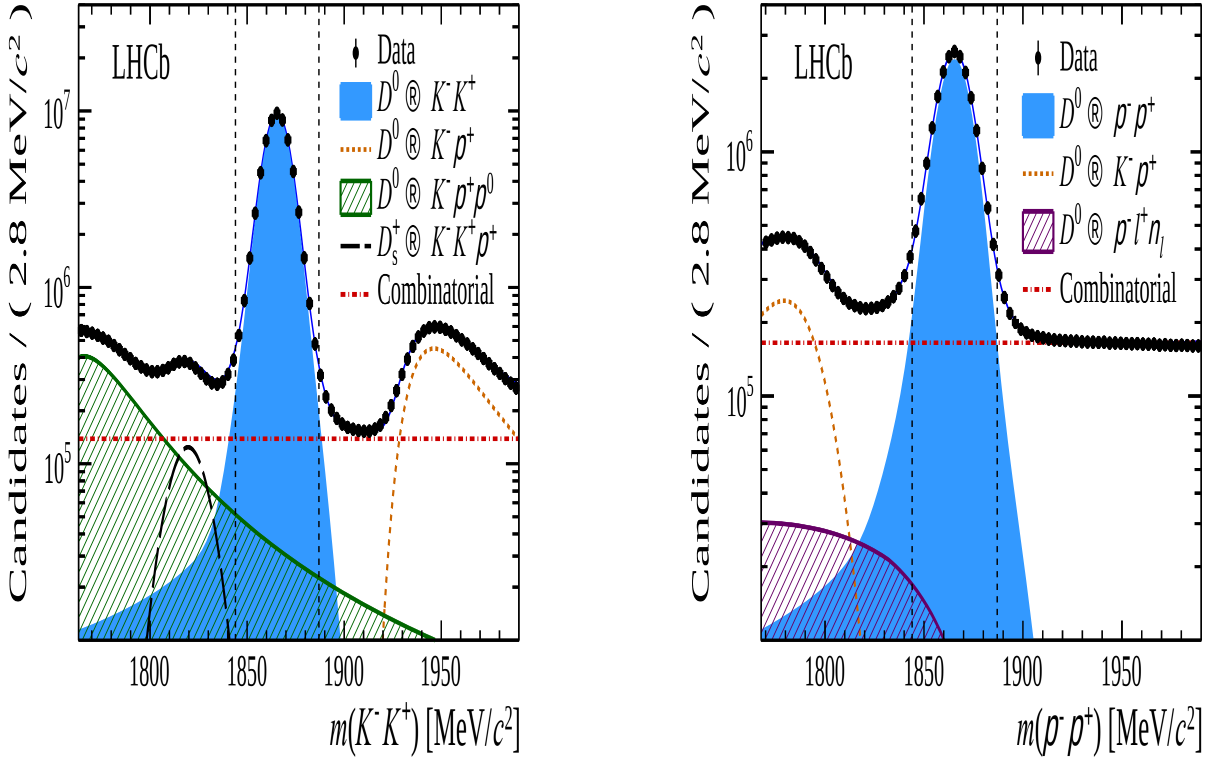
Mistag (wrong muon)

Evaluated on the $B \to D^0(\to K^-\pi^+)\mu X$ control sample.

Most systematic uncertainties are assigned from data studies, and in all cases are <(<) statistical.

Peaking backgrounds

In the π-tagged analysis, the yields and raw asymmetries of $D^0 \to K^-\pi^+\pi^0$ and $D^0 \to \pi^- l^+ \nu_l$ background decays are measured by fits to $m(K^-K^+)$ and $m(\pi^-\pi^+)$ mass spectra and extrapolated to the signal region.



Background from secondary decays

B→D*X decays contaminate the sample of prompt D* mesons produced in the primary vertex, which are used in the π-tagged analysis.

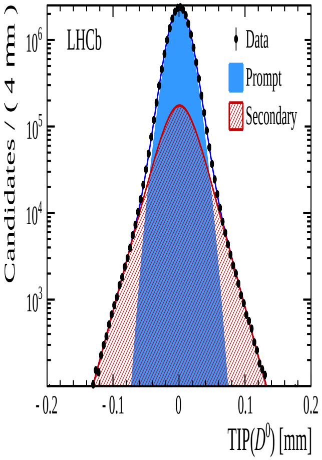
The fraction of secondary mesons is determined by fitting the distribution of the D^0 impact parameter in the plane transverse to the beam (TIP).

$$\mathrm{TIP} = \frac{\hat{n}_z \wedge \vec{p}}{|\hat{n}_z \wedge \vec{p}|} \cdot (\vec{x}_{\mathrm{DV}} - \vec{x}_{\mathrm{PV}})$$

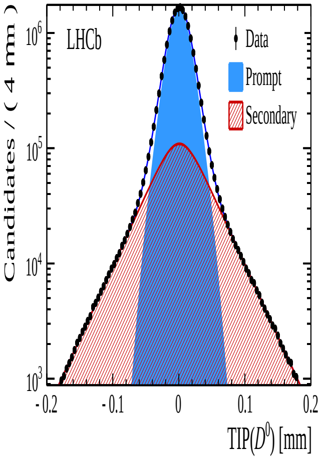
By knowing the amount of contamination, a systematic uncertainty on ΔA_{CP} can be assessed precisely.

Study performed in bins of $t/\tau(D^0)$ as background depends on decay time.

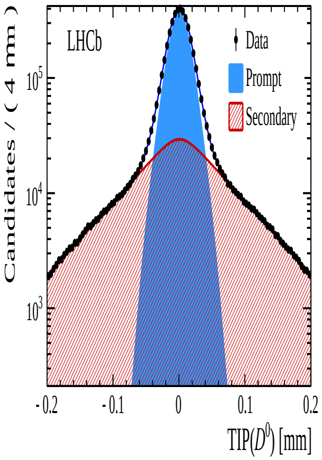
t/τ<1.5



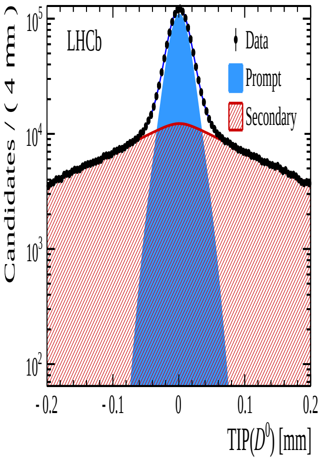
1.5<t/τ<3.0



3.0<t/τ<4.5



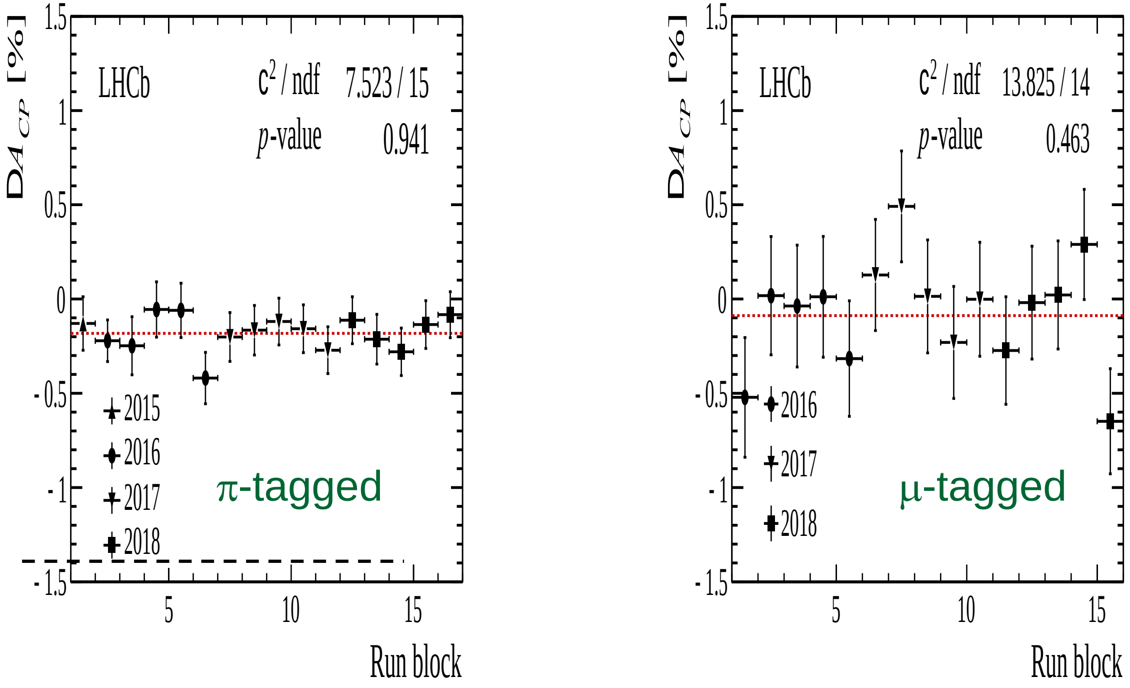
t/τ>4.5



Stability of the results

Thorough checks of how stable the result (that I have not yet told you!) is across the data set have been performed.

For example, sample split according to data taking year & magnet polarity:

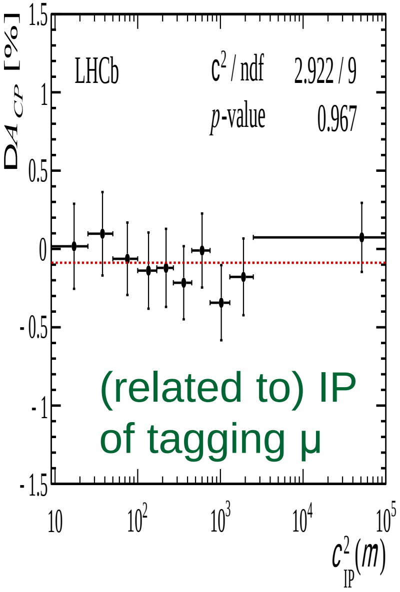


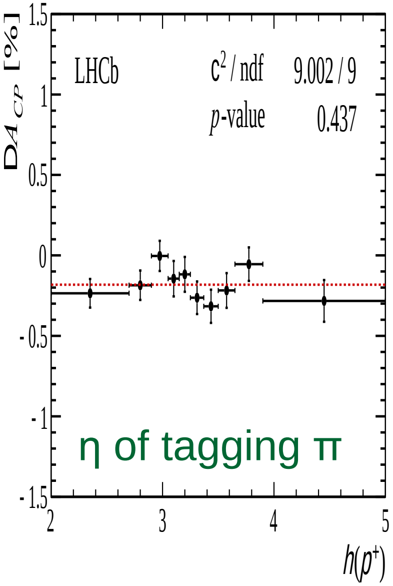
No evidence seen for any dependencies.

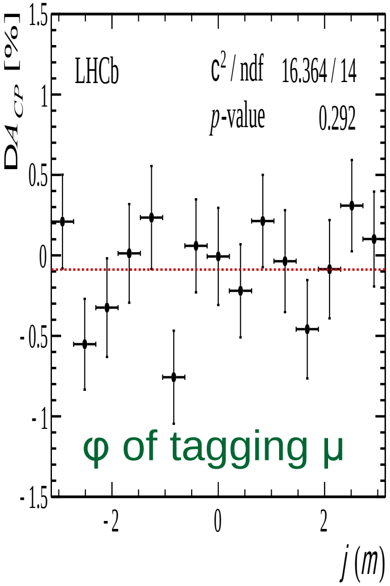
Stability of the results

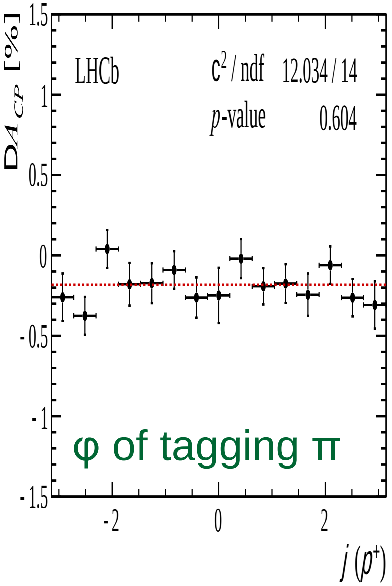
ΔA_{CP} measured as a function of various kinematic & geometrical variables.

Some examples (from many):









No evidence seen for any dependencies.

Cross-checks

Furthermore, several cross-checks have been performed.

In all cases, variations have been found to be compatible with statistical fluctuations on ΔA_{CP}, when measured with:

- ❑ Alternative PID cuts
- ❑ Alternative fiducial cuts
- ❑ Alternative hardware trigger requirements
- ❑ …

Measurement performed using background events in place of signal events, where one expects zero asymmetry → $\Delta A_{bkg} = (-2.3 \pm 4.1) \times 10^{-4}$.

Full featured fit replaced by simple-minded event counting after background subtraction → variations well below the overall systematic uncertainty.

ΔA_{CP} results

Run 2 data (6 fb^{-1}) [PRL 122 (2019) 211803] :

$$\Delta A_{CP}^{\pi-\text{tagged}} = [-18.2 \pm 3.2\,(\text{stat.}) \pm 0.9\,(\text{syst.})] \times 10^{-4}$$

$$\Delta A_{CP}^{\mu-\text{tagged}} = [-9 \pm 8\,(\text{stat.}) \pm 5\,(\text{syst.})] \times 10^{-4}$$

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Compatible with Run 1 results [JHEP 07 (2014) 041; PRL 116 (2016) 191601].

Combination of Run 1 and Run 2 results yields:

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

ΔA_{CP} results

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Combination of Run 1 and Run 2 results yields:

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

CP violation observed at $\boldsymbol{5.3\sigma}$!!

50+ years of CP violation

<u>1956</u>
Parity violation
T. D. Lee,
C. N. Yang and
C. S. Wu *et al.*

<u>1963</u>
Cabibbo Mixing
N. Cabibbo

<u>1964</u>
Strange particles:
***CP* violation in K**
meson decays
J. W. Cronin,
V. L. Fitch *et al.*

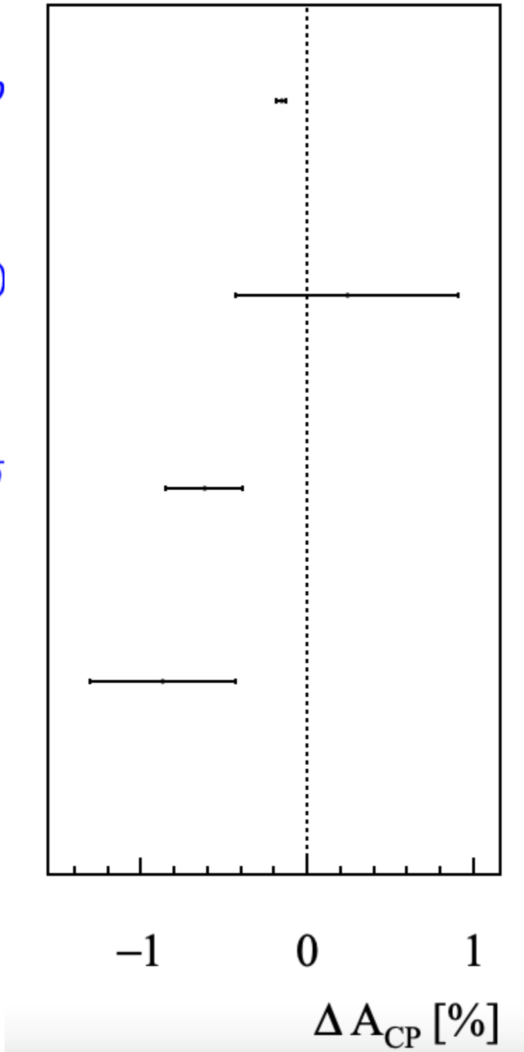
<u>1973</u>
The CKM matrix
M. Kobayashi and
T. Maskawa

<u>2001</u>
Beauty particles:
***CP* violation in B^0**
meson decays
BaBar and Belle
collaborations

<u>2019</u>
Charm particles:
***CP* violation in D^0**
meson decays
LHCb collaboration

TODAY

Experimental status



9 fb^{-1} at $\sqrt{s} = 7, 13$ TeV pp — LHCb, PRL 122 (2019) 211803

385.8 fb^{-1} at $\Upsilon(4S)$ — BaBar, PRL 100 (2008) 061803

9.7 fb^{-1} at $\sqrt{s} =$ 1.96 TeV $p\bar{p}$ — CDF, PRL 109 (2012) 111801

976 fb^{-1} at $\Upsilon(4S)$ — Belle, preliminary [arXiv:1212.1975]

Does result agree with the Standard Model ?

Hard to say. Hadronic effects mean that calculations are very difficult in the charm system. Most theorists had expected a lower value.

e.g. prediction using QCD sum rules

- A. Khodjamirian and A. Petrov [Phys. Lett. B774 (2017) 235]
- $|\Delta A_{CP}| \leq (2.0 \pm 0.3) \times 10^{-4}$
- Prediction smaller than the measured value by a factor of 7!

But few would say that observed value is *impossible* within the SM (*e.g.* QCD sum rules work well in B physics, but could break down for charm).

Far too early to be invoking non-SM explanations, however:

- Light Z′: M. Chala, A. Lenz, A. V. Rusov & J. Scholtz [JHEP 1907 (2019) 161]
- Various scenarios with heavy new particles: A. Dery & Y. Nir [arXiv:1909.11242]

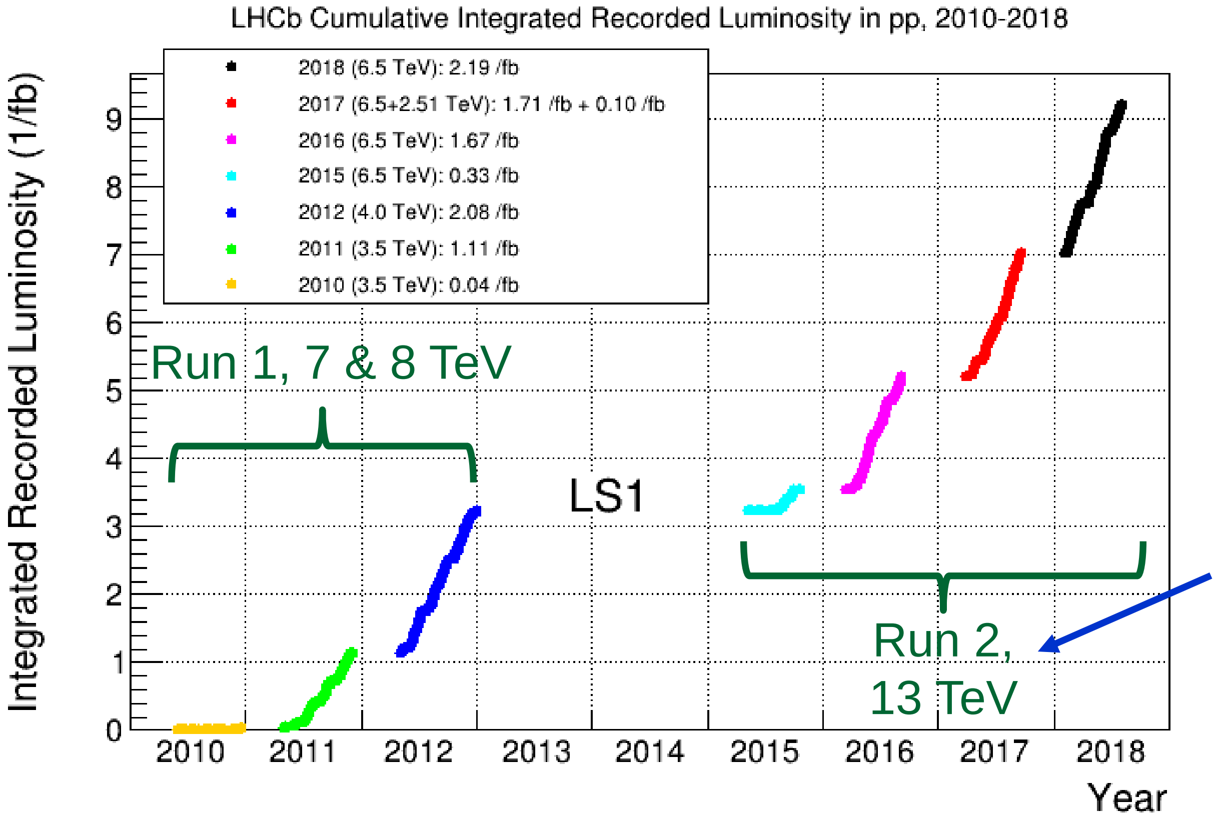
Best hope of progress is experimental:

- Individual measurements of $A_{CP}(KK)$ and $A_{CP}(\pi\pi)$;
- Make measurements in other modes where less, *e.g.* $A_{CP}(D^+ \rightarrow \pi^+\pi^0)$, or more, *e.g.* $A_{CP}(D^0 \rightarrow K_S K_S)$ CPV is expected in SM;
- Intensify search for CPV in mixing-related observables.

Charm studies – the coming decade & beyond

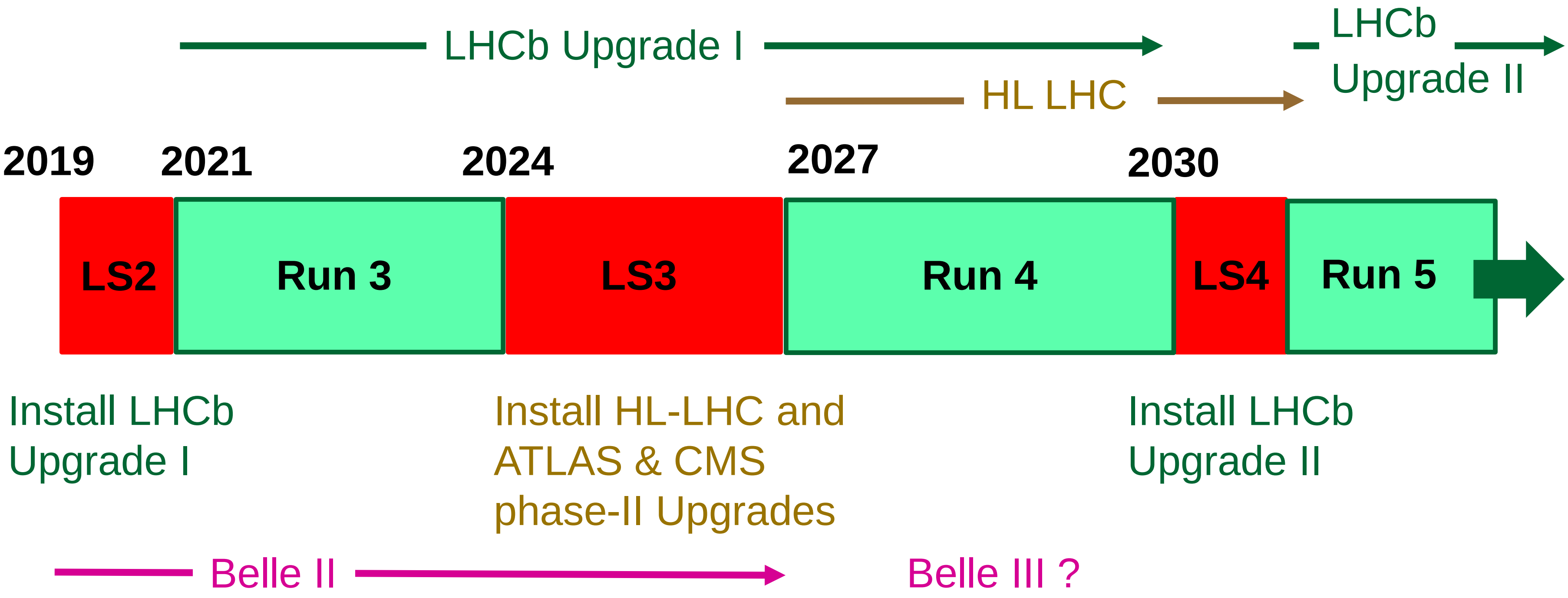
Thorough exploitation of the existing data set

First things first – although the full data set has been used to measure ΔA_{CP} no other CPV studies have yet been published (either concerning charm or beauty) that make use of the complete sample. Surprises are guaranteed !



Largely unexploited. And it is here that the bulk of the statistics lie, thanks to 2x higher cross-section and to improved trigger.

The LHC schedule – current planning



LHCb Upgrade I

HL LHC

LHCb Upgrade II

2019 2021 2024 2027 2030

LS2 | **Run 3** | **LS3** | **Run 4** | **LS4** | **Run 5**

Install LHCb Upgrade I

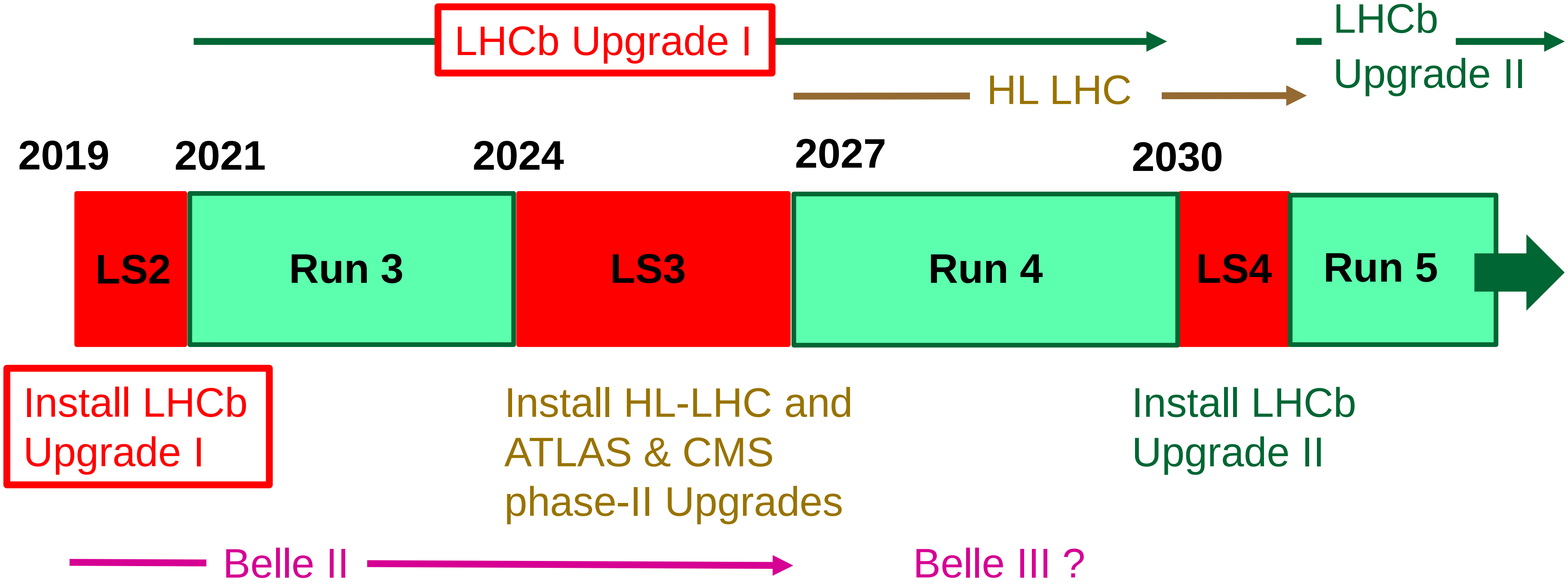
Install HL-LHC and ATLAS & CMS phase-II Upgrades

Install LHCb Upgrade II

Belle II

Belle III ?

The LHC schedule – current planning



LHCb Upgrade I

HL LHC

LHCb Upgrade II

2019

2021

2024

2027

2030

LS2

Run 3

LS3

Run 4

LS4

Run 5

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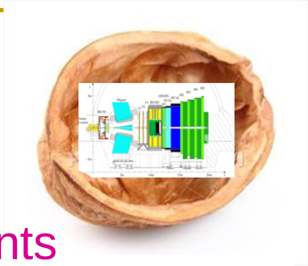
Install LHCb Upgrade II

Belle II

Belle III ?

LHCb Upgrade 1 (LS2) in a nutshell



Indirect search strategies for New Physics, *e.g.* precise measurements & the study of suppressed processes in the flavour sector become ever-more attractive following the experience of Runs1 & 2 that direct signals are elusive

Our knowledge of flavour physics has advanced spectacularly thanks to LHCb. Maintaining this rate of progress beyond Run 2 requires significant changes.

The LHCb Upgrade

1) Full software trigger

- Allows effective operation at higher luminosity
- Improved efficiency in hadronic modes

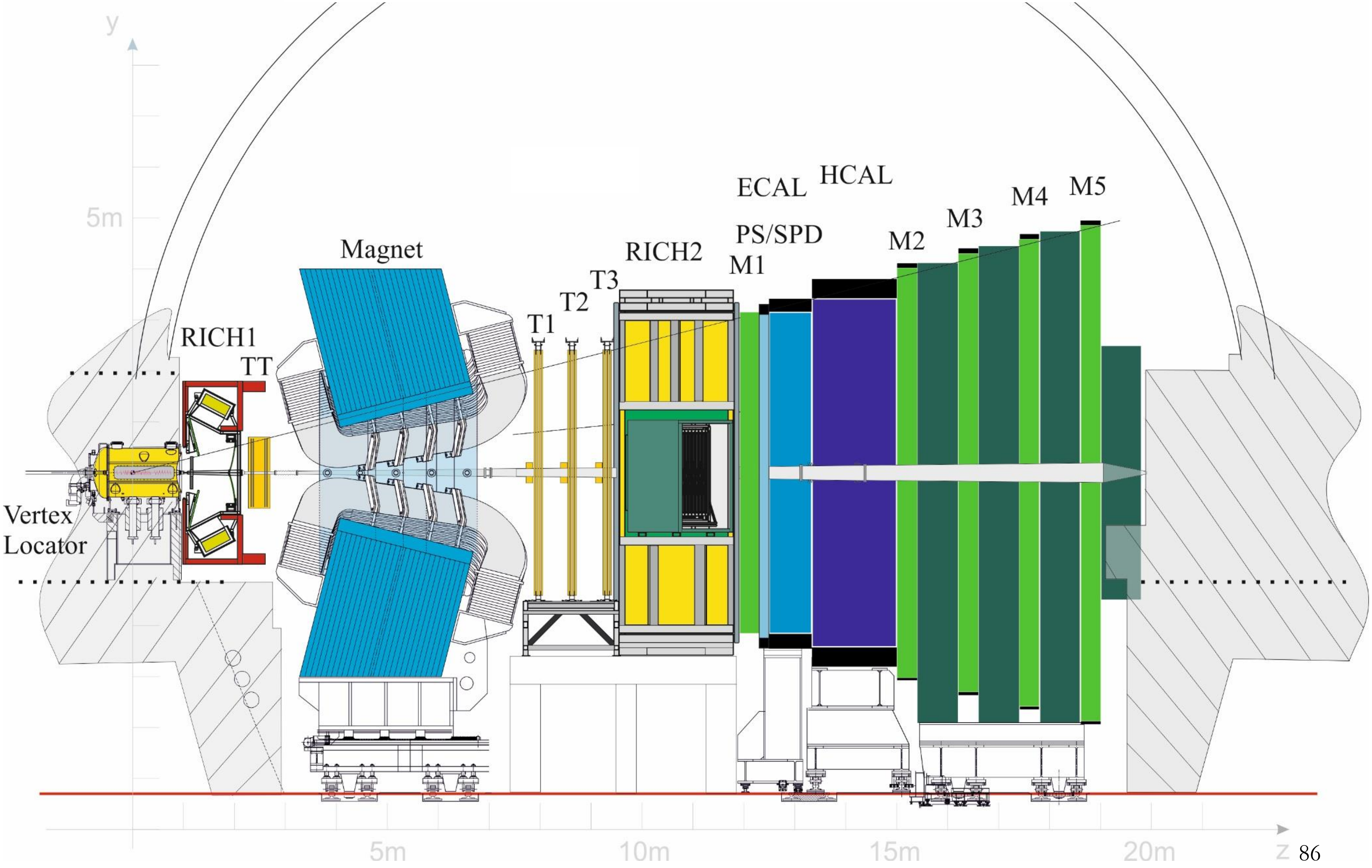
2) Raise operational luminosity to 2 x 10^{33} cm^{-2} s^{-1} (5x run 2 value)

Necessitates redesign of several sub-detectors & overhaul of readout

Upgrade 1 will yield charm samples > 10x those available from Run 1 & 2.

(And flexible trigger will allow for much wider range of measurements).

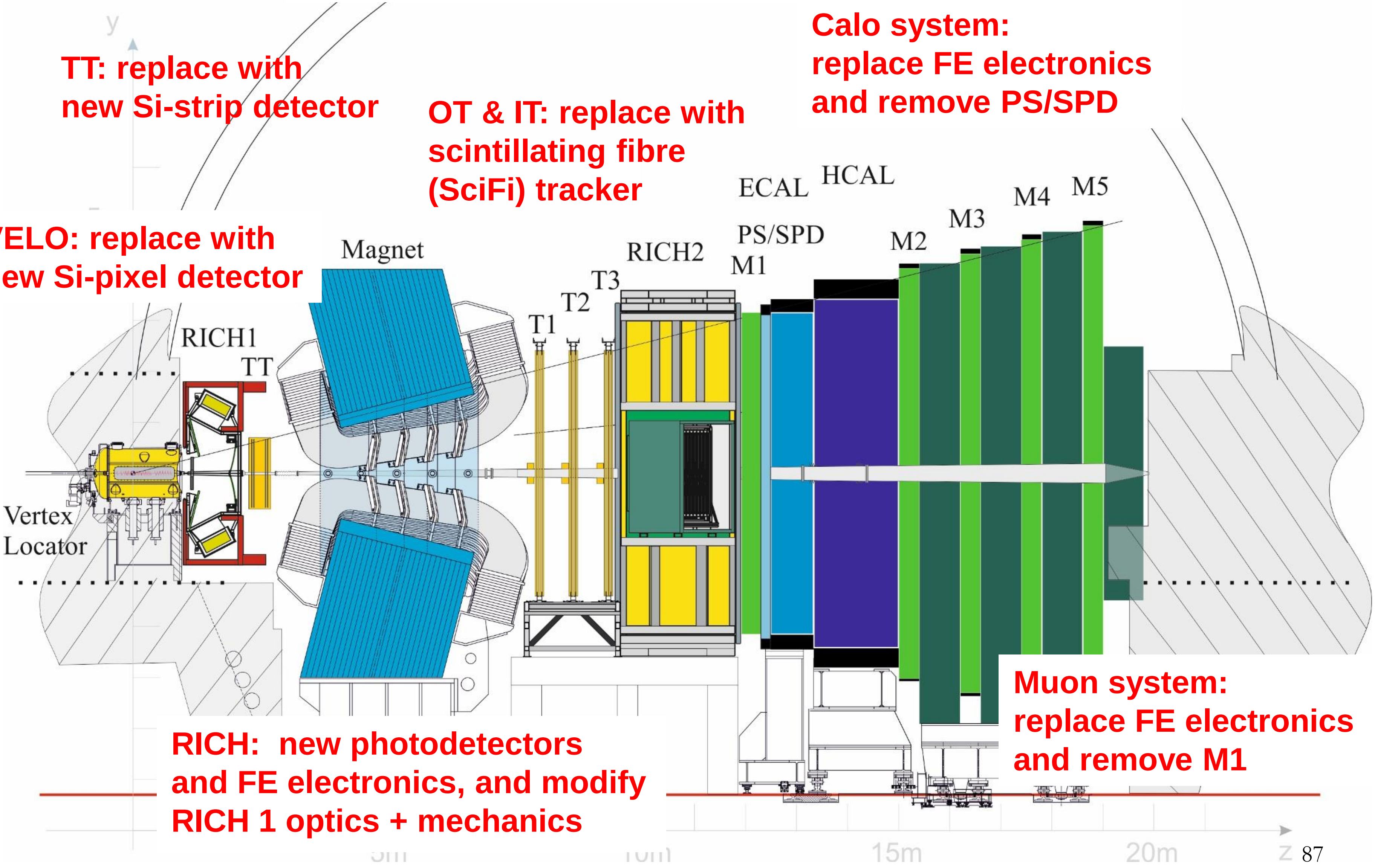
Run 1 & 2 detector



Required modifications

Full s/w trigger →

Replace read-out boards and DAQ



TT: replace with new Si-strip detector

OT & IT: replace with scintillating fibre (SciFi) tracker

Calo system: replace FE electronics and remove PS/SPD

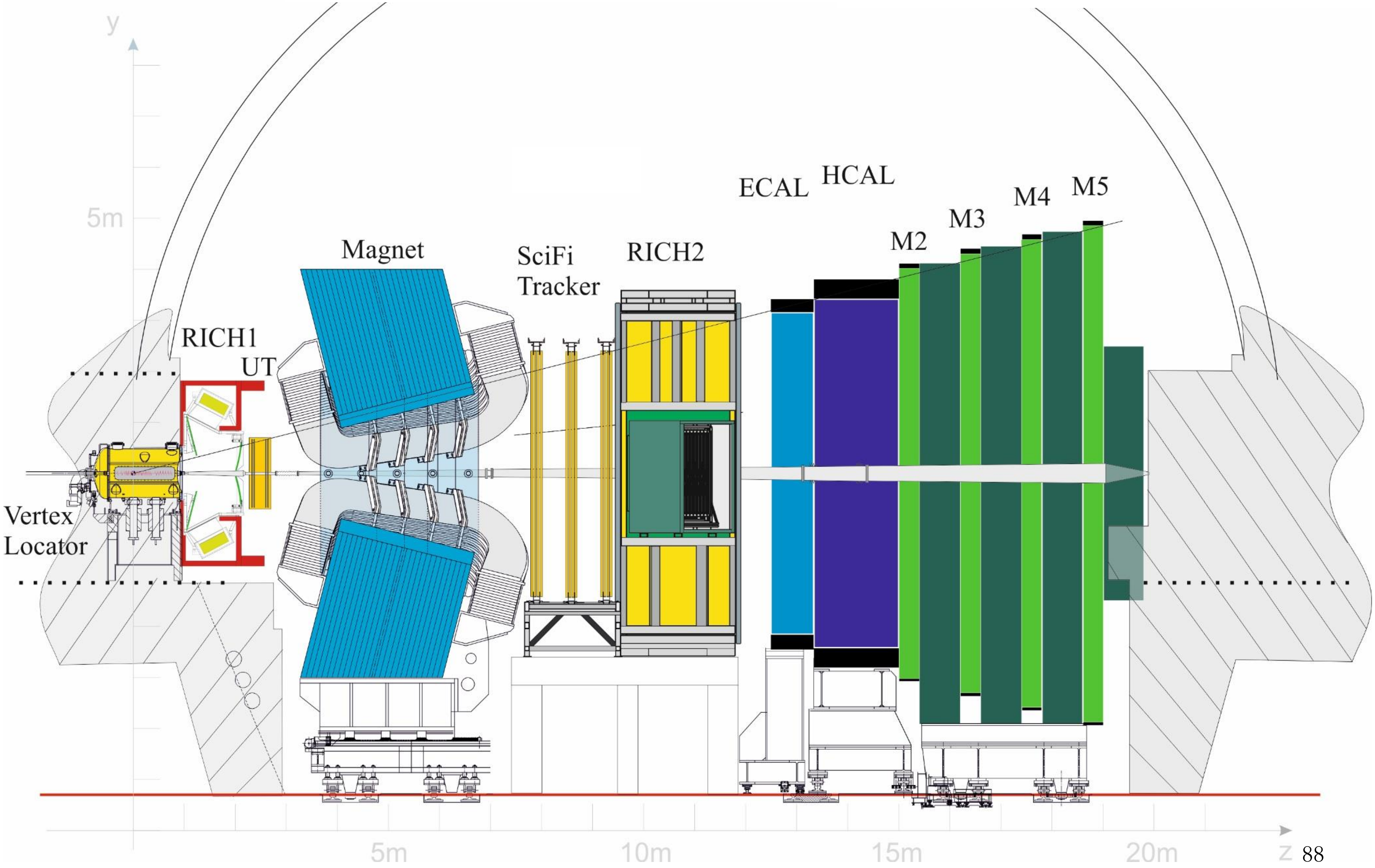
VELO: replace with new Si-pixel detector

RICH: new photodetectors and FE electronics, and modify RICH 1 optics + mechanics

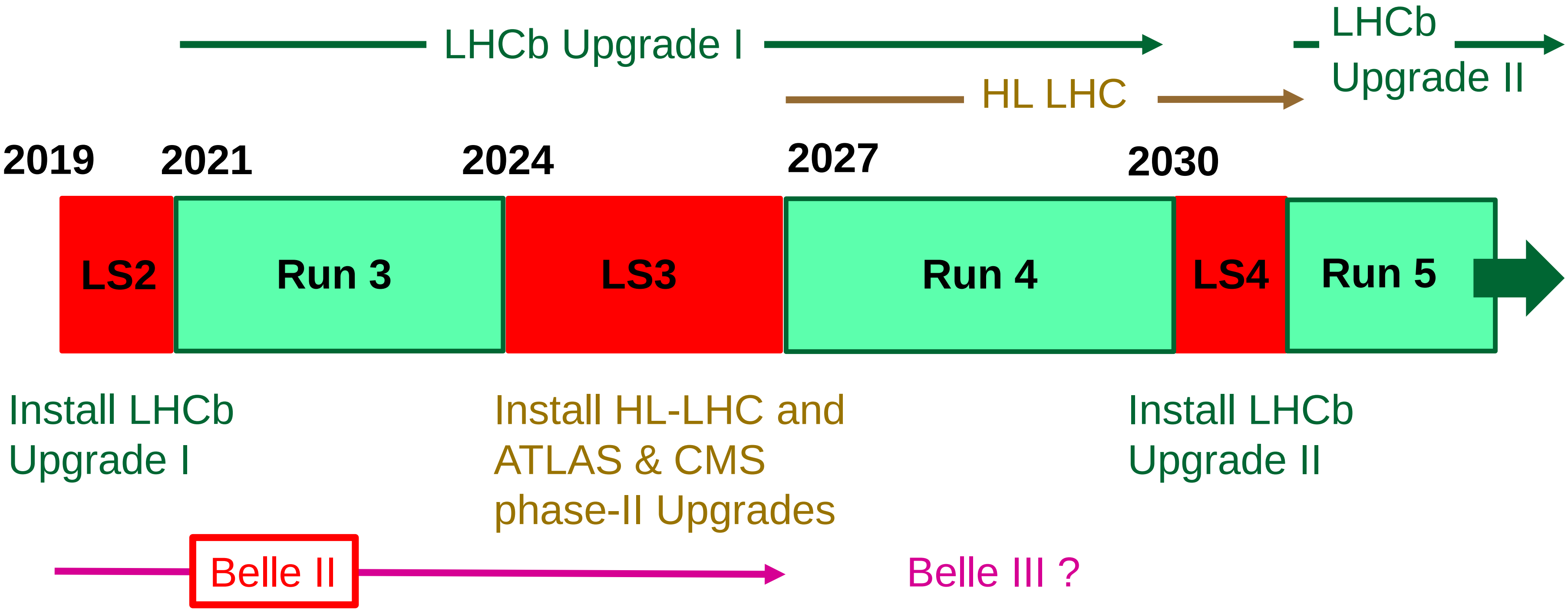
Muon system: replace FE electronics and remove M1

Upgrade I detector

Installation is occurring in LS2, *i.e.* right now! For monthly progress videos look here.



The LHC schedule – current planning

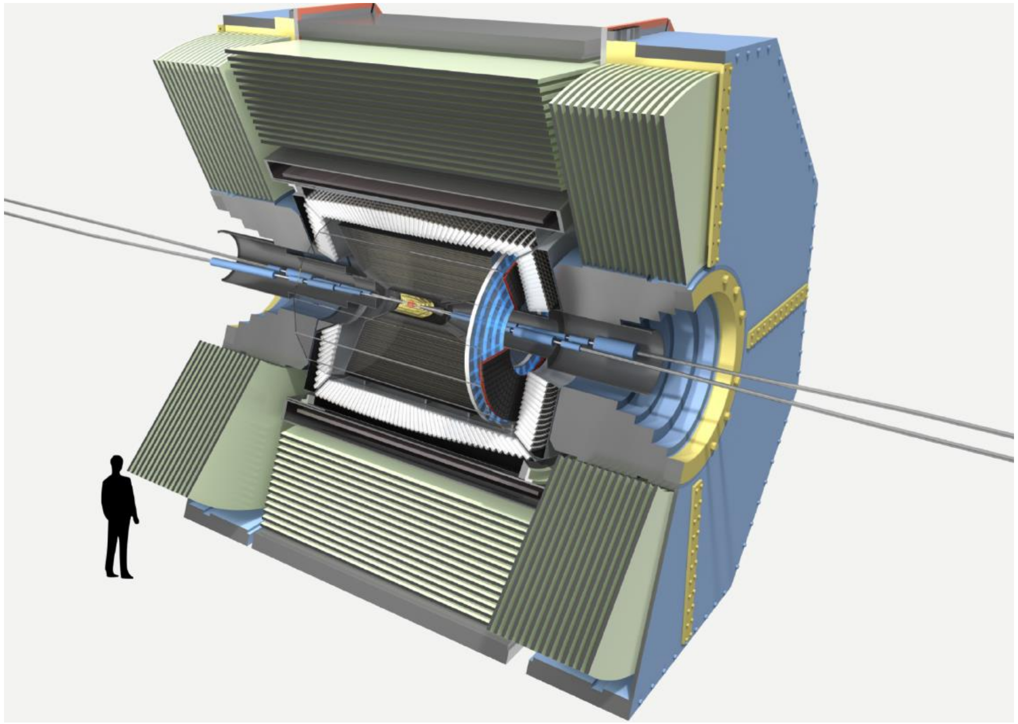


Belle II (experiment) & SuperKEKB (accelerator)

Belle II is a new generation
'B-factory' experiment
Starting operation at
KEK lab in Japan.

It builds on success of
BaBar and Belle, the
Experiments that led
Flavour physics in
the 2000s.

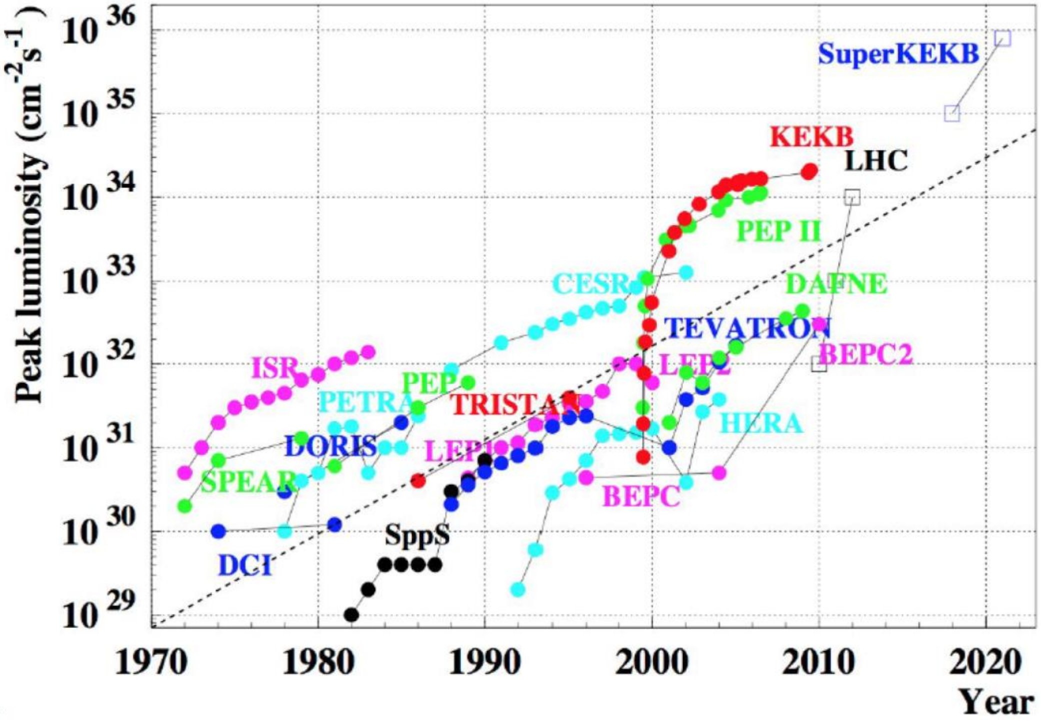
In contrast to LHC,
SuperKEKB is an
e^+e^- machine.

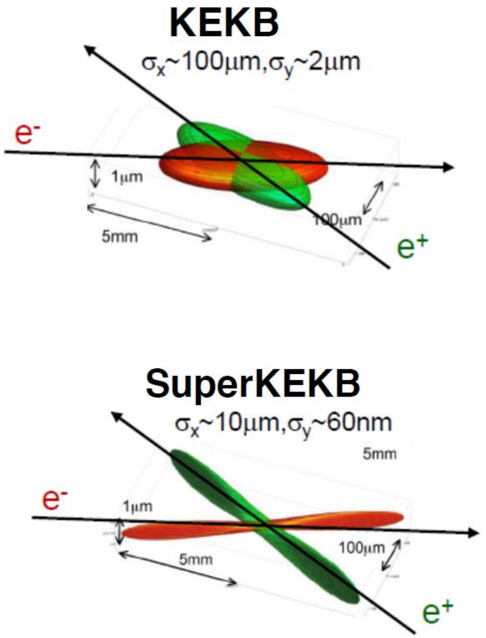


Production cross-section for charm & beauty is lower than at LHC, but analysis environment cleaner, so many complementary measurements are foreseen.

SuperKEKB

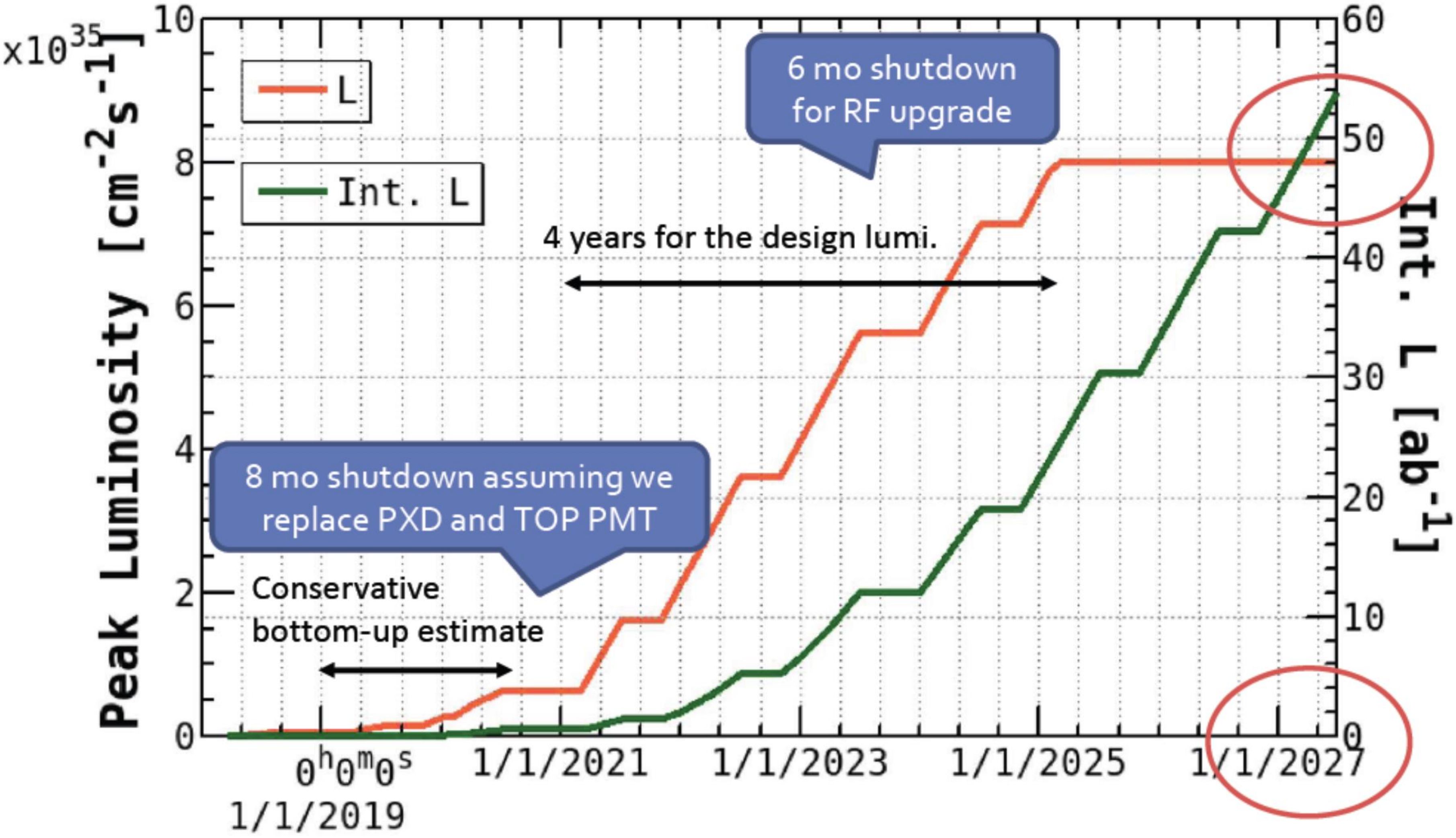
SuperKEKB goals: luminosity of 8 x 10^{35} cm^{-2}s^{-1} and 50 ab^{-1} by 2027





An ambitious 40-fold increase in luminosity on KEKB, to be achieved by squeezing the beams by ~1/20 and doubling the currents.

SuperKEKB and Belle II roadmap



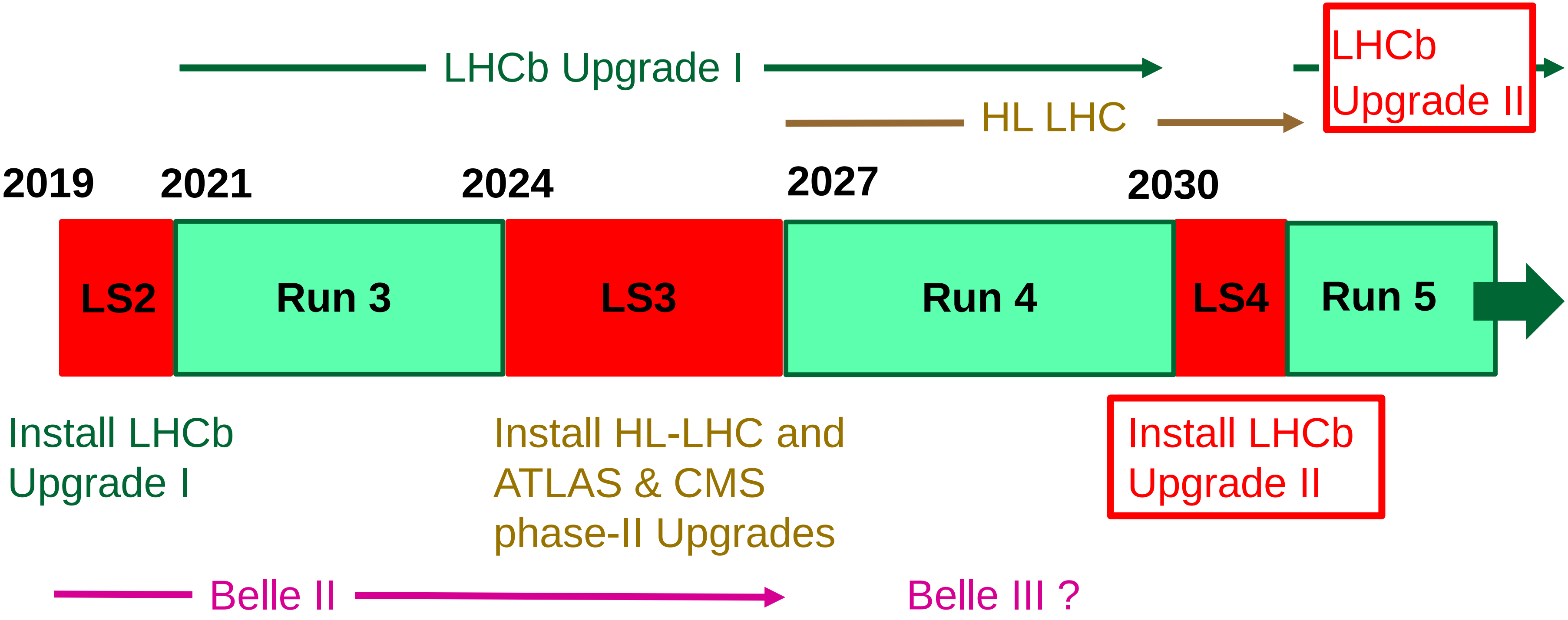
6 mo shutdown for RF upgrade

4 years for the design lumi.

8 mo shutdown assuming we replace PXD and TOP PMT

Conservative bottom-up estimate

The LHC schedule – current planning



LHCb Upgrade I

HL LHC

LHCb Upgrade II

2019 2021 2024 2027 2030

LS2 | Run 3 | LS3 | Run 4 | LS4 | Run 5

Install LHCb Upgrade I

Install HL-LHC and ATLAS & CMS phase-II Upgrades

Install LHCb Upgrade II

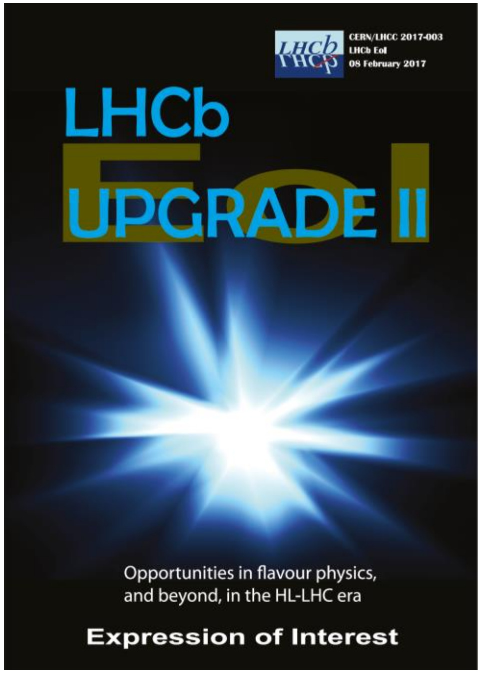
Belle II

Belle III ?

LHCb Upgrade II – the ultimate LHC flavour experiment

Begin after LS4 (2030). Operate at up to 2 x 10^{34} $cm^{-2}s^{-1}$ & collect (at least) 300 fb^{-1}.

Expression of interest



CERN/LHCC 2017-003
LHCb EoI
08 February 2017

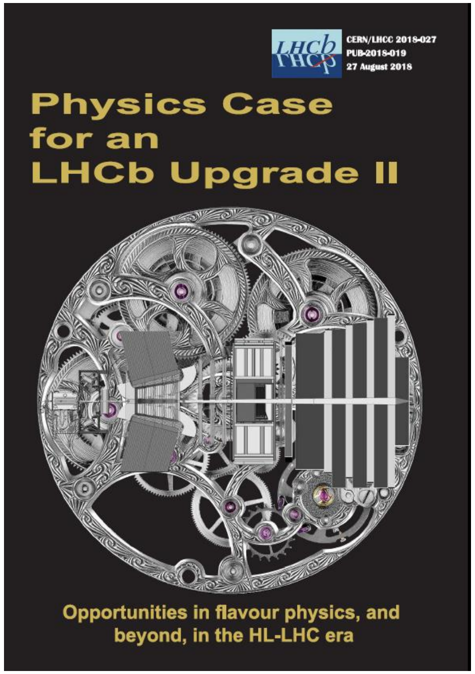
LHCb
EoI
UPGRADE II

Opportunities in flavour physics,
and beyond, in the HL-LHC era

Expression of Interest

[CERN-LHCC-2017-003]

Full physics case



CERN/LHCC 2018-027
PUB-2018-019
27 August 2018

**Physics Case
for an
LHCb Upgrade II**

**Opportunities in flavour physics, and
beyond, in the HL-LHC era**

[CERN-LHCC-2018-027,
also arXiv:1808.08865]

In parallel, many studies from the machine side, summarised in a report which identifies

"a range of potential solutions for operating LHCb Upgrade II at a luminosity of up to 2 x 10^{34} $cm^{-2}s^{-1}$ and permitting the collection of 300 fb^{-1} or more at IP8 during the envisaged lifetime of the LHC"

[CERN-ACC-NOTE-2018-038]

LHCb Upgrade II – the ultimate LHC flavour experiment

Begin after LS4 (2030). Operate at up to 2 x 10^{34} cm^{-2}s^{-1} & collect (at least) 300 fb^{-1}.

Expression of interest


CERN/LHCC 2017-003
LHCb EoI
08 February 2017

LHCb
EoI
UPGRADE II

…HC era
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[CERN-LHCC-2017-003]

Full physics case


CERN/LHCC 2018-02…
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Opportunities in flavour physics, and beyond, in the HL-LHC era

[CERN-LHCC-2018-027, also arXiv:1808.08865]

In paralle… …dies
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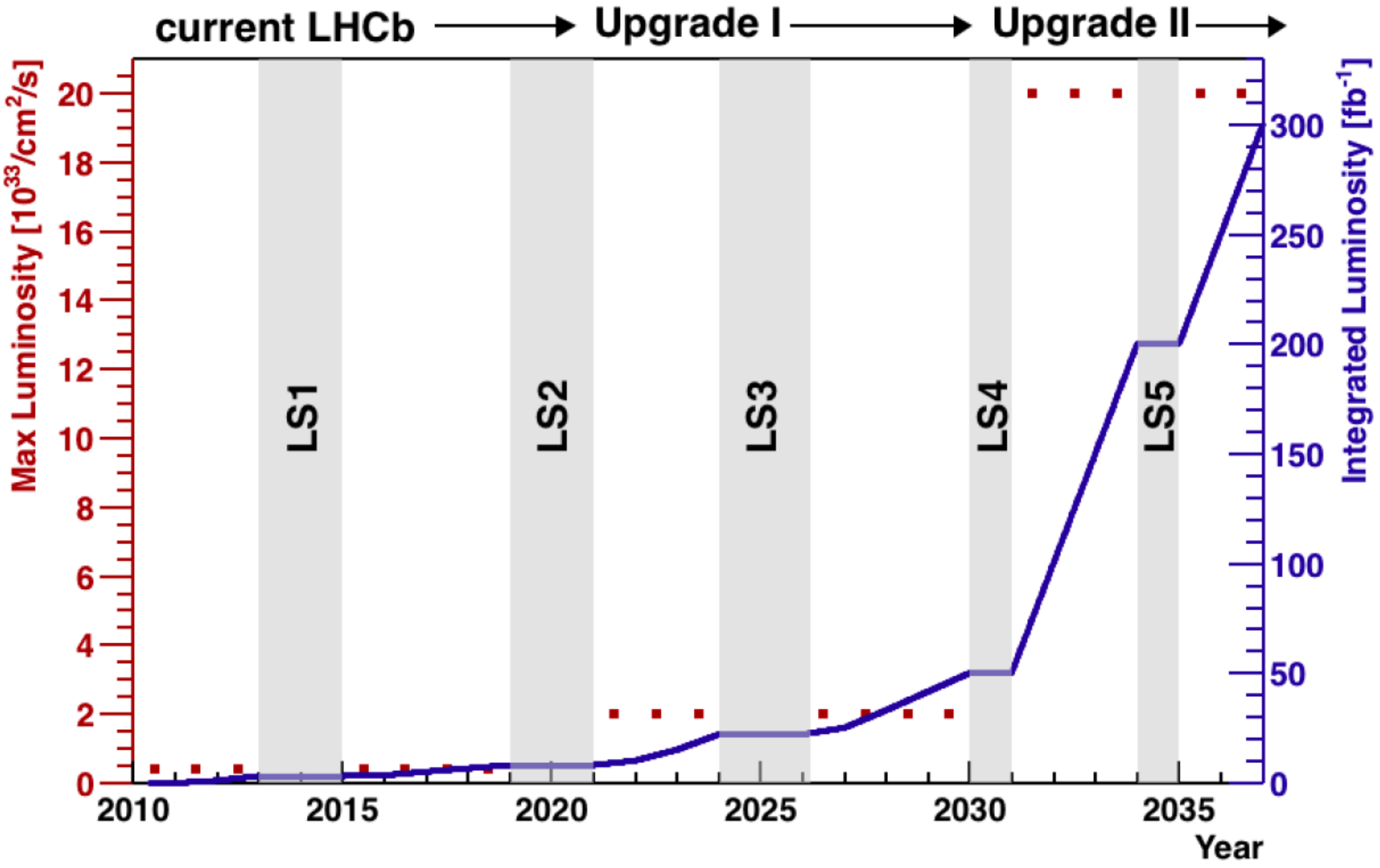
…range of potential solutions for operating LHCb Upgrade II at a luminosity of up to 2 x 10^{34} cm^{-2}s^{-1} and permitting the collection of 300 fb^{-1} or more at IP8 during the envisaged lifetime of the LHC”

[CERN-ACC-NOTE-2018-038]

Approved by LHCC and Research Board to proceed to TDRs

LHCb Upgrade II – the ultimate LHC flavour experiment

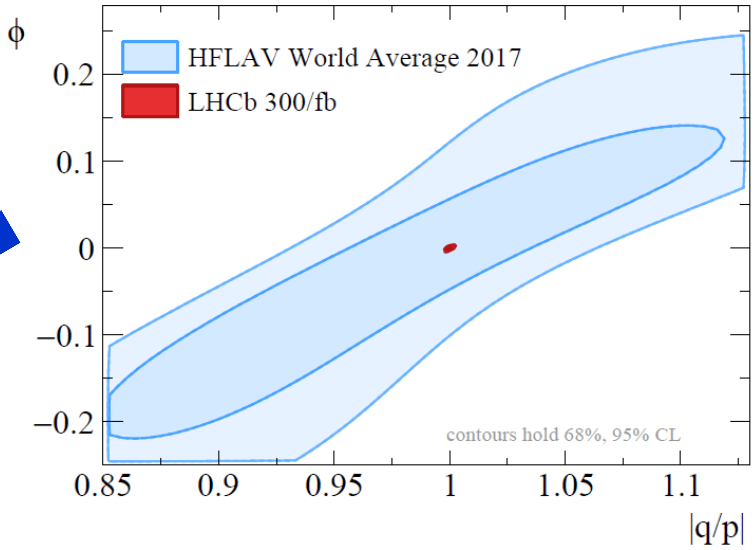


Charm physics potential of LHCb Upgrade II

Upgrade II will allow for an order-of-magnitude improvement in precision in current benchmark analyses, such as ΔA_{CP} [arXiv:1808.08865].

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	0.01	0.03
Run 1–5 (300 fb^{-1})	Prompt	4.9G	1.6G	0.003	0.007

New measurements will become accessible. Exquisite precision will be attainable in searches (and studies) of indirect CPV (*i.e.* mixing related, characterised by φ and |q/p| parameters).



Conclusions

Quark-flavour studies probe many of the least understood questions of the Standard Model, and are intrinsically sensitive to New Physics effects beyond

For many years charm physics had been a neglected sub-topic in this field, with all attention being paid to studies with beauty and strange hadrons.

The recent discoveries of mixing, and now CP violation, in charm have changed the narrative. Charm physics now is a vibrant discipline, which complements well the capabilities of her sisters. Much to look forward to in the years ahead.

Cinderella has truly come to the ball !

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

Backups

Can we explain the baryon-antibaryon asymmetry by known physics?

Qualitatively: yes!

The Standard Model in principle contains all the necessary ingredients.

And so it is possible to derive the ratio of the number of baryons to that of photons in the universe (related to the baryon-antibaryon asymmetry).

$$\eta = \frac{n_B}{n_\gamma} \sim \frac{(m_t^2 - m_u^2)(m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_b^2 - m_d^2)(m_b^2 - m_s^2)(m_s^2 - m_d^2)\,J}{M^{12}}$$

where $J \approx 3\times10^{-5}$ is the Jarlskog invariant [PRL 55 (1985) 1039] quantifying the size of violation in the Standard Model and M≈100 GeV is the electroweak scale at which the baryon asymmetry freezes out.

Can we explain the baryon-antibaryon asymmetry by known physics?

Quantitatively: no!

The previous equation gives $\eta \approx 10^{-19}$, whereas using Planck experimental data on cosmic microwave background one gets

$$\eta = (6.04 \pm 0.08) \times 10^{-10}$$

This is off by 10 orders of magnitude!

CP violation in the Standard Model is too small.

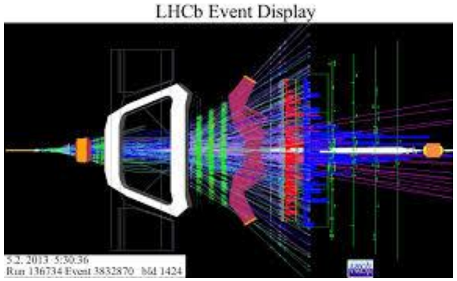
This is a strong indication that new sources of *CP* violation must exist in some beyond-the-SM physics, *e.g.* heavier yet-unknown particles abundantly present in the early universe whose decays violate CP very severely.

The data challenge

LHC operates at 40 MHz and does so for ~15% of year

LHCb raw event size ~100 kBytes

✖



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~ 15000 PetaBytes /yr (raw data alone)

Data rate

LHCb ~15000 PB.yr
Facebook ~180 PB / yr

~ 15000 PetaBytes/year is less than dealt with by search engines, but still considerably more than *e.g.* Facebook (~ 180 PB/year).

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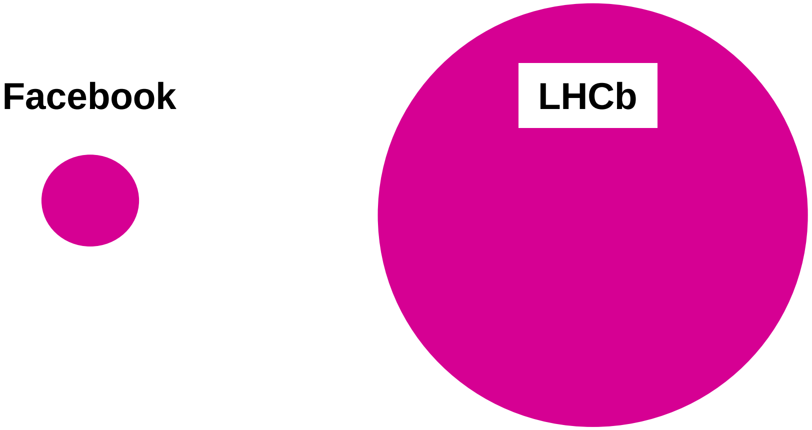

The data challenge

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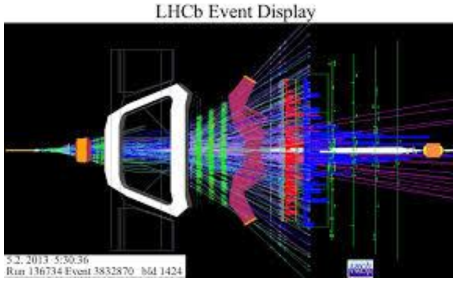


→

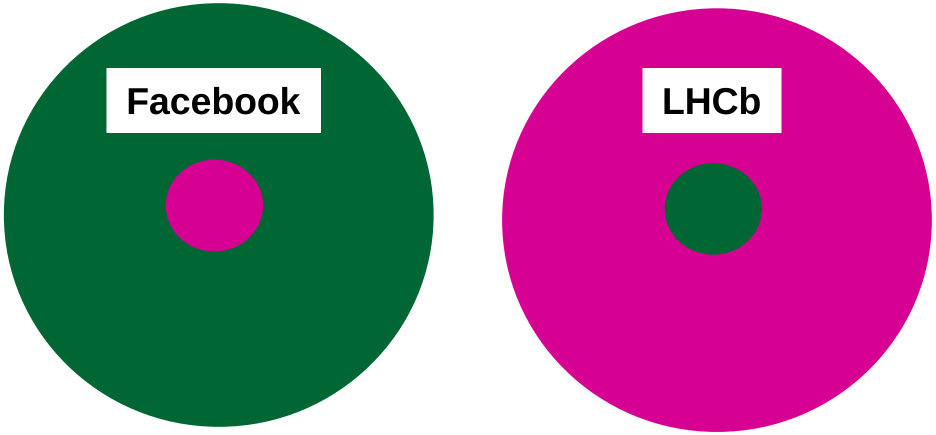
~ 15000 PetaBytes /yr (raw data alone)

~ 15000 PetaBytes/year is less than dealt with by search engines, but still considerably more than *e.g.* Facebook (~ 180 PB/year).

Public science has less money to spend on computing than Facebook.

Storage costs money. Better to process as much as possible in ‘real time’.

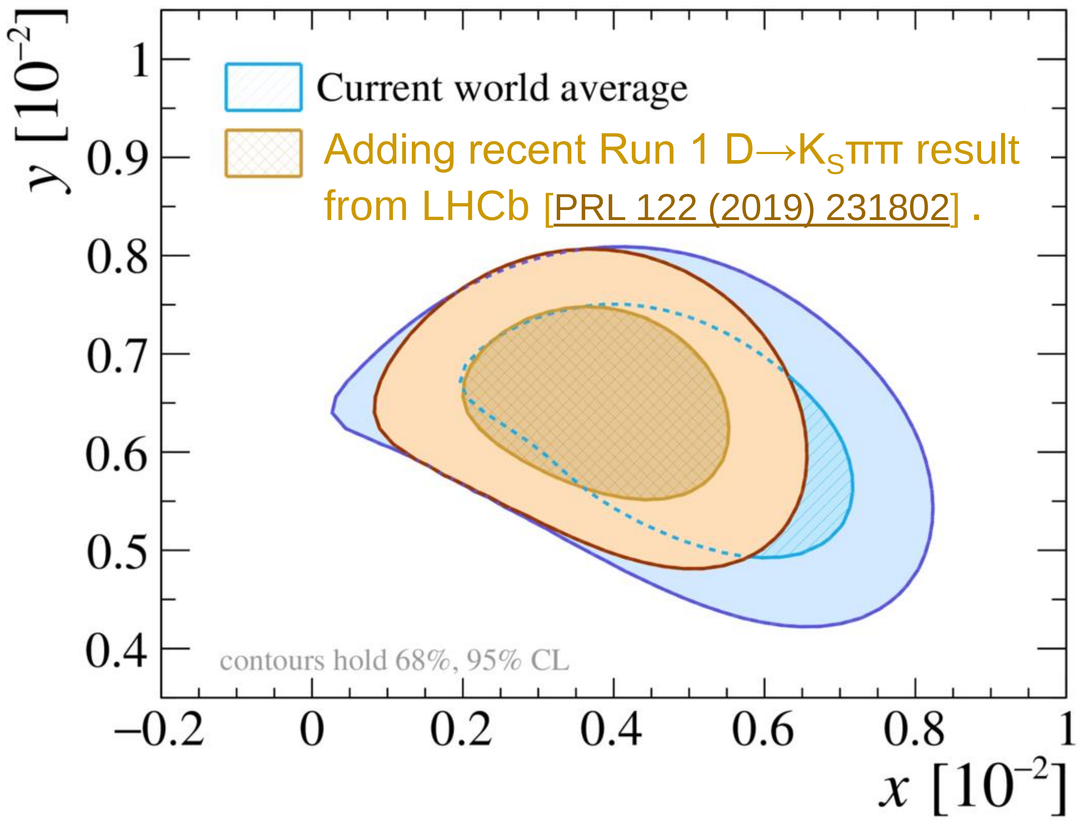
Data rate
LHCb ~15000 PB.yr
Facebook ~180 PB / yr



Computing budget
LHCb ~10M$ / yr
Facebook ~600 M$ /yr

Where are we now with charm mixing ?

y_D is now reasonably well known, but x_D less so. In fact there is still only ~3 σ evidence that x_D is non zero. Important to improve our knowledge of x_D, as size of mixing parameters modulated size of any indirect CPV observable.



Adding recent Run 1 D→$K_S\pi\pi$ result from LHCb [PRL 122 (2019) 231802] .

Search for indirect CPV in charm with Run 2 data

LHCb samples have grown rapidly, and now allow for high sensitivity searches for

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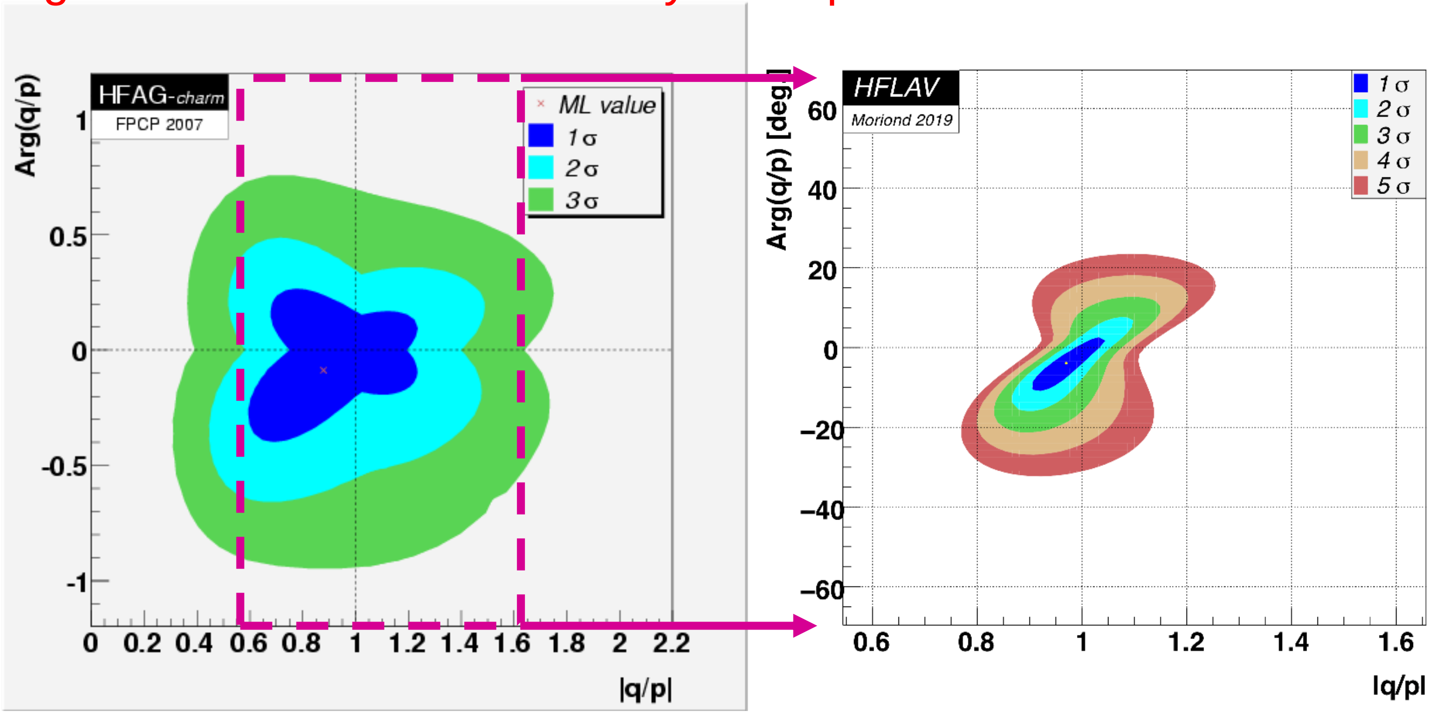
Significant increase in sensitivity since pre-LHC era…



…now starting to approach the region where indirect CPV could lurk !

$M(D^{*}\pi)$ [MeV/c^2]

[PRD 97 (2018) 031101]

Difference flat → no sign of indirect CPV (yet).

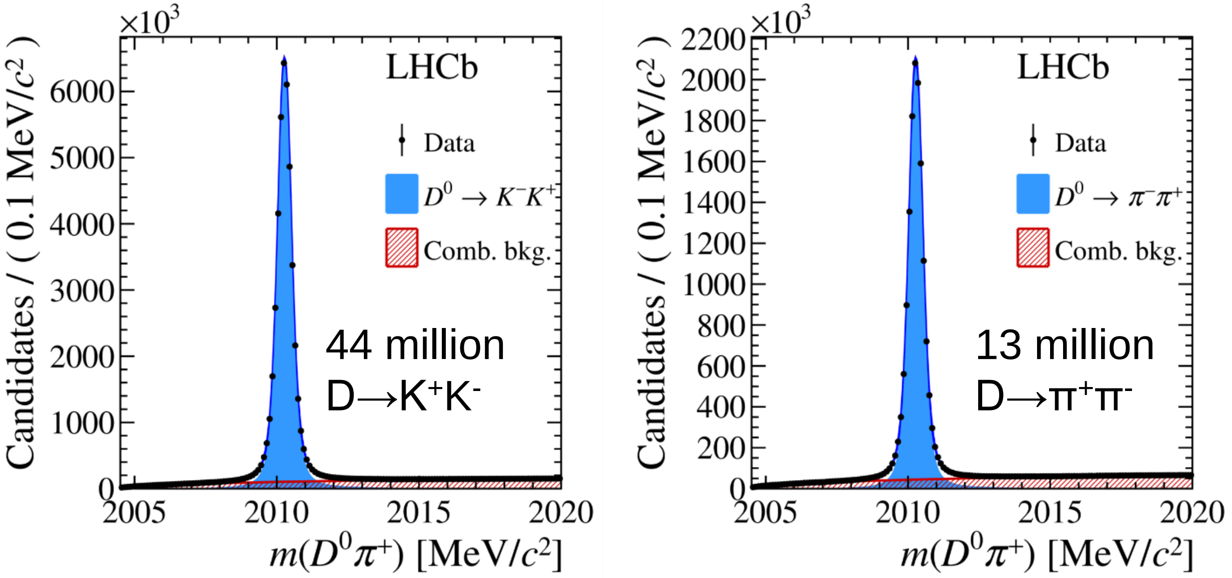
Dawn of a new era: observation of (direct) CPV in charm

[PRL 122 (2019) 211803]

ΔA_{CP} measurement, published earlier this year by LHCb, harnesses full statistical might of experiment, being first to use full Run 2 data set.

Method is intrinsically robust: *e.g.* syst. uncertainty on prompt analysis is < 10^{-4}.

Dull plots, because effect is tiny, and almost impossible to visualise



44 million D→K^+K^-

13 million D→$\pi^+\pi^-$

Using indirect CPV constraints in these channels can deduce

$$\boxed{\Delta a_{CP}^{\mathrm{dir}} = (-15.7 \pm 2.9) \times 10^{-4}}$$

i.e. direct CPV saturates result