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

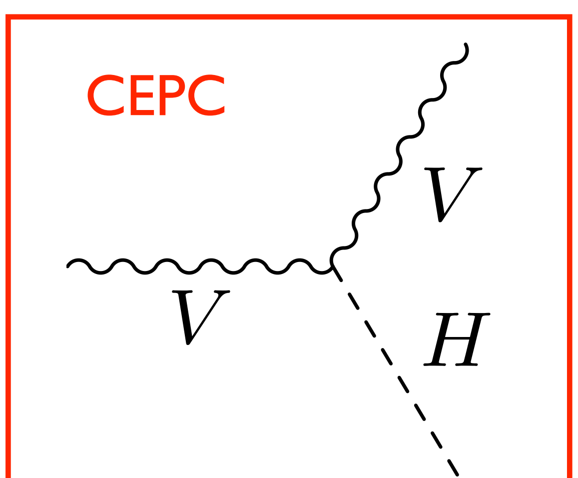
$$A(X_{J=0} \to VV) = \frac{1}{v}\left(g_1 m_V^2 \epsilon_1^* \epsilon_2^* + g_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + g_4 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu} \right)$$

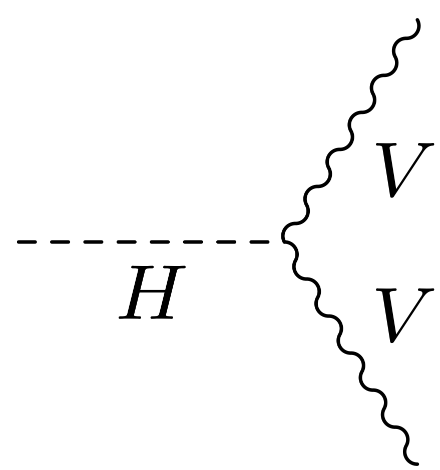
SM Higgs | High order 0+ | 0-

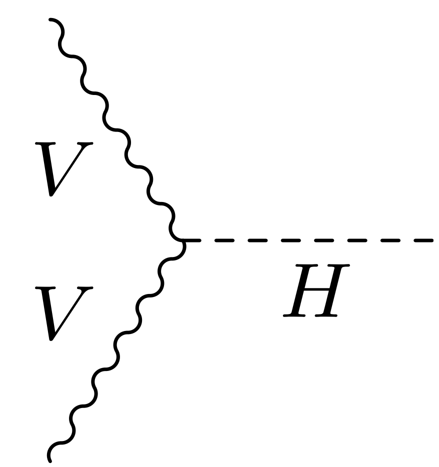
- Define experimental measurements "effective fraction of events"

$$f_{gi} = \frac{|g_i|^2 \sigma_i}{|g_1|^2\sigma_1 + |g_2|^2\sigma_2 + |g_4|^2\sigma_4} \qquad \boxed{f_{\rm CP} \equiv f_{g4} \equiv f_{a3}}$$

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





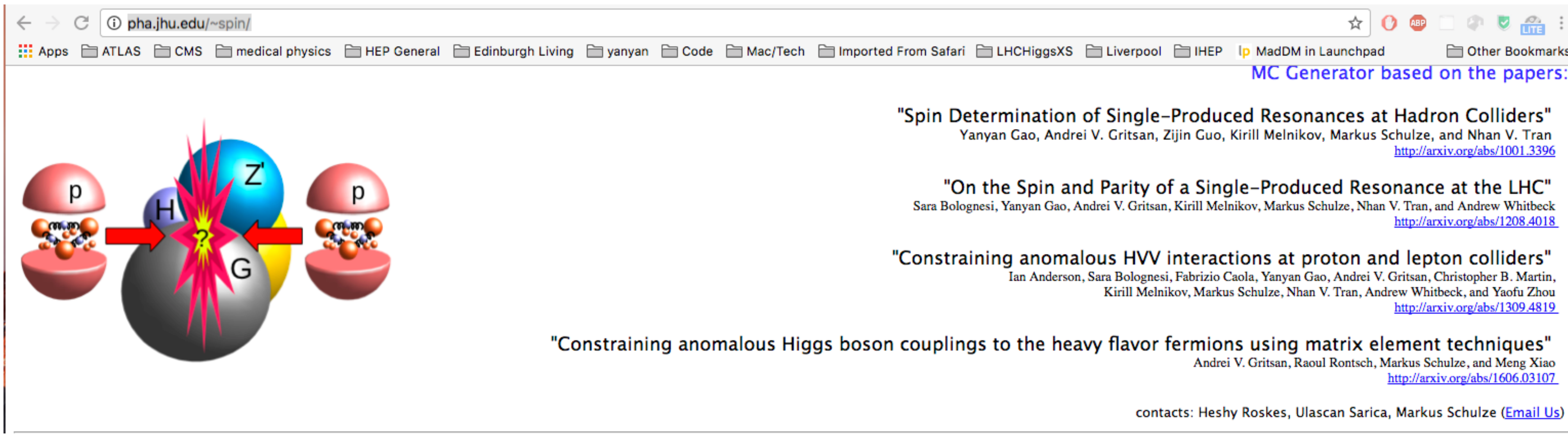


Overview of our paper

- “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



MC Generator based on the papers:

"Spin Determination of Single-Produced Resonances at Hadron Colliders"
Yanyan Gao, Andrei V. Gritsan, Zijin Guo, Kirill Melnikov, Markus Schulze, and Nhan V. Tran
http://arxiv.org/abs/1001.3396

"On the Spin and Parity of a Single-Produced Resonance at the LHC"
Sara Bolognesi, Yanyan Gao, Andrei V. Gritsan, Kirill Melnikov, Markus Schulze, Nhan V. Tran, and Andrew Whitbeck
http://arxiv.org/abs/1208.4018

"Constraining anomalous HVV interactions at proton and lepton colliders"
Ian Anderson, Sara Bolognesi, Fabrizio Caola, Yanyan Gao, Andrei V. Gritsan, Christopher B. Martin, Kirill Melnikov, Markus Schulze, Nhan V. Tran, Andrew Whitbeck, and Yaofu Zhou
http://arxiv.org/abs/1309.4819

"Constraining anomalous Higgs boson couplings to the heavy flavor fermions using matrix element techniques"
Andrei V. Gritsan, Raoul Rontsch, Markus Schulze, and Meng Xiao
http://arxiv.org/abs/1606.03107

contacts: Heshy Roskes, Ulascan Sarica, Markus Schulze (Email Us)

  - 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 $H \to ZZ \to 4l$ 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

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

polarisation vector ε

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

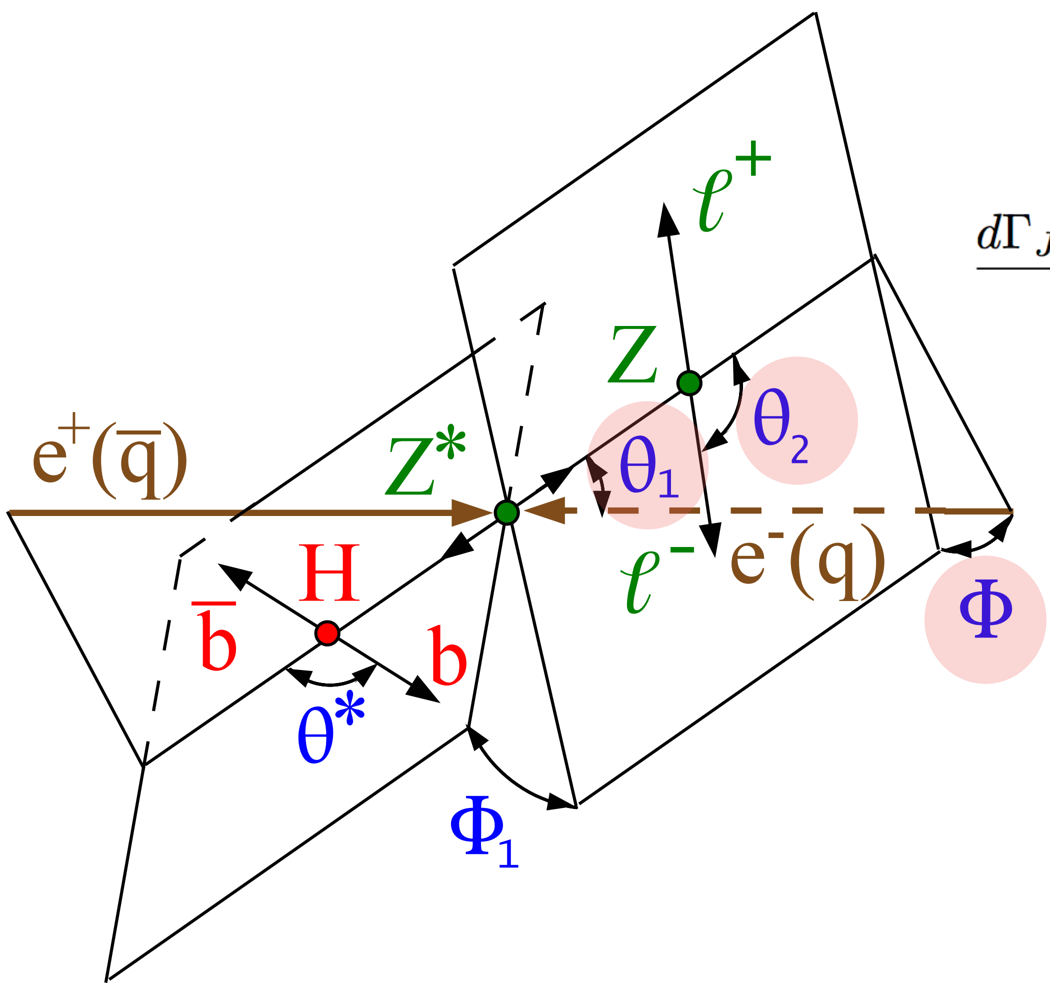
$$a_1 = g_1^{(0)} \frac{m_V^2}{m_X^2} + \frac{s}{m_X^2}\left(2 g_2^{(0)} + g_3^{(0)} \frac{s}{\Lambda^2}\right), \quad a_2 = -\left(2 g_2^{(0)} + g_3^{(0)} \frac{s}{\Lambda^2}\right), \quad a_3 = -2 g_4^{(0)}$$

Helicity amplitudes

$$\boxed{\begin{aligned} A_{00} &= -\frac{m_X^2}{v}\left(a_1 \sqrt{1+x} + a_2 \frac{m_1 m_2}{m_X^2} x \right), \\ A_{++} &= \frac{m_X^2}{v}\left(a_1 + i a_3 \frac{m_1 m_2}{m_X^2} \sqrt{x} \right), \\ A_{--} &= \frac{m_X^2}{v}\left(a_1 - i a_3 \frac{m_1 m_2}{m_X^2} \sqrt{x} \right), \end{aligned}}$$

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→ll decays
  - Differential angular distributions are fully predicted (basic QM)
  - These distributions carry information of helicity amplitudes hence couplings



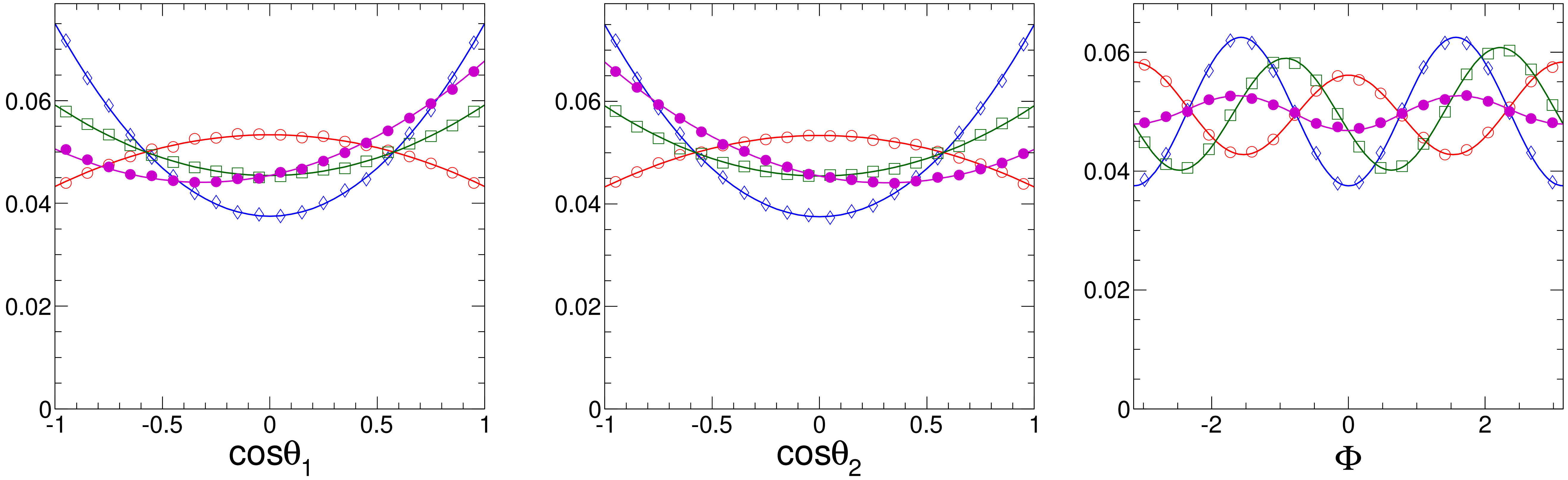
$$
\begin{aligned}
\frac{d\Gamma_{J=0}(s,\vec{\Omega})}{d\vec{\Omega}} \propto\ & 4\,|A_{00}|^2 \sin^2\theta_1 \sin^2\theta_2 \\
& + |A_{+0}|^2 \left(1 - 2R_1\cos\theta_1 + \cos^2\theta_1\right)\left(1 + 2A_{f_2}\cos\theta_2 + \cos^2\theta_2\right) \\
& + |A_{-0}|^2 \left(1 + 2R_1\cos\theta_1 + \cos^2\theta_1\right)\left(1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

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

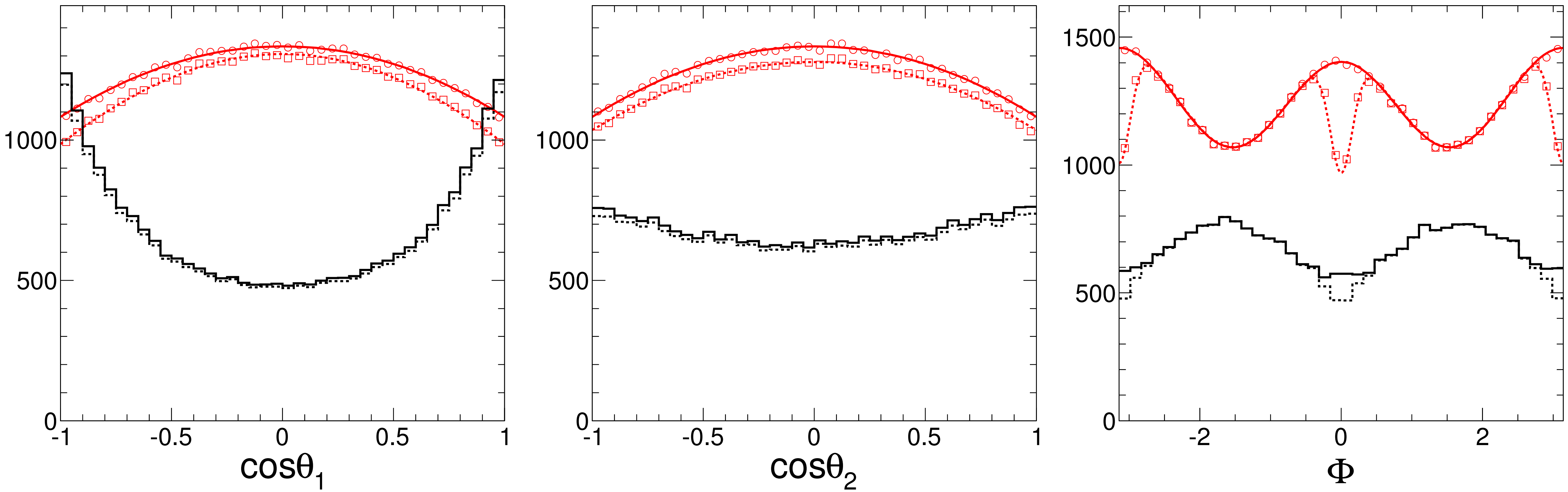
— 0+   — 0-   — f_{CP}=0.5, ϕ=0   — f_{CP}=0.5, ϕ=0



Acceptance

- Acceptance can be parameterised using step function

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



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 => overall 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 (fb^{-1})
Signal	e+e-→ZH→llbb	JHUGen	9.35 fb	8
Background	e+e-→ZZ→llbb	Madgraph	-	0.8

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

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

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

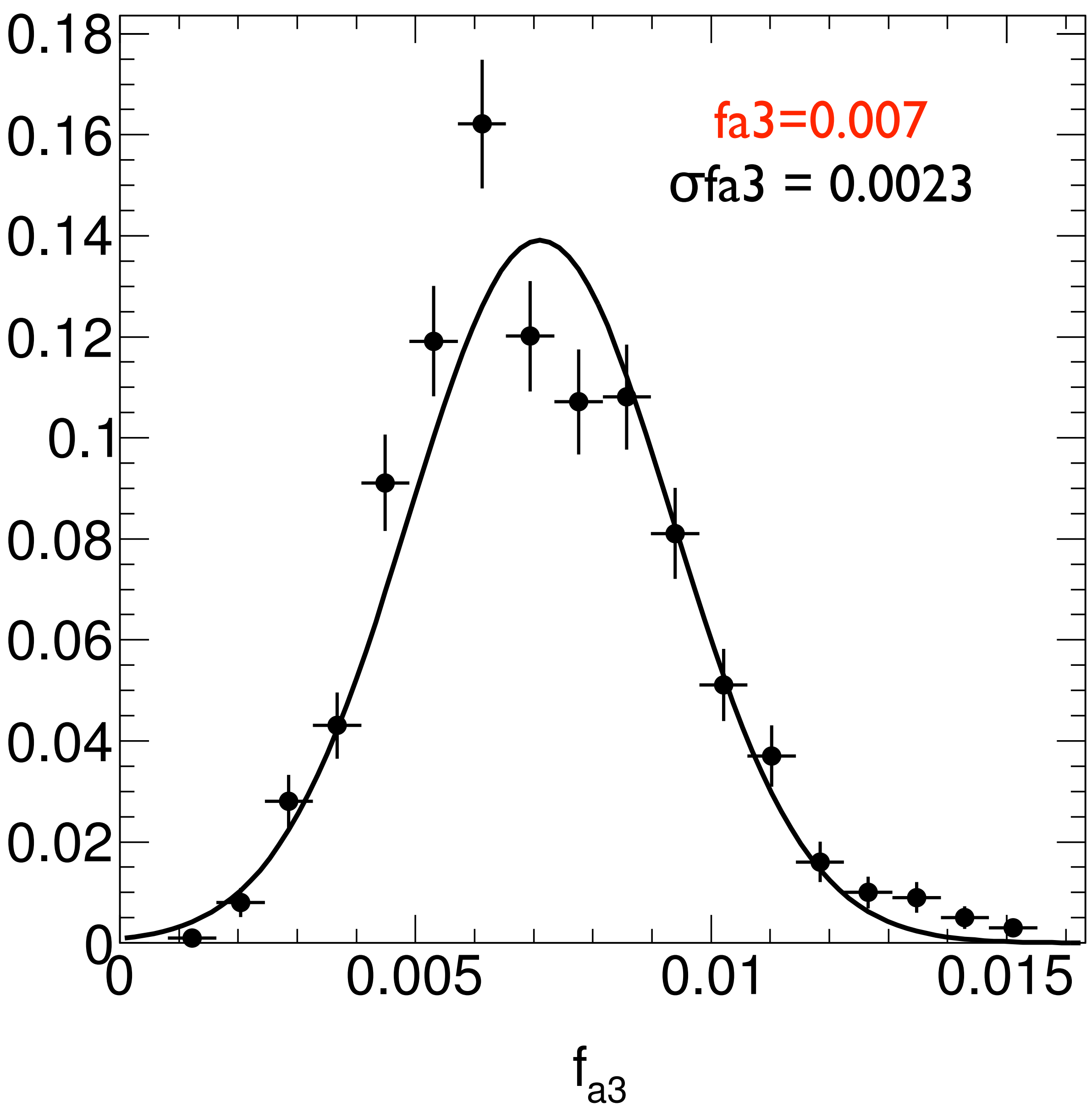
$$\mathcal{P}_{\rm sig}(\vec{x}_i; f_{a3}, \phi_{a3}) = (1 - f_{a3})\,\mathcal{P}_{0^+}(\vec{x}_i) + f_{a3}\,\mathcal{P}_{0^-}(\vec{x}_i) + \sqrt{f_{a3}(1 - f_{a3})}\,\mathcal{P}_{\rm int}(\vec{x}_i; \phi_{a3})$$

- 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

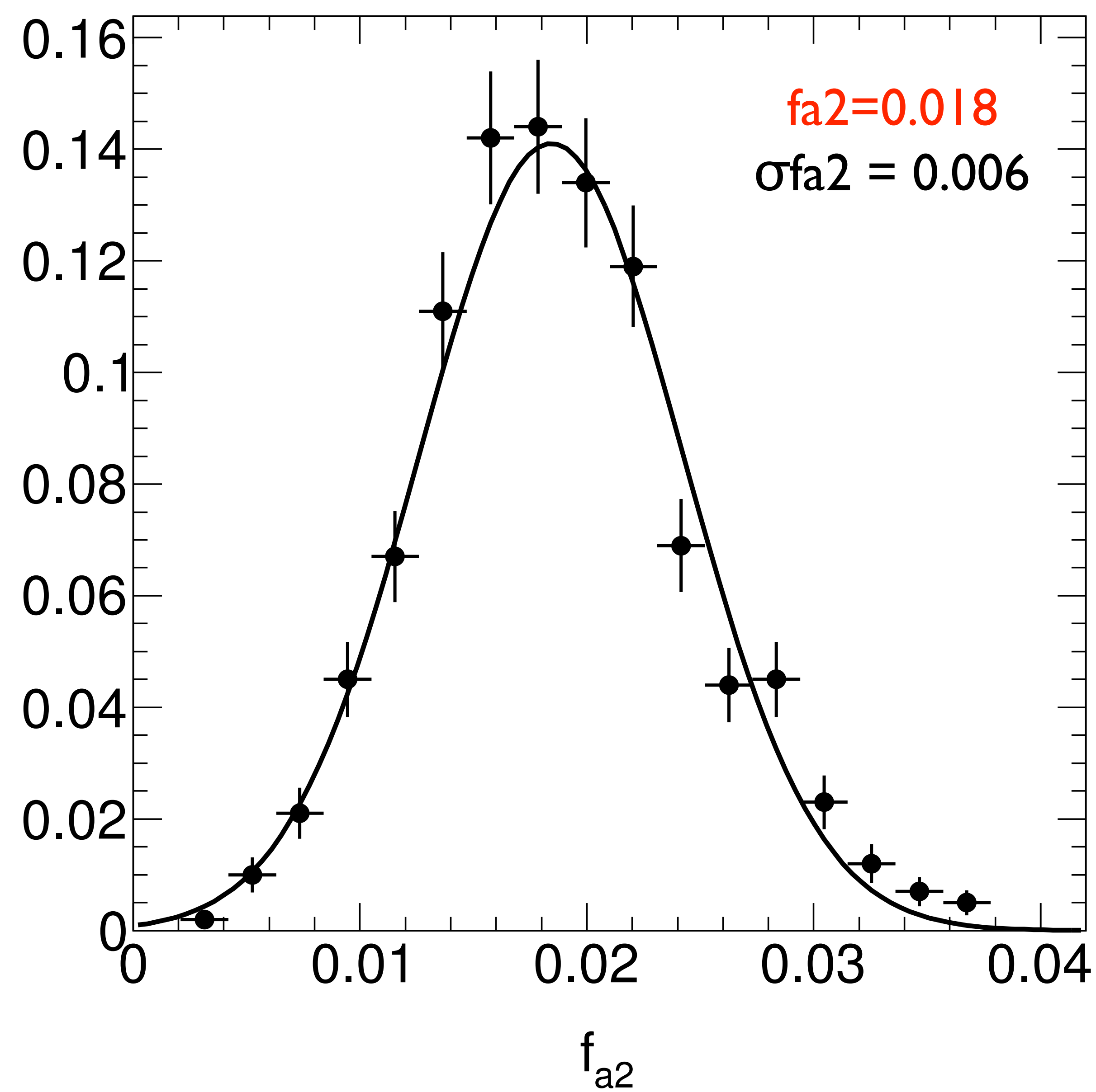
Statistical analysis (II)

- Quantify sensitivity as 3σ discovery value f/σ
  - Scan different f_{a3} and f_{a2} values until this is met
- For each trial f-value, perform pseudo-experiments to evaluate f/σ
  - Generate 1000 pseudo-datasets from expected PDF
  - For each toy data we perform a 3D ML fit as described in previous slide
    - With one parameter fitted: fa3 or fa2 floated
    - With 2 parameters fitted: (fa3, fa2), (fa3, phia3) or (fa2, phia2)
  - Check output of these 1000 fits and verify fit quality by checking pull distributions
  - Take Gaussian error of the fitted value as the sigma
  - Repeats until found the value of f which gives f/σ = 3
- These f-values obtained at CEPC are then converted to the equivalent values defined for H->ZZ decays for comparisons
  - Recall that the σ_2/σ_{SM} and σ_4/σ_{SM} depends on the m(Z*) which is different from CEPC and H->ZZ

Results (1D)



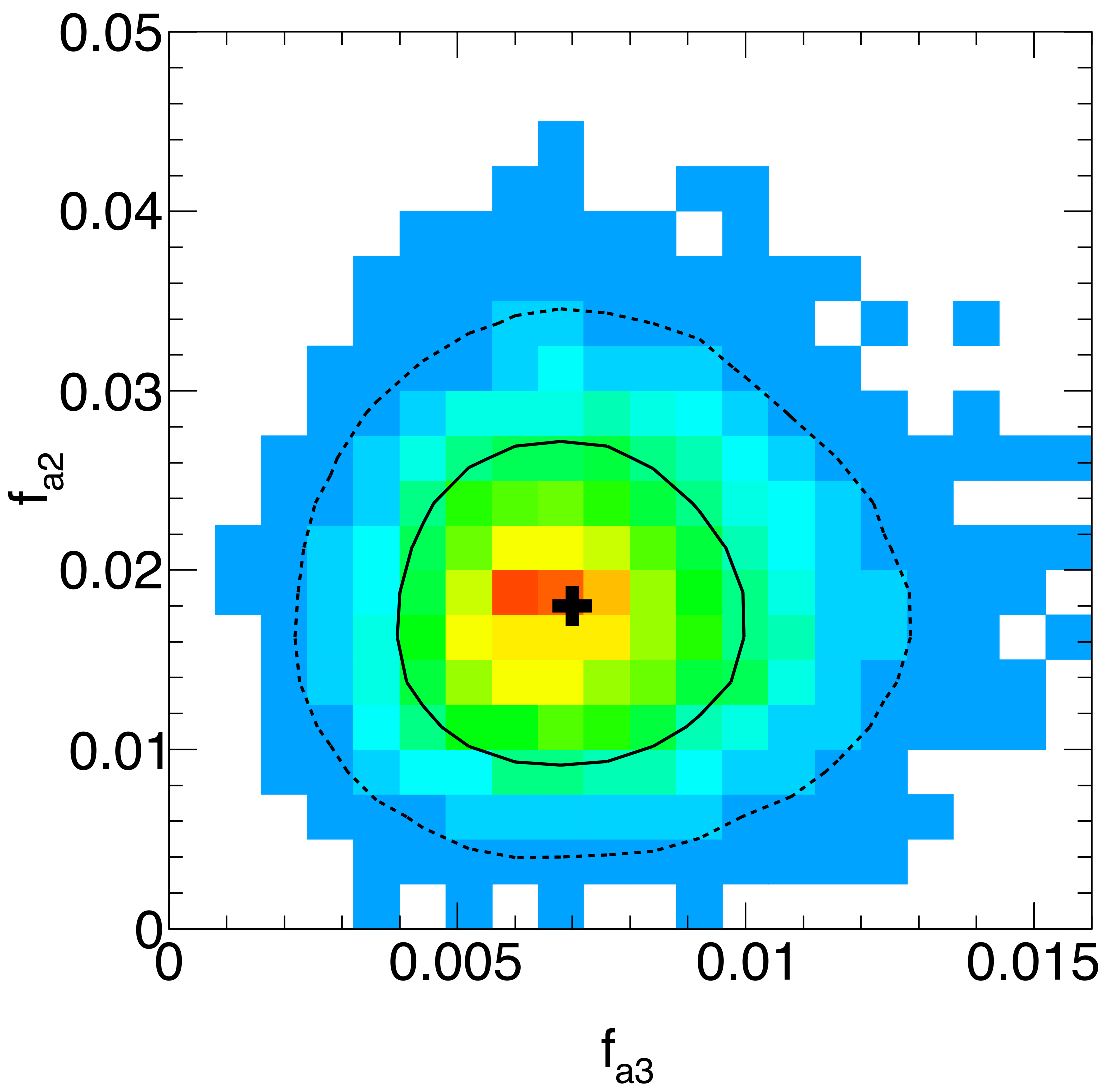
fa3=0.007
σfa3 = 0.0023
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
0.005
0.01
0.015
f_{a3}



fa2=0.018
σfa2 = 0.006
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
0.01
0.02
0.03
0.04
f_{a2}

Results (2D)

- Central values are the discovery sensitivity obtained in the 2 fits in previous slides



	HL-LHC	CEPC
fa2	0.06	2×10^{-4}
fa3	3.7×10^{-4}	1.3×10^{-4}