CP-parity of Higgs in $\Phi \to ZZ \to e^+e^-\mu^+\mu^-$ at CMS

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Physics@LHC, Kraków 2006

Outline

- Model & Observables
- Signal selection
- Determination of CP-parity
- Results

These foils were prepared with LaTeX on June 30, 2006.

Model

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

$$C_{\Phi ZZ} \sim g^{\mu\nu} + \frac{1}{m_Z^2} \tan\xi \cdot \epsilon^{\mu\nu\rho\sigma} k_{1\rho} k_{2\sigma},$$

  where $k_1 = (q_1 + q_2)$, $k_2 = (q_3 + q_4)$, $q_{i=1\ldots4}$ momenta of Z^0s and leptons, respectively;

  $\tan\xi$ describes deviation from Standard-Model scalar:
  $\xi = 0$ – scalar
  $\xi = \pm\pi/2$ – pseudoscalar
  for remaining values of ξ CP-violation

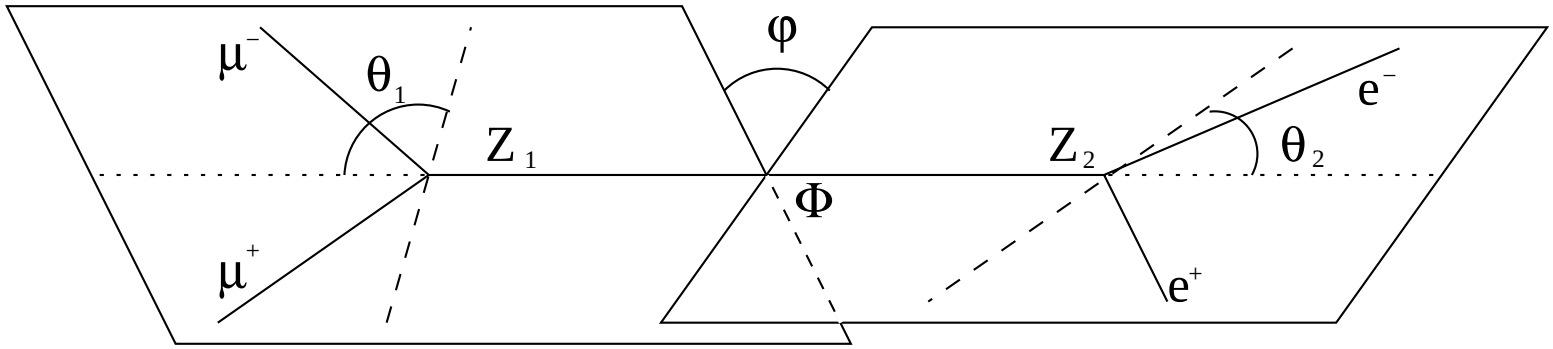
- Decay width:

$$d\Gamma(\xi) \sim H + \tan\xi \cdot I + \tan^2\xi \cdot A,$$

  where:
  H – scalar
  I – interference (CP-violating) term
  A – pseudoscalar

Observables

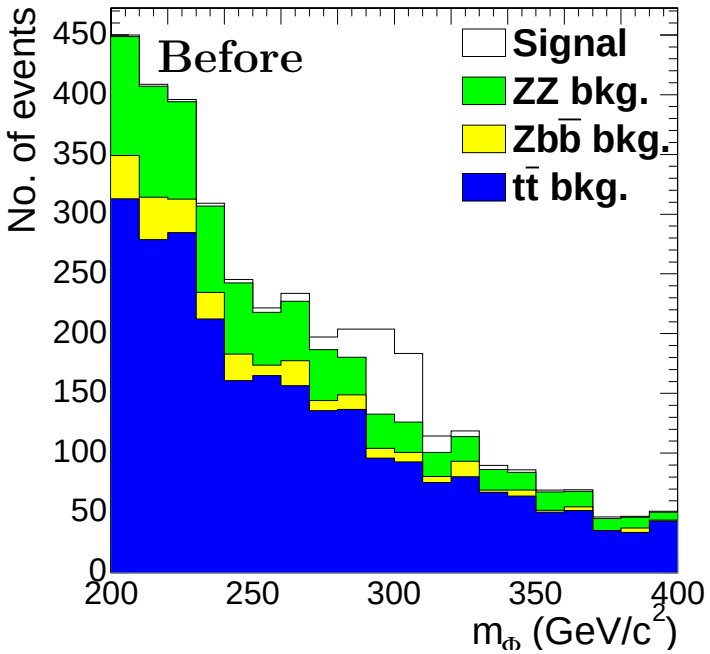
- Angular distributions distinguish between states with different ξ's
- Two distributions are used in the analysis:
  - Plane angle φ
    between decay planes of Z^0s in the Higgs boson rest frame
  - Polar angle $\theta_{1,2}$
    between momentum of negatively charged lepton (dashed line on Z's decay planes) in the Z^0 rest frame and the direction of Z^0 (dotted line) in the Higgs boson rest frame

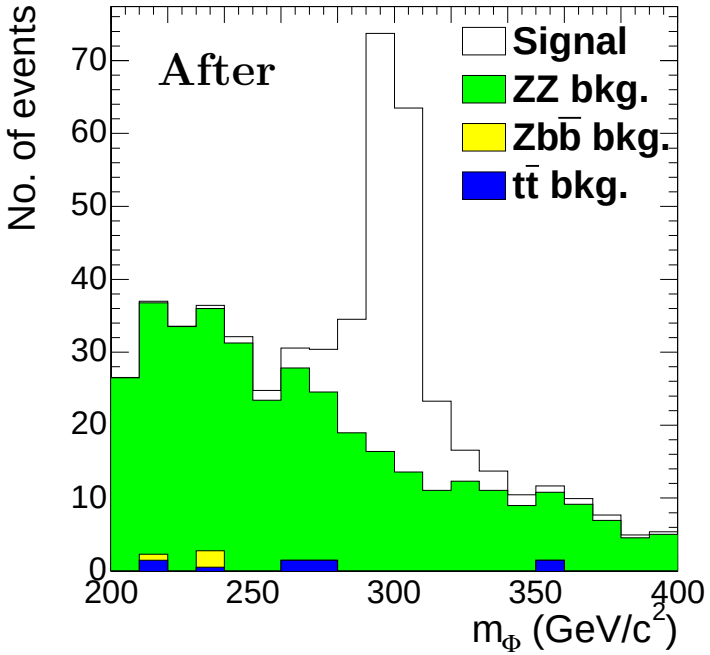


Signal selection

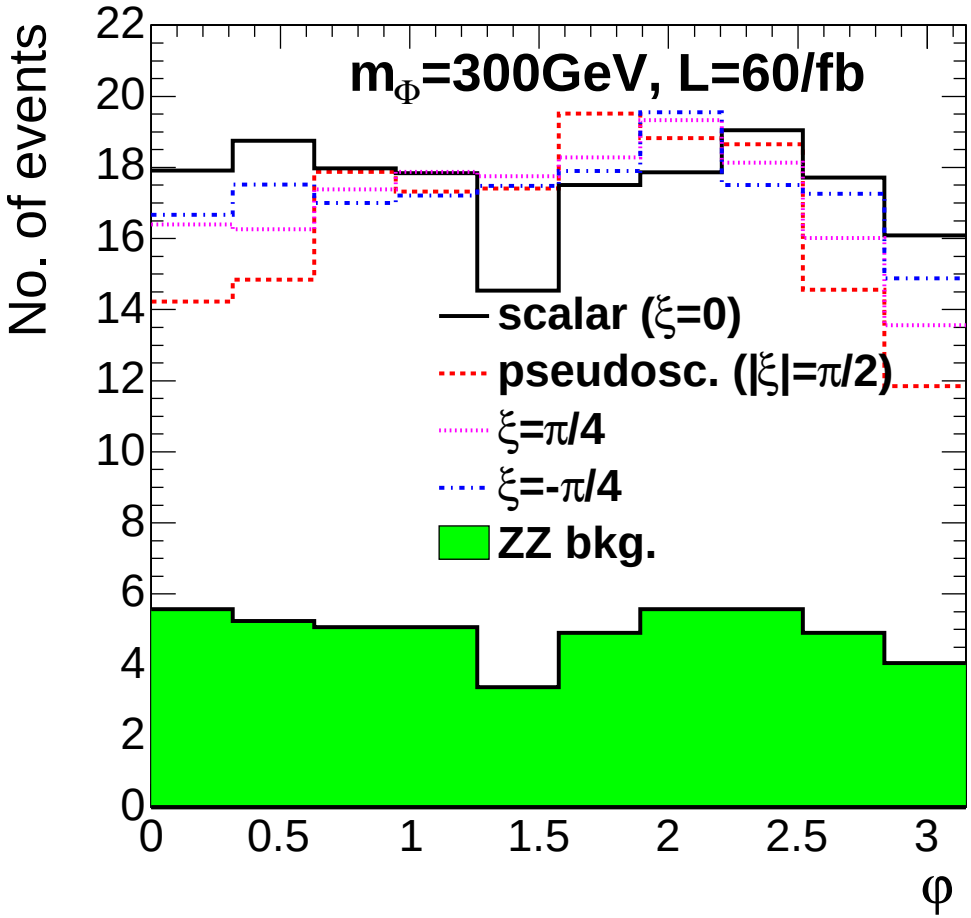
- Signal $\Phi \rightarrow ZZ \rightarrow e^+e^-\mu^+\mu^-$ (m_Φ=200, 300, 400 GeV):
  - Samples for CP-conserving states (scalar, pseudoscalar)
  - Samples with CP-violation $\tan\xi = \pm 0.1, \pm 0.4, \pm 1, \pm 4$
- Background:
  - $ZZ/\gamma^* \rightarrow e^+e^-\mu^+\mu^-$ (irreducible background)
  - $t\bar{t} \rightarrow e^+e^-\mu^+\mu^- + X$
  - $Zb\bar{b} \rightarrow e^+e^-\mu^+\mu^- + X$
- Selection:
  - Two pairs of isolated opposite-sign leptons $(e^+e^-)\,(\mu^+\mu^-)$
  - Each lepton pair compatible with Z^0 mass
  - Four-lepton mass in window around expected Higgs boson mass
- Signal/Background ratio ≥ 2 after selection
- All background types, but ZZ/γ^* negligible after selection for $m_\Phi > 2\,m_Z$, therefore not taken into account in further analysis
- Details in CMS Physics TDR vol. 2, Sect. 10.2.1

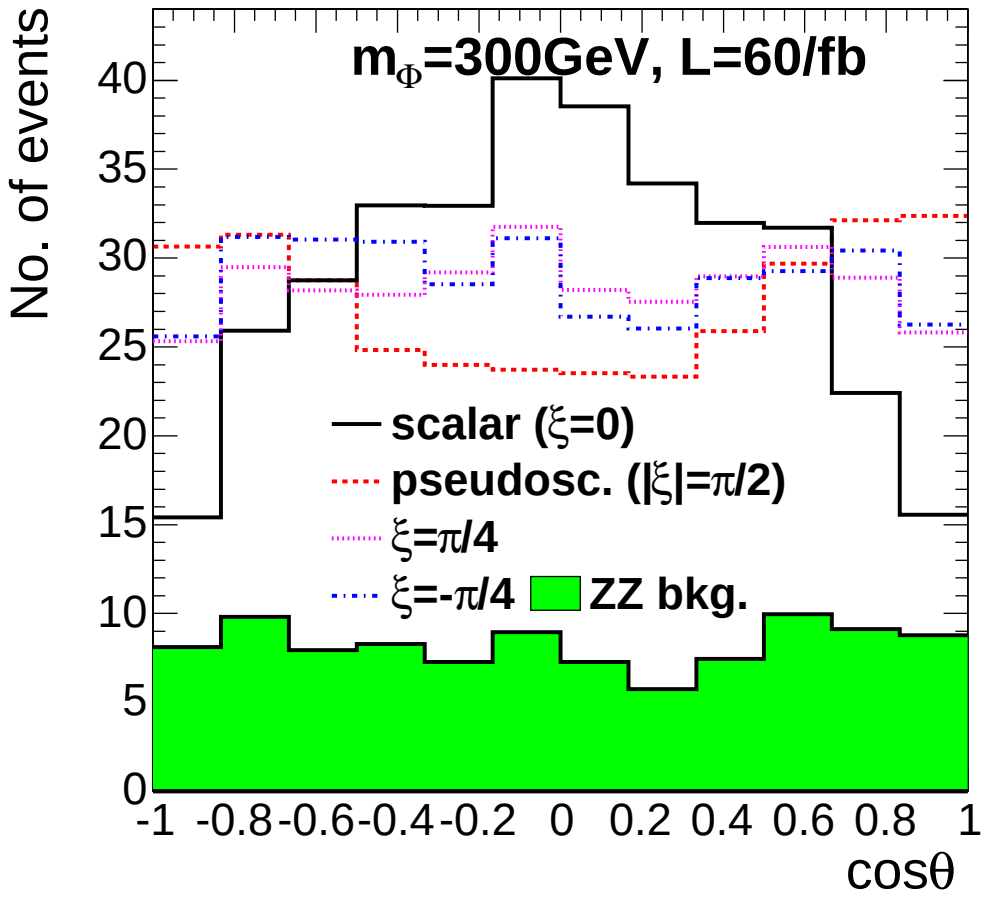
m_Φ=300 GeV, 60/fb





Reconstructed angular distributions





- Reconstructed angular distributions for m_Φ=300 GeV (normalized to 60/fb)
- Histograms for $\cos\theta$ contain sum of distributions for both θ_1 and θ_2

Determination of CP-parity – maximization of likelihood function

- Definition of likelihood function

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

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

where
$\{x_i\}$ – values of measured quantities for data event i,
R – fraction of signal in data sample,
$\mathcal{P}_B$ and $\mathcal{P}_S(\xi)$ – probability density functions for background and signal:

$$\mathcal{P}_B \equiv \mathcal{P}_B^M \cdot \mathcal{P}_B^\varphi \cdot \mathcal{P}_B^{\cos\theta_{1,2}}$$

$$\mathcal{P}_S(\xi) \equiv \mathcal{P}_S^M \cdot (\mathcal{P}_S^\varphi \cdot \mathcal{P}_S^{\cos\theta_{1,2}})(\xi),$$

where:
$\mathcal{P}^M$, $\mathcal{P}^\varphi$, $\mathcal{P}^{\cos\theta_{1,2}}$ – probability density functions for $m_{4\ell}$, φ and $\cos\theta_{1,2}$, respectively.

$\mathcal{P}$s obtained by MC technique (normalized histograms of given quantities after the selection).

Determination of CP-parity (cont.)

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

$$\mathcal{P}(\xi) \equiv \mathcal{P}_S^{\varphi} \cdot \mathcal{P}_S^{\cos\theta_{1,2}}(\xi) = (\mathcal{H} + \tan\xi \cdot \mathcal{I} + \tan^2\xi \cdot a^2\mathcal{A})/(1 + a^2\tan^2\xi)$$

– $\mathcal{H} \equiv \mathcal{P}_H^{\varphi} \cdot \mathcal{P}_H^{\cos\theta_{1,2}}$ and $\mathcal{A} \equiv \mathcal{P}_A^{\varphi} \cdot \mathcal{P}_A^{\cos\theta_{1,2}}$ – probabilities for scalar (H) and pseudoscalar (A)

– a^2 – a relative (mass dependent) strength of scalar and pseudoscalar couplings (a^2=0.51, 1.65, 1.79 for m_Φ=200, 300 400 GeV)

– $\mathcal{I}$ – an angular distribution for CP-violating interference term (I) is not a probability, therefore it is not possible simulate it separately

- Determination of $\mathcal{I}$:

After introducing $\mathcal{P}_\pm \equiv \mathcal{P}(\pm\pi/4) = (\mathcal{H} \pm \mathcal{I} + a^2\mathcal{A})/(1+a^2)$ we have

$$\mathcal{I} = \frac{1+a^2}{2} \cdot (\mathcal{P}_+ - \mathcal{P}_-)$$

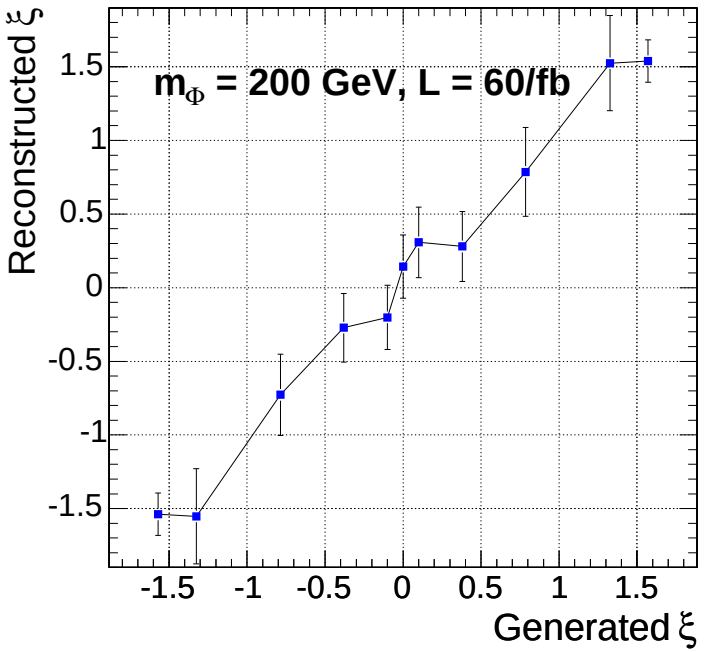
Finally:

$$\mathcal{P}(\xi) \equiv [\mathcal{H} + \tan\xi \cdot \frac{1+a^2}{2} \cdot (\mathcal{P}_+ - \mathcal{P}_-) + \tan^2\xi \cdot a^2\mathcal{A}]/(1 + a^2\tan^2\xi)$$

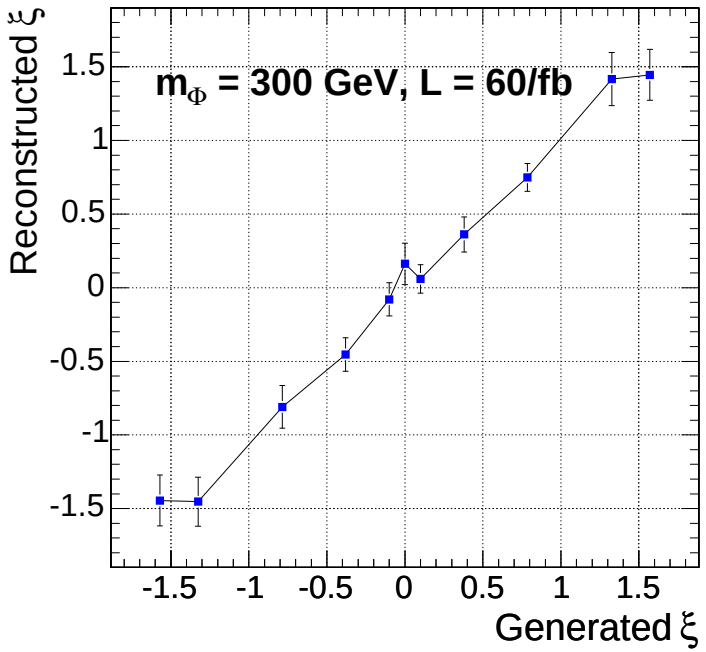
Results: ξ_{rec} as a function of ξ_{gen}

- Mean and standard deviation of the ξ-distribution from 200 pseudo-experiments are estimators of ξ and $\Delta\xi$, respectively.
- Results for SM cross-section & BR for signal, and for $\mathcal{L}$=60/fb.

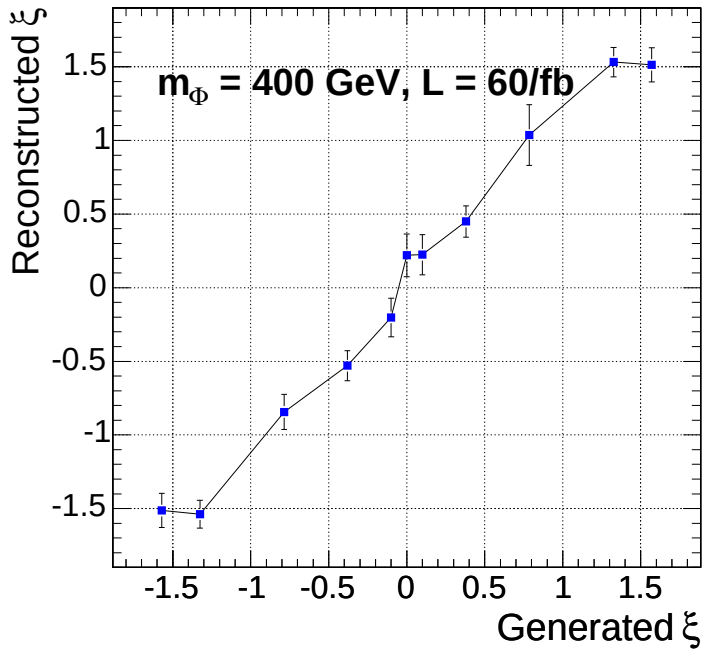
m_Φ=200 GeV



m_Φ=300 GeV



m_Φ=400 GeV



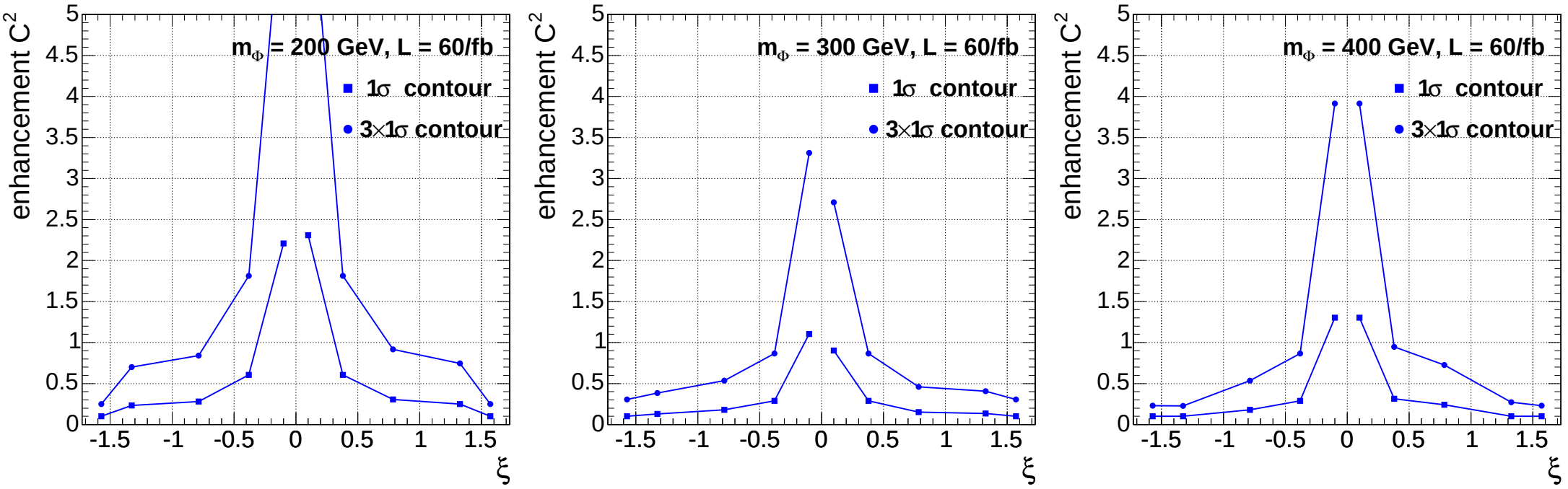
Results: exclusion limits for scalar ($\xi = 0$)

- Precision of ξ measurement $\Delta\xi \sim 1/C$, where

$$C^2 \equiv (\sigma \times BR)/(\sigma_{SM} \times BR_{SM})$$

that is:

$$\Delta\xi(\xi, C^2) = \frac{\Delta\xi_{SM}(\xi)}{\sqrt{C^2}}$$



Minimal C^2 needed to exclude scalar Higgs boson at $N\sigma$ level ($N = \xi/\Delta\xi$) for 60/fb

Summary

- Angular correlations of the Higgs boson decay products in $\Phi \to ZZ \to e^+e^-\mu^+\mu^-$ make possible to determine ΦZZ-coupling.
- Measurement of CP-violation in $\Phi \to ZZ \to e^+e^-\mu^+\mu^-$ using the CMS detector is feasible.
- Limits for cross-section needed to exclude scalar have been obtained.

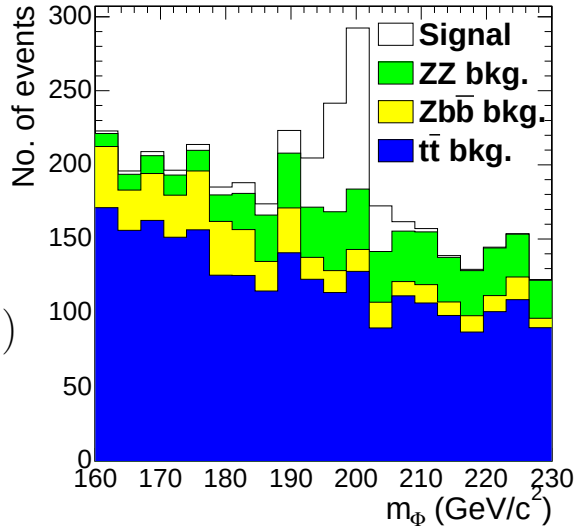
- Details in the CMS Physics TDR vol. 2 and the CMS Note-2006/094.

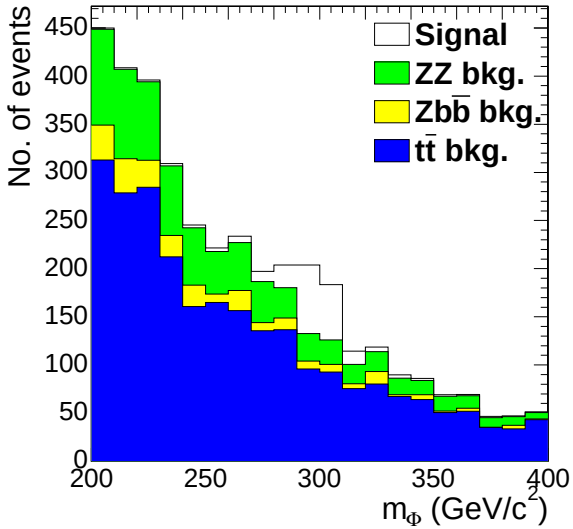
ADDITIONAL SLIDES

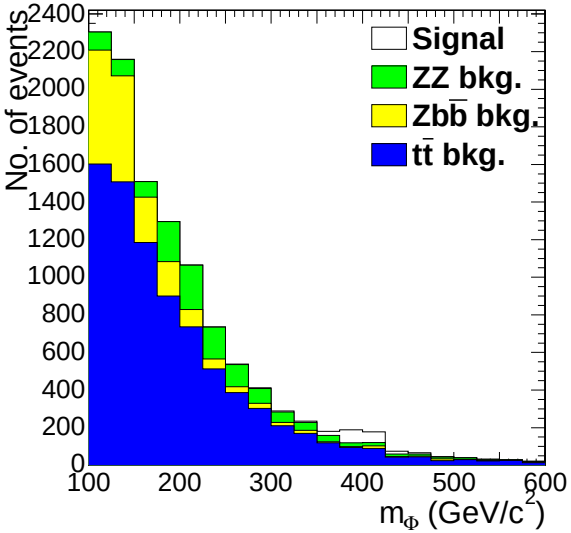
Selection: mass of 4 leptons

$m_\Phi = 200$ GeV | $m_\Phi = 300$ GeV | $m_\Phi = 400$ GeV

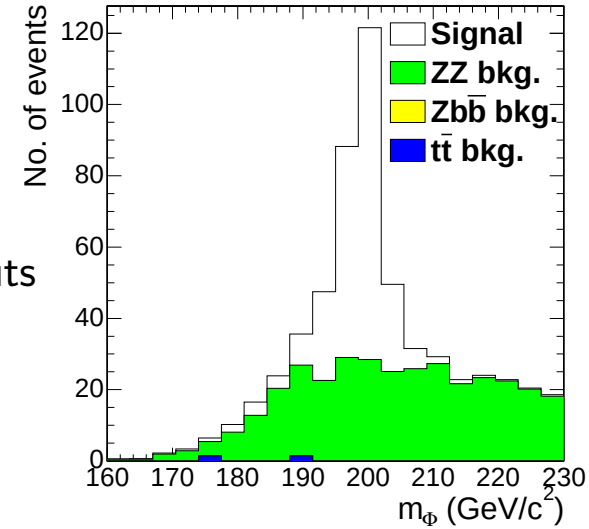
After reconstruction $(e^+e^-)\,(\mu^+\mu^-)$

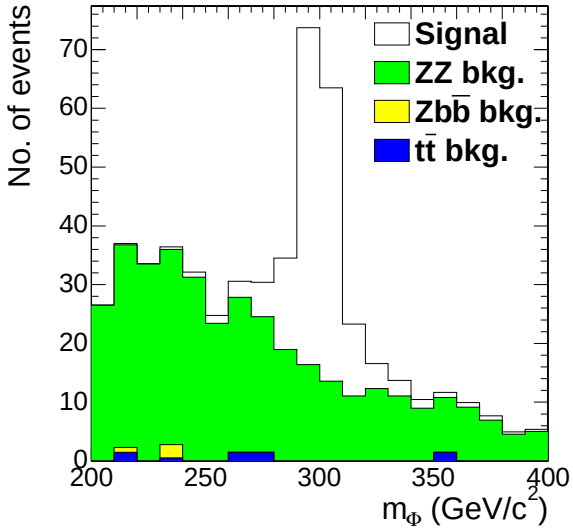


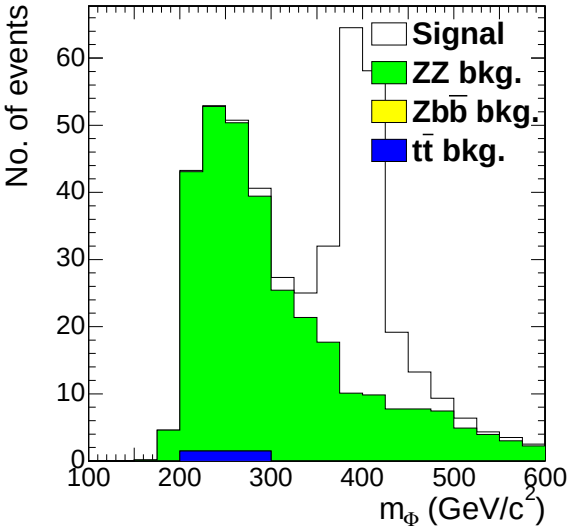




After Zs masses cuts

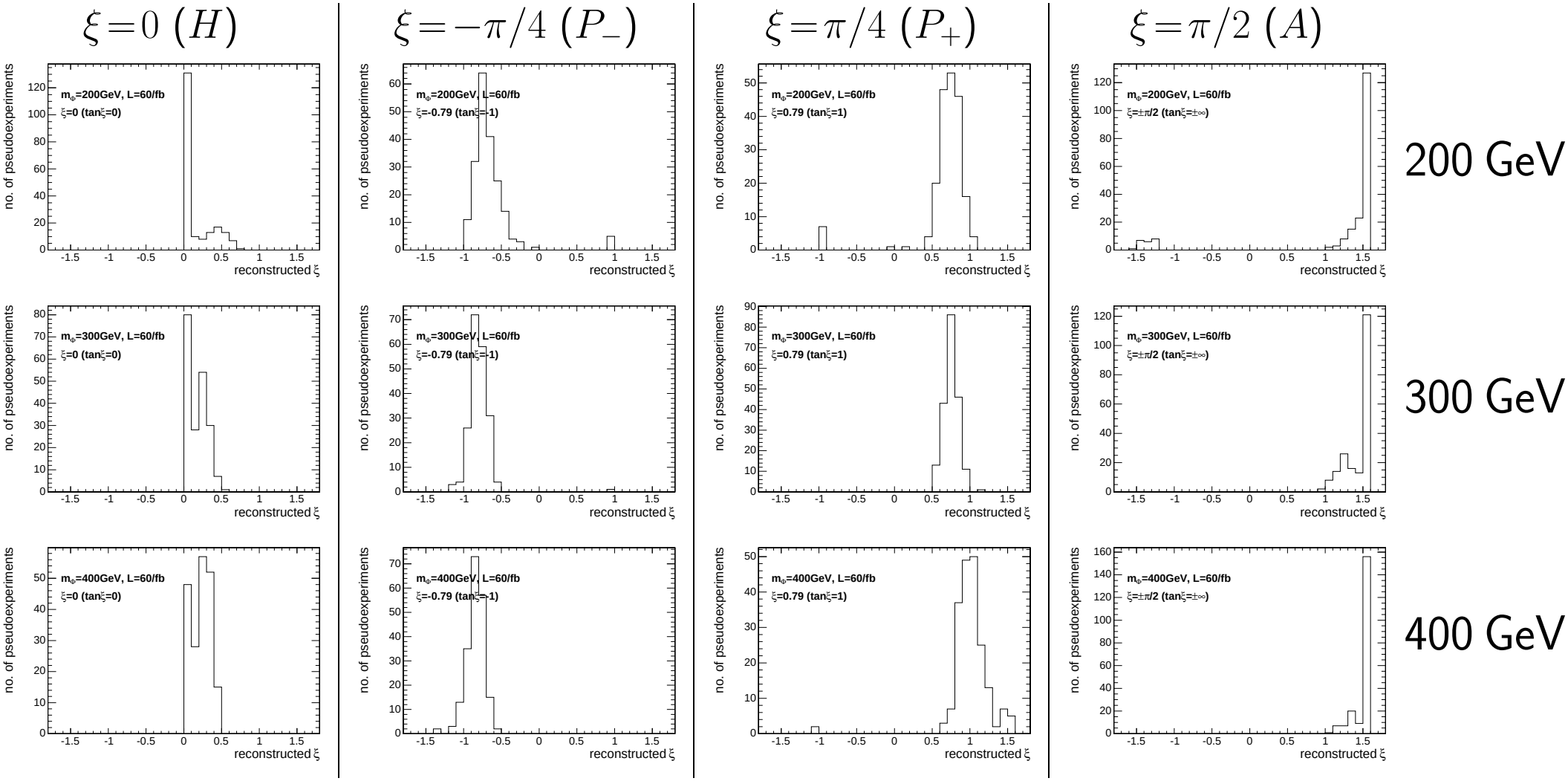






- Plots normalized to 60/fb (3 years of LHC at low lumi)

Distribution of reconstructed ξ-parameter



- ξ-distributions for 200 pseudoexperiments for $\mathcal{L}$=60/fb