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CP violation in $B_s \to \phi\mu^+\mu^-$ at the FCC-*ee*

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Outline

1. Introduction
2. $B_s^0 \to \phi\mu^+\mu^-$ @ FCC-*ee*
3. New Physics
4. Summary

based on: 2506.08089 in collaboration with Tsz Hong Kwok,
Zachary Polonsky, Valeriia Lukashenko and Ben Kilminster

Outline

CP violation

SM

V_{CKM}

Strong CP problem

θ_{QCD}

Sakharov conditions

matter-antimatter asymmetry

Types

Mixing

mass vs. CP eigenstates

Decay

$|A_f| \neq |\overline{A}_{\bar{f}}|$

Interference of mixing and decay

time-dependent observables

Outline

FCC-ee

High statistics

at Z-pole

Good vertexing

IDEA detector

Good flavor tagging

Clean environment

Estimated yields

b-hadron	Belle II	LHCb	FCC-ee
B^0, $\bar{B}^0$	5.3×10^{10}	6×10^{13}	7.2×10^{11}
$B^{\pm}$	5.6×10^{10}	6×10^{13}	7.2×10^{11}
B_s^0, $\bar{B}_s^0$	5.7×10^{8}	2×10^{13}	1.9×10^{11}
$B_c^{\pm}$	–	4×10^{11}	1.1×10^{9}
Λ_b^0, $\bar{\Lambda}_b^0$	–	2×10^{13}	1.5×10^{11}

Production

Z-pole

$e^+e^- \to Z$

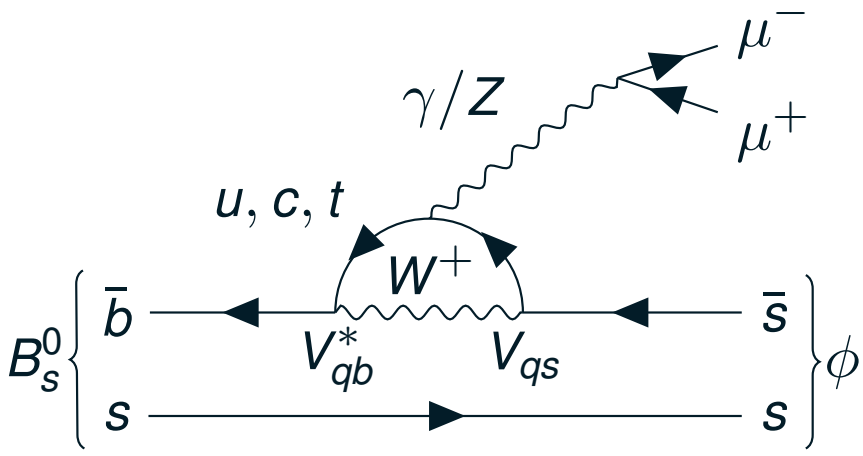
Z decay

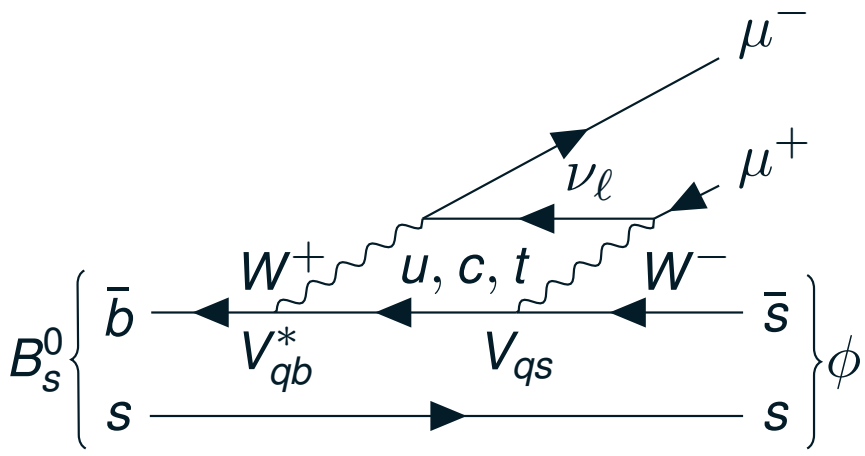
$Z \to b\bar{b}$

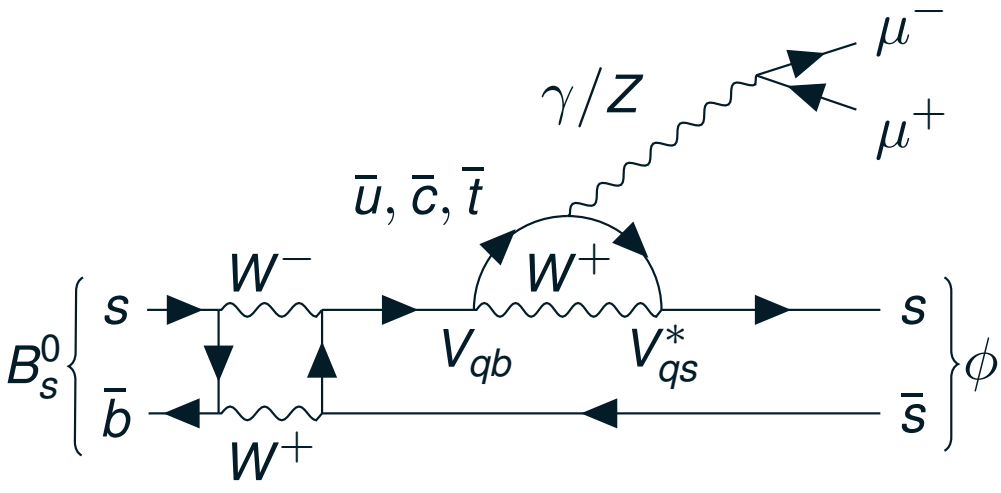
Signal

$B_s^0 \to \phi(\to K^+K^-)\mu^+\mu^-$

$B_s^0 \to \phi\mu^+\mu^-$







Background

Resonance

$B_s^0 \to \phi(\to K^+K^-)J/\psi(\to \mu^+\mu^-)$

Cascade

$B_s^0 \to D_s^- \mu^+ \nu_\mu$ followed by $D_s^- \to \phi(\to K^+K^-)\mu^- \bar{\nu}_\mu$

Combinatoric

from fragmentation

Measurements

Untagged vs Tagged

B_s^0 or $\overline{B}_s^0$

Time-dependent vs. Time-integrated

Time evolution

Advantage

Complementarity

Untagged Measurements

Branching ratio

$\mathrm{Br}(B_s^0 \to \phi\mu^+\mu^-)$

Time-dependent Decay Rate

$$\Gamma_{B_s^0\to\phi\mu^+\mu^-}(t) + \Gamma_{\bar{B}_s^0\to\phi\mu^+\mu^-}(t) \propto e^{-\Gamma_s t}\left(\cosh\tfrac{1}{2}\Delta\Gamma_s t + D_f \sinh\tfrac{1}{2}\Delta\Gamma_s t\right)$$

$\Delta\Gamma_s =$ decay rate difference

$D_f =$ observable

Tagged Measurements

Time-integrated CP-asymmetry

$$\langle A_{CP} \rangle = \frac{\Gamma_{B_s^0 \to \phi\mu^+\mu^-} - \Gamma_{\bar{B}_s^0 \to \phi\mu^+\mu^-}}{\Gamma_{B_s^0 \to \phi\mu^+\mu^-} + \Gamma_{\bar{B}_s^0 \to \phi\mu^+\mu^-}}$$

Time-dependent CP-asymmetry

$$A_{CP}(t) = \frac{C_f \cos \Delta m_s t - S_f \sin \Delta m_s t}{\cosh \frac{1}{2}\Delta\Gamma_s t + D_f \sinh \frac{1}{2}\Delta\Gamma_s t}$$

$\Delta m_s =$ mass difference

$C_f =$ observable

$S_f =$ observable

Outline

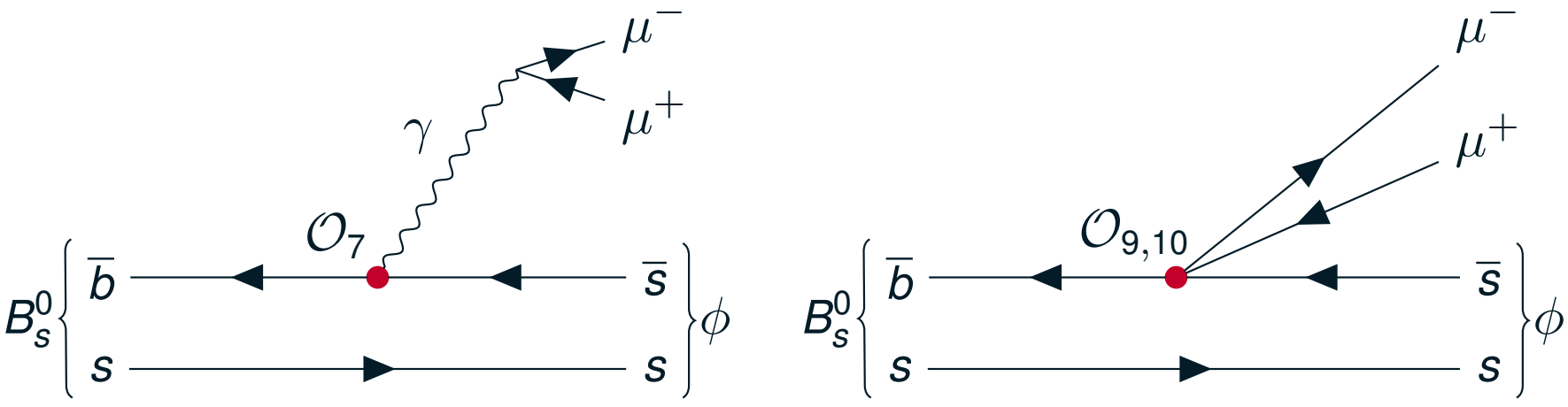
Effective Hamiltonian

$$\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i O_i \,,$$

$$O_7 = \frac{e}{(4\pi)^2} m_b [\bar{s}\sigma^{\mu\nu} P_R b] F_{\mu\nu}$$

$$O_9 = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)\,, \quad O_{10} = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \gamma_5 \mu)\,.$$

NP contributions



Angular coefficients

$$\frac{d^4\Gamma_{B_s^0\to\phi\mu^+\mu^-}}{dq^2\, d\cos\theta_K\, d\cos\theta_\ell\, d\phi} = \sum_i J_i(q^2) f_i(\theta_K, \theta_\ell, \phi)$$

$$= \frac{9}{32\pi}\big(J_{1s}\sin^2\theta_K + J_{1c}\cos^2\theta_K + J_{2s}\sin^2\theta_K\cos 2\theta_\ell$$
$$+ J_{2c}\cos^2\theta_K\cos 2\theta_\ell + J_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ J_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + J_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ J_{6s}\sin^2\theta_K\cos\theta_\ell + J_{6c}\cos^2\theta_K\cos\theta_\ell$$
$$+ J_7\sin 2\theta_K\sin\theta_\ell\sin\phi + J_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi$$
$$+ J_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\big)$$

Observables

Branching ratio

$$Br(B_s^0 \to \phi\mu^+\mu^-) = \frac{\int dq^2 \sum_i \kappa_i J_i(q^2)}{\Gamma_{tot}}$$

untagged time-dependent

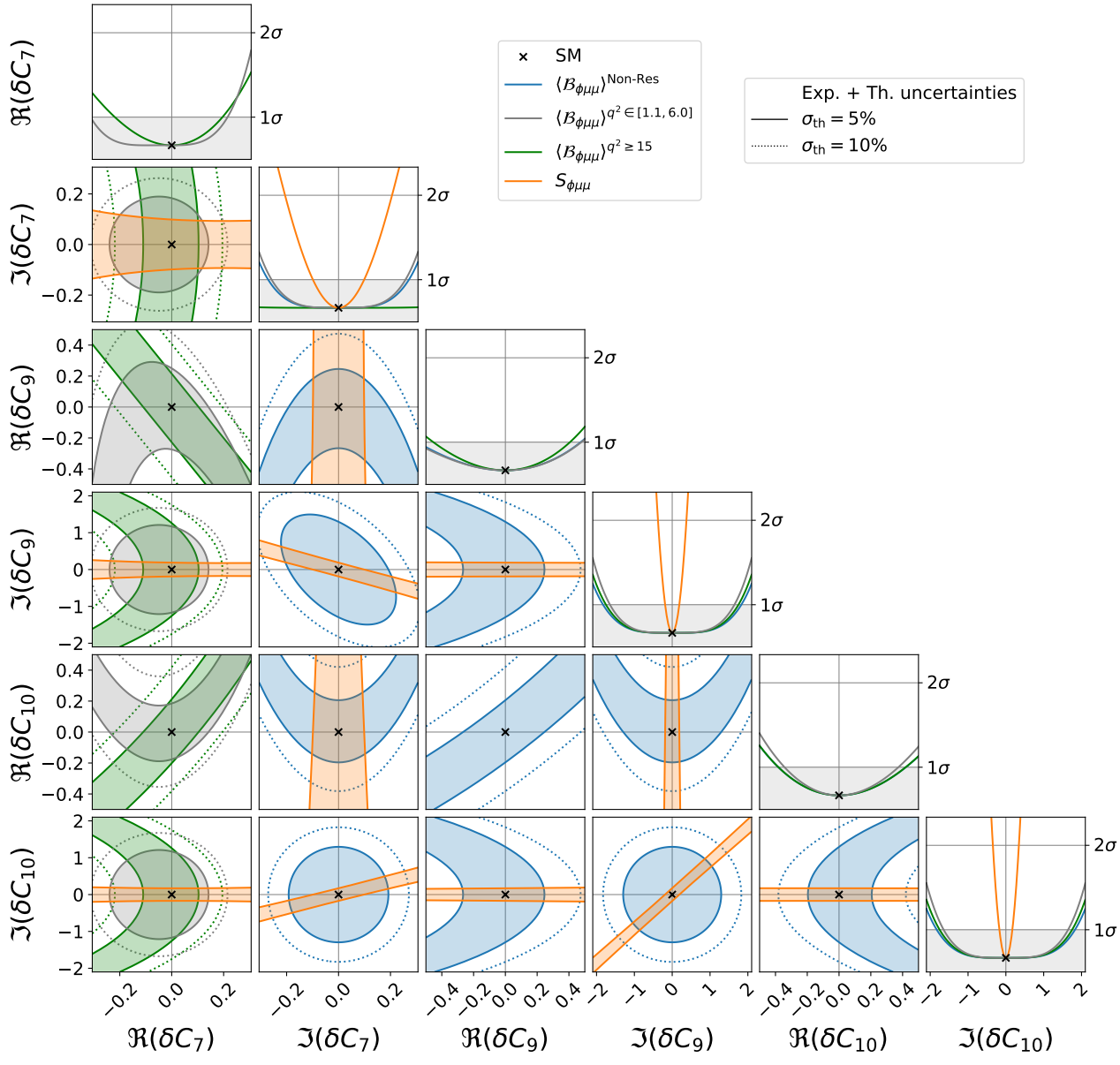
$$D_f = -\frac{\int dq^2 \sum_i \kappa_i \, h_i(A_i)}{\Gamma+\bar{\Gamma}}$$

tagged time-dependent

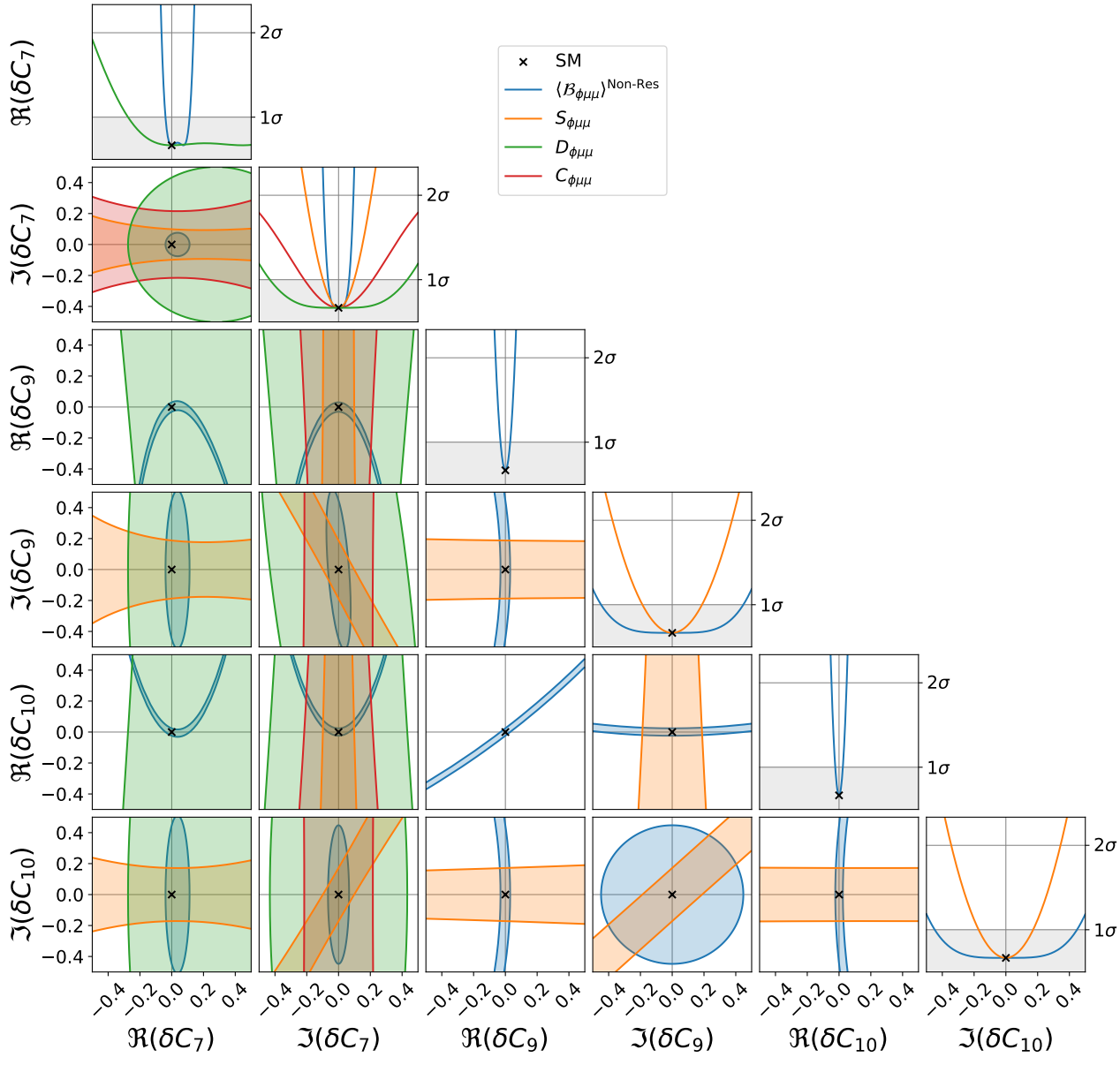
$$C_f = \frac{\int dq^2 \sum_i \kappa_i \left(J_i(q^2) - \bar{J}_i(q^2)\right)}{\Gamma+\bar{\Gamma}}$$

$$S_f = -\frac{\int dq^2 \sum_i \kappa_i \, s_i(A_i)}{\Gamma+\bar{\Gamma}}$$

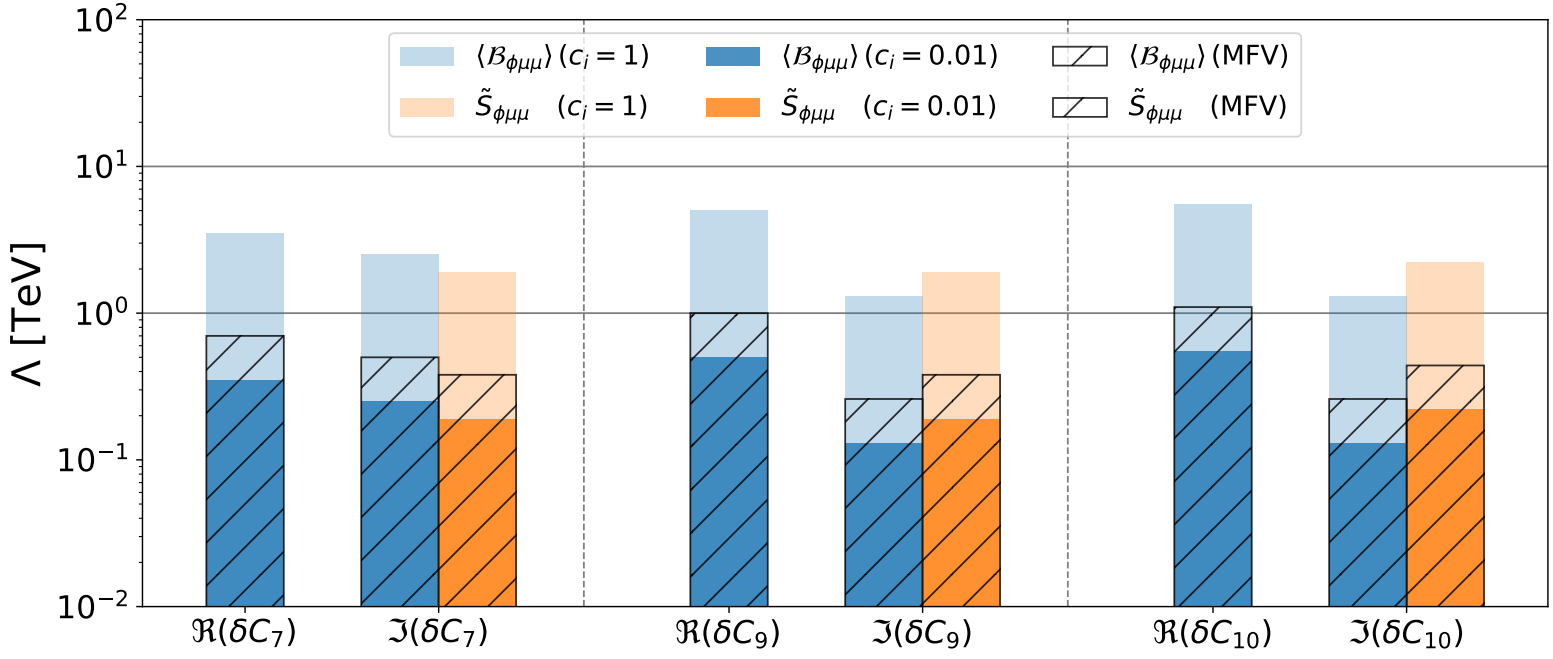
Constraints



Constraints



NP reach


10^2
10^1
10^0
10^{-1}
10^{-2}
Λ [TeV]
$\langle \mathcal{B}_{\phi\mu\mu} \rangle\,(c_i = 1)$
$\tilde{S}_{\phi\mu\mu}$ $(c_i = 1)$
$\langle \mathcal{B}_{\phi\mu\mu} \rangle\,(c_i = 0.01)$
$\tilde{S}_{\phi\mu\mu}$ $(c_i = 0.01)$
$\langle \mathcal{B}_{\phi\mu\mu} \rangle\,(\mathrm{MFV})$
$\tilde{S}_{\phi\mu\mu}$ (MFV)
$\Re(\delta C_7)$
$\Im(\delta C_7)$
$\Re(\delta C_9)$
$\Im(\delta C_9)$
$\Re(\delta C_{10})$
$\Im(\delta C_{10})$

Outline

Summary

FCC-*ee*

statistics, vertexing, clean

Time-(in)dependent observables

tagged vs. untagged

NP

Constraints on C_7, C_9, C_{10}