Flavour Physsics in the post-HL-LHC era

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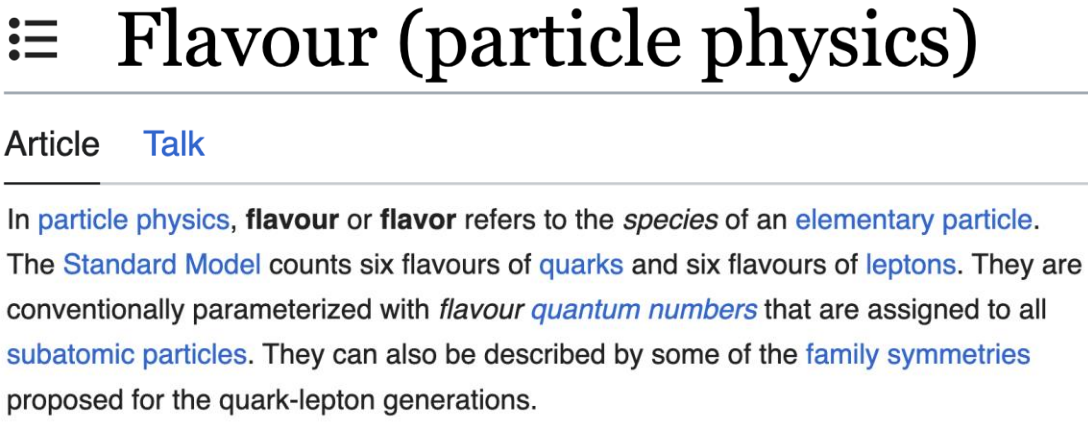
Workshop di Sezione su ESPP – Bologna, 7th November 2024

Outline

- Introduction on flavour physics
- Flavour physics now and after HL-LHC
- Flavour Physics at future facilities
  - Flavour physics at future e^+e^- colliders
  - Flavour physics at future hadron colliders
- Conclusions

What is flavour physics

WIKIPEDIA
L'enciclopedia libera

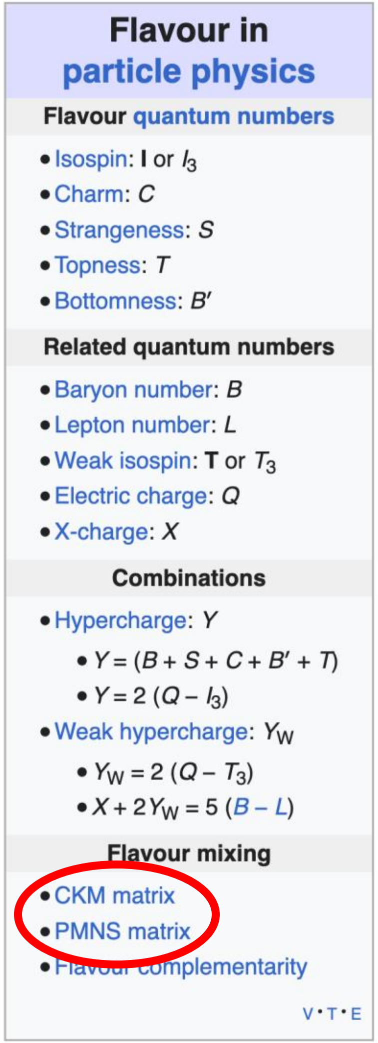


Flavour (particle physics)

Article Talk

In particle physics, **flavour** or **flavor** refers to the *species* of an elementary particle. The Standard Model counts six flavours of quarks and six flavours of leptons. They are conventionally parameterized with *flavour quantum numbers* that are assigned to all subatomic particles. They can also be described by some of the family symmetries proposed for the quark-lepton generations.

- Flavour physics is tightly connected with some of the most fundamental questions in particle physics
  - Why are there 3 families of fermions?
  - Where does the hierarchy of fermion masses comes from?
  - Why do we live in a matter-dominated universe?



Flavour in particle physics

Flavour quantum numbers

- Isospin: **I** or I_3
- Charm: C
- Strangeness: S
- Topness: T
- Bottomness: B'

Related quantum numbers

- Baryon number: B
- Lepton number: L
- Weak isospin: **T** or T_3
- Electric charge: Q
- X-charge: X

Combinations

- Hypercharge: Y
  - $Y = (B + S + C + B' + T)$
  - $Y = 2\,(Q - I_3)$
- Weak hypercharge: Y_W
  - $Y_W = 2\,(Q - T_3)$
  - $X + 2Y_W = 5\,(B - L)$

Flavour mixing

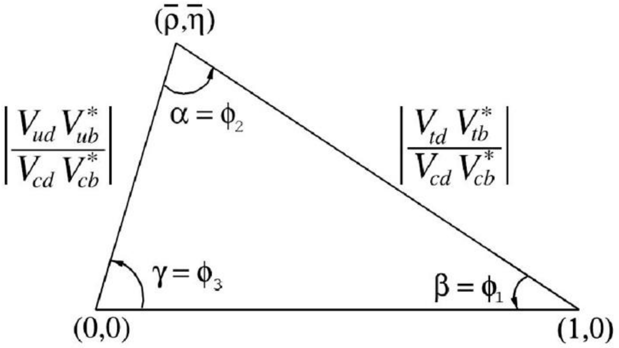
- CKM matrix
- PMNS matrix
- Flavour complementarity

V·T·E

The CKM matrix

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

3x3 complex unitary

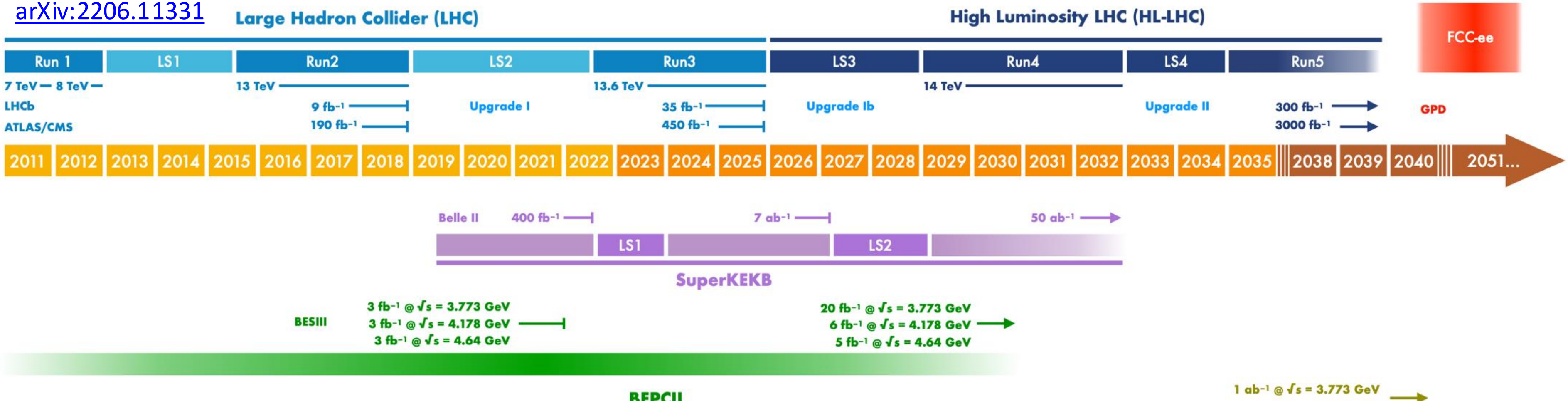


Unitary conditions

- The CKM matrix accommodates the mixing between mass and flavour eigenstates of quarks that arises from the electroweak symmetry breaking (Higgs mechanism)
- Encodes the strength of quark flavour-changing transitions
- Governs the breaking of CP symmetry in the SM

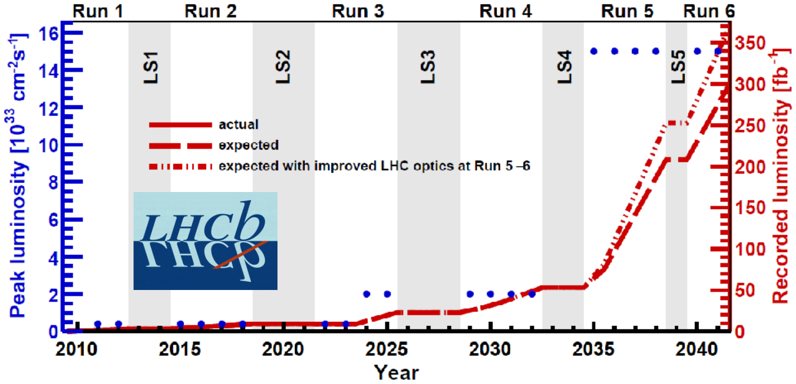
Timeline until end of HL-LHC

Thanks to F. Archilli and W. Altmannshofer
arXiv:2206.11331



Inputs from charm factories will be fundamental

The main contributors



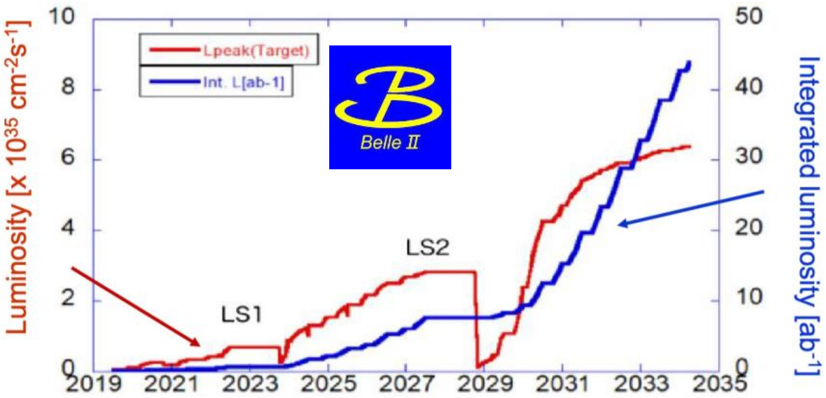
Phase	Runs	Int. lumi	Peak lumi	Comment
LHCb	1-2	9 fb^{-1}	4 x 10^{32} $cm^{-2}s^{-1}$	
LHCb UI	3-4	>50 fb^{-1}	2 x 10^{33} $cm^{-2}s^{-1}$	Full software trigger
LHCb UII	5-6	>300 fb^{-1}	1-1.5 x10^{34} $cm^{-2}s^{-1}$	

x2 efficiency on hadronic decays

Extrapolating from recent papers:

300/fb → 17.5M $B_s^0 \to J\psi(\mu^+\mu^-)\phi(K^+K^-)$

300/fb → 600k $B^+ \to D(4\pi)K^+$

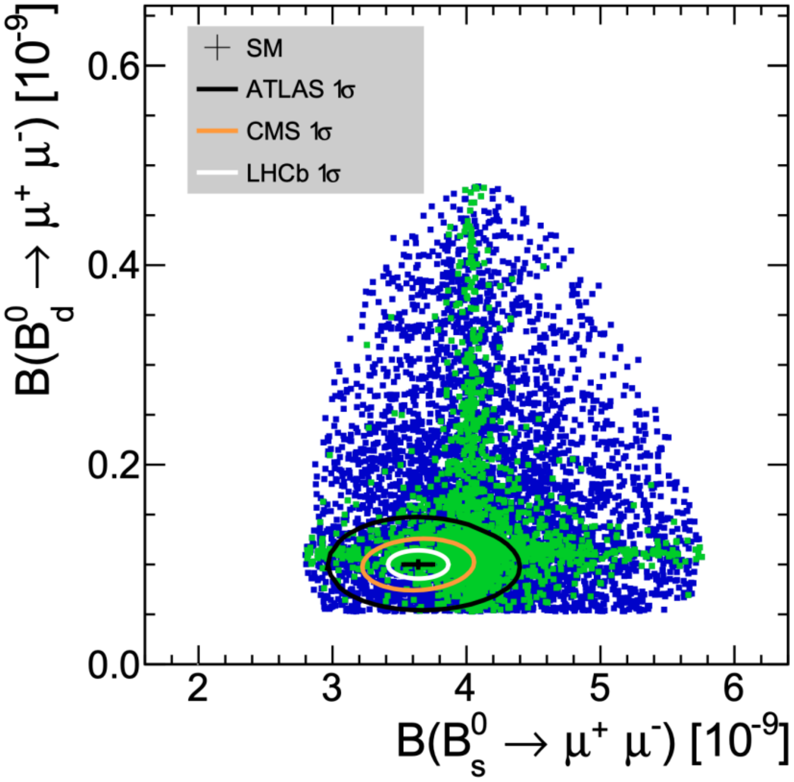


- Belle-II will integrate x50 the luminosity of Belle in the next 10 years
  - Profit from clean environment and quantum correlation of $B\bar{B}$ pairs
  - with a better detector
  - Belle-II is obtaining results already competitive with Belle with less than half the luminosity

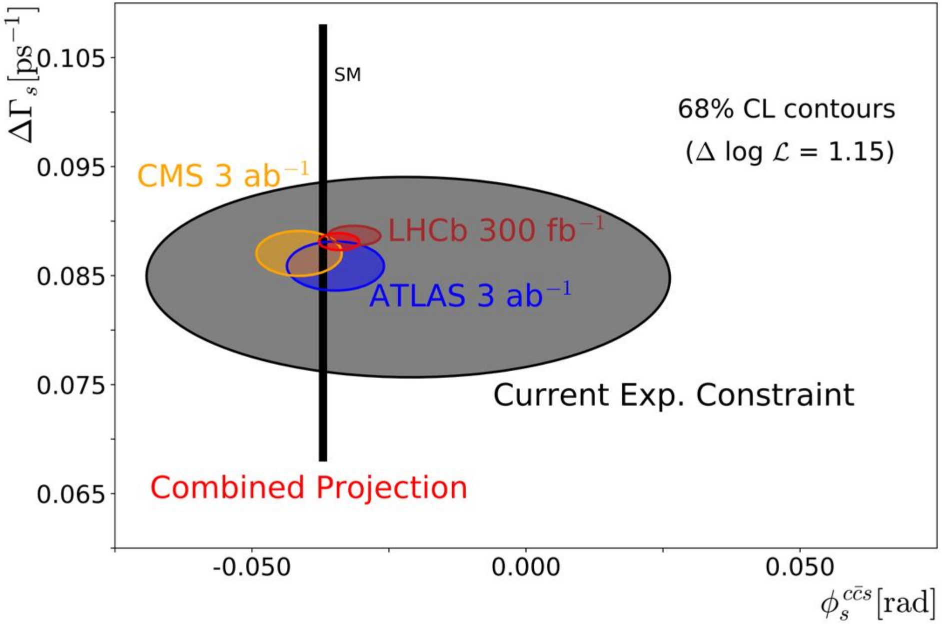
Reference number: 50/ab → 5x10^{10} $B\bar{B}$ pairs

Contribution from GPD at LHC

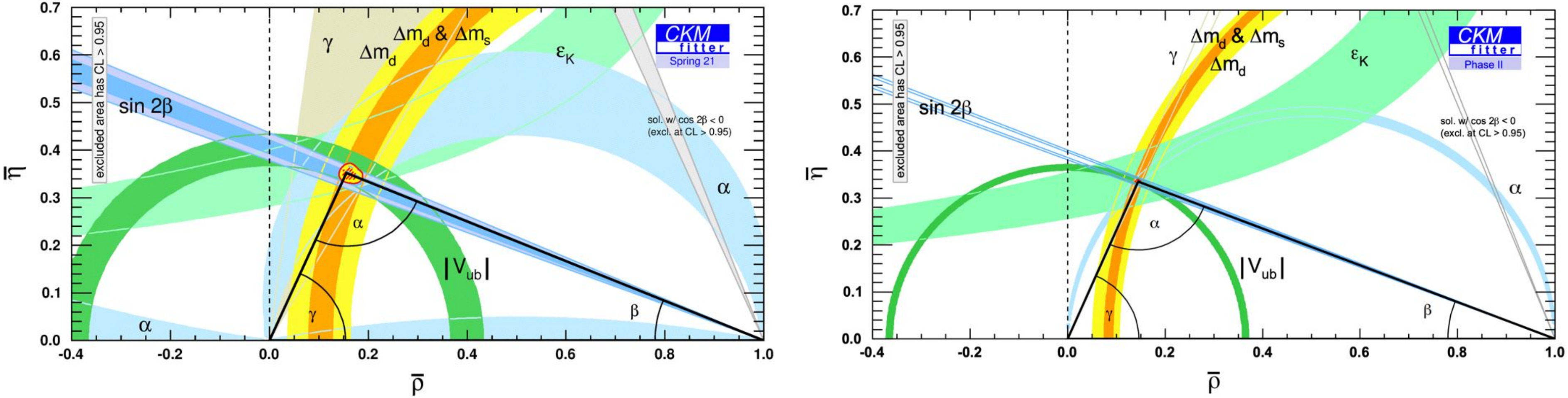
HL-LHC yellow paper



HL-LHC yellow paper



The landscape post HL-LHC

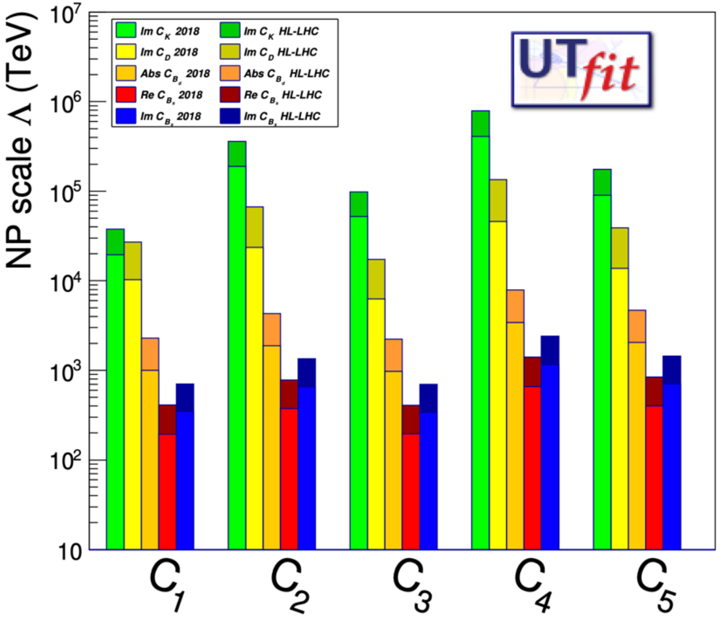


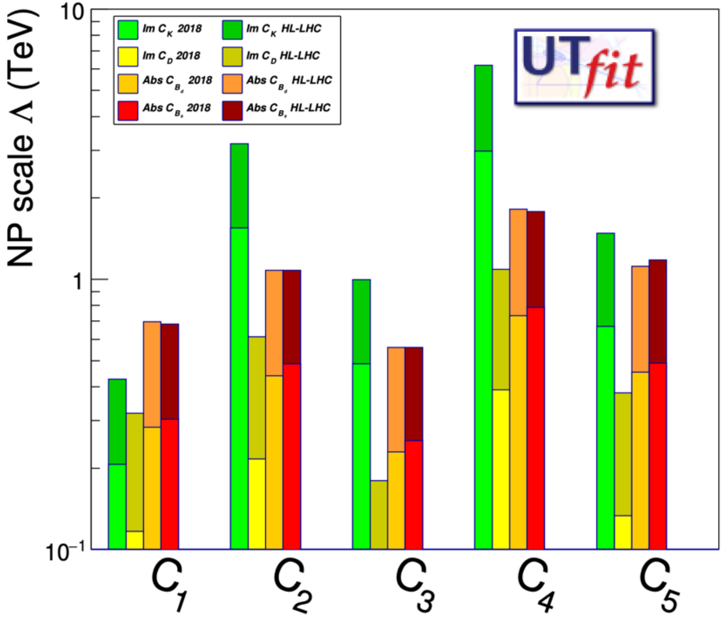
Precision on most of the constraints of the UT will be at its intrinsic limit

Improvements in lattice QCD inputs expected in the next 10 years are included and are fundamental

Constraining the UT to the per-mille level

HL-LHC yellow paper


New Physics with generic flavour couplings

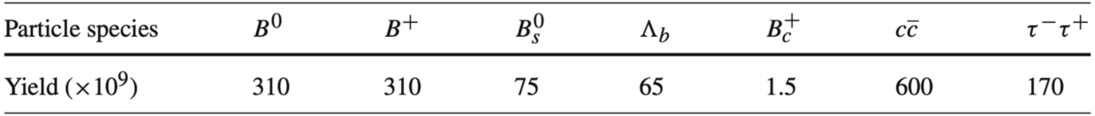

Minimal Flavour Violation scenario

In the HL-LHC era the constraint on the UT apex will be able to test the presence BSM particles with masses 3 times higher than now and well above those reachable with direct searches

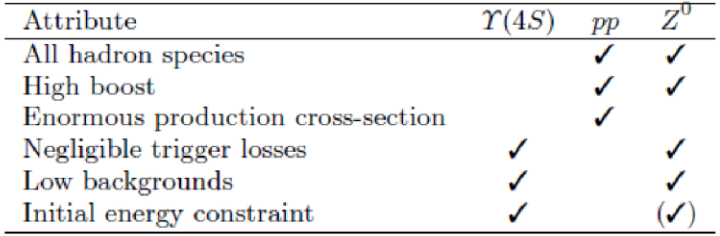
The FCC-ee as a flavour factory

- Large BF of Z^0 to $b\bar{b}$ and $c\bar{c}$ pairs combined with 6 x 10^{12} Z^0s, will provide a very large sample for flavour studies

EPC+ 136 (2021) 837



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



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

Cleaner environment brings also better flavour tagging → limiting factor at LHCb for time-dependent CPV measurements

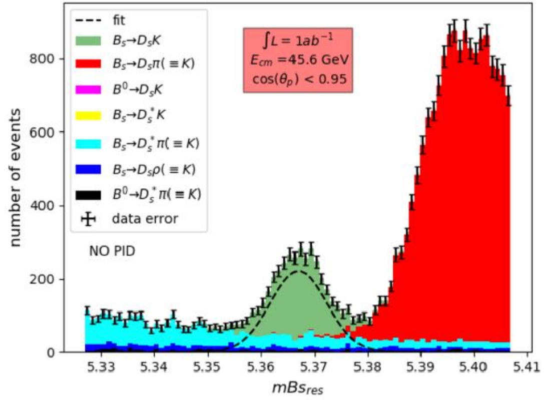
  - About one order of magnitude more than beauty hadrons produced at Belle-II (~50 x 10^9)
  - Production lower when compared to LHCb, but almost no trigger losses and much cleaner environment
    - Just considering BF, about 3.5M $B_s^0 \to J\psi(l^+l^-)\phi(K^+K^-)$ and 800k $B^+ \to D(4\pi)K^+$ → competitive with LHCb-U2
- Reason to rule out ILC/CLIC: not enough Z^0 to be competitive
- There are various key measurements were FCC-ee can be a game changer
- Final remark: at FCC-ee are expected 10^8 W^+W^- pairs that bring their own possibilities

CKM metrology

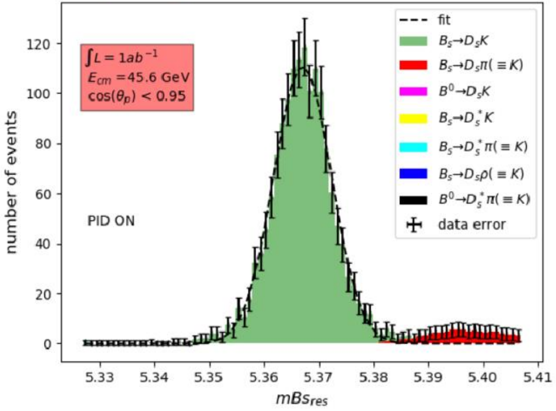
- As seen before, FCC-ee can be competitive with LHCb in terms of statistics
- Excellent example is the determination of γ angle of the UT from $B_s^0 \to D_s^- K^+$ decays
  - Expected ~1° precision on γ from this single mode (LHCb-U2 ~0.3° precision on γ overall)

arXiv:2107.05311

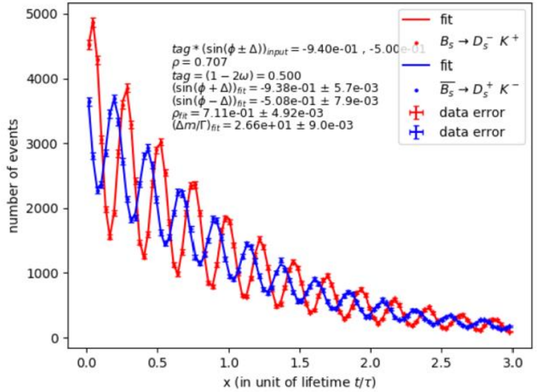
$B_s \to D_s K$ selection, no PID



$B_s \to D_s K$ selection, with PID



Fit to oscillations, for two of the four decay configurations



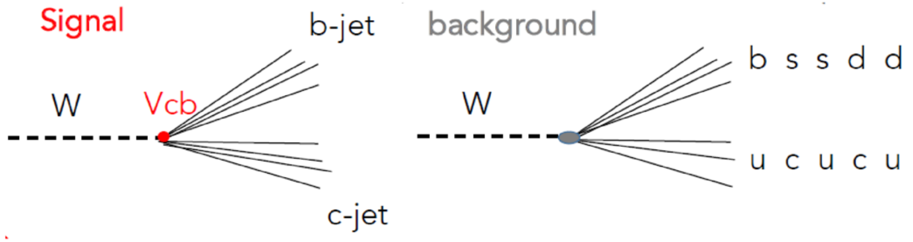
Advantages w.r.t. LHCb:

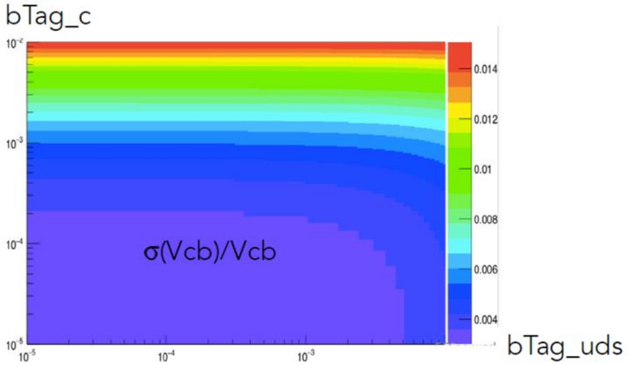
- Excellent mass resolution;
- Efficient use of modes with neutrals;
- Excellent flavour tagging.

Flavour with WW events

- Ultimate bottleneck in the search for BSM physics in B mixing will come from the knowledge of CKM element V_{cb} [PRD 102 (2020) 056023]
  - Current precision ~2% with longstanding discrepancy between inclusive and exclusive determination of V_{cb} → semileptonic decays are difficult to measure
- Promising to use on-shell W decays to hadronic jets exploiting 10^8 WW events expected
  - Precision driven by the capabilities of tagging the flavour of the jets
  - Technique usable also for other CKM elements (V_{cs})

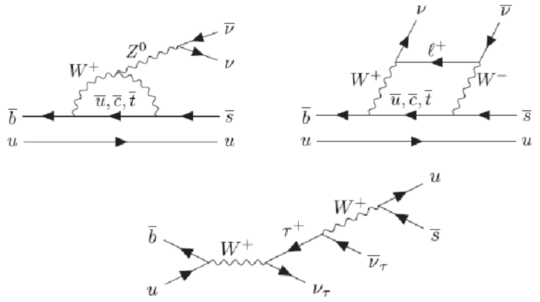
Preliminary study assuming ILD flavour-tagging performance indicates precision of 0.4% achievable [M-H. Schune, 2020].

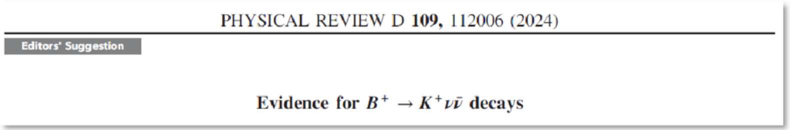




Flavour-changing neutral channel with neutrinos

- Transitions b→sl$^+$l$^-$ are a key measurement in flavour physics:
  - Anomalies about LFV and LFU are now back to SM, but tensions in other observables (BFs and angular observables)
  - Same decays but with neutrinos have the same sensitivity to BSM physics, and much cleaner theory (no charm-loop)




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

Editors' Suggestion

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

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

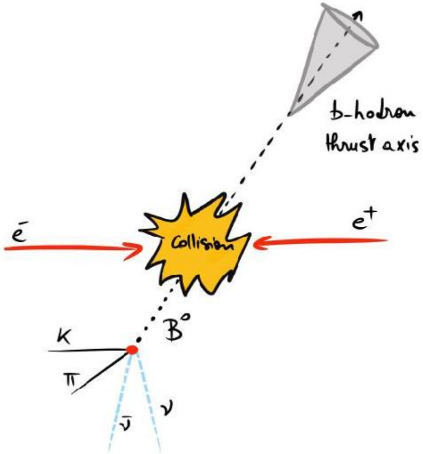
$B^0 \to K^0_S\nu\overline{\nu}$ $B^0_s \to \phi\nu\overline{\nu}$ $B^+ \to K^+\nu\overline{\nu}$

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

$B^0 \to K^{*+}\nu\bar{\nu}$

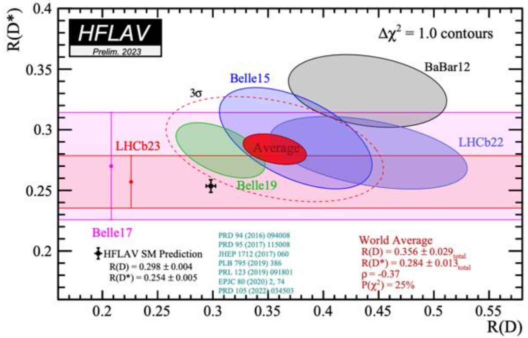
All with BF ~ 10^{-6}

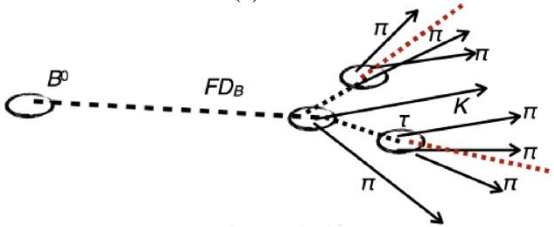
Physics reach studies performed in JHEP01(2024)144: Very promising thanks to the good separation of the two b-jets out of $Z^0 \to b\bar{b}$ and energy constraint

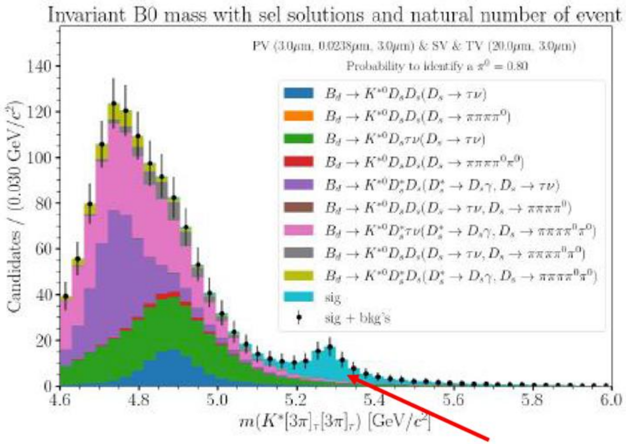


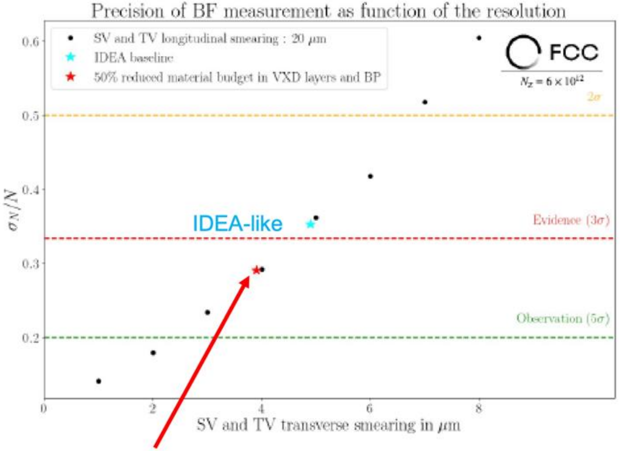
B decays with taus

- Long standing tension with SM in B→$D^{(*)}\tau\nu$ indicating possible LFV with taus
- Another mode considered for long time a golden channel for FCC-ee is B→$K^{(*)}\tau^+\tau^-$
  - BR ~ 10^{-7} and inaccessible to LHCb and Belle-II
  - Sensitivity on SM BF can be approached at FCC-ee









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

Signal, when reconstructed with very good resolution

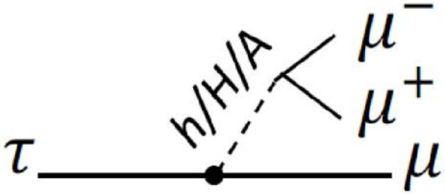
Excellent secondary vertex reconstruction is of the utmost importance (~few μm)

Tau physics

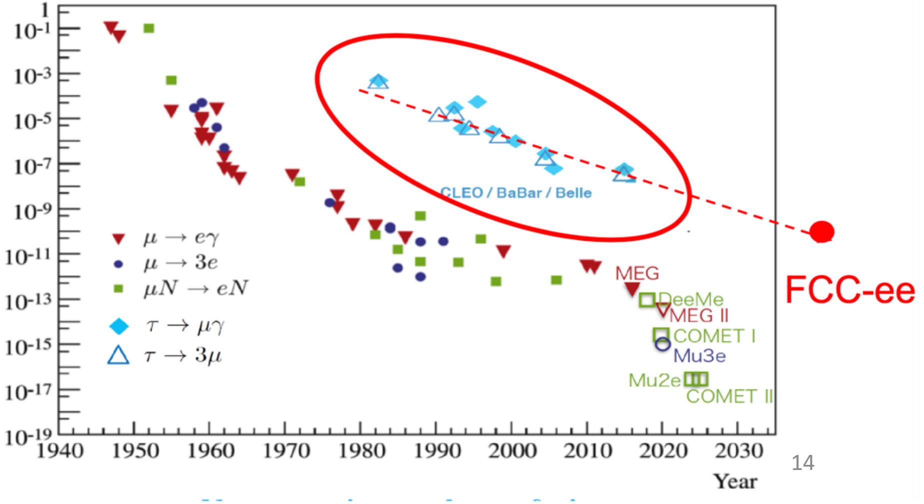
- FCC-ee offer the opportunity to exploit 10^{11} $\tau^+\tau^-$ pairs
- Taking the as benchmark the $\tau \rightarrow 3\mu$

  Current 90% CL

Belle	2.1×10^{-8}	[PLB 687 (2010) 139]
BaBar	3.3×10^{-8}	[PRD 81 (2010) 111101]
LHCb	4.6×10^{-8}	[JHEP 02 (2015) 121]



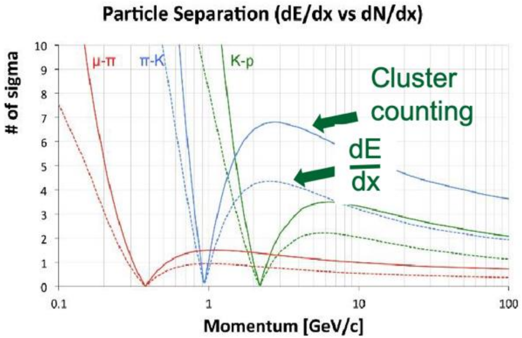
- FCC-ee has the opportunity to approach sensitivity to BF of 10^{-10}
  - LHC limited from backgrounds from B decays
  - LHC can't investigate other LFV decays like $\tau \rightarrow \mu\gamma$



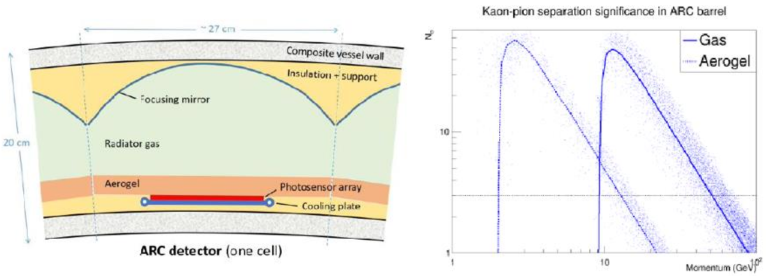
FCC-ee: detector requirements

- Everything that is good for a GPD is good also for a flavour-dedicated experiments but…
- Three key ingredients can be identified
  - Excellent PID: K-π separation is of the utmost importance

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

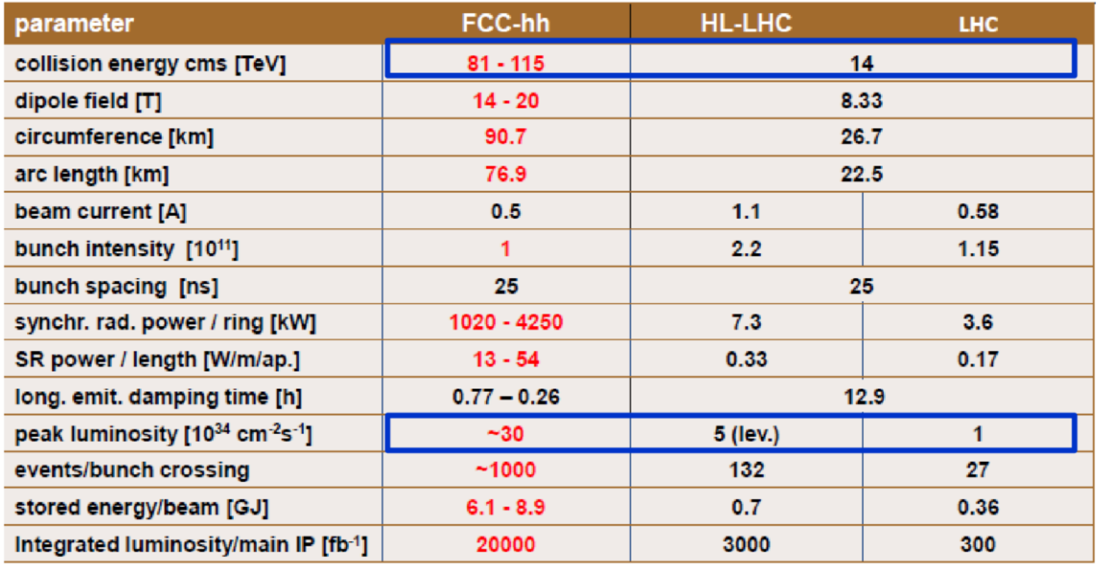


ARC cell and π-K separation
[Forty, Tat, FCC Physics Wkshp Krakow, Jan 2023]



  - Excellent vertexing: resolution on PV-SV separation of ~few μm is crucial for B decays with taus
  - Excellent e.m. calorimetry: decays with γ and π^0 will profit from the much cleaner environment with respect to LHC

Conditions at FCC-hh

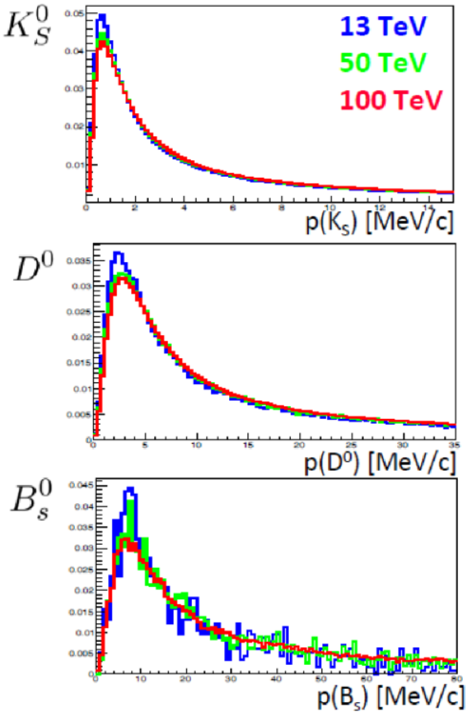


parameter	FCC-hh	HL-LHC	LHC
collision energy cms [TeV]	81 - 115	14	
dipole field [T]	14 - 20	8.33	
circumference [km]	90.7	26.7	
arc length [km]	76.9	22.5	
beam current [A]	0.5	1.1	0.58
bunch intensity [10^{11}]	1	2.2	1.15
bunch spacing [ns]	25	25	
synchr. rad. power / ring [kW]	1020 - 4250	7.3	3.6
SR 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

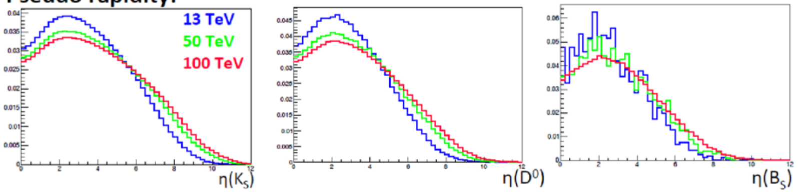
Production rate of b-mesons will be a factor 150-200x higher than at LHCb Upgrade II !

- For sure there is flavour physics that can profit from the FCC-hh
  - Large statistics is what flavour physics need
- LHCb proved that precision flavour physics can be done even in hadronic environment, but conditions at FCC-hh will be prohibitive
  - But new challenges is what we look for

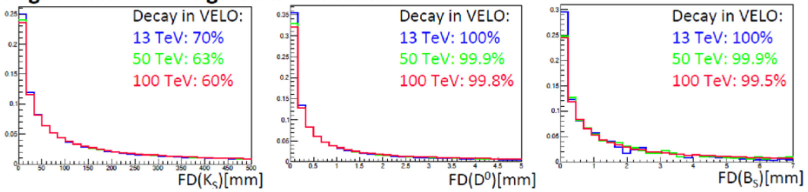
Physics at FCC-hh



Pseudo rapidity:



Flight distance along beam direction:



Decay in VELO:
13 TeV: 70%
50 TeV: 63%
100 TeV: 60%

Decay in VELO:
13 TeV: 100%
50 TeV: 99.9%
100 TeV: 99.8%

Decay in VELO:
13 TeV: 100%
50 TeV: 99.9%
100 TeV: 99.5%

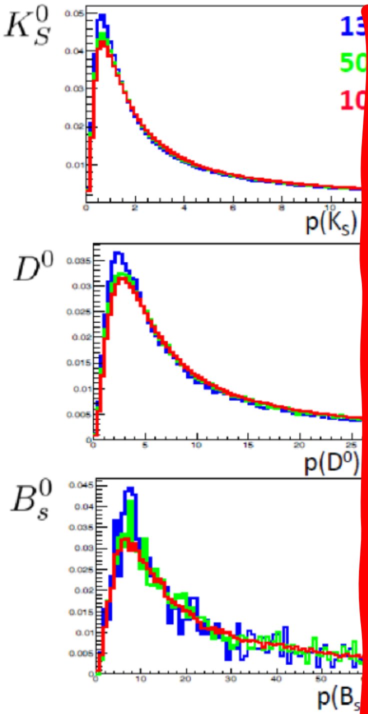
Flavour on a forward detector at 50 and 100 TeV

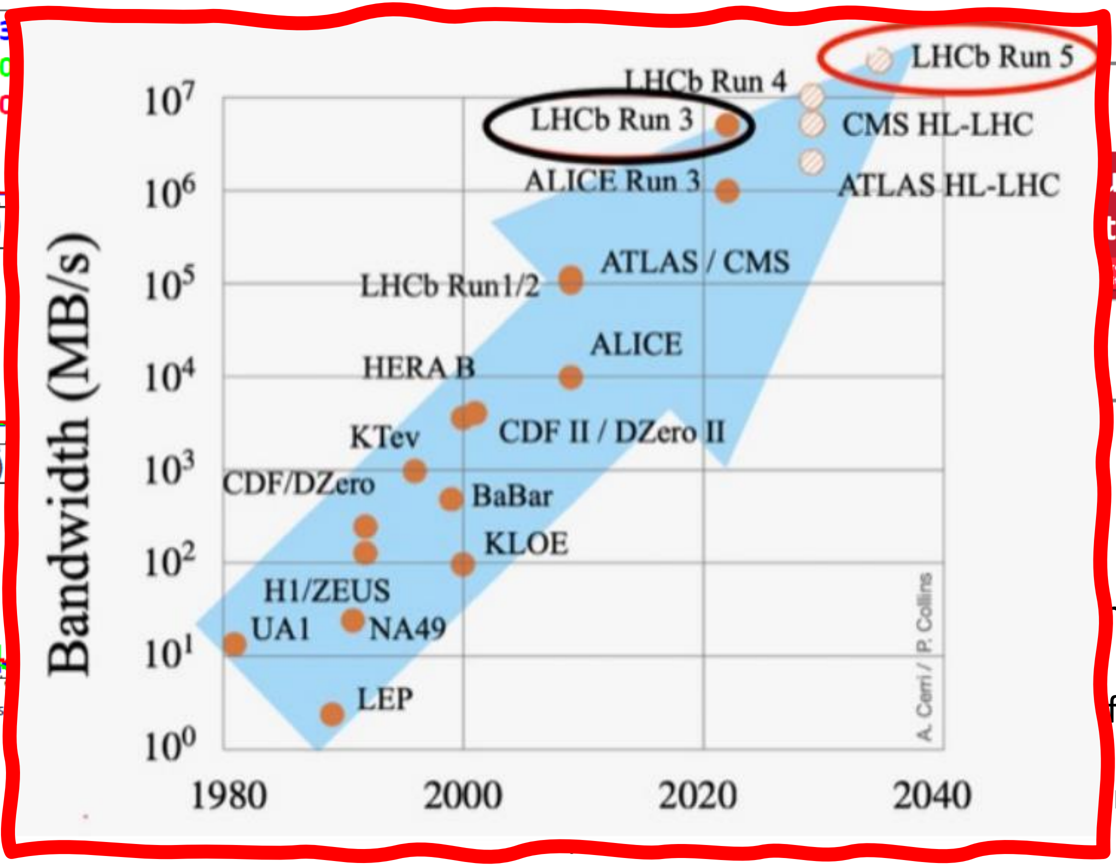
11/06/2020 Claire Prouve, Diego Martinez Santos, Marcos Romero Lamas, Veronika Chobanova
University of Santiago de Compostela

FPCP, 2020

- Somebody already gave thoughts to what flavour physics to do with FCC-hh
- Very interesting: kinematic distributions are not much different from what we have at LHC
  - Despite the much larger energy an “FCCb” detector for flavour physics will not have to be much bigger than LHCb
  - Main challenge remain the harsh environment in terms of radiation hardness and occupancy

Physics at FCC-hh



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FPCP, 2020

physics to do with

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Conclusions

- The landscape of flavour physics after HL-LHC will be one were BSM physics at the TeV scale will be put in tight corner
  - But much will remain to do, since it FP allows energies much higher than direct search to be investigated
  - Theory (lattice QCD, but not only) will have to keep the pace with experiments to fully profit from measurements
- The huge samples of Z^0 and WW at FCC-ee offer very exciting and unique opportunities
  - Profiting from the very clean environment and constrained energy
  - Nevertheless, flavour physics poses challenges in key detector features: PID, vertexing and calorimetry
- There are excellent arguments for a dedicated flavour experiment at FCC-hh
  - In order to profit from the huge increase of statistics that will be provided, detectors will have to cope with unprecedented challenges

Conclusions & Personal opinion

FCC-hh will increase the energy scale by a factor O(10) with respect to HL-LHC, but no evidence of BSM physics behind the corner is observed precision measurements. A first phase of precision measurements (FCC-ee) is fundamental.

- Theory (lattice QCD, but not only) will have to keep the pace with experiments to fully

The flood of data for flavour physicists promised by FCC-hh will pose incredible challenges in the forward direction. Even though forward direction is interesting also for other reasons, rethinking the geometry of flavour-dedicated experiment may be mandatory.

- Profiting from the very clean environment and constrained energy
- Nevertheless, flavour physics poses challenges in key detector features: PID, vertexing and

Role of theory community will be fundamental. The interpretation of measured quantities in terms of fundamental observables or BSM physics requires theory inputs.

- In order to profit from the huge increase of statistics that will be provided, detectors will have to cope with unprecedented challenges

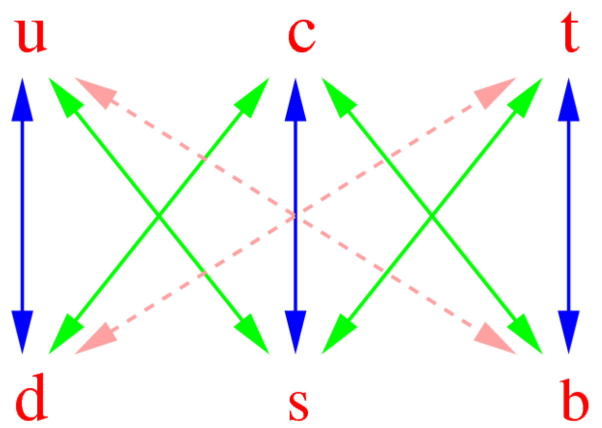
BACKUP

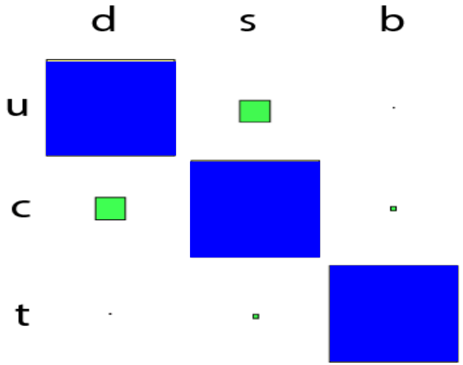
A story full of successes

1950’s	**Discovery of parity violation**
1960’s	**CP violation in K decays**
1970’s	**Discovery of J/ψ and charm quark**
1980’s	**Inference on top quark mass from B mixing**
2000’s	**CP violation in B decays**
2010’s	**Penta- and tetra-quarks**
2020’s	**CP violation in D decays**

Cartoon presented by N. Cabibbo at the Berkeley conference in 1966

The CKM matrix

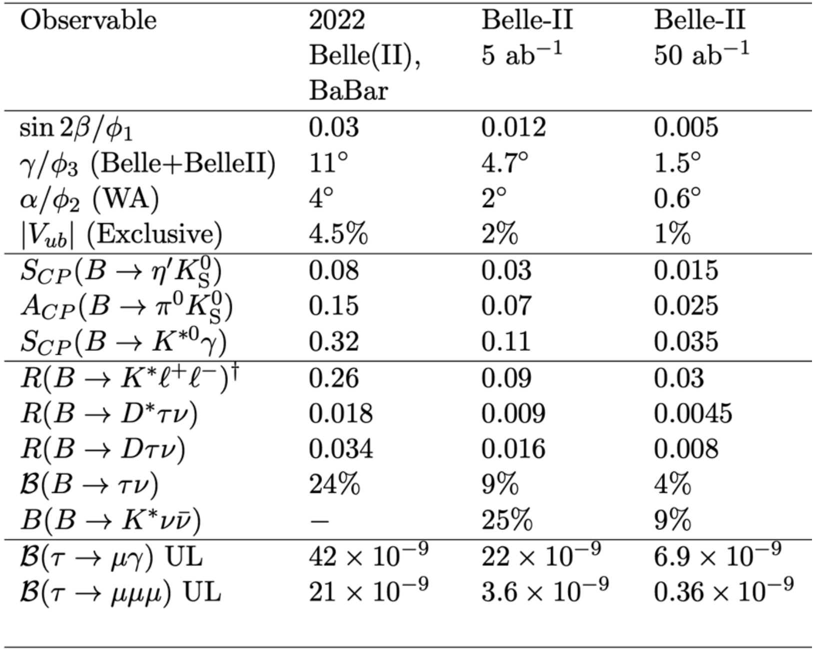




- The CKM matrix accommodates the mixing between mass and flavour eigenstates of quarks that arises from the electroweak symmetry breaking (Higgs mechanism)
- Encodes the strength of quark flavour-changing transitions
- Governs the breaking of CP symmetry in the SM

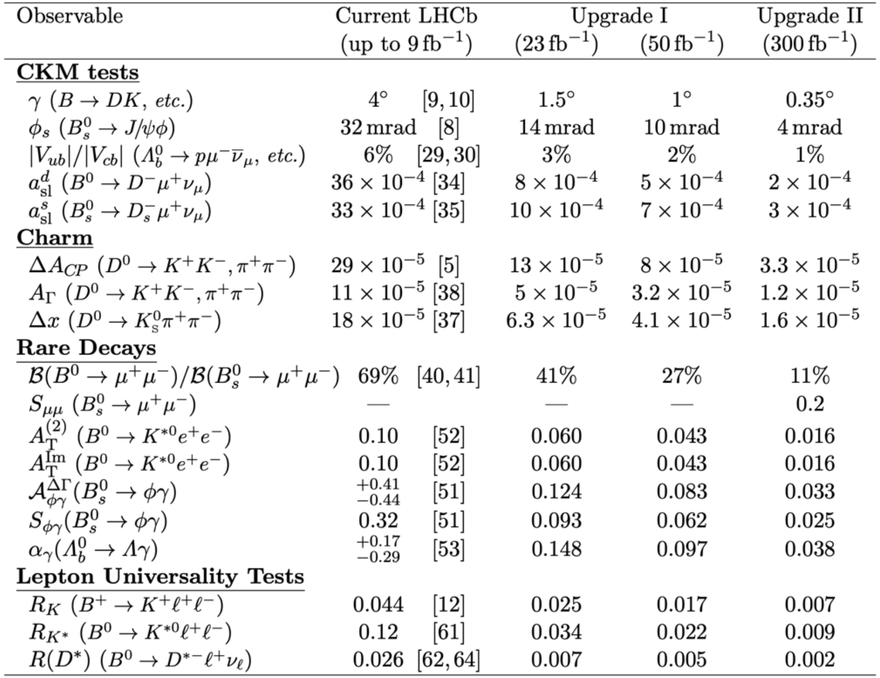
Physics reach for LHCb and Belle II

Belle II Upgrade snowmass white paper



Observable	2022 Belle(II), BaBar	Belle-II 5 ab^{-1}	Belle-II 50 ab^{-1}
$\sin 2\beta/\phi_1$	0.03	0.012	0.005
γ/ϕ_3 (Belle+BelleII)	11°	4.7°	1.5°
α/ϕ_2 (WA)	4°	2°	0.6°
$\lvert V_{ub}\rvert$ (Exclusive)	4.5%	2%	1%
$S_{CP}(B \to \eta' K^0_S)$	0.08	0.03	0.015
$A_{CP}(B \to \pi^0 K^0_S)$	0.15	0.07	0.025
$S_{CP}(B \to K^{*0}\gamma)$	0.32	0.11	0.035
$R(B \to K^* \ell^+ \ell^-)^\dagger$	0.26	0.09	0.03
$R(B \to D^* \tau \nu)$	0.018	0.009	0.0045
$R(B \to D \tau \nu)$	0.034	0.016	0.008
$\mathcal{B}(B \to \tau \nu)$	24%	9%	4%
$B(B \to K^* \nu \bar{\nu})$	–	25%	9%
$\mathcal{B}(\tau \to \mu \gamma)$ UL	42×10^{-9}	22×10^{-9}	6.9×10^{-9}
$\mathcal{B}(\tau \to \mu\mu\mu)$ UL	21×10^{-9}	3.6×10^{-9}	0.36×10^{-9}

LHCb Upgrade II FTDR (LHCb-TDR-023)

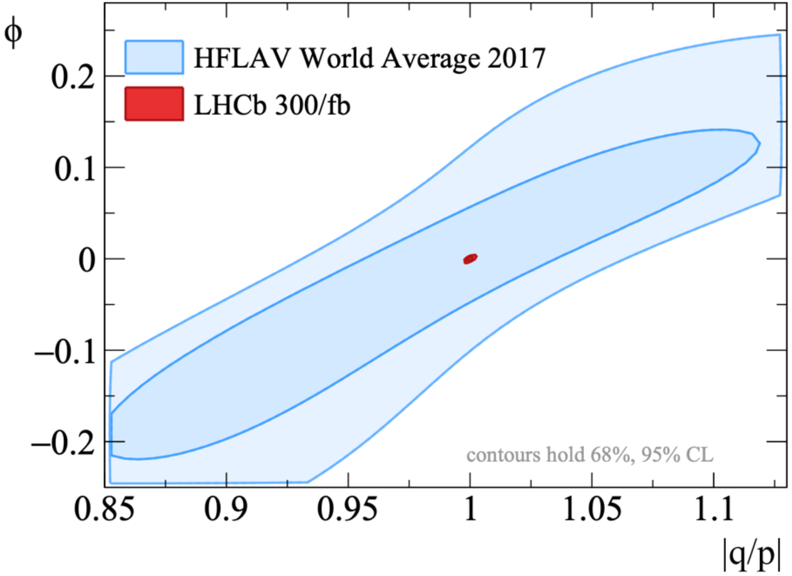


Observable	Current LHCb		Upgrade I		Upgrade II
	(up to 9 fb^{-1})		(23 fb^{-1})	(50 fb^{-1})	(300 fb^{-1})
CKM tests					
γ ($B \to DK$, *etc.*)	4°	[9, 10]	1.5°	1°	0.35°
ϕ_s ($B^0_s \to J/\psi\phi$)	32 mrad	[8]	14 mrad	10 mrad	4 mrad
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda^0_b \to p\mu^-\overline{\nu}_\mu$,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

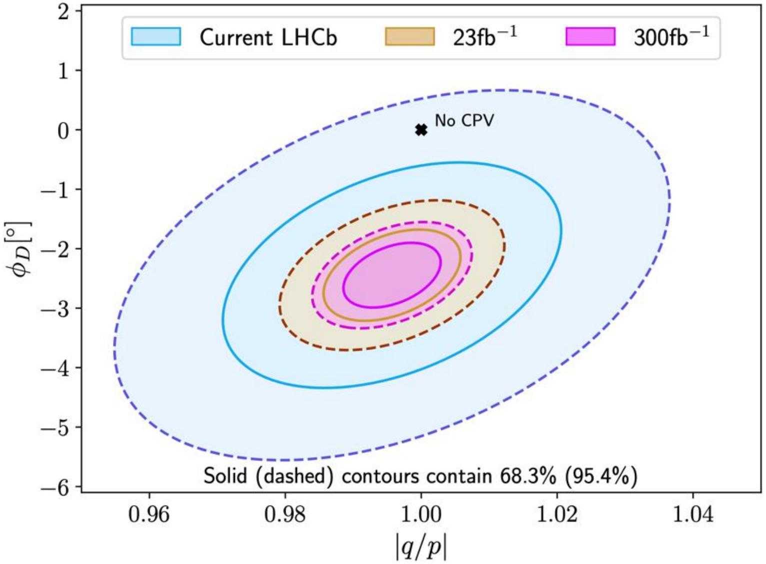
- It is fundamental to stress that LHCb and Belle II physics programmes complement each other exploiting the different environments provided by the LHC and KEK-II accelerators
- Nevertheless a large part of the programmes overlap allowing for mutual cross-check of key measurements

Test CPV in charm to unprecedented levels

arXiv:1808.08865



LHCb-TDR-023



LHCb (and its upgrades) will be the biggest charm factory ever

It is essential to exploit it,

but that will require extreme control of experimental and theoretical systematics