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CPV in e^+e^-H at 1 TeV ILC

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УНИВЕРЗИТЕТ
У КРАГУЈЕВЦУ

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- Ways to probe HVV vertices (V = Z, W) in Higgs production and decays
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- Method of the ψ_{CP} measurement
  - Preselection
  - MVA selection
  - Reconstructed CPV observable for signal and background
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Introduction

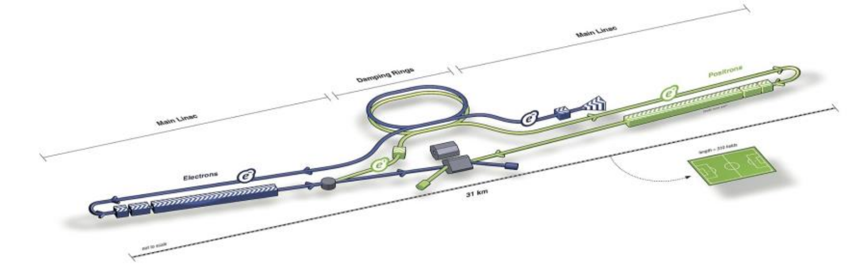
- Experimentally observed size of the CP violation (CPV) is insufficient to explain the baryon asymmetry of the Universe $\rightarrow$ search for new sources of the CPV beyond the SM is necessary
- Higgs boson is the only fundamental scalar discovered, related to quite a few unknowns (mass stabilization – hierarchy problem, contribution to the energy density of the Universe, connection to the dark matter and gravity, etc.)
- It is conceivable that new sources of CPV may be introduced in an extended Higgs sector.

- ILC precision to measure the CPV mixing angle (ψ_{CP}) between the Higgs scalar and pseudoscalar states seems to be the most promising in the fermionic $H \rightarrow \tau\tau$ decay at 250 GeV (Table 1, JHEP 2020, 139 (2020)) – *see D. Jeans talk*
- Other possibilities (i.e. HVV vertices) are worth exploiting as well as the other center-of-mass energies offered by the ILC staged physics programme
- Here we report on the status of the on-going CPV analysis in the eeH production at 1 TeV ILC

Table 1.

Collider	ψ_{CP}
HL-LHC	8°
HE-LHC	–
CEPC	–
FCC-ee$_{240}$	10°
ILC$_{250}$	4°

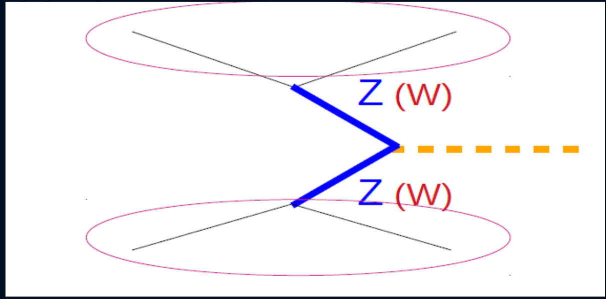
ILC & ILD

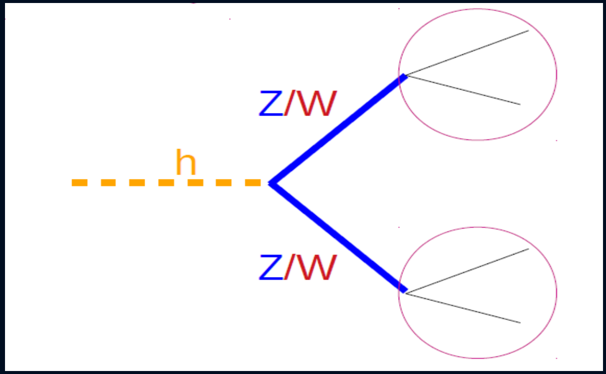


- The International Linear Collider (ILC) is a high-luminosity linear e^-e^+ collider with center-of-mass-energy range of 250 -500 GeV (extendable to 1 TeV) aimed for precision studies in the Higgs sector operating as a Higgs factory, detecting new physics phenomena in a direct or indirect way. It is designed to achieve a luminosity of $1.35 \cdot 10^{34}$ $cm^{-2}s^{-1}$ and provide an integrated luminosity of 400 fb^{-1} in the first four years of running (2 ab^{-1} in a little over a decade).
- The electron beam will be polarized to 80 %, and the baseline plan includes an undulator-based positron source which will deliver 30 % positron polarization
- The well-defined collision energy at the ILC, highly polarized beams and low background levels, will enable these precision measurements

- Excellent track momentum resolution: $\delta(1/p) = 2 \times 10^{-5}$ GeV^{-1}
- Very powerful vertex detectors: $\delta(SV) < 4\ \mu m$
- Jet energy resolution: $\sigma_{E,\,jet} < 3.5$ % over 100 GeV
- Lepton (electron and muon) identification efficiency: above 99 %
- Good hermeticity down to $\cos(\theta) \approx 0.984$

SM-like Higgs boson as a CPV mixture of CP even and odd states

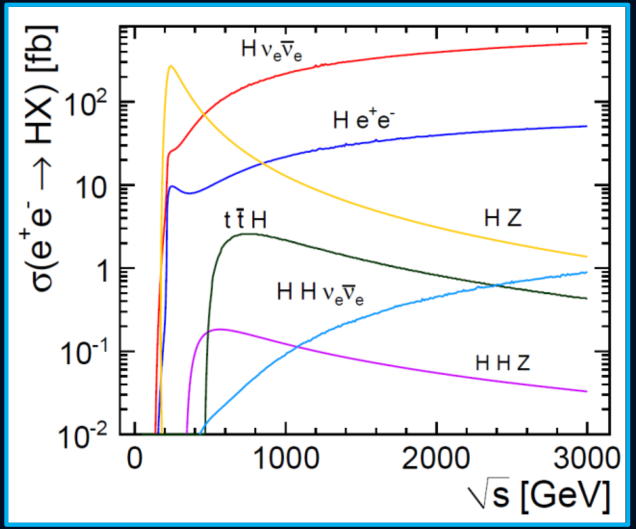




- SM-like Higgs boson could be a mixture of scalar (H) and pseudo-scalar state (A):

$$h = H \cdot \cos\psi \ + \ A \cdot \sin\psi$$

- Correlation between spin orientations of VV carries information on the Higgs CP state
- Numerous Higgs production processes at linear machines can be exploited (hZ, WW-fusion, ZZ-fusion) at various c.m. energies
- Both Higgs production and decays can be studied



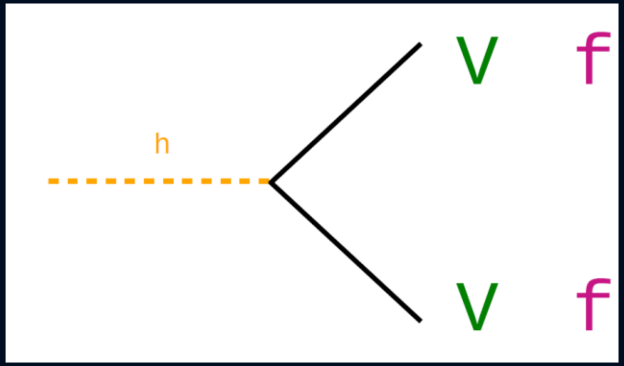
Ways to probe HVV vertices (V=Z, W) in Higgs production and decays

- hVV vertex (CPV at a loop level):

$$\mathscr{L}_{VVH} \sim M_Z^2 \,(1/v + a_V/\Lambda)\, Z_\mu Z^\mu\, h + (b_V/2\Lambda)\, Z_{\mu\nu} Z^{\mu\nu}\, h + (\tilde{b}_V/2\Lambda)\, Z_{\mu\nu} \tilde{Z}^{\mu\nu}\, h$$

- hff vertex (CPV at a tree level):

$$\mathscr{L}_{ffH} \sim g\, \bar{f}\, (\cos\psi_{CP} + i\, \gamma^5 \sin\psi_{CP})\, f\, h$$



- Suppressed effect in VV-fusion w.r.t. (i.e.) Higgs to ττ decay, but relatively high statistics available (~27000 inclusively produced Higgs bosons in ZZ-fusion in 1 ab^{-1} at 1 TeV ILC, however approximately half in the central tracker)

Ways to probe HVV vertices (V=Z, W) in Higgs production and decays

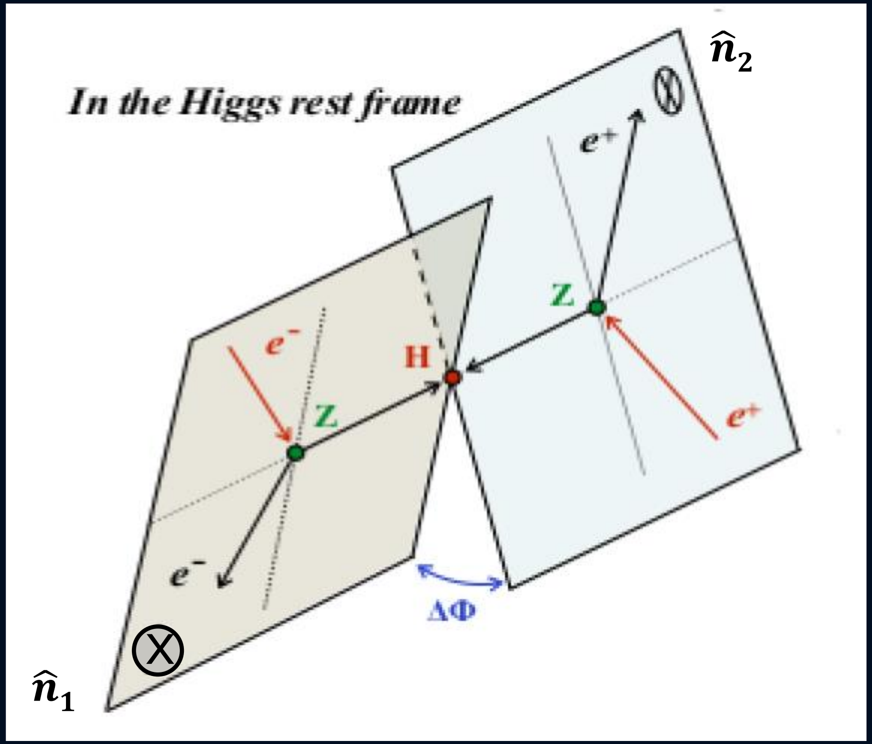
- Information on spin orientations of VV states is contained in the angle ϕ between production (decay) planes

- Angle between planes is the angle between unit vectors orthogonal to those planes:

$$\hat{n}_1 = \frac{q_{e_i^-} \times q_{e_f^-}}{|q_{e_i^-} \times q_{e_f^-}|} \quad \text{and} \quad \hat{n}_2 = \frac{q_{e_i^+} \times q_{e_f^+}}{|q_{e_i^+} \times q_{e_f^+}|} \qquad (1)$$

  - There is more than one way (convention) to define n_1 and n_2 from 3 vectors forming the planes (1st plane: initial electron, final electron, Z_{e-}; 2nd plane: initial positron, final positron, Z_{e+})
  - Orientation of n_1 and n_2 could be in the same hemisphere (angle between n_1 and n_2 smaller than 180 deg.) or in the opposite (angle between n_1 and n_2 larger than 180 deg.)

Higgs production in ZZ-fusion



- Since vectors n_1 and n_2 have the same direction, the angle between planes can be retrieved through the arccos function as:

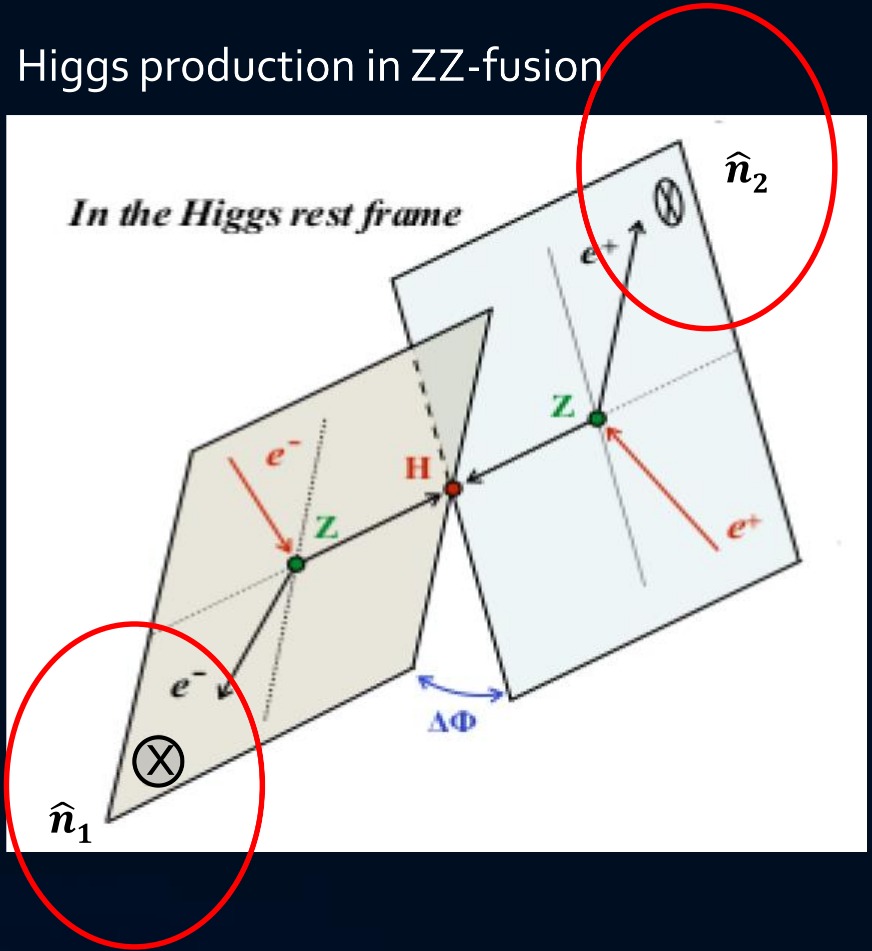
- $\phi = \ a \ \arccos(\pm \hat{n}_1 \cdot \ \hat{n}_2)$

- Sign $\pm$ retain natural domain of arccos function (witch has a feature of returning angles from I and II quadrants also for angles larger than 180 deg.)

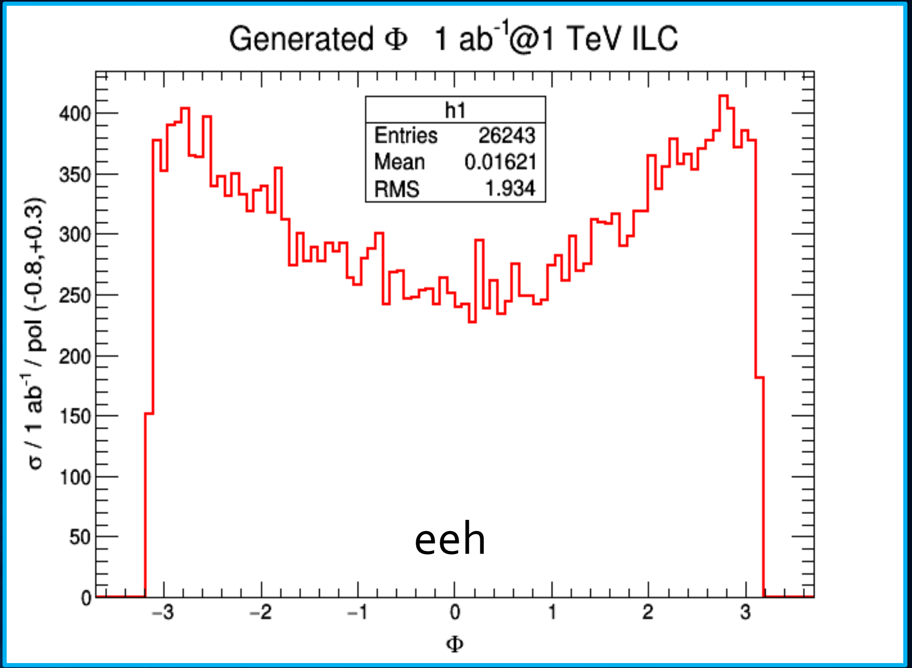
- *a* defines how the second (positron) plane is rotated w.r.t. the first (electron) plane; If it falls backwards (as illustrated) *a=-1*, otherwise *a=1*. Direction of Z in the e^- plane regulates the notion of direction (fwd. or back.) by the right hand rule

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

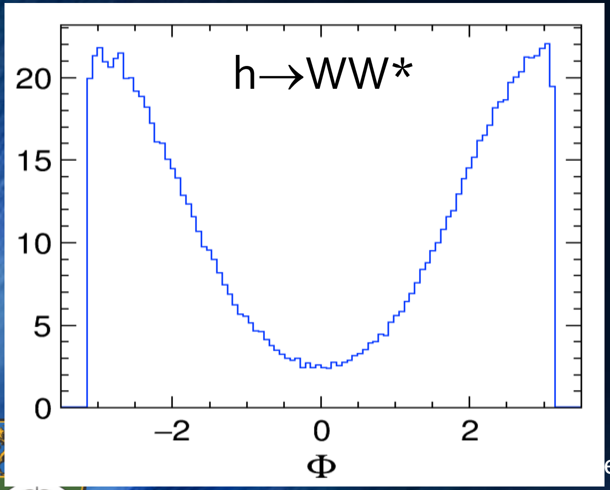
Higgs production in ZZ-fusion

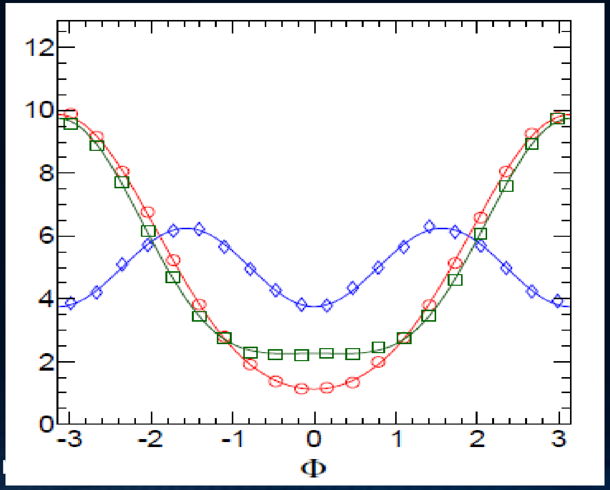


Examples of ϕ distributions



- We are correctly reproducing ϕ distributions at the generator level both for hVV production and decay vertices $(V = Z, W)$
- All distributions are obtained for $\psi_{CP} = 0$





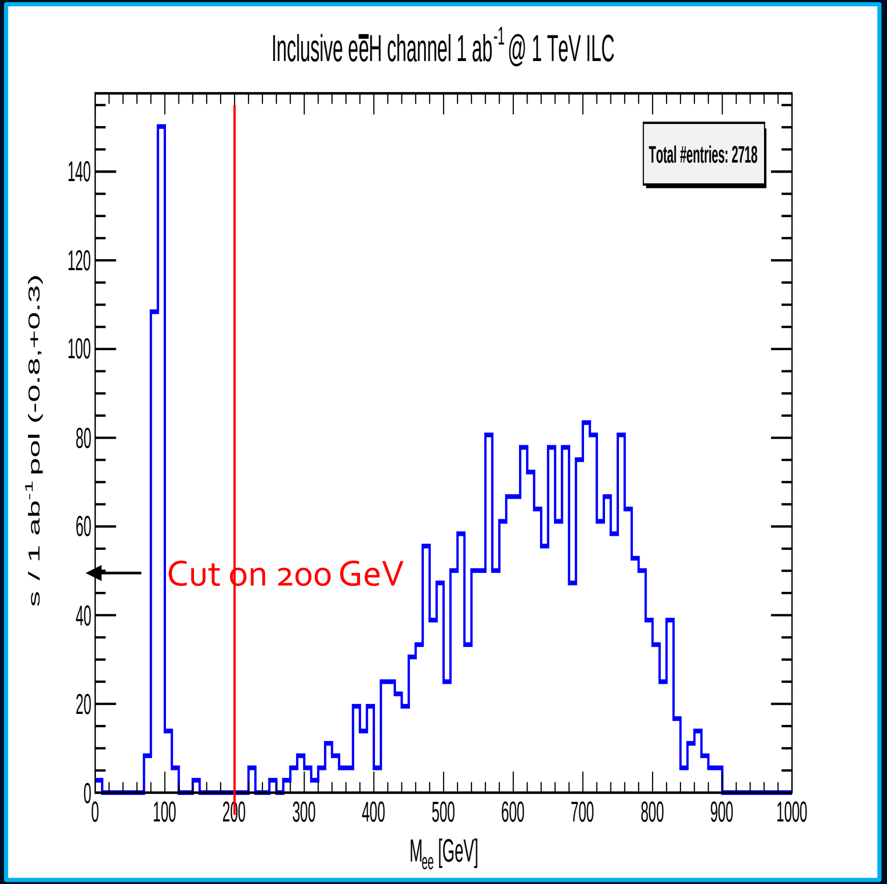
S. Bolognesi et al.,
On the spin and parity of a single produced resonance at the LHC, arXiv:1208.4018 [hep-ph] for Higgs to ZZ* and WW* decays

J^+_m (red circles), J^+_h (green squares), J^-_h (blue diamonds)

scenario	X production	$X \to VV$ decay	comments
0^+_m	$gg \to X$	$g_1^{(0)} \neq 0$ in Eq.(9)	SM Higgs boson scalar
0^+_h	$gg \to X$	$g_2^{(0)} \neq 0$ in Eq.(9)	scalar with higher-dimension operators
0^-	$gg \to X$	$g_4^{(0)} \neq 0$ in Eq.(9)	pseudo-scalar

Method of the ψ_{CP} measurement

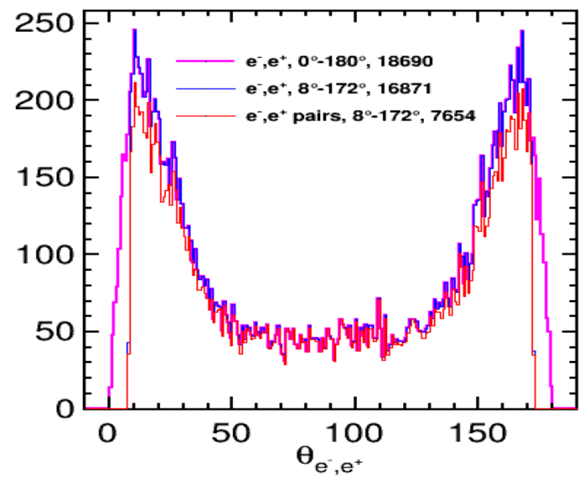
- Consider $H \to bb$ and $H \to WW \to 4$ *jets* decays
  - *1. Cover most of the Higgs width* ($\sim 80\ \%$)
  - *2. Avoid high cross-section* $e^+e^- \to e^+e^-\gamma$ *background present in inclusive reconstruction*
  - *3. Combine results*
- Select ZZ-fusion (signal is mixed with HZ) using $m\ (e^+e^-)$
- Isolate 2 leptons (e^+e^-)
- Reconstruct ϕ
- Suppress background with MVA
- *Describe ϕ of the signal and background with PDFs*
- *Reconstruct ϕ of the signal from pseudo-data $(S + B)$*
- Fit ψ_{CP} from the ϕ distribution
- Repeat pseudo experiments
- Combine channels



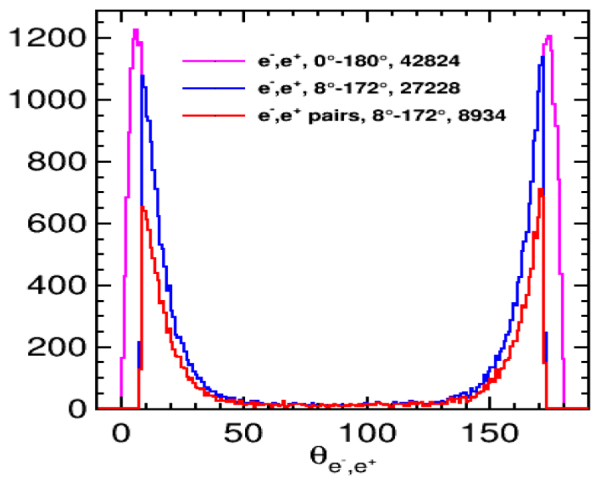
Dilepton mass distribution

Higgs production in ZZ-fusion

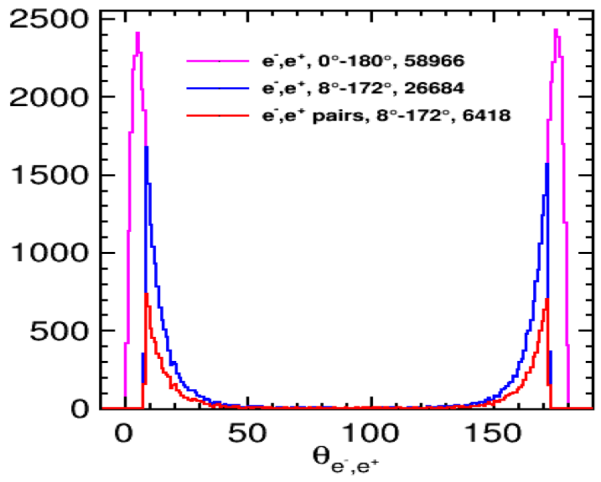
- WHIZARD v1.95, 500GeV/0.5 ab^{-1}, 1 TeV/ 1 ab^{-1} , 1.4 TeV/1 ab^{-1}, unpolarized
- t-channel process, electrons (spectators) are scattered forward - not full statistics available in the tracker
- Due to this fact 1 TeV is the optimal energy for this study (already at i.e. 1. 4 TeV the number of events with both electron is the tracker is ~1/5 of the available statistics) . At 500 GeV i.e. x-section for ZZ fusion is relatively small (7.2 fb) and number of events in the tracker is order of magnitude smaller than at 1 TeV
- Around $7{\cdot}10^3$ eeh events with both e+ and e- in the tracker in 1 ab^{-1} at 1 TeV ILC with (-0.8, +0.3) polarized beams



82 % @ 500 GeV



41.7 % @ 1 TeV



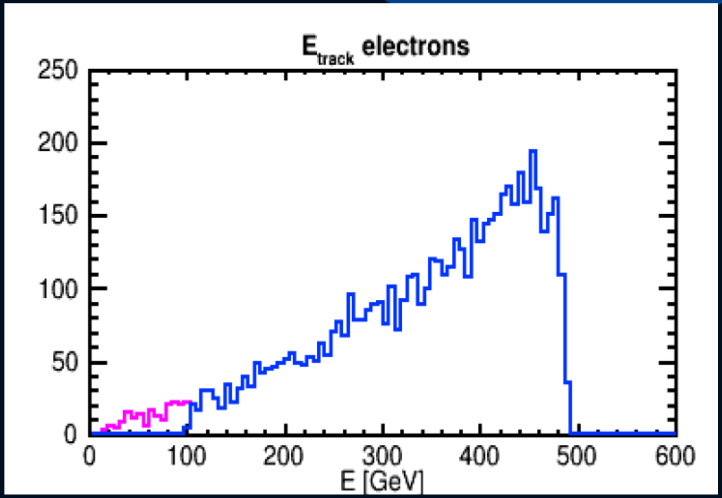
21.8 % @ 1.4 TeV

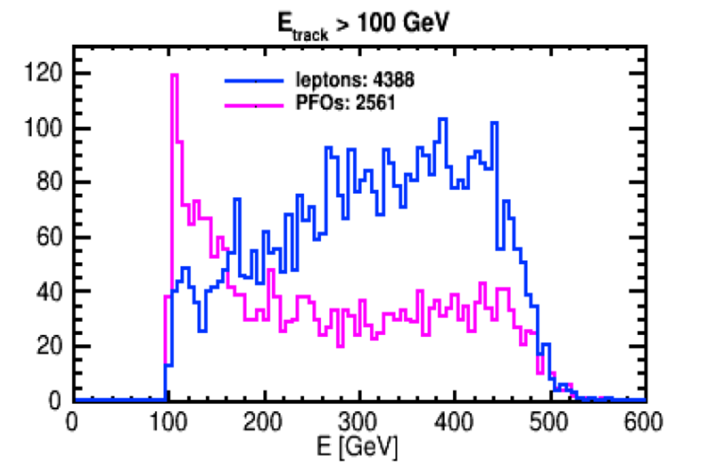
Preselection

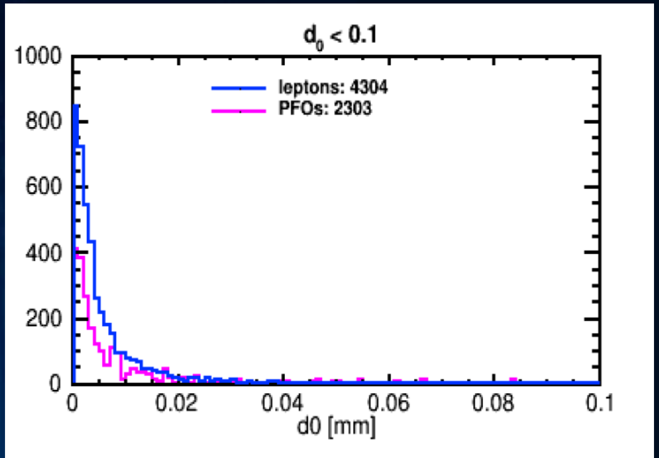
- ILC samples at 1 TeV, assuming $\mathcal{L} = 1\ \text{ab}^{-1}$, generated with LR polarization (-1, 1) are normalized to polarization (-0.8, +0.3):

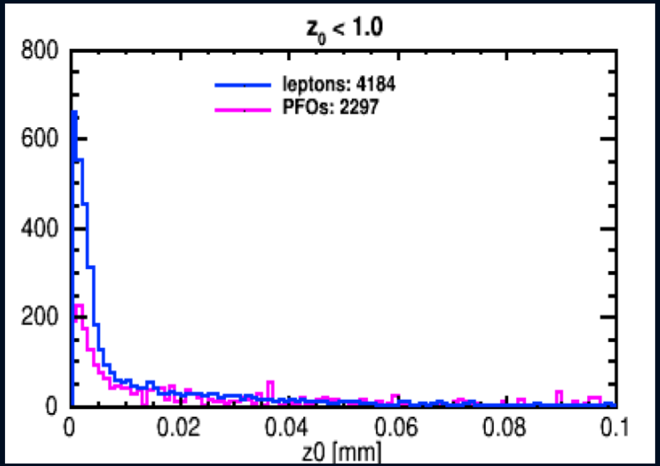
$$W_{\text{pol}} = \left(\frac{1 - P_{e_-}}{2}\right) \cdot \left(\frac{1 + P_{e_+}}{2}\right) = \left(\frac{1 - (-0.8)}{2}\right) \cdot \left(\frac{1 + 0.3}{2}\right) = 0.585$$

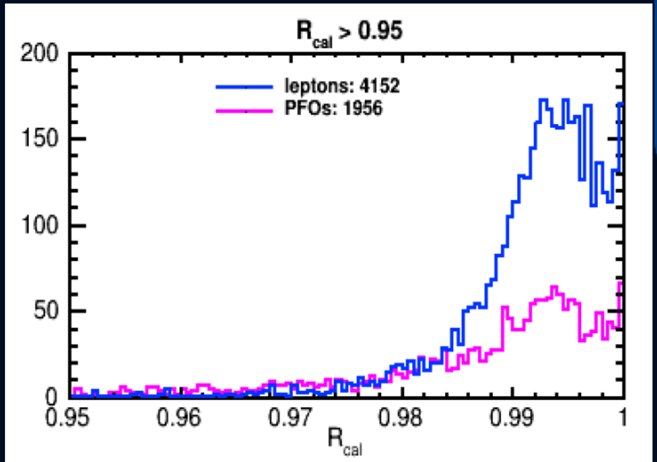
- Preselection: find 2 isolated electrons (e^+e^-)
- Goal: find electrons spectators from ZZ-fusion and reduce high cross-section backgrounds
- Requirements:
  - Track energy: $E_{\text{track}} > 100\ \text{GeV}$ – spectators are energetic (3.3% loss)
  - Impact parameter: $d_0 < 0.1, z_0 < 1.0$
  - Ratio of deposition: $R_{\text{cal}} > 0.95$
  - Optimize cone vs. track energy

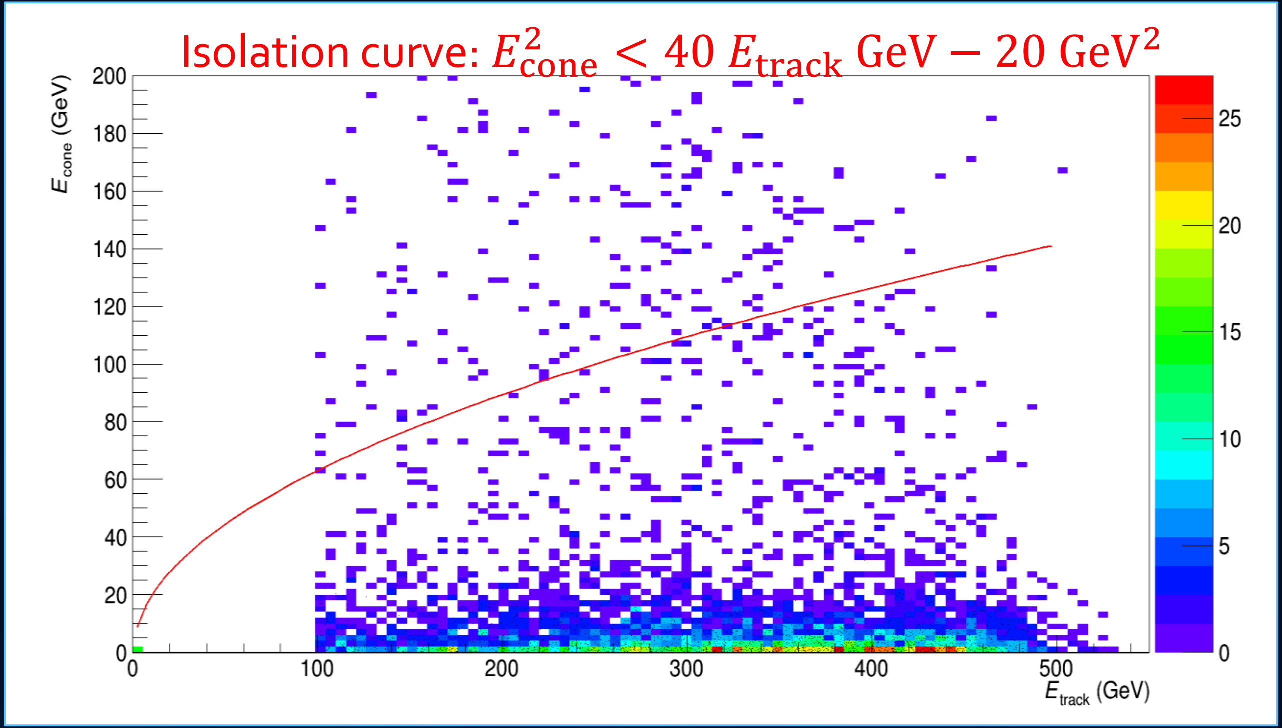





$d_0 < 0.1$
leptons: 4304
PFOs: 2303
d0 [mm]


$z_0 < 1.0$
leptons: 4184
PFOs: 2297
z0 [mm]


$R_{cal} > 0.95$
leptons: 4152
PFOs: 1956
R_{cal}


Isolation curve: $E^2_{\text{cone}} < 40\ E_{\text{track}}\ \text{GeV} - 20\ \text{GeV}^2$
E_{cone} (GeV)
E_{track} (GeV)

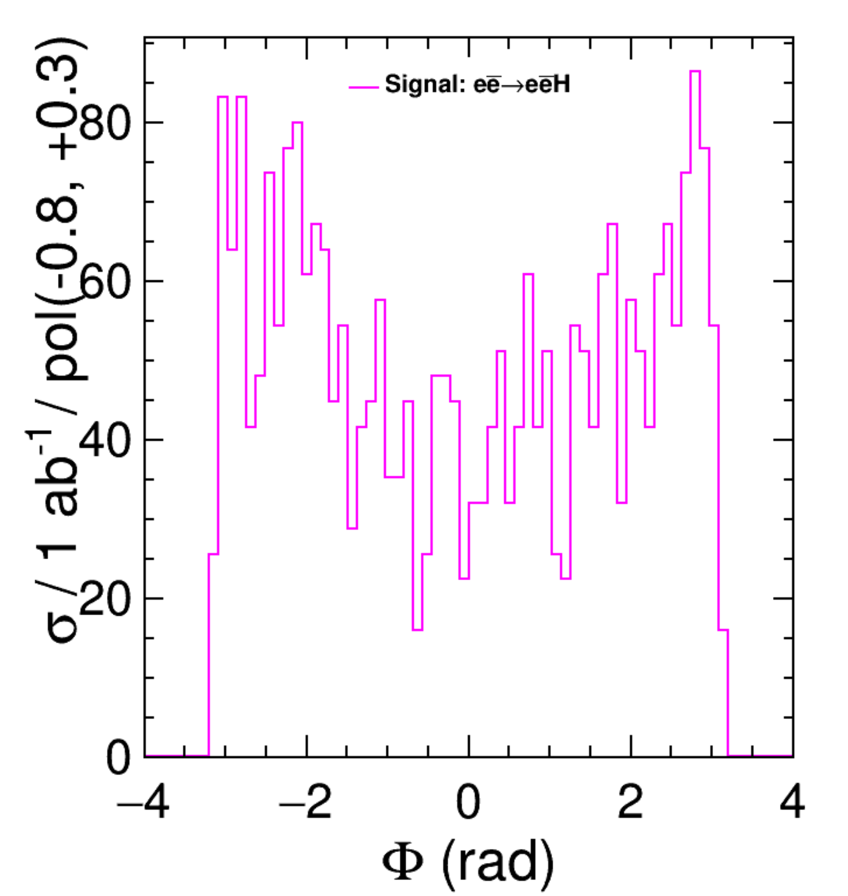
Signal and background preselection efficiencies

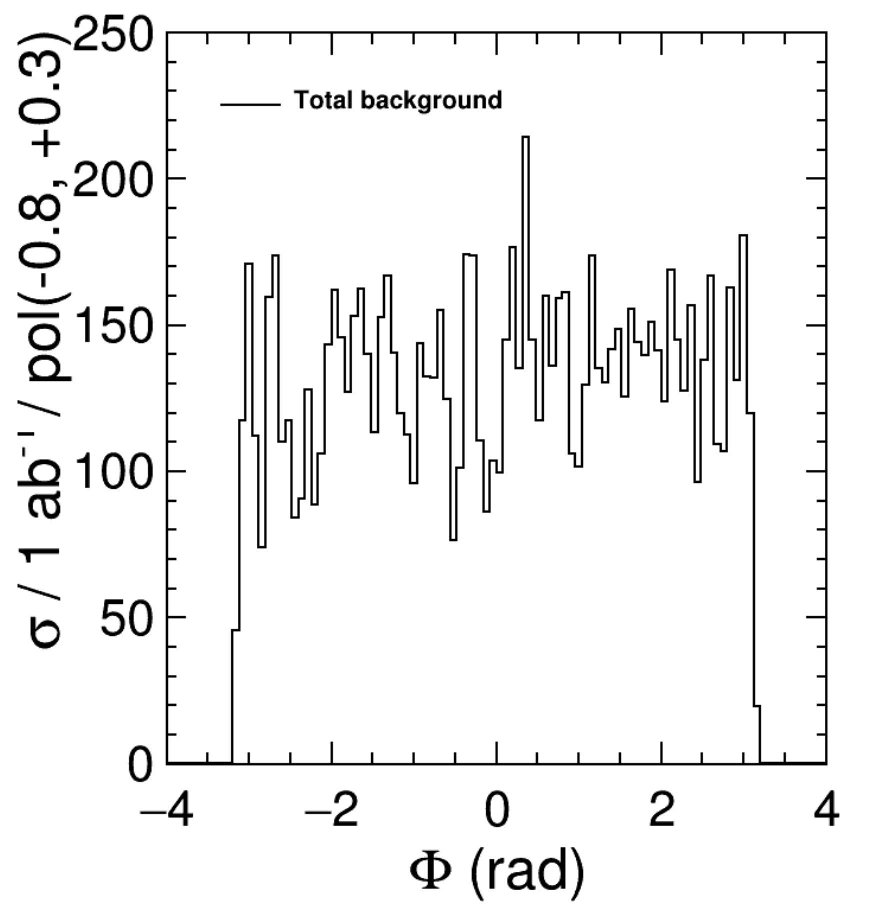
$1\ \text{TeV}/1\ \text{ab}^{-1}$ $/\text{pol}(-80\%, +30\%)$	Sample	σ [fb]	Input	Output	Efficiency [%]
Signal:	$e^+e^- \to e^+e^- H(H \to b\bar{b})$	15.1	$N_{true} = 1121$* $N^{\text{norm}}_{\text{signal}} = 3600$	$N_{true} = 875$* $N^{\text{norm}}_{\text{sig/iso}} = 2800$	78 %
Background samples:	$e^-e^+ \to e^-e^+ q\bar{q}$**	2577.3	$N^{norm}_{ev} = 226160$	$N_{true} = 1447$ $N^{norm}_{ev} = 5470$	2.42 %
	$e^-e^+ \to e\nu qq$***	8963.3	$N^{norm}_{ev} = 1730000$	$N_{true} = 428$ $N^{norm}_{ev} = 346$	0.02 %
	$e^-e^+ \to q\bar{q}$ **	9375.3	$N^{norm}_{ev} = 877528$	$N^{norm}_{ev} = 4$	0.0046 ‰
	$\gamma\gamma \to q\bar{q}q\bar{q}$	126.0	N^{norm}_{ev} =73835	$N_{true} = 282$ $N^{norm}_{ev} = 930$	1.26 %
	$\gamma\gamma \to e^-e^+ q\bar{q}$	3.1	N^{norm}_{ev} =1817	$N^{norm}_{ev} = 5$	0.25 %

** Small current sample size, ** q=b, ***q=b,c*

B:S=2.5:1

Reconstructed CPV observable for signal and background

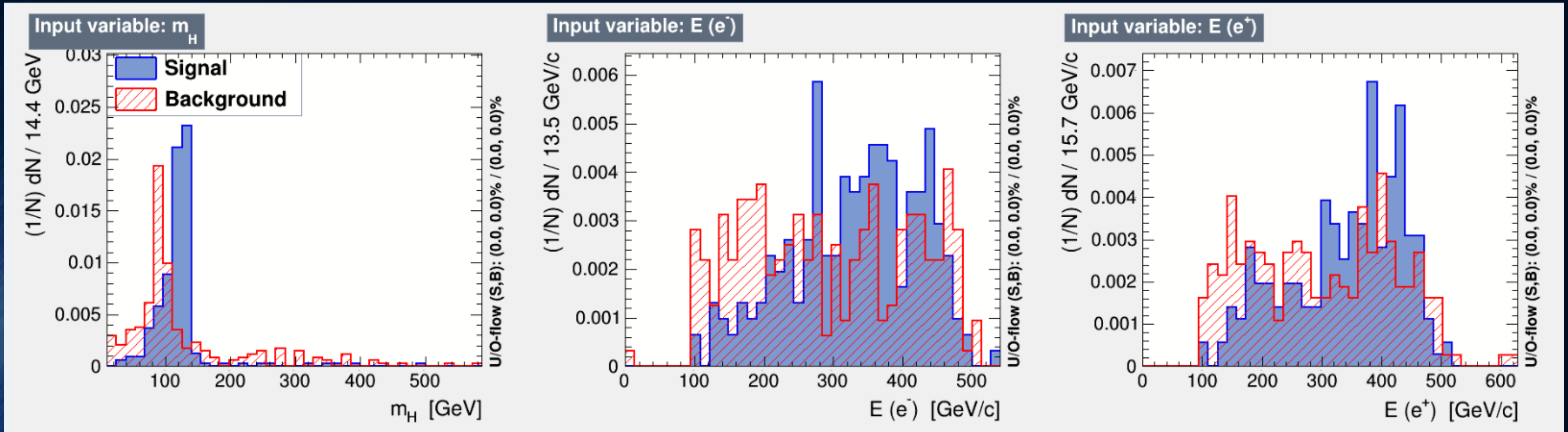




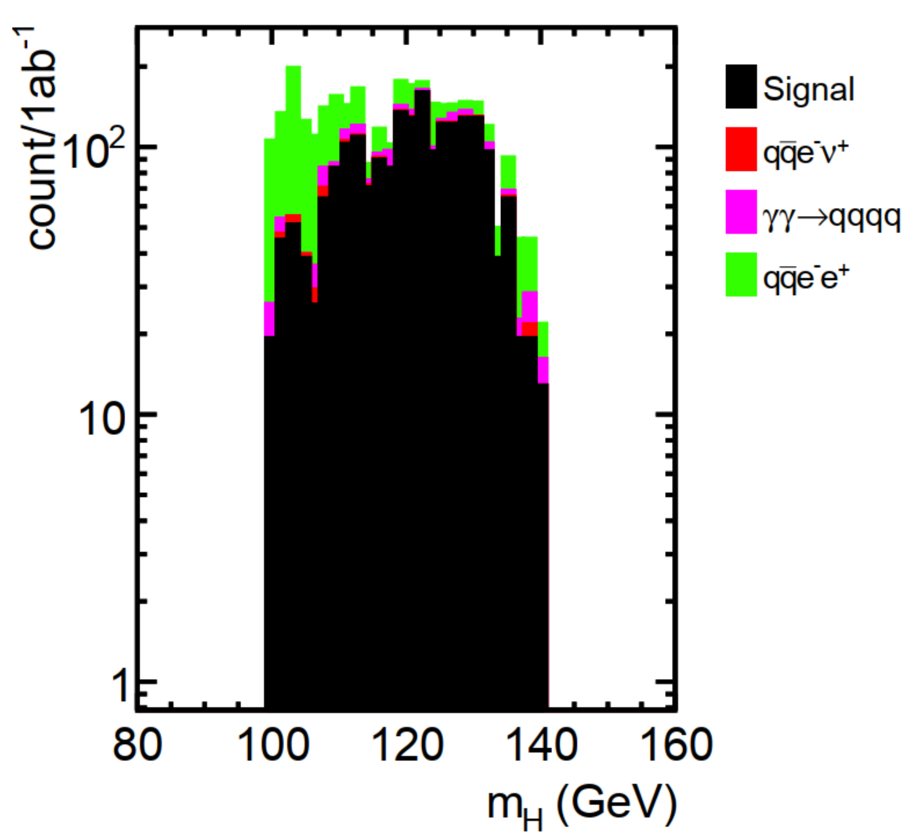
After preselection

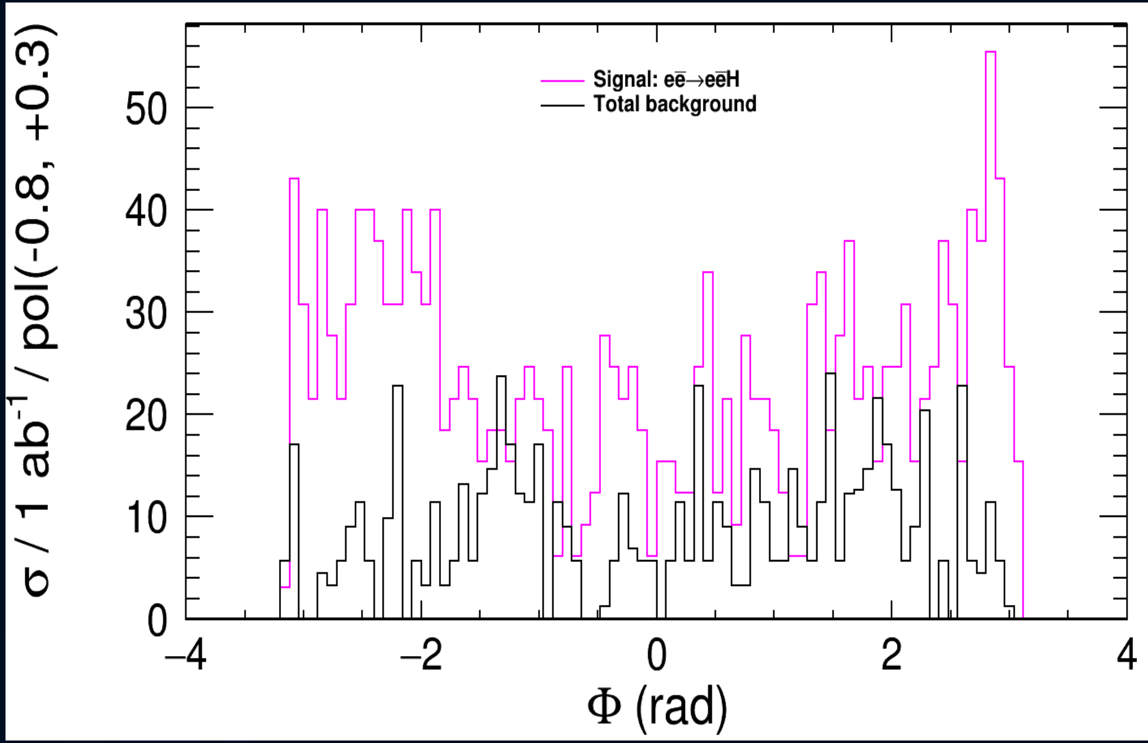
MVA selection

- MVA is trained with 14 sensitive variables: p_{e^-}, p_{e^+}, E_{e^-}, E_{e^+}, $p_{T(e^-e^-)}$, $p_{T(e^+e^+)}$, $p_{T(q_1)}$, $p_{T(q_2)}$, E_{q_1},E_{q_2}, m_H, E_H, $p_{T(H)}$, p_T^{miss}
- Three the most sensitive observables are: m_H,$E_{e^-}$and E_{e^+}
- Best significance ~ 42 for BDT > 0.013 (training)
- BDT efficiency ~ 70%, B:S= 1:2.6
- Approximately ¼ of the available signal statistics analyzed



After MVA





- MVA reverses backround to signal ratio to 1: 2.6
- Shapes maintained, yet large signal fluctuations
- Additional signal samples will be added

Summary

- Only few results of the CPV Higgs mixing angle measurements are available from the future projects. Primarily in the (more sensitive) Higgs fermionic decays and at lower center-of-mass energies

- 1 TeV ILC offers optimal statistics (cross-section – pseudorapidity interplay) to probe CPV also in the HVV vertices

- Sensitive angle ϕ between Higgs production planes is reconstructed in ZZ-fusion with the expected behavior for $\psi_{CP}=0$. Polarized data samples are fully simulated with 1 ab^{-1} (0.2 ab^{-1}) of integrated luminosity for background (signal). Result will be further improved since only ¼ of available signal statistics is used

- Background ϕ distribution is CPV insensitive and it is effectively suppressed with the staged event selection

- Further improvements are on the way (additional MVA observables, combination of results from samples with different polarization schemes).

BACKUP

Higgs decays: $H \rightarrow WW^*$ and $H \rightarrow ZZ^*$

- Unit vectors orthogonal to decay planes (one possible definition):

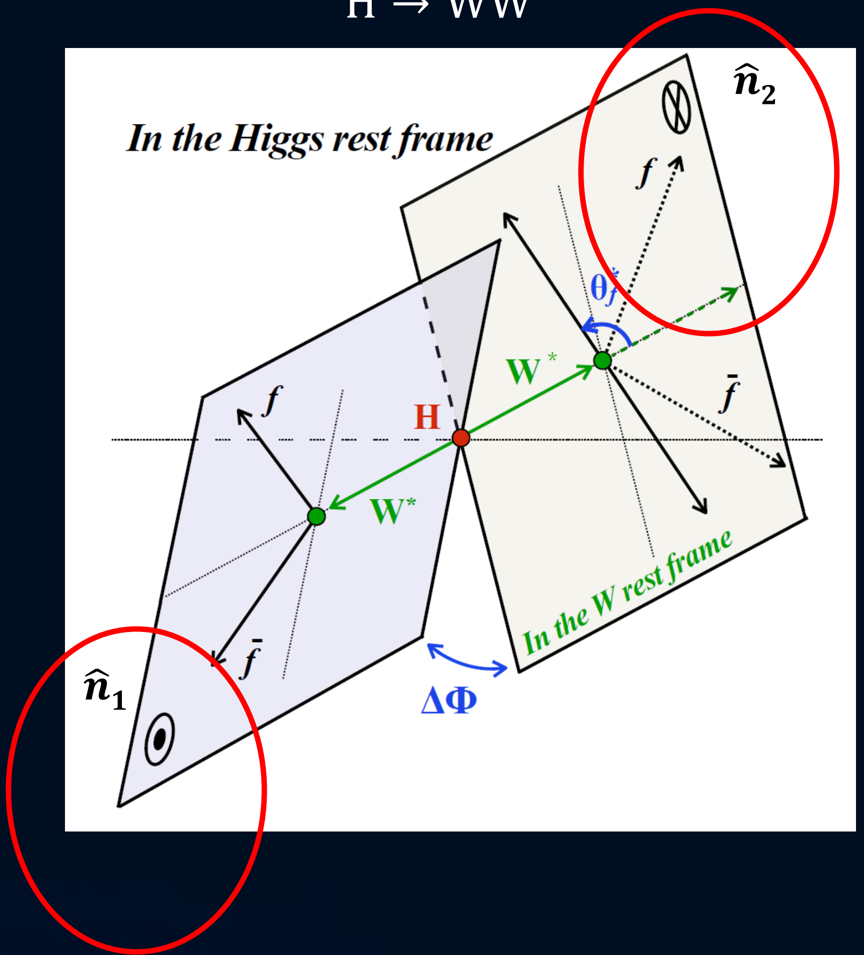
$$\hat{n}_1 = \frac{q_{f(V)} \times q_{\bar{f}(V)}}{|q_{f(V)} \times q_{\bar{f}(V)}|} \quad \text{and} \quad \hat{n}_2 = \frac{q_{f(V^*)} \times q_{\bar{f}(V^*)}}{|q_{f(V^*)} \times q_{\bar{f}(V^*)}|}$$

- n_1 and n_2 are now in 'the opposite' directions, to preserve correct arcos output (in the range 0-180 deg.) define ϕ as:

$$\phi = \; a \arccos(-\,\hat{n}_1 \cdot \hat{n}_2)$$

- where a defines how the second (off-shell boson V^*) plane is rotated w.r.t. the first (on-shell boson) plane; If it falls backwards (as illustrated) $a = -1$, otherwise $a = 1$. Direction of the on-shell boson (V) regulates the notion of direction (fwd. or back.)
- $a = \frac{q_V \cdot (\hat{n}_1 \times \hat{n}_2)}{|q_V \cdot (\hat{n}_1 \times \hat{n}_2)|}$
- It is essential to distinguish between fermion and antifermion (jet-charge)

H → WW*



- Examples of possible definitions of n_1 and n_2 in ZZ-fusion:

1. $\phi_1 = \arccos(+\hat{n}_1 \cdot \hat{n}_2)$ where $\hat{n}_1 = \frac{q_{e_i^-} \times q_{e_f^-}}{|q_{e_i^-} \times q_{e_f^-}|}$ and $\hat{n}_2 = \frac{q_{e_i^+} \times q_{e_f^+}}{|q_{e_i^+} \times q_{e_f^+}|}$

2. $\phi_2 = \arccos(-\hat{n}_1 \cdot \hat{n}_2)$ where $\hat{n}_1 = \frac{q_{Z_{e^-}} \times q_{e_i^-}}{|q_{Z_{e^-}} \times q_{e_i^-}|}$ and $\hat{n}_2 = \frac{q_{Z_{e^-}} \times q_{e_f^+}}{|q_{Z_{e^-}} \times q_{e_f^+}|}$

3. $\phi_3 = \arccos(+\hat{n}_1 \cdot \hat{n}_2)$ where $\hat{n}_1 = \frac{q_{Z_{e^-}} \times q_{e_i^-}}{|q_{Z_{e^-}} \times q_{e_i^-}|}$ and $\hat{n}_2 = \frac{q_{Z_{e^+}} \times q_{e_f^+}}{|q_{Z_{e^+}} \times q_{e_f^+}|}$

- No matter how we define a unit vector orthogonal to a production (decay) plane, consistently defined ϕ leads to the same results (in production and decay).