H→ZZ* SM and anomalous coupling measurement

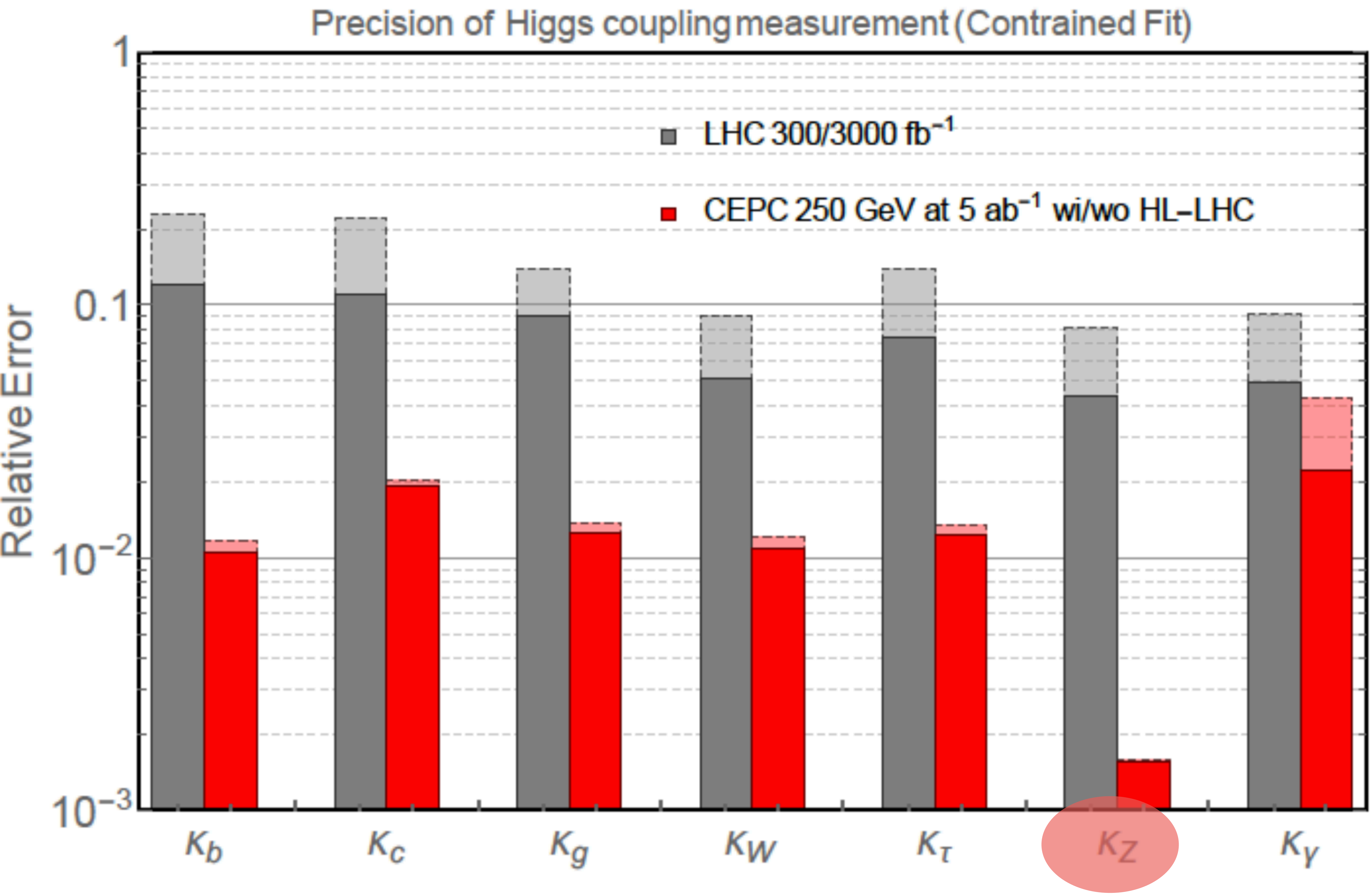
Yanyan Gao

University of Liverpool

Summarising many contributions in the Higgs white paper under preparation

CEPC Rome workshop, 25-May-2018

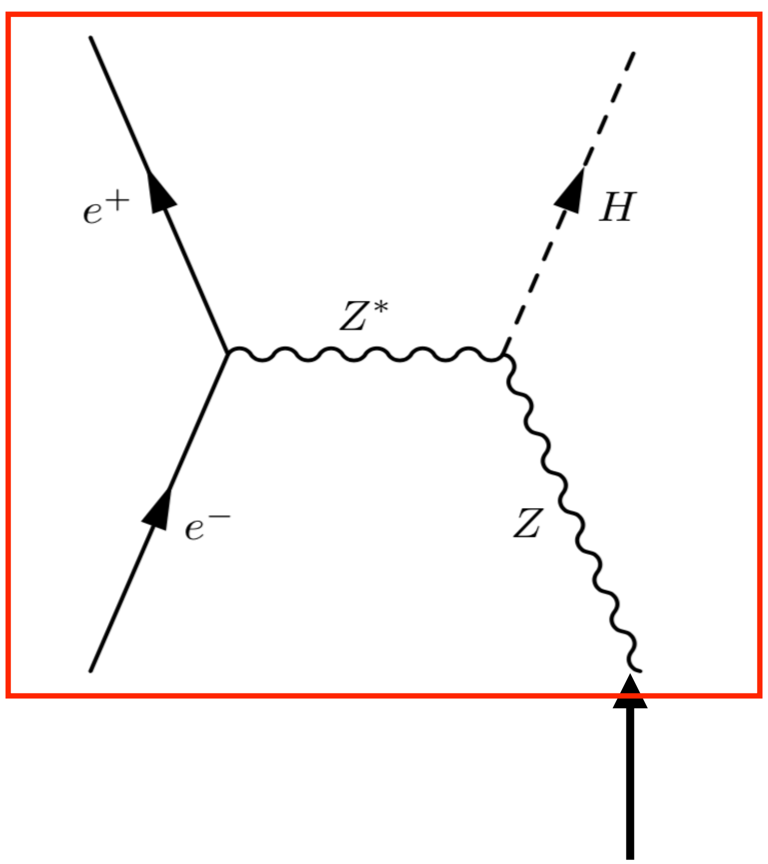
The big picture



Higgs production at the CEPC

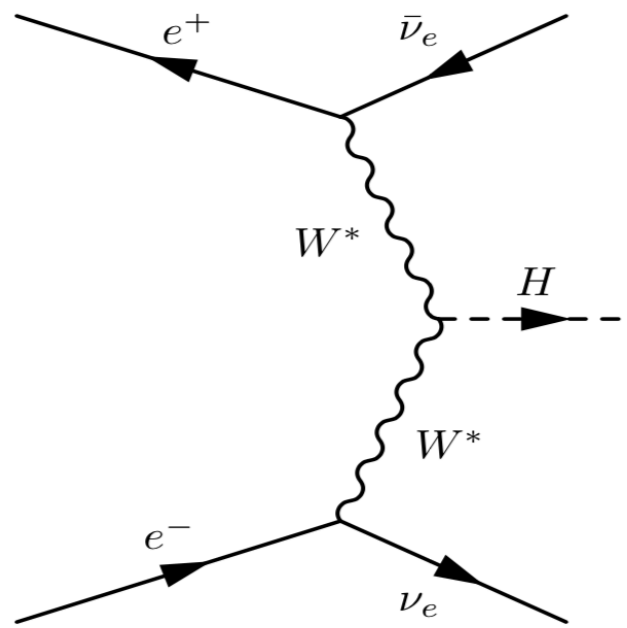
At sqrt(s)=240 GeV, assuming mH=125 GeV

212 fb

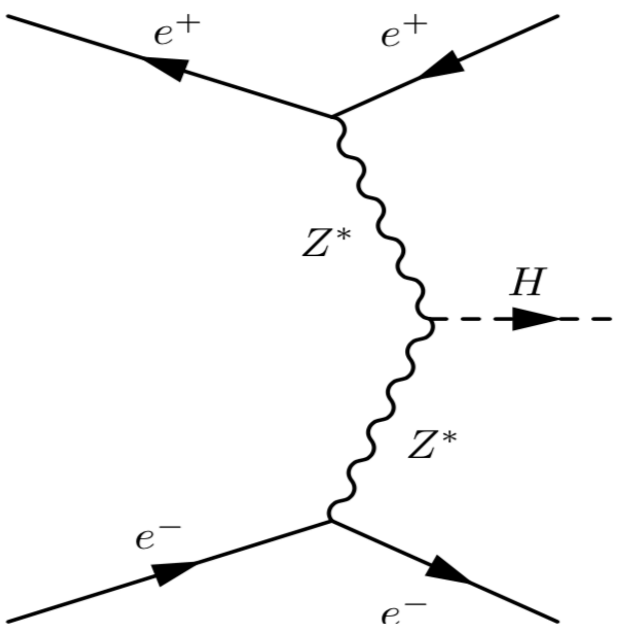


All Z-decays (ll, qq, νν) are usable

6.72 fb



0.63 fb

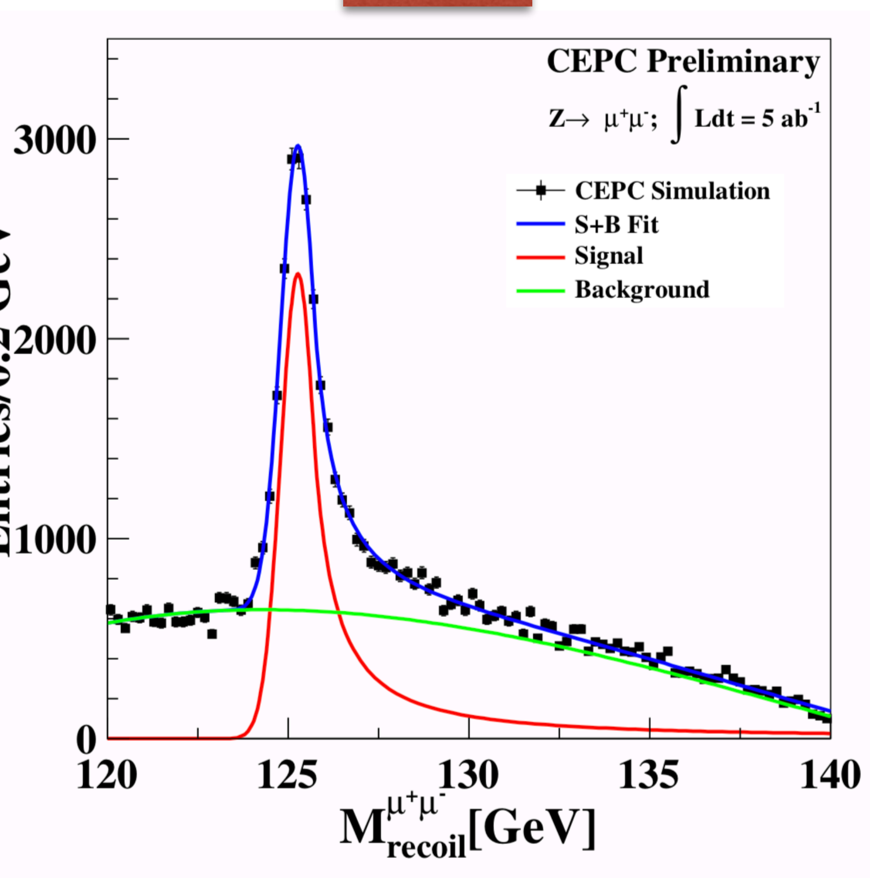


At the LHC, sqrt(s) = 14 TeV: σ(gg→H→ZZ→4l) = 49.85E3*1.25E-04=6.23 fb
σ(pp→ZH) = 883 fb (*limited by systematics in H→bb or BF in other decays*)

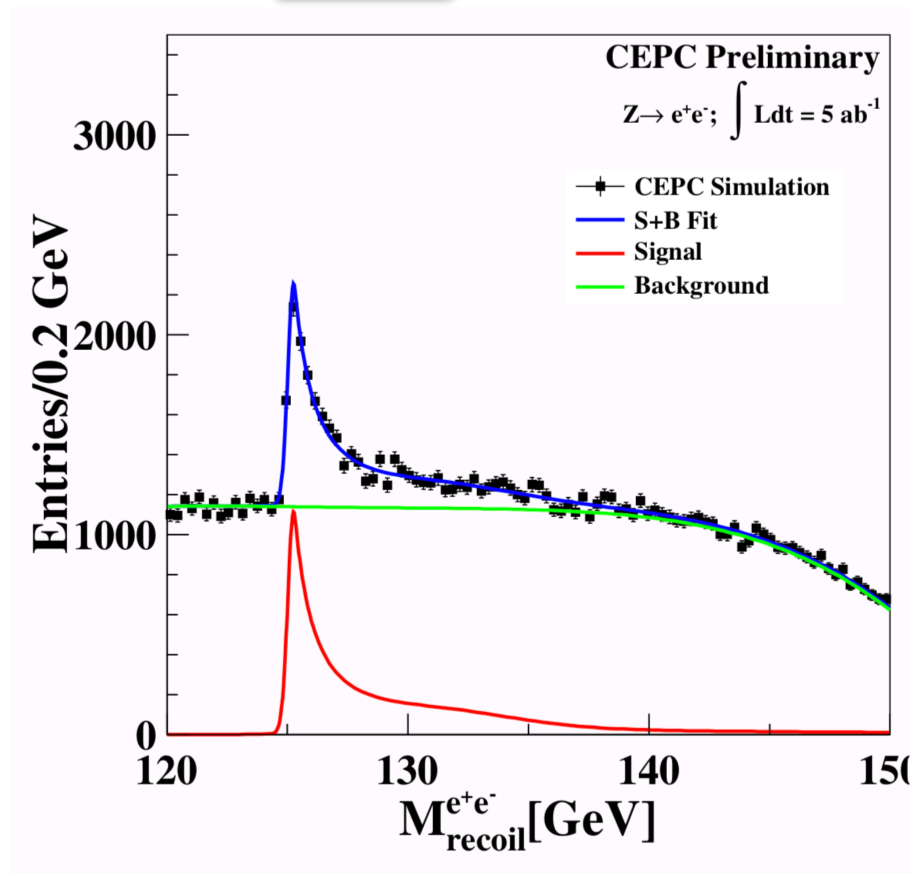
All studies shown later assume integrated luminosity of 5ab^{-1}

Higgs boson tagging using recoil mass

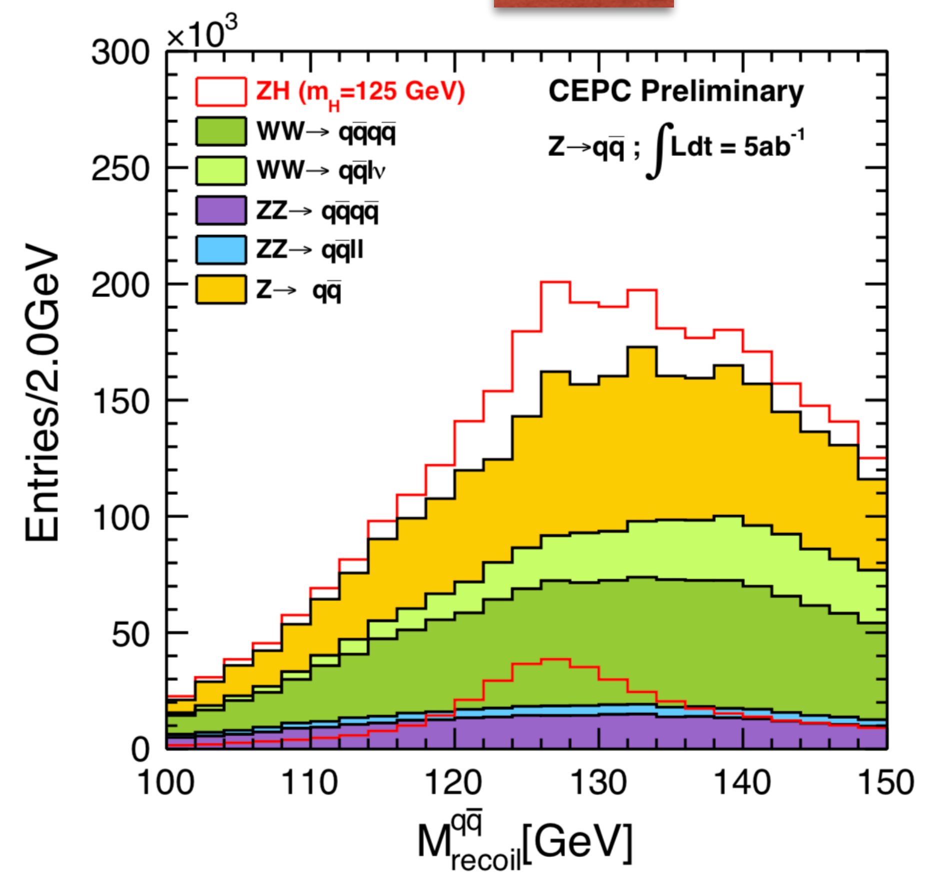
$Z \to \mu\mu$



$Z \to ee$



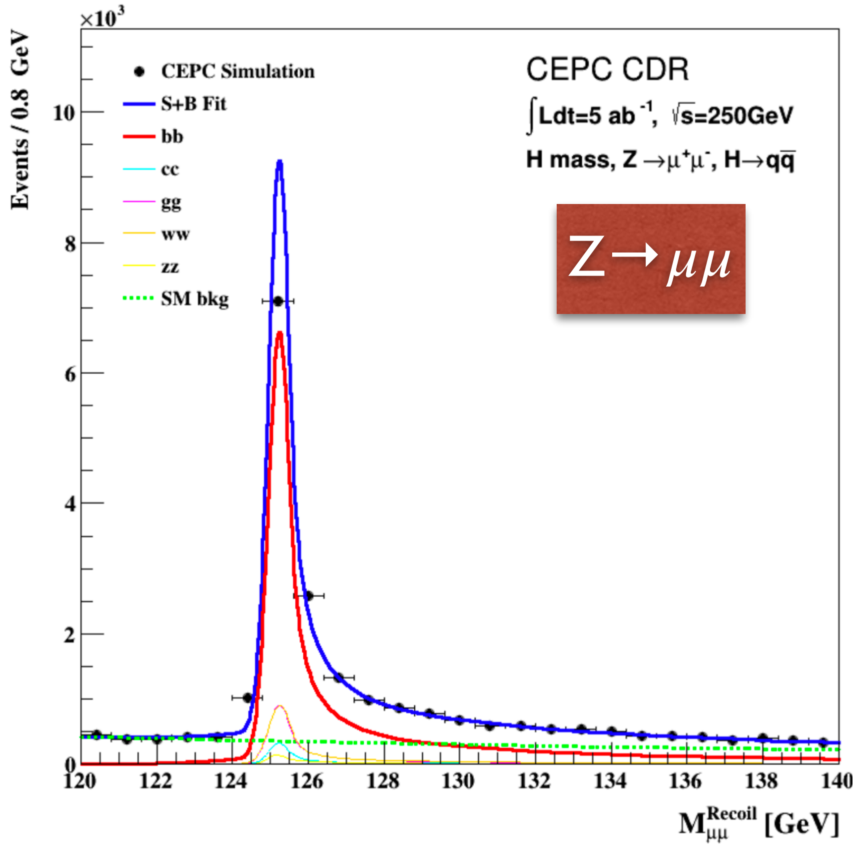
$Z \to qq$

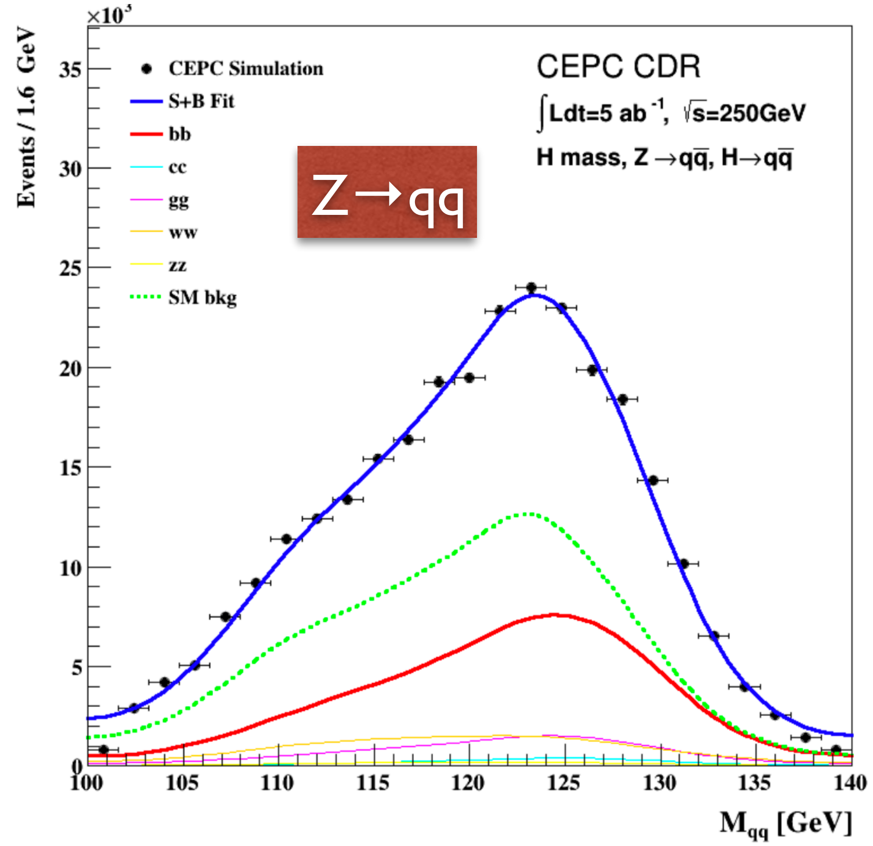


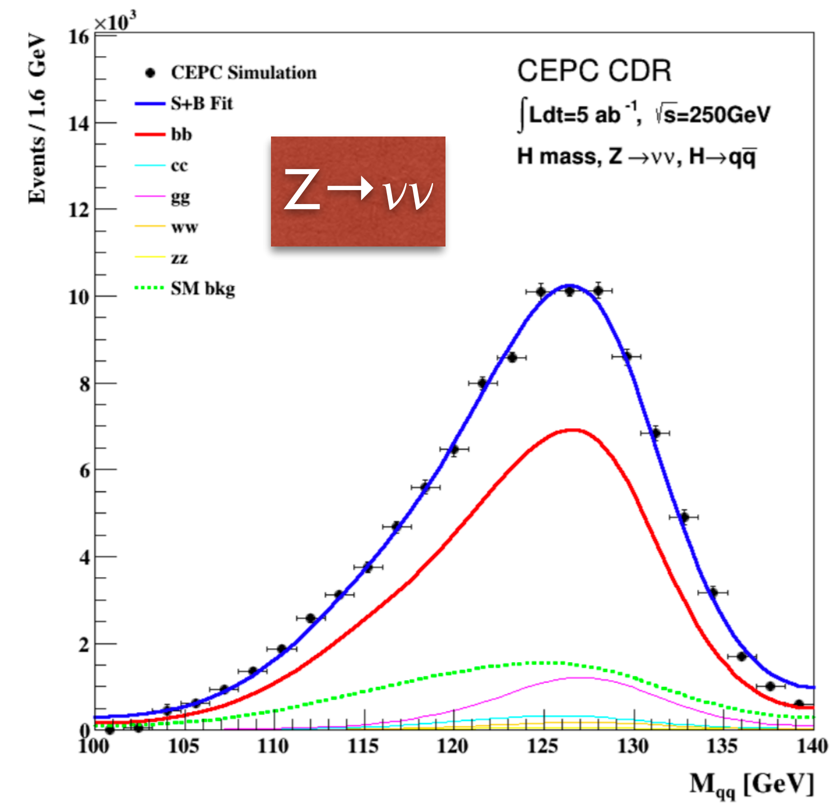
Z decay mode	Δm_H (MeV)	$\Delta\sigma(ZH)/\sigma(ZH)$
e^+e^-	14	2.1%
$\mu^+\mu^-$	6.5	0.9%
$q\bar{q}$	–	$\boxed{0.65\%}$
$e^+e^- + \mu^+\mu^- + q\bar{q}$	5.9	0.5%

$\sigma(ZH)\times BF(H\rightarrow ff)$

- Combined with the inclusive $\sigma(ZH)$ measurements, individual decay channels allow for independent Higgs boson branching fraction measurements

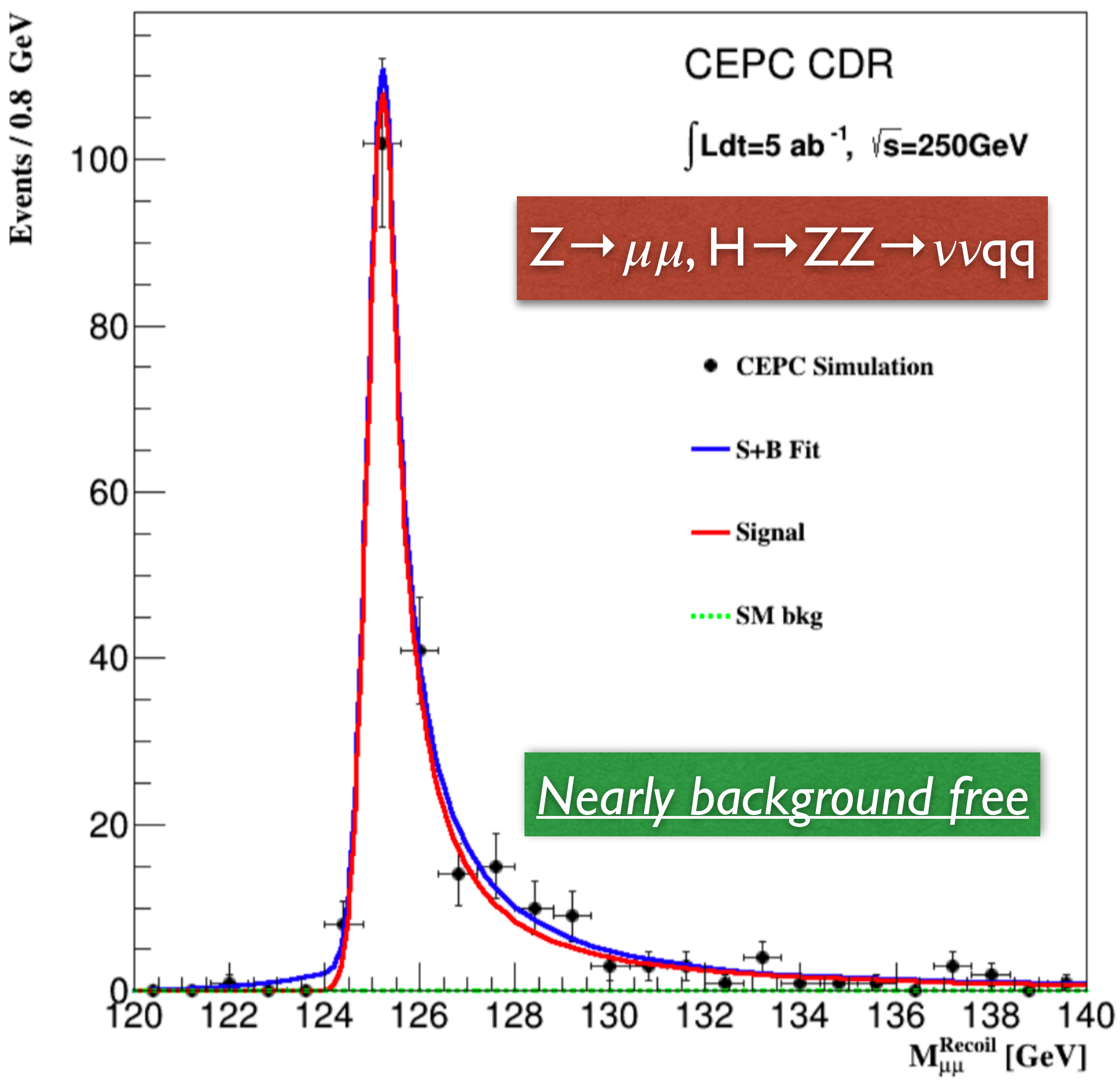


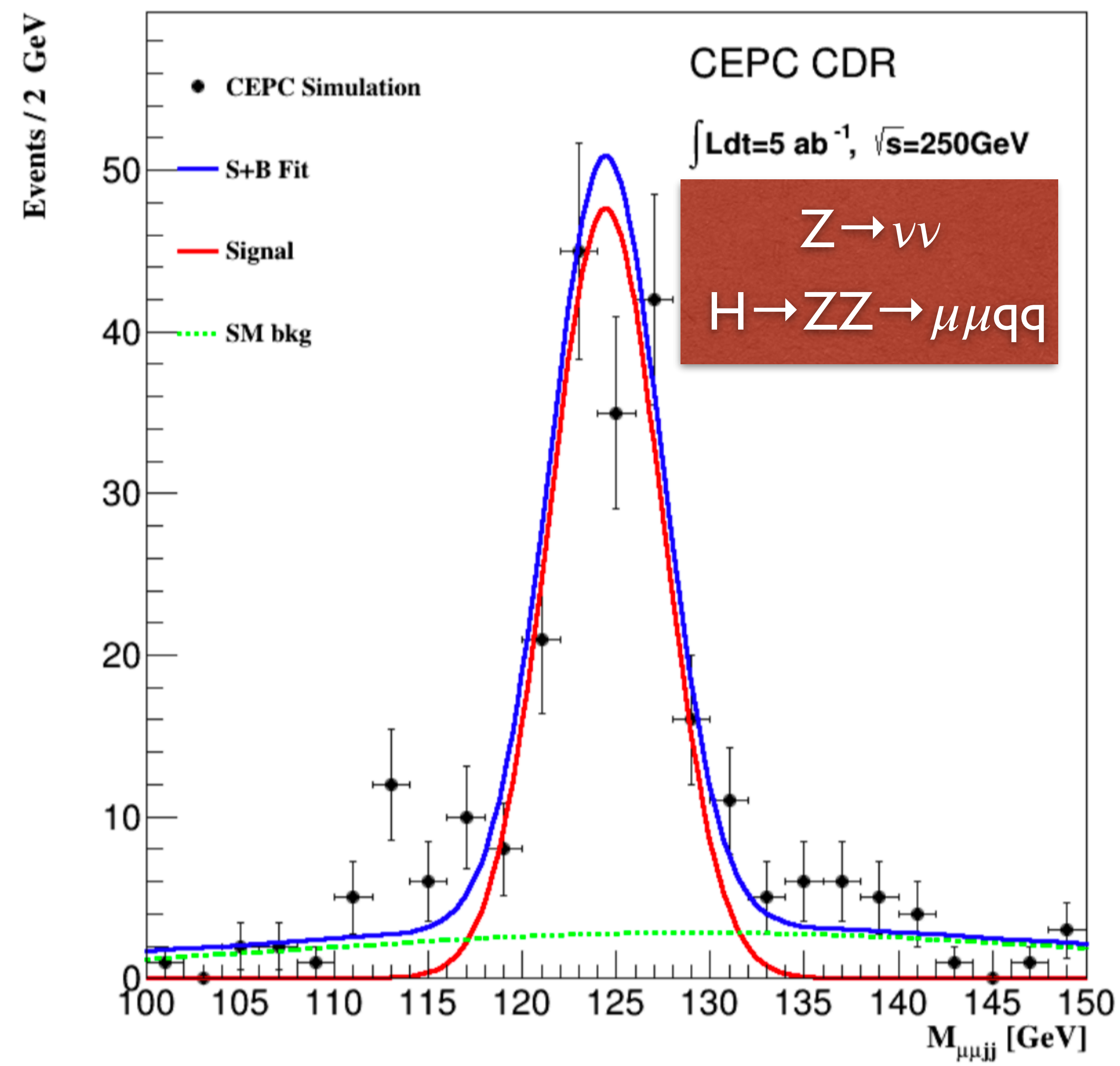




Z decay mode	$H\rightarrow b\bar{b}$	$H\rightarrow c\bar{c}$	$H\rightarrow gg$
$Z\rightarrow e^+e^-$	1.3%	14.1%	7.9%
$Z\rightarrow \mu^+\mu^-$	1.0%	10.5%	5.4%
$Z\rightarrow q\bar{q}$	0.4%	8.1%	5.4%
$Z\rightarrow \nu\bar{\nu}$	0.4%	3.8%	1.6%
Combined	0.3%	3.2%	1.5%

$\sigma(ZH) \times BF(H \to ZZ^*)$





Decay final state		Precision
$Z \to e^+e^-$	$H \to ZZ^* \to \ell^+\ell^- q\bar{q}$	19.3%
$Z \to \mu^+\mu^-$	$H \to ZZ^* \to \nu\bar{\nu} q\bar{q}$	$\boxed{7.3\%}$
$Z \to \nu\bar{\nu}$	$H \to ZZ^* \to \ell^+\ell^- q\bar{q}$	$\boxed{8.2\%}$
Combined		5.2%

Anomalous HVV couplings

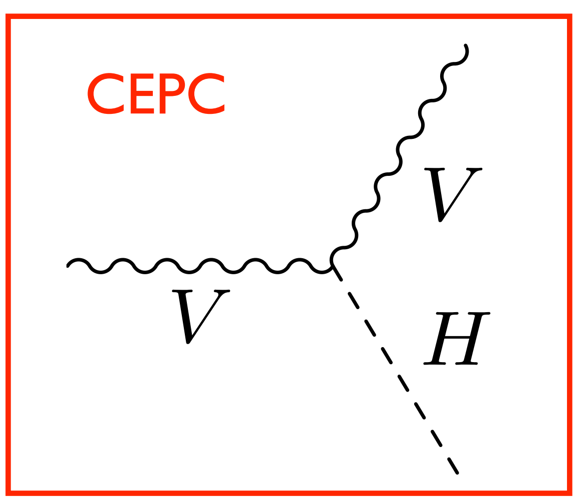
- CEPC offers a great opportunity to ping down the Lorentz structure of the H→ZZ
- Scattering amplitude approach (alternative to EFT)

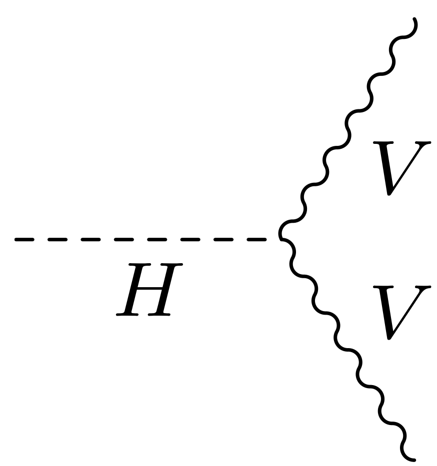
$$A(X_{J=0} \to VV) = \frac{1}{v}\left(g_1 m_V^2 \epsilon_1^* \epsilon_2^* + g_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + g_4 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}\right)$$

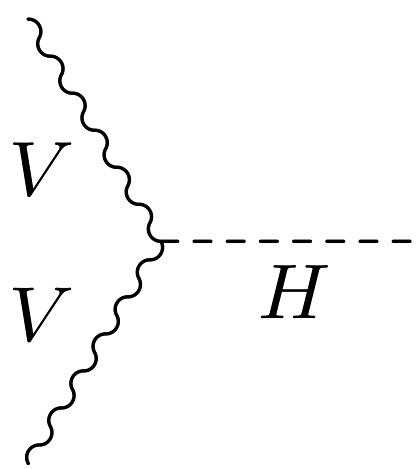
SM Higgs | High order 0+ | 0-

- Define experimental measurements "effective fraction of events"

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





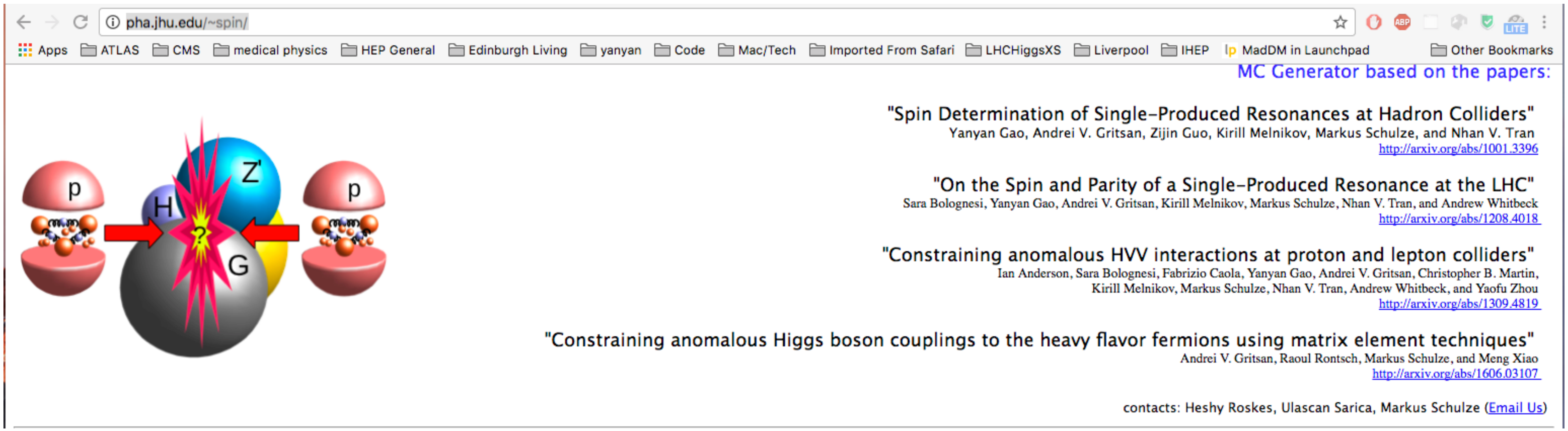


Analysis tools for anomalous couplings

- "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 analysis (MELA) to maximising kinematics usage
    - Used a consistent statistical approach to compare HL-LHC/e+e- collider sensitivities
- Some of these tools have been adopted at the LHC (esp. MELA in CMS)

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 in many LHC (CMS/ATLAS) analyses (Higgs/EXO) in 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)

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

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

$\downarrow$ polarisation vector ε

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

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

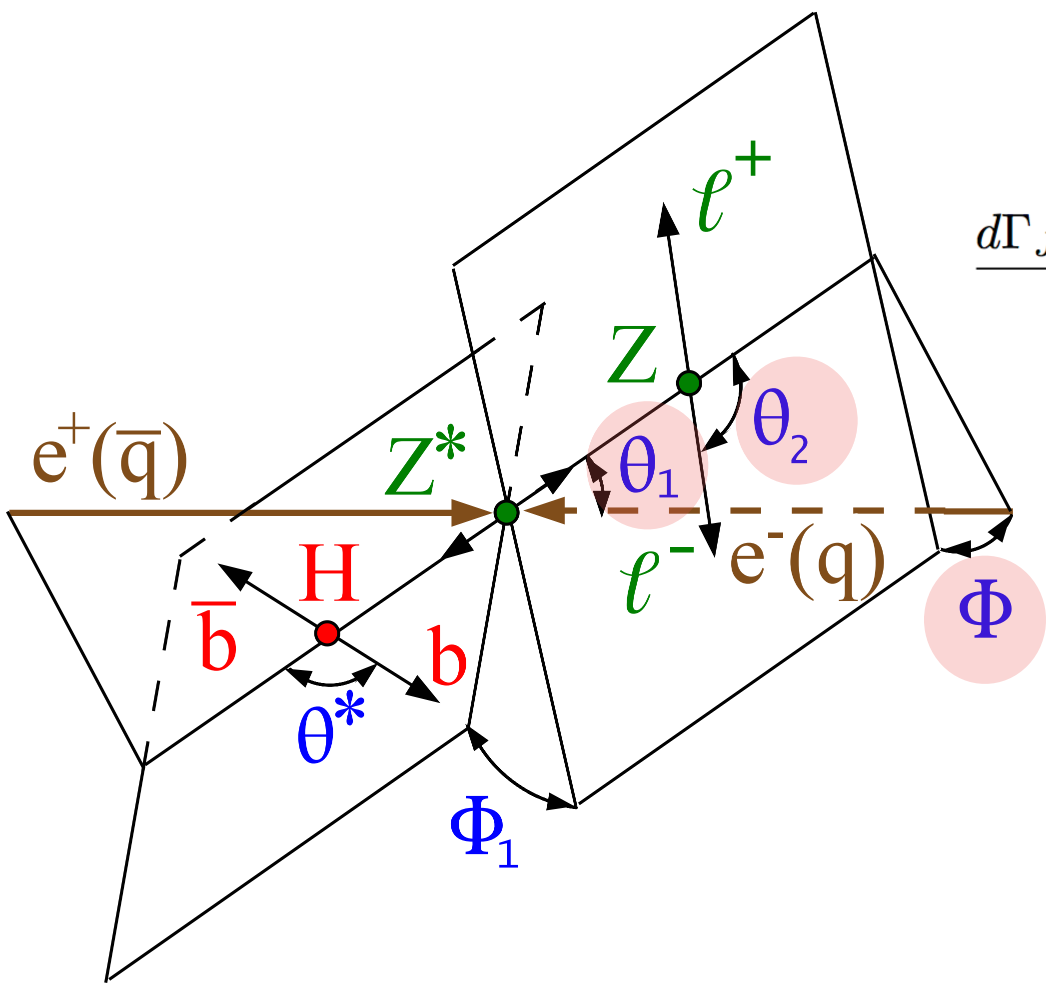
$\downarrow$

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
- For spin-0 resonances, if we ignore the trivial flat H->bb decay angular distribution, we end up with 3 angles
  - $\Omega = \{\theta_1, \theta_2, \phi\}$, calculated based on 4-momentum of the Higgs and Z->ll
  - The 3D angular distributions, which depend on anomalous couplings through helicity amplitudes, can be analytically calculated
  - We can extract the anomalous couplings by fitting directly these angles in data



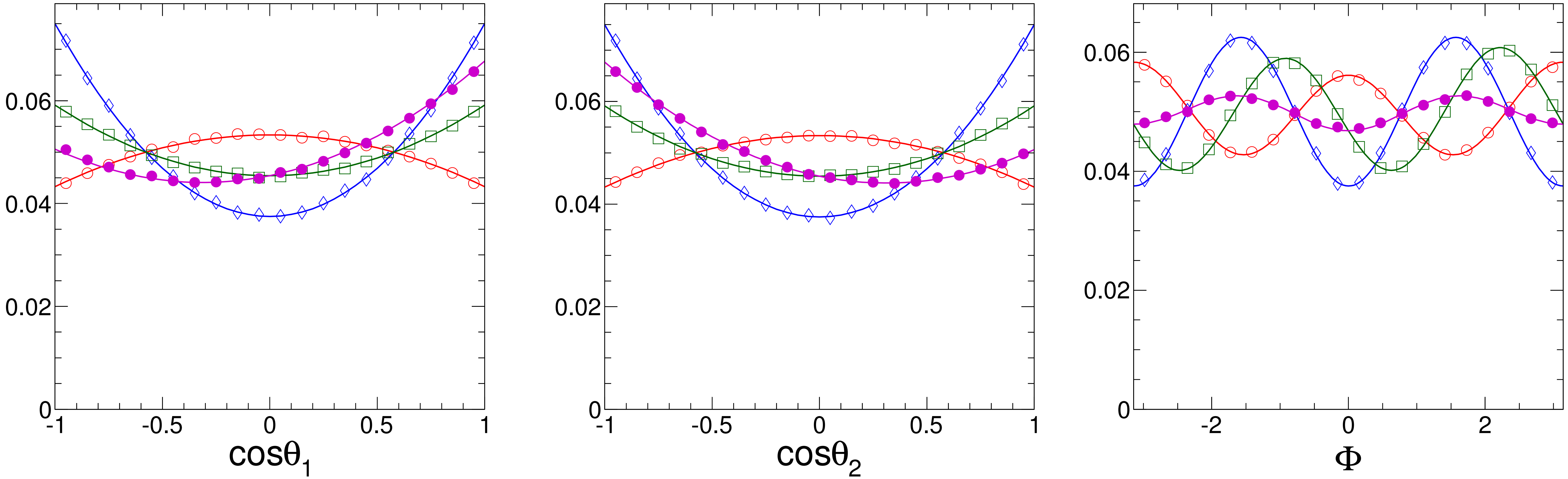
$$
\begin{aligned}
\frac{d\Gamma_{J=0}(s,\vec{\Omega})}{d\vec{\Omega}} \propto\ & 4\,|A_{00}|^2 \sin^2\theta_1 \sin^2\theta_2 \\
&+ |A_{+0}|^2 \left(1 - 2R_1\cos\theta_1 + \cos^2\theta_1\right)\left(1 + 2A_{f_2}\cos\theta_2 + \cos^2\theta_2\right) \\
&+ |A_{-0}|^2 \left(1 + 2R_1\cos\theta_1 + \cos^2\theta_1\right)\left(1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

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

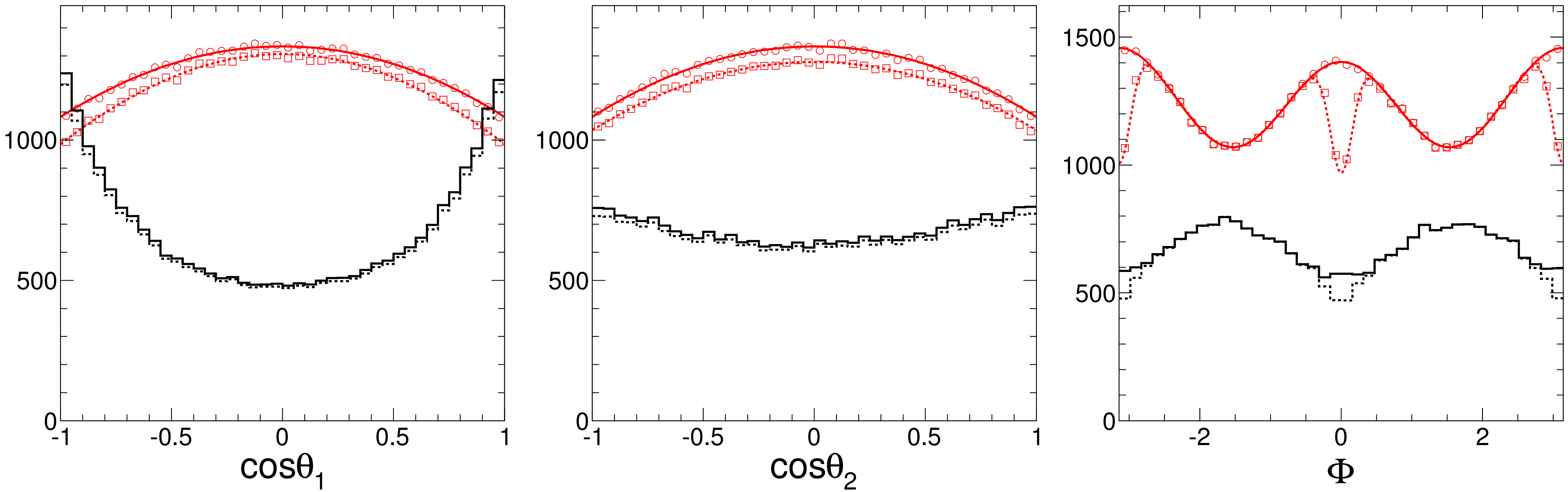
— 0+ — 0- — f_{CP}=0.5, ϕ=0 — f_{CP}=0.5, ϕ=0



Acceptance

- Acceptance can be parameterised using step function

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



Proof-of-principle analysis

- Proof-of-principle analyses based on truth level quantities (no smearing)
  - **Caveat: these studies need to be repeated using realistic CEPC simulation**
- Event selection and efficiencies based on back-of-envelope calculations
  - Acceptance cuts: leptons pT > 5 GeV, $|\eta| < 2.4$
  - Lepton efficiency impact => overall 80% per event level
- Background events
  - Modelled with ZZ->μμbb
  - Assumed to be 10% of signal under the Higgs boson peak

	Process	Generator	nEvents (fb^{-1}) after selection
Signal	e+e-→ZH→llbb	JHUGen	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

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

observables

Parameters of interests

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

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

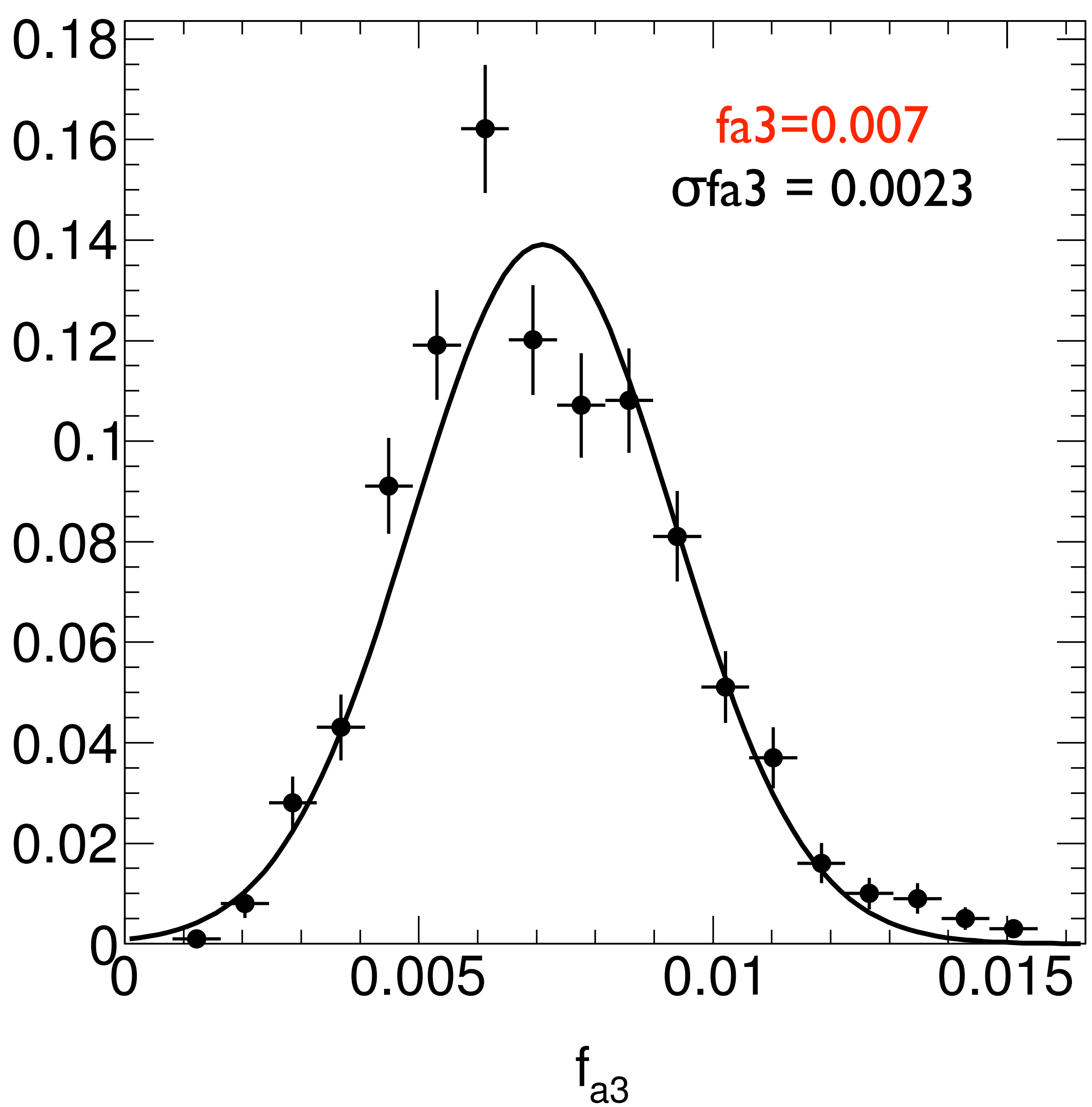
$$\mathcal{P}_{\text{sig}}(\vec{x}_i; f_{a3}, \phi_{a3}) = (1 - f_{a3})\,\mathcal{P}_{0^+}(\vec{x}_i) + f_{a3}\,\mathcal{P}_{0^-}(\vec{x}_i) + \sqrt{f_{a3}(1 - f_{a3})}\,\mathcal{P}_{\text{int}}(\vec{x}_i; \phi_{a3})$$

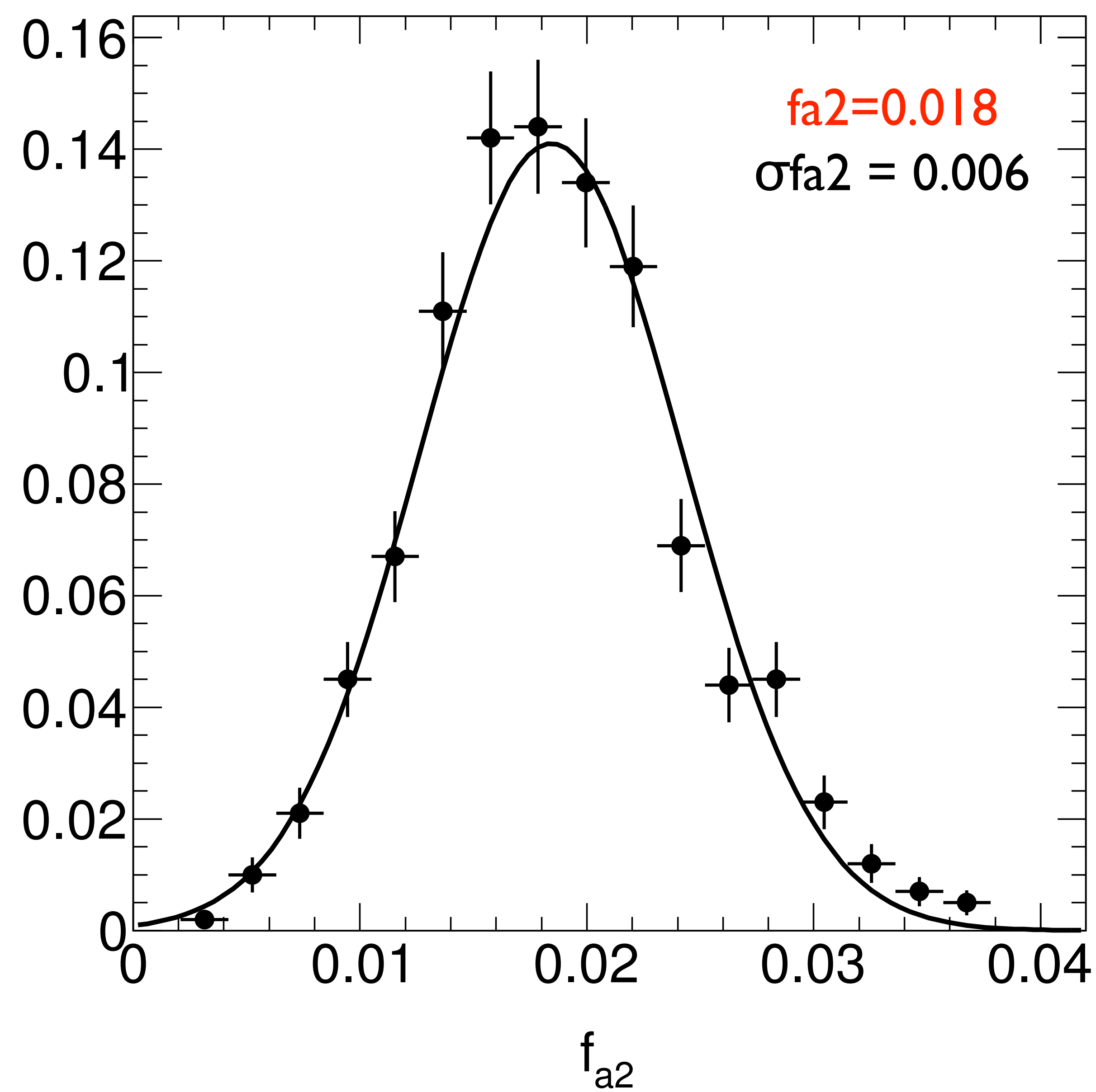
- Choice of $\vec{x}_i, \vec{\zeta}$
  - Most optimal: full kinematics information in multi-dimensional space
    - Challenging: detector response and background parameterisations in multi-dimensions
  - With less statistics, one can collapse the full angular PDF into matrix element likelihood

Statistical analysis (II)

- Quantify sensitivity as the smallest f-values that can enable 3σ evidence
  - Manually 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 (toy-data) 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)
  - Evaluate the fit outputs from these 1000 fits
    - Validate first fit performance by making sure pull distributions are as expected
    - Take Gaussian error of the fitted value as the σ
  - Iterative over several steps to find the smallest f which gives mean/σ = 3
- These f-values obtained at CEPC are converted to the equivalent values defined for H->ZZ decays for consistent 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

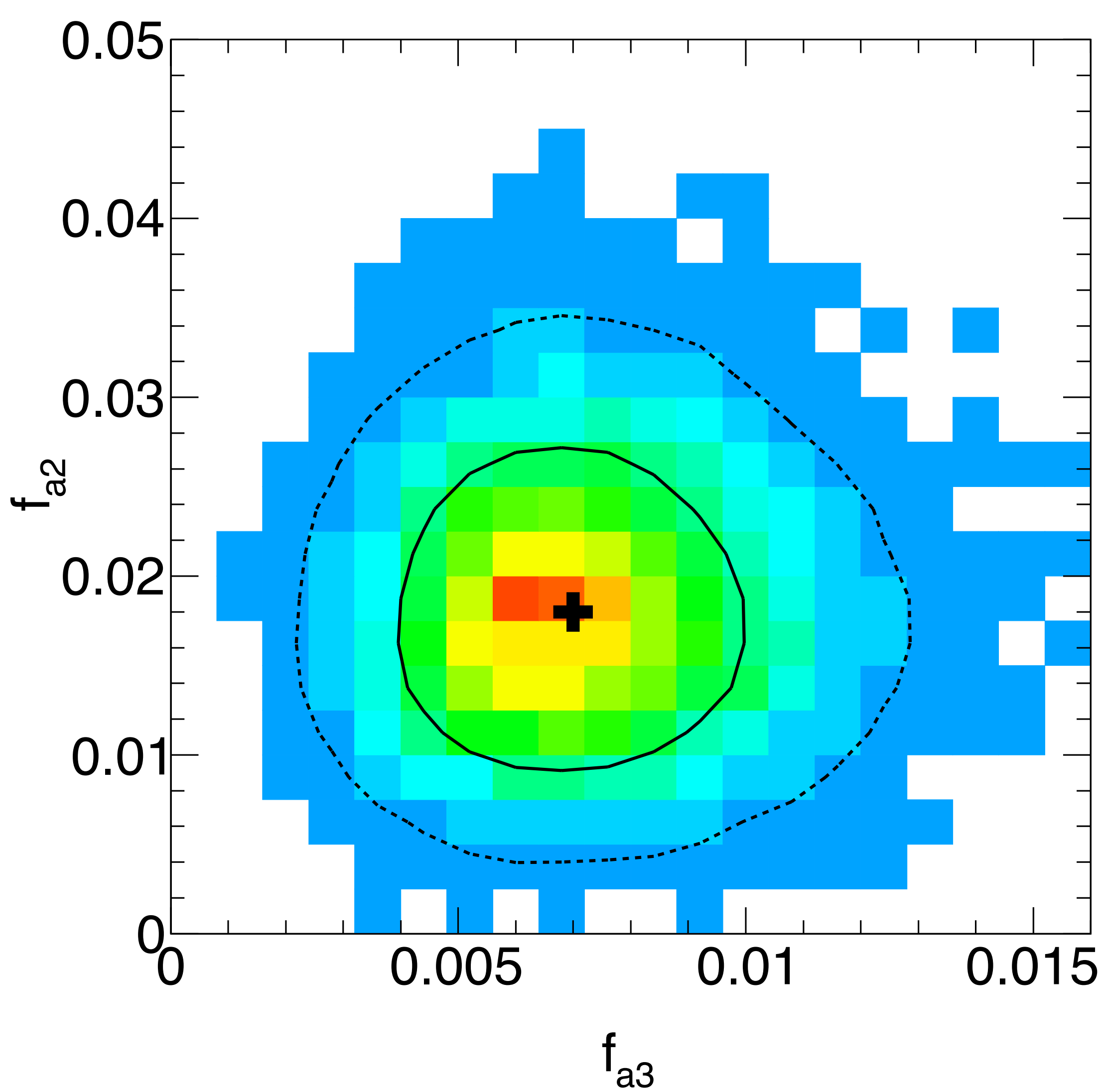
Results (1D)


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


fa2=0.018
σfa2 = 0.006
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
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
- For the HL-LHC:
  - Main sensitivity of fa3 comes from the VBF ($H\to\gamma\gamma$)and ZH productions modes rather than H->ZZ decays as the high dimensional operators get significant enhancement w.r.t. m(Z*)
  - Only $H\to ZZ$ decay channel has been feasible for the fa2



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

Summary and plans

- The well defined c.o.m. and clean environment at e+e- colliders allow for rich variety of measurements and many different final states (far beyond the classic ZH→$\mu\mu$bb)

	σ(ZH)	σ(ZH)×			
		BF(H→bb)	BF(H→cc)	BF(H→gg)	BF(H→ZZ)
Precision	0.5%	0.5%	3.2%	1.5%	5.2%
Most 2 sensitive Channels	Z→qq/$\mu\mu$	Z→$\nu\nu$/qq			ZH→($\nu\nu$)($\mu\mu$qq) ZH→($\mu\mu$)($\nu\nu$qq)

- Proof-of-principle anomalous coupling measurement are presented using only ZH→$\mu\mu$bb
  - Based on general scattering amplitudes (independent approach w.r.t. EFT)
    - A factor of 3 improvement in the fraction of CP-violating contribution
    - <u>Two orders of magnitude improvement in the fraction of loop-induced 0+ contribution</u>
  - Need to update with state-of-the-art CEPC simulation conditions
  - Plenty room for improvements: extending to other Z-tagged final states and Higgs decays

Backup slides

HL-LHC vs e+e- colliders in f_{CP} ($\equiv f_{a3}$)

			HZZ/HWW					
collider	energy	$\mathcal{L}$	$H \to VV^*$		$V^* \to VH$		$V^*V^* \to H$	
	GeV	fb^{-1}	f_{CP}	δf_{CP}	f_{CP}	δf_{CP}	f_{CP}	δf_{CP}
pp	14 000	300	0.18	0.06	6×10^{-4}	4×10^{-4}	18×10^{-4}	7×10^{-4}
pp	14 000	3 000	0.06	0.02	3.7×10^{-4}	1.2×10^{-4}	4.1×10^{-4}	1.3×10^{-4}
e^+e^-	250	250	✓		21×10^{-4}	7×10^{-4}	✓	
e^+e^-	350	350	✓		3.4×10^{-4}	1.1×10^{-4}	✓	
e^+e^-	500	500	✓		11×10^{-5}	4×10^{-5}	✓	
e^+e^-	1 000	1 000	✓		20×10^{-6}	8×10^{-6}	✓	
$\gamma\gamma$	125		✓					

High-energy behaviour of ZH cross-sections