H→ZZ anomalous coupling measurement for CEPC

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Introduction

- The LHC experiments have carved a broad picture of the Higgs boson
  - Overall yields, extreme alternative spin and CP hypothesis
  - Far from confirming the Lorentz structure of the interactions e.g. H→ZZ

$$A(X_{J=0} \to VV) = \frac{1}{v}\left(g_1 m_V^2 \epsilon_1^* \epsilon_2^* + g_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + g_4 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu} \right)$$

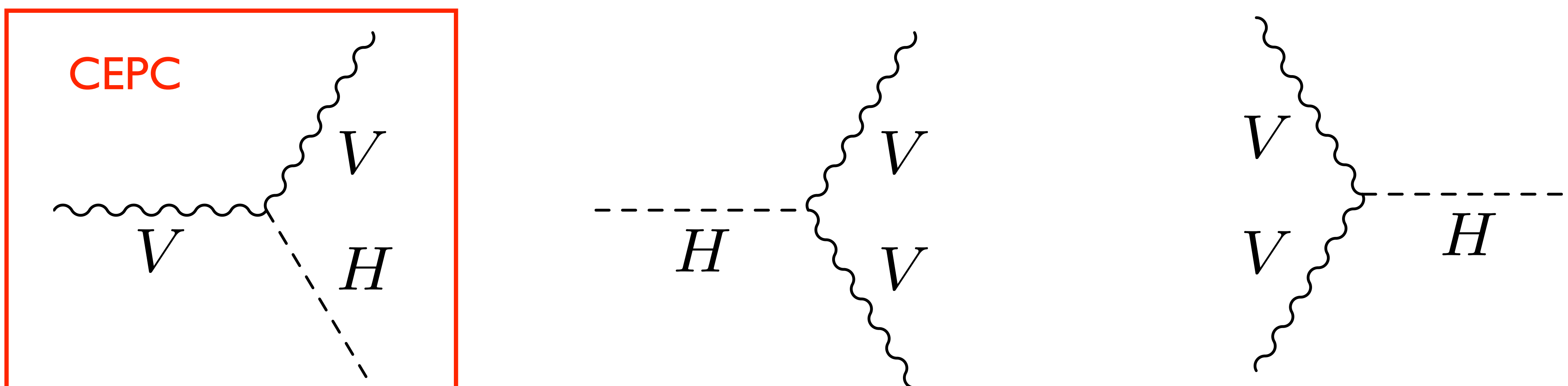
SM Higgs | High order 0+ | 0-

- Define experimental measurements "effective fraction of events"

$$f_{gi} = \frac{|g_i|^2 \sigma_i}{|g_1|^2 \sigma_1 + |g_2|^2 \sigma_2 + |g_4|^2 \sigma_4}$$

$$f_{CP} \equiv f_{g4} \equiv f_{a3}$$

- CEPC offers a great opportunity to ping down the Lorentz structure of the H→ZZ



Overview of our paper

- "Constraining anomalous HVV interactions at proton and lepton colliders"
  - Phys. Rev. D 89, 035007 (https://arxiv.org/abs/1309.4819)
  - 4 theorists: K. Melnikov, F. Caola, M. Schulze, Y. Zhou
  - 7 experimentalists: I. Anderson, S. Bolognesi, Y. Gao, A. V. Gritsan, C. Martin, N. Tran, A. Whitebeck
- This paper provided a single consistent framework to estimate the ultimate sensitivities of the anomalous couplings measurements of the HVV interaction vertex
  - Developed a consistent MC to model the HVV interaction vertex in productions and decays of the Higgs for both pp and ee colliders
  - Introduce matrix element likelihood approach (MELA) to maximising kinematics usage
  - Used a consistent statistical approach to estimate discovery potentials for HL-LHC/e+e- collider
- Both experimental tools (MC/MELA) are suitable for CEPC Higgs studies
  - Would be nice to repeat born-level analysis with CEPC detector simulation for CDR

JHUGen generator

- Public generator: http://www.pha.jhu.edu/~spin/
  - JHU stands for Johns Hopkins University as all authors are/were JHU students/pdocs/academics

  - Output lhe files, can interface with Pythia and Powheg
- Used extensively in the LHC (CMS/ATLAS) Higgs/EXO analysiesin the last 5 years
  - Especially in the H→ZZ→4l in the Higgs discovery and CP property measurements phase
  - Sustained extensive validations vs other generators (e.g. madgraph) and internal cross-checks
- e+e- collider sector is added in 2013 for this paper (US Snowmass 2013)
- Happy to support CEPC/SppC studies

Couplings → Helicity amplitudes

- Rewrite the HVV amplitudes in helicity based →kinematic distributions
  - Our earlier papers: https://arxiv.org/abs/1001.3396 https://arxiv.org/pdf/1208.4018.pdf

$$A(X \to V_1 V_2) = \frac{1}{v}\left(g_1^{(0)} m_V^2 \epsilon_1^* \epsilon_2^* + g_2^{(0)} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + g_3^{(0)} f^{*(1),\mu\nu} f_{\mu\alpha}^{*(2)} \frac{q_{2\nu} q_1^{\alpha}}{\Lambda^2} + g_4^{(0)} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}\right)$$

↓ polarisation vector ε

$$A(X \to V_1 V_2) = v^{-1} \epsilon_1^{*\mu} \epsilon_2^{*\nu} \left(a_1 g_{\mu\nu} m_X^2 + a_2\, q_\mu q_\nu + a_3 \epsilon_{\mu\nu\alpha\beta}\, q_1^{\alpha} q_2^{\beta}\right)$$

$$a_1 = g_1^{(0)} \frac{m_V^2}{m_X^2} + \frac{s}{m_X^2}\left(2g_2^{(0)} + g_3^{(0)} \frac{s}{\Lambda^2}\right), \quad a_2 = -\left(2g_2^{(0)} + g_3^{(0)} \frac{s}{\Lambda^2}\right), \quad a_3 = -2g_4^{(0)}$$

↓

Helicity amplitudes

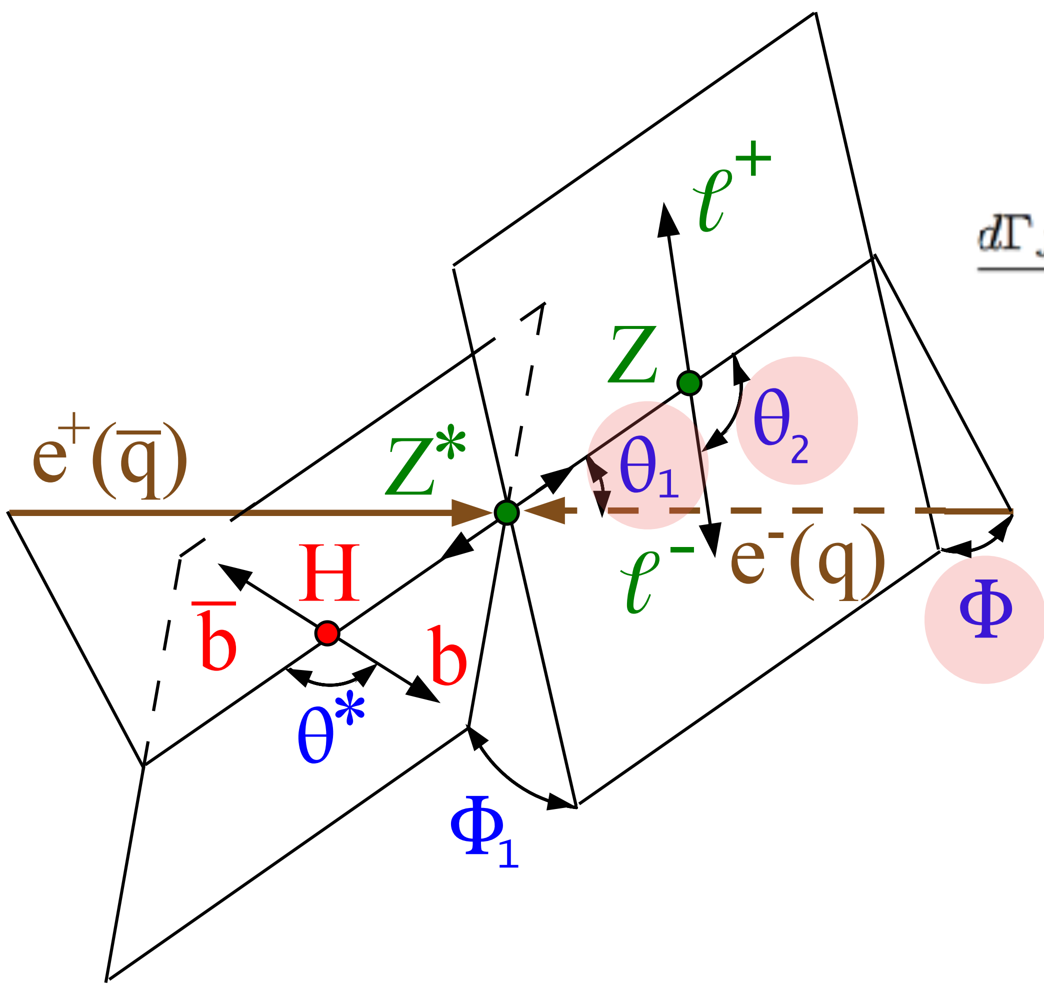
$$A_{00} = -\frac{m_X^2}{v}\left(a_1 \sqrt{1+x} + a_2 \frac{m_1 m_2}{m_X^2} x\right),$$

$$A_{++} = \frac{m_X^2}{v}\left(a_1 + i a_3 \frac{m_1 m_2}{m_X^2} \sqrt{x}\right),$$

$$A_{--} = \frac{m_X^2}{v}\left(a_1 - i a_3 \frac{m_1 m_2}{m_X^2} \sqrt{x}\right),$$

Angular calculations ↔ helicity amplitudes

- Five angles are needed to describe the full chain
    - Full kinematics also include constant term m_Z and m_{Z^*} (250 GeV) (Referred to as m1, m2)
- Assume we are dealing with spin-0 Higgs like boson, angular information reduces to
    - $\Omega = \{\theta_1, \theta_2, \phi\}$, depends only on the $Z \rightarrow ll$ decays
    - Differential angular distributions are fully predicted (basic QM)
    - These distributions carry information of helicity amplitudes hence couplings



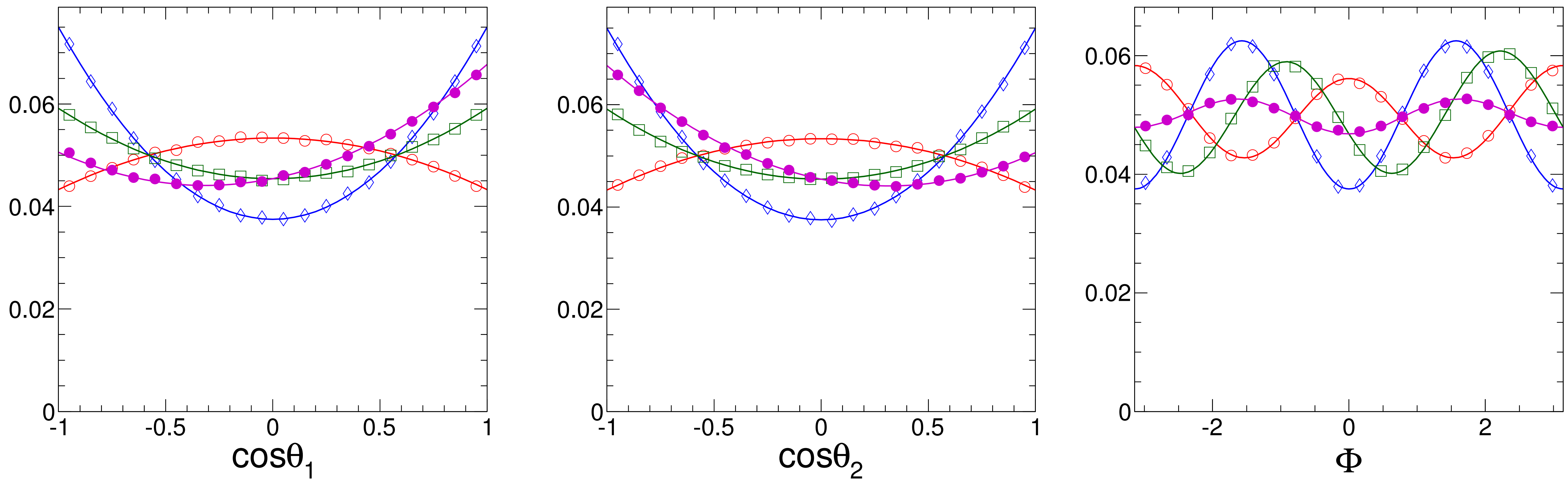
$$
\begin{aligned}
\frac{d\Gamma_{J=0}(s,\vec{\Omega})}{d\vec{\Omega}} \propto\ & 4\,|A_{00}|^2 \sin^2\theta_1 \sin^2\theta_2 \\
& + |A_{+0}|^2 \left(1 - 2R_1\cos\theta_1 + \cos^2\theta_1\right)\left(1 + 2A_{f_2}\cos\theta_2 + \cos^2\theta_2\right) \\
& + |A_{-0}|^2 \left(1 + 2R_1\cos\theta_1 + \cos^2\theta_1\right)\left(1 - 2A_{f_2}\cos\theta_2 + \cos^2\theta_2\right) \\
& - 4|A_{00}||A_{+0}|(R_1 - \cos\theta_1)\sin\theta_1(A_{f_2} + \cos\theta_2)\sin\theta_2\cos(\Phi + \phi_{+0}) \\
& - 4|A_{00}||A_{-0}|(R_1 + \cos\theta_1)\sin\theta_1(A_{f_2} - \cos\theta_2)\sin\theta_2\cos(\Phi - \phi_{-0}) \\
& + 2|A_{+0}||A_{-0}|\sin^2\theta_1\sin^2\theta_2\cos(2\Phi - \phi_{-0} + \phi_{+0})\,.
\end{aligned}
\quad \text{(A2)}
$$

Ideal projections

- Compare the numerical simulation with analytical distributions at born level without cuts
    - First step of validations of both approach

Lines: analytical calculation Dots: JHUGen MC

— 0+ — 0- — f_{CP}=0.5, ϕ=0 — f_{CP}=0.5, ϕ=0



Event selections

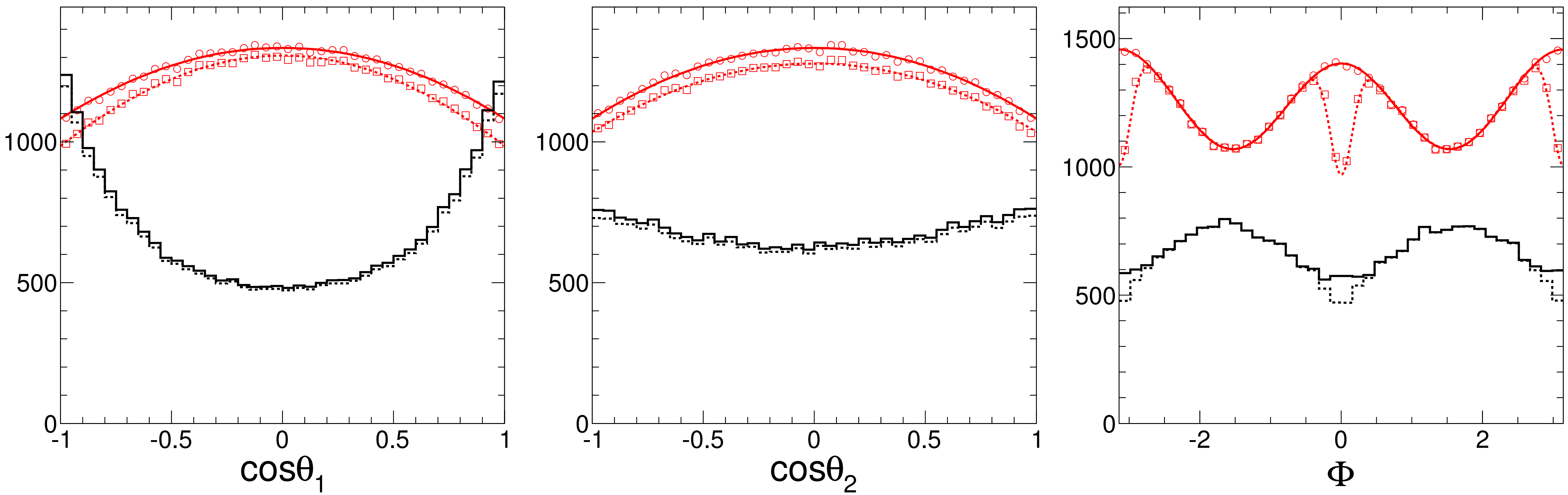
- Consider only the (ll bb) final states
  - As the H->bb angular information is not used, can easily extend to include other decays
- Acceptance selections
  - Leptons pT > 5 GeV, $|\eta| < 2.4$
  - Lepton efficiency impact => overal 80% per event level
  - No smearing is applied
- Assume relative 10% background modelled with ZZ->μμbb
  - Back-of-envelope estimations in 2013, very preliminary

	Process	Generator	$\sigma \times BR$	nEvents (250 fb^{-1})
Signal	e+e-→ZH→llbb	JHUGen	9.35 fb	1870
Background	e+e-→ZZ→llbb	Madgraph	-	187

Acceptance

- Acceptance can be parameterised using step function

$$\mathcal{G}(m_1, m_2, \vec{\Omega}) = \prod_{\ell} \theta(|\eta_{\max}| - |\eta_\ell(m_1, m_2, \vec{\Omega})|), \quad \text{(B6)}$$



Statistical analysis to extract couplings (e.g. f_{a3})

- Multi-dimensional fit to observed kinematic distribution through maximum likelihood fit

$$\mathcal{L} = \exp\left(-n_{\rm sig} - n_{\rm bkg}\right) \prod_i^N \left(n_{\rm sig} \times \mathcal{P}_{\rm sig}(\vec{x}_i;\ \vec{\zeta}) + n_{\rm bkg} \times \mathcal{P}_{\rm bkg}(\vec{x}_i)\right)$$

observables

Parameters of interests

$$\vec{x}_i = \{m_1, m_2, \vec{\Omega}\}_i$$

$$\vec{\zeta} = \{f_{a2}, \phi_{a2}, f_{a3}, \phi_{a3}, \ldots\}$$

$$\mathcal{P}_{\rm sig}(\vec{x}_i; f_{a3}, \phi_{a3}) = (1 - f_{a3})\,\mathcal{P}_{0^+}(\vec{x}_i) + f_{a3}\,\mathcal{P}_{0^-}(\vec{x}_i) + \sqrt{f_{a3}(1 - f_{a3})}\,\mathcal{P}_{\rm int}(\vec{x}_i; \phi_{a3})$$

- Choice of $\vec{x}_i, \vec{\zeta}$
  - Most optimal: full kinematics information in multi-dimensional space
  - Challenging: detector response and background parameterisations in multi-dimensions
  - Balance these two factors also depends on the available statistics

MELA discriminants

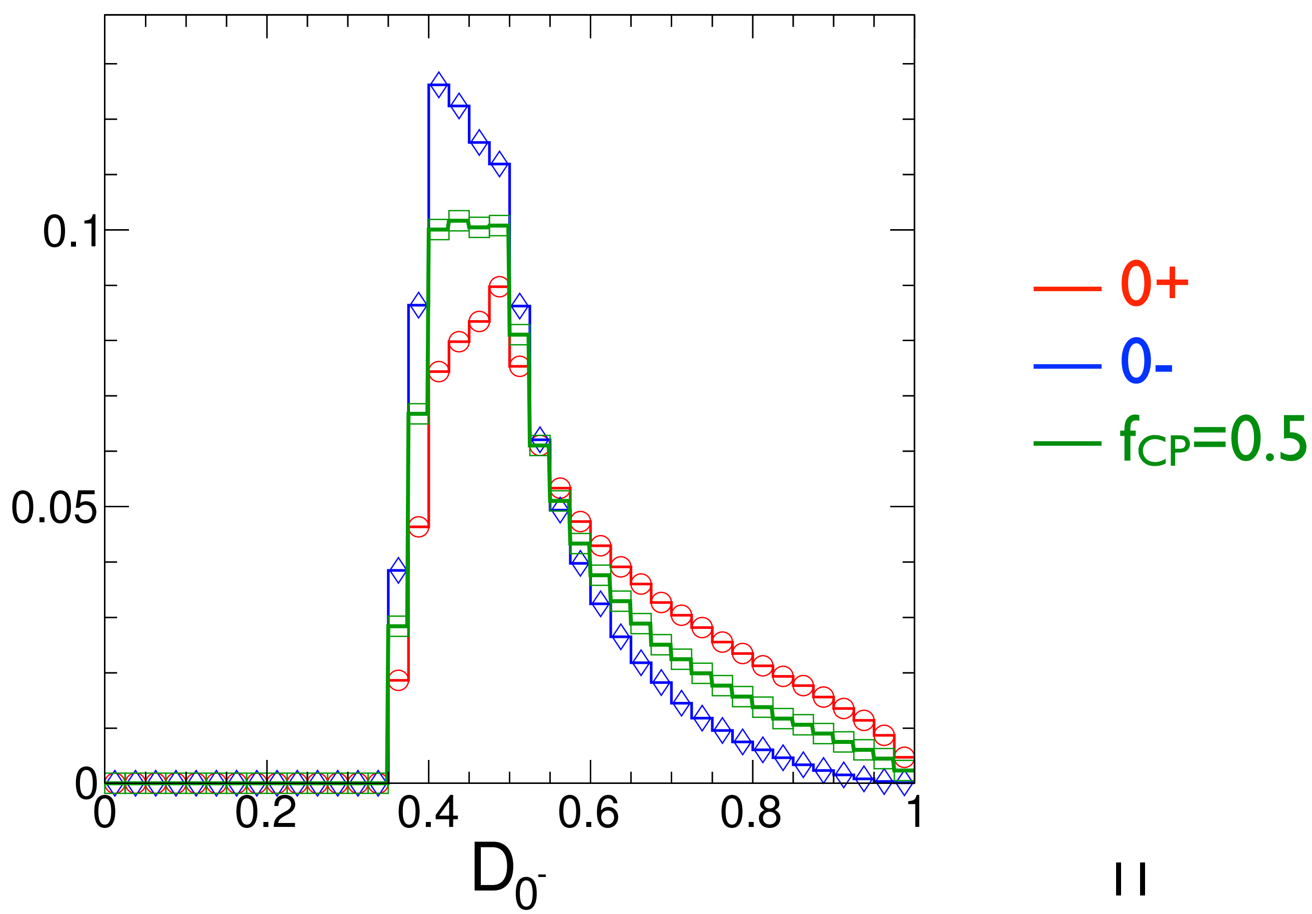
- Collapse full angular information (including correlation) into discriminants
  - Particularly useful when statistics is too challenging for a full 3-D fit (used often at LHC H->4l)
  - Start from expected probability distributions (full kin.) of interesting processes (e.g. P_{0+}, P_{0-})
    - Can be from analytical calculations or numerical values obtained directly from MC program
  - Construct linear combination of relevant processes to separate two hypotheses

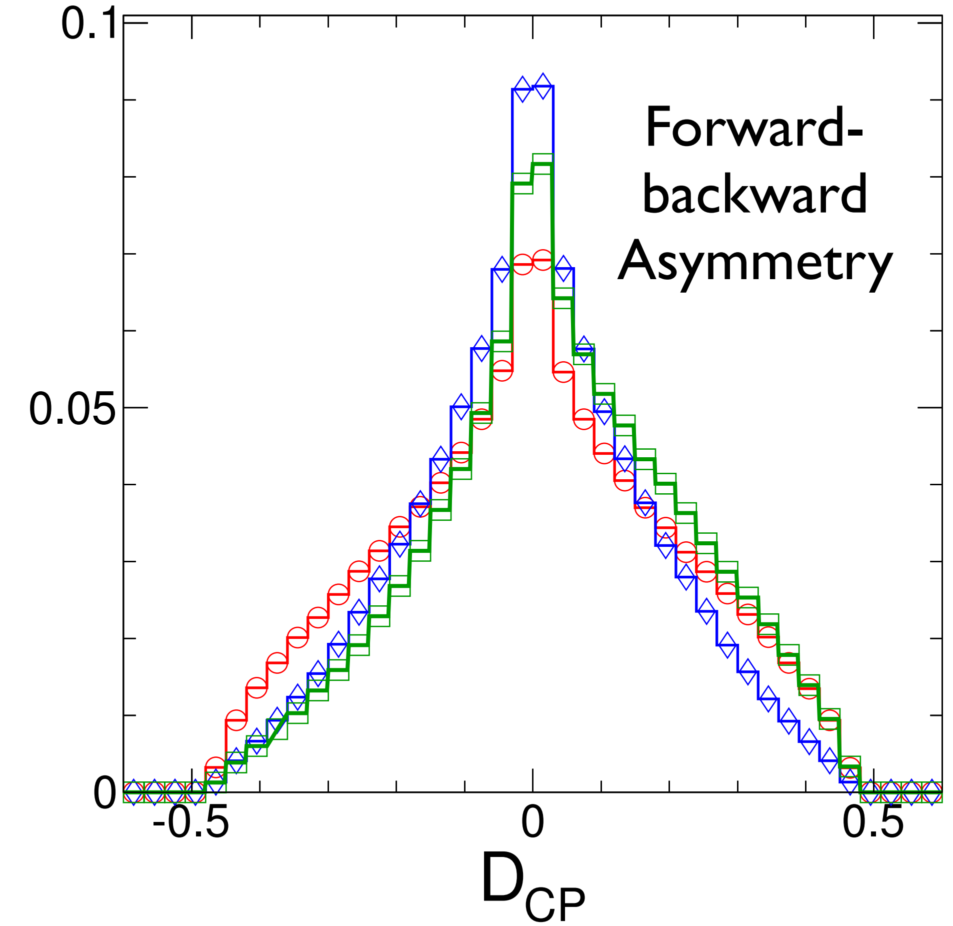
0+ vs 0-

$$D_{0^-} = \frac{\mathcal{P}_{0^+}}{\mathcal{P}_{0^+} + \mathcal{P}_{0^-}} = \left[1 + \frac{\mathcal{P}_{0^-}(m_1, m_2, \vec{\Omega})}{\mathcal{P}_{0^+}(m_1, m_2, \vec{\Omega})}\right]^{-1}$$

0+ vs 0+/0- interference

$$D_{CP} = \frac{\mathcal{P}_{\rm int}(m_1, m_2, \vec{\Omega}; \phi_{a3})}{\mathcal{P}_{0^+}(m_1, m_2, \vec{\Omega}) + \mathcal{P}_{0^-}(m_1, m_2, \vec{\Omega})}$$





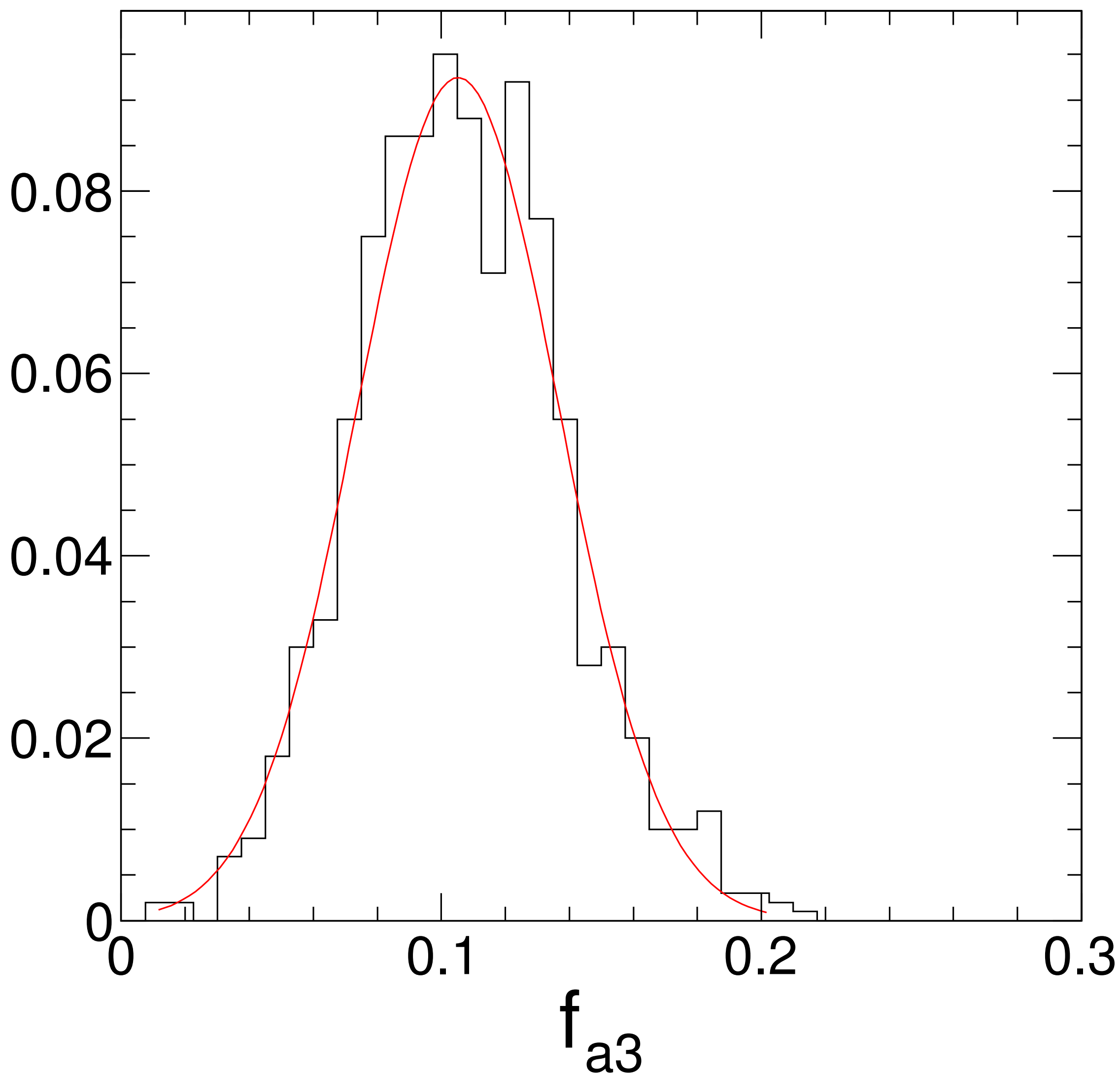
Statistical analysis (II)

- Quantify 3σ discovery sensitivity for f_{a3}

$$f_{a3}/\sigma(f_{a3}) = 3$$

- Sample through different fa3 values

- For a given f_{a3} perform pseudo-experiments to evaluate the expected precision of f_{a3}
  - Generate 1000 pseudo-datasets either from expected probability function or MC datasets
  - For each toy data we perform ML fit
  - Check output of these 1000 fits
    - Verify fit quality by checking pull distributions
  - Take Gaussian error of the fitted fa3 as σ(fa3)



Compare different approaches

- Illustrate the loss of sensitivity using partial kinematics

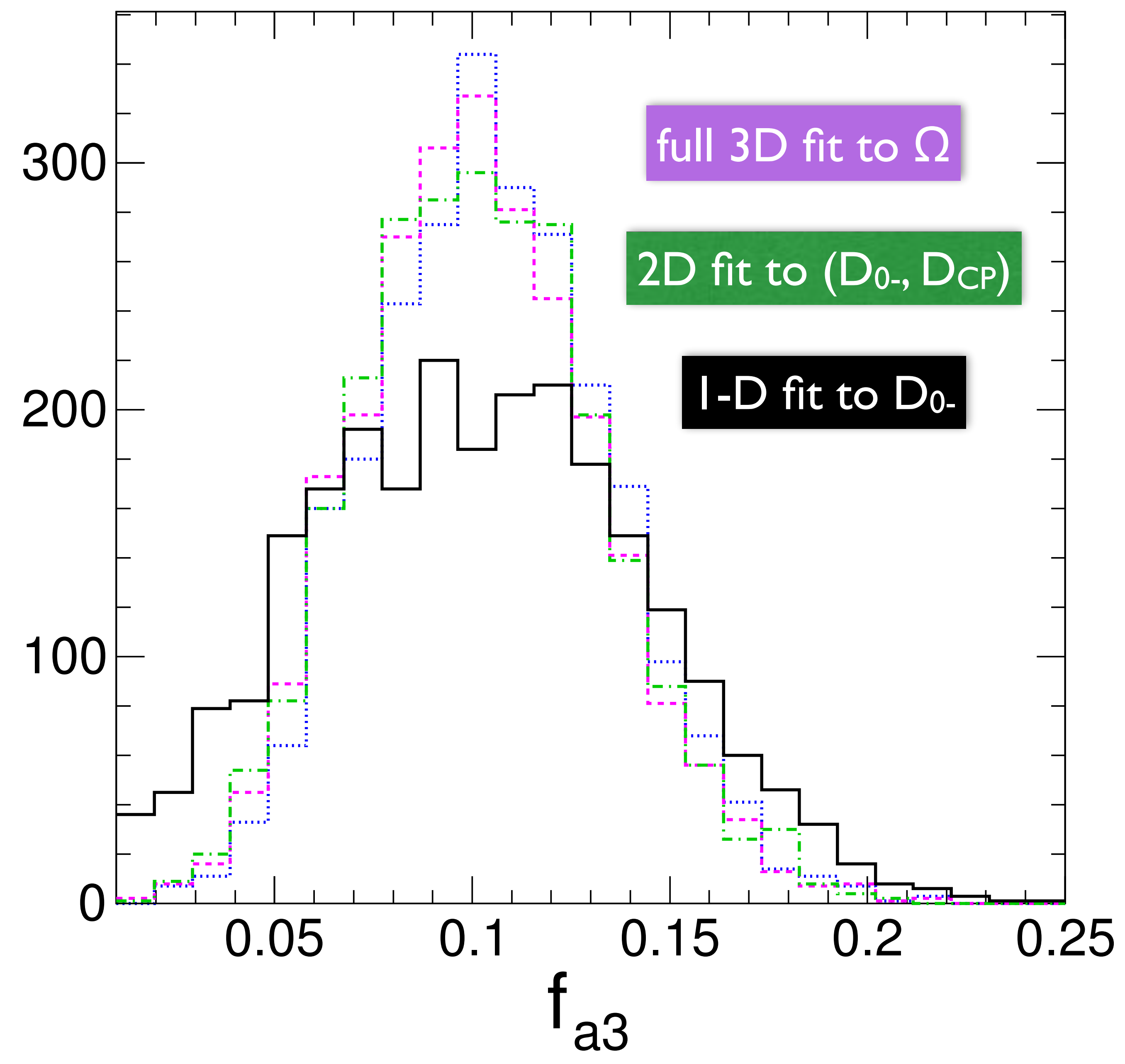
$$1\text{D}: \vec{x}_i = \{D_{0-}\}_i, \vec{\zeta} = \{f_{a3}\}$$

$$2\text{D}: \vec{x}_i = \{D_{0-}, D_{CP}\}_i, \vec{\zeta} = \{f_{a3}, \phi_{a3}\}$$

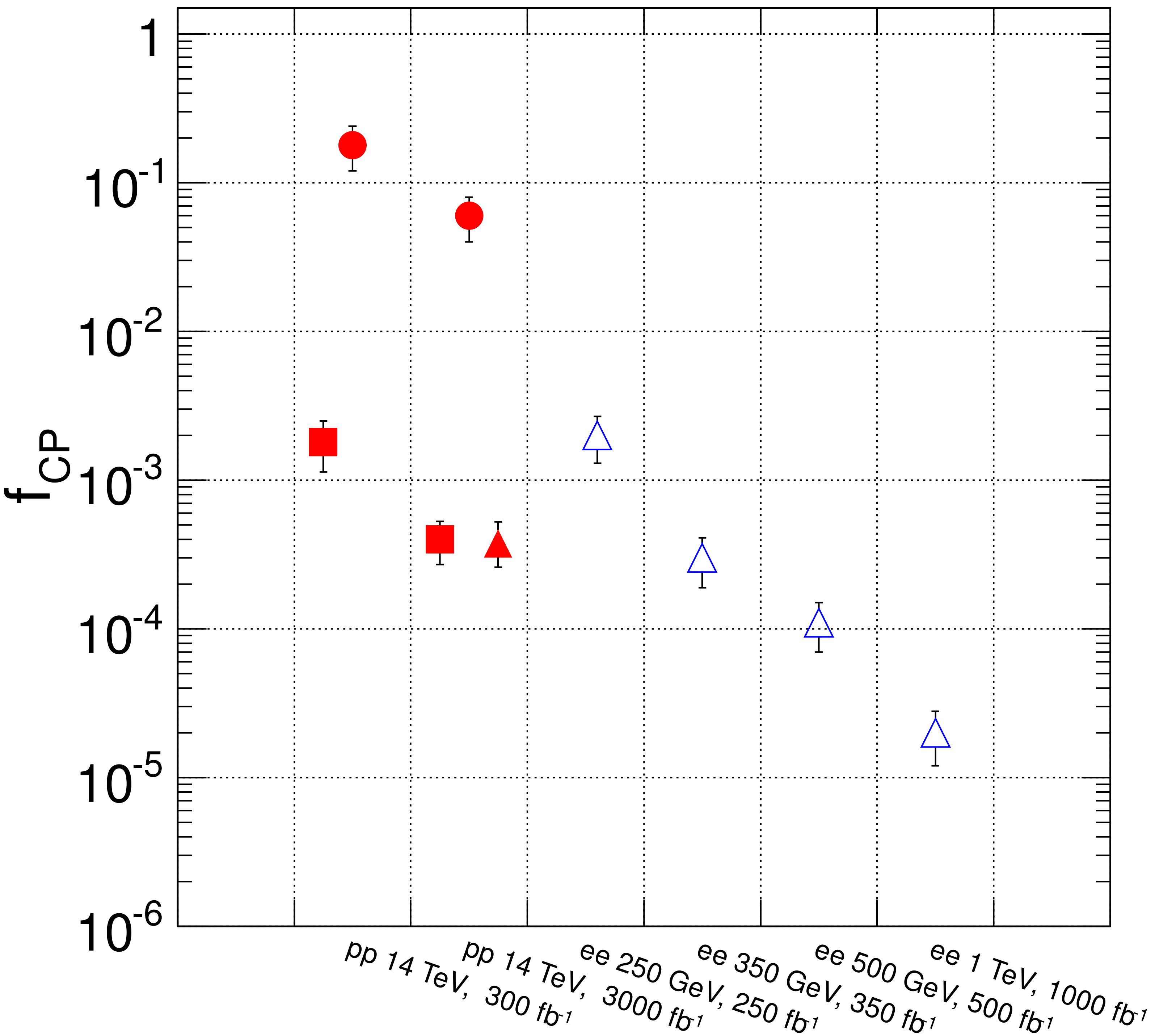
$$3\text{D}: \vec{x}_i = \{\theta_1, \theta_2, \phi\}_i, \vec{\zeta} = \{f_{a3}, \phi_{a3}\}$$

  - Using signal only fits
    - Conclusion does not change when including background
- Main loss in 1D fit ignoring interference
  - Interference scales to sqrt(fa3)
  - important for small fa3
- Sensitivity is recovered by adding D_{CP}

Generate: fa3 = 0.18



Global picture



- LHC VBF and pp->ZH analysis can deteriorate drastically as pileup ↑
- What about f_{CP} constraints instead of discovery?
- What about ee→ZH including detector simulation and inclusive H decay?

Summary and future plans

- Anomalous coupling measurement of HZZ interaction vertex is interesting for the CEPC
- Introduced two experimental tools suitable for CEPC/SppC
  - JHUGen MC generator
  - Matrix element likelihood approach
- Presented very rough sensitivity studies using born-level quantities
  - Quantified as the discovery potential for a given f_{CP}
- Very interested in applying the similar techniques to CEPC detector simulation
  - Can be added as a straightforward plug-in on top of the existing analyses
  - Ideal 1-2 months project for students
    - Look for collaborators
  - Otherwise, can this be added as it is for CEPC CDR?