Digest of ESPPU project submissions. Collider Physics

Jon Butterworth, Caterina Doglioni, Monica D’Onofrio, Tim Gershon, Frank Krauss, Josh McFayden

Overview

- 263 submissions - clearly impossible to summarise even the relevant ones
  - Not summarising some submissions that are clearly very important e.g. HL-LHC upgrades, detector R&D, software & computing, sustainability, communication strategies, EDI etc.
  - The main strategic discussion can proceed acknowledging that these aspects will play a role for community support

- There is little change in the submissions to the nominal "Plan A" scenario
  - There is push-back in some submissions to the full FCC-ee+hh integrated program
  - UK input was strongly supportive of the FCC tunnel:
    - *The community has a large contingent in support of the integrated programme of FCC-ee followed by FCC-hh, as well as a large contingent in favour of considering FCC-hh as the next collider at CERN.*

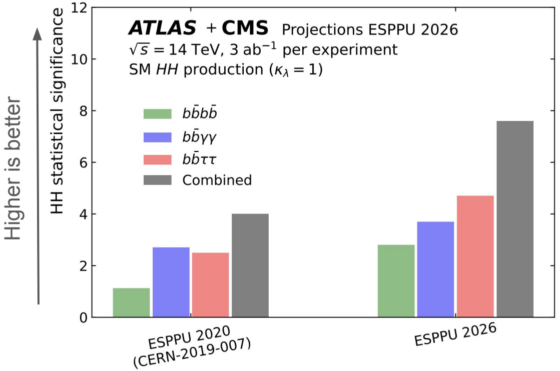
So this talk will focus on:

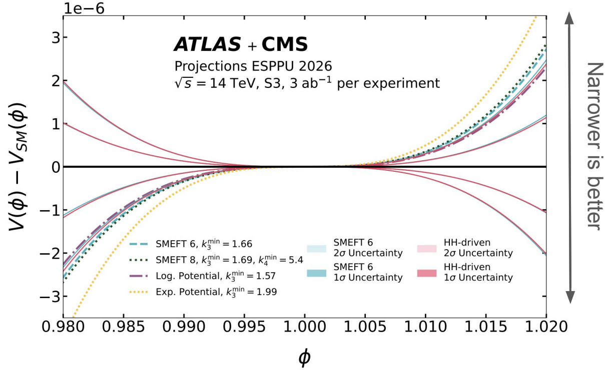
- Submissions that give new information or ideas
- Discussion on prioritisation of *alternative* or *Plan B* scenarios
- Emphasis on proposals rather than specific physics prospects

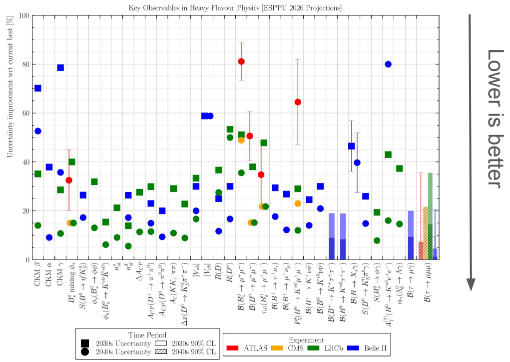
HL-LHC projections

NEW

- LHC experiments have updated their HL-LHC projections
  - [Highlights of the HL-LHC physics projections by ATLAS and CMS]
  - [Projections for Key Measurements in Heavy Flavour Physics]
- New key messages mostly related to new prospects:
  - Di-Higgs (7 sigma - huge improvement), exclusion of First Order Phase Transition
  - Order of magnitude improvements on current flavour observables (including Belle II)
- In general (HL-)LHC is proving to be a precision machine
  - Blurring the lines between traditional precision vs search machines
  - Improvements in analysis techniques (using ML), MC modelling (N>=2LO in QCD)







ECR input

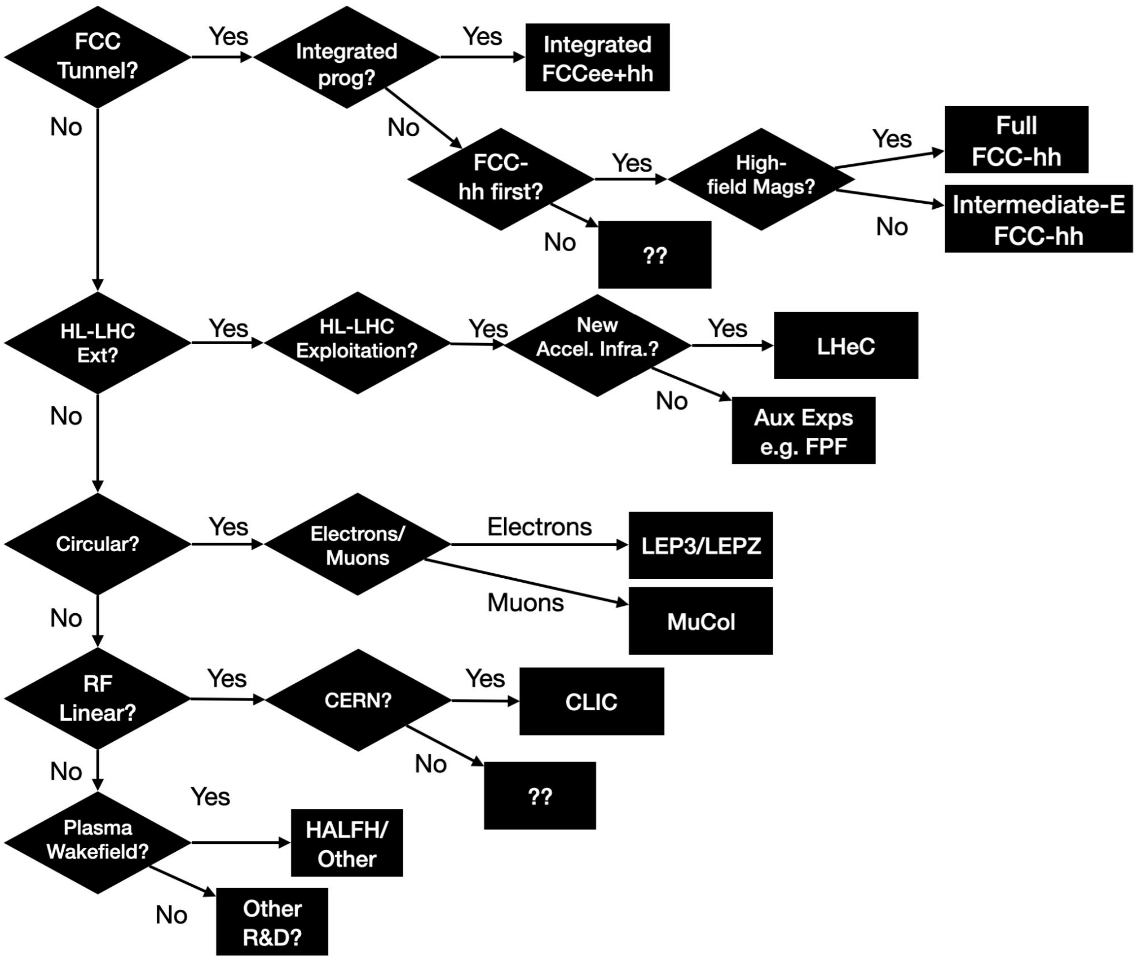
NEW

- Early Career Researcher Input to the European Strategy for Particle Physics Update
  - 936 participants, December 2024–January 2025.
  - Some emphasis on career prospects, DEI and mental health, communication, sustainability
  - A significant majority of ECRs (79%) support the development of a next flagship collider
  - Future collider selection should be guided by technological innovation as the driving factor.
  - Deliberately refrain from recommending any specific collider facility
  - Urge for a clear recommendation on the next European flagship collider from ESPPU process

- US ECR input
  - 105 participants, February–March 2025
  - 70% preferred to prioritize Muon Collider R&D over Higgs factory construction
  - Even split between direct to FCC-hh vs full FCC-ee+hh program
  - Physics program of the FCC-hh was rated as more exciting
  - Excitement for all projects increases if they are brought about sooner.

Possible alternatives and/or Plan Bs

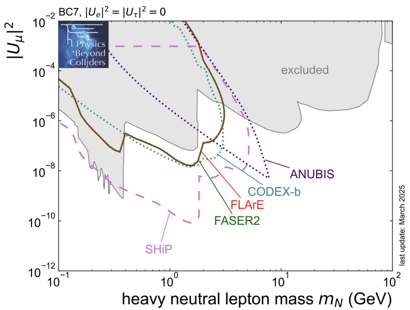
- Need to prioritise alternative/Plan B options
- Can consider prioritisation based on some kind of decision tree
- TODO: Add timeline and costs

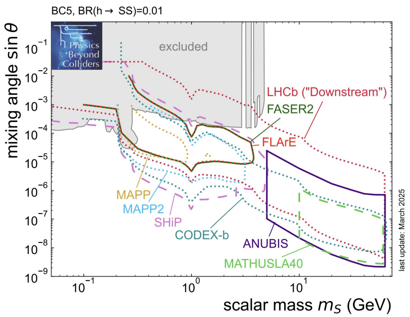


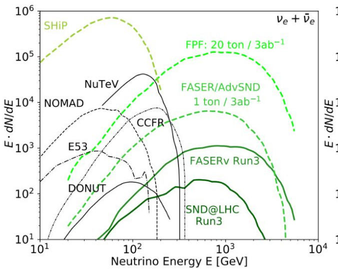
Extended exploitation of HL-LHC

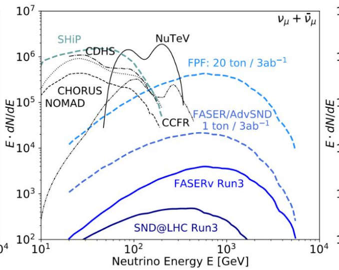
- Ways to extend physics program of HL-LHC
- Suite of beam dump and auxiliary (HL-)LHC experiments
  - Summary Report of the Physics Beyond Colliders Study at CERN
  - Direct comparison of LLP and neutrino programs at planned experiments for selected benchmarks

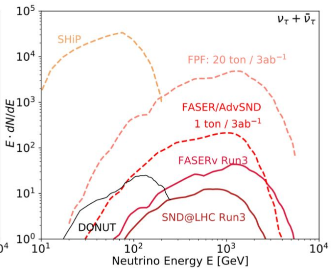
NEW

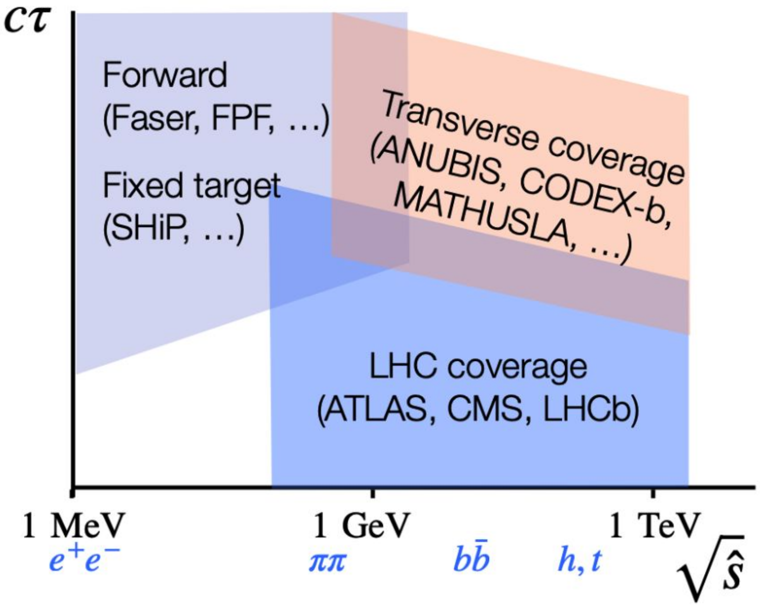






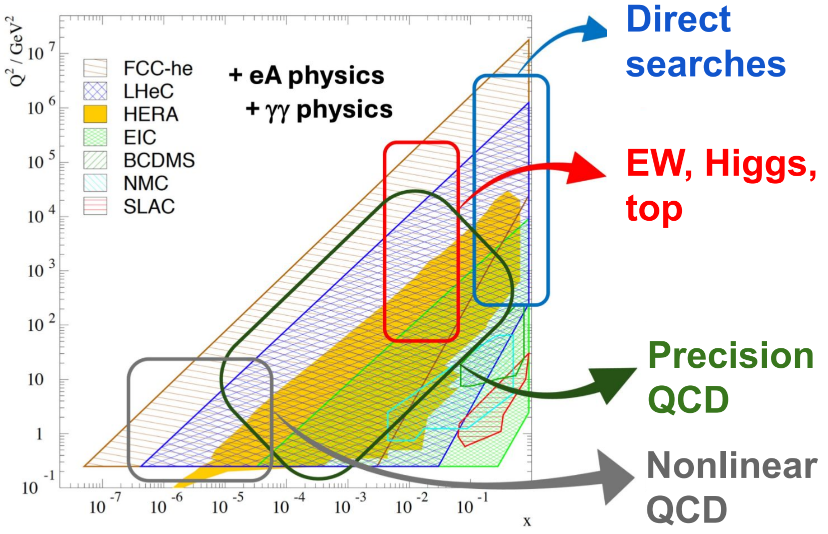






Extended use of LHC tunnel - I

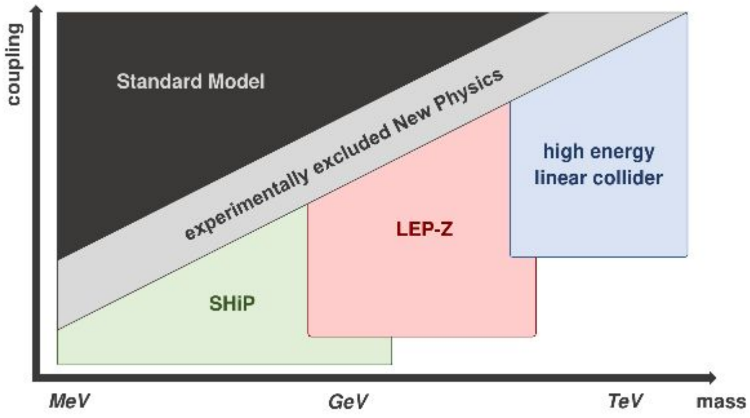
- LHeC
  - The Large Hadron electron Collider (LHeC) as a bridge project for CERN
    - Potential to be general purpose experiment.
    - Could start only after the current HL-LHC, but can run in parallel if, e.g. HL LHC is extended
  - Phase-One LHeC
    - Proposal to build a LHeC (20 GeV electrons) to run concurrently with LHC run 5 (ie before the baseline LHeC proposal)
    - Science case based on alphaS and PDF precision, EW/Higgs physics



Extended use of LHC tunnel II

- LEP3
  - LEP3: A High-Luminosity e+ e− Higgs & Electroweak Factory in the LHC Tunnel
  - LEP3 programme (Z for 5, WW for 4, ZH for 6 years), improves Higgs precision w.r.t. HL-LHC
  - Claim is to have a stronger EW programme compared to LC, and similar Higgs

- Concurrent Z-factory and Linear collider
  - A Possible Future Use of the LHC Tunnel
  - Dual strategy: Z-factory (LEP-Z rather than LEP3, a few 10^12 Z's) in the LHC tunnel + linear collider (unclear whether con-currently or later)
  - Physics case: weakly interacting particles in the few

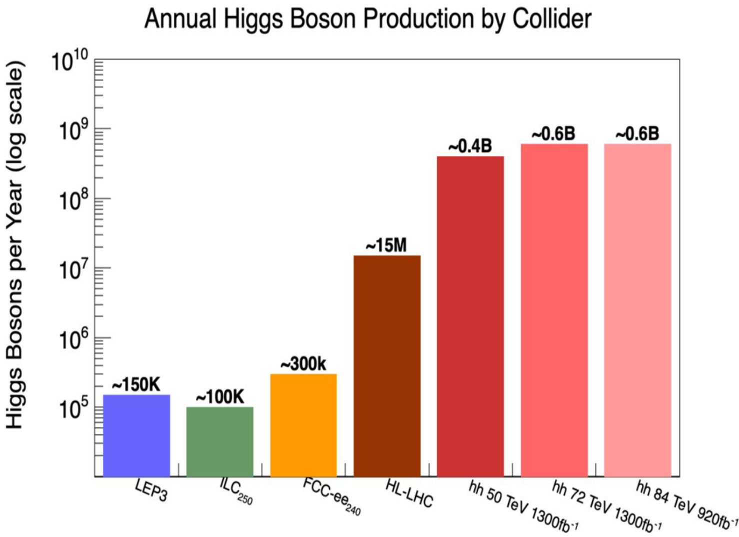


New perspectives?

NEW

- High-field magnet timelines: [High Field Magnet Programme – European Strategy Input]
  - LTS FCC-hh could be commissioned by 2050-2055.
    - 14T baseline, 4.5K operation, 12T = 73TeV CoME.
  - Commissioning of an HTS-based FCC-hh by 2060-2070

- Lower-energy FCC-hh: [Physics Prospects for a near-term Proton-Proton Collider]
  - Cost and time savings direct pp in the FCC tunnel
  - Any energy from focussed R&D on current mag tech
    - Adds a 50 TeV scenario to previous
  - Comparable or better Kappa measurements from HL-LHC+FCC-hh vs HL-LHC+FCC-ee



Linear Collider

Linear Collider Vision

- Global vision:
  - A Linear Collider Vision for the Future of Particle Physics
  - Discuss staged approach starting with known tech then upgrading with future tech for higher energies and/or luminosities

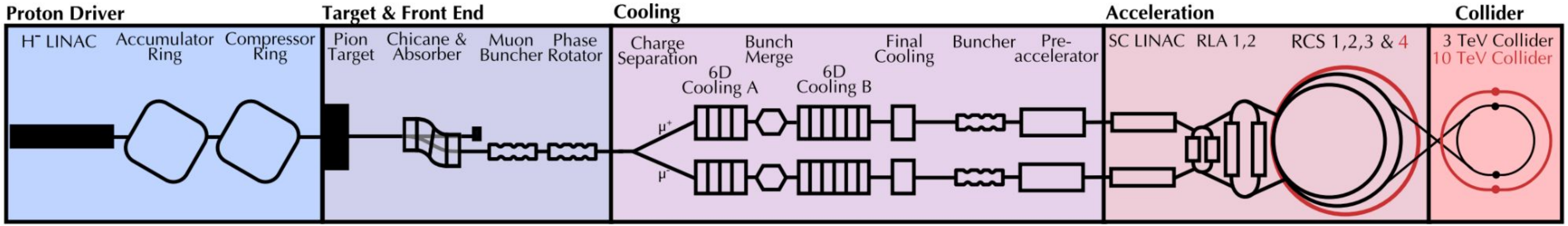
- ILC
  - Status of the International Linear Collider
  - Mainly cost estimate updates

- Linear collider options at CERN:
  - The Linear Collider Facility (LCF) at CERN
  - The Compact Linear e e Collider (CLIC)
  - ESPPU INPUT: C3 within the "Linear Collider Vision"
  - HALHF: a hybrid, asymmetric, linear Higgs factory using plasma- and RF-based acceleration

Intensive R&D projects

NEW

- Muon Collider
  - The Muon Collider
  - United States Muon Collider Community White Paper
    - Formation of a US Muon Collider Collaboration launched, to work closely with the International Muon Collider Collaboration hosted by CERN.

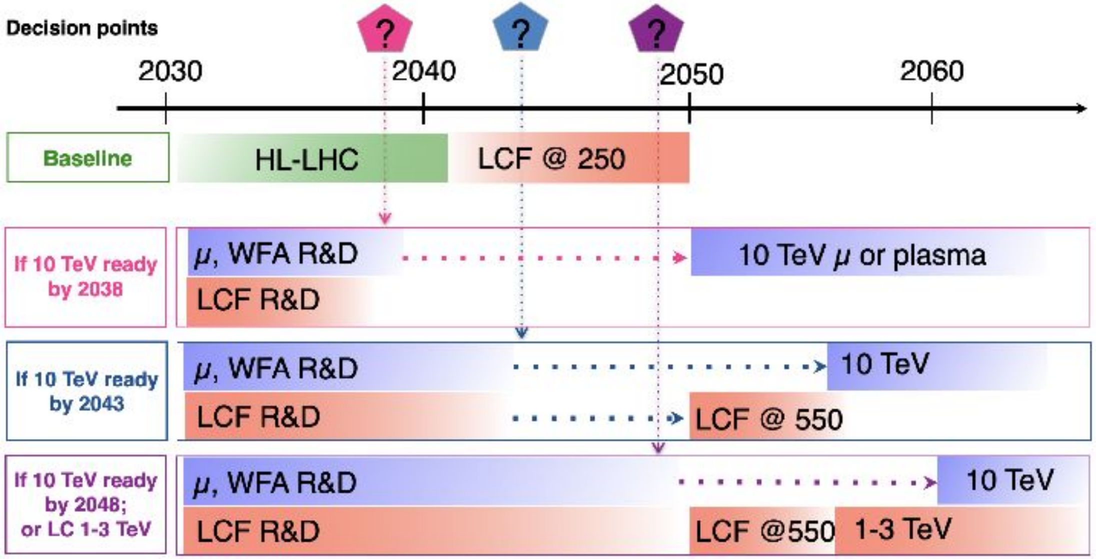


- Plasma Wakefield acceleration
  - AWAKE - Input to the European Strategy for Particle Physics Update
  - Contribution of ALEGRO to the Update of the European Strategy on Particle Physics
  - Formation of a 10 TeV Wakefield Collider Design Study group

Flexibility?

NEW

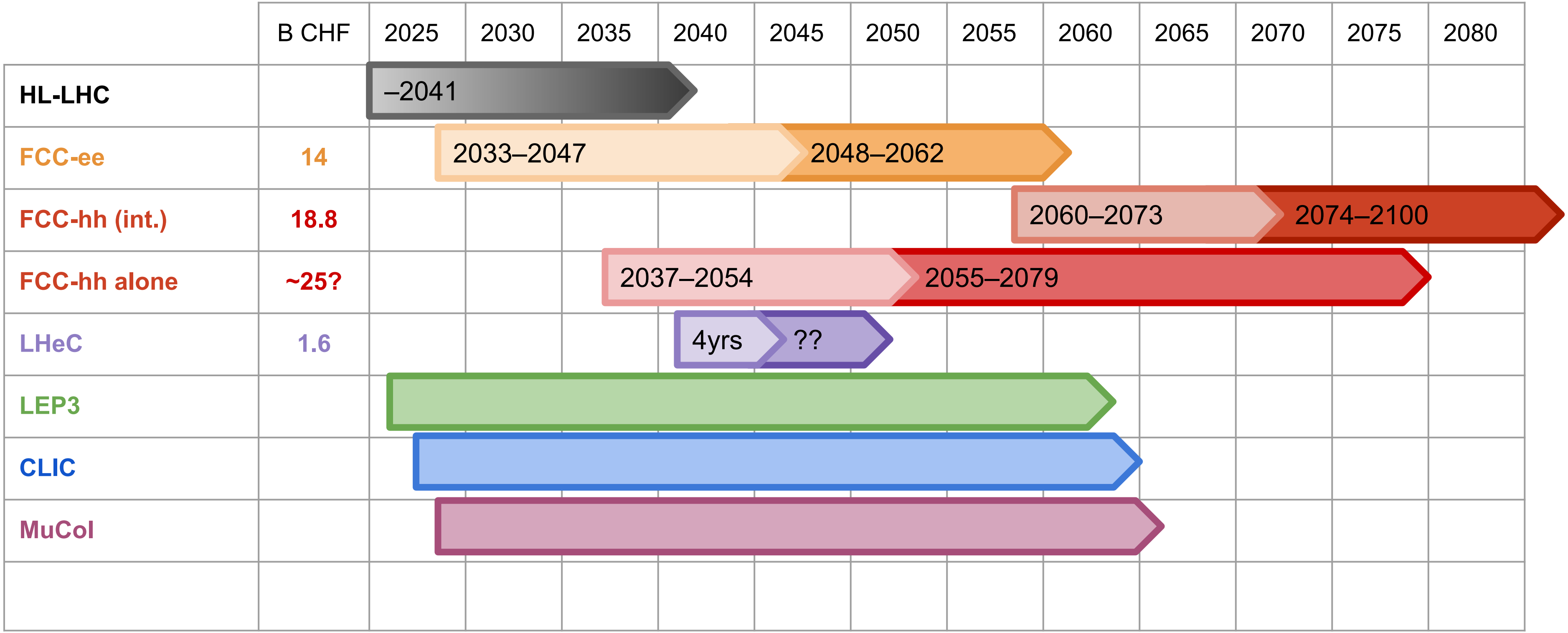
- A contribution discussing a flexible strategy for 10 TeV pCM asap
  - A Flexible Strategy for the Future of Particle Physics at CERN
- Overarching goal: 10 TeV as fast as possible, with muons, wakefield (WFA), C3 while having a ee Higgs factory (in the LHC tunnel or as linear collider)
- High-level strategy document
- Aim is to define decision points between a Linear Collider Facility (LCF)
- A possible alternative vision to FCC



Discussion

-

Timeline


B CHF
2025
2030
2035
2040
2045
2050
2055
2060
2065
2070
2075
2080
HL-LHC
–2041
FCC-ee
14
2033–2047
2048–2062
FCC-hh (int.)
18.8
2060–2073
2074–2100
FCC-hh alone
~25?
2037–2054
2055–2079
LHeC
1.6
4yrs
??
LEP3
CLIC
MuCol

Todo

- https://indico.cern.ch/event/1439855/contributions/6461564/

Back-ups

UK submission Plan A statements

- The community has a large contingent in support of the integrated programme of FCC-ee followed by FCC-hh, as well as a large contingent in favour of considering FCC-hh as the next collider at CERN.

UK submission ECR statements

- The UK ECR community stresses the importance of a definitive decision made in this round of the ESPPU for the next European flagship collider project to ensure the retention of talent in particle physics. Additionally, ECRs strongly endorse the continued UK commitment to a breadth of non-collider projects.

Software, Computing and ML

- **Submissions: 167, 168, 187, 18, 107, 127, 138, 185, 123, 124, 240, 150, 180, 9**
- By addressing HL-LHC computing needs properly (including careers for people working on software & computing infrastructure) we will be ready for future colliders
    - Career point: not much room for dedicated, permanent HEP Research Technical Professionals (computing/hardware) → e.g. technical debt
    - Synergy point: successful solutions can be shared and supported across data-intensive disciplines (e.g. data management, distributed computing incl GridPP)
- Data and analysis preservation, including reinterpretation and proper metadata, are necessary for legacy collider analyses (LHC / HL-LHC)
- Use of ML keeps growing and requires proper infrastructure
- Communication of results is important and should continue to be strongly supported by labs (including CERN)
    - INSPIRE-HEP, HEPData, arXiv, Zenodo, PDG, CERN Open Data portal, RIVET, MCPlots…

Sustainability

- **Submissions: 265, 162**
- Community recommendations *(document was UK-led)*, e.g.:
  - Measure emissions and environmental impacts of our labs (this is in place, should be done systematically)
  - Embed environmental sustainability & impact mitigation throughout the scientific programme - including lifecycle assessments, energy / compute resource procurement, harmful gases, biodiversity loss assessment, and travel
- Best practices for future facilities as outcome of working group on sustainability of future accelerators
  - Generally with community recommendations and suggest systematic and quantitative ways to measure/tackle environmental impact
- CERN can play a leading role and demonstrate commitment to Net Zero

PBC report

4.11 Summary of the proposals at CERN

Location	Proposal	Status	Cost category	Earliest operation
EHN1	NA61/SHINE ions	Addendum submitted to SPSC in 2024	C0	Run 4
	NA61/SHINE-LE	Proposal submitted to SPSC in 2024	C1	Run 4
	NA64 - Phase 2 – e	Proposal to be submitted to SPSC	C0	Run 4
	NA64 - Phase 2 – e^+	Conceptual Design	N/A	Run 4
	NA64 - Phase 2 – h	Conceptual Design	N/A	Run 4
	DICE/NA60+	Proposal to be submitted to SPSC in 2025	C2	Run 4
EHN2	NA64 - Phase 2 – μ	Proposal to be submitted to SPSC	C0	Run 4
	NA66/AMBER - Phase 2	Conceptual Design	C1/C2	Run 4
	MUonE	Conceptual Design	C1	Run 4
To be defined	SBN	Conceptual Study	N/A	Run 5
LHC	FPF	LoI to be submitted to LHCC in 2025	C3	Run 4
	SND@HL-LHC	Proposal submitted to LHCC in 2024	C1	Run 4
	ANUBIS	Data taking with prototype detector (proANUBIS)	N/A	Run 4
	CODEX-b	Data taking with prototype detector (CODEX-β)	N/A	Run 4
	MAPP-2	LoI to be submitted to LHCC in 2025	C1	Run 4
	MATHUSLA40	Data taking with prototype detectors	N/A	Run 4
	ALADDIN	Preparation of proposal to LHCC	C2	Run 4
	LHCspin	Conceptual Study	N/A	Run 5
	AION	EoI to be submitted to LHCC in 2025	C1	Run 4
	GF	Conceptual Study	N/A	After Run 5

Energy / Intensity frontier - colliders

(several) Key submissions

- HL-LHC related: ATLAS+CMS (Physics, upgrade, computing)
  - Physics Highlight: New key messages mostly related to new prospects i.e. in diHiggs (7 sigma - huge improvement), exclusion of First Order Phase Transition
  - Upgrade (n.189, n.177) and Computing (n.101, n.175)
- Intermediate collider projects
  - LHeC - first phase (E ele 20 GeV), bridge - default (50 GeV E ele)
    - DIS submission including also complementarities with EIC
  - Linear collider options (ie at CERN): vision document (global) + various submissions on e+e-
  - Low energy proton-proton (FCC tunnel needed for low-energy FCC)
- FCC:
  - FCC-ee and FCC-hh physics case, projects etc.
- Muon collider:
  - https://indico.cern.ch/event/1439855/abstracts/191122/

Energy / Intensity frontier - colliders

(several) Key submissions

- HL-LHC related: ATLAS+CMS (Physics, upgrade, computing)
  - Physics Highlight: New key messages mostly related to new prospects i.e. in diHiggs (7 sigma - huge improvement), exclusion of First Order Phase Transition
  - Upgrade (n.189, n.177) and Computing (n.101, n.175)
- Intermediate collider projects
  - LHeC - first phase (E ele 20 GeV), bridge - default (50 GeV E ele)
    - DIS submission including also complementarities with EIC
  - Linear collider options (ie at CERN): vision document (global) + various submissions on e+e-
  - Low energy proton-proton (FCC tunnel needed for low-energy FCC)
- FCC:
  - FCC-ee and FCC-hh physics case, projects etc.
- Muon collider:
  - https://indico.cern.ch/event/1439855/abstracts/191122/

Flavour at colliders

Key submissions

- 223. Projections for Key Measurements in Heavy Flavour Physics
  - Joint submission from ATLAS, CMS, LHCb & Belle II, taking data from
    - 81. Discovery potential of LHCb Upgrade II
    - 205. The Belle II Experiment at SuperKEKB
    - ATLAS & CMS projections at, e.g., ATL-PHYS-PUB-2025-016, CMS-NOTE-2025-004
- 196. Prospects in flavour physics at the FCC
  - Mostly focussed on FCC-ee at Z pole, brief FCC-hh discussion
    - Flavour physics also possible at other hh colliders, but not discussed in e.g. 239. Physics Prospects for a near-term Proton-Proton Collider
  - No dedicated flavour at CEPC submission, but sensitivity expected to be ~same as FCC-ee (see arXiv:2412.19743)
- 140. A Linear Collider Vision for the Future of Particle Physics
  - Limited Z pole programme, main relevance in $|V_{cb}|$ and other CKM matrix elements using on-shell W decays
- 188. LEP3: A High-Luminosity e+e− Higgs & Electroweak Factory in the LHC Tunnel and 165. A Possible Future Use of the LHC Tunnel
  - $O(10^{12})$ $Z \to bb$ decays so potentially similar flavour physics programme to FCC-ee/CEPC, not discussed in detail

223. Projections for Key Measurements in Heavy Flavour Physics

Tables with projected sensitivities for a range of observables.
Don't try to read the details. Summary plots on next slide.

Today

Experiment Assumed data sample	ATLAS 20.3-99.7 fb^{-1}	CMS 116-140 fb^{-1}	LHCb 2-9 fb^{-1}	Belle II 364-1075 fb^{-1}
CKM angles				
β	—	—	0.57° [15]	1.2° [16]
α	—	—	—	6.6° [17]
γ	—	—	2.8° [18]	13° [17]
ϕ_s [mrad]	42 [19]	23 [20]	20 [21]	—
***CP* violation in loop-dominated decays**				
$S(B^0 \to \eta' K^0_S)$	—	—	—	0.087 [17]
$\phi_s(B^0_s \to \phi\phi)$ [mrad]	—	—	69 [22]	—
$\phi_s(B^0_s \to K^{*0}\overline{K}^{*0})$ [mrad]	—	—	130 [23]	—
***CP* violation in $B^0_{(s)}$–$\overline{B}^0_{(s)}$ mixing**				
a^s_{sl} [10^{-4}]	—	—	33 [24]	—
a^d_{sl} [10^{-4}]	—	—	36 [25]	40 [26]
***CP* violation in the charm sector**				
ΔA_{CP} [10^{-5}]	—	—	29 [27]	630 [16]
$A_{CP}(D^{+,0} \to \pi^{+,0}\pi^0)$ [10^{-5}]	—	—	900 [28], —	870, 750
$A_\Gamma(KK, \pi\pi)$ [10^{-5}]	—	—	11 [29]	—
$\Delta x(D^0 \to K^0_S\pi^+\pi^-)$ [10^{-5}]	—	—	18 [30]	140 [31]
Semileptonic *B* decays				
$\lvert V_{ub}\rvert$	—	—	6% [32]	6.3% [33]
$\lvert V_{cb}\rvert$	—	—	—	1.7% [34]
$R(D)$, $R(D^*)$	—	—	14% [35], 6% [36]	12%, 7% [17]
Leptonic *B* decays				
$\mathcal{B}(B^0_s \to \mu^+\mu^-)$ [10^{-9}]	$^{+0.8}_{-0.7}$ [37]	0.45 [38]	0.48 [39]	—
$\mathcal{B}(B^0 \to \mu^+\mu^-)$ [10^{-10}]	$< 2.1^*$ [37]	< 1.5 [38]	0.79 [39]	—
$\tau_{\text{eff}}(B^0_s \to \mu^+\mu^-)$ [ps]	$^{+0.45}_{-0.18}$ [40]	0.23 [38]	0.29 [39]	—
$S(B^0_s \to \mu^+\mu^-)$	—	—	—	—
$\mathcal{B}(B^+ \to \tau^+\nu_\tau)$	—	—	—	34% [17]
$\mathcal{B}(B^+ \to \mu^+\nu_\mu)$	—	—	—	41% [17]
Flavour-changing neutral current $b \to s\ell\ell$ decays				
$P'_5(B^0 \to K^{*0}\mu^+\mu^-)$ [10^{-3}] †	390 [41]	100 [42]	111 [43]	—
$\mathcal{B}(B^{+,0} \to K^{+,*0}\nu\overline{\nu})$	—	—	—	57%, 110% [17]
$\mathcal{B}(B^{+,0} \to K^{+,*0}\tau^+\tau^-)$ [10^{-4}]	—	—	—	< 10, < 18 [44]
Flavour-changing neutral current $b \to s\gamma$ decays				
$\mathcal{B}(B \to X_s\gamma; E_\gamma > 1.6\,\text{GeV})$	—	—	—	$(16-18)$% [17]
$S(B^0 \to K^0_S\pi^0\gamma)$	—	—	—	0.27 [45]
$S(B^0_s \to \phi\gamma)$	—	—	0.32 [46]	—
$A^{(2)}_T(B^0 \to K^{*0}e^+e^-$; very low $q^2)$	—	—	0.10 [47]	0.76 [48]
$\alpha_\gamma(\Lambda^0_b \to \Lambda^0\gamma)$	—	—	0.26 [49]	—
Lepton flavour violation in τ decays				
$\mathcal{B}(\tau^+ \to \mu^+\gamma)$ [10^{-8}]	—	—	—	< 7.5 [16]
$\mathcal{B}(\tau^+ \to \mu^+\mu^+\mu^-)$ [10^{-8}]	< 37.6 [50]	< 2.9 [51]	< 4.6 [52]	< 1.8 [53]

† The sensitivity for the P'_5 variable is quoted for the range $q^2 \in [4.0, 6.0]\,\text{GeV}^2$ for ATLAS and LHCb and $q^2 \in [4.3, 6.0]\,\text{GeV}^2$ for CMS.

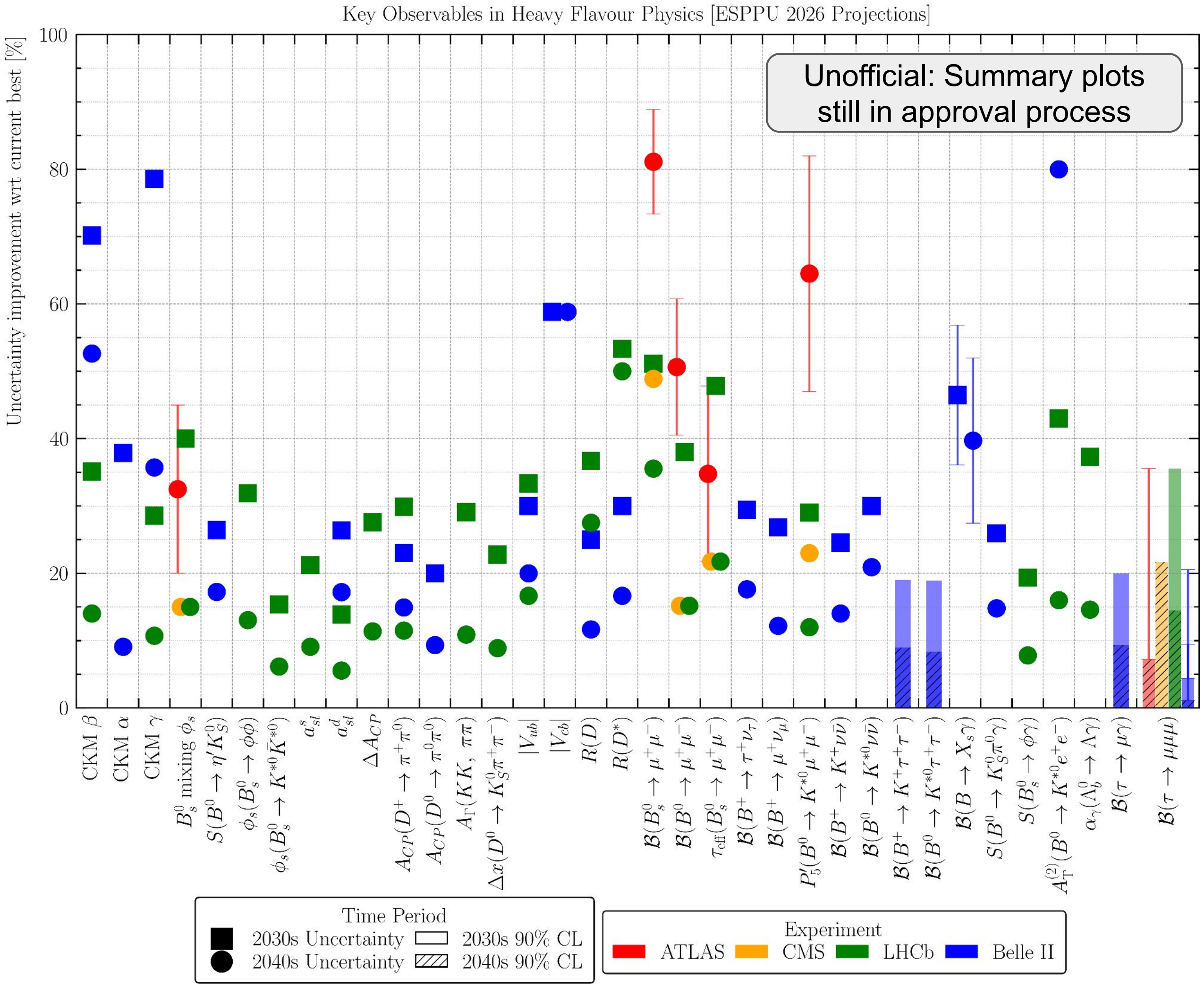
Experiment Assumed data sample	ATLAS 3000 fb^{-1}	CMS 3000 fb^{-1}	LHCb 300 fb^{-1}	Belle II 50 ab^{-1}
CKM angles				
β	—	—	0.08°	0.3°
α	—	—	—	0.6°
γ	—	—	0.3°	1.0°
ϕ_s [mrad]	$(4-9)$	3	3	—
***CP* violation in loop-dominated decays**				
$S(B^0 \to \eta' K^0_S)$	—	—	—	0.015
$\phi_s(B^0_s \to \phi\phi)$ [mrad]	—	—	9	—
$\phi_s(B^0_s \to K^{*0}\overline{K}^{*0})$ [mrad]	—	—	8	—
***CP* violation in $B^0_{(s)}$–$\overline{B}^0_{(s)}$ mixing**				
a^s_{sl}	—	—	3	—
a^d_{sl}	—	—	2	6.2
***CP* violation in the charm sector**				
ΔA_{CP} [10^{-5}]	—	—	3.3	60
$A_{CP}(D^{+,0} \to \pi^{+,0}\pi^0)$ [10^{-5}]	—	—	100, —	130, 70
$A_\Gamma(KK, \pi\pi)$ [10^{-5}]	—	—	1.2	—
$\Delta x(D^0 \to K^0_S\pi^+\pi^-)$ [10^{-5}]	—	—	1.6	40
Semileptonic *B* decays				
$\lvert V_{ub}\rvert$	—	—	1%	1.2%
$\lvert V_{cb}\rvert$	—	—	—	1.0%
$R(D)$, $R(D^*)$	—	—	3.3%, 3.0%	1.4%, 1.0%
Leptonic *B* decays				
$\mathcal{B}(B^0_s \to \mu^+\mu^-)$ [10^{-9}]	$(0.33-0.40)$	0.22	0.16	—
$\mathcal{B}(B^0 \to \mu^+\mu^-)$ [10^{-10}]	$(0.32-0.48)$	0.12	0.12	—
$\tau_{\text{eff}}(B^0_s \to \mu^+\mu^-)$ [ps]	$^{+(0.07-0.11)}_{-(0.05-0.08)}$	0.05	0.05	—
$S(B^0_s \to \mu^+\mu^-)$	—	—	0.2	—
$\mathcal{B}(B^+ \to \tau^+\nu_\tau)$	—	—	—	6%
$\mathcal{B}(B^+ \to \mu^+\nu_\mu)$	—	—	—	5%
Flavour-changing neutral current $b \to s\ell\ell$ decays				
$P'_5(B^0 \to K^{*0}\mu^+\mu^-)$ [10^{-3}] †	$(47-82)$	23	12	—
$\mathcal{B}(B^{+,0} \to K^{+,*0}\nu\overline{\nu})$	—	—	—	8%, 23%
$\mathcal{B}(B^{+,0} \to K^{+,*0}\tau^+\tau^-)$ [10^{-4}]	—	—	—	< 0.9, < 1.5
Flavour-changing neutral current $b \to s\gamma$ decays				
$\mathcal{B}(B \to X_s\gamma; E_\gamma > 1.6\,\text{GeV})$	—	—	—	$(4.7-8.8)$%
$S(B^0 \to K^0_S\pi^0\gamma)$	—	—	—	0.04
$S(B^0_s \to \phi\gamma)$	—	—	0.025	—
$A^{(2)}_T(B^0 \to K^{*0}e^+e^-$; very low $q^2)$	—	—	0.016	0.08
$\alpha_\gamma(\Lambda^0_b \to \Lambda^0\gamma)$	—	—	0.038	—
Lepton flavour violation in τ decays				
$\mathcal{B}(\tau^+ \to \mu^+\gamma)$ [10^{-8}]	—	—	—	< 0.7
$\mathcal{B}(\tau^+ \to \mu^+\mu^+\mu^-)$ [10^{-8}]	$< (0.13-0.64)$	< 0.39	< 0.26	$< (0.02-0.17)$

† The sensitivity for the P'_5 variable is quoted for the range $q^2 \in [4.0, 6.0]\,\text{GeV}^2$ for ATLAS and LHCb and $q^2 \in [4.3, 6.0]\,\text{GeV}^2$ for CMS.

2040s
(end of HL-LHC and Belle II)

Typically expect an order of magnitude improvement in sensitivity.
Some observables become systematically limited.

Great discovery potential in theoretically clean processes if BSM physics is hiding in loops. Strong constraints on models and EFTs if not.



Improvements by 2040s (end of HL-LHC and SuperKEKB) typically an order of magnitude compared to today

Most impact from LHCb and Belle II, with important contributions from ATLAS and CMS – world averages will be even better with multiple precise measurements

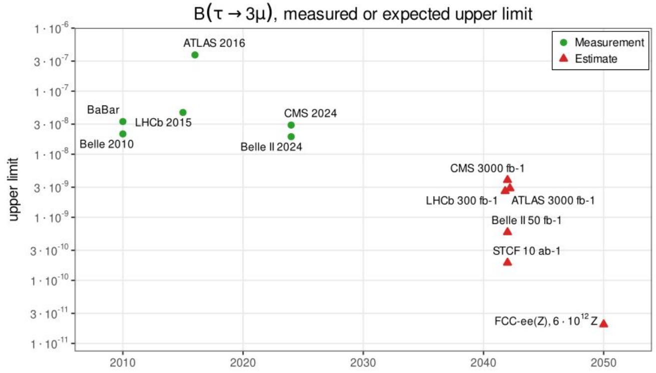
196. Prospects in flavour physics at the FCC

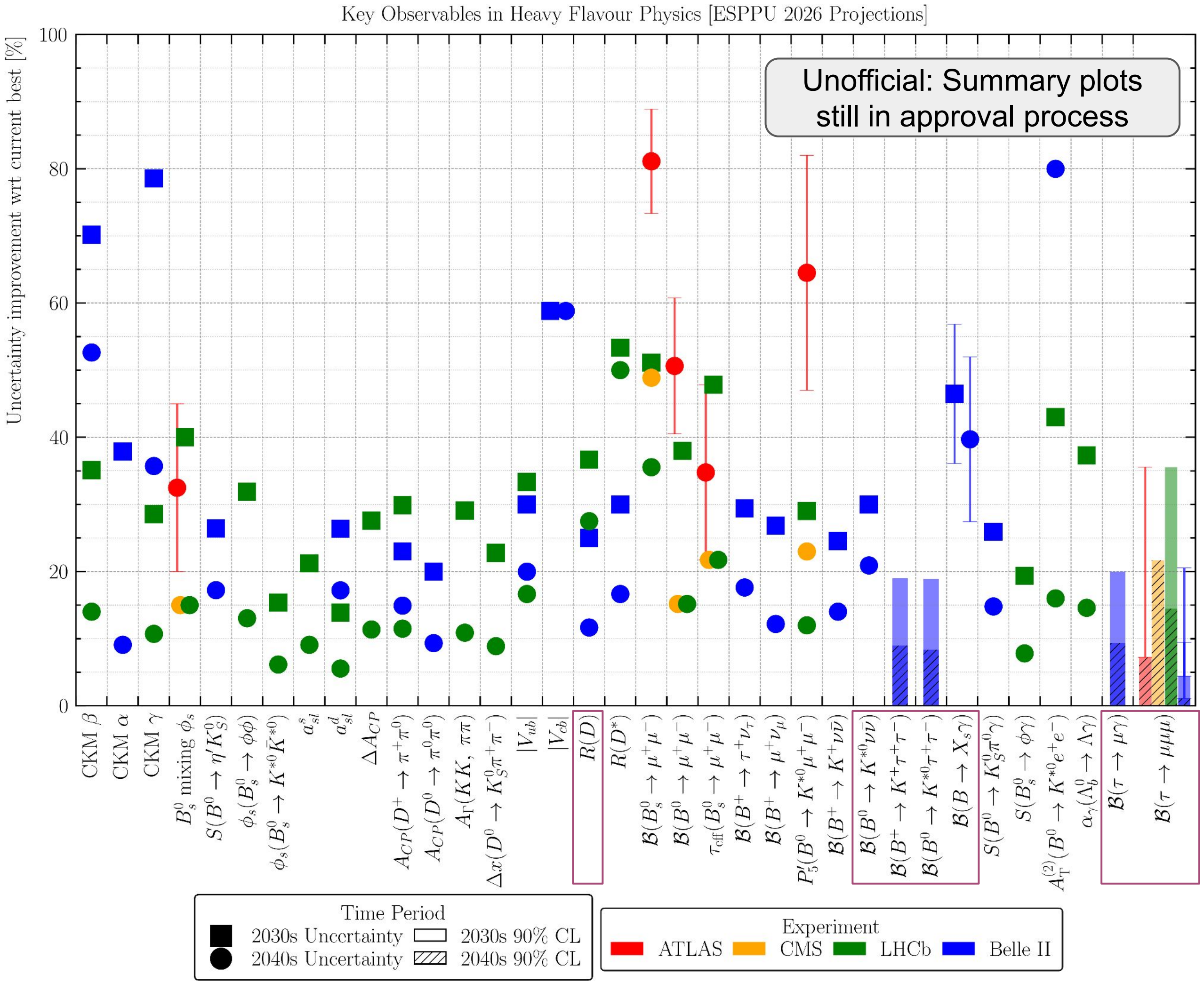
Number of produced b and c hadrons small compared to (HL-)LHC, but advantages due to $e^+e^- \to Z$ production environment (see table below)

- Especially for modes with missing energy (νs) and τ physics
  - Significantly better than Belle II and LHC experiments for
    - $B \to K^{(*)}\tau\tau$ – sensitivity to SM branching fraction of $O(10^{-7})$
    - $B \to K^{(*)}\nu\nu$ – BFs at O(%) level precision and studies of q^2 distribution
    - τ LFV sensitivity (see figure)
- Can also be competitive for some other key observables

Table 1: Advantageous attributes for flavour-physics studies at Belle II ($\Upsilon(4S)$), the LHC (pp) and FCC-ee (Z).

Attribute	$\Upsilon(4S)$	pp	Z	Caveats
All hadron species		✓	✓	Some production rates (e.g. B_c) not known
High boost		✓	✓	
Enormous production cross-section		✓		
Negligible trigger losses	✓		✓	
High geometrical acceptance	✓		✓	
Low backgrounds	✓		✓	Boost and detector expected to compensate for extra fragmentation particles relative to $\Upsilon(4S)$
Flavour-tagging power	✓		✓	Better than pp but not as good as $\Upsilon(4S)$
Initial-energy constraint	✓		(✓)	





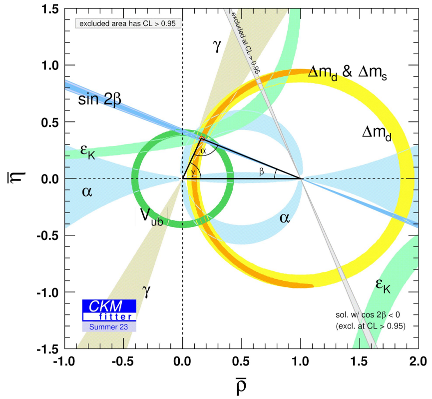
Improvements by 2040s (end of HL-LHC and SuperKEKB) typically an order of magnitude compared to today

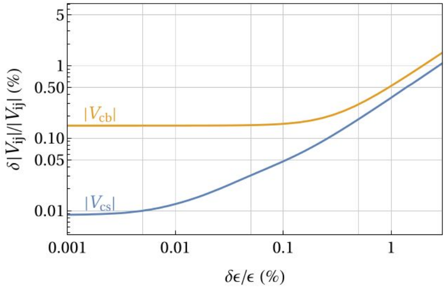
Most impact from LHCb and Belle II, with important contributions from ATLAS and CMS – world averages will be even better with multiple precise measurements

Further large improvements expected from FCC-ee for certain observables

CKM matrix elements from on-shell W decays

- Knowledge of $|V_{cb}|$ important in global CKM fits
  - e.g. dominates width of ε_K band in constraints on Unitarity Triangle
- Current knowledge limited by tension between inclusive and exclusive determinations of b→c process
  - likely to be resolved with Belle II data but systematic limitation around 1%
- Measurements with on-shell W decays have completely different theoretical and experimental uncertainties
  - statistical uncertainty could reach 0.15% at either FCC-ee or LC with $O(10^8)$ $e^+e^- \to W^+W^-$
  - jet-tagging performance can be calibrated using Z data
  - running of CKM matrix elements with energy scale could be probed
- Possibilities to make similar measurements at LHC using top decays under investigation





Systematic uncertainty on jet tagging efficiency

PBC comparisons

- Takes into account maturity of the background estimates:
  - solid = extrapolation of existing data sets
  - dashed = full MC simulations
  - dotted = toy MC simulations or ~zero background assumption
-