CPV in e^+e^-H (ZZ-fusion) at 1 TeV ILC

STATUS UPDATE

TATJANA AGATONVIC-JOVIN ET AL.
VINCA INSTITUTE OF NUCLEAR SCIENCES, UNIVERSITY OF BELGRADE

Outline

- SM-like Higgs boson as a CPV mixture of CP even and odd states
- Way to probe HVV vertices (V=Z, W) in Higgs production and decay
- Proposed method of measurement
- Higgs production in ZZ-fusion
  - Signal and background at 1 TeV ILC
  - Preselection
  - Reconstructed CPV observable for signal and background
- Production request

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

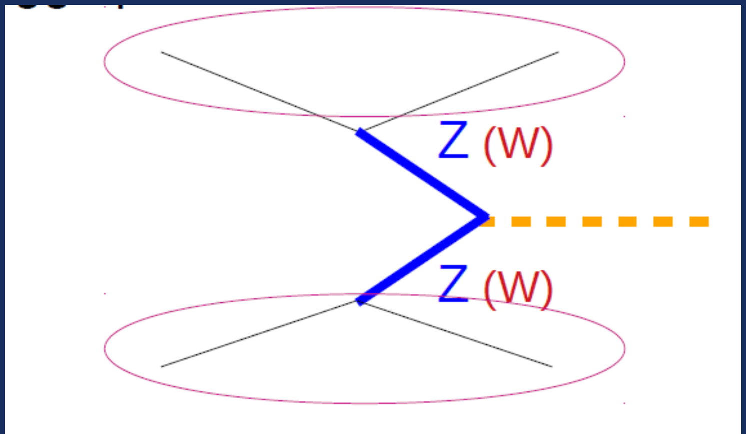
- SM-like Higgs boson could be a mixture of scalar (H) and pseudo-scalar state (A):

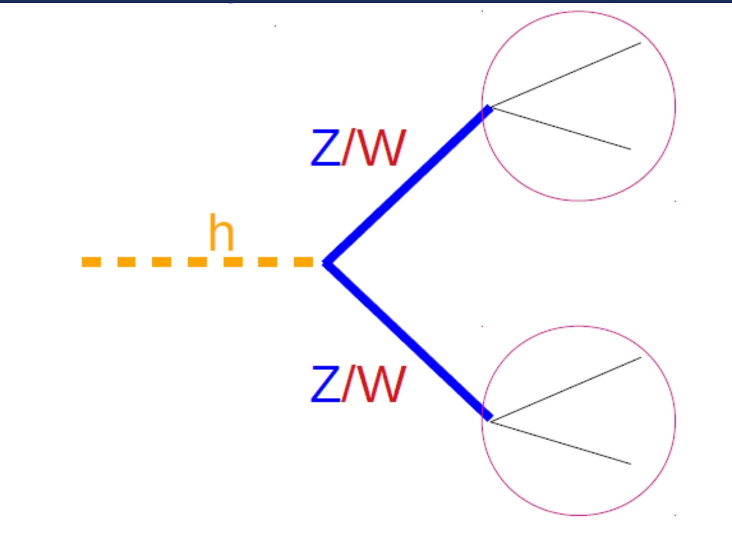
  $$h = H\cdot \cos\psi \; + \; A\cdot \sin\psi$$

- 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





Way to probe HVV vertices (V=Z, W) in Higgs production and decay

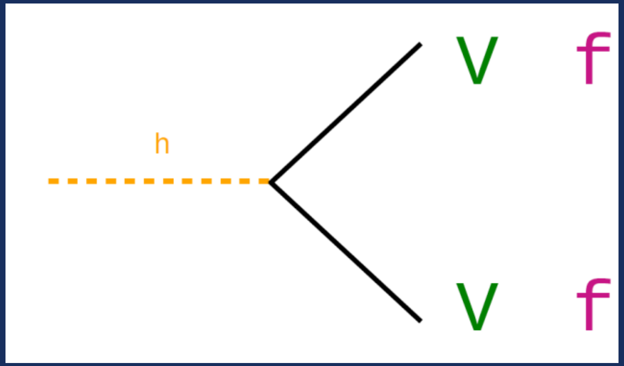
- hVV vertex (CPV at a loop level):

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

- hff vertex (CPV at a tree level):

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

- Suppressed effect w.r.t. (i.e.) Higgs to ττ decay, but relatively high statistics available (number of events inclusive Higgs boson in 1 ab^{-1} at 1 TeV ILC)



Way to probe HVV vertices (V=Z, W) in Higgs production and decay

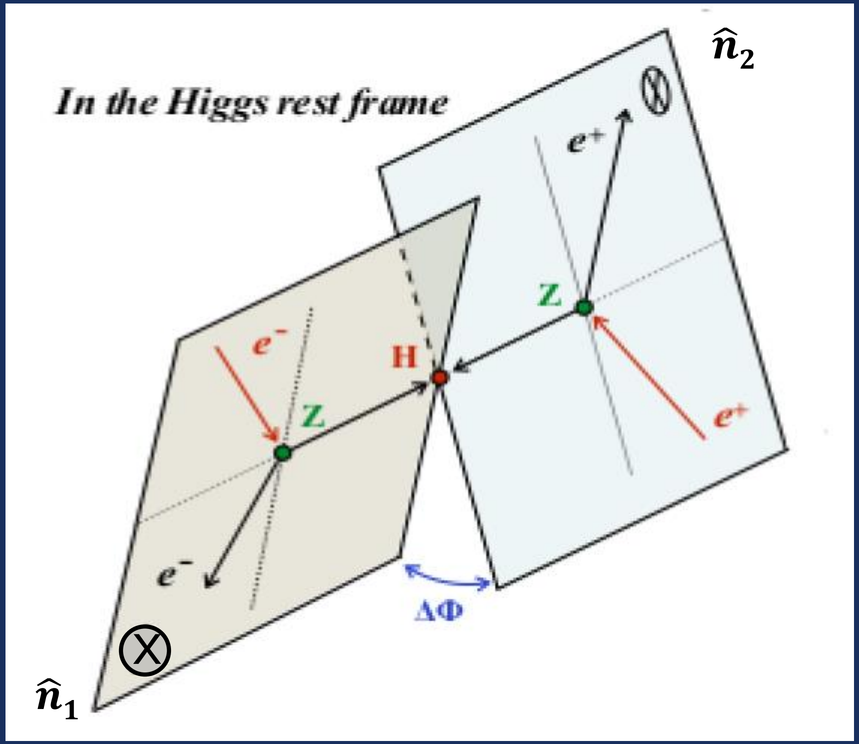
- Information on spin orientations of VV states is contained in the angle between production (decay) planes

- 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+})
  - Depending on the convention, 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.)
  - With the definition in (1), unit vectors n_1 and n_2 share the same hemisphere

Higgs production in ZZ-fusion



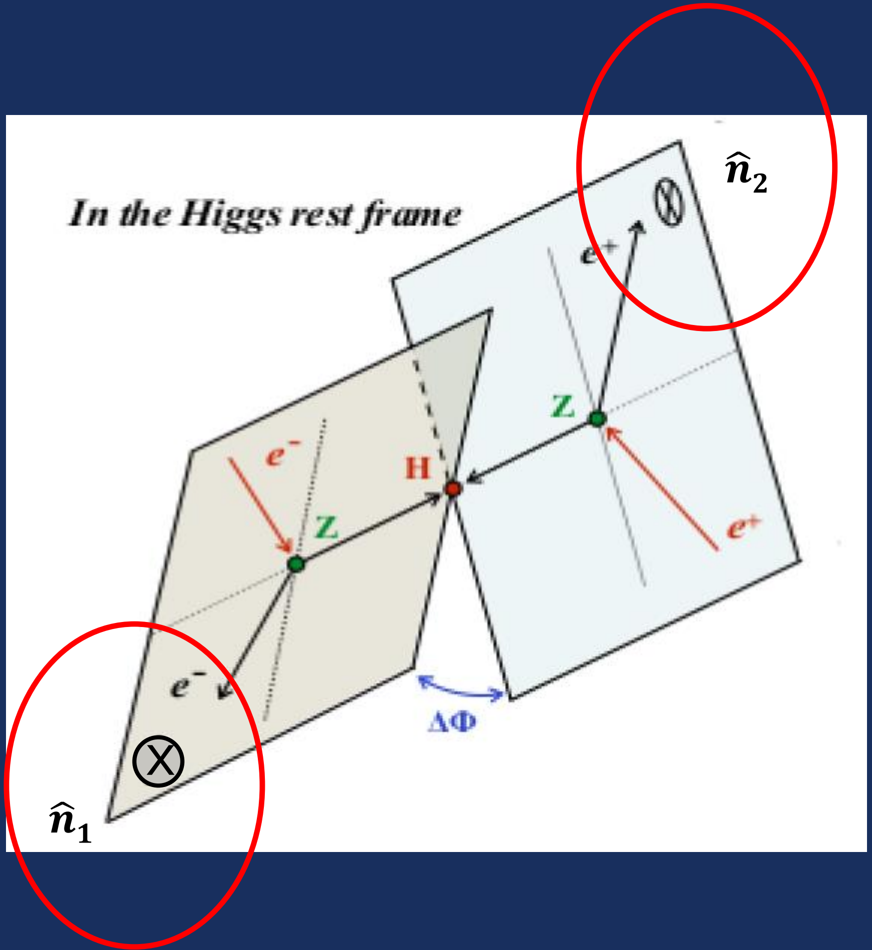
- Since orientation of vectors n_1 and n_2 is 'the same' , the angle between planes can be retrieved through the arccos function as:

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

- Sign $\pm$ retain natural domain of arccos function

- where *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.)

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



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

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

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

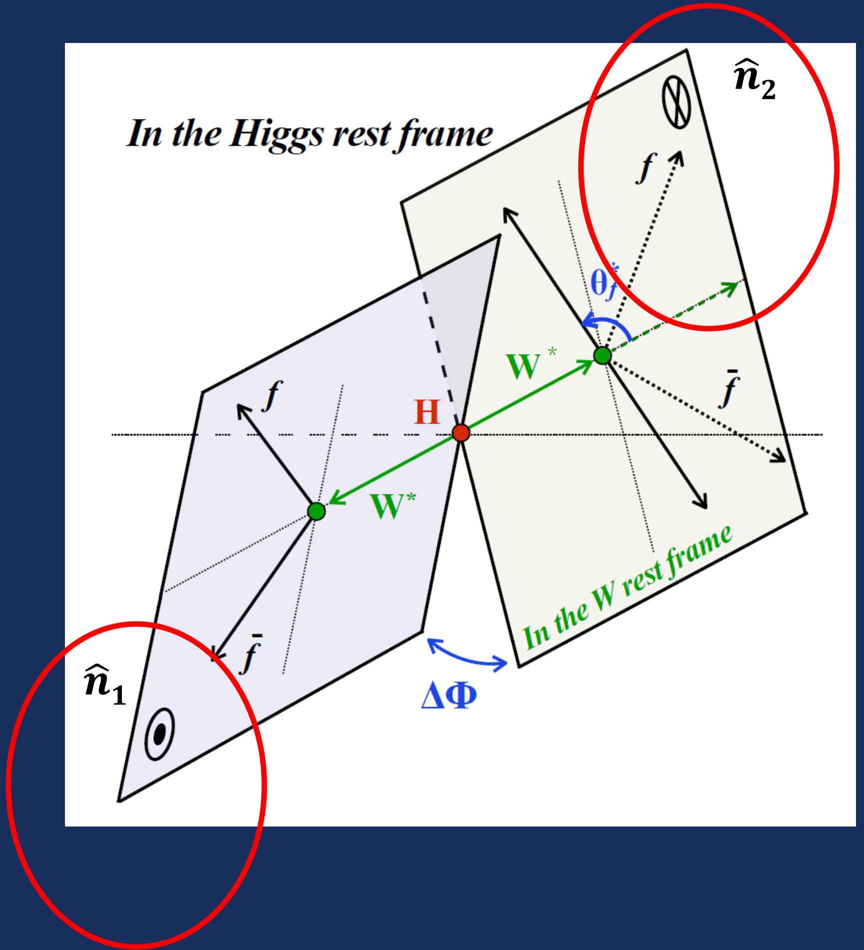
- n_1 and n_2 are now in 'the opposite' directions, to preserve correct arcos output (in the range 0-180 deg.) define ϕ as:

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

- 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.)

- $a = \dfrac{q_V \cdot (\hat{n}_1 \times \hat{n}_2)}{|q_V \cdot (\hat{n}_1 \times \hat{n}_2)|}$

- It is essential to distinguish between fermion and antifermion (jet-charge)



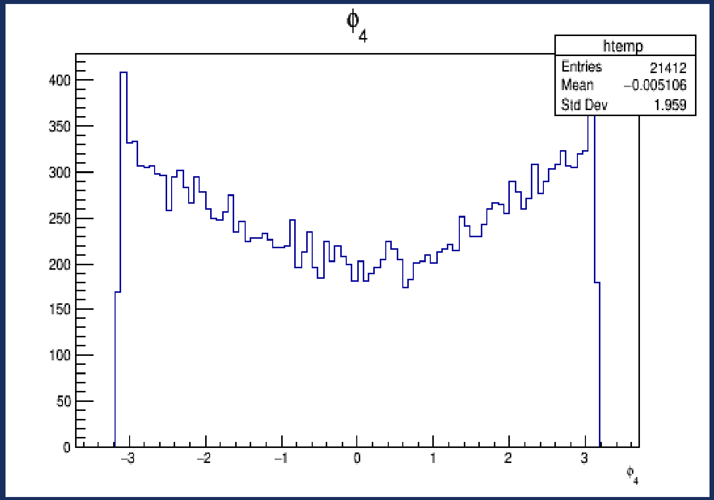
- Examples of possible definitions of n_1 and n_2 in ZZ-fusion:

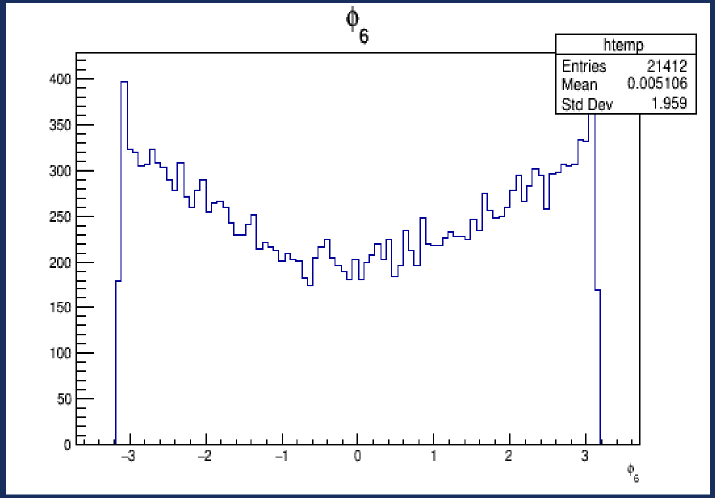
1. $\phi_1 = \arccos(+\hat{n}_1 \cdot \hat{n}_2)$ where $\hat{n}_1 = \frac{q_{e_i^-} \times q_{e_f^-}}{|q_{e_i^-} \times q_{e_f^-}|}$ and $\hat{n}_2 = \frac{q_{e_i^+} \times q_{e_f^+}}{|q_{e_i^+} \times q_{e_f^+}|}$

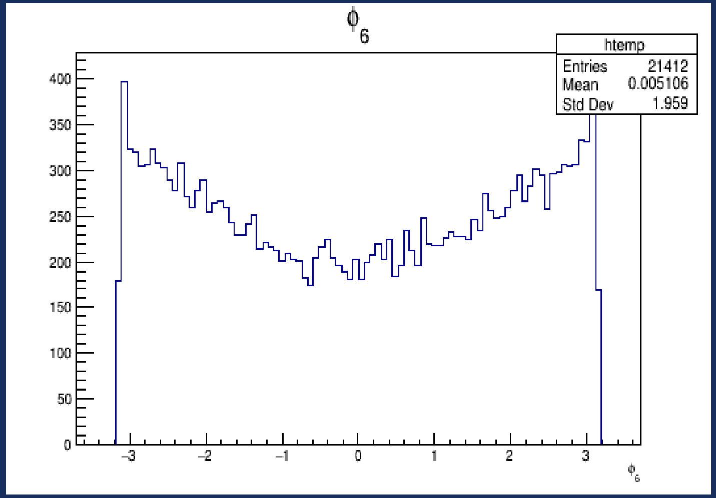
2. $\phi_2 = \arccos(-\hat{n}_3 \cdot \hat{n}_4)$ where $\hat{n}_3 = \frac{q_{Z_{e^-}} \times q_{e_i^-}}{|q_{Z_{e^-}} \times q_{e_i^-}|}$ and $\hat{n}_4 = \frac{q_{Z_{e^-}} \times q_{e_f^+}}{|q_{Z_{e^-}} \times q_{e_f^+}|}$

3. $\phi_3 = \arccos(+\hat{n}_5 \cdot \hat{n}_6)$ where $\hat{n}_5 = \frac{q_{Z_{e^-}} \times q_{e_i^-}}{|q_{Z_{e^-}} \times q_{e_i^-}|}$ and $\hat{n}_6 = \frac{q_{Z_{e^+}} \times q_{e_f^+}}{|q_{Z_{e^+}} \times q_{e_f^+}|}$

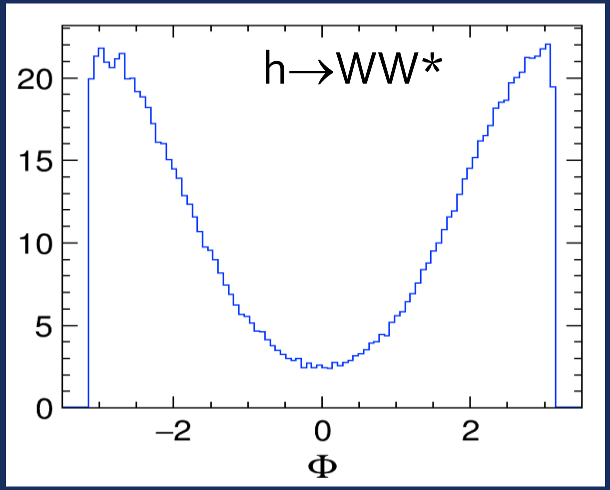
- No matter how we define a unit vector orthogonal to a production (decay) plane, consistently defined ϕ leads to the same results (in production and decay).

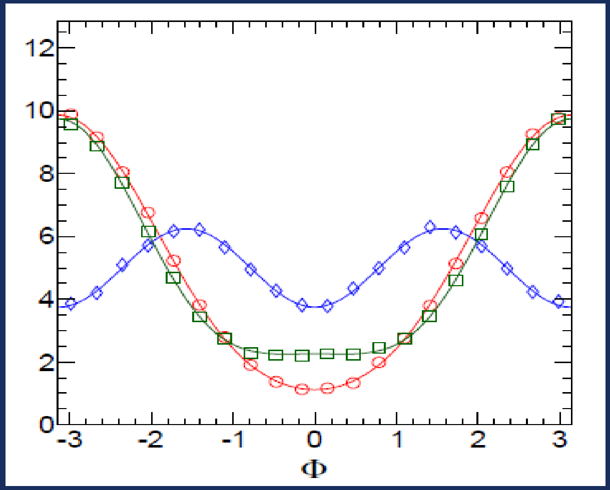






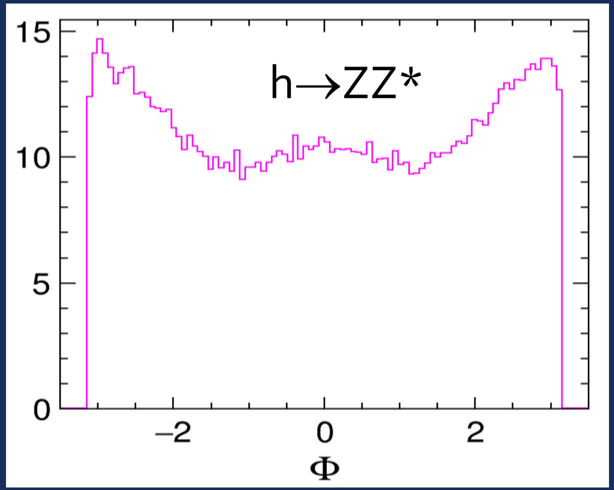
ϕ distributions in Higgs decays to WW^* and ZZ^*

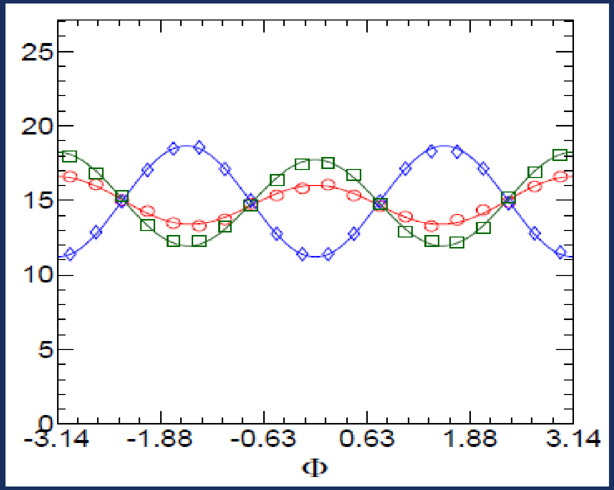




J_m^+ (red circles), J_h^+ (green squares), J_h^- (blue diamonds)

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



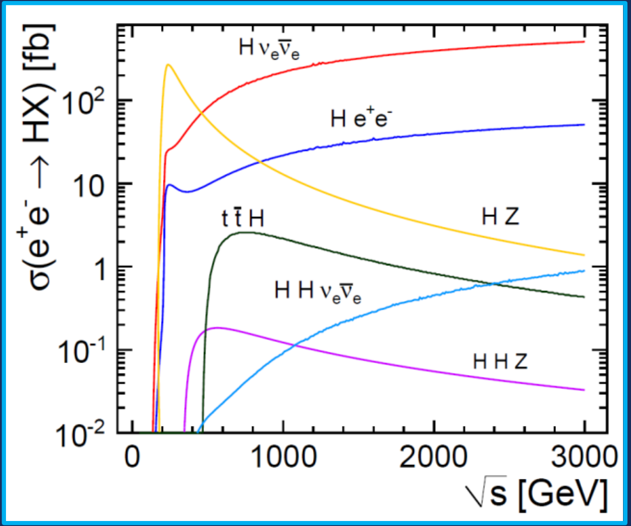


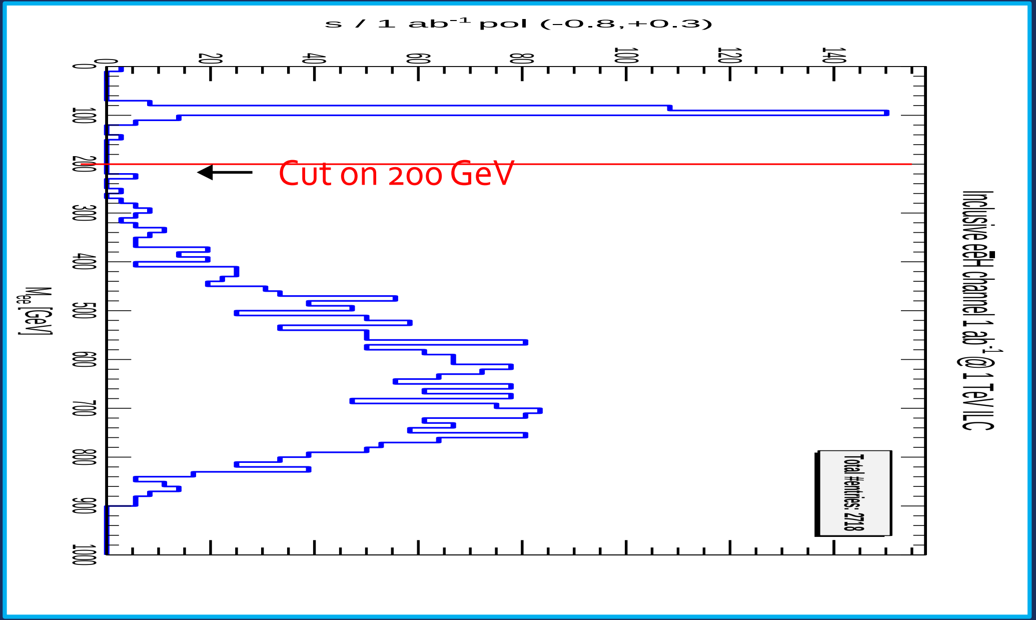
We are correctly reproducing ϕ distributions at the generator level both for HVV decay vertices $(V = Z, W)$

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

Proposed method

- 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

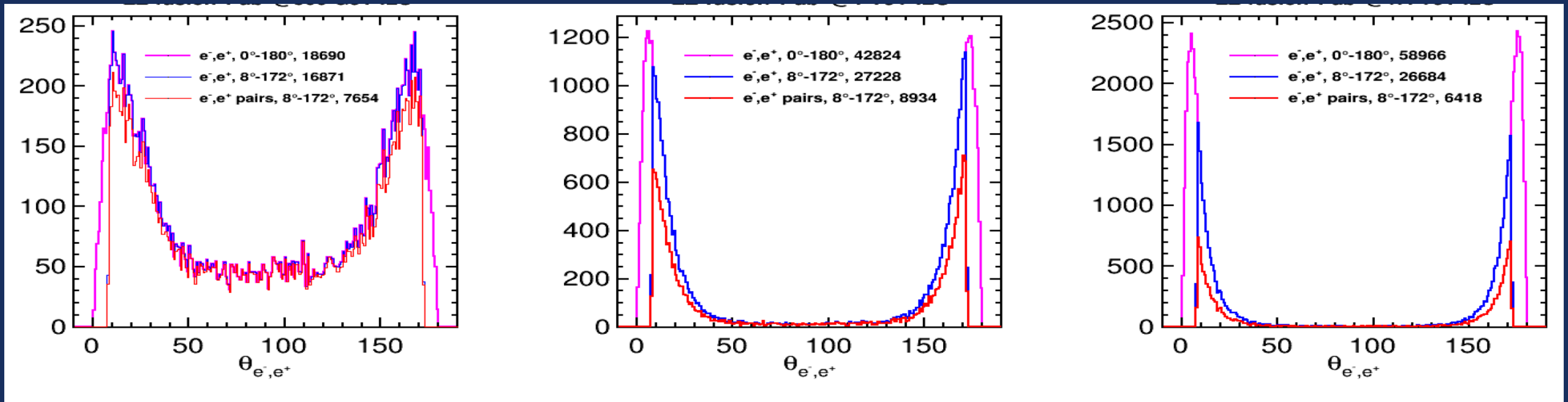




Dilepton mass distribution

Higgs production in ZZ-fusion

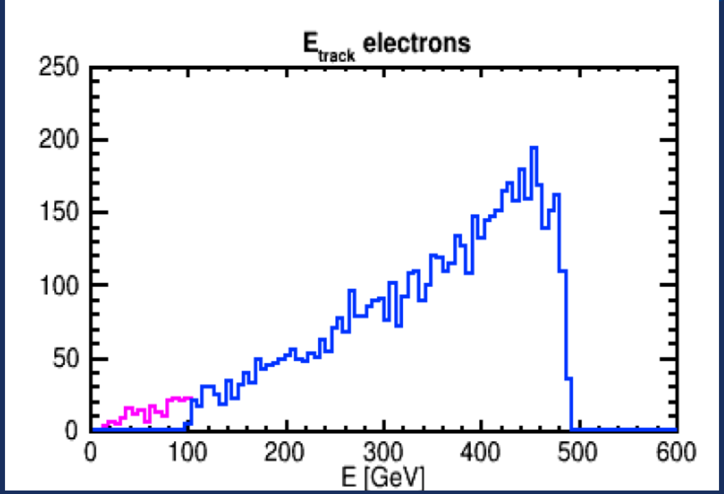
- WHIZARD v1.95, 500GeV/0.5 ab^{-1}, 1 TeV/ 1 ab^{-1} , 1.4 TeV/1 ab^{-1}, unpolarized
- t-channel process, electrons (spectators) are scattered forward - not full statistics available in the tracker
- Due to this fact 1 TeV is the optimal energy for this study (already at i.e. 1. 4 TeV the number of 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 8-9·10^3 events with both e+ and e- in the tracker in 1 ab^{-1} at 1 TeV ILC

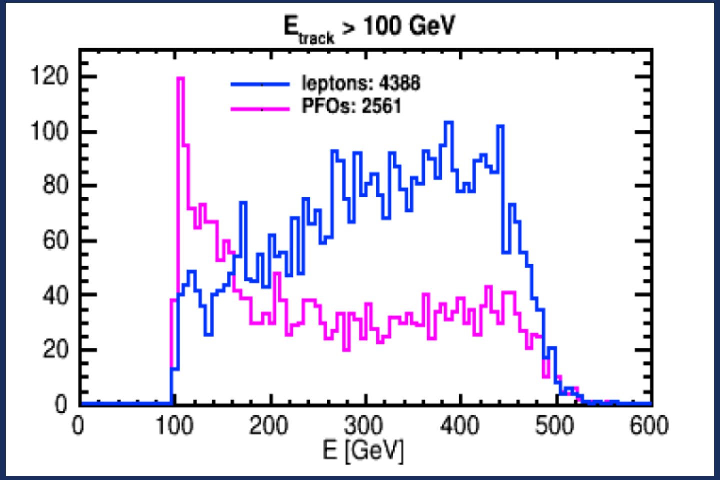


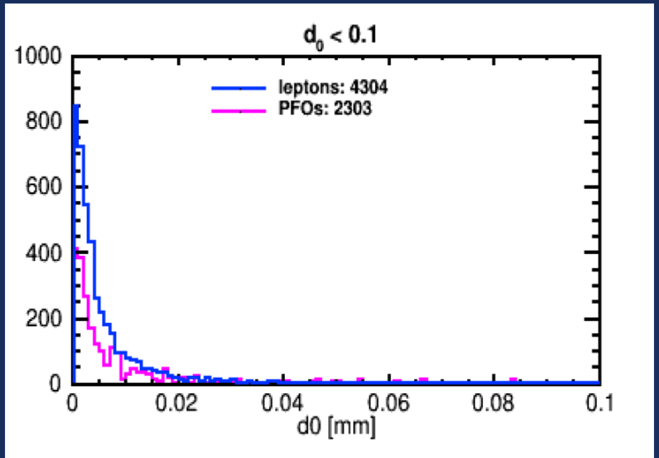
82 % @ 500 GeV
41.7 % @ 1 TeV
21.8 % @ 1.4 TeV

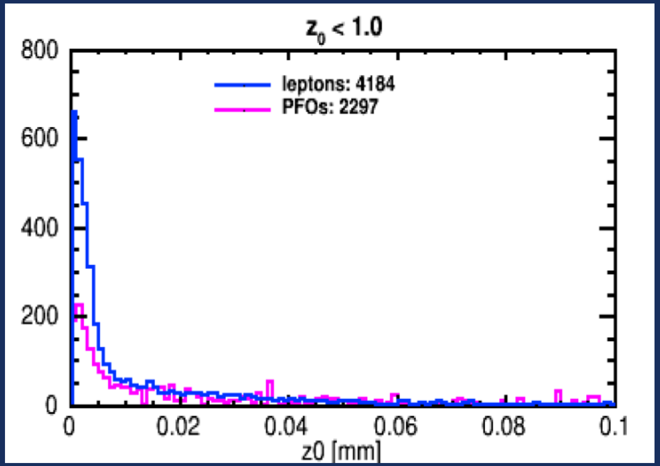
Preselection

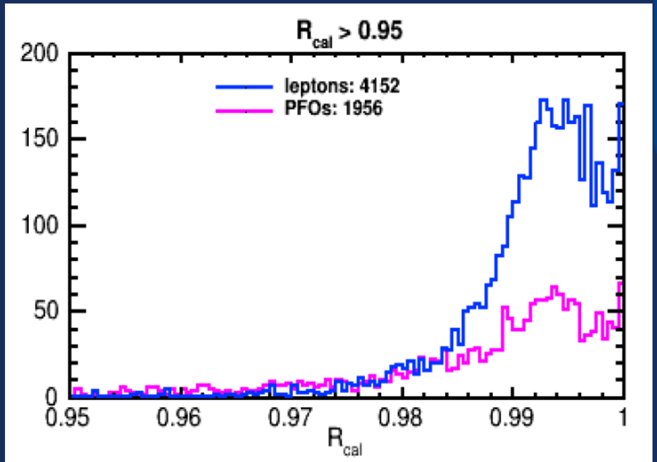
- ILC sample at 1 TeV, normalized to 1 ab^{-1}, with LR polarization (-1, 1), normalized to (-0.8, +0.3) as:
- $W_{\text{pol}} = \left(\frac{1-P_{e_-}}{2}\right) \cdot \left(\frac{1+P_{e_+}}{2}\right) = \left(\frac{1-(-0.8)}{2}\right) \cdot \left(\frac{1+0.3}{2}\right) = 0.585$
- Preselection: find 2 isolated electrons (e^+e^-)
- Goal: reduce high cross-section backgrounds
- Requirements:
  - Track energy: $E_{\text{track}} > 100$ 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

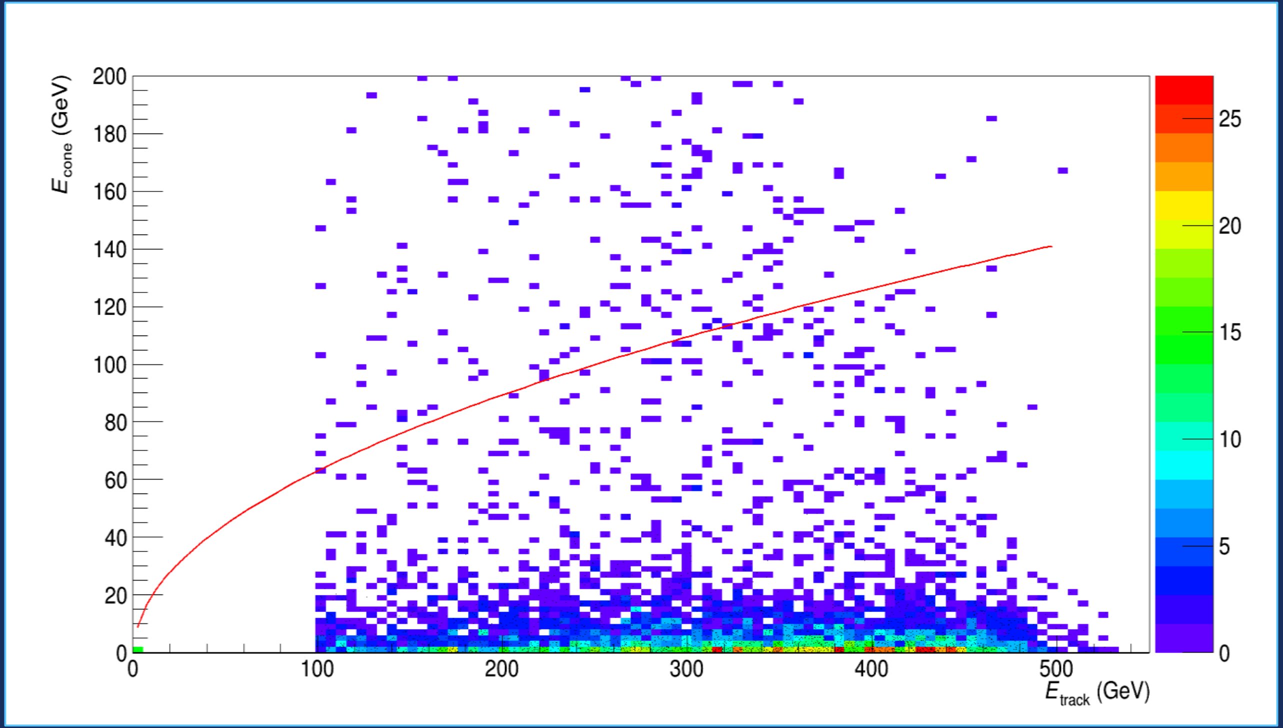












Isolation curve:

$E_{\mathrm{cone}}^2 < 40\ E_{\mathrm{track}}\ \mathrm{GeV} - 20\ \mathrm{GeV}^2$

Signal and considered available background samples

- Preselection efficiencies -

$1\ \mathrm{TeV}/1\ \mathrm{ab}^{-1}$ /pol$(-80\%, +30\%)$	Sample	σ [fb]	Input	Output	Efficiency [%]
Signal:	$e^+e^- \to e^+e^-H(H \to b\bar{b})$	28.6	$N_{\mathrm{reco}}^{\mathrm{tot}} = 6012$; $N_{\mathrm{reco}}^{\mathrm{norm}} = 16713$ $N_{\mathrm{signal}} = 1121$; $N_{\mathrm{signal}}^{\mathrm{norm}} = 3116$	$N_{\mathrm{sig/iso}} = 873$ $N_{\mathrm{sig/iso}}^{\mathrm{norm}} = 2426$	78 %
Background samples:	$e^-e^+ \to e^-e^+q\bar{q}$	2577.3	$N_{ev} = 59793$; $N_{ev}^{norm} = 34978$	$N_{ev} = 1447$ $N_{ev}^{norm} = 846$	2.42 %
	$e^-e^+ \to e^-\bar{\nu}q\bar{q}$	8963.3	$N_{ev} = 2069073$; $N_{ev}^{norm} = 1210407$	$N_{ev} = 428$ $N_{ev}^{norm} = 250$	0.02 % (0.2 ‰)
	$e^-e^+ \to q\bar{q}$	9375.3	$N_{ev} = 217488$; $N_{ev}^{norm} = 127230$	$N_{ev} = 1$	0.0046 ‰
	$\gamma\gamma \to q\bar{q}q\bar{q}$	473.7 263.7 263.6 126.0	$N_{ev}\ (\mathrm{e_Bp_B}) = 40000$ $N_{ev}(\mathrm{e_Bp_W}) = 30000$ $N_{ev}(\mathrm{e_Wp_B}) = 30000$ $N_{ev}(\mathrm{e_Wp_W}) = 13000$	$N_{ev} = 0$ $N_{ev} = 1$ $N_{ev} = 0$ $N_{ev} = 282$; $N_{ev}^{norm} = 164$	– 0.033 ‰ – 1.26 %
	$\gamma\gamma \to e^-e^+q\bar{q}$	$\sim 1 - 10^1$	$N_{ev}\ (\mathrm{e_Bp_B}) = 42565$ $N_{ev}(\mathrm{e_Bp_W})$ = need to estimate $N_{ev}(\mathrm{e_Wp_B}) = 10000$ $N_{ev}(\mathrm{e_Wp_W}) = 10000$	$N_{ev} = 212$; $N_{ev}^{norm} = 106$ $N_{ev}(\mathrm{e_Bp_W}) = -$ $N_{ev}(\mathrm{e_Wp_B}) = 0$ $N_{ev}(\mathrm{e_Wp_W}) = 0$	0.25 % – – –
	$\gamma\gamma \to q\bar{q}$	$\sim 10^3 - 10^5$	$N_{ev}\ (\mathrm{e_Bp_B}) = 61193$ $N_{ev}(\mathrm{e_Bp_W}) = 61105$ $N_{ev}(\mathrm{e_Wp_B}) = 61106$ $N_{ev}(\mathrm{e_Wp_W}) = 63058$	$N_{ev}\ (\mathrm{e_Bp_B}) = 0$ $N_{ev}(\mathrm{e_Wp_W}) = 5$ $N_{ev}(\mathrm{e_Bp_W}) = 0$ $N_{ev}(\mathrm{e_Wp_W}) = 0$	– 0.04 ‰ – –

Flavour inclusion – background processes

$\gamma\gamma \to q\bar{q}q\bar{q}$

```
aa_4f_production/aa_4f/E1000-B1b_ws.
Paa_xxyy.Gwhizard-1.95.eB.pB.I35653/
whizard.aa_xxyy_o.out

! WHIZARD version 1.95 (Feb 25 2010)
 ! Process aa_xxyy_o:
 !  gamma gamma ->   u a-u   d a-d
 !  gamma gamma ->   u a-u   d a-s
 !  gamma gamma ->   u a-u   d a-b
 !  gamma gamma ->   u a-u   s a-d
 !  gamma gamma ->   u a-u   s a-s
 !  gamma gamma ->   u a-u   s a-b
 !  gamma gamma ->   u a-u   b a-d
 !  gamma gamma ->   u a-u   b a-s
 !  gamma gamma ->   u a-u   b a-b
 !  gamma gamma ->   u a-c   d a-d
 !  gamma gamma ->   u a-c   d a-s
 !  gamma gamma ->   u a-c   d a-b
 !  gamma gamma ->   u a-c   s a-d
 !  gamma gamma ->   u a-c   s a-s
 !  gamma gamma ->   u a-c   s a-b
 !  gamma gamma ->   u a-c   b a-d
 !  gamma gamma ->   u a-c   b a-s
 !  gamma gamma ->   u a-c   b a-b
 !  gamma gamma ->   c a-u   d a-d
 !  gamma gamma ->   c a-u   d a-s
 !  gamma gamma ->   c a-u   d a-b
 !  gamma gamma ->   c a-u   s a-d
 !  gamma gamma ->   c a-u   s a-s
 !  gamma gamma ->   c a-u   s a-b
 !  gamma gamma ->   c a-u   b a-d
 !  gamma gamma ->   c a-u   b a-s
 !  gamma gamma ->   c a-u   b a-b
 !  gamma gamma ->   c a-c   d a-d
 !  gamma gamma ->   c a-c   d a-s
 !  gamma gamma ->   c a-c   d a-b
 !  gamma gamma ->   c a-c   s a-d
 !  gamma gamma ->   c a-c   s a-s
 !  gamma gamma ->   c a-c   s a-b
 !  gamma gamma ->   c a-c   b a-d
 !  gamma gamma ->   c a-c   b a-s
 !  gamma gamma ->   c a-c   b a-b
```

$e^-e^+ \to e^-e^+q\bar{q}$

```
4f_production/singleZee/semileptonic/events_eL_pR/
! sze_sl0dd    | omega |    | e-,e+ -> e-:e+,e-:e+,
d:s:b:dbar:sbar:bbar,d:s:b:dbar:sbar:bbar
! sze_sl0uu    | omega |    | e-,e+ ->
u:c:ubar:cbar,u:c:ubar:cbar,e-:e+,e-:e+
```

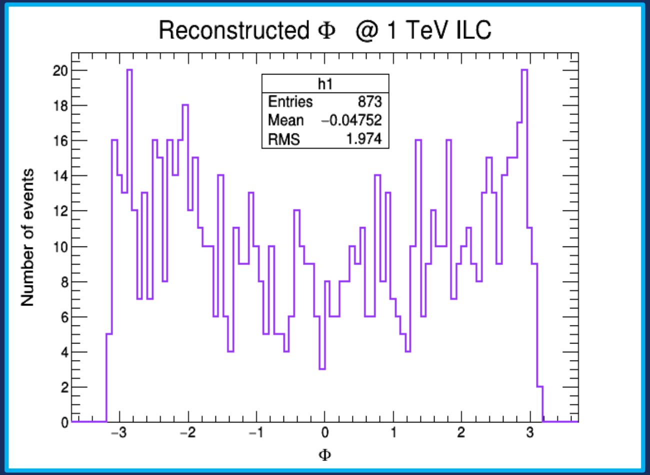
$e^-e^+ \to e^-\bar{\nu}q\bar{q}$

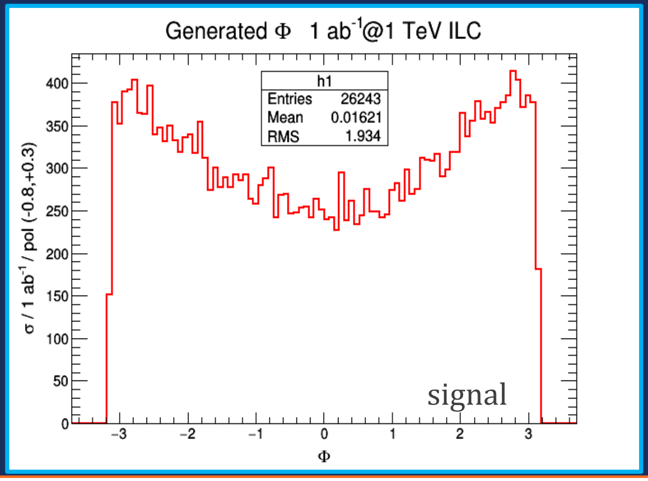
```
4f_production/singleW/semileptonic/events_eL_pR/
! sw_sl0qq    | omega |    | e-,e+ ->
u:c:ubar:cbar,d:s:b:dbar:sbar:bbar,e-:e+,nue:nuebar
```

$e^-e^+ \to q\bar{q}$

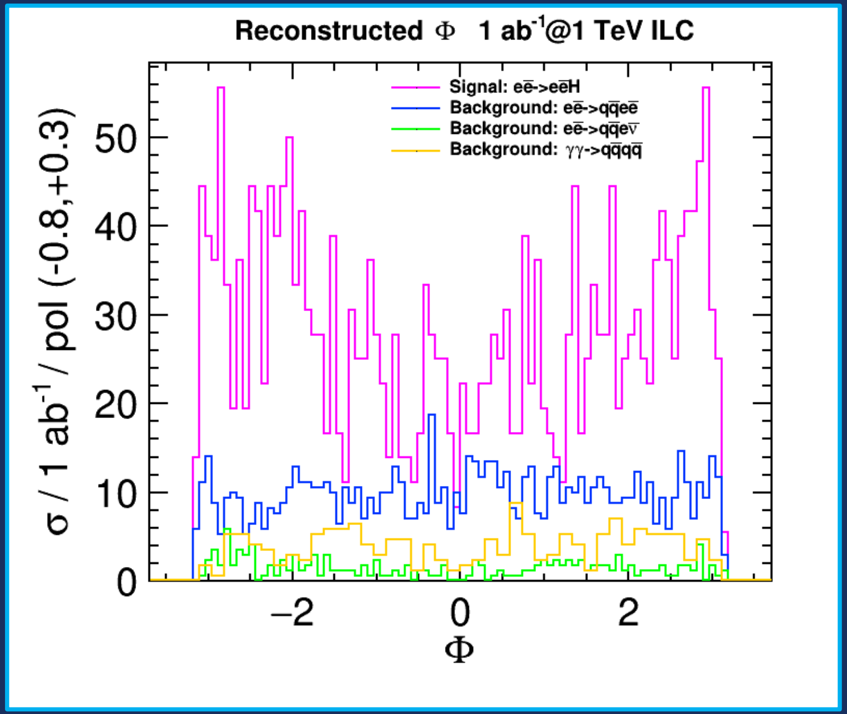
```
2f_production/Z/hadronic/events_eL_pR/
! z_h0dq    | omega |    | e-,e+ -> d:dbar,d:dbar
! z_h0sq    | omega |    | e-,e+ -> s:sbar,s:sbar
! z_h0bq    | omega |    | e-,e+ -> b:bbar,b:bbar
! z_h0uq    | omega |    | e-,e+ -> u:ubar,u:ubar
! z_h0cq    | omega |    | e-,e+ -> c:cbar,c:cbar
```

Reconstructed CPV observable for signal and background

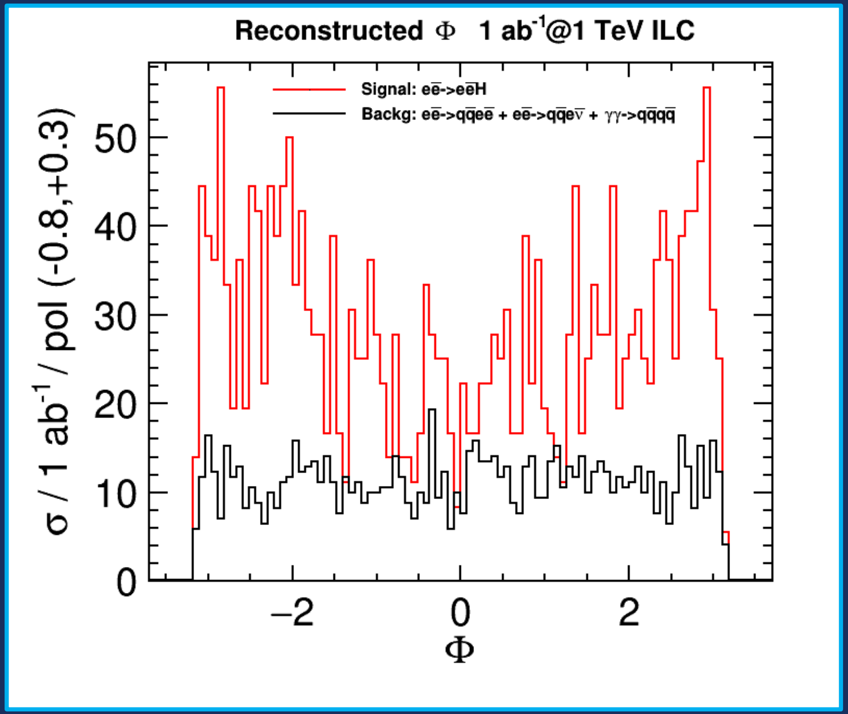




Reconstructed signal reproduce shape, but the statistics is low (nedovoljna)



Superimposed signal and background

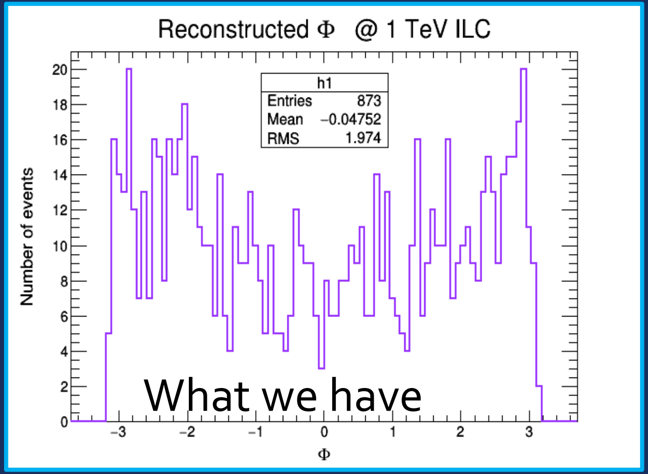


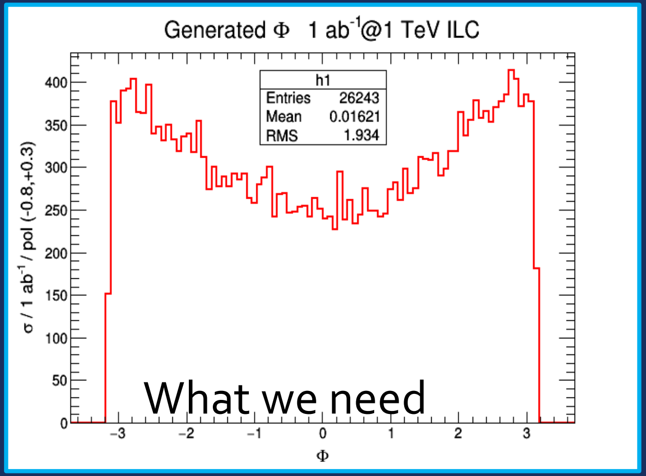
Superimposed signal and summed background

$S/B \approx 2$

Production request

- One of the advantages of the ILC analysis is the full simulation studies
- We have all the background samples
- We have excellent background suppression at the preselection level (will be even better after the MVA)
- All we need is a signal for CPV fit
- Minimal request is 27000 ZZ-fusion events on the generator level





Summary

- 1 TeV ILC offers optimal conditions to probe CPV in the HZZ vertices
- Sensitive observable ϕ (angle between production planes) is reconstructed with expected behavior, in the full simulation
- Background ϕ distribution is CPV insensitive
- **Higher signal statistics is crucial for the ψ_{CP} fit!**
- Background is very suppressed already at the preselection level
- Negligible contamination (i.e. ~ ‰, preliminary) of the total background w.r.t signal expected after MVA