Snowmass-2021: CP-violating Higgs Couplings

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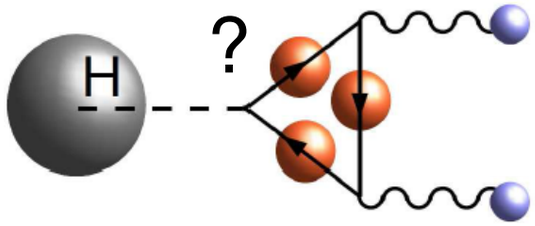
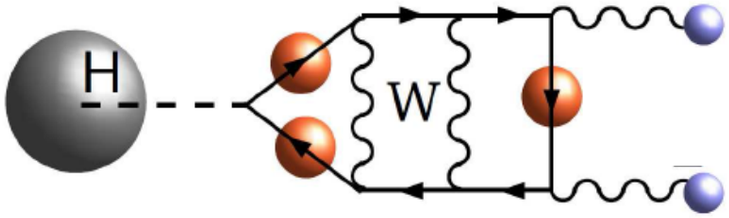
Snowmass Energy Frontier Group-01 Meeting

CP-violating H(125) Coupling

- "Snowmass" is the planning exercise ⇒ focus on future facilities
  - — identify key reference measurements to compare facilities
  - — highlight strong and weak aspects / complementarity in Physics reach
  - — chance to develop analysis tools / approaches, but secondary
- CP-violating H(125) couplings provide such a reference
  - — potential baryogengesis connected to the Higgs sector
  - — complementarity to the EDM measurements
  - — tiny in the SM, excellent null-test
  - — well-defined stand-alone reference measurement
  - — input to the global EFT fits, which currently focus on CP-even Operators
  - — $pp,\ e^+e^-,\ \gamma\gamma,\ \mu^+\mu^-\ (\sqrt{s})$ have their unique features in CP of H(125)





CPV from Snowmass-2013

- Higgs Working Group Report of the Snowmass-2013 Community Planning Study

  Chapter 1.4 devoted to spin and CP: arXiv:1310.8361

  – pp, e^+e^-, $\gamma\gamma$, $\mu^+\mu^-$ ($\sqrt{s}$) have their unique features in CP of H(125)

Collider	pp	pp	e^+e^-	e^+e^-	e^+e^-	e^+e^-	$\gamma\gamma$	$\mu^+\mu^-$	target
E (GeV)	14,000	14,000	250	350	500	1,000	126	126	(theory)
$\mathcal{L}$ (fb^{-1})	300	3,000	250	350	500	1,000	250		
spin-2^+_m	$\sim 10\sigma$	$\gg 10\sigma$	$>10\sigma$	$>10\sigma$	$>10\sigma$	$>10\sigma$			
$VVH^\dagger$	0.07	0.02	✓	✓	✓	✓	✓	✓	$< 10^{-5}$
$VVH^\ddagger$	$4\cdot 10^{-4}$	$1.2\cdot 10^{-4}$	$7\cdot 10^{-4}$	$1.1\cdot 10^{-4}$	$4\cdot 10^{-5}$	$8\cdot 10^{-6}$	–	–	$< 10^{-5}$
$VVH^\diamond$	$7\cdot 10^{-4}$	$1.3\cdot 10^{-4}$	✓	✓	✓	✓	–	–	$< 10^{-5}$
ggH	0.50	0.16	–	–	–	–	–	–	$< 10^{-2}$
$\gamma\gamma H$	–	–	–	–	–	–	0.06	–	$< 10^{-2}$
$Z\gamma H$	–	✓	–	–	–	–	–	–	$< 10^{-2}$
$\tau\tau H$	✓	✓	0.01	0.01	0.02	0.06	✓	✓	$< 10^{-2}$
ttH	✓	✓	–	–	0.29	0.08	–	–	$< 10^{-2}$
$\mu\mu H$	–	–	–	–	–	–	–	✓	$< 10^{-2}$

spin=0 established by now

† estimated in $H \to ZZ^*$ decay mode

‡ estimated in $V^* \to HV$ production mode

$^\diamond$ estimated in $V^*V^* \to H$ (VBF) production mode

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$\mu\mu H$	–	–	–	–	–	–	–	✓	$< 10^{-2}$

† estimated in $H \to ZZ^*$ decay mode

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targeted couplings

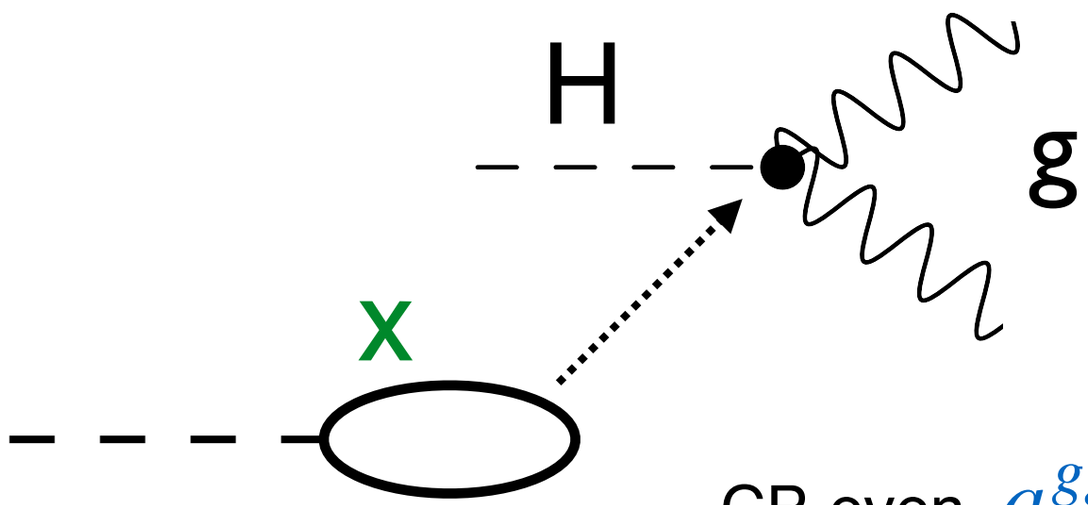
theoretical interest

comparison across facilities

parameters of interest

Targeted CP-sensitive Couplings

- Look at effective couplings, either within EFT or not

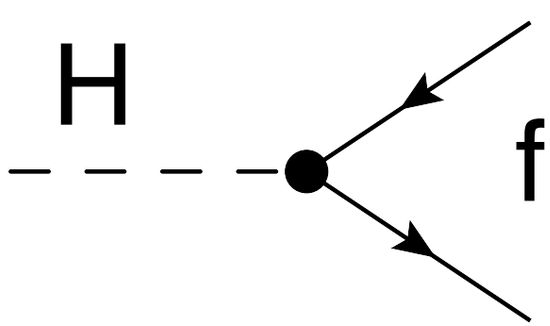


(same for $H \to \gamma\gamma, Z\gamma$)

CP-even a_2^{gg} & CP-odd a_3^{gg} couplings

e.g. fermion loop $a_2^{gg} = -\alpha_s \kappa_Q/(6\pi)$ & $a_3^{gg} = -\alpha_s \tilde{\kappa}_Q/(4\pi)$

- Target HVV, Hgg, Hff couplings



$$A(\mathrm{Hff}) = -\frac{m_\mathrm{f}}{v}\bar{\psi}_\mathrm{f}\left(\kappa_\mathrm{f} + \mathrm{i}\,\tilde{\kappa}_\mathrm{f}\gamma_5\right)\psi_\mathrm{f}$$

CP-even CP-odd

Targeted CP-sensitive Parameters

- Somewhat more complicated with V=Z,W

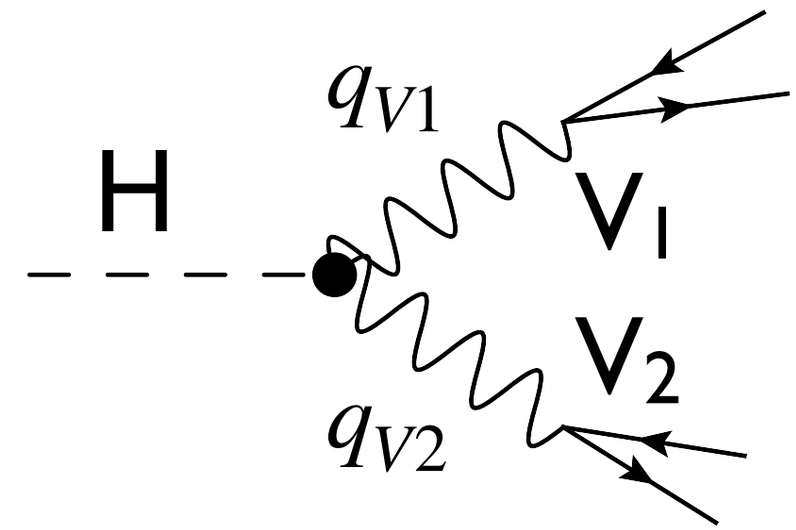
$$A(\mathrm{HVV}) = \frac{1}{v}\left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{VV}} q_{\mathrm{V2}}^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} + \frac{\kappa_3^{\mathrm{VV}}(q_{\mathrm{V1}} + q_{\mathrm{V2}})^2}{\left(\Lambda_{\mathrm{Q}}^{\mathrm{VV}}\right)^2}\right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^*$$

$$+\frac{1}{v} a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \frac{1}{v} a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu},$$

tree-level SM

CP-even

CP-odd



- May attempt full EFT expansion, but not necessarily the goal in this study…

$$\left|A_{\mathrm{CP\,even}}\right|^2 \qquad +2\mathrm{Re}\left(A_{\mathrm{CP\,even}} A_{\mathrm{CP\,odd}}^*\right) \qquad +\left|A_{\mathrm{CP\,odd}}\right|^2$$

do not constrain to SM rate

$\int = 0 \;\Rightarrow$ kinematic distributions

true CP-sensitive observation but not always available

suppressed in EFT

have to be clear if this term dominates

$$f_{CP} = \frac{\left|A_{\mathrm{CP\,odd}}\right|^2}{\left|A_{\mathrm{CP\,even}}\right|^2 + \left|A_{\mathrm{CP\,odd}}\right|^2} = \sin^2(\alpha_{\mathrm{eff}})$$

parameter of interest

Theoretical Models and connection to EDM/B/EW

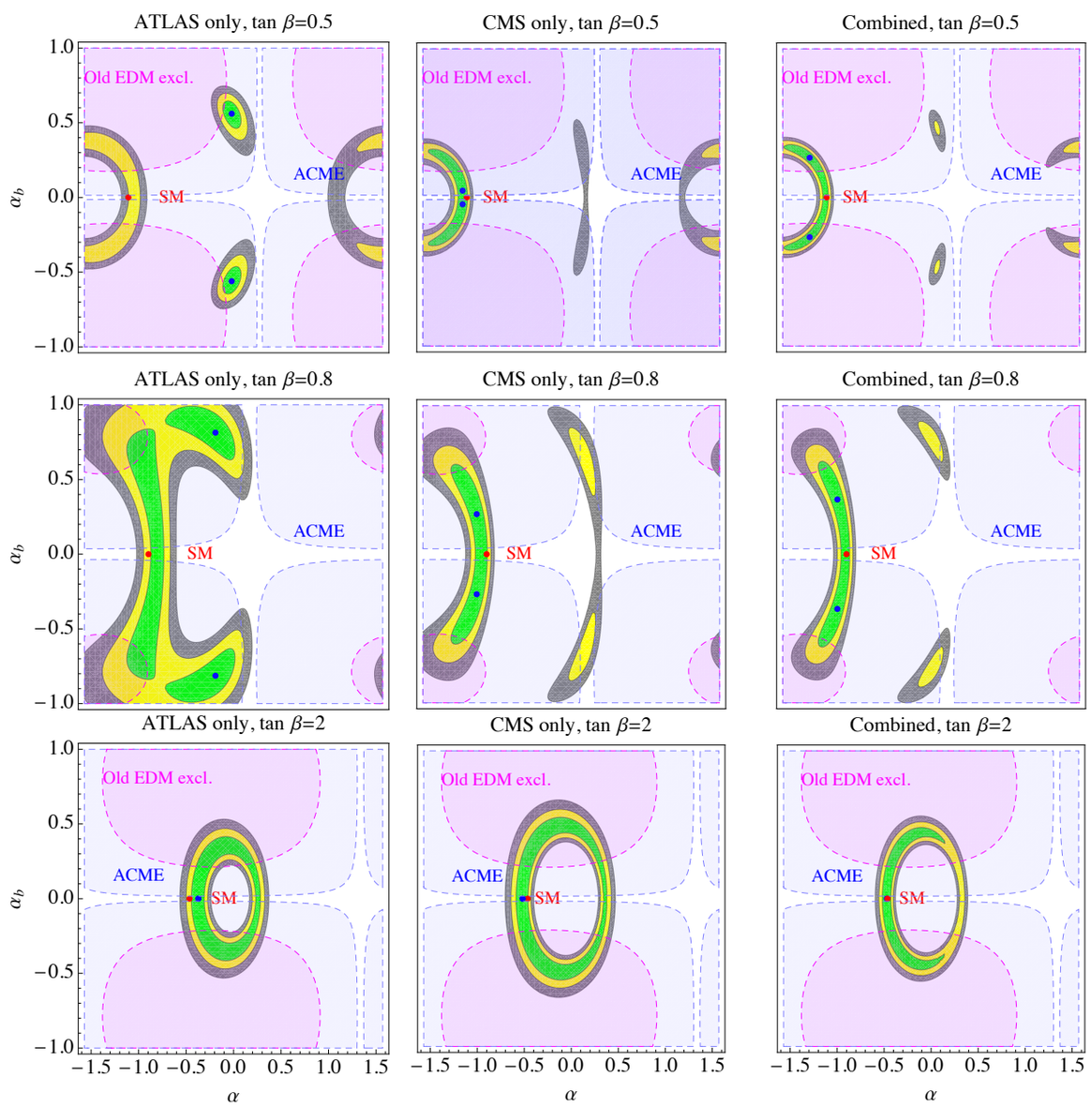
- Representative model analysis

Hff in 2HDM: arXiv:1304.0773

— motivated $f_{CP} < 0.01 \ (\alpha_b < 0.1)$

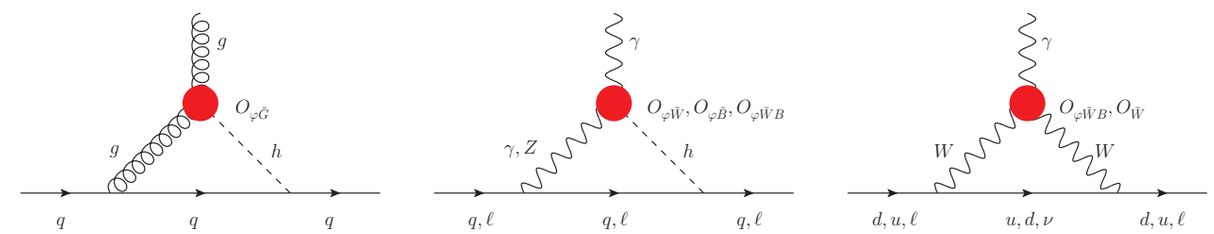
— to be updated to more recent results

allowed range for CP-odd α_b

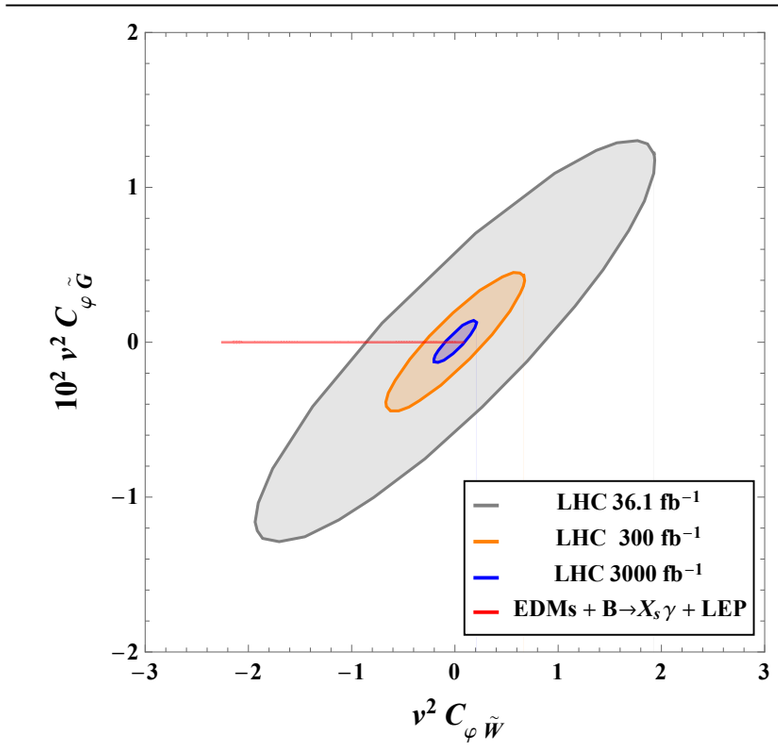


- EFT analysis of EDM and LHC:

From tabletop to the LHC: arXiv:1903.03625



	Low energy	LHC (3000 fb^{-1})
$v^2\, C_{\varphi\tilde{B}}$	$[-0.4, 0.00]$	$[-0.3, 0.3]$
$v^2\, C_{\varphi\tilde{W}}$	$[-2.3, 0.02]$	$[-0.17, 0.17]$
$v^2\, C_{\varphi\tilde{W}B}$	$[-1.3, 0.01]$	$[-0.39, 0.39]$
$v^2\, C_{\varphi\tilde{G}}$	$[-1.3, 1.3] \cdot 10^{-5}$	$[-9.0, 9.0] \cdot 10^{-4}$



Unique features of Facilities: $\gamma\gamma$ production

- Photon collider is unique with focus on $H\gamma\gamma$ coupling
  - photon beam polarization is critical for CP
  - most interesting parameter:

$$\mathcal{A}_3 = \frac{|A_{\parallel}|^2 - |A_{\perp}|^2}{|A_{\parallel}|^2 + |A_{\perp}|^2} = \frac{2\mathcal{R}e\,(A^*_{--}A_{++})}{|A_{++}|^2 + |A_{--}|^2} = \frac{|a_2|^2 - |a_3|^2}{|a_2|^2 + |a_3|^2} = (1 - 2f_{CP})$$

Detecting and Studying Higgs Bosons at a Photon-Photon Collider: arXiv:hep-ph/0110320

  - measure as asymmetry between $\parallel$ and $\perp$ linear polarizations

    for $E_0 = 110$ GeV and $\lambda = 1\,\mu$m: $f_{CP} = \sin^2(\alpha^{\gamma\gamma}) \sim \pm\,0.06$

    at $2.5 \cdot 10^{34} \times 10^7 = 250\,\mathrm{fb}^{-1}$

- Interesting to revisit and compare to pp and e^+e^-
  - need fair comparison: information from polarization, not cross section

Unique features of Facilities: $\mu^+\mu^-$ production

- Muon collider is unique with focus on $H\mu\mu$ coupling
  - — muon beam transverse polarization is critical for CP
  - — not many fermion couplings can be tested with polarization and CP

    later we will discuss $H\tau\tau$ and Htt (both 3rd family)
  - — same transverse polarization ⇒ CP-even
  - — opposite polarization ⇒ CP-odd

How Valuable is Polarization at a Muon Collider? A Test Case: Determining the CP Nature of a Higgs Boson:
arXiv:hep-ph/0003091

- Unique feature of the muon collider
  - — though comes with a price of lumi, likely not a priority at first stage

Unique features of Facilities: e^+e^- production

- e^+e^- collider $\rightarrow Z^* \rightarrow ZH \;\Rightarrow\; HZZ, HZ\gamma, H\gamma\gamma$ couplings

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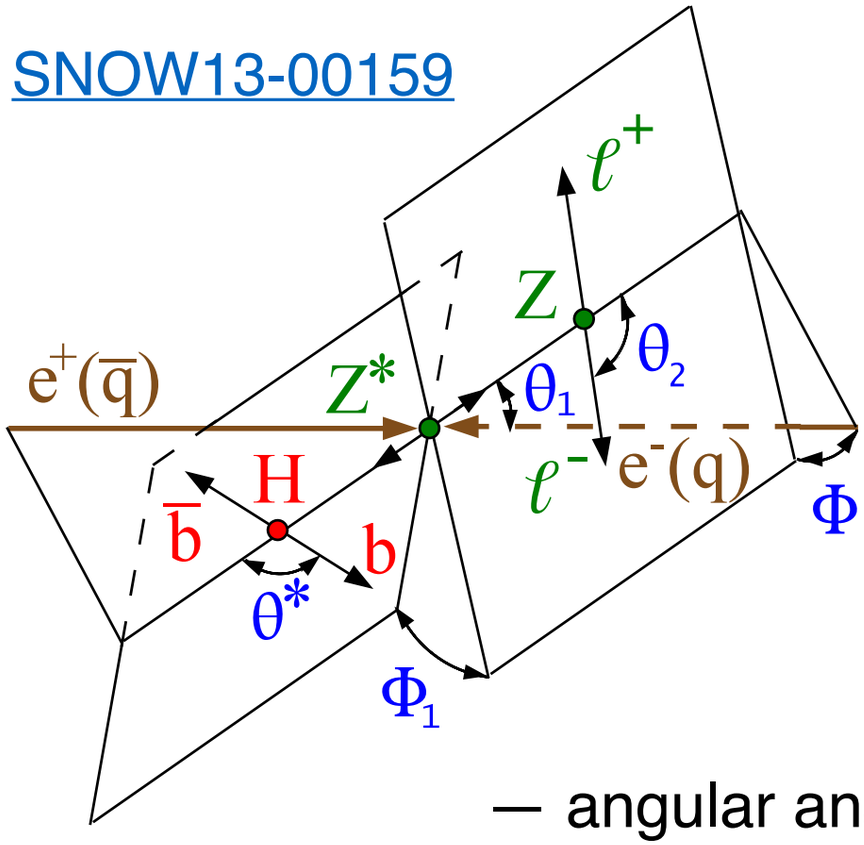
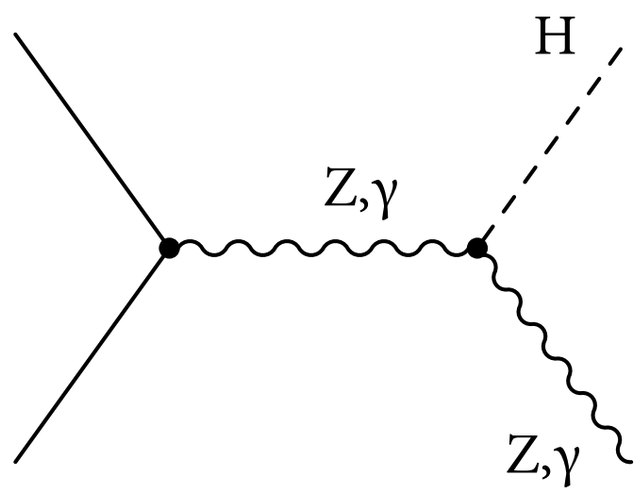
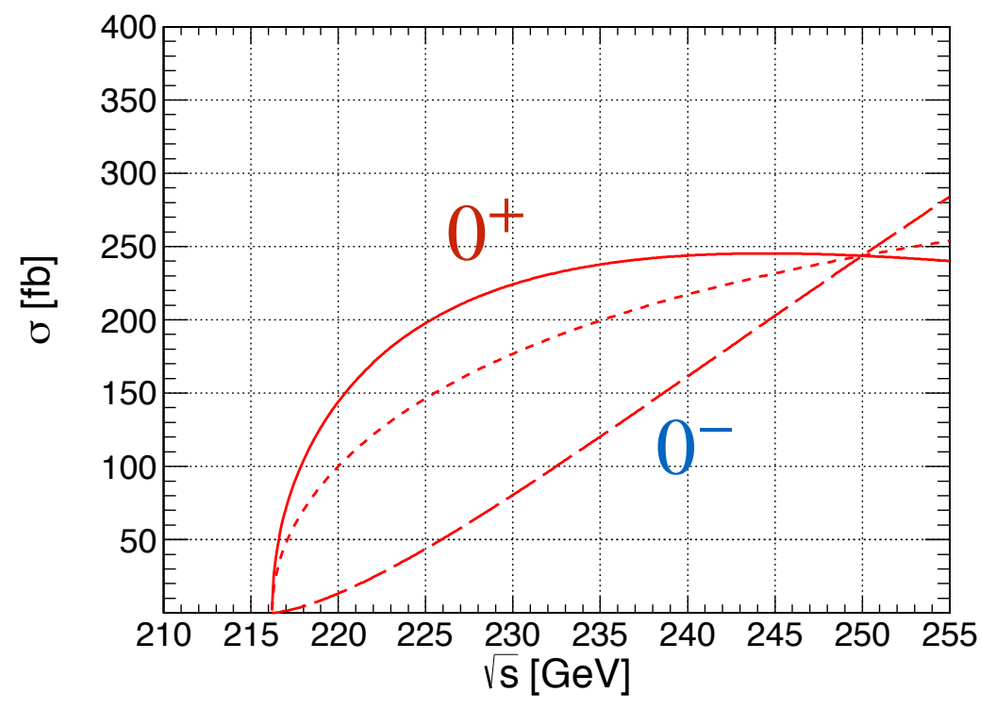
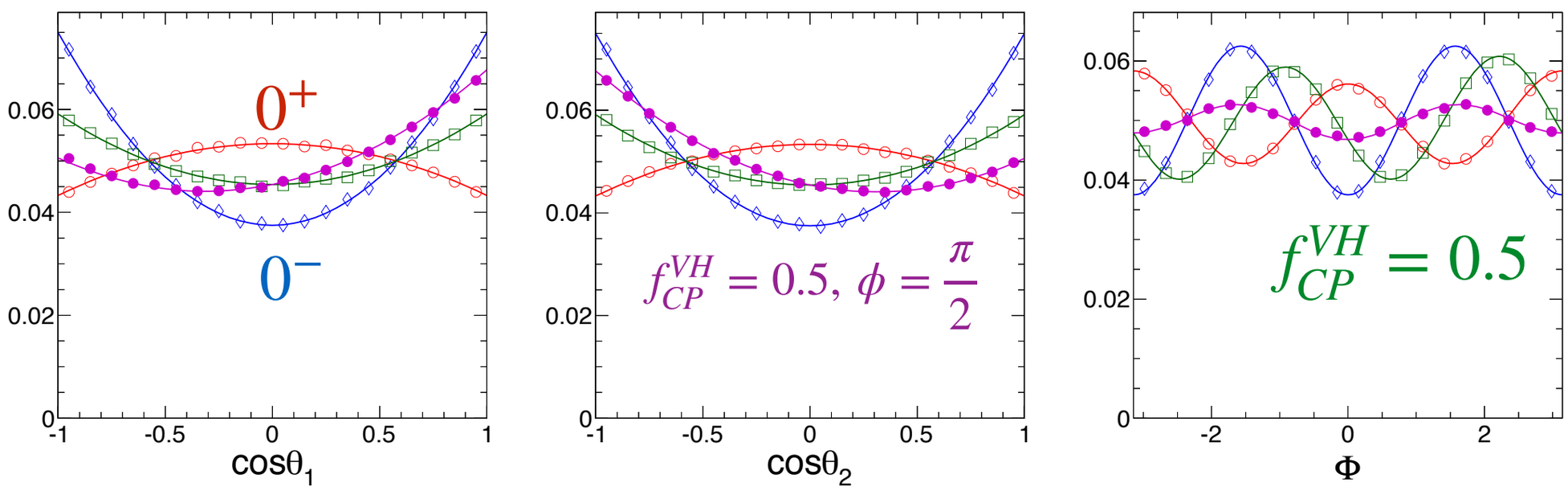




— threshold scan = q^2 dependence



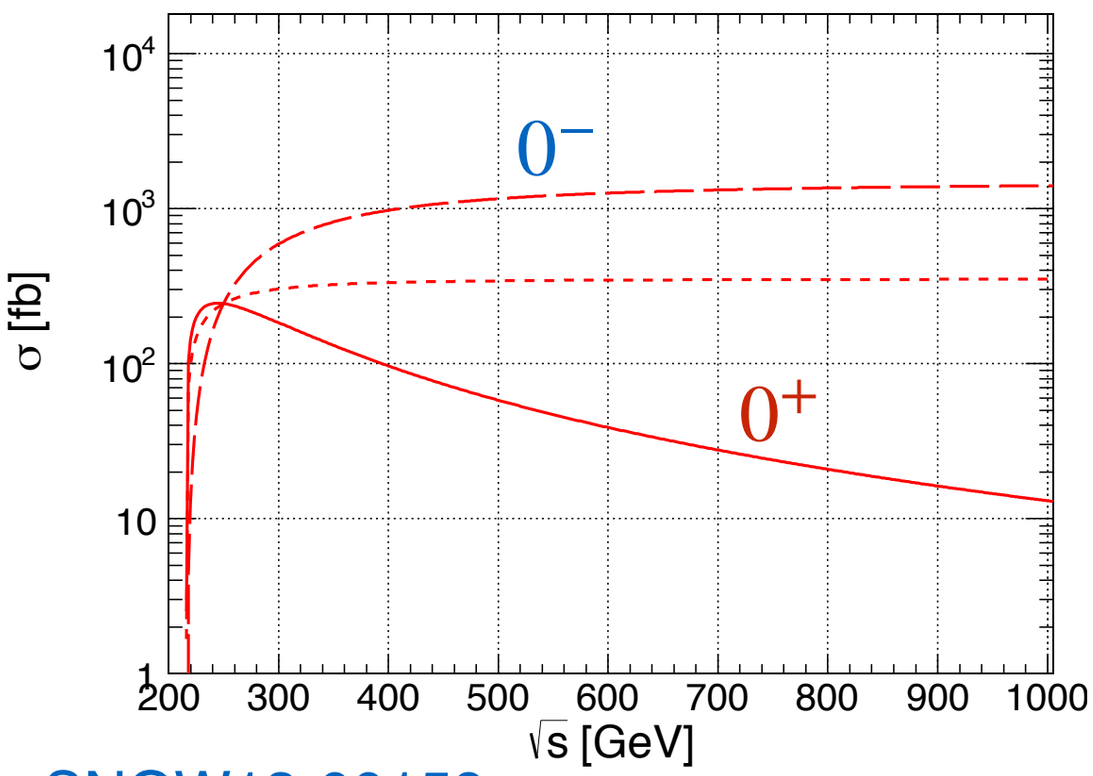
— angular analysis = polarization



e^+e^- production at higher energies (LC)

- e^+e^- collider $\rightarrow Z^* \rightarrow ZH$
- Scan q^2 dependence of HVV couplings

  $\Rightarrow$ increased sensitivity (without cutoff)



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- Linear collider $e^+e^- \rightarrow t\bar{t}H$

cross section dependence studied of 0^+ *vs.* 0^-

need dedicated CP-sensitive study (see LHC studies)

- VBF $e^+e^- \rightarrow \nu\bar{\nu}H$

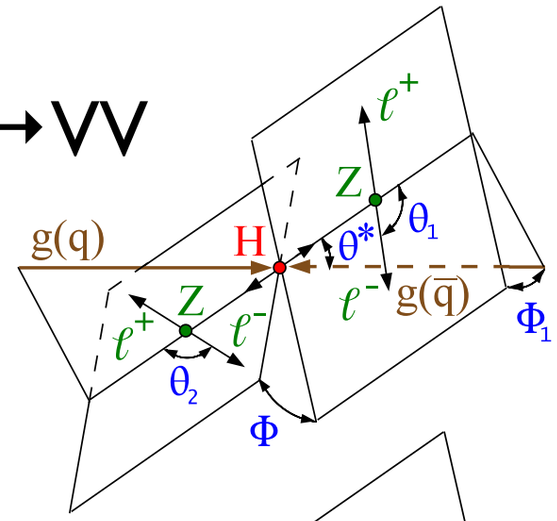
not much angular information

q^2-dependence through p_T^H ...

Unique features of Facilities: pp production

- $pp \to V^* \to VH \;\Rightarrow\; HWW, HZZ, HZ\gamma, H\gamma\gamma, Hgg$ couplings

H→VV

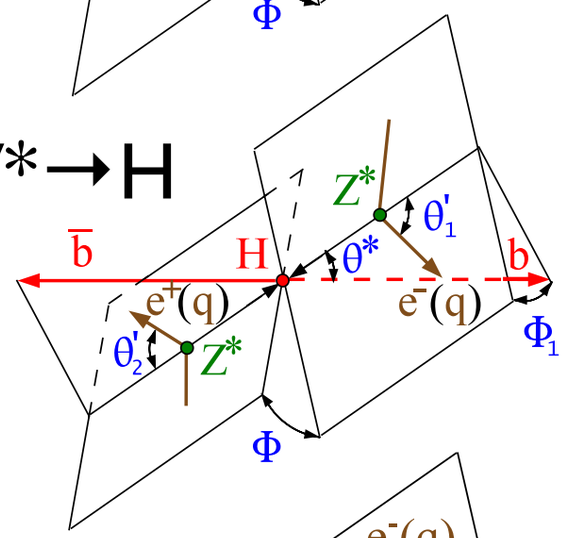


also VBF $V^*V^* \to H$ and decay $H \to VV$

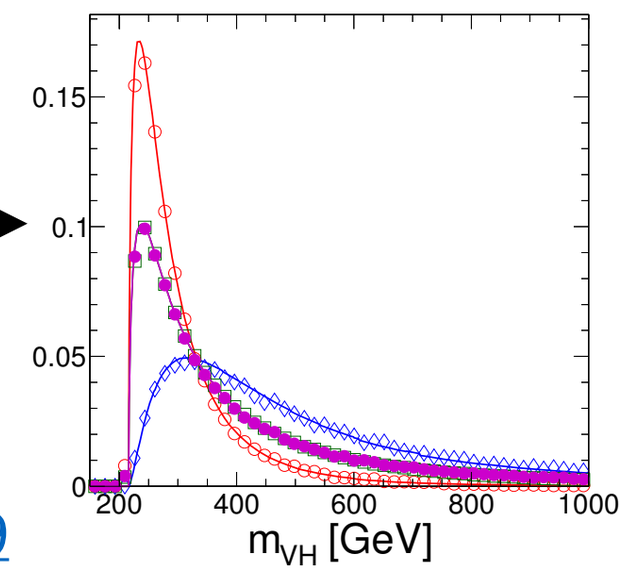
pp unique $gg \to H$

benefit from LHC experience

V*V*→H



— scan of q^2-dependence - - - - - →



— polarization measurement

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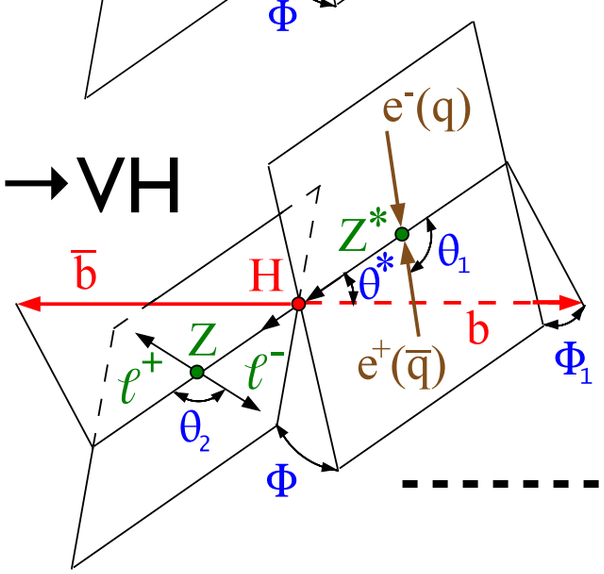
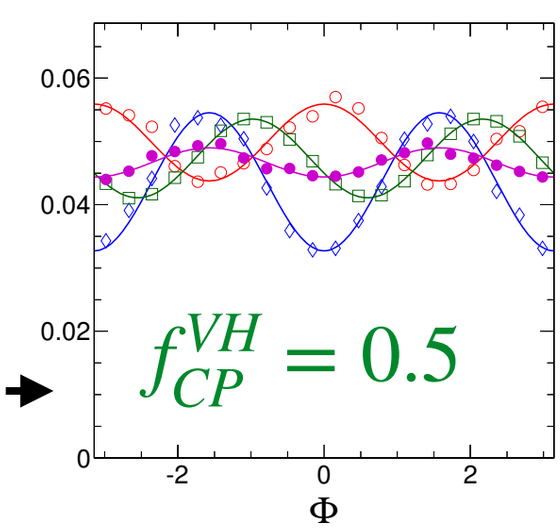
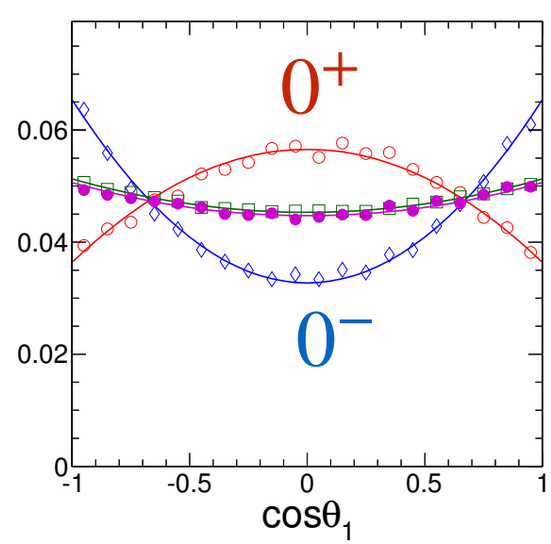
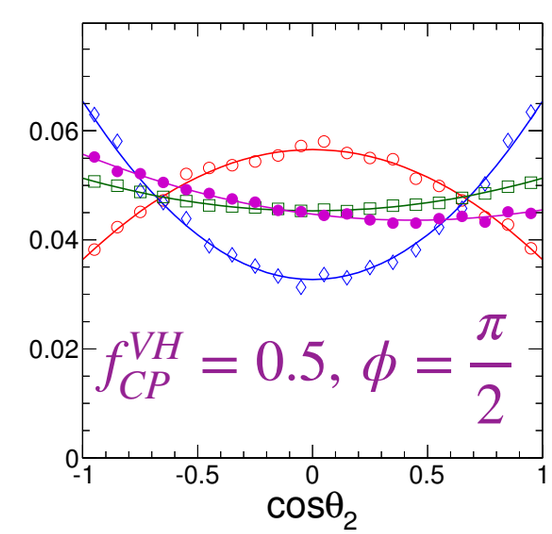
V*→VH









Compare Facilities: e^+e^- and pp

- pp leads to wider spectrum of production modes, more decays
  - — but reach in HVV comparable
  - — $q^2 = s$ at e^+e^-, from PDFs at pp ⇒ pros and cons

Collider	pp	pp	e^+e^-	e^+e^-	e^+e^-	e^+e^-
E (GeV)	14,000	14,000	250	350	500	1,000
$\mathcal{L}$ (fb^{-1})	300	3,000	250	350	500	1,000
$VVH^\dagger$	0.07	0.02	✓	✓	✓	✓
$VVH^\ddagger$	$4\cdot10^{-4}$	$1.2\cdot10^{-4}$	$7\cdot10^{-4}$	$1.1\cdot10^{-4}$	$4\cdot10^{-5}$	$8\cdot10^{-6}$
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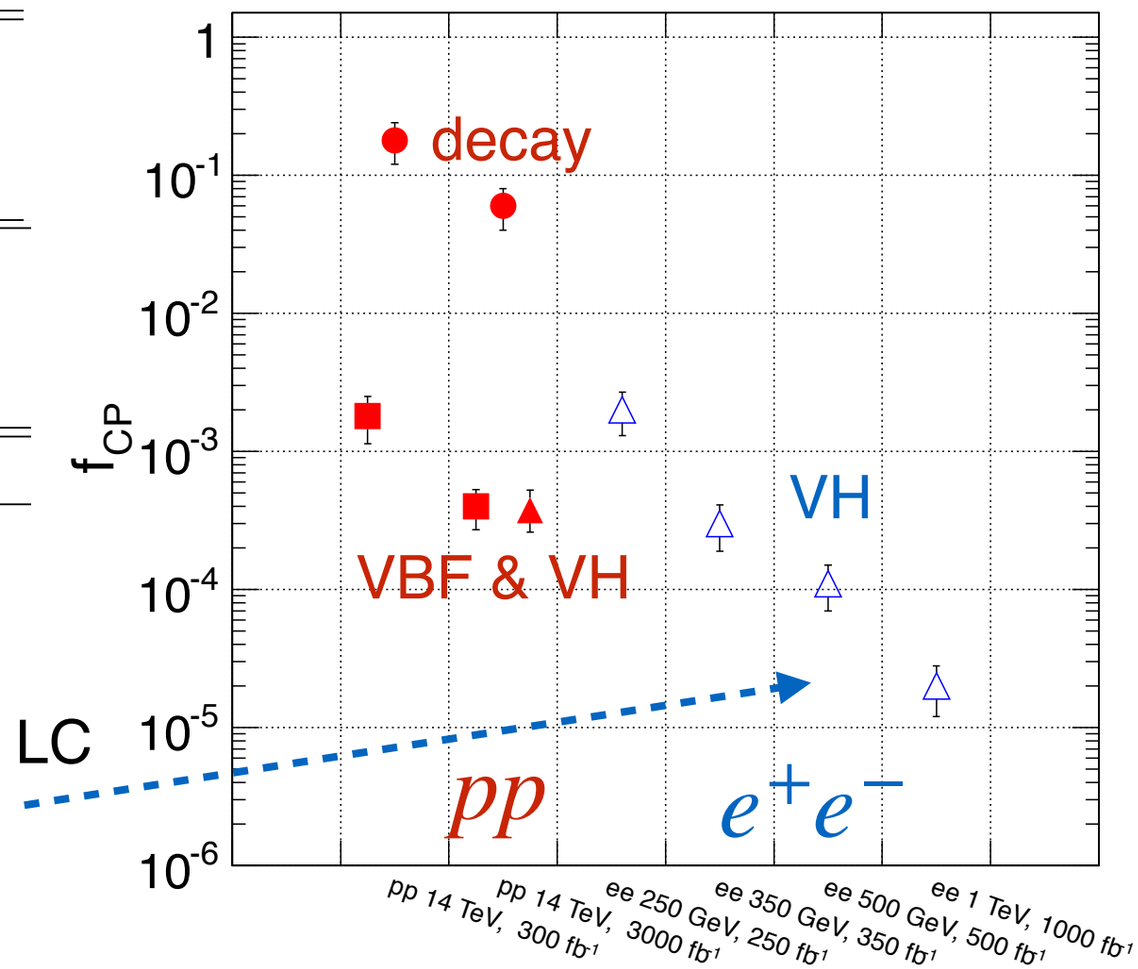
ggH	0.50	0.16	–	–	–	–

arXiv:1310.8361



— benefit from q^2 sensitivity at LC

— may want to compare with q^2 "roll-off"

not clearly defined…

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Update to recent LHC projections to HL-LHC

- Higgs Physics at the HL-LHC and HE-LHC

  WG2 report: arXiv:1902.00134

  earlier HVV projections are confirmed:

  with CMS & ATLAS full simulation

Collider	pp	pp
E (GeV)	14,000	14,000
$\mathcal{L}$ (fb^{-1})	300	3,000
$VVH^\dagger$	0.07	0.02
$VVH^\ddagger$	$4\cdot10^{-4}$	$1.2\cdot10^{-4}$
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$VV \to H \to 4\ell$ production

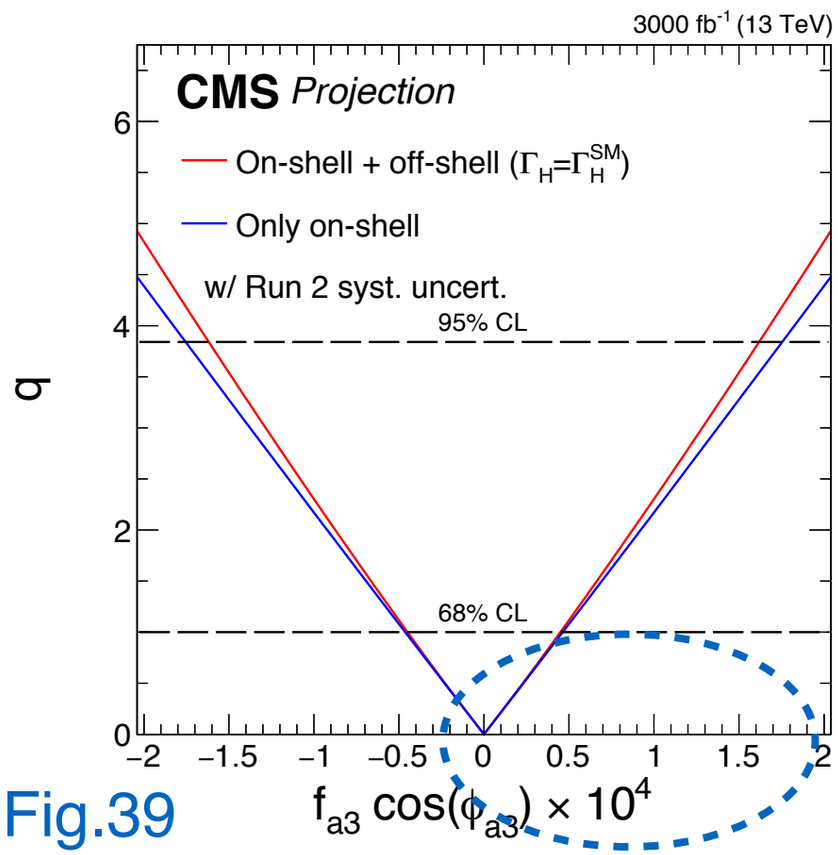


Fig.39

$H \to ZZ \to 4\ell$ decay

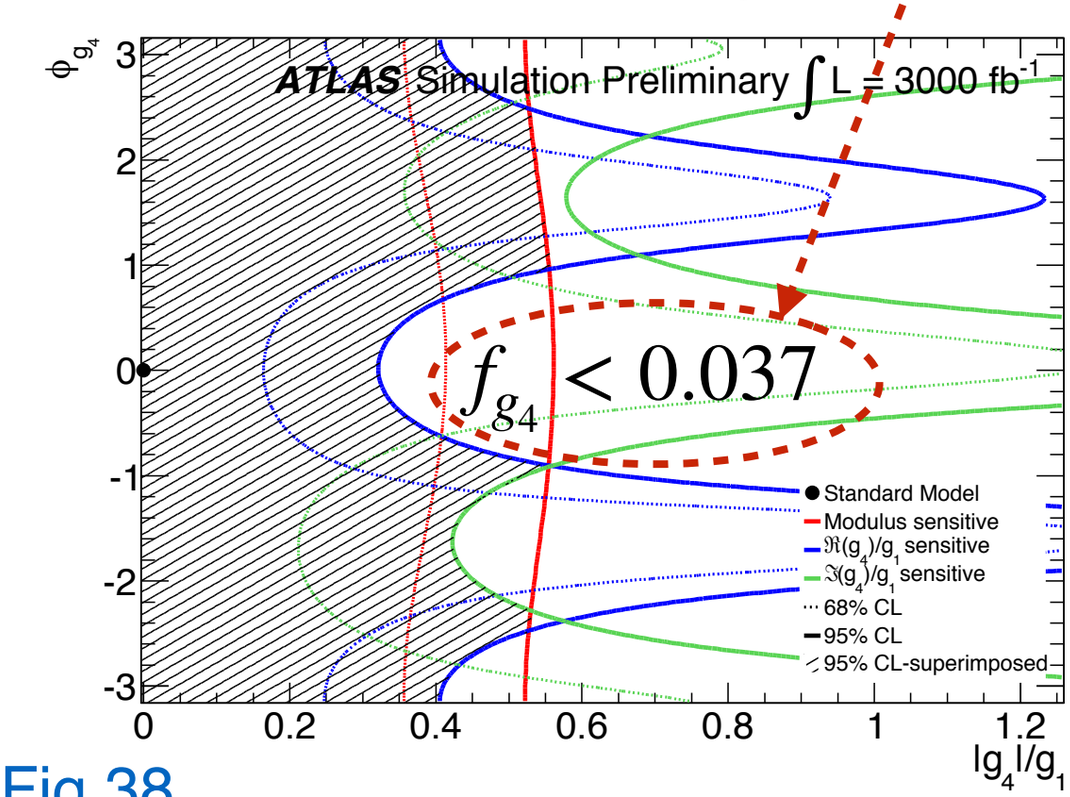


Fig.38

- agreement with most recent pheno HVV and Hgg projections arXiv:2002.09888

Update to recent LHC projections to HL-LHC

- Higgs Physics at the HL-LHC and HE-LHC

  WG2 report: arXiv:1902.00134

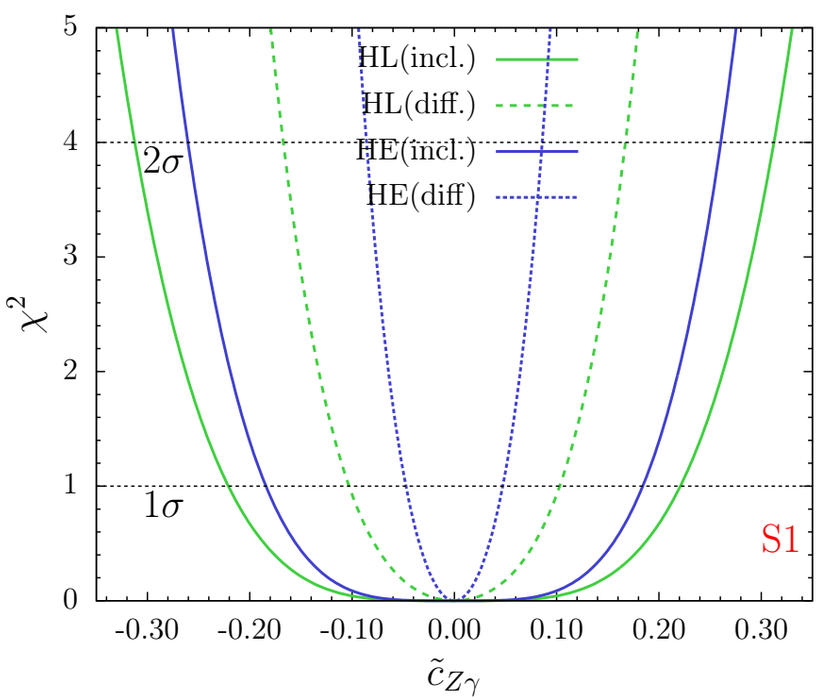
— Global fits also target CP-odd couplings

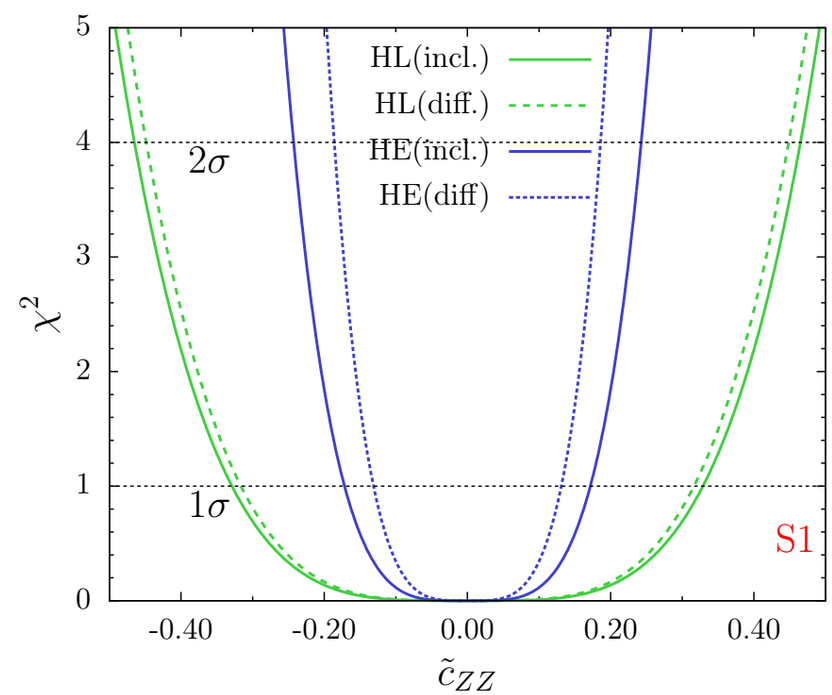
$$\chi^2(\tilde{c}_{Z\gamma}, \tilde{c}_{ZZ}) = \sum_{i,f} \frac{(\mu_{i,f} - \mu_{i,f}^{\text{obs.}})^2}{\Delta_{i,f}^2}$$

— be careful to interpret yield as CP…

CP-even CP-odd

$$\mu_{ZH}^{14\text{TeV}} = 1.00 + 0.54\,\tilde{c}_{Z\gamma}^2 + 2.80\,\tilde{c}_{ZZ}^2 + 0.95\,\tilde{c}_{Z\gamma}\tilde{c}_{ZZ}$$
$$\mu_{WH}^{14\text{TeV}} = 1.00 + 0.84\,\tilde{c}_{Z\gamma}^2 + 3.87\,\tilde{c}_{ZZ}^2 + 3.63\,\tilde{c}_{Z\gamma}\tilde{c}_{ZZ}$$
$$\mu_{\text{VBF}}^{14\text{TeV}} = 1.00 + 0.25\,\tilde{c}_{Z\gamma}^2 + 0.45\,\tilde{c}_{ZZ}^2 + 0.45\,\tilde{c}_{Z\gamma}\tilde{c}_{ZZ}$$



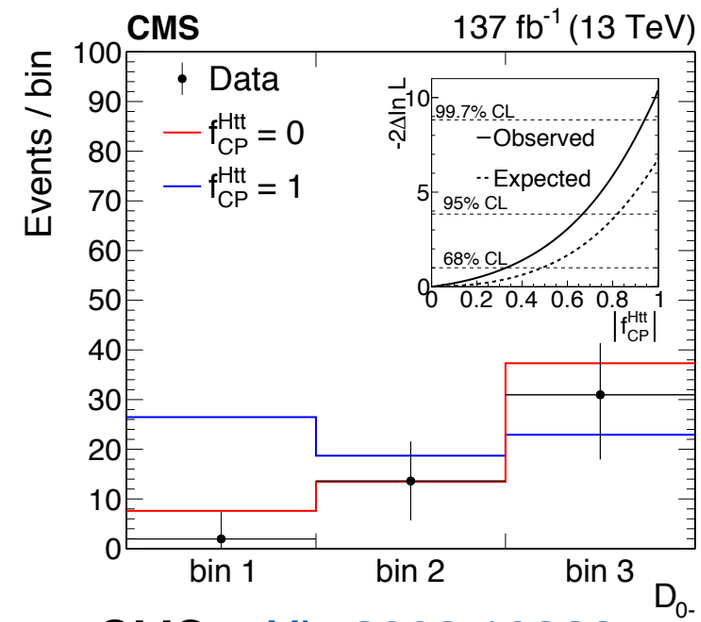


Fermion couplings: $t\bar{t}H$ at pp

- Very first test of CP in Hff this year:
  - $t\bar{t}H$ spin-off from Snowmass-2013

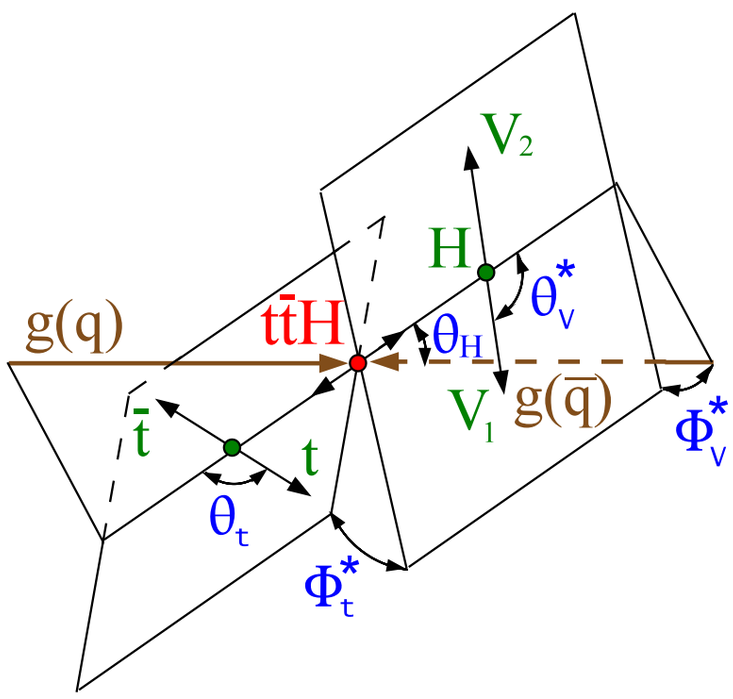
pheno projection agreement with CMS/ATLAS: arXiv:1606.03107

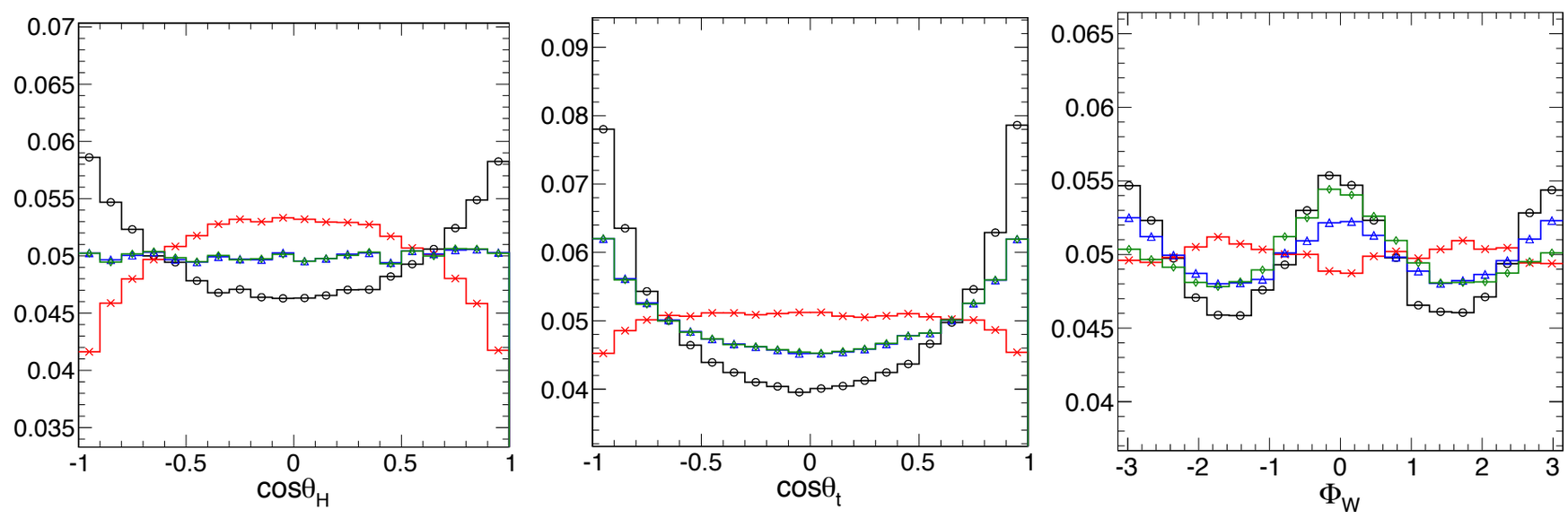
  - reach $f_{CP} \sim 0.1 \;\; (\alpha \sim 18^\circ)$ at HL-LHC
  - no sensitivity to $2\mathrm{Re}\left(A_{\mathrm{CP\,even}} A^*_{\mathrm{CP\,odd}}\right)$
  - similar in tH ; no sensitivity to $b\bar{b}H$, or other light q



CMS arXiv:2003.10866

ATLAS arXiv:2004.04545

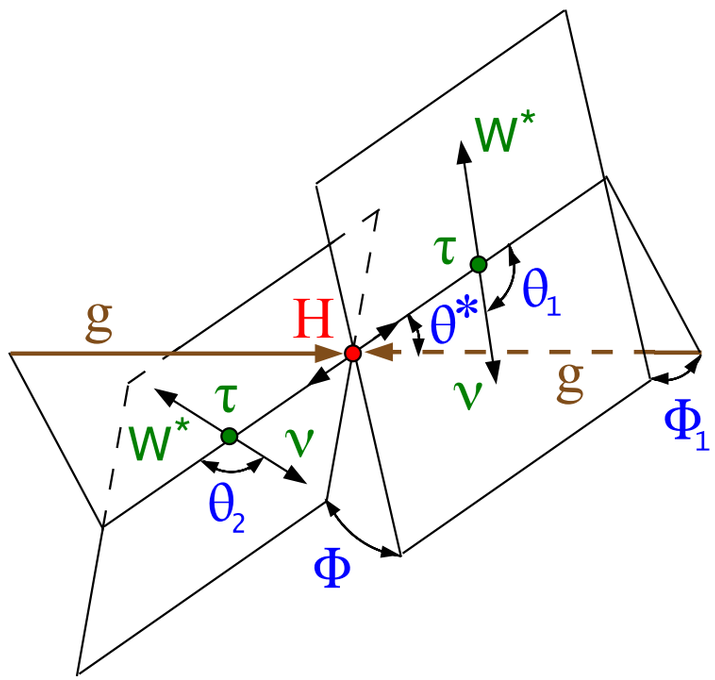




- Make comparison to LC e^+e^-, but looks statistics limited…

Decay: $H \to \tau^+\tau^-$ at e^+e^- and pp

- Decay approach generally the same for all facilities, statistics-limited



- Polarization in $H \to \tau^+\tau^-$ for CP in Hff

  pp pheno studies at Snowmass-2013: arXiv:1308.1094

  — reach $f_{CP} \sim 0.04$ $(\alpha \sim 11^\circ)$ at HL-LHC

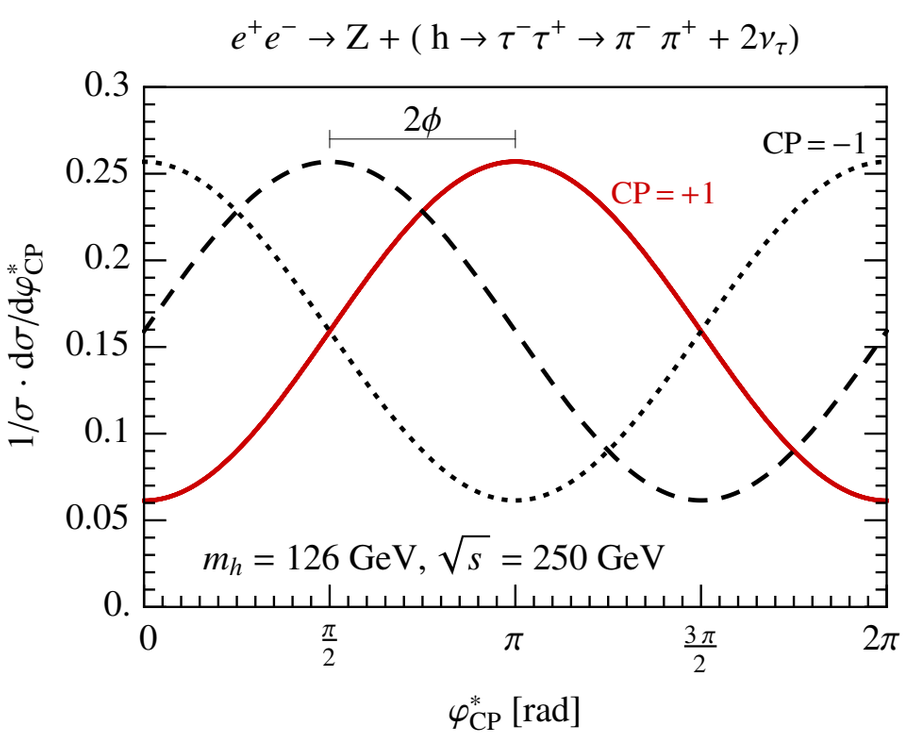
  — will benefit from ATLAS and CMS studies…

  e^+e^- pheno studies at Snowmass-2013: arXiv:1308.2674

  — the only CP in Hff at e^+e^- $\sqrt{s} < 500$ GeV

  — reach $f_{CP} \sim 0.008$ $\left(\alpha \sim 5^\circ\right)$ at e^+e^- ref. lumi

  — e^+e^- benefits from clean environment



$$\tau \to l + \nu_l + \nu_\tau\,, \qquad l = e, \mu\,,$$
$$\tau \to \pi + \nu_\tau\,,$$
$$\tau \to \rho + \nu_\tau \to \pi + \pi^0 + \nu_\tau\,,$$
$$\tau \to a_1 + \nu_\tau \to \pi + 2\pi^0 + \nu_\tau\,,$$
$$\tau \to a_1^{L,T} + \nu_\tau \to 2\pi^\pm + \pi^\mp + \nu_\tau\,.$$

Summary and Plans

- Higgs CP is a good reference measurement for Snowmass-2021
  - Snowmass-2013 is already a good starting point
- Benefit from the past 7 years + 1 year ahead of us…
  - sharpen theoretical expectations / models
  - connect to broader EFT
  - recent ATLAS & CMS analyses provide good guide for pp
  - comparison to e^+e^- may be improved
  - $\gamma\gamma$ & $\mu^+\mu^-$ date back to Snowmass-2001, but may be not a priority…
- Focus on CP in:
  - HWW, HZZ — dominant tree-level HVV
  - $HZ\gamma, H\gamma\gamma, Hgg$ — loop HVV with massless V
  - $Htt, H\tau\tau, H\mu\mu$ — fermion Hff

& think about anything else…