Determination of the Higgs CP structure in ZZ* decays at 3 TeV CLIC

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INTRODUCTION

- Higgs boson is the only fundamental scalar we know
- Any deviation from that (i.e. being composite or having different spin or CP parity) would be sign of a new physics

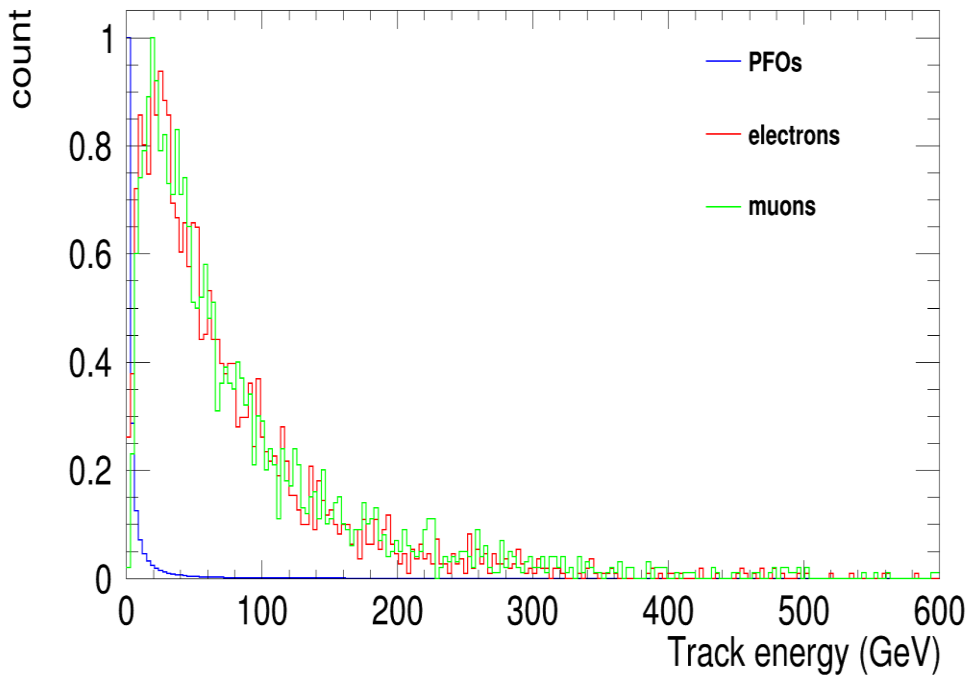
Experimental determination of the Higgs boson properties is currently among the most crucial tasks

- In principle, Higgs (or any other resonance) spin, parity, and, more generally, the tensor structure of the boson couplings can be obtained from the angular and mass distributions of the resonance decay products
- Utilization of the full kinematic information
- ZZ, WW (in the leptonic or semileptonic channel) and $\gamma\gamma$ decays are of particular interest

Lepton colliders, and CLIC in particular at the highest energies, offers excellent statistics and a clean experimental environment for this type of measurement

EVENT SAMPLE

- $H \rightarrow ZZ^* \rightarrow 4\ell$ is the ideal channel due to the fully (and easily) reconstructable kinematics and low backgrounds
- However, in 5 ab^{-1}, only 600 out of $2 \cdot 10^6$ decays (0.3 permille) is signal (at 3 TeV)
- At the first instance we look into semileptonic ZZ* final state where $ZZ^* \rightarrow qq\ell\ell$
- Starting from $2 \cdot 10^6$ Higgs bosons, we end up with ~ 3000 (semileptonic) signal events, considering only μ and e in 5 ab^{-1}.
  - $\sigma(e^+e^- \rightarrow H\nu\nu) \sim 415$ fb
  - $BR(H \rightarrow ZZ^*) = 2.9\%$
  - $BR(Z \rightarrow qq) \approx 70\%$, $BR(Z \rightarrow ll) \approx 10\%$



Lepton and PFO track energy at 3TeV

STRATEGY OF THE ANALYSIS

- Let us assume that Higgs boson is quantum superposition of two states with different CP parities (minimally coupled through higher order operators):

$$H = \cos\alpha \cdot J_0^+ + \sin\alpha \cdot J_0^-$$

where α is the mixing angle. What is a precision (CL, significance) to determine α at 3 TeV CLIC?

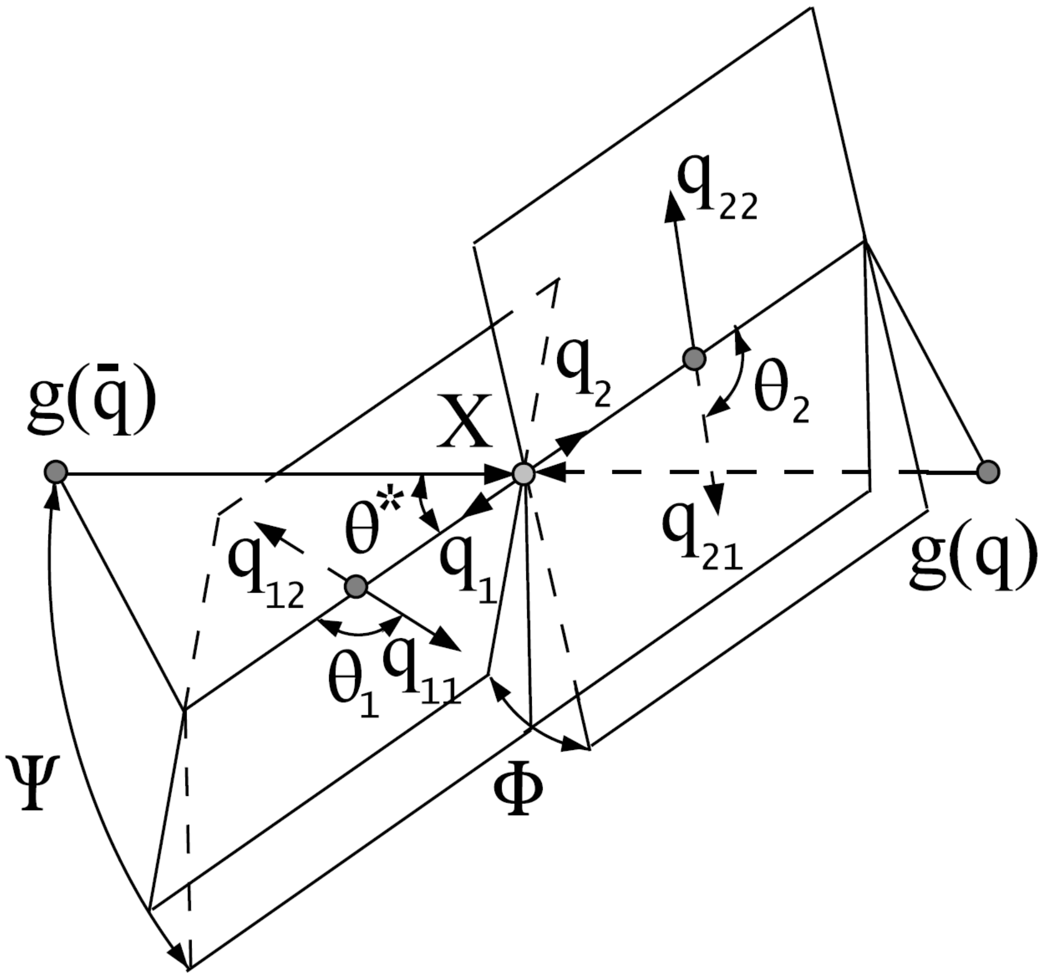
- Firstly, sensitive observables to Higgs CP structure have to be identified
- Signal has to be separated from background (as in our previous analysis for g_{HZZ} at 3 TeV), through the usual steps:
  - Preselection
  - MVA analyses

we are about here

- Sensitive observables have to be fitted on simulated signal and background ⇨ PDF determined
- Pseudodata to be fitted with the combined PDFs to extract α and its uncertainty

EVENT KINEMATICS

- $e^+e^- \to X(q) \to V_1(q_1)\, V_2(q_2)$,
- $V_1 \to f(q_{11})\, f(q_{12})$, $V_2 \to f(q_{21})\, f(q_{22})$ where:
  - $X = H$
  - $V_1 = Z$ (vector boson is on-shell Z boson)
  - $V_2 = Z^*$ (vector boson is off-shell Z boson)
  - q_{ij} - momenta of the final state particle from on-shell (i=1) or off-shell (i=2) Z boson decay into particle (j=1) or antiparticle (j=2)
- Momentum conservation implies:
  - $q_i = q_{i1} + q_{i2}$, $m_i^2 = q_i^2$ and $q = q_1 + q_2$,
- Higgs boson is produced on the mass shell:
  - $q^2 = (q_1 + q_2)^2 = m_X^2$



Two invariant masses m_1 and m_2 and 5 angles: θ^*, Φ, Φ_1, θ_1, θ_2 are 7 observables that fully characterize the kinematics of the process in the Higgs reference frame.

SENSITIVE OBSERVABLES

- On-shell and off-shell Z boson masses m_1 and m_2
- Angles can be measured explicitly knowing momenta of reconstructed fermions
- θ^* is the on-shell Z boson polar angle in the Higgs reference frame:
  $\hat{q}_1 = (sin\theta^* cos\Phi^*, sin\theta^* sin\Phi^*, cos\theta^*)$, where the azimuthal angle Φ^* is arbitrary
- Φ and Φ_1 are two azimuthal angles between 3 planes constructed from the Higgs, Z and Z* decay products, in the Higgs reference frame:

$$\Phi = \frac{\boldsymbol{q}_1 \cdot (\hat{\boldsymbol{n}}_1 \times \hat{\boldsymbol{n}}_2)}{|\boldsymbol{q}_1 \cdot (\hat{\boldsymbol{n}}_1 \times \hat{\boldsymbol{n}}_2)|} \times \cos^{-1}(-\hat{\boldsymbol{n}}_1 \cdot \hat{\boldsymbol{n}}_2),$$

$$\Phi_1 = \frac{\boldsymbol{q}_1 \cdot (\hat{\boldsymbol{n}}_1 \times \hat{\boldsymbol{n}}_{\rm sc})}{|\boldsymbol{q}_1 \cdot (\hat{\boldsymbol{n}}_1 \times \hat{\boldsymbol{n}}_{\rm sc})|} \times \cos^{-1}(\hat{\boldsymbol{n}}_1 \cdot \hat{\boldsymbol{n}}_{\rm sc}),$$

where

$$\hat{\boldsymbol{n}}_1 = \frac{\boldsymbol{q}_{11} \times \boldsymbol{q}_{12}}{|\boldsymbol{q}_{11} \times \boldsymbol{q}_{12}|}, \qquad \hat{\boldsymbol{n}}_2 = \frac{\boldsymbol{q}_{21} \times \boldsymbol{q}_{22}}{|\boldsymbol{q}_{21} \times \boldsymbol{q}_{22}|},$$

$$\hat{\boldsymbol{n}}_{\rm sc} = \frac{\hat{\boldsymbol{n}}_z \times \boldsymbol{q}_1}{|\hat{\boldsymbol{n}}_z \times \boldsymbol{q}_1|} \text{ and } \hat{\boldsymbol{n}}_z = (0, 0, 1).$$

- Angles θ_1 and θ_2 are defined in the Z and Z* reference frame respectively:

$$\hat{\boldsymbol{n}}_1 = \frac{\boldsymbol{q}_{11} \times \boldsymbol{q}_{12}}{|\boldsymbol{q}_{11} \times \boldsymbol{q}_{12}|}, \qquad \hat{\boldsymbol{n}}_2 = \frac{\boldsymbol{q}_{21} \times \boldsymbol{q}_{22}}{|\boldsymbol{q}_{21} \times \boldsymbol{q}_{22}|}$$

SENSITIVITY TO HIGGS (SCALAR) SPIN-PARITY

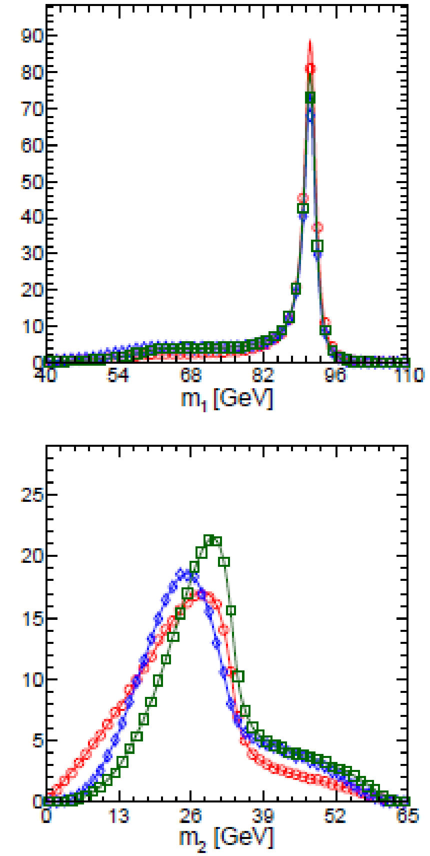
It is possible to distinguish between different CP states of a scalar;

It is possible to probe spin other than 0;

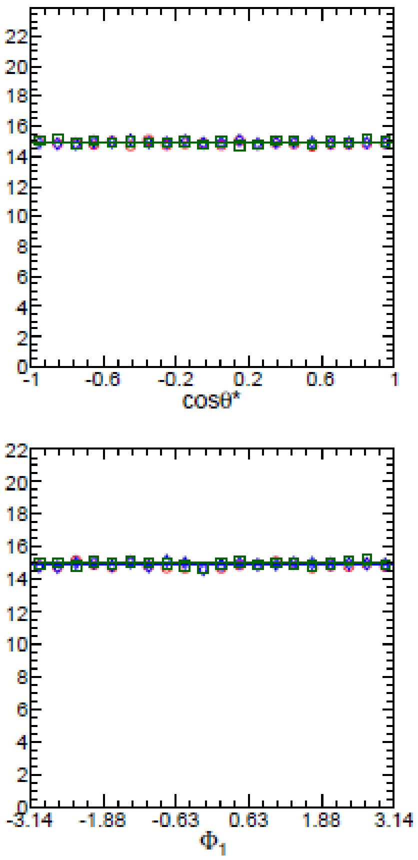
This also holds for any other (new?) resonance X.

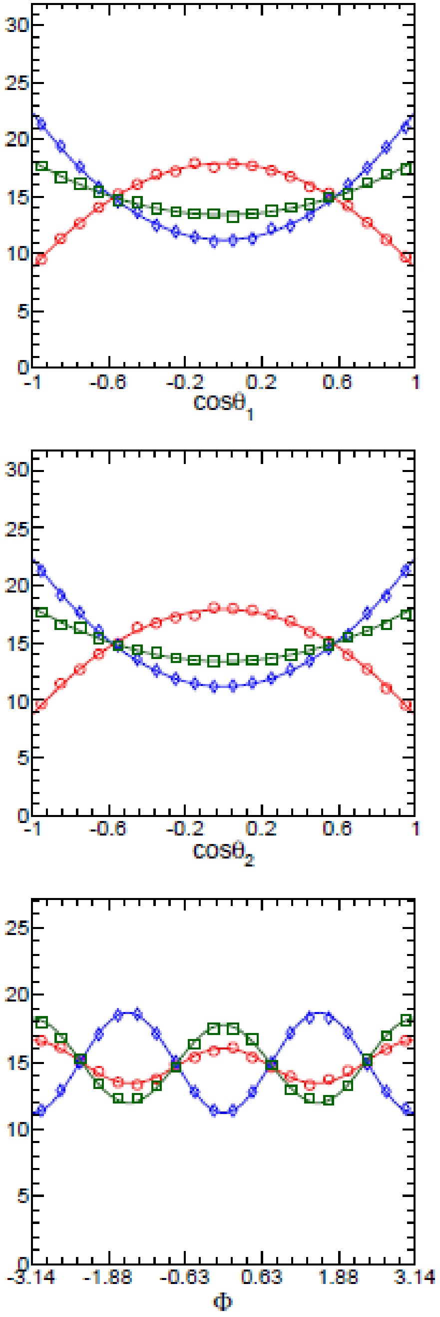
- ○ J_m^+ (red circles),
- □ J_h^+ (green squares),
- ♦ J_h^- (blue diamonds)

index m - minimal couplings
index h - couplings with higher-dimension operators

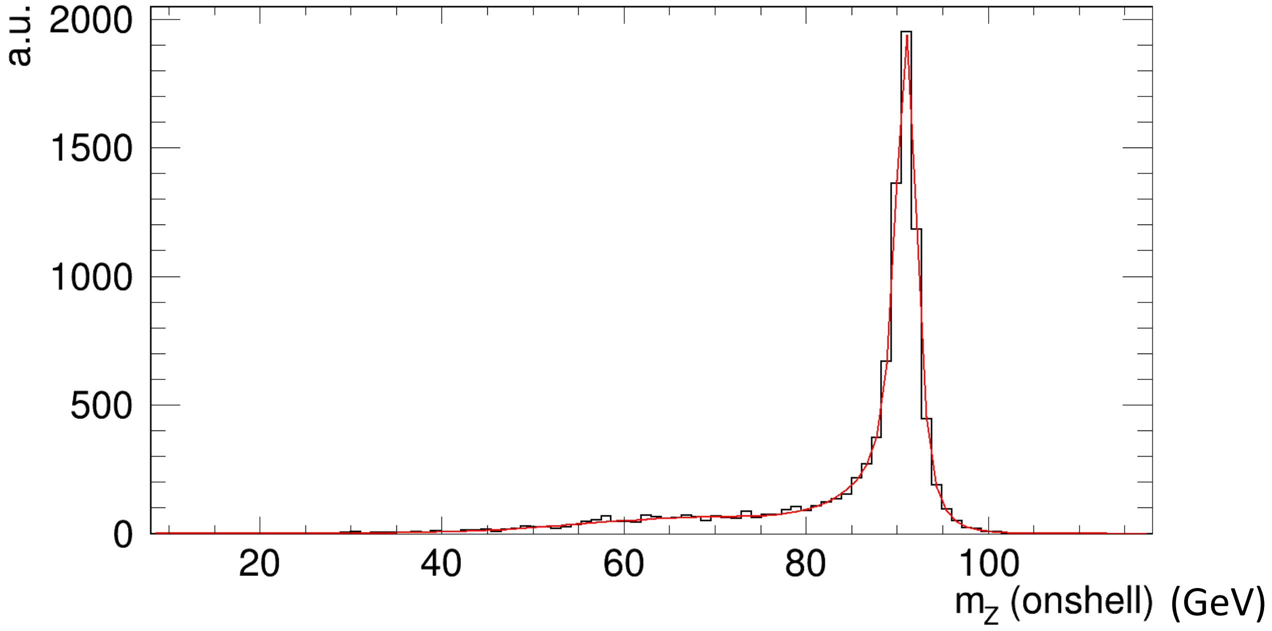


[1] S. Bolognesi et al., *On the spin and parity of a single-produced resonance at the LHC*, arXiv:1208.4018 [hep-ph]





RECONSTRUCTION OF SENSITIVE OBSERVABLES



- Reconstruction of sensitive observables is performed at the generated level with ~ 9200 signal events in 2.29 ab^{-1}
- Initial form of PDFs is determined

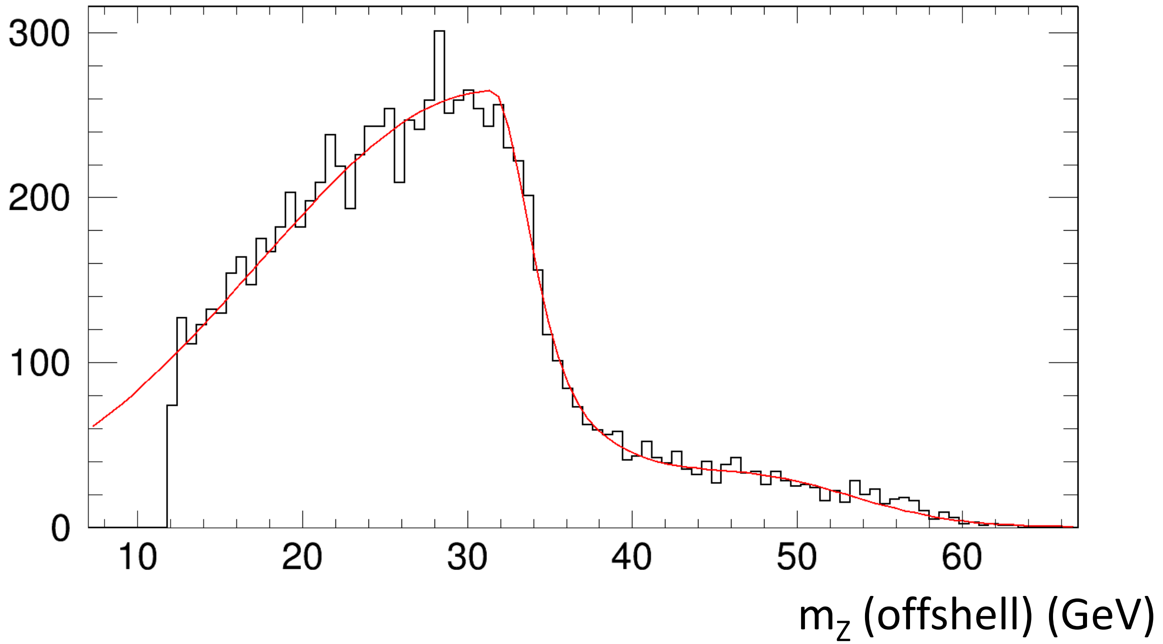
Entries	9234
Mean	85.14
Std Dev	11.59
χ^2 / ndf	77.99 / 70
p0	1462 ± 60.4
p1	472.2 ± 48.1
p2	1.073 ± 0.029
p3	0.1409 ± 0.0057
p4	0.1033 ± 0.0214
p5	4.991 ± 0.471
p6	1.817 ± 0.122
p7	90.98 ± 0.03
p8	56.97 ± 2.98
p9	12.54 ± 0.60
p10	67.25 ± 1.10

$$f = p_0^2 \cdot f_{flat} + p_1^2 \cdot f_{exp} + p_8^2 \cdot gaus \longrightarrow gaus = p_8 \cdot \exp(-0.5 \cdot \left(\frac{x - p_9}{p_{10}}\right)^2)$$

$$\begin{cases} f_{flat} = \exp\frac{(x-p_7)^2}{2\cdot p_2^2 + p_3\cdot(x-p_7)^2}, \text{ for x < 91 GeV} \\ f_{flat} = \exp\frac{(x-p_7)^2}{2\cdot p_2^2 + p_4\cdot(x-p_7)^2}, \text{ for x > 91 GeV} \end{cases}$$

$$\begin{cases} f_{exp} = \exp\left(-\frac{(x-p_7)^2}{2\cdot p_2^2 + p_5\cdot|x-p_7|}\right), \text{ for x < 91 GeV} \\ f_{exp} = \exp\left(-\frac{(x-p_7)^2}{2\cdot p_2^2 + p_6\cdot|x-p_7|}\right), \text{ for x > 91 GeV} \end{cases}$$

RECONSTRUCTION OF SENSITIVE OBSERVABLES



χ^2 / ndf	91.1 / 76
p0	124.4 ± 22.3
p1	139.9 ± 22.6
p2	14.16 ± 0.46
p3	2.058 ± 0.334
p4	2.9e−09 ± 2.3e+00
p5	5.155 ± 1.125
p6	31.53 ± 0.34
p7	24.09 ± 4.36
p8	5.993 ± 0.652
p9	47.96 ± 1.14

$$f = p_0 \cdot gaus1 + p_1 \cdot \mathrm{exponential} + p_7 \cdot gaus2$$

$$\mathrm{gaus2} = \exp\left(-0.5 \cdot \left(\frac{x - p_9}{p_8}\right)^2\right)$$

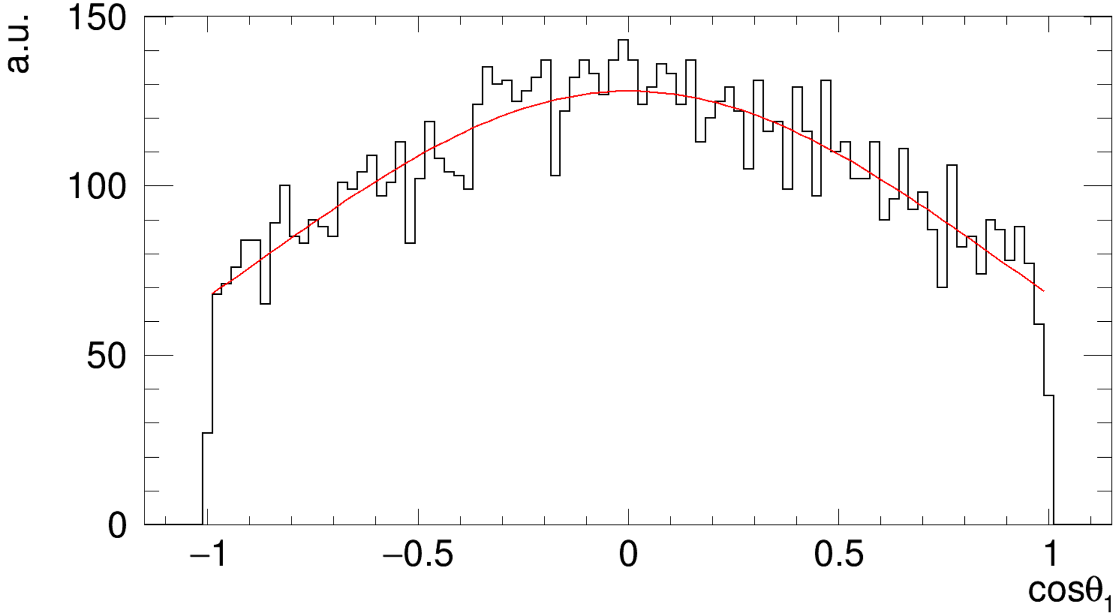
$$gaus1 = \exp\left(-0.5 \cdot \left(\frac{x - p_6}{p_2}\right)^2\right), \text{ for x < 91 GeV}$$

$$gaus1 = \exp\left(-0.5 \cdot \left(\frac{x-p_6}{p_3}\right)^2\right), \text{ for x > 91 GeV}$$

$$f_{exp} = \exp\left(-\frac{(x-p_6)^2}{2 \cdot p_2^2 + p_4 \cdot |x-p_6|}\right), \text{ for x < 91 GeV}$$

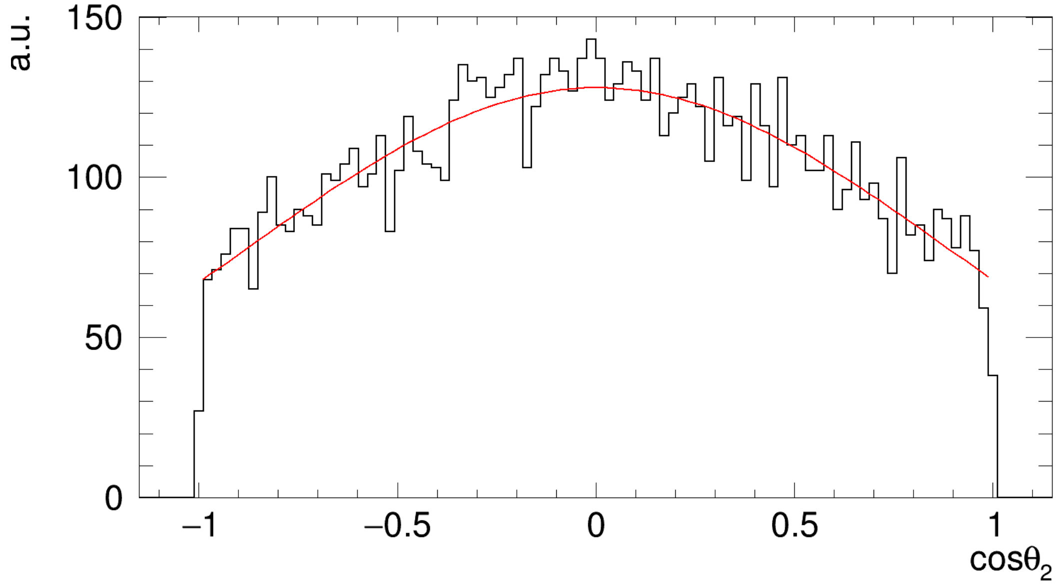
$$f_{exp} = \exp\left(-\frac{(x-p_6)^2}{2 \cdot p_3^2 + p_5 \cdot |x-p_6|}\right), \text{ for x > 91 GeV}$$

RECONSTRUCTION OF SENSITIVE OBSERVABLES



$$f = 128 \cdot \exp(-0.5 \cdot \left(\frac{x - p_1}{p_2}\right)^2)$$

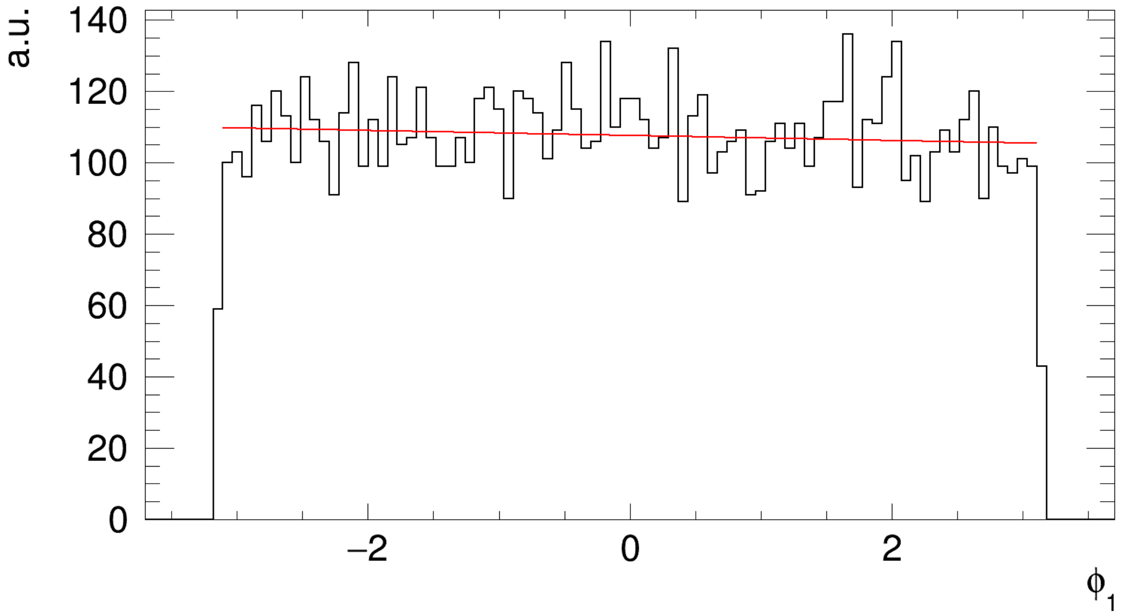
Entries	9234
Mean	0.003125
Std Dev	0.5298
χ^2 / ndf	78.99 / 83
Constant	128 ± 1.9
Mean	0.004191 ± 0.015670
Sigma	0.8853 ± 0.0271

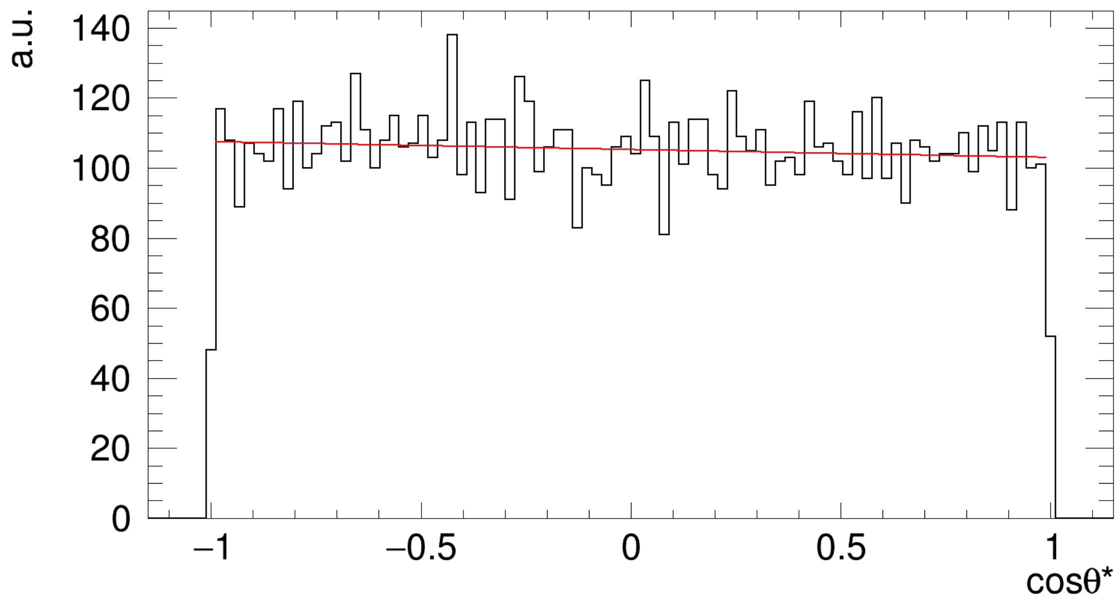


$$f = 125.9 \cdot \exp(-0.5 \cdot \left(\frac{x - p_1}{p_2}\right)^2)$$

Entries	9234
Mean	0.001819
Std Dev	0.5337
χ^2 / ndf	87.29 / 83
Constant	125.9 ± 1.9
Mean	0.006578 ± 0.017006
Sigma	0.9249 ± 0.0306

- Φ_1 and *cos* θ^* distributions are flat for scalar resonance.





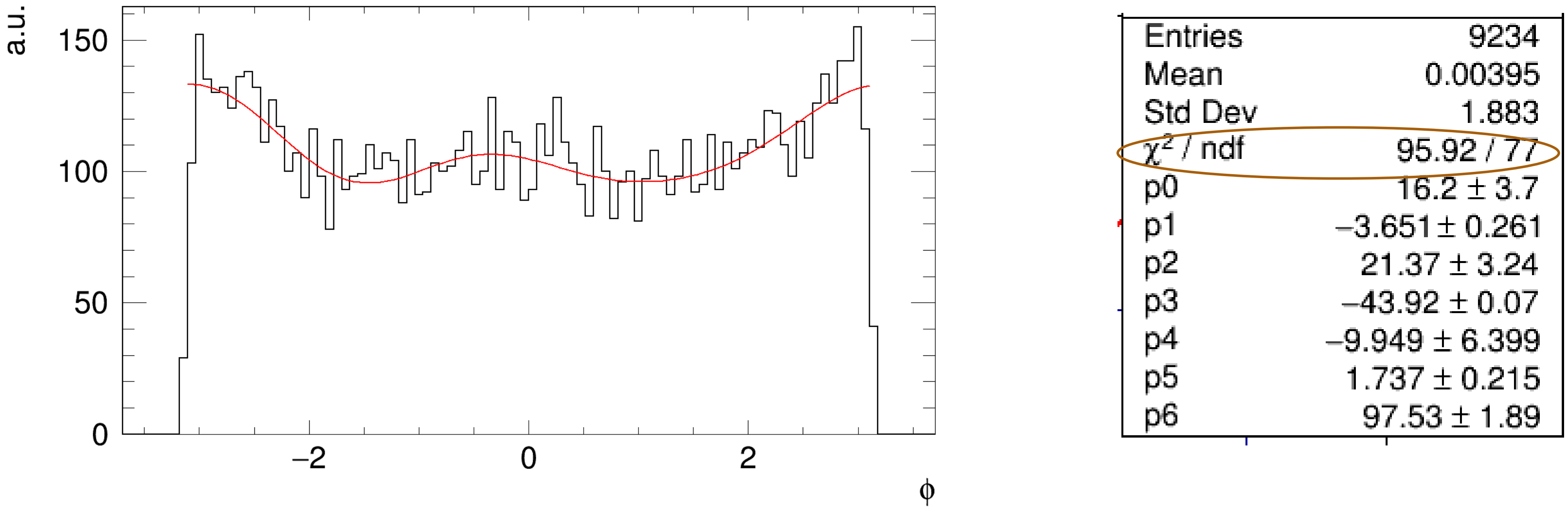
$$f = p_0 \cdot x + p_1$$

Entries	9234
Mean	−0.02388
Std Dev	1.8
χ^2 / ndf	90.37 / 82
p0	−0.703 ± 0.626
p1	107.6 ± 1.1

$$f = p_0 \cdot \exp(-0.5 \cdot \left(\frac{x - p_1}{p_2}\right)^2$$

Entries	9234
Mean	−0.00712
Std Dev	0.5765
χ^2 / ndf	76.85 / 84
p0	−2.262 ± 1.937
p1	105.3 ± 1.1

RECONSTRUCTION OF SENSITIVE OBSERVABLES



$$f = p_0 \cdot \cos(x + p_1) + p_2 \cdot cos^2(x + p_3) + p_4 \cdot cos^3(x + p_5) + p_6$$

- Possible reconstruction (detector) effects:
  - p_T uncertainties Helicity angles are defined in Lorentz frames which differ from the lab. frame, they are affected by uncertainties in all track parameters and, most importantly, by p_T
  - Non-uniform reconstruction efficiencies (within detector acceptance)

LIST OF BACKGROUND PROCESSES

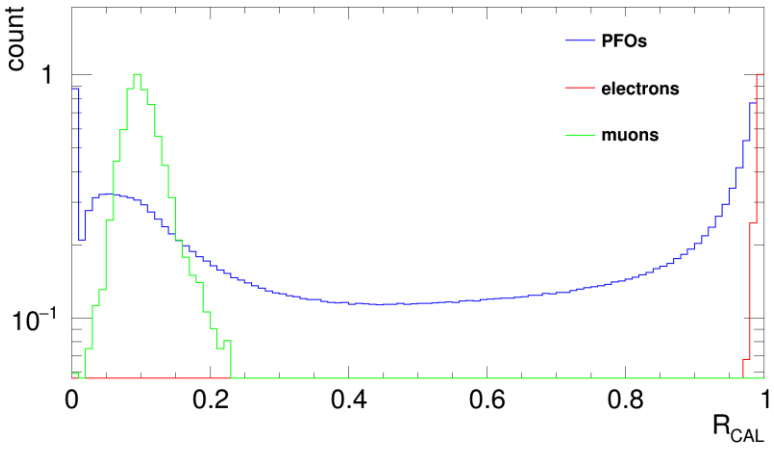
Signal process	**σ [fb]**	**N@5ab^{-1}**
$e^+e^- \to H\nu_e\bar{\nu}_e, H \to ZZ^*, ZZ^* \to q\bar{q}l^+l^-$	1.2	5.9 x 10^3
Background		
$e^+e^- \to H\nu_e\bar{\nu}_e, H \to WW, WW \to q\bar{q}q\bar{q}$	43.5	2.18 x 10^5
$e^+e^- \to H\nu_e\bar{\nu}_e, H \to b\bar{b}$	232.8	1.162 x 10^6
$e^+e^- \to H\nu_e\bar{\nu}_e, H \to c\bar{c}$	11.7	5.8 x 10^4
$e^+e^- \to H\nu_e\bar{\nu}_e, H \to gg$	35.28	1.76 x 10^5
$e^+e^- \to H\nu_e\bar{\nu}_e, H \to others$	91.36	4.6 x 10^5
$e^+e^- \to q\bar{q}l^+l^-$	3319.6	16.598 x 10^6
$e^+e^- \to q\bar{q}l\nu$	5560.9	27.804 x 10^6
$e^+e^- \to q\bar{q}\bar{\nu}_e\nu_e$	1317.5	6.587 x 10^6
$\gamma\gamma \to q\bar{q}l^+l^-$	20293.4	101.5 x 10^6
$\gamma\gamma \to q\bar{q}$	112038.6	560.2 x 10^6
$e^\pm\gamma \to q\bar{q}e$	20661	103.3 x 10^6
$e^\pm\gamma \to q\bar{q}\nu$	36832.4	184.2 x 10^6

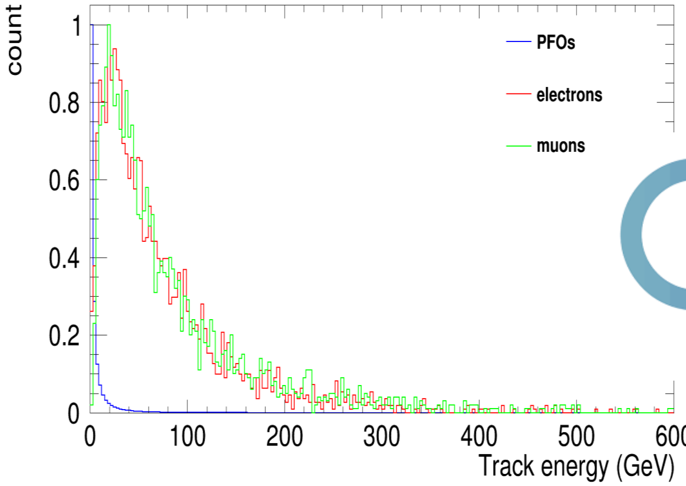
LEPTON ISOLATION PRESELECTION

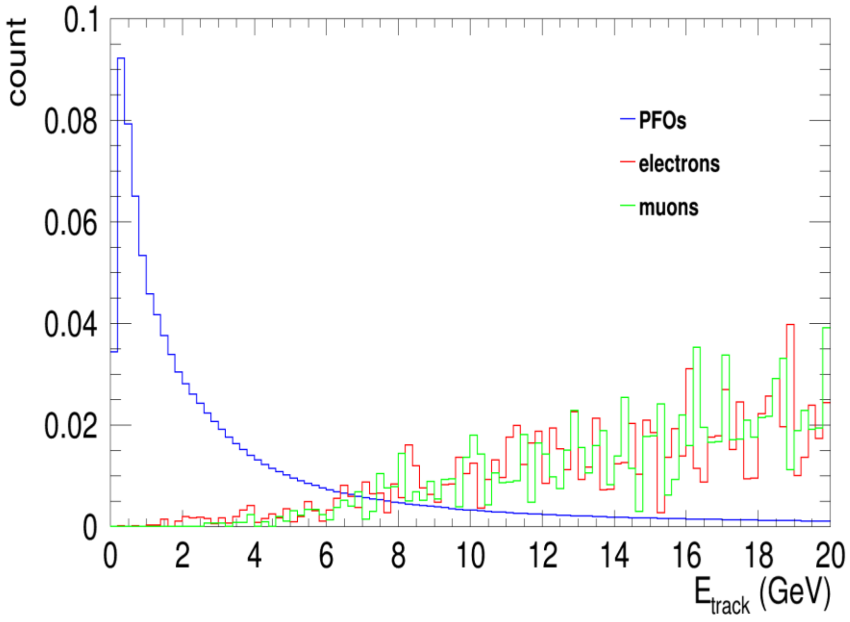
- Find exactly two isolated leptons per event:
  - $E_{track} > 6$ GeV
  - $E_{cone} < 2E_{track}^2 + 0.2\ \text{GeV}E_{track} + 50\ \text{GeV}^2$
  - ECAL depositions:
    $R_{CAL} = 0.02 - 0.35$ and $R_{CAL} > 0.94$

Lepton isolation efficiency ~ 87% (H→ZZ* BR measurement), while the signal is preselected with the efficiency ~61%

Room for some fine tuning (improvements)

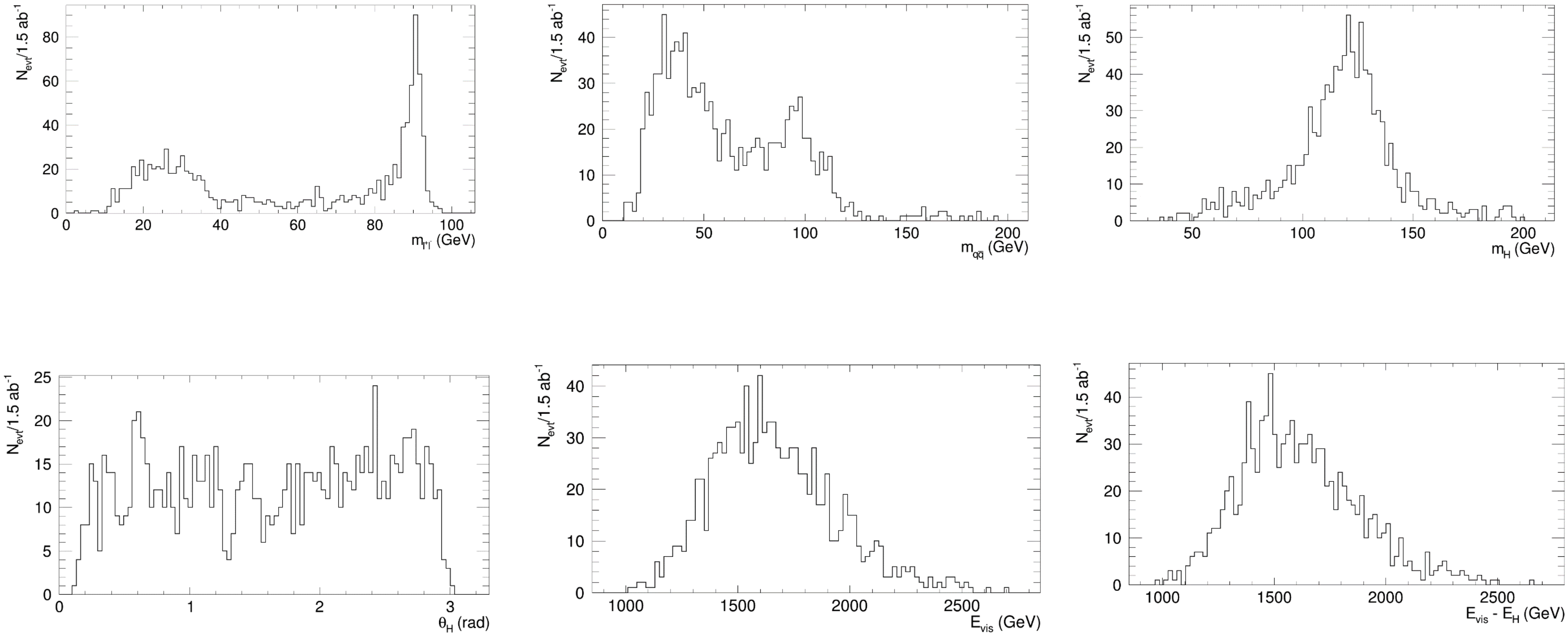


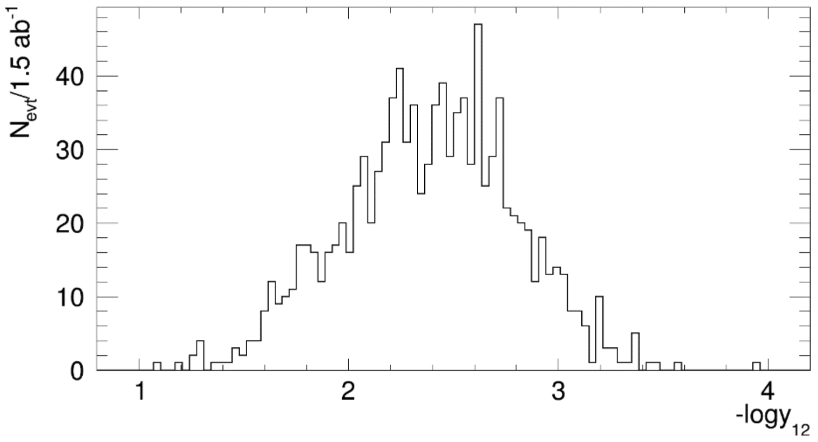


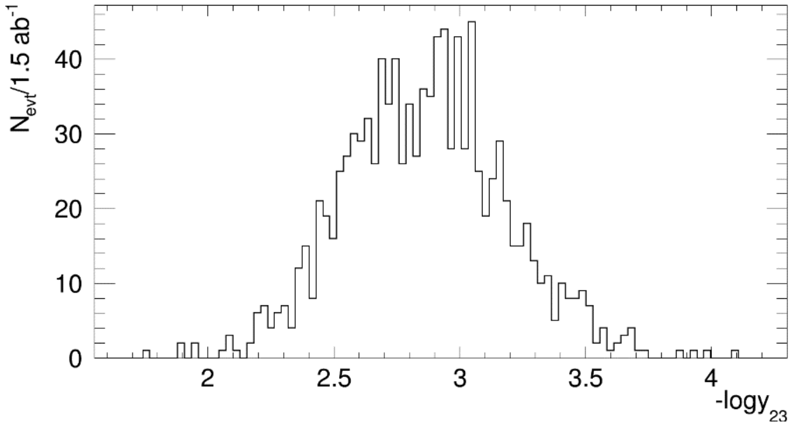


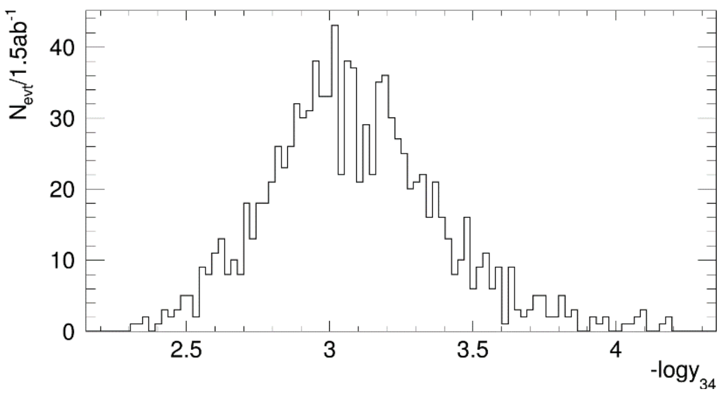
MVA VARIABLES IDENTIFIED

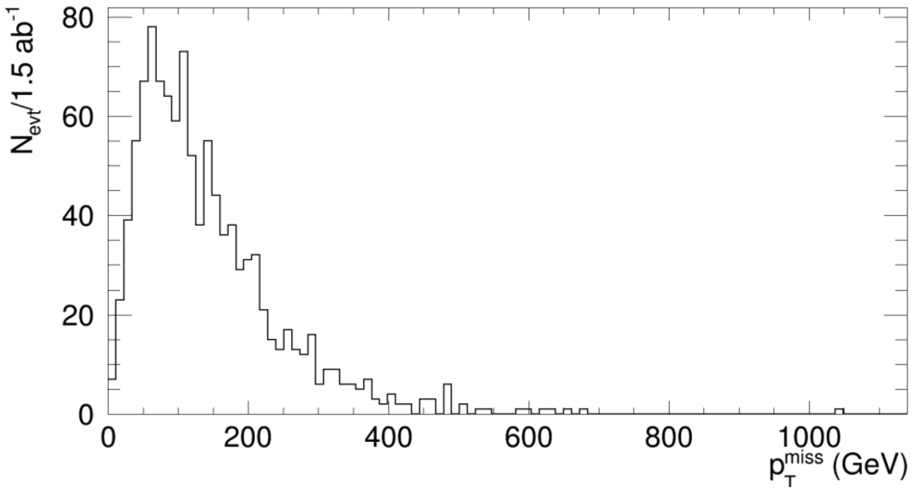
- $m_{l^+l^-}, m_{q\bar{q}}, m_H$ - mass of pair of leptons, quarks and mass of Higgs candidate
- $E_{vis}, E_{vis} - E_H$ - visible energy of event, difference between visible and the Higss energy
- $-\log y_{34}, -\log y_{23}, -\log y_{12}$ - jet transition variables
- $P(b)^{jet_1}, P(b)^{jet_2}$ - b-tag probability of the jets
- $P(c)^{jet_1}, P(c)^{jet_2}$ - c-tag probability of the jets
- p_T^{miss} - missing transverse momentum
- θ_H - polar angle of the Higgs candidate
- N_{PFO} - number of particle-flow objects in the event

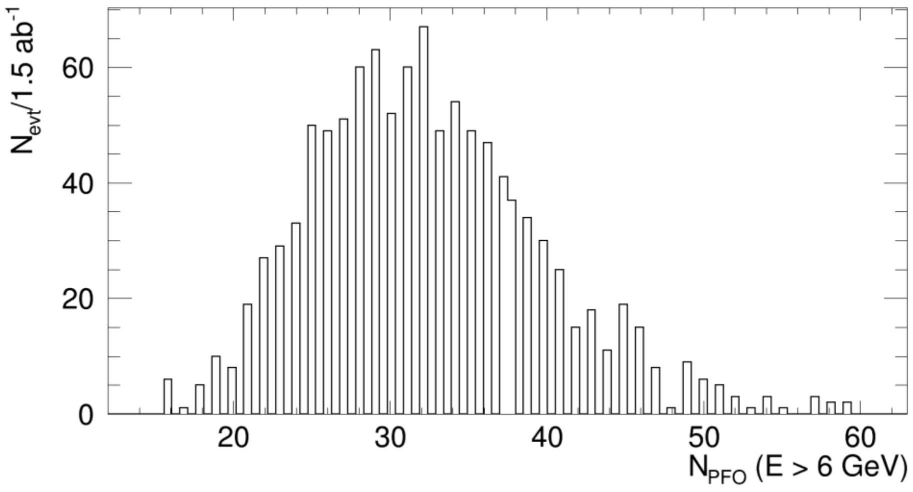

N_evt/1.5 ab^-1
m_l+l- (GeV)
m_qq̄ (GeV)
m_H (GeV)
θ_H (rad)
E_vis (GeV)
E_vis - E_H (GeV)

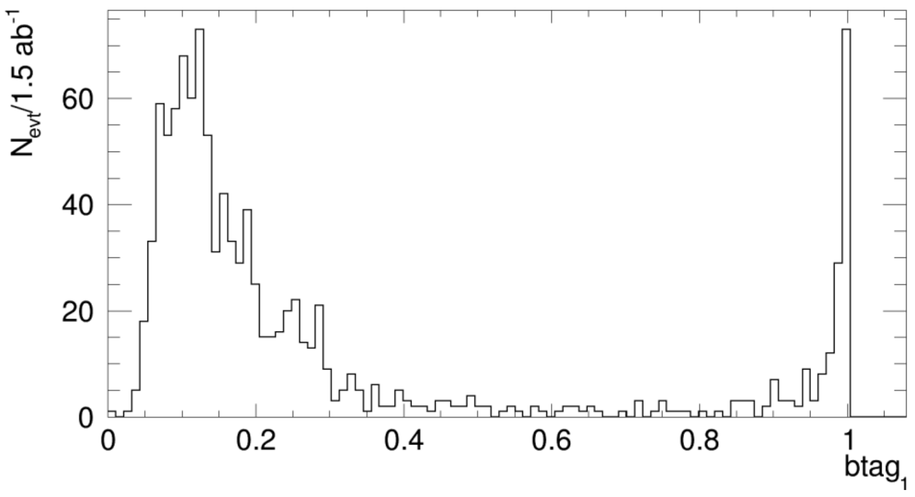

$N_{evt}/1.5\ ab^{-1}$
$-logy_{12}$


$N_{evt}/1.5\ ab^{-1}$
$-logy_{23}$

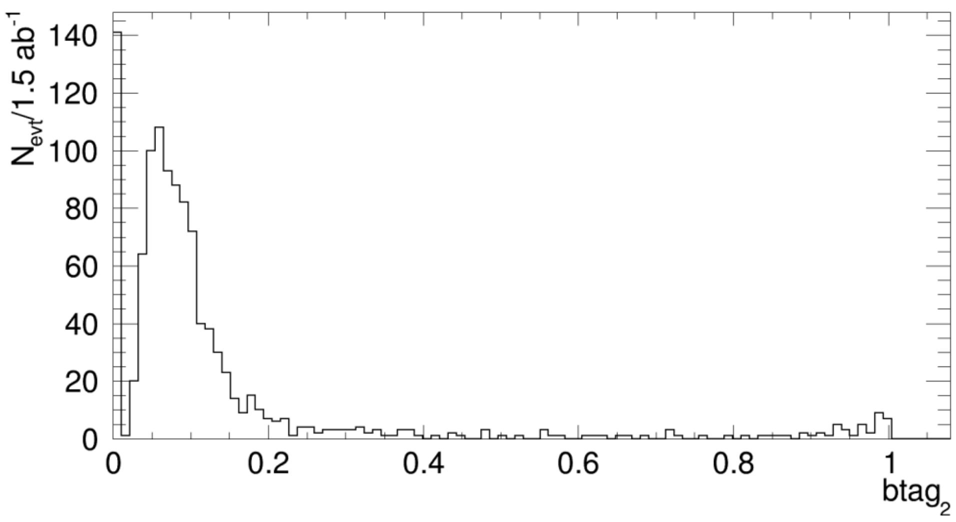

$N_{evt}/1.5ab^{-1}$
$-logy_{34}$


$N_{evt}/1.5\ ab^{-1}$
p_T^{miss} (GeV)

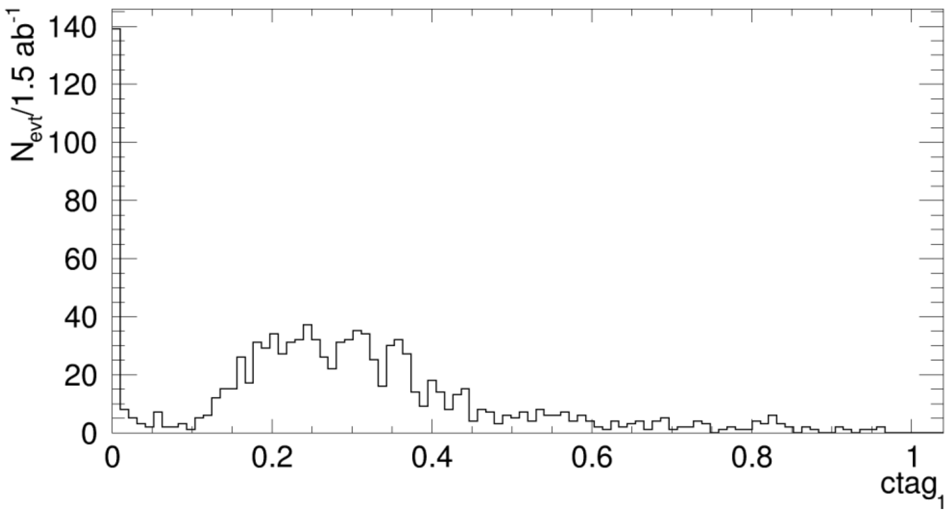

$N_{evt}/1.5\ ab^{-1}$
N_{PFO} (E > 6 GeV)



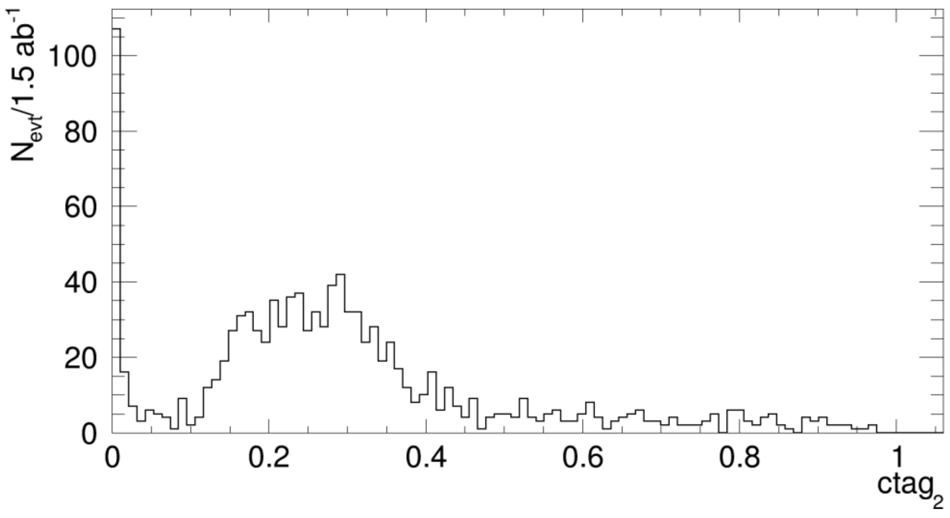
N_{evt}/1.5 ab^{-1}
0
20
40
60
0
0.2
0.4
0.6
0.8
1
$btag_1$



N_{evt}/1.5 ab^{-1}
0
20
40
60
80
100
120
140
0
0.2
0.4
0.6
0.8
1
$btag_2$



N_{evt}/1.5 ab^{-1}
0
20
40
60
80
100
120
140
0
0.2
0.4
0.6
0.8
1
$ctag_1$



N_{evt}/1.5 ab^{-1}
0
20
40
60
80
100
0
0.2
0.4
0.6
0.8
1
$ctag_2$

SUMMARY

- Possibility of full kinematics reconstruction in H→ZZ* decay enables measurement of the Higgs CP structure
- If Higgs boson is a quantum superposition (mixture) of different CP states, mixing angle can determined from the sensitive helicity angles and Z(Z*) masses
- We have reconstructed the sensitive observables and prepare everything to perform signal and background separation in MVA and to fit the remain pseudo-data including both Higgs CP states

BACKUP

TABLE III: Expected separation significance $\mathcal{S}$ (Gaussian σ) between the SM Higgs boson scenario (0^+_m) and 0^- or 2^+_m hypotheses in the analyzed channels and combined, for the scenario corresponding approximately to 35 fb^{-1} of integrated luminosity at one LHC experiment.

scenario	$X \to ZZ$	$X \to WW$	$X \to \gamma\gamma$	combined
0^+_m vs background	7.1	4.5	5.2	9.9
0^+_m vs 0^-	4.1	1.1	0.0	4.2
0^+_m vs 2^+_m	2.2	2.5	2.5	4.2