Investigating CP-violation in General hZZ Coupling in $h \to ZZ \to 2e2\mu$ at CMS on LHC.

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Outline

- Model
- Methodology
- MC Samples
- Selection
- Results

The results presented here are preliminary and can't be propagated before they get approved by the CMS collaboration.

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Model

- An effective model of hZZ coupling with scalar ($g^{\mu\nu}$) and pseudoscalar ($\epsilon^{\mu\nu\rho\sigma}k_{1\rho}k_{2\sigma}$) terms (A.Skjold, P.Osland Phys. Lett. B**329**, 305 (1994), implemented in `Pythia`):

  $$C_{hZZ} \sim m_Z^2 g^{\mu\nu} + \eta \cdot \epsilon^{\mu\nu\rho\sigma}k_{1\rho}k_{2\sigma}$$

  where $k_1=(q_1+q_2)$, $k_2=(q_3+q_4)$, $q_{i=1\ldots4}$ momenta of Z^0s and leptons;
  η describes deviation from SM (scalar $\eta=0$, pseudoscalar $\eta=+\infty$, CP-violation $\eta\neq 0,+\infty$).

- Differential cross-section:

  $$d\sigma(\eta) \sim (\mathcal{H} + \eta\cdot\mathcal{V} + \eta^2\cdot\mathcal{A})/(1+\eta+\eta^2)$$

  where:
  – scalar: $\mathcal{H} = (1+4g_V^2g_A^2)(q_1\cdot q_3)(q_2\cdot q_4) + (1-4g_V^2g_A^2)(q_1\cdot q_4)(q_2\cdot q_3)$
  – mixing term:

  $$\mathcal{V} = -\frac{1}{m_Z^2}\epsilon_{\mu\nu\rho\sigma}q_1^\mu q_2^\nu q_3^\rho q_4^\sigma[\,(1+4g_V^2g_A^2)\{(q_1\cdot q_3)+(q_2\cdot q_4)\} \\ -(1-4g_V^2g_A^2)\{(q_1\cdot q_4)+(q_2\cdot q_3)\}\,]$$

  – pseudoscalar:

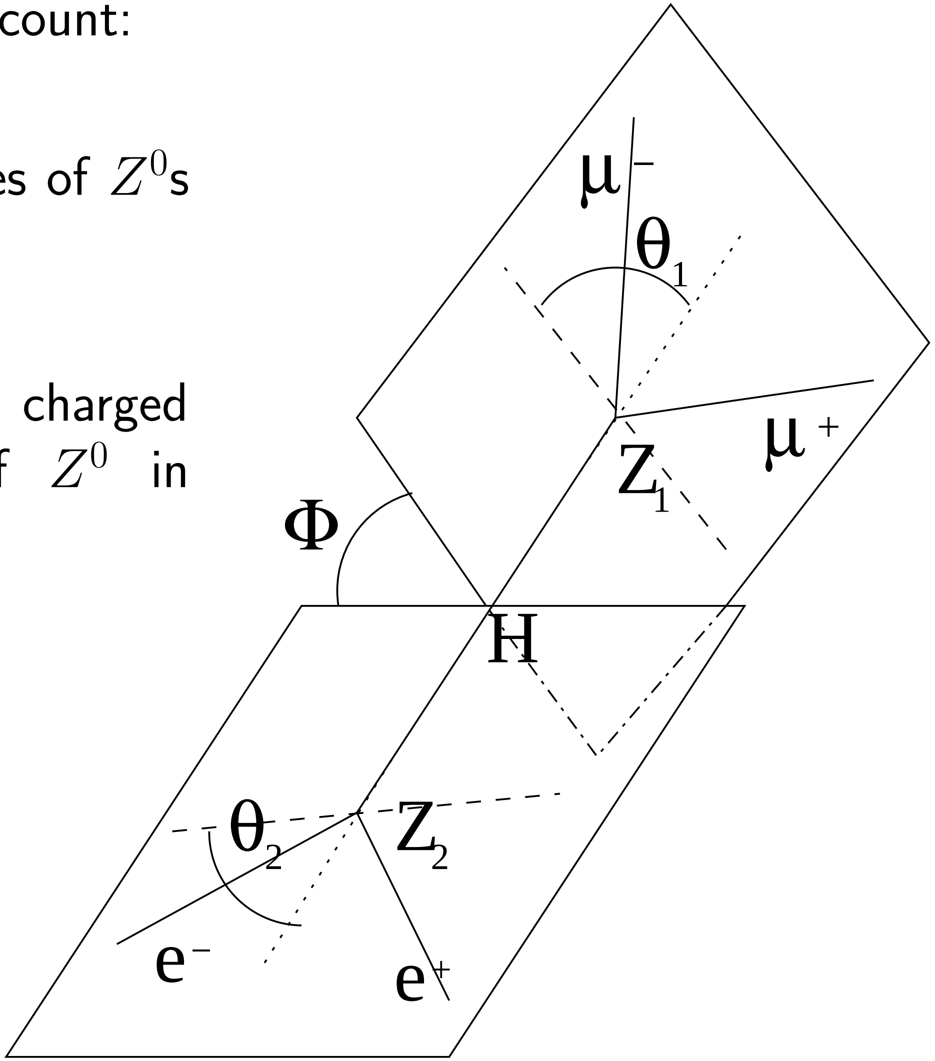
  $$\mathcal{A} = \frac{1}{m_Z^4}\{-2[(q_1\cdot q_3)(q_2\cdot q_4)+(q_1\cdot q_4)(q_2\cdot q_3)]^2 - 2(q_1\cdot q_2)^2(q_3\cdot q_4)^2 \\ +(q_1\cdot q_2)(q_3\cdot q_4)[\,\{(q_1\cdot q_3)+(q_2\cdot q_4)\}^2+\{(q_1\cdot q_4)+(q_2\cdot q_3)\}^2 \\ +4g_V^2g_A^2\{(q_1\cdot q_3)-(q_1\cdot q_4)+(q_2\cdot q_3)-(q_2\cdot q_4)\} \\ \{(q_1\cdot q_3)+(q_1\cdot q_4)-(q_2\cdot q_3)-(q_2\cdot q_4)\}\,]\}$$

Methodology: definition of observables

- Angular distributions distinguish between states with different η's
- Two distributions taken in to account:

– Plane angle ϕ
measured between decay planes of Z^0s in the higgs rest frame.

– Cosine of polar angle $\cos\theta$
measured between negatively charged lepton and the direction of Z^0 in the Z^0 boson rest frame.



Methodology: determination of η

- Method: maximization of likelihood function

$$\mathcal{L}(\eta,R) \equiv -2 \sum_{x_i \in data} \log \mathcal{Q}(\eta,R;\ x_i)$$

where

$$\mathcal{Q}(\eta,R;\ x_i) \equiv R \cdot \mathcal{PDF}_S(\eta;\ x_i) + (1-R) \cdot \mathcal{PDF}_B(x_i)$$

where
R – fraction of signal in data sample (1^{st} parameter of fit),
$\mathcal{PDF}_B$ and $\mathcal{PDF}_S(\eta)$ – probability density functions for background and signal:

$$\mathcal{PDF}_B \equiv \mathcal{P}_B^M \cdot \mathcal{P}_B^\phi \cdot \mathcal{P}_B^{\cos\theta}$$

$$\mathcal{PDF}_S(\eta) \equiv \mathcal{P}_S^M \cdot (\mathcal{P}_S^\phi \cdot \mathcal{P}_S^{\cos\theta})(\eta)$$

where
$\mathcal{P}^M$, $\mathcal{P}^\phi$, $\mathcal{P}^{\cos\theta}$ – probability density functions for $m_{4\ell}$, ϕ and $\cos\theta$ respectively obtained by MC simulation.

Methodology: determination of η (cont.)

- Definition of signal part of $\mathcal{Q}$-function according to expression for $d\sigma(\eta)$:

$$\mathcal{P}_S^{\phi} \cdot \mathcal{P}_S^{\cos\theta}(\eta) \equiv (\mathcal{H} + \eta \cdot \mathcal{V} + \eta^2 \cdot \mathcal{A})/(1 + \eta + \eta^2)$$

where
– $\mathcal{H} \equiv \mathcal{P}_H^{\phi} \cdot \mathcal{P}_H^{\cos\theta}$ and $\mathcal{A} \equiv \mathcal{P}_A^{\phi} \cdot \mathcal{P}_A^{\cos\theta}$ are PDFs for scalar (H) and pseudoscalar (A)

– $\mathcal{V}$ is normalized angle distribution for mixing term (V), but it isn't PDF (isn't positive) thus it can't be simulated separately

- Determination of $\mathcal{V}$ from PDF for $\eta = 1$ ($\mathcal{J}$)

$$\mathcal{J} \equiv \mathcal{P}_S^{\phi} \cdot \mathcal{P}_S^{\cos\theta}(\eta = 1) = (\mathcal{H} + \mathcal{V} + \mathcal{A})/3$$

$$\Longrightarrow \mathcal{V} = 3\,\mathcal{J} - \mathcal{H} - \mathcal{A}$$

and finally:

$$\mathcal{P}_S^{\phi} \cdot \mathcal{P}_S^{\cos\theta}(\eta) \equiv [(1 - \eta) \cdot \mathcal{H} + \eta \cdot 3\,\mathcal{J} + (\eta^2 - \eta) \cdot \mathcal{A}]/(1 + \eta + \eta^2)$$

MC samples

- Signal $h \rightarrow ZZ \rightarrow 2e2\mu$:
  - Samples generated for three masses above ZZ threshold m_h=200, 300, 400 GeV
  - Samples used for PDFs (scalar (H), pseudoscalar (A) and η=1 (J)) – 10k. evts.
  - For CP-violating case samples with η=0.1, 0.4, 4 – 5k. evts.
- Background:
  - $ZZ^* \rightarrow 2e2\mu$ – 20k. evts.
  - $t\bar{t} \rightarrow 2e2\mu$ – 48k. evts.
  - $Zb\bar{b} \rightarrow 2e2\mu$ – 4k. evts.
- All samples generated with low-lumi pile-up ($\sim$3.5 evts./evt.).
- Numbers of generated events correspond to events after "detector acceptance" preselection:
  $-2e$ with p_t>5 GeV & η<2.7
  -2μ with p_t>3 GeV & η<2.5
- Full simulation & reconstruction of the CMS detector were used.

Selection

- Selection for Higgs boson in $h \rightarrow ZZ \rightarrow 2e2\mu$ channel (by D.Futyan, D.Giordano)
  - Di-electron or di-muon trigger at L1 & HLT ("$Z \rightarrow 2\ell$-trigger")
  - Reconstructed two lepton pairs e^+e^- and $\mu^+\mu^-$
  - All 4 leptons originate at one vertex
    - **a)** Transverse distance from beam to $\mu^+\mu^-$-vertex $<$ 0.11 mm
    - **b)** χ^2 for compatibility of $\mu^+\mu^-$ and e^+e^- vertexes $<$ 95
    - **c)** Significance of transverse IP of all leptons $<$ 10.5
  - Isolation (tracker only)

    Cut on Σp_t of tracks ($p_t > 0.9$ GeV, $N_{hit} \geq 5$) inside sum of cones with $\Delta R = 0.25$ around each lepton.
  - Kinematic cuts
    - **a)** Cuts on p_ts of leptons ($p_{t1}, p_{t2}, p_{t3}, p_{t4}$)
    - **b)** Cuts on mass of Z/Z^* candidates:
      - ∗ Symmetric window around Z candidate (Δm_{Z1})
      - ∗ Asymmetric mass window in mass of Z^* candidate ($m_{Z2}^{min} \div m_{Z2}^{max}$)
    - **c)** Mass window in four lepton mass (mass of higgs candidate) ($m_H^{min} \div m_H^{max}$)

- Cut optimization performed automatically to maximize significance:

$$S = \sqrt{2lnQ}, \text{ where } Q = \left(1 + \frac{N_S}{N_B}\right)^{N_S+N_B} e^{-N_S}$$

Selection (cont.) – cross-sections

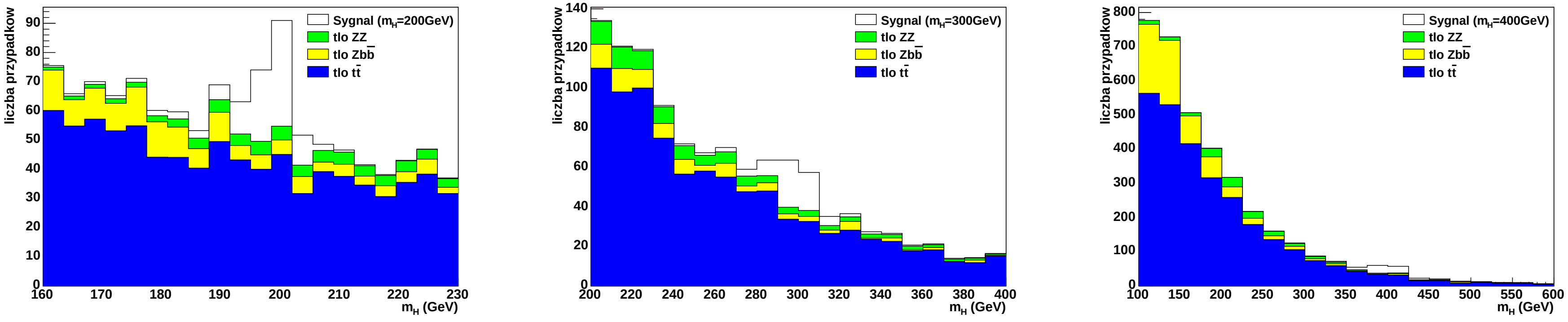
	$m_h = 200$ GeV				$m_h = 300$ GeV				$m_h = 400$ GeV			
	sig.	ZZ	$t\bar{t}$	$Zb\bar{b}$	sig.	ZZ	$t\bar{t}$	$Zb\bar{b}$	sig.	ZZ	$t\bar{t}$	$Zb\bar{b}$
σ_{tot} (pb)	17.86	21.2	886	525	9.41	21.2	886	525	8.71	21.2	886	525
$\sigma_{tot} \cdot \epsilon \cdot BR$	7.65	11.81	817.52	116.38	5.08	11.81	817.52	116.38	4.45	11.81	817.52	116.38
rec. $2\mu 2e$	5.46	6.71	173.02	32.77	3.74	6.71	173.02	32.77	3.35	6.71	173.02	32.77
Z mass	3.89	3.74	0.09	$<$0.02	2.69	2.17	0.14	0.05	2.46	1.59	0.10	$<$0.02
H mass	3.34	0.58	$<$0.03	$<$0.02	2.10	0.23	$<$0.03	$<$0.02	2.02	0.16	$<$0.03	$<$0.02
S/B	$\sim$ 5.3				$\sim$ 7.5				$\sim$ 9.6			

- All cross-section, but σ_{tot} in fb.
- ϵ stands for "detector acceptance" efficiency
- Signal cross-section & BR assumed to be independent from value of η;
  SM cross-section & BR are assumed.
- Only $q\bar{q} \rightarrow ZZ^*$ contribution for ZZ^* cross-section taken in account;
  Contribution of $gg \rightarrow ZZ^*$ ($\sim$20% of $\sigma_{q\bar{q} \rightarrow ZZ}$) not included.
- All background types, but ZZ^* negligible after selection for $m_h > 2m_Z$
  $\Longrightarrow$ not taken in account in further analysis.

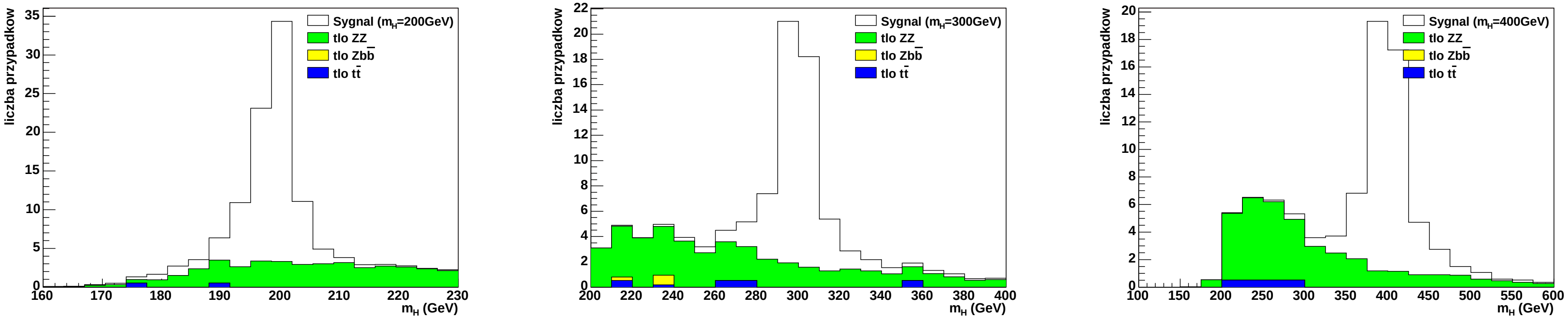
Selection (cont.) – mass of 4 leptons

$m_h = 200$ GeV $m_h = 300$ GeV $m_h = 400$ GeV

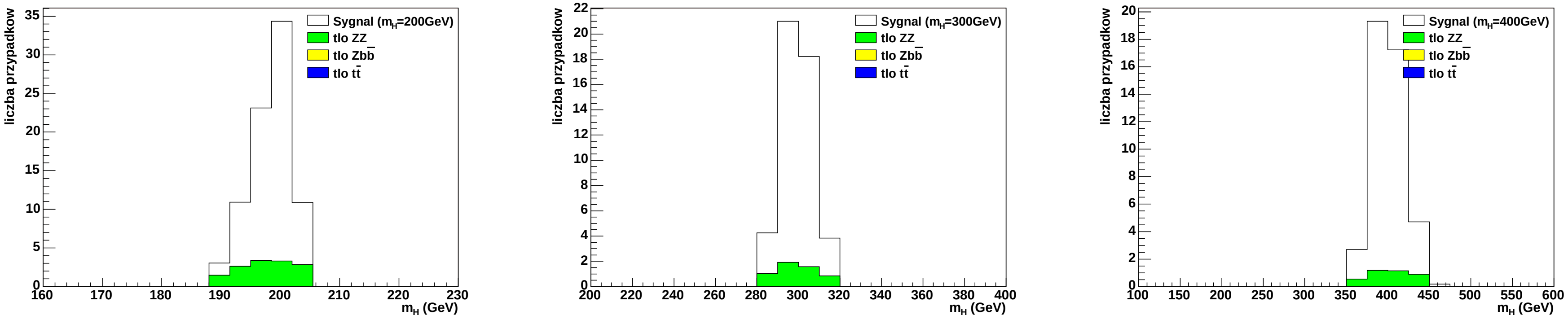
rec. $2\mu 2e$



Z mass cut

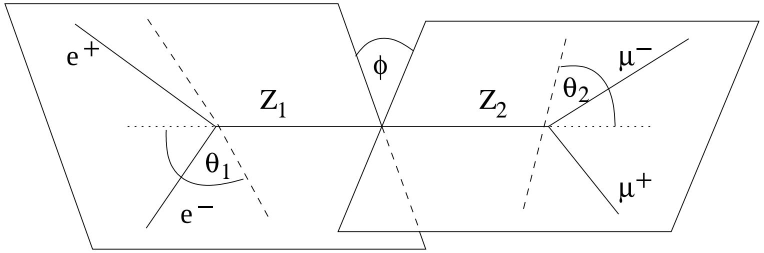


H mass cut



- Plots normalized to 20/fb.

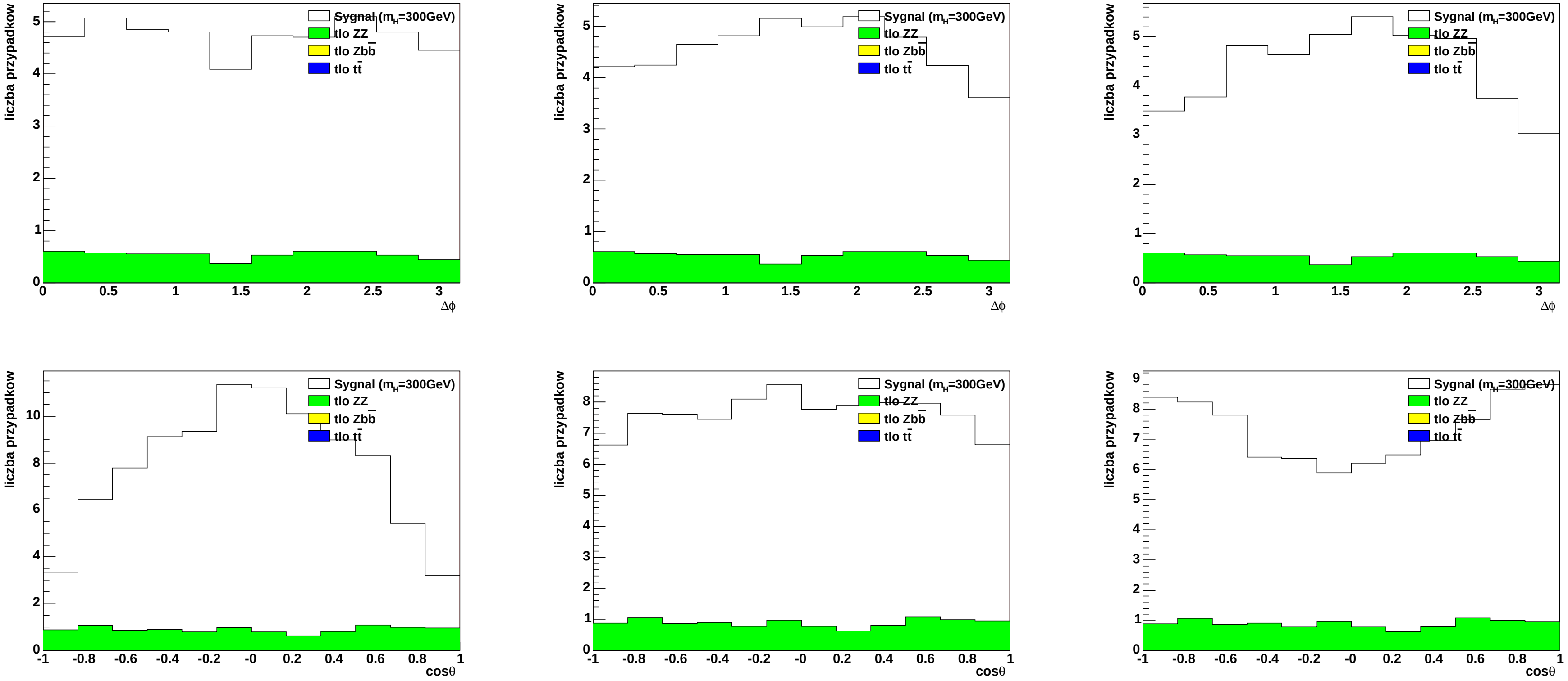
Selection (cont.) – angle distributions



$\eta = 0\,(H)$ $\eta = 1\,(J)$ $\eta = +\infty\,(A)$

ϕ

$\cos\theta$



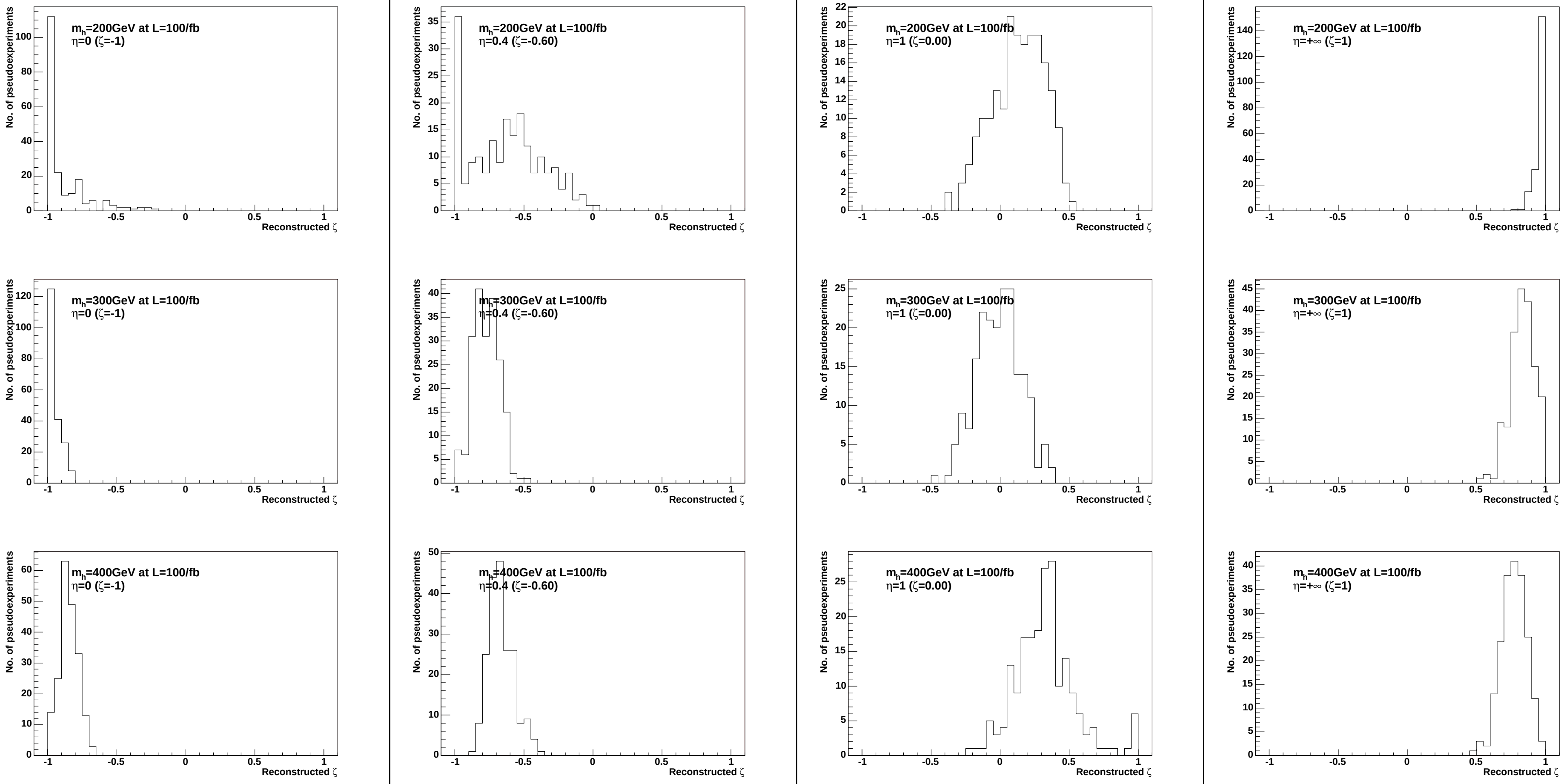
- Reconstructed angle distributions for m_h=300 GeV
- Plots normalized to 20/fb
- Histograms for $\cos\theta$ contain sum of distributions for both Z^0s
- Angle distributions aren't very smooth – bigger MC samples needed for better estimation of PDFs

Results

Results for $\mathcal{L}$=100/fb – distribution of parameter ζ for 200 pseudoexperiments, where

$$\zeta = \begin{cases} \eta - 1 & (0 < \eta \leq 1) \\ 1 - 1/\eta & (\eta > 1) \end{cases}$$

$\eta=0\ (\zeta=-1)$ | $\eta=0.4\ (\zeta=-0.6)$ | $\eta=1\ (\zeta=0)$ | $\eta=+\infty\ (\zeta=1)$



m_h=200 GeV

m_h=300 GeV

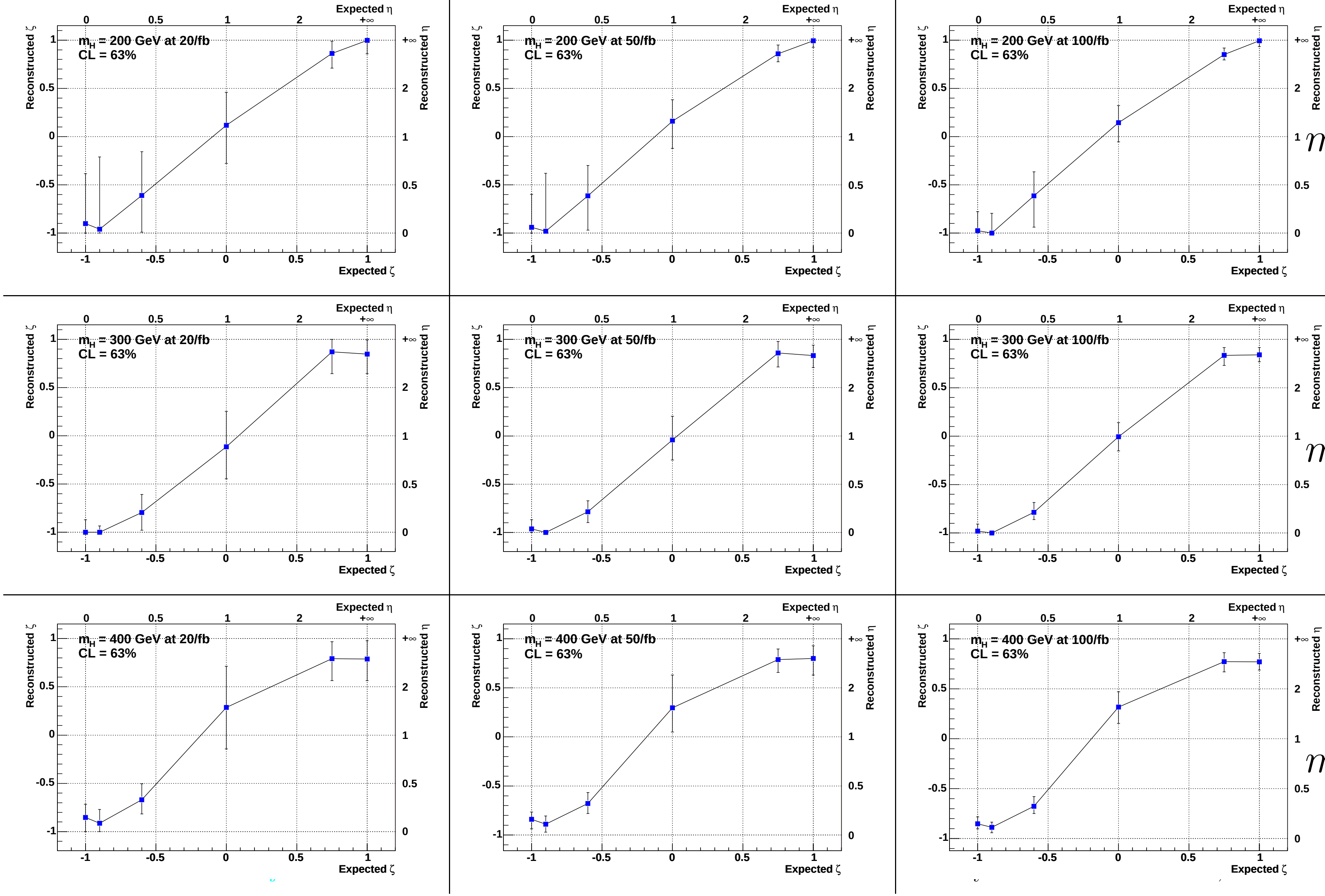
m_h=400 GeV

Results (cont.)

- Median of distribution of parameter η is taken as an estimator of true value of η.
- Errors are defined by values of η giving the same number of experiments on both sides of the median.
- Range defined by errors corresponds to 63% of experiments.
- Pseudoexperiments for three integrated luminosities $\mathcal{L}$=20, 50, 100/fb were performed

Results (cont.) – ζ_{rec} in function ζ_{true}

$\mathcal{L}$=20/fb | $\mathcal{L}$=50/fb | $\mathcal{L}$=100/fb



m_h=200 GeV

m_h=300 GeV

m_h=400 GeV

Summary

- Measurement of CP-violation in $h \rightarrow ZZ \rightarrow 2e2\mu$ in CMS is possible.
- Quite good accuracy and precision of determination of η parameter were obtained.
- To improve results smoother angle distributions for PDFs are needed $\Longrightarrow$ bigger MC samples for H, A and J (η=1).

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