Determination of CPV Higgs mixing angle in ZZ-fusion at 1.4 TeV CLIC

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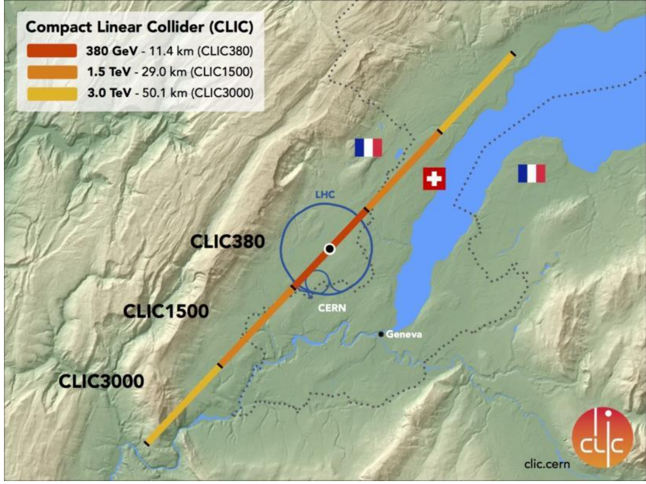
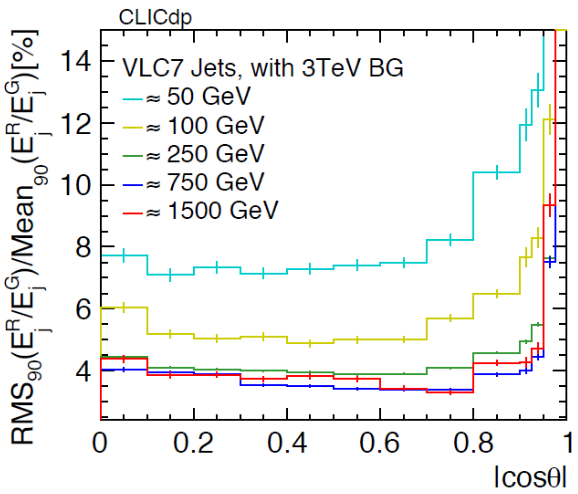
Overview

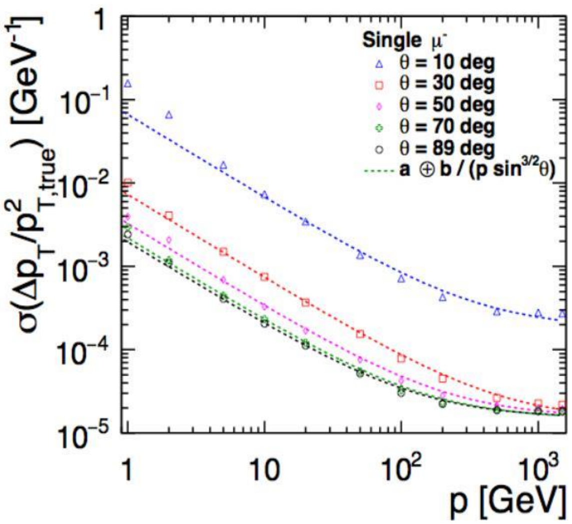
- Accelerator and Detector for CLIC
- Higgs studies at CLIC
  - Higgs couplings
  - Higgs self-coupling
  - BSM Higgs physics
- CPV in ZZ-fusion at 1.4 TeV CLIC
  - Sensitive observable
  - Event selection
  - Reconstruction of sensitive observable
- Summary

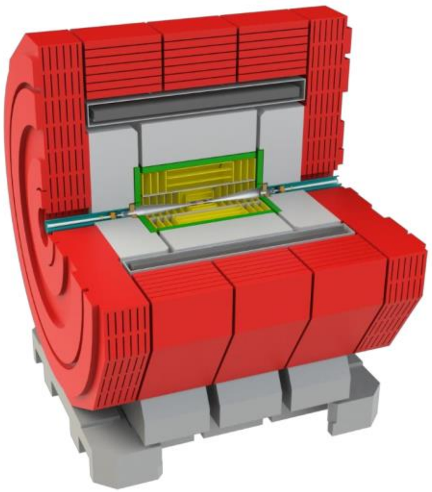
Accelerator & detector

- CLIC is a mature option for e^+e^- collider at CERN
- Energy staged from 380 GeV up to 3 TeV
- Two-beam acceleration scheme (acceleration gradient 100 MV/m)
- Proven technology at CLIC Test Facility CLEAR (CTF3)









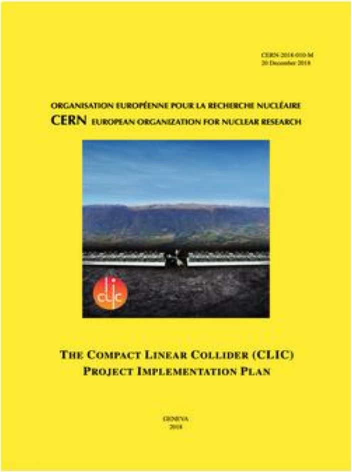
CLICdet

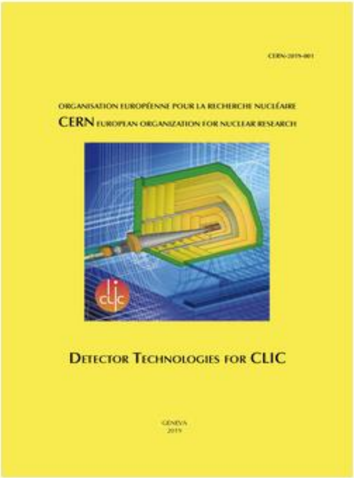
- Optimized for physics program in broad range of studies
- Particle reconstruction and identification with Particle Flow Algorithm
- Jet energy resolution (3-5)% →separation of H/W/Z jets
- Efficient lepton identification and p_T measurement $(\Delta p_T/p_T^2) \sim 2{\cdot}10^{-5}$ GeV^{-1}

Status of the project

- Mature project, ready for construction if recommended by the next EPPS
- Key accelerator technologies have been proven
- The full project status has been presented in series of Yellow reports

- Genuine advantages of a high energy e^+e^- collider
  - Clean experimental environment, no pile-up, no trigger→uncertainies are dominated by statistics
  - Luminosity rises with energy
  - Highest energy reach brings excellent precision for the Higgs self-coupling measurement as well as BSM physics reach





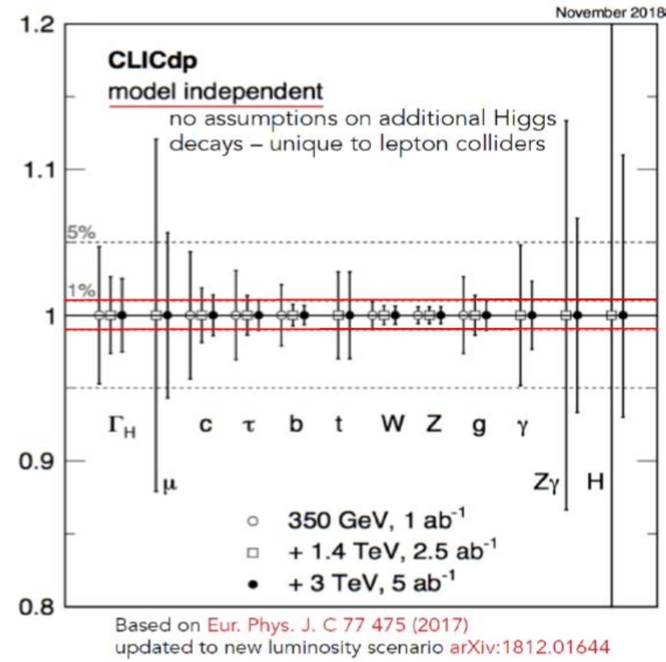
CERN-2018-005-M CERN-2018-009-M CERN-2018-010-M CERN-2019-001

Higgs studies

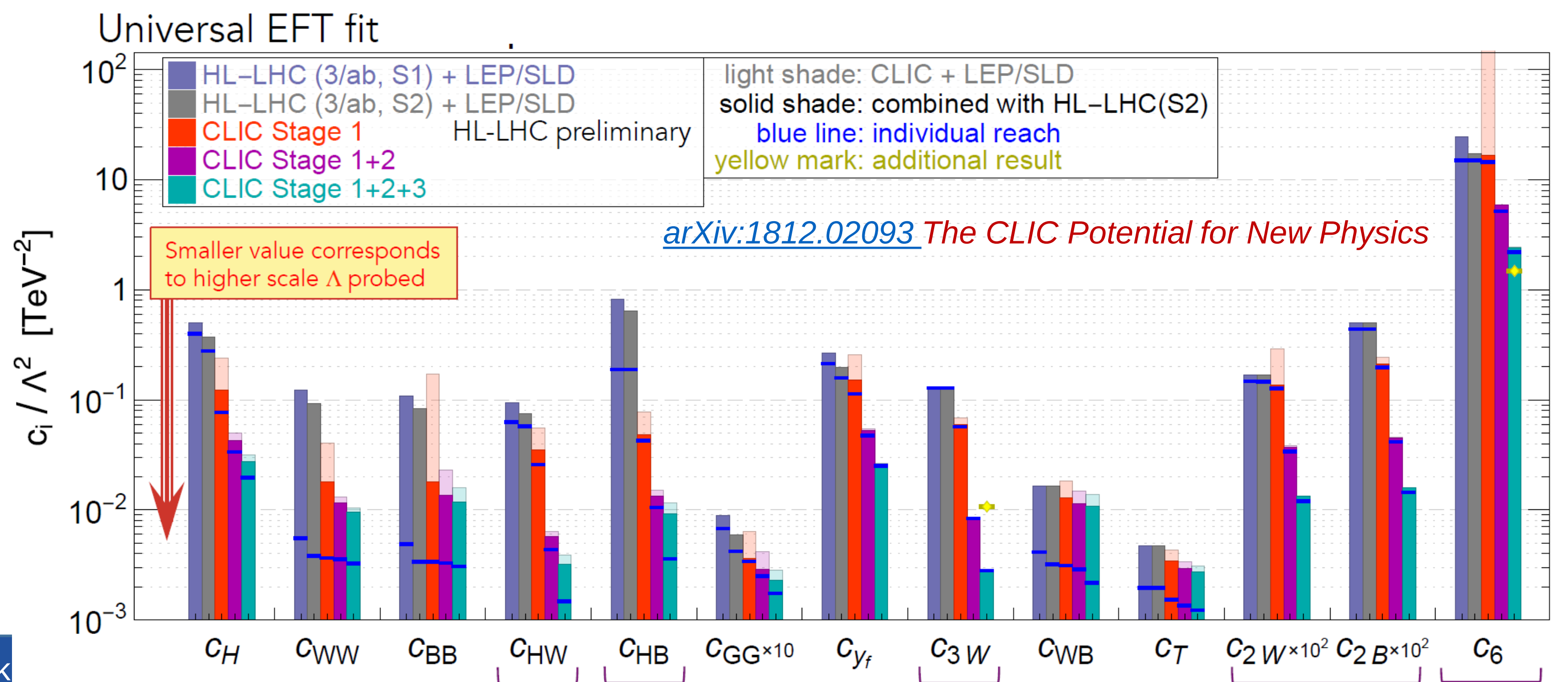
Higgs couplings

- At e^+e^- colliders:
  - Absolute measurement of a HZ cross section
  - Absolute measurement of Γ_H

- Most couplings (WW, ZZ, bb) can be determined well below 1% in a model-independent way



Sensitivity to probe new physics scale, an order of magnitude improvement w.r.t. HL-LHC

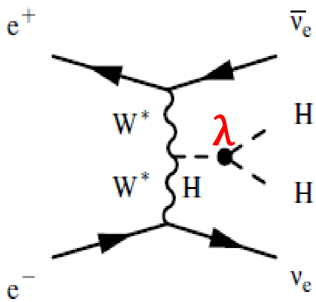


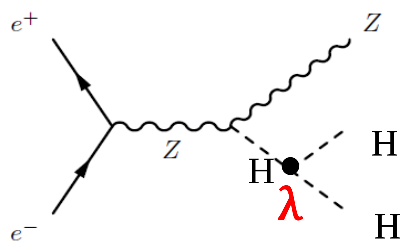
Higgs studies

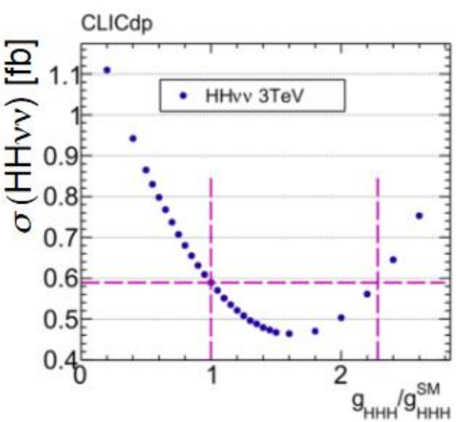
Higgs self-coupling

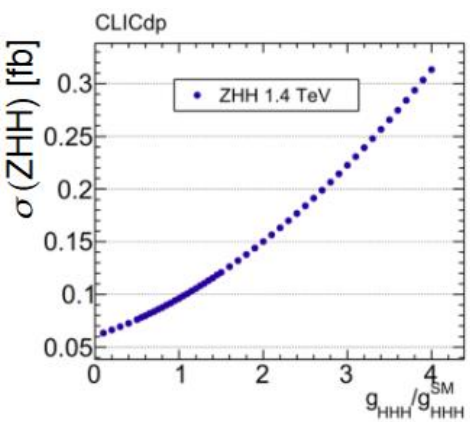
- Determines the shape of the Higgs potential
- Different behaviour of HHνν and HHZ x-section resolves ambiguity for non-SM values of λ

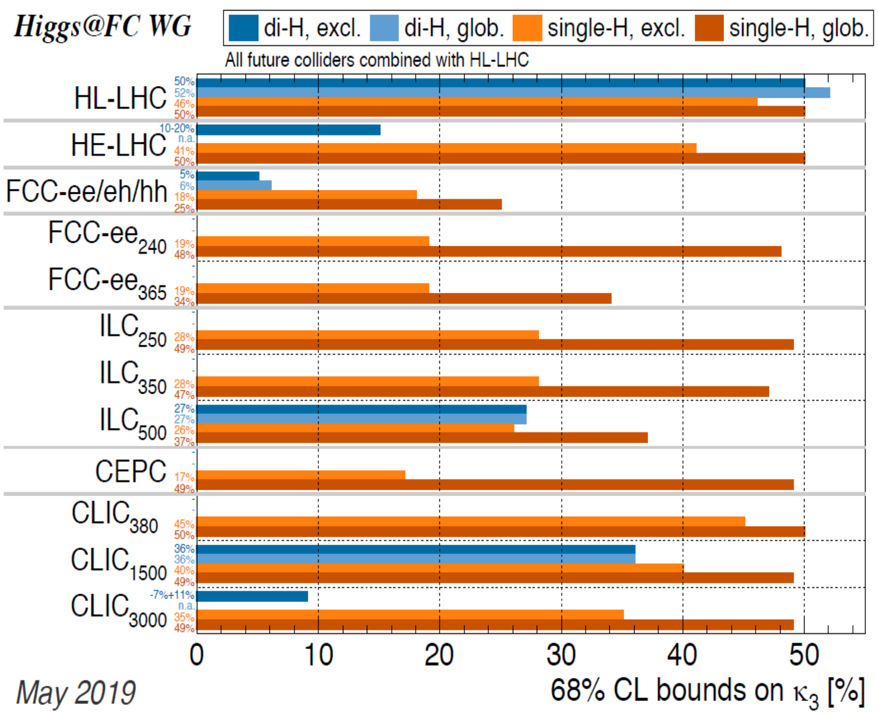
- CLIC has excellent sensitivity in Higgs self-coupling measurement
  - Combined result (1.4 TeV + 3 TeV) λ/λ^{SM} = (-8%, +11%) at 68% CL











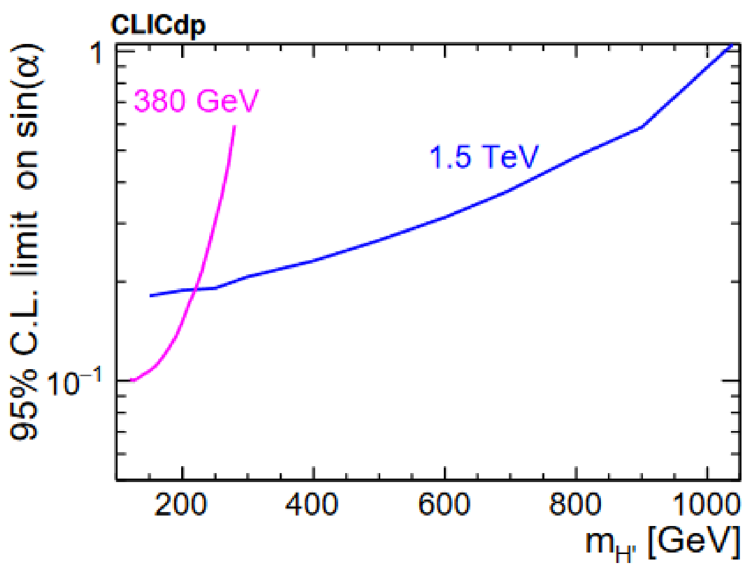
Higgs BSM studies

Invisible Higgs decays in VFDM

- Connection between SM and dark matter sector
- Extended Higgs sector with additional scalar ϕ mixed in with *h*

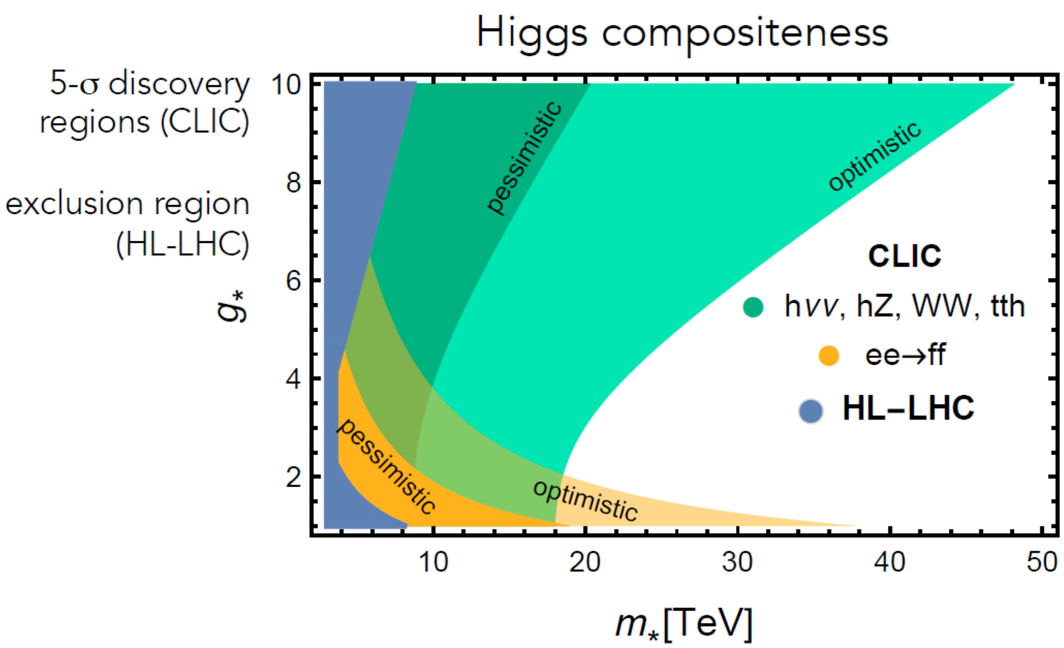
$$\begin{pmatrix} H \\ H' \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ \phi \end{pmatrix}$$

- BR(H→inv) ~ $sin^2\alpha$, BR(H'→inv) ~100%
- 95% CL limits on sinα up to 1 TeV $m_{H'}$



Composite Higgs

- Composite Higgs would affect couplings – EFT limits of the characteristic coupling strength *g** and mass scale *m**
  - CLIC can *discover* compositeness up to ≥10TeV compositeness scale
  - Significantly above the HL-LHC exclusion range



Higgs BSM studies

CPV in the Higgs sector

- Baryon asymmetry of the Universe is still unresolved phenomena
- New source of CPV can be introduced in the extended Higgs sector
- HVV and Hff vertices can be probed in various Higgs production and decay channels
- There are very few results at future colliders, mostly in $H \rightarrow \tau\tau$ and ttH

Our study:

- Generic model of CPV mixing (via angle Ψ_{CP}) of scalar and pseudoscalar states:

$$h = H \cdot cos\Psi_{CP} + A \cdot sin\Psi_{CP}$$

- Changing the tensor structure of g_{HZZ} coupling

$$g_{HZZ} = ig \frac{M_Z}{cos\theta_W} (\lambda_H \cdot g^{\mu\nu} + \lambda_A \cdot \varepsilon^{\mu\nu\rho\sigma} \frac{(p_1 + p_2)_\rho (p_1 + p_2)_\sigma}{M_Z^2})$$

where $\lambda_H = \cos\Psi_{CP}$, $\lambda_A = \sin\Psi_{CP}$, p_1, p_2 are the 4-momenta of the vector bosons

CPV in the Higgs sector

Sensitive observable

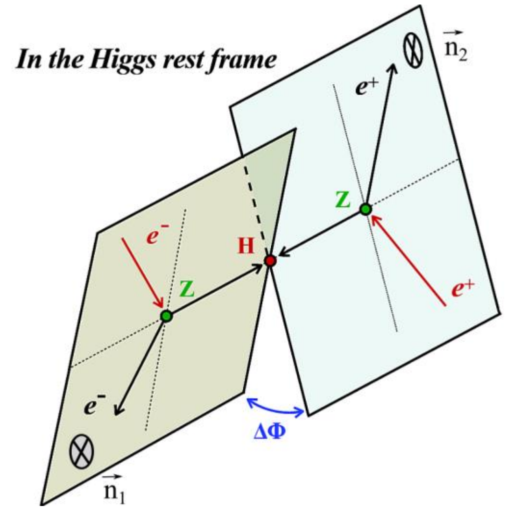
- Information on spin orientations of VV states is contained in the angle ΔΦ between production planes

- ΔΦ can be retrieved as the angle between unit vectors ($\vec{n}_1$ and $\vec{n}_2$) orthogonal to these planes:

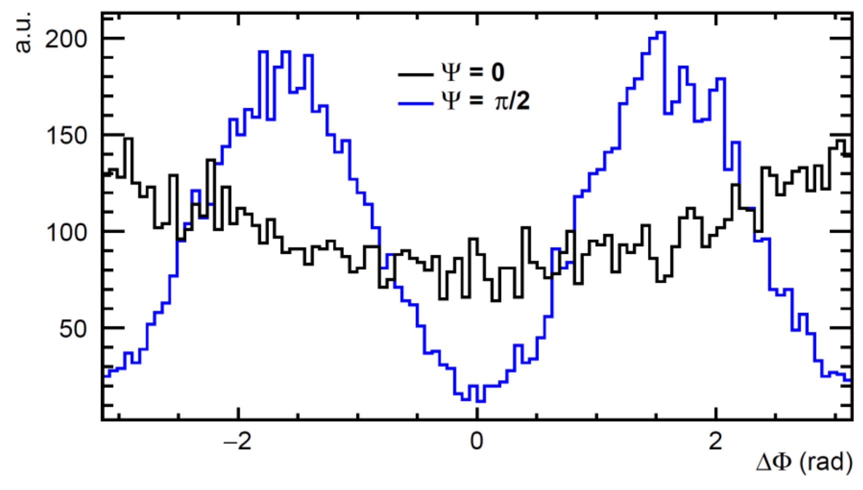
$$\Delta\Phi = a \cdot \arccos(\hat{n}_1 \cdot \hat{n}_2), \qquad a = \frac{q_{Z_{e^-}} \cdot (\hat{n}_1 \times \hat{n}_2)}{|q_{Z_{e^-}} \cdot (\hat{n}_1 \times \hat{n}_2)|}$$

and $$\hat{n}_1 = \frac{q_{e_i^-} \times q_{e_f^-}}{|q_{e_i^-} \times q_{e_f^-}|}, \qquad \hat{n}_2 = \frac{q_{e_i^+} \times q_{e_f^+}}{|q_{e_i^+} \times q_{e_f^+}|}$$

- a defines how the second (positron) plane is rotated w.r.t. the first (electron) plane; If it falls backwards (as illustrated) a = *-1*, otherwise a = *1*. Direction of Z in the e^- plane regulates the notion of direction (fwd. or back.) using the right-hand rule.



Whizard v2.8.3 pure scalar ($\Psi = 0$) and pseudoscalar ($\Psi = \pi/2$)

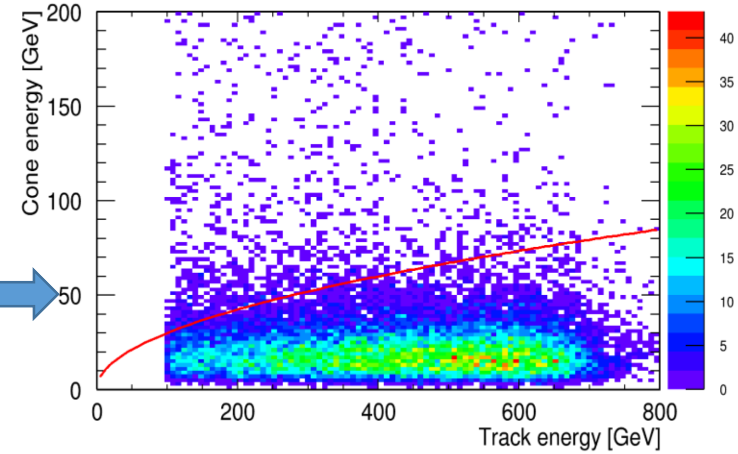


CPV in the Higgs sector

Method

- Higgs boson is produced in ZZ-fusion
- Consider $H \rightarrow b\bar{b}$ to obtain clear signature e^+e^- + 2b-jets

1. Isolate electrons (E_{track}, d_0, z_0, R_0, $E_{ECAL}/(E_{ECAL}+E_{HCAL})$, E_{track} vs. E_{cone} + 2 e per event
2. Suppress background with MVA
3. Reconstruct $\Delta\Phi$
4. Fit Ψ_{CP} from $\Delta\Phi$ distribution
5. Repeat pseudo-experiments to extract MAD



* Expected in the tracker, others are in the full range

Process	σ (fb)	Expected in 2.5 ab^{-1}
$e^+e^- \rightarrow Hee, H \rightarrow b\bar{b}$	4.16*	~10,400*
$e^+e^- \rightarrow q\bar{q}l^+l^-$	2725.8	6,814,500
$e^+e^- \rightarrow q\bar{q}l\nu$	4309.7	10,774,250
$e^+e^- \rightarrow q\bar{q}\bar{\nu}_e\nu_e$	787.7	1,969,250
$e^+e^- \rightarrow q\bar{q}$	4009.5	10,023,750
$\gamma\gamma \rightarrow q\bar{q}ee$	4.54	14,950

1.
- ε_{pres} = 80%
- Background efficiency:
  - $\gamma\gamma \rightarrow q\bar{q}ee \sim 8\%$
  - All others $\lesssim 1\%$

2.
- BDT cut-off value: 0.1654
- BDT efficiency: 94%

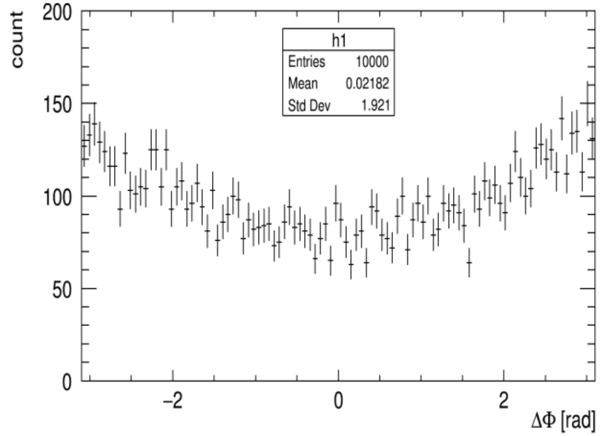
Total signal efficiency (preselection + BDT): 75%

- Signal events after MVA: 7810 / 2.5 ab^{-1}
- Background events after MVA: <1 / 2.5 ab^{-1}

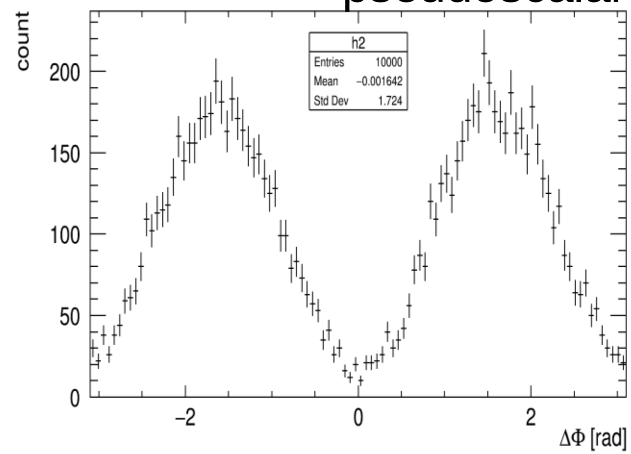
3 (4) Reconstruct ΔΦ

- Generator level first

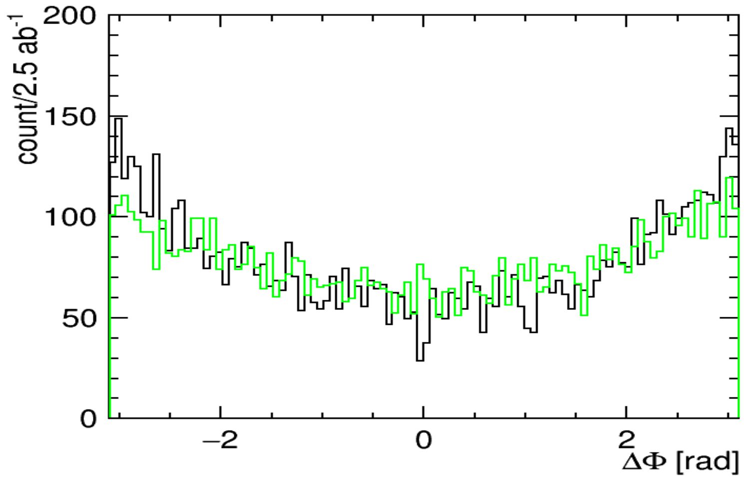
scalar



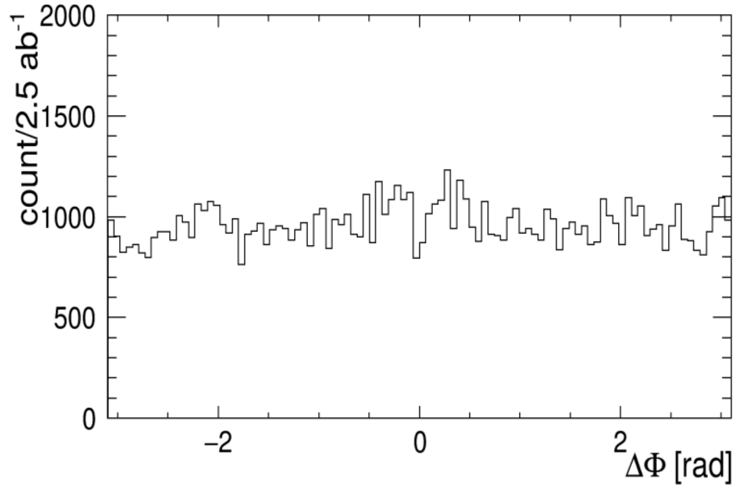
pseudoscalar



Full simulation, reconstruction, selection vs. generated signal



CP insensitive background



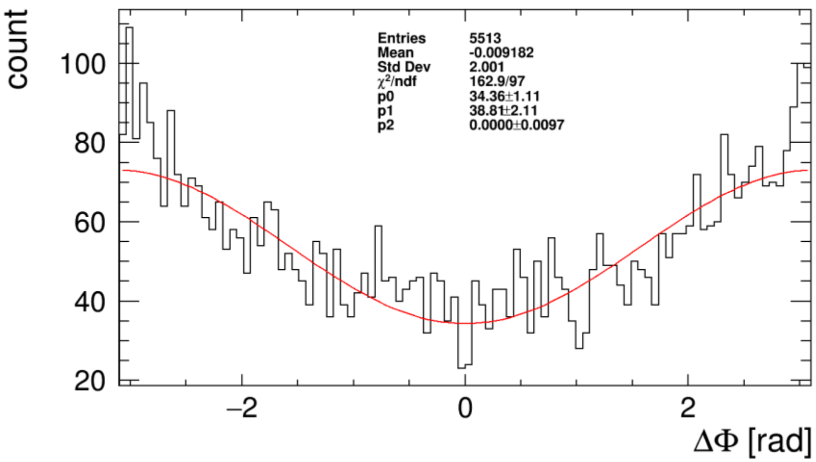
Summary

- CLIC is a mature project, ready for construction already after the next EPPS
- Multi-TeV energy stages enable measurement of the Higgs properties with enhanced precision and in synergy with the HL-LHC
- Measurement of the Higgs self-coupling with excellent sensitivity and discovery potential for BSM physics benefit from the highest center-of-mass energies
- CPV in the Higgs sector is an interesting BSM option. We look into ZZ-fusion at 1.4 TeV CLIC
- Preliminary study indicates promising sensitivity of the reconstructed observable to measure CPV mixing angle between scalar and pseudoscalar states

Additional material

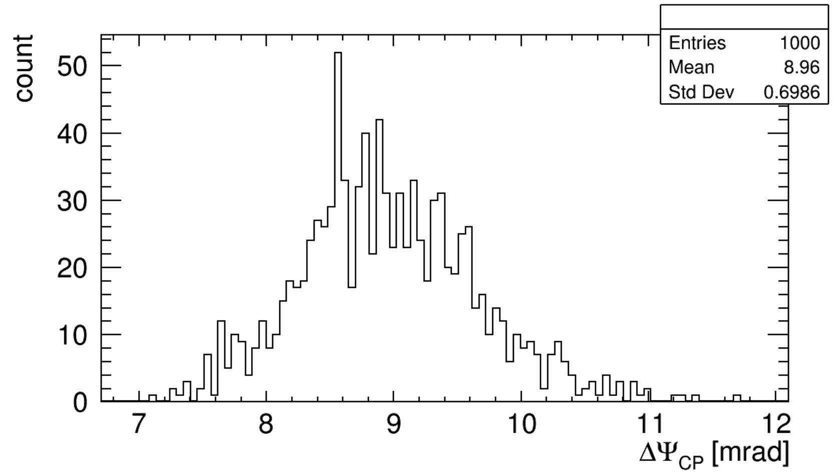
Pseudoexperiments

Single pseudoexperiment



$$\Delta\psi_{CP} = (0.0 \pm 9.7) mrad$$

MAD − median of the absolute deviations of repeated measurement



$$\Delta\psi_{CP} = (0.0 \pm 9.0) mrad$$

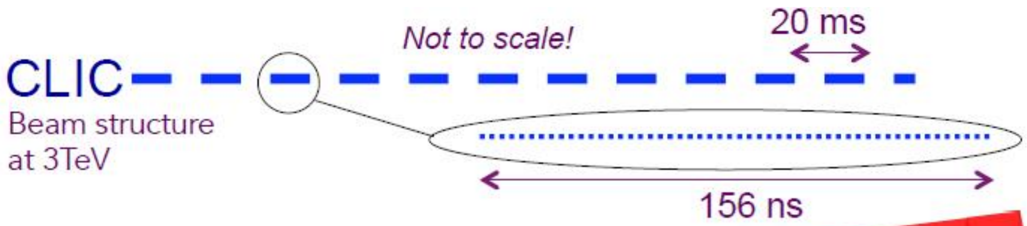
Higgs coupling sensitivity

	Benchmark	HL-LHC	HL-LHC + CLIC 380 ($4\,ab^{-1}$)	HL-LHC + CLIC 380 ($1\,ab^{-1}$) + 1500 ($2.5\,ab^{-1}$)	HL-LHC + FCC-ee 240	HL-LHC + FCC-ee 365
$g^{eff}_{HZZ}[\%]$	$SMEFT_{ND}$	3.6	0.3	0.2	0.5	0.3
$g^{eff}_{HWW}[\%]$	$SMEFT_{ND}$	3.2	0.3	0.2	0.5	0.3
$g^{eff}_{H\gamma\gamma}[\%]$	$SMEFT_{ND}$	3.6	1.3	1.3	1.3	1.2
$g^{eff}_{HZ\gamma}[\%]$	$SMEFT_{ND}$	11.	9.3	4.6	9.8	9.3
$g^{eff}_{Hgg}[\%]$	$SMEFT_{ND}$	2.3	0.9	1.0	1.0	0.8
$g^{eff}_{Htt}[\%]$	$SMEFT_{ND}$	3.5	3.1	2.2	3.1	3.1
$g^{eff}_{Hcc}[\%]$	$SMEFT_{ND}$	–	2.1	1.8	1.4	1.2
$g^{eff}_{Hbb}[\%]$	$SMEFT_{ND}$	5.3	0.6	0.4	0.7	0.6
$g^{eff}_{H\tau\tau}[\%]$	$SMEFT_{ND}$	3.4	1.0	0.9	0.7	0.6
$g^{eff}_{H\mu\mu}[\%]$	$SMEFT_{ND}$	5.5	4.3	4.1	4.	3.8
$\delta g_{1Z}[\times 10^2]$	$SMEFT_{ND}$	0.66	0.027	0.013	0.085	0.036
$\delta\kappa_\gamma[\times 10^2]$	$SMEFT_{ND}$	3.2	0.032	0.044	0.086	0.049
$\lambda_Z[\times 10^2]$	$SMEFT_{ND}$	3.2	0.022	0.005	0.1	0.051

From European Strategy Briefing Book and arXiv:2001.05278

- CLIC baseline
- CLIC longer first stage

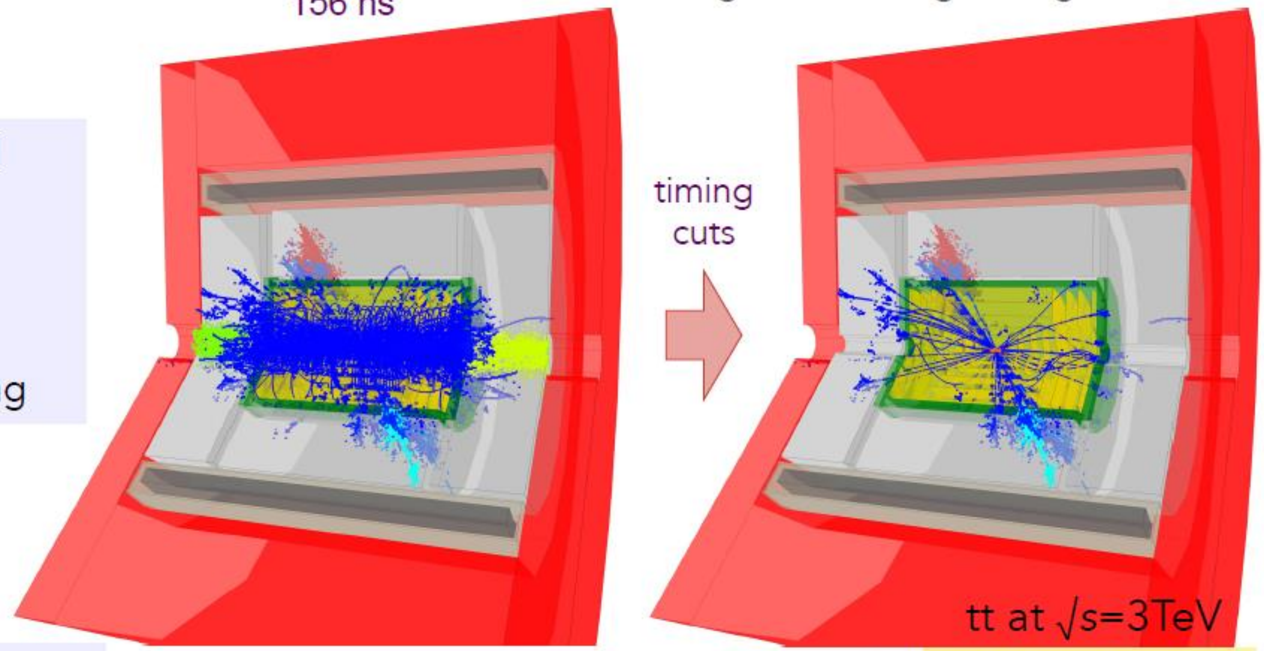
Collider environment



High bunch charge density
–> beam-related backgrounds
small effect at $\sqrt{s}$=380GeV
large effect at high energies

Precise timing required for beam background rejection

1ns in calorimetry,
5ns in vertexing/tracking



CALICE / FCAL

CLICdp vertexing/ tracking programme

High precision:

- jet energy resolution
  –> fine-grained calorimetry
- momentum resolution
- impact parameter resolution

$\sigma(E)/(E) \sim 3.5\%$ for $E>100$GeV

$\sigma(p_T)/p_T^2 \sim 2\times10^{-5}$ GeV^{-1}

$\sigma_{d0} \sim 5\oplus15/(p[\text{GeV}]\sin^{3/2}\theta)$ µm