Higgs CP

Comparison of LHC and e+e- collider

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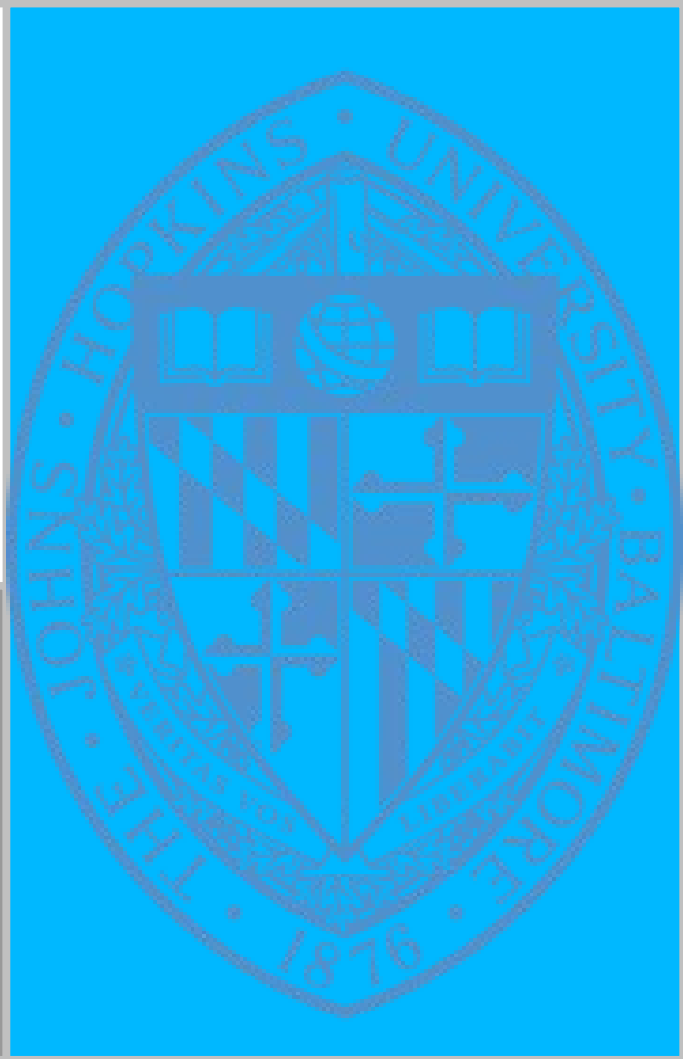
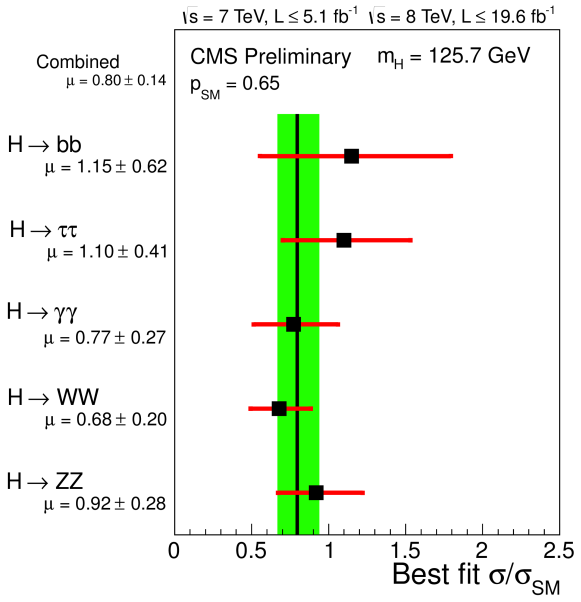


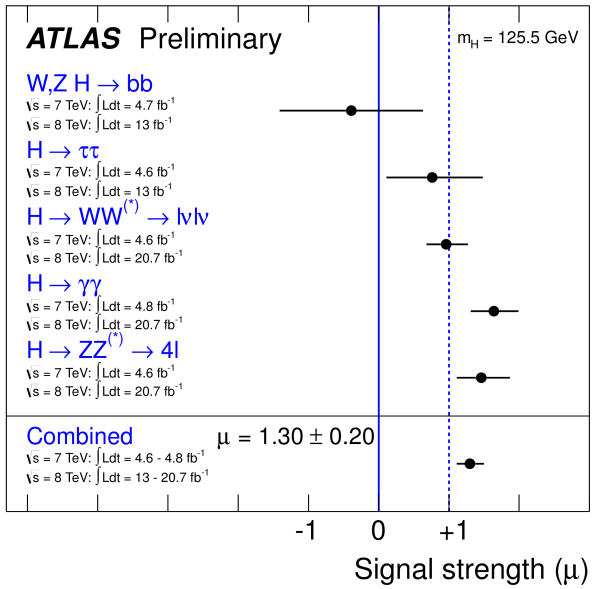
Snowmass: Seattle Energy Frontier Workshop

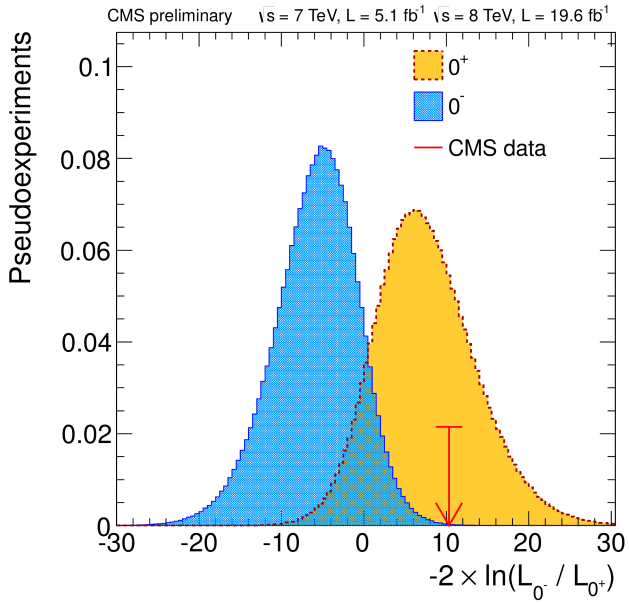
July 1, 2013

History

- Discovery of scalar resonance m_H~125 GeV resonance







- Early measurements → Consistent with SM Higgs
  - Measuring properties with H→VV decay kinematics
    - Likely not spin-1, spin-2, or pure CP-odd scalar

Is there CP violation in the Higgs sector?

Outline

- How much can we constrain CP-violation in H → ZZ* amplitude with LHC?
  - 1D approach with MELA discriminant
  - Multidimensional approach
- How much can we constrain CP-violation in Z* → ZH with an e+e- collider?
  - Multidimensional approach
- Comparison of results between LHC and e+e- collider

Properties with HZZ

- Most general HZZ amplitude

$$\mathscr{A}(HV_1V_2) \propto a_1 m_V^2 \epsilon_1\epsilon_2 + a_2 f^1_{\mu\nu} f^{2,\mu\nu} + a_3 f^1_{\mu\nu} \tilde{f}^{2,\mu\nu}$$

- Parameterized in terms of 4 parameters
  - Cross section treated separately ("couplings")

$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1+|a_2|^2\sigma_2+|a_3|^2\sigma_3}$$

$$\phi_{a3} = Arg(\frac{a_3}{a_1})$$

$$f_{a2} = \frac{|a_2|^2\sigma_2}{|a_1|^2\sigma_1+|a_2|^2\sigma_2+|a_3|^2\sigma_3}$$

$$\phi_{a2} = Arg(\frac{a_2}{a_1})$$

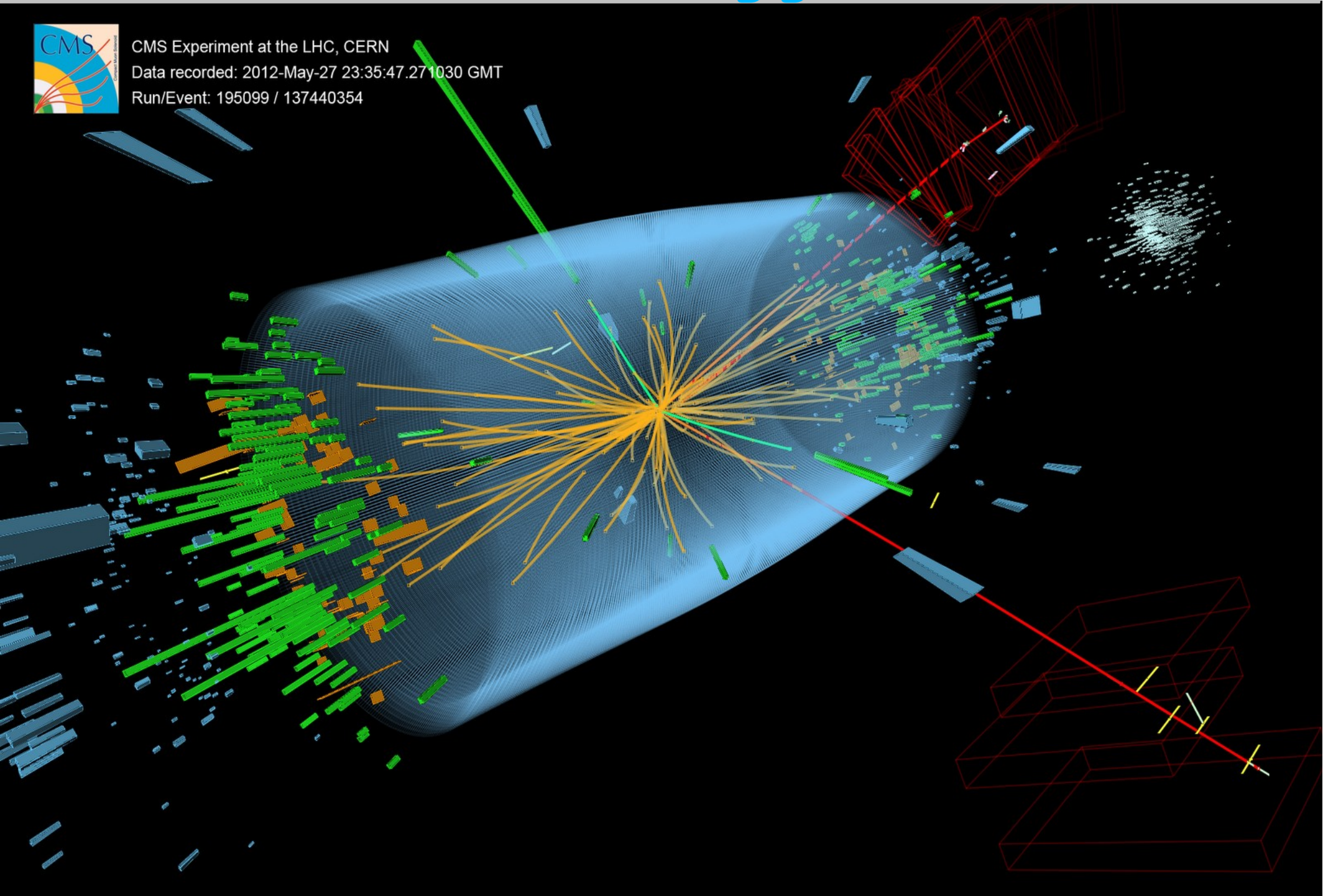
$$\sigma_i = \int |\mathscr{A}(a_i = 1, a_{j\neq i} = 0)|^2 d\Omega$$

- Different models manifest themselves uniquely in angular and mass distributions (kinematics)

Event Generator

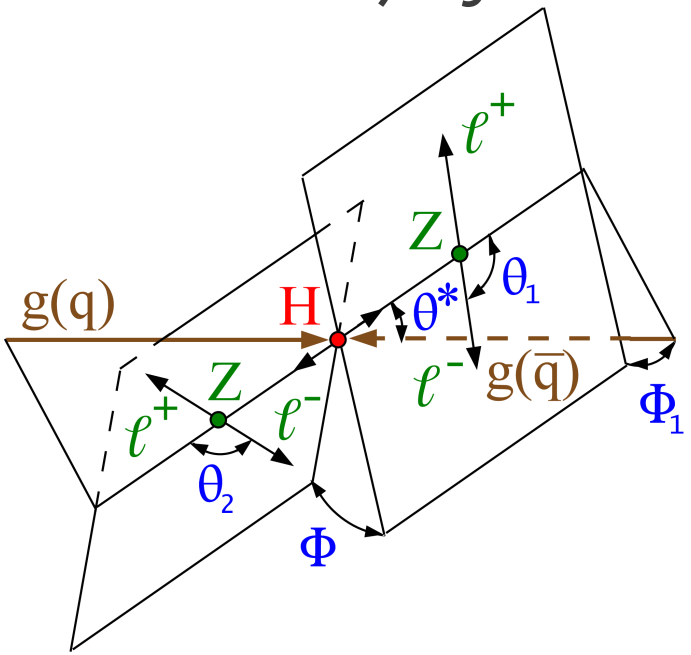
- Need generator to study production of arbitrary scalar models
- JHUGen - arXiv:1208.4018, arXiv:1001.3396
  - LO monte carlo generator
    - Integrates NLO production from other generators
  - production for LHC/Tevatron: $q\bar{q}\,; g\,g$
  - spin-0, 1, 2 models at LHC
    - Decays to : ZZ, WW, γγ
  - Documentation and code can be found: http://www.pha.jhu.edu/spin/
- New development: $e^+e^- \rightarrow ZH$
  - All couplings and spin correlations included

Higgs CP at LHC



ZZ Kinematic Variables

- ZZ decays can be fully described (in ZZ rest frame) by 8 variables[1]
  - Masses: m_{ZZ}, m_{Z}, m_{Z^*}
  - Helicity angles: $\cos\theta_1$, $\cos\theta_2$, Φ
  - Production angles: Φ_1, $\cos\theta^*$



  - p_T, Y of H distinguish production mechanisms (not relevant for this talk)
- Different couplings are reflected in the 7D probability density function (PDF)

$$P_{sig}(m_{ZZ}, m_{Z}, m_{Z^*}, \cos\theta_1, \cos\theta_2, \Phi, \Phi_1, \cos\theta^* ; f_{a2}, f_{a3}, \varphi_{a2}, \varphi_{a3})$$

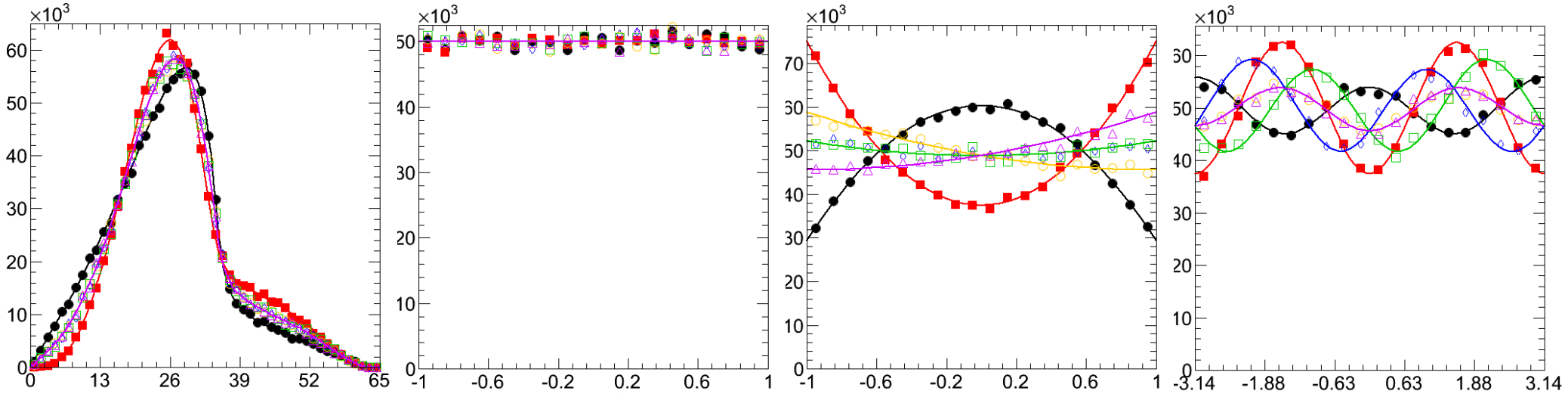
[1] arXiv:1001.3369

Spin-0 Kinematics (LHC)

- Kinematic distributions can be described:
  - MC simulation (JHUGen)
  - Analytically[1]

0+ (SMH)
pseudoscalar
$f_{a3}=.5, \varphi_{a3}=0$

$f_{a3}=.5, \varphi_{a3}=\pi/2$
$f_{a3}=.5, \varphi_{a3}=\pi$
$f_{a3}=.5, \varphi_{a3}=3\pi/2$



m_{Z*} $\cos\theta^*$ $\cos\theta_1$ Φ

- Full matrix element information expected to provide sensitivity to both f_{a3} and φ_{a3}

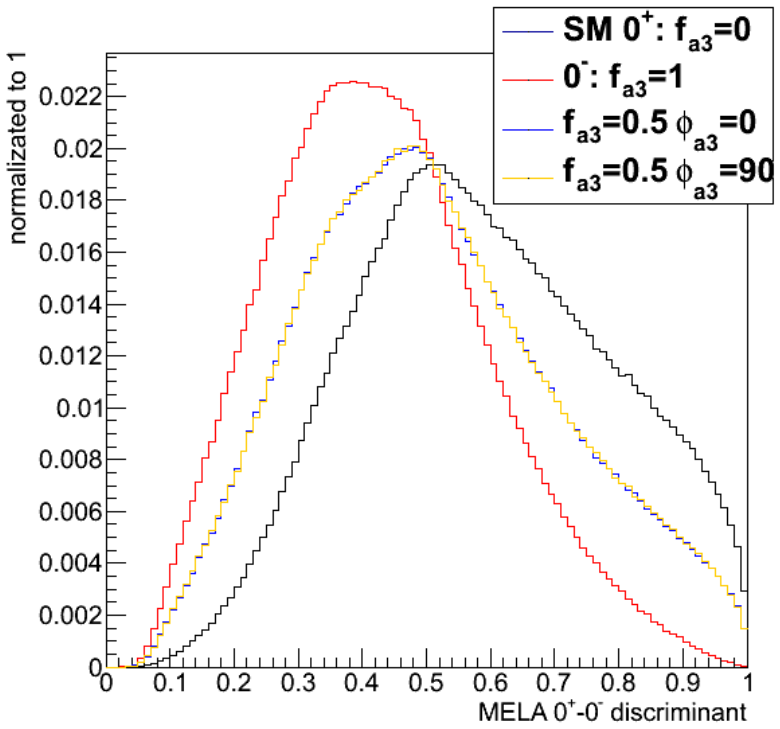
[1]arXiv:1208.4018

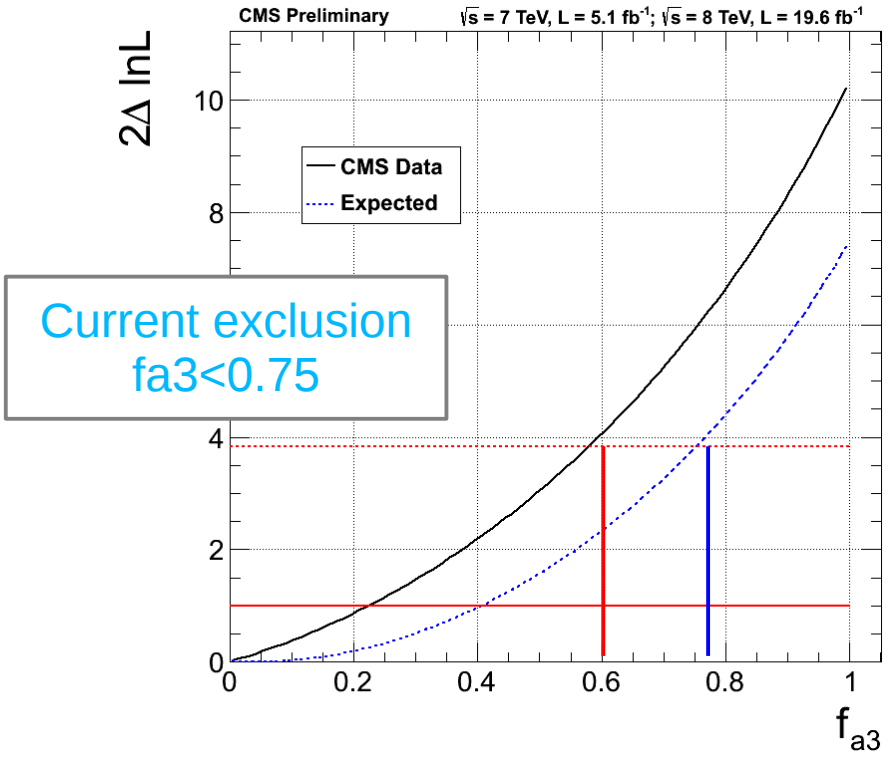
CP measurements at LHC

- Use MELA to discriminate SM Higgs from pseudoscalar

$$D = \left(1 + P_{sig}(fa3=1, fa2=0) / P_{sig}(fa3=0, fa2=0)\right)^{-1}$$

  - hypothesis testing (as done on CMS & ATLAS)
  - measure f_{a3} directly



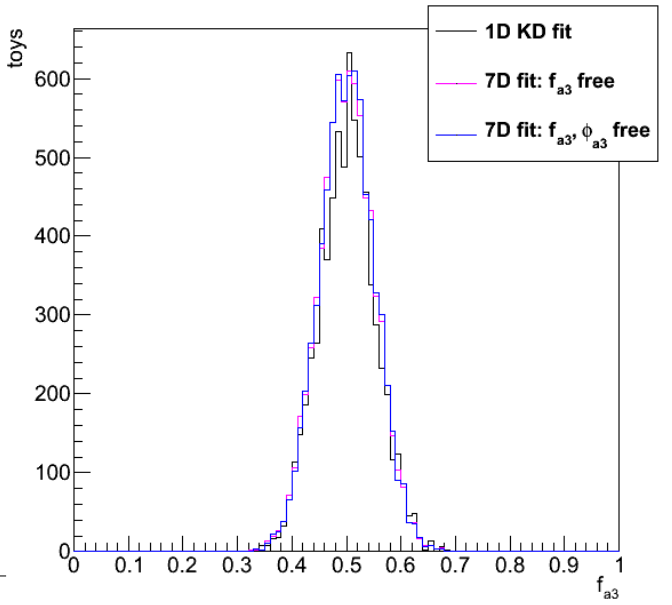


7D versus 1D

$$L = f_{a3} P_{CP-odd}(D) + (1 - f_{a3}) P_{SMH}(D)$$

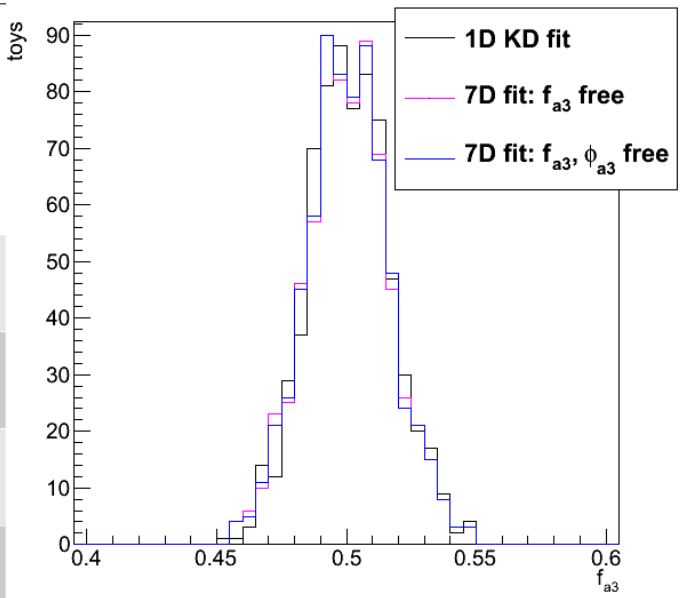
$$L = P_{SMH}(\vec{\Omega}; f_{a3}, \varphi_{a3})$$

- Naïve projection to
  - 300/fb and 3k/fb @ 14 TeV
  - no background/det. effects



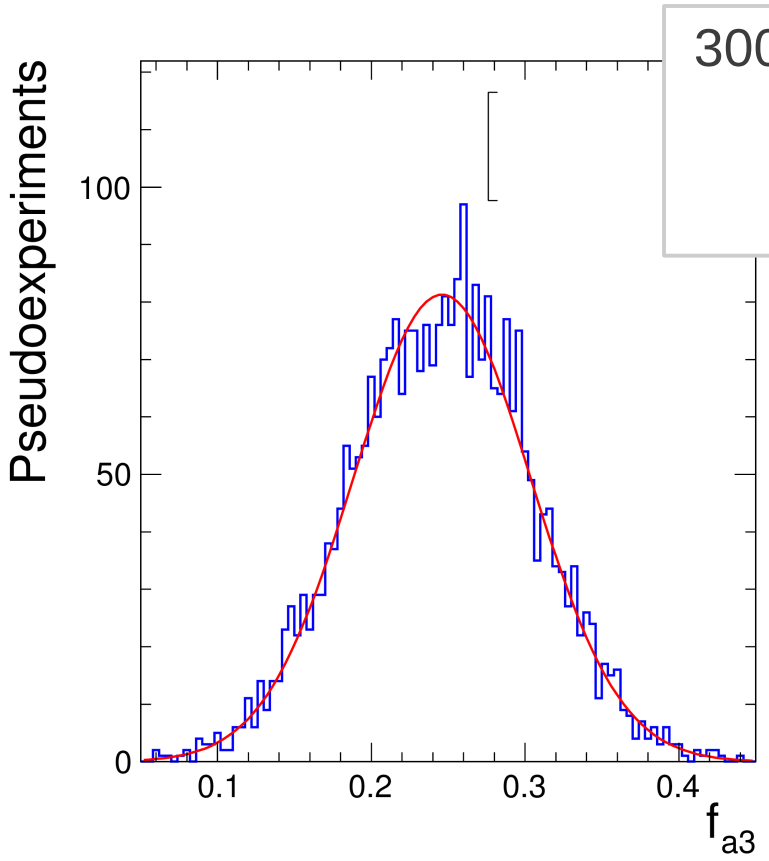
Precision of fits

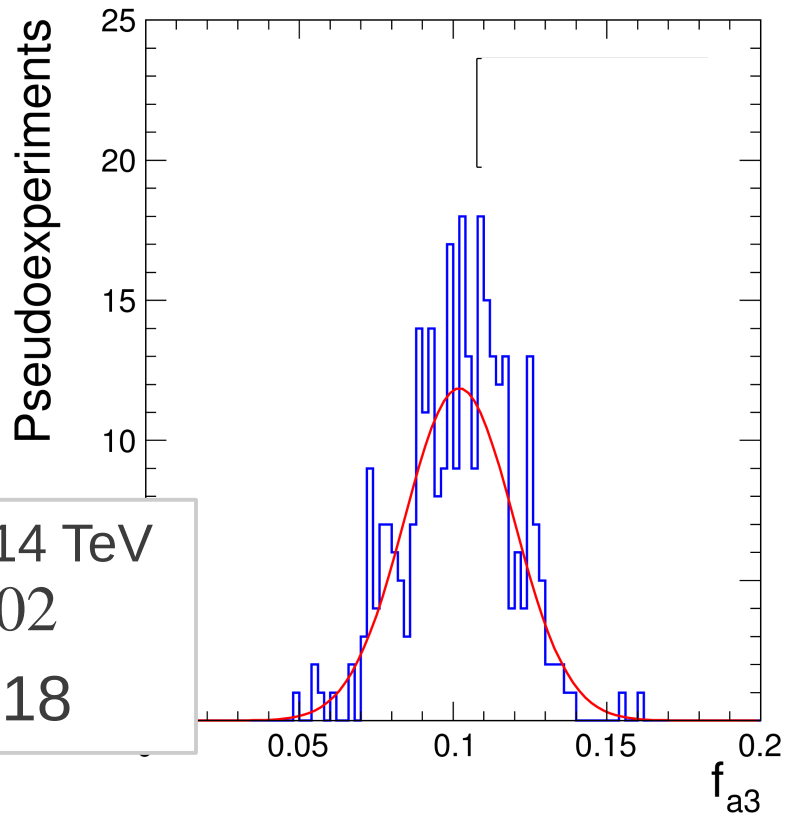
lum	fa3	1D fit	7D fit (fa3 free)	7D fit (fa3, phia3 free)
300	.5	.0504±.0004	.0504±.0005	.0504±.0005
3k	.5	.0156±.0004	.0161±.0005	.0163±.0005
300	.25	.0481±.0004	.0464±.0004	.0459±.0003
3k	.1	.0148±.0004	.0129±.0003	.0126±.0003



LHC Sensitivity

- Using 1D fits and including background and detector effects
  - Signal yield:600 (6000)
    background yield: 80 (800) } 300,3000 /fb @ 14 TeV
  - Apply momentum smearing and acceptance cuts

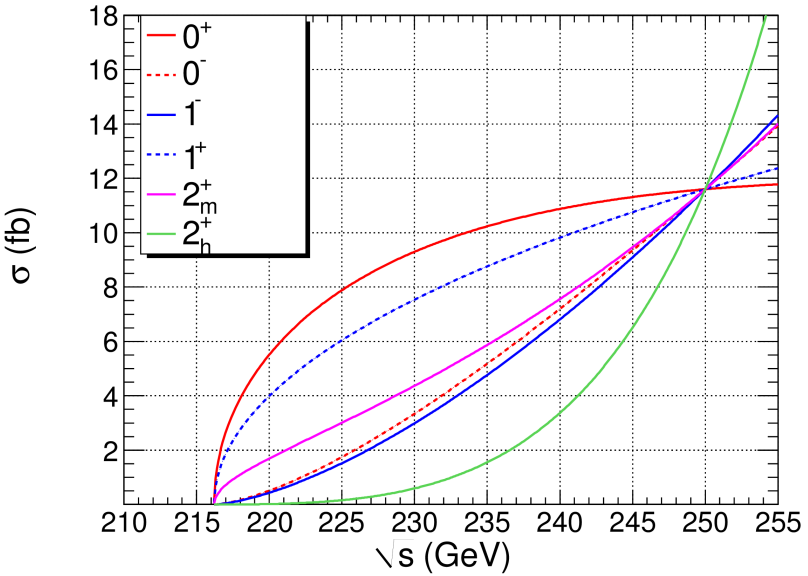


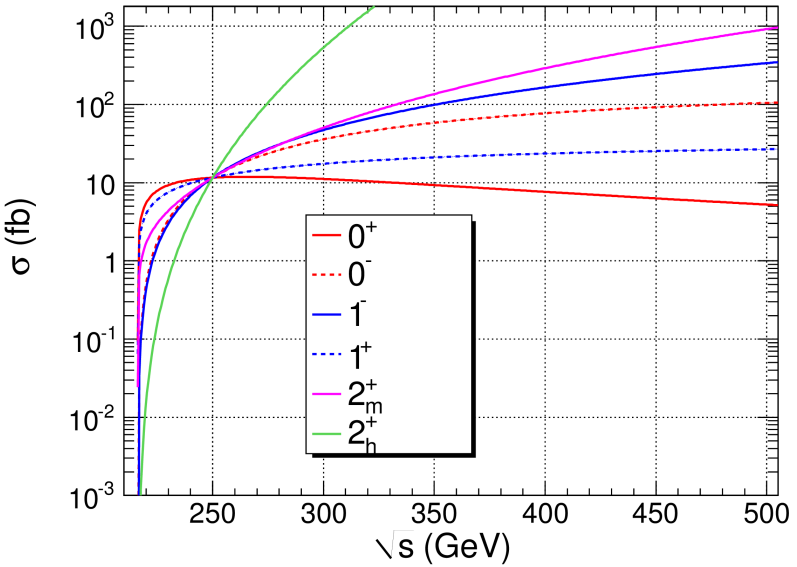


Higgs CP in e+e−

CP Measurements

- LHC, H → ZZ*, may become sensitive to $f_{a3}=0.1$
  - Corresponds a3/a1 = 0.83
  - f_3(e+e- @ 250)=0.854 ; f_3(e+e- @ 500)=0.992 (a3/a1 const)
- Properties can be inferred from
  - √s dependence of rate or kinematics
  - Combination of rates and kinematics

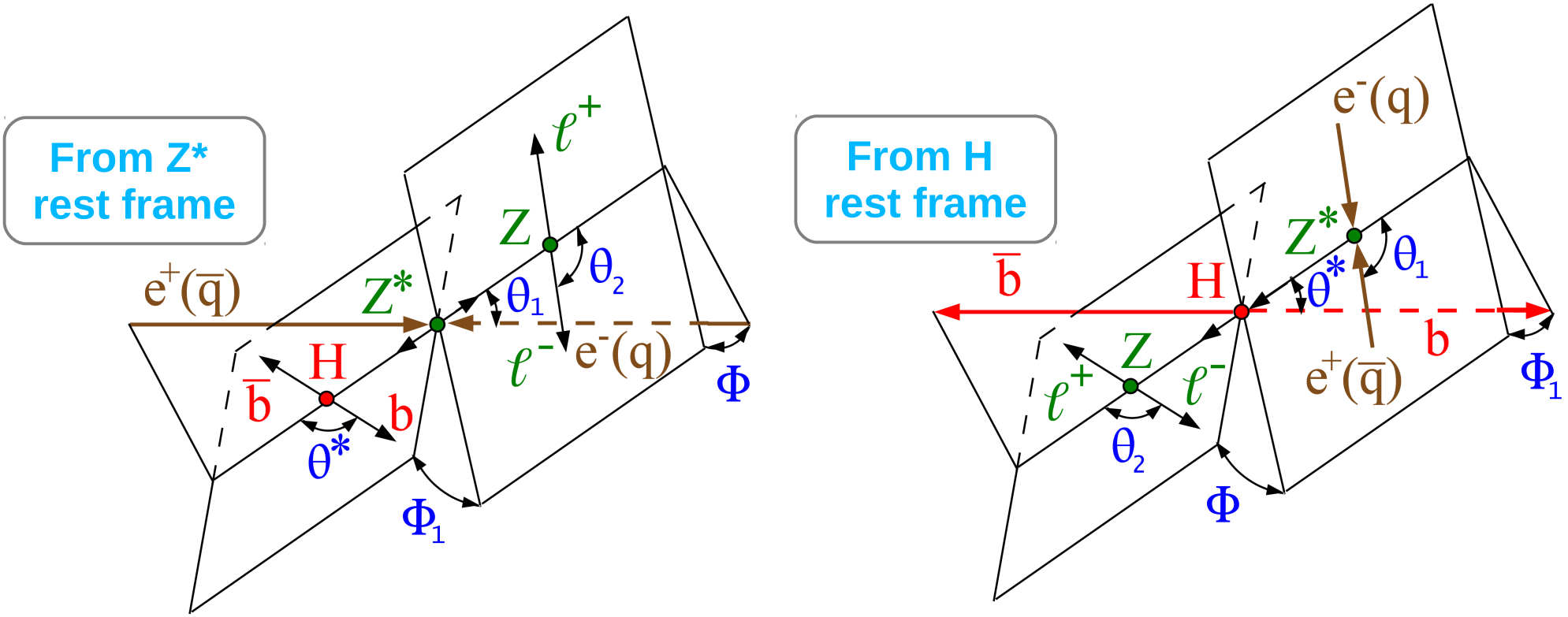




  - Calculation based on arXiv:1208.4018 consistent with hep-ph/0106315

Z*→ZH Kinematic Variables

- Same topology as H → ZZ* but in different frame
  - Z, H masses on shell



  - Angular distributions are the same

$$P_{sig}(\cos\theta_1, \cos\theta_2, \Phi, \Phi_1, \cos\theta^* ; f_{a2}, f_{a3}, \varphi_{a2}, \varphi_{a3})$$

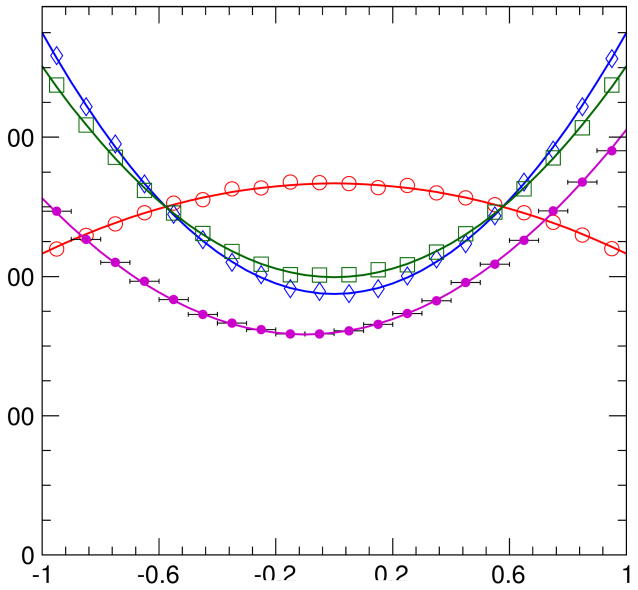
[1] arXiv:1208.4018

Spin-0 Kinematics

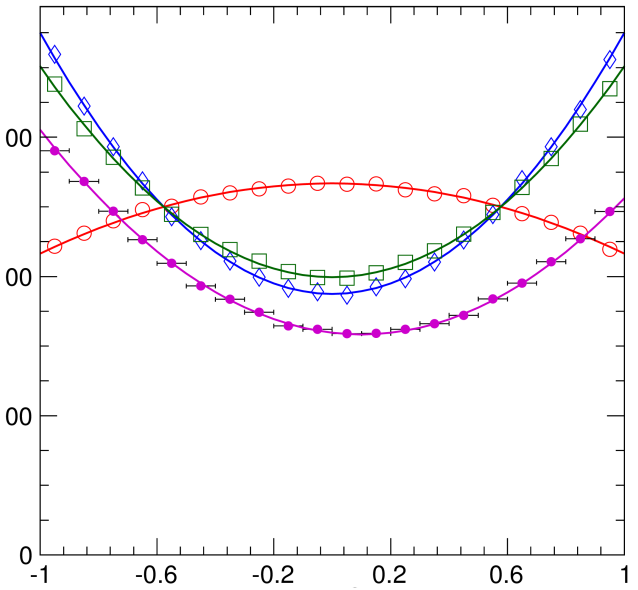
- Kinematic distributions can be described:
  - MC simulation (JHUGen)
  - Analytically[1]

SM Higgs $f_{a3} = 0.1$ $\Phi_{a3}=0$

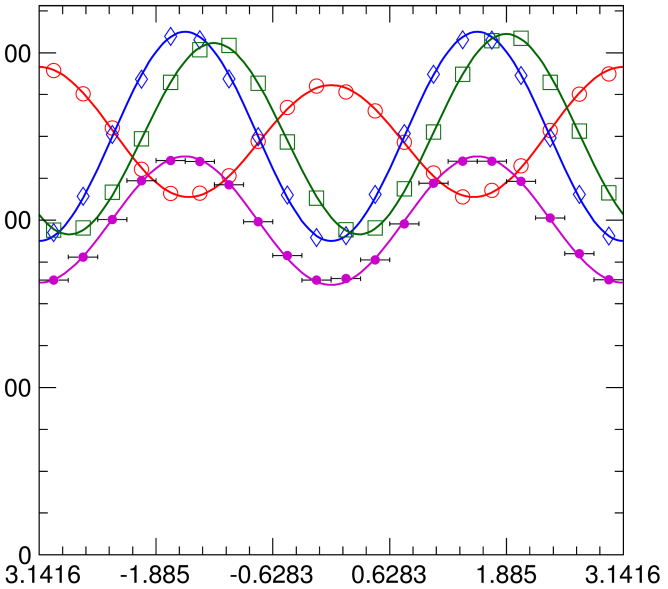
pseudoscalar $f_{a3} = 0.1$ $\Phi_{a3}=\pi/2$



$\cos\theta_1$



$\cos\theta_2$



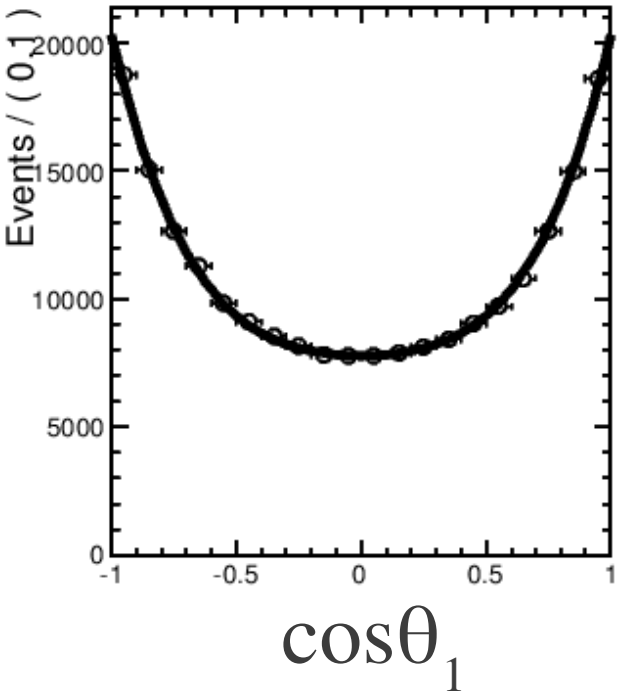
Φ

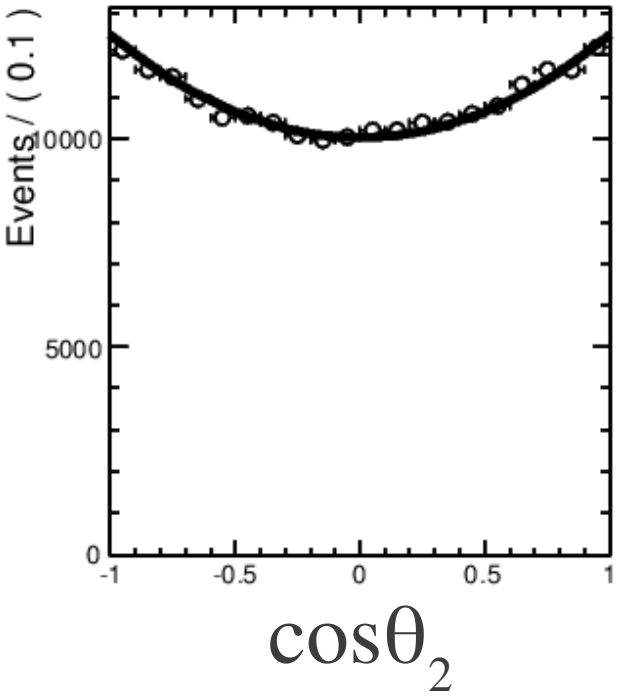
- Angular distributions sensitive to f_{a3} and Φ_{a3}

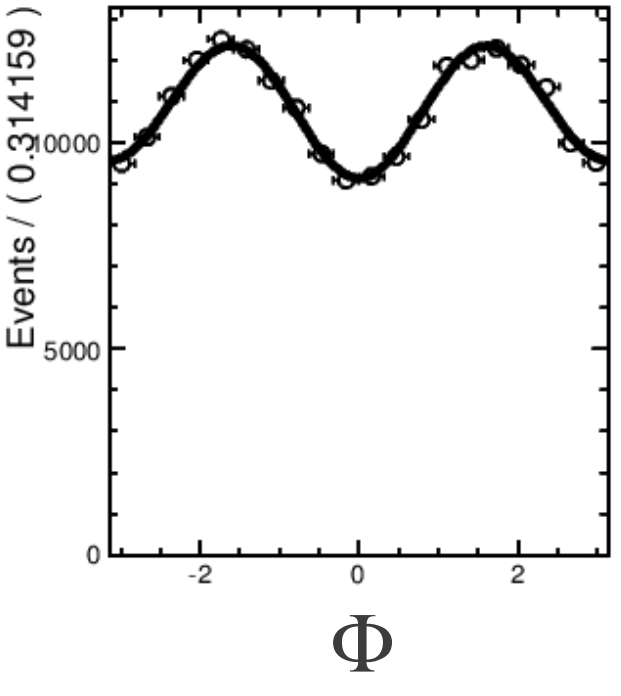
[1]arXiv:1208.4018

Multi-Dimensional Fits

- Background shapes taken from continuum ZZ
  - Select events where 115< m_H <140
- Modeled with empirical, uncorrelated, PDF
  - Found to provide consistent description of full simulation







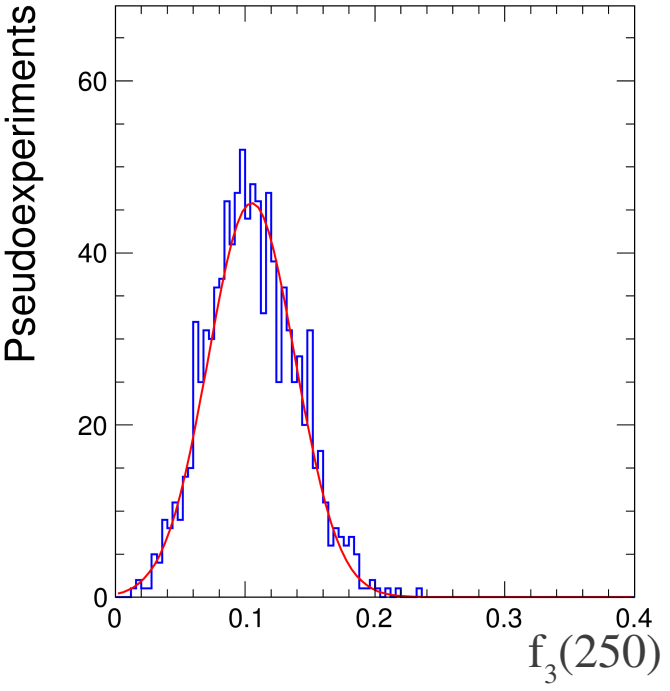
e^+e^- Sensitivity (250 GeV)

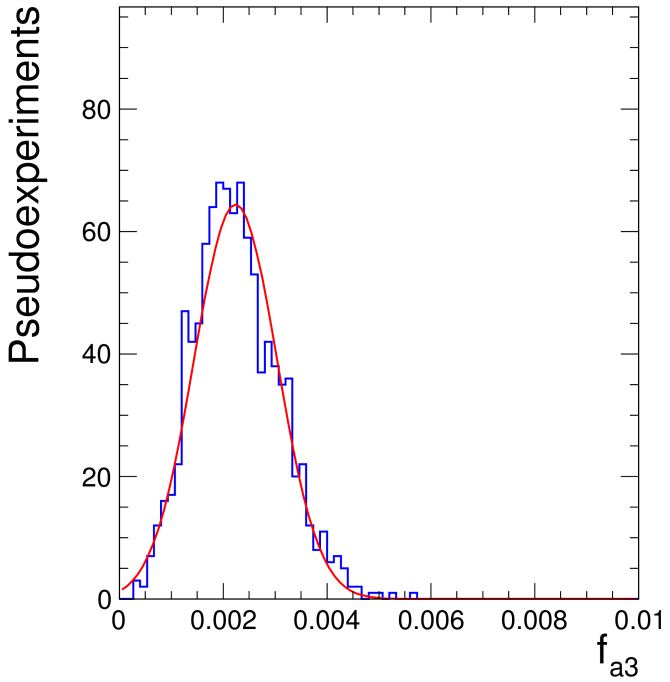
- Using 3D model:
  - Generate experiments
    - 2k signal 200 background
  - fitting for f_3 and Φ_3
    - Expect sensitivity to $f_3(250) = 0.1$

$$f_3(250) = .105$$
$$\sigma(f_3) = 0.036$$

    - Correspond to $f_{a3} = 0.0022$

$$f_{a3} = 2.2 \times 10^{-3}$$
$$\sigma(f_{a3}) = 8.0 \times 10^{-4}$$





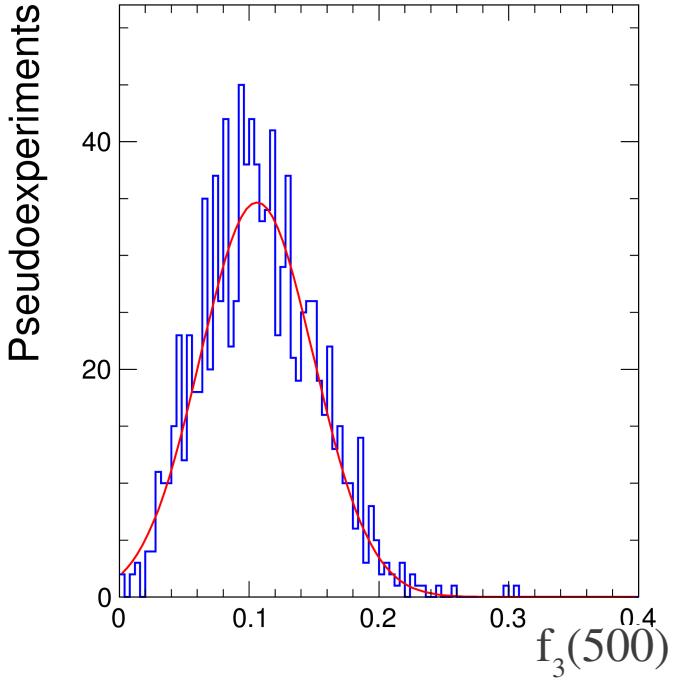
e^+e^- Sensitivity (500 GeV)

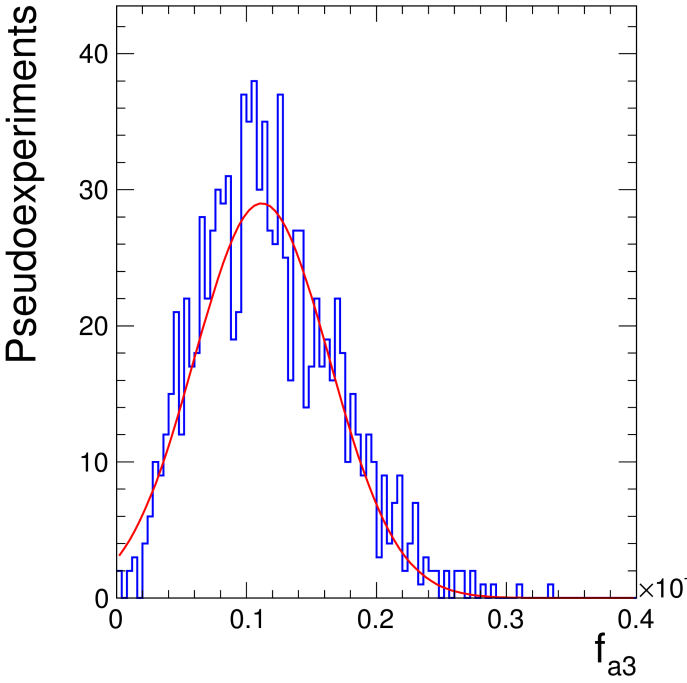
- Using 3D model:
  - Generate experiments
    - 1k signal, 100 background
  - fitting for f_3 and Φ_3
    - Expected sensitivity to $f_3(500) = 0.1$

$$f_3(500) = .106$$
$$\sigma(f_3) = 0.044$$

- Correspond to $f_{a3} = 0.00011$

$$f_{a3} = 1.1 \times 10^{-4}$$
$$\sigma(f_{a3}) = 5.2 \times 10^{-5}$$

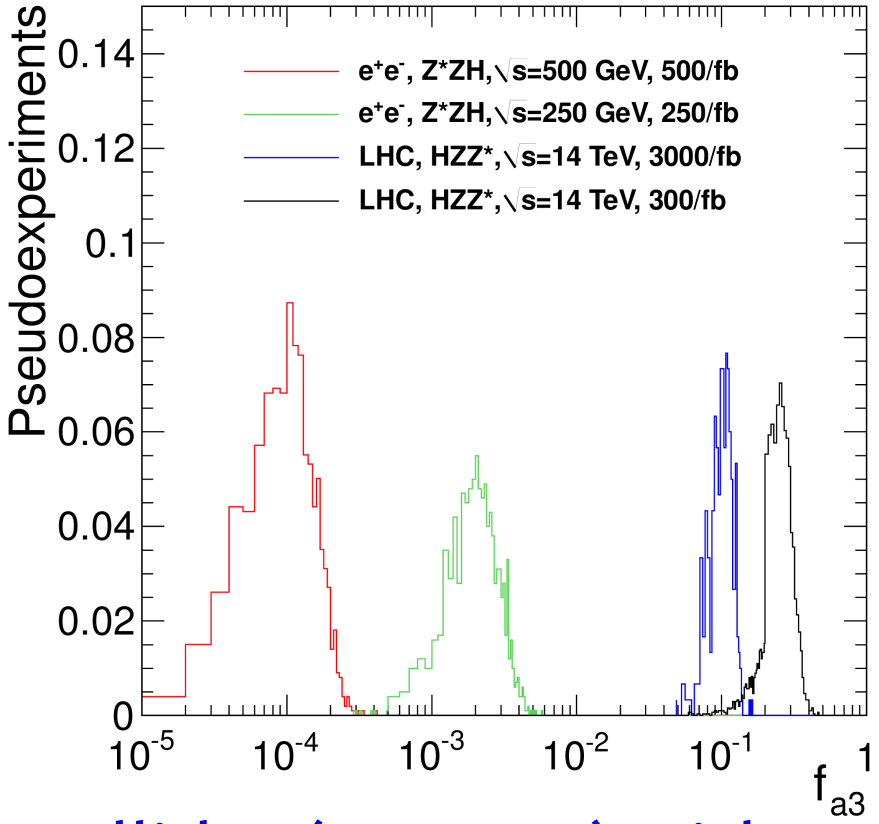




Summary

- Tools developed to measure CP-violation in HZZ
  - Event generation with all coupling and spin correlations
  - Full analytical description of kinematics
  - LHC: H → ZZ*
  - e+e-: Z* → ZH

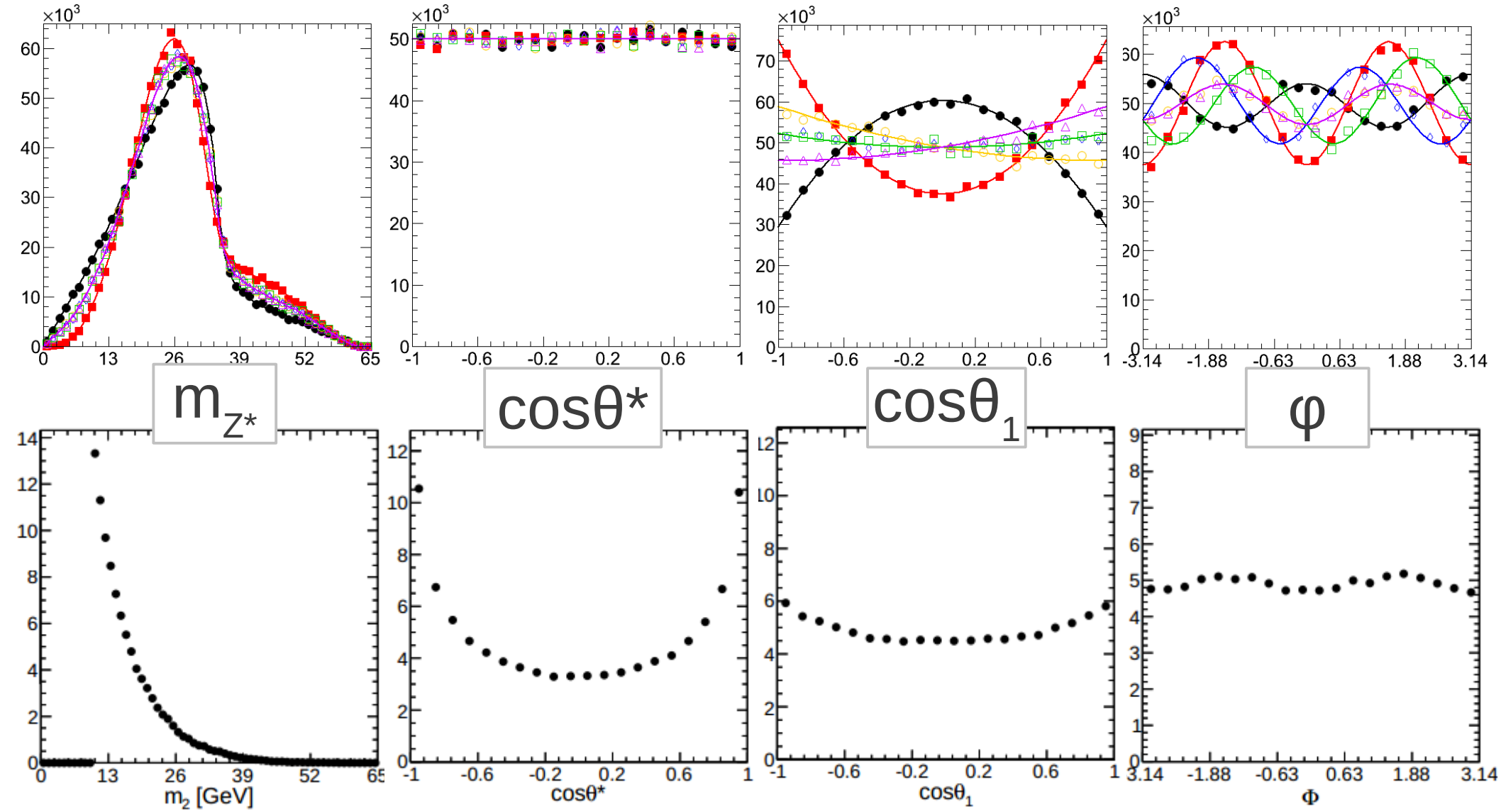
	fa3	Error
LHC (H → ZZ*) 300/fb	0.25	5.8×10^{-2}
LHC (H → ZZ*) 3000/fb	0.1	1.8×10^{-2}
e+e- → Z* → HZ √s=250 GeV	2.2×10^{-3}	8.0×10^{-4}
e+e- → Z* → HZ √s=500 GeV	1.1×10^{-4}	5.2×10^{-5}



- Significant improvement for e^+e^- collider (Z* → ZH) with respect to H→ZZ* on LHC

BACKUP

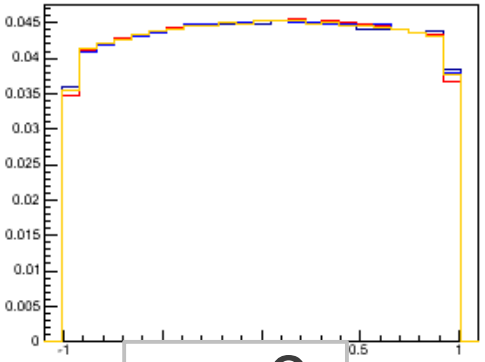
Spin-0 Kinematics (LHC)



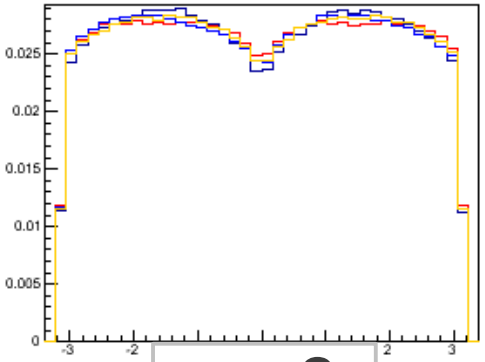
- Full matrix element information expected to:
  - provide ~20% improvement in signal sensitivity
  - provide sensitivity to both fa3 and phia3

LHC (H → ZZ*) det. effects

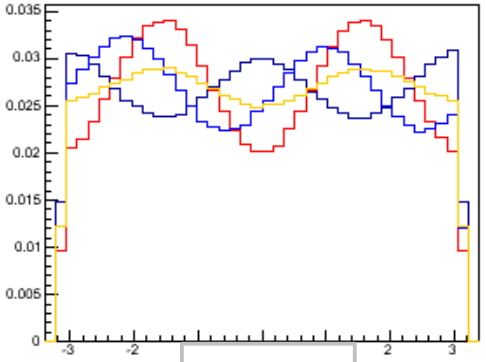
cosθ*



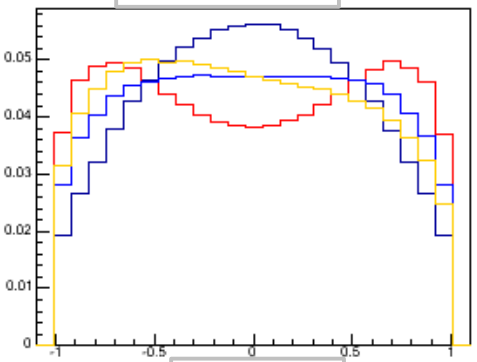
Φ_1



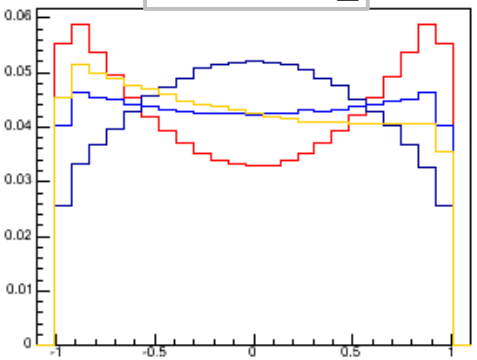
Φ



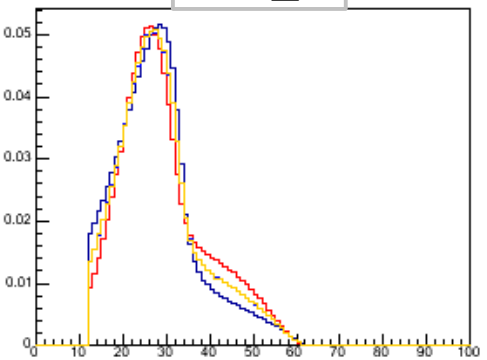
$\cos\theta_2$



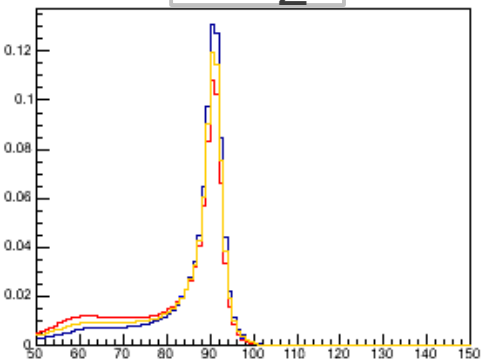
$\cos\theta_1$

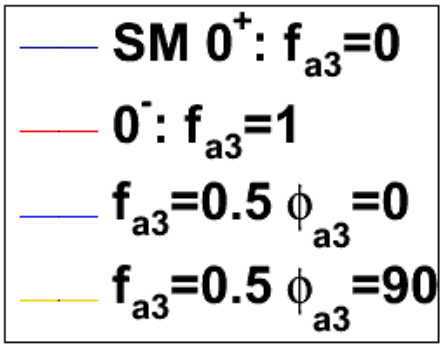


m_{Z^*}



m_Z





e+e− (Z* → HZ) det. effects

- Background shapes taken from continuum ZZ
  - Select events where 105< m_H <140
  - Leptons: $p_{T,l}$ > 5 GeV, |η|<2.4

- Signal model with acceptance cuts: