Future flavour at colliders

Guy Wilkinson
University of Oxford

Colour meets flavour, Bad Honnef
19 March 2024

What are we doing here ?

i.e. which idiot decided it would be a good idea to have an after-dinner presentation after a hard day of lectures, and when the bar is open and calling ?

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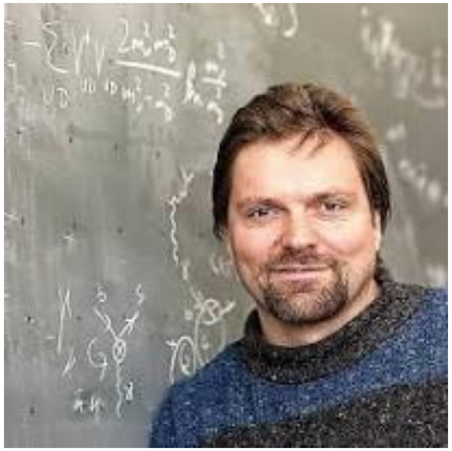
Well… please don't blame the speaker. The real culprits are close at hand.



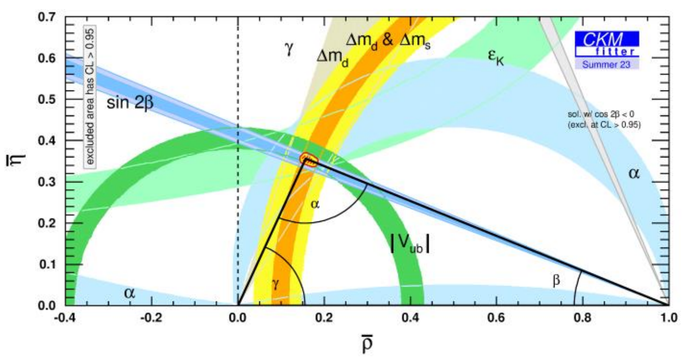
What are we doing here ?

visual indicator of how far away we are from the end of the talk

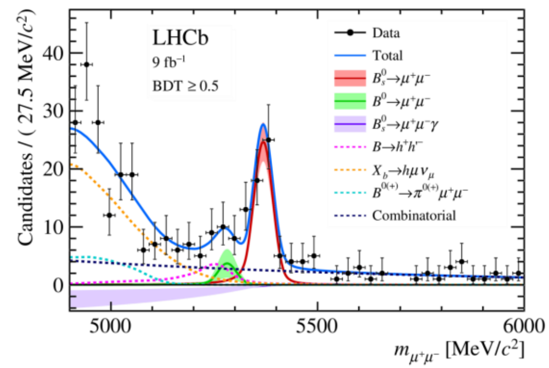
Flavour physics – mission accomplished ?

The 21st century 'age of flavour' (B-factories + Tevatron + LHCb *et al.*) has seen a enormous volume of results, and corresponding increase in knowledge. Many of the key questions in the flavour sector are (apparently) now settled.

CKM paradigm works well...

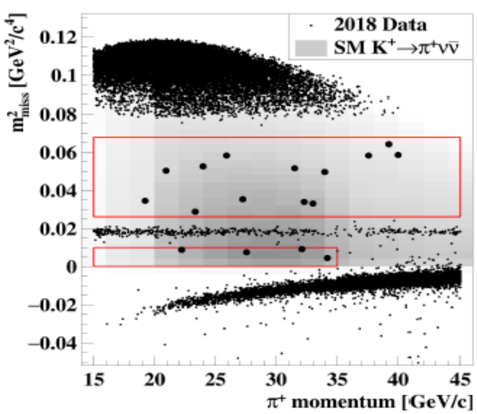


…golden FCNC decays in B sector (*e.g.* $B_s \to \mu\mu$) observed with SM-like BFs…



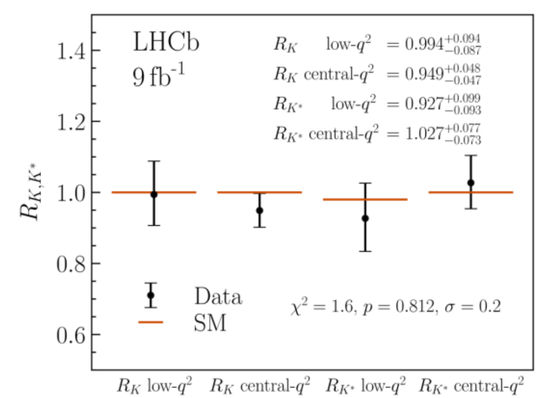
PRL 128 (2022) 041801

…same is looking to be true in kaon sector (*e.g.* $K^+ \to \pi^+ \nu \bar{\nu}$)…



JHEP 06 (2021) 093

...and even the most interesting anomalies eventually turn to dust.



PRD 108 (2023) 032002

So, why persevere with flavour studies ?

The big picture answer:

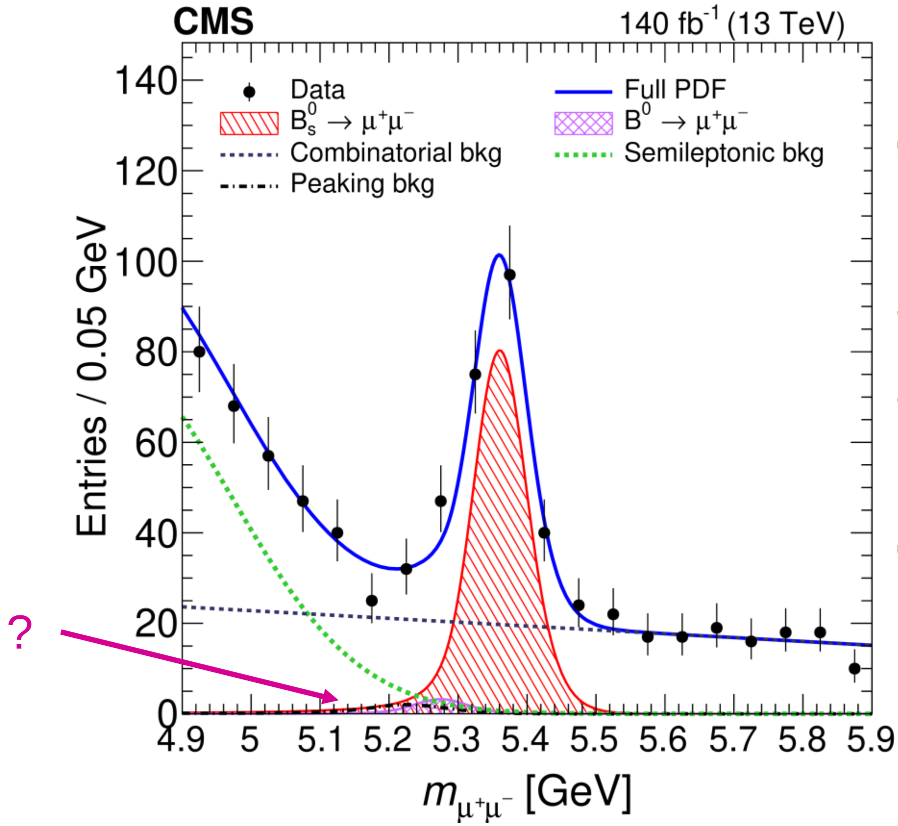
- The SM is incomplete;
- Many of the mysteries in the SM (& the cosmos) are related to flavour;
- Flavour observables can probe much higher mass scales than direct searches.

And some specific considerations:

- We *know* there are important phenomena still to be observed (*e.g.* mixing-induced CPV in B^0_s system, mixing related CPV in charm, $B^0\to\mu\mu$ *etc.*);
- Similarly, there are many important measurements that can be made, which are unfeasible with current sample sizes (*e.g.* electroweak Penguin studies with $b\to dl^+l^-$ decays, or precise study of P_5' with $B^0\to K^*e^+e^-$);
- A very large number of current observables are *theoretically clean* &/or *statistics limited*, so higher precision is strongly motivated (*e.g.* sin2β, γ, φ_s, R_K, R_{K^*}, $BR(B^0_s\to\mu\mu)/BR(B^0\to\mu\mu)$ *etc*);
- A rich field where surprises are guaranteed (*e.g.* no one was expecting charm mixing, direct charm CPV, the X(3872), pentaquarks…).

Example of known unknowns: BF($B^0 \to \mu\mu$)

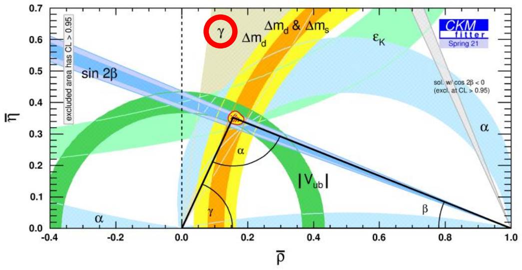
Finding $B^0 \to \mu\mu$ and measuring the ratio BF($B^0 \to \mu\mu$)/BF($B_s \to \mu\mu$) (~ 3% in SM) is an essential next step in flavour studies. The ratio of BFs is theoretically pristine, and also serves as an excellent test of Minimal Flavour Violation.



[PLB 842 (2023) 137955]

Example of known unknowns: value of CKM γ with sub-degree precision

CKM paradigm drives Unitarity Triangle at leading order, but very possible New Physics is still present. Need ever more precise measurements of Triangle parameters.



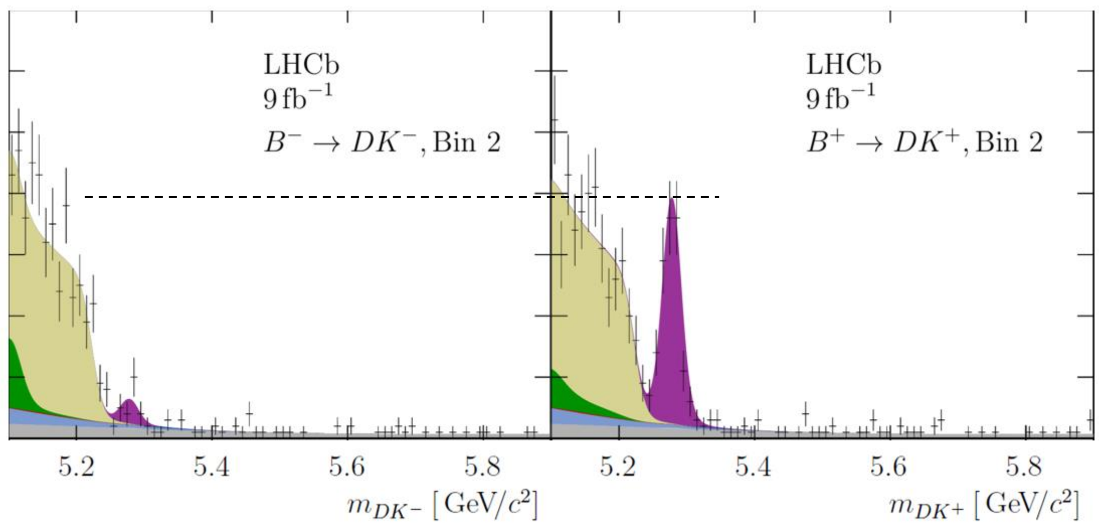
Excellent example is angle γ, which can be determined in B→DK decays with negligible theoretical uncertainty.

$$\gamma = \left(63.8^{+3.5}_{-3.7}\right)^{o}$$

[LHCb-CONF-2022-03]

Statistically limited !

Largest CPV asymmetry ever observed – LHCb B→D(K3π)K



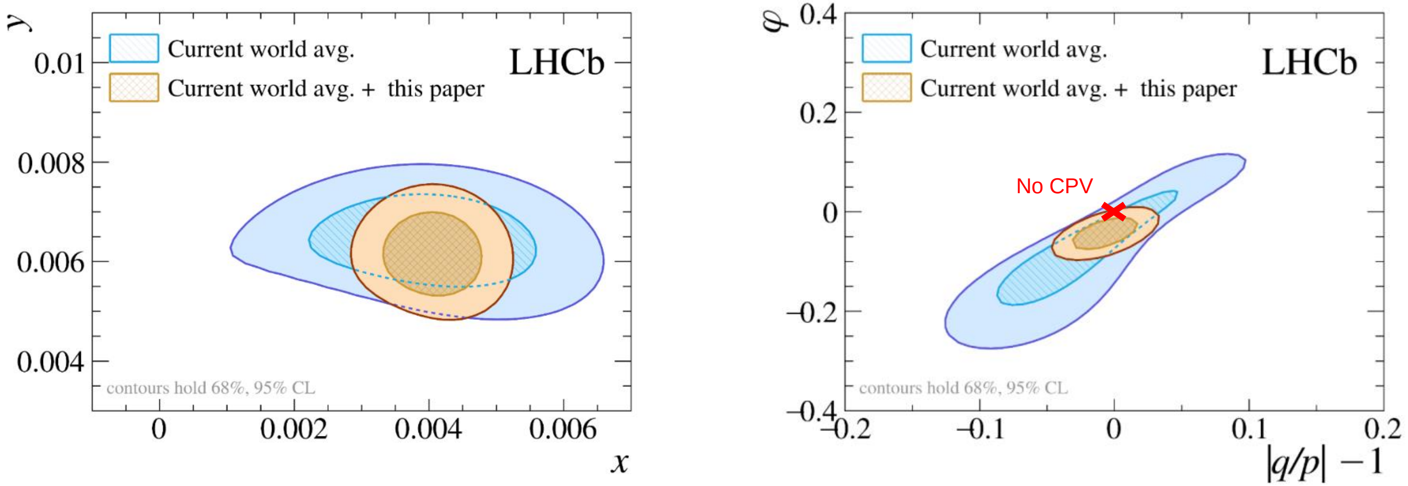
[JHEP 07 (2022) 138]

Also important to improve measurements of sin2β, φ_s (*i.e.* CPV in $B_s \to J/\psi\varphi$)…

Example of known unknowns: is there New Physics in charm mixing CPV?

CPV has been seen in the kaon and B sector in mixing-related phenomena, but not in the D^0 system*, where a priori it is known to be extremely small within SM. New Physics could enhance this. LHCb Run 1-2 data have made big advances….

e.g. Improvement in mixing parameters (x,y) and CPV parameters (φ, |q/p|) from Run 1-2 LHCb $D^0 \to K^0_S \pi\pi$ mixing analysis [PRL 127 (2021) 111801].



Highly desirable to improve precision on CPV parameters by ~ order of magnitude.

* CPV has been seen in decay amplitudes (*i.e.* 'direct') [PRL 122 (2019) 211803]. Larger samples are needed to fully characterise this phenomenon also.

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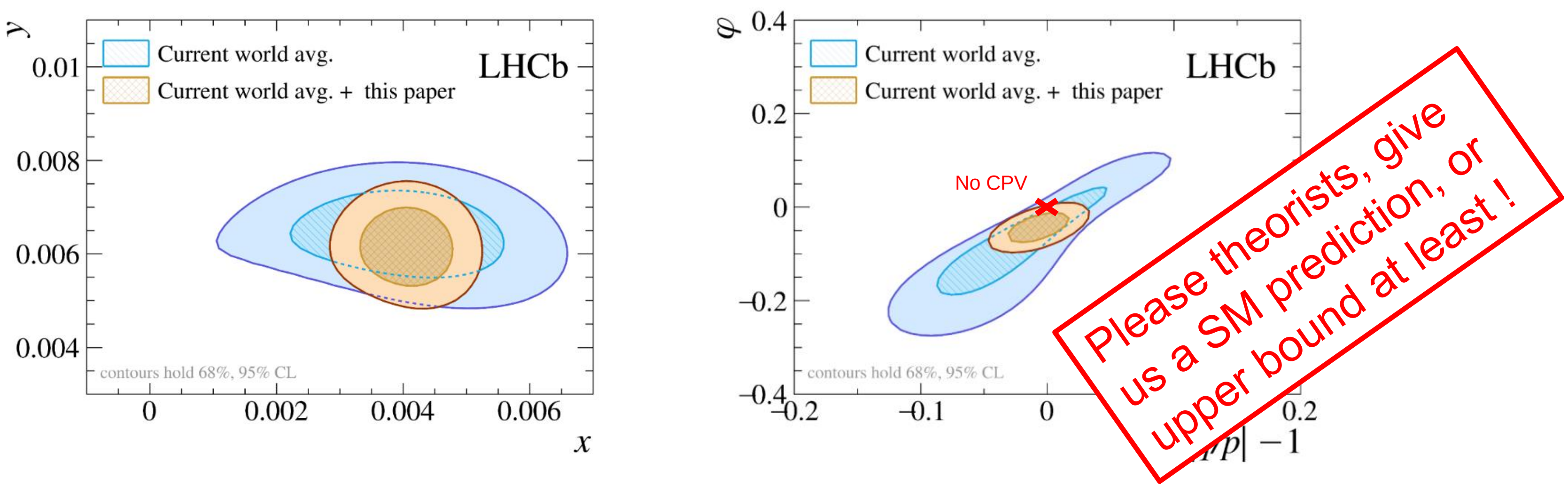

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Unwise to assume ~10% (or even 0.1%) is 'good enough'

Courtesy Browder and Soni

"A special search at Dubna was carried out by E. Okonov and his group. They did not find a single $K_L \rightarrow \pi^+ \pi^-$ event among 600 decays into charged particles [12] (Anikira et al., JETP 1962). At that stage the search was terminated by the administration of the Lab. The group was unlucky."

-Lev Okun, "The Vacuum as Seen from Moscow"

BR ($K^0_L \rightarrow \pi\pi$) ~ 2 x 10^{-3} Cronin, Fitch *et al.* , 1964

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

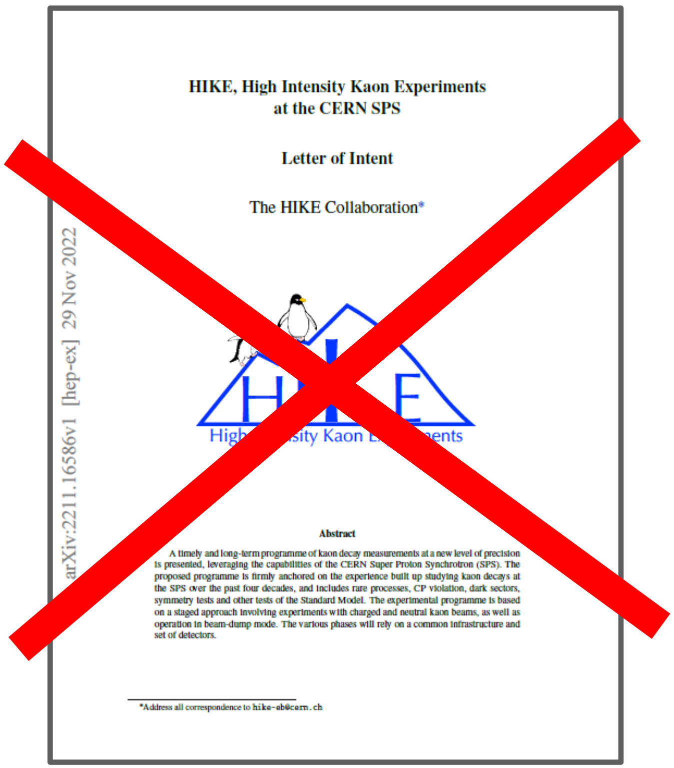
Belle II Belle II+ ? FCC-ee …. FCC-hh

BESIII STCF CEPC …. SPPC

2020s 2030s 2040s 2070s

A minute's silence for the death of kaon physics ?

This is a talk about colliders, so I had intended to say nothing about kaon physics. However, it would be inappropriate not to mention the very recent news of the demise of HIKE, the proposed successor to NA62. End of kaon physics at CERN ?



HIKE, High Intensity Kaon Experiments
at the CERN SPS

Letter of Intent

The HIKE Collaboration*

arXiv:2211.16586v1 [hep-ex] 29 Nov 2022

Abstract

A timely and long-term programme of kaon decay measurements at a new level of precision is presented, leveraging the capabilities of the CERN Super Proton Synchrotron (SPS). The proposed programme is firmly anchored on the experience built up studying kaon decays at the SPS over the past four decades, and includes rare processes, CP violation, dark sectors, symmetry tests and other tests of the Standard Model. The experimental programme is based on a staged approach involving experiments with charged and neutral kaon beams, as well as operation in beam-dump mode. The various phases will rely on a common infrastructure and set of detectors.

*Address all correspondence to hike-eb@cern.ch

One is reminded of Decca's comment when deciding not to sign the Beatles:

"guitar groups are on the way out"

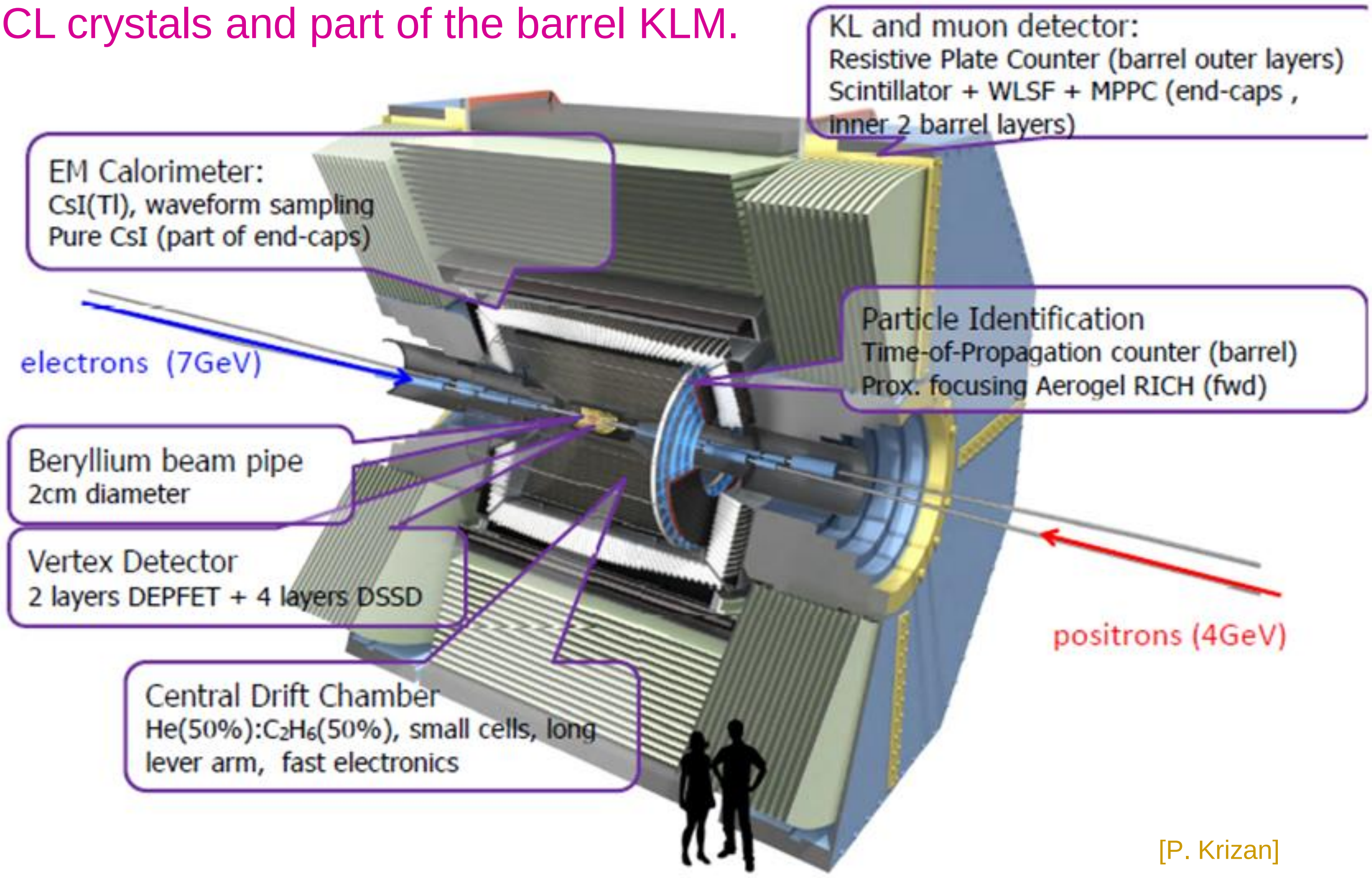
"the Beatles have no future in showbusiness"

But there were many record companies, and there are not so many HEP labs.

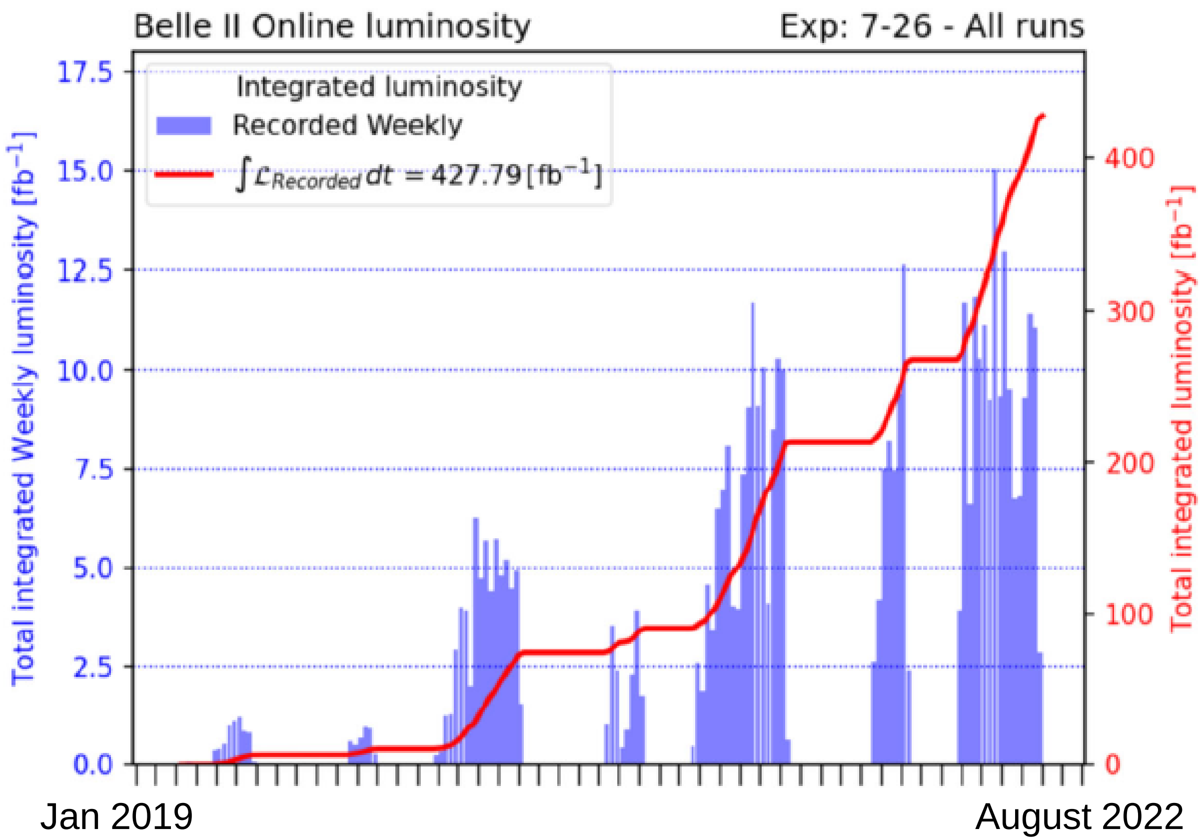
Belle II - flavour physics at the $\Upsilon(4S)$

Belle II detector

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



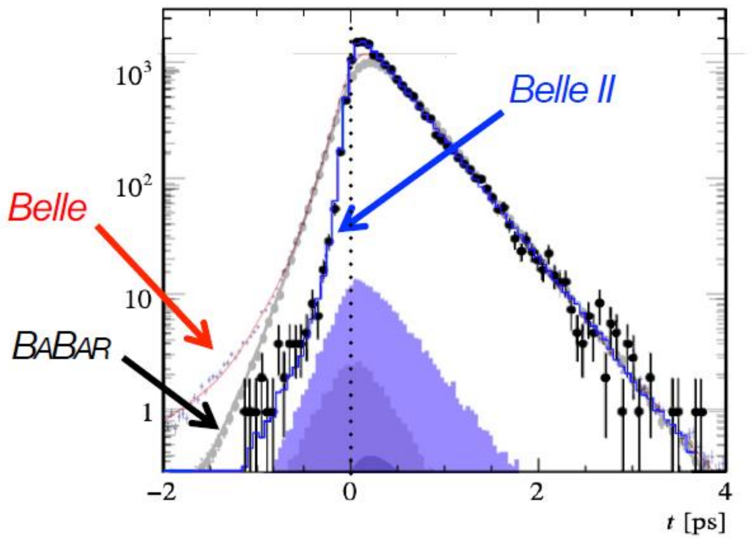
SuperKEKB and Belle II – the story so far



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

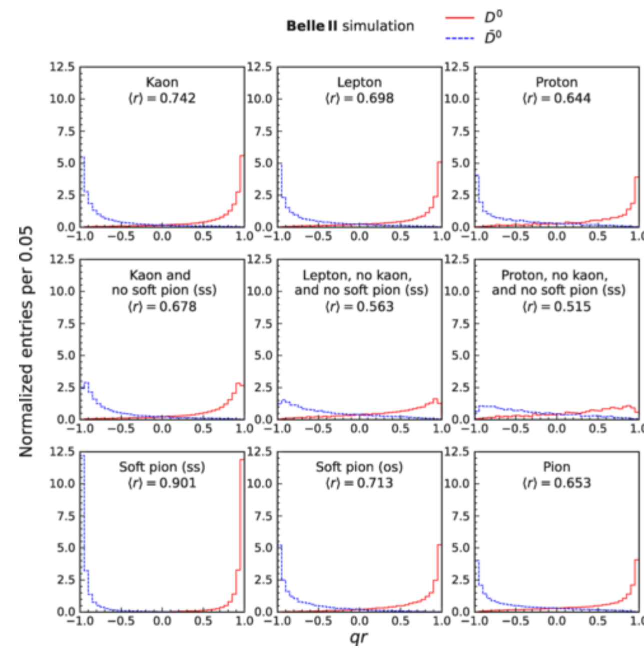
Belle II – improved detector, with improved methods

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.

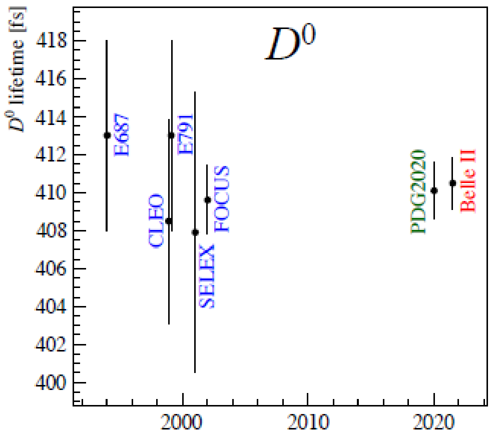


[PRD 107 (2023) 112010]

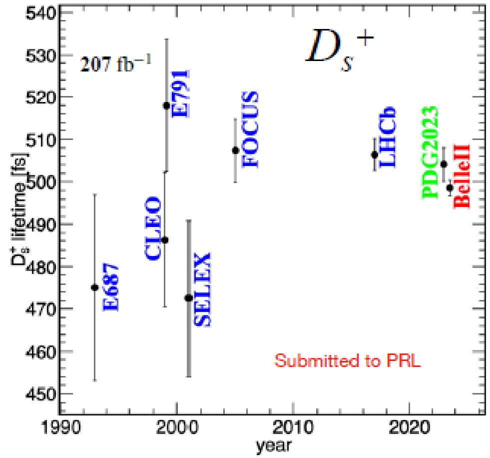
Doubles sample size w.r.t. D* tags.

Charm-lifetime measurements

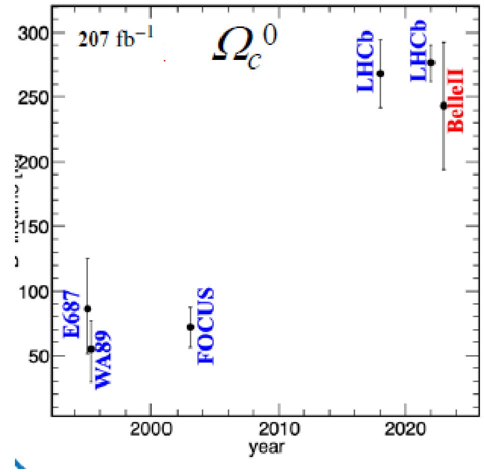
[PRL 127 (2021) 211801]

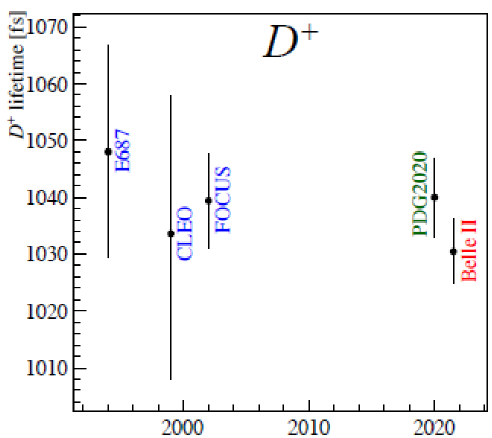


[PRL 131 (2023) 171803]

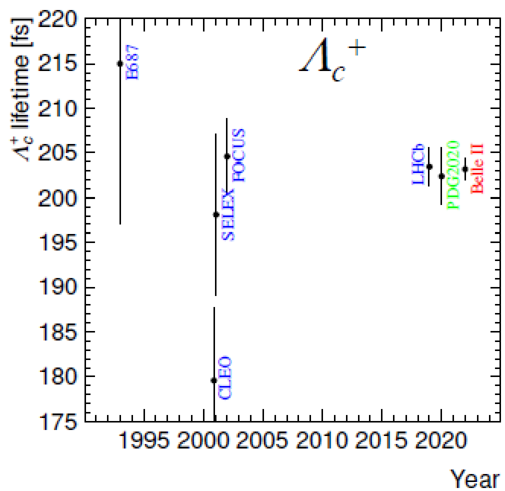


[PRD 107 (2023) L031103]





[PRL 127 (2021) 211801]



[PRL 130 (2023) 071802]

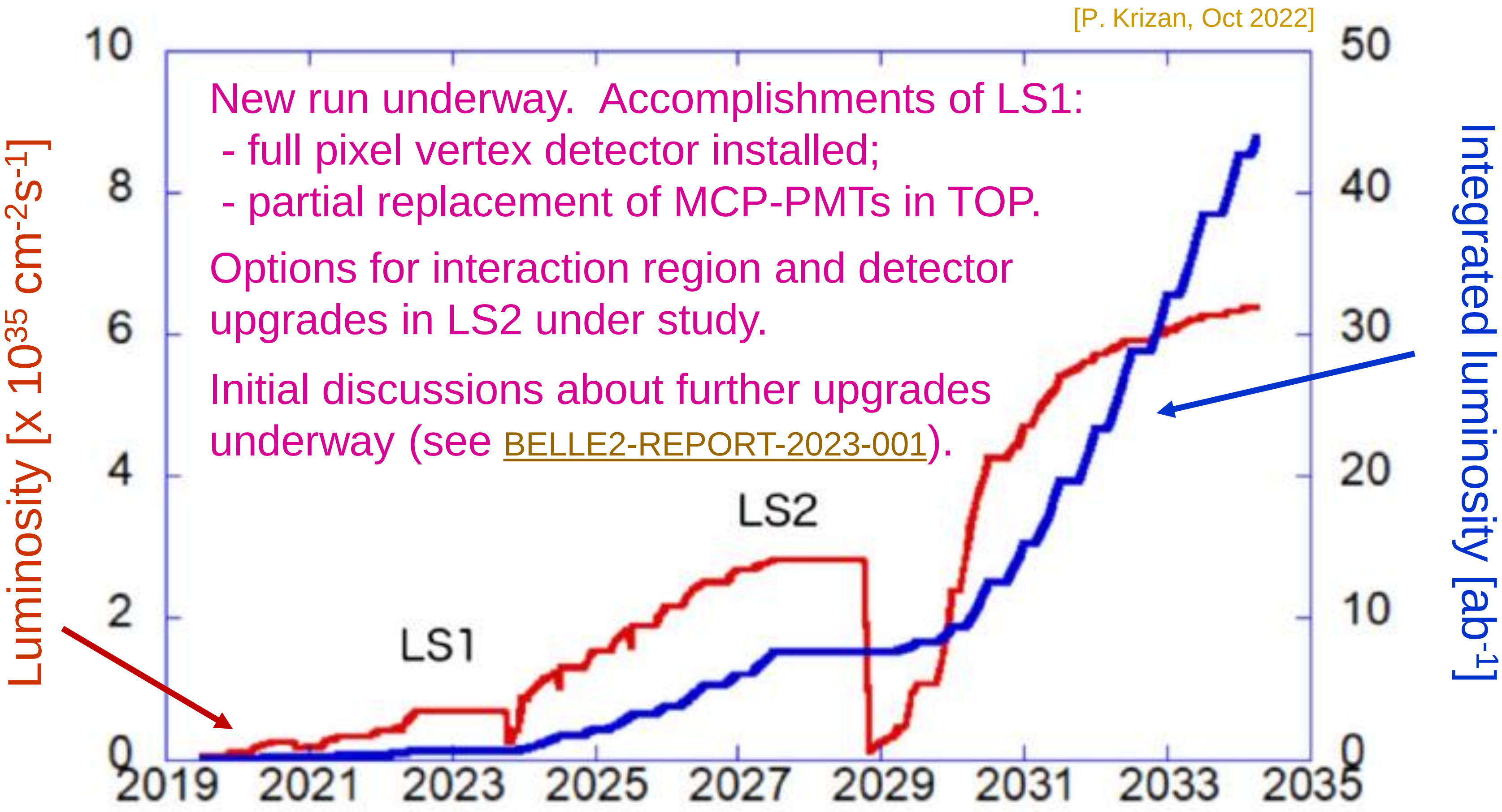
Belle II capabilities clearly demonstrated by series of (mostly) world-best charm lifetime measurements.

SuperKEKB and Belle II roadmap

New run underway. Accomplishments of LS1:
- full pixel vertex detector installed;
- partial replacement of MCP-PMTs in TOP.

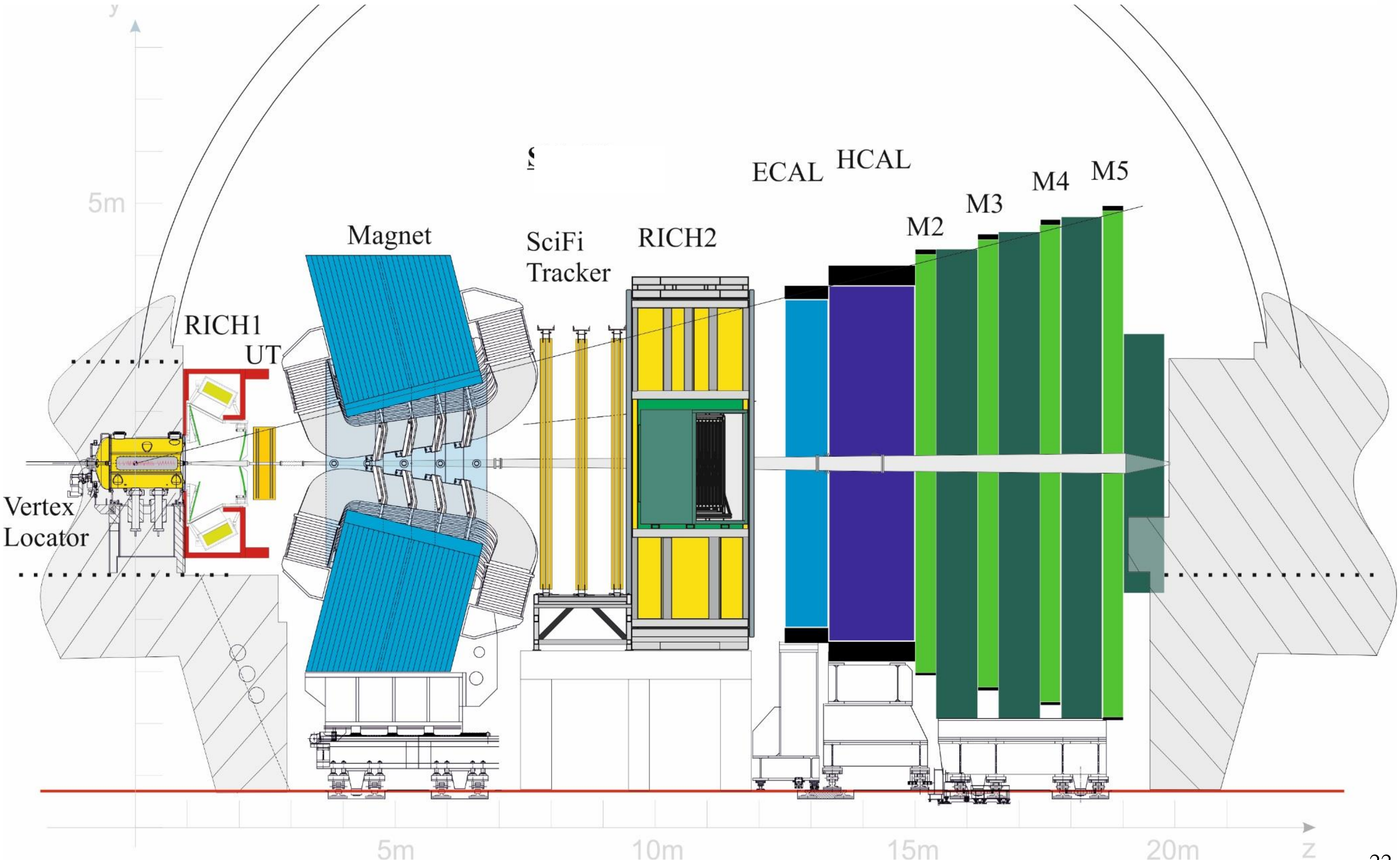
Options for interaction region and detector upgrades in LS2 under study.

Initial discussions about further upgrades underway (see BELLE2-REPORT-2023-001).

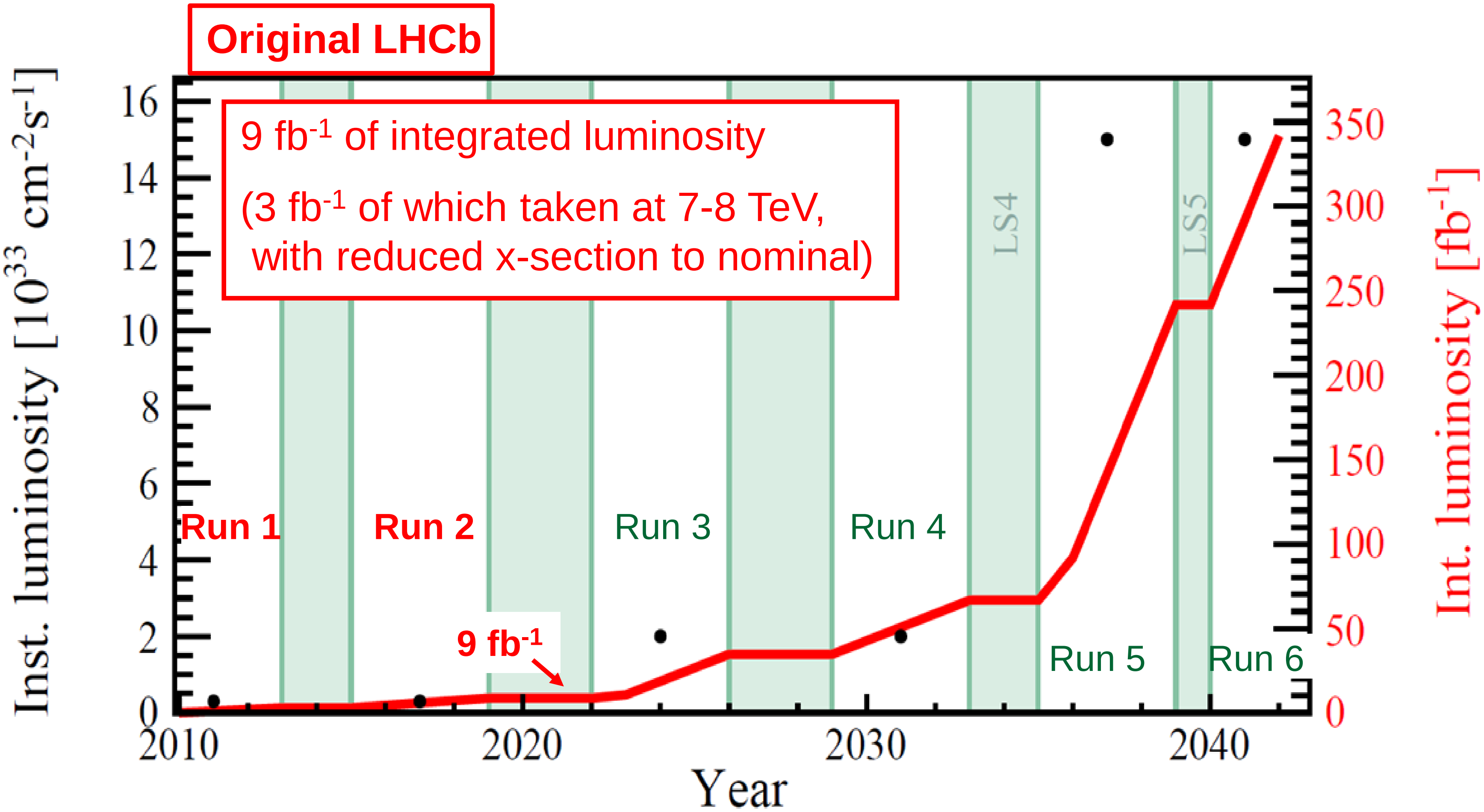


Flavour physics at the LHC – in the near and further future

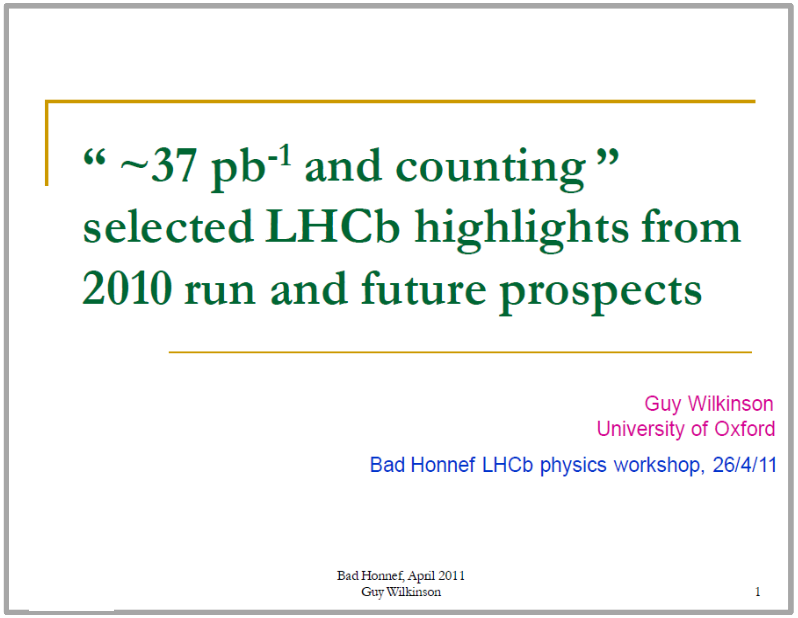
LHCb Run 1 & 2 detector



LHCb timeline: Upgrades I and II



13 years previously

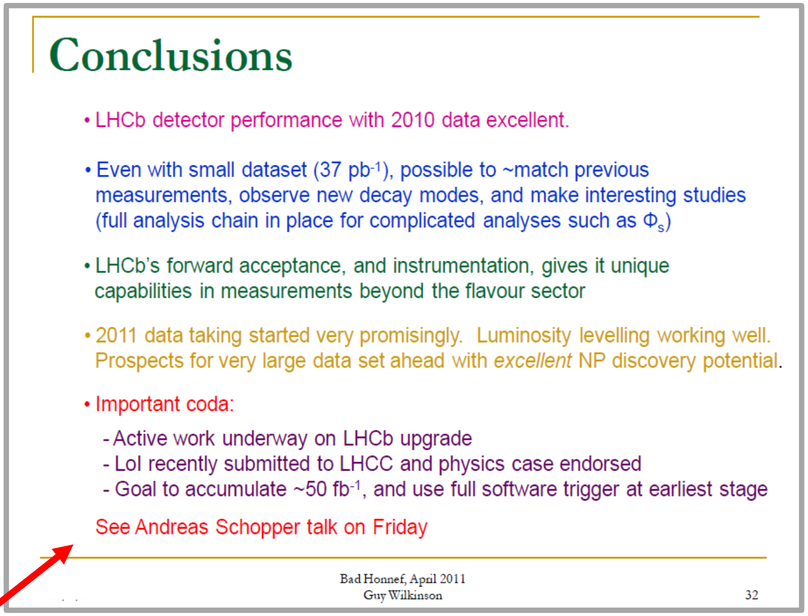


“ ~37 pb^{-1} and counting ”
selected LHCb highlights from 2010 run and future prospects

Guy Wilkinson
University of Oxford

Bad Honnef LHCb physics workshop, 26/4/11

Bad Honnef, April 2011
Guy Wilkinson 1



Conclusions

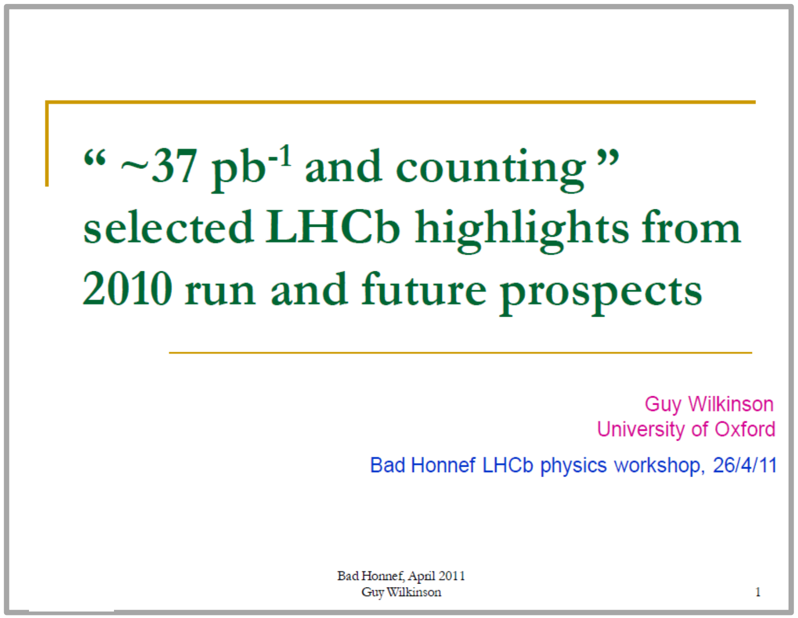
- LHCb detector performance with 2010 data excellent.
- Even with small dataset (37 pb^{-1}), possible to ~match previous measurements, observe new decay modes, and make interesting studies (full analysis chain in place for complicated analyses such as Φ_s)
- LHCb’s forward acceptance, and instrumentation, gives it unique capabilities in measurements beyond the flavour sector
- 2011 data taking started very promisingly. Luminosity levelling working well. Prospects for very large data set ahead with *excellent* NP discovery potential.
- Important coda:
  - Active work underway on LHCb upgrade
  - LoI recently submitted to LHCC and physics case endorsed
  - Goal to accumulate ~50 fb^{-1}, and use full software trigger at earliest stage

See Andreas Schopper talk on Friday

Bad Honnef, April 2011
Guy Wilkinson 32

But there was something even more exciting happening that Friday…

13 years previously



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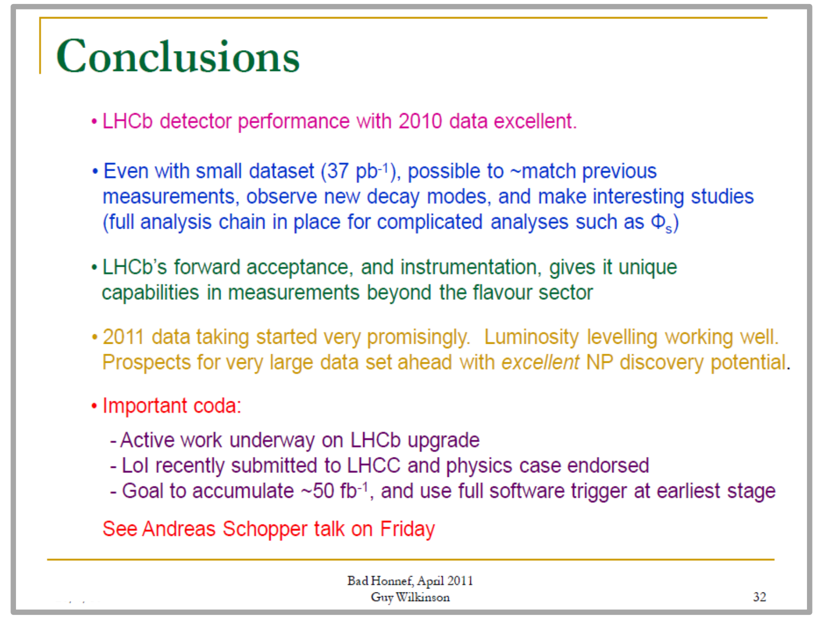

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Bad Honnef, April 2011
Guy Wilkinson 32

29 March 2011, wedding

March 2024, ‘photoshop-gate’

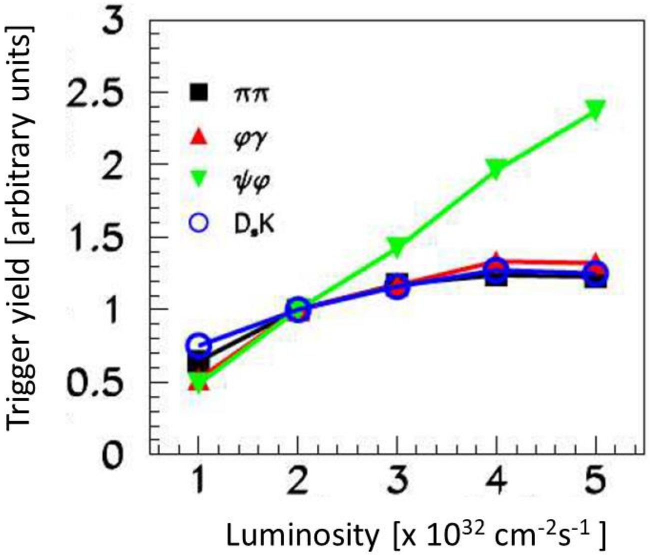
LHCb Upgrade I – driving ideas

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

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

Why not go higher ?

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



Muonic final states

Hadronic final states

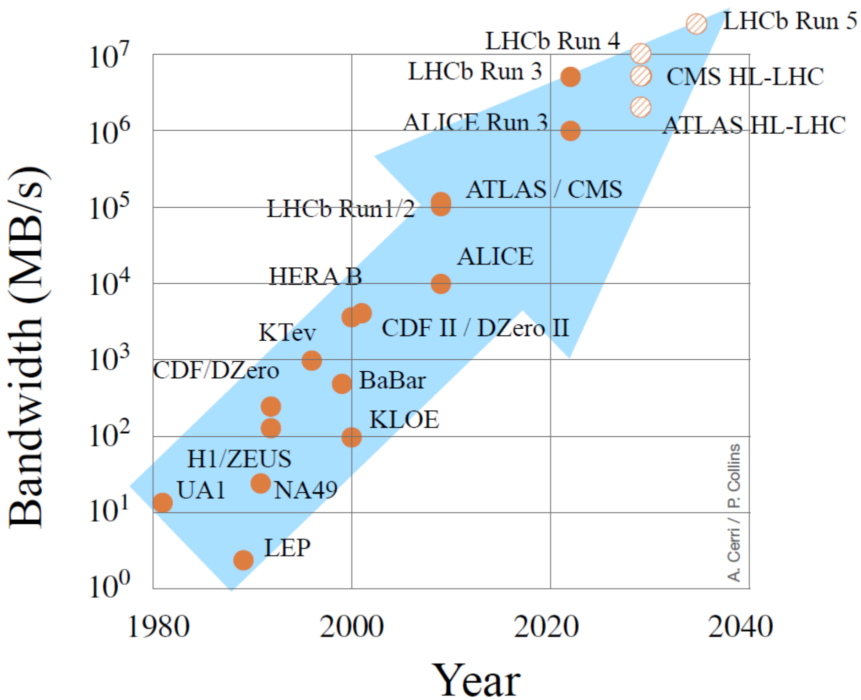
How to get around this?

- 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.

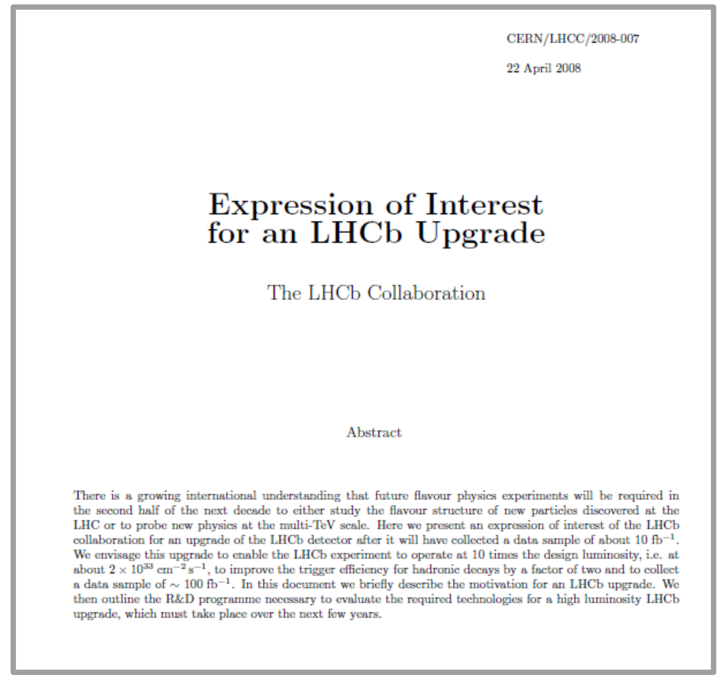
Aim to raise luminosity to 2 x 10^{33} $cm^{-2}s^{-1}$ and increase collected data sample from 9 fb^{-1} (Run 1 and 2) to ~50 fb^{-1} (Runs 3 and 4), with higher efficiency.

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

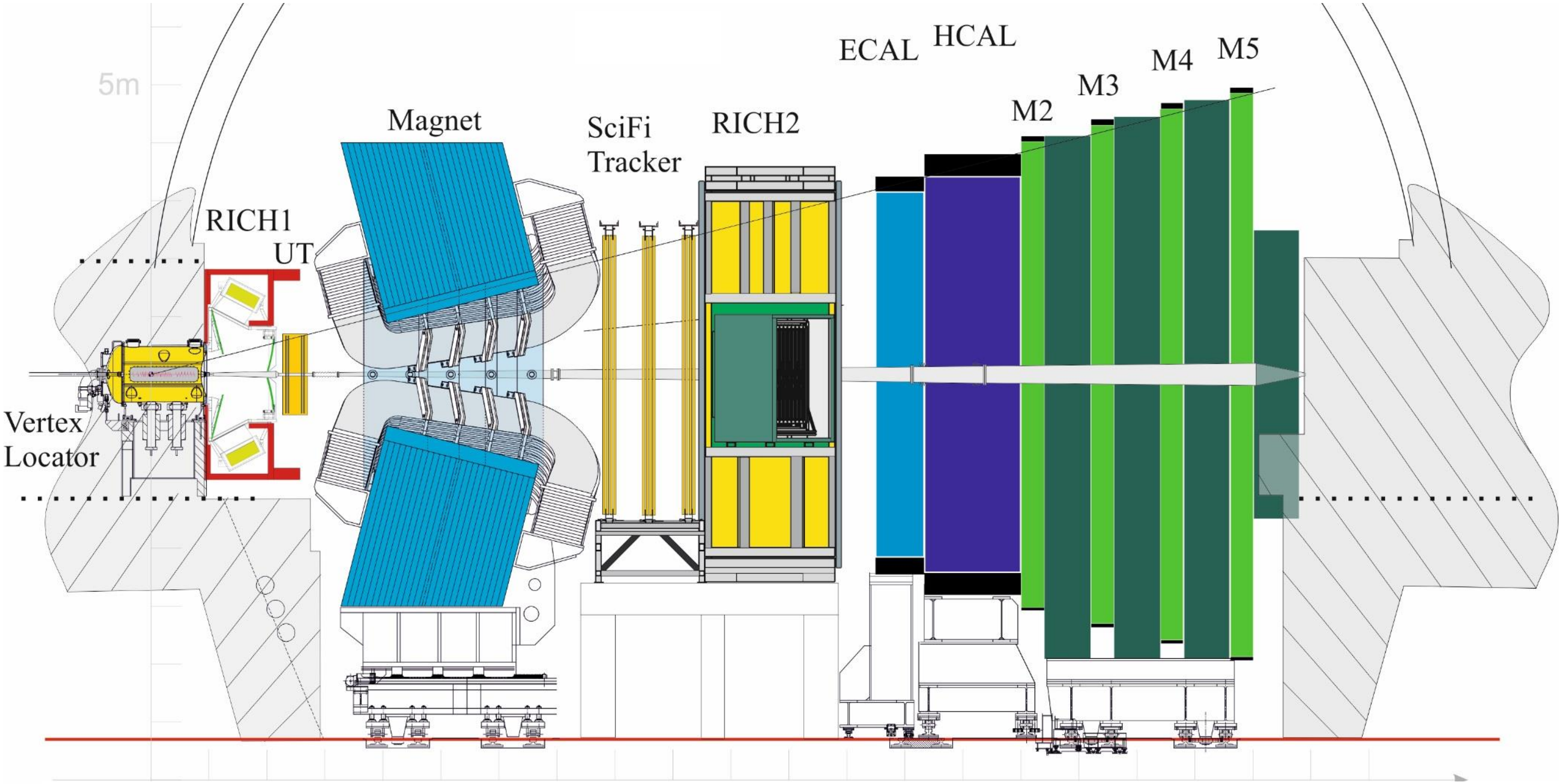
Abstract

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 $2 \times 10^{33}\ cm^{-2}\,s^{-1}$, to improve the trigger efficiency for hadronic decays by a factor of two and to collect a data sample of $\sim 100\ fb^{-1}$. 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]

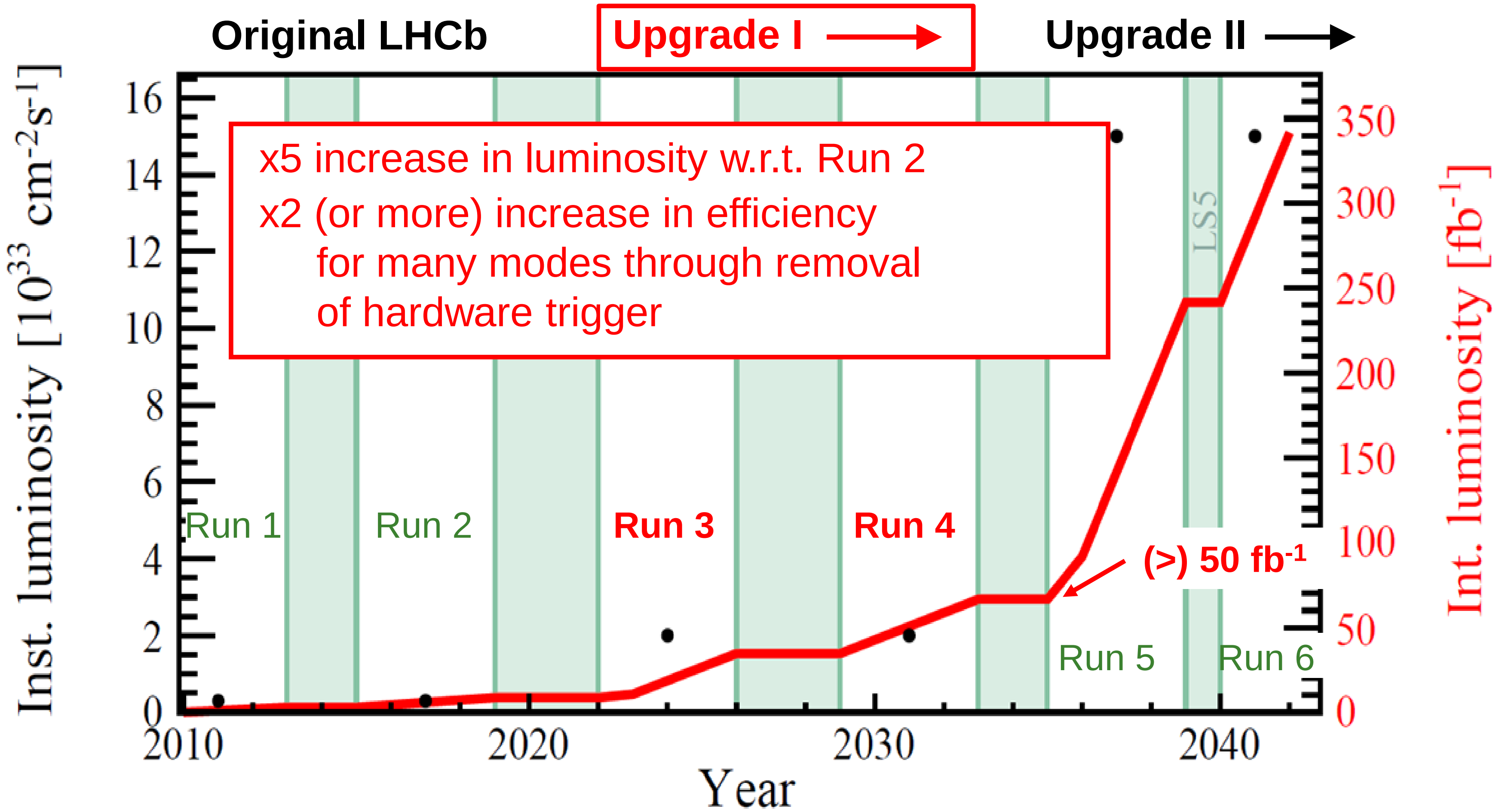
LHCb Upgrade I – the future is now

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

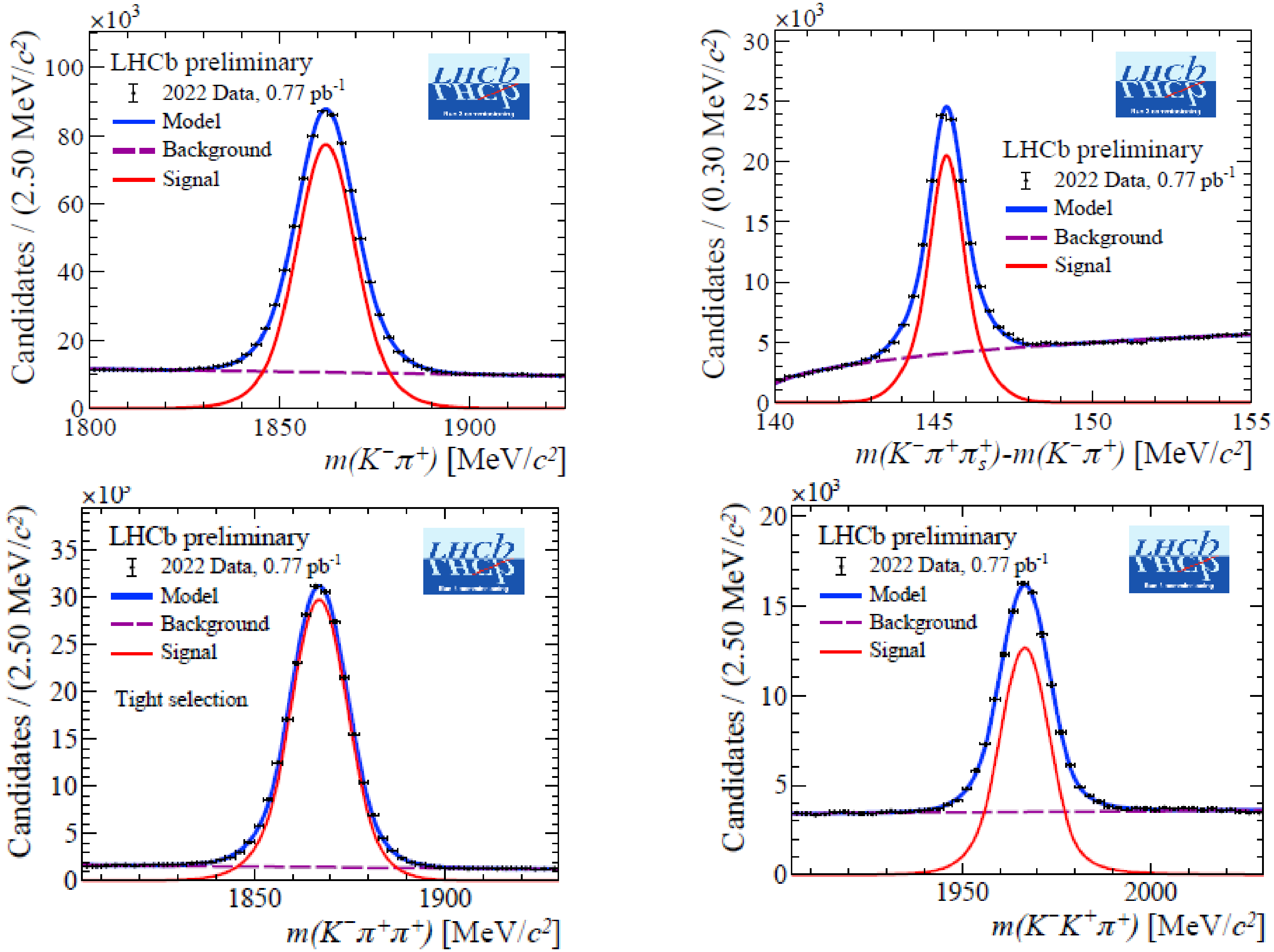


Commissioned during 2022 and 2023. Full physics operation expected this year.

LHCb timeline: Upgrades I and II

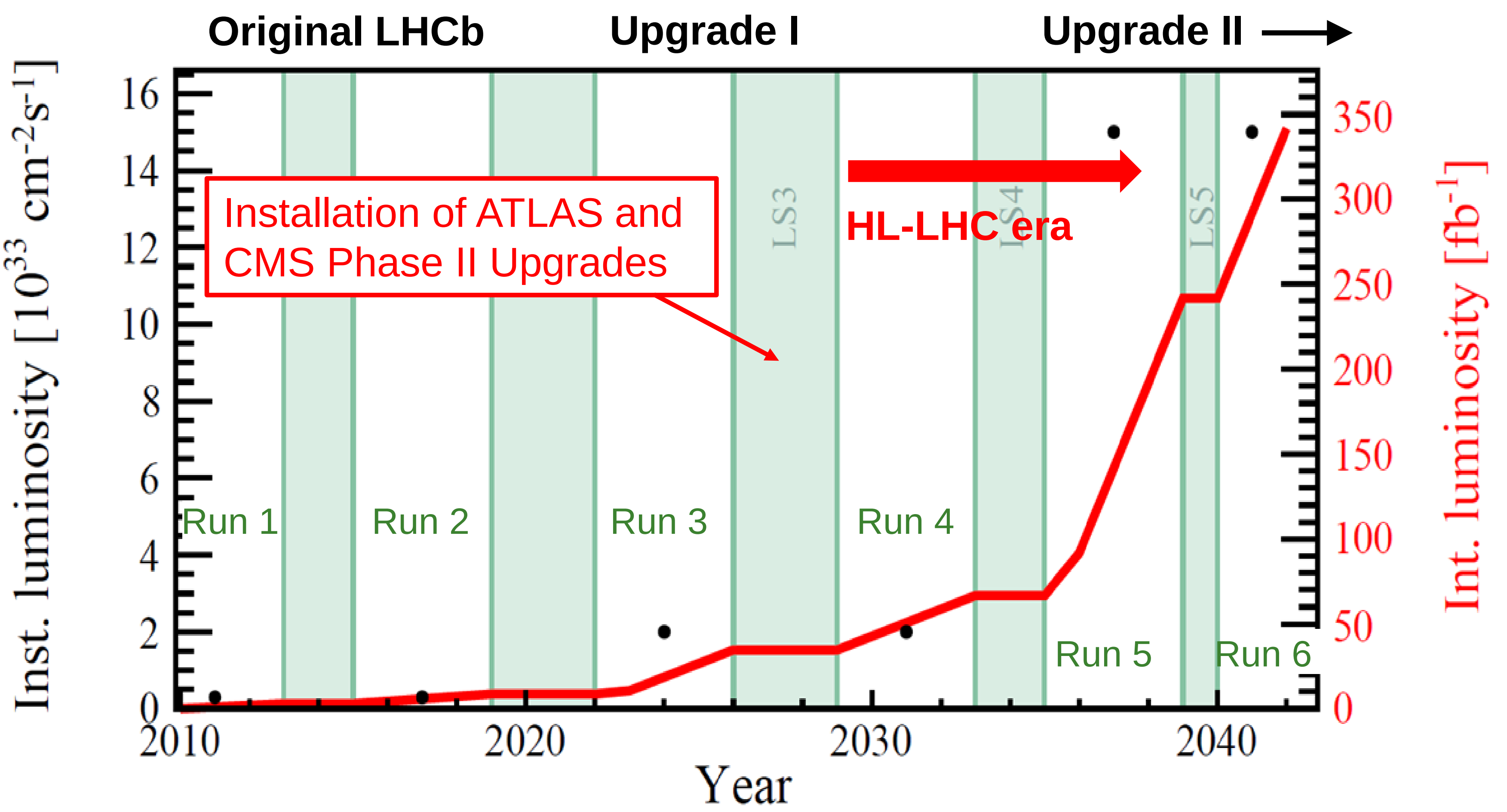


First charm peaks from Upgrade I



[LHCb-FIGURE-2023-011]

Don’t forget, there are other experiments at the LHC…

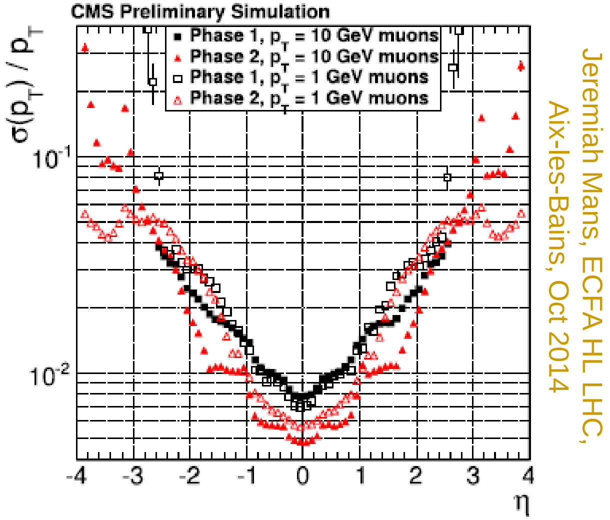


ATLAS and CMS Phase II Upgrades

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

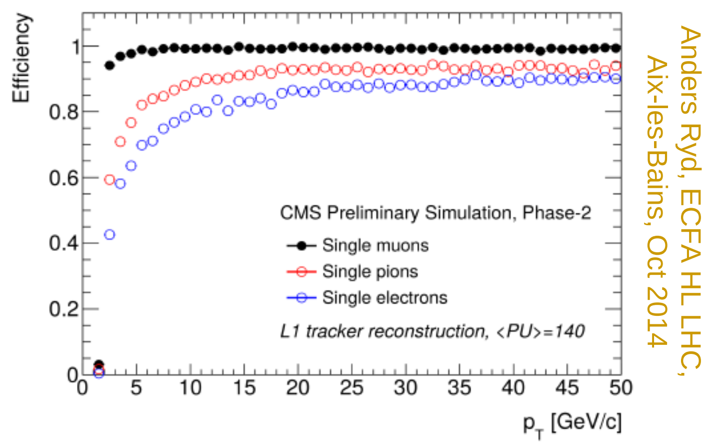
New capabilities of experiments after Phase-II Upgrade (CMS in particular) will strengthen their capabilities in flavour physics

e.g. new CMS tracker



Significantly improved p resolution

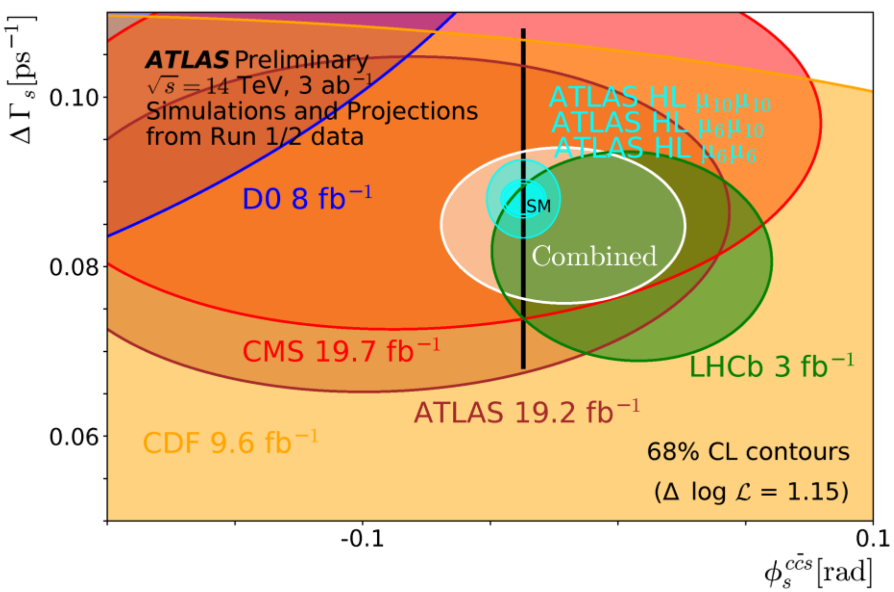
e.g. CMS new L1 track trigger



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

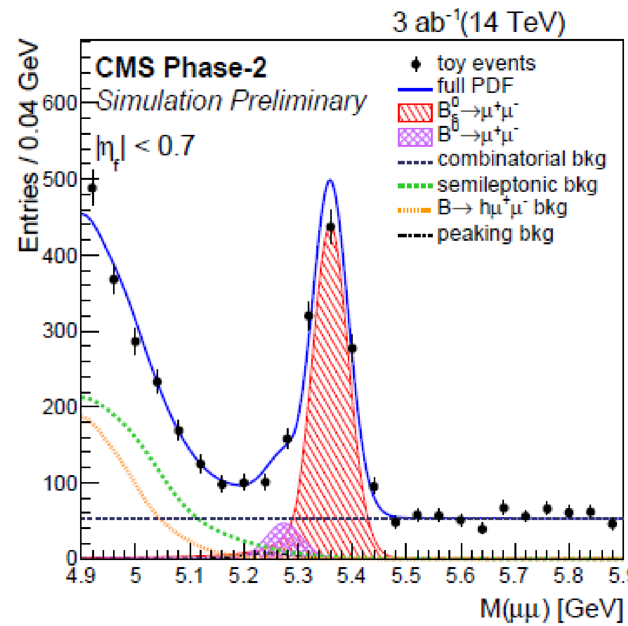
B-physics prospects at the HL-LHC with ATLAS and CMS

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



[ATL-PHYS-PUB-2018-041]

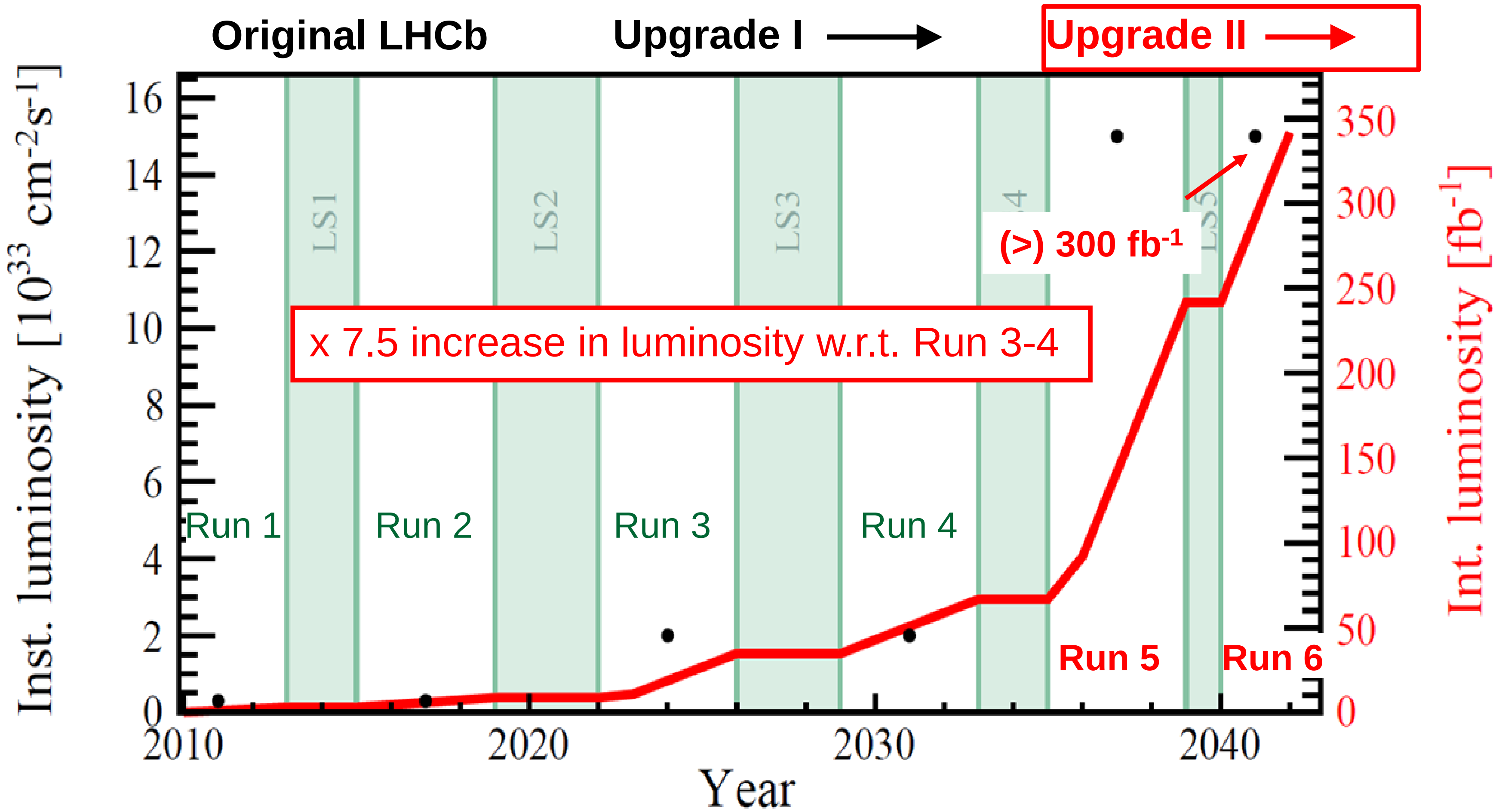
CMS prospects for $B^0_{(s)} \to \mu\mu$ in barrel region with 3 ab^{-1}.



[CMS-PAS-FTR-18-013]

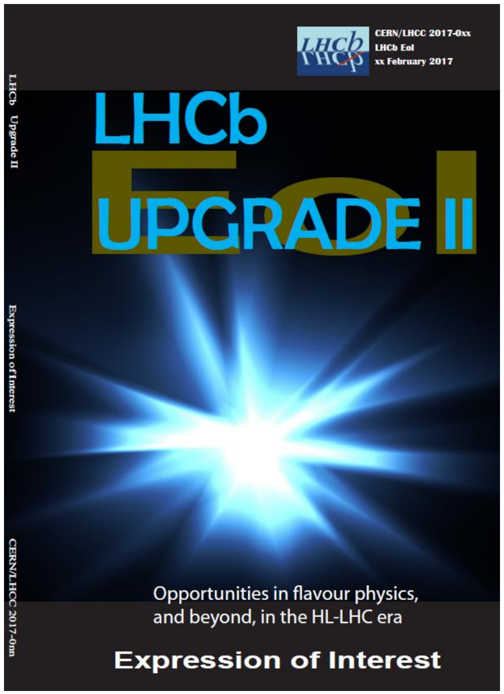
Also see recent Snowmass White Paper [ATL-PHYS-PUB-2022-018,CMS-PAS-FTR-22-001].

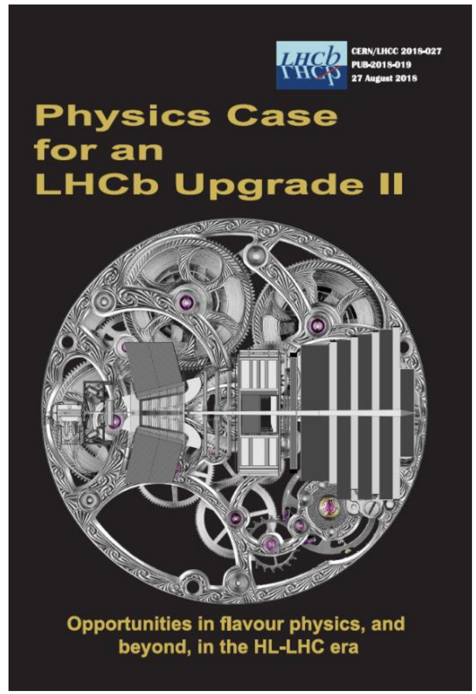
LHCb timeline: Upgrades I and II



LHCb Upgrade II

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



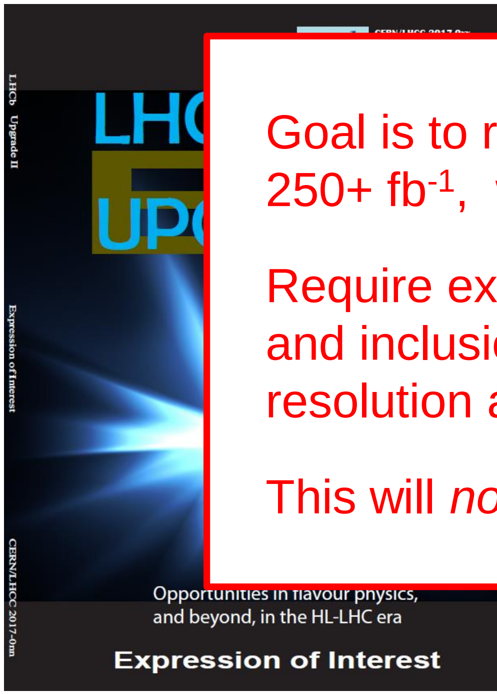


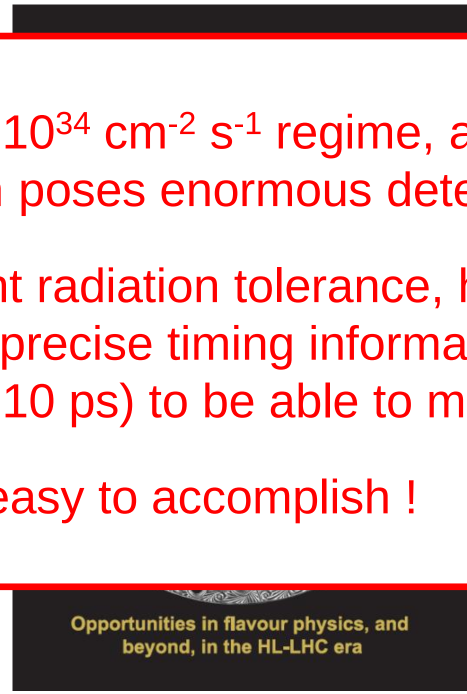
[CERN-LHCC-2017-003] [CERN-LHCC-2018-027] [CERN-LHCC-2021-012]

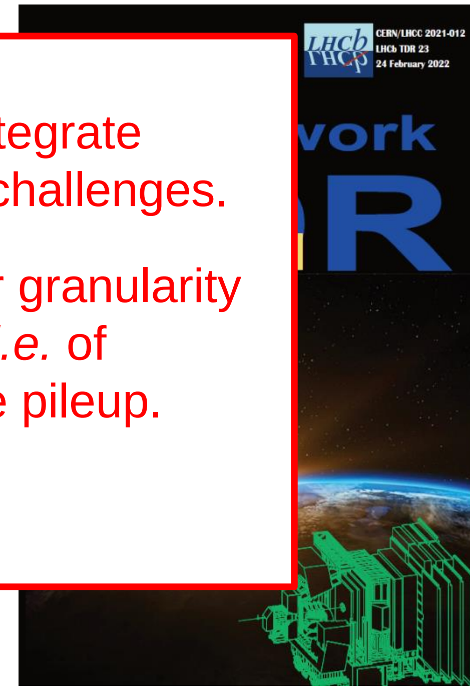
Now part of the CERN baseline plan. Framework approved by LHCC. Work underway on ‘scoping document’, which will consider some (slightly) less ambitious scenarios to that in Framework TDR. Substantial funding already allocated in UK.

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 approved by LHCC. Work underway on 'scoping document', which will consider some (slightly) less ambitious scenarios to that in Framework TDR. Substantial funding already allocated in UK.

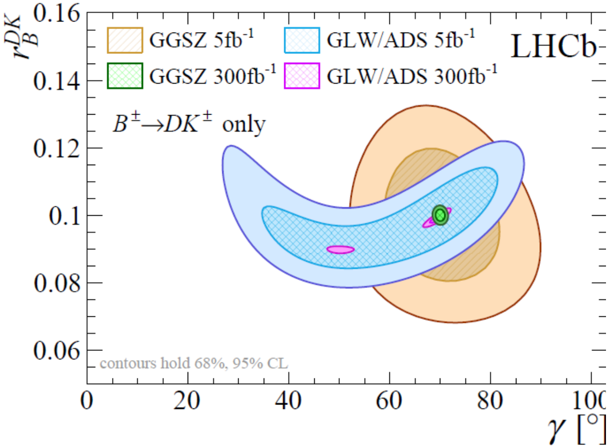
LHCb Upgrade II Physics reach – the obligatory table

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [275]	0.031	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–
CKM tests					
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [609]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [610]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	–	11 mrad	Under study [611]
a_{sl}^s	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–
$\boldsymbol{B_s^0, B^0 \to \mu^+\mu^-}$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [612]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$\boldsymbol{b \to c\ell^-\bar{\nu}_l}$ **LUV studies**					
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002	–
$R(J/\psi)$	0.24 [220]	0.071	–	0.02	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [613]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	–
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x \sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

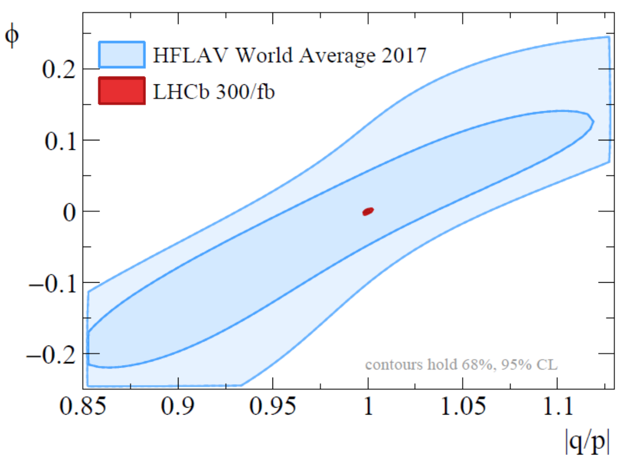
Upgrade-II physics highlights

Too much to cover – here are a few examples:

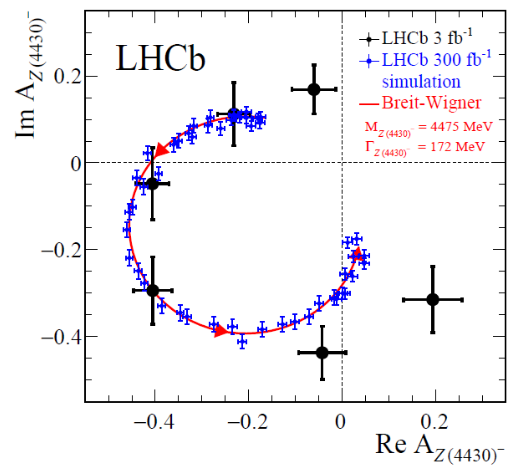
γ determination: sub-degree precision



CPV in charm down to 10^{-5}



High precision spectroscopy studies



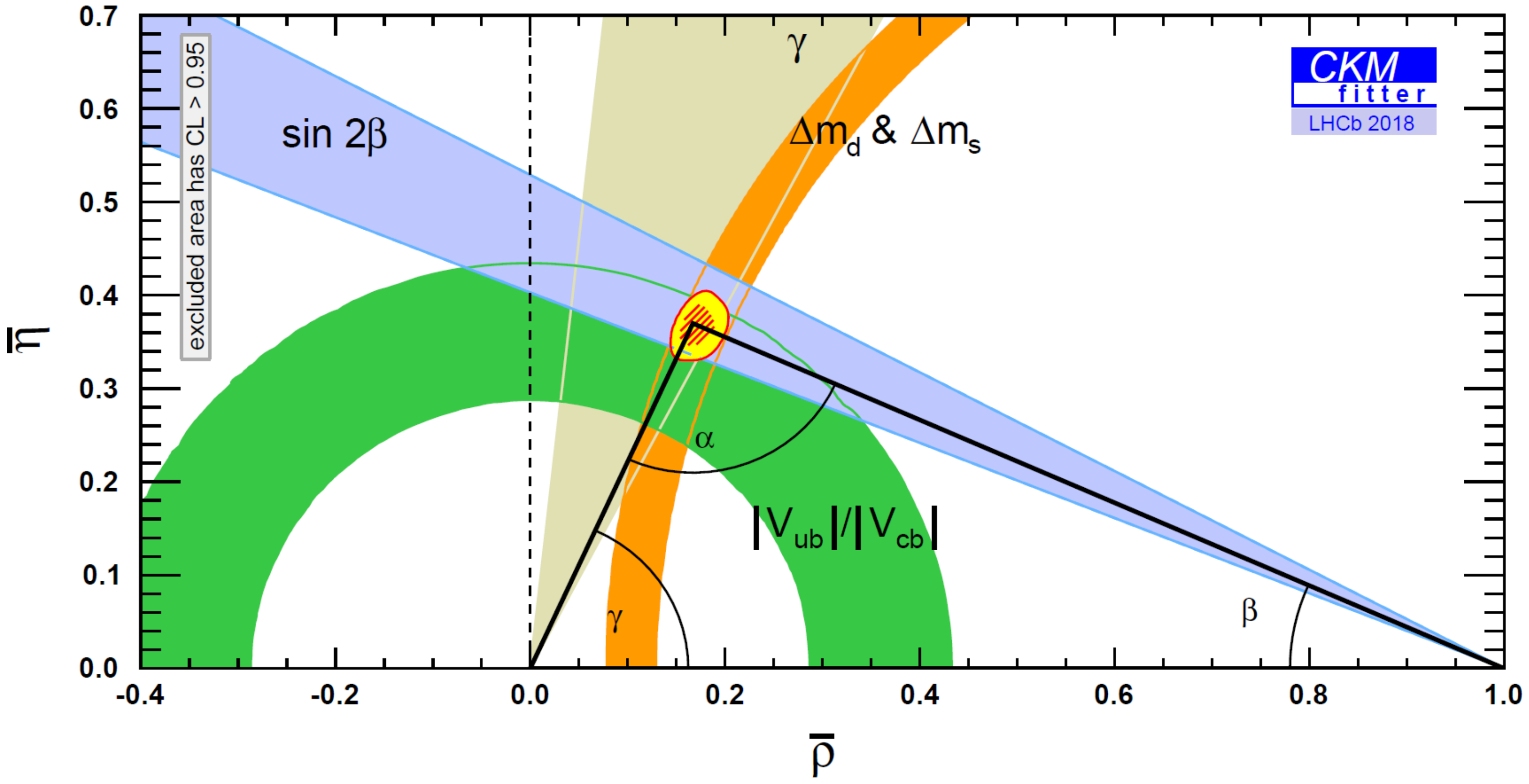
Two key points:

- Many key theoretically clean observables will remain statistics limited even after Upgrade I (*e.g.* γ, φ_s, sin2β, R_K and friends, $B(B^0\to\mu\mu)/B(B_s\to\mu\mu)$…
- Also, will be able to access new observables *e.g.* angular studies of $b\to de^+e^-$.

This will enable great advances in CPV tests, and will give an almost doubling of the New Physics mass scale (w.r.t. start of HL-LHC era) to which we are sensitive.

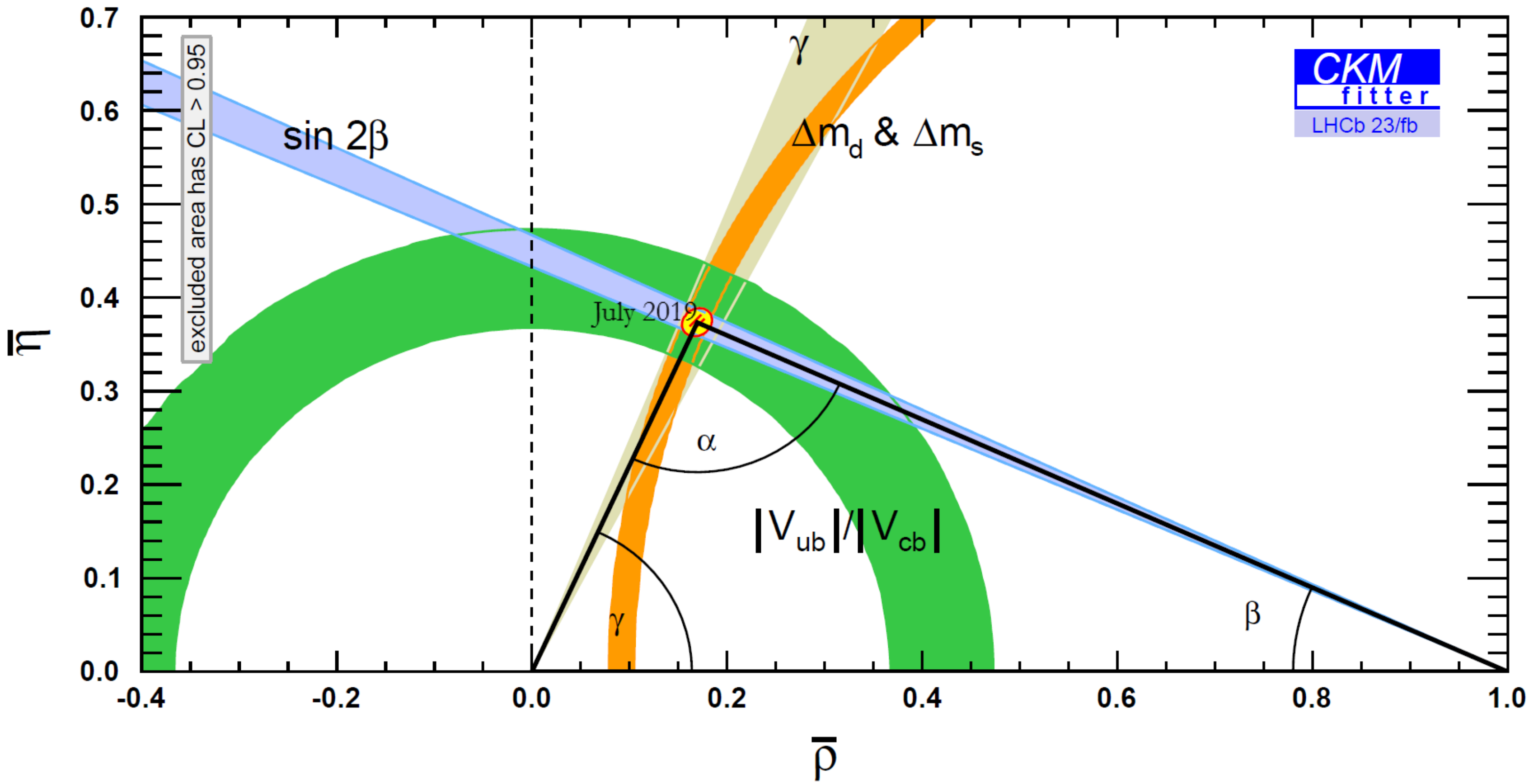
Evolution of constraints on Unitarity Triangle

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



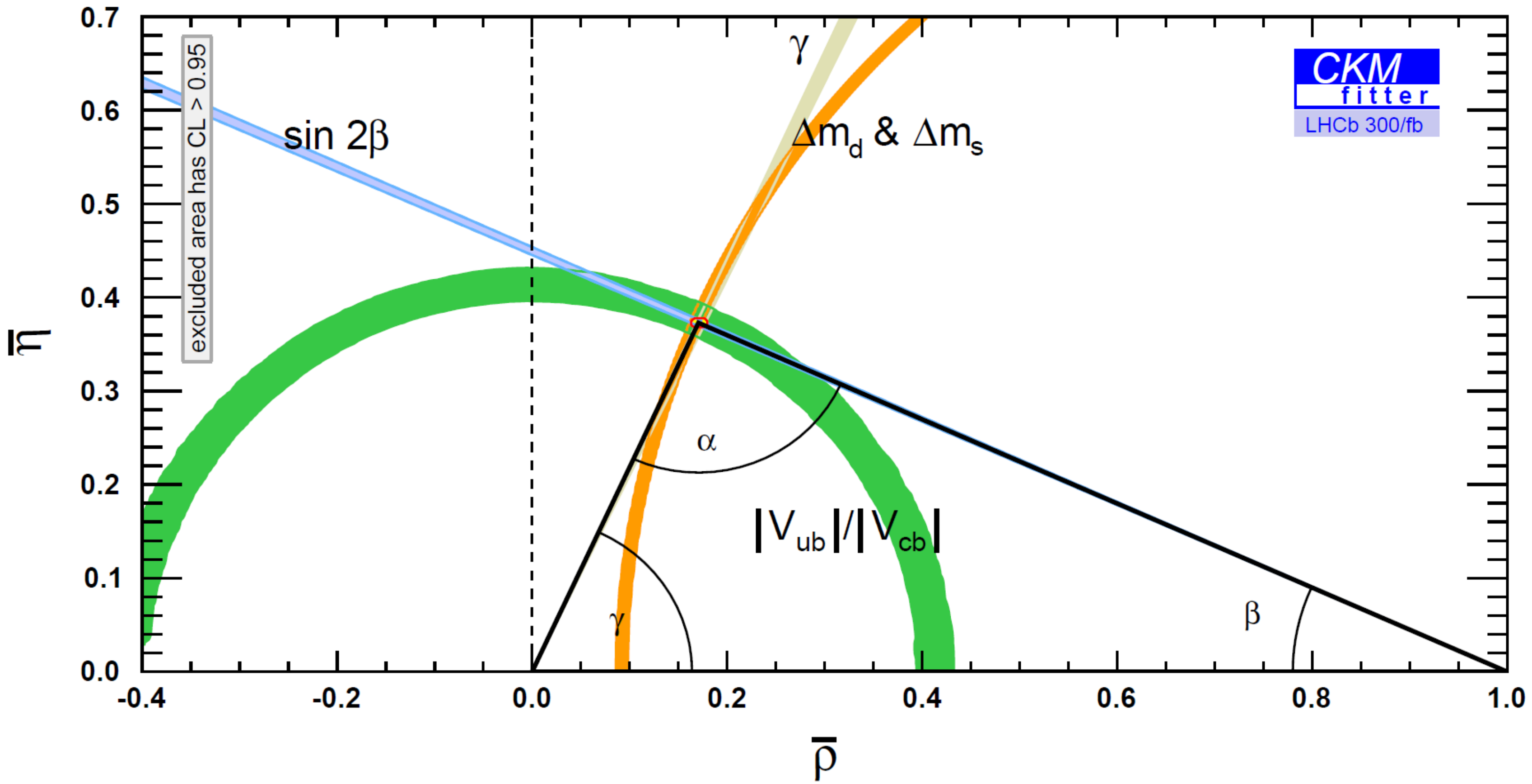
Evolution of constraints on Unitarity Triangle

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



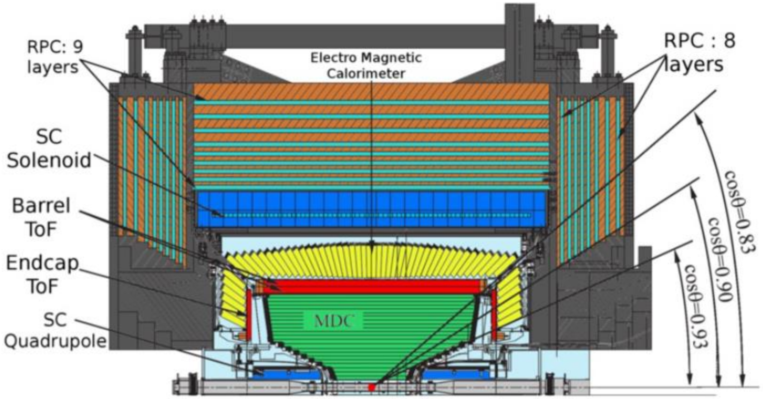
Evolution of constraints on Unitarity Triangle

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



Physics opportunities at and near charm threshold

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 [arXiv:1912.05983]. Data taking will likely continue for much of this decade.

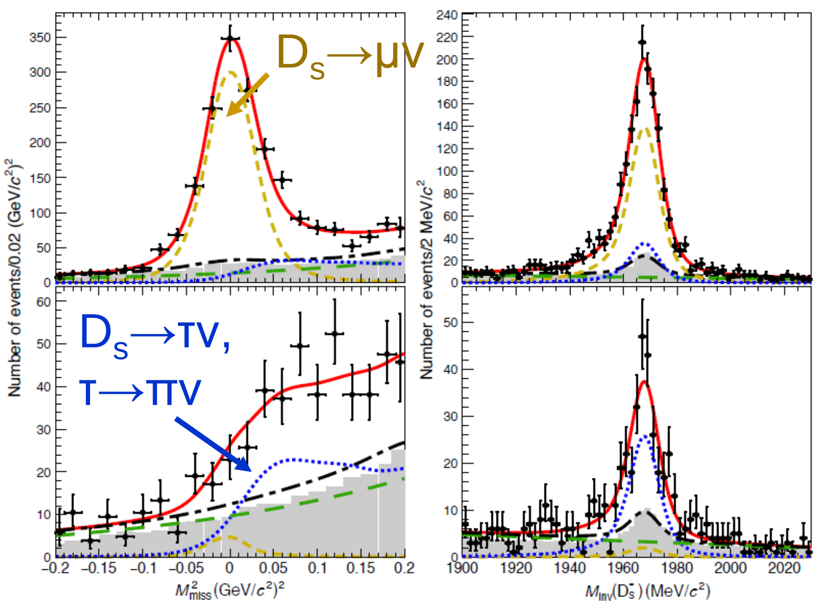
More data taking at 3770 MeV has been ongoing, and has now concluded with total sample of 20 fb^{-1}.

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

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)

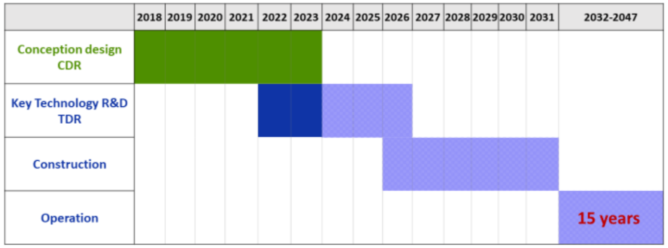
Letter

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.

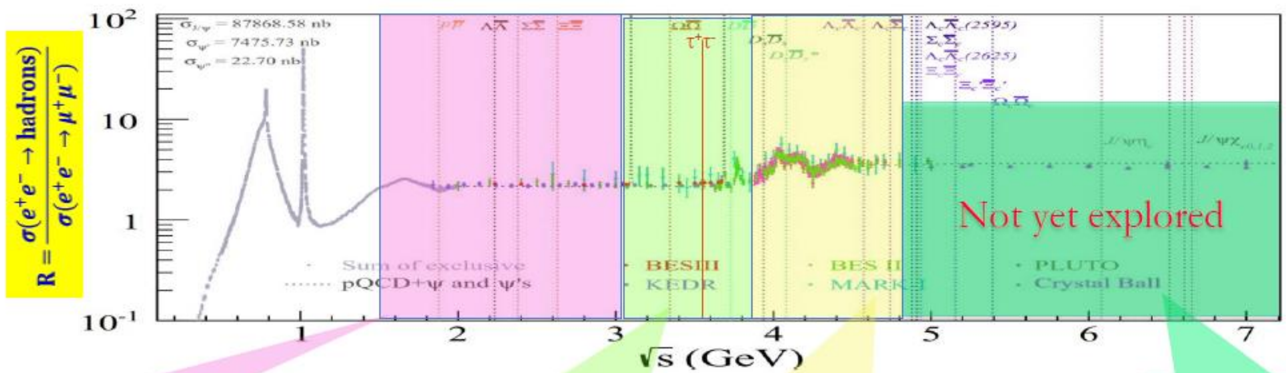
Such results will become ever more interesting with the growing data sets.

Super Tau Charm Factory



Proposed facility in Heifei China that would be begin early 2030s. [physics CDR: arXiv:2303.15790]

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)

[physics CDR: arXiv:2303.15790]

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.

Charm & tau data sets are approaching target samples at Belle II, and are cleaner, which is promising for *e.g*. FCNC searches.

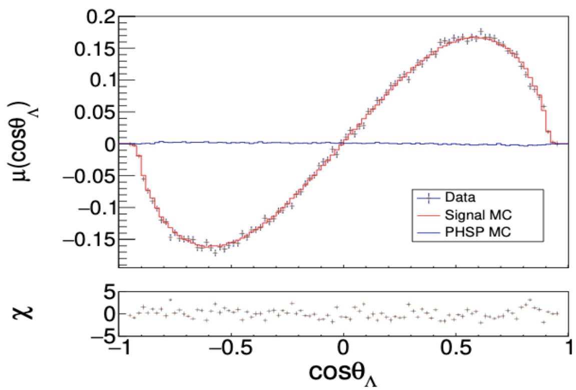
No boost, so no time-dependent CPV measurements, but interesting time integrated options in *C*-even systems, *e.g.* DDbar*→γ(DDbar), where mixing effects enhanced. Complementary to studies at Belle II and LHCb Upgrade I.

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			

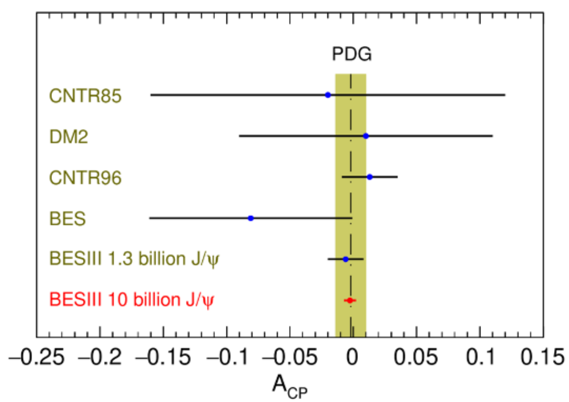
STCF unique opportunities – search for CPV in hyperon decay

CPV in baryon system has still not been observed (*surely* it will for b-baryons in LHC Run 3 ???). This phenomenon can be probed in distribution of J/Ψ's decays into quantum-correlated hyperon-antihyperon pairs, as demonstrated at BESIII.

An observable in J/Ψ→Λ Λ bar production sensitive to polarization



CPV asymmetry in J/Ψ→Λ Λ bar production



[PRL 129 (2022) 131801]

For further studies with Λ's and Ξ's see:

Nature 606 (2022) 64

PRL 129 (2022) 131801

PRD 103 (2023) L011101

and, for a review:

Sci. Bull. 67 (2022) 1840

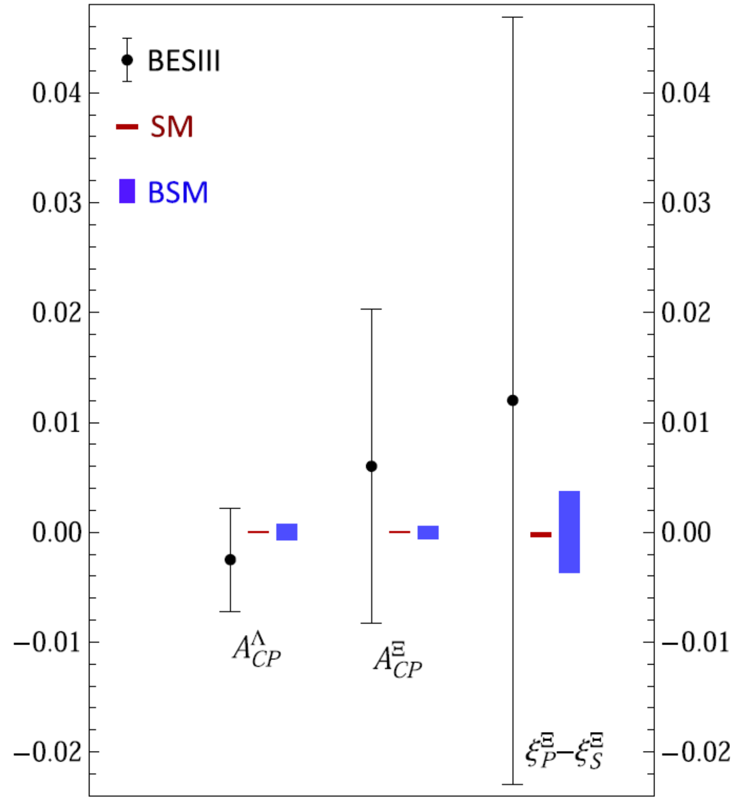
These studies were made with 10 billion J/Ψ & 5 x 10^8 Ψ(3686) decays. However, "you never have enough J/Ψ events!" (Steve Olsen) & STCF offers ~10^2 x more.

STCF unique opportunities – search for CPV in hyperon decay

With STCF event yields can approach level of effects expected in SM for CPV observables (10^{-4} – 10^{-5}), and test BSM models.

(Note that because of presence of both S and P waves in decay, BSM effects in hyperons may be different than in kaon mixing and decays.)

Accelerator tricks, such as longitudinal polarization and monochromotization, considered for second phase of STCF, can increase sensitivity still further.

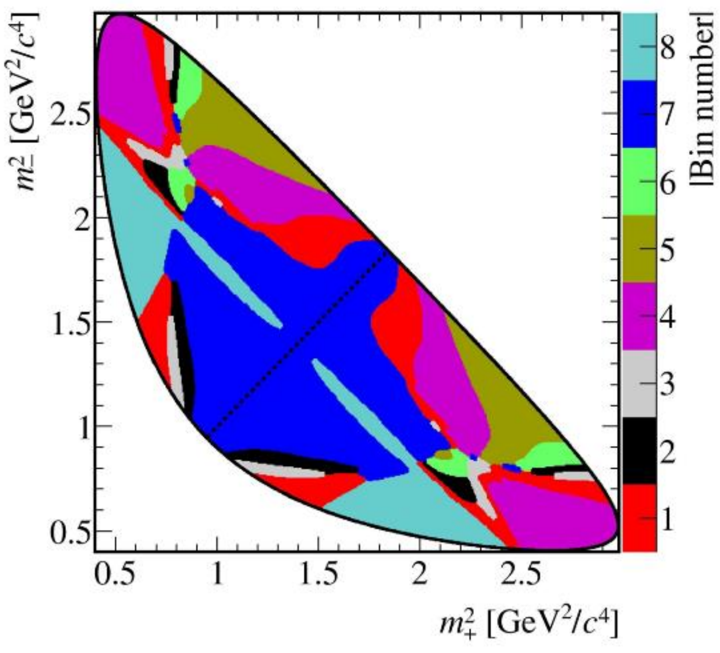


[Sci. Bull. 67 (2022) 1840]

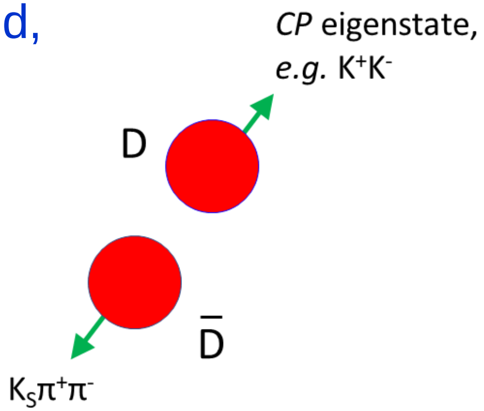
STCF unique opportunities – super-precise strong-phase measurements

Measurement of CKM angle γ (and charm-mixing studies) at LHCb and Belle II require knowledge of CP-conserving strong phases in D decays, *e.g.* $D \rightarrow K_S\pi\pi$.

Binned Dalitz plot of $D \rightarrow K_S\pi\pi$. Need to know strong phase in each region.



Best (and almost only) place to access this strong-phase information, is at charm threshold, *i.e.* BESIII (now) & STCF (future).



By tagging one meson in CP eigenstate, the other meson is fixed to be of opposite CP, which gives access to strong-phase info.

STCF unique opportunities – super-precise strong-phase measurements

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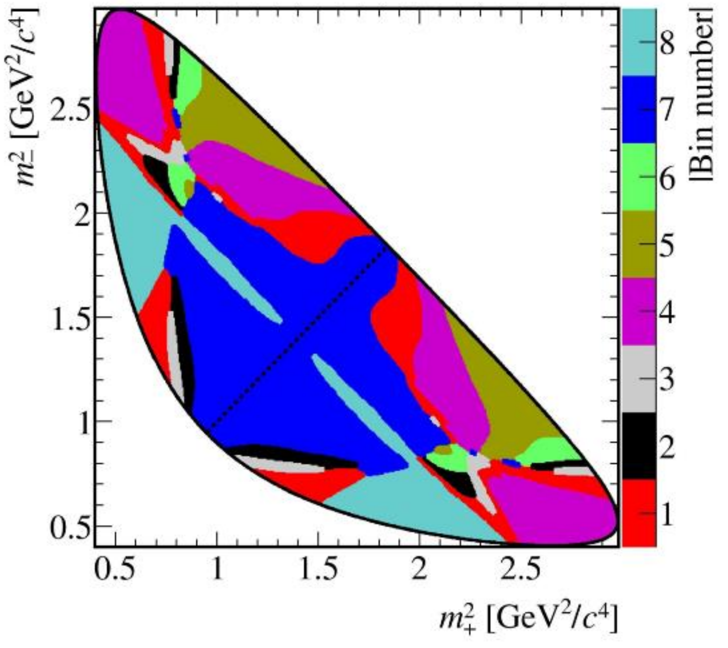
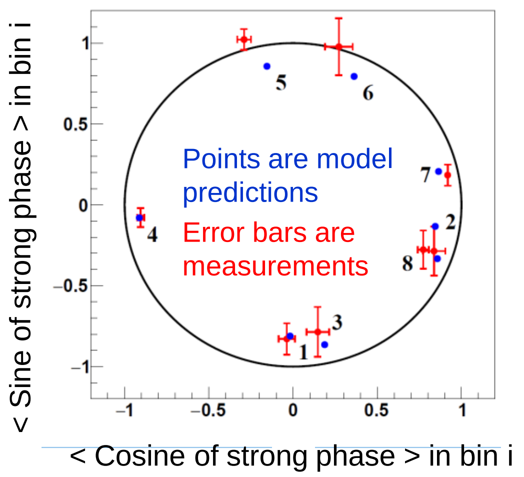


This has been done at BESIII, & is a vital input to current LHCb γ determination.

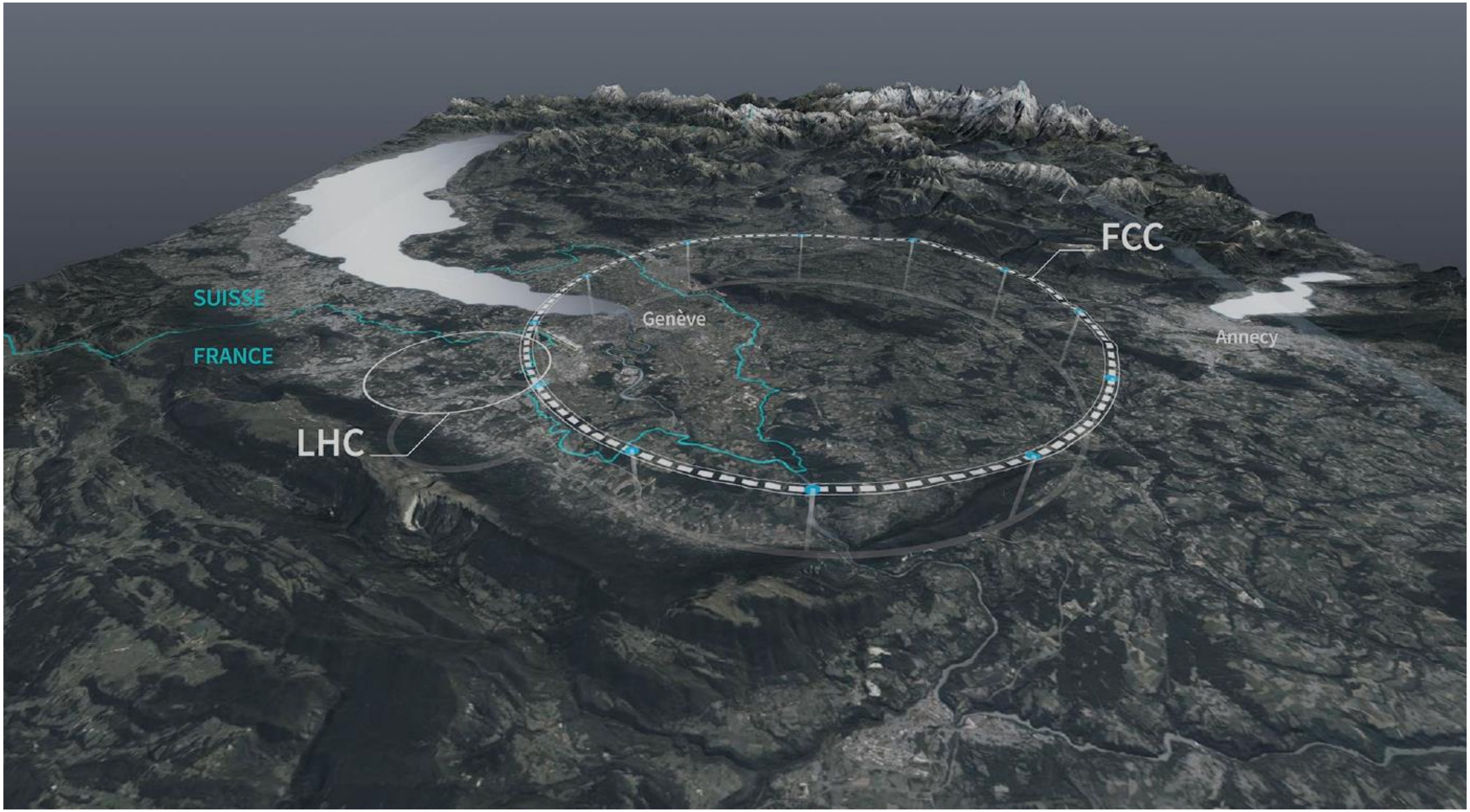


[PRD 101 (2020) 112002]

But will need to be done much better in future, hence role of STCF will be crucial.

Go Big or Go Home – flavour at the FCC

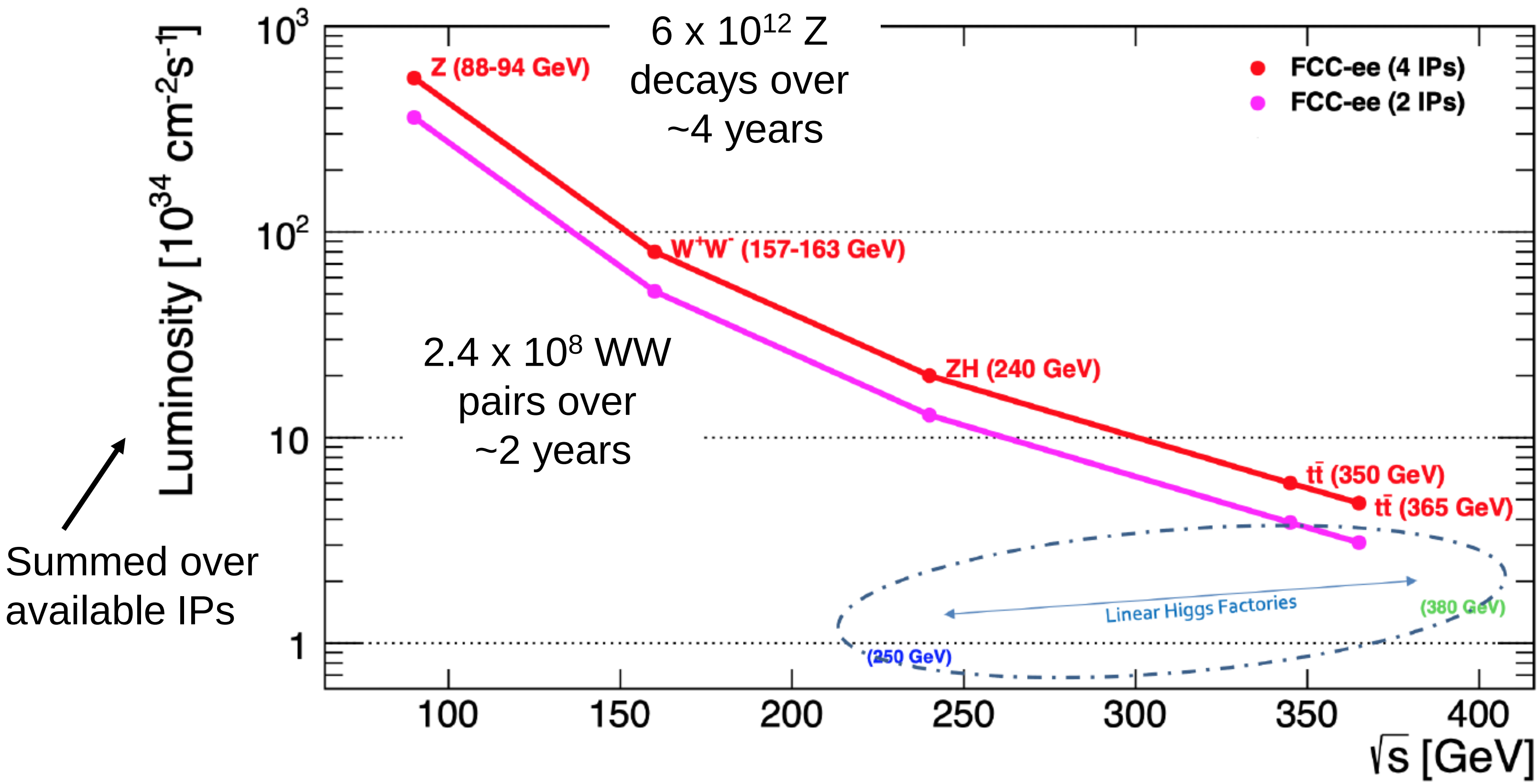
The Future Circular Collider (FCC)



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 and WW threshold offer remarkable prospects for precision EW studies and also for explorations in heavy flavour.

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	✓		(✓)

In crude terms, the event yields will be one order of magnitude higher than those hoped for at Belle II with 50 ab^{-1} (trigger prevents no general comparison with LHCb).

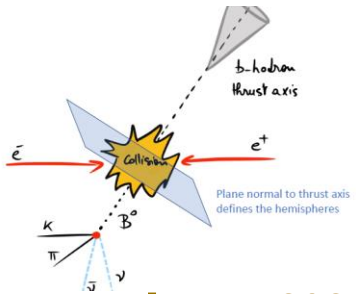
Particle species	B^0	B^+	B^0_s	Λ_b	B^+_c	$c\bar{c}$	$\tau^-\tau^+$
Yield ($\times 10^9$)	310	310	75	65	1.5	600	170

If the detectors have the right characteristics, then great physics can be done over all areas.   But in which measurements can FCC-ee be *truly* transformative ?

(Some) transformative measurements in flavour at FCC-ee

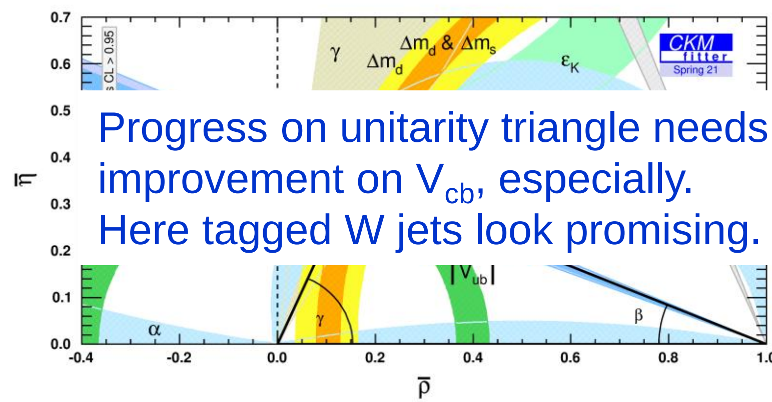
Leptonic and semi-leptonic decays

$B \to K^* \nu\nu$, $B_s \to \phi \nu\nu$ [JHEP 01 (2024) 144]



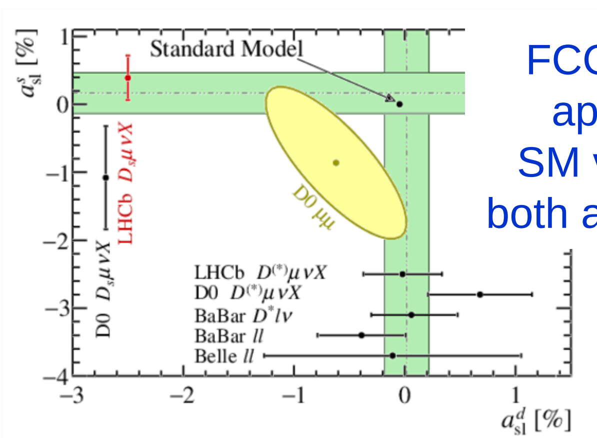
also $B_c \to \tau\nu$ [JHEP 2021 133]

Measurements of CKM elements



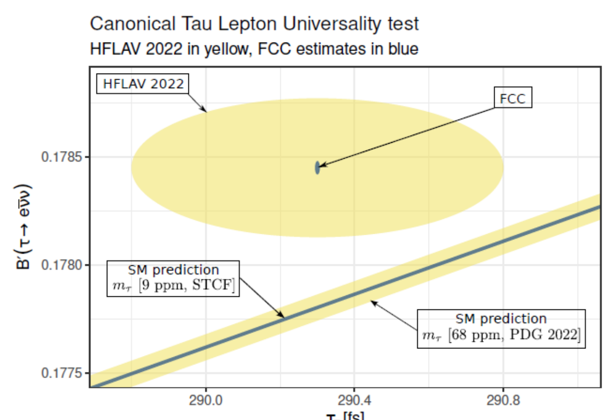
Progress on unitarity triangle needs improvement on V_{cb}, especially. Here tagged W jets look promising.

CPV mixing asymmetries



FCC-ee can approach SM values of both a^s_{sl} and a^d_{sl}.

Tau physics

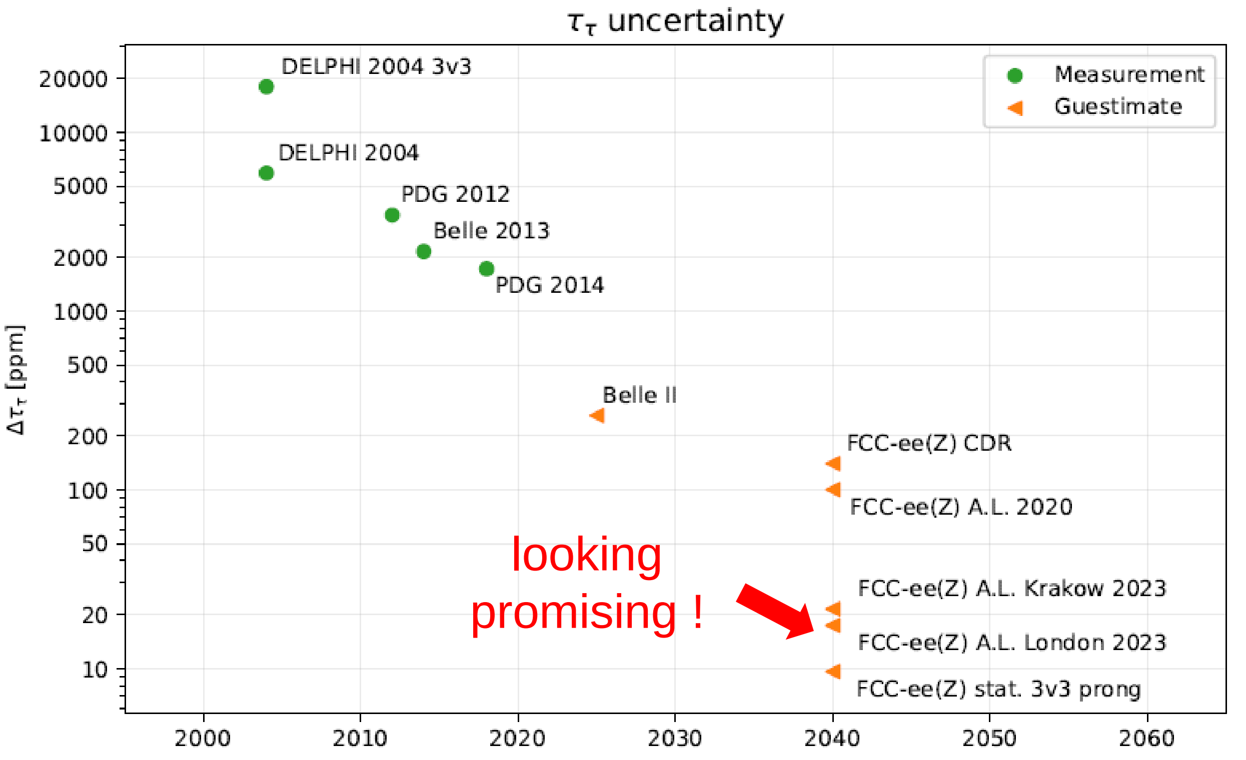


and flavour-violating decays

[Luisiani]

FCC-ee: the systematic challenge

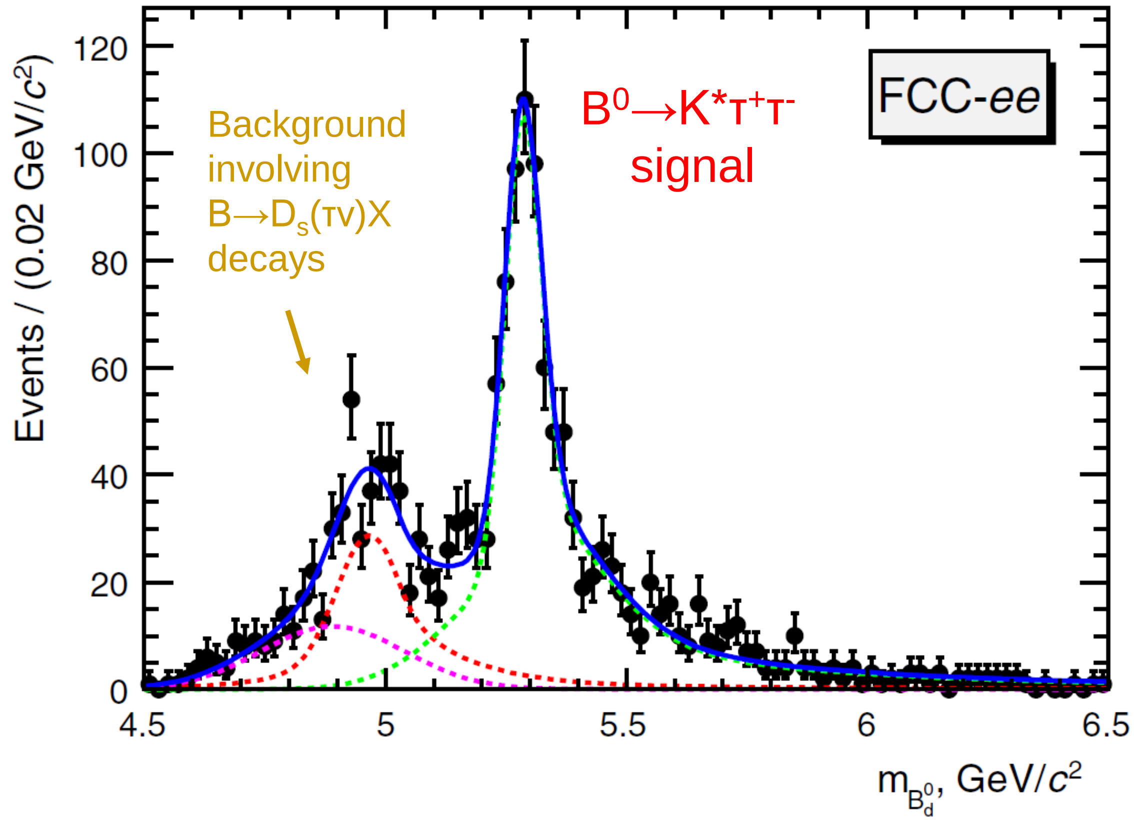
Enormous event yields will demand corresponding systematic control, and much thought is already being given to this, e.g. tau lifetime.



[Alberto Lusiani, FCC Week 2023]

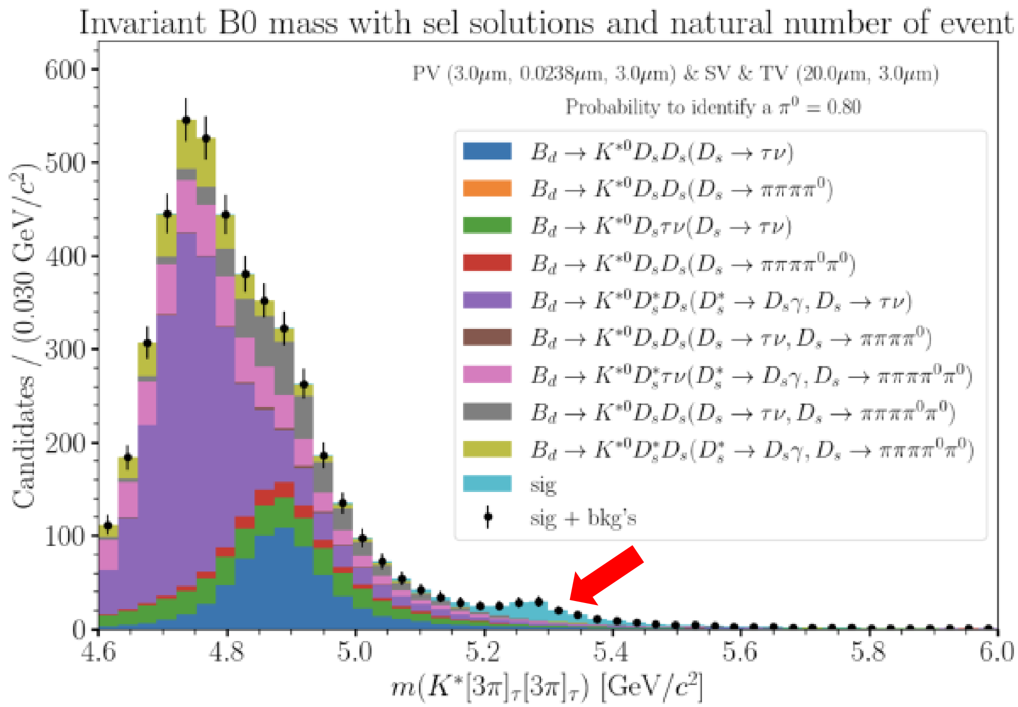
Taking a closer look sometimes makes clear how demanding some of these measurements are

This used to be the poster child of FCC-ee flavour physics



Taking a closer look sometimes makes clear how demanding some of these measurements are

Including more realistic backgrounds, and reconstruction, but taking a less idealistic performance for the vertex resolutions.

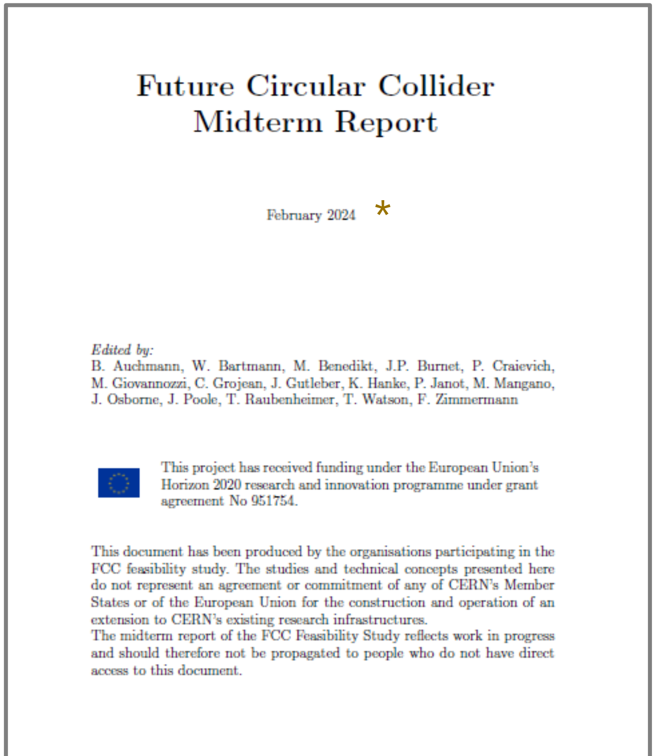


[Tristan Miralles, FCC Week 2023]

Tougher, but by no means impossible. And real data always brings smart ideas.

Five-year feasibility study
Four-and-a-bit

~700 page Midterm Report submitted late last year


Future Circular Collider
Midterm Report

February 2024 *

Edited by:
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This document has been produced by the organisations participating in the FCC feasibility study. The studies and technical concepts presented here do not represent an agreement or commitment of any of CERN's Member States or of the European Union for the construction and operation of an extension to CERN's existing research infrastructures.
The midterm report of the FCC Feasibility Study reflects work in progress and should therefore not be propagated to people who do not have direct access to this document.

Reviewed by a Scientific Advisory Committee & a Cost Review Panel. Feedback very positive.

"The SPC would like to congratulate the FCC Feasibility Study team for successfully producing its Midterm Report, which substantially satisfies the designated deliverables specified by Council in 2022."

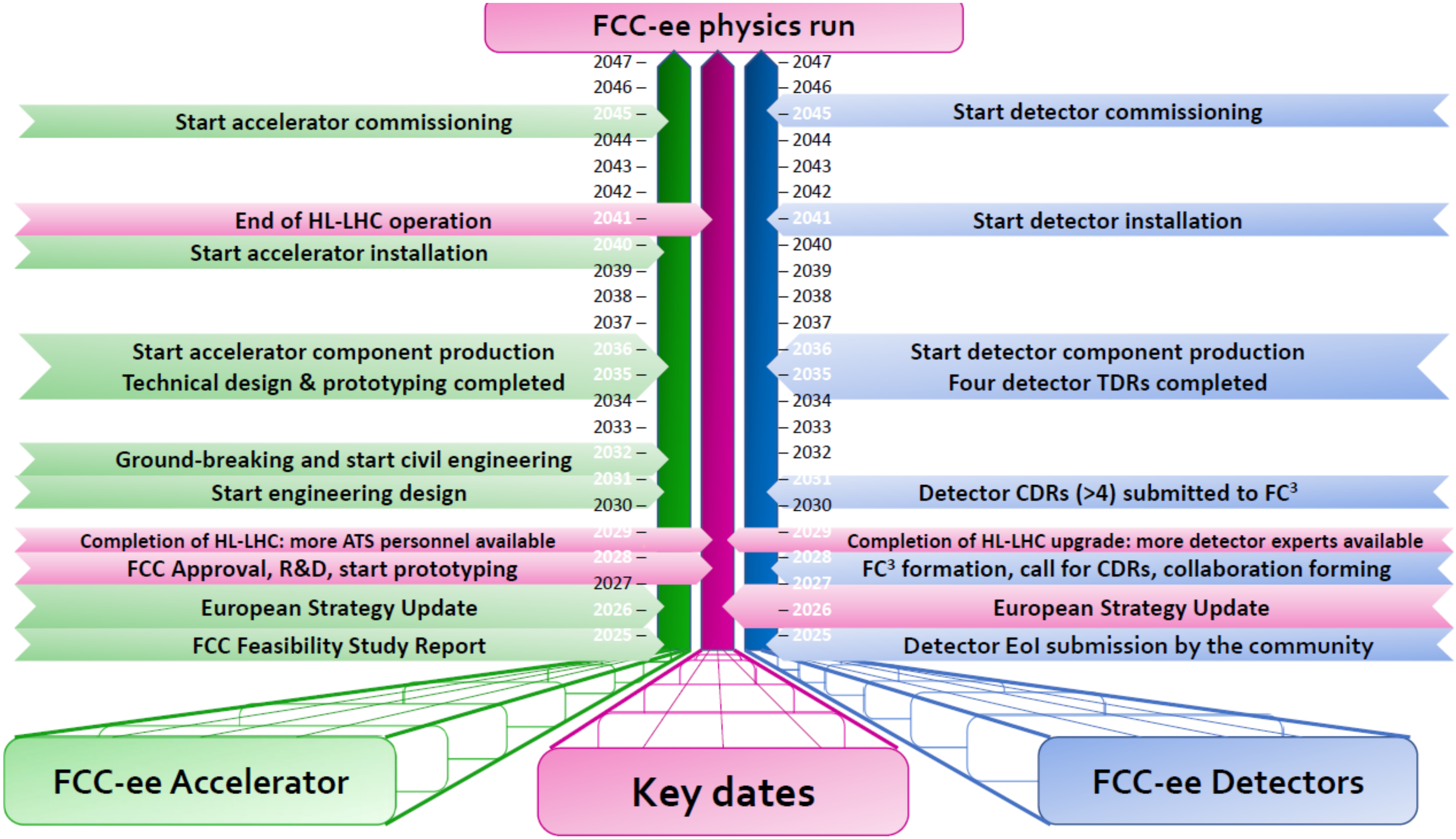
Hugh Montgomery, SPC Chair, Feb 2024

One immediate consequence: end-date of Feasibility Study brought forward, with Final Report now scheduled for early 2025.

* Date of version released to CERN Users

Countdown to physics

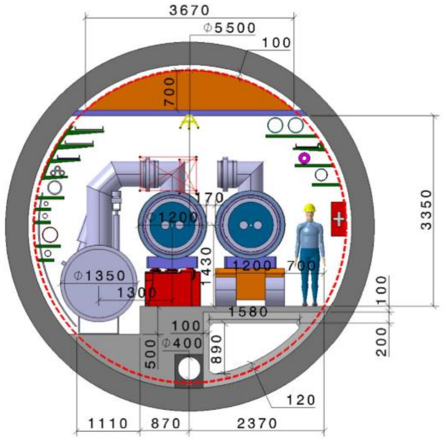
(options for [modest] acceleration of schedule currently under discussion)



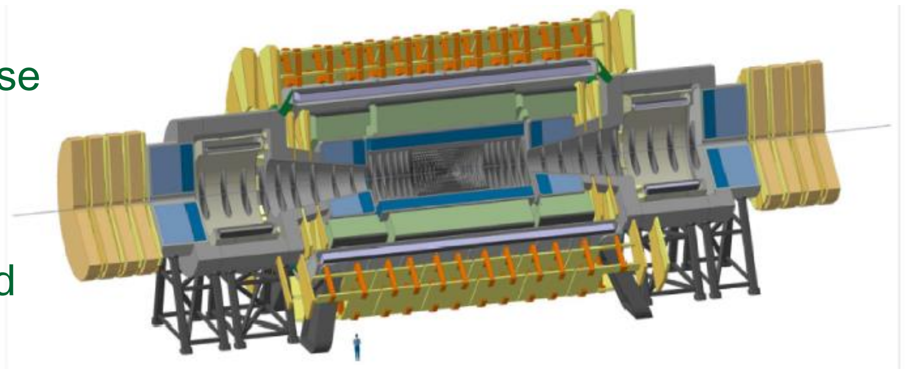
The further future (~2070): FCC-hh

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

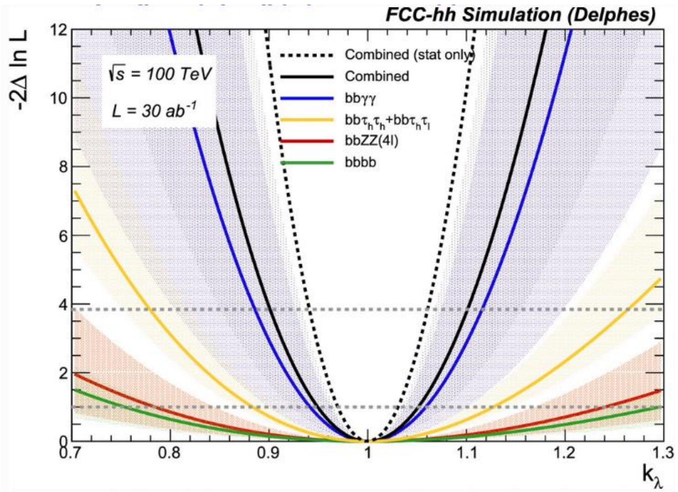


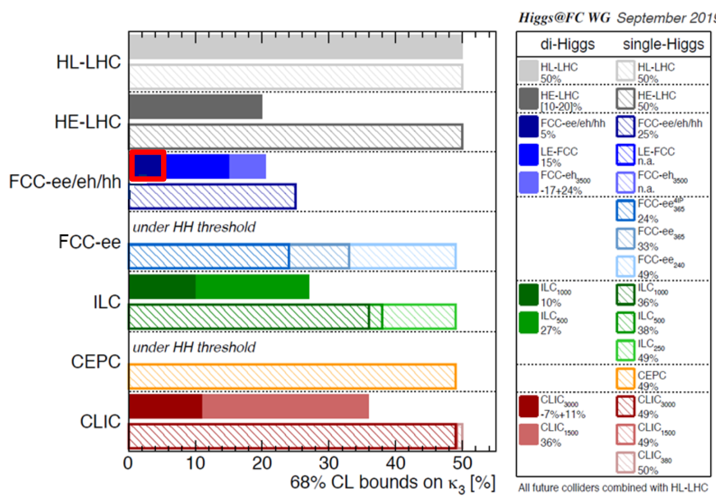
Extreme challenges include: need for 16 T dipole fields, very high radiation levels, pileup up to 1000, and huge data processing / storing requirements.

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%.

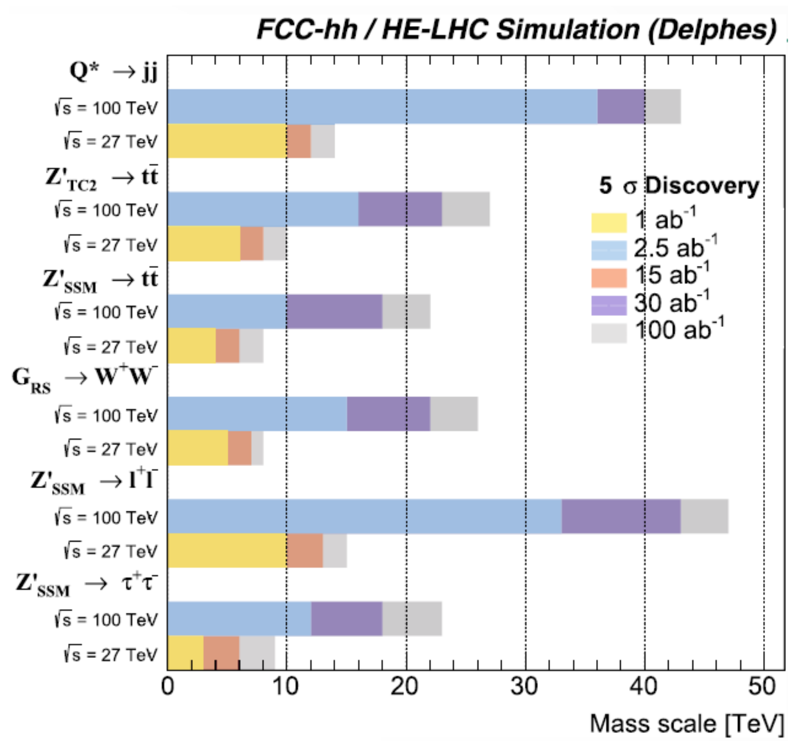
Eur. Phys. C 80 (2020) 1030





Remarkable direct-search potential

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



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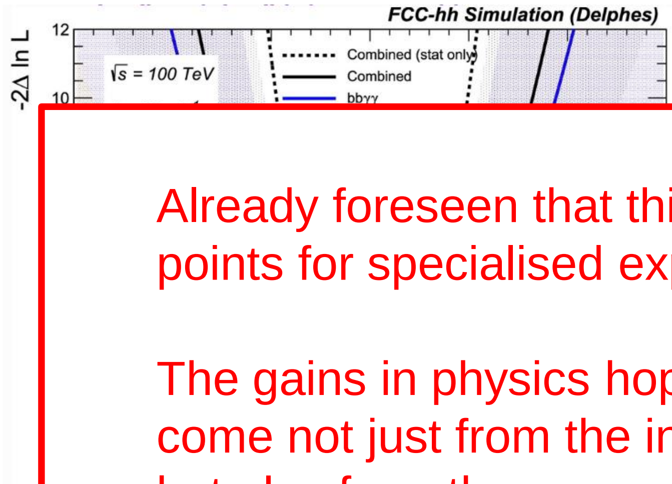
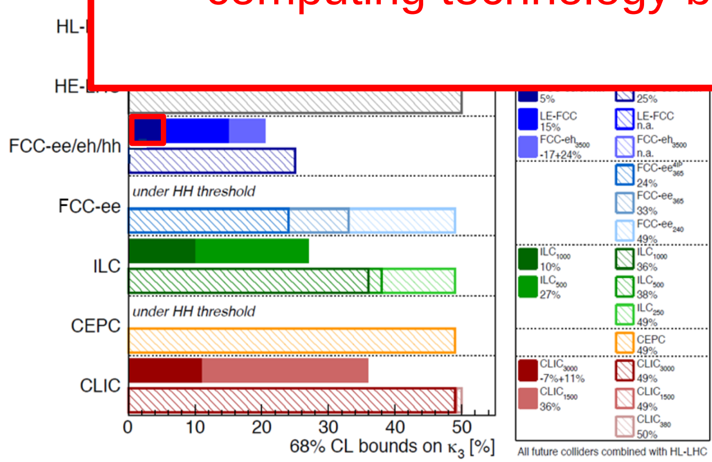
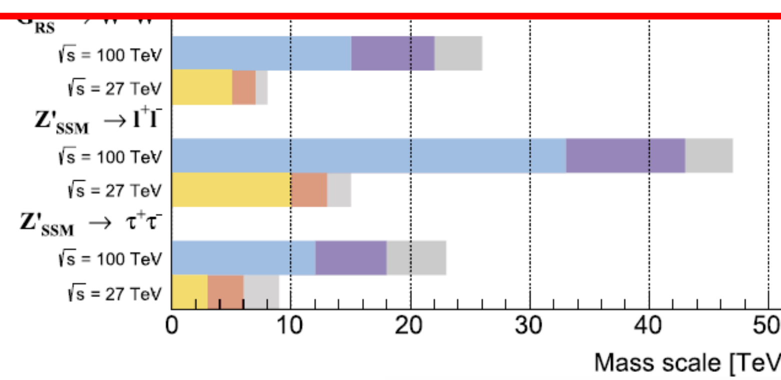


Remarkable direct-search potential

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

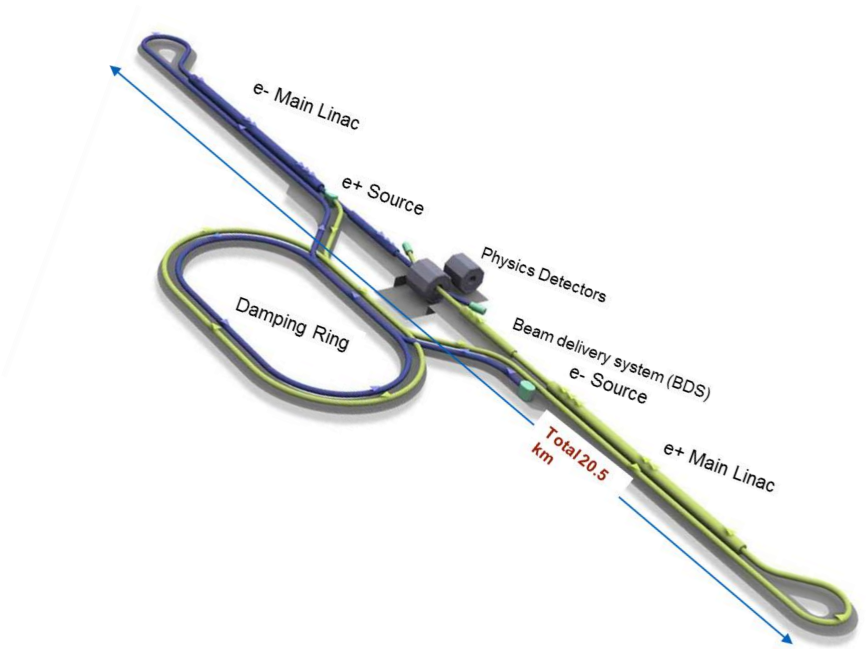
The gains in physics hoped for at such an experiment will come not just from the increase in cross section and luminosity, but also from the presumed strides forward in detector and computing technology between now and ~2070.





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.

Conclusions

In the first two decades of this century flavour physics has undergone a period of super-inflation, with enormous progress in our knowledge of the beauty and charm sectors, in particular.

Although this period has brought a wealth of intriguing results, it has not yet brought any clear sign of New Physics…

…nil desperandum ! The goals of flavour physics remain as important and well motivated as ever (big questions, sensitivity to high mass scales, important observables that are theoretically clean, or just need more statistics to access).

There are many exciting flavour physics projects ongoing, and proposed for the near, nearish and further future. This is surely something worth drinking to !

Backups

A closer look at charm: 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]
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 as Belle (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

A closer look at charm: projected yields in CPV benchmark modes

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	$D^0 \to K^+\pi^-$			D^0 … $^{+}$ $^{-}$ ^{0}		D^0 … $K^0\pi^+\pi^-$		
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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 ?)

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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.

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A closer look at charm: 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}
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High yields requires exquisite systematic control

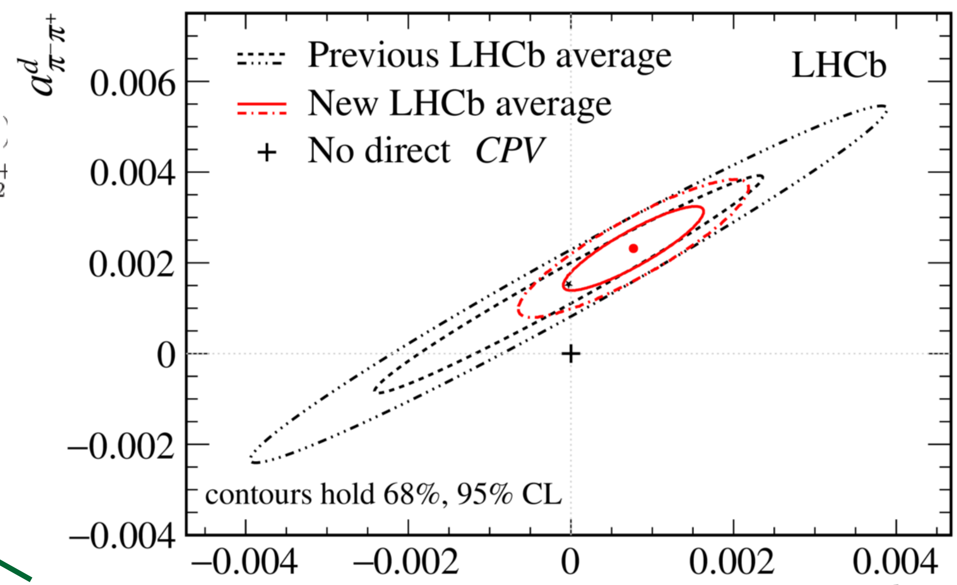
Can LHCb control its systematics to match the tiny statistical uncertainties ? So far, yes ! Key uncertainties are small by definition (ΔA_{CP}), or set by control channels.

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

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

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

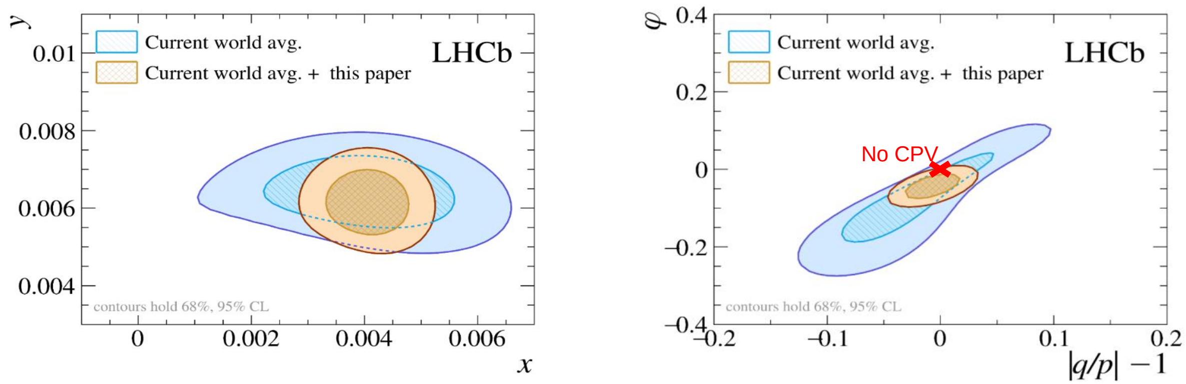
[arXiv:2209.03179]

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].

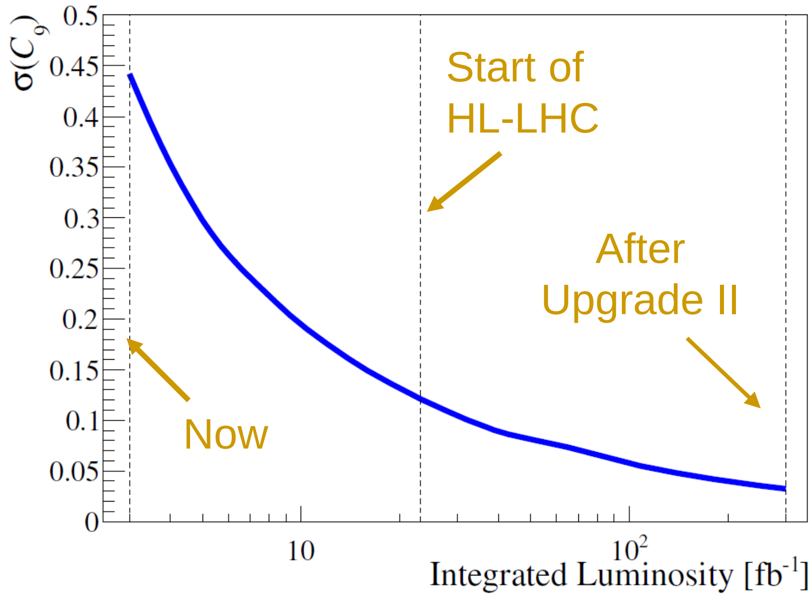


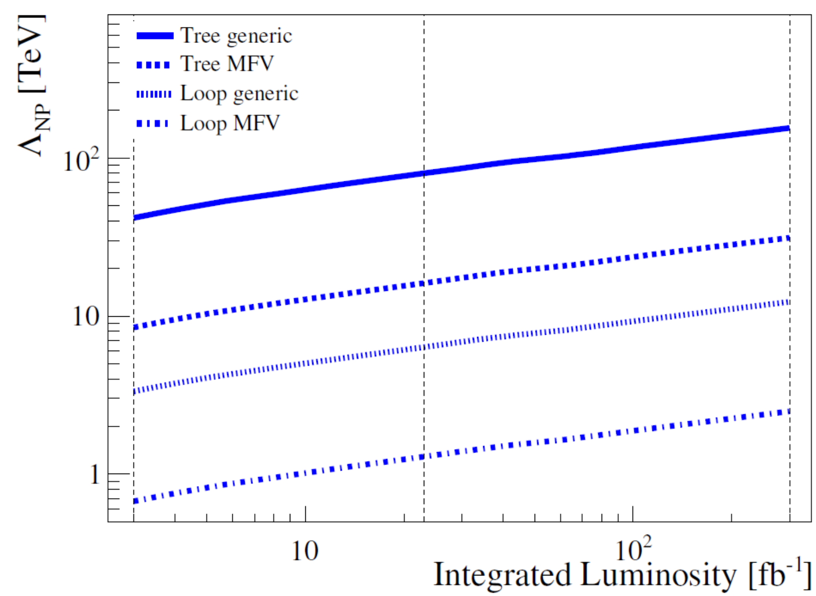
- Improve our sensitivity to charm FCNCs & search for effects of New Physics.

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

New Physics sensitivity through FCNCs

Improving sensitivity to the Wilson coefficient C_9 and the corresponding limits on New Physics mass scales, under different assumptions, from R_K and R_{K^*} .





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

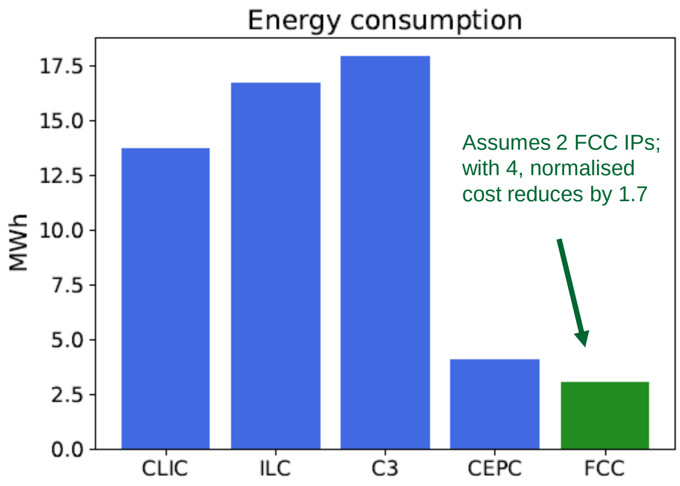
This corresponds to 1.6 TWh/year, to be compared to 1.4 TWh/year for HL-LHC.

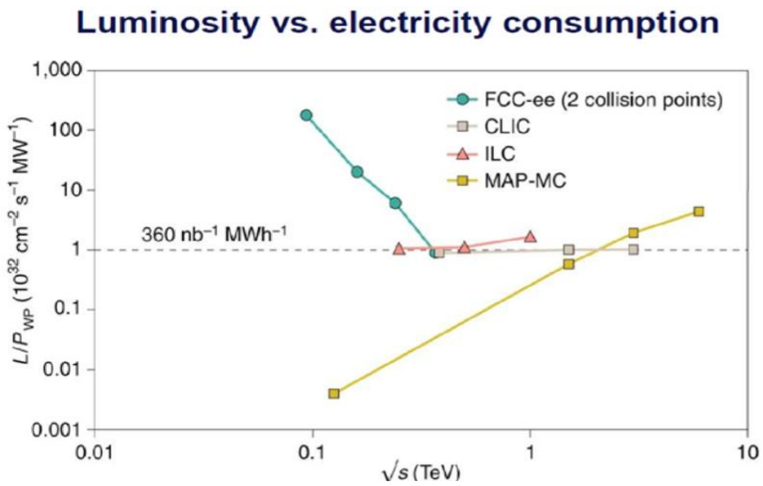
As a comparison, P(ILC$_{240}$)=140 MW and P(CLIC$_{380}$)=110 MW. This is not full story ! Both produce 2-4 less Higgs than FCC-ee$_{240}$, with 3-6 times longer running time.

Power costs – a closer look

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

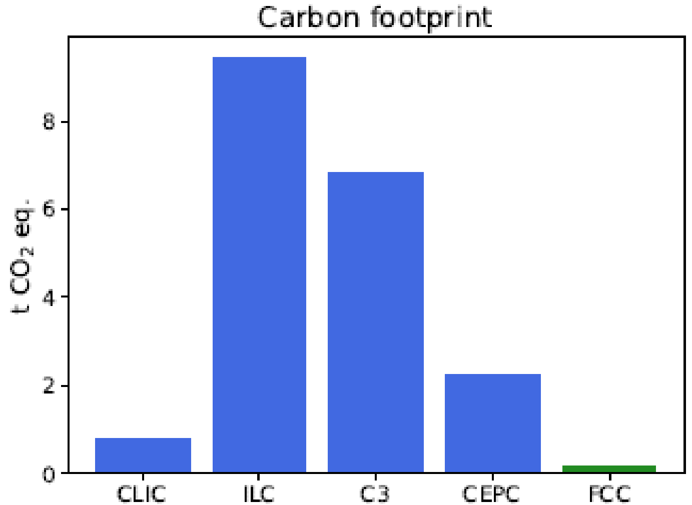
[arXiv:2208.10466]





[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…