Higgs CPV Mixing at 1 TeV ILC

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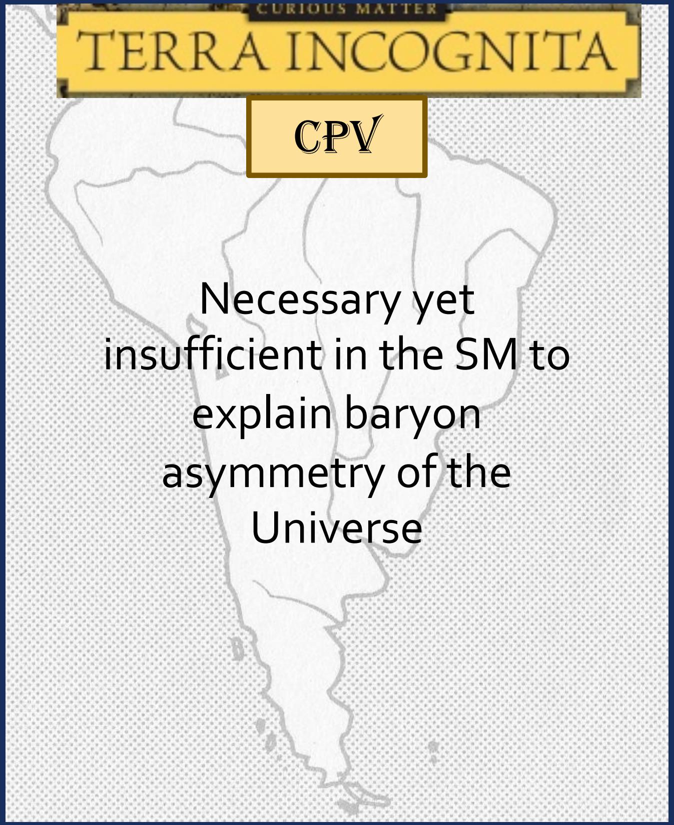
- Preselection exercise
- Production request

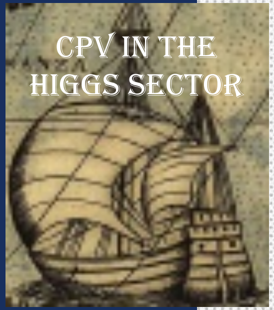
Motivation

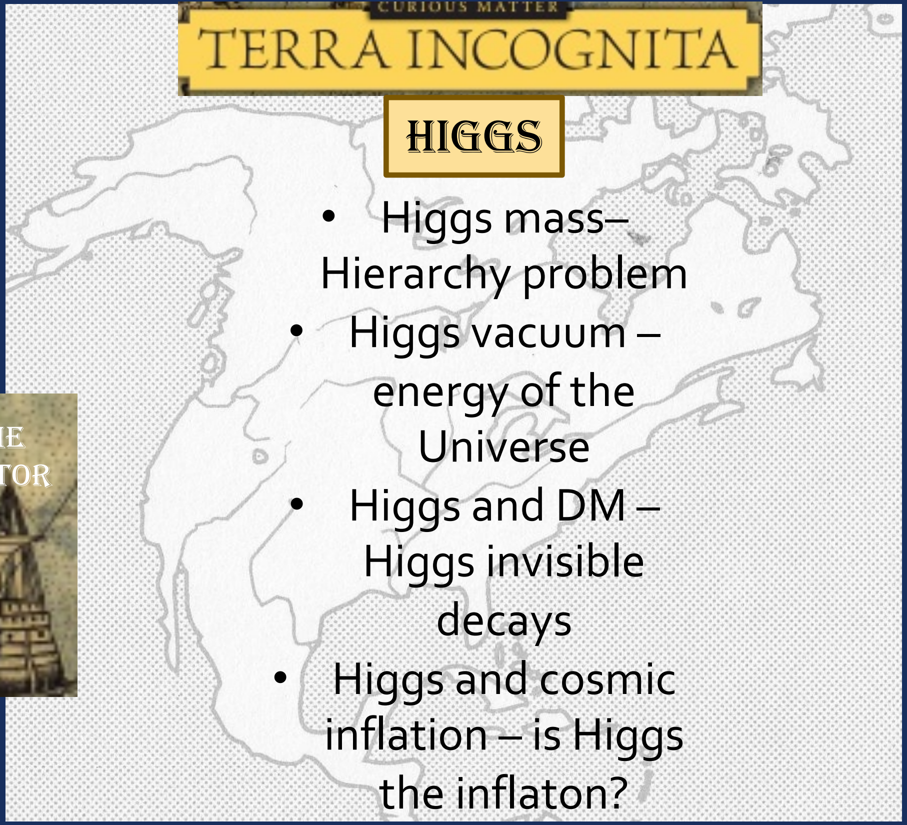


CPV

Necessary yet insufficient in the SM to explain baryon asymmetry of the Universe

Are they connected?





HIGGS

- Higgs mass– Hierarchy problem
- Higgs vacuum – energy of the Universe
- Higgs and DM – Higgs invisible decays
- Higgs and cosmic inflation – is Higgs the inflaton?

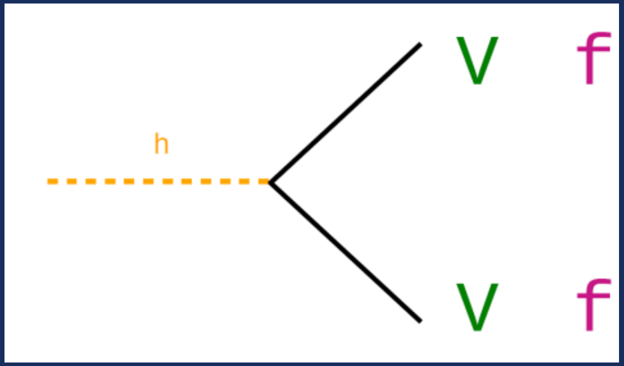
Motivation

- CPV (BSM physics) is required to explained bariogenesis
- CPV provided in the SM (i.e. CKM matrix) is insufficient
- Could CP be violated in the Higgs sector?
- hVV vertex (CPV at a loop level):

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

- Hff vertex (CPV at a tree level):

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



Ways to probe CPV in the Higgs sector

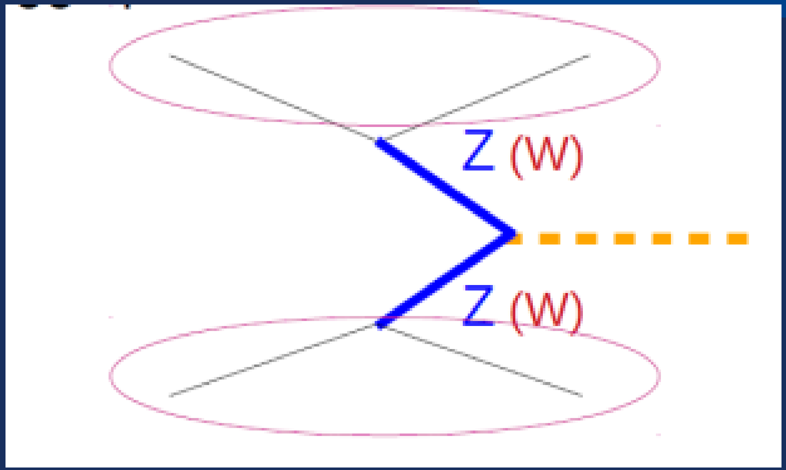
- SM-like Higgs boson could be a mixture of scalar (H) and pseudo-scalar state (A):

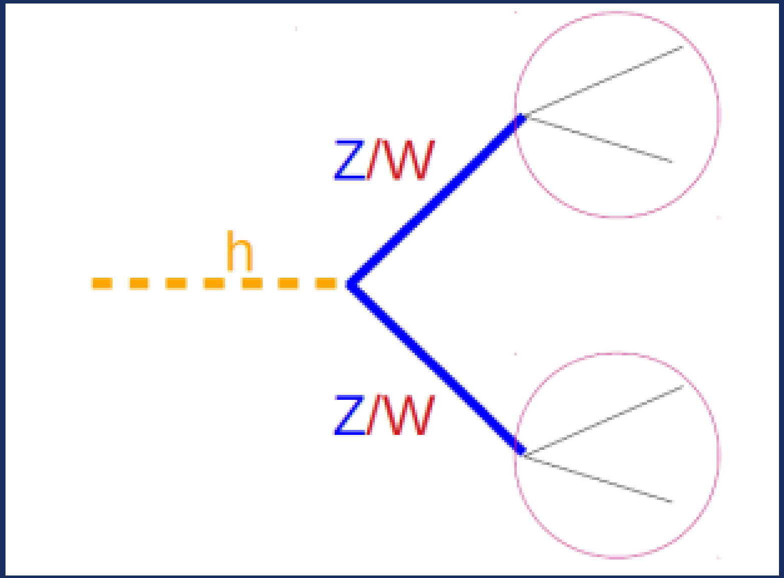
$$h_m = H \cdot cos\psi_{CP} \;+\; A \cdot sin\psi_{CP}$$

- Correlation between spin orientations of VV (or ff) carries information on the Higgs CP state

- Numerous Higgs production processes at linear machines (hZ, WW-fusion, ZZ-fusion) at various c.m. energies

- Both Higgs production and decays can be exploited





Method of the analysis

- Define sensitive observable(s)
- Event selection:
  - Preselection
  - MVA analysis
- PDFs of the reconstructed CPV observable for signal and background
- Pseudo-experiment to fit our reconstructed sensitive observable in order to extract CPV mixing angle
- Multiple pseudo-experiments (with the fixed Higgs CPV mixing angle) to determine statistical uncertainty from the pull distribution

Inclusive Higgs production in ZZ-fusion

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

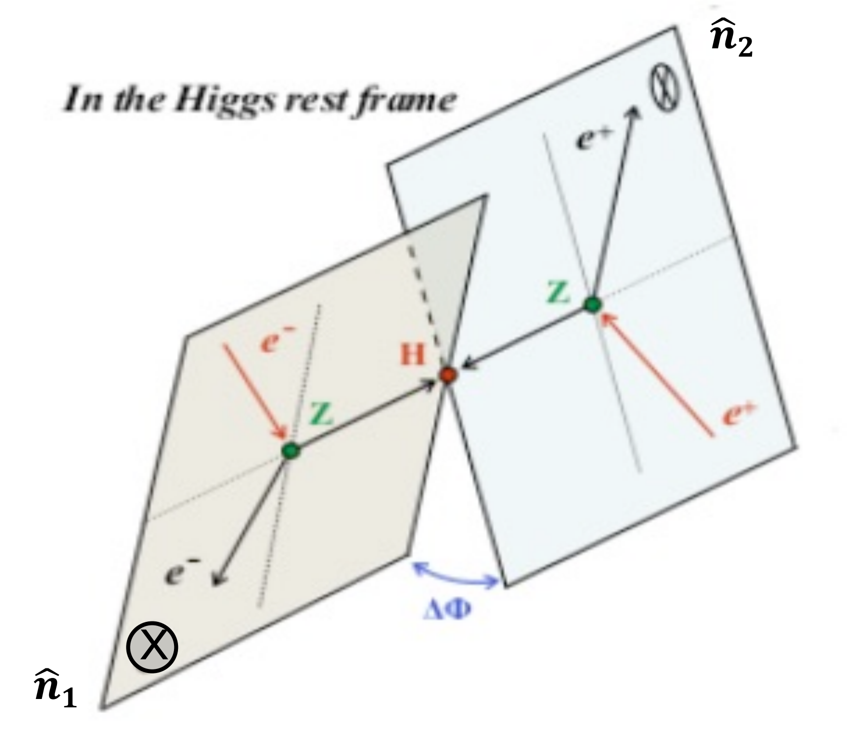
- Angle between planes is angle between unit vectors orthogonal to those planes:

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

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

- 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.)

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

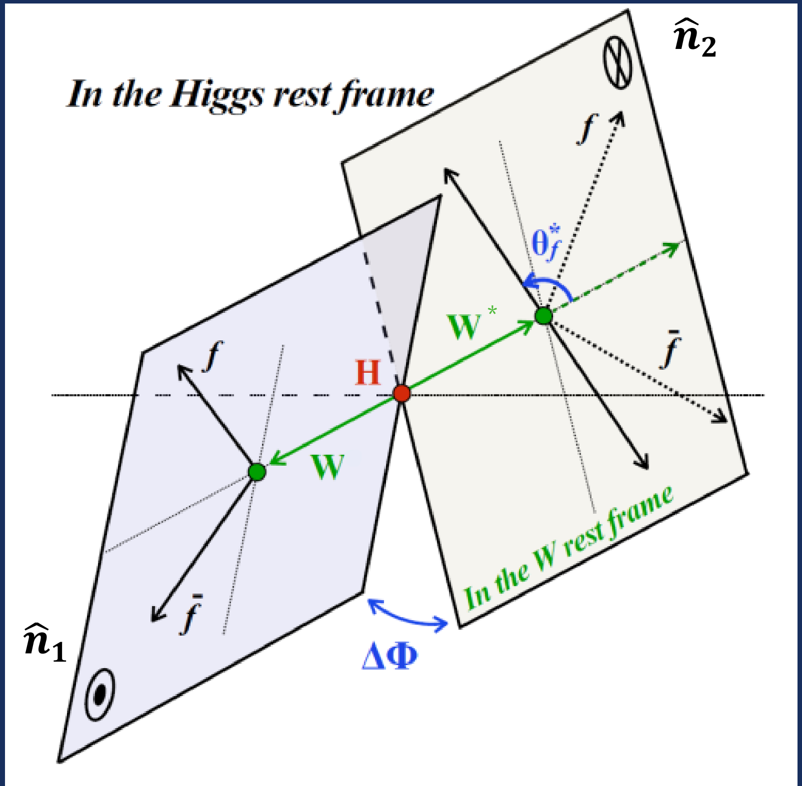


Higgs decays (as a cross-check): $H \to WW^*$ and $H \to ZZ^*$

- Unit vectors orthogonal to decay planes are now opposite:

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

- $\phi = a \arccos(-\hat{n}_1 \cdot \hat{n}_2)$
- 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 in case of semileptonic ZZ decays)

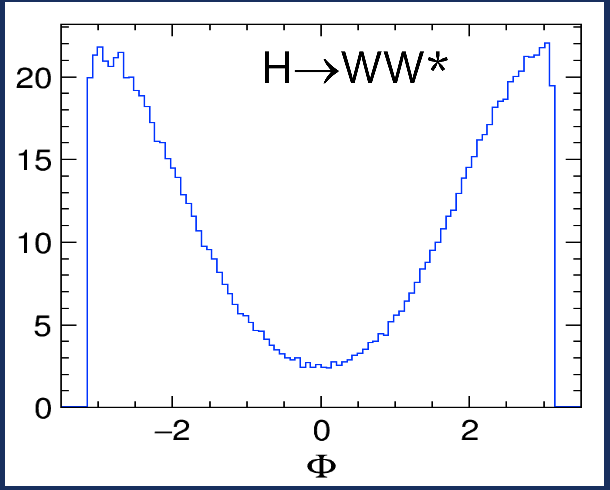


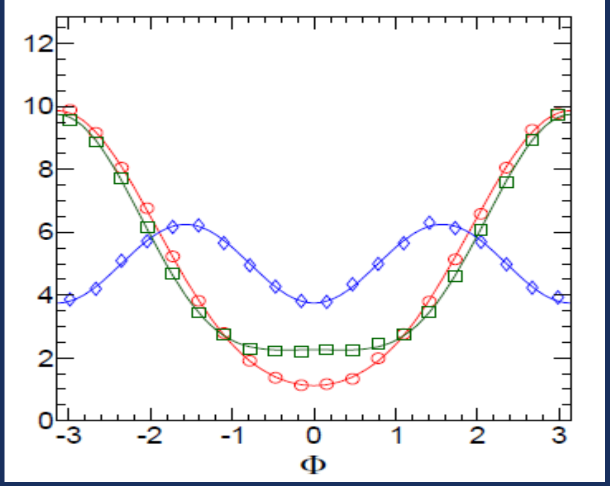
ϕ distributions

WHIZARD v3.0.0 generator level

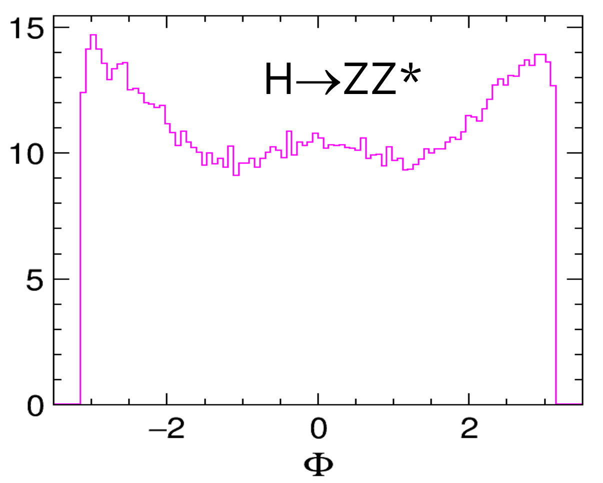
J_m^+ (red circles), J_h^+ (green squares), J_h^- (blue diamonds)

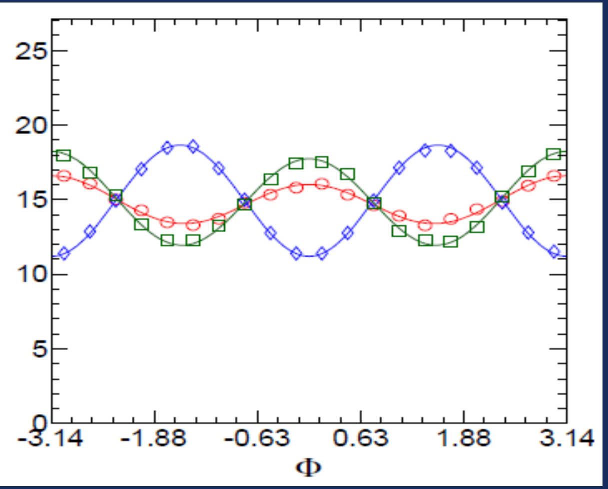
scenario	X production	$X \to VV$ decay	comments
0_m^+	$gg \to X$	$g_1^{(0)} \neq 0$ in Eq. (9)	SM Higgs boson scalar
0_h^+	$gg \to X$	$g_2^{(0)} \neq 0$ in Eq. (9)	scalar with higher-dimension operators
0^-	$gg \to X$	$g_4^{(0)} \neq 0$ in Eq. (9)	pseudo-scalar

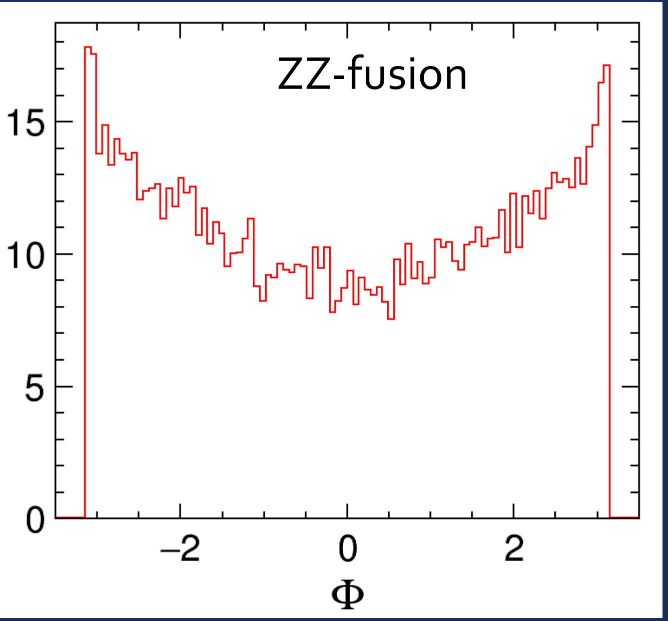




We are correctly reproducing ϕ distributions for $H \to VV$ decays $(V = Z, W)$; $\psi_{CP} = 0$



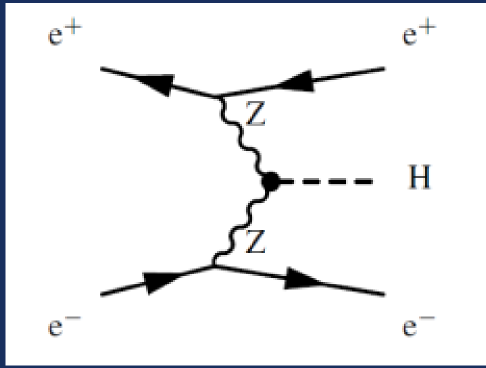




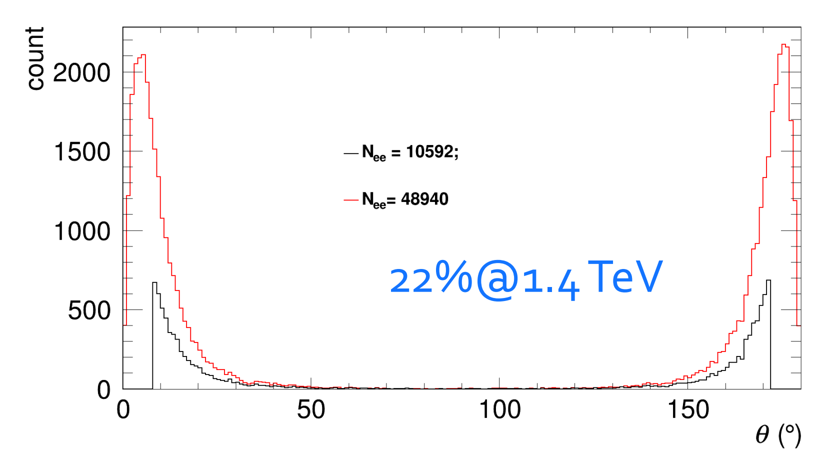
S. Bolognesi et al.,
On the spin and parity of a single produced resonance at the LHC,
arXiv:1208.4018 [hep-ph] for Higgs to ZZ* and WW* decays

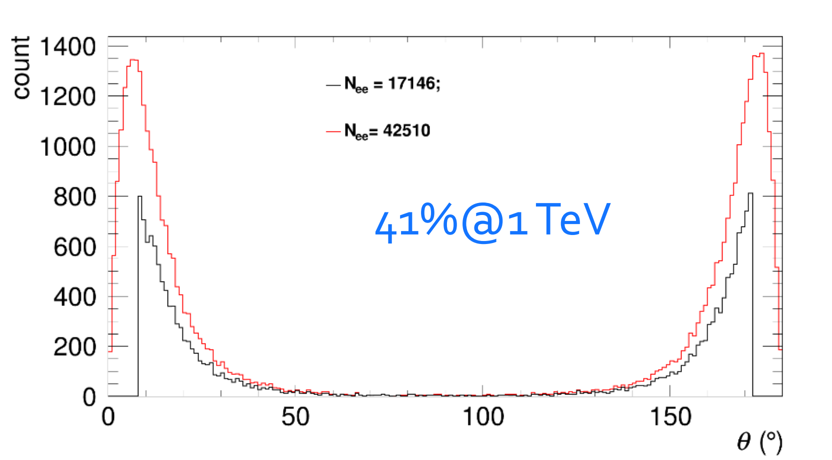
Preselection exercise

- ZZ-fusion at 1.4 TeV@ 1 ab^{-1}
- WHIZARD v1.95, including ISR and BS and luminosity spectrum
- ILCSoft 2017-12-21
- t-channel process, electrons are scattered forward
  ➡ not full statistics in the tracker at >1 TeV energies,
  yet 8-9·10^3 events in 1 ab^{-1} with both e+ and e- in the tracker
- At 500 GeV (due to $\sigma, \mathcal{L}, N_{tr}$) available number of events is ~3 times smaller than @ 1 TeV
- Isolated e^-/e^+ identification
  - Track energy: E_{track} > 100 GeV
  - Impact parameter: $d_0 < 0.04$, $z_0 < 0.1$, $r_0 < 0.1$
  - Ratio of deposition: $R_{cal} > 0.94$
  - Cone energy: optimized with isolation curve

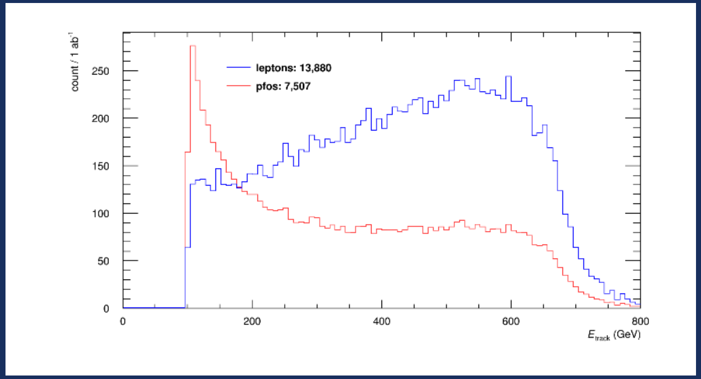


Polar angle distribution

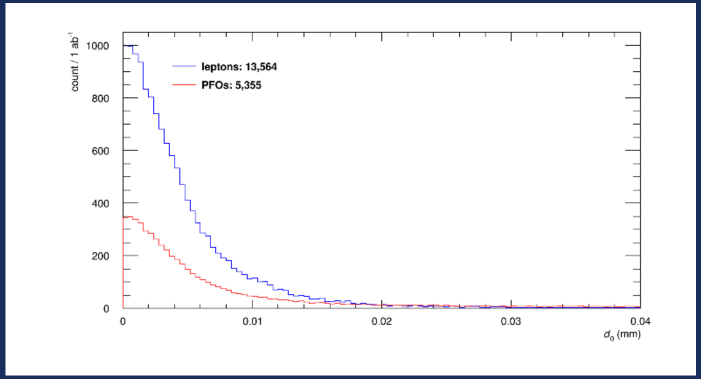




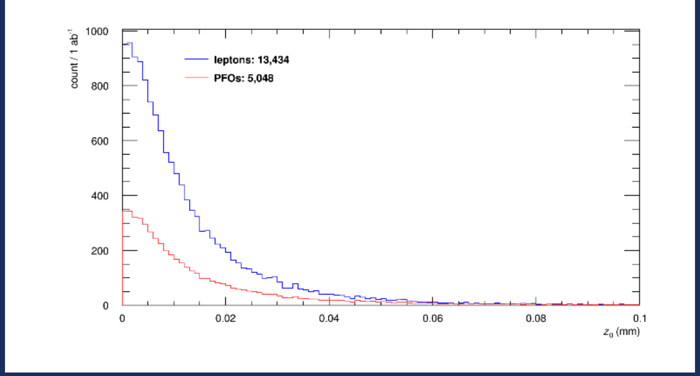
$E_{track} > 100$ GeV



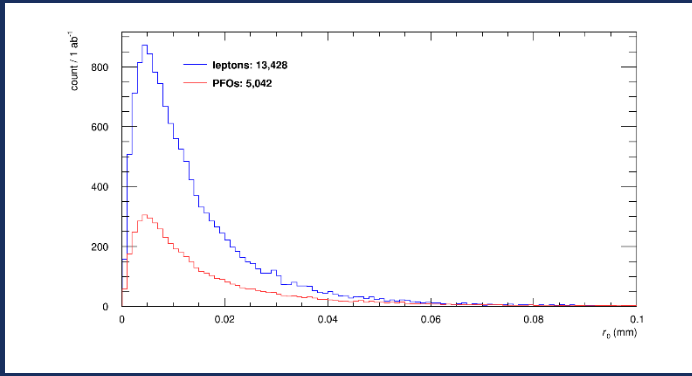
$d_0 < 0.04$ mm



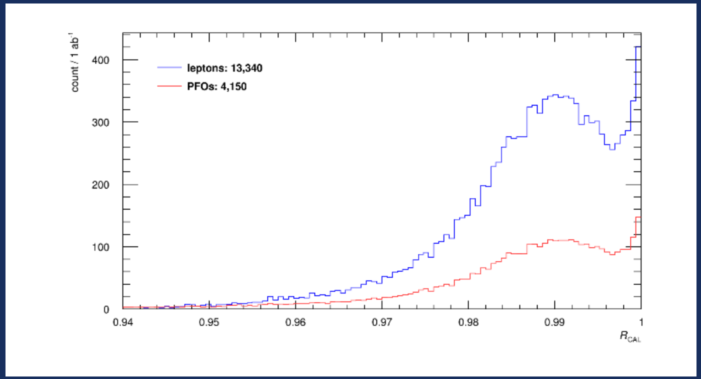
$z_0 < 0.1$ mm



$r_0 < 0.1$ mm



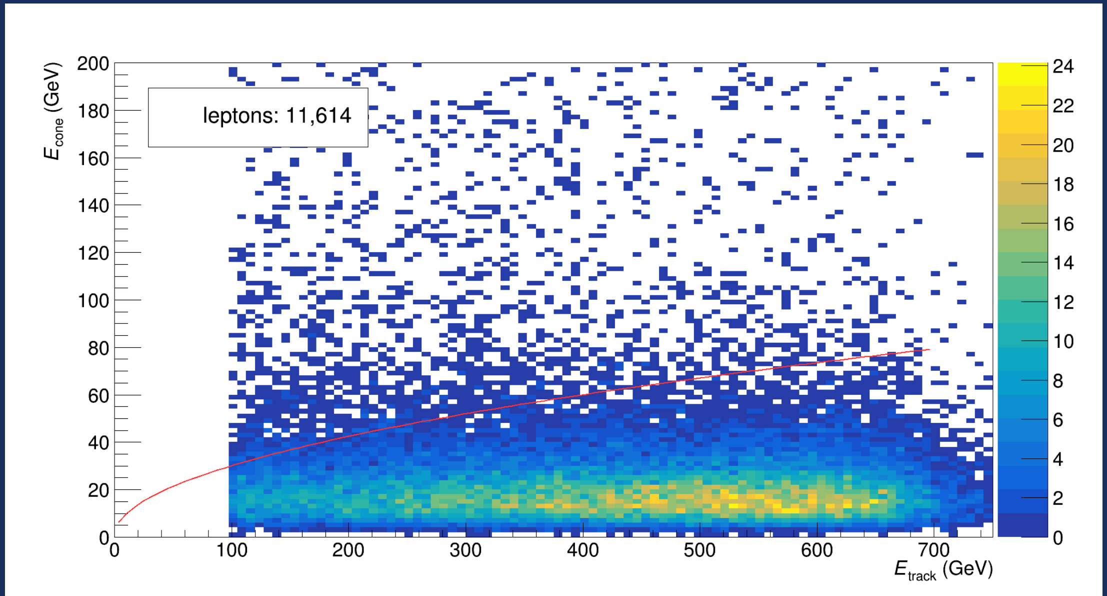
$R_{cal} > 0.94$



1 ab^{-1} at 1.4 TeV

Preselection exercise cont.

- $E_{\text{cone}}^2 < 30\, E_{\text{track}}^2 + 0.01\text{ GeV}\, E_{\text{track}} + 0.01\text{ GeV}^2$



@1.4 TeV @ 1 ab^{-1}	Input	E_{track}	E_{track} && $d_0/z_0/r_0$	E_{track} && $d_0/z_0/r_0$ && R_{CAL}	E_{track} && $d_0/z_0/r_0$ && R_{CAL} && $E_{cone} = f(E_{track})$
Number of ee events in the tracker	N_{ev} = 7,060	N_{ev} = 6,940 (1.7%)	N_{ev} = 6,714 (4.9%)	N_{ev} = 6,670 (5.52%)	N_{ev} = 5,807 (17.7%, *Eff*~82%)

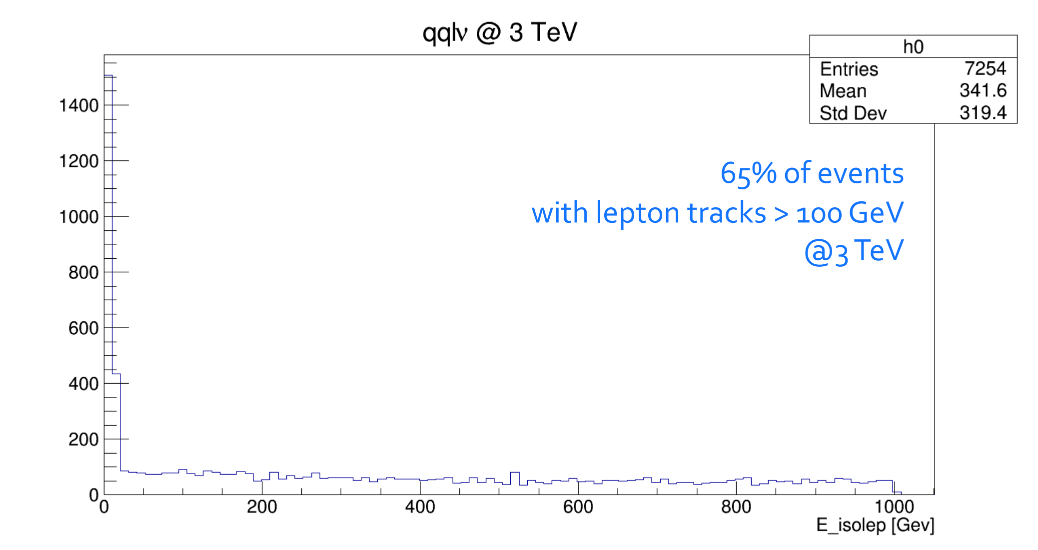
Production request

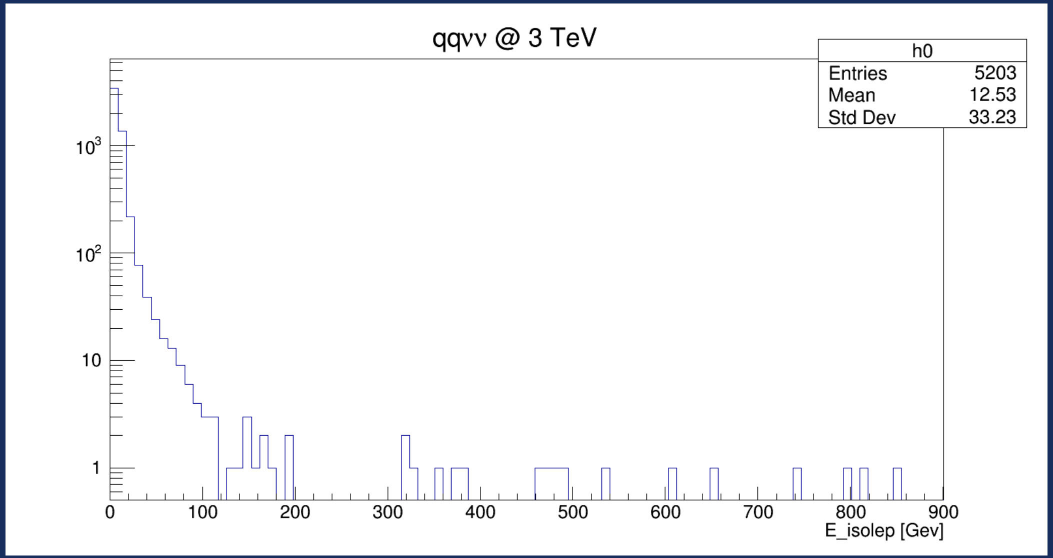
Processes @ 1 TeV, 1 ab-1 ILC	Cross section [fb]	N @ 1 ab-1	Production request
Signal			
$e^+e^- \to He^+e^-, H \to X$ *(2 e + 2 jets)*	21	21 x 10^3	100 000
Background			
1) $e^+e^- \to q\bar{q}l^+l^-$	2.6 x 10^3	2.6 x 10^6	10^6
2) $e^+e^- \to q\bar{q}\nu\nu$	300-400	300 x 10^3	NOT RELEVANT
3) $e^+e^- \to q\bar{q}l\nu$	~ 5 x 10^3	5 x 10^6	10^6
4) $\gamma\gamma \to e^+e^-q\bar{q}$	~ 10^4	10^7	~ 10^6

Conclusion

- Possibility that CP is violated in the Higgs sector raises several intriguing questions (here we quote D. Jeans in our contribution for Snowmass https://www.snowmass21.org/docs/files/summaries/EF/SNOWMASS21-EF1_EF2_DanielJeans-113.pdf) :
  - What is a precision at the different colliders & energies ?
  - What are critical or advantageous detector aspects? (e.g. quark charge identification)
  - How do these measurements all fit together ?
  - What is their relative importance ?
- We have successfully reconstructed ϕ distributions for both Higgs production (ZZ-fusion) and decays (ZZ^*, WW^*)
- Method of the analysis is proposed
- Possible preselection for $e^-e^+ \rightarrow e^-e^+H$ is developed
- Now we need ILC@1 TeV samples of signal and background

BACKUP


qqlν @ 3 TeV
h0
Entries 7254
Mean 341.6
Std Dev 319.4
65% of events
with lepton tracks > 100 GeV
@3 TeV
E_isolep [Gev]


qqνν @ 3 TeV
h0
Entries 5203
Mean 12.53
Std Dev 33.23
E_isolep [Gev]