Flavour Physics at Hadron Colliders
Lecture IV: charm physics at the LHC, and future prospects for hadron-collider flavour studies

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Future Flavours, ICTS
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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 discovery of CP violation in charm decays
  - the discovery of direct CP violation in charm
- The need for higher precision

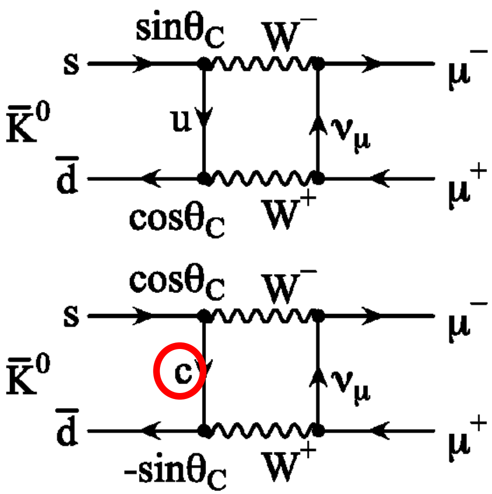
- LHCb Upgrade I
- The ATLAS and CMS Phase II Upgrades
- LHCb Upgrade II
- Flavour physics at the FCC
- Conclusions

Charm – a glorious history

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

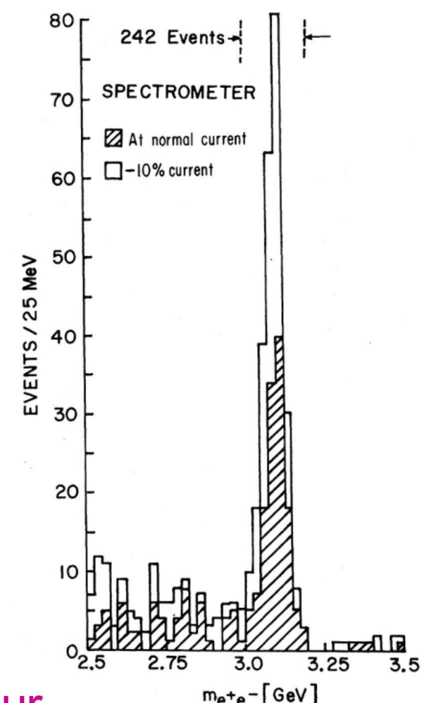
[Glashow, Iliopoulos & Maiani, PRD 2 (1970)1285]

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.

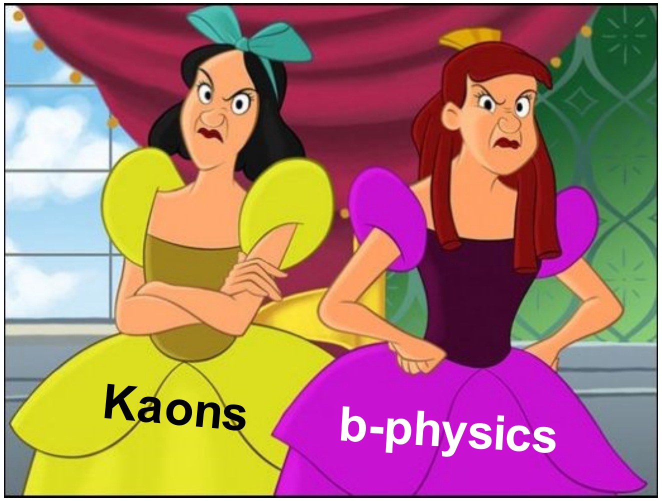
"I know she invented fire, but what has she done recently?" [I. Bigi, arXiv:0808.1773]

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.

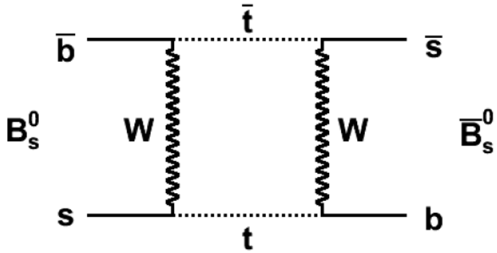
And indeed, early this century, charm's fairy-godmother moment arrived.

Neutral meson mixing - reminder

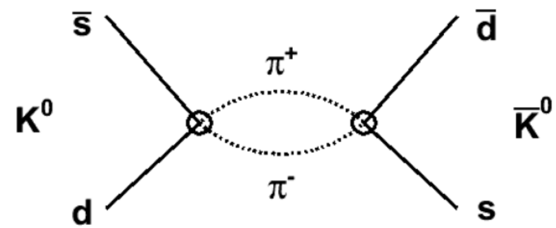
Flavour oscillations, or mixing, are an important phenomenon in neutral meson physics, and for have been established for many years in K^0, B^0 and B^0_s systems.

Caused by either:

Virtual, short-range (box diagrams)

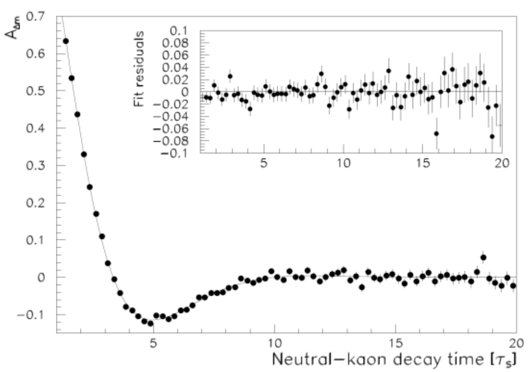


or:

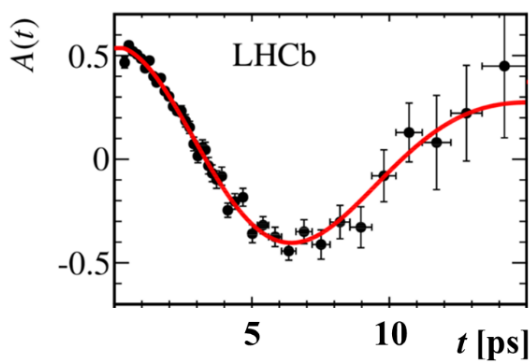


On-shell, long-range (common intermediate states)

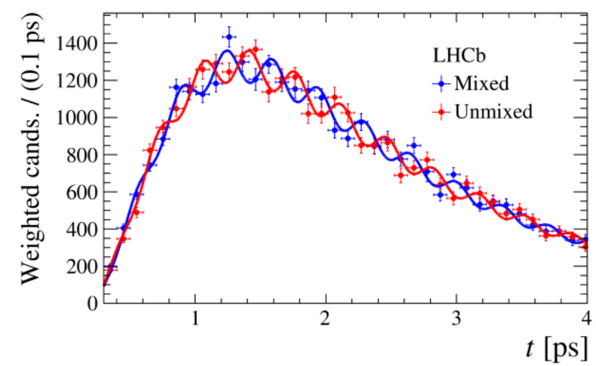
Slow for K^0 mesons … quicker for B^0 mesons… even quicker for B^0_s mesons.



[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

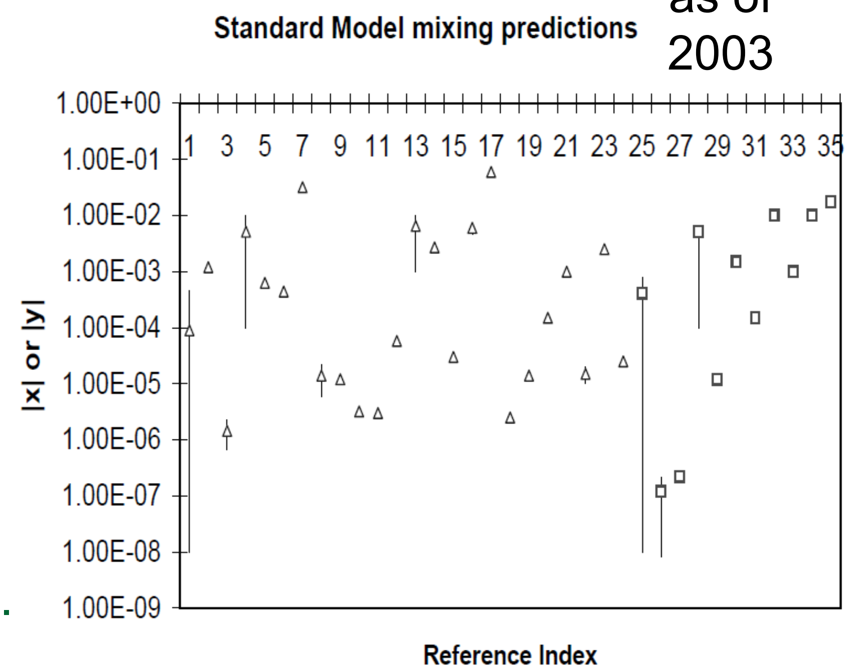
$x \equiv \Delta m/\Gamma$ short range $\quad\quad$ $y \equiv \Delta\Gamma/2\Gamma$ long range

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.

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]).

as of 2003



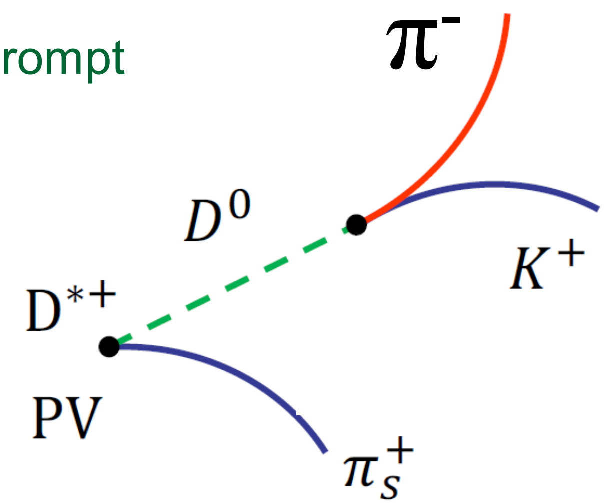
[A.A. Petrov, hep-ph/0311371]

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'.

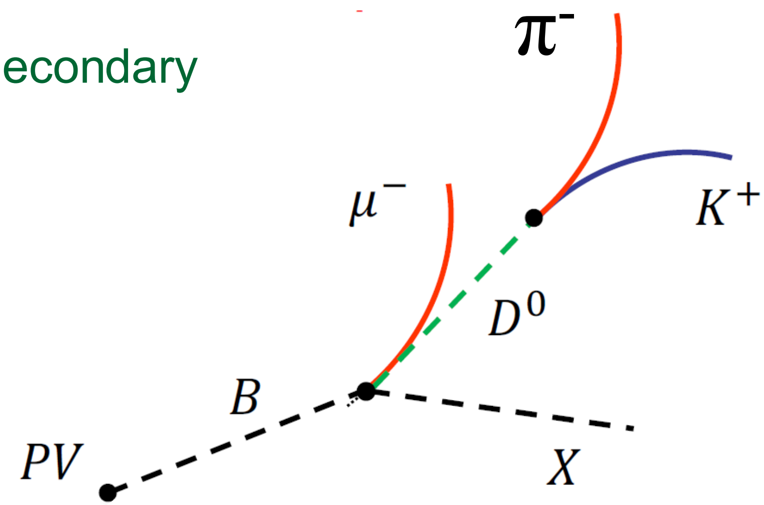
Experimentally this is done by flavour tagging the D^0 at birth, which is easier to do than in the B meson case, because the signatures are cleaner and more efficient.

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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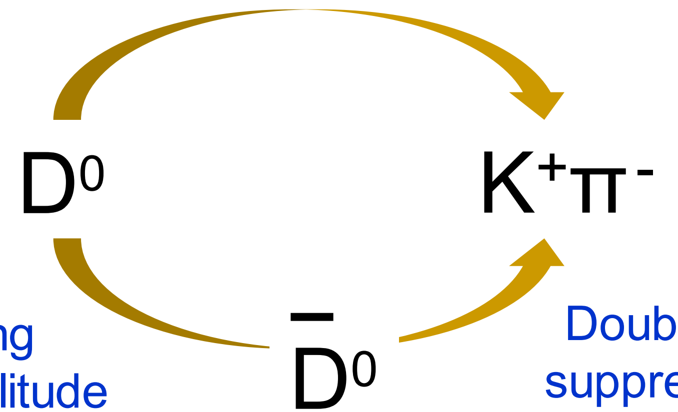
Decay-time dependent rate ≈ | Cabibbo-favoured (CF) amplitude |^2



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 rotated by a strong phase…

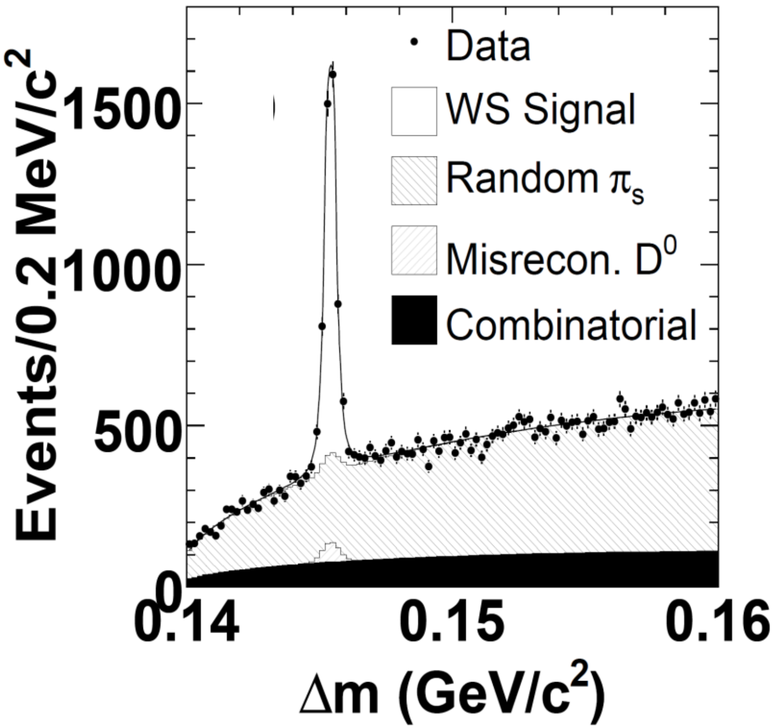
…these small, so mixing signature is a linear, not oscillatory effect.

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

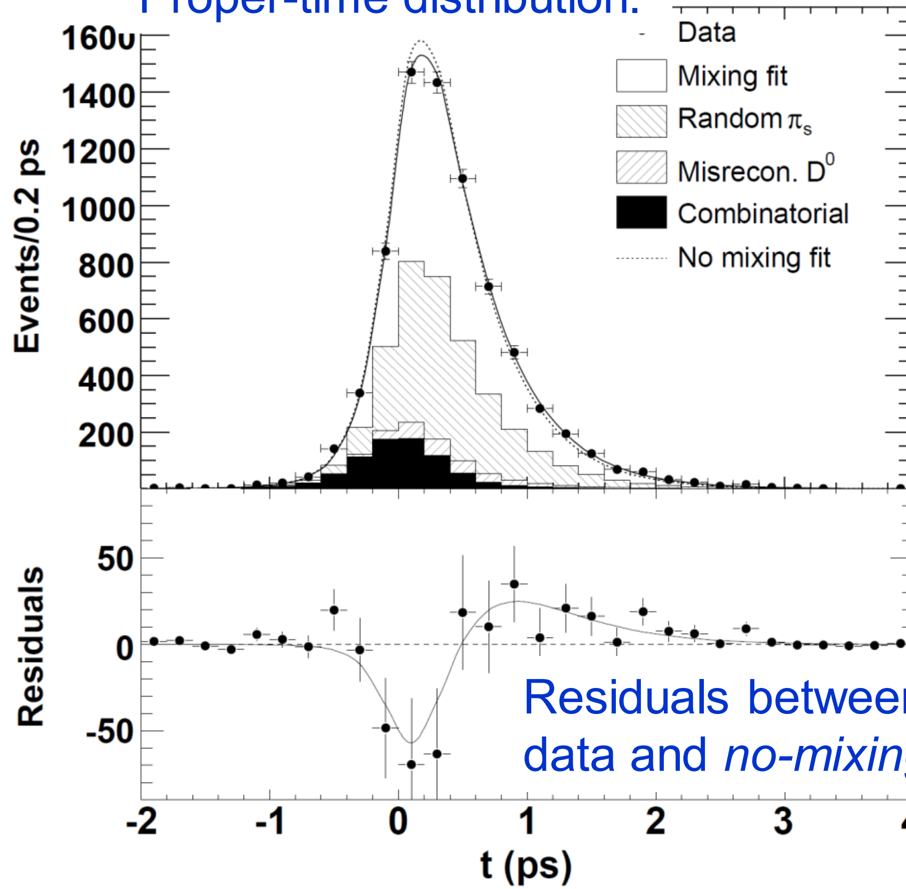
First evidence from the B-factories !

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]

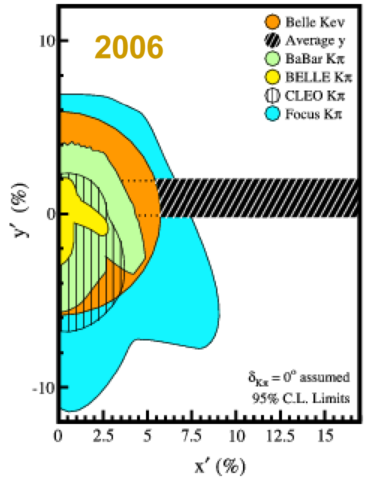
A rekindling of interest, and the rise of the hadron machines

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

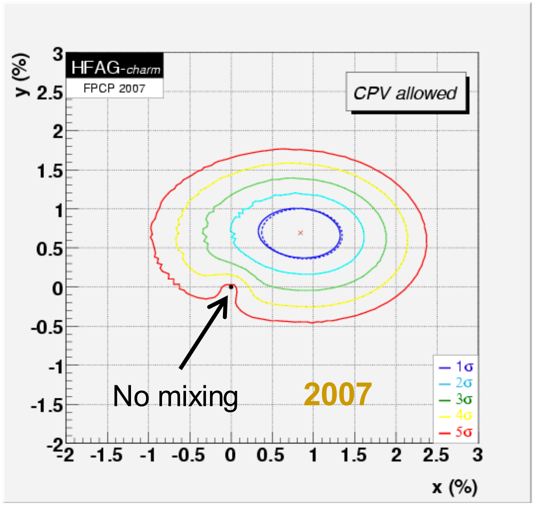
The ensemble of results showed that mixing was happening, but was less clear on the values of the parameters driving it (especially *x*).

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.

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

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]

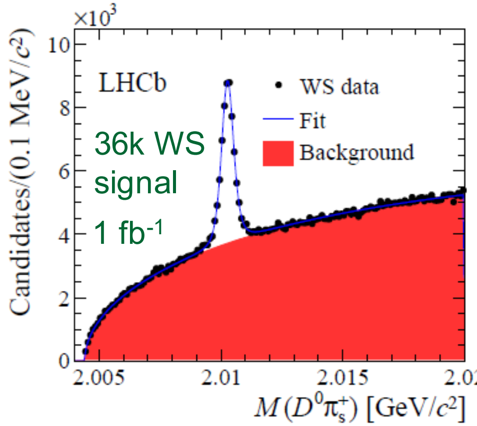
'Easy' mode at hadron machine	Hard mode at hadron machine	Medium mode at hadron machine

(see arXiv:2011.04443 for references)

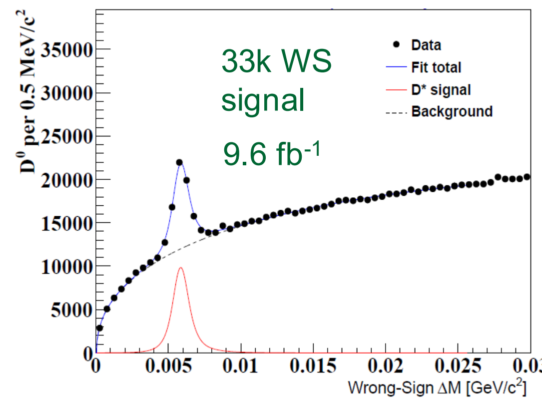
All considerations that apply to beauty physics (e.g. acceptance, instrumentation & trigger) remain true for charm. Its just a little harder to trigger on, as it has lower p_T.

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.



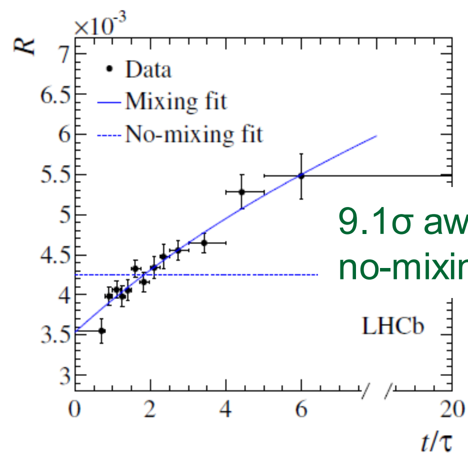
[LHCb, PRL 110 (2013) 101802]



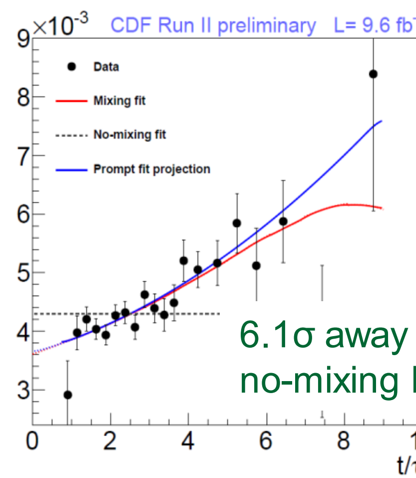
[CDF, PRL 111 (2013) 231802]

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

Linear slope comes from mixing-decay interference.



9.1σ away from no-mixing hyp.

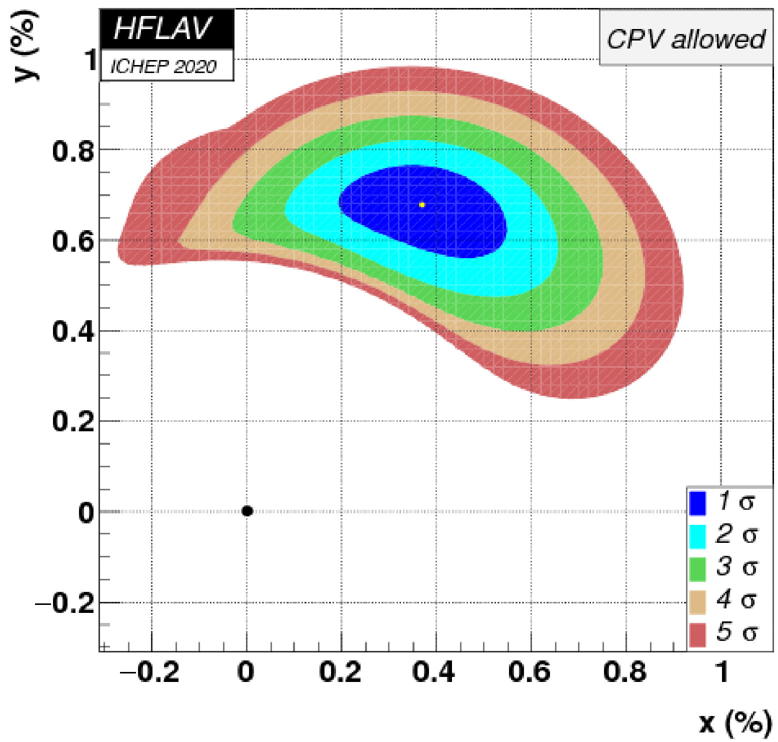


6.1σ away from no-mixing hyp.

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.

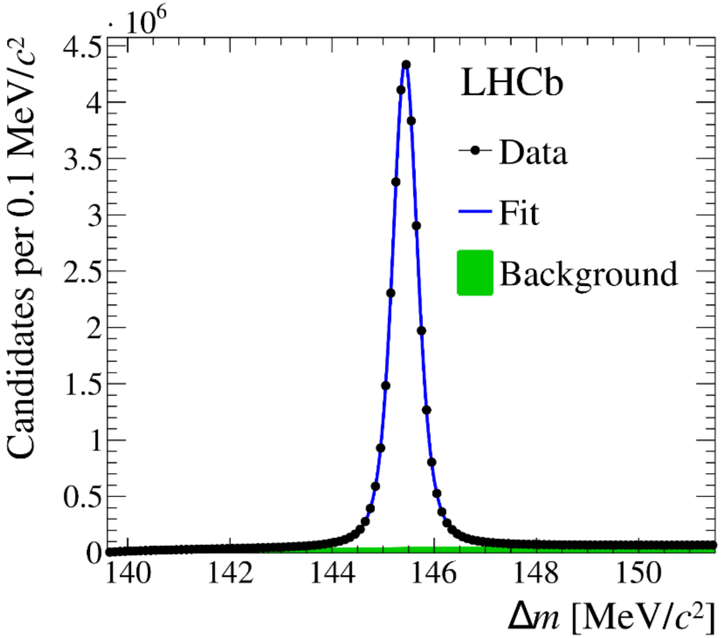
From discovery to precision

‘Wrong sign’ $K\pi$ and parallel measurements refined with growing LHCb data sets. Precision on mixing signal increased, and by ~2020 *y* is very well known.



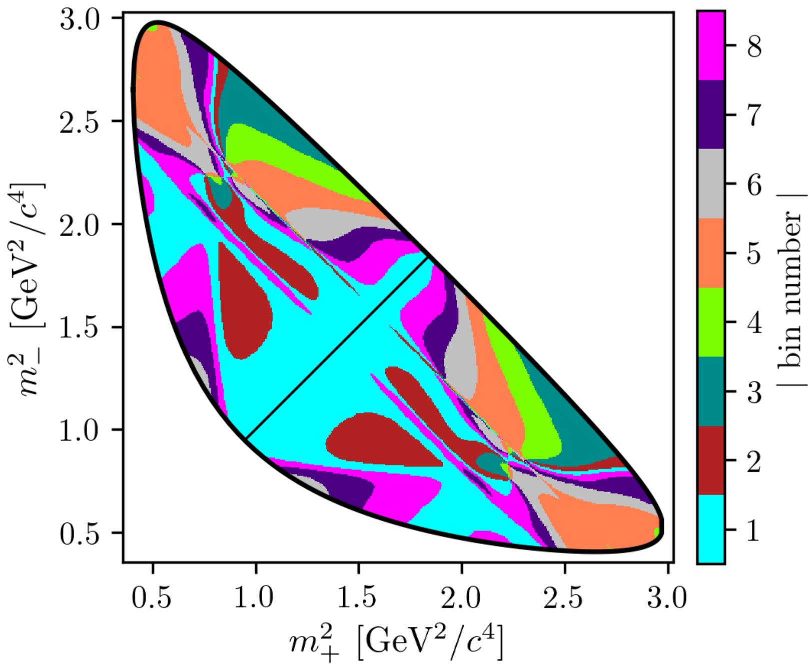
However, ensemble of measurements still do not exclude a zero value of *x*.

D^0-$\bar{D}^0$ 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).



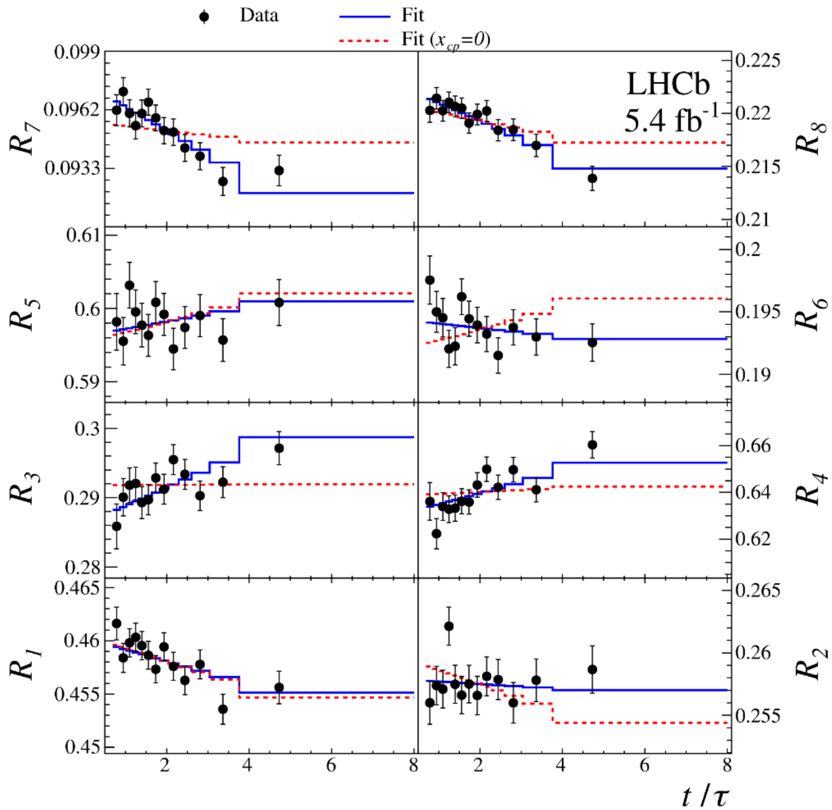
As in γ analysis, divide Dalitz plot into bins, whose strong-phase characteristics are known from BESIII measurements.

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

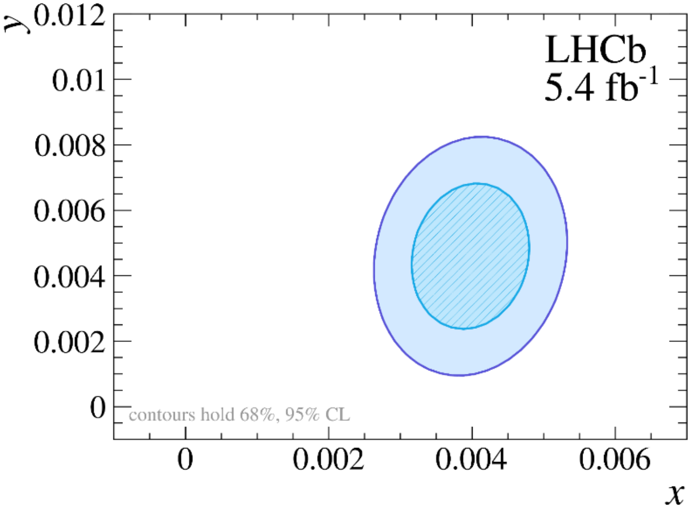
Use data-driven method to correct for trigger-induced correlations between decay time and phase space.

D^0-$\bar{D}^0$ oscillations with $D^0 \to K_S\pi^+\pi^-$ 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)

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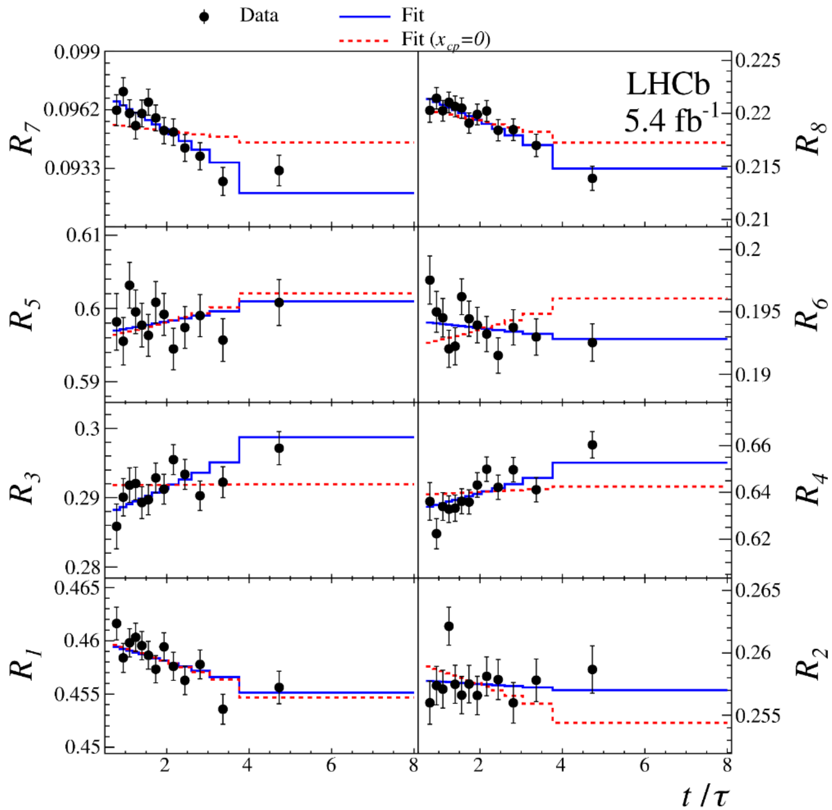

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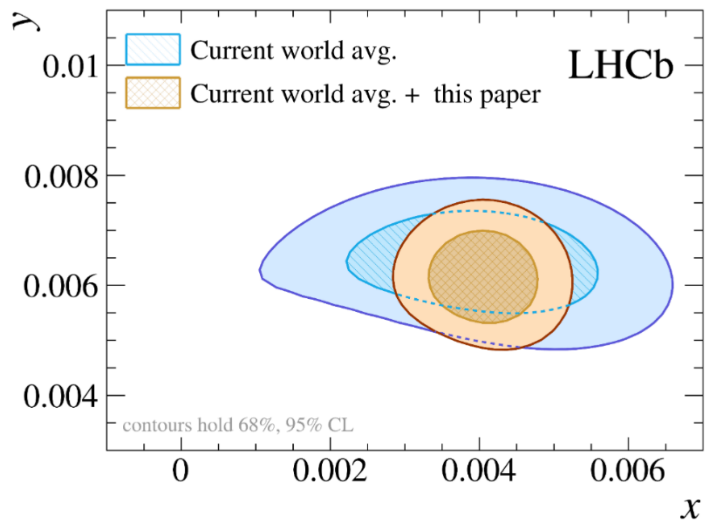


[PRL 127 (2021) 111801]

A huge step forward in precision !

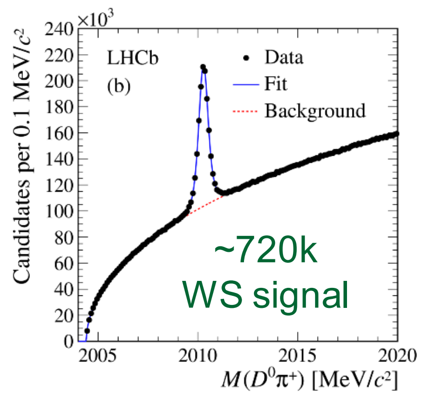
(Just like WS $K\pi$ measurement, but strong phase, and thus slope, varies bin to bin)

CP violation in charm-mixing phenomena

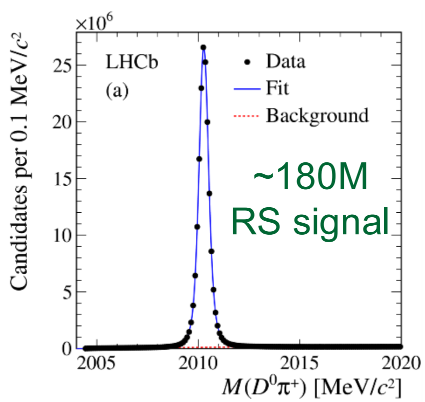
Seeing charm oscillations is exciting in itself, but the fact that the mixing parameters are not too small is excellent news for CP violation searches in mixing-related phenomena (*i.e.* effects analogous to those observed in neutral kaon and beauty).

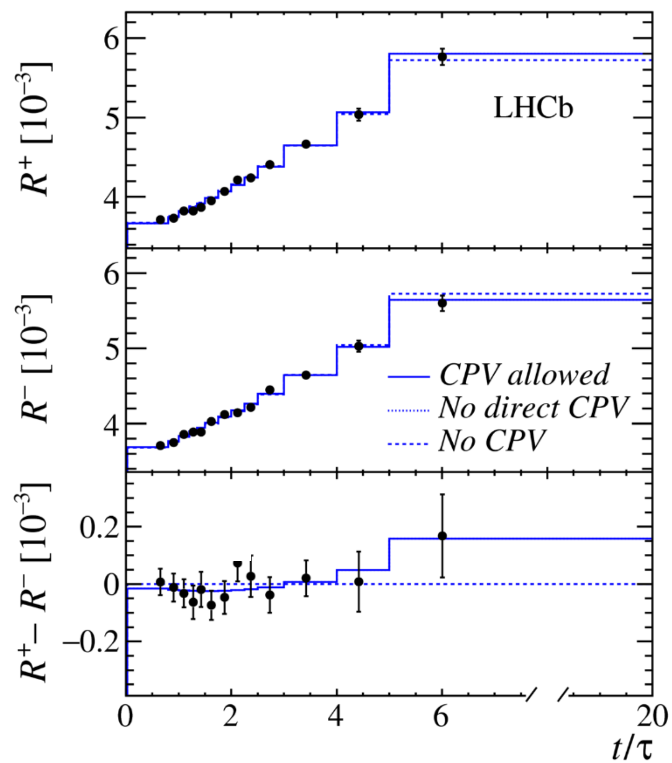
To look for these we essentially look for differences in mixing between D^0 and $\bar{D}^0$.

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



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





For D^0…

…and D^0bar…

…and difference of both.

[PRD 97 (2018) 031101]

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

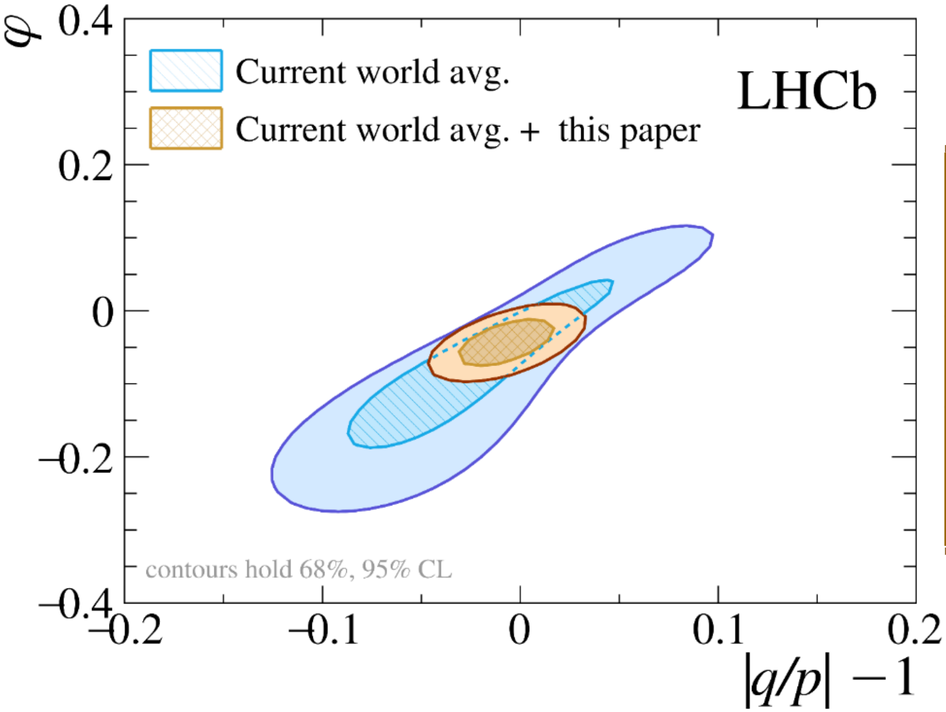
CP violation in charm-mixing phenomena

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 $K\pi$ 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]

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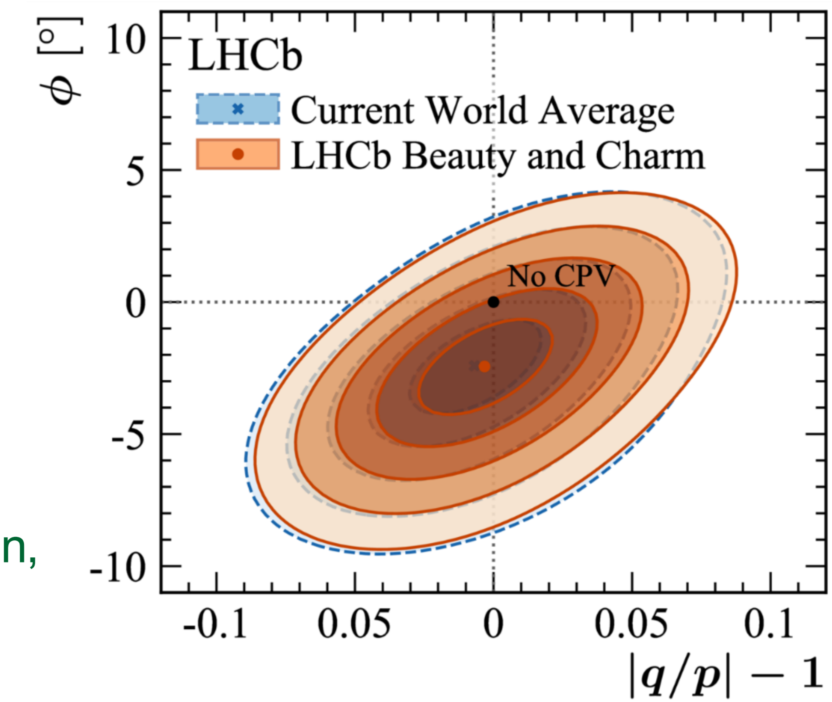
Current LHCb data, which saturate world average, give a precision of +/- 0.016 on |*q*/*p*| and +/- 1.20 on ϕ_D*.

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]

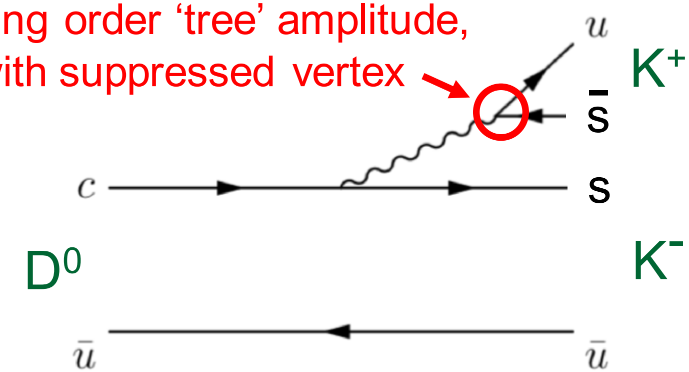
* There is a very precise, new LHCb measurement [arXiv:2202.09106] of the parameter y_{CP} that is not included in this average.

Searches for direct CPV in charm

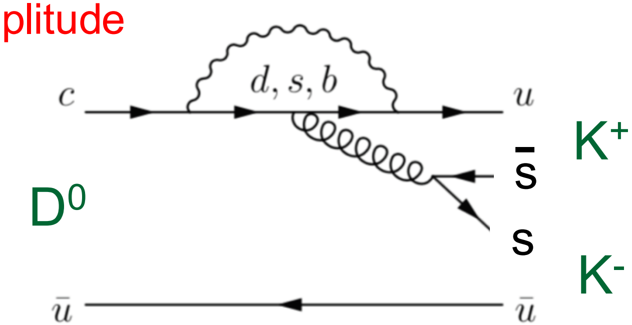
'direct CPV' or 'CPV in decay'

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*:

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

- $\mathcal{A}_{CP}(f)$: what we are after
- $\mathcal{A}_D(f)$: detection asymmetry for final state
  must be zero for decays of D^0 into two pseudoscalars !
- $\mathcal{A}_D(\pi_s)$: detection asymmetry for slow pion
- $\mathcal{A}_P(D^{*+})$: 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.

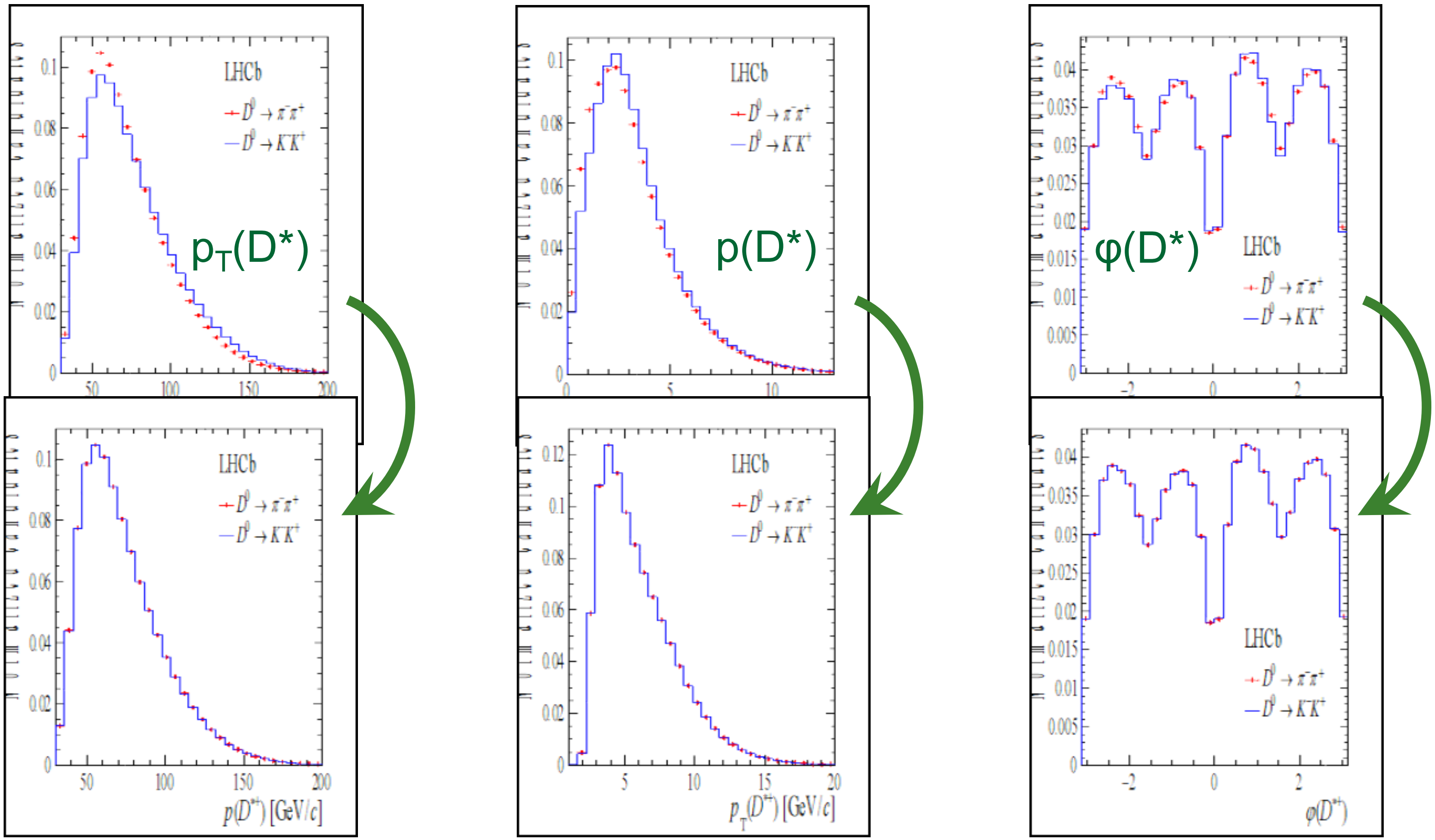
So measure ΔA_{CP} , the *difference* between the two raw asymmetries:

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

Kinematic re-weighting

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

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:

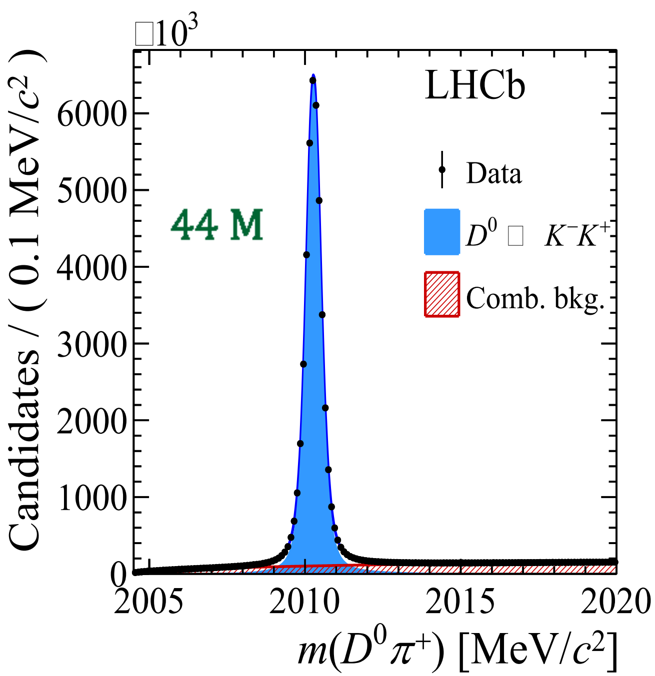


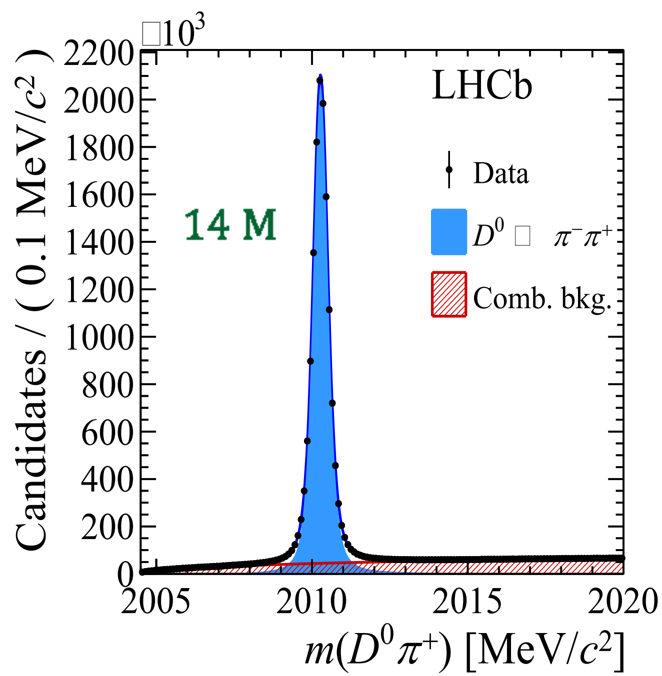
Determination of A_{raw}

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

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

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



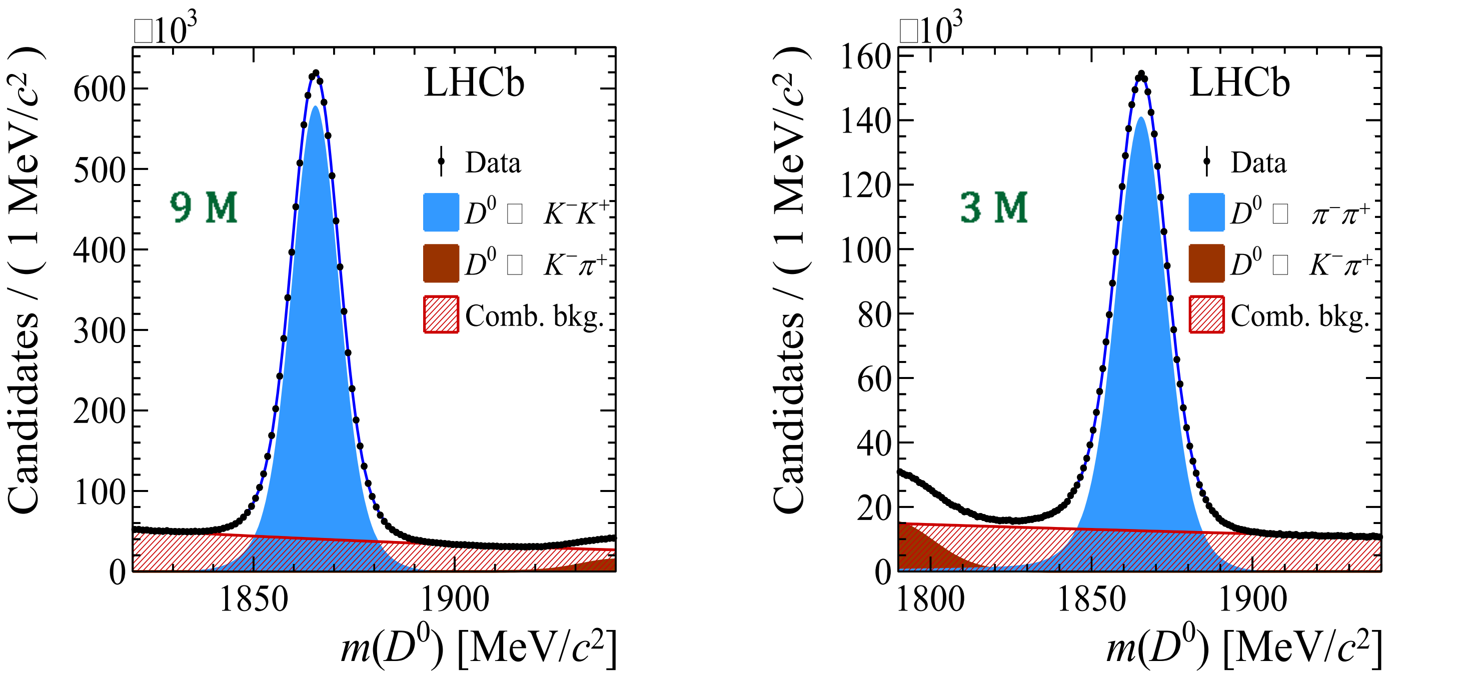


Determination of A_{raw}

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

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

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



Systematic uncertainties

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.

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

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] :

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

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

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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:

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

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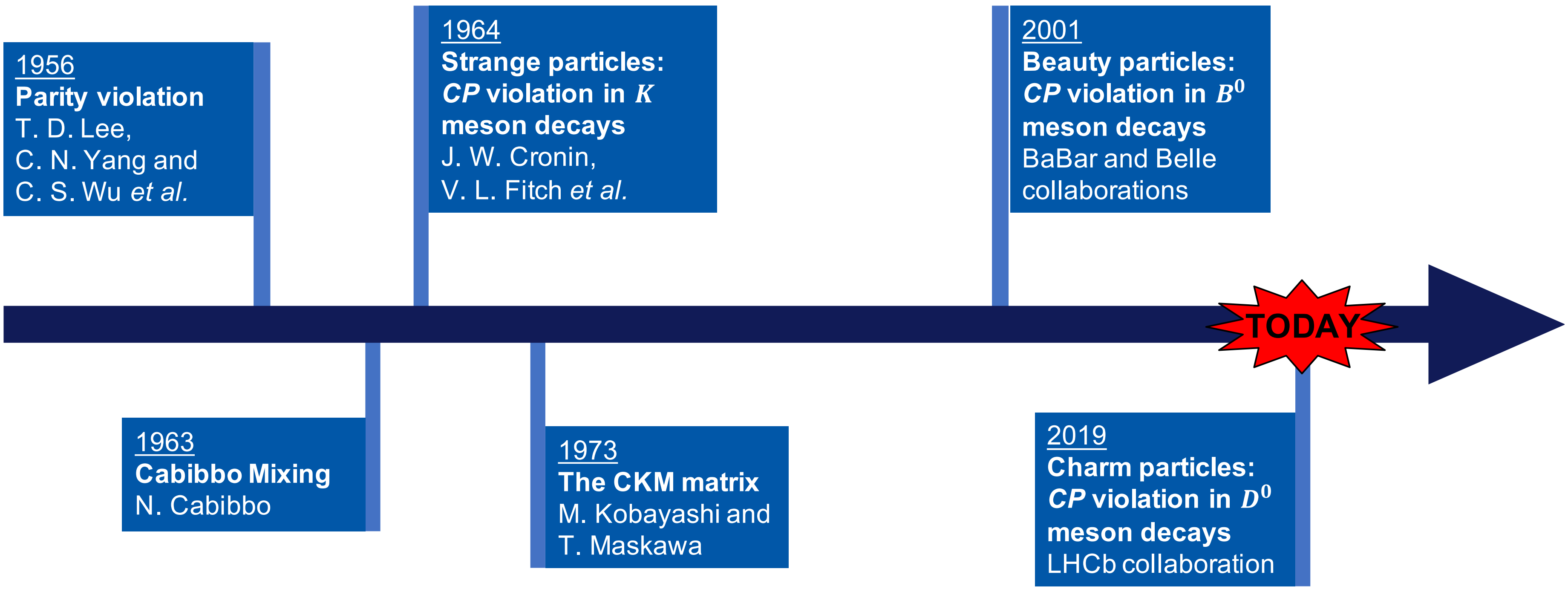
CP violation observed at $\boldsymbol{5.3\sigma}$!!

50+ years of CP violation



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]

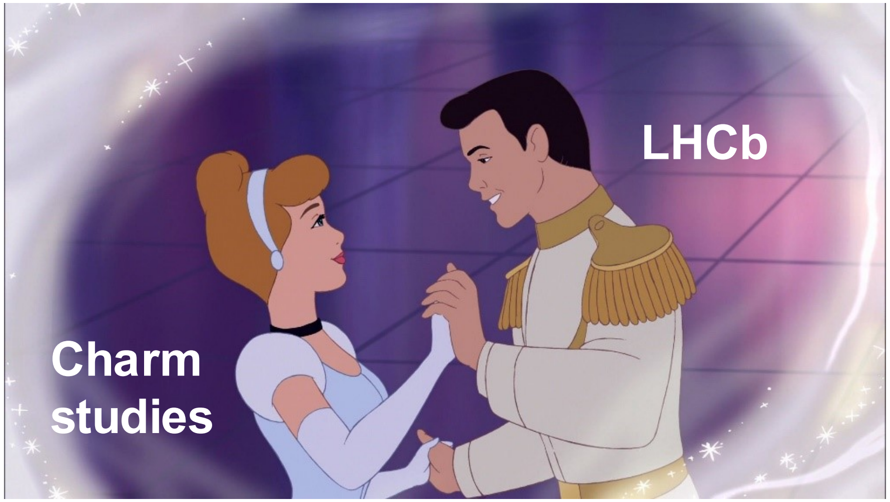
Best hope of progress is experimental:

- Individual measurements of $A_{CP}(KK)$ and $A_{CP}(\pi\pi)$;
- Make measurements in other modes where less, *e.g.* $A_{CP}(D^+\to\pi^+\pi^0)$, 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

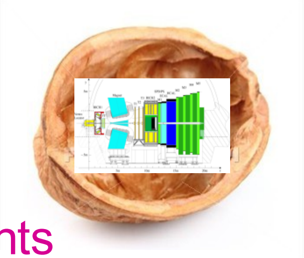
Charm is one topic where higher precision is required. There are many more:

- 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.

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

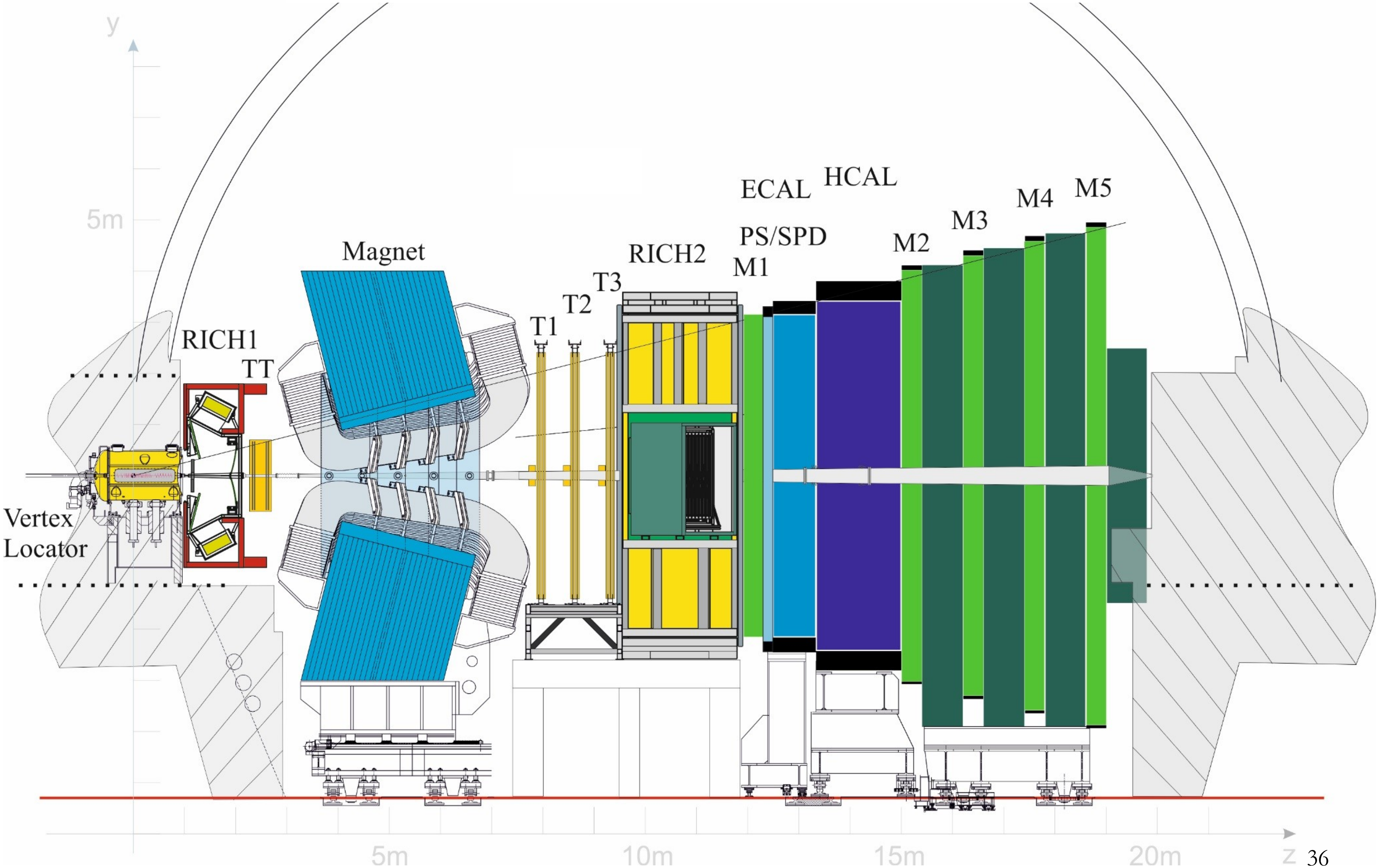
2) Raise operational luminosity to 2 x 10^{33} cm^{-2} s^{-1} (5x Run 2 value)

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 →

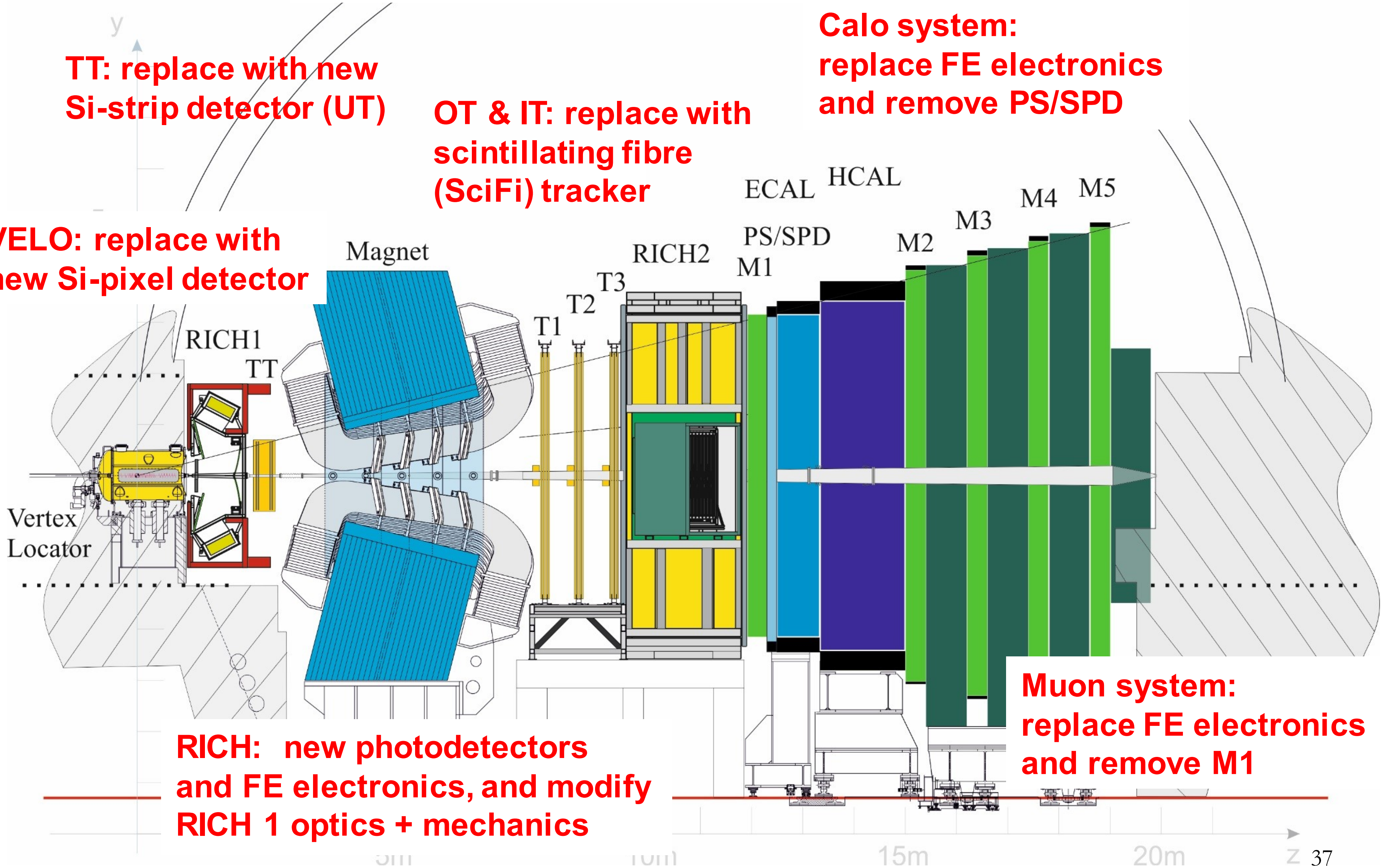
Replace read-out boards and DAQ

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



Muon system: replace FE electronics and remove M1

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

Required modifications

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

This is the critical step !

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

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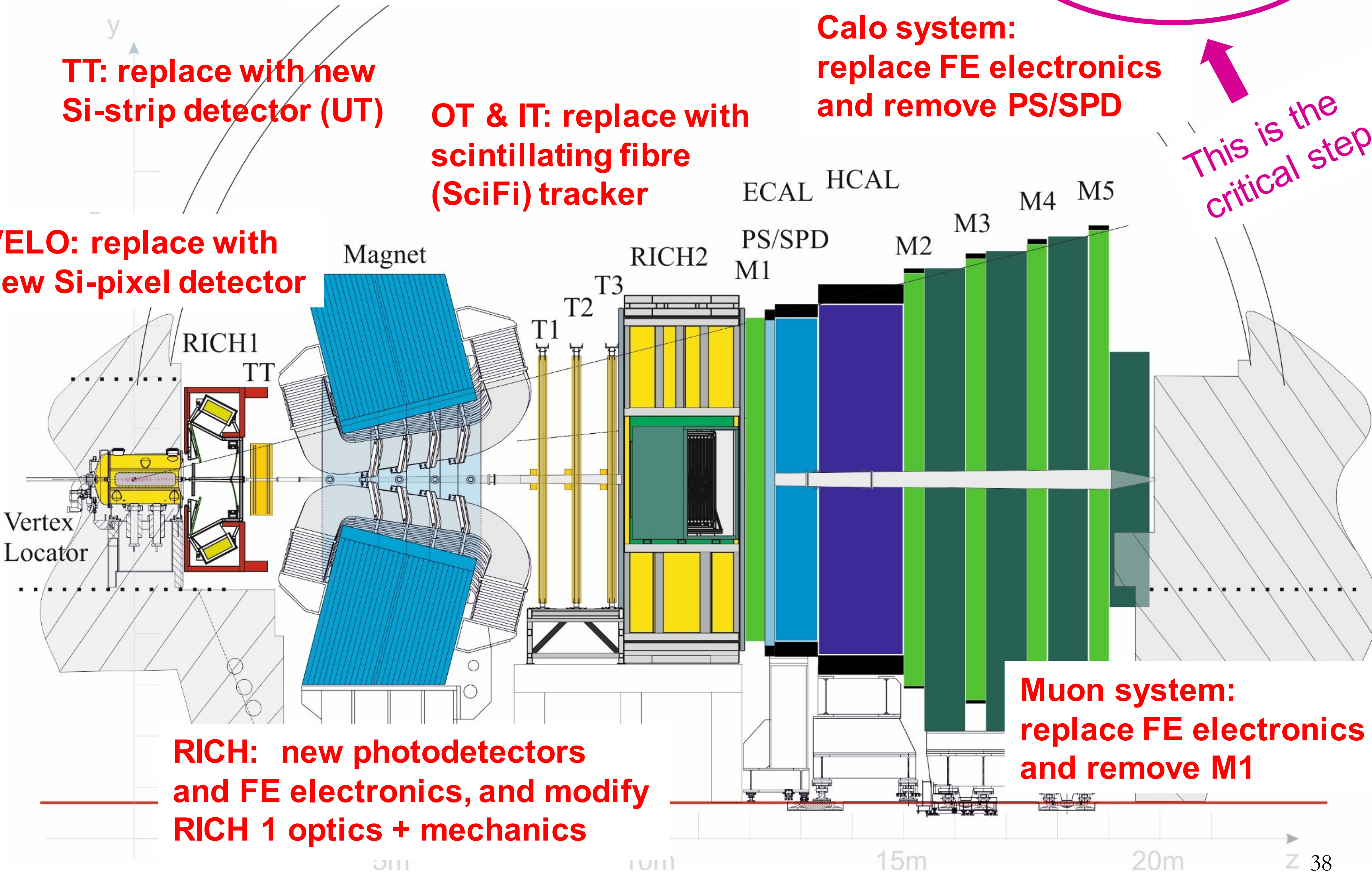

RICH: new photodetectors and FE electronics, and modify RICH 1 optics + mechanics

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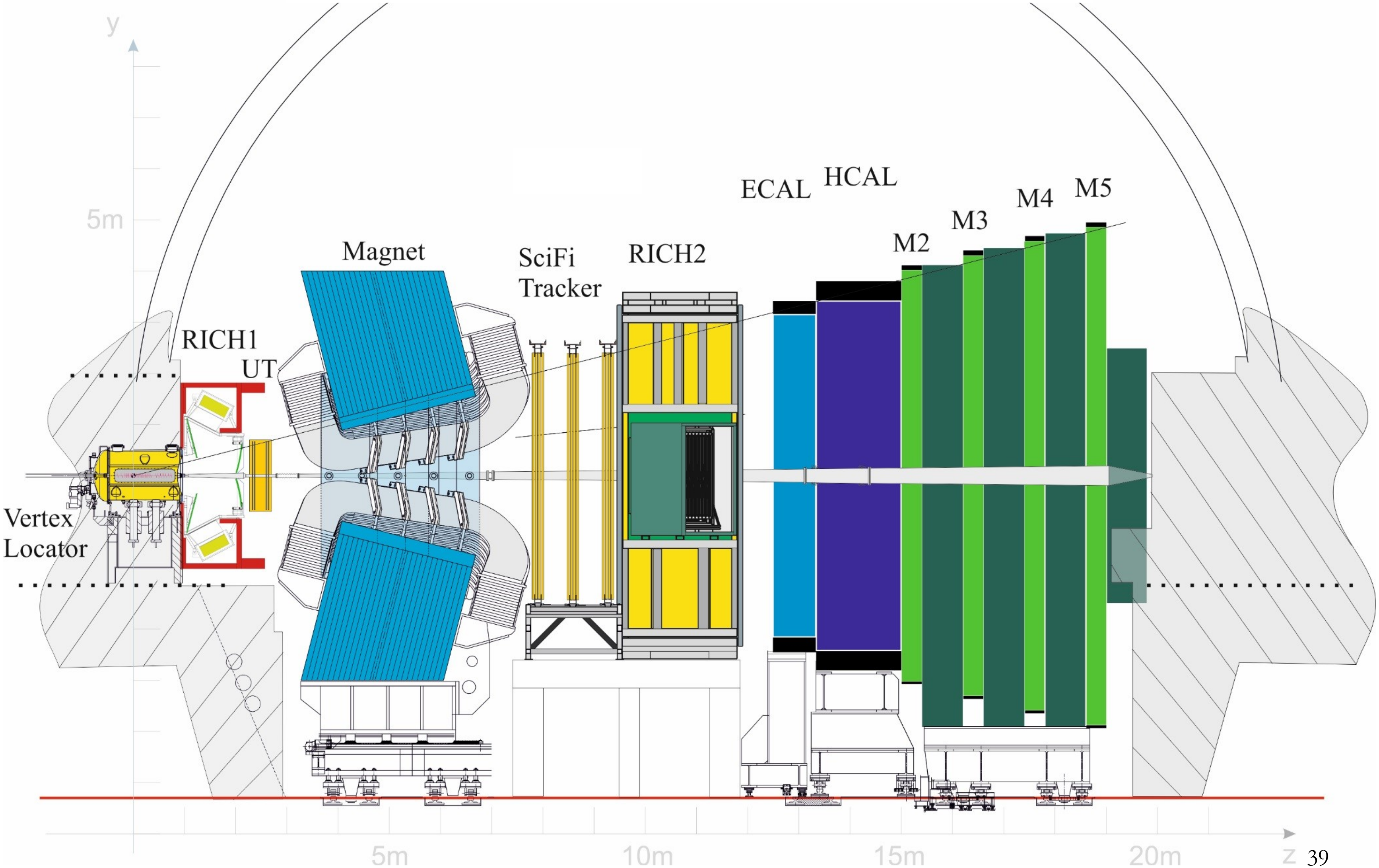
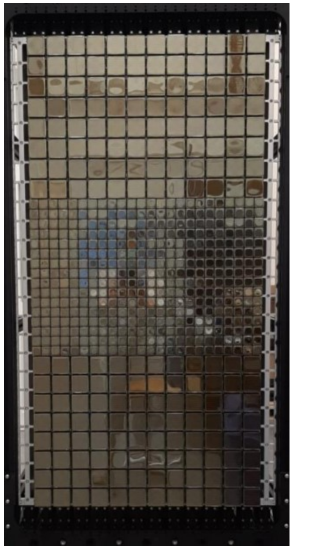
Upgrade I detector



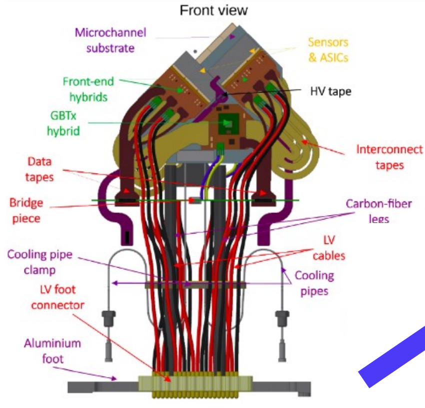
LHCb Upgrade I is now !

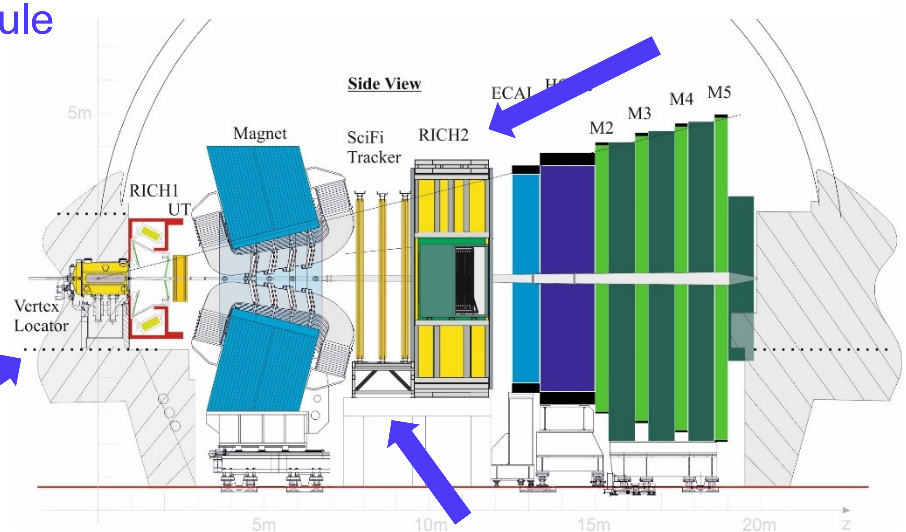
Essentially a new experiment – almost all subdetectors replaced, & all read out to a software trigger farm at 40 MHz !

Half of RICH2 photodetector plane

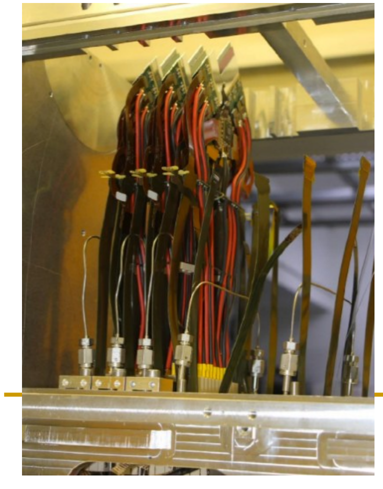


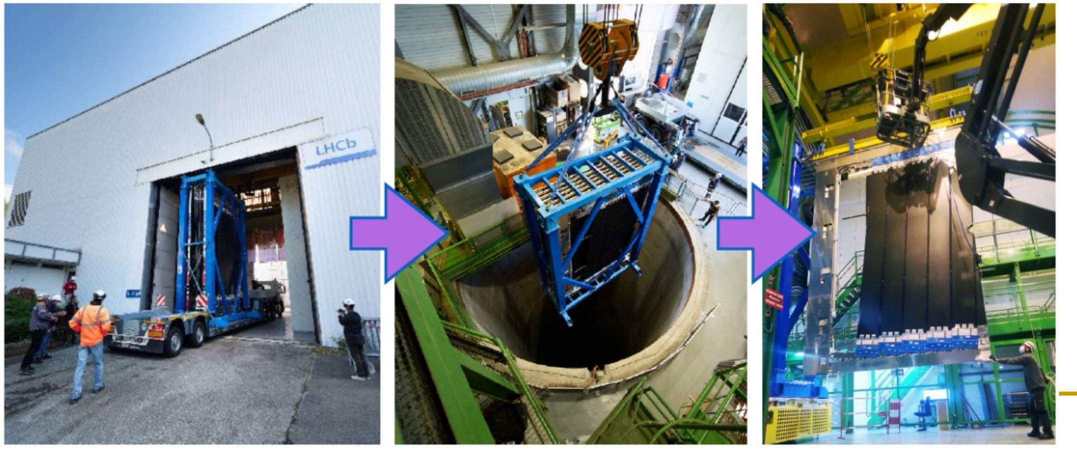
Schematic of VELO module





Installed VELO modules



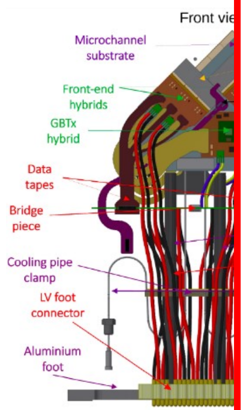


Scintillator-fibre (SciFi) tracker being installed

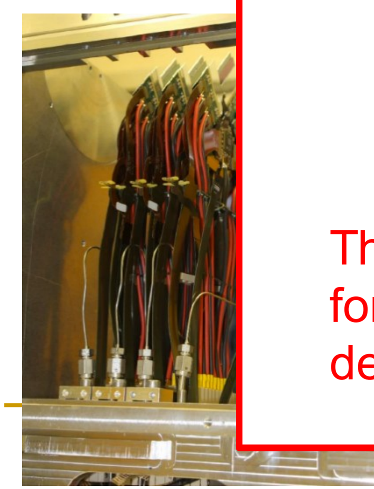
LHCb Upgrade I is now !

Essentially a
replaced, & a

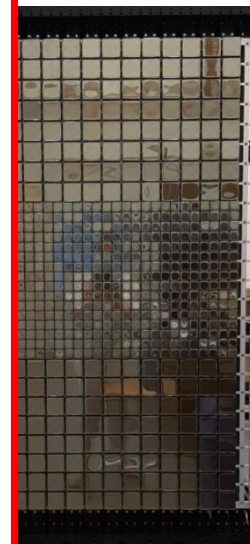
Schematic of



Installed VELO

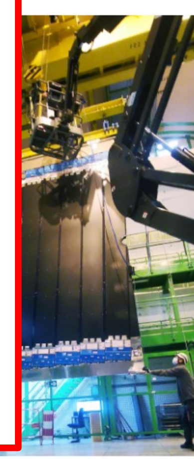


Half of RICH2
photodetector plane



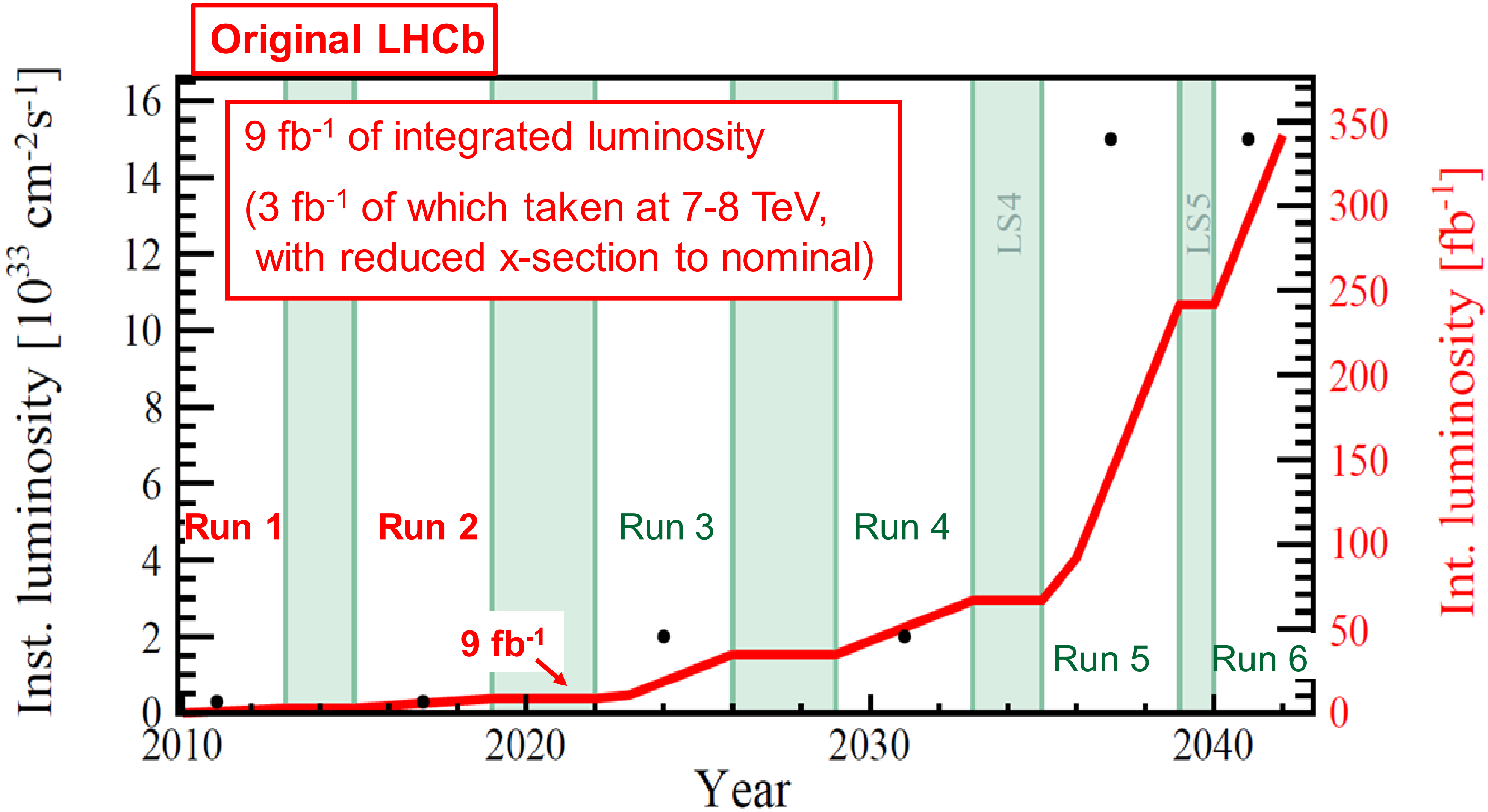
Just last Friday the second (and final) half of the VELO arrived at the experimental site.

The (almost) complete experiment will be ready for collisions within a few weeks. The final sub-detector, the UT, will be installed later this year.

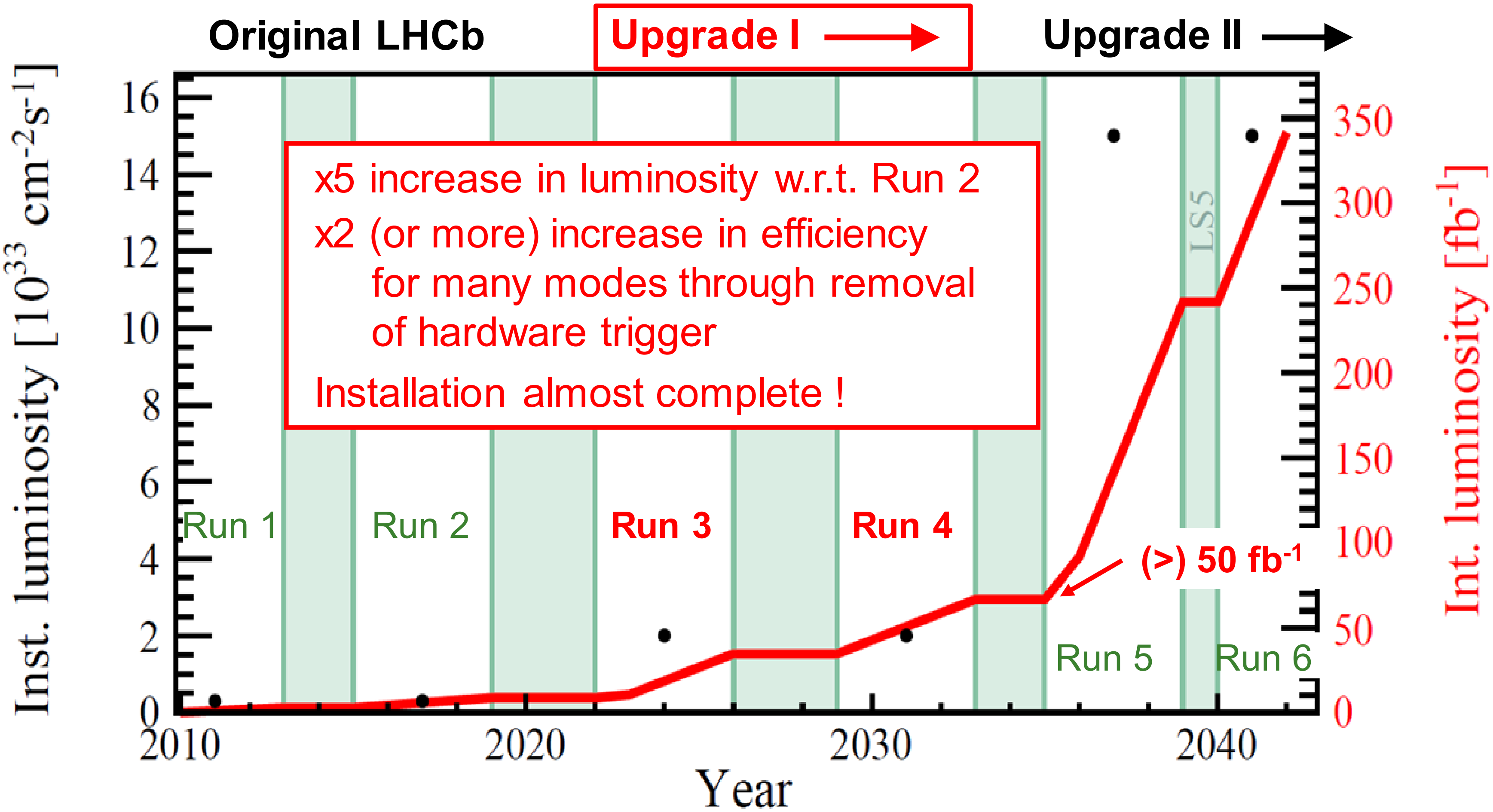


Scintillator-fibre (SciFi) tracker being installed

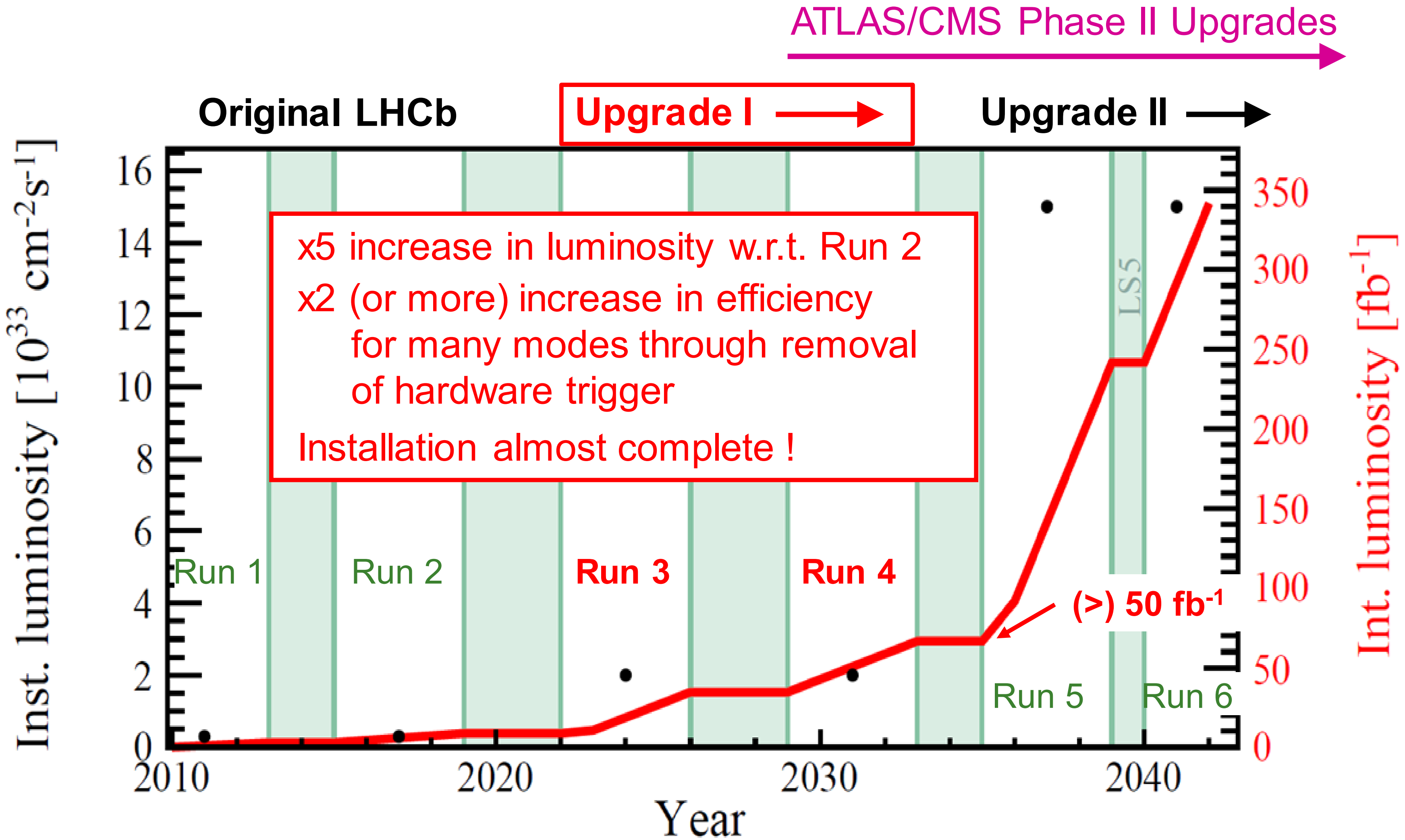
LHCb timeline: Upgrades I and II



LHCb timeline: Upgrades I and II



LHCb timeline: Upgrades I and II



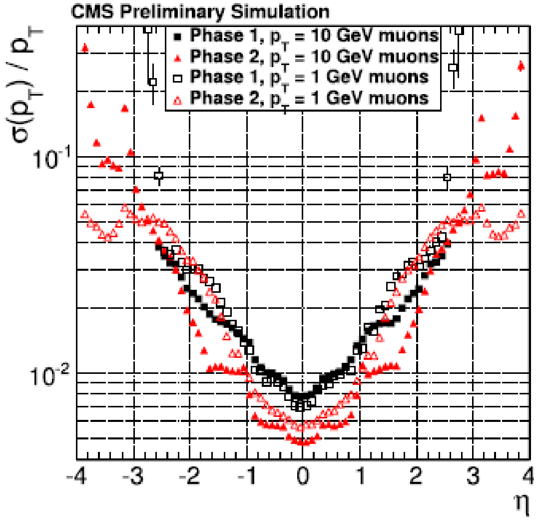
Run 4 is also when the High Luminosity LHC will begin. This makes little difference for LHCb Upgrade I, but is when ATLAS and CMS Phase II Upgrades will start.

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

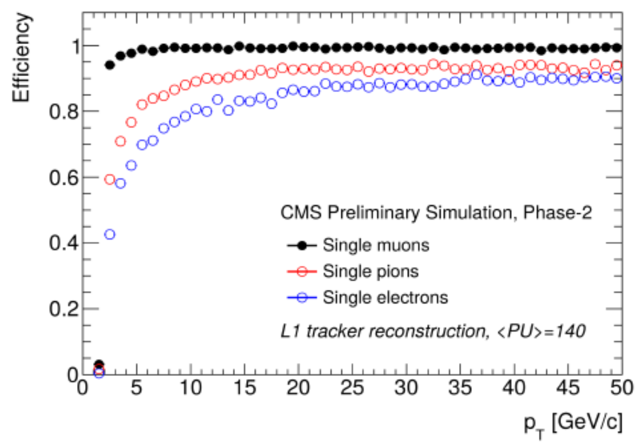
e.g. new CMS tracker



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

Significantly improved p resolution

e.g. CMS new L1 track trigger

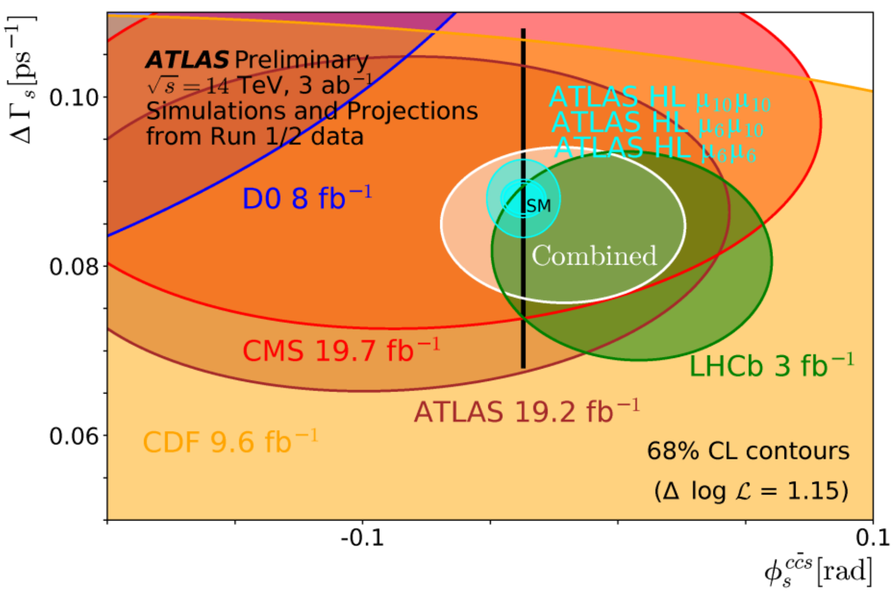


Anders Ryd, ECFA HL LHC, Aix-les-Bains, Oct 2014

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

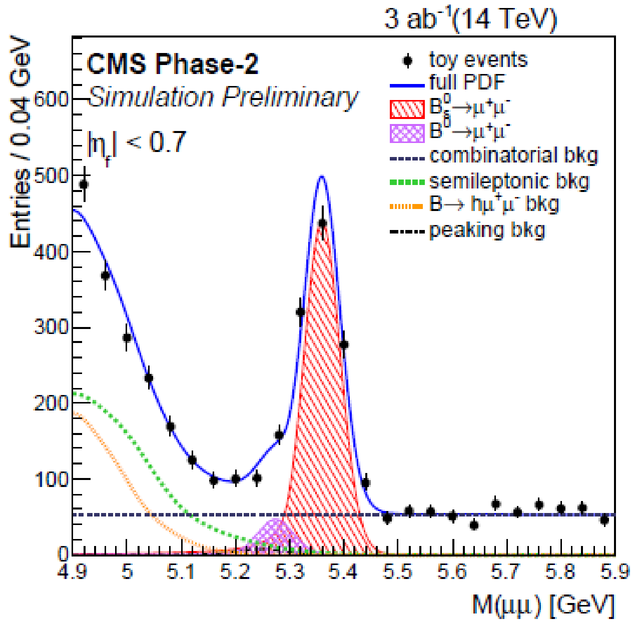
B-physics prospects at the HL-LHC with ATLAS and CMS

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



[ATL-PHYS-PUB-2018-041]

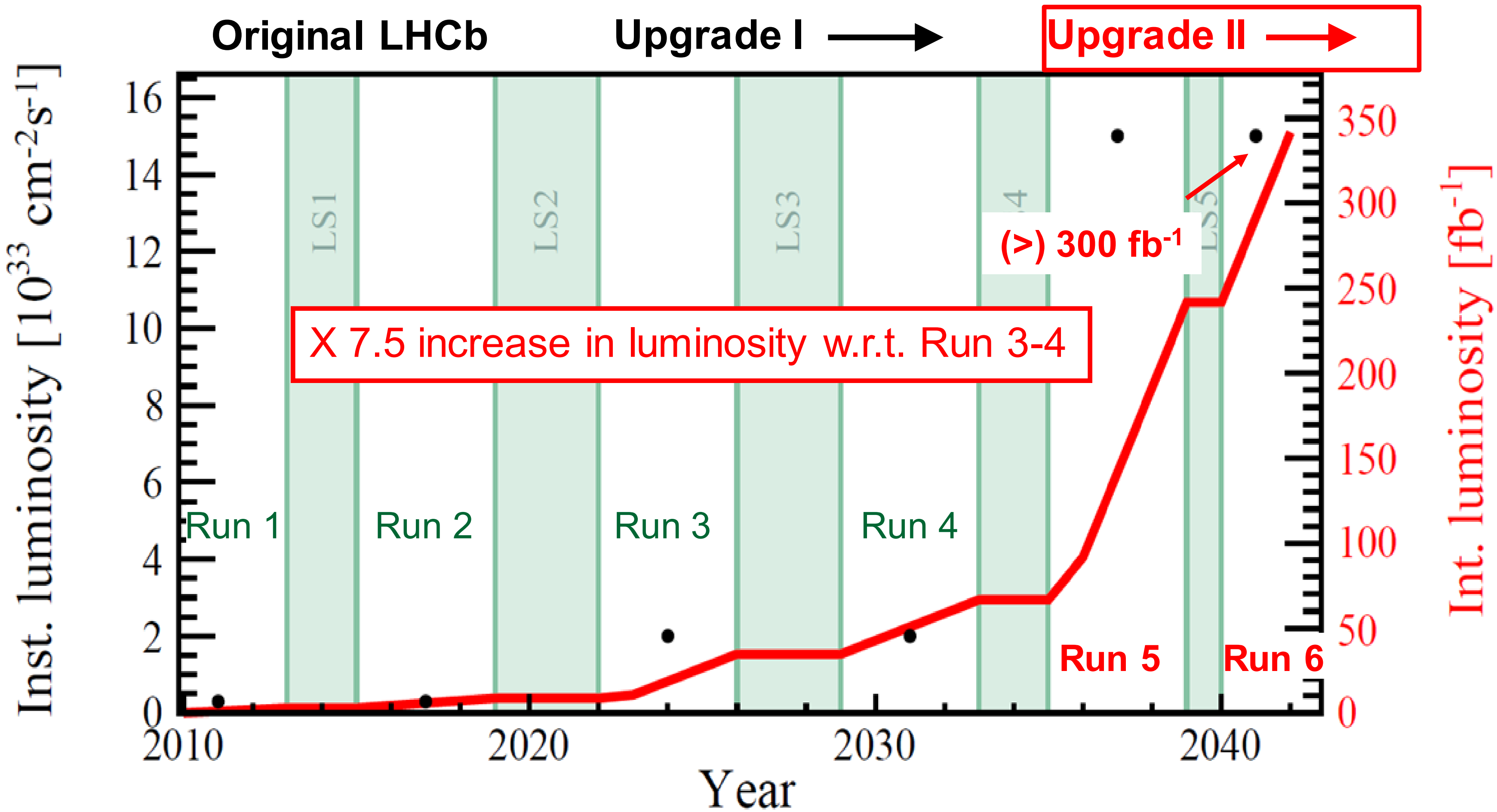
CMS prospects for $B^0_{(s)} \to \mu\mu$ in barrel region with 3 ab^{-1}.



[CMS-PAS-FTR-18-013]

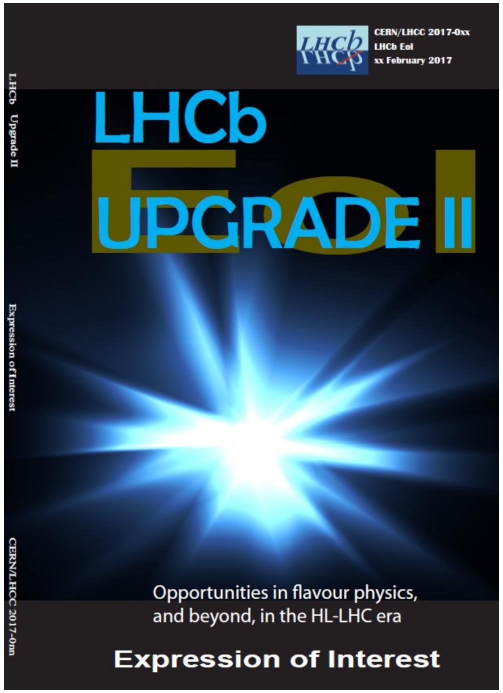
Also see recent Snowmass White Paper [ATL-PHYS-PUB-2022-018,CMS-PAS-FTR-22-001].

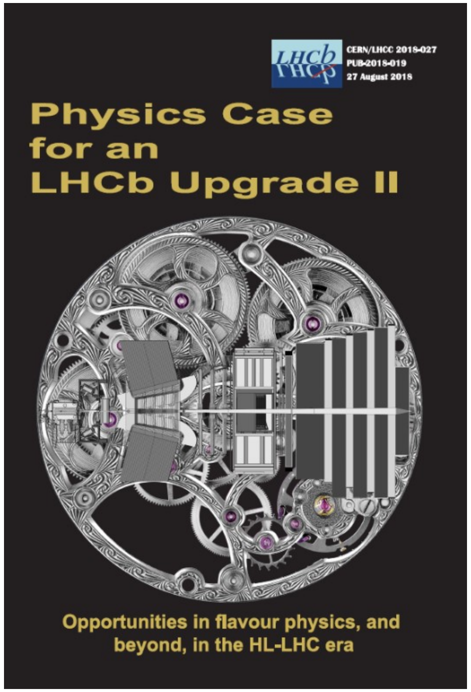
LHCb timeline: Upgrades I and II



LHCb Upgrade II

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





[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

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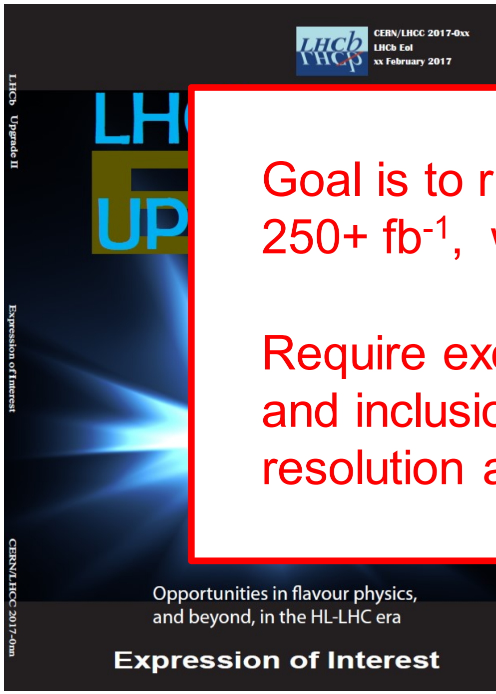
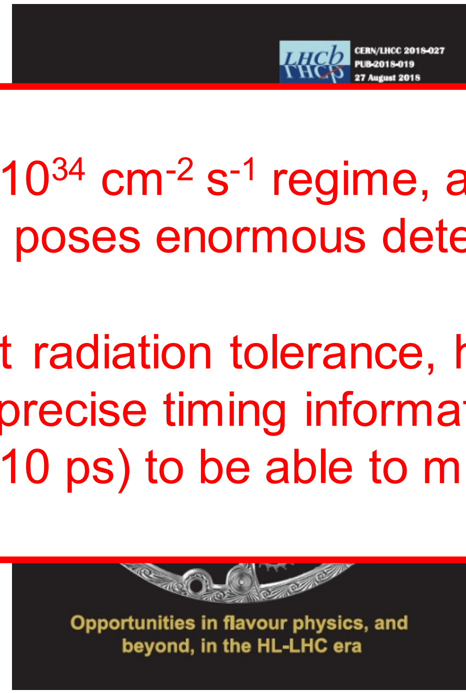
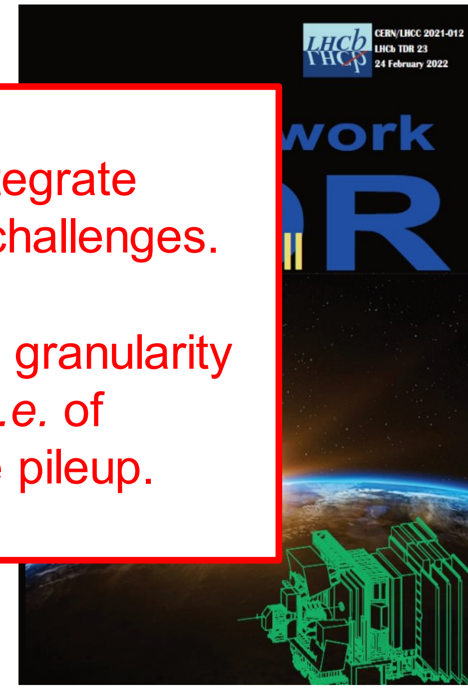






Goal is to run in 10^{34} cm^{-2} s^{-1} regime, and integrate 250+ fb^{-1}, which poses enormous detector challenges.

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.

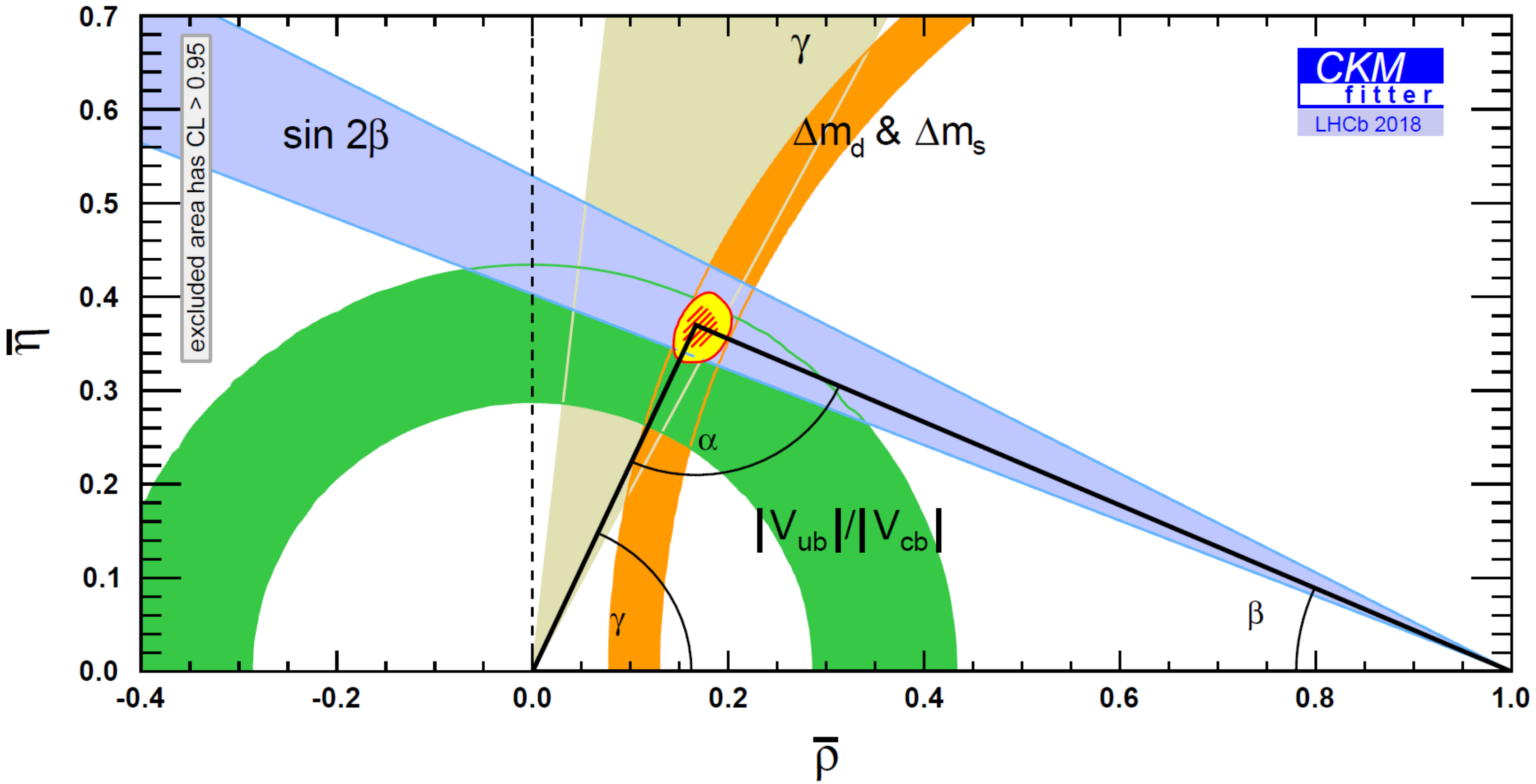
Projected uncertainties for representative observables

Observable	Current LHCb (up to 9 fb^{-1})		Upgrade I ($23\,\text{fb}^{-1}$)	Upgrade I ($50\,\text{fb}^{-1}$)	Upgrade II ($300\,\text{fb}^{-1}$)
CKM tests					
γ ($B \to DK$, *etc.*)	4°	[9, 10]	1.5°	1°	0.35°
ϕ_s ($B_s^0 \to J/\psi\phi$)	32 mrad	[8]	14 mrad	10 mrad	4 mrad
$\vert V_{ub}\vert/\vert V_{cb}\vert$ ($\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$, *etc.*)	6%	[29, 30]	3%	2%	1%
a_{sl}^d ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4}	[34]	8×10^{-4}	5×10^{-4}	2×10^{-4}
a_{sl}^s ($B_s^0 \to D_s^-\mu^+\nu_\mu$)	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 ($D^0 \to K_S^0\pi^+\pi^-$)	18×10^{-5}	[37]	6.3×10^{-5}	4.1×10^{-5}	1.6×10^{-5}
Rare Decays					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	69%	[40, 41]	41%	27%	11%
$S_{\mu\mu}$ ($B_s^0 \to \mu^+\mu^-$)	—		—	—	0.2
$A_{\text{T}}^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
A_{T}^{Im} ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$\mathcal{A}_{\phi\gamma}^{\Delta\Gamma}(B_s^0 \to \phi\gamma)$	$^{+0.41}_{-0.44}$	[51]	0.124	0.083	0.033
$S_{\phi\gamma}(B_s^0 \to \phi\gamma)$	0.32	[51]	0.093	0.062	0.025
$\alpha_\gamma(\Lambda_b^0 \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$	[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]

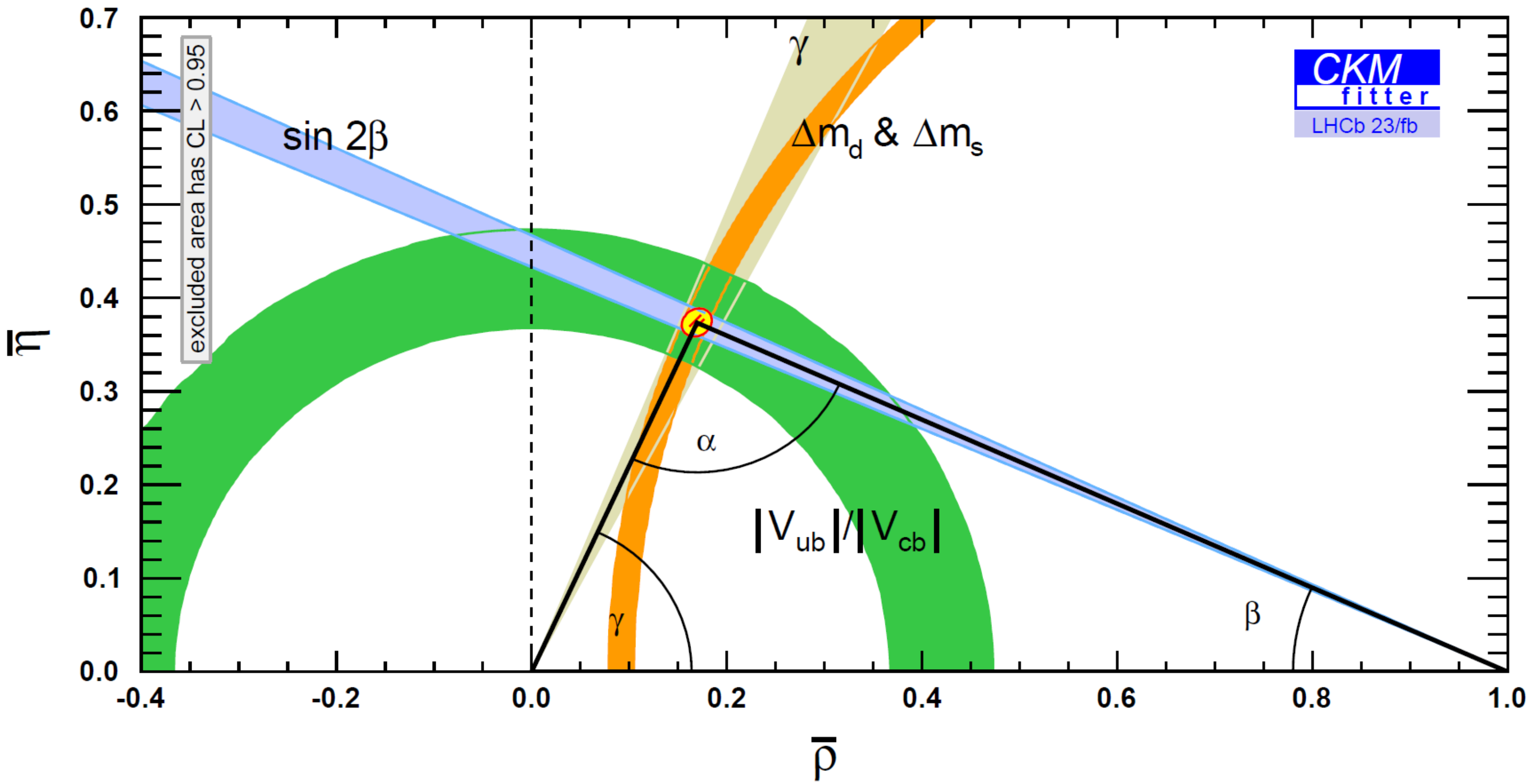
Evolution of constraints on Unitarity Triangle

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



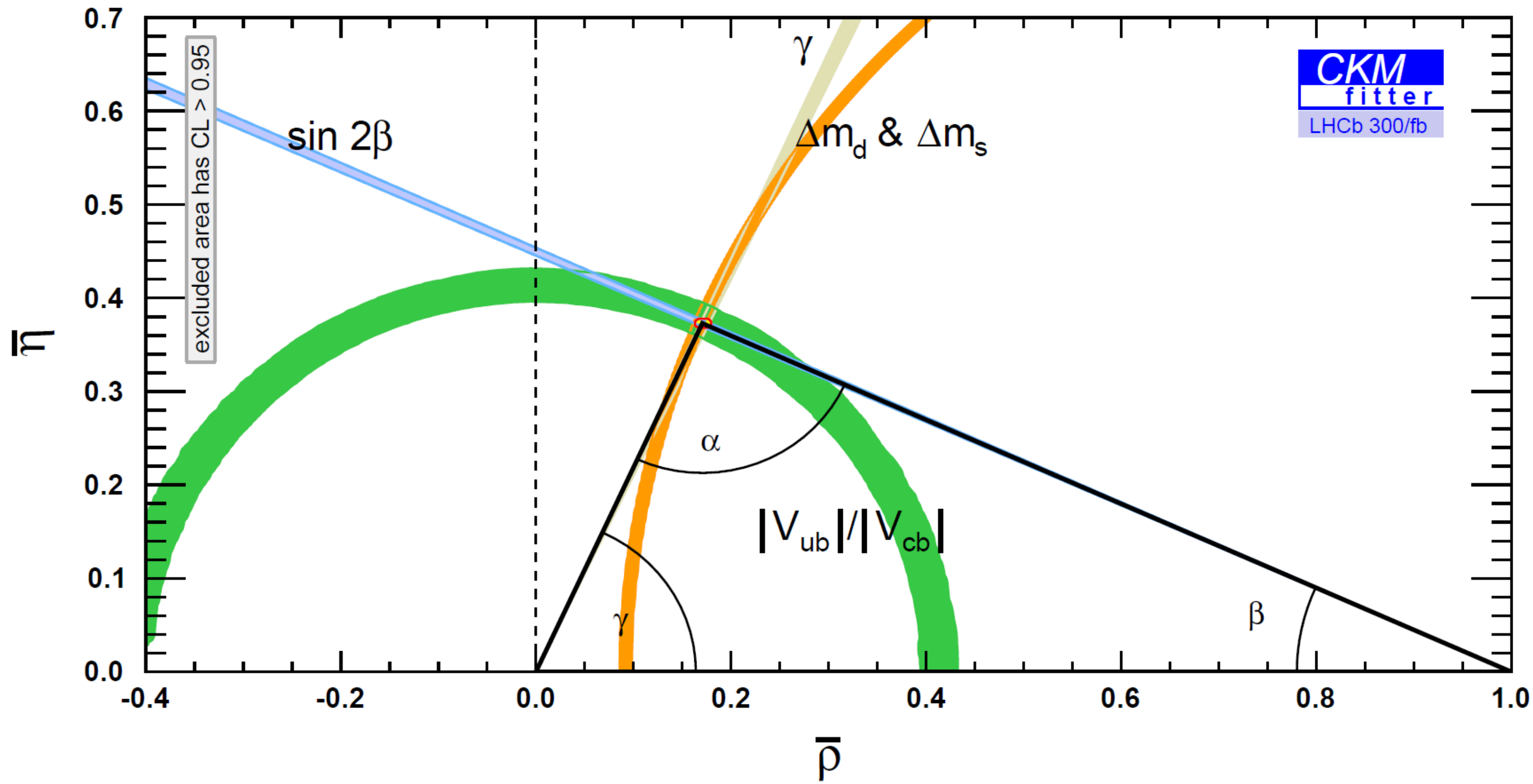
Evolution of constraints on Unitarity Triangle

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

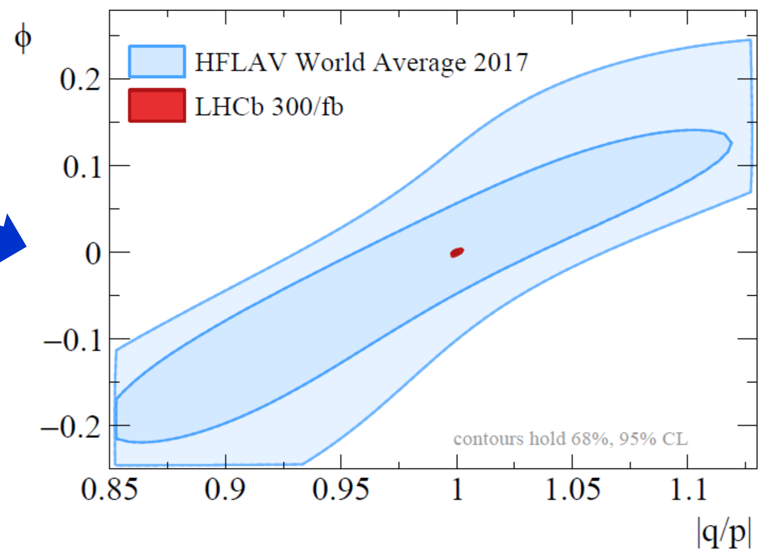


Charm physics potential of LHCb Upgrade II

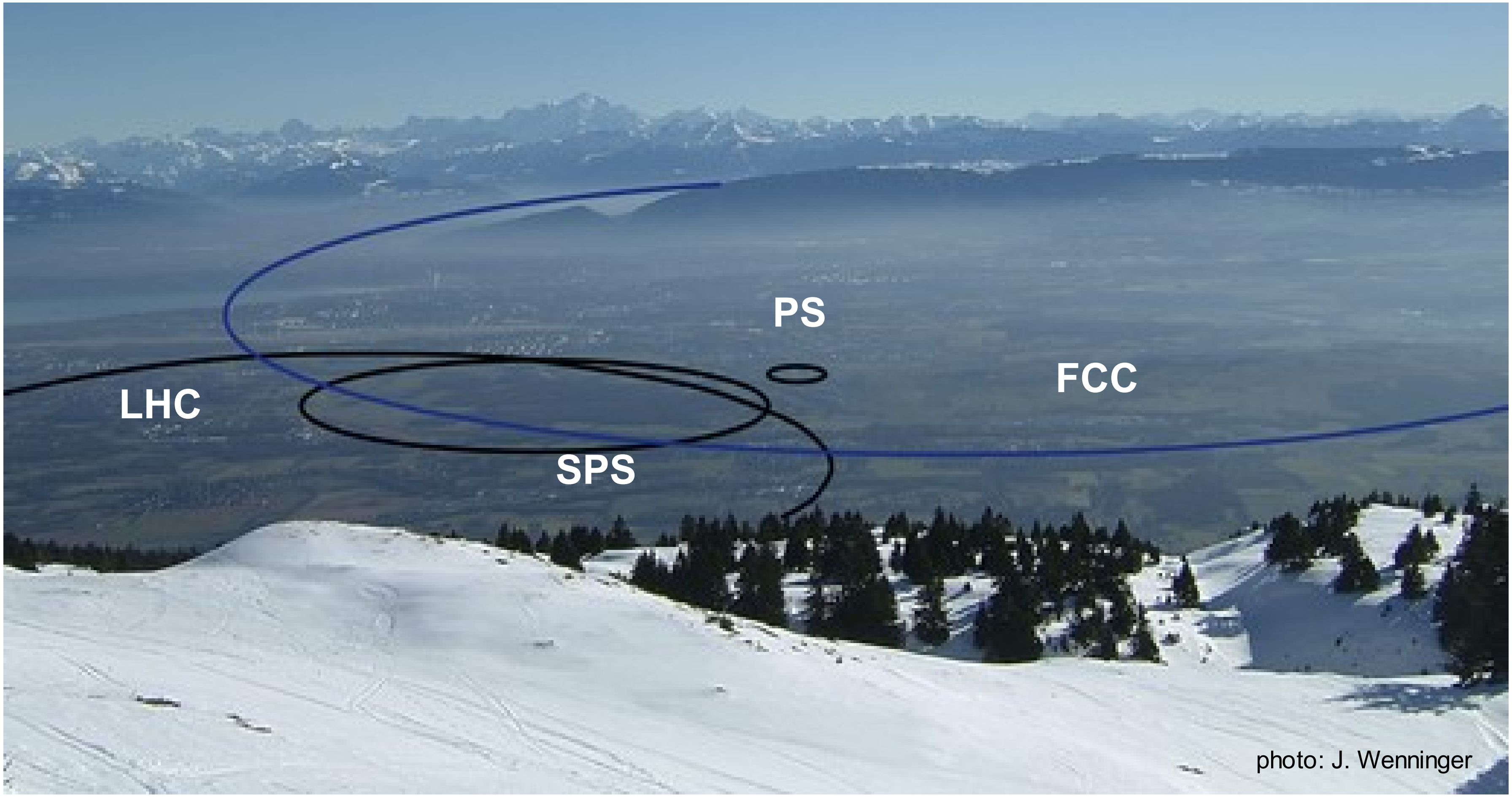
Upgrade II will allow for an order-of-magnitude improvement in precision in current benchmark analyses, such as ΔA_{CP} [arXiv:1808.08865].

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



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, but beyond the remit of this talk (see Stephane Monteil seminar, Friday).

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, about to take data, will bring this increase in precision.

It will be complemented by the Phase II Upgrades of ATLAS and CMS, with a further 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, flavour studies at hadron colliders will re-boot and enter a new era of precision with FCC-hh.

Finally

Come and join LHCb –

for a future of flavour !