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Jan. 18, 2022

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Prologue

"Don't just leave flavor physics to flavor physicists."

[Someone Awesome, 2019?]

"Non-flavor physicists must be amused first."

[me, 2022]

Disclaimer: Priorities are given to numerical results with (fast or full) simulations in stead of theory.
Apologize for any important missing contributions due to personal ignorance and prejudice.

Recent progress on Flavor Physics Opportunities at $e^{-}e^{+}$ Colliders

- Introduction
  - Theory motivation: Why flavor physics?
  - Project overview: experiment and data.
- Recent progress
  - CKM and CPV parameter measurements.
  - Semileptonic and leptonic decays.
  - Low multiplicity and τ physics.
- Community activities.

Theoretical Motivation

Two fundamental driving forces for studying flavor physics:

Probing new physics (NP).

Sensitive to particular new physics.

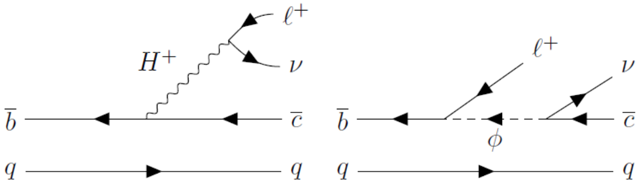
Understanding the SM itself.

"Traditional", but really?

Flavor Physics Probing BSM

Inclusive decay width of heavy flavor (W-induced charged current):

$$\Gamma_{\rm SM} \sim \frac{G_F^2 m_f^5}{192\pi^3} \times \text{const} \propto \frac{m_f^5}{m_W^4} .$$



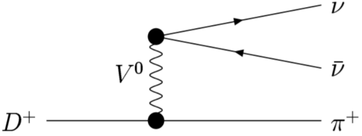
Assuming new physics with scale $\Lambda_{\rm NP} \gtrsim$ TeV contributes as:

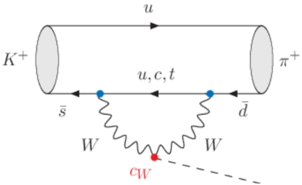
$$\Gamma_{\rm BSM} \propto \frac{m_f^5}{\Lambda_{\rm NP}^2 m_W^2} \text{ (w/ interference), or } \frac{m_f^5}{\Lambda_{\rm NP}^4} \text{ (w/o interference) .}$$

Moderate suppression $\left(\frac{m_W^2}{\Lambda_{\rm NP}^2} \text{ or } \frac{m_W^4}{\Lambda_{\rm NP}^4} \gg \frac{m_f^4}{\Lambda_{\rm NP}^4}\right)$ at low costs.

Flavor Physics Probing BSM (II)

Stronger features if looking for flavor-changing-neutral currents (FCNC), CPV, lepton flavor universality violation (LFUV), lepton flavor violation (LFV), lepton number violation (LNV), baryon number violation (BNV)...

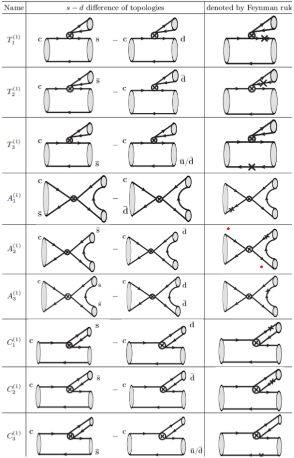




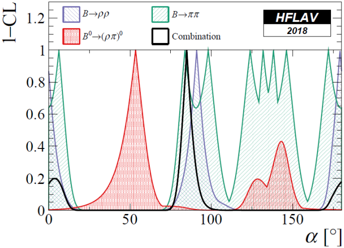
Also chances for direct BSM productions: light resonances, long-lived particles (LLPs), missing energy...

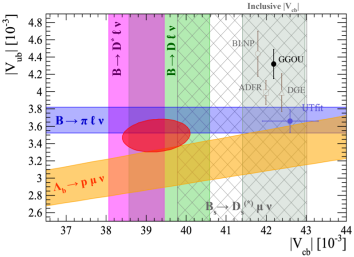
Knowing the SM $\not\Rightarrow$ Full Understanding

Some amplitudes of D decay to 2 pesudoscalars [Müller et al., 2015]



Measurements to be improved [Amhis et al., 2019]





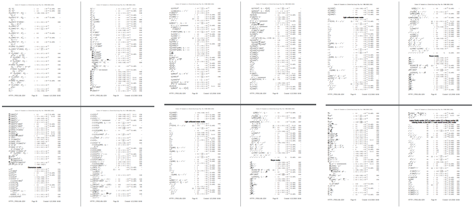
Tensions within the SM [Ricciardi and Rotondo, 2020]

A Closer Look at the SM

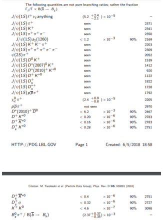
All cases call for more data:
Measuring rates $\to$ differential Xsecs $\to$ amplitude analysis ...

Another example, from PDG 2021:

B^0: $\gtrsim 200$ CPV entries, ~ 570 decay entries, 20+ pages:



B_c: ZERO CPV entry, $\lesssim 50$ decay entries:



The following quantities are not pure branching ratios; rather the fraction $\Gamma_i/\Gamma \times B(\overline{b} \to B_c)$.

$J/\psi(1S)\ell^+\nu_\ell$ anything	$(5.2\ ^{+2.4}_{-2.1}) \times 10^{-5}$			–
$J/\psi(1S)\pi^+$	seen			2371
$J/\psi(1S)K^+$	seen			2341
$J/\psi(1S)\pi^+\pi^+\pi^-$	seen			2350
$J/\psi(1S)a_1(1260)$	< 1.2	$\times 10^{-3}$	90%	2169
$J/\psi(1S)K^+K^-\pi^+$	seen			2203
$J/\psi(1S)\pi^+\pi^+\pi^+\pi^-\pi^-$	seen			2309
$\psi(2S)\pi^+$	seen			2052
$J/\psi(1S)D^0K^+$	seen			1539
$J/\psi(1S)D^*(2007)^0K^+$	seen			1412
$J/\psi(1S)D^*(2010)^+K^{*0}$	seen			920
$J/\psi(1S)D^+K^{*0}$	seen			1122
$J/\psi(1S)D_s^+$	seen			1822
$J/\psi(1S)D_s^{*+}$	seen			1728
$J/\psi(1S)p\overline{p}\pi^+$	seen			1792
$\chi_c^0\pi^+$	$(2.4\ ^{+0.9}_{-0.8}) \times 10^{-5}$			2205
$p\overline{p}\pi^+$	not seen			2970
$D^*(2010)^+\overline{D}^0$	< 6.2	$\times 10^{-3}$	90%	2467
D^+K^{*0}	< 0.20	$\times 10^{-6}$	90%	2783
$D^+\overline{K}^{*0}$	< 0.16	$\times 10^{-6}$	90%	2783
$D_s^+K^{*0}$	< 0.28	$\times 10^{-6}$	90%	2751

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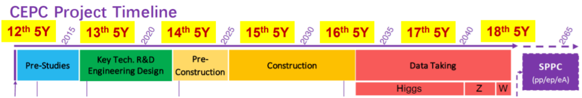
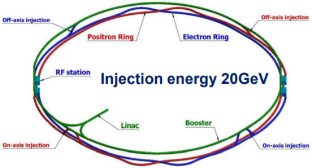
Citation: M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018)

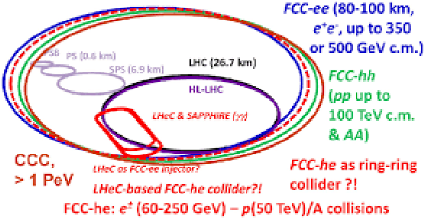
$D_s^+\overline{K}^{*0}$	< 0.4	$\times 10^{-6}$	90%	2751
$D_s^+\phi$	< 0.32	$\times 10^{-6}$	90%	2727
K^+K^0	< 4.6	$\times 10^{-7}$	90%	3098
$B_s^0\pi^+$ / $B(\overline{b} \to B_s)$	$(2.37^{+0.37}_{-0.35}) \times 10^{-3}$			–

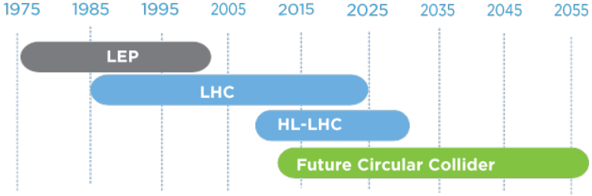
Future e^+e^- Colliders



- 100 km collider and booster ring



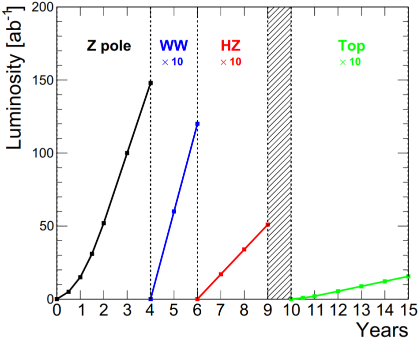




Plan Ahead for the Future Z Factories

	ttbar	Higgs	W	Z
Number of IPs	2			
Hour glass Factor	0.89	0.9	0.9	0.97
Luminosity per IP[1e34/cm^2/s]	0.5	5.0	16	115

Operation mode		ZH	Z	W^+W^-	ttbar (new)
$\sqrt{s}$ [GeV]		~ 240	~ 91.2	~ 160	~ 360
Run time [years]		7	2	1	7.7
CDR	L / IP [$\times 10^{34}$ cm^{-2}s^{-1}]	3	32	10	
	$\int L\,dt$ [ab^{-1}, 2 IPs]	5.6	16	2.6	
	Event yields [2 IPs]	1×10^6	7×10^{11}	2×10^7	
Latest	L / IP [$\times 10^{34}$ cm^{-2}s^{-1}]	5.0	115	15.4	0.5
	$\int L\,dt$ [ab^{-1}, 2 IPs]	9.3	57.5	4.0	1.0
	Event yields [2 IPs]	1.7×10^6	2.5×10^{12}	3×10^7	3×10^5



CEPC [Dong et al., 2018] $\approx 2.5\times$Tera-Z

FCC-ee [Abada et al., 2019] $\approx 7\times$ Tera-Z

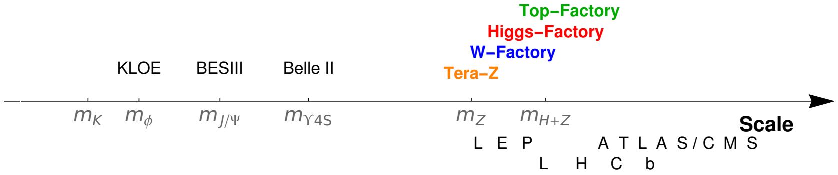
The Giga-Z project at ILC [Fujii et al., 2019] also contributes, rescale results by $1/\sqrt{1000} \approx 0.03$.

Flavor Physics at Future e^+e^- colliders

Z Factory $\supseteq$ Flavor Factory

Flavor physics "for free".

Channel	Belle II	LHCb	Giga-Z	Tera-Z
B^0, $\bar{B}^0$	5.3×10^{10}	$\sim 6 \times 10^{13}$	1.2×10^8	1.2×10^{11}
$B^\pm$	5.6×10^{10}	$\sim 6 \times 10^{13}$	1.2×10^8	1.2×10^{11}
B_s, $\bar{B}_s$	5.7×10^8	$\sim 2 \times 10^{13}$	3.2×10^7	3.2×10^{10}
$B_c^\pm$	-	$\sim 4 \times 10^{11}$	2.2×10^5	2.2×10^8
Λ_b, $\bar{\Lambda}_b$	-	$\sim 2 \times 10^{13}$	1.0×10^7	1.0×10^{10}
c, $\bar{c}$	2.6×10^{11}	$\gtrsim 10^{14}$	2.4×10^8	2.4×10^{11}
τ^+, τ^-	9×10^{10}	-	7.4×10^7	7.4×10^{10}



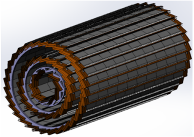
VS. B Factories

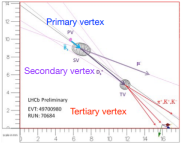
- Much higher b quark boost
- Abundant heavy b hadron

VS. Hadron Colliders

- Clean environment
- Direct missing momenta measurement

Key Detector Features for Flavor Physics



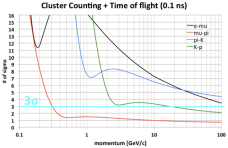


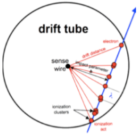
Tracking sys. grants $\mathcal{O}(10)$ fs sensitivity.

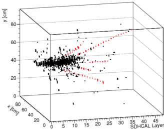
- High time precision for CPV measurements.
- Authentic c/τ reconstruction inside a jet.
- Greater purity for displaced signals.

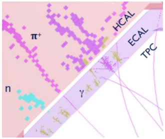
Advanced PID coming from the combination of different methods.

- Flavor tagging for everything.
- Suppressing backgrounds in general.
- Clean leptonic/baryonic modes.









Calorimetry gives neutral energy and angular resolution.

- Better $\not{p}$ measurement for neutrinos.
- Excited states such as D_s^* and radiative decays.
- Distinguishing π^0/η..., allowing h^0X modes.

See also Peter Krizan and Philip Allport's talks.

Vs. Current/Upgraded Experiments: How do Golden Modes Look Like?

Multiple charged tracks	Vs. B factories, low track energy
Multiple short time scales	Vs. B factories, low track displacement
h^0 or γ (but not too many)	Vs. LHCb, larger noise
e instead of μ ?	Vs. Hadron colliders, relying on MS
ν or other invisible fellas	Vs. Hadron colliders, low sensitivity
Λ or $K_S \to h^+h^-$	Vs. Hadron colliders, low acceptance
Baryonic modes (p or $\Sigma^\pm$?)	Vs. both, advanced PID
Heavy hadrons ($B_s,\ B_c,\ \Lambda_b\ ,\Xi_b$ ...)	Vs. B factories, Limited $\sqrt{s}$
Multi-heavy-flavor (B_c, exotics...)	Vs. both, unique @ the Z pole
...	...

Key Detector Performances for Flavor Physics

Flavor physics is the very demanding for the detector.

To fully unleash the Tera-Z power:

Detector "benchmarks"	Typical physics interpretation
$\pi/K \gtrsim 4\sigma,\ p/K \gtrsim 2\sigma$ @50 GeV $\pi/K \gtrsim 5\sigma,\ p/K \gtrsim 3\sigma$ @$\lesssim 2$ GeV	Greatly reduced mis-ID/comb. systematics, tagging power, soft tracks...
$\mu/\pi \gtrsim 1(2)\sigma$ @$<(>)4$GeV (in jets?) $e/\pi \gtrsim 3\sigma$, $e/\mu \gtrsim 5\sigma$ (in jets?)	Unambiguous sign of different leptons (non-trivial physics when ℓ meets h)
$\sigma_{p_T,\mathrm{track}}/p_T^2 \lesssim 2\times 10^{-5}$ GeV^{-1}	Unprecedented narrow $m_{\ell\ell}$ peaks
$\sigma_{\mathrm{IP}} \lesssim 5 \bigoplus 10/p_T\ \mu$m	(Multiple) short time scales recovered
$\sigma_{E,\mathrm{ECAL}}/E \lesssim 5\%/\sqrt{E} \bigoplus 0.5\%$ $\sigma_{\theta,\mathrm{ECAL}} \lesssim 5$ mrad	Recognize single $\gamma/\pi^0/$... in jets Able to find peaks w/ neutrals
$\sigma_{E,\mathrm{HCAL}}/E \lesssim 50\%/\sqrt{E}$ @ 50 GeV	With the above $\Rightarrow \not{p}$, m_{jj} and m_{recoil}
$\gamma/K^0/n$ discrimination?	New channels & lower bkgs.

Aggressive, more realistic with $N_{\mathrm{detector}} > 1$?

Challenges in Software, Resources, and Analyses

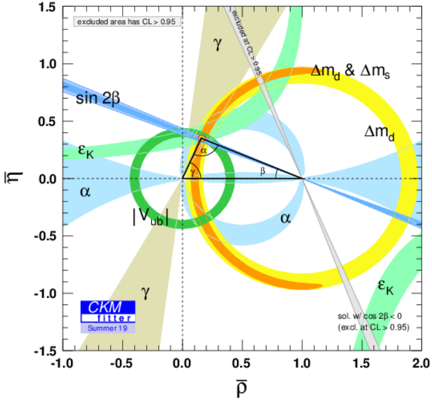
Authentic full detector simulation is expensive, cost $\gg$ MC generators:

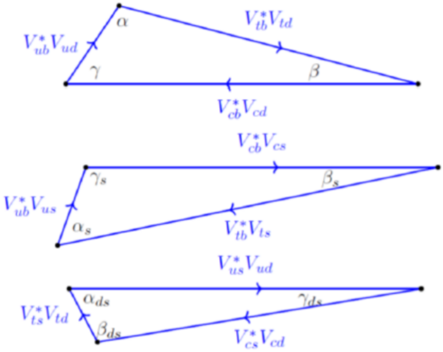
- Storage requirement for 10^{12} fully simulated $e^+e^- \to Z$: $\mathcal{O}(1)$ EB$\sim \mathcal{O}(10^6)$ TB.
- Time needed: $\mathcal{O}(10^{10})$ CPU hours.
- Calibration and development of packages...
- Validation of generated samples...

Most problems can be avoided at current stage by fast simulation and smart strategy.

Physics: CKM and CPV

Current status of the unitarity triangle



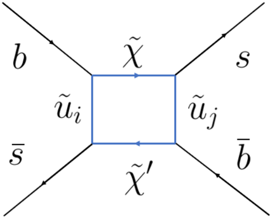


Can also probed by the other two triangles.

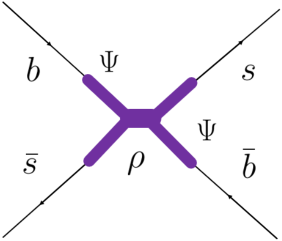
Opportunities with CKM and CPV

Cracks of the CKM picture indicate NP.

SUSY-like:



Composite-like:

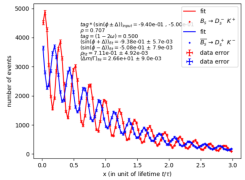


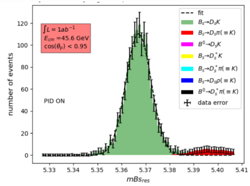
Goal of CKM Measurements

FCC-ee proposed target [Charles et al., 2020], see also [Abada et al., 2019].

$\|V_{ud}\|$	0.97437	±0.00021	id	id	id
$\|V_{us}\| f_+^{K\to\pi}(0)$	0.2177	±0.0004	id	id	id
$\|V_{cd}\|$	0.2248	±0.0043	±0.003	id	id
$\|V_{cs}\|$	0.9735	±0.0094	id	id	id
Δm_d [ps^{-1}]	0.5065	±0.0019	id	id	id
Δm_s [ps^{-1}]	17.757	±0.021	id	id	id
$\|V_{cb}\|_{\mathrm{SL}} \times 10^3$	42.26	±0.58	±0.60	±0.44	id
$\|V_{cb}\|_{W\to cb} \times 10^3$		—	—	—	±0.17
$\|V_{ub}\|_{\mathrm{SL}} \times 10^3$	3.56	±0.22	±0.042	±0.032	id
$\|V_{ub}/V_{cb}\|$ (from Λ_b)	0.0842	±0.0050	±0.0025	±0.0008	id
$\mathcal{B}(B\to\tau\nu)\times 10^4$	0.83	±0.24	±0.04	±0.02	±0.009
$\mathcal{B}(B\to\mu\nu)\times 10^6$	0.37	—	±0.03	±0.02	id
$\sin 2\beta$	0.680	±0.017	±0.005	±0.002	±0.0008
α [°] (mod 180°)	91.9	±4.4	±0.6	id	id
γ [°] (mod 180°)	66.7	±5.6	±1	±0.25	±0.20
β_s [rad]	-0.035	±0.021	±0.014	±0.004	±0.002
$A_{\mathrm{SL}}^d \times 10^4$	-6	±19	±5	±2	±0.25
$A_{\mathrm{SL}}^s \times 10^5$	3	±300	±70	±30	±2.5

Progress in CKM Measurements

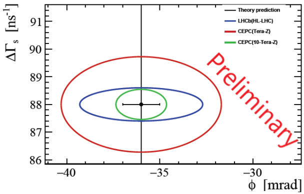




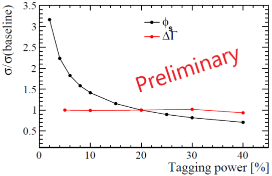
FCC study for various CPV measurements
Fast simulation, tagging power $\simeq 22\%$

Using $B_s \to D_s K^\pm$, $B_s \to J/\psi\phi$ [Aleksan et al., 2021a], & $B^\pm \to D^0(\bar{D}^0)K^\pm$ [Aleksan et al., 2021b] $\Rightarrow$

- $\sigma(\alpha_s) \simeq \sigma(\gamma) \simeq 0.4°$
- $\sigma(\beta_s) \simeq 0.035°$
- $\sigma(\gamma_s) \sim \mathcal{O}(1°)$



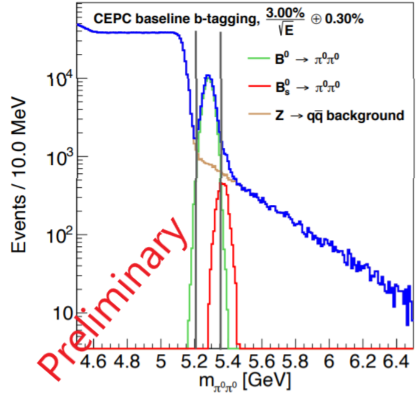
CEPC study of $B_s \to J/\psi\phi$ [Zhao, 202X]
Full simulaiton, Tera-Z, tagging power $\simeq 20\%$
$\sigma(\beta_s) \simeq 0.12°$ (Compatible w/ the above)



Using fully charged channels only.

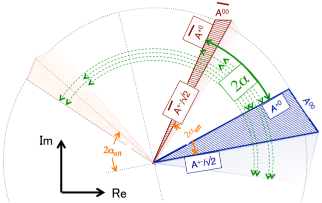
The less constrained angle $\alpha(\phi_2)$ determined via the $b \to u\bar{u}d$ transition $(B \to \pi\pi, \rho\rho...)$ [Charles et al., 2017, Altmannshofer et al., 2018].

Bottleneck: $B_{(s)} \to 2\pi^0 \to 4\gamma$, suppressed mode, SM BR$\lesssim 10^{-6}$. [Wang, 202X]



Accuracy	$B^0 \to \pi^0\pi^0$	$B^0_s \to \pi^0\pi^0$
17%/√E⊕1% (CEPC baseline)	~1.32%	~23.1%
3%/√E⊕0.3% (σ_{mB} ~30 MeV)	~0.44%	~4.4%

More importantly, $B \to \rho\rho \to 4\pi$, allows vertexing.



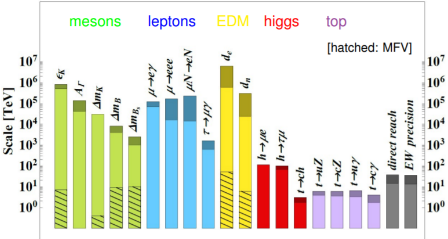
$\sigma(\alpha) < 1^\circ$ if $\sigma(\text{BR}(B \to \rho\rho))$ better than $\sigma(\text{BR}(B \to \pi^0\pi^0))$.

Other Prospects in CKM Measurements

One of the most precise measurements of $|V_{cb}|$ by inclusive $W \to cb$ measurements (Stat. only!)
Need W factory mode (10^8 WW pairs).

Also from measuring B_c decays (1%), need to understand $Z \to b\bar{b}c\bar{c}$ to fix inclusive B_c fraction [Charles et al., 2020].

Lifetime, mass difference, CPV in meson mixings... [Ellis et al., 2019]



Interlude

It's the right time to take a deep breath because I have just finished most CPV related pages.

FCCC and FCNC B Anomalies

If lepton flavor universality are not violated, good theoretical predictions for the following ratios:

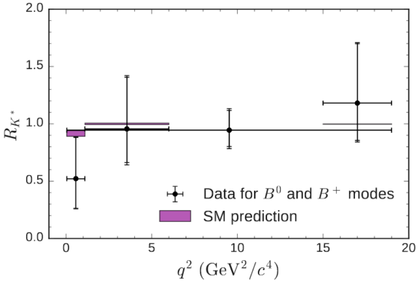
$$R_{K^{(*)}} \equiv \frac{\text{BR}(B \to K^{(*)}\mu^+\mu^-)}{\text{BR}(B \to K^{(*)}e^+e^-)} \ , \tag{1}$$

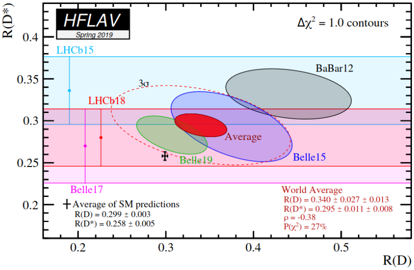
$$R_{D^{(*)}} \equiv \frac{\text{BR}(B \to D^{(*)}\tau\nu)}{\text{BR}(B \to D^{(*)}\ell\nu)} \ , \tag{2}$$

$$R_{J/\psi} \equiv \frac{\text{BR}(B_c \to J/\psi\tau\nu)}{\text{BR}(B_c \to J/\psi\ell\nu)} \ . \tag{3}$$

Systematic uncertainty largely cancel.

B Anomalies Indicating LFUV

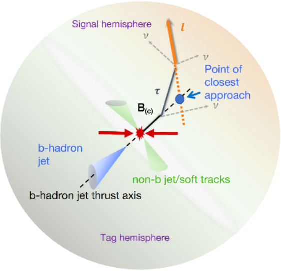




	Experimental	SM Prediction	Comments
R_K	$0.846^{+0.044}_{-0.041}$	1.00 ± 0.01	$m_{\ell\ell} \in [1.0, 6.0]$ GeV^2, via $B^\pm$.
R_{K^*}	$0.69^{+0.12}_{-0.09}$	0.996 ± 0.002	$m_{\ell\ell} \in [1.1, 6.0]$ GeV^2, via B^0.
R_{pK}	$0.86^{+0.14}_{-0.11} \pm 0.05$	~ 1	$m_{\ell\ell} \in [0.1, 6.0]$ GeV^2, via Λ_b.
R_D	0.340 ± 0.030	0.299 ± 0.003	B^0 and $B^\pm$ combined.
R_{D^*}	0.295 ± 0.014	0.258 ± 0.005	B^0 and $B^\pm$ combined.
$R_{J/\psi}$	$0.71 \pm 0.17 \pm 0.18$	0.25-0.28	
R_{Λ_c}	0.242 ± 0.076 new!	0.324 ± 0.004	[Aaij et al., 2022]

[Tanabashi et al., 2018][Altmannshofer et al., 2018][Aaij et al., 2021][Aaij et al., 2020].

FCCC and FCNC (Semi)Leptonic b Decays



Charged current $B_c \to \tau\nu$ [Zheng et al., 2020, Amhis et al., 2021]. Absolute precision $\sim 10^{-4}$

$R_{J/\psi}, R_{D_s^{(*)}}, R_{\Lambda_c}$ [Kwok et al., 202X].

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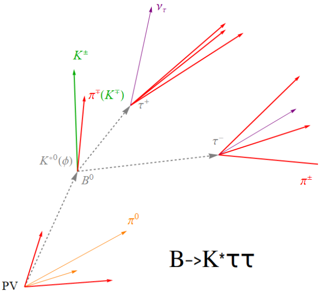
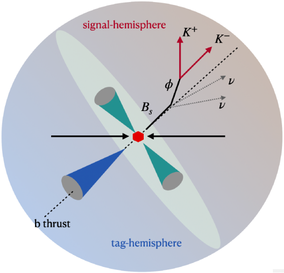


Neutral current $b \to s\tau\tau$ decays [Li and Liu, 2020].

Absolute precision $\lesssim 10^{-6}$

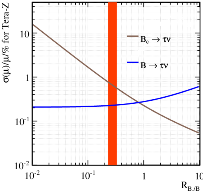


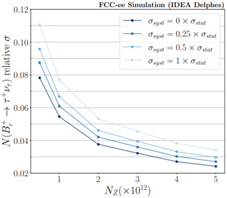
Neutral current $B_s \to \phi\nu\bar{\nu}$ decay [Li et al., 2022]

Absolute precision $\sim 10^{-7}$.

Many unique modes, as Tera-Z is good at τ and ν in general.

Charged Current Decays





$B_c \to \tau\nu$ @ Tera-Z

[Zheng et al., 2020, Amhis et al., 2021]

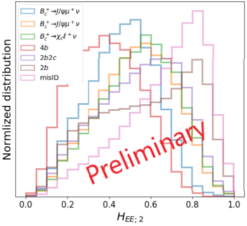
For both $\tau \to \mu\nu$ and $\tau \to 3\pi\nu$ decays, reaching $\mathcal{O}(1\%)$ precision.

Various $b \to c\tau(\ell)\nu$ decays

[Kwok et al., 202X]

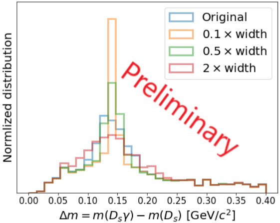
$\tau \to \mu\nu$ mode, (stat. only):

- $\sigma(R_{J/\psi}) \lesssim 3\%$.
- $\sigma(R_{D_s^{(*)}}) \lesssim 0.5\%$, w/ correlation $\lesssim 0.5$.
- $\sigma(R_{\Lambda_c}) \lesssim 0.3\%$.



⇑ Evt. shapes for B_c prod.

⇓ $D_s^* \to D_s\gamma$ tagging.



FCNC $b \to s\tau\tau$ Decays

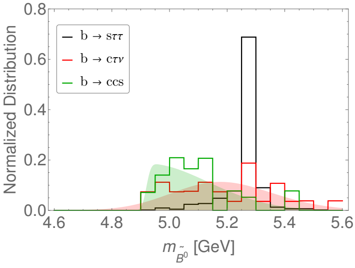
	Properties	Decay Mode	BR
$\tau^\pm$	$m = 1.777$ GeV	$\pi^\pm\pi^\pm\pi^\mp\nu$	9.3%
	$c\tau = 87.0\ \mu$m	$\pi^\pm\pi^\pm\pi^\mp\pi^0\nu$	4.6%
$D_s^\pm$	$m = 1.968$ GeV	$\tau^\pm\nu$	5.5%
	$c\tau = 151\ \mu$m	$\pi^\pm\pi^\pm\pi^\mp + X$	$> 6\%$
$D^\pm$	$m = 1.870$ GeV	$\tau^\pm\nu$	$< 0.12\%$
	$c\tau = 311\ \mu$m	$\pi^\pm\pi^\pm\pi^\mp + X$	$> 4\%$

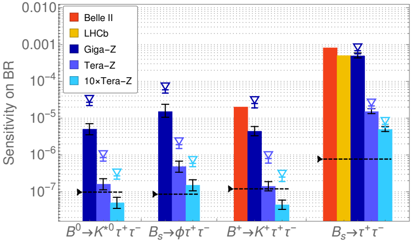
Background types		Typical BR
$b \to c\bar{c}s$	(e.g. $B_s \to K^{*0} D_s^{(*)+} D^{(*)-}$)	$\mathcal{O}(10^{-2} - 10^{-3})$
$b \to c\tau\nu$	(e.g. $B^0 \to K^{*0} D_s^{(*)-} \tau^+\nu$)	$\mathcal{O}(10^{-3} - 10^{-5})$
$b \to c\bar{u}d$	(e.g. $B^0 \to D^{(*)-}\pi^+\pi^+\pi^-$)	$\mathcal{O}(10^{-2} - 10^{-3})$

$\Leftarrow$ Extremely large bkg from $D_{(s)}$ fakeing $\tau \to 3\pi\nu$.

- Calorimetry removing X.
- Vertexing for kinematics.
- Excellent PID.
- ...

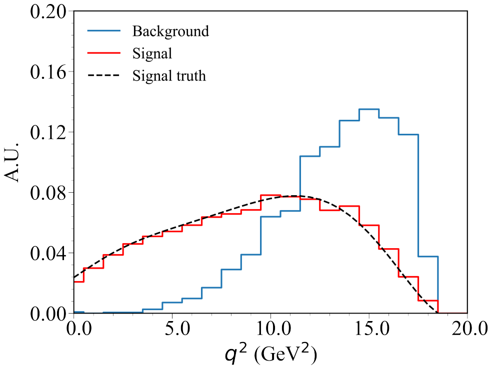
Approaching SM rates: $\sigma(\text{BR}(bs\tau\tau)) \lesssim \mathcal{O}(10^{-5} - 10^{-6})$ [Li and Liu, 2020]



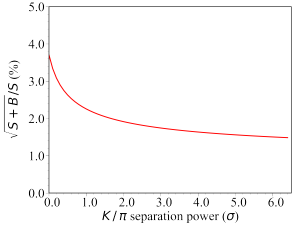


FCNC $b \to s\nu\bar{\nu}$ Decay

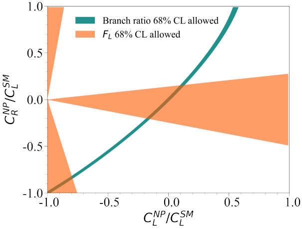
$B_s \to \phi\nu\bar{\nu}$ (full sim.), one of the best channels [Li et al., 2022].



Robust against PID:



Estimated ϕ polarization:



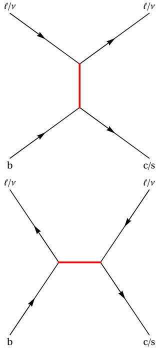
Reconstruction with a simple algorithm

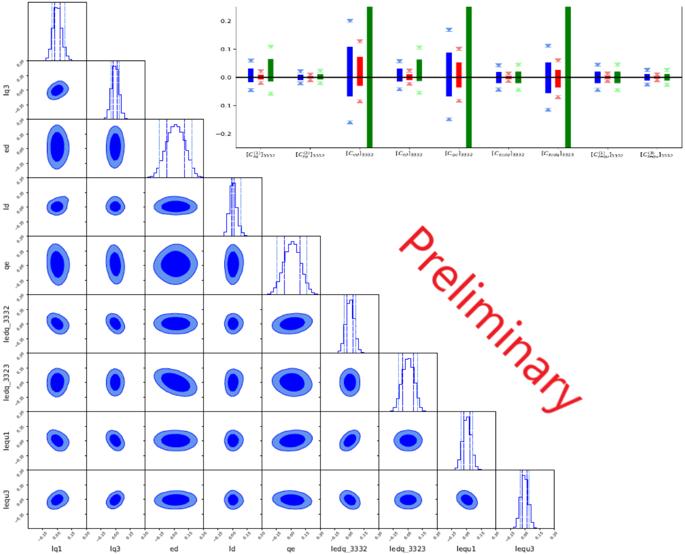
$\sigma(E_{B_s}) \lesssim 2$ GeV, $\sigma(q^2 \equiv m^2_{\nu\bar{\nu}}) \lesssim 3$ GeV^2.

σ(BR) $\lesssim 2\%$, $\sigma(F_L) \lesssim 10\%$.

SMEFT Fits of LFUV Opeartors

NP effects are parameterized by 9 SMEFT terms.





$\Rightarrow$ Tera-Z, $10\times$Tera-Z, Tera-Z w/o $b\to s\tau\tau$

Probing $\Lambda_{\rm NP}\sim 10$ TeV [Kwok et al., 202X]

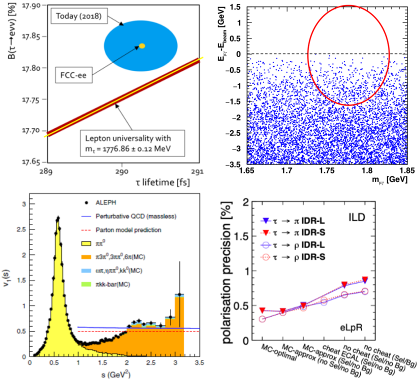
Interlude (II)

Hold on, we are not done with τ yet!

Low multiplicity and τ physics

The high purity and large statistics ($\gtrsim 10^{-10}$) of $Z \to \tau\tau$ leave huge room for τ physics. [Dam, 2019]

- Flavor universality tests via $\tau \to \ell\nu\bar{\nu}$.
- SM suppressed/forbidden τ decay modes.
- Precise measurement of hadronic τ channels, especially for high s ($E_\nu \sim 0$).
- Polarization of τ in Z decay are sensitive EW probes.



Low multiplicity and τ physics

Current validations focus on lepton flavor/number violating modes [Altmannshofer et al., 2018][Dam, 2019][Yu, 202X]

Measurement	Current	FCC Projection	Update	Comments
Lifetime [sec]	$\pm 5 \times 10^{-16}$	$\pm 1 \times 10^{-18}$		3-prong decays, stat. limited
BR($\tau \to \ell\nu\bar{\nu}$)	$\pm 4 \times 10^{-4}$	$\pm 3 \times 10^{-5}$		Assumed $0.1\times$ syst.(ALEPH)
m(τ) [MeV]	± 0.12	$\pm 0.004 \pm 0.1$		$\sigma(\vec{p}_{\rm track})$ limited
BR($\tau \to 3\mu$)	$< 2.1 \times 10^{-8}$	$\mathcal{O}(10^{-10})$	✓	bkg free
BR($\tau \to 3e$)	$< 2.7 \times 10^{-8}$	$\mathcal{O}(10^{-10})$		bkg free
BR($\tau^\pm \to e\mu\mu$)	$< 2.7 \times 10^{-8}$	$\mathcal{O}(10^{-10})$		bkg free
BR($\tau^\pm \to \mu ee$)	$< 1.8 \times 10^{-8}$	$\mathcal{O}(10^{-10})$		bkg free
BR($\tau \to \mu\gamma$)	$< 4.4 \times 10^{-8}$	$\sim 2 \times 10^{-9}$	$\mathcal{O}(10^{-10})$	$Z \to \tau\tau\gamma$ bkg , $\sigma(p_\gamma)$ limited
BR($\tau \to e\gamma$)	$< 3.3 \times 10^{-8}$	$\sim 2 \times 10^{-9}$		$Z \to \tau\tau\gamma$ bkg, $\sigma(p_\gamma)$ limited
BR($Z \to \tau\mu$)	$< 1.2 \times 10^{-5}$	$\mathcal{O}(10^{-9})$	✓	$\tau\tau$ bkg, $\sigma(\vec{p}_{\rm track})$ & $\sigma(E_{\rm beam})$ limited
BR($Z \to \tau e$)	$< 9.8 \times 10^{-6}$	$\mathcal{O}(10^{-9})$		$\tau\tau$ bkg, $\sigma(\vec{p}_{\rm track})$ & $\sigma(E_{\rm beam})$ limited
BR($Z \to \mu e$)	$< 7.5 \times 10^{-7}$	$10^{-8} - 10^{-10}$	$\mathcal{O}(10^{-9})$	PID limited

Slightly stronger than the luminosity-projected Belle II limits (~ 50 more channels to go!).

Exclusive Z Hadronic Decays

Similar samples also used to validate exclusive, low-multiplicity hadronic Z decays [Grossman et al., 2015]

- Probing hadron behaviors at high energy scales.
- $Z \to X\gamma$ channels help calibration of $H \to X\gamma$, which measures light quark Yukawas.

Measurement	Current	FCC Projection	Update	Comments
BR($Z \to \tau\mu$)	$< 1.2 \times 10^{-5}$	$\mathcal{O}(10^{-9})$	✓	$\tau\tau$ bkg, $\sigma(\vec{p}_{\rm track})$ & $\sigma(E_{\rm beam})$ limited
BR($Z \to \tau e$)	$< 9.8 \times 10^{-6}$	$\mathcal{O}(10^{-9})$		$\tau\tau$ bkg, $\sigma(\vec{p}_{\rm track})$ & $\sigma(E_{\rm beam})$ limited
BR($Z \to \mu e$)	$< 7.5 \times 10^{-7}$	$10^{-8} - 10^{-10}$	$\mathcal{O}(10^{-9})$	PID limited
$Z \to \pi^+\pi^-$			$\mathcal{O}(10^{-10})$	$\sigma(\vec{p}_{\rm track})$ limited, good PID
$Z \to \pi^+\pi^-\pi^0$			$\mathcal{O}(10^{-9})$	$\tau\tau$ bkg
$Z \to J/\psi\gamma$	$< 1.4 \times 10^{-6}$		$10^{-9} - 10^{-10}$	$\ell\ell\gamma+\tau\tau\gamma$ bkg
$Z \to \rho\gamma$	$< 2.5 \times 10^{-5}$		$\mathcal{O}(10^{-9})$	$\tau\tau\gamma$ bkg, $\sigma(\vec{p}_{\rm track})$ limited

Community Activities

05:30 **Use cases for an extreme electromagnetic resolution** ¶ 30m
Speaker: Roy Aleksan (Université Paris-Saclay (FR))
FCCee-week-2020_... | FCCee-week-2020_... | Recording

06:00 **Flavours at FCC-ee** 20m
Speaker: Stephane Monteil (Université Clermont Auvergne (FR))
Flavours_FCCee_20... | Recording

08:00 **Flavour studies at the Tera-Z factory** 30m
Speaker: LINGFENG LI (HKUST)
Slides_comm.pdf

10:00 **Study of Bs -> Ds K at FCC-ee and constraints on detector** ¶ 25m
Speaker: Roy Aleksan (Université Paris-Saclay (FR))
FCCee-week-2020_... | FCCee-week-2020_... | Recording

03:50 **Flavour tagging in W decays** 25m
Speaker: Paolo Azzurri (INFN Sezione di Pisa, Universita' e Scuola Normale Superiore, P)
azzurriFCCeeWHF.p...

05:00 **Higgs coupling to charm and flavour tagging** 25m
Speakers: Loukas Gouskos (CERN), Michele Selvaggi (CERN)
lg_fccee_workshop...

05:25 **Tau-identification in the Dual readout calorimeter** 20m
Speakers: Stefano Giagu, Stefano Giagu (Sapienza Universita e INFN, Roma I (IT))
tauID_DualReadout...

05:45 **First steps with flavour physics studies at FCC-ee** ¶ 25m
Speaker: Donal Hill (EPFL - Ecole Polytechnique Federale Lausanne (CH))
FCC_workshop_Nov...

10:30 **$b \to s\tau\tau$ at a Tera-Z** *30'*
Speaker: Lingfeng Li (Brown University)
Material: Slides

11:00 **Flavor/CPV prospects and opportunities at a Tera-Z** *30'*
Speaker: Zoltan Ligeti (UC Berkeley)
Material: Slides

11:30 **Lepton identification and backgrounds for flavor studies at the CEPC** *30'*
Speaker: Dan YU (IHEP)
Material: Slides

12:00 **Tests of lepton flavor universality at high-energy e+e- colliders** *30'*
Speaker: Andreas Crivellin (PSI)

14:00 **Strange jet tagging** *30'*
Speaker: Yuichiro Nakai (Shanghai Jiao Tong University)
Material: Slides

14:30 **LFV Z decays at a Tera-Z factory** *30'*
Speaker: Xabier Marcano (Madrid U)
Material: Slides

15:00 **Prospects for $B_c \to \tau\nu$** *30'*
Speaker: Yasmine Amhis (IJCLab Orsay)
Material: Slides

10:30 **Physics analyses and detector requirement study from Benchmark study of B0/Bs->2 pi0** *24'*
Speaker: Yuexin Wang
Material: Slides

10:54 **Jet Charge Reconstruction based on leading jet charged particle** *24'*
Speaker: CUI Hanhua
Material: Slides

11:18 **Physics analyses and detector optimization study based on Benchmark study of H->bb, cc, gg** *24'*
Speaker: 朱永峰
Material: Slides

Flavor Physics White Paper

- To quantify flavor physics potential with benchmark analyses.
- To motivate design optimization & maximize the physics output
- Possibility: from CEPC specific → generic future e^+e^- colliders.

Contents

Regular meetings on the flavor physics WP

Future workshop planned: March - April.

Summary

- Tera-Z (and beyond) is a powerful machine for flavor physics studies, as it is for EW, Higgs, QCD, and BSM studies.
- Flavor physics at Tera-Z benefit from:
  1. Large luminosity (from accelerator physics)
  2. Clean environment and moderate energy (from m_Z)
  3. Good or even revolutionary detectors (from detector R&D)
- Recent progresses including:
  1. Certain CKM element measurements.
  2. (Semi)leptonic decays to resolve B anomalies.
  3. Rare τ and Z exclusive decay modes.
- The community is still moving forward.

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