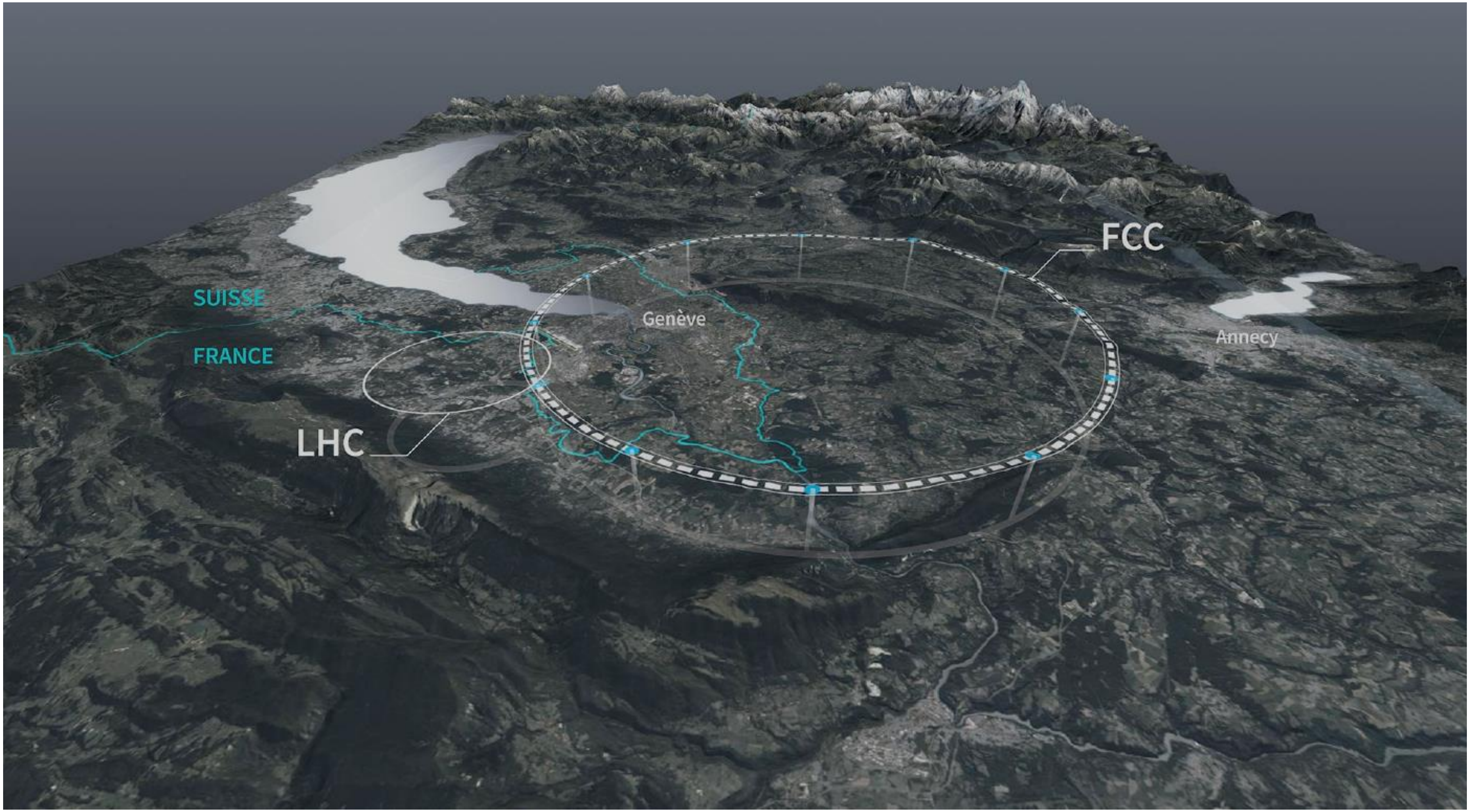
Flavour physics at the FCC



HQL 2025, Peking University
19/9/25

Guy Wilkinson
University of Oxford and CERN

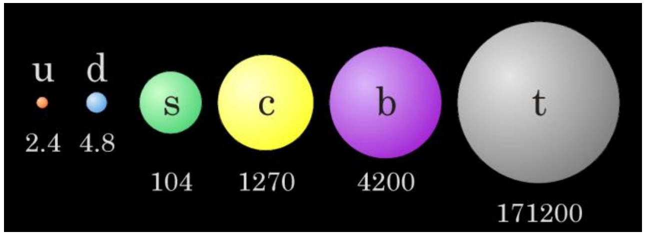
Outline

- Importance of flavour
- Flavour physics now, and in the coming two decades
- FCC – the essentials
- FCC-ee as a flavour factory
- Examples of key flavour measurements at FCC-ee
- Detector requirements
- Flavour physics at FCC-hh
- Conclusions
- Workshop announcement

Why flavour ?

Flavour encompasses many of the open questions of the Standard Model.

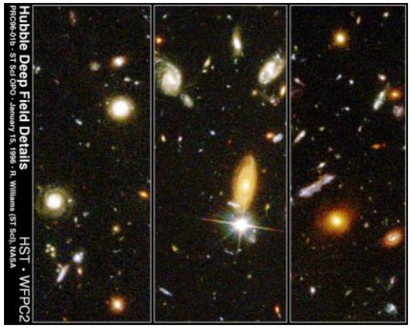
- Why 3 generations of quarks, and why the extreme hierarchy of masses ?



- What determines the hierarchical structure of the CKM matrix ?

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

- The CKM paradigm accommodates CP violation, but it does not really explain it. Furthermore, can the study of quark flavour tell us anything about the matter-antimatter asymmetry ?

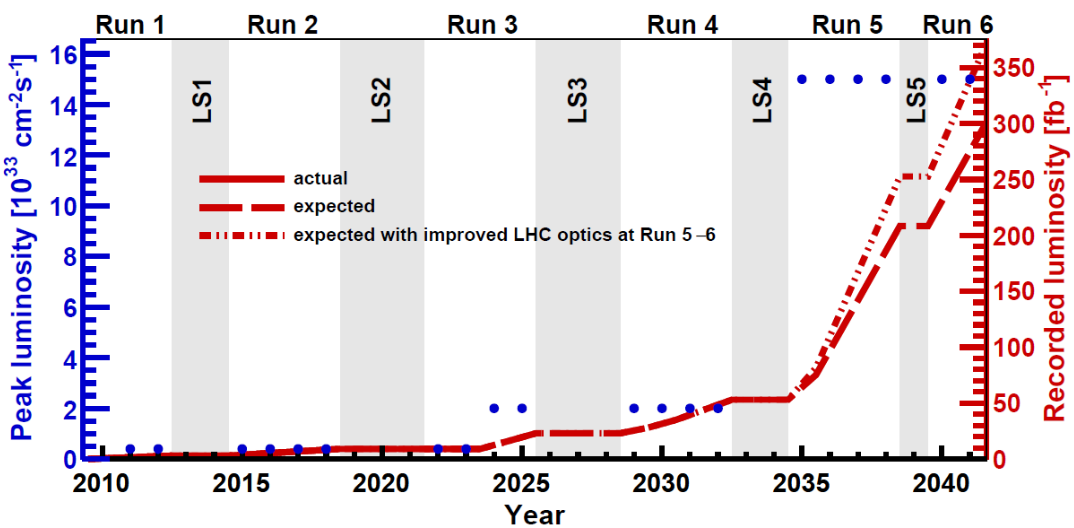


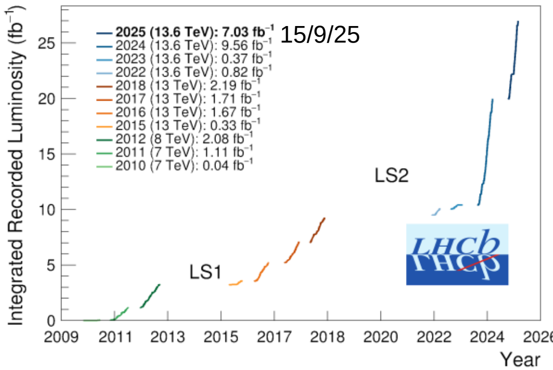
Furthermore, flavour measurements are a tool of discovery in their own right. Studies of loop-dominated rare transitions probe mass scales *far* above what are accessible in direct searches !

LHCb: status and prospects

Past performance, current operation, and future goals.

Phase	Runs	Int. lumi	Peak lumi	Comment
LHCb	1-2	9 fb^{-1}	4 x 10^{32} $cm^{-2}s^{-1}$	
LHCb UI	3-4	>50 fb^{-1}	2 x 10^{33} $cm^{-2}s^{-1}$	Full software trigger
LHCb UII	5-6	>300 fb^{-1}	1-1.5 x10^{34} $cm^{-2}s^{-1}$	Full software trigger

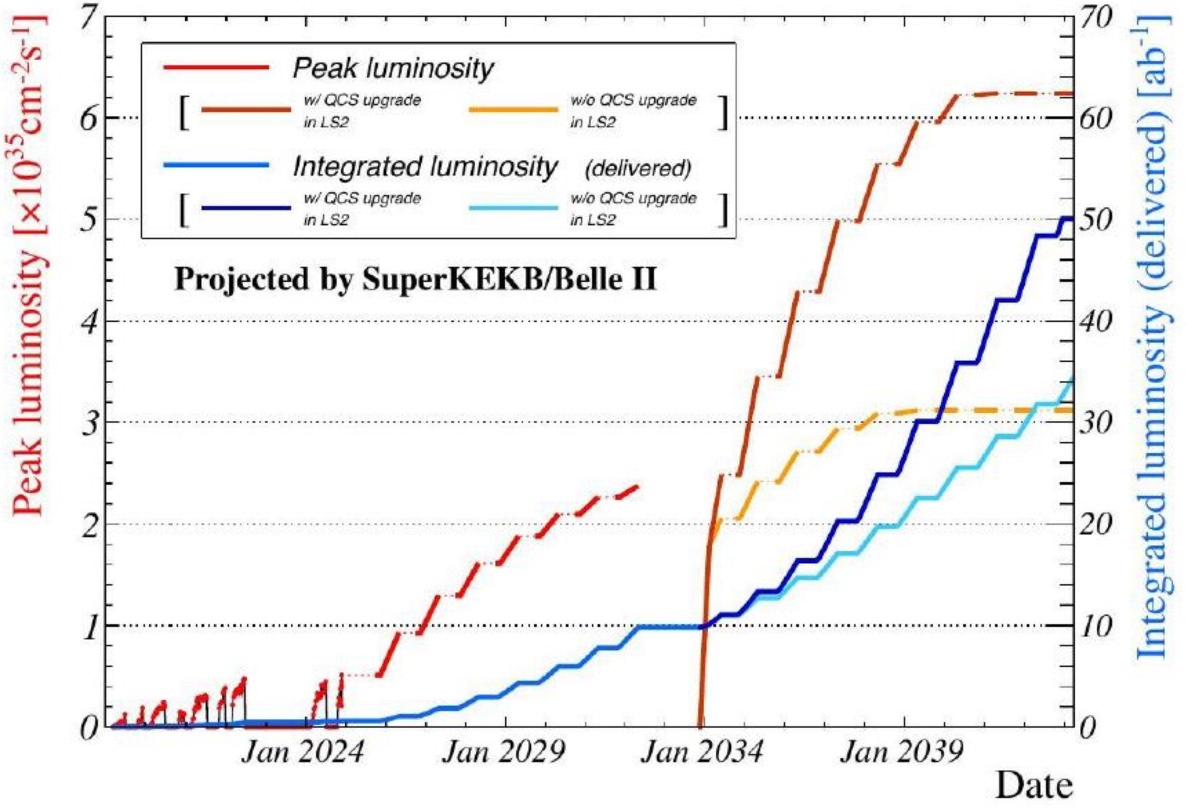




Run 3 proceeding very well (after slowish start).

Everything known by 2040s ? No !! Many important measurements still statistics limited, and some impossible because of challenges of hadronic environment.

Belle II and SuperKEKb



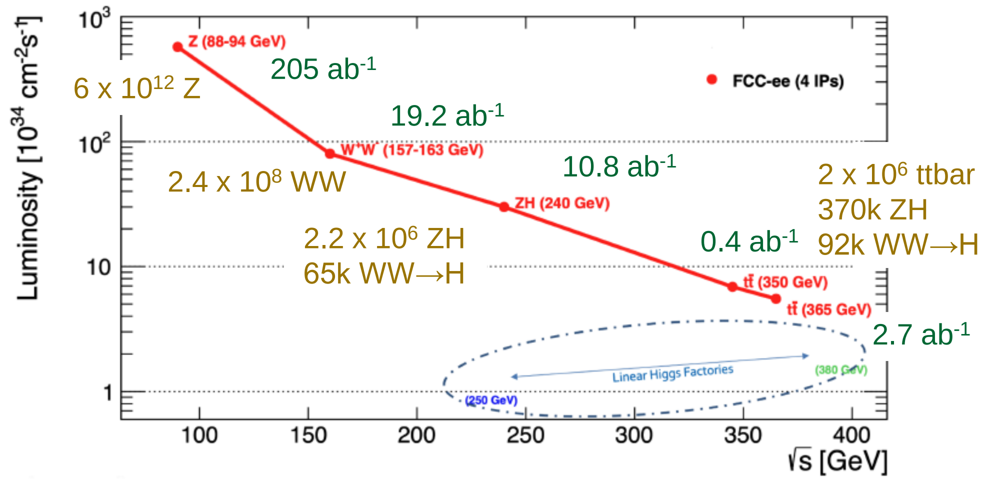
[K. Trabelsi, EPS Marseille, July 2025]

Sorld record lumi of 5.1 x 10^{34} $cm^{-s}s^{-1}$, with integrated luminosity of ~500 fb^{-1} at Y(4S). Goal is to accumulate 10 ab^{-1}, and then push onwards to 50 ab^{-1}. Many world-leading results already produced, exploiting unique environment.

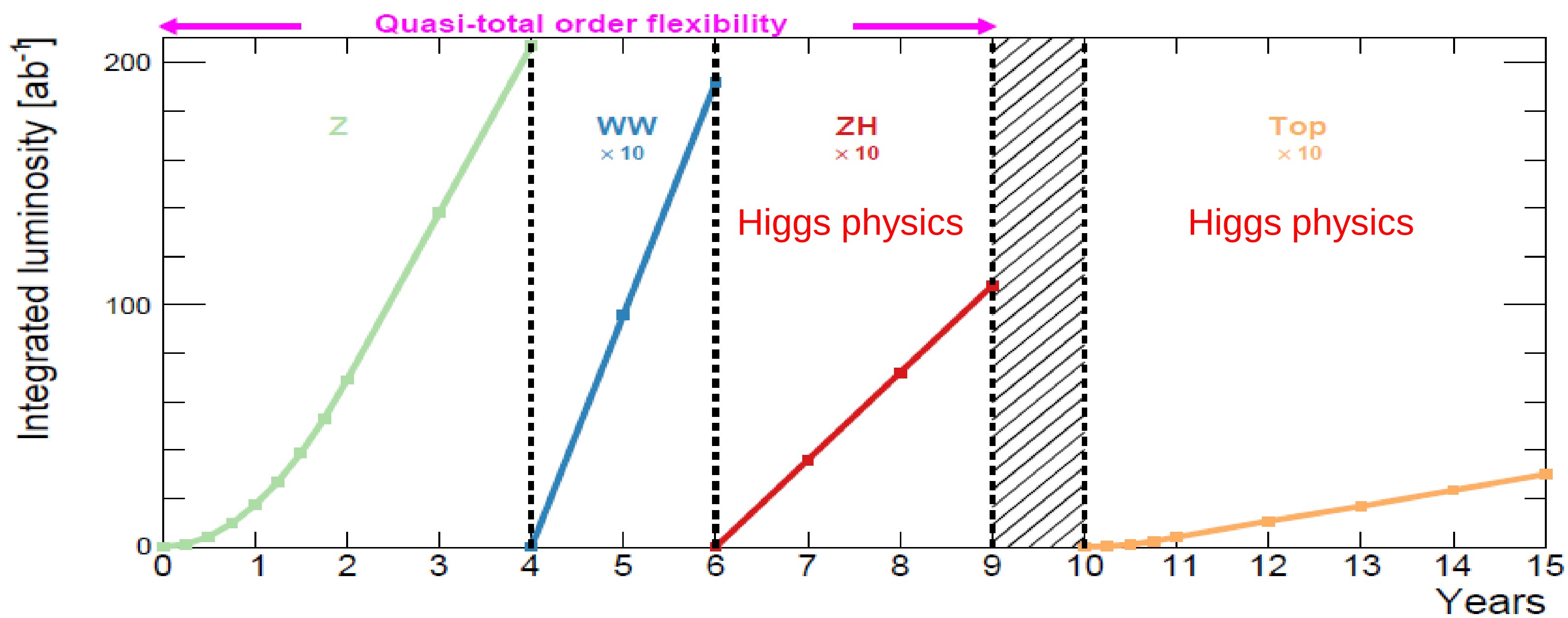
FCC-ee essentials and enabling characteristics

FCC-ee enabling characteristics:

- Huge samples → extreme precision;
- Four (+) energy points, explored in a compact 15-year programme;
- With exciting options for extension (*e.g.* Higgs-pole run).



Physics goals encompass Higgs studies:



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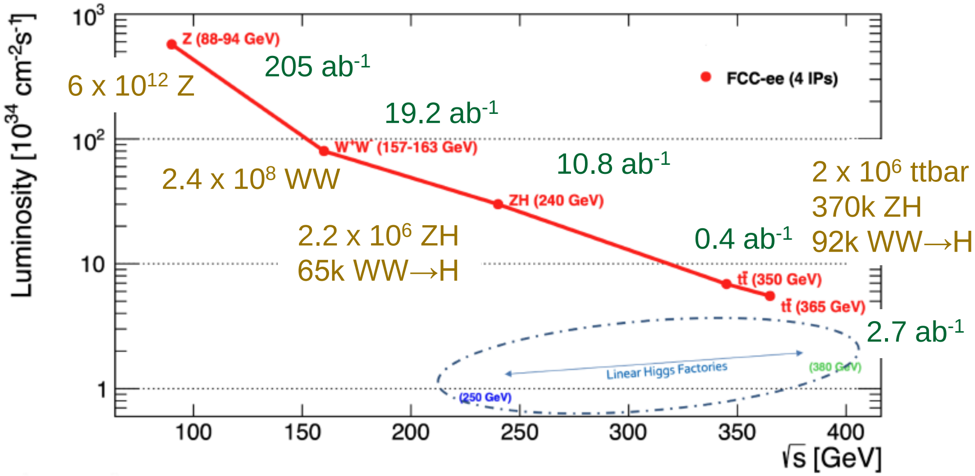
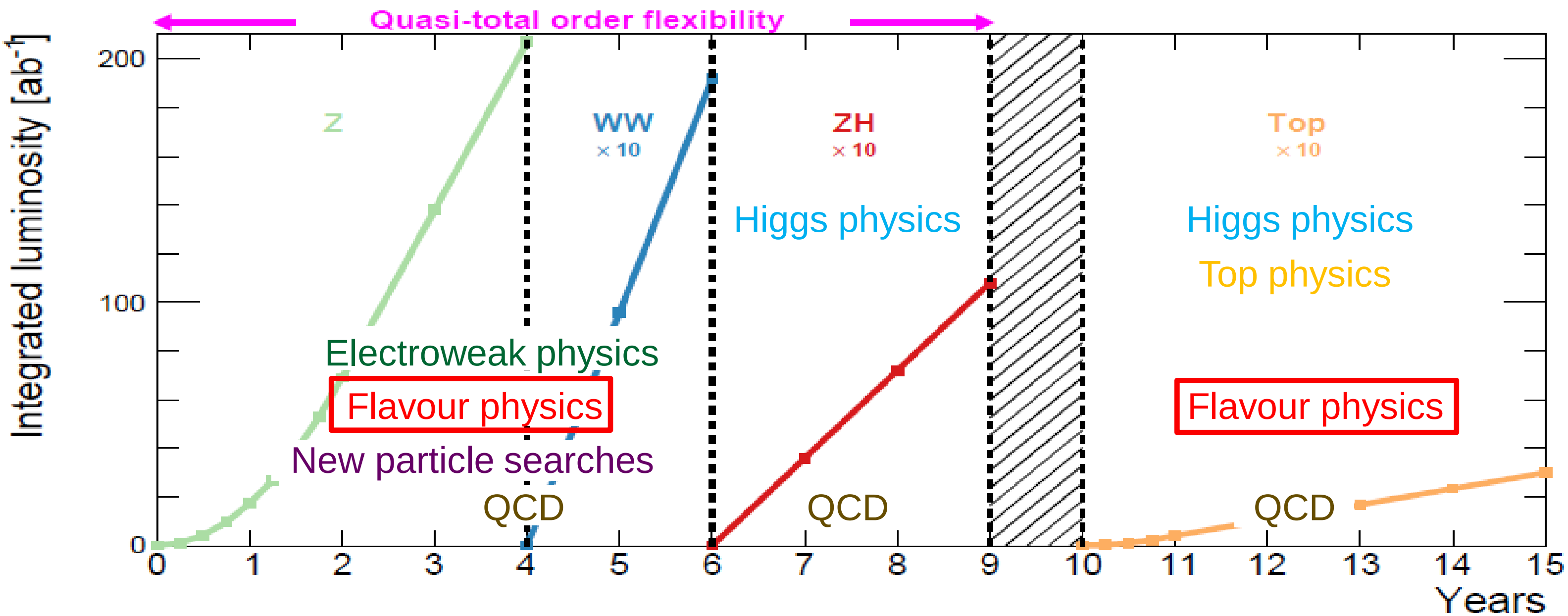
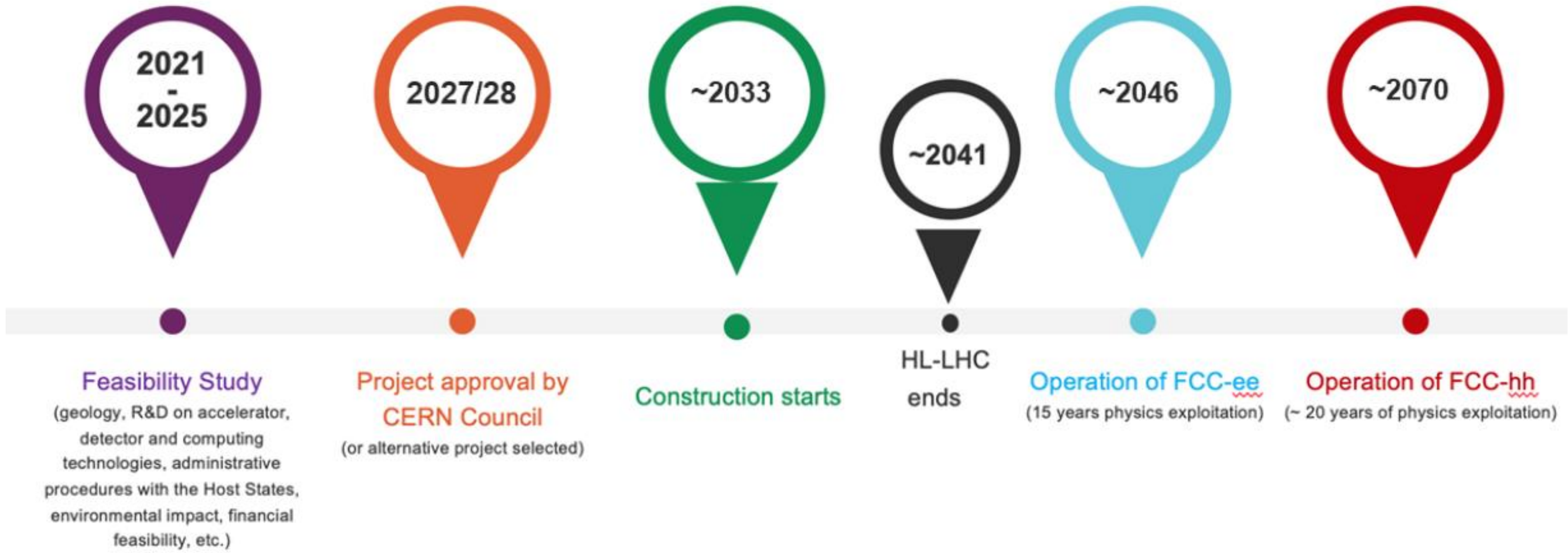


Physics goals encompass Higgs studies, and *much* more, incld. flavour :



FCC timeline



Overall FCC-ee schedule

- 04/2025 – 06/2027 pre-TDR entire project
- 01/2026 – 12/2030 environmental evaluation and project authorisation
- **01/2028 assumed project approval by CERN Council**
- 01/2028 – 06/2032 CE design and tendering
- 01/2032 TDR for collider and technical infrastructure
- **01/2033 – 06/2041 CE construction work**
- 07/2039 – 12/2043 technical infrastructure installation
- **07/2041 – 06/2045 accelerator installation**
- 06/2046 HW commissioning completed
- **07/2046 start of beam commissioning and operation**
- **01/2048 nominal beam operation**

Injector Project schedule

- 12/2028 TDR injector project
- 01/2028 – 12/2030 CE design and tendering
- 01/2029 – 12/2031 Accelerator and technical infrastructure engineering designs
- **01/2031 – 12/2034 Civil construction work**
- 01/2032 – 12/2040 Component production (rates for RF structures as for SwissFEL)
- 01/2034 – 12/2036 Technical infrastructure installation
- **01/2035 – 12/2040 Component installation and testing**
- **01/2041 HW commissioning**
- **01/2042 Beam commissioning**

FCC physics – source materials

Intense physics, experiment and detector studies have been conducted since launch of Feasibility Study (FS) in 2021, summarised in Volume 1 of FS Report (FSR).

Future Circular Collider
Feasibility Study Report

Volume 1

Physics, Experiments, Detectors

April 1, 2025

Submitted to the European Physics Journal ST, a joint publication of EDP Sciences, Springer Science+Business Media, and the Società Italiana di Fisica.

[CDS, arXiv:2505.00272, submitted to EPJC]

In addition, focused 10-page documents have been prepared for the ESPPU:

The FCC integrated programme: a physics manifesto	[CDS, ESPPU #241, arXiv:2504.02634]
Prospects in EW, Higgs and top physics at FCC	[CDS, ESPPU #217]
Prospects in BSM physics at FCC	[CDS, ESPPU #242]
FCC: QCD physics	[CDS, ESPPU #209]
Prospects for flavour physics at FCC	[CDS, ESPPU #196]
Prospects for physics at FCC-hh	[CDS, ESPPU #227]
Expressions of interest for the development of detector concepts and sub-detector systems for the FCC	[CDS, ESPPU #95]

FCC-ee as a flavour factory

High branching fraction of Z^0 into bbbar & ccbar, together with 6 x 10^{12} of Z^0s foreseen at FCC-ee, will provide very large sample for flavour studies.

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

Putting `very large' in context:

- For B^0 and B^+, >10x more than Belle II (if Belle II reaches 50 ab^{-1}) plus heavier b-hadrons;
- Compared to LHCb, the production rate is lower, but no trigger loss, high acceptance + flavour-tagging power and low backgrounds.

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

Let's look at a few key measurements, where FCC-ee will be game-changing.

Note that `TeraZ' is essential for these studies - `GigaZ' at ILC lacks the statistics.
Final remark is that the ~10^8 W^+W^- events of FCC-ee bring their own possibilities…

[(1)] Calculated under the assumptions given in EPC+ 136 (2021) 837 .
Assumes 5 x 10^{12} Z decays, while Midterm Report assumes 6 x 10^{12}.

FCNCs with neutrinos

$b \to s l^+ l^-$ transitions have been topic of intensive study at all b-physics experiments.

- Many observables, and high sensitivity to New Physics contributions;
- Several interesting anomalies - 'R_K, R_{K^*} saga' at LHCb has ended, but there remain tantalising tensions with SM in BFs and certain angular observables;
- Interest further raised by first results in $b \to s\nu\bar{\nu}$ transitions, from Belle II

PHYSICAL REVIEW D **109**, 112006 (2024)

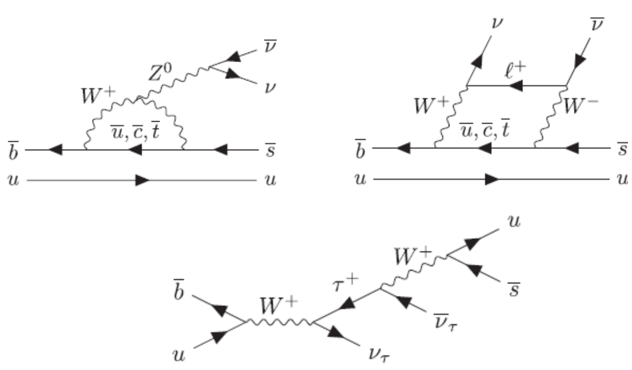
Editors' Suggestion

Evidence for $B^+ \to K^+ \nu\bar{\nu}$ decays

BF($B^+ \to K^+ \nu\bar{\nu}$) = $[2.3 \pm 0.5(\text{stat})^{+0.5}_{-0.4}(\text{syst})] \times 10^{-5}$ 2.7σ above SM

Theoretically, much cleaner than charged-lepton case (no charm loops).

Also sensitive to 3rd generation through ν_τ contributions.



FCNCs with neutrinos

Decays of interest:
(generally BFs of ~10^{-6})

$B^0 \to K^0_S \nu\bar{\nu}$ $B^0_s \to \phi\nu\bar{\nu}$ $B^+ \to K^+\nu\bar{\nu}$ $B^0 \to K^{*+}\upsilon\bar{\upsilon}$

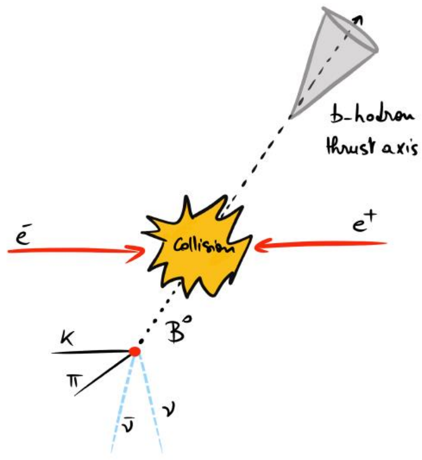
$B^0 \to K^{*0}\nu\bar{\nu}$ $\Lambda^0_b \to \Lambda\nu\bar{\nu}$ $B^+_c \to D^+_s\nu\bar{\nu}$

B^0 and B^+ modes can be probed at Belle II, modulo statistics. Inaccessible at LHCb.
All feasible at FCC-ee, with $B^0 \to K^{*0}\nu\bar{\nu}$ and $B^0_s \to \phi\nu\bar{\nu}$ the most straightforward.

Studies of physics reach in these modes reported in [Amhis *et al.*, JHEP 01 (2024) 144].

Thrust axis allows events to be separated into two hemispheres (separated b jets an important benefit at FCC-ee, which helps with combinatorics).

BDT making use of vertex information, reconstructed energy in each hemisphere *etc.* gives excellent signal to background discrimination.

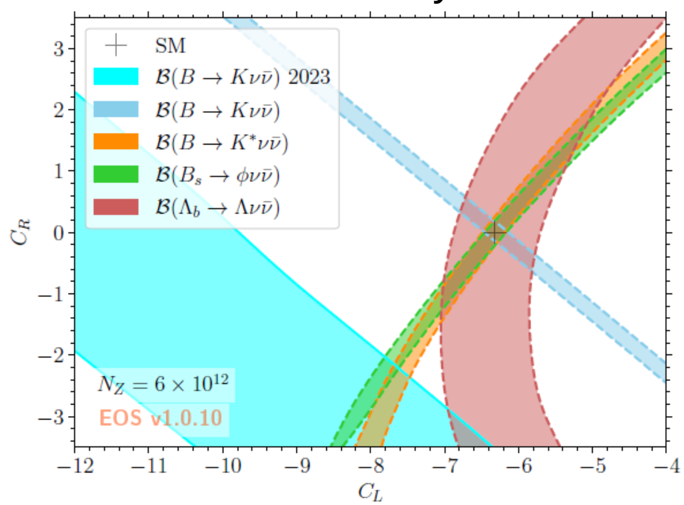


FCNCs with neutrinos

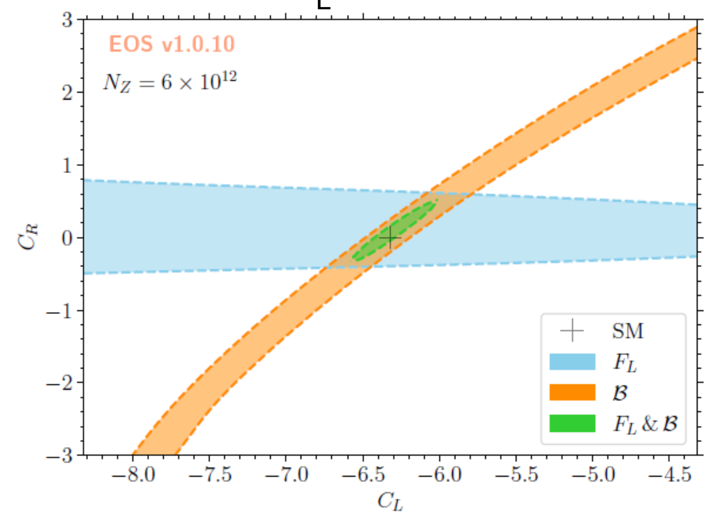
Studies in [JHEP 01 (2024) 144] indicate BF can be measured with a statistical uncertainty of 0.5% for $B^0 \to K^{*0}\nu\overline{\nu}$ and 1.2% for $B_s^0 \to \phi\nu\overline{\nu}$. Limiting systematic will come from knowledge of b-fragmentation and be of similar size.

BF measurements allow for CKM info ($|V_{tb}V_{ts}^*|$) to be extracted, assuming form factors well known enough (realistic expectation for ~2045), or to probe for NP

BFs alone – many modes



BF and F_L - $B^0 \to K^{*0}\nu\overline{\nu}$



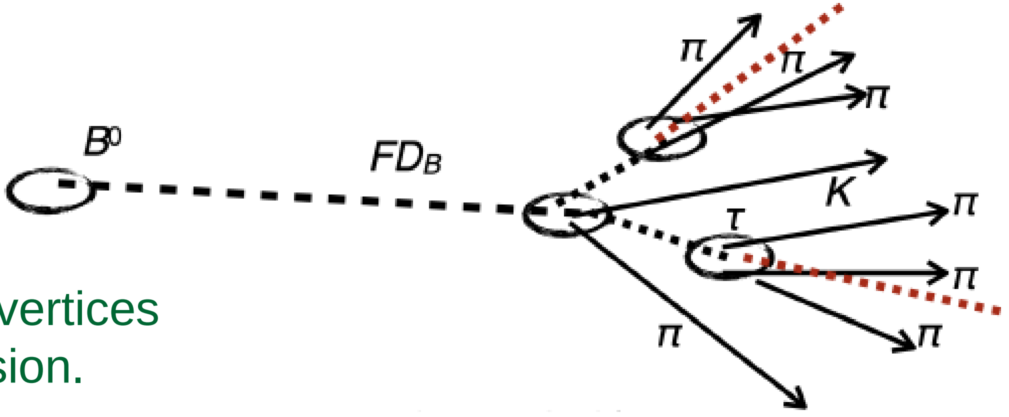
Measurements of longitudinal polarisation of vector meson and full differential analysis, will also be feasible with very interesting precision – rich prospects !

B decays with taus

Many interesting NP models predict deviations in transitions involving third generation leptons (and recall the long-standing R_D, R_{D^*} anomalies, where there are hints that semi-tauonic tau decays violate lepton universality).

$B^{+(0)} \rightarrow K^{+(*)}\tau^+\tau^-$ is the golden FCNC decay with taus, but very rare in SM (~10^{-7}), well below current limits (10^{-3}-10^{-4}). Inaccessible at Belle II or LHCb.

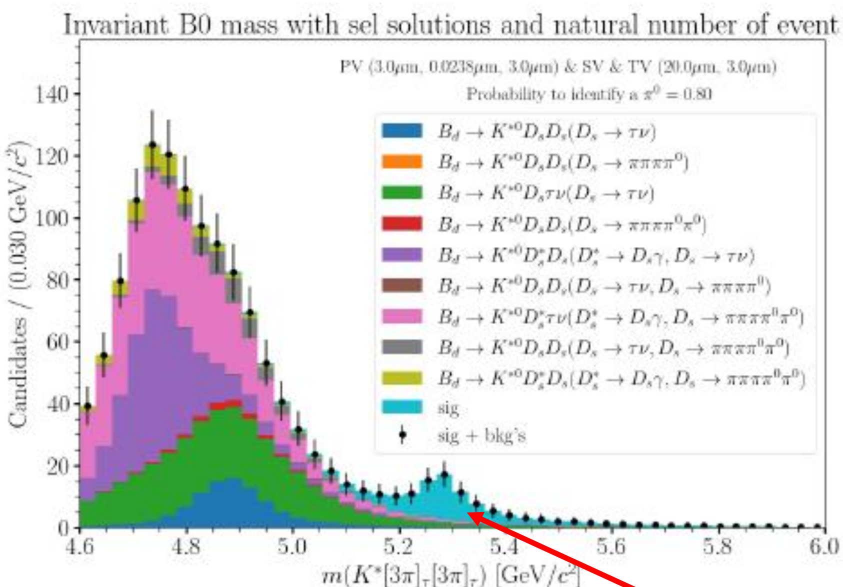
To reconstruct fully the kinematics of the decay, in order to achieve the best background suppression, it is necessary to reconstruct all the decay vertices with the best possible precision.

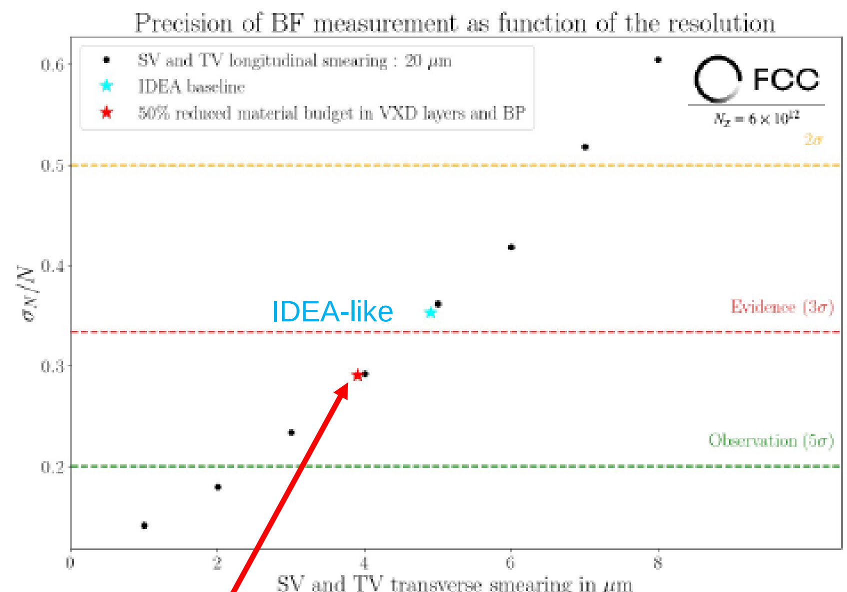


Long considered a target mode for FCC-ee…

B decays with taus

It will be difficult, but it seems that we can approach the SM BF (and very likely be sensitive to any significant enhancements) – a remarkable prospect !





[T. Miralles, Annecy, 30/1/24]

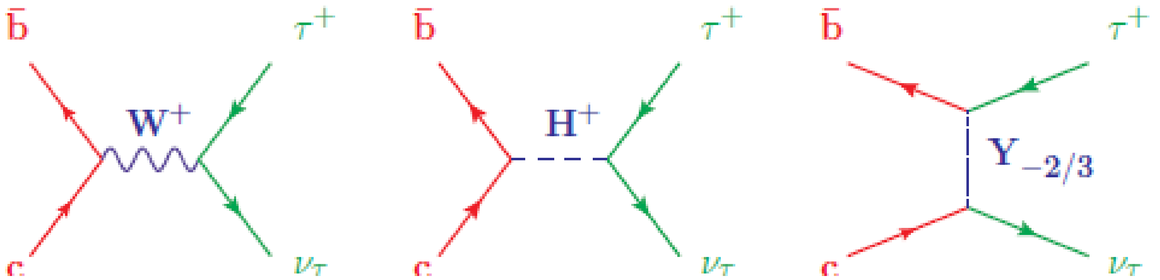
Signal, when reconstructed with very good resolution

However, reaching this level requires the best possible secondary-vertex resolution (~few μm). A detector-performance driver, even beyond initial concepts (*e.g.* IDEA).

Also, a good example of why it is necessary to collect so many Z decays !

B decays with taus

Another nice example, manifestly impossible at Belle II and LHCb, is observation and BF measurement of $B_c^+ \to \tau^+ \nu_\tau$, which is sensitive to *e.g.* 2HDM models and certain leptoquark models (relevant for the R_D, R_{D^*} anomalies).



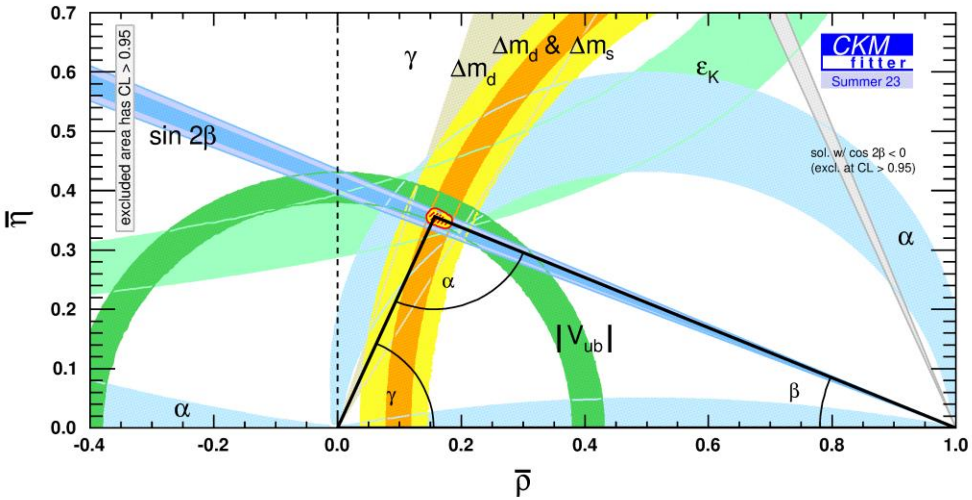
Not particularly rare decay (~10^{-2}), but B_c production is low, and backgrounds high.

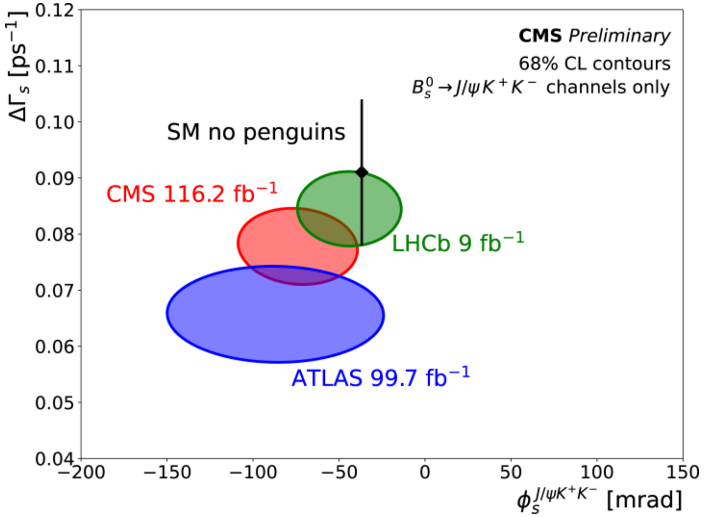
Studies performed in [Amhis *et al.*, JHEP 2021 (2021) 133] suggest multivariate selection making use of 3-prong decays, vertex and reconstructed energy info should be sufficient to beat down background, including from $B^+ \to \tau^+ \nu_\tau$ and reconstruct several 1000 decays at high purity. Unique to FCC-ee (or CEPC) !

Similar CEPC study exists using leptonic decays [Zheng *et al.*, CPC 45 (2021) 023001] .

CKM studies

A promising way to search for New Physics in CKM studies with b decays is to probe for non-SM contributions in B^0 or B^0_s mixing. Requires advances in knowledge of *e.g.* sin2β & φ_s, but also the other parameters of Unitarity Triangle (+ lattice QCD!).





There will be substantial progress over the coming ~15 years at LHC (and we hope Belle II), and from lattice, but there is an opportunity for FCC-ee to make big impact.

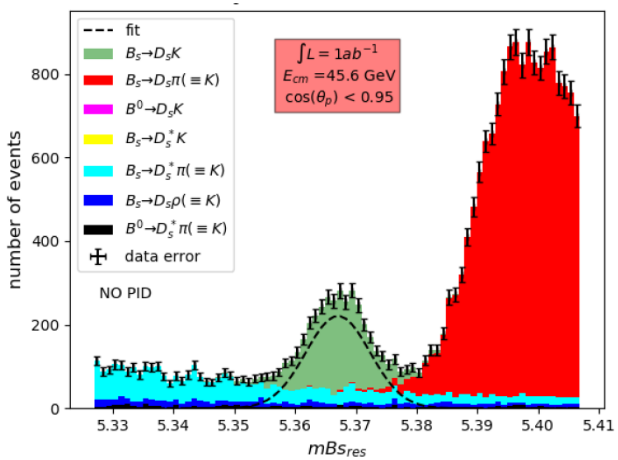
Particular strengths: flavour tagging, high multiplicity modes, modes with neutrals.

CKM studies – CP violation

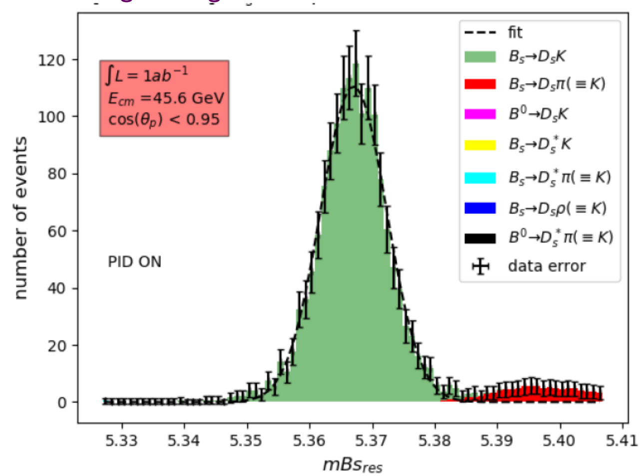
FCC-ee will certainly be able to exploit b-meson samples collected at Z pole to make exquisite measurements of key CP-violating parameters, *i.e.* β,γ,φ_s, and others.

e.g. measure γ with sub-degree precision in $B_s \to D_s K$ [Aleksan *et al.*, arXiv:2107.05311].

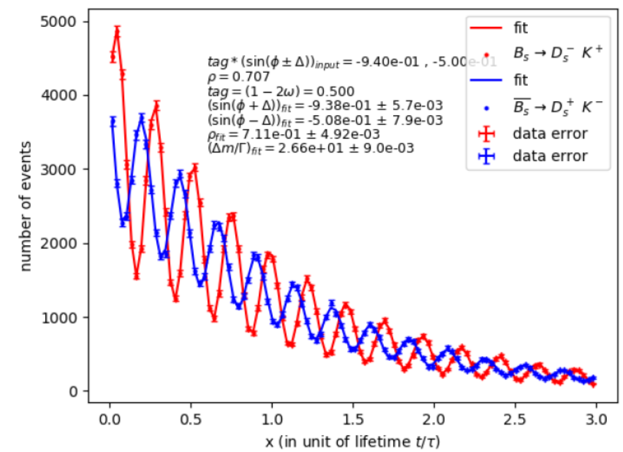
$B_s \to D_s K$ selection, no PID



$B_s \to D_s K$ selection, with PID



Fit to oscillations, for two of the four decay configurations



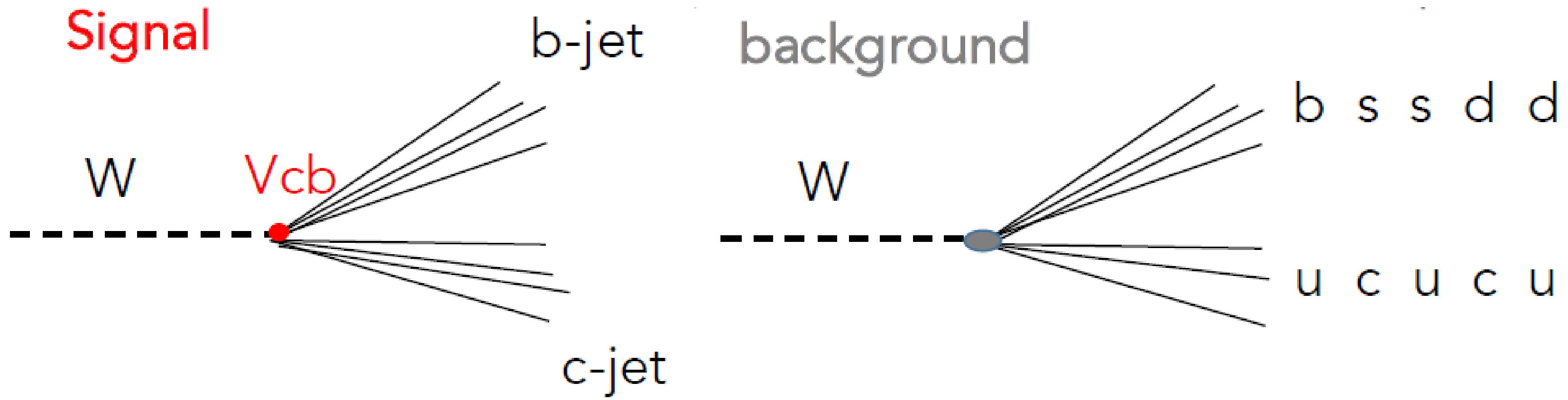
Advantages w.r.t. LHCb:

- Excellent mass resolution;
- Efficient use of modes with neutrals;
- Excellent flavour tagging.

Flavour with WW events

A likely ultimate bottleneck in the search for NP in B^0, B^0_s mixing will come from knowledge of V_{cb} [Charles *et al.* , PRD 102 (2020) 056023]. Current precision ~2%, with longstanding inclusive/exclusive problem. Semileptonic b decays are *difficult* !

Very promising complementary and alternative approach is to make measurement using on-shell W decays from WW running. Here we expect ~10^8 events.

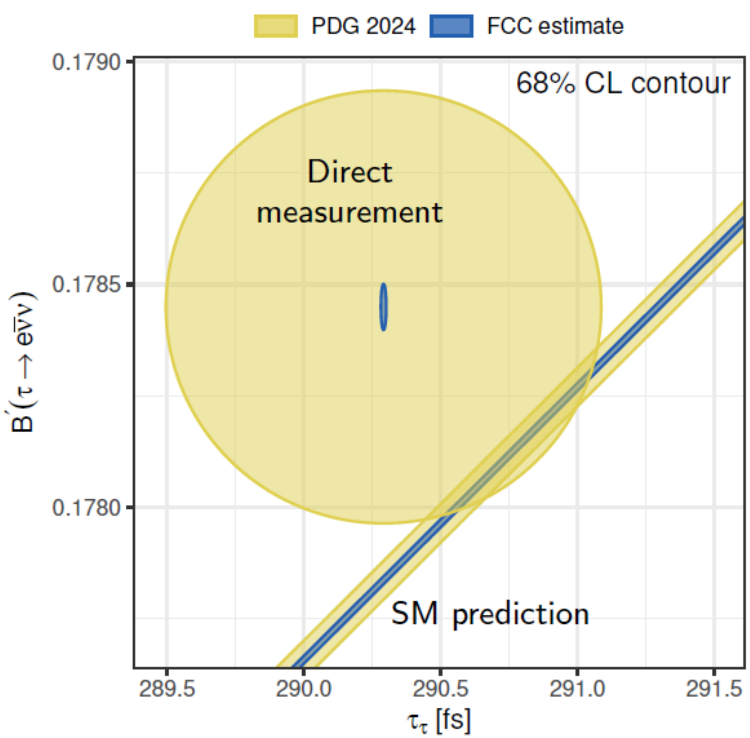


Ultimate precision will be dictated by performance of the jet-flavour taggers. Foreseen statistical precision of $|V_{cb}|$= 0.15%. Z sample will allow tagging efficiency to be controlled to this level. Similar technique can be used for $|V_{ts}|$ in ttbar events.

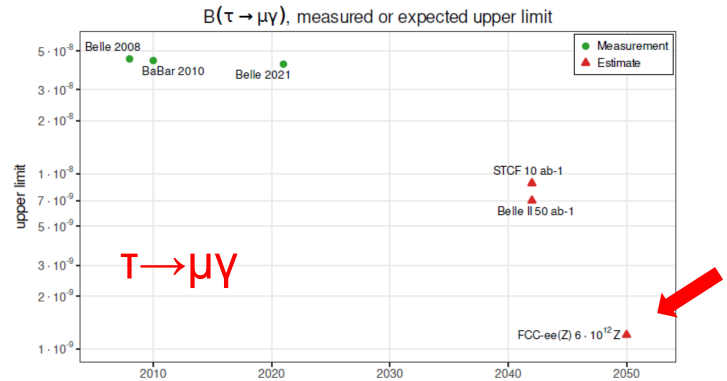
Tau physics at FCC-ee

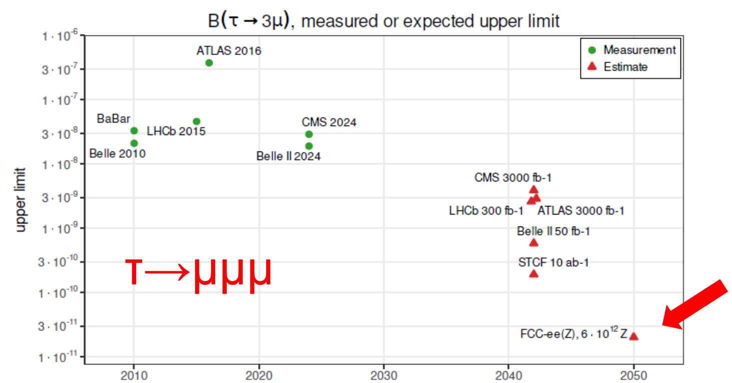
Tau-physics leadership passed from LEP to BaBar & Belle (II). FCC-ee will deliver (at least) 3-4 x more taus than at Belle II, with equally clean environment & boost.

Lifetime and BF measurements to test lepton universality



Tau lepton flavour violation searches





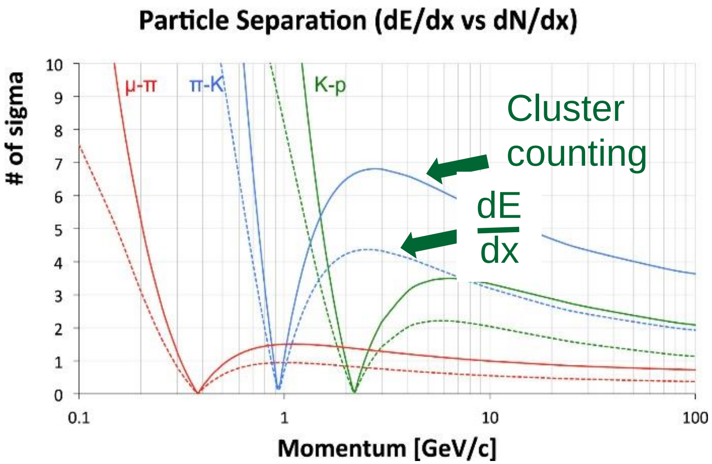
FCC-ee: detector requirements for flavour

What are the detector requirements for these measurements ? Any detector optimised for *e.g.* Higgs or EW measurements will also be capable of excellent flavour programme, but there are certain attributes that are particularly important.

(1) Particle identification (PID), *i.e.* π-K discrimination;

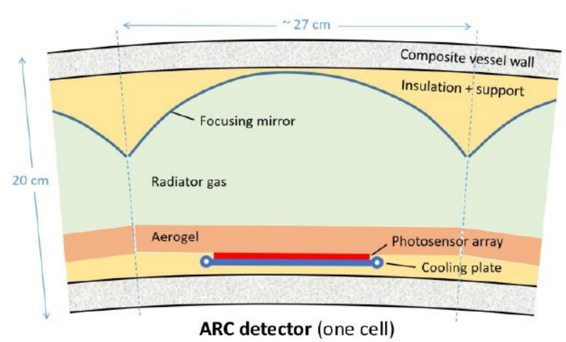
IDEA drift chamber promises to deliver excellent PID through cluster counting. Alternatively, equip an experiment with a compact RICH system, *e.g.* `ARC'.

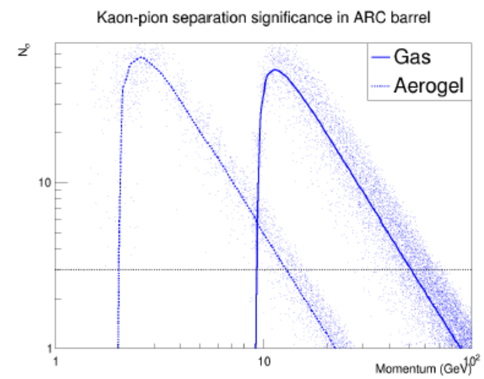
[Chiarello *et al.*, NIM A 936 (2019) 503]



ARC cell and π-K separation

[Forty, Tat, FCC Physics Wkshp Krakow, Jan 2023]





(2) Best possible vertex resolution (recall $B^0 \to K^{*0}\tau^+\tau^-$ requirements);

(3) ECAL with best possible energy resolution for π^0 reconstruction.

With 4 interaction points, FCC-ee can accommodate a detector optimised for flavour !

Flavour in the 2070s

LHCb has demonstrated that a highly successful flavour programme is possible at a *pp* collider. Good guess that there will still be lots still to do in the 2070s. What though are the advantages, and challenges, of flavour at FCC-hh ?

parameter	FCC-hh	HL-LHC	LHC
collision energy cms [TeV]	81 - 115	14	
dipole field [T]	14 - 20	8.33	
circumference [km]	90.7	26.7	
arc length [km]	76.9	22.5	
beam current [A]	0.5	1.1	0.58
bunch intensity [10^{11}]	1	2.2	1.15
bunch spacing [ns]	25	25	
synchr. rad. power / ring [kW]	1020 - 4250	7.3	3.6
SR power / length [W/m/ap.]	13 - 54	0.33	0.17
long. emit. damping time [h]	0.77 – 0.26	12.9	
peak luminosity [10^{34} cm^{-2}s^{-1}]	~30	5 (lev.)	1
events/bunch crossing	~1000	132	27
stored energy/beam [GJ]	6.1 - 8.9	0.7	0.36
Integrated luminosity/main IP [fb^{-1}]	20000	3000	300

Production rate of b-mesons will be a factor 150-200x higher than at LHCb Upgrade II !

The problem is of course, that we do not yet know how to build detectors that can survive and trigger in this environment. This also is the opportunity. If the radiation-hardness challenges can be overcome, it is not unreasonable to hope that the advances in computing power will allow an even higher proportion of b-decays to be captured and used for physics, than at the HL-LHC.

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Opportunity unique to FCC-hh !
(Not much b-physics at a muon collider.)

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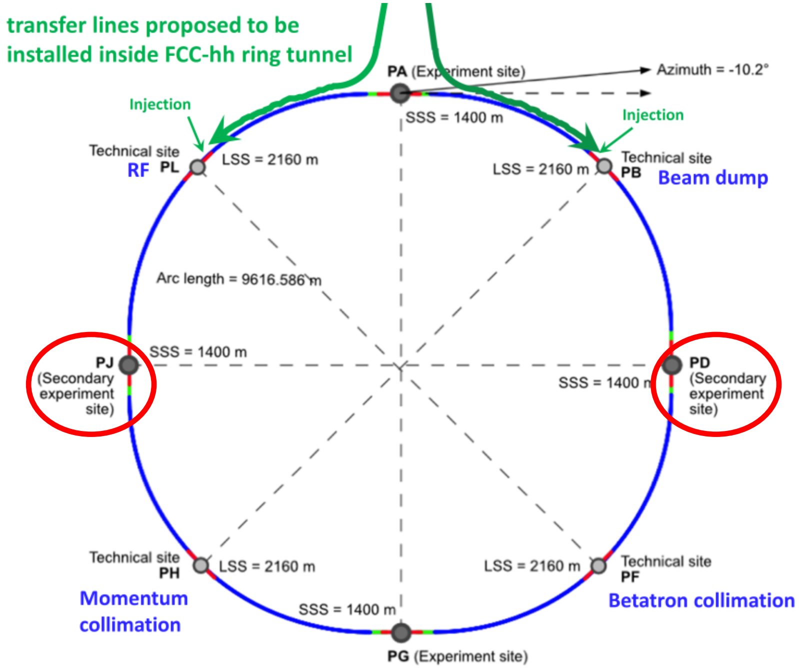
Flavour in the 2070s

LHCb has demonstrated that a highly successful flavour programme is possible at a *pp* collider. Is it feasible to have a flavour experiment at FCC-hh ?



Well, there is certainly space around the ring. FCC-hh will re-inhabit the same four experimental caverns of FCC-ee.

The big ones will be for the General Purpose Detectors, the `secondary caverns' are smaller, but still large, & could house e.g. FCCb and FCC-HI.

FCCb – dimensions and layout ?

This question has already been studied by Spanish colleagues (Santiago) !

arXiv:2012.02692v1 [hep-ex] 4 Dec 2020

Fast simulation of a forward detector at 50 and 100 TeV proton-proton colliders

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Abstract

We evaluate the performance of an LHCb-like detector using a fast simulation of proton-proton collisions at center-of-mass energies of 50 and 100 TeV. The study shows that detector acceptances and resolutions could be similar to those at the LHC. Together with the increase of production cross-sections of light particles with higher energy, such a hypothetical experiment could reach unprecedented sensitivities in flavor observables.

arXiv:2012.02692

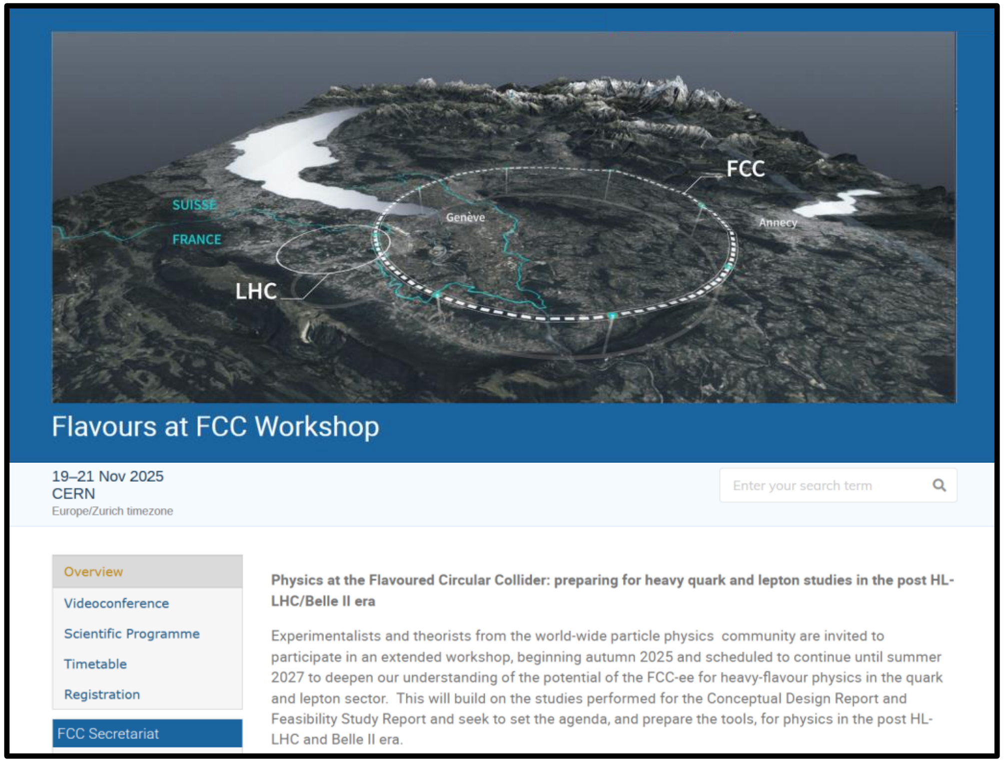
Flavour on a forward detector at 50 and 100 TeV

11/06/2020 Claire Prouve, Diego Martinez Santos, Marcos Romero Lamas, Veronika Chobanova
University of Santiago de Compostela

FPCP, 2020

Workshop: the flavoured circular collider

In order to understand better the capabilities of FCC-ee in flavour physics, we will very soon launch an extended (~2 year) workshop, with a kick-off event at CERN on 19-21 November. Announcement imminent. Sign up and join the efforts !



https://indico.cern.ch/event/1588013/overview

Conclusions

Much will remain to be done in flavour physics after the HL-LHC.

The Z pole and WW threshold runs at FCC-ee offer exciting opportunities to make transformative measurements in the flavour sector.

These opportunities are *unique* to a circular machine, *i.e.* FCC-ee (or CEPC) !

To realise full potential of FCC-ee flavour programme will require (at least) one experiment capable of high performance PID and π^0 and η reconstruction.

There are excellent arguments for a dedicated flavour experiment at FCC-hh.

Sign up for the Flavoured Circular Collider workshop !

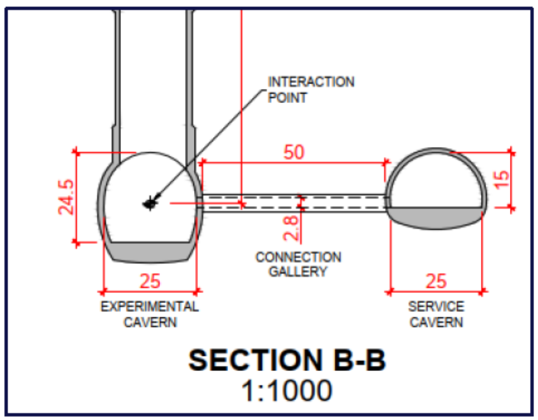
Backups

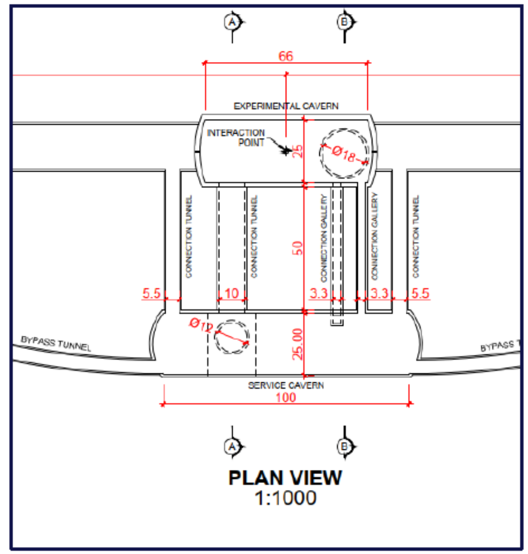
Flavour in the 2070s

LHCb has demonstrated that a highly successful flavour programme is possible at a *pp* collider. Is it feasible to have a flavour experiment at FCC-hh ?

Tim Watson, 2024 Annecy Physics workshop (link):

Secondary ('small') cavern layout

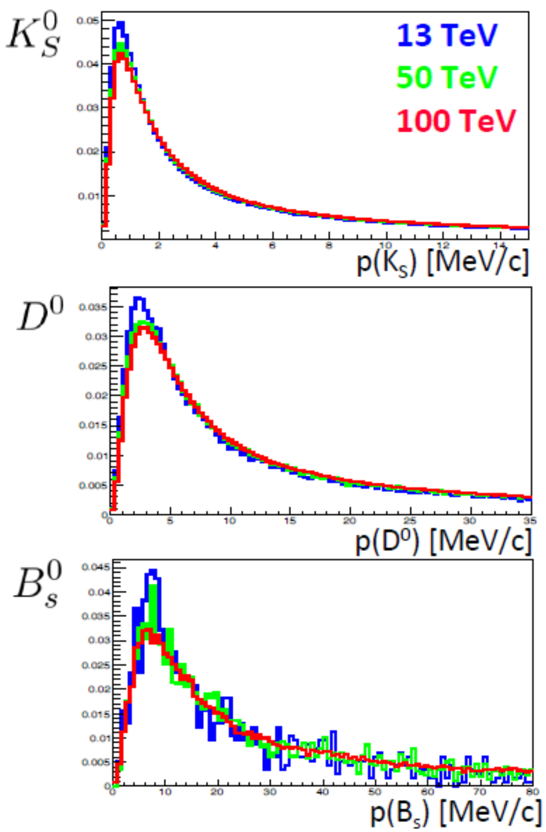


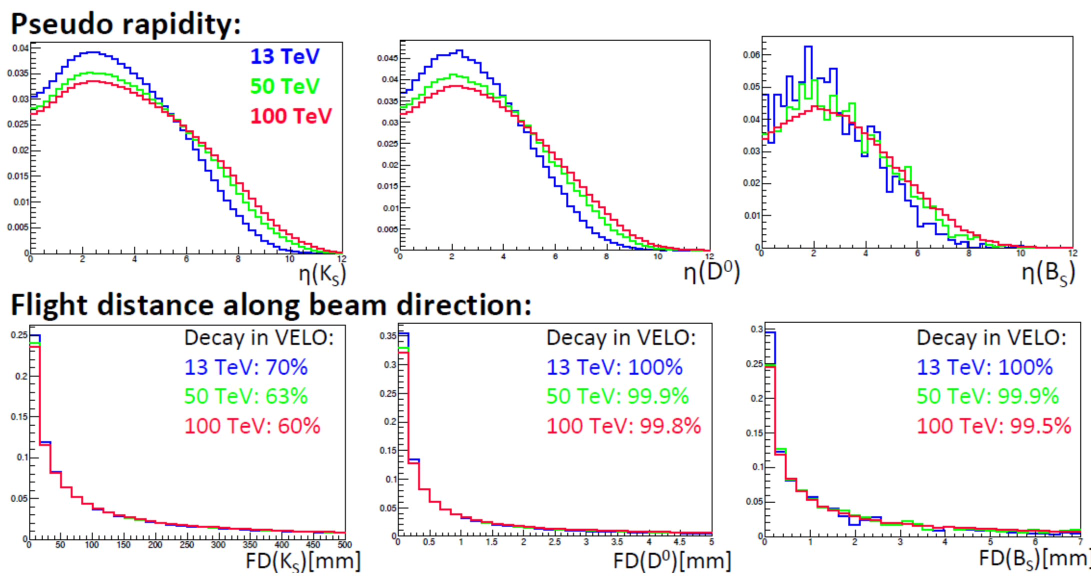


Max length of 66 m available, & 20-odd m in height. Large compared to LHCb (20 m high & < 10 m in height / width), but what about a 100 TeV experiment ?

FCCb – dimensions and layout ?

Nothing changes very much; FCCb won't need to be much longer than LHCb.
Certainly any increase in size will be < x2, so absolutely fine for 'small cavern'.





Of course other geometries are conceivable, but for time being a forward spectrometer layout remains a good baseline… further studies welcome !