CP sensitivity in $e^+e^- \to ZH$
Snowmass and beyond

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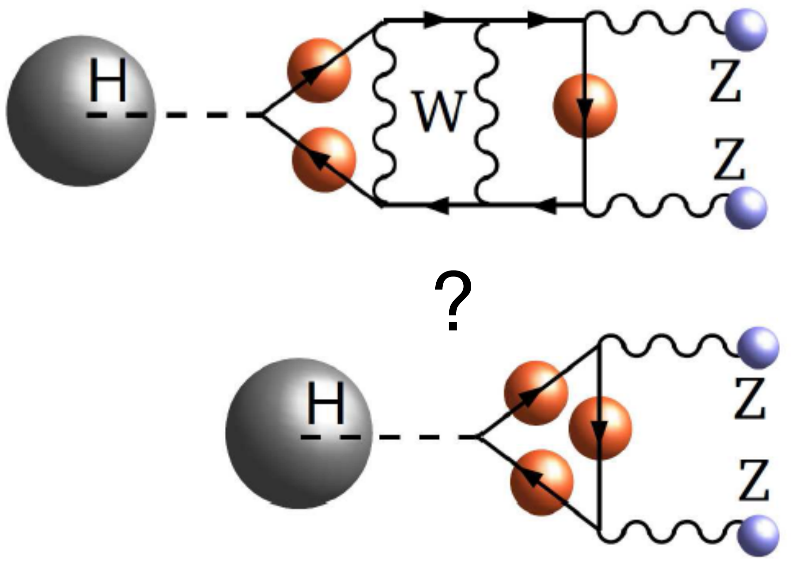
ECFA HTE mini-workshop on e+e- physics at 240-350 GeV

CP-violating H(125) Couplings

- CP-violating H(125) couplings



— tiny in the SM, excellent null-test

— potential baryogengesis connected to the Higgs sector

— well-defined stand-alone reference measurement

— may be part of the bigger EFT (Effective Field Theory) studies

but simpler to deal with, no global fit

— competition with the legacy of LHC and HL-LHC

but can take advantage of LHC development

Snowmass White Paper on Higgs CP

- Dedicated Snowmass White Paper: arXiv:2205.07715 (update 29 Nov 2022)

Snowmass White Paper: Prospects of CP-violation measurements with the Higgs boson at future experiments

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- Quick overview:

Snowmass-2022

TABLE I: List of expected precision (at 68% C.L.) of CP-sensitive measurements of the parameters f_{CP}^{HX} defined in Eq. (2). Numerical values are given where reliable estimates are provided, ✓ mark indicates that feasibility of such a measurement could be considered. The $e^+e^- \to ZH$ projections are performed with $Z \to \ell\ell$ in Appendix B but scaled to a ten times larger luminosity to account for $Z \to q\bar{q}$.

Collider	pp	pp	pp	e^+e^-	e^+e^-	e^+e^-	e^+e^-	e^-p	$\gamma\gamma$	$\mu^+\mu^-$	$\mu^+\mu^-$	target
E (GeV)	14,000	14,000	100,000	250	350	500	1,000	1,300	125	125	3,000	(theory)
$\mathcal{L}$ (fb^{-1})	300	3,000	30,000	250	350	500	1,000	1,000	250	20	1,000	
HZZ/HWW	$4.0\cdot10^{-5}$	$2.5\cdot10^{-6}$	✓	$3.9\cdot10^{-5}$	$2.9\cdot10^{-5}$	$1.3\cdot10^{-5}$	$3.0\cdot10^{-6}$	✓	✓	✓	✓	$< 10^{-5}$
$H\gamma\gamma$	–	0.50	✓	–	–	–	–	–	0.06	–	–	$< 10^{-2}$
$HZ\gamma$	–	~1	✓	–	–	–	~1	–	–	–	–	$< 10^{-2}$
Hgg	0.12	0.011	✓	–	–	–	–	–	–	–	–	$< 10^{-2}$
$Ht\bar{t}$	0.24	0.05	✓	–	–	0.29	0.08	✓	–	–	✓	$< 10^{-2}$
$H\tau\tau$	0.07	0.008	✓	0.01	0.01	0.02	0.06	–	✓	✓	✓	$< 10^{-2}$
$H\mu\mu$	–	–	–	–	–	–	–	–	–	✓	–	$< 10^{-2}$

Starting Point: Snowmass-2013

- Start from Snowmass-2013, several developments in 10 years:
  - reliable LHC results on most measurements
  - more studies supporting future proposals (including White Papers)
  - phenomenological development, EFT…
- Focus on: CP in $HZZ/HWW, HZ\gamma, H\gamma\gamma, Hgg, Htt, H\tau\tau, H\mu\mu$

kept lumi from 2013

Same parameters of interest as in Snowmass-2013 arXiv:1310.8361

$$f_{CP}^{HX} \equiv \frac{\Gamma_{H\to X}^{\text{CP odd}}}{\Gamma_{H\to X}^{\text{CP odd}} + \Gamma_{H\to X}^{\text{CP even}}}$$

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	$\sim 10\sigma$	$\gg 10\sigma$	$>10\sigma$	$>10\sigma$	$>10\sigma$	$>10\sigma$			$>5\sigma$
$VVH^\dagger$	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	–	–	$< 10^{-2}$
$\mu\mu H$	–	–	–	–	–	–	–	✓	$< 10^{-2}$

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

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

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

not enough studies

Snowmass-2013

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

Collider	pp	pp	pp	e^+e^-	e^+e^-	e^+e^-	e^+e^-	e^-p	$\gamma\gamma$	$\mu^+\mu^-$	$\mu^+\mu^-$	target
E (GeV)	14,000	14,000	100,000	250	350	500	1,000	1,300	125	125	3,000	(theory)
$\mathcal{L}$ (fb^{-1})	300	3,000	30,000	250	350	500	1,000	1,000	250	20	1,000	
$H\gamma\gamma$	–	0.50	✓	–	–	–	–	–	0.06	–	–	$< 10^{-2}$
$HZ\gamma$	–	~ 1	✓	–	–	–	~ 1	–	–	–	–	$< 10^{-2}$

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

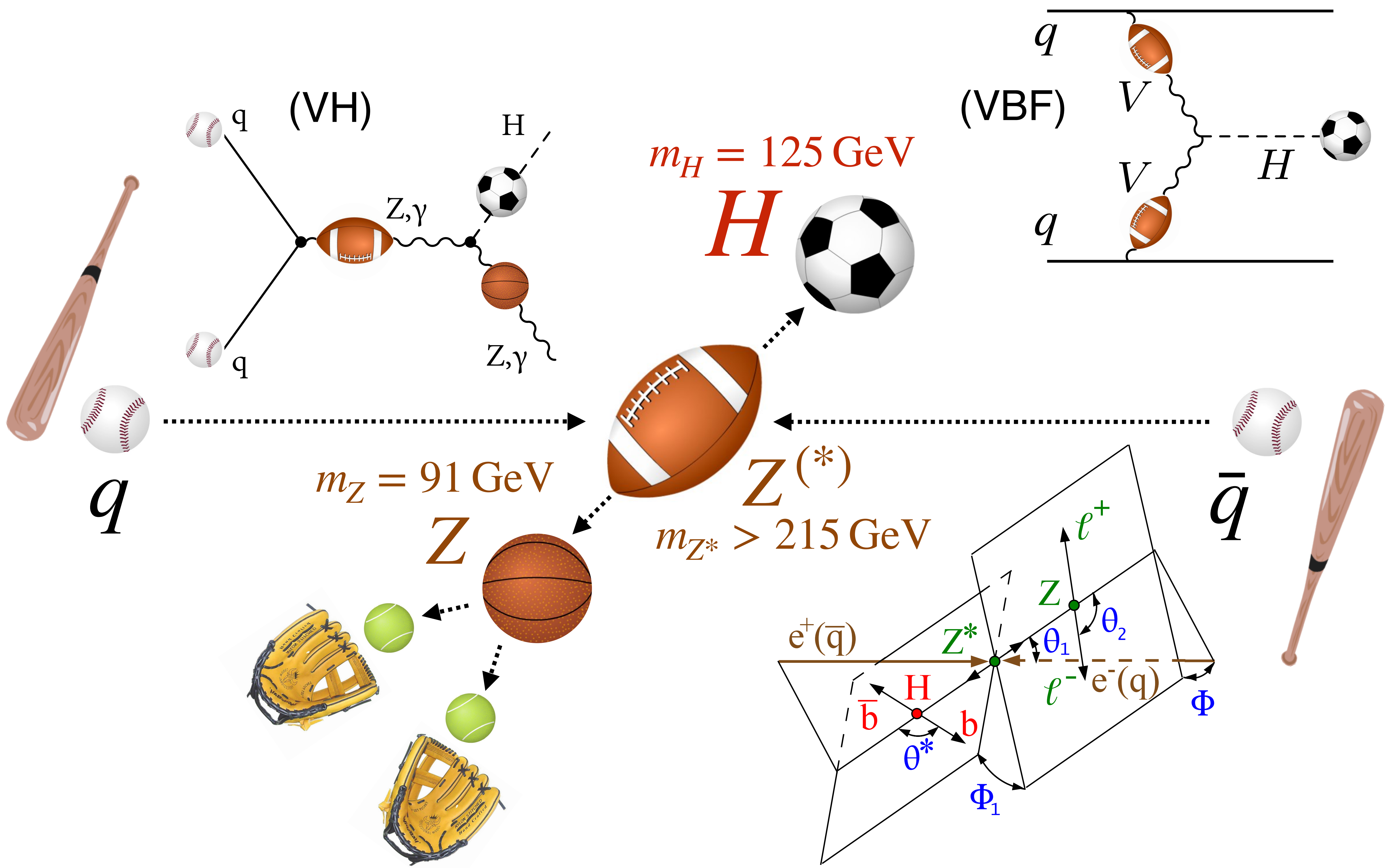
How Valuable is Polarization at a Muon Collider? A Test Case: Determining the CP Nature of a Higgs Boson:
arXiv:hep-ph/0003091

- Unique feature of the muon collider (CP in coupling to 2nd family)
  - — though comes with a price of lumi, likely not a priority at first stage

Collider	pp	pp	pp	e^+e^-	e^+e^-	e^+e^-	e^+e^-	e^-p	$\gamma\gamma$	$\mu^+\mu^-$	$\mu^+\mu^-$	target
E (GeV)	14,000	14,000	100,000	250	350	500	1,000	1,300	125	125	3,000	(theory)
$\mathcal{L}$ (fb^{-1})	300	3,000	30,000	250	350	500	1,000	1,000	250	20	1,000	
$H\mu\mu$	–	–	–	–	–	–	–	–	–	✓	–	$< 10^{-2}$

- High energy $\mu^+\mu^-$: associated production $t\bar{t}H$, VBF

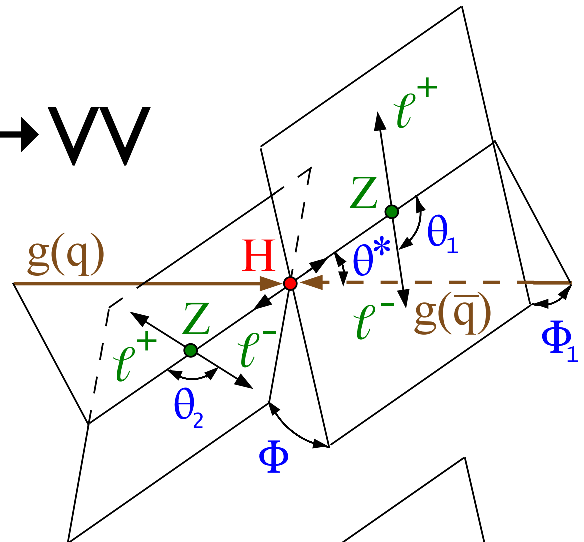
Unique features of Facilities: *pp* production



Unique features of Facilities: *pp* production

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

H→VV

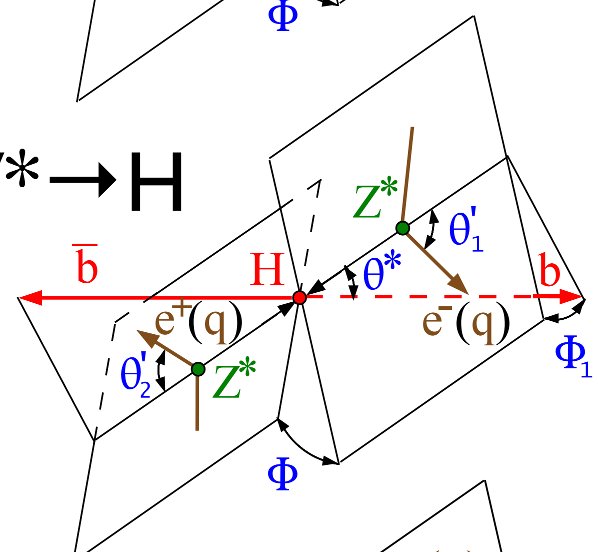


also VBF $V^*V^* \to H$ and decay $H \to VV$

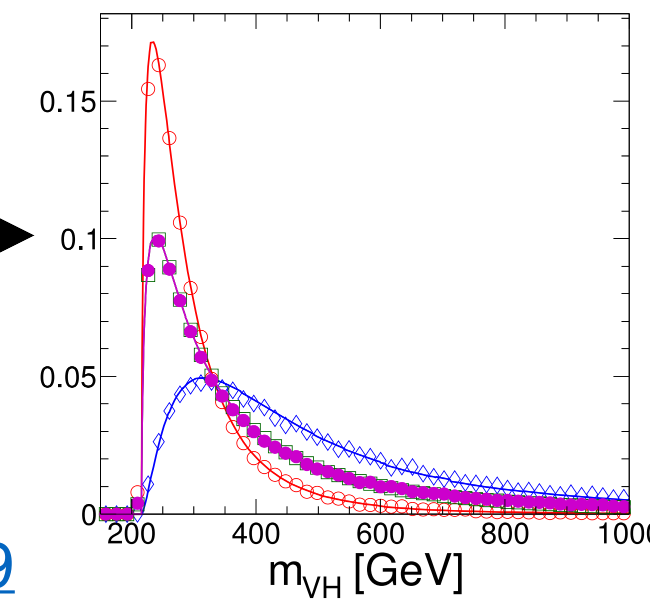
pp unique $gg \to H$

benefit from LHC experience

V*V*→H



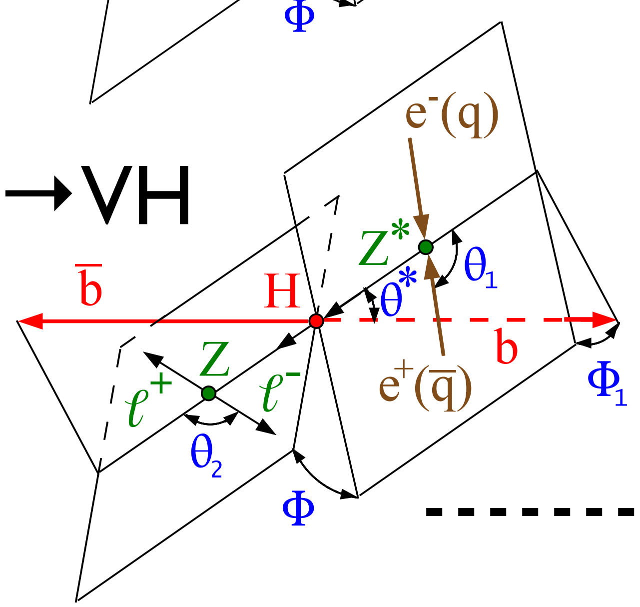
— scan of q^2-dependence

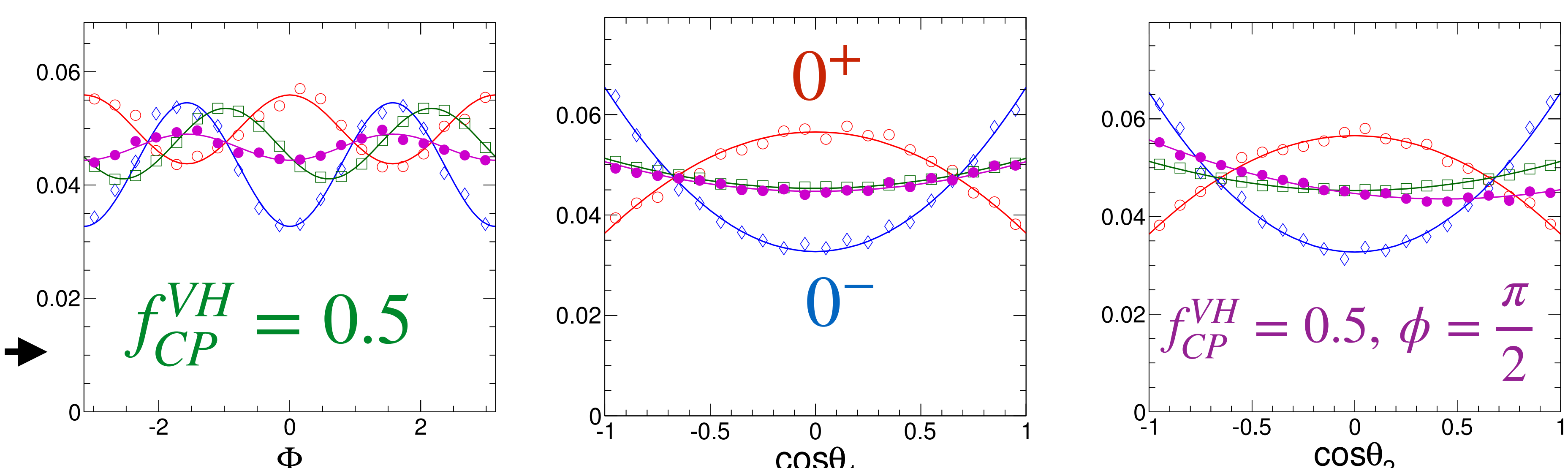


— polarization measurement

[SNOW13-00159](#)

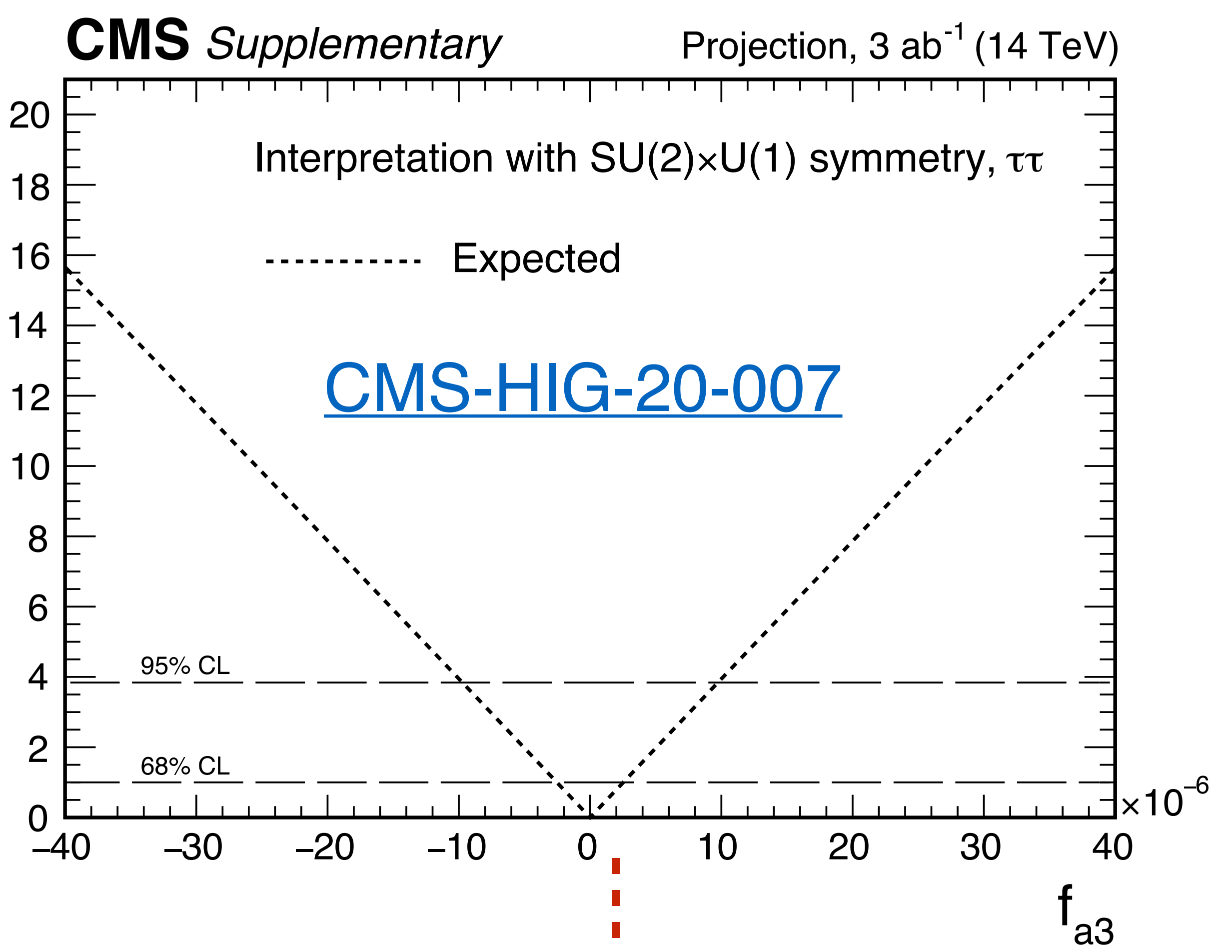
V*→VH





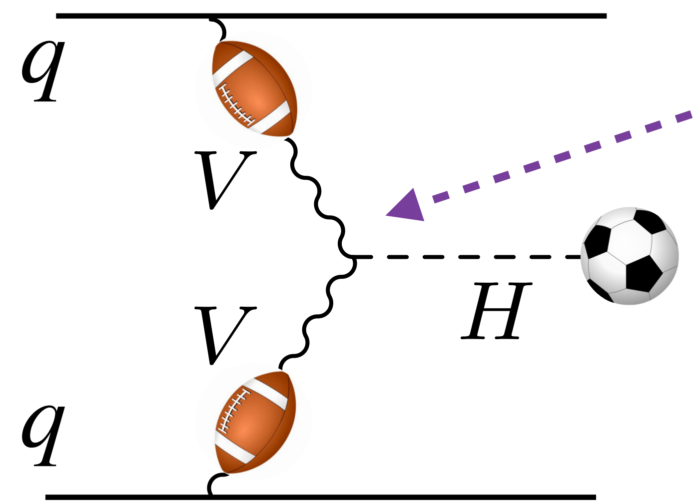
HZZ, HWW in pp production

- Update Snowmass-2013 (pheno) with recent LHC (mutual benefit):



mostly VBF topology (VH similar)

$H \to VV$ not as sensitive due to low q^2



tree-level in SM

BSM relative contribution suppressed

benefit from multiple H decay modes

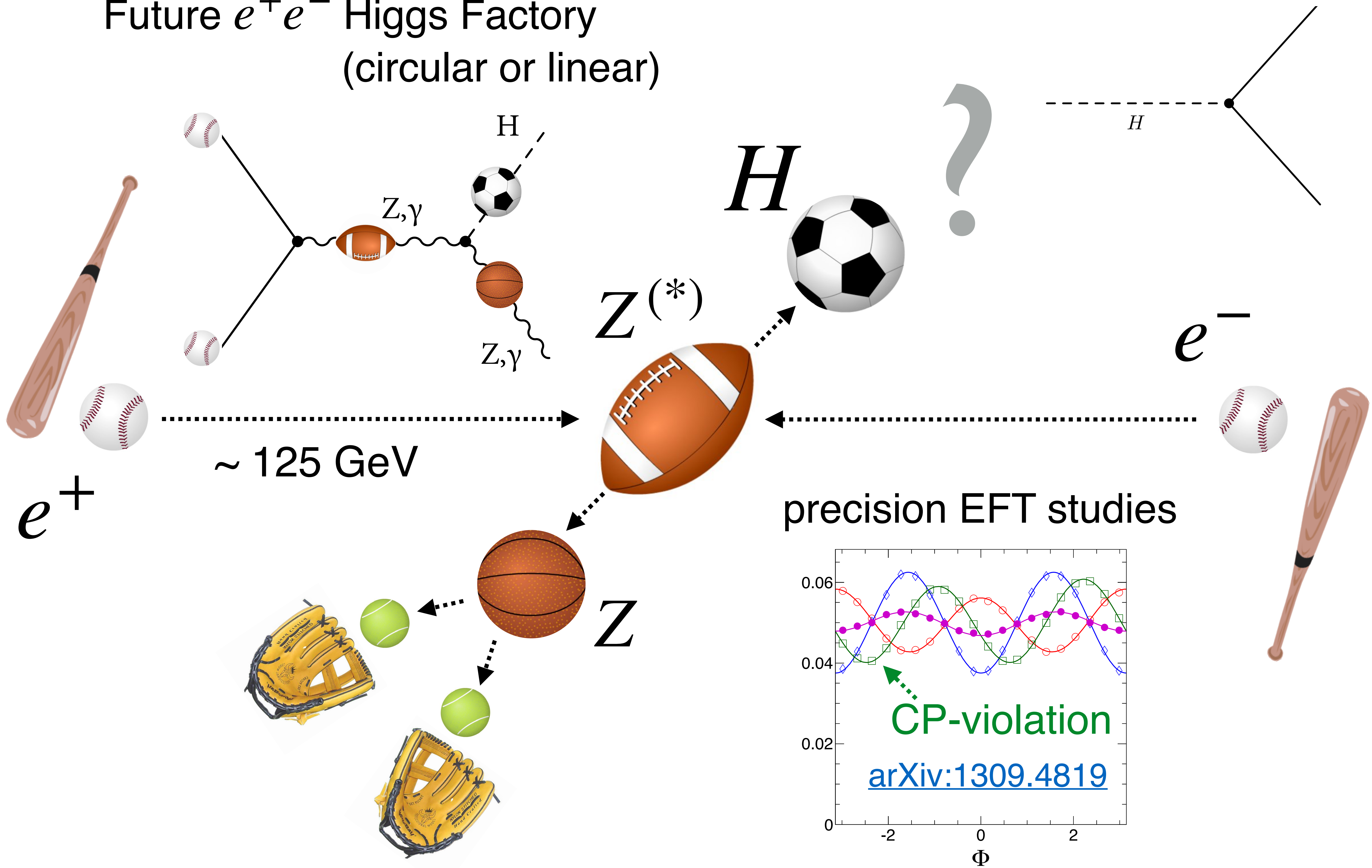
Collider	pp	pp	pp	e^+e^-	e^+e^-	e^+e^-	e^+e^-	e^-p	$\gamma\gamma$	$\mu^+\mu^-$	$\mu^+\mu^-$	target
E (GeV)	14,000	14,000	100,000	250	350	500	1,000	1,300	125	125	3,000	(theory)
$\mathcal{L}$ (fb^{-1})	300	3,000	30,000	250	350	500	1,000	1,000	250	20	1,000	
HZZ/HWW	$4.0 \cdot 10^{-5}$	$2.5 \cdot 10^{-6}$	✓	$3.9 \cdot 10^{-5}$	$2.9 \cdot 10^{-5}$	$1.3 \cdot 10^{-5}$	$3.0 \cdot 10^{-6}$	✓	✓	✓	✓	$< 10^{-5}$

$\sim 10^{-8}$ (?)

- A lot more in BACKUP

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

Future e^+e^- Higgs Factory
(circular or linear)

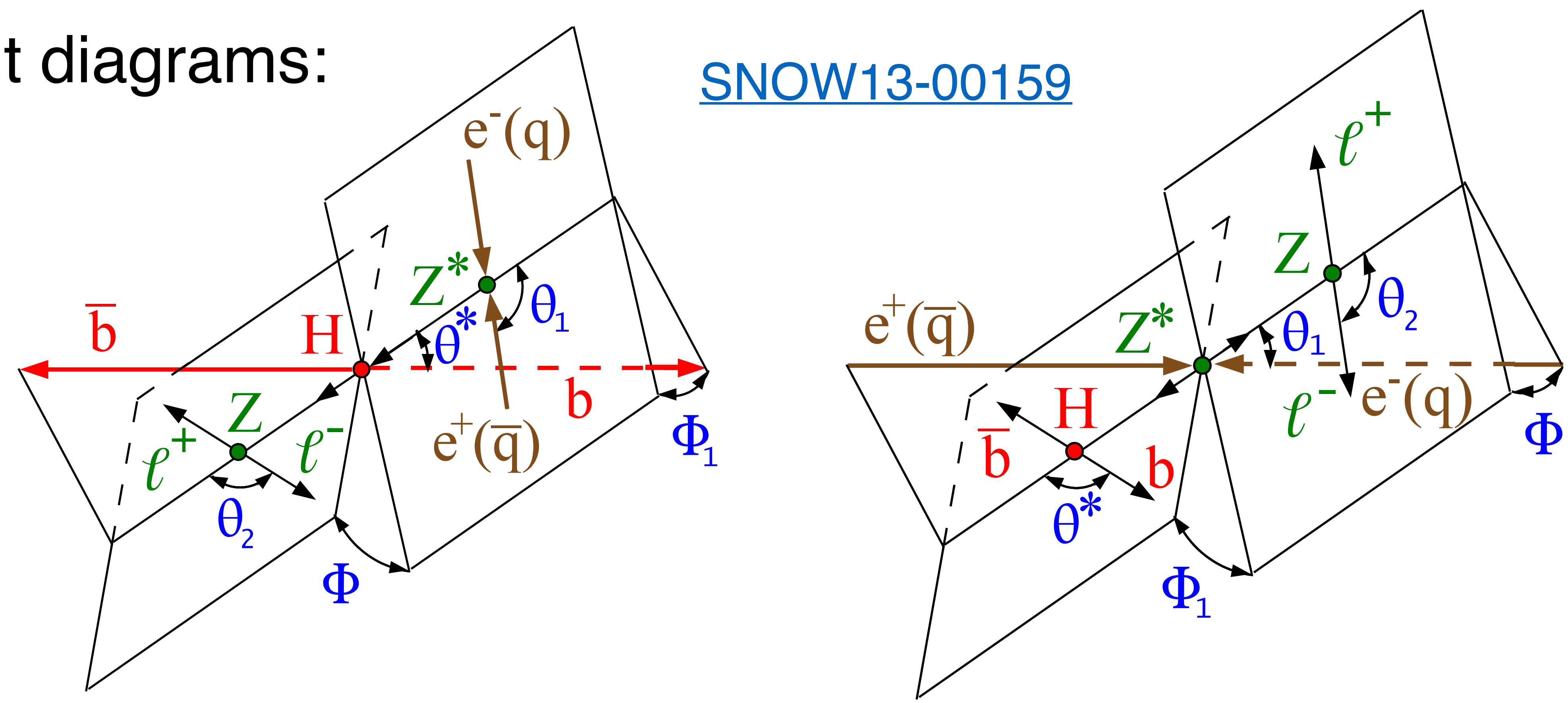


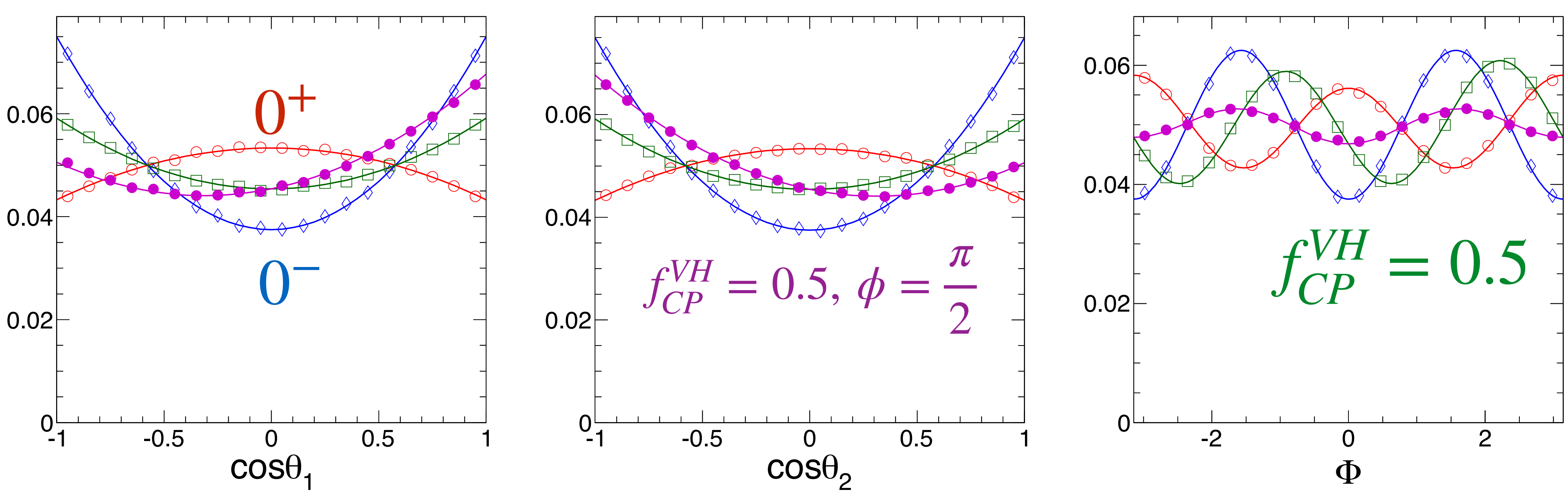
Unique features of Facilities: e^+e^- production

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

equivalent diagrams:

SNOW13-00159





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

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

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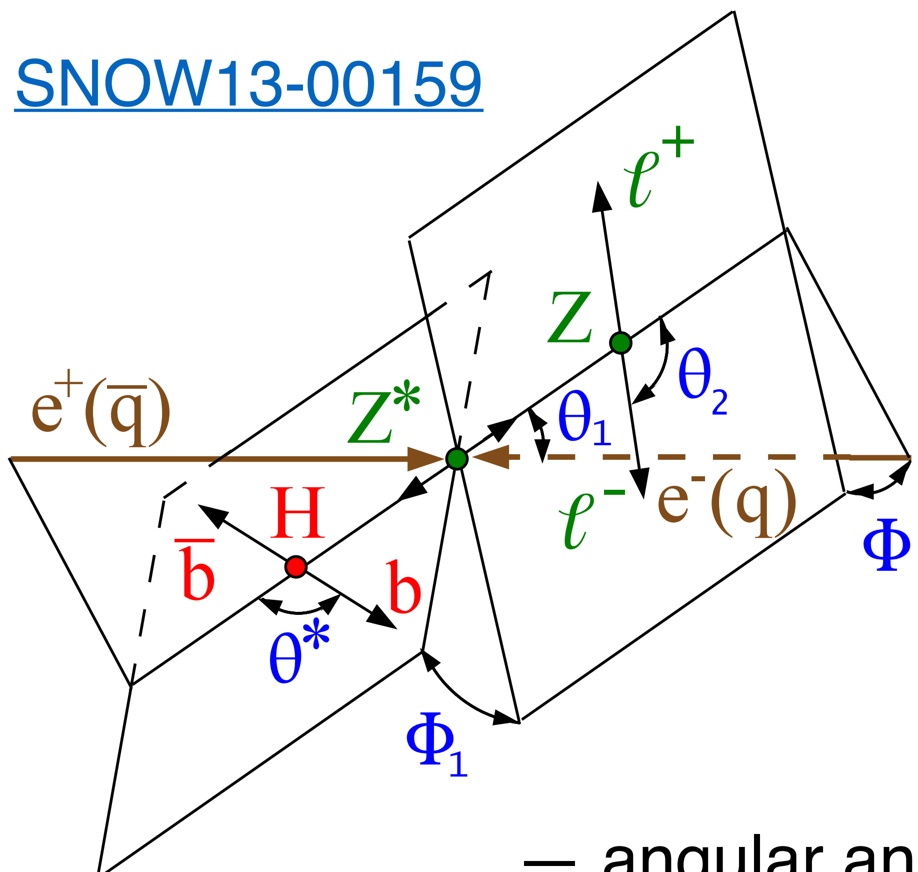
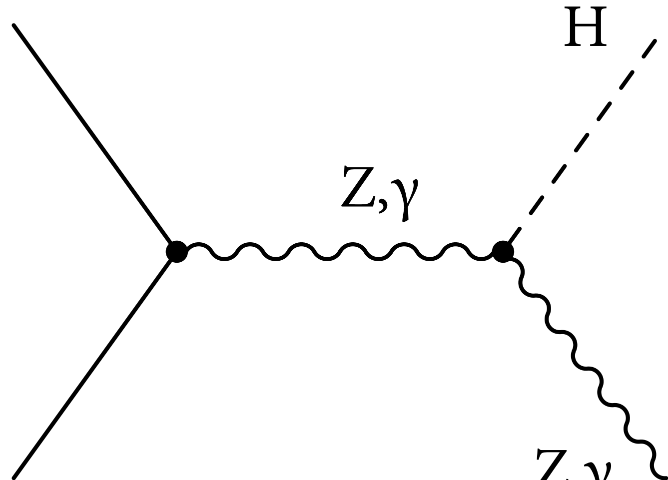
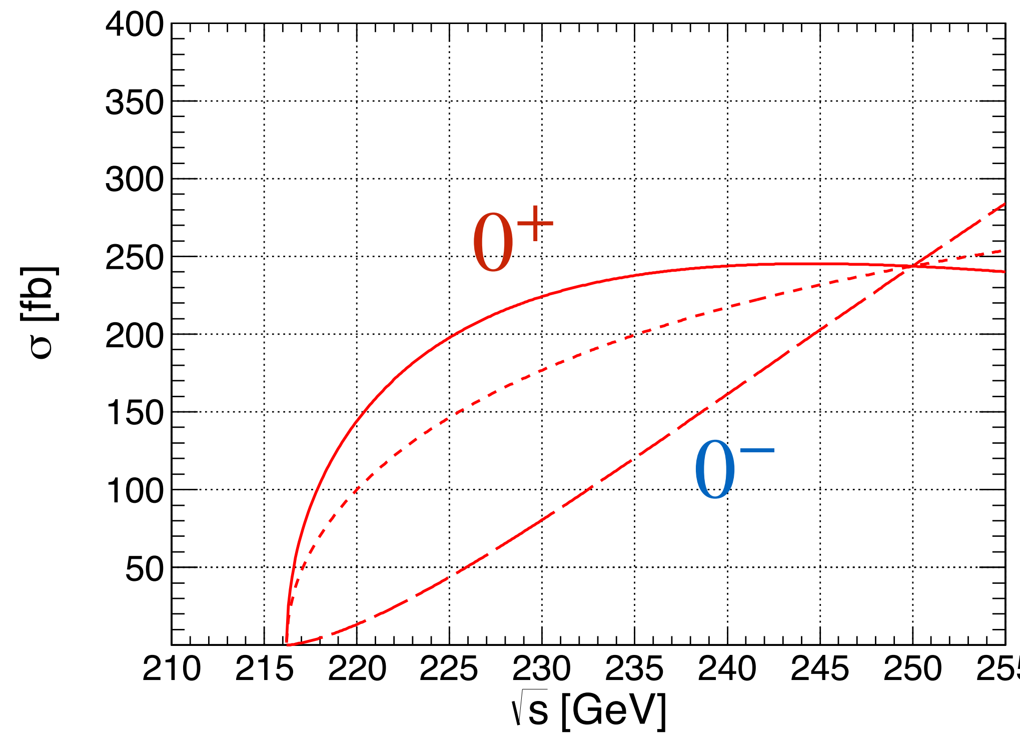
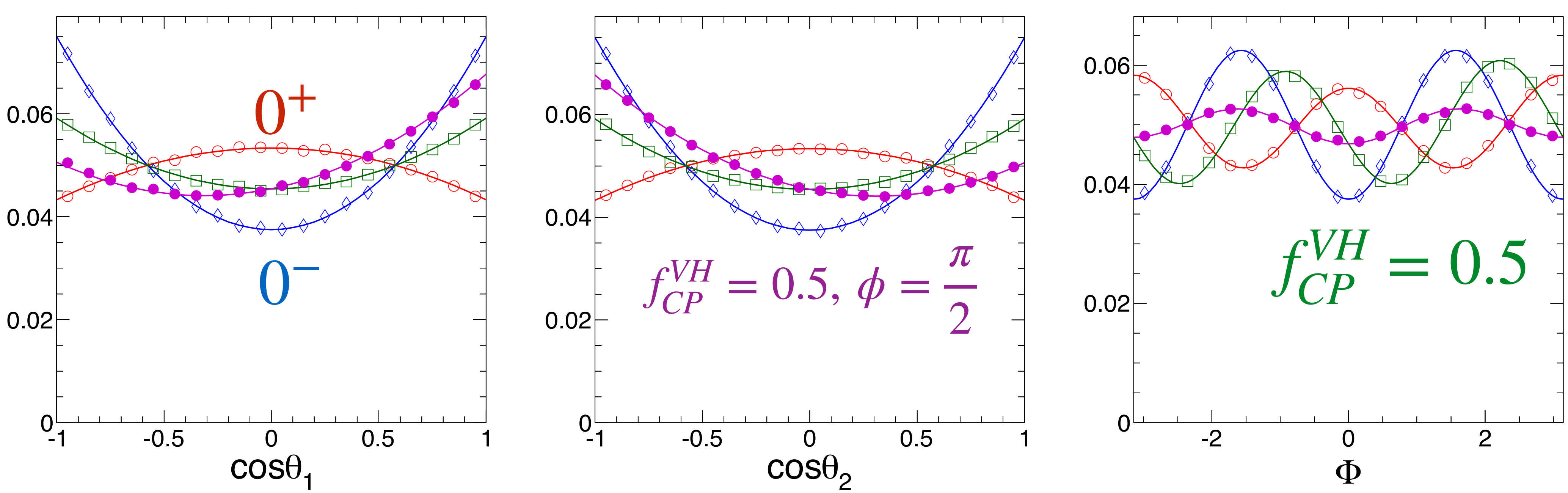


— threshold scan = q^2 dependence





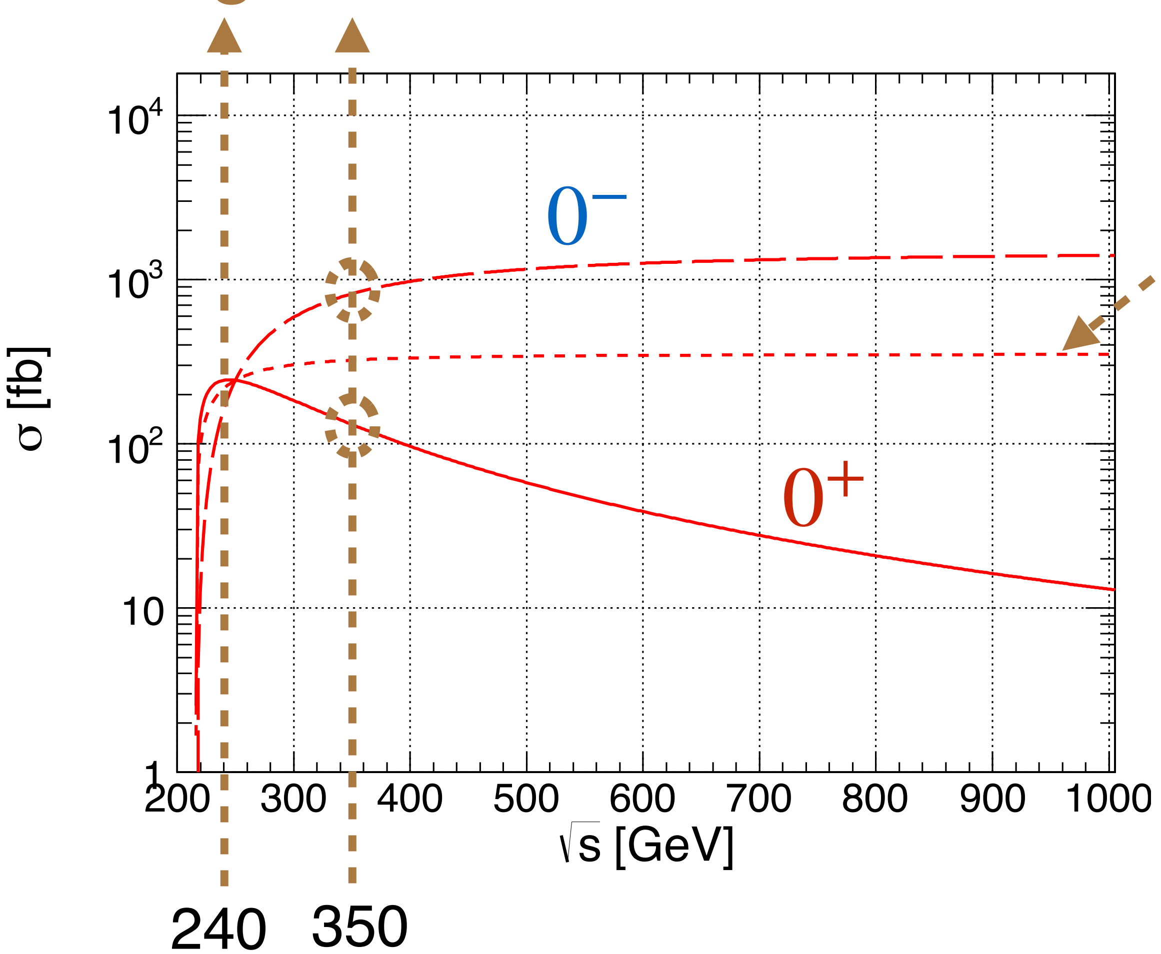
— angular analysis = polarization



e^+e^- production at higher energies (340 GeV)

- e^+e^- collider $\to Z^* \to ZH$
- Scan q^2 dependence of HVV $\Rightarrow$ increased sensitivity (no cutoff)

big effect from 240 to 350 GeV



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but not genuine CP effect
CP-even higher-dim operator

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

not much angular information
q^2-dependence through p_T^H …

- VBF $e^+e^- \to e^+e^-H$

recent study (ICHEP-2022)
does not surpass $e^+e^- \to Z^* \to ZH$
at intermediate energies

e^+e^- production at 240 and 350 GeV

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

Collider	pp	pp	pp	e^+e^-	e^+e^-	e^+e^-	e^+e^-	e^-p	$\gamma\gamma$	$\mu^+\mu^-$	$\mu^+\mu^-$	target
E (GeV)	14,000	14,000	100,000	250	350	500	1,000	1,300	125	125	3,000	(theory)
$\mathcal{L}$ (fb^{-1})	300	3,000	30,000	250	350	500	1,000	1,000	250	20	1,000	
HZZ/HWW	$4.0\cdot10^{-5}$	$2.5\cdot10^{-6}$	✓	$3.9\cdot10^{-5}$	$2.9\cdot10^{-5}$	$1.3\cdot10^{-5}$	$3.0\cdot10^{-6}$	✓	✓	✓	✓	$< 10^{-5}$
$H\gamma\gamma$	–	0.50	✓	–	–	–	–	–	0.06	–	–	$< 10^{-2}$
$HZ\gamma$	–	$\sim$1	✓	–	–	–	$\sim$1	–	–	–	–	$< 10^{-2}$

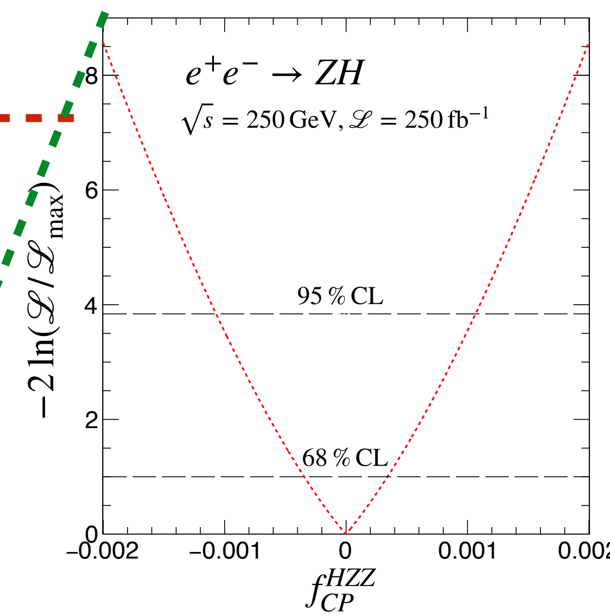
see also arXiv:2203.11707 in agreement

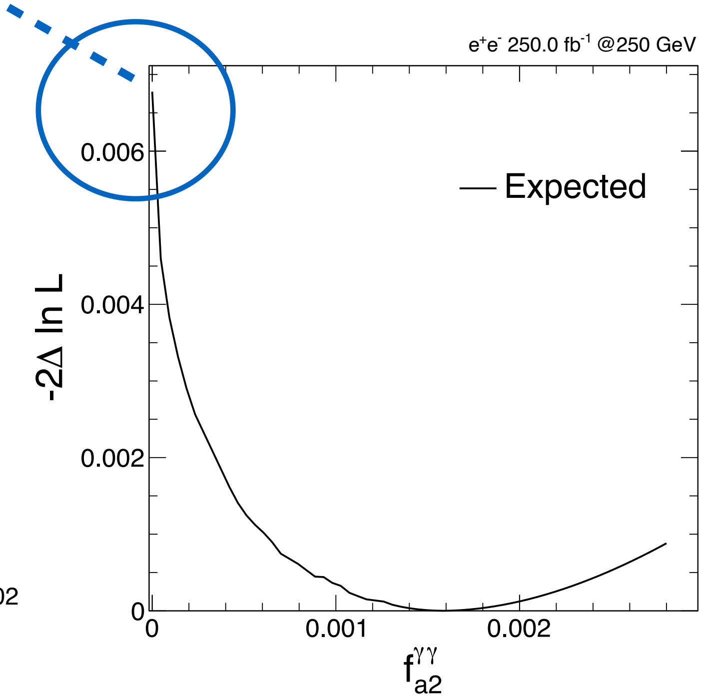
Appendix B: Recent updates of the studies at an electron-positron collider

Contributed by Lucas S. Mandacarú Guerra and Savvas Kyriacou.

lumi $\times$ 10 to cover $Z \rightarrow q\bar{q}$

E (GeV)	$\mathcal{L}$ (fb^{-1})	f_{CP}^{HVV}	$f^{\gamma\gamma}$	$f^{Z\gamma}$	$f_{CP}^{\gamma\gamma}$	$f_{CP}^{Z\gamma}$
250	250	$\pm3.4\cdot10^{-4}$	< 0.144	< 0.234	–	–
250	2,500	$\pm3.9\cdot10^{-5}$	< 0.037	< 0.079	–	–
350	350	$\pm1.2\cdot10^{-4}$	< 0.058	< 0.088	–	–
350	3,500	$\pm2.9\cdot10^{-5}$	< 0.016	< 0.032	–	–
500	500	$\pm4.3\cdot10^{-5}$	< 0.028	< 0.039	–	–
500	5,000	$\pm1.3\cdot10^{-5}$	< 0.009	< 0.016	–	–
1,000	1,000	$\pm1.0\cdot10^{-5}$	< 0.009	< 0.014	–	–
1,000	10,000	$\pm3.0\cdot10^{-6}$	< 0.004	$0.0050^{+0.0026}_{-0.0028}$	–	±0.96





fractions in $H \rightarrow 2e2\mu$: $f^{\gamma\gamma}_{\rm ref.SM} = 0.0016$ $\quad f^{Z\gamma}_{\rm ref.SM} = 0.0050$

$f^{\gamma\gamma}_{\rm ref.SM} = 0.0016$

e^+e^- production at 240 and 350 GeV

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

Collider	pp	pp	pp	e^+e^-	e^+e^-	e^+e^-	e^+e^-	e^-p	$\gamma\gamma$	$\mu^+\mu^-$	$\mu^+\mu^-$	target
E (GeV)	14,000	14,000	100,000	250	350	500	1,000	1,300	125	125	3,000	(theory)
$\mathcal{L}$ (fb^{-1})	300	3,000	30,000	250	350	500	1,000	1,000	250	20	1,000	
HZZ/HWW	$4.0\cdot10^{-5}$	$2.5\cdot10^{-6}$	✓	$3.9\cdot10^{-5}$	$2.9\cdot10^{-5}$	$1.3\cdot10^{-5}$	$3.0\cdot10^{-6}$	✓	✓	✓	✓	$< 10^{-5}$
$H\gamma\gamma$	–	0.50	✓	–	–	–	–	–	0.06	–	–	$< 10^{-2}$
$HZ\gamma$	–	~1	✓	–	–	–	~1	–	–	–	–	$< 10^{-2}$

- Room for improvement:
  — target 7.2 ab^{-1} for 4 IPs in 3 years at FCC 240 GeV
  ~1 ab^{-1} at FCC 350 GeV, ~2 ab^{-1} at 365 GeV
  — target all main Z and H final states
  — include full detector simulation & all backgrounds
  — q^2 interplay between 240 GeV and 350 GeV

Summary on Higgs CP

- As part of Snowmass several conclusions:
  - e^+e^- comparable to HL-LHC in Higgs CP, except Hgg
  - pp HL reach full spectrum of Higgs CP, except $H\mu\mu$
  - $\gamma\gamma$ at 125 GeV + polarize unique CP in $H\gamma\gamma$
  - $\mu^+\mu^-$ at 125 GeV + polarize unique CP in $H\mu\mu$ (2nd family)
  - e^-p allow CP in VBF, ttH
  - pp at 100 TeV the furthest reach, including CP in $HV\gamma$

HWW, HZZ
$HZ\gamma, H\gamma\gamma, Hgg$
$Htt, H\tau\tau, H\mu\mu$

- Framework for FCC studies
  - benefit from detailed simulation of signal & background

$$e^+e^- \to Z^*/\gamma^* \to Z/\gamma^* H$$

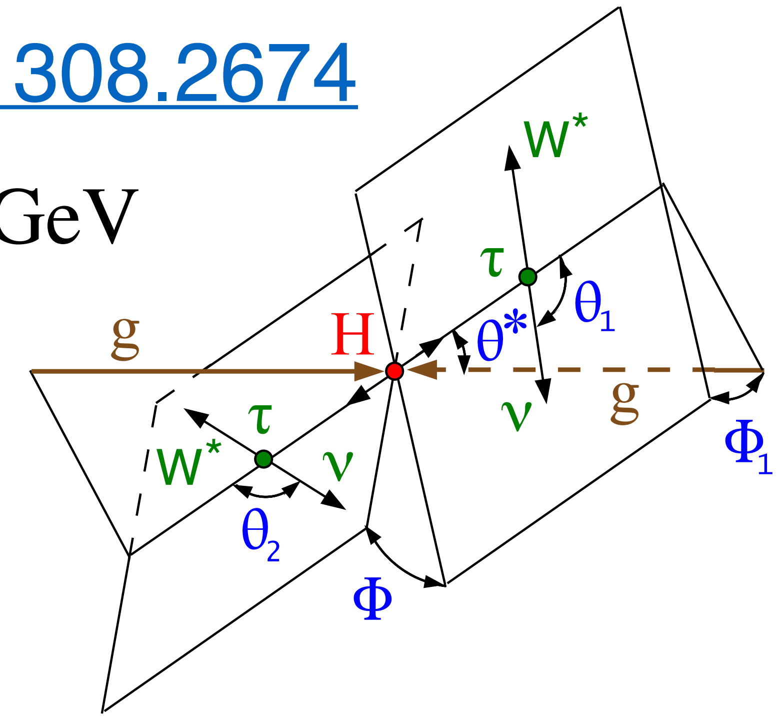
  - explore $Z/\gamma^* \to \ell^+\ell^-/q\bar{q}/\nu\bar{\nu}$ and $H \to \text{any}$
  - can start from SM simulation and re-weight for BSM (but lack of $\gamma^* H$, γH)
  - need to agree on lumi scenarios (e.g. Snowmass and FCC differ)

BACKUP

Fermion couplings at an e^+e^- collider

- e^+e^- pheno studies at Snowmass-2013: arXiv:1308.2674
  - $H \to \tau\tau$ the only CP in Hff at e^+e^- $\sqrt{s} < 500$ GeV
  - reach $f_{CP} \sim 0.008$ $(\alpha \sim 5^\circ)$ at e^+e^- ref. lumi

  note: worse at higher $\sqrt{s}$: no vertex in $e^+e^- \to \nu\bar{\nu}H$



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

  cross section dependence studied of 0^+ *vs.* 0^- at Snowmass-2013

  recent similar study in arXiv:1807.02441

  need dedicated CP-sensitive study (see LHC studies)

from Snowmass-2013

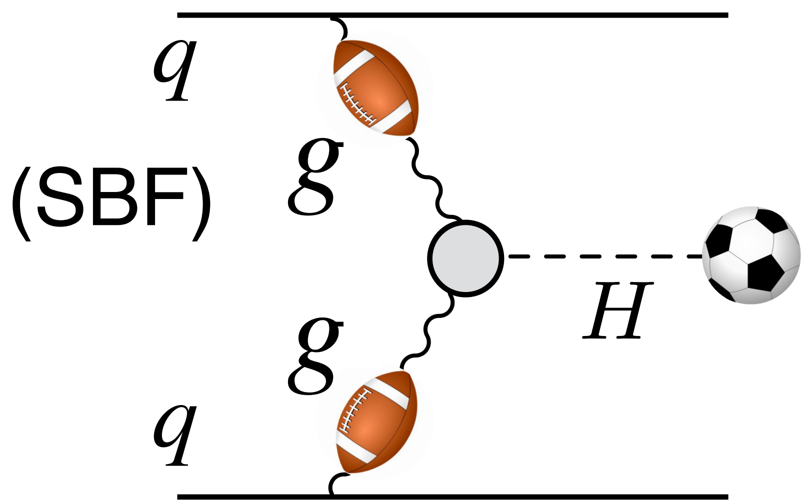
Collider	pp	pp	pp	e^+e^-	e^+e^-	e^+e^-	e^+e^-	e^-p	$\gamma\gamma$	$\mu^+\mu^-$	$\mu^+\mu^-$	target
E (GeV)	14,000	14,000	100,000	250	350	500	1,000	1,300	125	125	3,000	(theory)
$\mathcal{L}$ (fb^{-1})	300	3,000	30,000	250	350	500	1,000	1,000	250	20	1,000	
$Ht\bar{t}$	0.24	0.05	✓	–	–	0.29	0.08	✓	–	–	✓	$< 10^{-2}$
$H\tau\tau$	0.07	0.008	✓	0.01	0.01	0.02	0.06	–	✓	✓	✓	$< 10^{-2}$
$H\mu\mu$	–	–	–	–	–	–	–	–	–	✓	–	$< 10^{-2}$

Gluon fusion in *pp* production

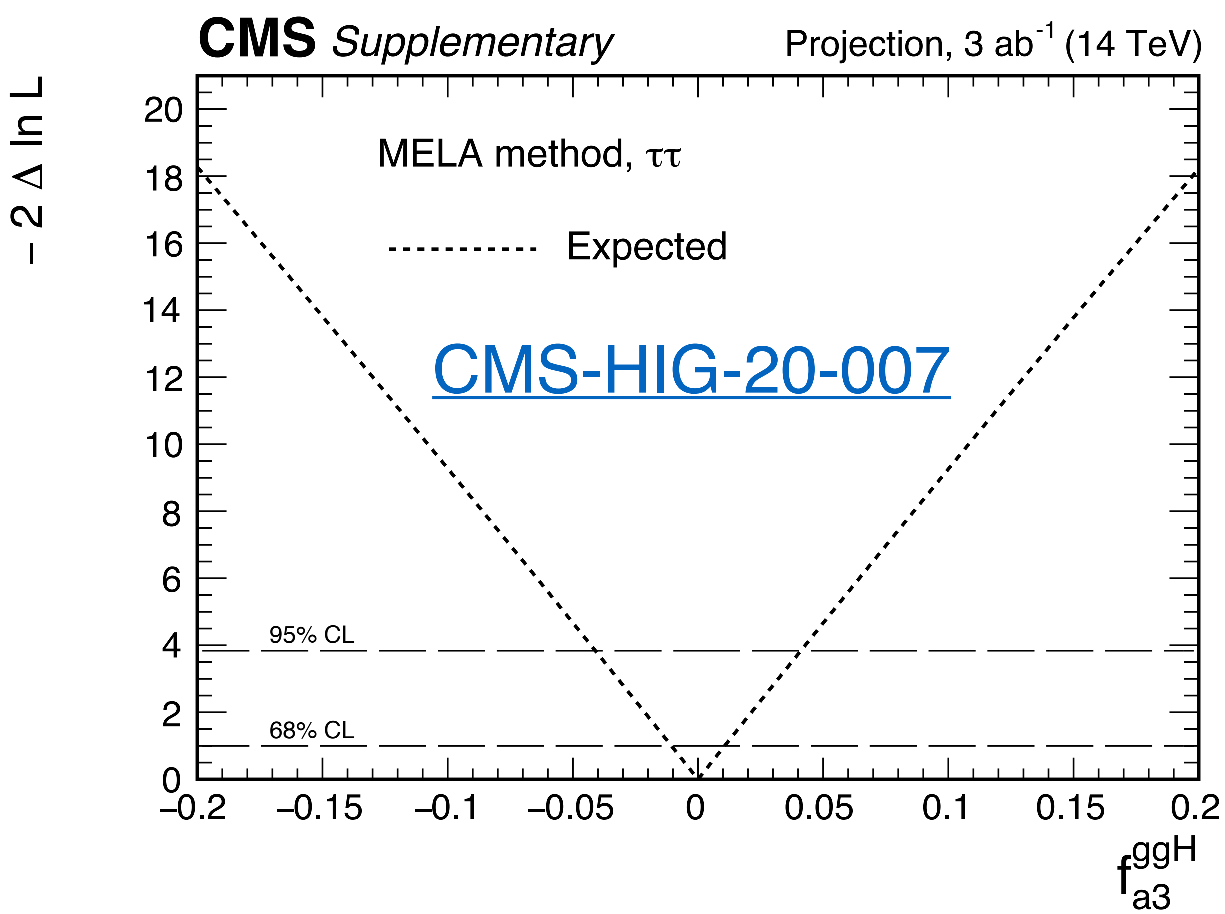
- *pp* is unique to measure Hgg coupling

BSM loop (point-like) or SM fermion loop

$$a_2^{gg} = -\alpha_s \kappa_Q/(6\pi) \quad \& \quad a_3^{gg} = -\alpha_s \tilde{\kappa}_Q/(4\pi)$$



- Update Snowmass-2013 (pheno) with recent LHC (mutual benefit):



Collider	pp	pp	pp
E (GeV)	14,000	14,000	100,000
$\mathcal{L}$ (fb^{-1})	300	3,000	20,000
Hgg	0.12	0.011	✓

benefit from multiple H decay modes

$H\gamma\gamma, HZ\gamma$ in pp production

- CP in photon couplings appear challenging at all colliders

poor precision in VBF and VH

$H \to \gamma\gamma (Z\gamma)$

constrain $(a_2^{V\gamma})^2 + (a_3^{V\gamma})^2$

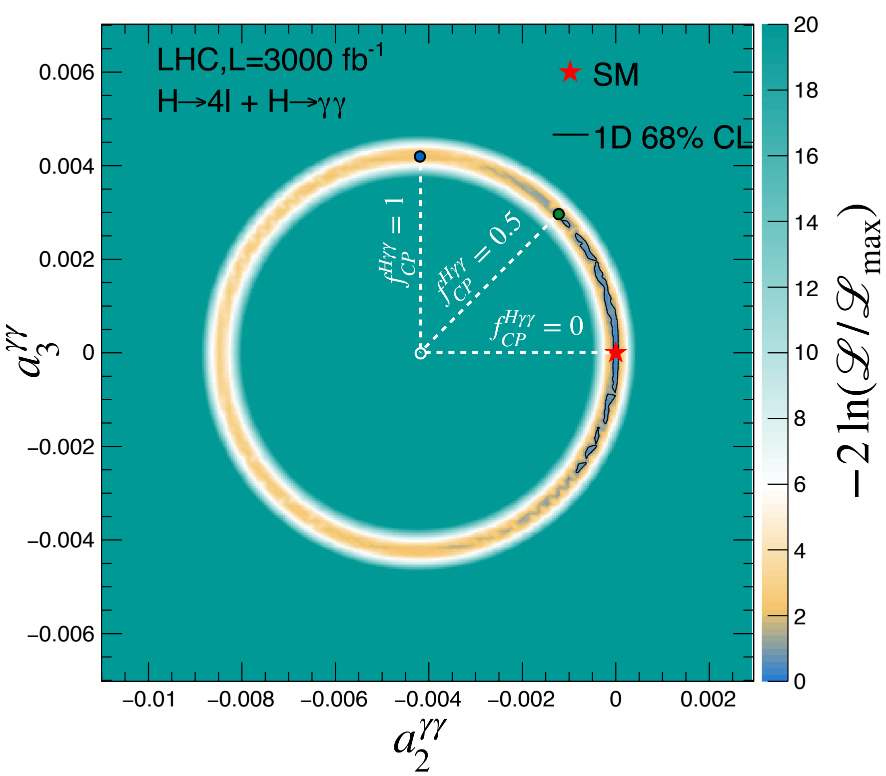
$H \to \gamma^*\gamma^* (Z\gamma^*) \to 4\ell$

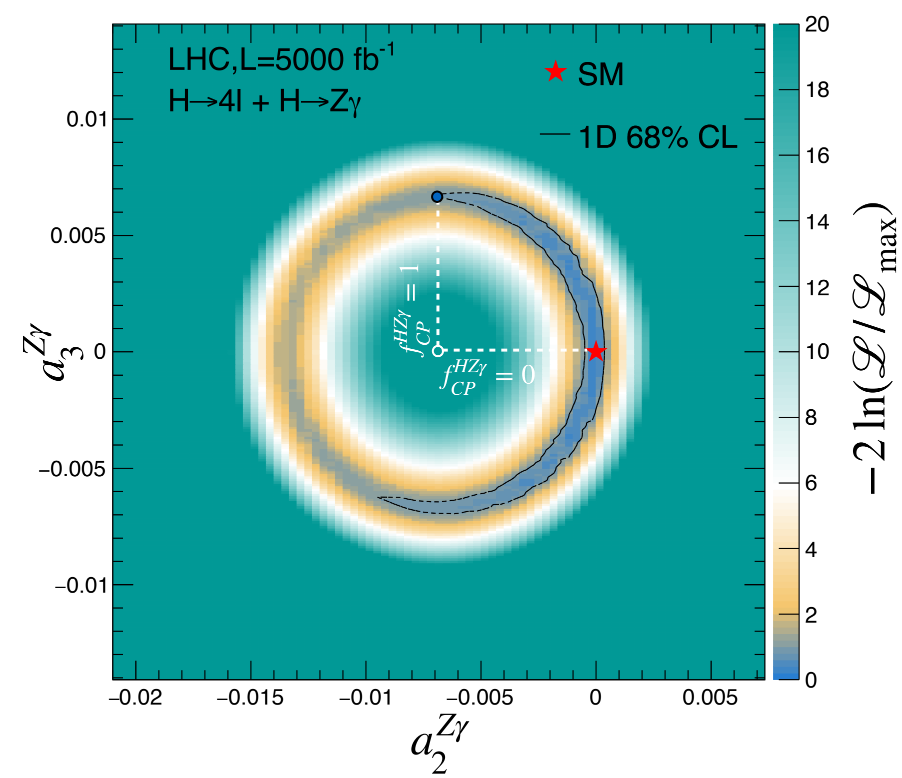
resolve $a_2^{V\gamma} / a_3^{V\gamma}$

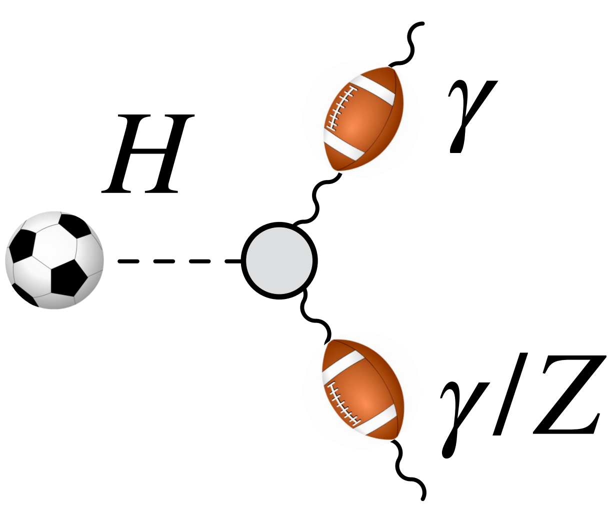
expect good constraints at pp 100 TeV

Appendix A: Recent updates of the studies at a hadron collider

Contributed by Jeffrey Davis, Savvas Kyriacou, and Jeffrey Roskes.







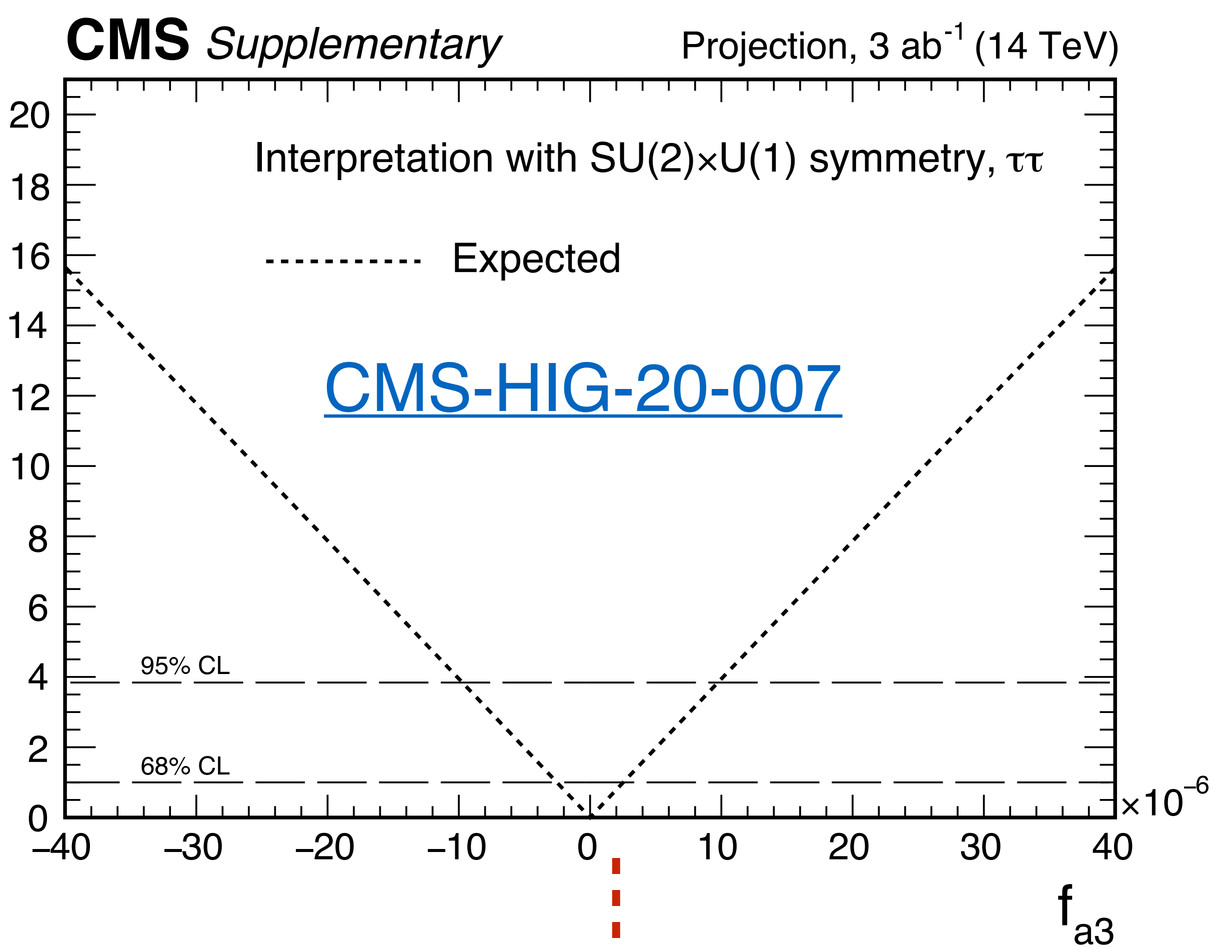
Collider	pp	pp	pp	e^+e^-	e^+e^-	e^+e^-	e^+e^-	e^-p	$\gamma\gamma$	$\mu^+\mu^-$	$\mu^+\mu^-$	target
E (GeV)	14,000	14,000	100,000	250	350	500	1,000	1,300	125	125	3,000	(theory)
$\mathcal{L}$ (fb^{-1})	300	3,000	30,000	250	350	500	1,000	1,000	250	20	1,000	

< 0.05 (?)

$H\gamma\gamma$	–	0.50	✓	–	–	–	–	–	0.06	–	–	$< 10^{-2}$
$HZ\gamma$	–	~ 1	✓	–	–	–	~ 1	–	–	–	–	$< 10^{-2}$

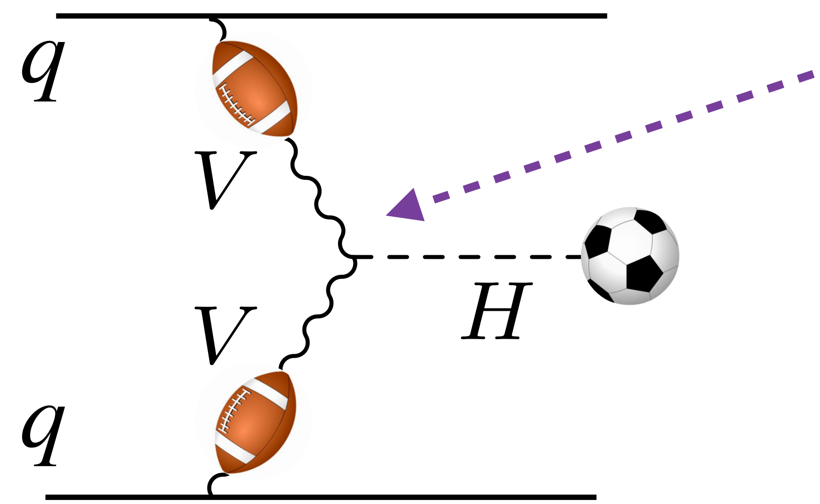
HZZ, HWW in pp production

- Update Snowmass-2013 (pheno) with recent LHC (mutual benefit):



mostly VBF topology (VH similar)

$H \to VV$ not as sensitive due to low q^2



tree-level in SM

BSM relative contribution suppressed

benefit from multiple H decay modes

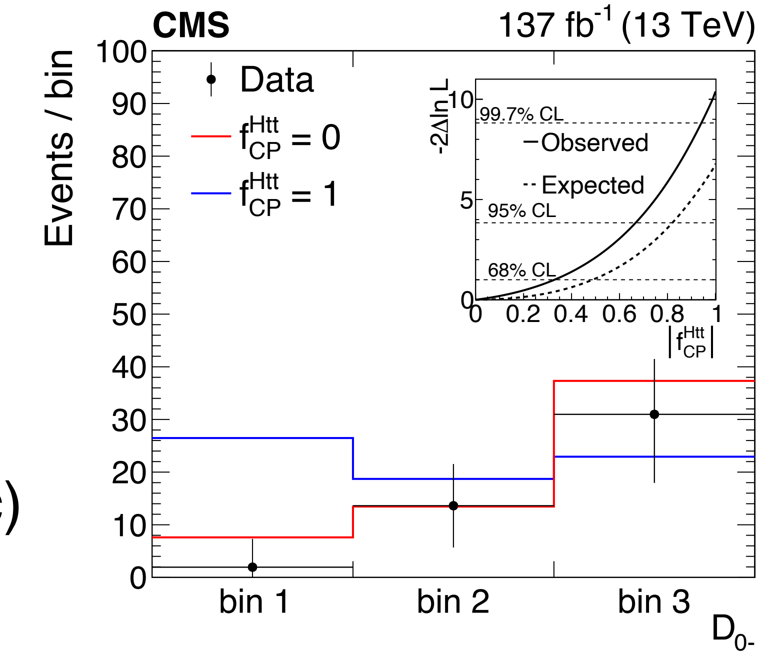
Collider	pp	pp	pp	e^+e^-	e^+e^-	e^+e^-	e^+e^-	e^-p	$\gamma\gamma$	$\mu^+\mu^-$	$\mu^+\mu^-$	target
E (GeV)	14,000	14,000	100,000	250	350	500	1,000	1,300	125	125	3,000	(theory)
$\mathcal{L}$ (fb^{-1})	300	3,000	30,000	250	350	500	1,000	1,000	250	20	1,000	
HZZ/HWW	$4.0\cdot10^{-5}$	$2.5\cdot10^{-6}$	✓	$3.9\cdot10^{-5}$	$2.9\cdot10^{-5}$	$1.3\cdot10^{-5}$	$3.0\cdot10^{-6}$	✓	✓	✓	✓	$< 10^{-5}$

$\sim 10^{-8}$ (?)

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

- Very first test of CP in Hff in 2020:

  — $t\bar{t}H$ spin-off from Snowmass-2013 (arXiv:1606.03107)
  pheno projection agreement with CMS/ATLAS



CMS arXiv:2003.10866
ATLAS arXiv:2004.04545

no sensitivity to $2\mathrm{Re}\left(A_{\mathrm{CP\,even}}A^*_{\mathrm{CP\,odd}}\right)$ (semi-leptonic, hadronic)

— need di-lepton channel for CP interf: arXiv:1507.07926

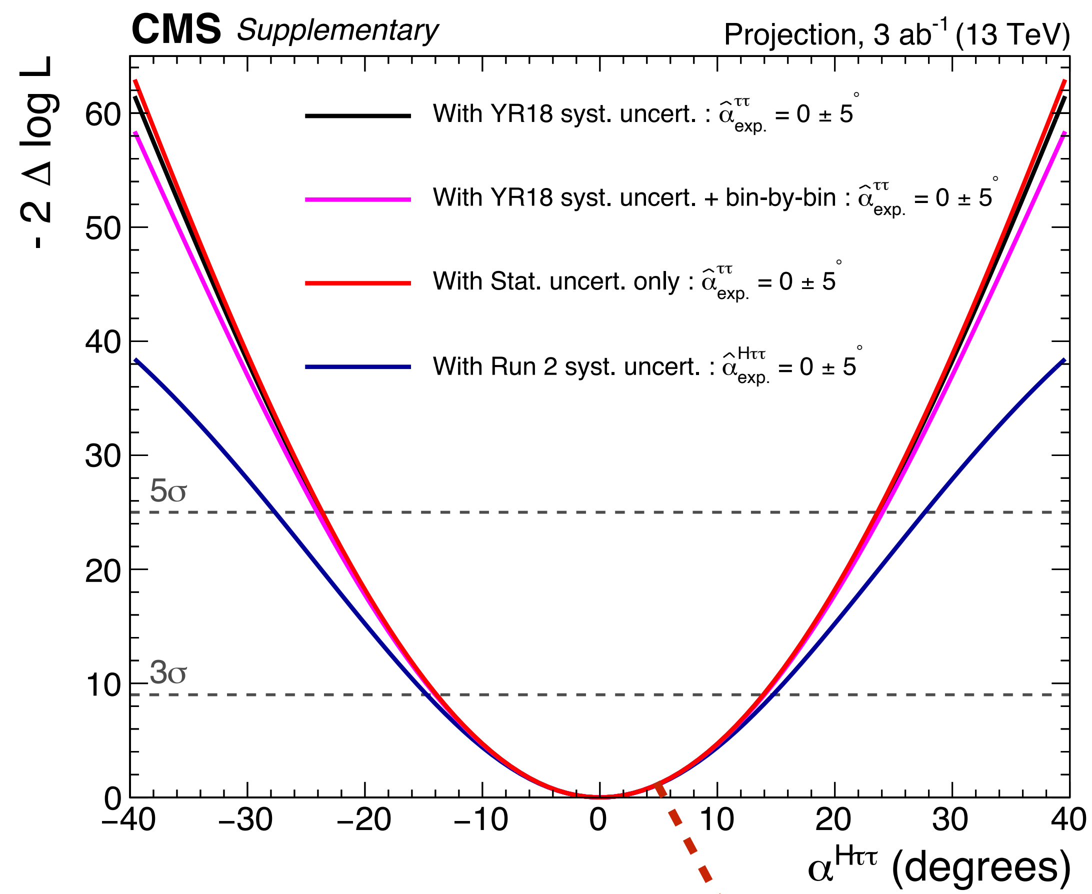
— reach $f_{CP} \sim 0.05$ $(\alpha \sim 13°)$ at HL-LHC arXiv:2110.07635
pheno projection with di-leptonic, semi-leptonic, hadronic $t\bar{t}$ decay

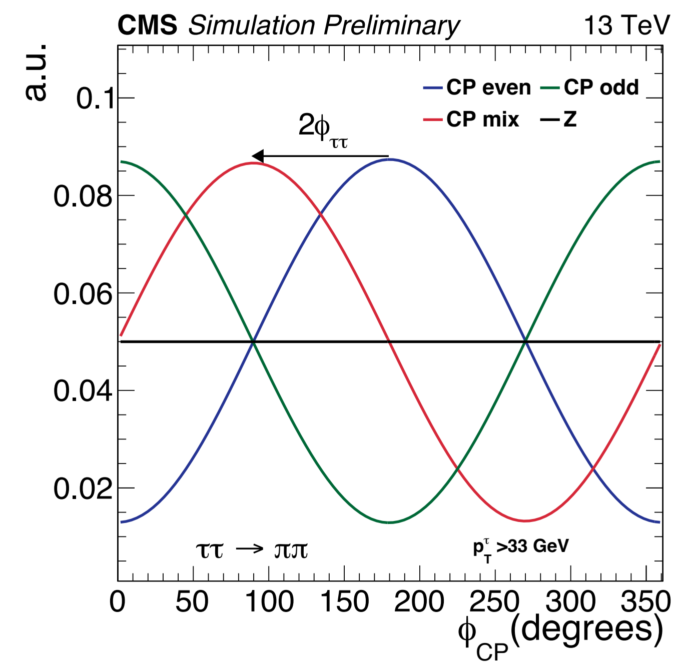
— similar in tH ; no sensitivity to $b\bar{b}H$, or other light q

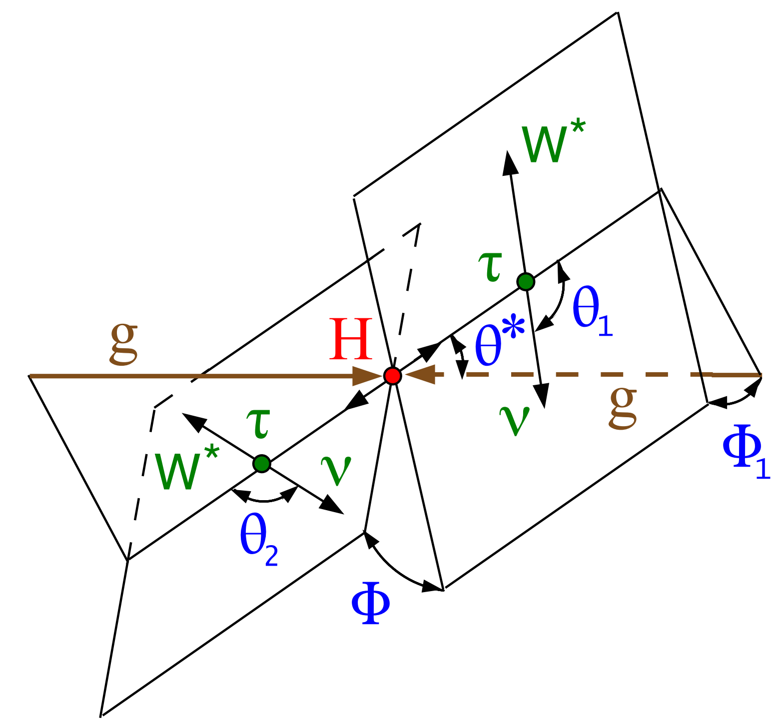
Collider	pp	pp	pp	e^+e^-	e^+e^-	e^+e^-	e^+e^-	e^-p	$\gamma\gamma$	$\mu^+\mu^-$	$\mu^+\mu^-$	target
E (GeV)	14,000	14,000	100,000	250	350	500	1,000	1,300	125	125	3,000	(theory)
$\mathcal{L}$ (fb^{-1})	300	3,000	30,000	250	350	500	1,000	1,000	250	20	1,000	
$Ht\bar{t}$	0.24	0.05	✓	–	–	0.29	0.08	✓	–	–	✓	$< 10^{-2}$

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

- Very first test of CP in $H\tau\tau$ in 2020 CMS: CMS-HIG-20-006







pp pheno studies at Snowmass-2013: arXiv:1308.1094

— reach $f_{CP} \sim 0.008 \; (\alpha \sim 5^\circ)$ at HL-LHC CMS-HIG-20-006

Collider	pp	pp	pp	e^+e^-	e^+e^-	e^+e^-	e^+e^-	e^-p	$\gamma\gamma$	$\mu^+\mu^-$	$\mu^+\mu^-$	target
E (GeV)	14,000	14,000	100,000	250	350	500	1,000	1,300	125	125	3,000	(theory)
$\mathcal{L}$ (fb^{-1})	300	3,000	30,000	250	350	500	1,000	1,000	250	20	1,000	
$H\tau\tau$	0.07	0.008	✓	0.01	0.01	0.02	0.06	–	✓	✓	✓	$< 10^{-2}$

Overview of Higgs CP at Colliders

- Now cover all couplings at pp and e^+e^- colliders:

new numerical estimates for the first time (since 2013)

pp 100 TeV would be the best by $\times\, 100$, but more distant …

new entries (since 2013)

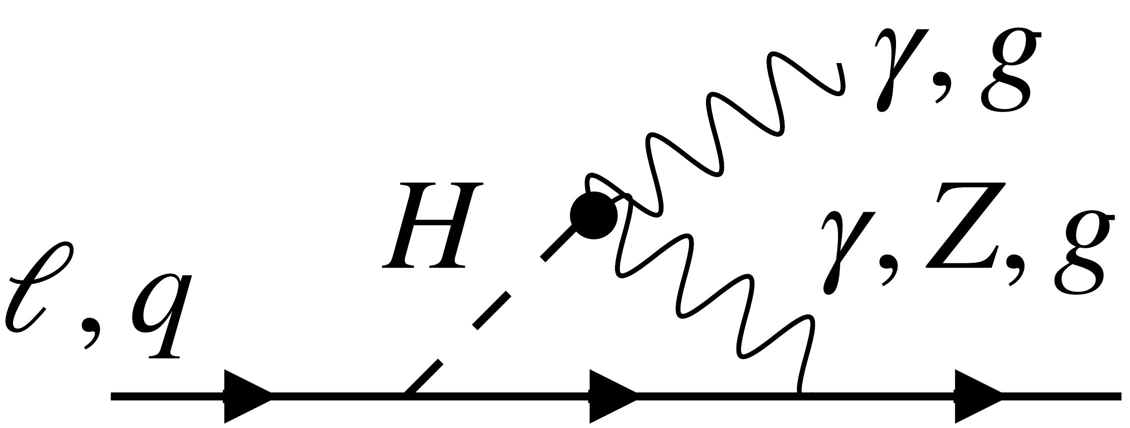
Collider	pp	pp	pp	e^+e^-	e^+e^-	e^+e^-	e^+e^-	e^-p	$\gamma\gamma$	$\mu^+\mu^-$	$\mu^+\mu^-$	target
E (GeV)	14,000	14,000	100,000	250	350	500	1,000	1,300	125	125	3,000	(theory)
$\mathcal{L}$ (fb^{-1})	300	3,000	30,000	250	350	500	1,000	1,000	250	20	1,000	
HZZ/HWW	$4.0\cdot10^{-5}$	$2.5\cdot10^{-6}$	✓	$3.9\cdot10^{-5}$	$2.9\cdot10^{-5}$	$1.3\cdot10^{-5}$	$3.0\cdot10^{-6}$	✓	✓	✓	✓	$< 10^{-5}$
$H\gamma\gamma$	–	0.50	✓	–	–	–	–	–	0.06	–	–	$< 10^{-2}$
$HZ\gamma$	–	~ 1	✓	–	–	–	~ 1	–	–	–	–	$< 10^{-2}$
Hgg	0.12	0.011	✓	–	–	–	–	–	–	–	–	$< 10^{-2}$
$Ht\bar{t}$	0.24	0.05	✓	–	–	0.29	0.08	✓	–	–	✓	$< 10^{-2}$
$H\tau\tau$	0.07	0.008	✓	0.01	0.01	0.02	0.06	–	✓	✓	✓	$< 10^{-2}$
$H\mu\mu$	–	–	–	–	–	–	–	–	–	✓	–	$< 10^{-2}$

revised numerical estimates

new dedicated studies show not enough precision

Higgs CP from EDM

- Electric Dipole Moment (EDM) of electron $d_e < 1.1 \times 10^{-29}\ e\,\text{cm}$



atoms/molecules $d_n < 1.8 \times 10^{-26}\ e\,\text{cm}$

$d_e^{\text{SM}} \sim 10^{-38}\ e\,\text{cm}$

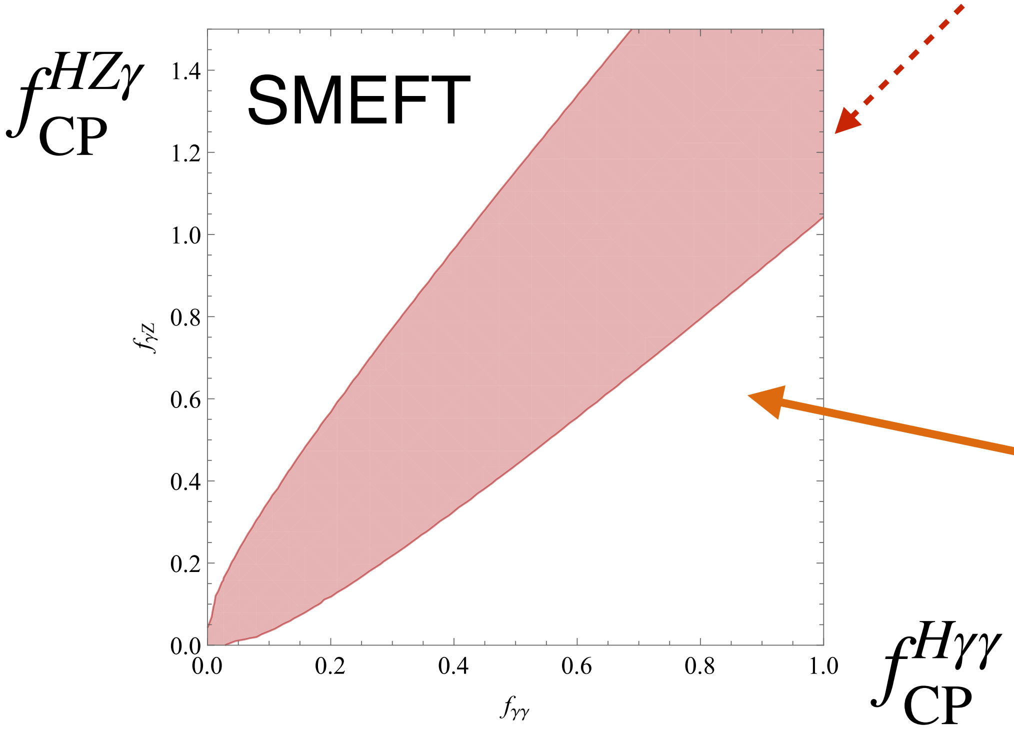
expect $\times 10^{-2}$ in ~10 years arXiv:2203.08103

Appendix C: EDM constraints

Contributed by Wouter Dekens.

HX coupling	Hgg	$H\gamma\gamma$	$HZ\gamma$	HZZ	$Ht\bar{t}$	$Hu\bar{u}$	Hdd	$H\tau\tau$	$H\mu\mu$	Hee
$f_{CP}^{HX}/(1-f_{CP}^{HX}) <$	0.12	$2.4 \cdot 10^{-8}$	$4.4 \cdot 10^{-8}$	$1.2 \cdot 10^{-13}$	$4.3 \cdot 10^{-7}$	0.72	0.039	$2.2 \cdot 10^{-2}$	36	$1.1 \cdot 10^{-6}$

only EDM



— assuming CP-even SM coupling to 1st family

— assuming one CP-odd coupling at a time

lost tight constraints with 3 couplings already

$f_{\text{CP}}^{H\gamma\gamma}, f_{\text{CP}}^{HZ\gamma}, f_{\text{CP}}^{HZZ}$