

Discussion Session: The Future of Flavour Physics

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Discussion Session
Flavour @ TH workshop
CERN May 8 - 12, 2023

According to ChatGPT ...

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What's the future of flavor physics?

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What's the future of flavor physics?



Flavor physics, which is the study of particles and their interactions involving the flavor of quarks and leptons, is a rapidly evolving field with many exciting developments in recent years. Here are some possible future directions for flavor physics:

1. Precision measurements of CKM parameters: The Cabibbo-Kobayashi-Maskawa (CKM) matrix describes the mixing between different generations of quarks, and precise measurements of its parameters can provide a sensitive test of the Standard Model and probe for new physics. Future experiments at the Large Hadron Collider (LHC) and the proposed Belle II experiment at the SuperKEKB accelerator in Japan will aim to make even more precise measurements of CKM parameters.
2. Search for new physics beyond the Standard Model: Flavor physics can also provide a window into physics beyond the Standard Model, which is the current best theory describing the behavior of elementary particles. Deviations from the Standard Model predictions in flavor observables could indicate the presence of new particles or interactions, such as those predicted by supersymmetry or extra dimensions. Future experiments at the LHC, as well as dedicated flavor experiments like Belle II and LHCb, will continue to search for new physics.

3. Neutrino physics: Neutrinos are elusive particles that interact only weakly with matter, making them difficult to detect. However, they play a crucial role in flavor physics, as they come in three different flavors and can change flavor as they travel through space. Future experiments like the Deep Underground Neutrino Experiment (DUNE) in the United States and the Hyper-Kamiokande experiment in Japan will study neutrino oscillations in great detail and may shed light on the origin of neutrino masses and the hierarchy problem.
4. Flavor in cosmology: The observed baryon asymmetry of the universe, where there is a slight excess of matter over antimatter, is one of the biggest mysteries in cosmology. Flavor physics may provide insights into this problem, as some theories of baryogenesis (the process that created the asymmetry) rely on CP-violating processes in flavor-changing interactions. Future experiments at the LHC and in dedicated flavor experiments could help to test these theories and shed light on the nature of the baryon asymmetry.

Overall, the future of flavor physics looks very promising, with exciting developments expected in precision measurements, searches for new physics, neutrino physics, and cosmology.

The Basic Questions

$$\begin{aligned}\mathcal{L}_{\text{SM}} \sim & \Lambda^4 + \Lambda^2 H^2 + \lambda H^4 \\ & + \bar{\Psi} \not{D} \Psi + (D_\mu H)^2 + (F_{\mu\nu})^2 + F_{\mu\nu} \tilde{F}^{\mu\nu} \\ & + Y H \bar{\Psi} \Psi\end{aligned}$$

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$$+ Y H \bar{\Psi} \Psi$$

CC problem

Hierarchy problem

Vacuum stability?

Strong CP problem

SM flavor puzzle

Q1: What is the origin of the hierarchies in the SM sources of flavor violation?

The Basic Questions

The diagram illustrates the Standard Model Lagrangian, \mathcal{L}_{SM} , and its associated problems. The Lagrangian is written as:

$$\mathcal{L}_{\text{SM}} \sim \Lambda^4 + \Lambda^2 H^2 + \lambda H^4 + \bar{\Psi} \not{D} \Psi + (D_\mu H)^2 + (F_{\mu\nu})^2 + F_{\mu\nu} \tilde{F}^{\mu\nu} + Y H \bar{\Psi} \Psi + \frac{1}{\Lambda} (LH)^2 + \frac{1}{\Lambda^2} \sum_i \mathcal{O}_i^{\text{dim}6} + \dots$$

Callouts identify the following issues:

- CC problem**: Points to the Λ^4 term.
- Hierarchy problem**: Points to the $\Lambda^2 H^2$ term.
- Vacuum stability?**: Points to the λH^4 term.
- Strong CP problem**: Points to the $F_{\mu\nu} \tilde{F}^{\mu\nu}$ term.
- SM flavor puzzle**: Points to the $Y H \bar{\Psi} \Psi$ term.
- Neutrino masses**: Points to the $\frac{1}{\Lambda} (LH)^2$ term.
- Flavorful new physics?**: Points to the $\frac{1}{\Lambda^2} \sum_i \mathcal{O}_i^{\text{dim}6}$ term.

Q1: What is the origin of the hierarchies in the SM sources of flavor violation?

Q2: Are there other sources of flavor violation beyond the SM?

Should we do more flavour model building?

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Is there “intrinsic” value in
precision determinations of CKM parameters?

- The Near Future:

“ R_K and R_{K^*} are gone. What now?”

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- The Midterm Future:

What will we learn with 50 ab^{-1} from Belle II?

What with 300 fb^{-1} from LHCb?

Kaons (NA62, KOTO), pions (PIONEER), muons (mu2e)

Will there be a super tau charm factory?

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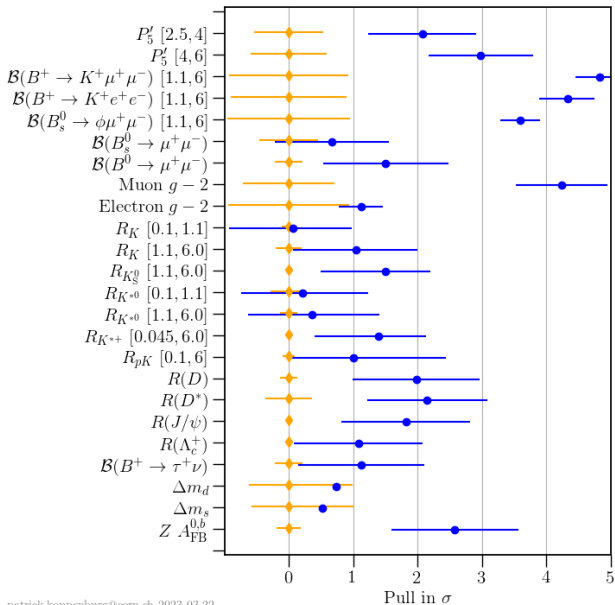
Will there be a super tau charm factory?

- The Far Future:

What comes after that?

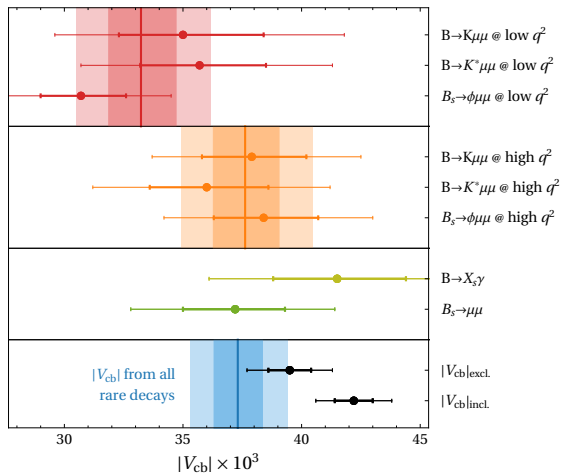
Flavour program at FCC-ee/CEPC? FCC-hh/SppC? Muon collider?

Not All Anomalies Are Gone



patrick.koppenburg@cern.ch 2023-03-22

The Role of V_{cb}



WA, Lewis 2112.03437

- ▶ Predictions for $b \rightarrow s \mu \mu$ rates depend sensitively on $|V_{cb}|$.
- ▶ Since many years there are tensions between **inclusive and exclusive determinations of V_{cb}** .
- ▶ The rare B decay rates could be partially explained by a **(very) low $|V_{cb}|$** .
- ▶ **Why do almost all rare decay fits use the inclusive V_{cb} value?**

Controlling Hadronics: $B \rightarrow K$ Form Factors

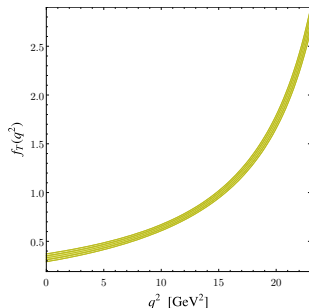
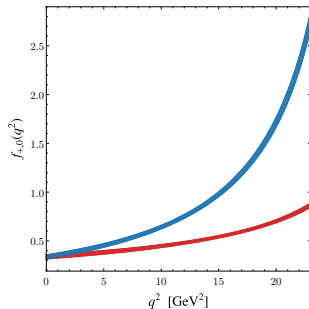
- ▶ $B \rightarrow K$ form factors are determined with **percent level precision** from **lattice calculations**!

Fermilab/MILC 1509.06235

HPQCD 1306.2384, 2207.12468

- ▶ I get a bit nervous seeing such a high precision. **Do we really trust them?**

[On the right I am plotting the form factors from the combination by Becirevic, Piazza, Sumensari 2301.06990 with 2σ uncertainties]



Controlling Hadronics: $B \rightarrow K^*$ Form Factors

- ▶ **LCSR + lattice** combinations by

Bharucha, Straub, Zwicky 1503.05534

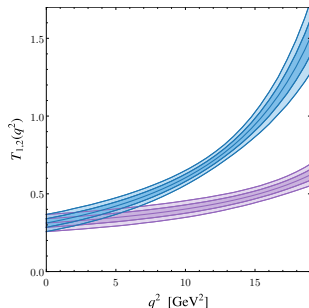
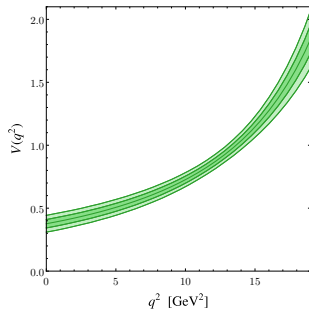
Gubernari, Kokulu, van Dyk 1811.00983

Gubernari, Reboud, van Dyk, Virto 2206.03797

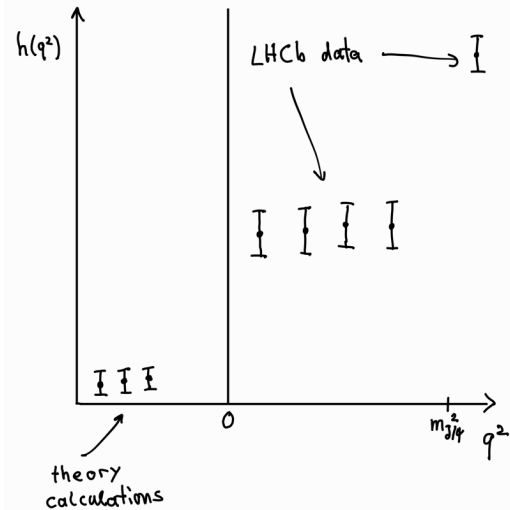
- ▶ Uncertainties around **5% - 10%**

- ▶ How reliable are the uncertainties?
What even is a $B \rightarrow K^*$ form factor?
Better to do $B \rightarrow K\pi$?

[On the right I am plotting
form factors from BSZ]



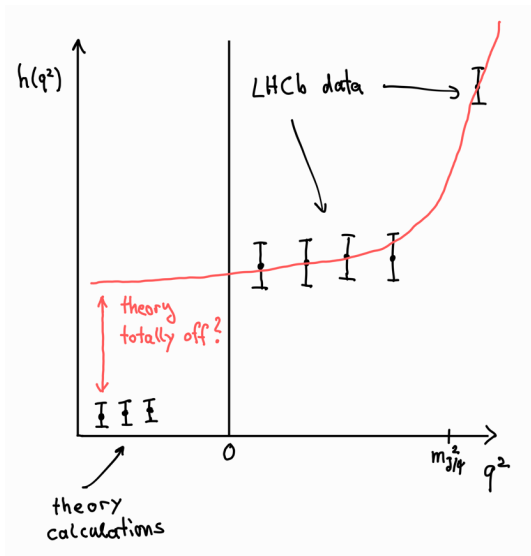
Controlling Hadronics: “Charm Loops”



[Note: This is highly oversimplified]

Parameterize them and fit them to data and/or theory calculations

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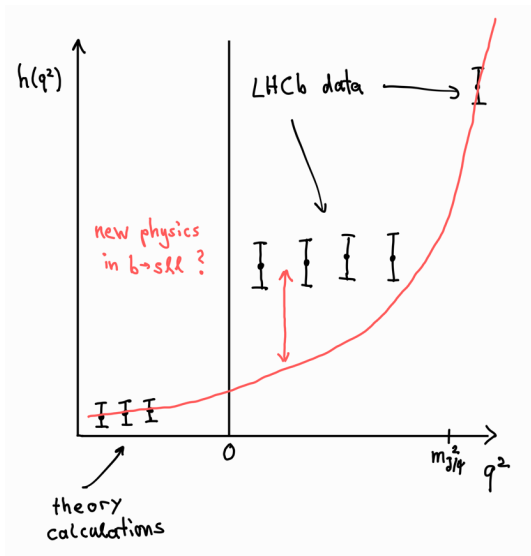


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How **reliable** are the theory calculations?

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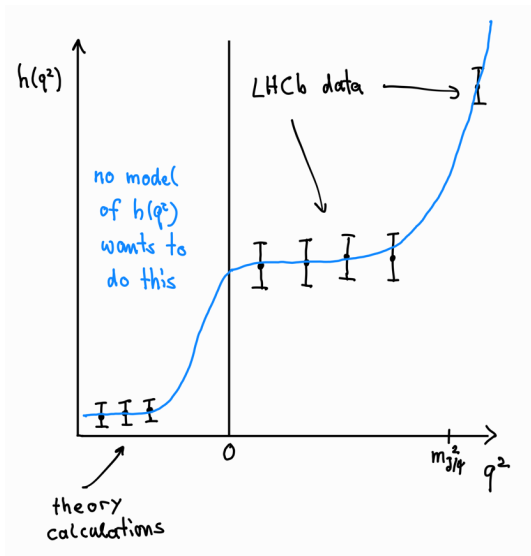


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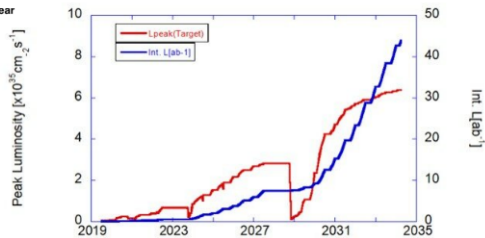
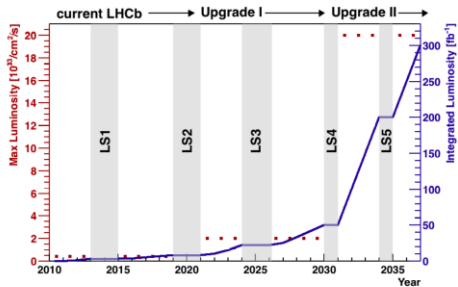
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How **reliable** are the theory calculations?

How **flexible** are the parameterizations of the non-local effects?

Is there too much focus on Anomalies?

Looking Ahead



(Some) Expected Results from Belle II

Observables	Expected the. accuracy	Expected exp. uncertainty	Facility (2025)
UT angles & sides			
ϕ_1 [°]	***	0.4	Belle II
ϕ_2 [°]	**	1.0	Belle II
ϕ_3 [°]	***	1.0	LHCb/Belle II
$ V_{cb} $ incl.	***	1%	Belle II
$ V_{cb} $ excl.	***	1.5%	Belle II
$ V_{ub} $ incl.	**	3%	Belle II
$ V_{ub} $ excl.	**	2%	Belle II/LHCb
<i>CP</i> Violation			
$S(B \rightarrow \phi K^0)$	***	0.02	Belle II
$S(B \rightarrow \eta' K^0)$	***	0.01	Belle II
$\mathcal{A}(B \rightarrow K^0 \pi^0) [10^{-2}]$	***	4	Belle II
$\mathcal{A}(B \rightarrow K^+ \pi^-) [10^{-2}]$	***	0.20	LHCb/Belle II
(Semi-)leptonic			
$\mathcal{B}(B \rightarrow \tau \nu) [10^{-6}]$	**	3%	Belle II
$\mathcal{B}(B \rightarrow \mu \nu) [10^{-6}]$	**	7%	Belle II
$R(B \rightarrow D \tau \nu)$	***	3%	Belle II
$R(B \rightarrow D^* \tau \nu)$	***	2%	Belle II/LHCb
Radiative & EW Penguins			
$\mathcal{B}(B \rightarrow X_s \gamma)$	**	4%	Belle II
$A_{CP}(B \rightarrow X_{s,d} \gamma) [10^{-2}]$	***	0.005	Belle II
$S(B \rightarrow K_S^0 \pi^0 \gamma)$	***	0.03	Belle II
$S(B \rightarrow \rho \gamma)$	**	0.07	Belle II
$\mathcal{B}(B_s \rightarrow \gamma \gamma) [10^{-6}]$	**	0.3	Belle II
$\mathcal{B}(B \rightarrow K^+ \nu \bar{\nu}) [10^{-6}]$	***	15%	Belle II
$R(B \rightarrow K^+ \ell \ell)$	***	0.03	Belle II/LHCb
Charm			
$\mathcal{B}(D_s \rightarrow \mu \nu)$	***	0.9%	Belle II
$\mathcal{B}(D_s \rightarrow \tau \nu)$	***	2%	Belle II
$A_{CP}(D^0 \rightarrow K_S^0 \pi^0) [10^{-2}]$	**	0.03	Belle II
$ q/p (D^0 \rightarrow K_S^0 \pi^+ \pi^-)$	***	0.03	Belle II
$A_{CP}(D^+ \rightarrow \pi^+ \pi^0) [10^{-2}]$	**	0.17	Belle II
Tau			
$\tau \rightarrow \mu \gamma [10^{-10}]$	***	< 50	Belle II
$\tau \rightarrow e \gamma [10^{-10}]$	***	< 100	Belle II
$\tau \rightarrow \mu \mu \mu [10^{-10}]$	***	< 3	Belle II/LHCb

(Some) Expected Results from LHCb

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
$R_K (1 < q^2 < 6 \text{ GeV}^2 c^4)$	0.1 274	0.025	0.036	0.007	–
$R_{K^*} (1 < q^2 < 6 \text{ GeV}^2 c^4)$	0.1 275	0.031	0.032	0.008	–
$R_\phi, R_{\rho K}, R_\pi$	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–
CKM tests					
γ , with $B_s^0 \rightarrow D_s^+ K^-$	$(\begin{smallmatrix} +17 \\ -22 \end{smallmatrix})^\circ$ 136	4°	–	1°	–
γ , all modes	$(\begin{smallmatrix} +5.0 \\ -5.8 \end{smallmatrix})^\circ$ 167	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \rightarrow J/\psi K_S^0$	0.04 609	0.011	0.005	0.003	–
ϕ_s , with $B_s^0 \rightarrow J/\psi \phi$	49 mrad 44	14 mrad	–	4 mrad	22 mrad 610
ϕ_s , with $B_s^0 \rightarrow D_s^+ D_s^-$	170 mrad 49	35 mrad	–	9 mrad	–
ϕ_s^{SS} , with $B_s^0 \rightarrow \phi \phi$	154 mrad 94	39 mrad	–	11 mrad	Under study 611
a_{sl}^s	33×10^{-4} 211	10×10^{-4}	–	3×10^{-4}	–
$ V_{ub} / V_{cb} $	6% 201	3%	1%	1%	–
$B_s^0, B^0 \rightarrow \mu^+ \mu^-$					
$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-)/\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$	90% 264	34%	–	10%	21% 612
$\tau_{B_s^0 \rightarrow \mu^+ \mu^-}$	22% 264	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$b \rightarrow c \ell^- \bar{\nu}_\ell$ 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}	–
$A_\Gamma (\approx x \sin \phi)$	2.8×10^{-4} 240	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	–
$x \sin \phi$ from $D^0 \rightarrow K^+ \pi^-$	13×10^{-4} 228	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x \sin \phi$ from multibody decays	–	$(K3\pi) 4.0 \times 10^{-5}$	$(K_S^0 \pi\pi) 1.2 \times 10^{-4}$	$(K3\pi) 8.0 \times 10^{-6}$	–

$b \rightarrow d \ell \ell$ Decays at LHCb

In the future expect a $b \rightarrow d \ell \ell$ program that parallels the effort for $b \rightarrow s \ell \ell$ decays

- this includes many processes:

$$B^0 \rightarrow \mu^+ \mu^-, \quad B^+ \rightarrow \pi^+ \ell^+ \ell^-, \quad B^0 \rightarrow \pi^+ \pi^- \ell^+ \ell^-, \quad B_s \rightarrow K_S \ell^+ \ell^-, \\ B_s \rightarrow K^*(\rightarrow K \pi) \ell^+ \ell^-, \quad \Lambda_b \rightarrow p \pi \ell^+ \ell^-$$

- and many observables:

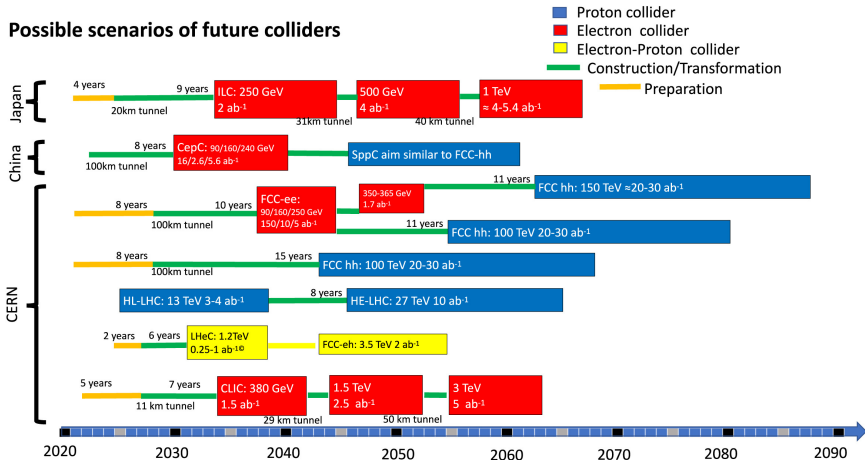
branching ratios, angular distributions, LFU ratios

$$R_\pi = \frac{\int_{q_{\min}^2}^{q_{\max}^2} dq^2 \text{BR}(B \rightarrow \pi \mu^+ \mu^-)}{\int_{q_{\min}^2}^{q_{\max}^2} dq^2 \text{BR}(B \rightarrow \pi e^+ e^-)}$$

- already existing measurements of $b \rightarrow d$ processes can be used to probe new physics (Rusov 1911.12819; Bause, Gisbert, Golz, Hiller 2209.04457)
- $b \rightarrow d$ will become the new $b \rightarrow s$ (after high-lumi phase, will have \sim comparable statistics for $b \rightarrow d$ as there is now for $b \rightarrow s$)

Landscape of Future Colliders

Possible scenarios of future colliders



Running on the Z pole allows one to probe the flavor structure of Z couplings with extreme precision.

Circular e^+e^- Colliders are Flavor Factories

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In addition one gets very large samples of
all b hadrons, c hadrons, τ 's
with large boost in a clean environment.

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\Rightarrow unique sensitivity to a large number of flavor processes that are not accessible at LHC(b) or Belle II

b Hadrons from 10^{13} Z bosons

FCC-ee Snowmass Whitepaper 2203.06520

Particle production (10^9)	B^0/\bar{B}^0	B^+/B^-	B_s^0/\bar{B}_s^0	B_c^+/\bar{B}_c^-	$\Lambda_b/\bar{\Lambda}_b$	$c\bar{c}$	$\tau^+\tau^-$
Belle II	27.5	27.5	n/a	n/a	n/a	65	45
FCC-ee	620	620	150	4	130	600	170

► CEPC vs. Belle II:

- order of magnitude more B^+ and B^0 , unique opportunities for B_s , B_c , and Λ_b .
- $b\bar{b}$ from Z decays are **highly boosted**.

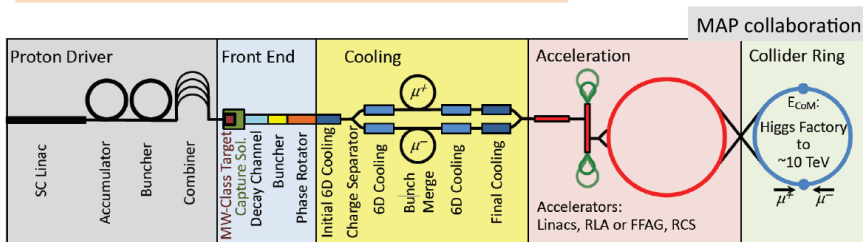
► CEPC vs. LHCb:

- lower yields at CEPC, but **cleaner environment**.
- much easier access to final states with neutrals (π^0 , γ , neutrinos).

$$B_s \rightarrow \tau\tau, \quad B \rightarrow K^*\tau\tau, \quad B_s \rightarrow \phi\nu\bar{\nu}, \quad B_c \rightarrow \tau\nu, \dots$$

A Muon Collider?

Muon collider design is driven by finite muon lifetime



Short, intense proton bunches to produce hadronic showers

Muon are captured, bunched and then cooled by ionisation cooling in matter

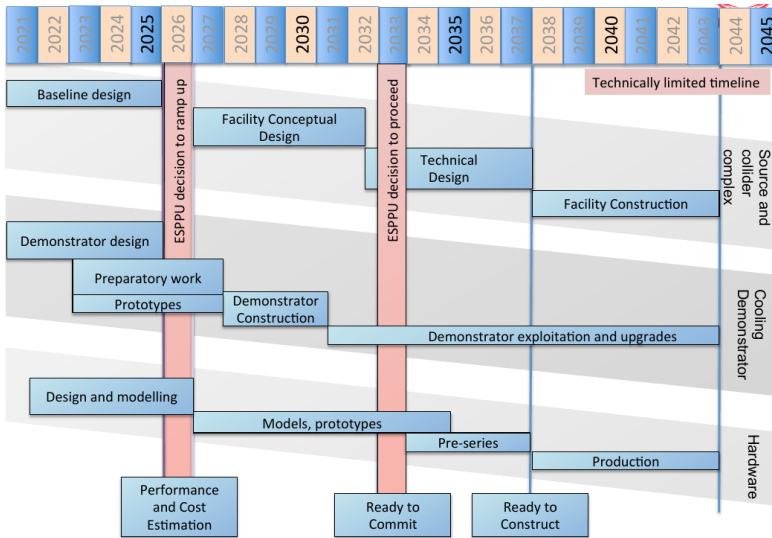
Acceleration to collision energy

Collision

Protons produce pions
Pions decay to muons

talk by D. Schulte @ Muon Collider Agora, Feb 16 2022

A Muon Collider!



talk by D. Schulte @ Muon Collider Agora, Feb 16 2022

The Future of Flavor Physics

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give me a one sentence summary



The future of flavor physics looks promising, with a focus on precision measurements of CKM parameters, searches for new physics beyond the Standard Model, neutrino physics, and flavor in cosmology.