Experimental Flavour Physics Lecture IV: charm physics, and future prospects for flavour studies

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Lecture plan

Lecture I	Why study flavour and where ? Focus on how to do this at hadron machines, in particular the LHC and LHCb. Closing digression on hadron spectroscopy.
Lecture II	Unitarity Triangle metrology and CPV measurements
Lecture III	New Physics searches through studies of Flavour-Changing Neutral Currents (and other processes)
Lecture IV	Charm physics, and future prospects for experimental flavour studies

Today !

Upfront admission: I will be saying a lot about LHCb.

Lecture-IV outline (two distinct topics)

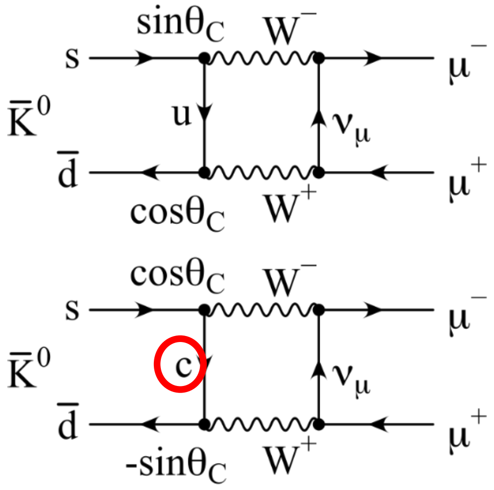
- Charm physics: a glorious past, followed by years of neglect
- The charm renaissance and the role of hadron colliders
    - mixing measurements
    - the search for CP violation in charm decays
    - the discovery of direct CP violation in charm
- The need for higher precision
- Belle II
- LHCb Upgrade I
- The ATLAS and CMS Phase II Upgrades
- LHCb Upgrade II
- Flavour physics at the FCC
- Conclusions

Charm – a glorious history

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

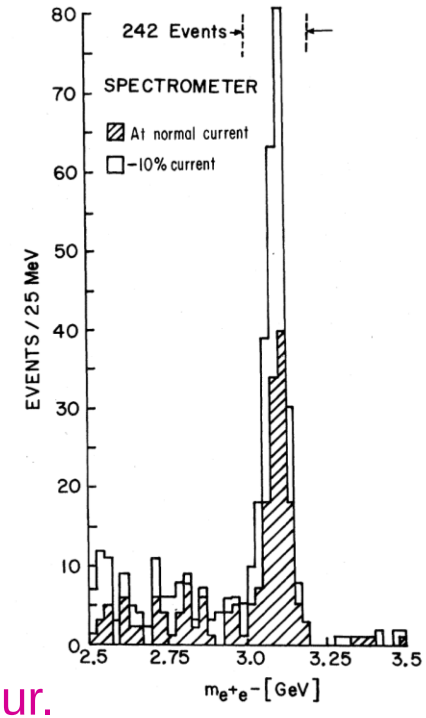
[Glashow, Iliopoulos & Maiani, PRD 2 (1970)1285]

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.

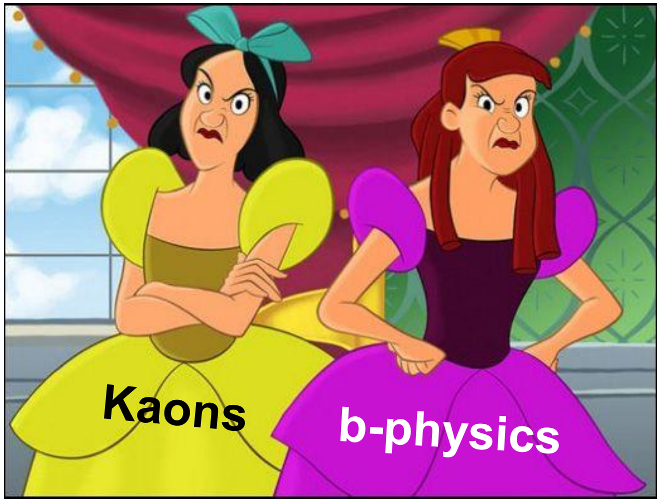
"I know she invented fire, but what has she done recently?" [I. Bigi, arXiv:0808.1773]

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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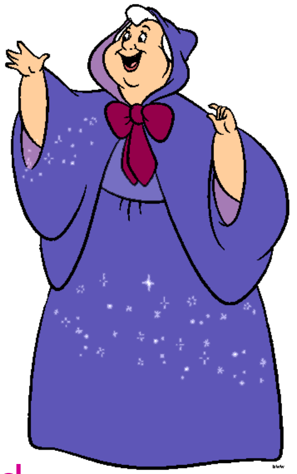
Yet, this neglect was always unjustified:

- 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.



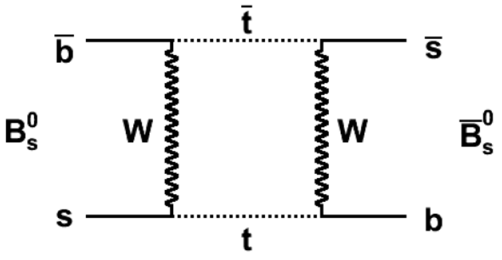
And indeed, early this century, charm’s fairy-godmother moment arrived.

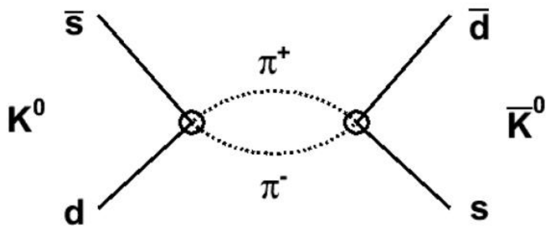
Neutral meson mixing - reminder

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: or:

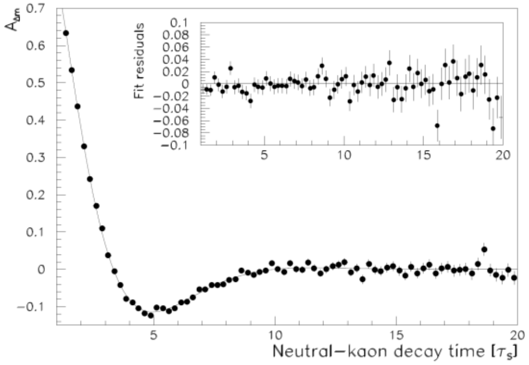
Virtual,
short-range
(box diagrams)



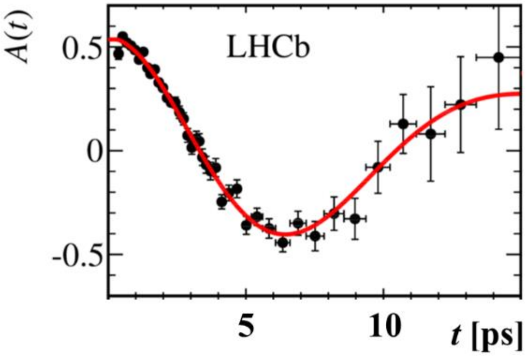


On-shell,
long-range
(common
intermediate
states)

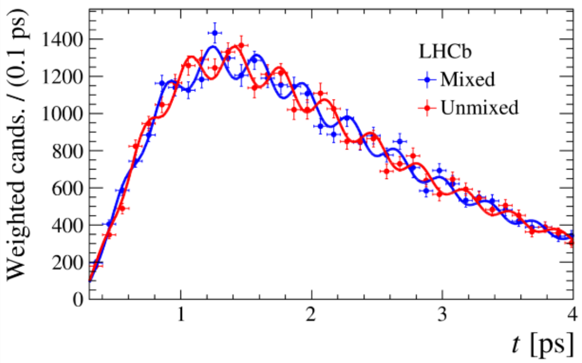
Slow for K^0 mesons … quicker for B^0 mesons… even quicker for B^0_s mesons.



[CPLEAR, PLB 444 (1998) 38]



[LHCb, EPJC 76 (2016) 412]



[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’).

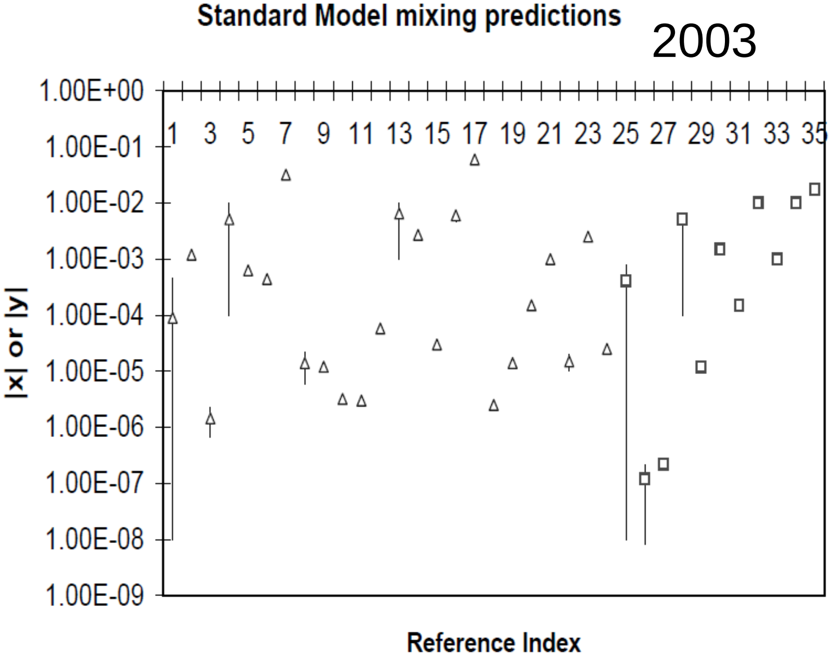
D^0-$\overline{D}^0$ oscillations

In charm the parameters that describe the mixing / oscillations are

$x \equiv \Delta m/\Gamma$ short range $y \equiv \Delta\Gamma/2\Gamma$ long range

where Δm ($\Delta\Gamma$) is the mass (width) splitting between the mass eigenstates.

Because of difficulties of making calculations in the charm system, the range in predicted values for *x* and *y* was very wide (but always small !).



as of 2003

[A.A. Petrov, hep-ph/0311371]

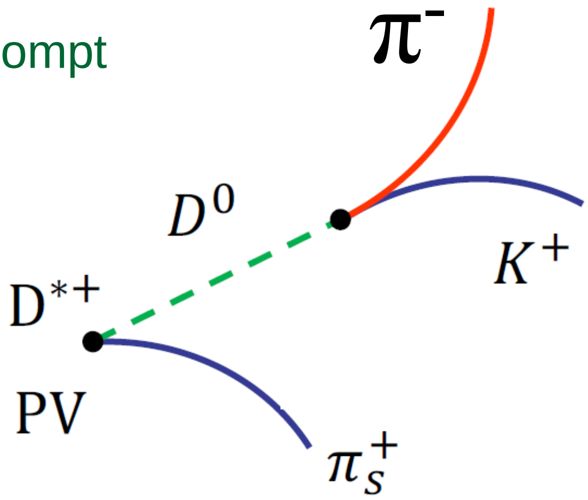
The situation has since improved, no doubt guided by the results we will discuss, but the question remains a challenging one (see, *e.g.* [Lenz and Wilkinson, Ann. Rev. Nucl. Part. Sci. 71 (2021) 59]).

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’.

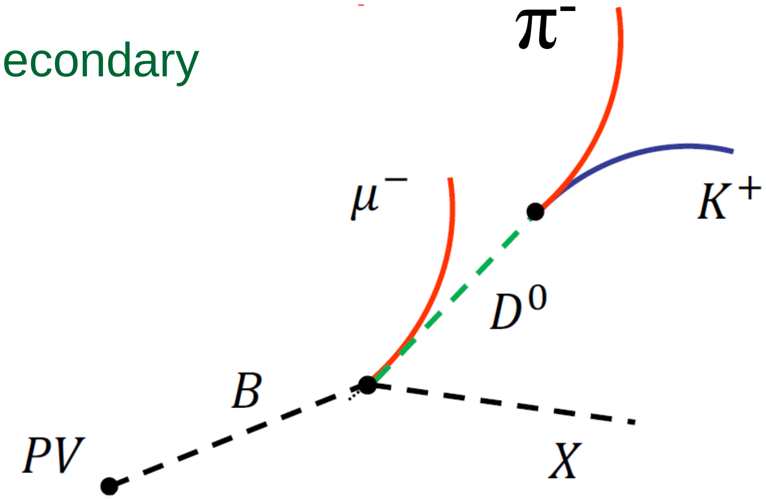
Experimentally this is done by flavour tagging the D^0 at birth, which is easier to do than in the B meson case, because the signatures are cleaner and more efficient.

Prompt



Using a ‘slow pion’ from D^{*+} decay – the most powerful method

Secondary



Using charm produced in semileptonic B decays, and looking at the charge of muon – useful addition at LHCb

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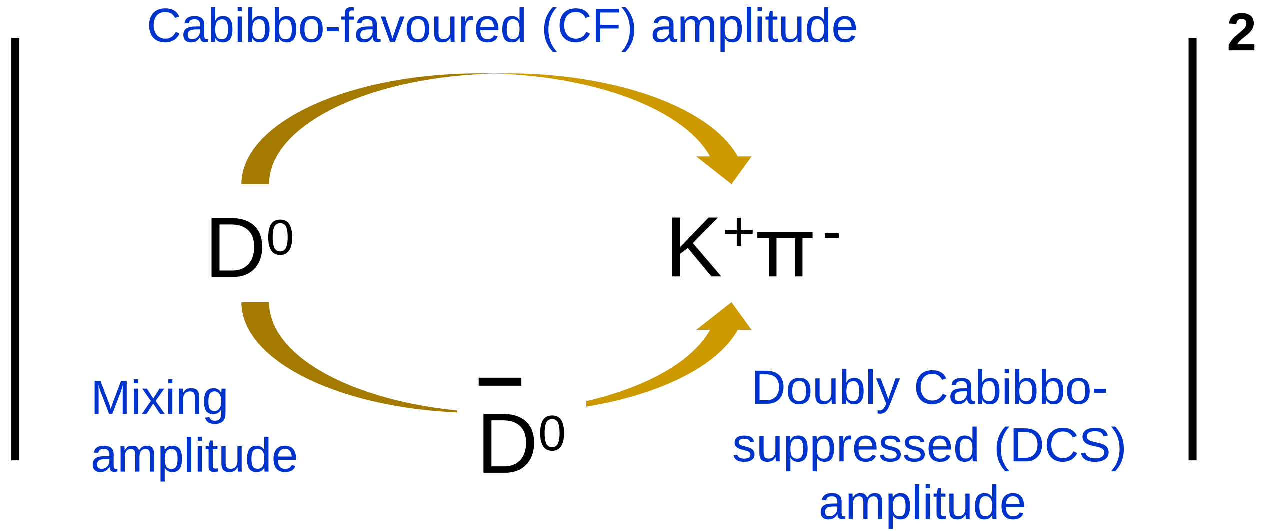
Decay-time dependent rate ≈



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 rotated by a strong phase…

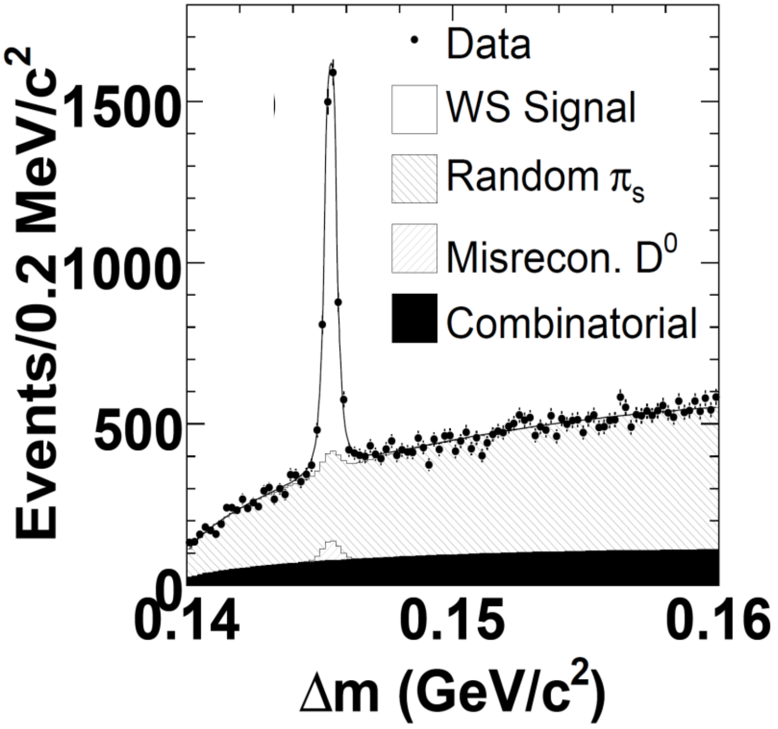
…these small, so mixing signature is a linear, not oscillatory effect.

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

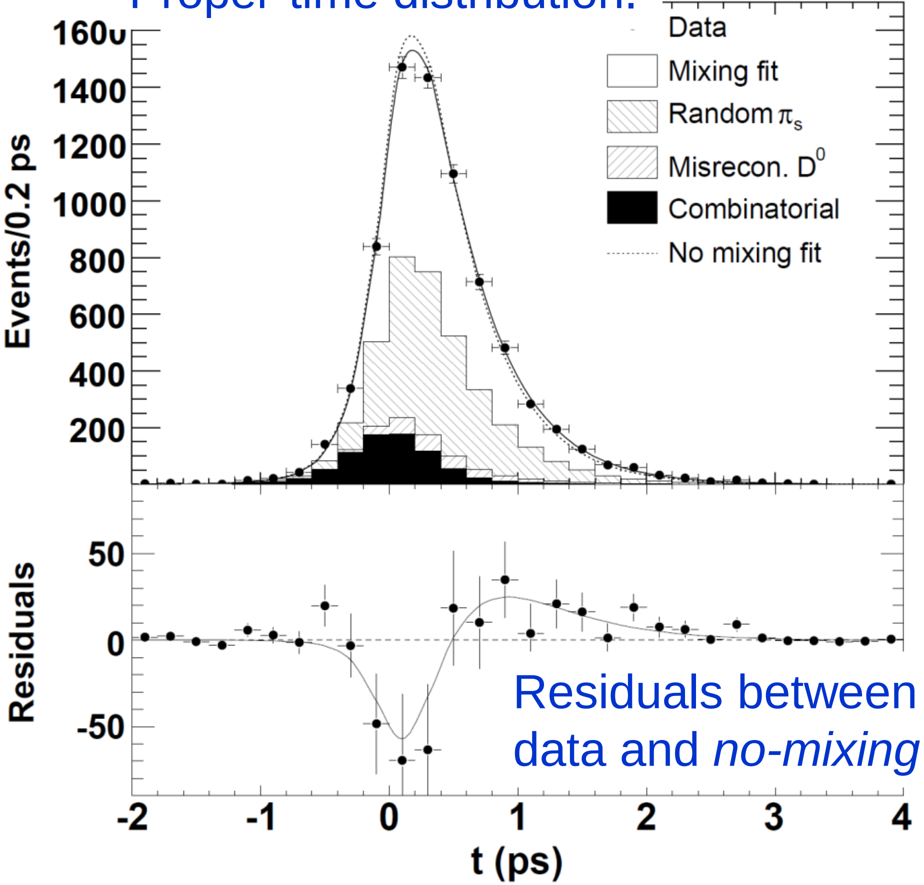
First evidence from the B-factories !

B factories produced large 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]

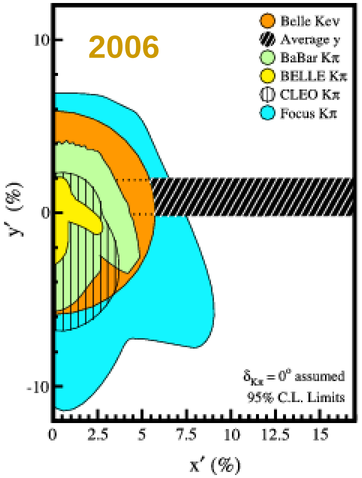
A rekindling of interest, and the rise of the hadron machines

As the B factory results firmed up, the picture changed very rapidly.

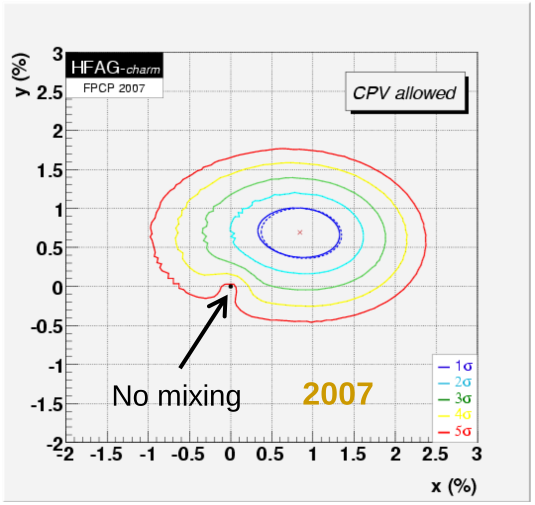
The ensemble of results showed that mixing was happening, but was less clear on the values of the parameters driving it (especially *x*).

This rekindled interest in charm, particularly for hadron machines where the potential is enormous.

Excluded regions



"All results are null."
Ian Shipsey, Charm 2006.



Measurement contours;
no-mixing excluded at 5σ

e.g. the charm cross section at the LHC is around 20x that of beauty production !

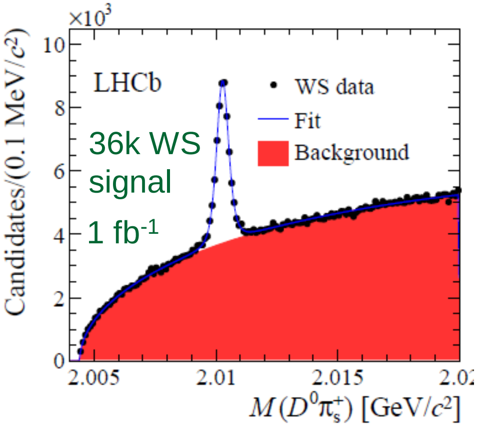
All considerations that apply to beauty physics (e.g. acceptance, instrumentation & trigger) remain true for charm. Its just a little harder to trigger on, as it has lower p_T.

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.

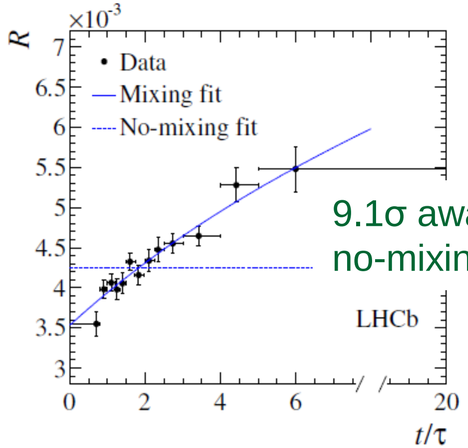
This is the WS/RS ratio vs. proper time.

Linear slope comes from mixing-decay interference.



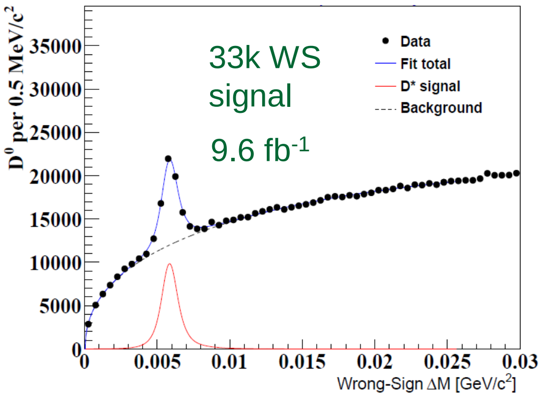
36k WS signal

1 fb^{-1}



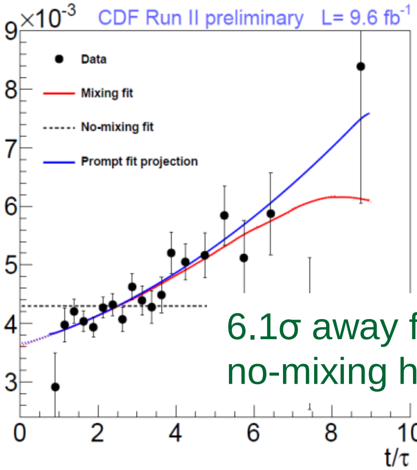
9.1σ away from no-mixing hyp.

[LHCb, PRL 110 (2013) 101802]



33k WS signal

9.6 fb^{-1}



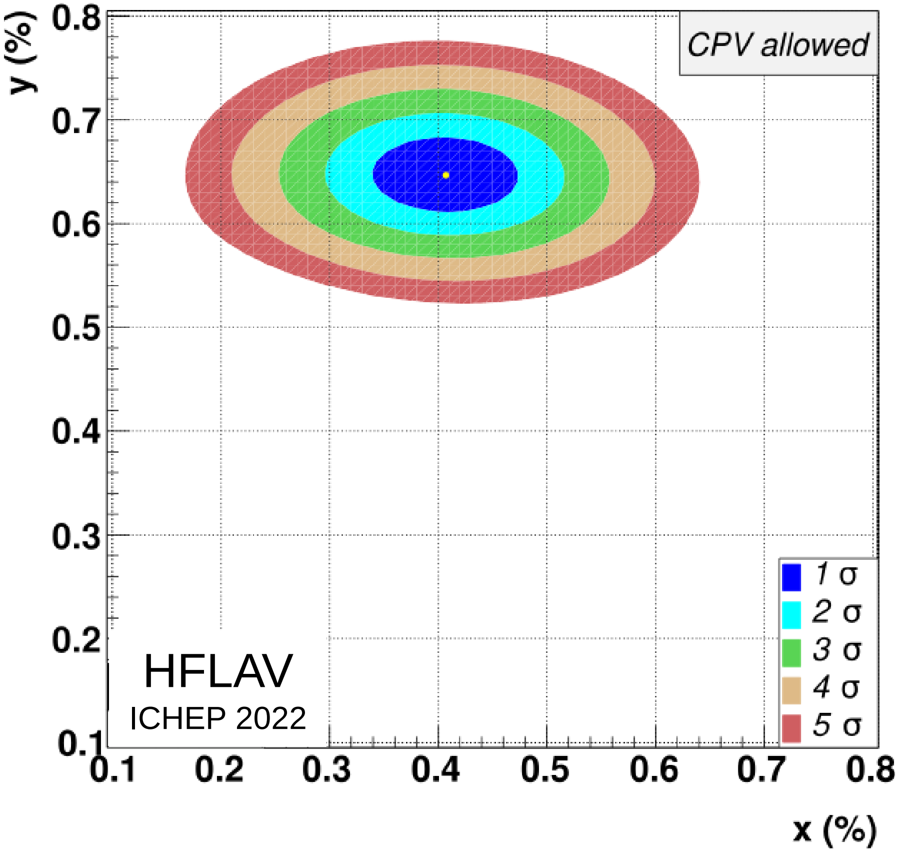
6.1σ away from no-mixing hyp.

[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.

From discovery to precision

‘Wrong sign’ Kπ and parallel measurements refined with growing LHCb data sets. Precision on mixing signal increased, and mixing parameters now known to ~10%.

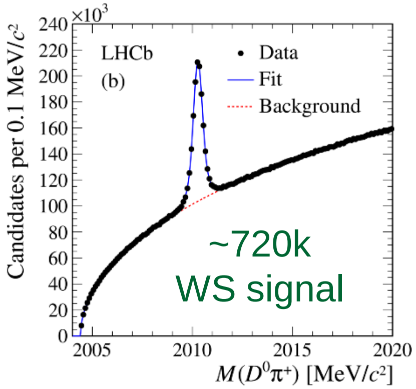


CP violation in charm-mixing phenomena

Seeing charm oscillations is exciting in itself, but the fact that the mixing parameters are not too small is excellent news for CP violation searches in mixing-related phenomena (*i.e.* effects analogous to those observed in neutral kaon and beauty).

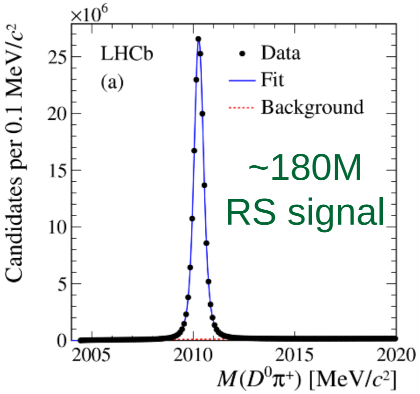
To look for these we essentially look for differences in mixing between D^0 and $\bar{D}^0$.

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

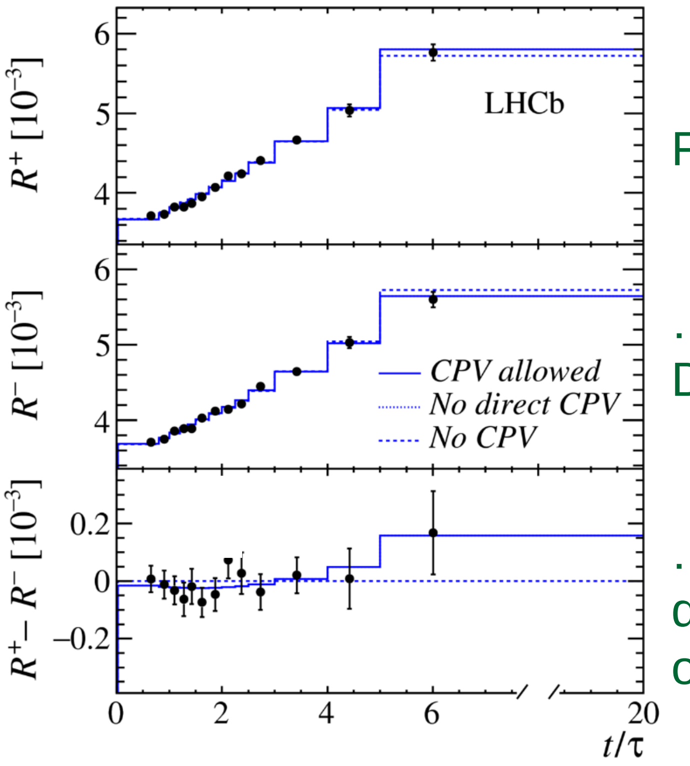


~720k WS signal

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



~180M RS signal



For D⁰…

…and D⁰bar…

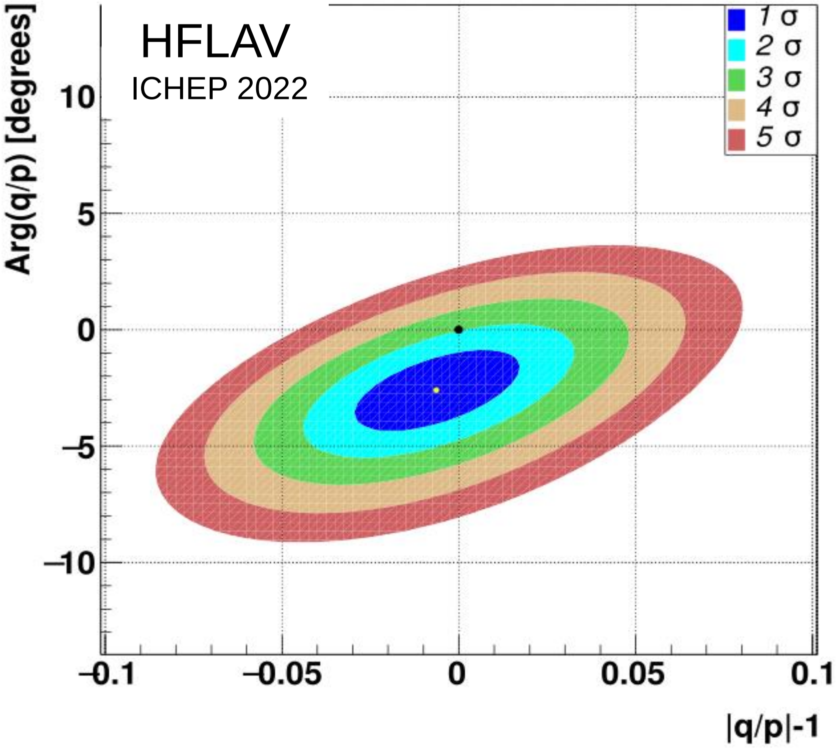
…and difference of both.

[PRD 97 (2018) 031101]

No indication of any difference, so CP violation must be very small (as expected).

CP violation in charm-mixing phenomena

CPV in charm-mixing phenomena can be characterised by a non-zero value of |q/p|-1, or a non-trivial phase of q/p (look back to Lecture II for definitions).



Results compatible with CP conservation, but there is a two-sigma tension.
Very intriguing – any signal at this level of precision would be an exciting surprise !

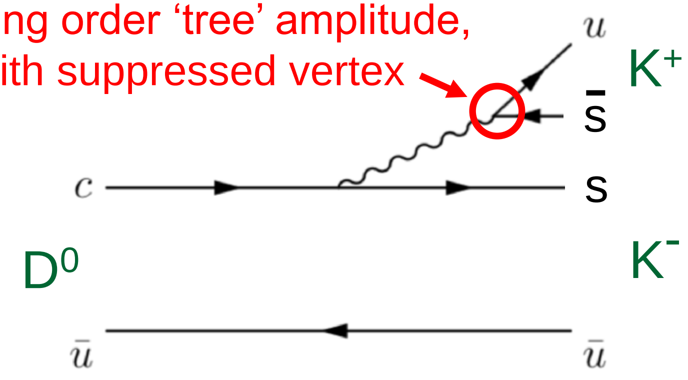
However, another category of CPV *has* been observed in the charm system.

Searches for direct CPV in charm

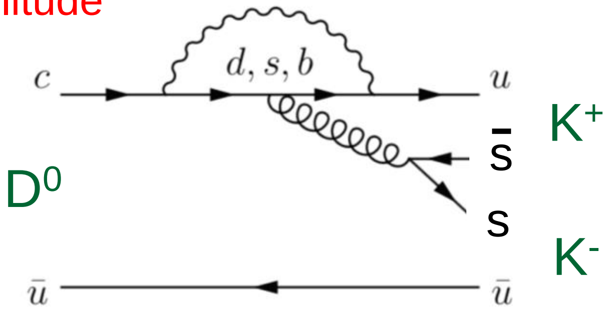
'direct CPV' or 'CPV in decay'

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

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

Measurement is performed using pion-tagged D^0's from D^*'s and muon-tagged D^0's from B's.

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

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

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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.

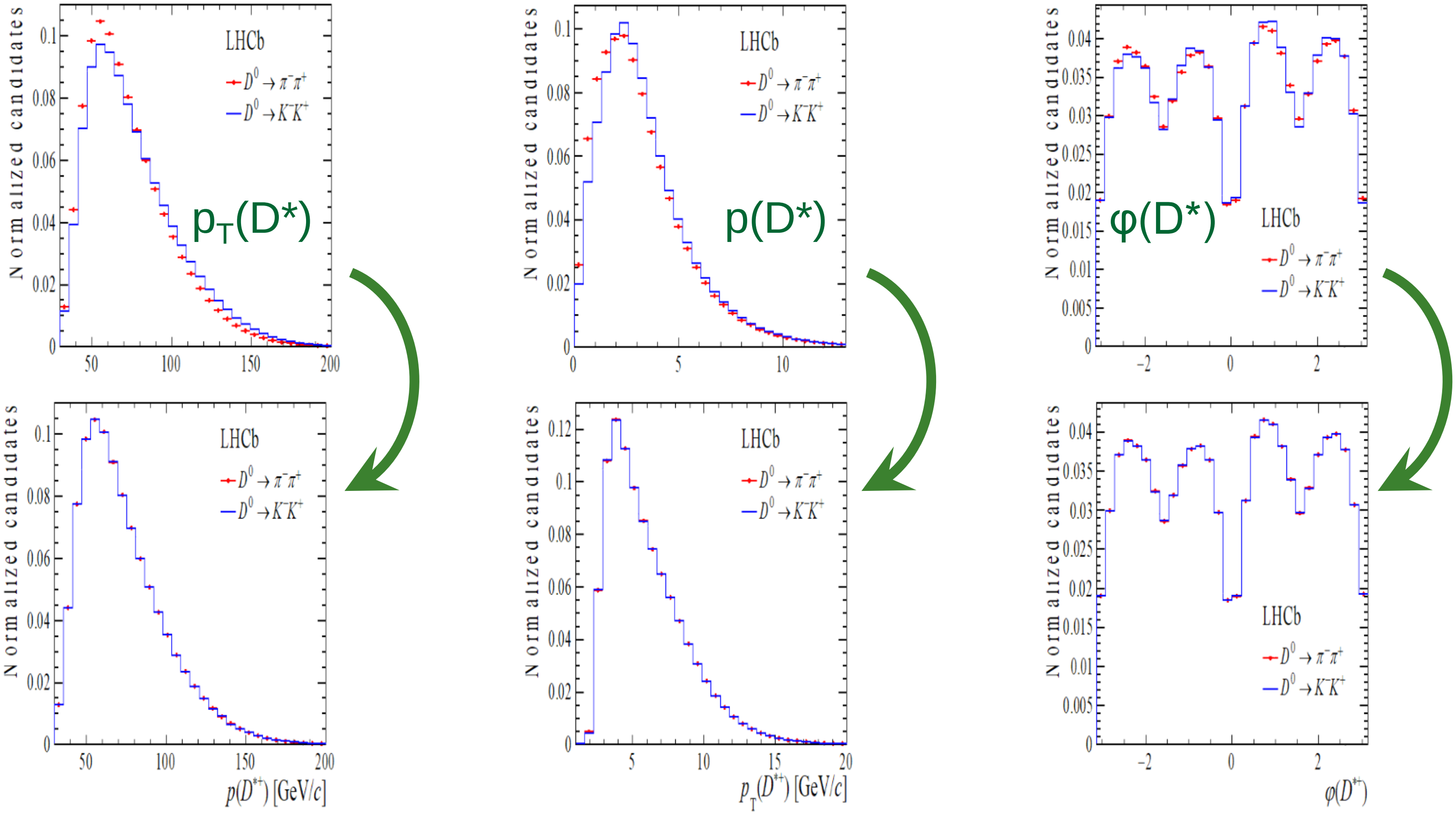
So measure ΔA_{CP} , the *difference* between the two raw asymmetries:

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

Kinematic re-weighting

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

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:

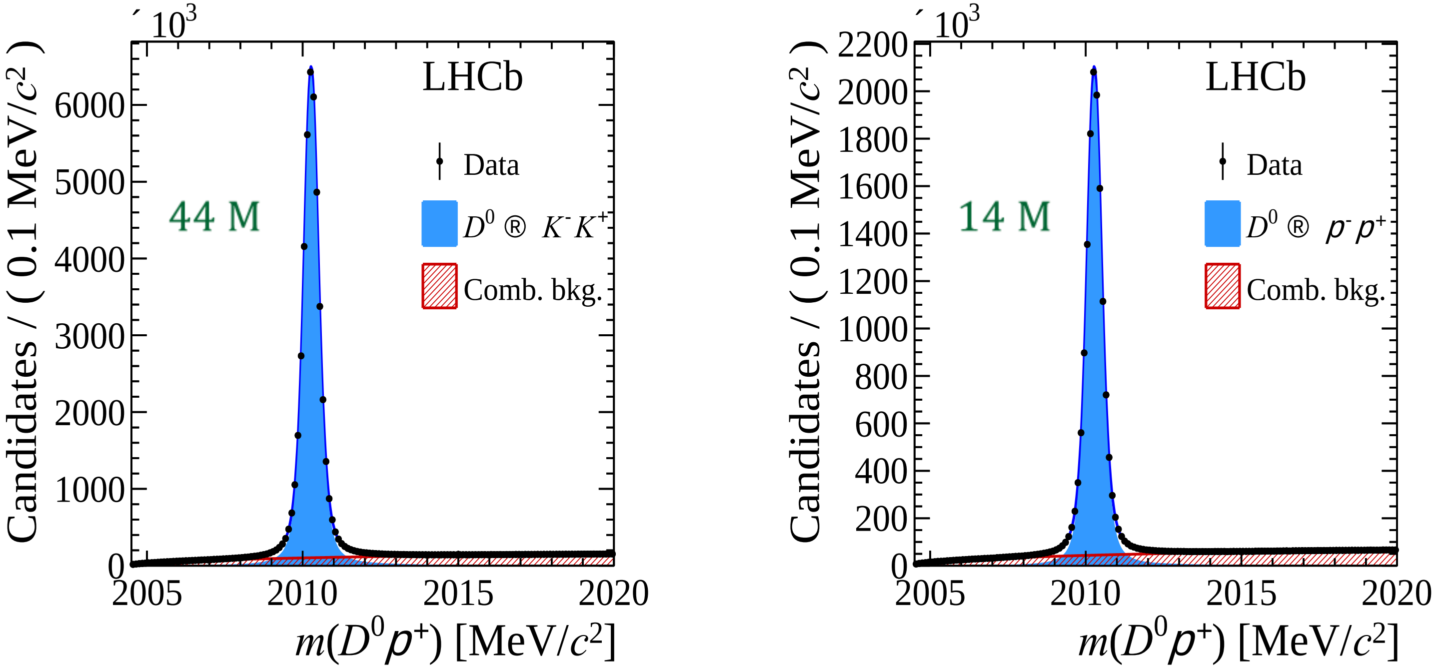


Determination of A_{raw}

In the π-tagged analysis we fit the $m(D^0\pi)$ 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 44 million signal decay for K^+K^- and 14 million for $\pi^+\pi^-$ are used.

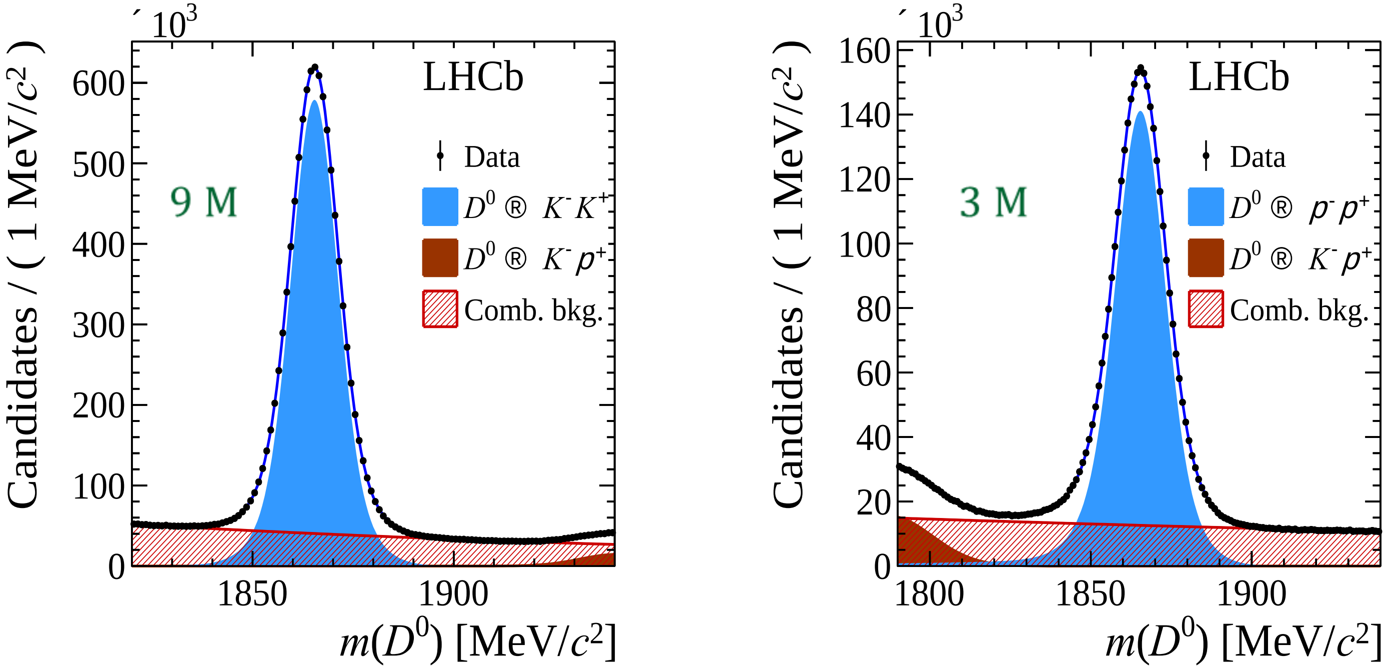


Determination of A_{raw}

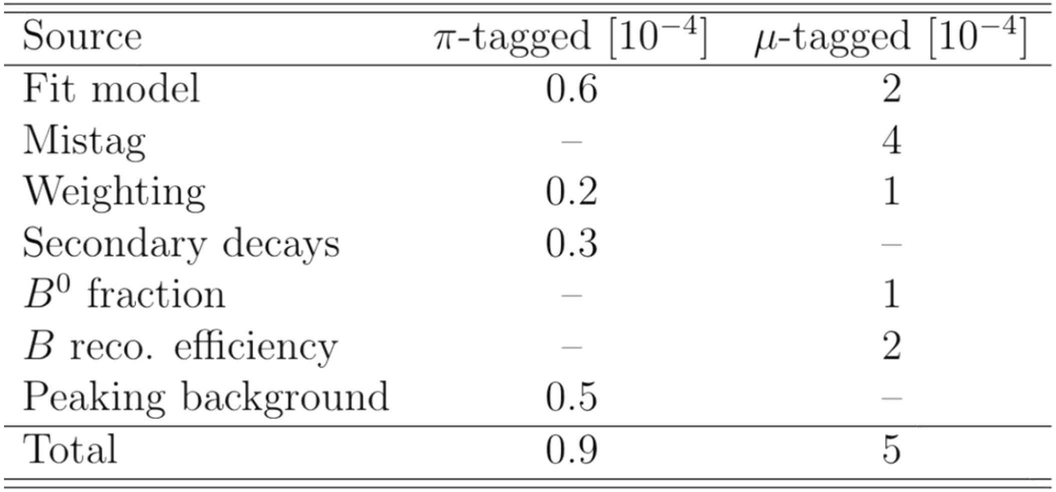
In the μ-tagged analysis we fit the *m*(D^0) distributions corresponding to the two flavour tags.

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

About 9 million signal decay 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. $D^0\to K^-\pi^+\pi^0$, $D^0\to\pi^- l^+\upsilon_l$ 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.

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

ΔA_{CP} results

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

$$\begin{aligned}\Delta A_{CP}^{\pi-\text{tagged}} &= [-18.2 \pm 3.2\,(\text{stat.}) \pm 0.9\,(\text{syst.})] \times 10^{-4} \\ \Delta A_{CP}^{\mu-\text{tagged}} &= [-9 \pm 8\,(\text{stat.}) \pm 5\,(\text{syst.})] \times 10^{-4}\end{aligned}$$

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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:

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

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

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

50+ years of CP violation

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

2019
Charm particles:
***CP* violation in D^0**
meson decays
LHCb collaboration

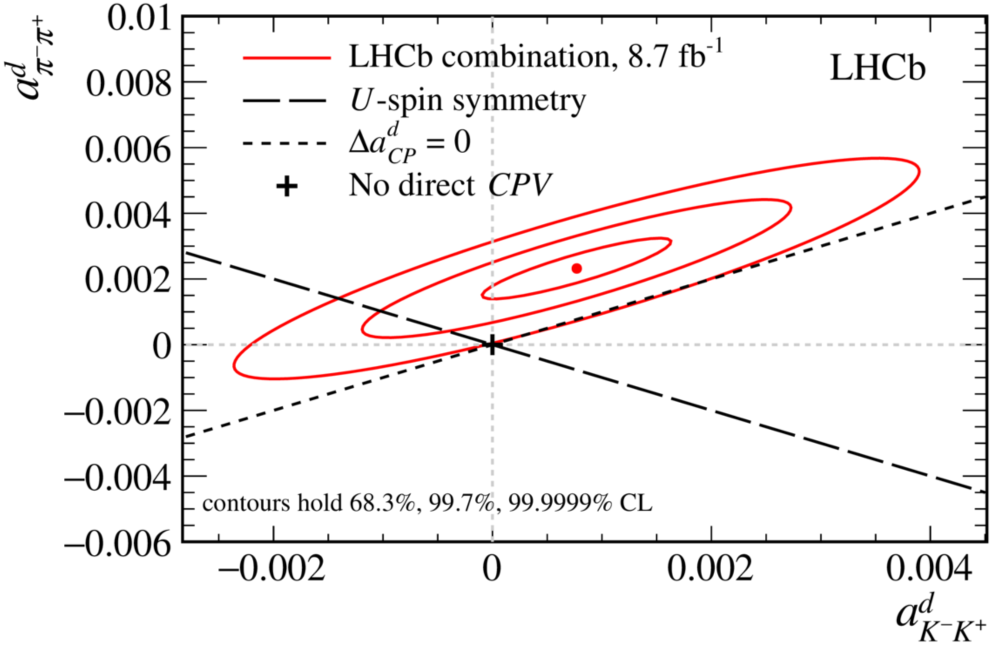
TODAY

Is the CPV coming from $D^0 \to K^+K^-$ or $D^0 \to \pi^+\pi^-$

In a recent paper [arXiv:2209.03179], LHCb has measured the CP asymmetry in $D^0 \to K^+K^-$ alone. This necessitates constraining the 'nuisance parameters' of the production and detection asymmetries from measurements in several Cabibbo-favoured control channels where the CPV is expected to be negligible.

Find $$\mathcal{A}_{CP}(K^-K^+) = [6.8 \pm 5.4\,(\text{stat}) \pm 1.6\,(\text{syst})] \times 10^{-4}$$

which, being consistent with zero, implies the ΔA_{CP} result is driven by $D^0 \to \pi^+\pi^-$.



This is somewhat surprising, as the naïve expectation (from `U-spin symmetry') is that the direct CPV in the two channels should be equal and opposite.

Await more data !

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:

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

Cinderella comes to the ball

Charm physics is now firmly re-established as a leading discipline in flavour studies.

The B factories played an critical role in initiating this revival, but is the statistical power of LHCb that has revolutionised the field.

The discovery of CP violation in decay has opened a new era in flavour studies, and the sensitivity to mixing-related CPV has now reached a very interesting level.

What we need now is a further step up in precision…

The need for improved precision

Charm is one topic where higher precision is required. There are many more:

- Improved measurements of the angle γ;
- Improved measurements of $B^0_{(s)}\rightarrow\mu\mu$;
- Studies of semi-leptonic asymmetries (not discussed here);
- Improved measurements of ϕ_s and $\sin 2\beta$;
- Further exploration of observables in electroweak penguins with muons and electrons;
- ... Many others.

Roughly ordered in terms of theoretical purity

Significant increases in precision will not come from continuing to operate the Run 1 / 2 LHCb detector. A step change in sensitivity requires radical changes.

Flavour - the road ahead

(approved experiments) (proposed experiments)

LHCb Upgrade I LHCb Upgrade II

Belle II Belle II+ ? FCC-ee …. FCC-hh

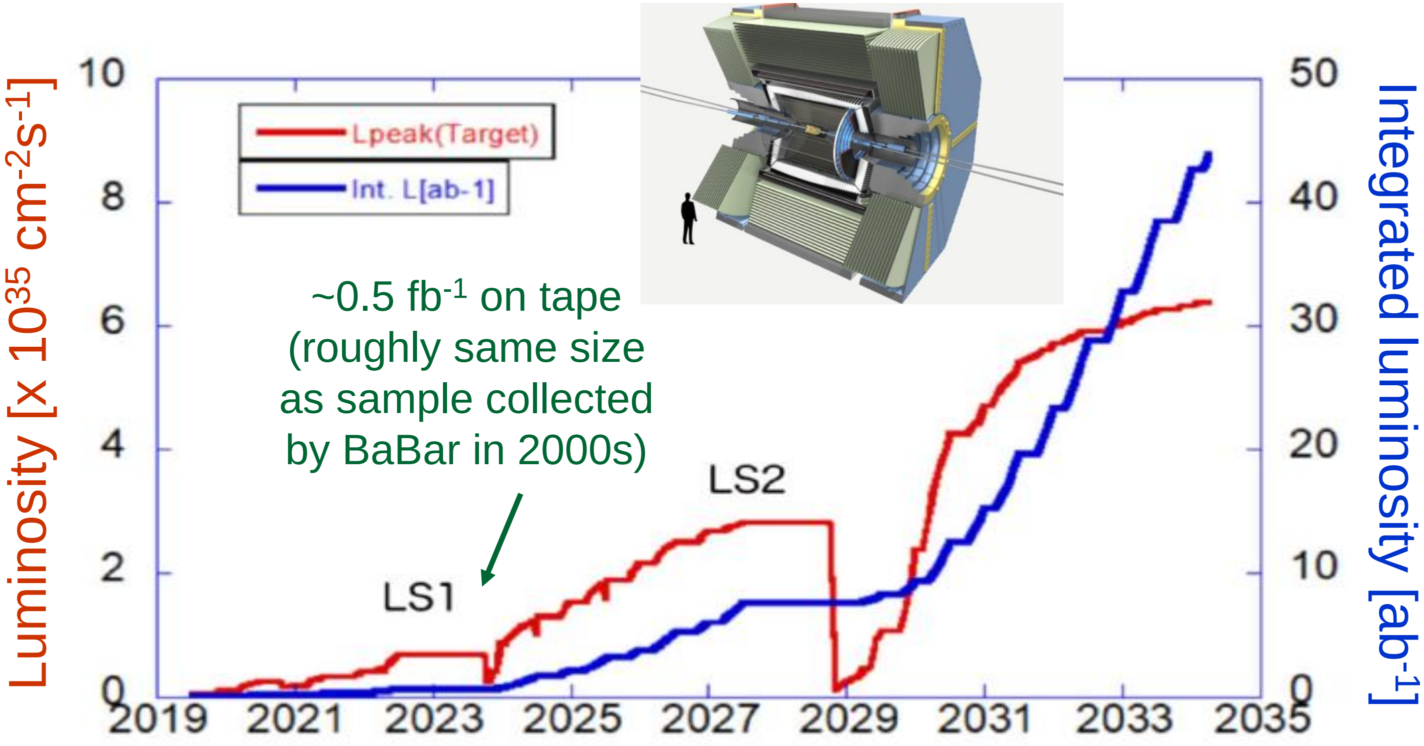
BESIII STCF CEPC …. SPPC

2020s 2030s 2040s 2070s

Meanwhile in Japan…

tifr involvement

The Belle II experiment is getting into its stride. Belle II, like LHCb, is a dedicated flavour-physics detector, but one operating in the very different environment of e^+e^- collisions. It aims to collect 5-10 ab^{-1} (5-10x Belle) by 2027, and more afterwards.

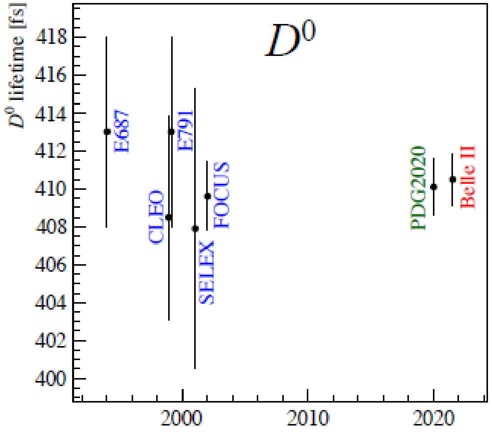


~0.5 fb^{-1} on tape (roughly same size as sample collected by BaBar in 2000s)

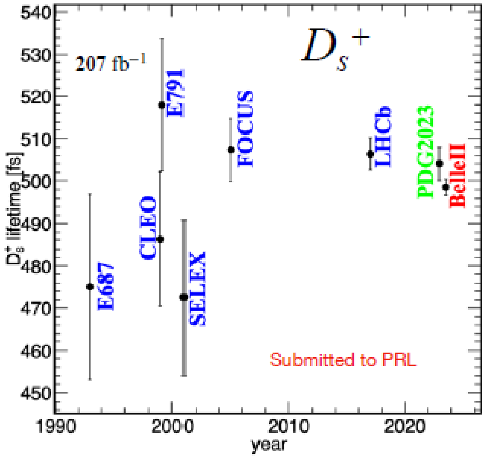
Charm-lifetime measurements

[Alan Schwartz, this conference]

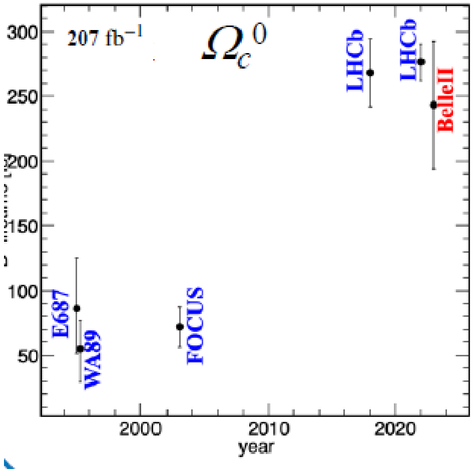
[PRL 127 (2021) 211801]

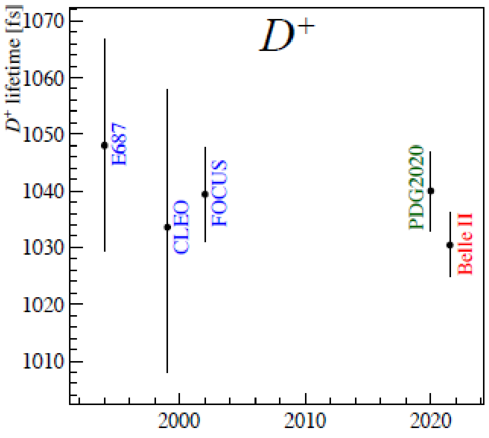


[arXiv:2306.00365]

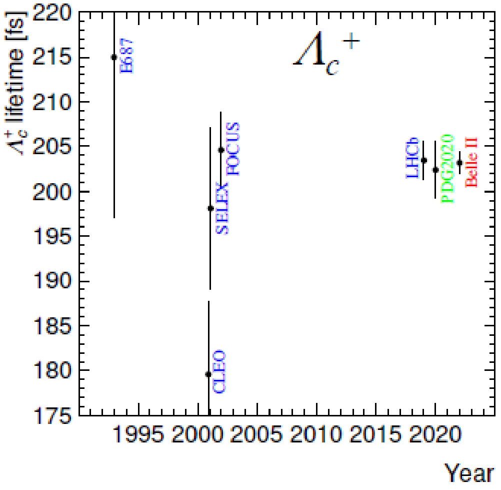


[PRD 107 (2023) L031103]





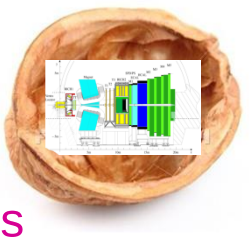
[PRL 127 (2021) 211801]



[PRL 130 (2023) 071802]

Belle II capabilities already demonstrated by series of (mostly) world-best charm lifetime measurements.

LHCb Upgrade I 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 Runs 1 & 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

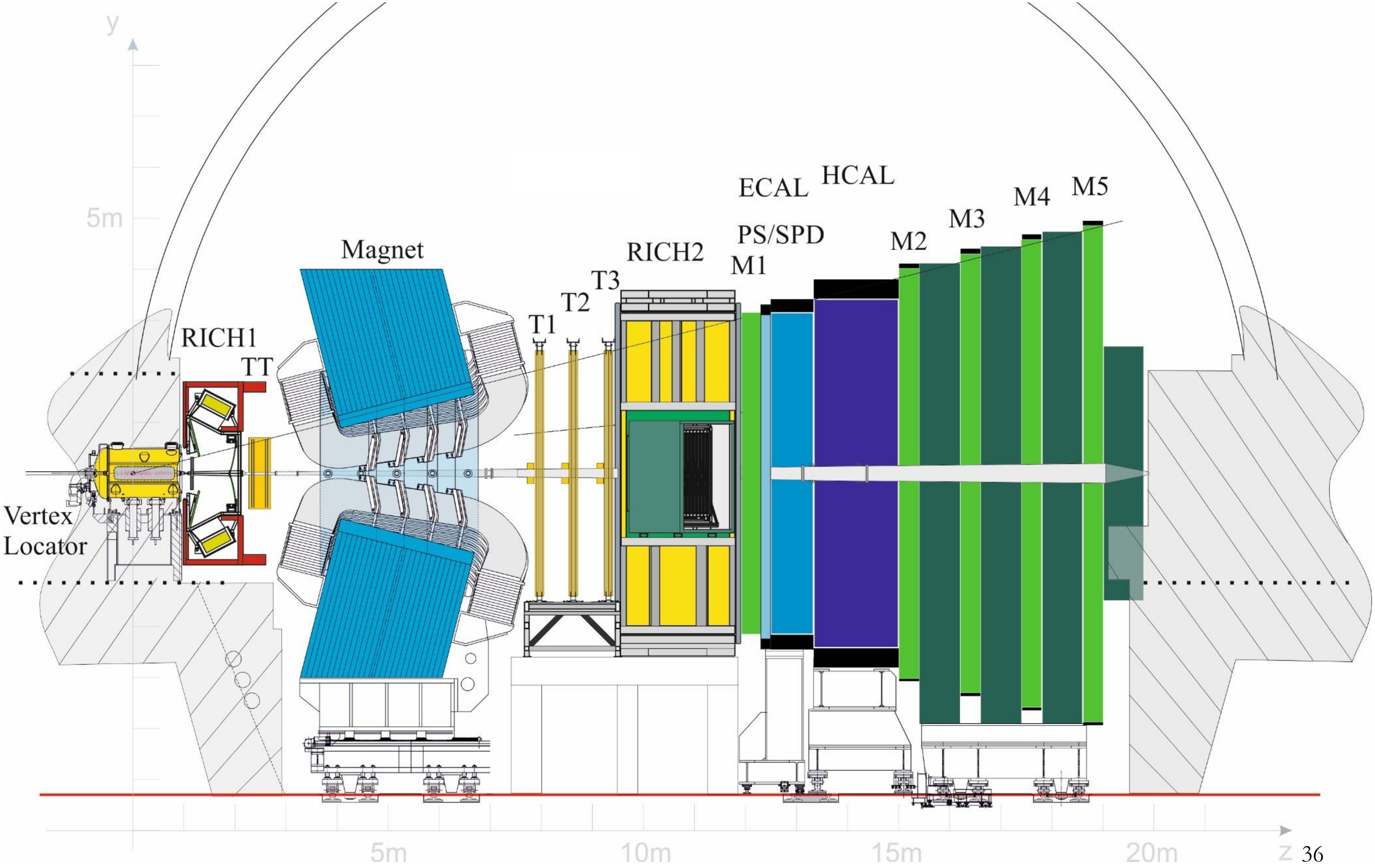
2) Raise operational luminosity to 2 x 10^{33} cm^{-2} s^{-1} (5x Run 2 value)

Necessitates redesign of several sub-detectors & overhaul of readout

Upgrade I will yield hadronic samples > 10x those available from Runs 1 & 2.

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

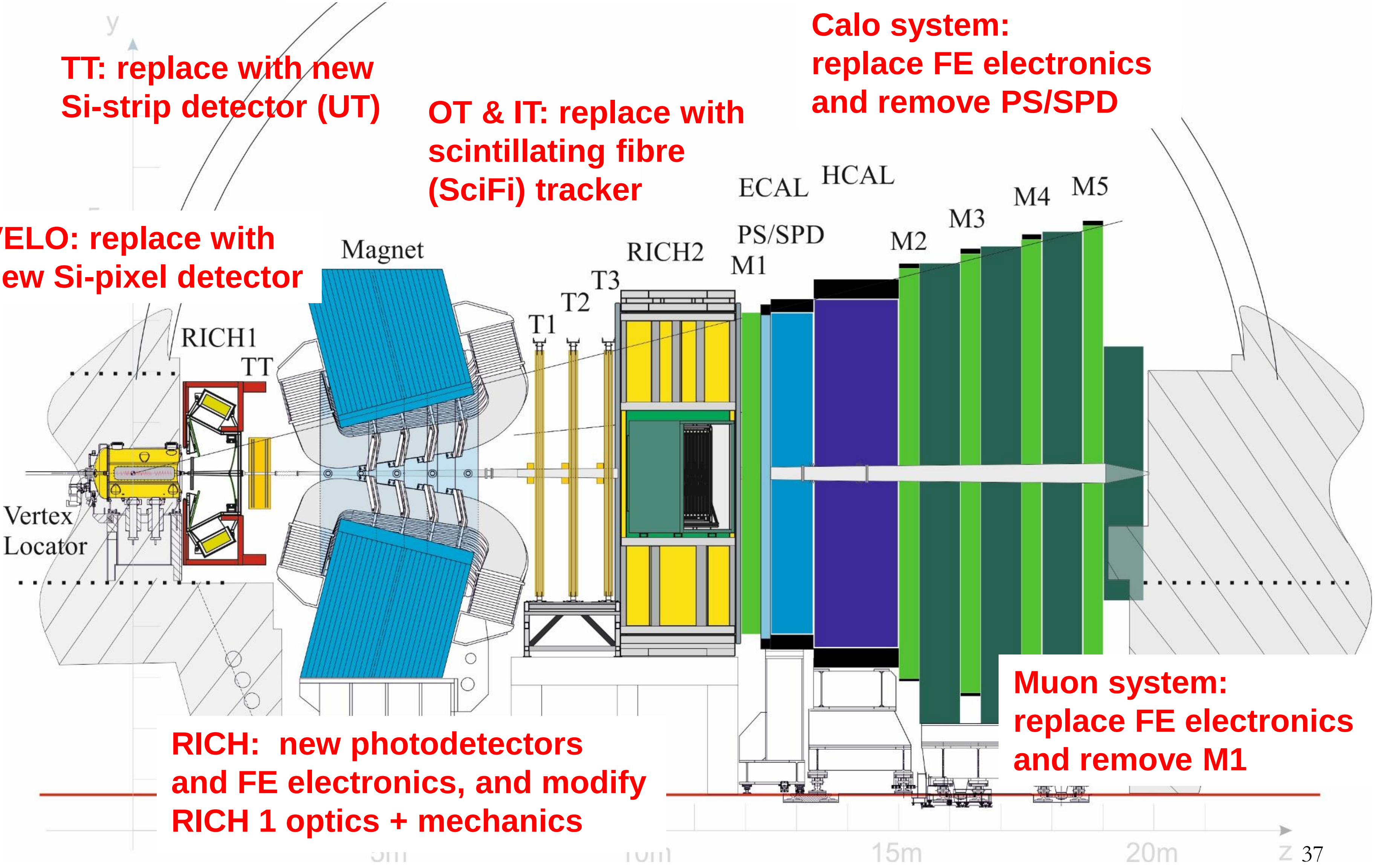
Run 1 & 2 detector



Required modifications

Full s/w trigger →

Replace read-out boards and DAQ



TT: replace with new Si-strip detector (UT)

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

Calo system: replace FE electronics and remove PS/SPD

VELO: replace with new Si-pixel detector

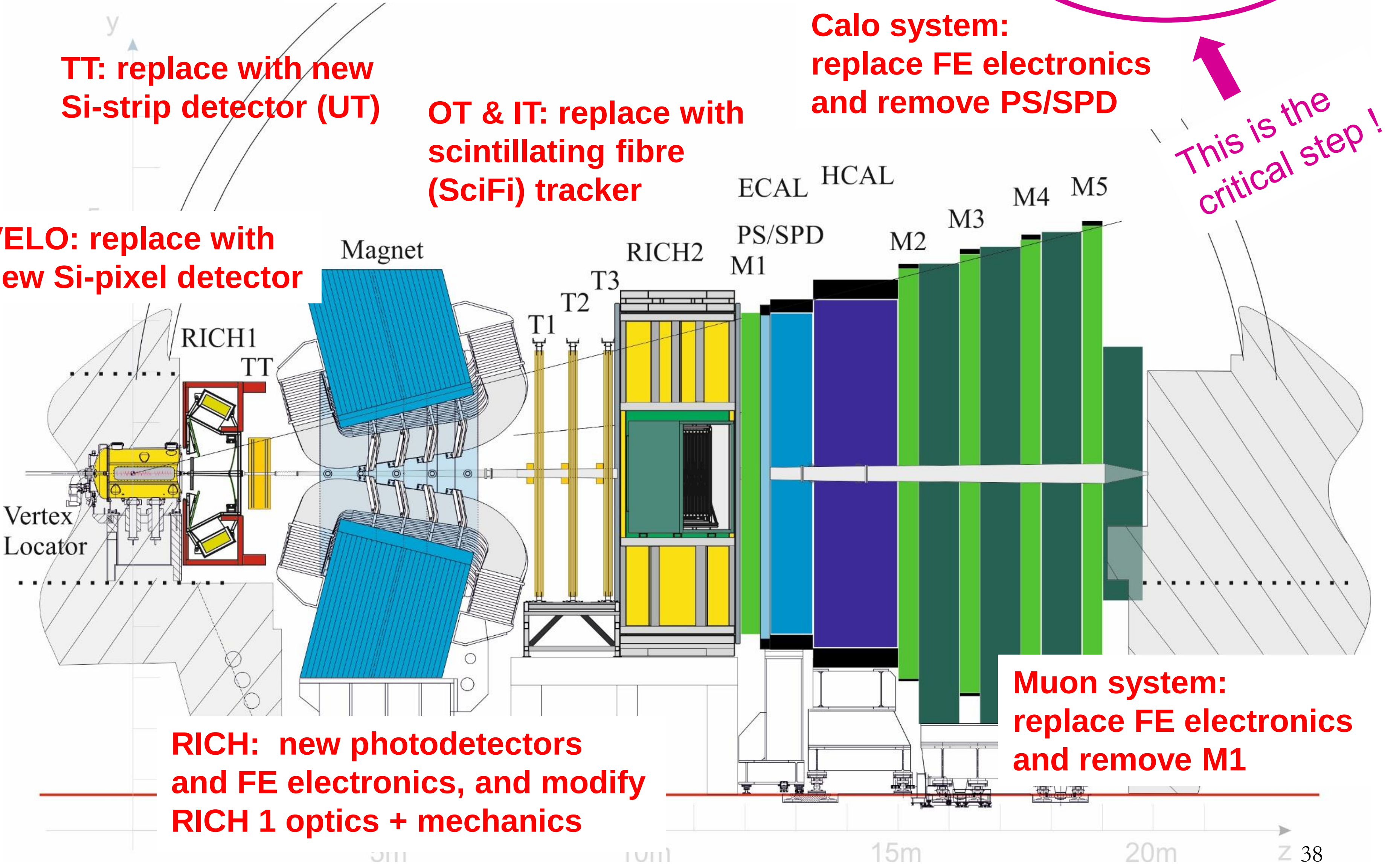
RICH: new photodetectors and FE electronics, and modify RICH 1 optics + mechanics

Muon system: replace FE electronics and remove M1

Required modifications

Full s/w trigger →
Replace read-out boards and DAQ

This is the critical step !



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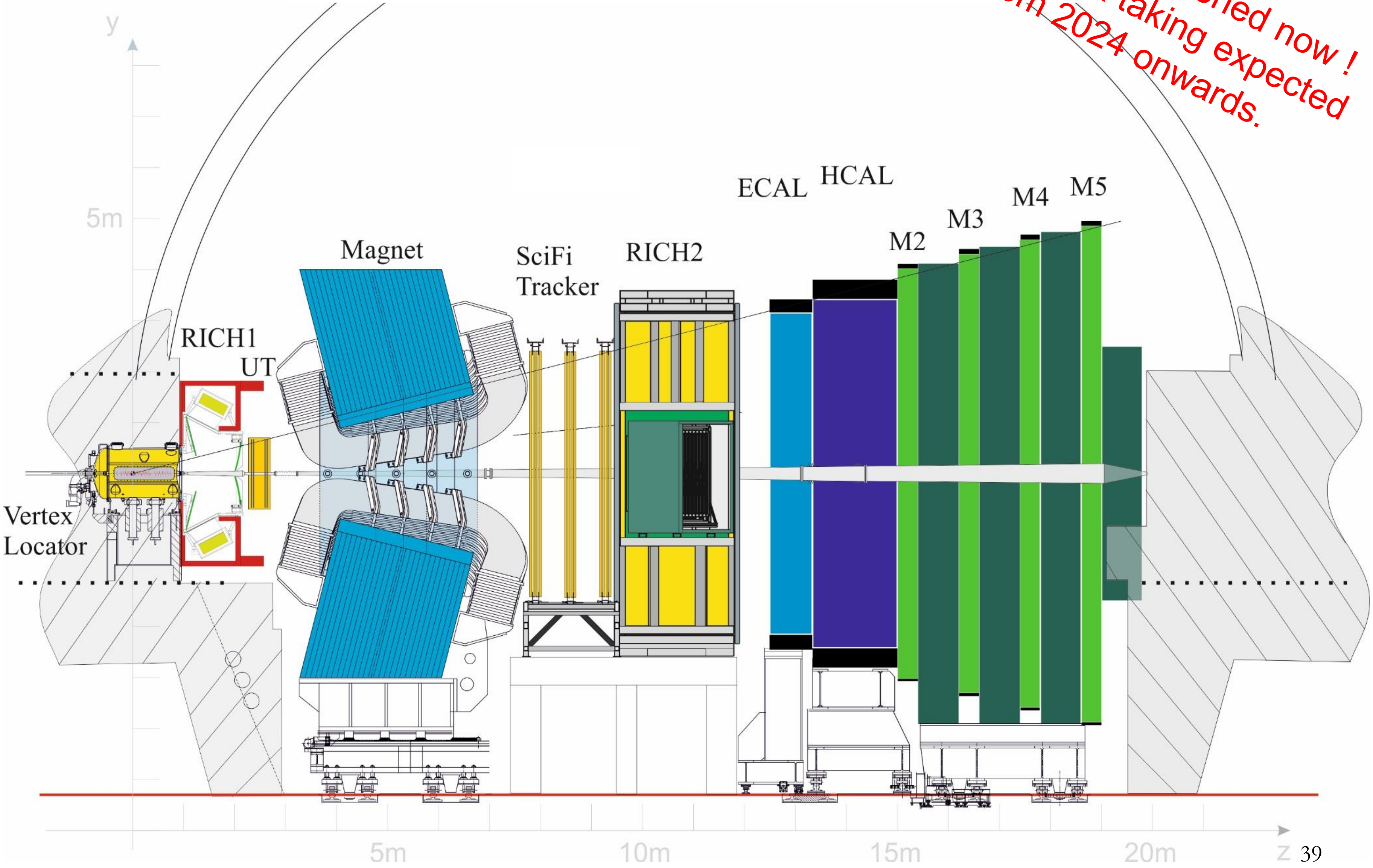
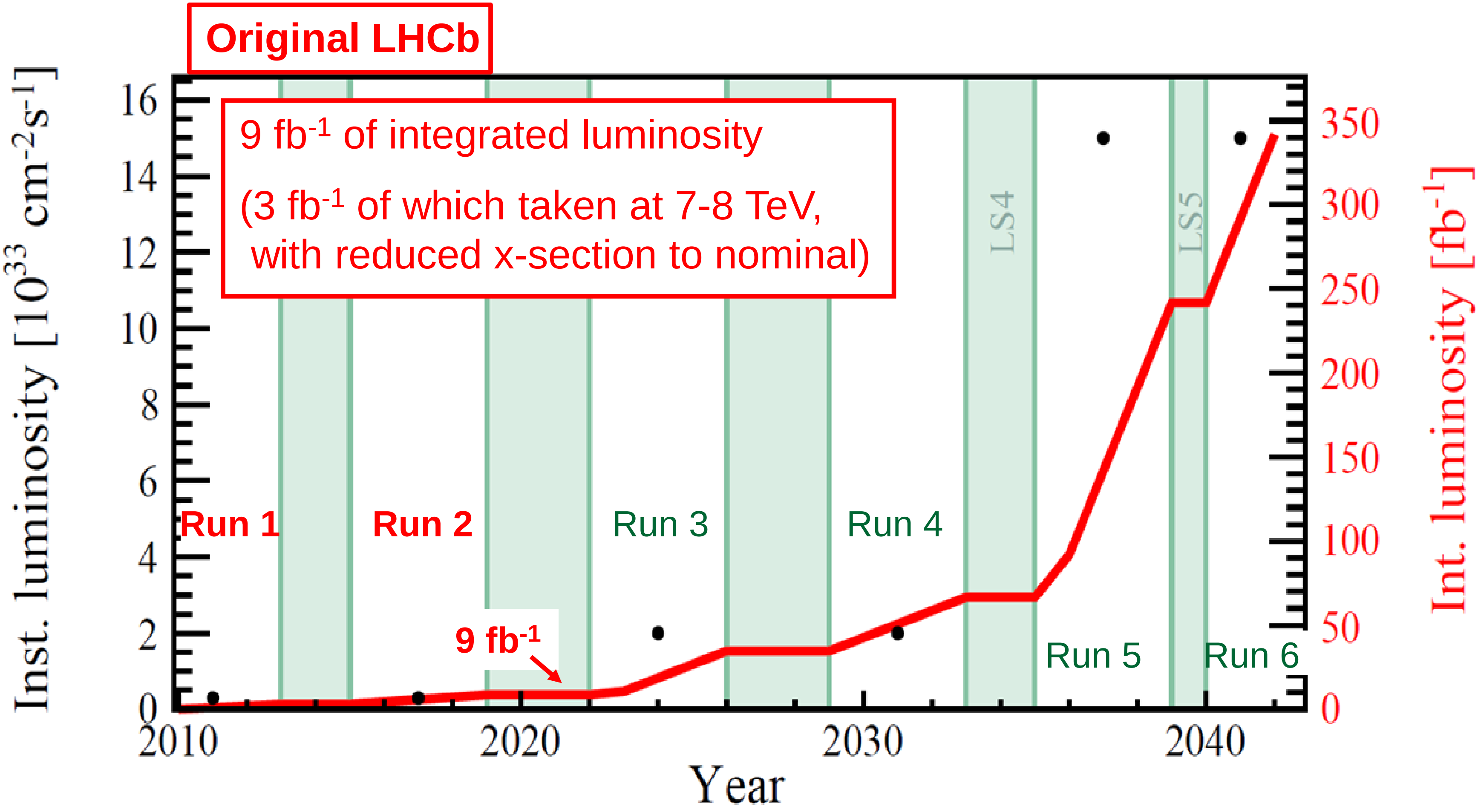
Muon system: replace FE electronics and remove M1

Upgrade I detector

Being commissioned now !
Serious data taking expected
from 2024 onwards.



LHCb timeline: Upgrades I and II



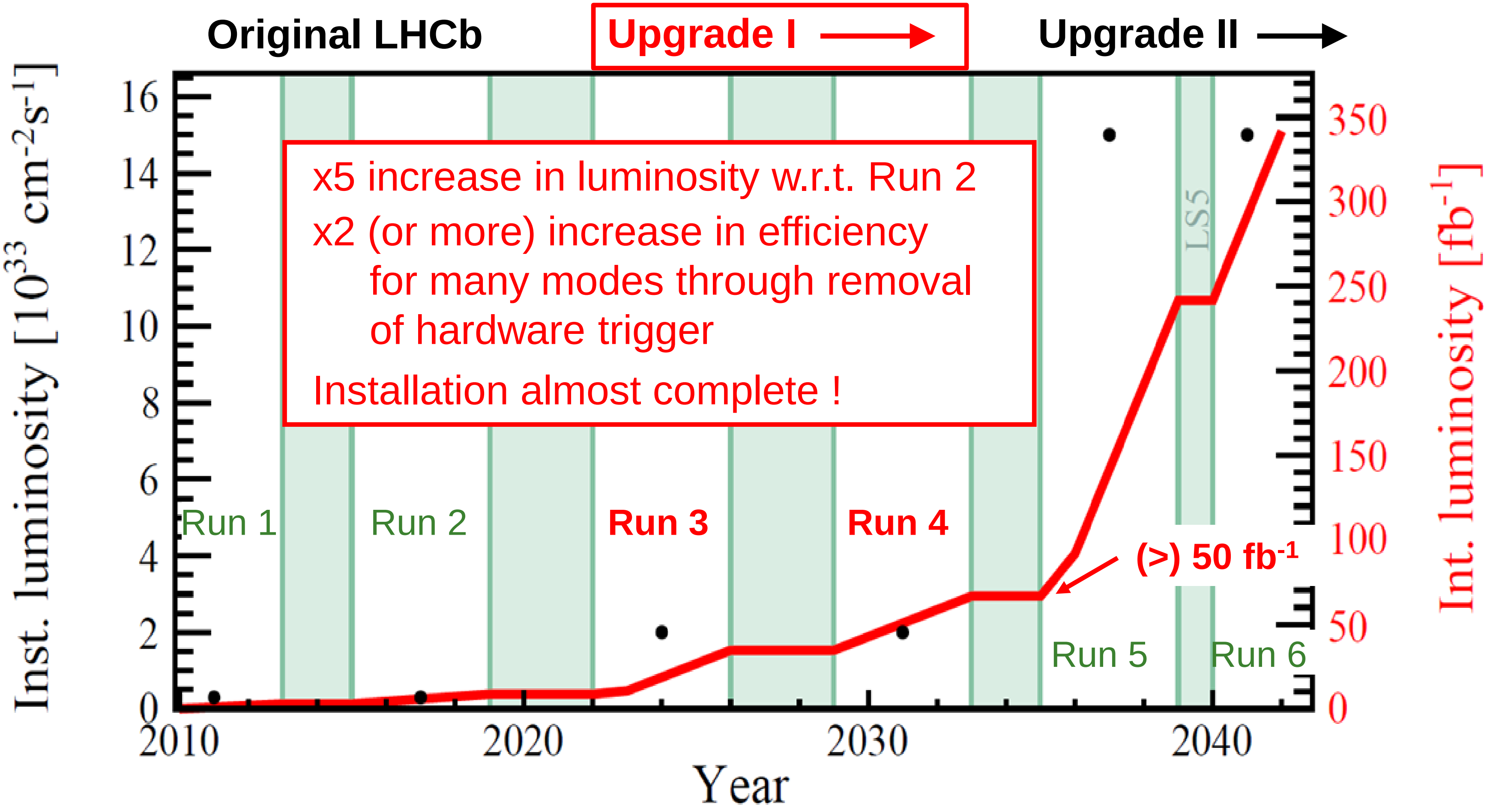
Original LHCb

9 fb^{-1} of integrated luminosity

(3 fb^{-1} of which taken at 7-8 TeV, with reduced x-section to nominal)

9 fb^{-1}

LHCb timeline: Upgrades I and II



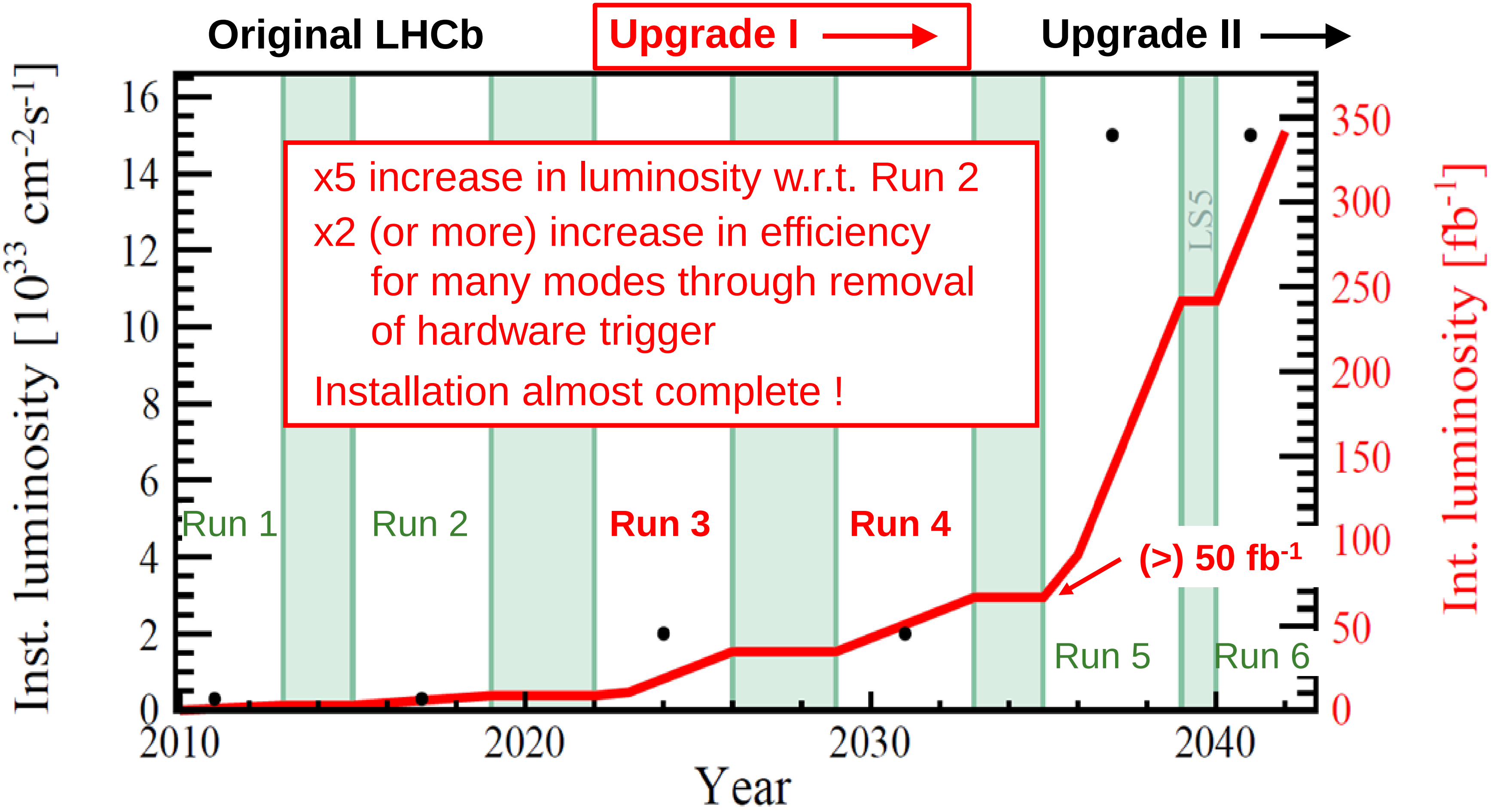
x5 increase in luminosity w.r.t. Run 2

x2 (or more) increase in efficiency for many modes through removal of hardware trigger

Installation almost complete !

LHCb timeline: Upgrades I and II

ATLAS/CMS Phase II Upgrades →



x5 increase in luminosity w.r.t. Run 2

x2 (or more) increase in efficiency for many modes through removal of hardware trigger

Installation almost complete !

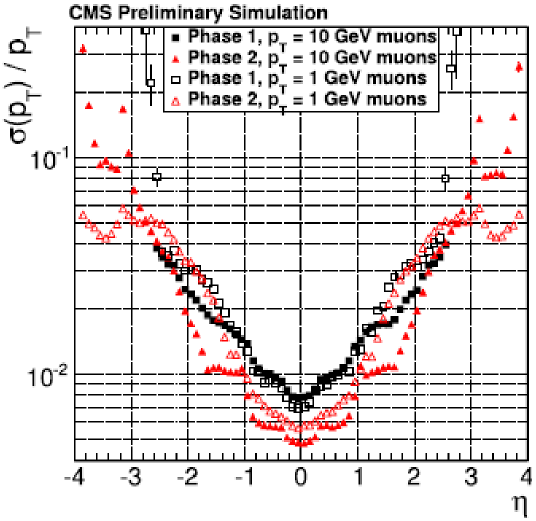
Run 4 is also when the High Luminosity LHC will begin. This makes little difference for LHCb Upgrade I, but is when ATLAS and CMS Phase II Upgrades will start.

ATLAS and CMS Phase II Upgrades

In Runs 1 and 2 ATLAS and CMS have already made high quality B-physics measurements in modes with di-muon final states.

New capabilities of experiments after Phase-II Upgrade (CMS in particular) will strengthen their capabilities in flavour physics

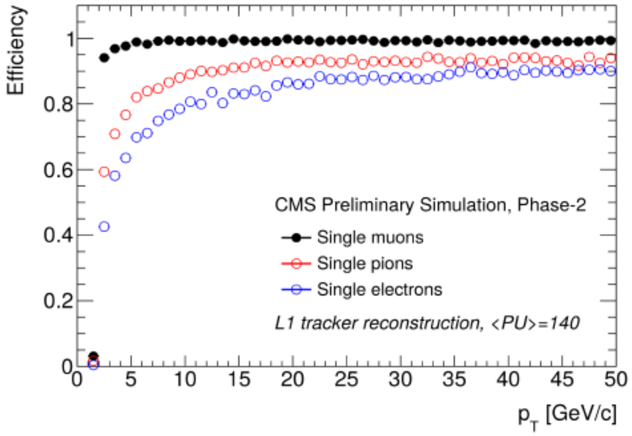
e.g. new CMS tracker



Jeremiah Mans, ECFA HL LHC, Aix-les-Bains, Oct 2014

Significantly improved p resolution

e.g. CMS new L1 track trigger

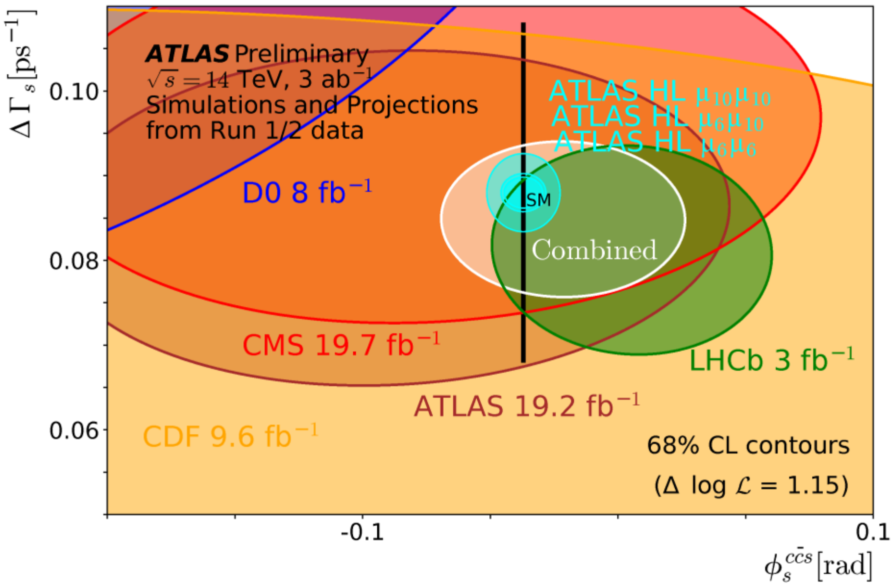


Anders Ryd, ECFA HL LHC, Aix-les-Bains, Oct 2014

Could allow CMS to accumulate large samples even in hadronic modes!

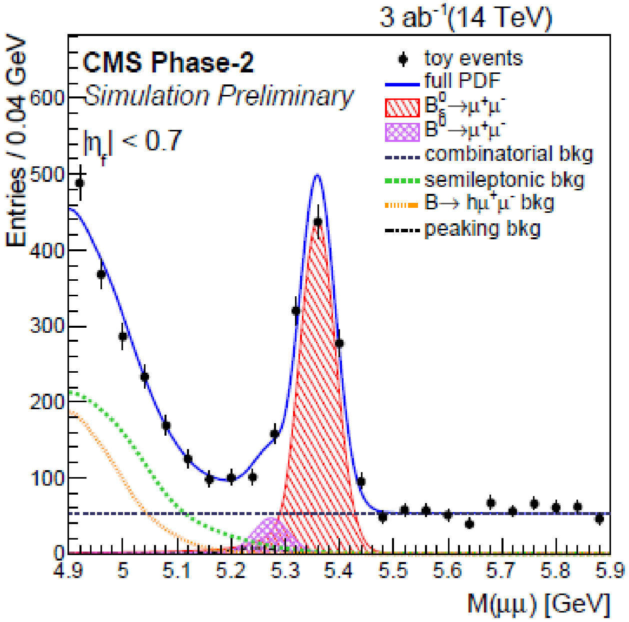
B-physics prospects at the HL-LHC with ATLAS and CMS

ATLAS prospects for φ_s with 3 ab^{-1} for different trigger thresholds.



[ATL-PHYS-PUB-2018-041]

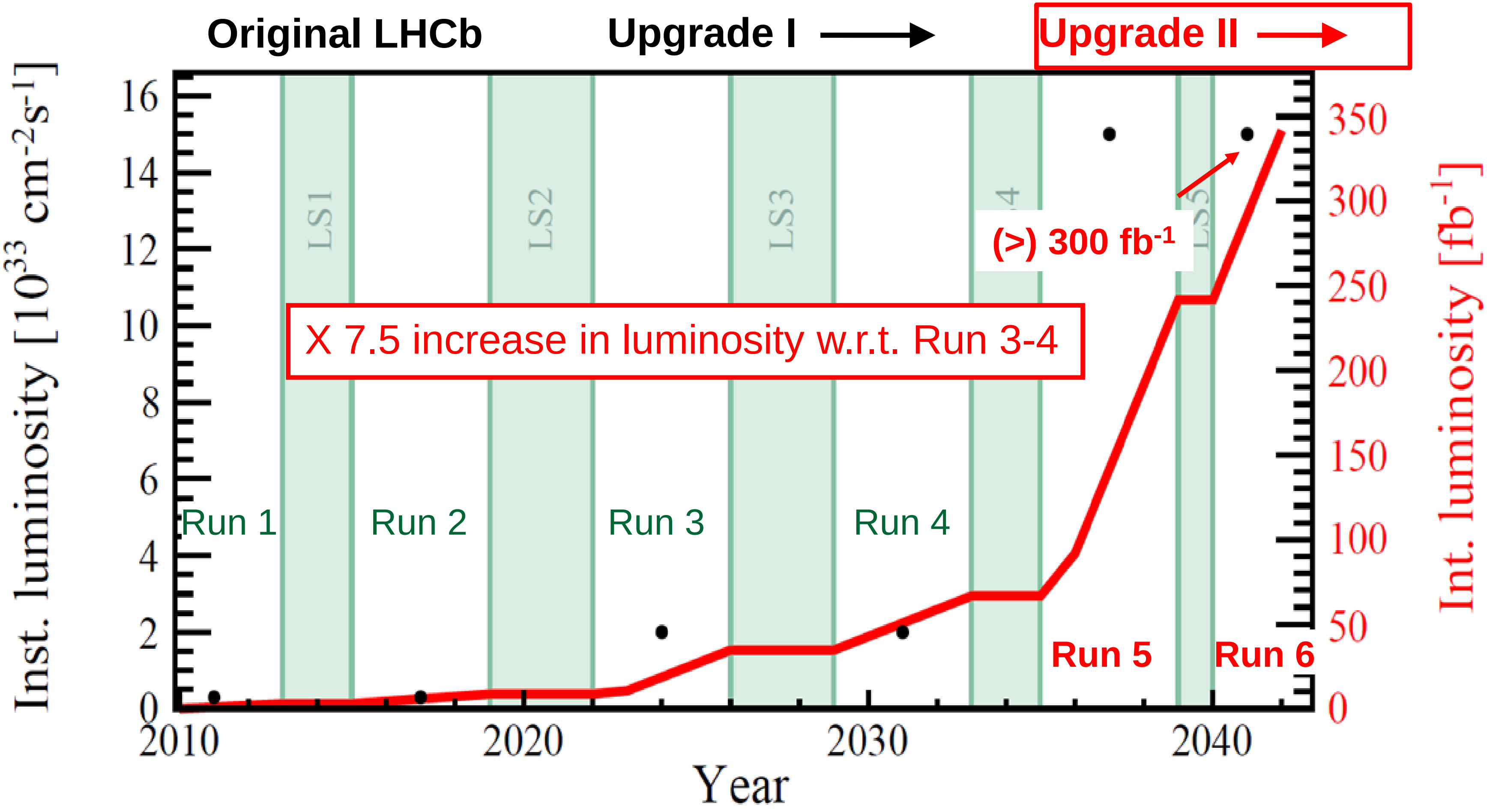
CMS prospects for $B^0_{(s)} \to \mu\mu$ in barrel region with 3 ab^{-1}.



[CMS-PAS-FTR-18-013]

Also see recent Snowmass White Paper [ATL-PHYS-PUB-2022-018,CMS-PAS-FTR-22-001].

LHCb timeline: Upgrades I and II



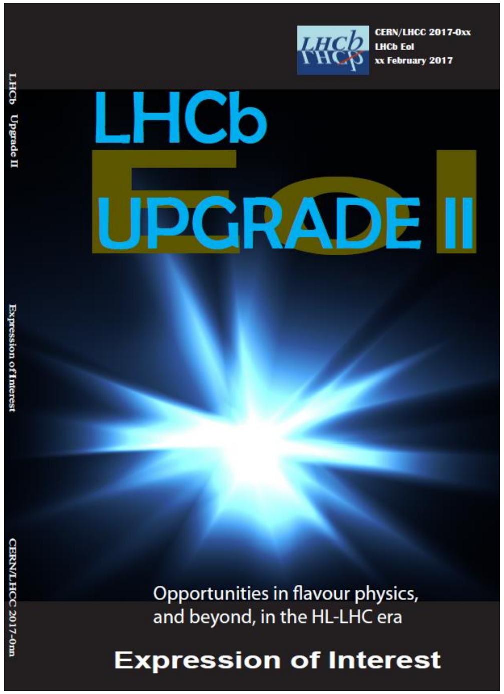
Original LHCb **Upgrade I** → **Upgrade II** →

X 7.5 increase in luminosity w.r.t. Run 3-4

(>) 300 fb^{-1}

LHCb Upgrade II

Steady progress towards plans for an Upgrade II, that will operate in Runs 5 and 6.



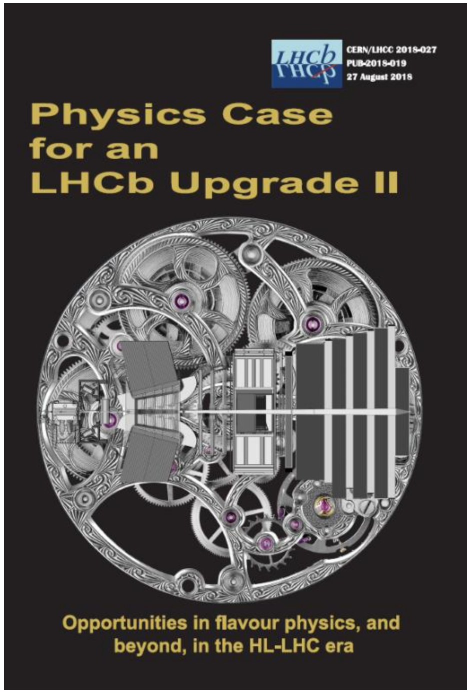
CERN/LHCC 2017-0xx
LHCb EoI
xx February 2017

LHCb
UPGRADE II
EoI

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

Expression of Interest

LHCb Upgrade II Expression of Interest CERN/LHCC 2017-0xx



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 2021-012
LHCb TDR 23
24 February 2022

Framework
LHCb
UPGRADE II
TDR

[CERN-LHCC-2017-003] [CERN-LHCC-2018-027] [CERN-LHCC-2021-012]

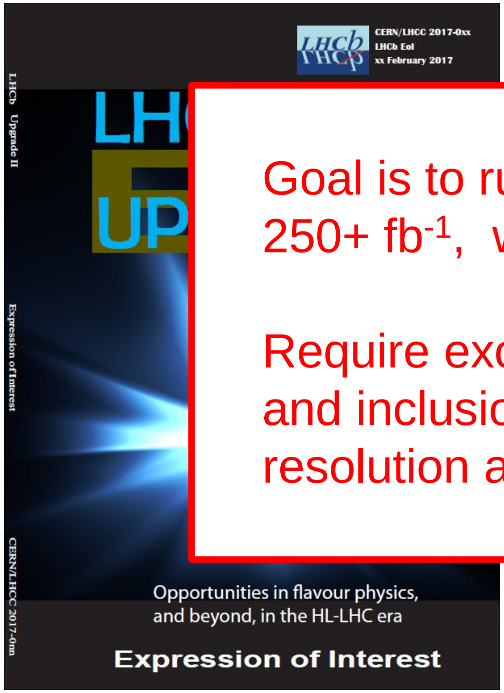
Now part of the CERN baseline plan. Framework TDR recently approved by LHCC.

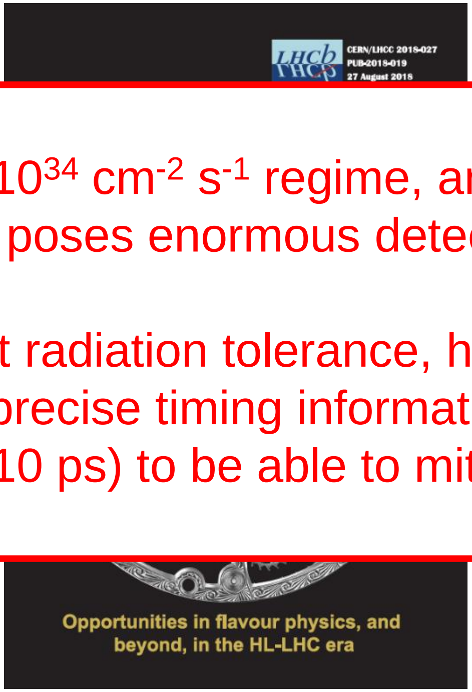
LHCb Upgrade II

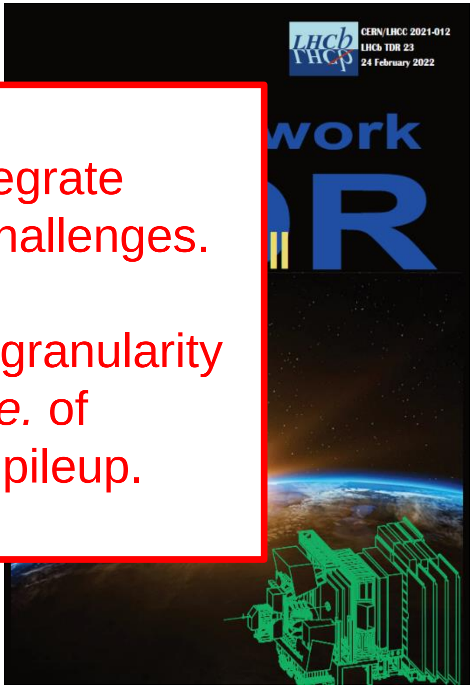
Steady progress towards plans for an Upgrade II, that will operate in Runs 5 and 6.

Goal is to run in 10^{34} cm^{-2} s^{-1} regime, and integrate 250+ fb^{-1}, which poses enormous detector challenges.

Require excellent radiation tolerance, higher granularity and inclusion of precise timing information (*i.e.* of resolution a few 10 ps) to be able to mitigate pileup.



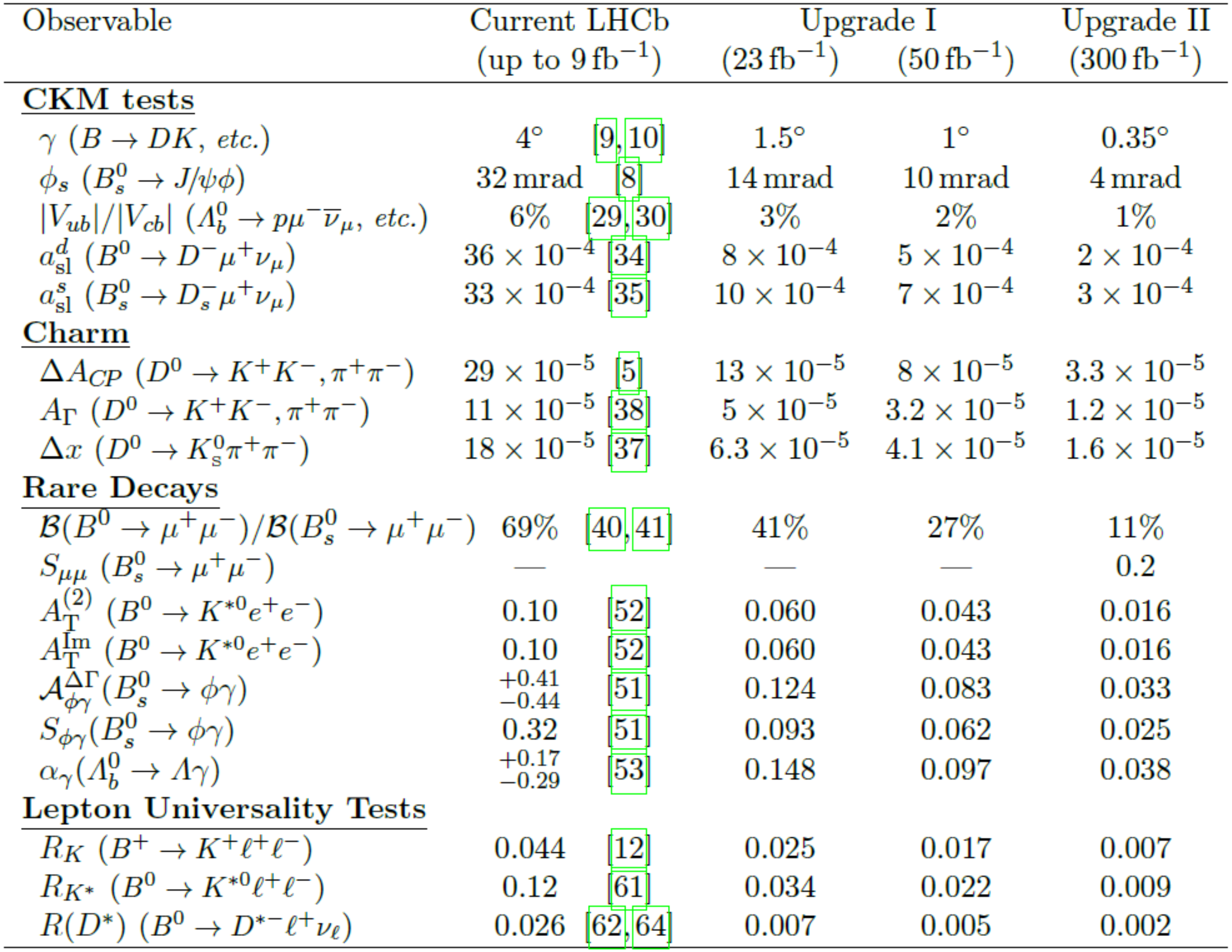




[CERN-LHCC-2017-003] [CERN-LHCC-2018-027] [CERN-LHCC-2021-012]

Now part of the CERN baseline plan. Framework TDR recently approved by LHCC.

Projected uncertainties for representative observables

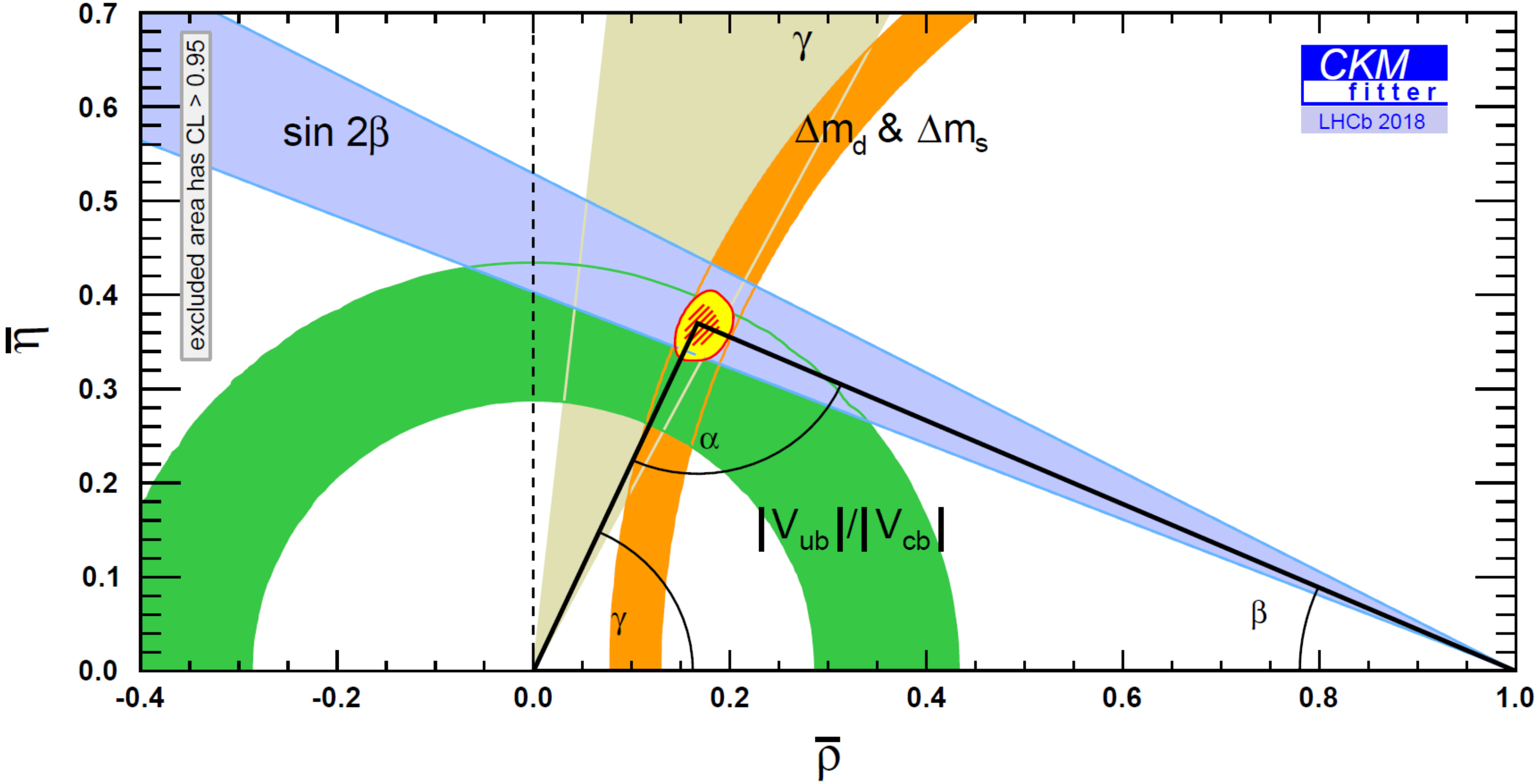


Observable	Current LHCb (up to 9 fb^{-1})	Upgrade I (23 fb^{-1})	Upgrade I (50 fb^{-1})	Upgrade II (300 fb^{-1})
CKM tests				
γ ($B \to DK$, *etc.*)	4° [9, 10]	1.5°	1°	0.35°
ϕ_s ($B^0_s \to J/\psi\phi$)	32 mrad [8]	14 mrad	10 mrad	4 mrad
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda^0_b \to p\mu^-\overline{\nu}_\mu$, *etc.*)	6% [29, 30]	3%	2%	1%
a^d_{sl} ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4} [34]	8×10^{-4}	5×10^{-4}	2×10^{-4}
a^s_{sl} ($B^0_s \to D^-_s\mu^+\nu_\mu$)	33×10^{-4} [35]	10×10^{-4}	7×10^{-4}	3×10^{-4}
Charm				
ΔA_{CP} ($D^0 \to K^+K^-, \pi^+\pi^-$)	29×10^{-5} [5]	13×10^{-5}	8×10^{-5}	3.3×10^{-5}
A_Γ ($D^0 \to K^+K^-, \pi^+\pi^-$)	11×10^{-5} [38]	5×10^{-5}	3.2×10^{-5}	1.2×10^{-5}
Δx ($D^0 \to K^0_{\text{S}}\pi^+\pi^-$)	18×10^{-5} [37]	6.3×10^{-5}	4.1×10^{-5}	1.6×10^{-5}
Rare Decays				
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$	69% [40, 41]	41%	27%	11%
$S_{\mu\mu}$ ($B^0_s \to \mu^+\mu^-$)	—	—	—	0.2
$A^{(2)}_{\text{T}}$ ($B^0 \to K^{*0}e^+e^-$)	0.10 [52]	0.060	0.043	0.016
A^{Im}_{T} ($B^0 \to K^{*0}e^+e^-$)	0.10 [52]	0.060	0.043	0.016
$\mathcal{A}^{\Delta\Gamma}_{\phi\gamma}(B^0_s \to \phi\gamma)$	$^{+0.41}_{-0.44}$ [51]	0.124	0.083	0.033
$S_{\phi\gamma}(B^0_s \to \phi\gamma)$	0.32 [51]	0.093	0.062	0.025
$\alpha_\gamma(\Lambda^0_b \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$ [53]	0.148	0.097	0.038
Lepton Universality Tests				
R_K ($B^+ \to K^+\ell^+\ell^-$)	0.044 [12]	0.025	0.017	0.007
R_{K^*} ($B^0 \to K^{*0}\ell^+\ell^-$)	0.12 [61]	0.034	0.022	0.009
$R(D^*)$ ($B^0 \to D^{*-}\ell^+\nu_\ell$)	0.026 [62, 64]	0.007	0.005	0.002

[CERN-LHCC-2021-012]

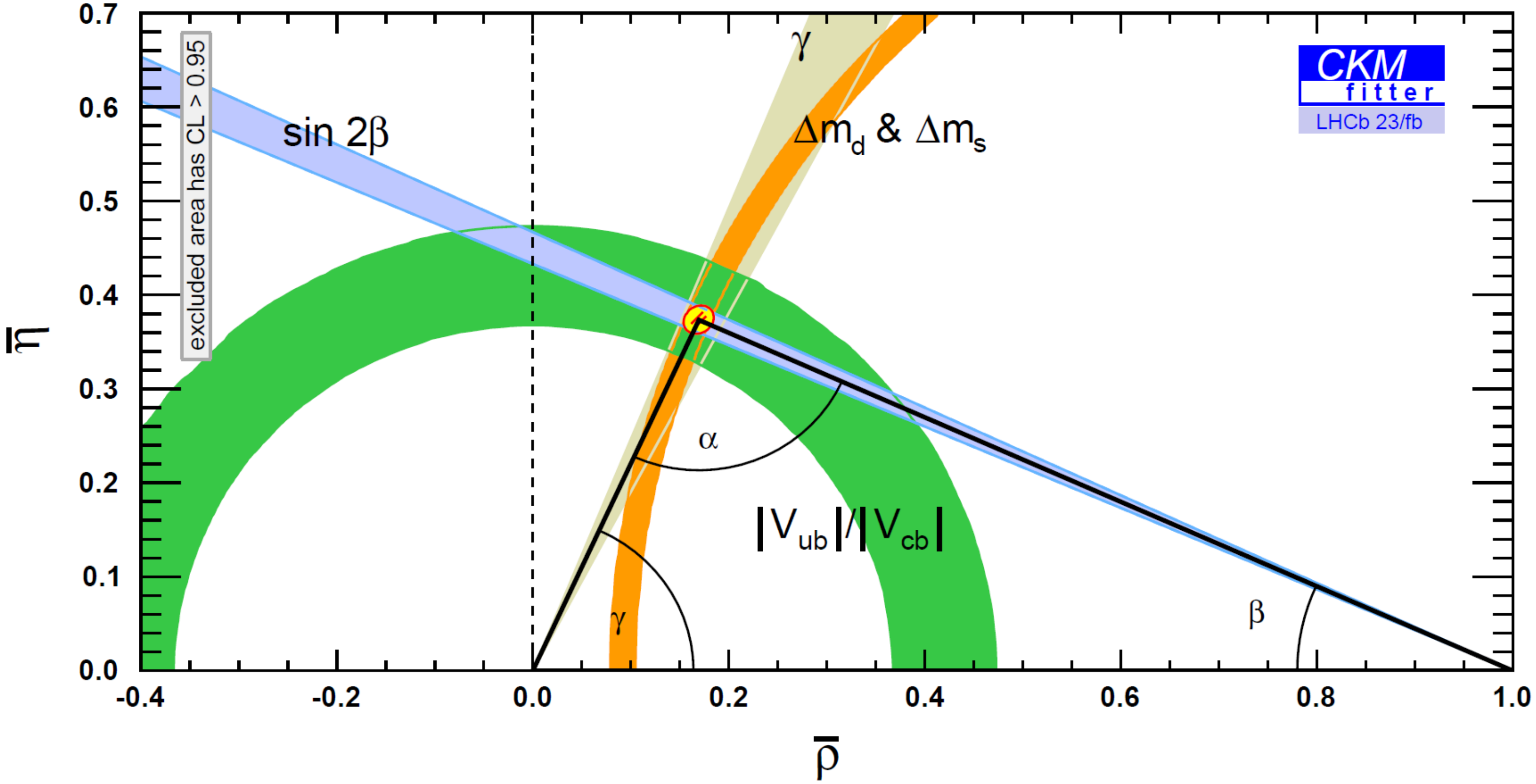
Evolution of constraints on Unitarity Triangle

UT plotted using constraints from LHCb alone (+ lattice QCD): 2018 status



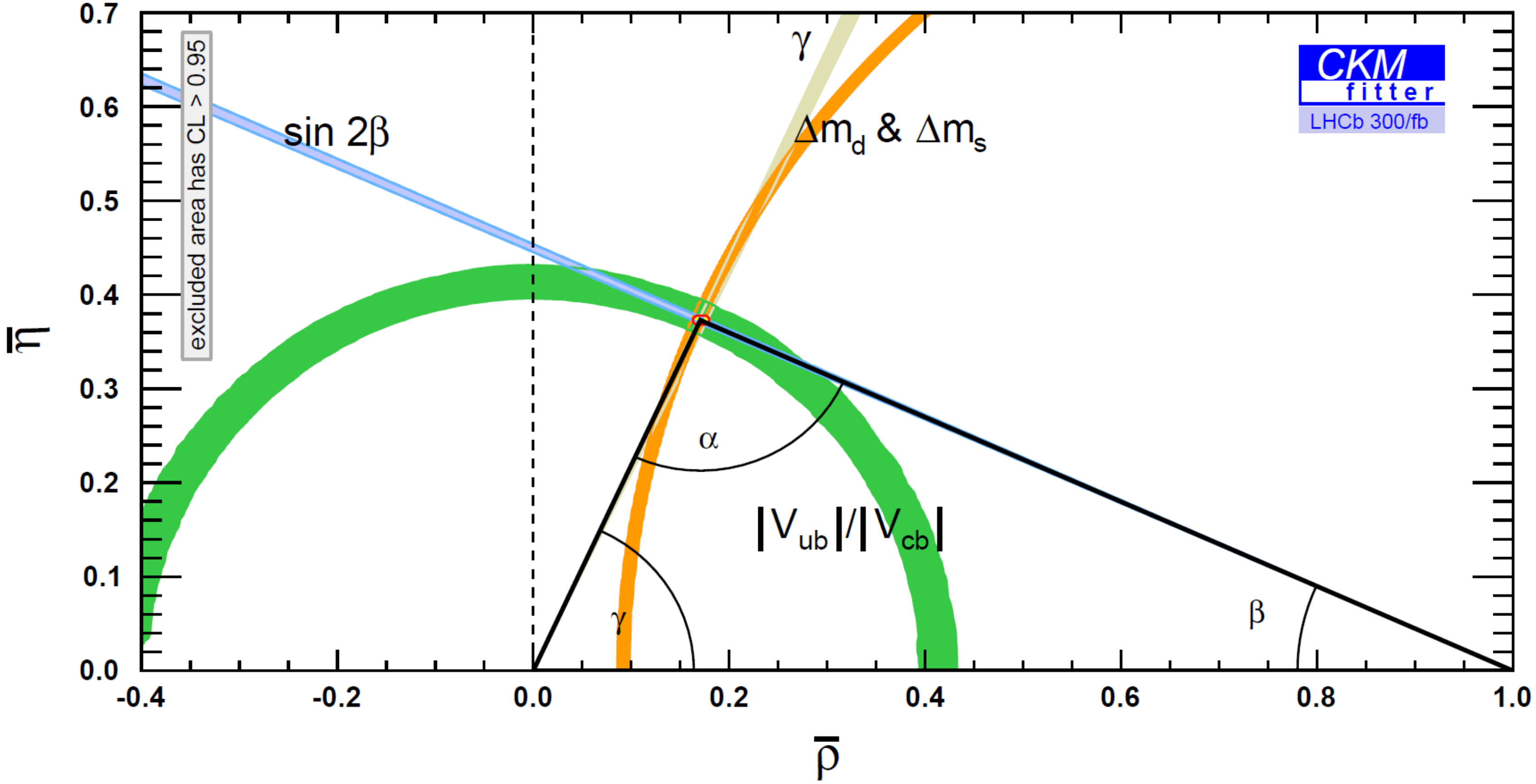
Evolution of constraints on Unitarity Triangle

UT plotted using constraints from LHCb alone (+ lattice QCD): start of HL-LHC



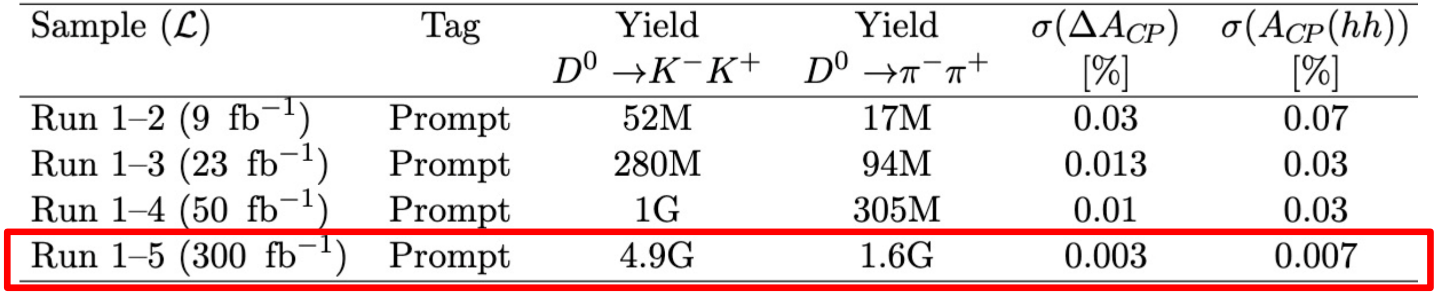
Evolution of constraints on Unitarity Triangle

UT plotted using constraints from LHCb alone (+ lattice QCD): after Upgrade II



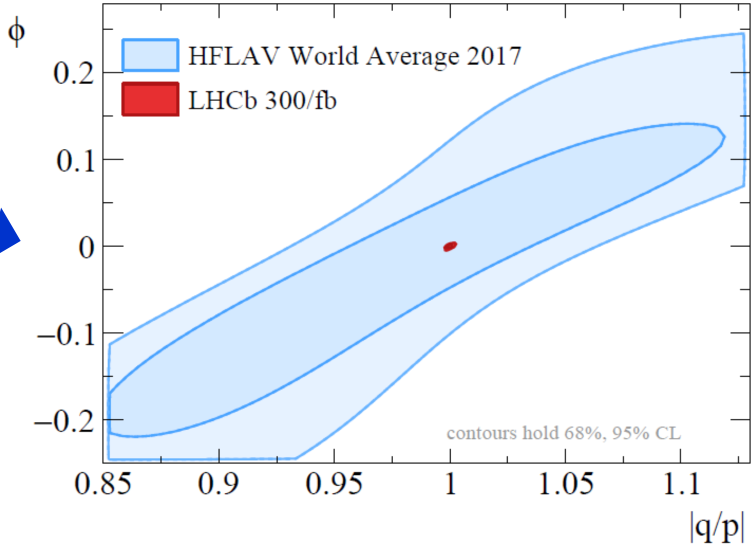
Charm physics potential of LHCb Upgrade II

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).



Flavour physics beyond the LHC

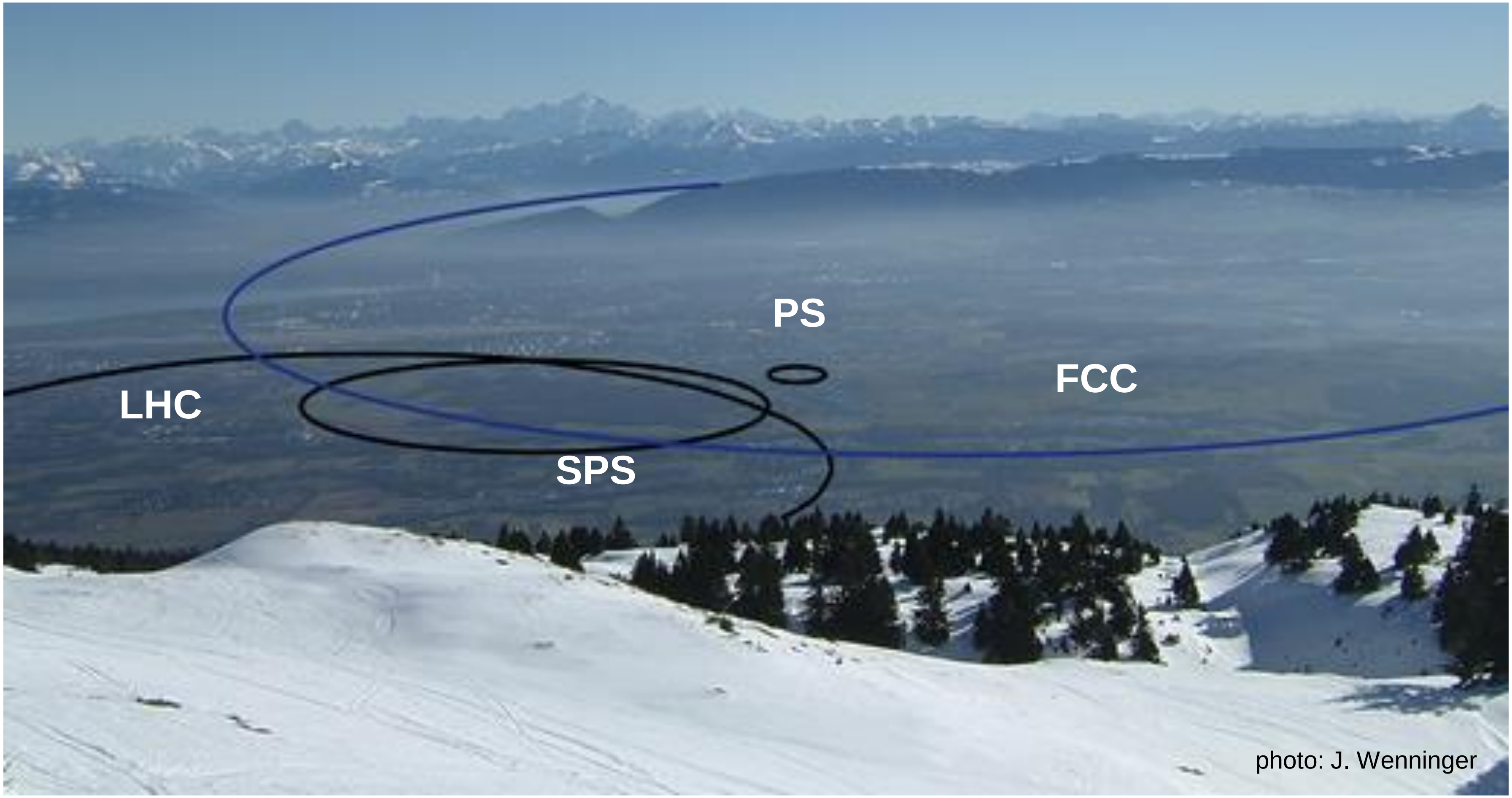


photo: J. Wenninger

Flavour physics opportunities at the FCC

The Future Circular Collider (FCC) is a CERN project currently undergoing a 5 year feasibility study, that would begin operation in the 2040s. A tunnel of 90+ km would be constructed that would house two consecutive accelerators.

FCC-ee

A very high luminosity e^+e^- machine that would operate at a range of collision energies, including the Z pole where 10^{12} $b\bar{b}$ pairs would be produced. Exceptional flavour-physics opportunities.

FCC-hh

A hadron collider with E_{CM} ~ 100 TeV and luminosity 3×10^{35} cm^{-2} s^{-1}. The ring would be equipped with two general purpose detectors, in the spirit of ATLAS and CMS, but would also have dedicated interaction regions for other physics, including flavour. A new-generation experiment (FCCb ?) would benefit from the higher cross section, and the advances in technology and computing that will occur in the coming decades. FCCb >> LHCb !

Conclusions, part 1

Charm physics has had a renaissance in recent years and is once more a vibrant and frontier area of flavour studies.

LHCb has played a leading role in this revival, with super-precise mixing measurements and the discovery of direct CPV being highlights.

Only LHCb has the precision to refine these measurements and probe for the next breakthrough, *e.g.* CPV in mixing-related phenomena.

Conclusions, part 2

Despite the huge increase in precision the LHC has brought for many flavour observables, there is strong motivation to increase the sensitivity still further.

LHCb Upgrade I, now being commissioned will bring this increase in precision. Many complementary results are expected (and starting to arrive) from Belle II.

Further progress will be enabled by the Phase II Upgrades of ATLAS and CMS, with a step change coming from Upgrade II of LHCb – this will complete the full exploitation of the LHC as a flavour factory.

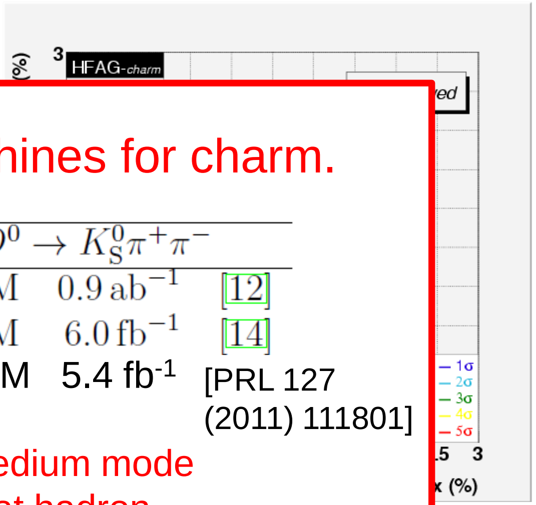
Looking still further forward, the FCC (both –ee and –hh) will open a new frontier for flavour studies.

Backups

A rekindling of interest, and the rise of the hadron machines

As the B factory results firmed up, the picture changed very rapidly.

Excluded regions



The
that
was
para

Without question, hadron colliders are the go-to machines for charm.

	$D^0 \to K^+\pi^-$			$D^0 \to \pi^+\pi^-\pi^0$			$D^0 \to K^0_S\pi^+\pi^-$		
BaBar/Belle	11.5k	$1.0\,\mathrm{ab}^{-1}$	[10]	126k	$0.5\,\mathrm{ab}^{-1}$	[11]	1.2M	$0.9\,\mathrm{ab}^{-1}$	[12]
CDF	32.7k	$9.6\,\mathrm{fb}^{-1}$	[13]		/		0.3M	$6.0\,\mathrm{fb}^{-1}$	[14]
LHCb	722k	$5.0\,\mathrm{fb}^{-1}$	[15]	566k	$2.0\,\mathrm{fb}^{-1}$	[16]	30.6M	$5.4\,\mathrm{fb}^{-1}$	[PRL 127 (2011) 111801]

‘Easy’ mode at hadron machine

Hard mode at hadron machine

Medium mode at hadron machine

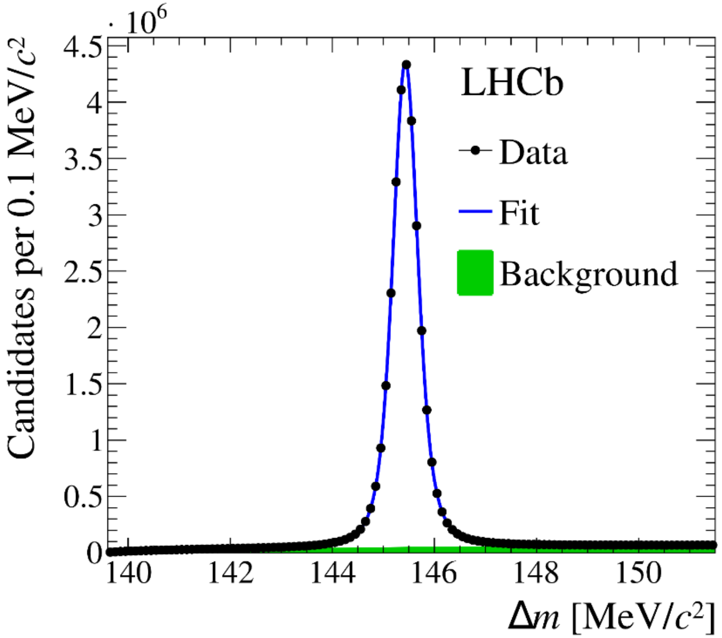
(see arXiv:2011.04443 for references)

This
part
whe

e.g. the charm cross section at the LHC is around 20x that of beauty production !

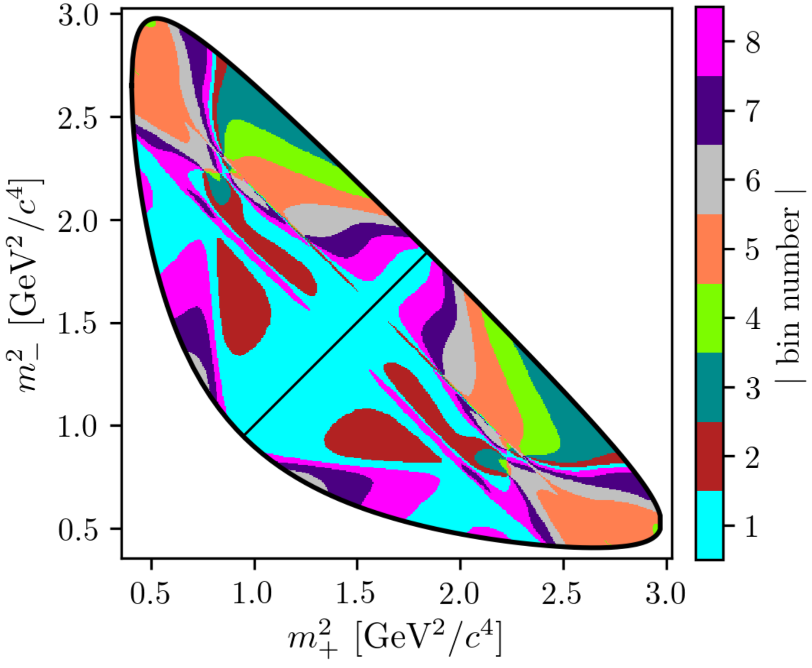
All considerations that apply to beauty physics (e.g. acceptance, instrumentation & trigger) remain true for charm. Its just a little harder to trigger on, as it has lower p_T.

D^0-$\overline{D}^0$ oscillations with $D^0 \to K_S\pi^+\pi^-$ at LHCb



The rich resonance structure of $D^0 \to K_S\pi^+\pi^-$ very advantageous for mixing & CPV studies.

Recent LHCb result [PRL 127 (2021) 111801] exploits 5.4 fb^{-1} of data, corresponding to 31 million decays (x30 B-factory samples).



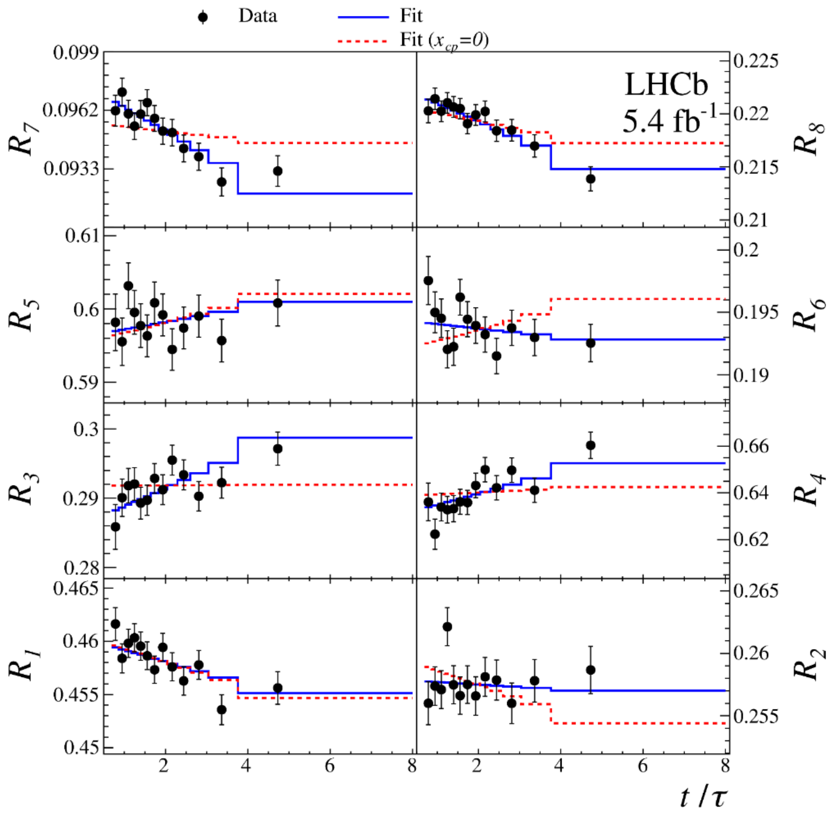
As in γ analysis, divide Dalitz plot into bins, whose strong-phase characteristics are known from BESIII measurements.

Study time-dependence of ratio of symmetric bins (the 'bin flip' method [PRD 99 (2019) 012007] . Particularly sensitive to x.

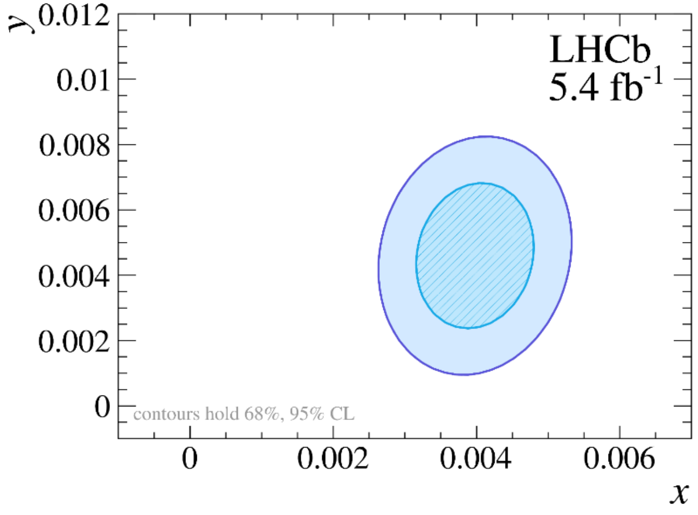
Use data-driven method to correct for trigger-induced correlations between decay time and phase space.

D^0-$\bar{D}^0$ oscillations with $D^0 \rightarrow K_S \pi^+ \pi^-$ at LHCb

Ratio of bin populations vs. proper time.
Slope indicates presence of mixing.



$$x = (3.98^{+0.56}_{-0.54}) \times 10^{-3},$$
$$y = (\ 4.6^{+1.5}_{-1.4}\ ) \times 10^{-3},$$



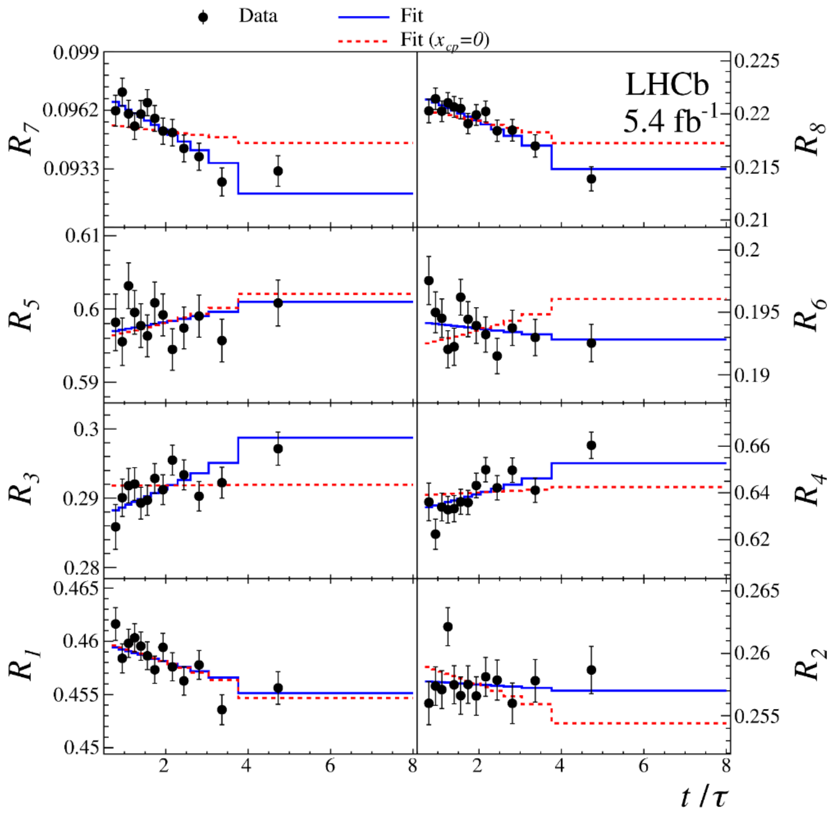
[PRL 127 (2021) 111801]

x non-zero with significance of >7σ !

(Just like WS Kπ measurement, but strong phase, and thus slope, varies bin to bin)

D^0-$\bar{D}^0$ oscillations with $D^0 \rightarrow K_S\pi^+\pi^-$ at LHCb

Ratio of bin populations vs. proper time.
Slope indicates presence of mixing.



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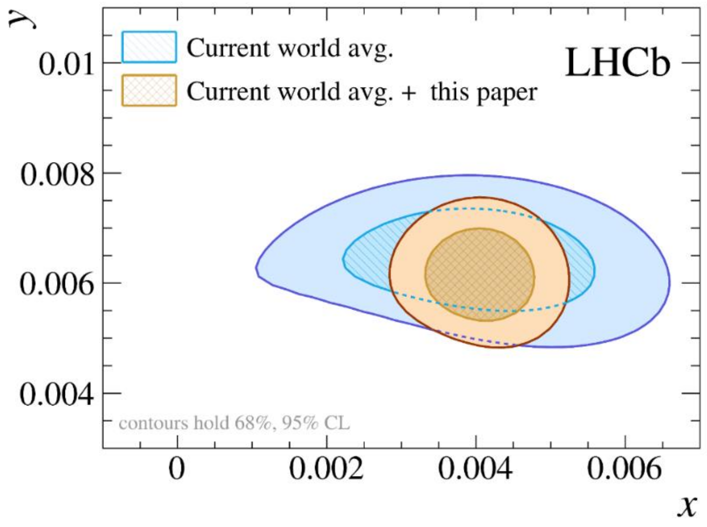


[PRL 127 (2021) 111801]

A huge step forward in precision !

(Just like WS $K\pi$ measurement, but strong phase, and thus slope, varies bin to bin)

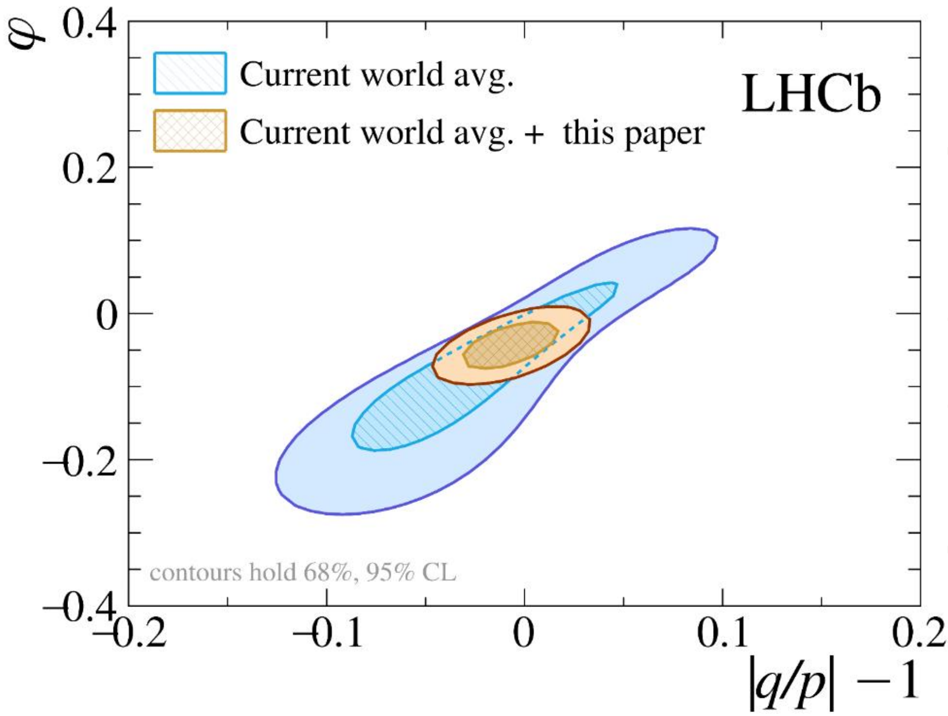
CP violation in charm-mixing phenomena

Taking p and q to be the coefficients that relate the mass eigenstates to the flavour eigenstates,

$$D_{1,2} = pD^0 \mp q\overline{D}^0$$

and ϕ_D to be the weak phase between the mixing and decay amplitudes, then CP violation would manifest itself in either $|q/p| \neq 1$ or $\phi_D \neq 1$.

In constraining these parameters, the wrong sign Kπ analysis is an important input, but again it is the recent $D \rightarrow K_S\pi\pi$ study that has particular weight.



[PRL 127 (2021) 111801]

CP violation in charm-mixing phenomena

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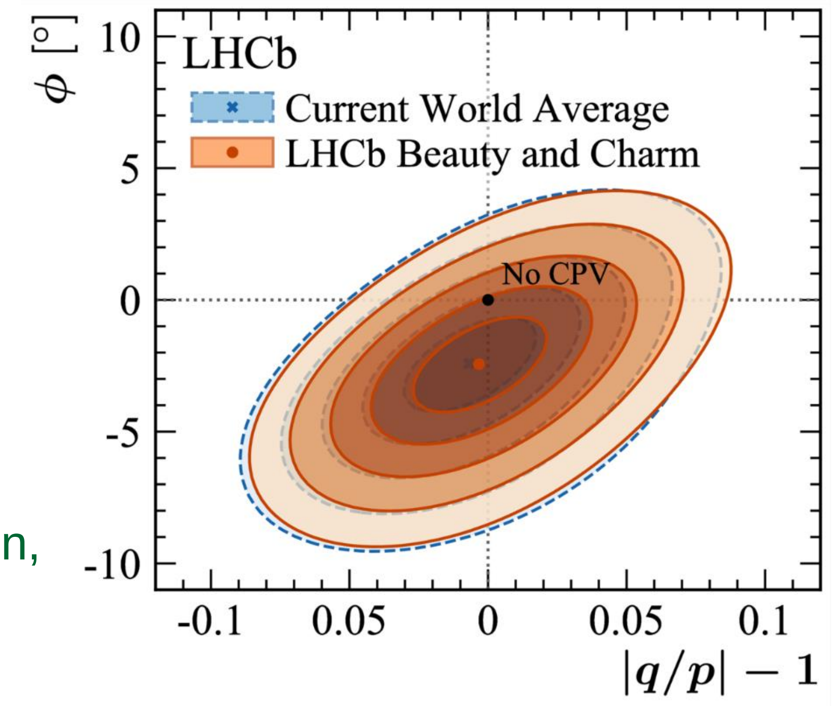
Current LHCb data, which saturate world average, give a precision of +/- 0.016 on |*q*/*p*| and +/- 1.20 on ϕ_D*.

Results are compatible with no CP violation, but there is a 2 sigma tension, so situation is very interesting (any signal of this size would be extremely surprising for theorists…).

There is another category of CP violation, and here LHCb has already delivered.



[JHEP 12 (2021) 141]

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* There is a very precise, new LHCb measurement [arXiv:2202.09106] of the parameter y_{CP} that is not included in this average.