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Theoretical challenges related to future colliders

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CERN

Outline

1. Introduction
2. Prospects
3. Theoretical challenges
4. Summary

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Possible future colliders

Circular

FCC, CEPC

Linear

ILC, CLIC, C^3

Muon

MuCol

New environment

Higher (other) energies

$\rightarrow$ new effects

Higher luminosities

Higher precision $\rightarrow$ uncertainties, quantum corrections

New experiments

new, best suited observables

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SM parameters

CKM

V_{cs}, V_{cb}

Electroweak parameters

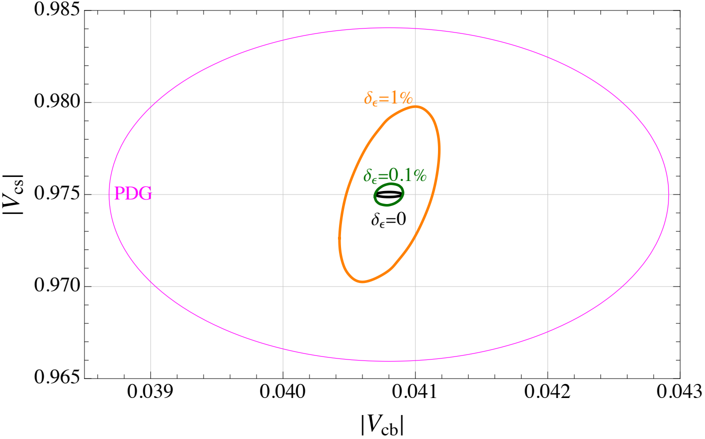
M_Z, M_W, m_t

Higgs self-coupling λ

Not measured yet

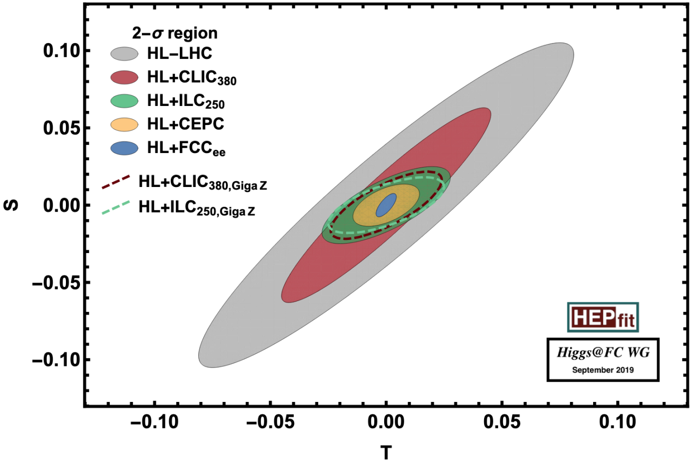
V_{cs} vs. V_{cb}

Marzocca/Szewc/Tammaro: 2405.08880



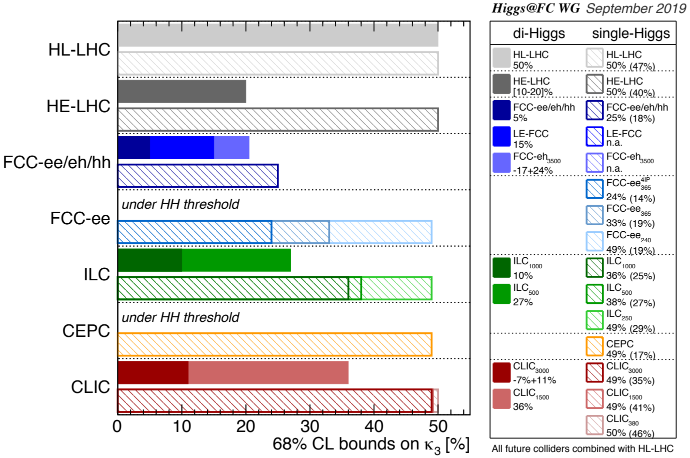
S and T parameters

Snowmass: 2203.06520



Higgs self-coupling

De Blas et al.: 1905.03764



Beyond the SM

CP violation

Axions?

Compositness

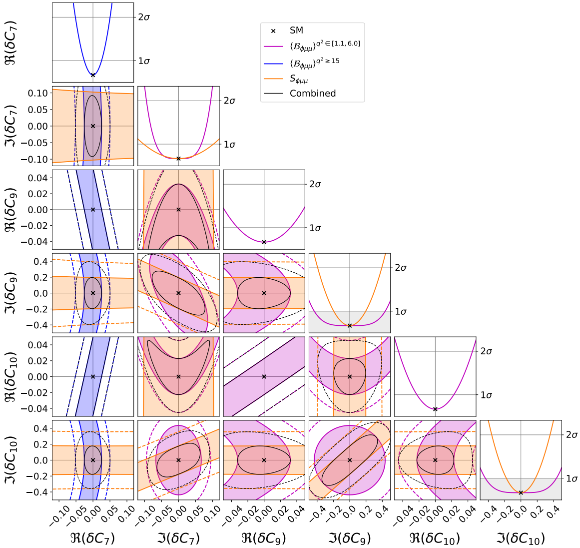
Higgs = composite?

New particles

LQ, Z', DM

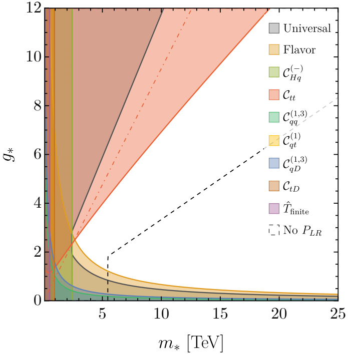
CP violation: $B_s^0 \to \phi\mu^+\mu^-$

JA/Kilminster/Kwok/Lukashenko/Polonsky

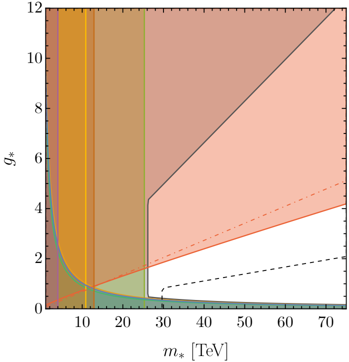


Composite Higgs

Stefanek: 2407.09593



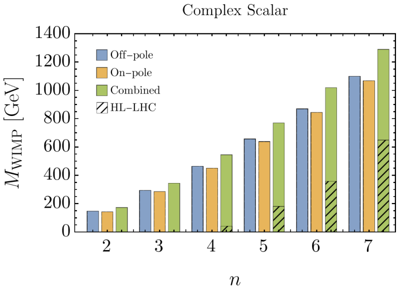
(a) Right compositeness (current)

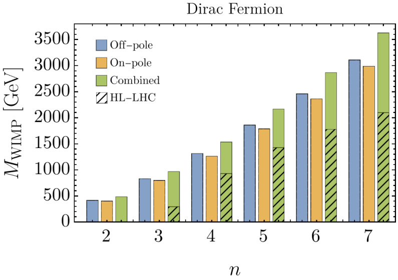


(b) Right compositeness (FCC-ee)

DM bounds on mass

Maura/Stefanek/You: 2412.14241





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Precision of α_{em}

High statistics

Statistical uncertainty decreases

Current uncertainty: $\delta\alpha_{\text{em}}(m_Z^2)$

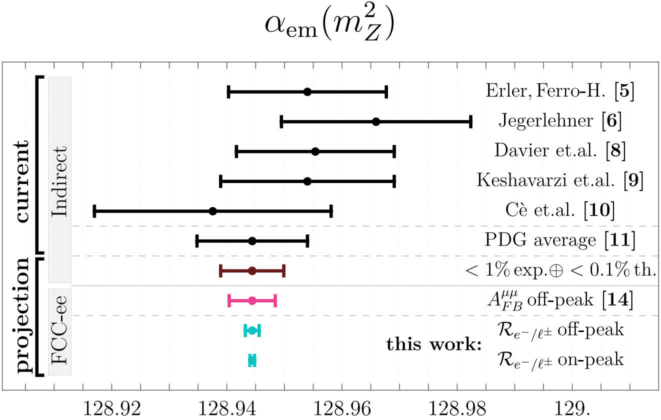
$\mathcal{O}(10^{-4})$

Solution

Measure it at FCC-ee

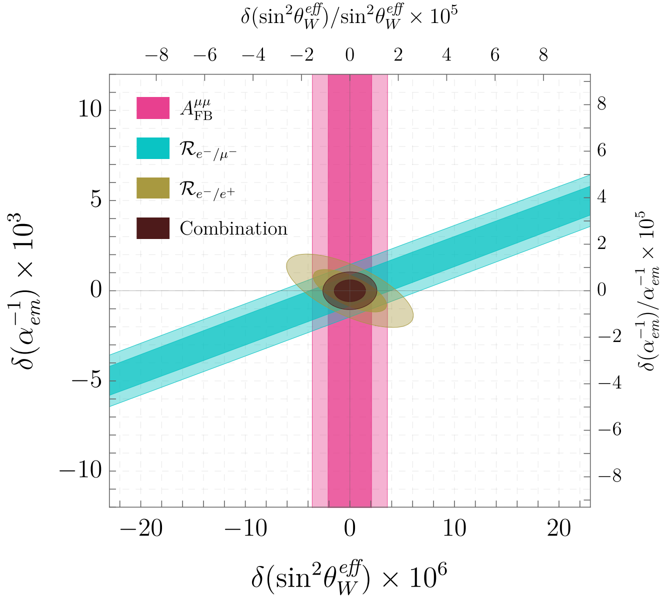
α_{em} at FCC-ee

Riembau: 2501.05508



α_{em} at FCC-ee

Riembau: 2501.05508



Running effects

Running couplings

$g_s(\mu), g(\mu)$...

Truncation

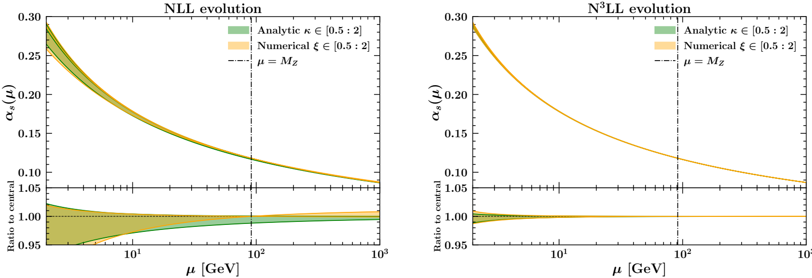
$\mu \frac{d}{d\mu} g_s = -\beta_0 \frac{g_s^3}{16\pi^2} - \beta_1 \frac{g_s^5}{(16\pi^2)^2} + \mathcal{O}(g_s^7)$

Need

Higher orders, error estimation

Running of α_s

Bertone/Bozzi/Hautmann: 2407.20842



More precise predictions: Terra-Z

Quantity	Current precision	FCC-ee stat. (syst.) precision	Required theory input	Theory status as of today	Needed theory improvement[†]
m_Z	2.0 MeV	0.004 (0.1) MeV	non-resonant $e^+e^- \to f\bar{f}$, initial-state radiation (ISR)	NLO, ISR logarithms up to 6th order	NNLO for $e^+e^- \to f\bar{f}$
Γ_Z	2.3 MeV	0.004 (0.012) MeV			
$\sin^2\theta^\ell_{\rm eff}$	4×10^{-5}	$2(1.2) \times 10^{-6}$			
m_W	13.3 MeV	0.18 (0.16) MeV	lineshape of $e^+e^- \to WW$ near threshold	NLO ($e^+e^- \to 4f$ or EFT framework)	NNLO for $e^+e^- \to WW$, $W \to f\bar{f}$ in EFT setup
HZZ coupling	–	0.1%	cross-sect. for $e^+e^- \to ZH$	NLO EW plus partial NNLO QCD/EW	full NNLO EW
$m_{\rm top}$	290 MeV	8 (2.5) MeV	threshold scan $e^+e^- \to t\bar{t}$	N^{3}LO QCD, NNLO EW, resummations up to NNLL, $\mathcal{O}$(30 MeV) scale uncert.	Matching fixed orders with resummations, merging with MC, α_s (input)

from Matthew McCullough @ FCC Workshop

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Future Colliders

Higher statistics, precision

Better knowledge of parameters

α_{em}, running couplings etc.

More precise predictions

Loop corrections, MC