Flavour at FCC(-ee)

Jernej F. Kamenik

Main reference: FCC CDR Vol 1. Eur.Phys.J.C 79 (2019) 6, 474 (with updates)

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Scope of Flavour Physics @ FCC(-ee)

- Flavour physics reach with O(10^{13}) Z decays (10^8 W, 10^6 Higgs, top)
  - rare decays of c- and b-hadrons and CP violation in the heavy-quark sector
  - rare lepton decays
  - rare Z, (W, h, t?) decays
- In the context of ultimate potential of the LHCb upgrade and Belle II experiments.

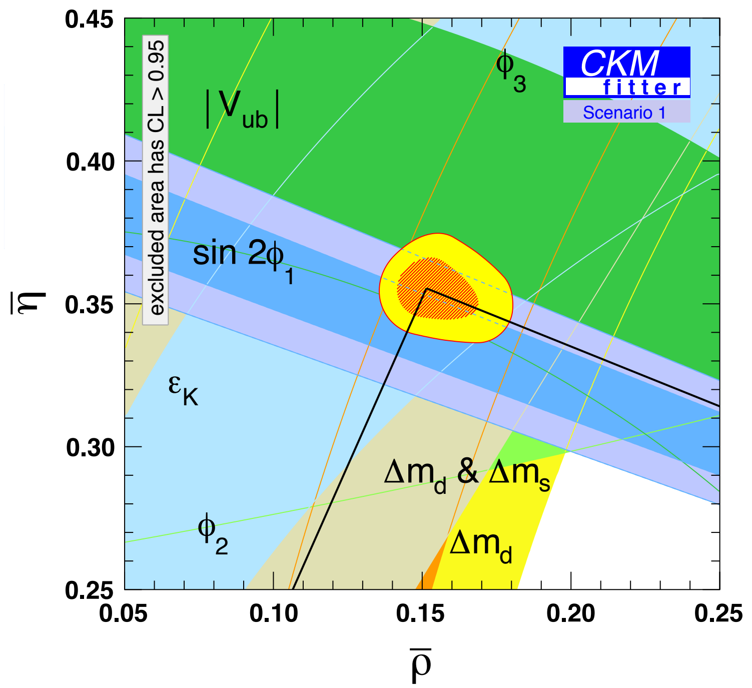
Working point	Lumi. / IP [10^{34} cm^{-2}.s^{-1}]	Total lumi. (2 IPs)	Run time	Physics goal
Z first phase	100	26 ab^{-1} /year	2	
Z second phase	200	52 ab^{-1} /year	2	150 ab^{-1}

Particle production (10^9)	B^0	B^-	B^0_s	Λ_b	$c\bar{c}$	$\tau^-\tau^+$
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-ee	400	400	100	100	800	220

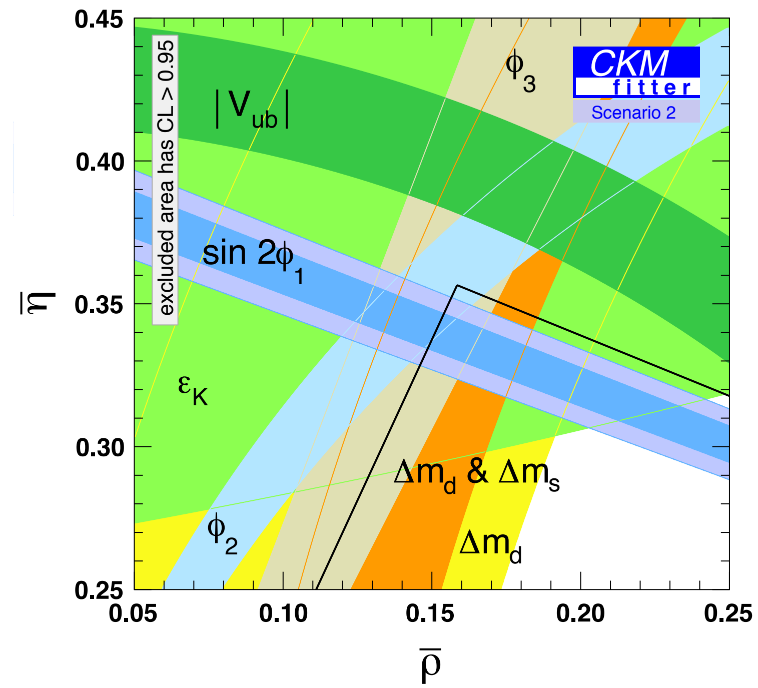
Flavor physics circa 2030: possible scenarios

WA

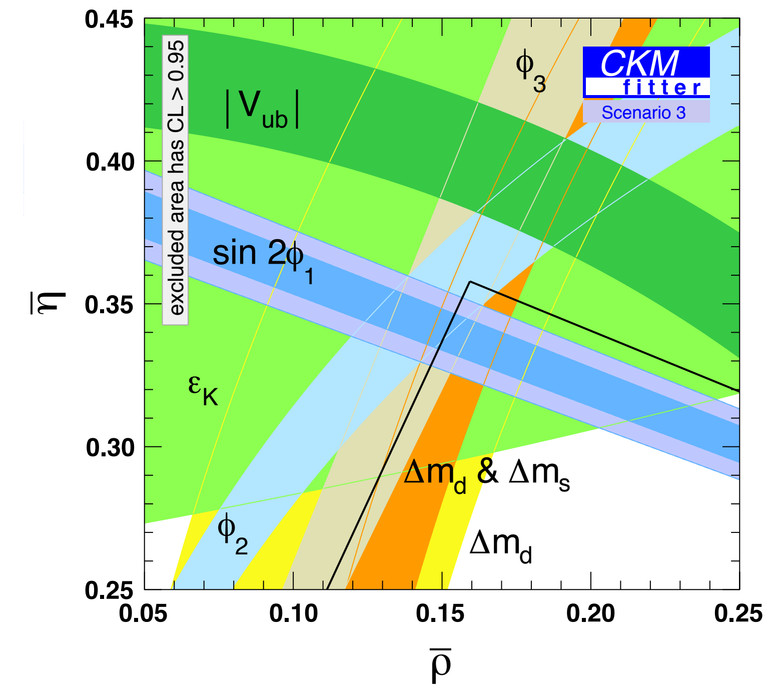
Now



50 ab^{-1} Belle II

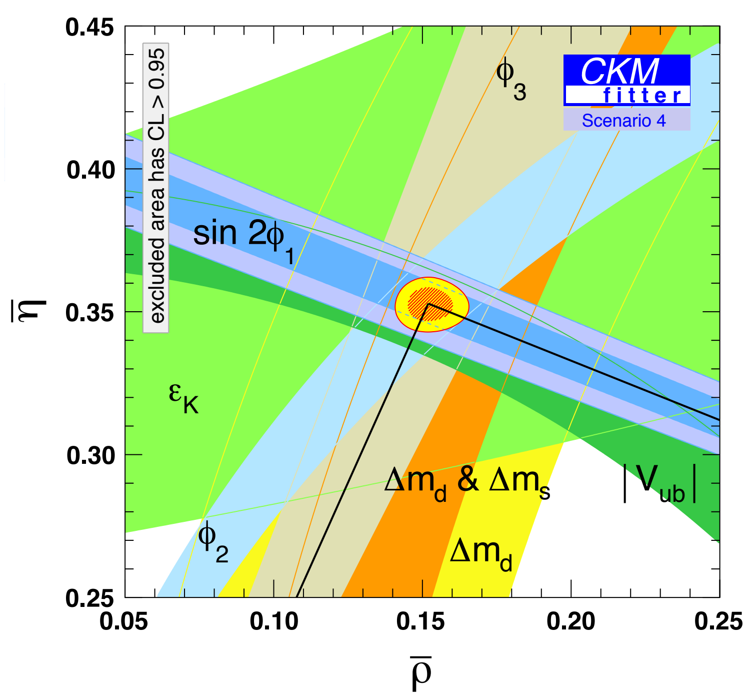


50 ab^{-1} Belle II + LHCb



SM-like

50 ab^{-1} Belle II



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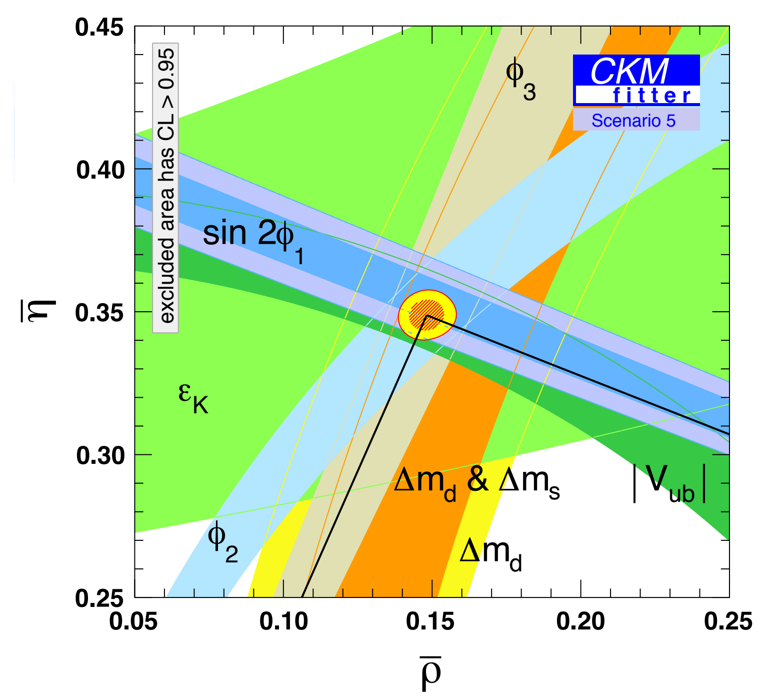
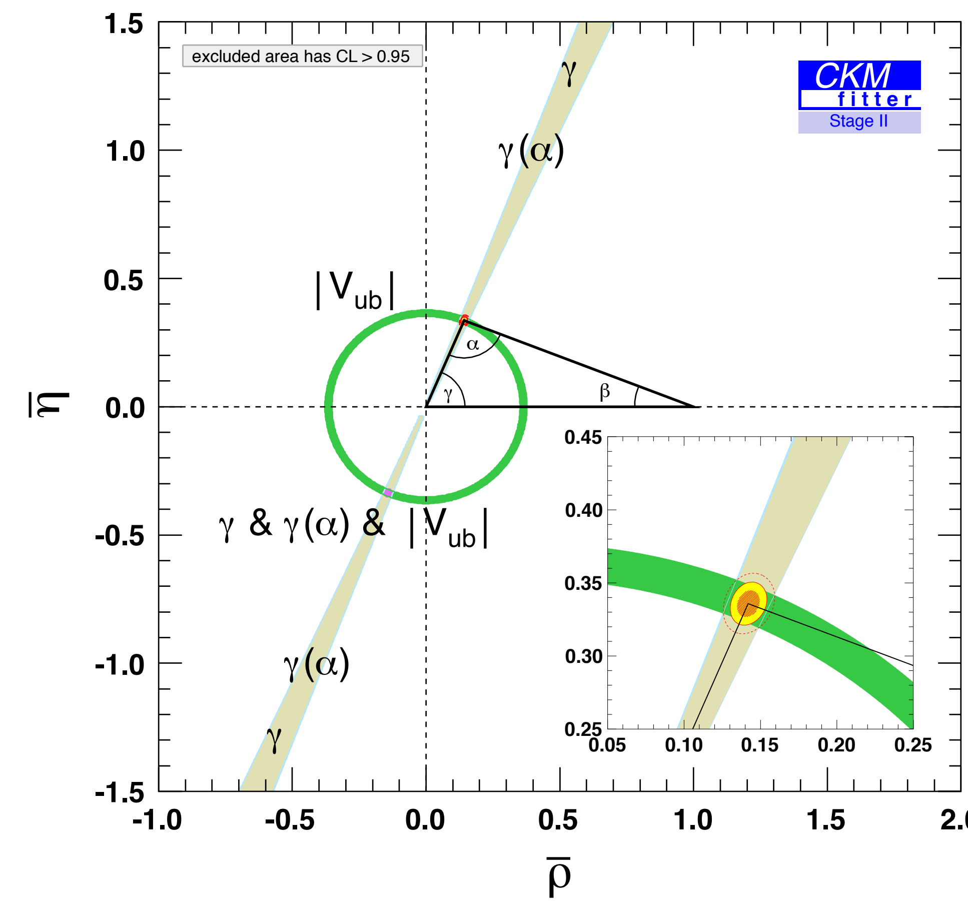


+ discoveries or bounds from high-pT LHC searches

FCC-ee flavour physics benchmarks & explorations

Part 1: CKM determination

- BSM motivated tree-level obs. fit
  - $|V_{ub}|(B \to \pi \ell \nu)$
  - $\gamma(B \to DK)$

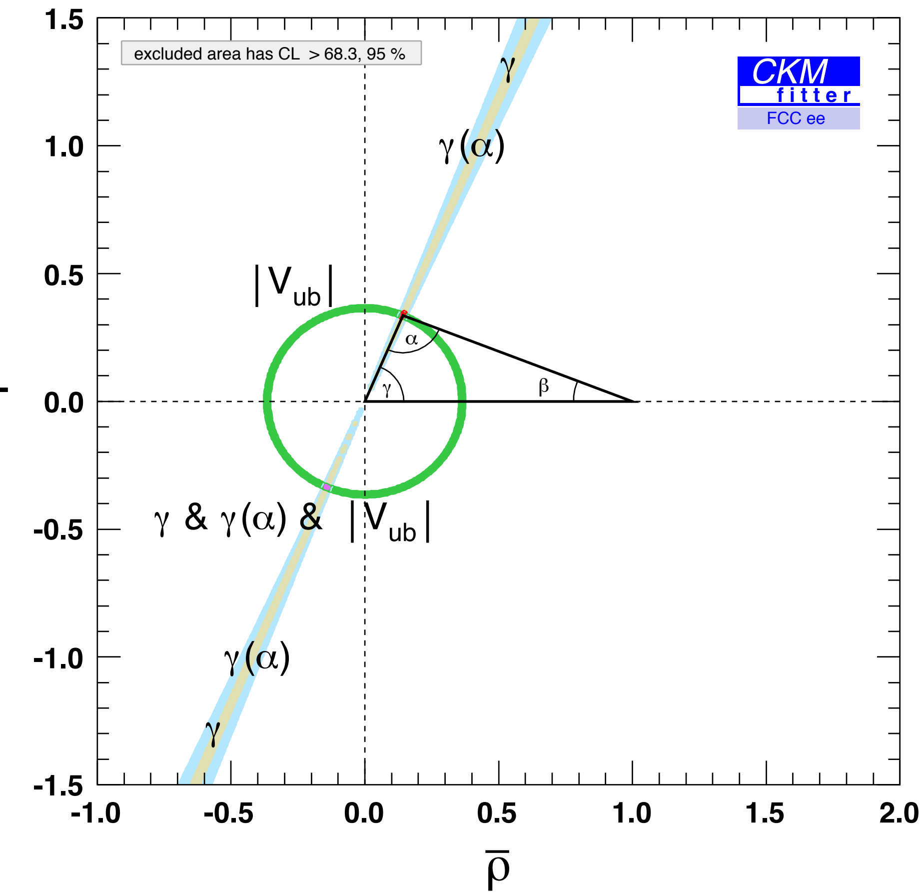


Observable / Experiments	Current W/A	Belle II (50 /ab)	LHCb-U1 (23/fb)	FCC-*ee*
CKM inputs				
γ (uncert., rad)	$1.296^{+0.087}_{-0.101}$	1.136 ± 0.026	1.136 ± 0.025	
$\|V_{ub}\|$ (precision)	5.9%	2.5%	6%	

FCC-ee flavour physics benchmarks & explorations

Part 1: CKM determination

- BSM motivated tree-level obs. fit
- improved stat. precision @FCC-ee
- $|V_{ub}|$ will require comparable theory progress (Lattice)



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CKM inputs				
γ (uncert., rad)	$1.296^{+0.087}_{-0.101}$	1.136 ± 0.026	1.136 ± 0.025	1.136 ± 0.004
$\lvert V_{ub}\rvert$ (precision)	5.9%	2.5%	6%	1%

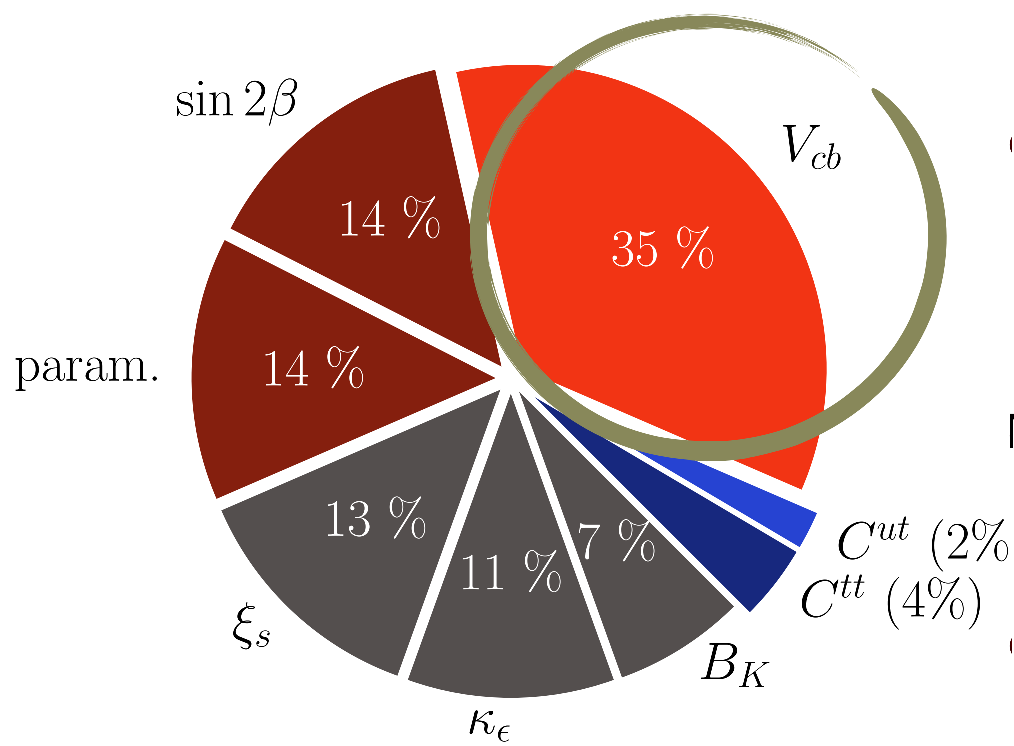
see also
LHCb, 1808.08865
Zupan & Brod, 1308.5663

FCC-ee flavour physics benchmarks & explorations

Part 1: CKM determination

- Complementary measurements of $|V_{cb}|$ (and $|V_{ub}|$)
  - CKM fit requires knowledge of $|V_{ub}/V_{cb}|$
  - Th. predictions of CPV in K decays rely on $|V_{cb}|$

Theory Error budget in ε_K



M. Gorbahn @ Beauty 2020

FCC-ee flavour physics benchmarks & explorations

Part 1: CKM determination

- Complementary measurements of $|V_{cb}|$ (and $|V_{ub}|$)
  - using $B_{u,c} \to \mu\nu, \tau\nu$

$$Br(B^- \to \tau^- \bar{\nu}(\gamma))_{\rm SM} = 1.13(1) \times 10^{-4} \left(\frac{f_B}{0.2\rm GeV}\right)^2 \left(\frac{|V_{ub}|}{4 \times 10^{-3}}\right)^2$$

$$\left[\frac{\Gamma(B^+ \to \tau^+\nu)}{\Gamma(B_c^+ \to \tau^+\nu)}\right]_{SM^*} = 0.782 \left|\frac{V_{ub} f_B}{V_{cb} f_{B_c}}\right|^2$$

  - Theoretically cleaner compared to exclusive semileptonic decays

FCC-ee flavour physics benchmarks & explorations

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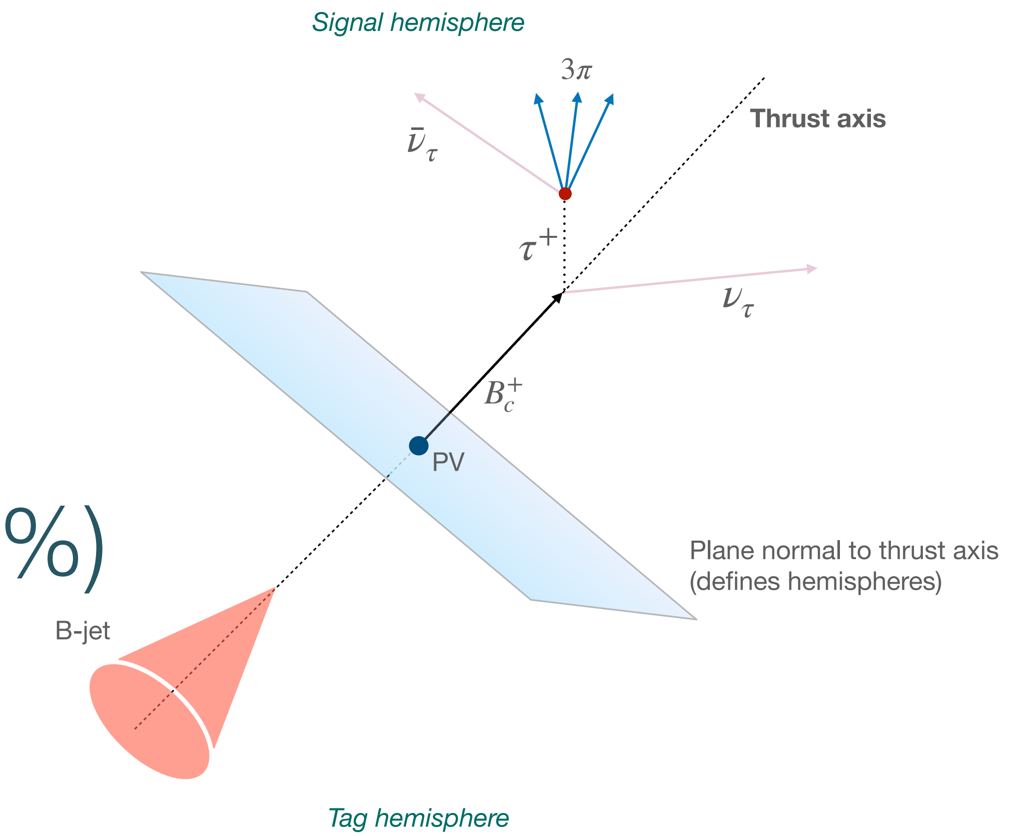
  - Exp. feasibility studies of $B_c \to \tau\nu$: important normalizing mode

$$\mathcal{B}(B_c^+ \to J/\psi \mu^+ \nu_\mu)$$

  - relative signal yield precision O(few %)



Amhis et al., 2105.13330
Zheng et al., 2007.08234

FCC-ee flavour physics benchmarks & explorations

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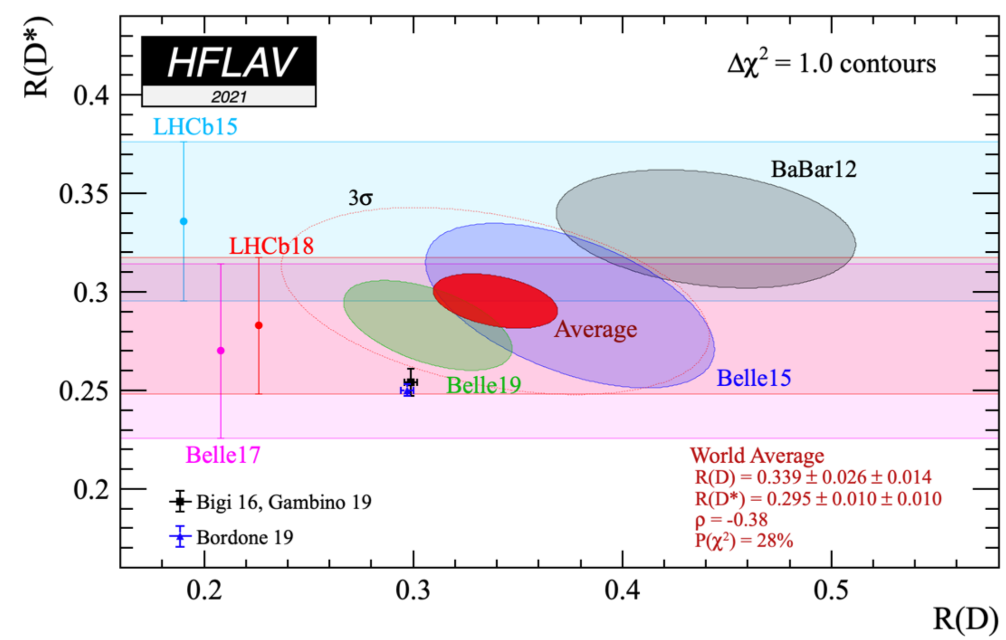
  - alternative test of LFU in c.c. B decays



$$R(D^{(*)}) \equiv \frac{\Gamma(B \to D^{(*)}\tau\nu)}{\Gamma(B \to D^{(*)}\ell\nu)}$$

Amhis et al., 2105.13330
Zheng et al., 2007.08234

see also LHCb, 1711.05623

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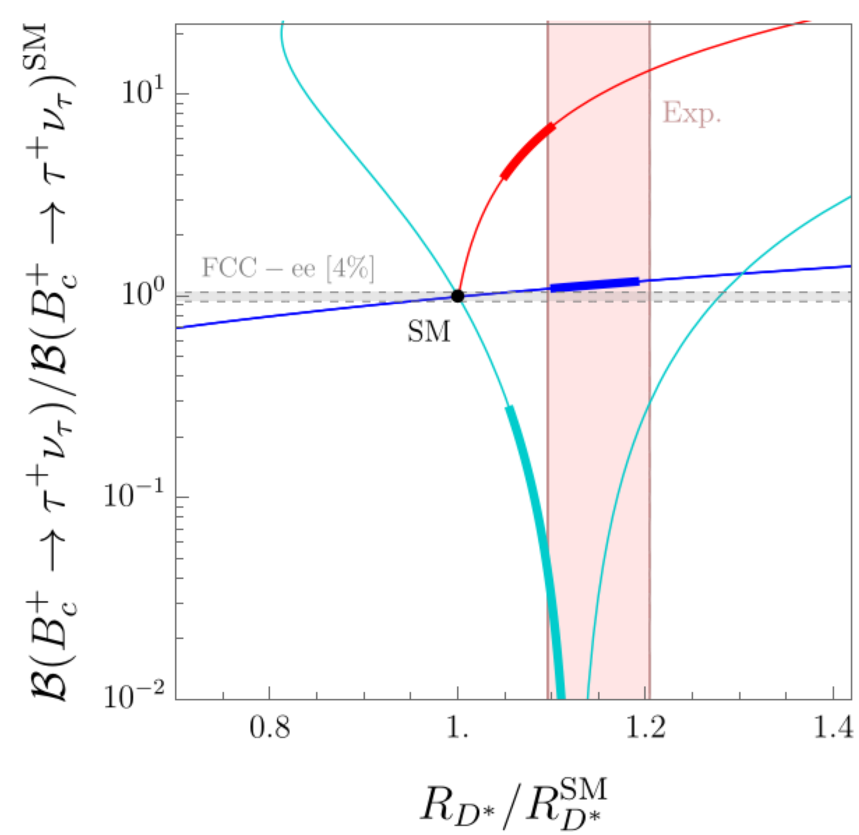

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FCC-ee flavour physics benchmarks & explorations

Part 1: CKM determination

- Complementary measurements of $|V_{cb}|$ (and $|V_{ub}|$)
  - using $B_{u,c} \to \mu\nu, \tau\nu$
  - using on-shell $W \to cb$
    - $\sigma(e^+e^- \to W^+W^-) \sim 10\mathrm{pb}$ (in energy range of FCC-ee)
    - With SM value of $\mathcal{B}(W^+ \to c\bar{b}) \sim 10^{-3}$ a precision of $\delta V_{cb}/V_{cb} \sim 0.1\%$ might be within reach...
    - Relies crucially on efficient c- and b-jet identification

FCC-ee flavour physics benchmarks & explorations

Part 2: CPV in ΔB=2

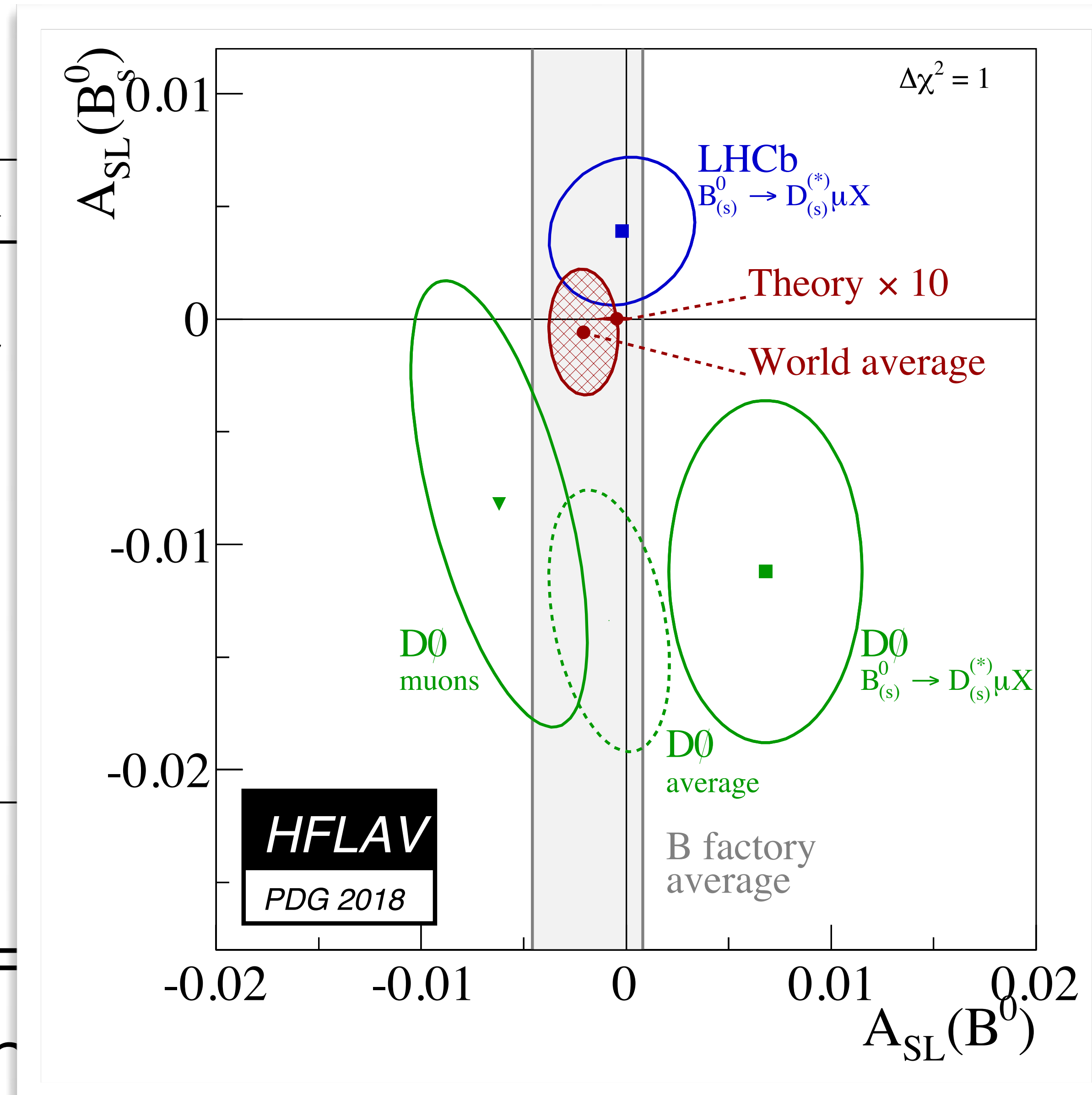
Observable / Experiments	Current W/A	Belle II (50 /ab)	LHCb-U1 (23/fb)	FCC-ee
Mixing-related inputs				
$\sin(2\beta)$	0.691 ± 0.017	0.691 ± 0.008	0.691 ± 0.009	
ϕ_s (uncert. rad 10^{-2})	-1.5 ± 3.5	n/a	-3.65 ± 0.05	
Δm_d (ps^{-1})	0.5065 ± 0.0020	same	same	
Δm_s (ps^{-1})	17.757 ± 0.021	same	same	
$a_{\rm fs}^d$ (10^{-4}, precision)	23 ± 26	-7 ± 15	-7 ± 15	
$a_{\rm fs}^s$ (10^{-4}, precision)	-48 ± 48	n/a	0.3 ± 15	

- Uncertainties in most ΔB=2 observables will start to be systematics/theory dominated
- Notable exceptions: ϕ_s, $a_{\rm fs} = \dfrac{\Gamma(\bar{B}_q^0 \to B_q^0 \to f) - \Gamma(B_q^0 \to \bar{B}_q^0 \to \bar{f})}{\Gamma(\bar{B}_q^0 \to B_q^0 \to f) + \Gamma(B_q^0 \to \bar{B}_q^0 \to \bar{f})}$

FCC-ee flavour physics benchmarks & explorations

Part 2: CPV in ΔB=2

Observable / Experiments	Current W/A	C-*ee*
Mixing-related inputs		
$\sin(2\beta)$	0.691 ± 0.017	
ϕ_s (uncert. rad 10^{-2})	-1.5 ± 3.5	
Δm_d (ps^{-1})	0.5065 ± 0.0020	
Δm_s (ps^{-1})	17.757 ± 0.021	
a_{fs}^d (10^{-4}, precision)	23 ± 26	
a_{fs}^s (10^{-4}, precision)	-48 ± 48	



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FCC-ee flavour physics benchmarks & explorations

Part 2: CPV in ΔB=2

Observable / Experiments	Current W/A	Belle II (50 /ab)	LHCb-U1 (23/fb)	FCC-*ee*
Mixing-related inputs				
$\sin(2\beta)$	0.691 ± 0.017	0.691 ± 0.008	0.691 ± 0.009	0.691 ± 0.005
ϕ_s (uncert. rad 10^{-2})	-1.5 ± 3.5	n/a	-3.65 ± 0.05	-3.65 ± 0.01
Δm_d (ps^{-1})	0.5065 ± 0.0020	same	same	same
Δm_s (ps^{-1})	17.757 ± 0.021	same	same	same
a_{fs}^d (10^{-4}, precision)	23 ± 26	-7 ± 15	-7 ± 15	-7 ± 2
a_{fs}^s (10^{-4}, precision)	-48 ± 48	n/a	0.3 ± 15	0.3 ± 2

- Significant improvement in both observables @FCC-ee
- Observation of CPV in B_d mixing possible (a_{fs})

S. Monteil @ FCC week 2019

- Not included ($\alpha_s,\gamma_s,\beta_s$) from ($B_s \to D_sK$, $B \to DK$, $B_s \to \phi\phi$)

Aleksan, Oliver & Perez, 2107.02002, 2107.05311

talks by R. Aleksan, E.Perez

Combining 1 & 2: Impact on CPV BSM in ΔB=2

Model-independent parametrization of BSM in ΔF=2

$$\langle B_q|\mathcal{H}^{\rm SM+NP}_{\Delta B=2}|\bar{B}_q\rangle = \langle B_q|\mathcal{H}^{\rm SM}_{\Delta B=2}|\bar{B}_q\rangle \left(1 + h_q e^{i\sigma_q}\right)$$

Assumptions:

- NP only at short distances (UV)
- CKM unitary (& determined from NP free obs.)

FCC-ee flavour physics benchmarks & explorations

Combining 1 & 2: Impact on CPV BSM in ΔB=2

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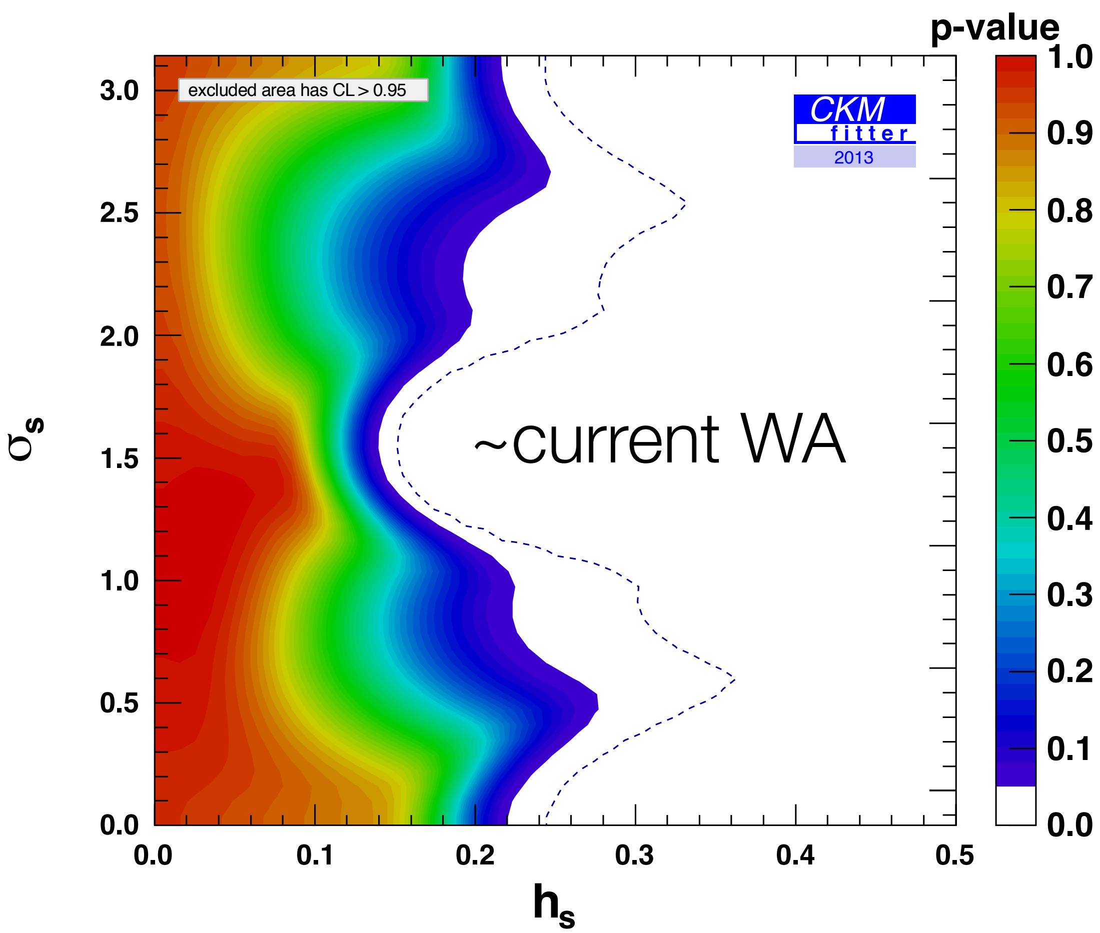

FCC-ee flavour physics benchmarks & explorations

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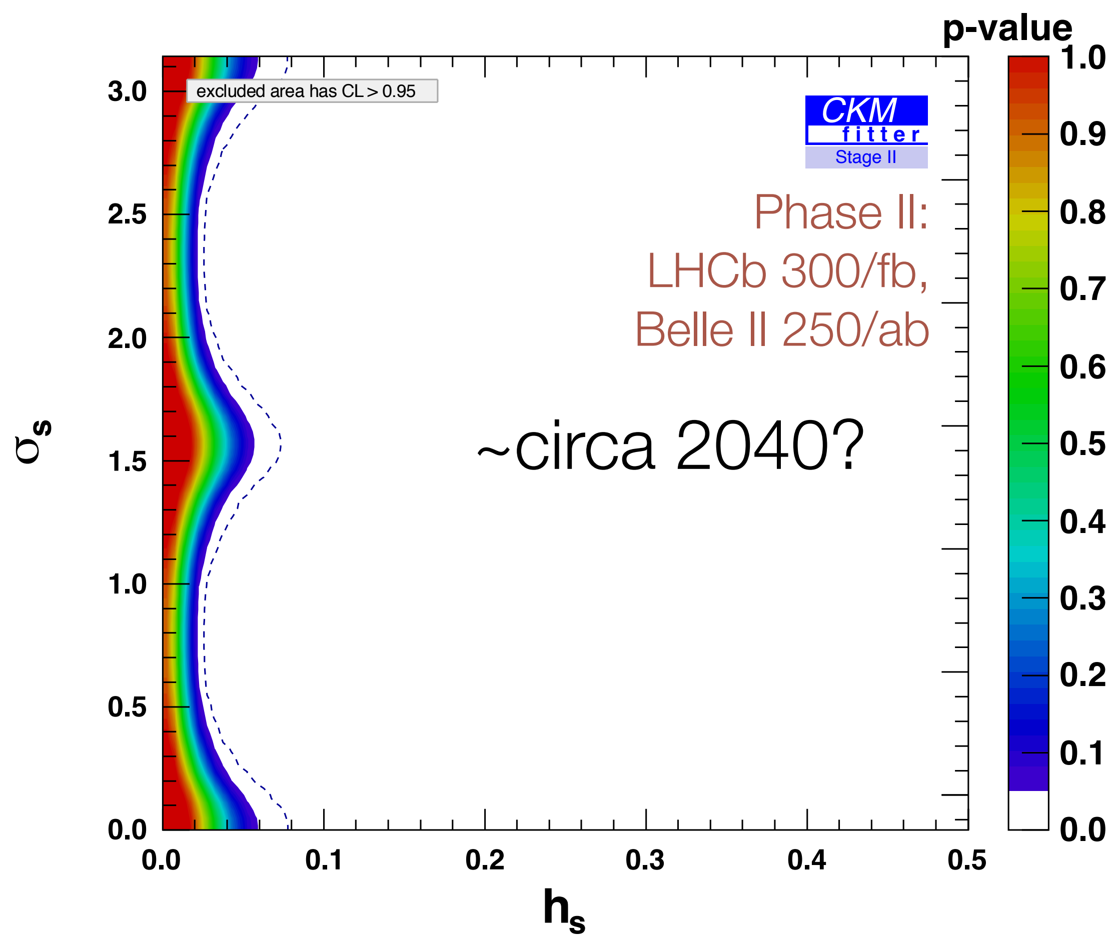

*TH progress (lattice)

FCC-ee flavour physics benchmarks & explorations

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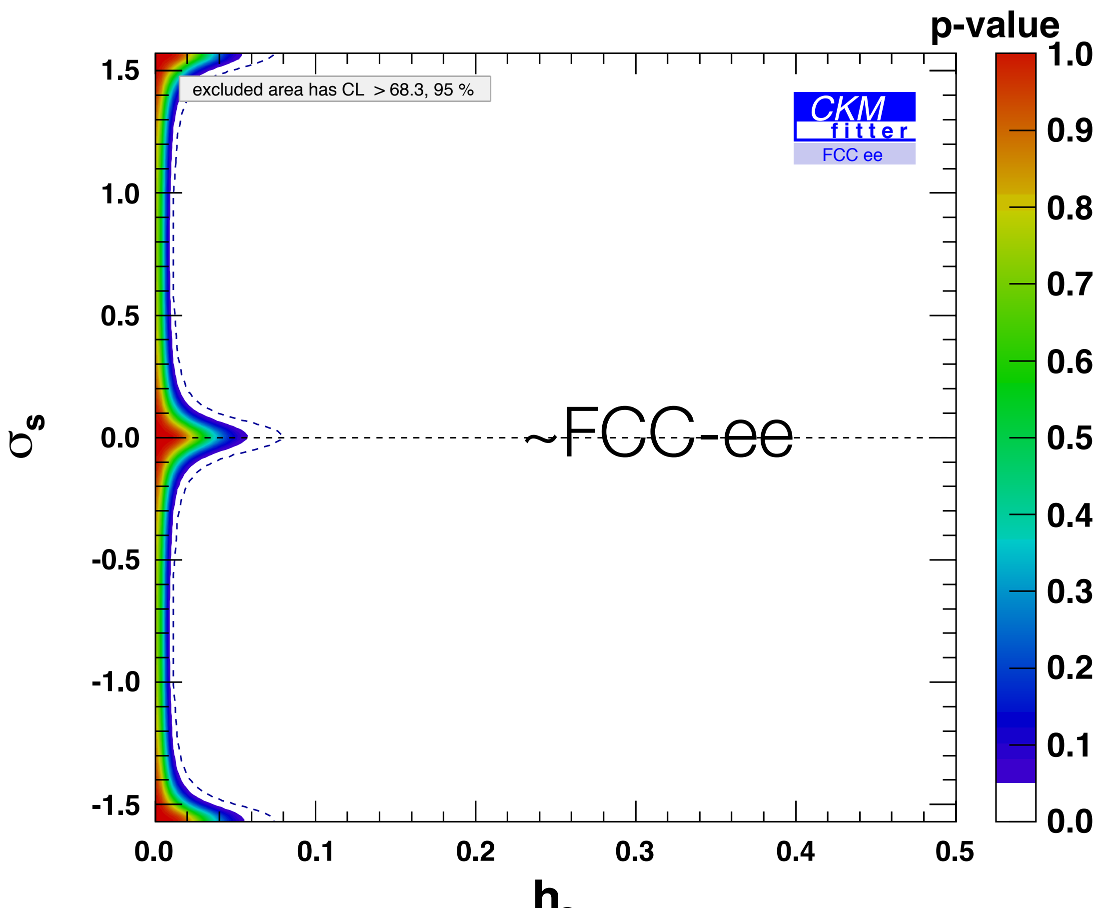

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FCC-ee flavour physics benchmarks & explorations

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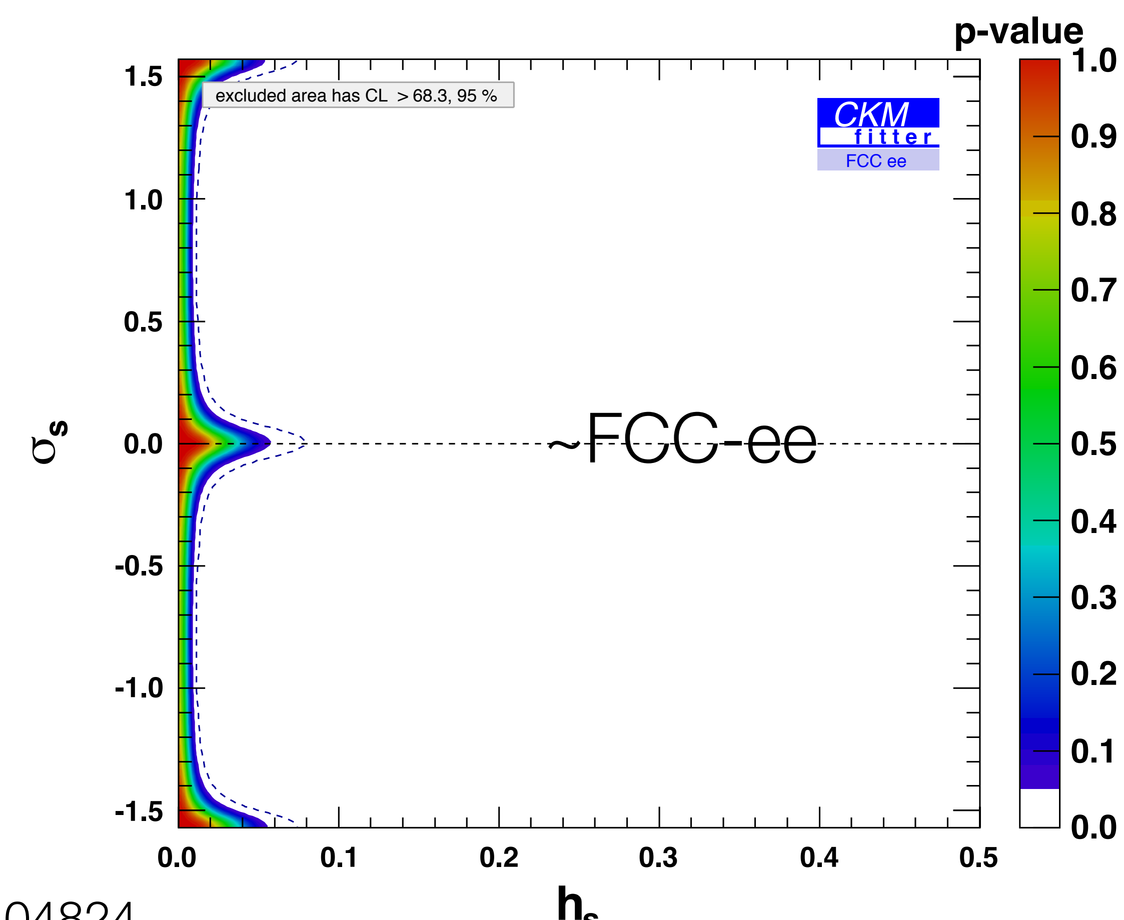
In terms of UV sensitivity

$$h \simeq 1.5\, \frac{|C_{ij}|^2}{|\lambda^t_{ij}|^2}\, \frac{(4\pi)^2}{G_F \Lambda^2} \simeq \frac{|C_{ij}|^2}{|\lambda^t_{ij}|^2} \left(\frac{4.5\,\text{TeV}}{\Lambda}\right)^2,$$

$$\sigma = \arg\left(C_{ij}\, \lambda^{t*}_{ij}\right),$$

For CKM like (MFV) : $\Lambda > 20\,\text{TeV}$

$$C_{ij} = \lambda^t_{ij} \equiv V_{ti} V^*_{tj}$$

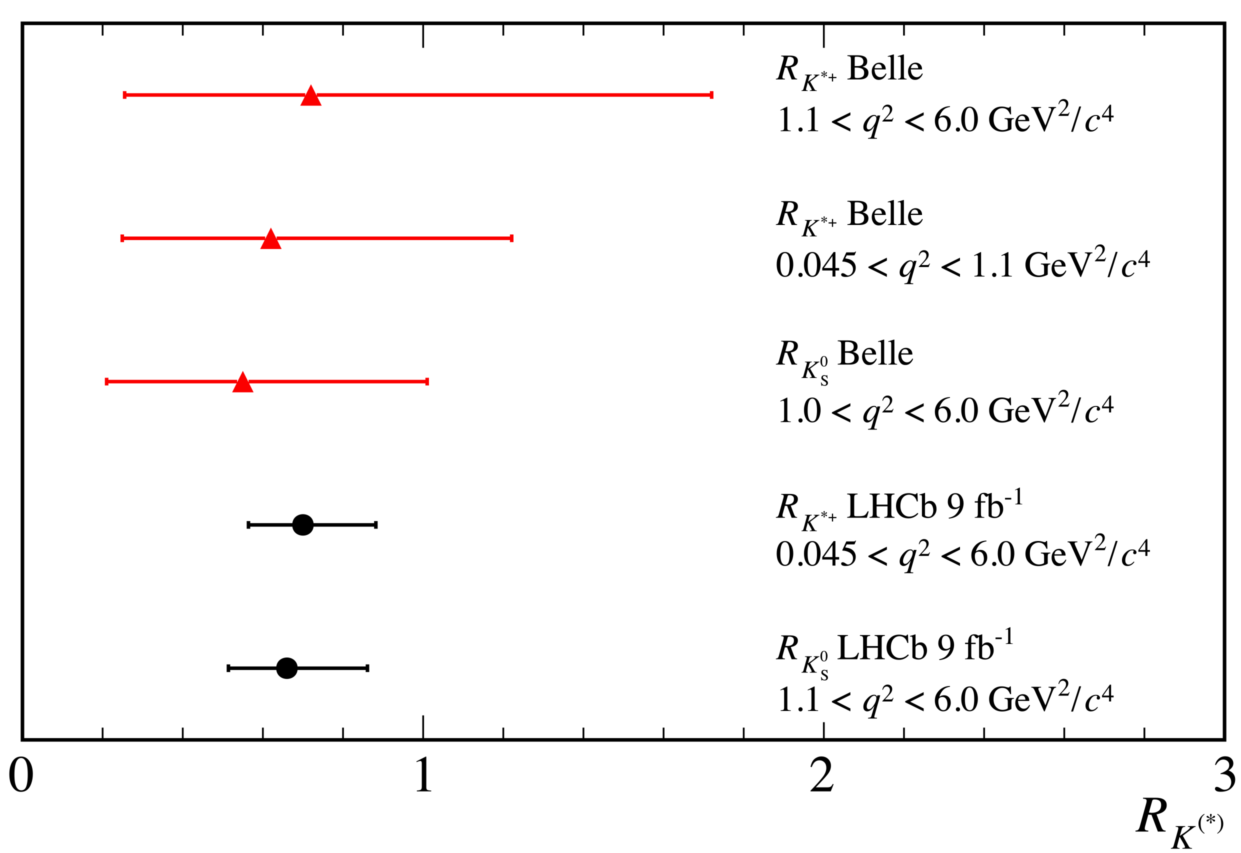


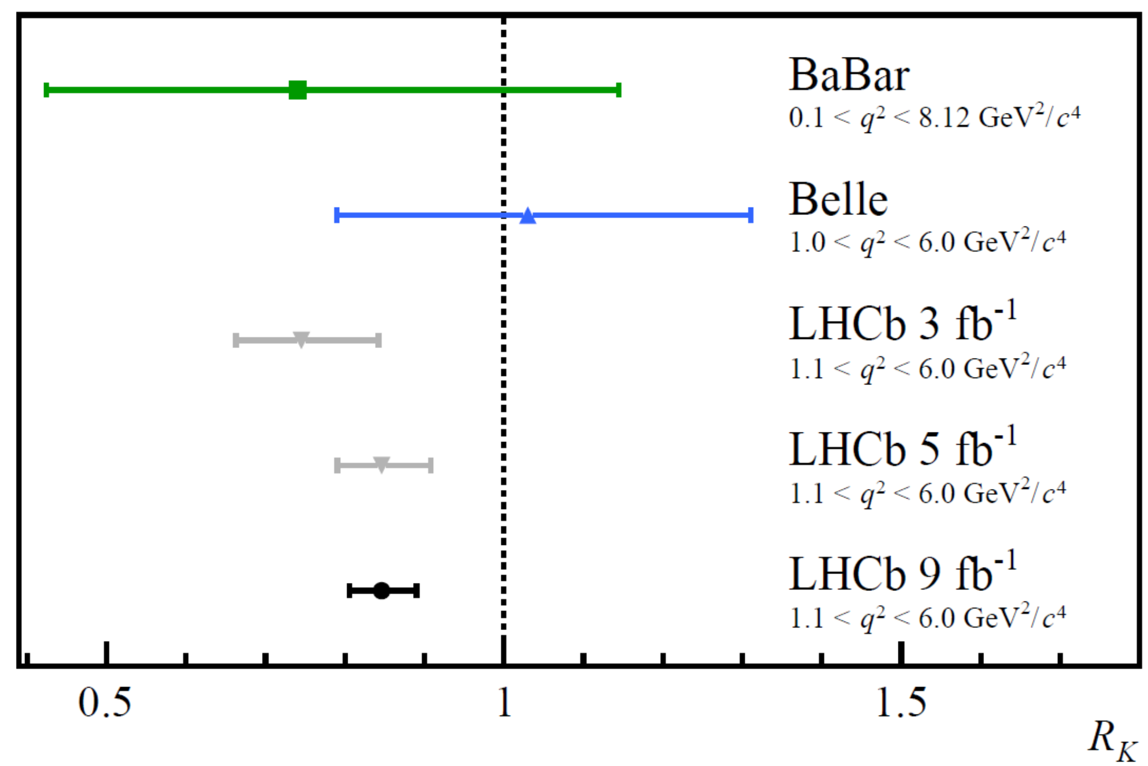
see also Charles et al., 2006.04824

FCC-ee flavour physics benchmarks & explorations

Part 3: Rare b-hadron decays to taus

Motived by current intriguing exp. situation in rare B decays





$$R_H \equiv \frac{\displaystyle\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{d\mathcal{B}(B\to H\mu^+\mu^-)}{dq^2}dq^2}{\displaystyle\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{d\mathcal{B}(B\to He^+e^-)}{dq^2}dq^2}$$

FCC-ee flavour physics benchmarks & explorations

Part 3: Rare b-hadron decays to taus

Motived by current intriguing exp. situation in rare B decays

- FCC-ee (unique) probe of SM predictions for $B \to K^{(*)}\tau^+\tau^-$

$$R_{K^+}^{\mu\tau} = 0.87 \pm 0.02 \quad , \quad R_{K^0}^{\mu\tau} = 0.87 \pm 0.02 \; , \quad 15 \text{ GeV}^2 < q^2 < 22 \text{ GeV}^2$$

$$R_{K^{*+}}^{\mu\tau} = 2.44 \pm 0.09 \; , \quad R_{K^{*0}}^{\mu\tau} = 2.45 \pm 0.08 \; , \quad 15 \text{ GeV}^2 < q^2 < 19.2 \text{ GeV}^2 .$$

J.F.K. et al., 1705.11106
Li & Liu, 2012.00665

+ Complete kinematical reconstruction

- Access to angular observables, tau polarization
- Detailed study of backgrounds & detector requirements in progress

see talk by T. Miralles

FCC-ee flavour physics benchmarks & explorations

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J.F.K. et al., 1705.11106
Li & Liu, 2012.00665

- Potentially also complementary leptonic mode $B_{(s)} \to \tau^+\tau^-$

$$\begin{aligned} \mathrm{BR}(B_s \to \tau^+\tau^-) &= (7.73 \pm 0.49) \times 10^{-7} \\ \mathrm{BR}(B_d \to \tau^+\tau^-) &= (2.22 \pm 0.19) \times 10^{-8} \end{aligned}$$

Bobeth et al., 1311.0903
see also
U. Haisch, 1206.1230

(Expected sensitivity at Belle II to BRs of O (10^{-4}) ~ O(10^{-5}))

see also
LHCb-CONF-2016-011

FCC-ee flavour physics benchmarks & explorations

Part 3: Rare b-hadron decays to taus, neutrinos

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(Expected sensitivity at Belle II to BRs of $O(10^{-4}) \sim O(10^{-5})$)

see also
LHCb-CONF-2016-011

- Potential improvement also on $B \to K^{(*)}\nu\nu$ (beyond Belle II)

see talk by M. Kenzie

FCC-ee flavour physics benchmarks & explorations

Part 4: Flavour violating Z decays

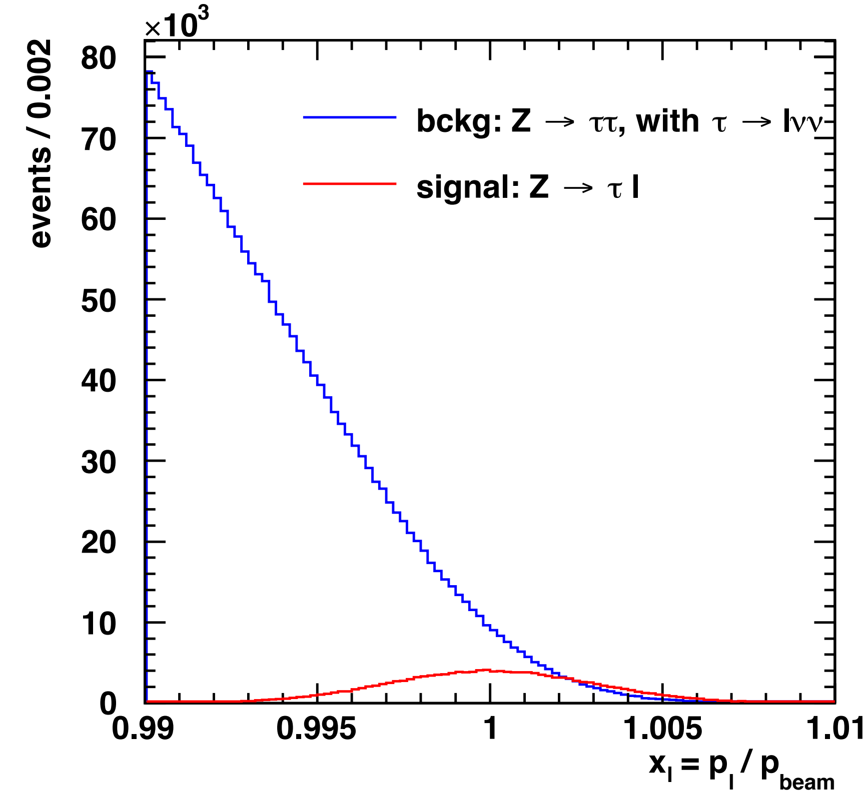
- Lepton flavour violating processes Z→eτ,τμ
  - complementary to lepton flavour violating τ decays
  - FCC-ee feasibility study:

see e.g. Illiana & Masip, hep-ph/0207328
L. Calibbi, X. Marcano, J. Roy, 2107.10273
(& talk by X. Marcano)

$$\mathcal{B}(Z \to \tau^{\pm}\mu^{\mp}) < 10^{-9} - 10^{-10}$$

  - would improve current limits by at least 3 orders of magnitude

M. Dam, SciPostPhys.Proc.1,041(2019)
see also De Romeri et al. JHEP 1504 (2015) 051



FCC-ee flavour physics benchmarks & explorations

Part 4: Flavour violating Z decays

- Lepton flavour violating processes Z→eτ,τμ
- Similar possibility in the quark sector? i.e. $Z \to j_b j_{\not b}$
  - Motivation: Probing FCNC Z-penguins directly

    c.f. Isidori & Guadagnoli, 1302.3909
  - In SM $\mathcal{B}(Z \to s\bar{b}) \sim 10^{-8}$ - could be probed to 1% level?

Need very efficient b-, s-tagging!

	no PID	$\epsilon_K = 95\%$	$\epsilon_K = 90\%$
ϵ_s	7×10^{-2}	4×10^{-2}	3×10^{-2}
ϵ_b	3×10^{-4}	4×10^{-5}	5×10^{-5}

Preliminary study in context of LC

Duarte-Campderros et al., 1811.09636

FCC-ee flavour physics benchmarks & explorations

Part 5: tau physics

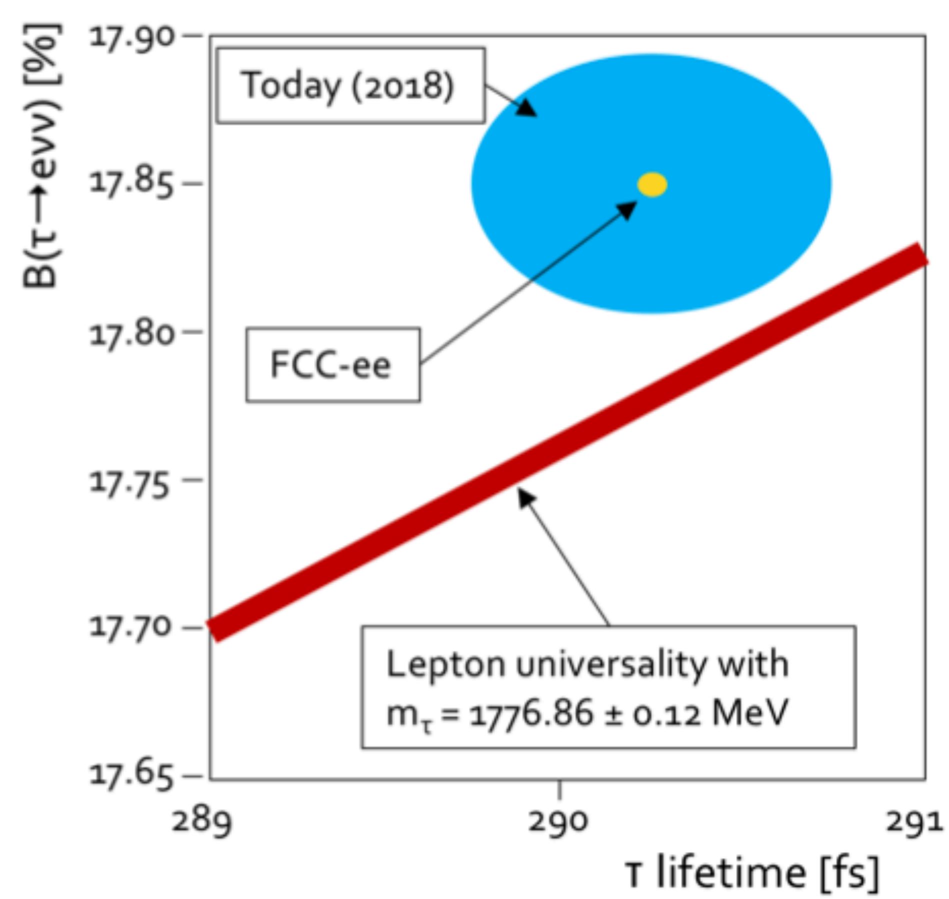
- Several tau properties and decays could be determined more precisely

- Interesting implications for LFU (in tau decays) & CKM unitarity

  see e.g.
  Allwicher, Isidori, Semilovic, 2109.03833
  M. Dam, SciPostPhys.Proc.1,041(2019)
  Eur. Phys. J. Plus 136, 963 (2021)
  talk by A. Lusiani

- Would possibly require improved calculations

Property	Current WA	FCC-ee stat	FCC-ee syst
Mass [MeV]	1776.86 +/- 0.12	0.004	0.1
Electron BF [%]	17.82 +/- 0.05	0.0001	0.003
Muon BF	17.39 +/- 0.05	0.0001	0.003
Lifetime [fs]	290.3 +/- 0.5	0.005	0.04



Conclusions

- FCC-ee could be a powerful and competitive probe of flavour physics post-2030
    - FCC-ee can compete favourably with ultimate precision of LHCb and Belle II
    - There are processes for which FCC-ee is unique
    - Luminosity is key. Many measurements reported here are statistically limited?!

Conclusions

- FCC-ee could be a powerful and competitive probe of flavour physics post-2030

- Effort underway to understand exp. precision with which rare decays of c- and b-hadrons and CP violation in heavy-quark sector & LFV processes could be measured
    - Flavour Physics defines shared (vertexing, tracking, calorimetry) and specific (hadronic PID) detector requirements
    - In the coming phase important interplay of physics performance with detector concepts
    - On theory side: go beyond benchmark modes — fill in possible gaps

Conclusions

- FCC-ee could be a powerful and competitive probe of flavour physics post-2030

- Effort underway to understand exp. precision with which rare decays of c- and b-hadrons and CP violation in heavy-quark sector & LFV processes could be measured

- Less explored areas include flavour studies using top & Higgs decays, spectroscopy, quarkonium physics, flavor conversion @ high-pT

  - Examples: top & Higgs decays to exclusive hadronic final states
    dilepton spectra @ FCC-hh

see e.g.
Mangano & Melia, 1410.7475
Kagan et al., 1406.1722
Konig et al., 1505.03870

see e.g. Garland et al., 2112.05127
talk by S. Jager