Experimental prospects in charm physics

Guy Wilkinson
University of Oxford

Charm 2023, Siegen
21 July 2023

Overview

- Priorities in charm physics (a personal view)
- Plans and prospects for Belle II and the LHCb Upgrades
- Charm threshold: BESIII and STFC
- FCC-ee and FCC-hh
- Other possibilities
- Conclusions

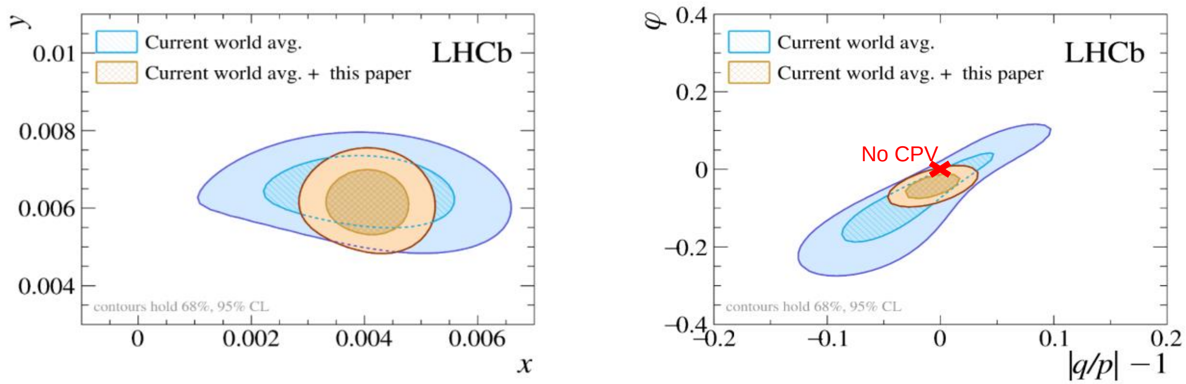
Many of these items already covered in some of the excellent talks this week, but repetition not bad in a presentation of this nature.

Priorities in charm physics – experimental drivers

The most important tasks in charm physics over the coming 10-20-30… years are:

- To characterize better our only signal of direct CPV (*i.e.* ΔA_{CP}), to find new manifestations of direct CPV, and reach consensus on whether these signals can be accommodated within SM;
- To advance our search for CPV in mixing-related phenomena (at the same time, improving still more our knowledge of the mixing parameters);

Examples of recent progress from [PRL 127 (2021) 111801].



- Improve our sensitivity to charm FCNCs & search for effects of New Physics.

A narrow view, not reflecting richness of topics covered this week ! I apologise for not covering prospects in intrinsic charm, charm in media, spectroscopy…

Spectroscopy - a 'field of dreams'

No attempt to summarise prospects of future facilities in spectroscopy. From experience of past two decades it is clear that any flavour machine will have major capabilities in this area. We have some idea of what we hope to be able to do, but surprises are guaranteed. Build it and they will come !

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

The cuckoos of physics

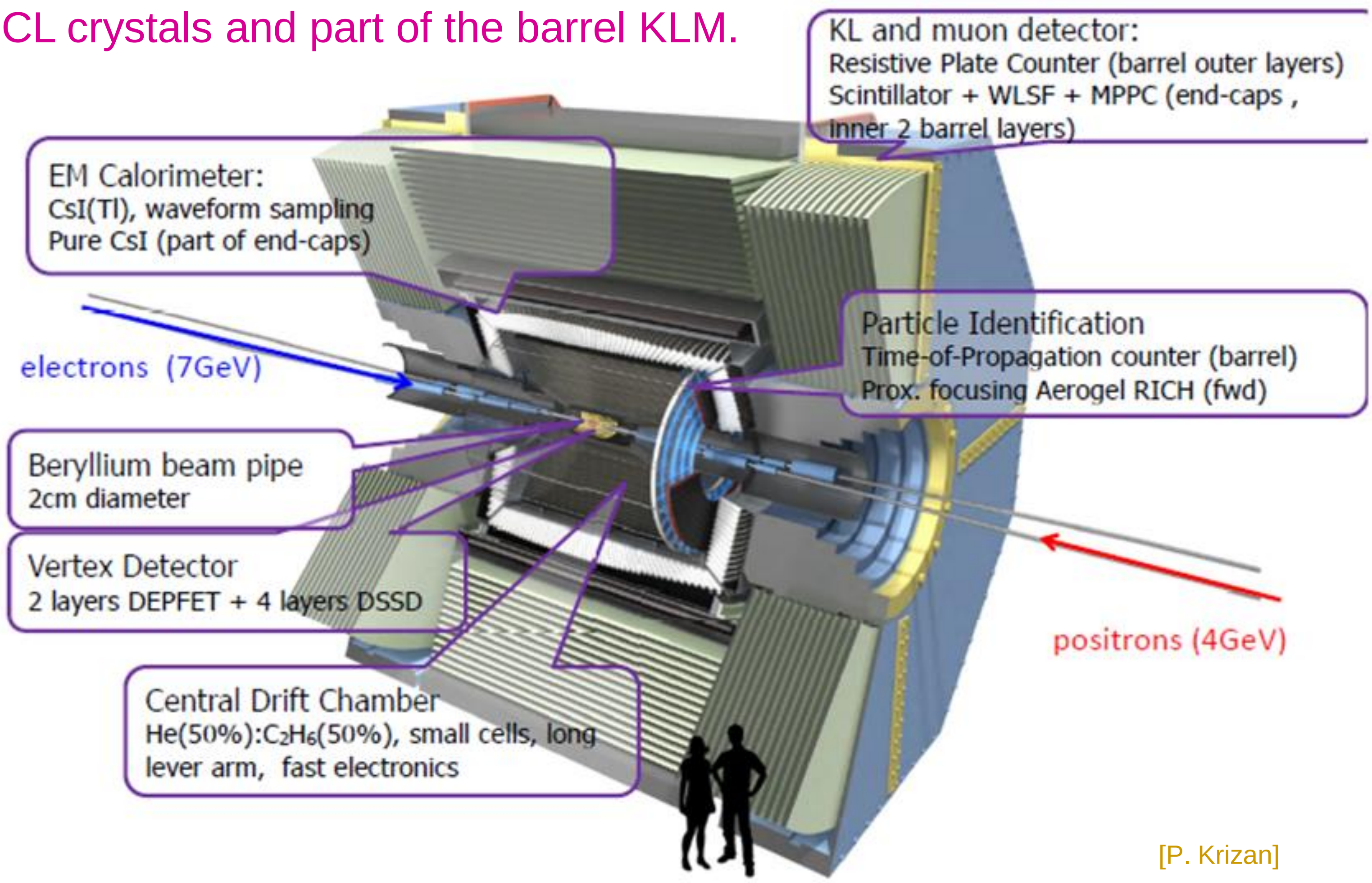
Note that the principal application of many of the listed facilities is not flavour physics, and most flavour experiments are optimised with B physics in mind.

Thus, charm physicists have to be like cuckoos, inhabiting homes that were not built for them. We may be squatters, but we have a beautiful song !

Belle II detector

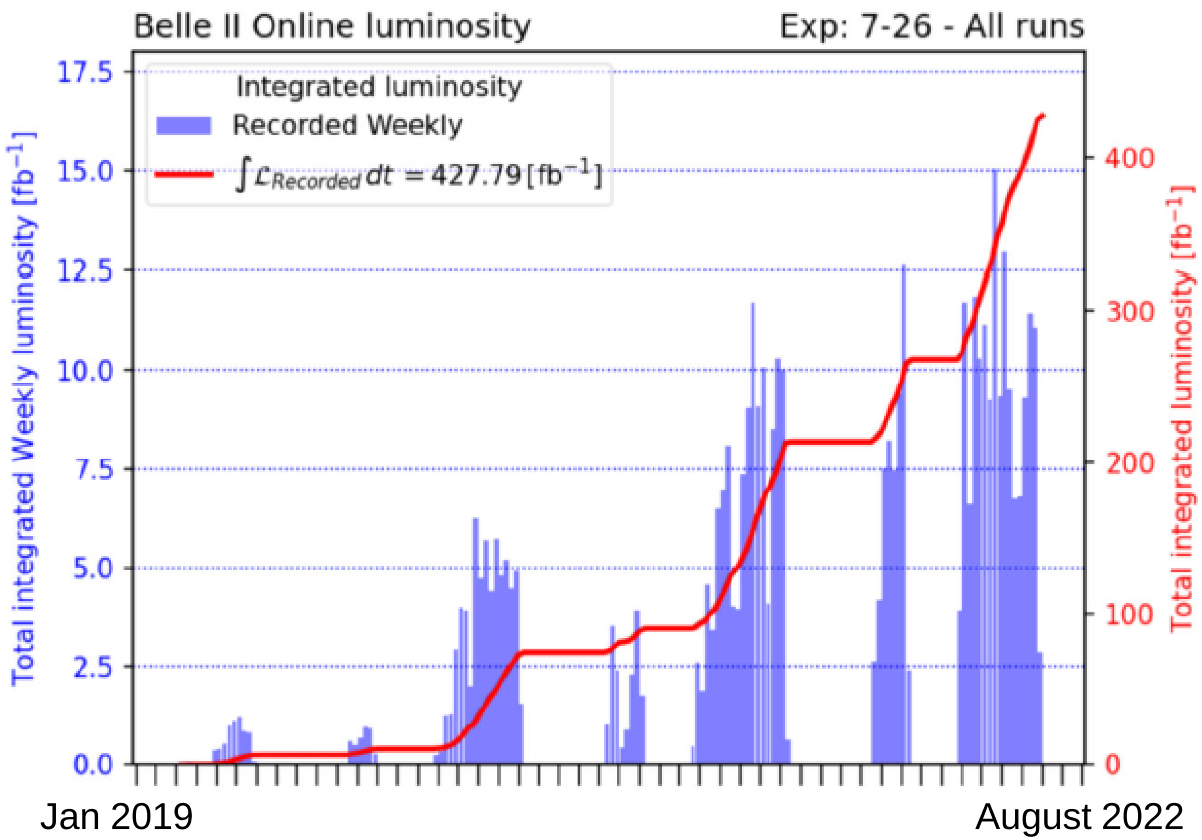
See talk of Alan Schwartz

All sub-detectors upgraded from Belle, except for ECL crystals and part of the barrel KLM.



[P. Krizan]

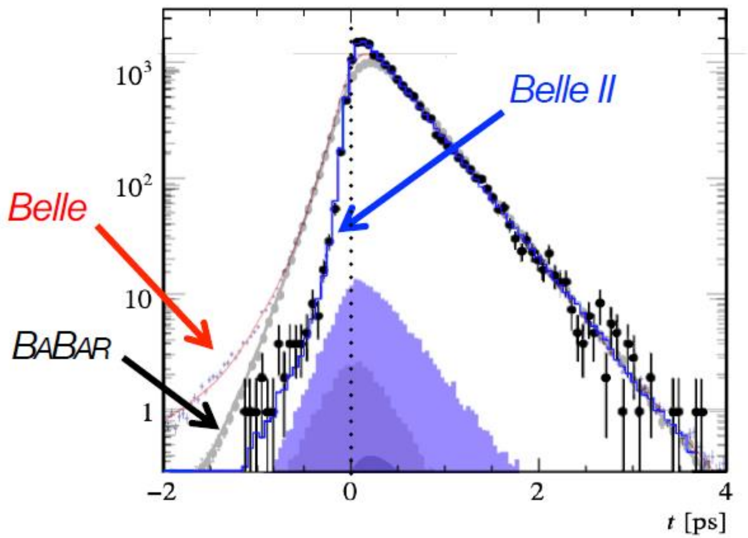
SuperKEKB and Belle II – the story so far



Reached world record instantaneous luminosity: 4.7 x 10^{34} $cm^{-2}s^{-1}$.
Integrated luminosity until now (shutdown): 428 fb^{-1} (similar to BaBar).

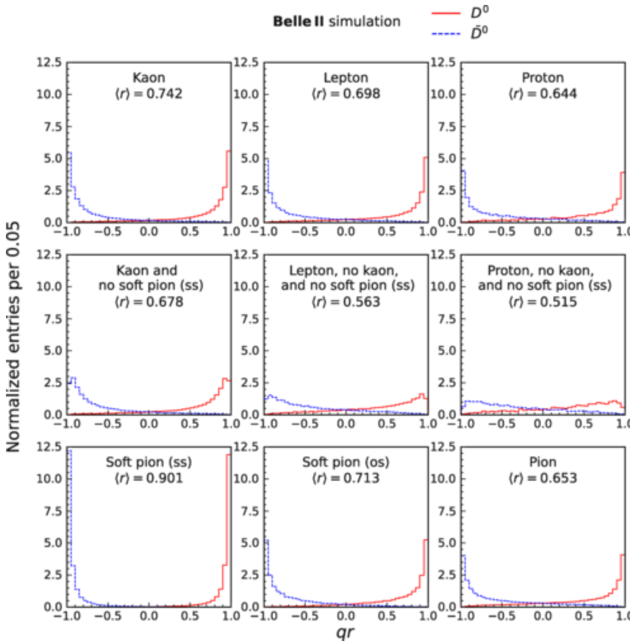
Belle II – improved detector, with improved methods

Factor of (>) two improvement in time resolution (80-90 fs).



Ergo, Belle II physics reach is not just a sqrt(N) scaling from Belle !

Augment classical D* flavour tag, with further tags from other charm hadron.



See talk of Marko Staric

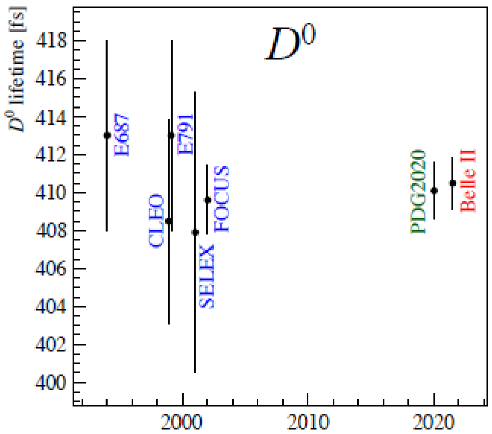
[PRD 107 (2023) 112010]

Doubles sample size w.r.t. D* tags.

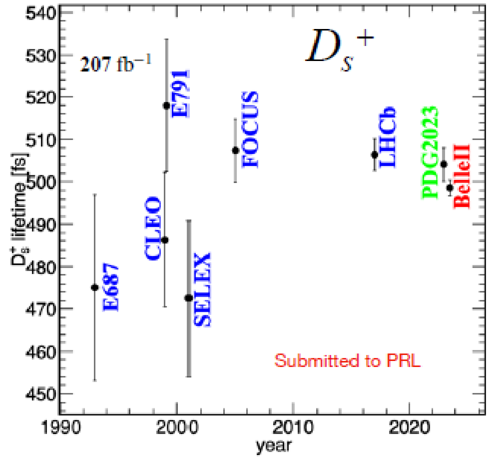
Charm-lifetime measurements

[Alan Schwartz, this conference]

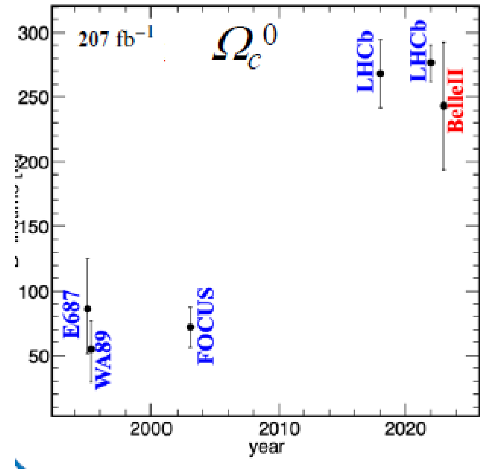
[PRL 127 (2021) 211801]

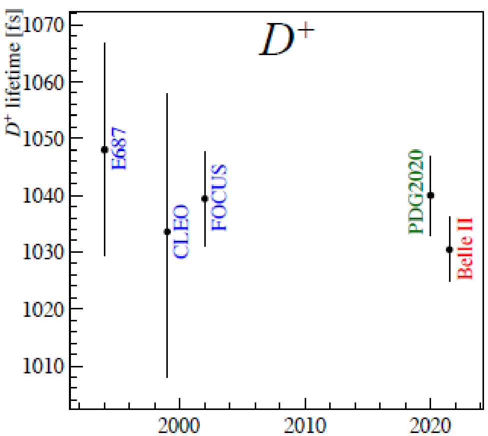


[arXiv:2306.00365]

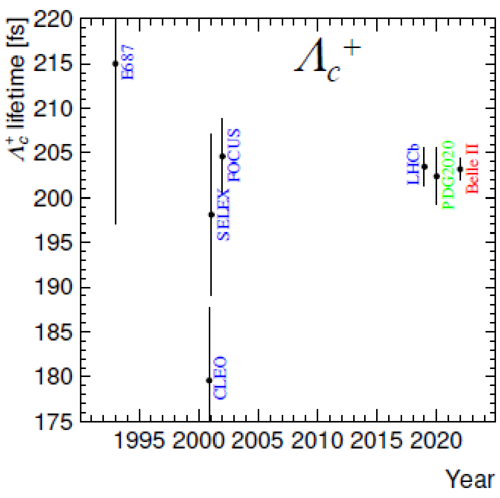


[PRD 107 (2023) L031103]





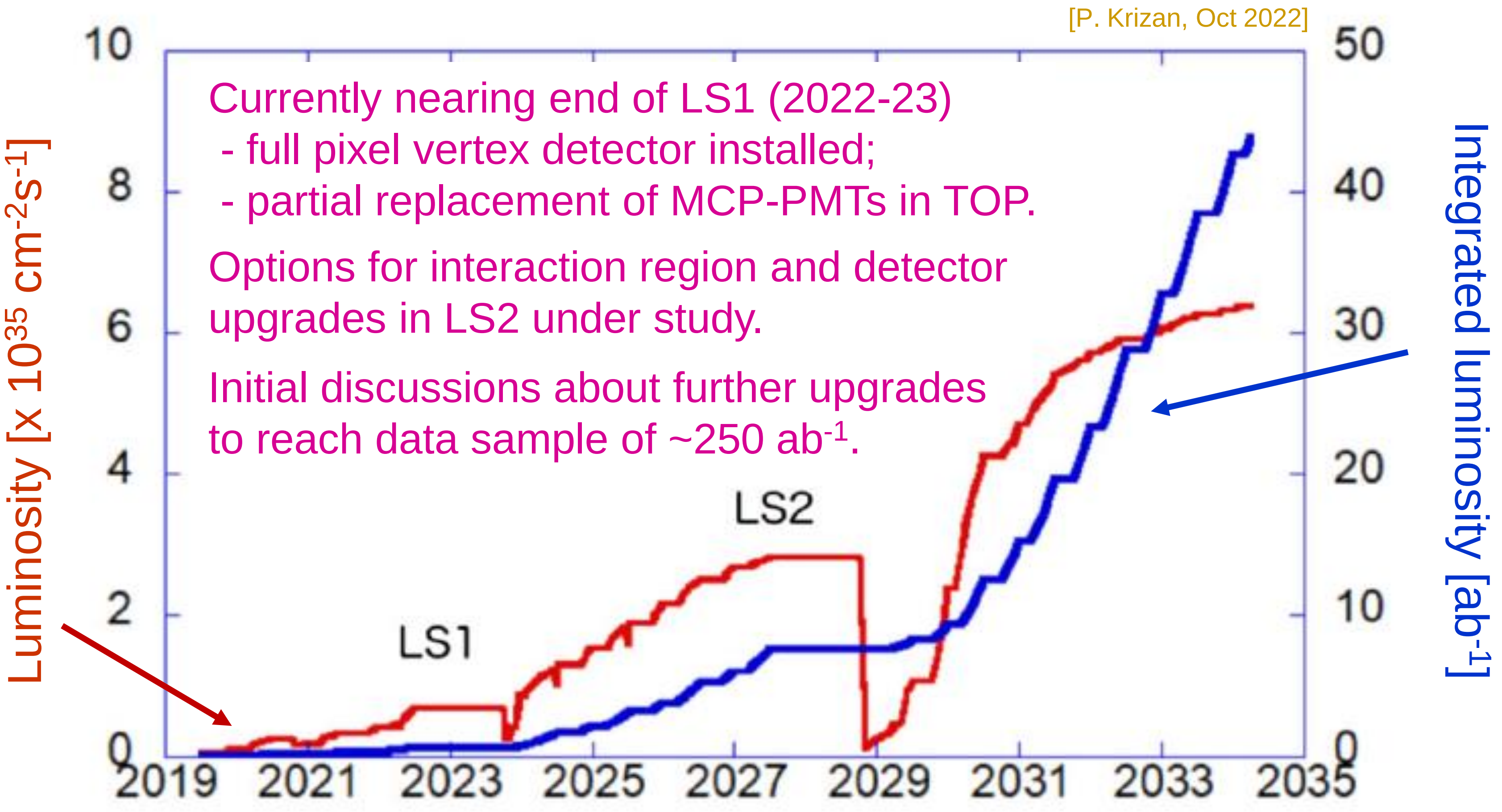
[PRL 127 (2021) 211801]



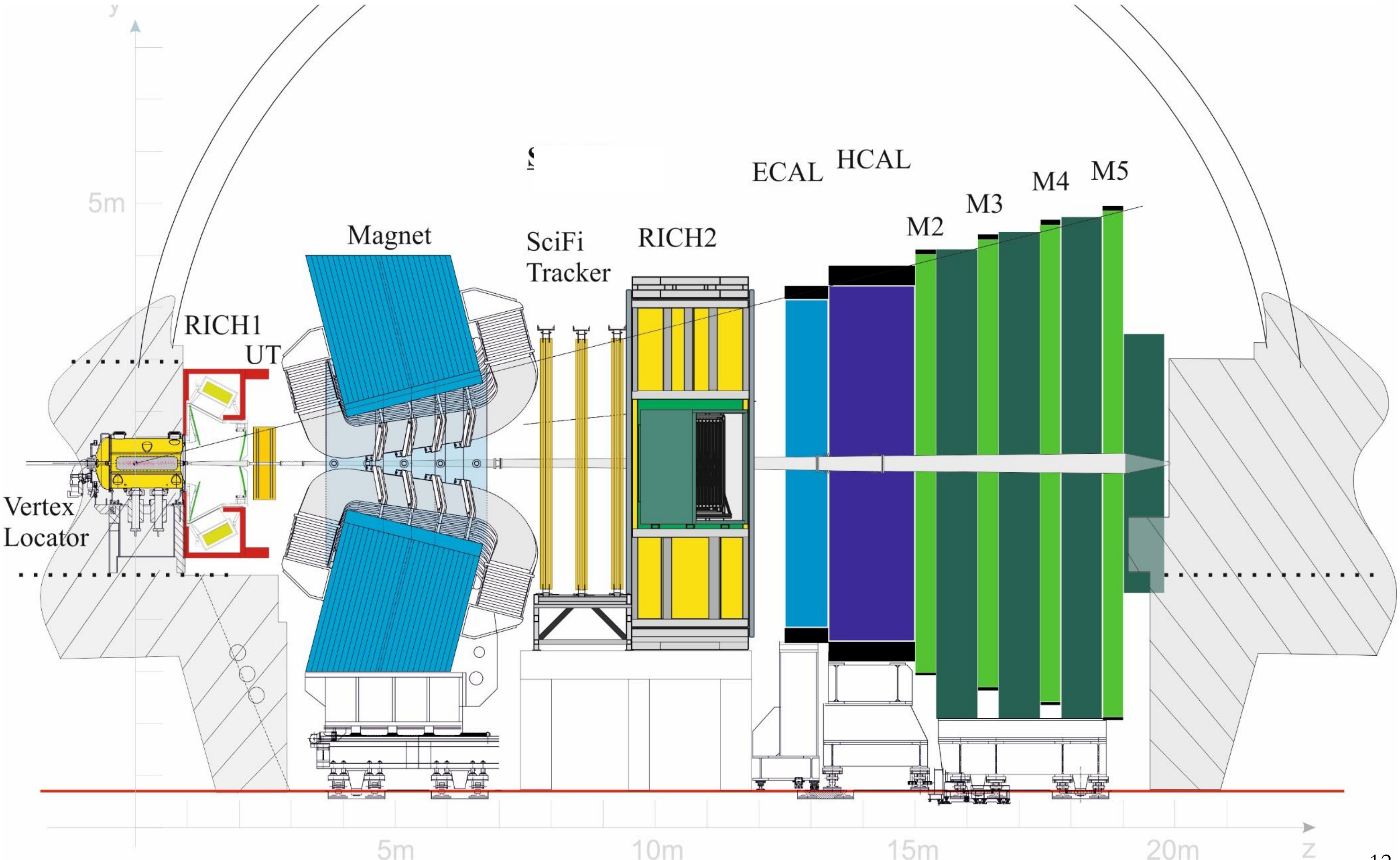
[PRL 130 (2023) 071802]

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

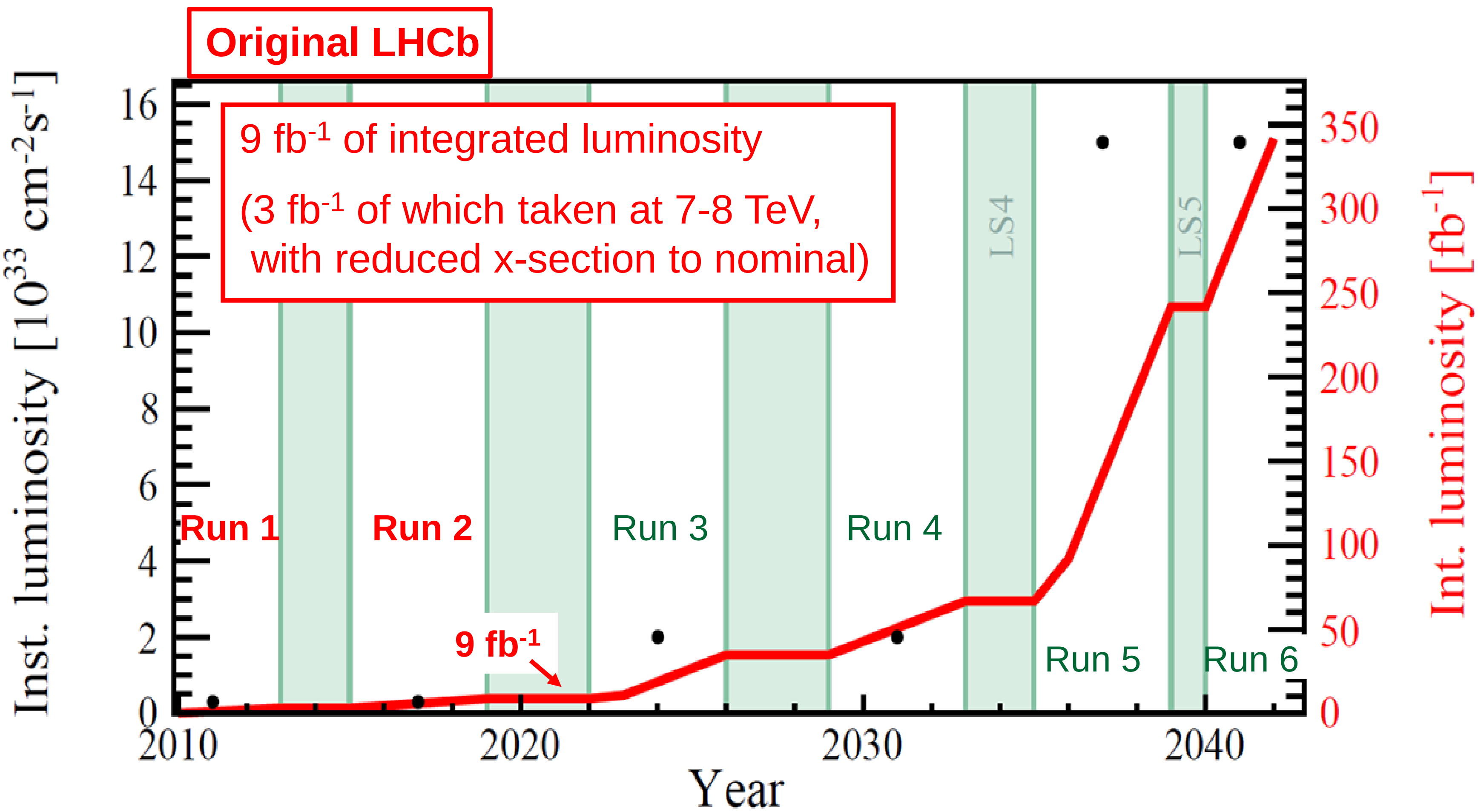
SuperKEKB and Belle II roadmap



LHCb Run 1 & 2 detector



LHCb timeline: Upgrades I and II



LHCb Upgrade I – driving ideas

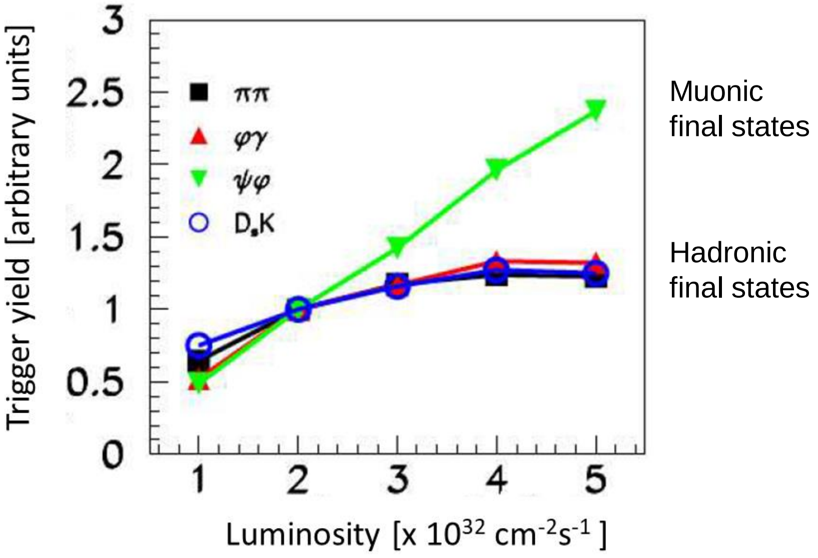
See talk of Giuia Tuci

LHCb operational luminosity in Run 2 plateaued at 4 x 10^{32} cm^{-2} s^{-1}.

Why not go higher ?

- Radiation damage and occupancy of detectors.
- Saturation of earliest level hardware trigger (L0) for hadronic final states.

[From CERN-LHCC-2011-001 for B decays. Story for charm similar.]



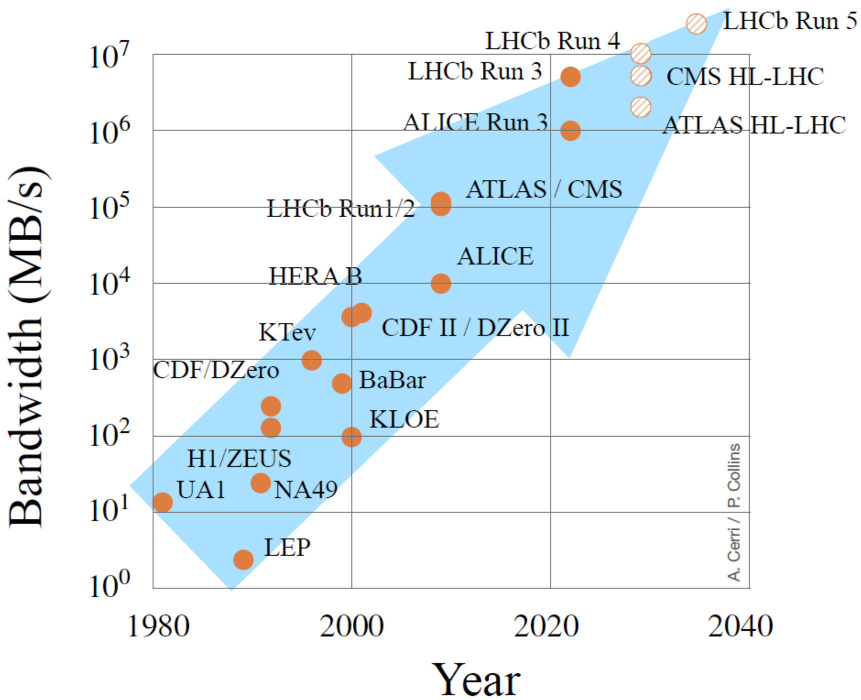
How to get around this?

- Redesign all critical sub-detectors.
- Remove L0 hardware trigger, and read out full detector every event into computer farm where full software trigger can be deployed. Removes saturation bottle neck and allows for higher luminosity. In principle brings higher efficiency, flexibility, and systematic robustness.

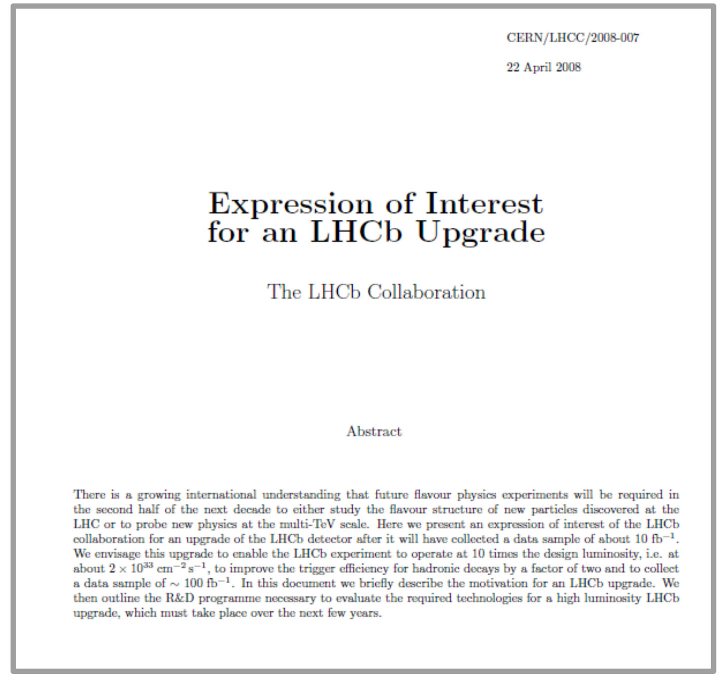
Aim to raise luminosity to 2 x 10^{33} $cm^{-2}s^{-1}$ and increase collected data sample from 9 fb^{-1} (Run 1 and 2) to ~50 fb^{-1} (Runs 3 and 4), with higher efficiency.

Audacious project, around 15 years in the planning

Implications of full software trigger



Expression of Interest (2008)



CERN/LHCC/2008-007

22 April 2008

Expression of Interest for an LHCb Upgrade

The LHCb Collaboration

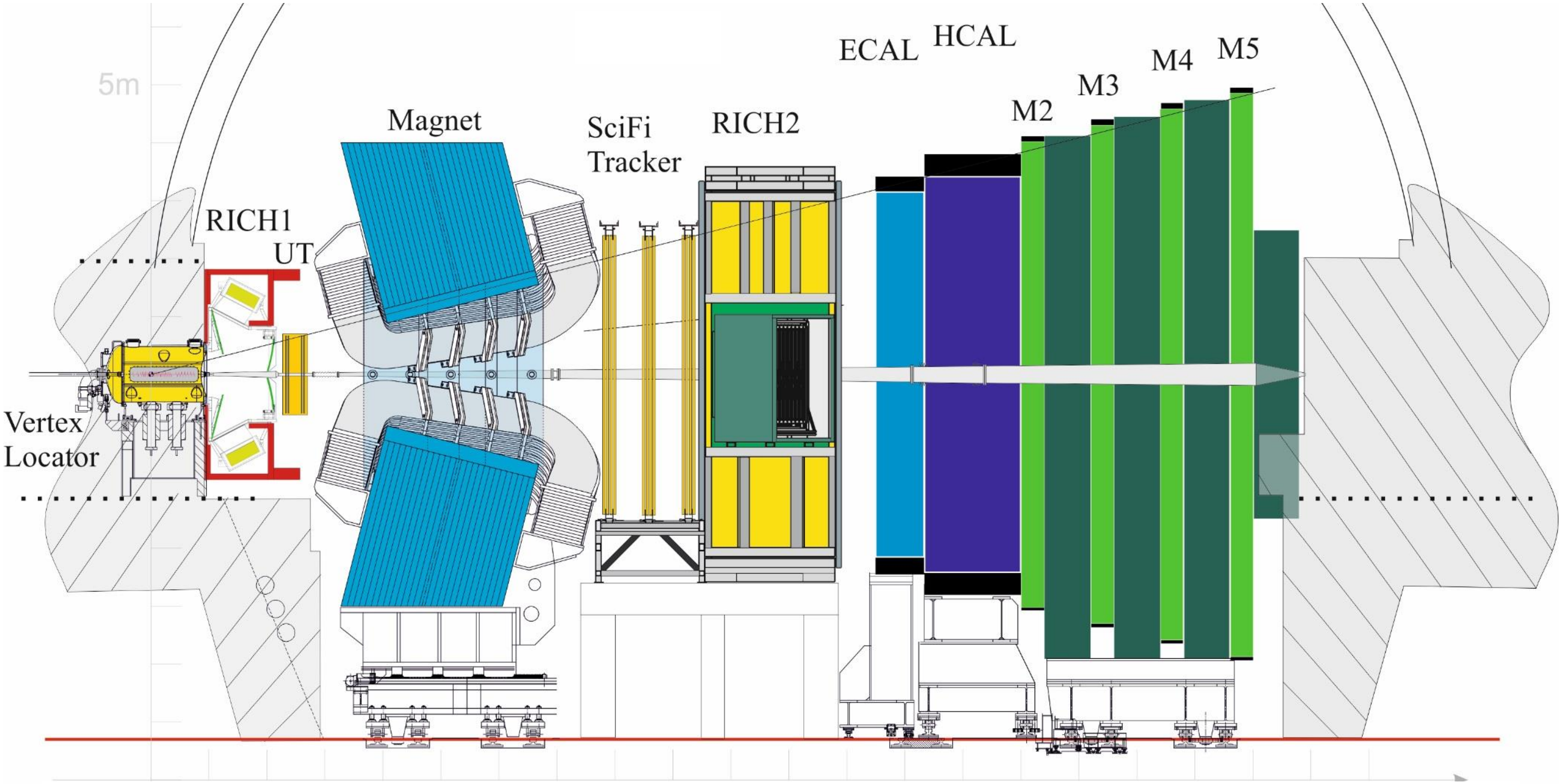
Abstract

There is a growing international understanding that future flavour physics experiments will be required in the second half of the next decade to either study the flavour structure of new particles discovered at the LHC or to probe new physics at the multi-TeV scale. Here we present an expression of interest of the LHCb collaboration for an upgrade of the LHCb detector after it will have collected a data sample of about 10 fb^{-1}. We envisage this upgrade to enable the LHCb experiment to operate at 10 times the design luminosity, i.e. at about 2×10^{33} $cm^{-2} s^{-1}$, to improve the trigger efficiency for hadronic decays by a factor of two and to collect a data sample of ~ 100 fb^{-1}. In this document we briefly describe the motivation for an LHCb upgrade. We then outline the R&D programme necessary to evaluate the required technologies for a high luminosity LHCb upgrade, which must take place over the next few years.

[CERN-LHCC-2008-007]

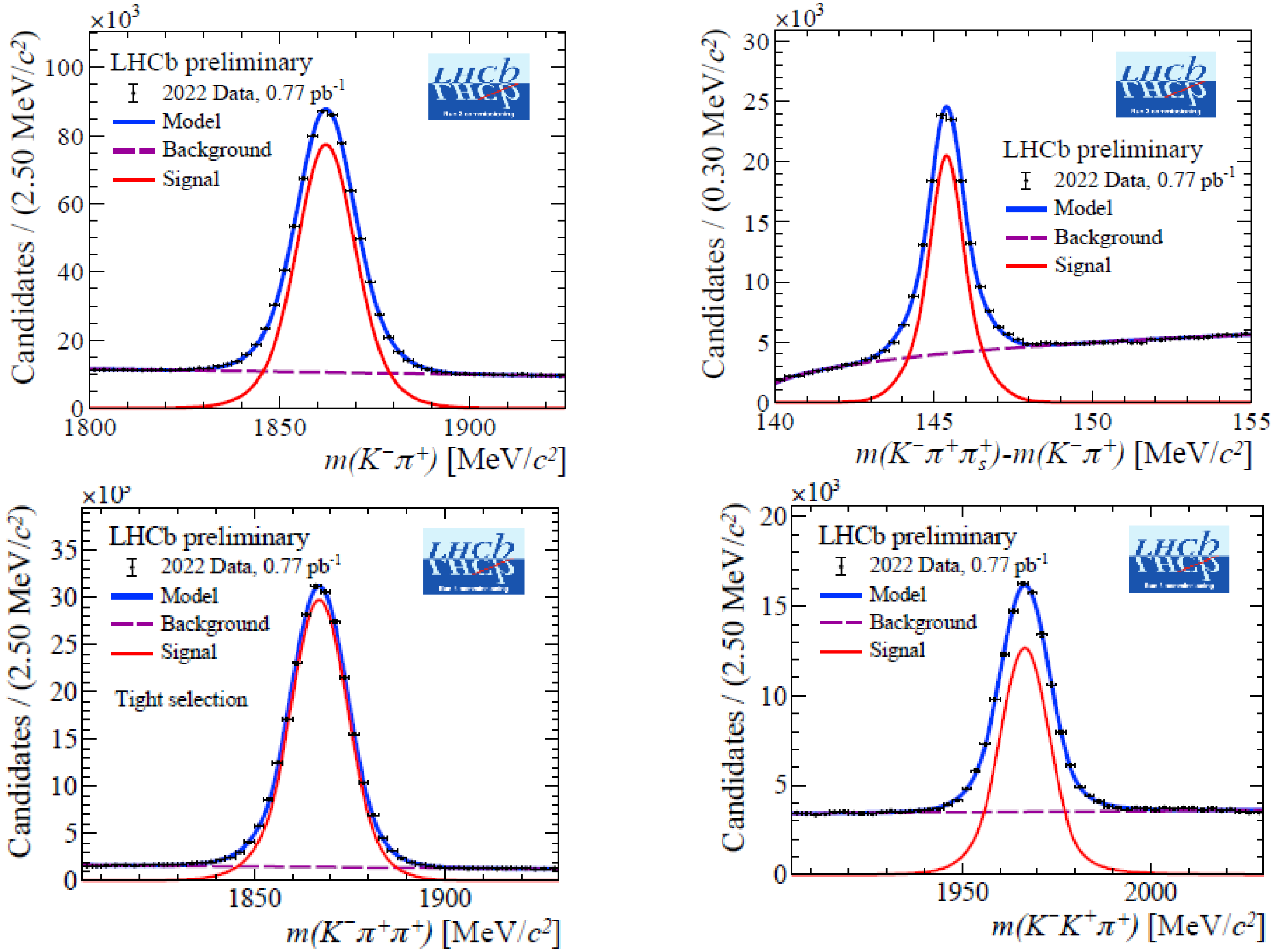
LHCb Upgrade I – the future is now

Superficially looks like Run 1 & 2 spectrometer, but all sub-detectors , apart from calorimeters and muon system new, with new read-out electronics throughout.



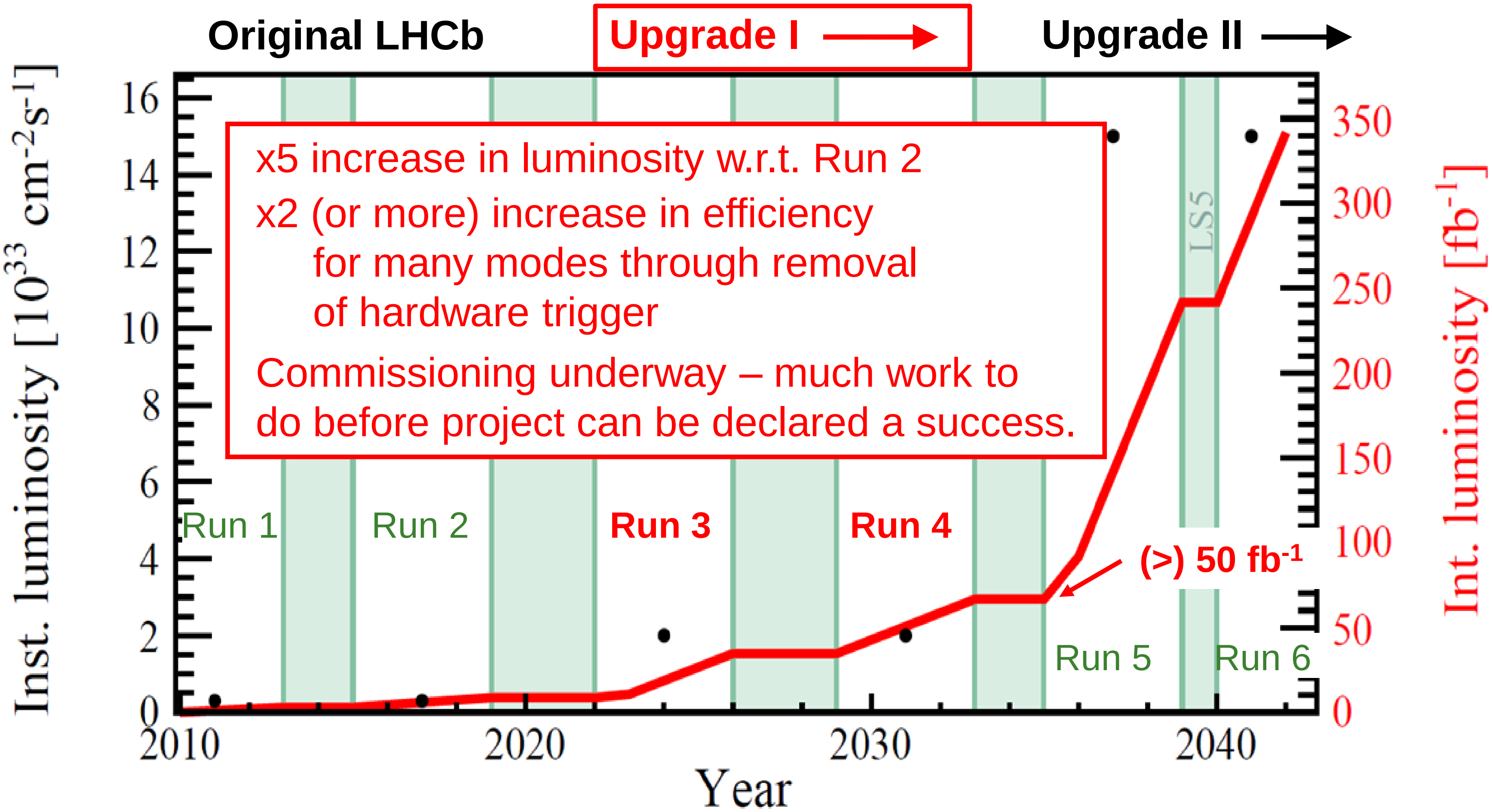
Operational since last year, with final component (the UT) added at the start of this year's run. Commissioning ongoing…. (this is not a trivial business).

First charm peaks from Upgrade I

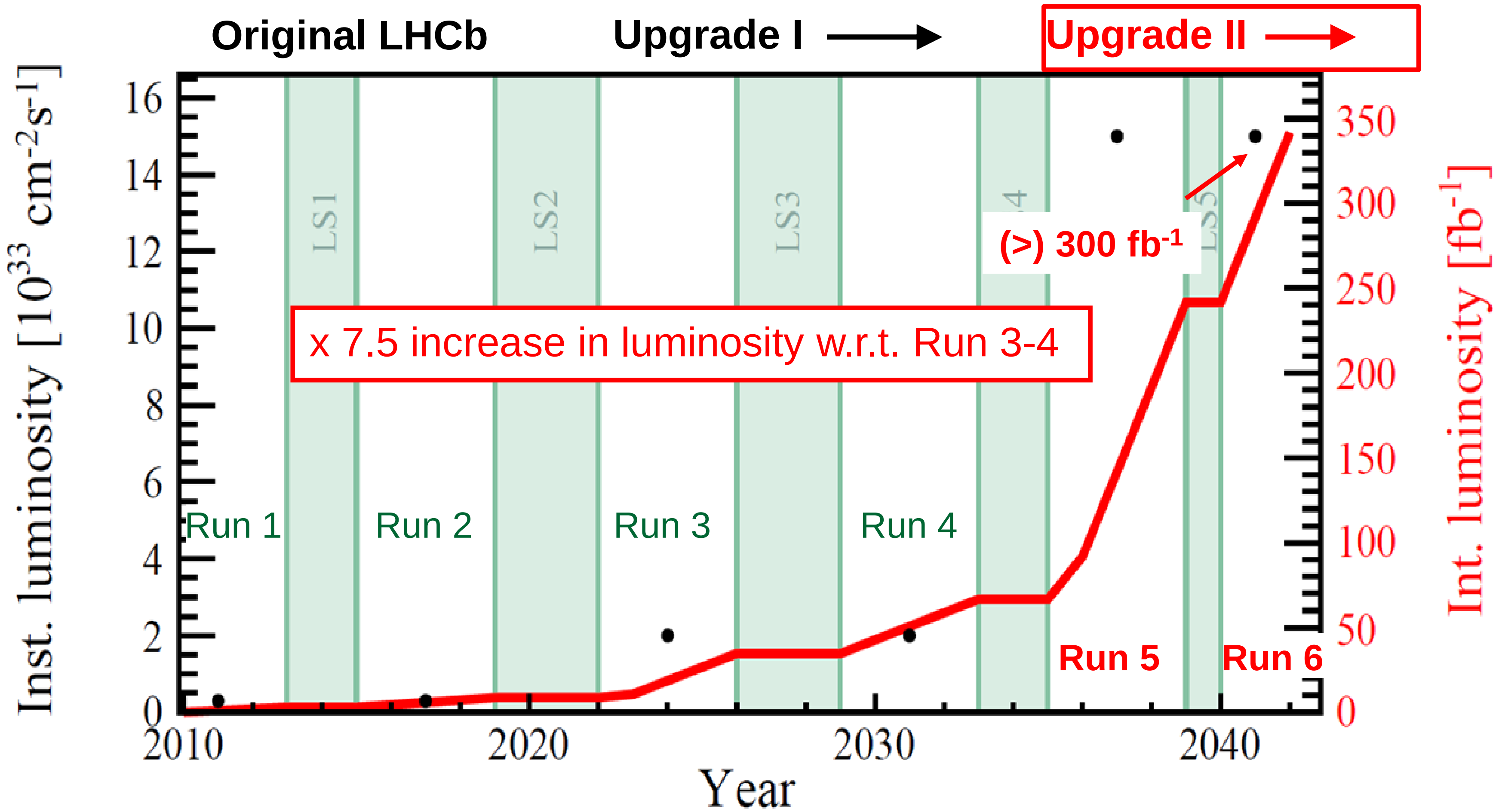


[LHCb-FIGURE-2023-011]

LHCb timeline: Upgrades I and II

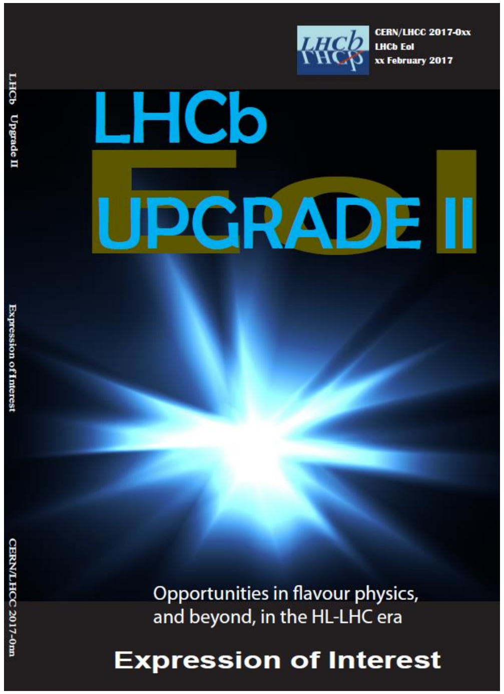


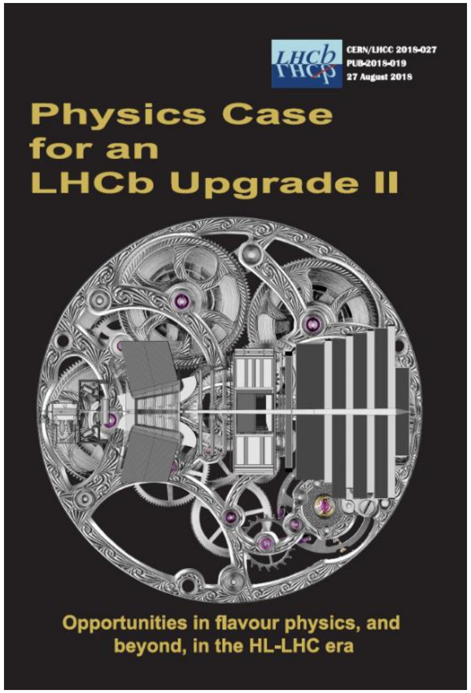
LHCb timeline: Upgrades I and II



LHCb Upgrade II

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



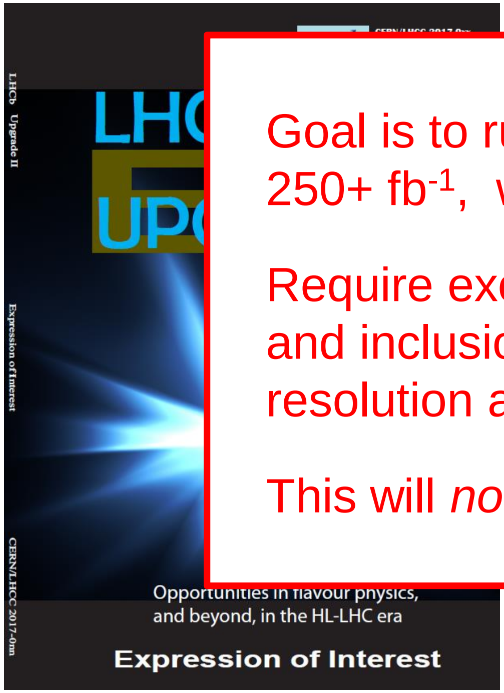


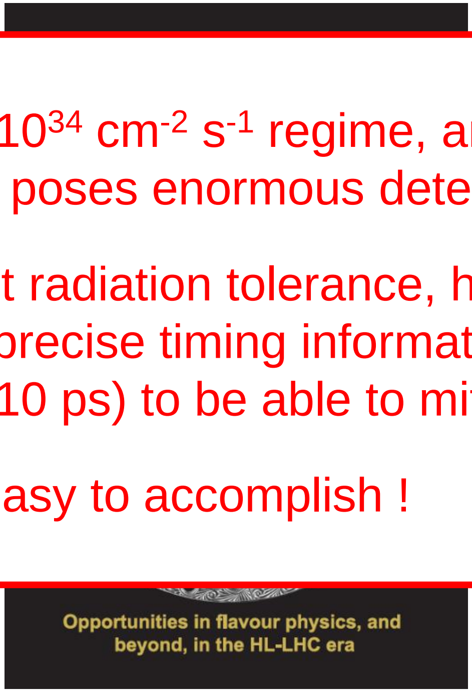
[CERN-LHCC-2017-003] [CERN-LHCC-2018-027] [CERN-LHCC-2021-012]

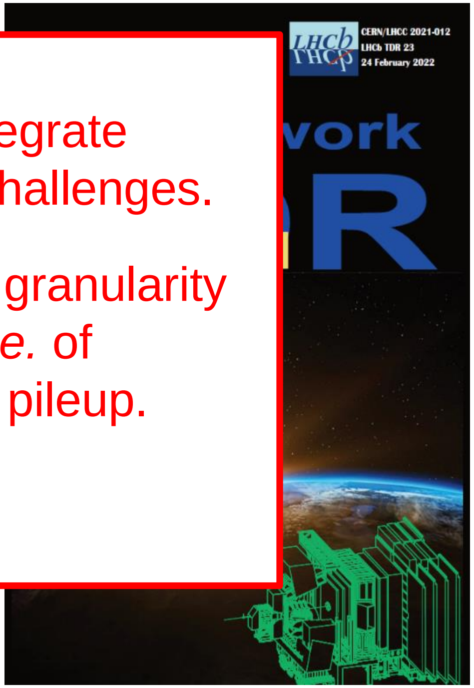
Now part of the CERN baseline plan. Framework TDR recently approved by LHCC. Work beginning on ‘scoping document’, which will consider some less ambitious scenarios to that in Framework TDR. Substantial funding already ‘awarded’ in UK.

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.

This will *not* be easy to accomplish !

[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. Work beginning on ‘scoping document’, which will consider some less ambitious scenarios to that in Framework TDR. Substantial funding already ‘awarded’ in UK.

“Events, dear boy, events”

(Former UK Prime Minister Harold Macmillan on what made his job challenging.)

CERN, Monday

Predicting future is a fool’s errand, and these plans and timelines we have seen are very much at the mercy of events.

Projected yields in CPV benchmark modes

Consider three benchmark modes and scale from published numbers.

	$D^0 \to K^+\pi^-$			$D^0 \to \pi^+\pi^-\pi^0$			$D^0 \to K_S^0\pi^+\pi^-$		
BaBar/Belle	11.5k	1.0 ab^{-1}	[1]	126k	0.5 ab^{-1}	[3]	1.2M	0.9 ab^{-1}	[5]
LHCb	722k	5.0 fb^{-1}	[2]	566k	2.0 fb^{-1}	[4]	30.6M	5.4 fb^{-1}	[6]
Belle II	225k	50 ab^{-1}		13M	50 ab^{-1}		67M	50 ab^{-1}	
LHCb UI	25M	50 fb^{-1}		44M	50 fb^{-1}		540M	50 fb^{-1}	
LHCb UII	170M	300 fb^{-1}		291M	300 fb^{-1}		3,370M	300 fb^{-1}	

Belle II: assume same reconstruction efficiency (rather unfair)
LHCb upgrades: scale for $\sigma(E_{CM})$ changes from Run 1, and increase of two in trigger efficiency for Upgrades (crude aspiration)

[1] Belle, PRL 112 (2014) 111801
[2] LHCb, PRD 97 (2018) 031101
[3] BaBar, PRD 93 (2016) 112014
[4] LHCb, PRL 122 (2019) 231802
[5] Belle, PRD 89 (2014) 091103
[6] LHCb, PRL 127 (2011) 111801

Projected yields in CPV benchmark modes

Consider three benchmark modes and scale from published numbers.

	$D^0 \to K^+\pi^-$			[illegible]			$D^0 \to K^0\pi^+\pi^-$		
BaBar/Belle	11.5k	1.0 ab^{-1}	[1]					ab^{-1}	[5]
LHCb	722k	5.0 fb^{-1}	[2]					fb^{-1}	[6]
Belle II	225k	50 ab^{-1}		13M	50 ab^{-1}		67M	50 ab^{-1}	
LHCb UI	25M	50 fb^{-1}		44M	50 fb^{-1}		540M	50 fb^{-1}	
LHCb UII	170M	300 fb^{-1}		291M	300 fb^{-1}		3,370M	300 fb^{-1}	

Comparing these, we deduce it will be a long road for Belle II to confirm the LHCb result for ΔA_{CP}. ($A_{CP}(KK)$ will probably come first ?)

Belle II: assume same reconstruction efficiency (rather unfair)

LHCb upgrades: scale for $\sigma(E_{CM})$ changes from Run 1, and increase of two in trigger efficiency for Upgrades (crude aspiration)

[1] Belle, PRL 112 (2014) 111801
[2] LHCb, PRD 97 (2018) 031101
[3] BaBar, PRD 93 (2016) 112014
[4] LHCb, PRL 122 (2019) 231802
[5] Belle, PRD 89 (2014) 091103
[6] LHCb, PRL 127 (2011) 111801

Projected yields in CPV benchmark modes

Consider three benchmark modes and scale from published numbers.

	$D^0 \to K^+\pi^-$			$D^0 \to \pi^+\pi^-\pi^0$			$D^0 \to K^0_S\pi^+\pi^-$		
BaBar/Belle	11.5k	1.0 ab^{-1}	[1]	126k	0.5 ab^{-1}	[3]	1.2M	0.9 ab^{-1}	[5]
Belle II	225k	50 ab^{-1}		13M	50 ab^{-1}		67M	50 ab^{-1}	
LHCb UI	25M	50 fb^{-1}		44M	50 fb^{-1}		540M	50 fb^{-1}	
LHCb UII	170M	300 fb^{-1}		291M	300 fb^{-1}		3,370M	300 fb^{-1}	

Opens up exciting possibilities for charm at Belle II. In particular, direct CPV searches in Belle II flagship channels, *e.g.* $\pi\pi\pi^0$, $K_S K_S$ will be of great interest.

Belle II: assume same reconstruction efficiency (rather unfair)
LHCb upgrades: scale for $\sigma(E_{CM})$ changes from Run 1, and increase of two in trigger efficiency for Upgrades (crude aspiration)

[1] Belle, PRL 112 (2014) 111801
[2] LHCb, PRD 97 (2018) 031101
[3] BaBar, PRD 93 (2016) 112014
[4] LHCb, PRL 122 (2019) 231802
[5] Belle, PRD 89 (2014) 091103
[6] LHCb, PRL 127 (2011) 111801

Projected yields in CPV benchmark modes

From LHCC-2021-012 :

additional modes such as $D^0 \to K^{\mp}\pi^{\pm}\pi^{+}\pi^{-}$ [3]. With the precision on $|q/p|$ and ϕ_D reaching 0.0020 and 0.15°, respectively, with 300 fb^{-1}, LHCb Upgrade II is the only planned facility with a realistic possibility of observing CP-violating phenomena in charm mixing.

(Current precision [JHEP 12 (2021) 141] from combined D and B fit is ± 0.016 on |q/p| and $\pm 1.2^o$ on ϕ_D.) Theorists, please give us a prediction !

Ba

LH

Belle II	225k	50 ab^{-1}	13M	50 ab^{-1}	67M	50 ab^{-1}
LHCb UI	25M	50 fb^{-1}	44M	50 fb^{-1}	540M	50 fb^{-1}
LHCb UII	170M	300 fb^{-1}	291M	300 fb^{-1}	3,370M	300 fb^{-1}

Belle II: assume same reconstruction efficiency (rather unfair)

LHCb upgrades: scale for $\sigma(E_{CM})$ changes from Run 1, and increase of two in trigger efficiency for Upgrades (crude aspiration)

[1] Belle, PRL 112 (2014) 111801
[2] LHCb, PRD 97 (2018) 031101
[3] BaBar, PRD 93 (2016) 112014
[4] LHCb, PRL 122 (2019) 231802
[5] Belle, PRD 89 (2014) 091103
[6] LHCb, PRL 127 (2011) 111801

High yields requires exquisite systematic control

Can LHCb control its systematics to match the tiny statistical uncertainties ? So far, yes ! Key uncertainties are small by definition (ΔA_{CP}), or set by control channels.

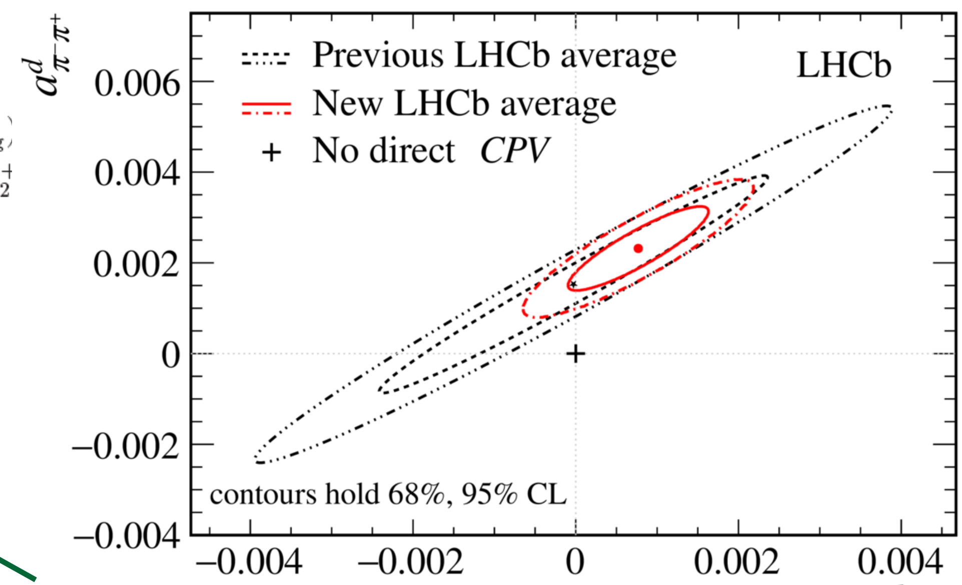
When determining $A_{CP}(KK)$, measurement of CP asymmetries in control channels gives access to necessary nuisance asymmetries.

$$A(K^-\pi^+) \approx A_P(D^{*+}) - A_D(K^+) + A_D(\pi^+) + A_D(\pi^+_{tag}$$
$$A(K^-\pi^+\pi^+) \approx A_P(D^+) - A_D(K^+) + A_D(\pi^+_1) + A_D(\pi^+_2$$
$$A(\overline{K}^0\pi^+) \approx A_P(D^+) + A(\overline{K}^0) + A_D(\pi^+),$$
$$A(\phi\pi^+) \approx A_P(D^+_s) + A_D(\pi^+),$$
$$A(\overline{K}^0K^+) \approx A_P(D^+_s) + A(\overline{K}^0) + A_D(K^+).$$

Using a suitable combination of above, and raw $A_{CP}(KK)$ yields

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

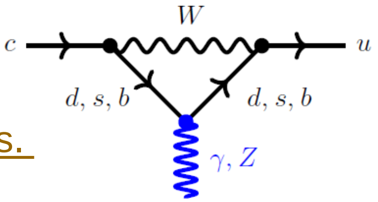
Reflects control channel yields



[arXiv:2209.03179]

Rare charm decays

[for review see Gisbert, Golz and Mitzel, Mod. Phys. Lett. A 36 (2021) 2130002]



The large event yields promised in the years ahead are only good news for the search for, and characterisation of (*e.g.* angular distributions, CP asymmetries *etc.*) rare charm decays. Excellent complementarity between experiments.

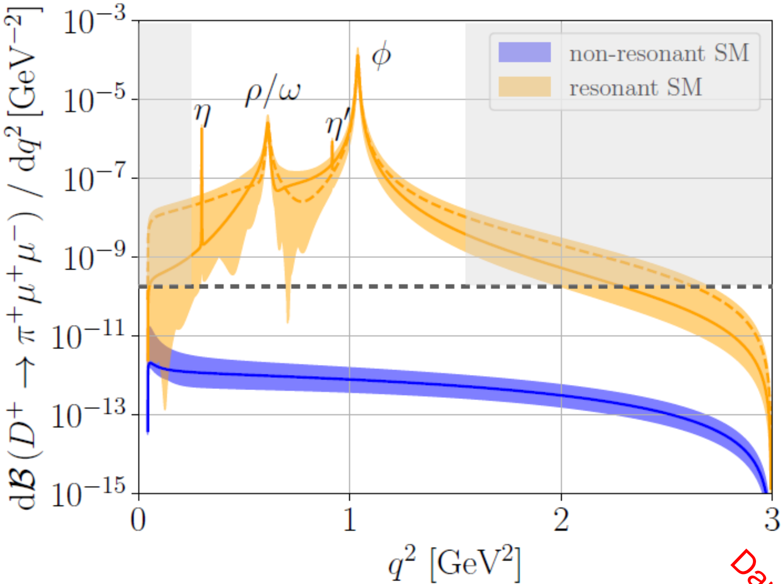
$c \to u\mu^+\mu^-$ LHCb

$c \to ue^+e^-$

$c \to u\gamma$

$c \to u\nu\bar{\nu}$

} Belle II (+ STFC & FCC-ee)

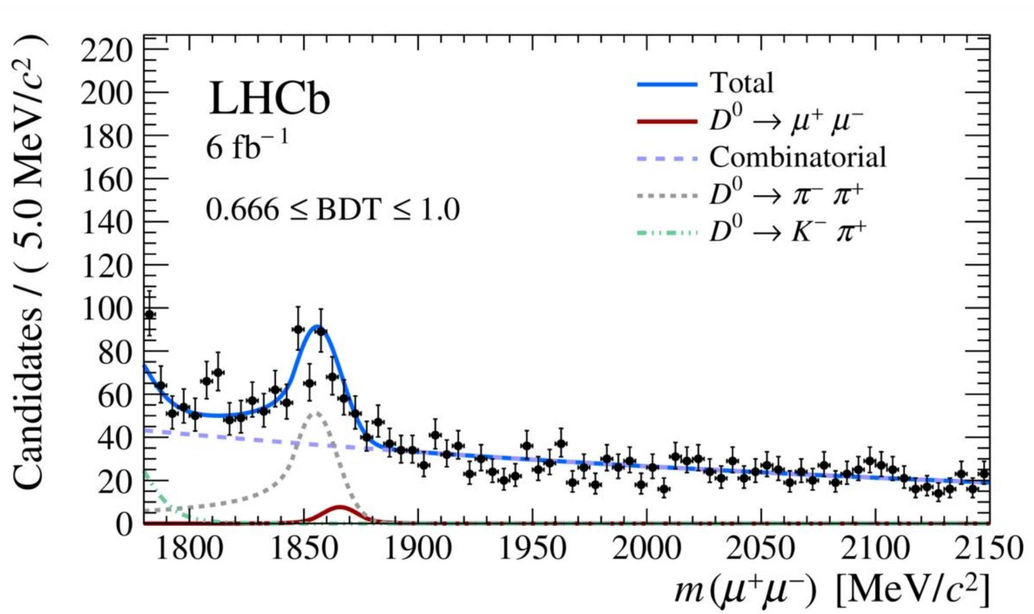


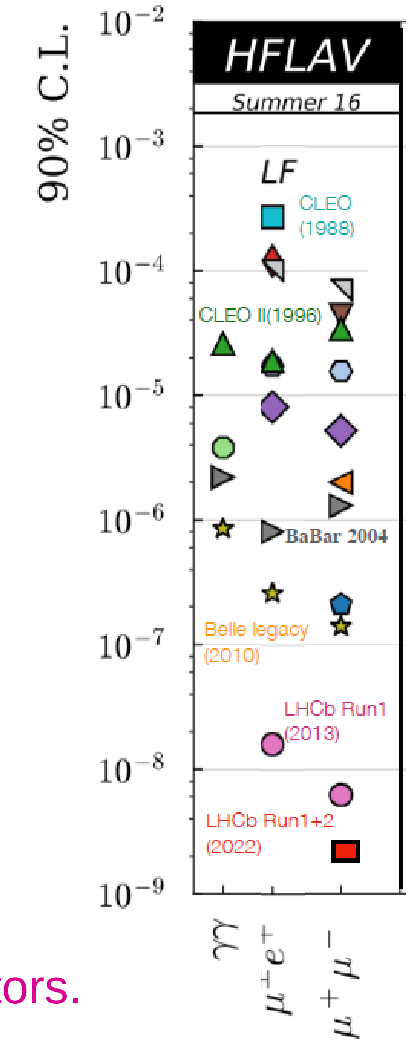
Current status: typical existing limits on $c \to u\mu^+\mu^-$ ~ 10^{-6} - 10^{-7} [LHCb, JHEP 06 (2021) 044], with observation and initial studies of $D^0 \to h^+h^-\mu^+\mu^-$ [LHCb, PRL 119 (2017) 181805, PRL 121 (2018) 091801]. Several radiative decays already observed at BaBar [PRD 78 (2008) 071101] and Belle [PRL 118 (2017) 051801].

See talk of Daniel Unverzagt

Statistics are not the whole story

LHCb has achieved spectacular progress in search for $D^0 \to \mu^+\mu^-$ [arXiv:2212.11203], attaining 3.1 x 10^{-9} (90% C.L.).

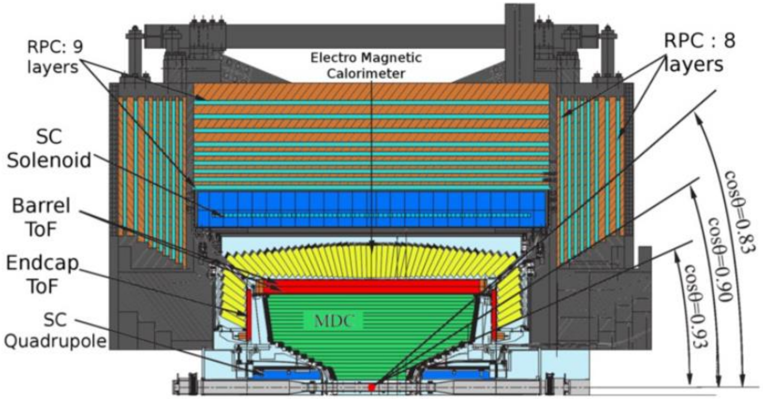




[Dominik Mitzel]

Further substantial progress looks tough, because of peaking hadronic background. (New experiment needed ?) Look forward to improved $D^0 \to \gamma\gamma$ searches from e^+e^- detectors.

BESIII status and prospects



Open charm programme to date based on:

- 8 fb^{-1} at 3770 MeV
- 0.5 fb^{-1} at 4409 MeV
- 3.2 fb^{-1} at 4178 MeV
- 0.6 fb^{-1} at 4600 MeV

Recently data set augmented by:

- 3.8 fb^{-1} above 4600 MeV

Future running possibilities in coming years discussed in 'White Book' [arXiv:1912.05983].

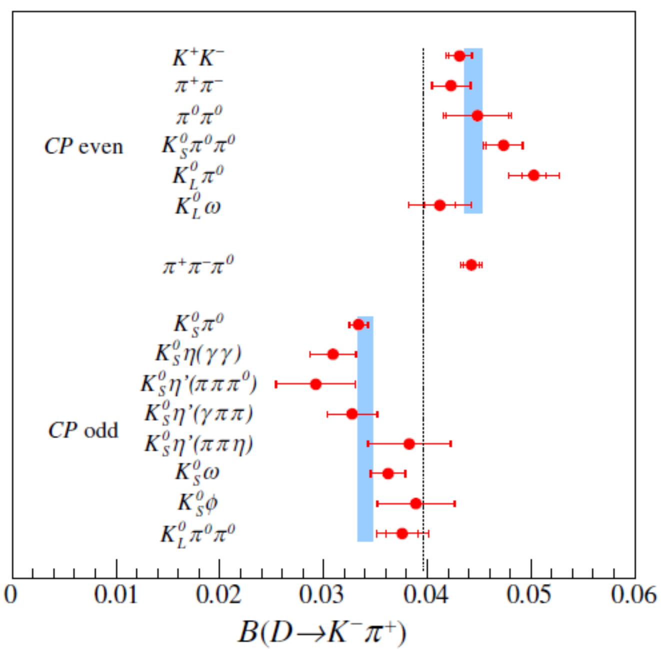
More data taking at 3770 MeV is ongoing, and will continue later this year, with goal of reaching ~20 fb^{-1}.

Detector upgrades foreseen (new drift chamber), also for BEPCII.

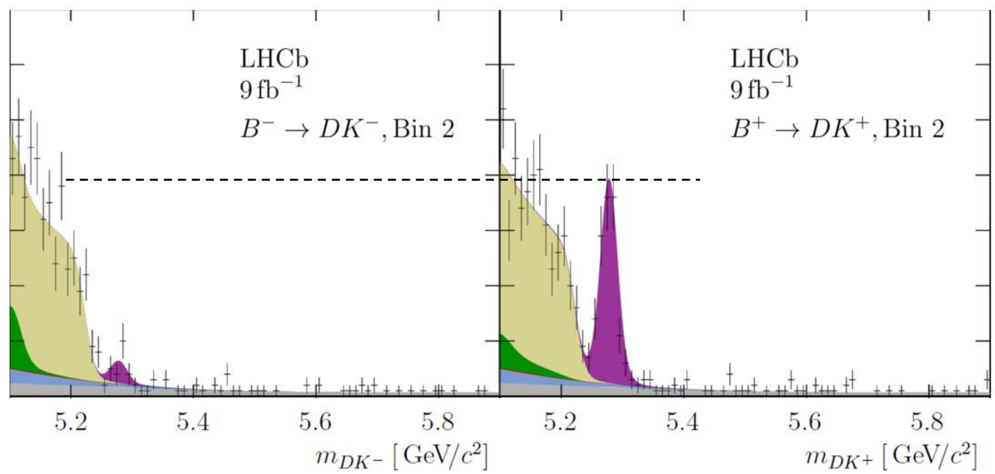
Physics with quantum-correlated $D\bar{D}$ pairs

Unique asset of charm threshold is ability to tag one meson in a CP eigenstate and gain sensitivity to strong phases, CP fraction or coherence factor in decay of other meson. Vital input to γ measurement and charm mixing studies at LHCb & Belle II.

e.g. CP-tagged BF of D→Kπ sensitive to strong-phase difference [EPJC 82 (2022) 1009].



e.g. interpretation of CP asymmetry in B→DK, D→Kππππ [arXiv:2209.03692] needs BESIII inputs.



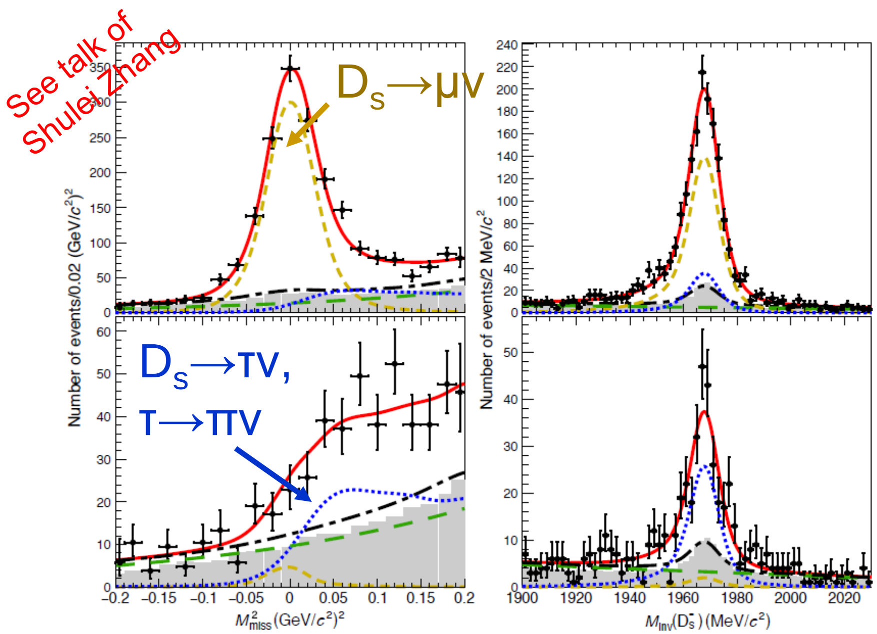
$$\gamma = \left(54.8\,^{+\,6.0}_{-\,5.8}\,^{+\,0.6}_{-\,0.6}\,\boxed{^{+\,6.7}_{-\,4.3}}\right)^\circ$$

More charm-threshold data essential !

Threshold physics is (almost) background free

Until now, samples at threshold have been modest compared to B factories and LHCb, but the extremely clean environment, enhanced by the ability to perform double-tag analyses have allowed for some very competitive and unique results.

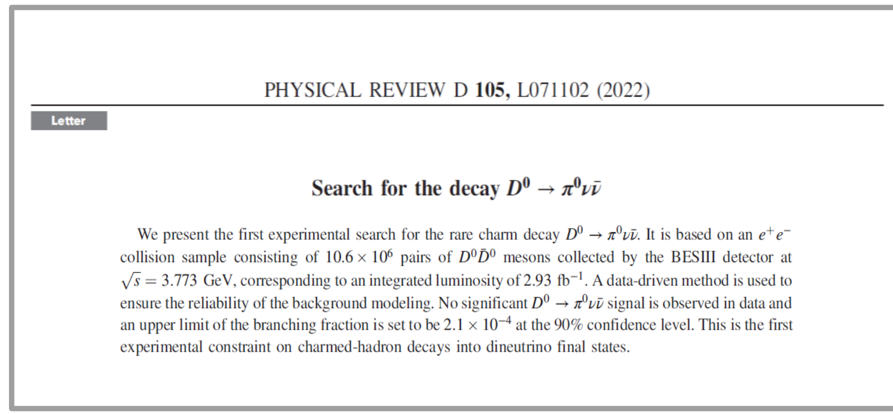
Competitive [PRD 104 (2021) 052009]



Missing mass squared, signal side

Invariant mass tag side

Unique [PRD 105 (2022) L071102]



PHYSICAL REVIEW D **105**, L071102 (2022)

Letter

Search for the decay $D^0 \to \pi^0 \nu \bar{\nu}$

We present the first experimental search for the rare charm decay $D^0 \to \pi^0 \nu \bar{\nu}$. It is based on an e^+e^- collision sample consisting of 10.6×10^6 pairs of $D^0\bar{D}^0$ mesons collected by the BESIII detector at $\sqrt{s} = 3.773$ GeV, corresponding to an integrated luminosity of 2.93 fb^{-1}. A data-driven method is used to ensure the reliability of the background modeling. No significant $D^0 \to \pi^0 \nu \bar{\nu}$ signal is observed in data and an upper limit of the branching fraction is set to be 2.1×10^{-4} at the 90% confidence level. This is the first experimental constraint on charmed-hadron decays into dineutrino final states.

Such results will become ever more interesting with the growing data sets.

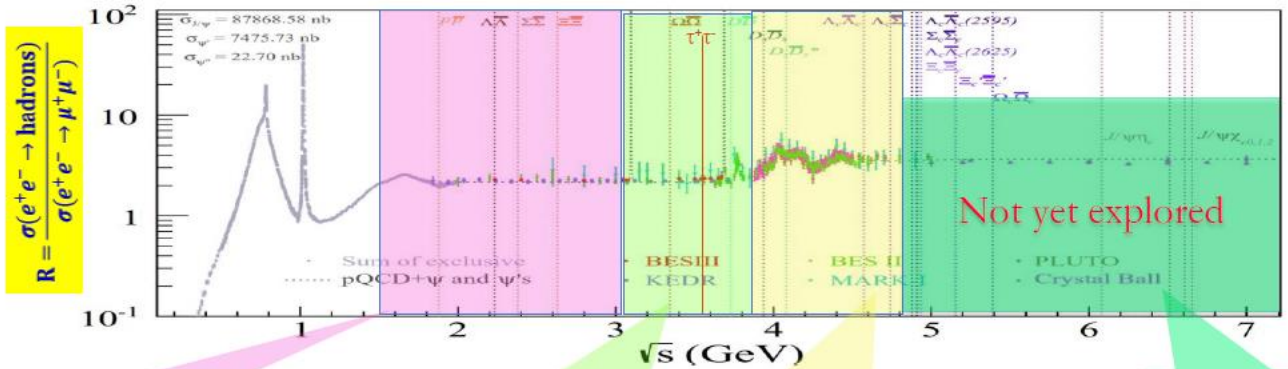
Super Tau Charm Factory (STCF)

See talk of Yangheng Zheng

Possible facility in China that could be begin early 2030s. [physics CDR: arXiv:2303.15790]

5 years	7 years	15 years
R&D and TDR	Construction	Data taking

Peak lumi of 0.5 x 10^{35} $cm^{-2}s^{-1}$ in first phase, with E_{CM} spanning 2-7 GeV. Possible second phase with higher luminosity and polarized electron beam.



- Nucleon/Hadron form factors
- Y(2175) resonance
- Mutltiquark states with s quark
- MLLA/LPHD and QCD sum rule predictions

- LH spectroscopy
- Gluonic and exotic
- LFV and CPV
- Rare and forbidden decays
- Physics with τ lepton

- XYZ particles
- Physics with D mesons
- f_D and f_{Ds}
- D_0-D_0 mixing
- Charm baryons

- New XYZ particle
- Hidden-charm pentaquark
- Multiquark state
- Di-charmonium state
- Charm baryons
- Hadron fragmentation

Super Tau Charm Factory (STCF)

Higher luminosity & longer running time per year → BESIII x 100.

Capable of integrating ~1 ab^{-1} / yr, corresponding to annual samples of *e.g.* 4 x 10^9 D^0, $D^{+/-}$, 10^8 D_s mesons.

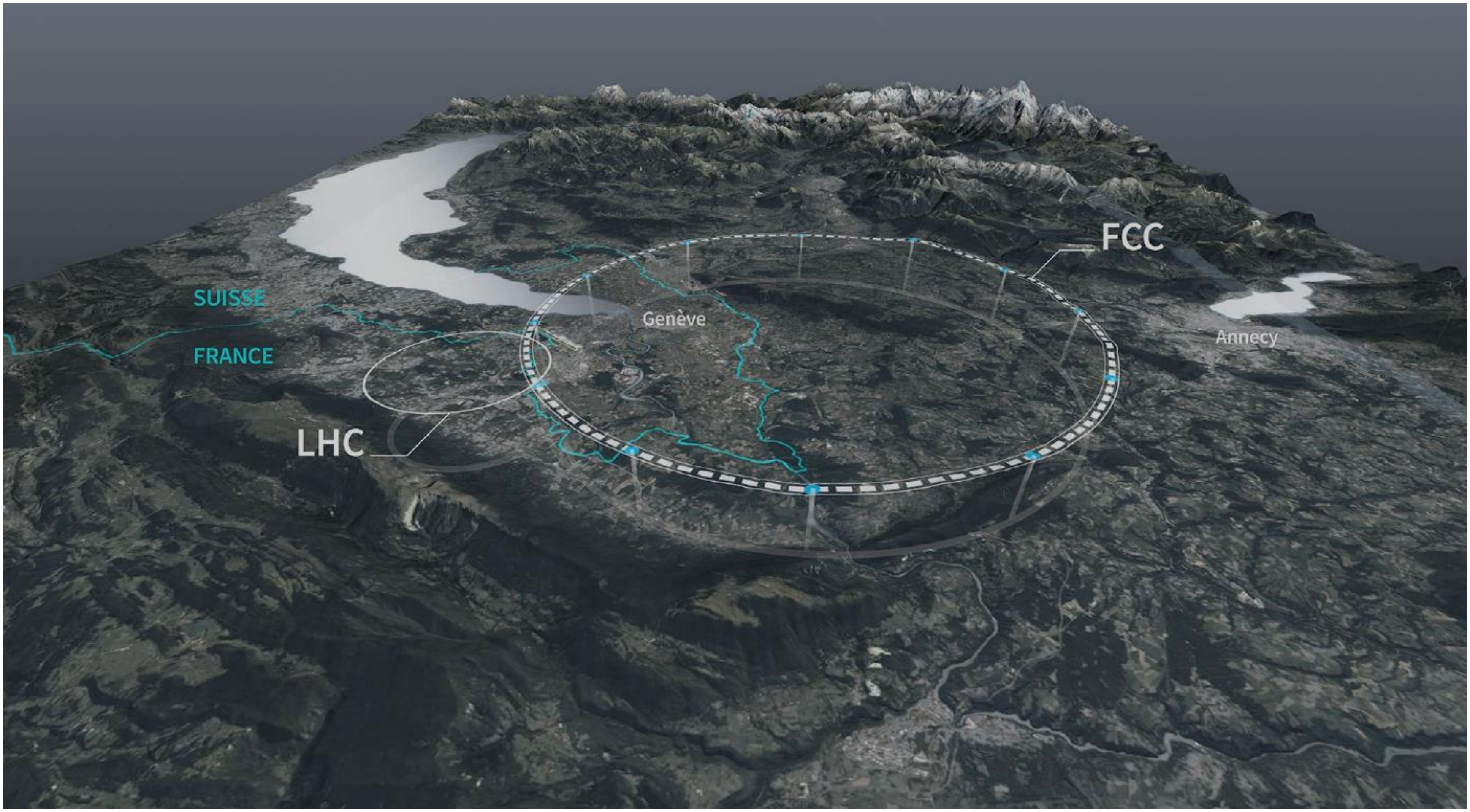
These data sets are approaching target samples at Belle II, which is very promising for FCNC searches.

No boost, so no time-dependent CPV measurements, but interesting time integrated options in *C*-even systems, *e.g.* DDbar*→γ(DDbar), where mixing effects enhanced. Complementary to studies at Belle II and LHCb Upgrade I.

[physics CDR: arXiv:2303.15790]

CME (GeV)	Lumi (ab^{-1})	Samples	σ(nb)	No. of Events	Remarks
3.097	1	J/ψ	3400	3.4×10^{12}	
3.670	1	$\tau^+\tau^-$	2.4	2.4×10^{9}	
3.686	1	$\psi(3686)$	640	6.4×10^{11}	
		$\tau^+\tau^-$	2.5	2.5×10^{9}	
		$\psi(3686)\to\tau^+\tau^-$		2.0×10^{9}	
3.770	1	$D^0\bar{D}^0$	3.6	3.6×10^{9}	
		$D^+\bar{D}^-$	2.8	2.8×10^{9}	
		$D^0\bar{D}^0$		7.9×10^{8}	Single tag
		$D^+\bar{D}^-$		5.5×10^{8}	Single tag
		$\tau^+\tau^-$	2.9	2.9×10^{9}	
4.009	1	$D^{*0}\bar{D}^0+c.c$	4.0	1.4×10^{9}	$CP_{D^0\bar{D}^0}=+$
		$D^{*0}\bar{D}^0+c.c$	4.0	2.6×10^{9}	$CP_{D^0\bar{D}^0}=-$
		$D_s^+D_s^-$	0.20	2.0×10^{8}	
		$\tau^+\tau^-$	3.5	3.5×10^{9}	
4.180	1	$D_s^{+*}D_s^-$+c.c.	0.90	9.0×10^{8}	
		$D_s^{+*}D_s^-$+c.c.		1.3×10^{8}	Single tag
		$\tau^+\tau^-$	3.6	3.6×10^{9}	
4.230	1	$J/\psi\pi^+\pi^-$	0.085	8.5×10^{7}	
		$\tau^+\tau^-$	3.6	3.6×10^{9}	
		$\gamma X(3872)$			
4.360	1	$\psi(3686)\pi^+\pi^-$	0.058	5.8×10^{7}	
		$\tau^+\tau^-$	3.5	3.5×10^{9}	
4.420	1	$\psi(3686)\pi^+\pi^-$	0.040	4.0×10^{7}	
		$\tau^+\tau^-$	3.5	3.5×10^{9}	
4.630	1	$\psi(3686)\pi^+\pi^-$	0.033	3.3×10^{7}	
		$\Lambda_c\bar{\Lambda}_c$	0.56	5.6×10^{8}	
		$\Lambda_c\bar{\Lambda}_c$		6.4×10^{7}	Single tag
		$\tau^+\tau^-$	3.4	3.4×10^{9}	
4.0–7.0	3	300-point scan with 10 MeV steps, 1 fb^{-1}/point			
> 5	2–7	Several ab^{-1} of high-energy data, details dependent on scan results			

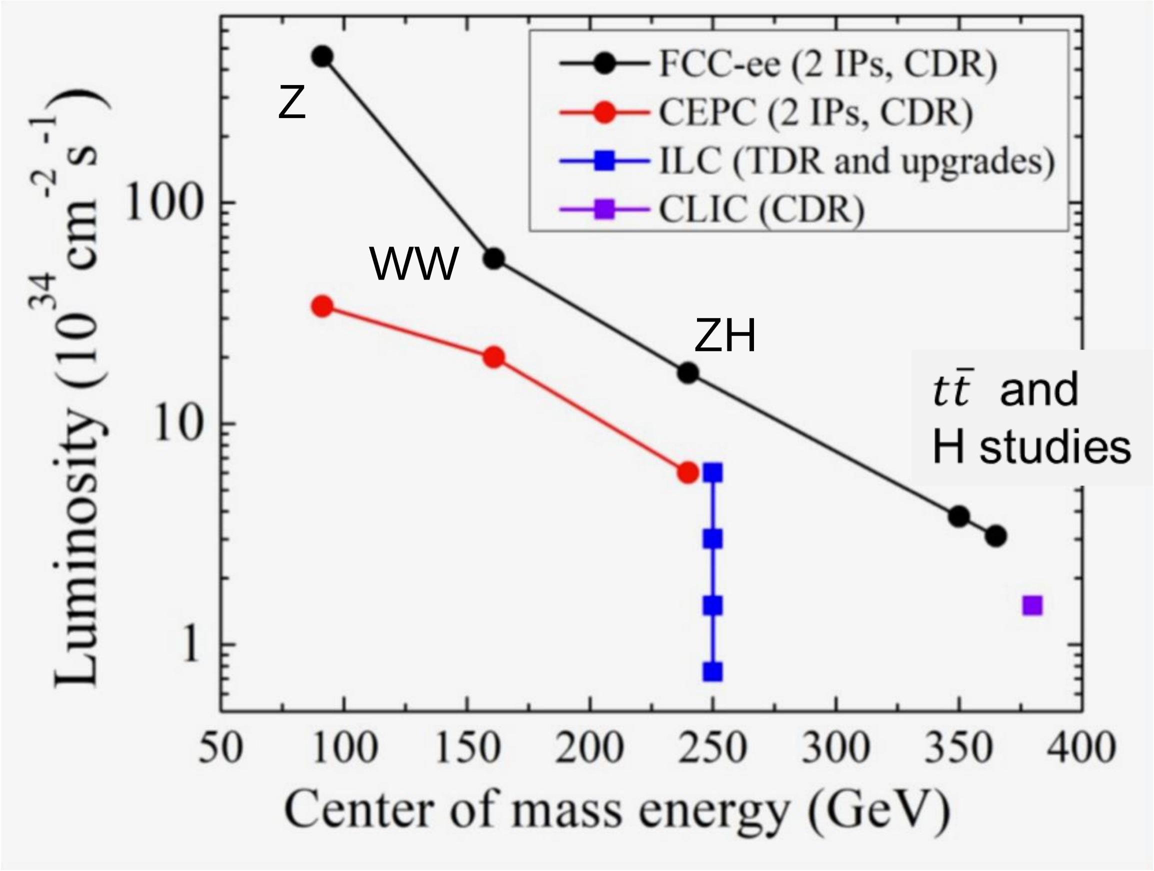
Go Big or Go Home – flavour at the FCC



FCC-ee: baseline run plan

CEPC in China
a very similar
machine

FCC-ee will perform Higgs studies at 240 GeV, but do much, much more.



The *enormous* luminosities at the Z (→ ~5 x 10^{12} decays*) offer remarkable prospects for precision EW studies and also for explorations in heavy flavour.

* Baseline luminosity wobbling about in preparation for midterm review, current Z-yield integrated over four IPs is 6 x 10^{12}.

FCC-ee as a flavour factory

In flavour physics, in comparison with Belle II and the LHC, FCC-ee will have almost the best of both worlds - although missing out on the entangled signal-only initial state of the B factories, and the eye-wateringly large cross section at the LHC.

Attribute	$\Upsilon(4S)$	pp	Z^0
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
Low backgrounds	✓		✓
Initial energy constraint	✓		(✓)

Example event yields in charm ~4 x 10^{11} D^0 mesons from primary production (and same sort of number from B decays), which is > x10 sample expected at Belle II.

➡ Sufficient for very serious programme of CPV studies (most likely the only opportunity to validate ΔA_{CP} observation at a second experiment);

Outstanding opportunities in FCNC studies, across wide range of channels.

Important that evolving detector designs are capable of seizing this opportunity.

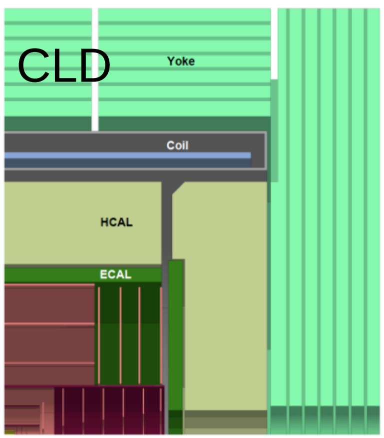
Detector challenges at FCC-ee

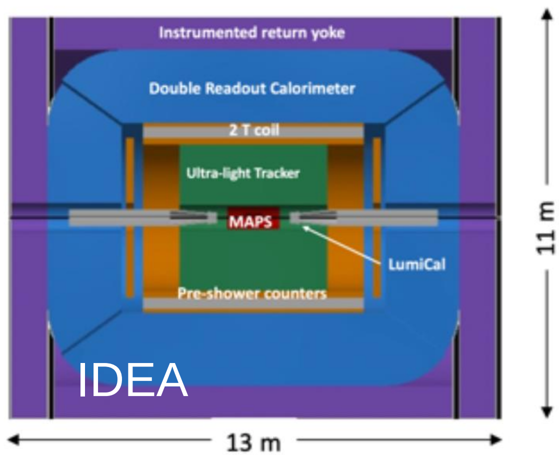
Event rates and radiation challenges modest compared with HL-LHC/FCC-hh.

On the other hand, extreme precision of Tera-Z puts unprecedented demands on stability of detector & operation, resolution of many components *e.g*. luminosity measurement at 10^{-5} (relative), 10^{-4} (absolute), acceptance definition at 10^{-5}.

in contrast, Higgs physics is 'easy' !

Early days, but three candidate experiment designs have emerged:





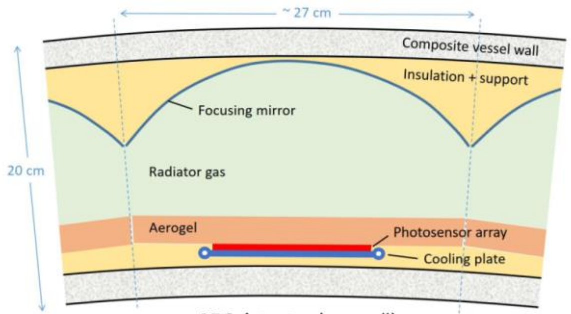
Noble liquid calo based concept

These are not set in stone ! Plenty of room of new ideas, optimisation *etc*.

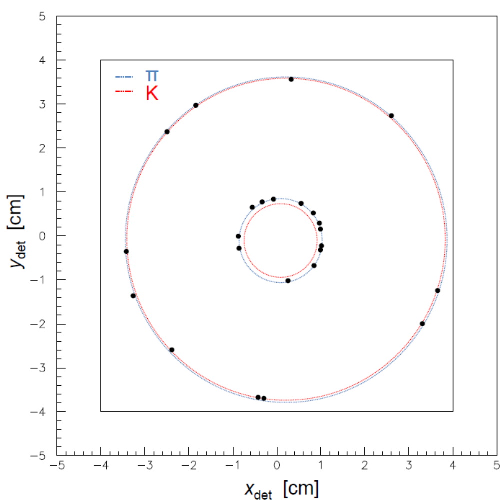
With four IPs rather than two as baseline, then the opportunities are even wider, *e.g.* there is no design that is optimal for flavour physics (dedicated PID, crystal calo *etc.*).

ARC – a RICH detector proposed for FCC-ee

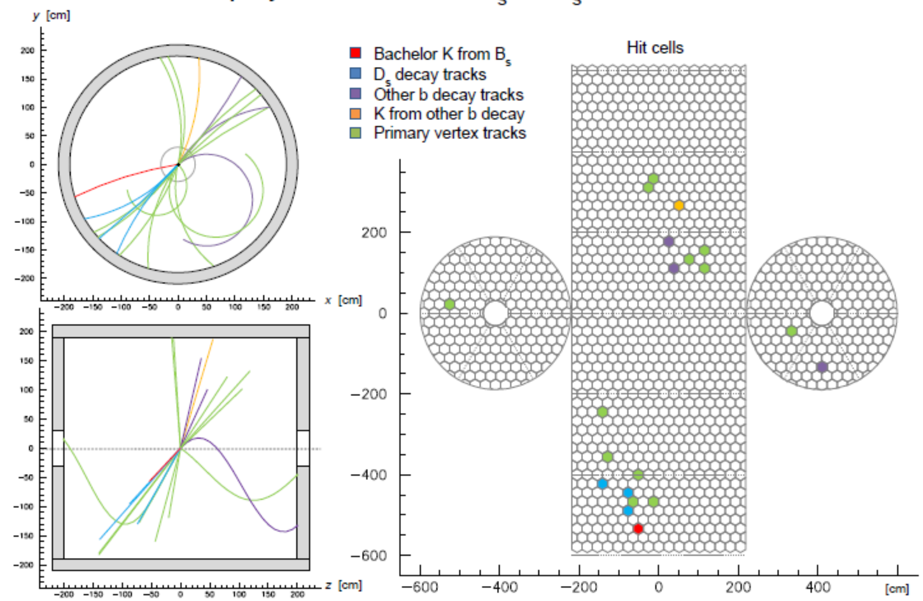
Conceptual development & optimisation of compact two-radiator RICH to provide PID over wide momentum range at FCC-ee (Forty [CERN], Tat, Wilkinson [Oxford])



ARC detector (one cell)

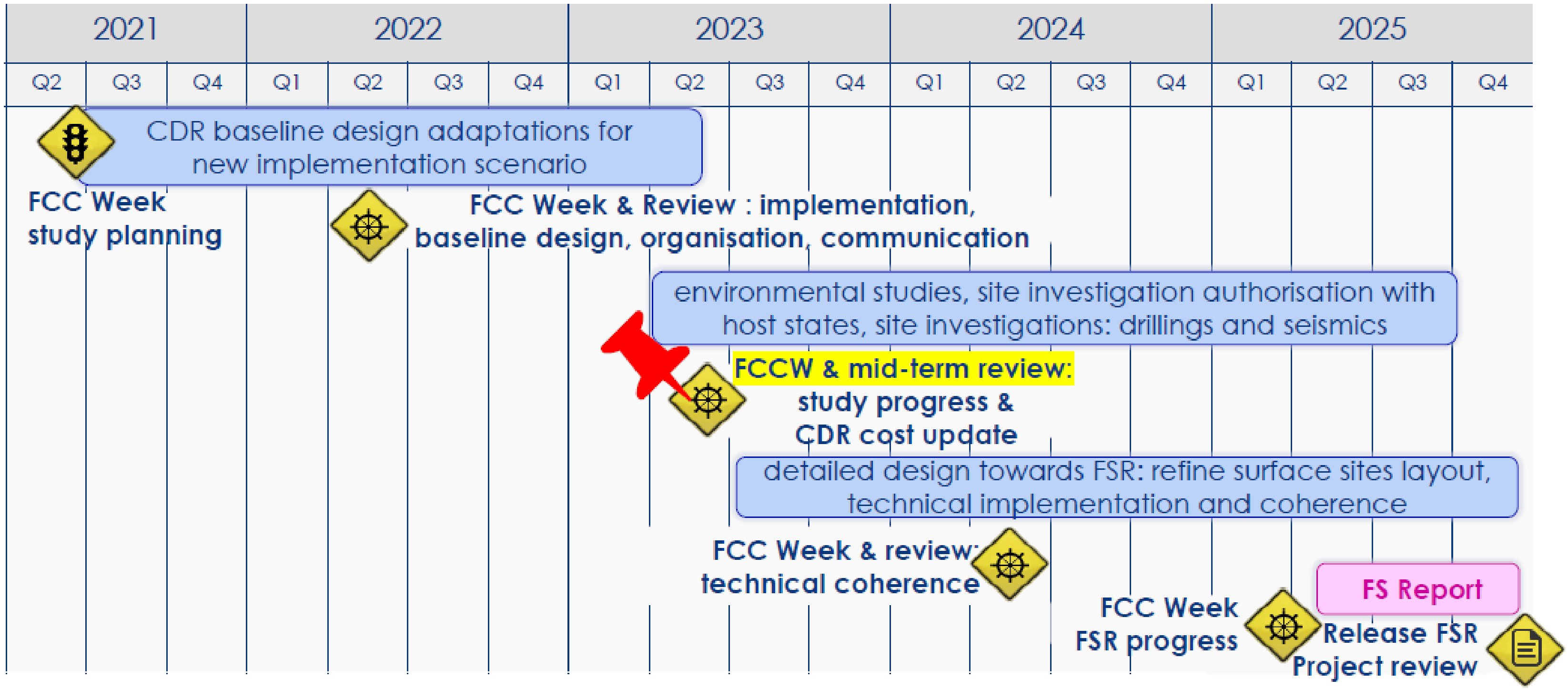


Display of a simulated $B_s \to D_s K$ event in ARC



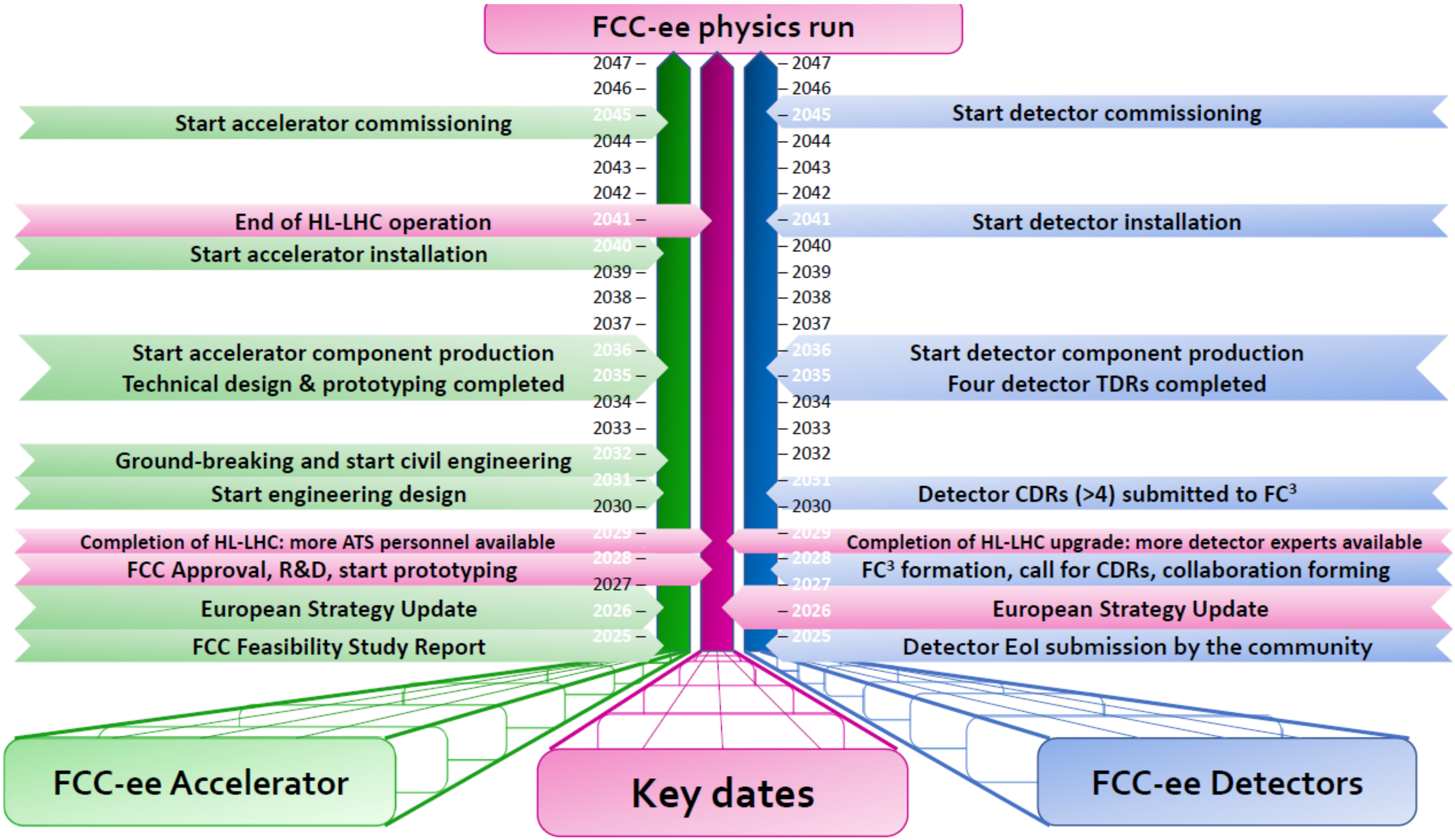
>3σ π-K separation from 2-50 GeV

Five-year feasibility study



Note mid-term review currently underway.

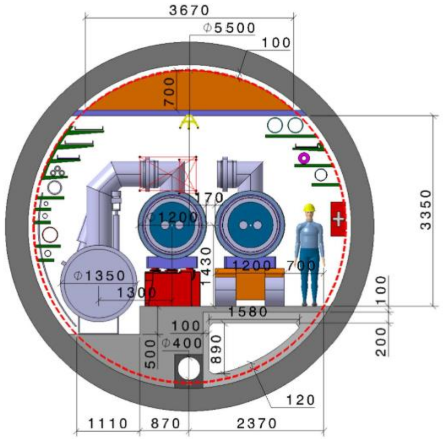
Countdown to physics



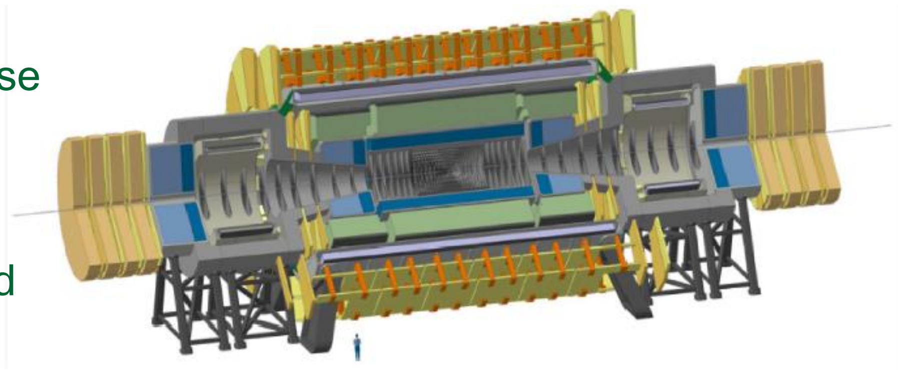
The further future (~2070): FCC-hh

ESPPU: *"Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage."*

FCC-hh will be such a machine, with the aim to collect 20 ab^{-1} per (general purpose) detector over a 25 year period, operating up to 3 x 10^{35} $cm^{-2}s^{-1}$.



Two 'general purpose detectors', with possibility of two interaction points for more specialised detectors, à la LHC

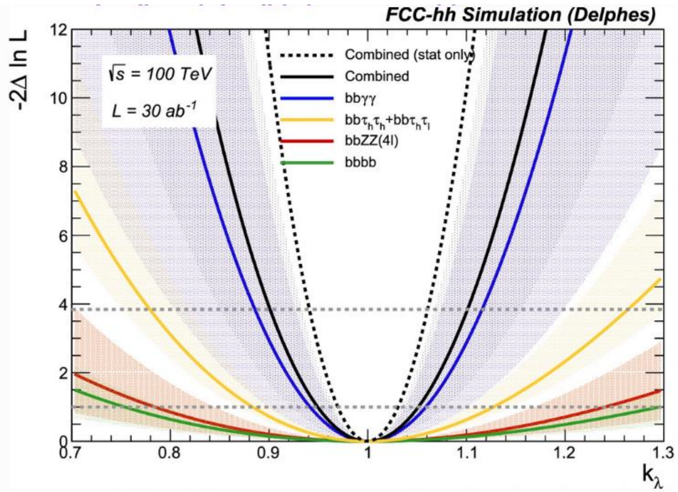


Extreme challenges include: need for 16 T dipole fields, very high radiation levels, pileup up to 1000, and huge data processing / storing requirements.

FCC-hh: the infinity machine

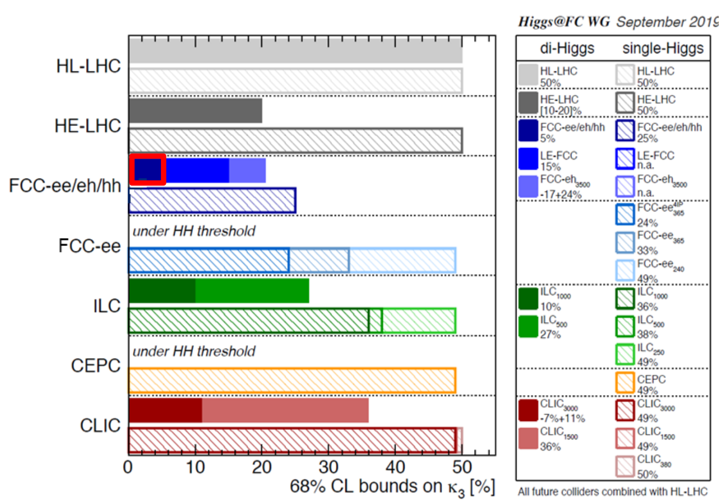
~30 ab^{-1} at 100 TeV provides astounding physics reach. Jewel in the crown: precision study of the Higgs potential, with self-coupling measured to 3.4 – 7.8%.

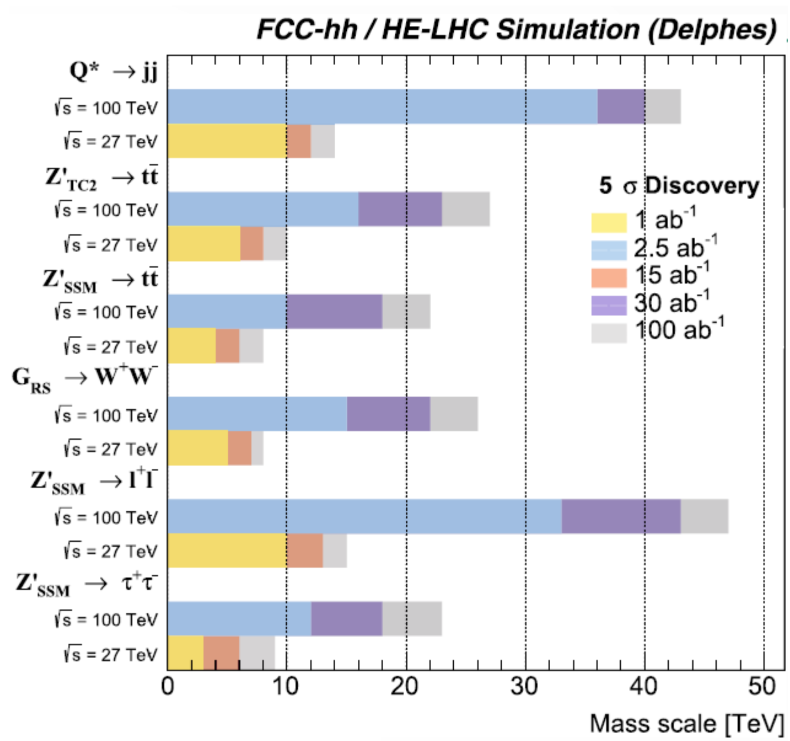
Eur. Phys. C 80 (2020) 1030



Remarkable direct-search potential

e.g. certain heavy resonances accessible up to beyond 30 TeV

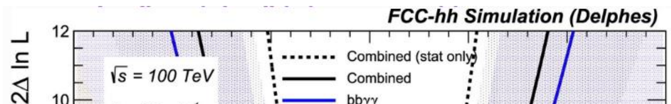




FCC-hh: the infinity machine

~30 ab^{-1} at 100 TeV provides astounding physics reach. Jewel in the crown: precision study of the Higgs potential, with self-coupling measured to 3.4 – 7.8%.

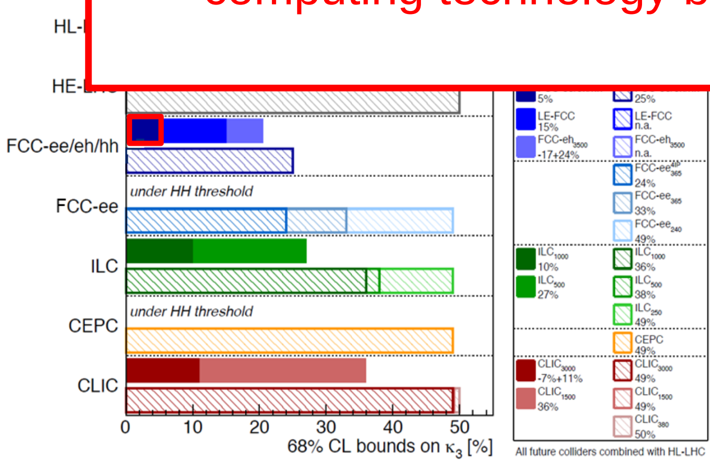
Eur. Phys. C 80 (2020) 1030

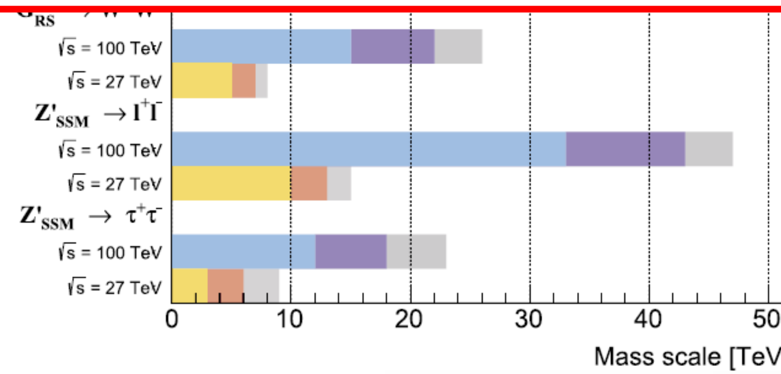


Remarkable direct-search potential

Already foreseen that this machine will have interaction points for specialised experiments, *e.g.* LHCb++.

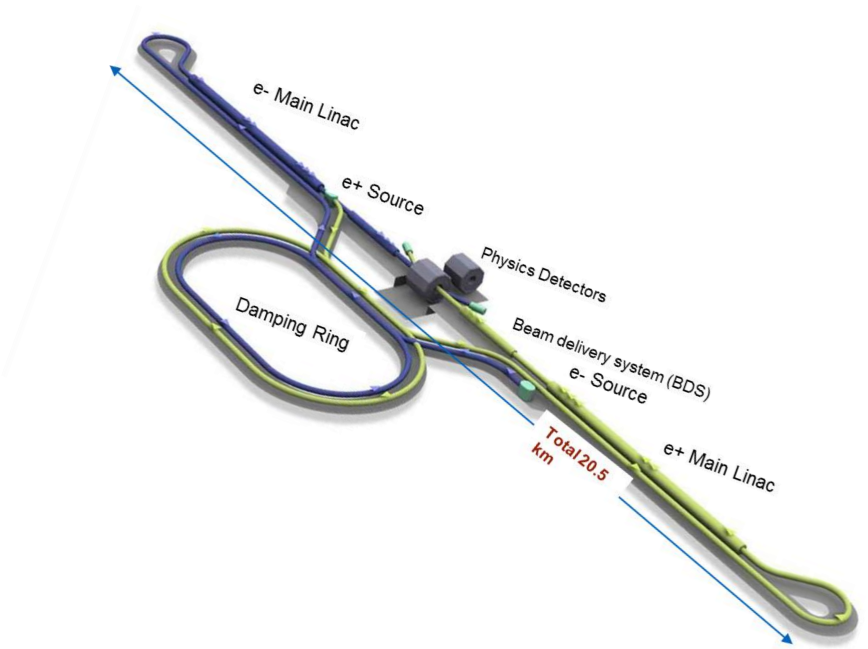
The gains in physics hoped for at such an experiment will come not just from the increase in cross section and luminosity, but also from the presumed strides forward in detector and computing technology between now and ~2070.





Accept no alternatives

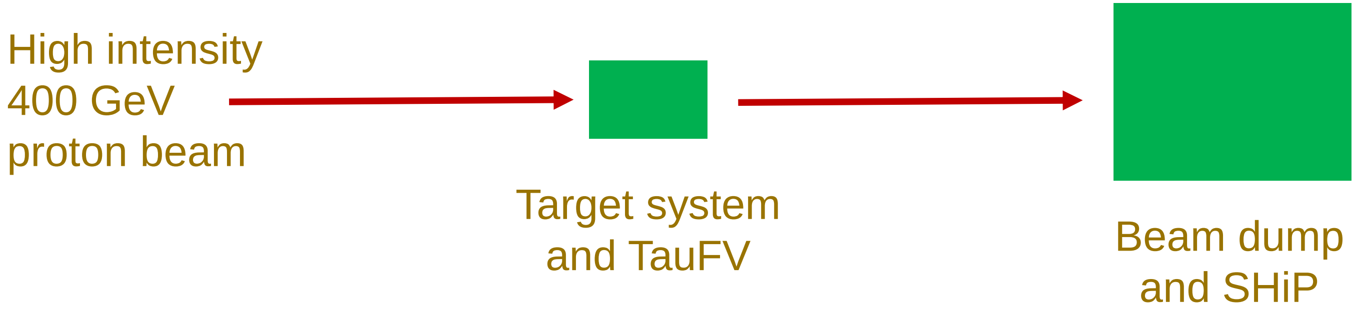
Some commentators advocate a strategy of a linear collider for Higgs studies followed by a muon collider for the high-energy frontier.



This approach has many drawbacks IMO. For flavour physics it would be a disaster.

Other sources of high yield charm ?

Very large samples of charm can be produced, by exposing a sequence targets to a high-intensity proton beam. TauFV was proposed upstream of the proposed SHiP experiment at the Beam Dump Facility (BDF) at the CERN SPS. Primary purpose was to search for $\tau \rightarrow \mu\mu\mu$ decays, with the taus produced in D_s decays.

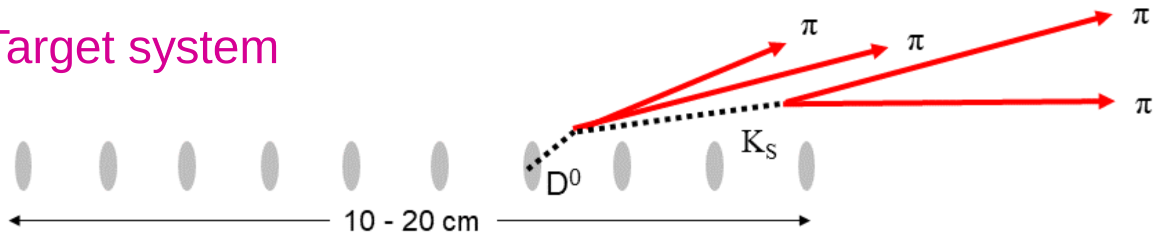


A total 2 mm of tungsten target would interact with 2% of the beam, and give 4×10^{18} PoT in five years of operation. 0.17% of interactions produce charm.

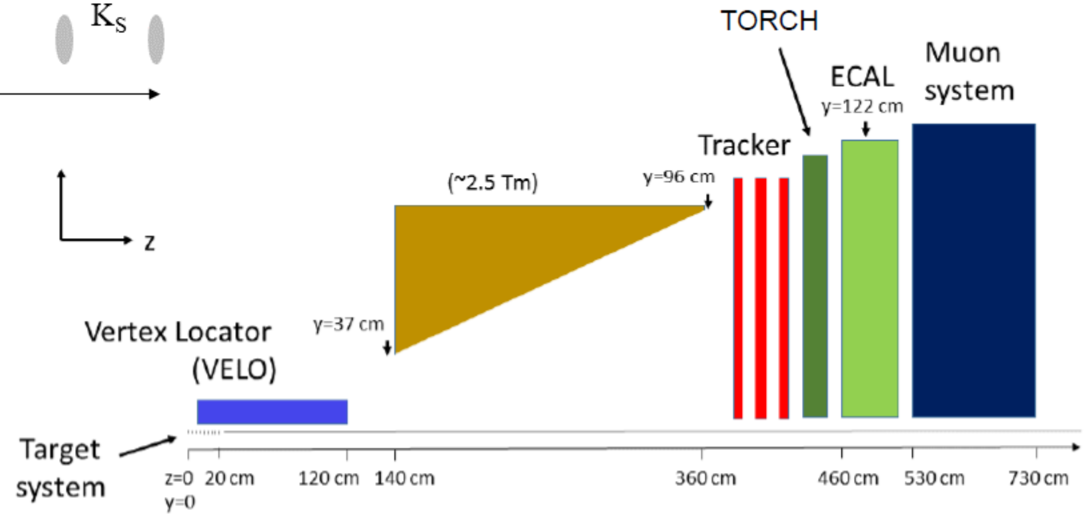
$\rightarrow 10^{15}$ D^0 mesons produced per year !

TauFV – more information

Target system



Spectrometer layout:
LHCb-like, but this time
it *is* a fixed-target detector.



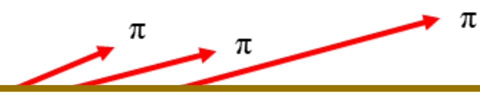
Excellent granularity and
O(10 ps) timing resolution to
separate the huge number of interactions in each spill.

Sample size potentially larger than LHCb UII, but a dedicated experiment, with little b 'contamination', and more modest in size – could be optimised for, *e.g.* neutrals.

However, data rate and radiation levels in certain regions extremely fierce.
Might be necessary to back off a little, &/or reduce the target mass ?

TauFV – more information

Target system



What happened ?

BDF and SHiP (and hence TauFV) killed following last EPPSU.

More recently

Refurbishment of ECN3 (NA61 beamline) under consideration.
SHiP and HIKE (future kaon experiments) potential customers.
No effort at present to study possibilities of TauFV-like experiment at this new location. This could be a missed opportunity…

…tle
b ‘contamination’, and more modest in size – could be optimised for, *e.g.* neutrals.

However, data rate and radiation levels in certain regions extremely fierce.
Might be necessary to back off a little, &/or reduce the target mass.

Conclusions

Much to look forward to at BESIII, Belle II and LHCb Upgrade I (but much work required to make this happen at latter two).

Excellent prospects in the following decade, from STFC, and in particular at LHCb Upgrade II (a huge experimental challenge).

The FCC is not just a machine for Higgs and search physics. Outstanding prospects in flavour physics also. The community should become engaged, as this will inform the detector conceptual designs.

Let us keep our eyes upon for other opportunities to advance our physics !

Looking forward to returning Siegen to discuss first charm results from FCC.

Backups

Meanwhile, in China…

Circular Electron Positron Collider (CEPC) is a Chinese project, whose main characteristics closely resemble those of FCC-ee. Indeed, over time, it has evolved closer & closer to FCC-ee design.

Operation mode		ZH	Z	W^+W^-	tt
$\sqrt{s}$ [GeV]		~240	~91.2	158-172	~360
L / IP [$\times 10^{34}$ $cm^{-2}s^{-1}$]	CDR (2018)	3	32	10	
	Latest	5.0	115	16	0.5

Ideal Accelerator Roadmap

- 2016-2021 MOST phase-1 accelerator R&D
- 2018-2023 MOST phase-2 accelerator R&D
- 2023-2028 MOST phase-3 accelerator R&D
- 2022-2023 Accelerator TDR completion
- 2023-2025 Site selection, engineering design, prototyping and industrialization
- 2026-2034 Construction and Installation

Accelerator TDR about to be complete, to be followed by two-year accelerator EDR phase.

Its best-case timeline places it ~10 years ahead of FCC-ee, with operation beginning in mid 2030s, but many uncertainties.

Watch closely !

Ideal Detector Roadmap

- 2016-2021 MOST phase-1 detector R&D
- 2018-2023 MOST phase-2 detector R&D
- 2023-2028 MOST phase-3 detector R&D
- Now -2024 Seek collaboration, detector R&D
- 2025-2026 Prepare international collaborations
- 2027-2028 Detector TDR completed
- 2028-2034 Detector construction
- 2033-2034 Installation

For summary see Xinchou Lou presentation at FCC Week 2022, Paris.

Timescales and finances

Statements of CERN DG in London FCC week (June '23)

"Construction of FCC-ee could start in the early 2030s and proceed in parallel to HL-LHC operation Physics exploitation could start within a few years of the end of HL-LHC (2045-2048)."

" I believe FCC is the best project for CERN's future→ we need to work together to make it happen"

Cost category	[MCHF]	%
Civil engineering	5,400	50
Technical infrastructure	2,000	18
Accelerator	3,300	30
Detector (CERN contrib.)	200	2
Total cost (2018 prices)	10,900	100

← Reminder of FCC-ee costs (Z, WW and HZ working points, and for two IP configuration)

Power costs

What is the power budget of FCC-ee, and how does it compare to the competition ?

		Z	W	H	TT
Beam energy (GeV)		45.6	80	120	182.5
Magnet current		25%	44%	66%	100%
Power ratio		6%	19%	43%	100%
PRF EL (MW)	Storage	146	146	146	146
PRFb EL (MW)	Booster	2	2	2	2
Pcryo (MW)	all	1,3	12,6	15,8	47,5
Pcv (MW)	all	33	34	36	40.2
PEL magnets (MW)	Stroage	6	17	39	89
PEL magnets (MW)	Booster	1	3	5	11
Experiments (MW)	Pt A & G	8	8	8	8
Data centers (MW)	Pt A & G	4	4	4	4
General services (MW)		36	36	36	36
Power during beam operation (MW)		237	262	291	384
Average power / year (MW)		143	157	173	224

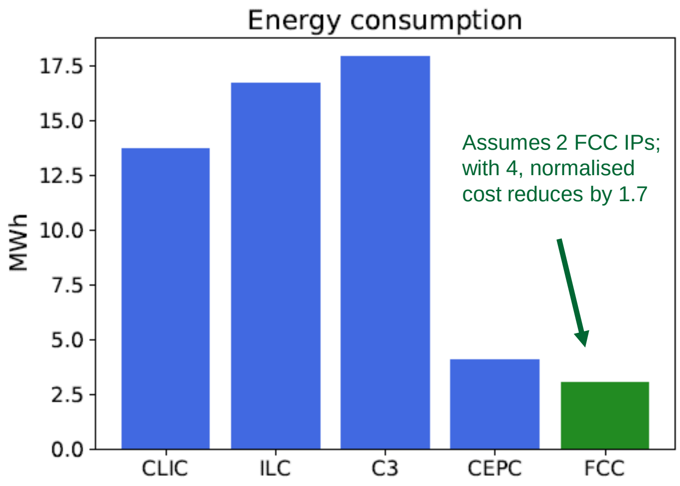
This corresponds to 1.6 TWh/year, to be compared to 1.4 TWh/year for HL-LHC.

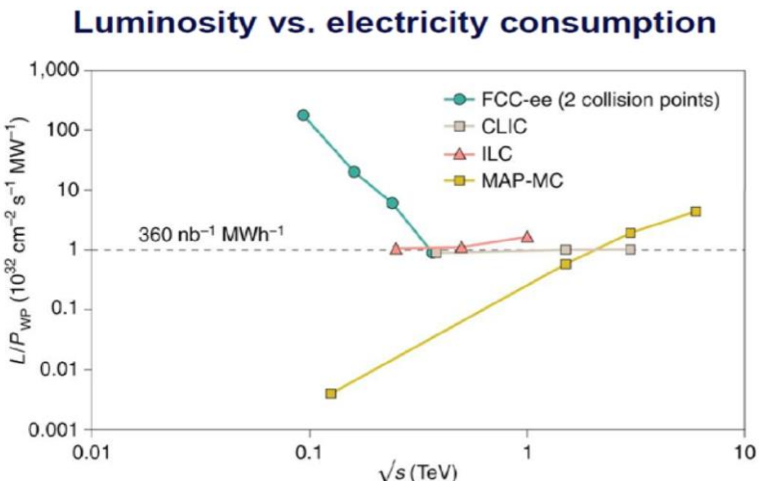
As a comparison, P(ILC_{240})=140 MW and P($CLIC_{380}$)=110 MW. This is not full story ! Both produce 2-4 less Higgs than FCC-ee_{240}, with 3-6 times longer running time.

Power costs – a closer look

Normalise energy use by physics outcome, *i.e.* number of Higgs boson, or lumi.

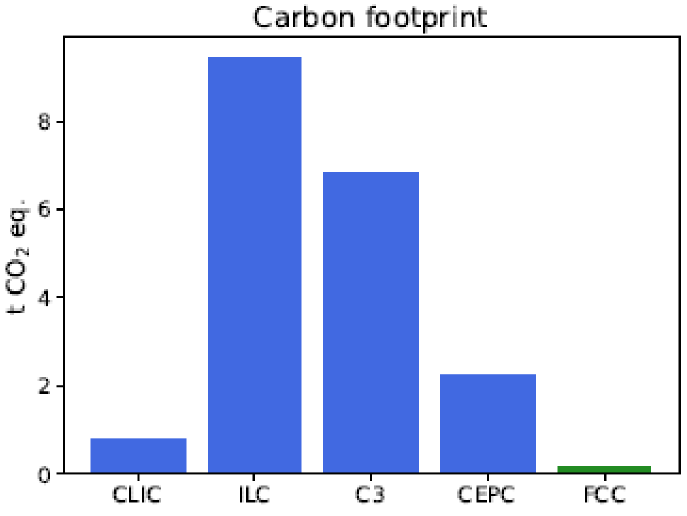
[arXiv:2208.10466]





[F. Zimmerman]

Comparison in terms of carbon footprint even starker – electricity at CERN almost carbon free.



Nonetheless, important to find ways to decrease overall energy use.

Higher efficiency RF, magnet systems (*e.g.* HTS), cable losses, efficient cooling…