Prospects for Measuring Higgs CP Violation at Future Colliders

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U. of Massachusetts, Amherst, Amherst Center for Fundamental Interactions
The CP Nature of the Higgs Boson, May 1, 2015

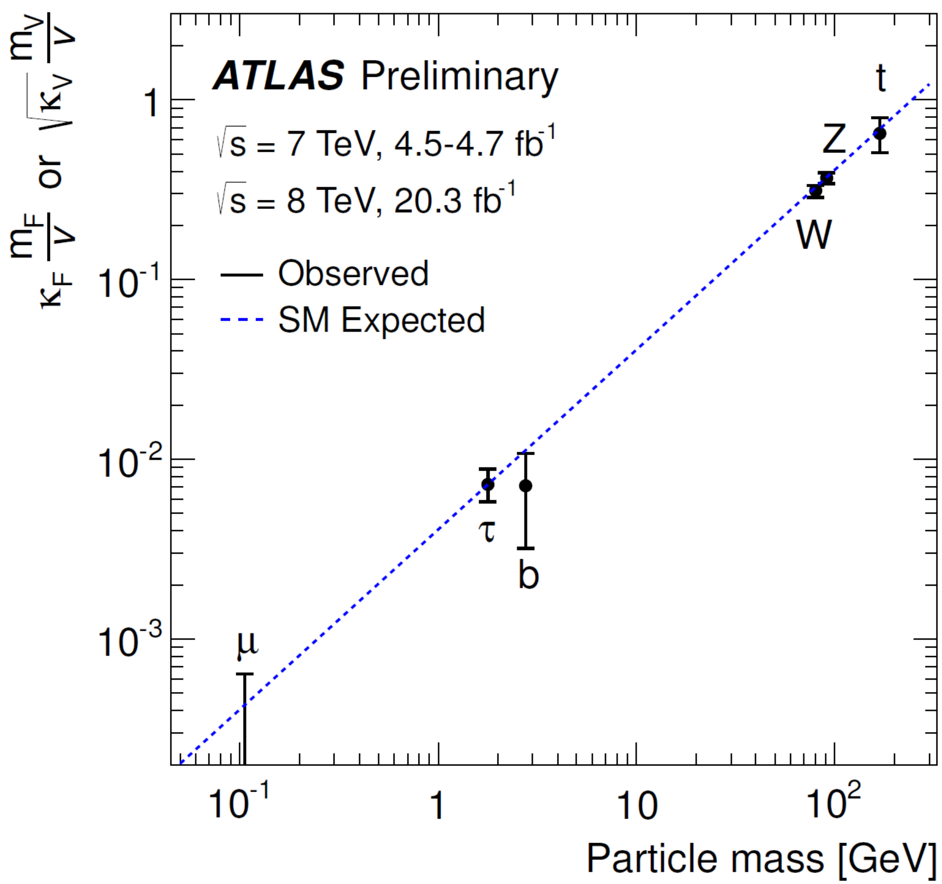
CP Violation – Motivated and Required

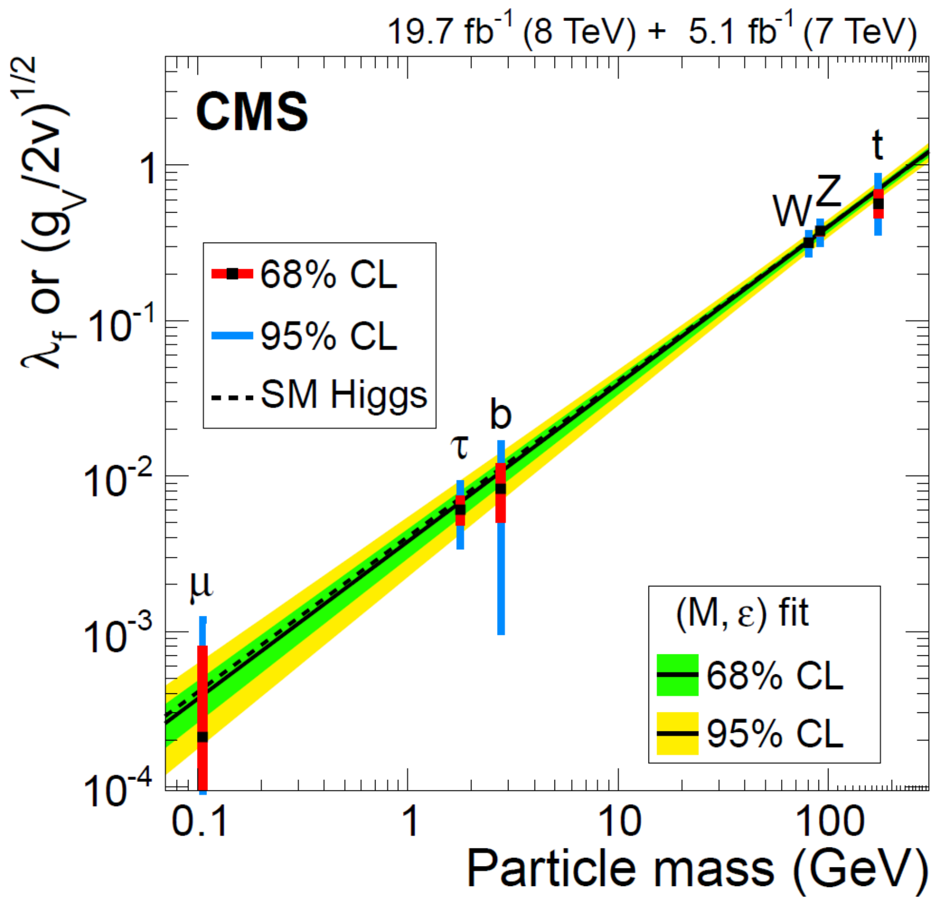
- Sakharov's three conditions for baryogenesis motivate searches for new sources of CP violation
  - Need B violation
  - Need C and CP violation
  - Need interactions to happen out of thermal equilibrium
- Our picture of baryogenesis is embarrassingly incomplete
  - SM EW baryogenesis is insufficient
  - Strongly motivates new sources of CPV

CP and the Higgs

- A natural place to test for CP violating phases is with Higgs physics: distinct NP sources
  - scalar-pseudoscalar admixture (*e.g.* scalar potential)
    - naïvely tested via rate suppression
  - couplings to gauge bosons (*e.g.* bosonic CPV)
    - for example, tested via acoplanarity measurement in $h \to ZZ^* \to 4l$
  - couplings to fermions (*e.g.* fermionic CPV)
    - tomorrow: test via $h \to \tau^+ \tau^- \to (\rho^+\nu)\ (\rho^-\nu) \to (\pi^+\pi^0)\nu\ (\pi^-\pi^0)\nu$
- Throughout, will focus on spin-0 Higgs
  - ATLAS and CMS (see talk by Whitbeck and *e.g.* CMS [1411.3441]) have excluded other spin possibilities

Current Higgs proportionality measurements





- These rate measurements only tell half of the story
  - Must also test **phases** (and **higher order moments** via Higgs EFT)

ATLAS-CONF-2015-007
CMS [1412.8662]

CP and the Higgs

- Precision Higgs physics is a central tenet of the LHC/HL-LHC program
  - Much effort is justifiably concentrated on coupling extractions
  - In order to be sensitive to deviation δ, should measure to δ/3 or δ/5 precision
    - Motivates a dedicated Higgs factory (ILC, FCCee, CEPC)
- Will summarize available CPV study prospects at future machines
  - Inherently different levels of rigor
  - Emphasize how different machines enable new search channels and tests of Higgs couplings
    - Also complementary to indirect tests (EDMs)

Machines

- e^+e^- collider
  - ILC: Linear collider has polarized beams, much less instantaneous luminosity
  - FCC-ee, CEPC: Circular collider has unpolarized beams, much better instantaneous luminosity
- pp collider
  - LHC & HL-LHC, FCC-hh, SPPC
- (Muon collider)
- (γγ collider)

Outline

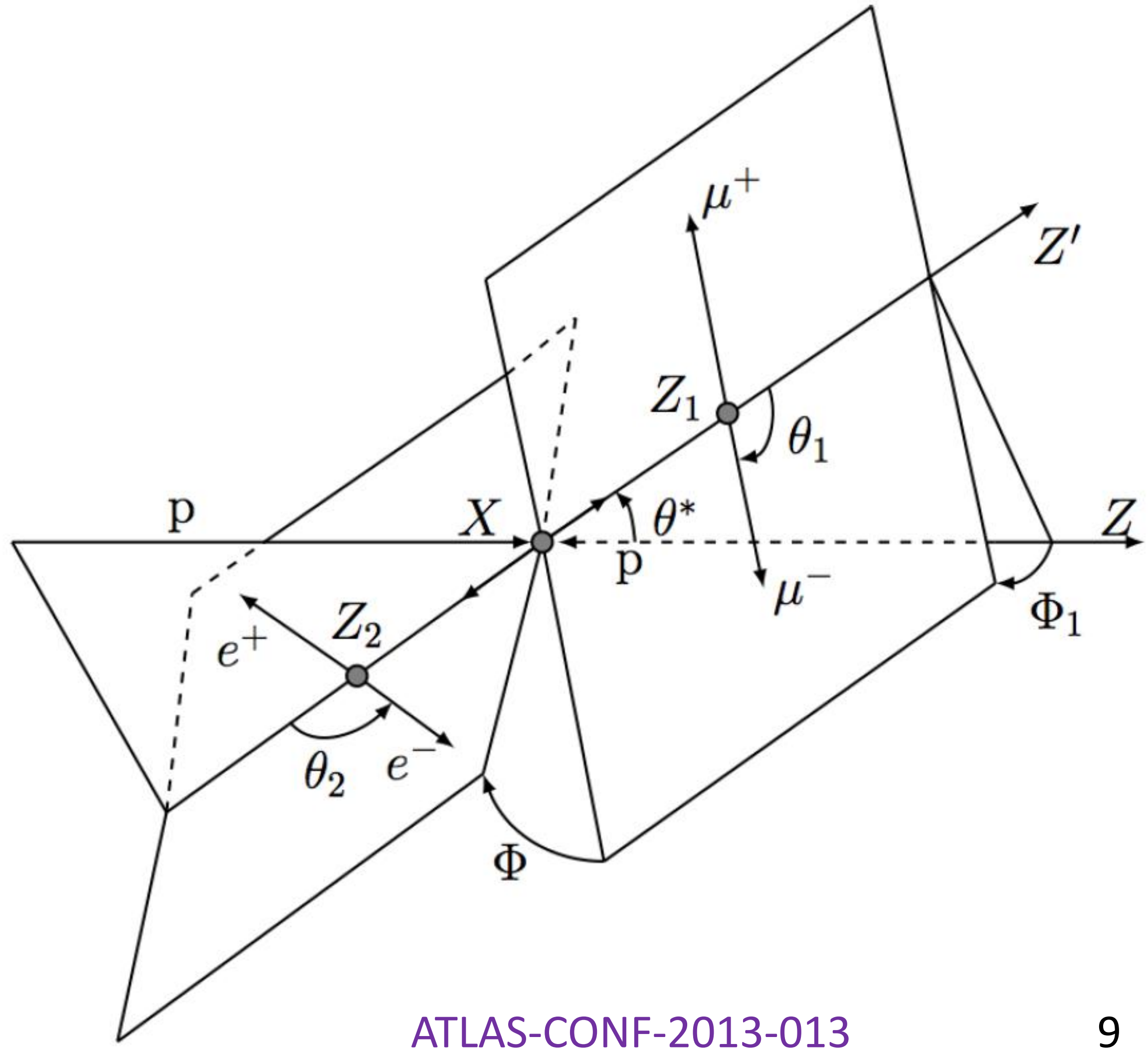
- Studied channels
  - ZZ, WW (A. Whitbeck)
  - gg (M. Dolan)
  - Zγ (M. Farina)
  - ττ (FY)
- The unlikely/impossible SM decay channels (w/o a unique collider)
  - ee, μμ, γγ, qq (q = u, d, s, c)
- Prospective channels
  - bb, tt (T. Liu)
- Open questions and summary

Basic CPV collider phenomenology

- NP CPV sources generally affect inclusive rates
  - Normalized differential distributions fold out rate information (by construction)
  - Need to have rates (=inclusive distributions=integrated luminosity) before asymmetry variables or differential distributions are meaningful
- Canonical observables
  - triple product of 3-vectors – CP-odd, T-odd combination
    - $\mathbf{p}_1 \cdot (\mathbf{p}_2 \times \mathbf{p}_3)$
  - angular distributions – uses decays of polarized intermediate particles
    - acoplanarity in $h \to ZZ^* \to 4$ leptons

Testing CPV in Higgs decays to (electroweak) gauge bosons

- For ZZ^*, measure acoplanarity angle Φ (angle between Z_1 and Z_2 decay planes)
- Golden channel
  - everything measureable, can reconstruct the Higgs rest frame and appropriate decay planes



ATLAS-CONF-2013-013

Testing CPV in Higgs decays to ZZ*

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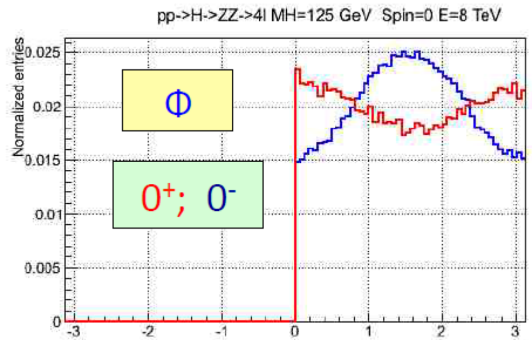
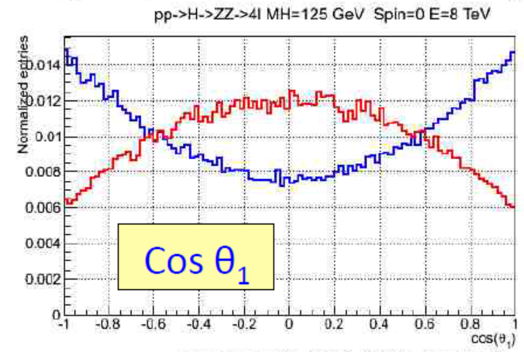
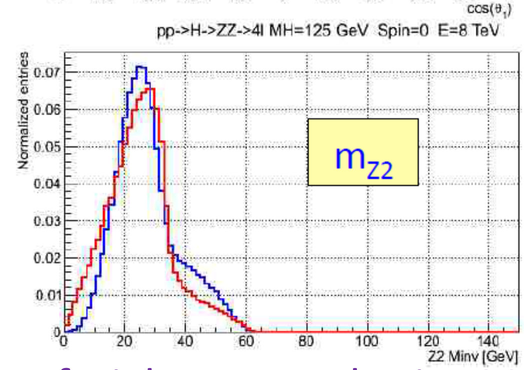
Final state observables

- Four-vectors of the final state particles give access to boson decay planes and to the tensor structure.
- Easier in ZZ*→4l case, harder in WW→lvlv case.
- Reasonable target: 10% CP-odd admixture corresponds to $f_{CP} < 10^{-5}$ in VV decays. (Snowmass)

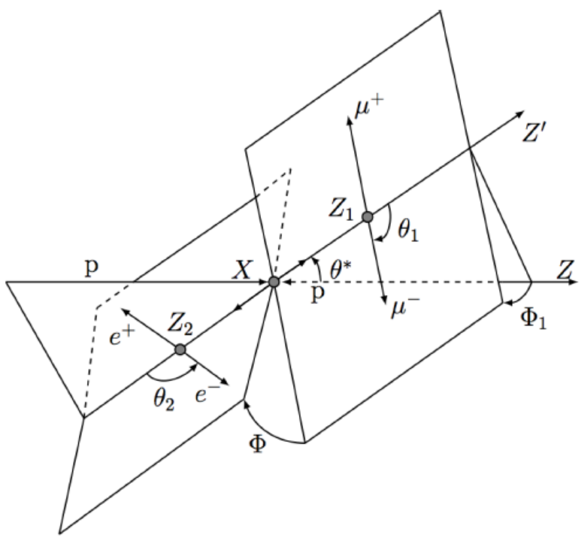






H→ZZ*→4l

$\cos\theta_{1,2}, \Phi, m_{Z1}, m_{Z2}, m_{4l}$



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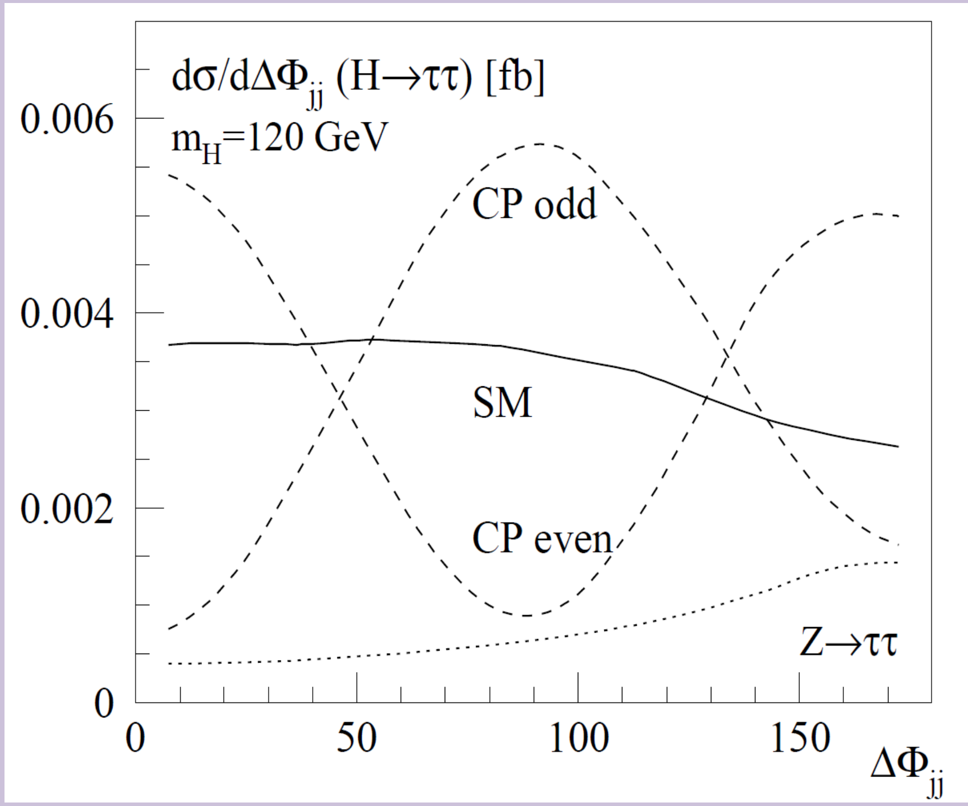
Testing CPV in Higgs production

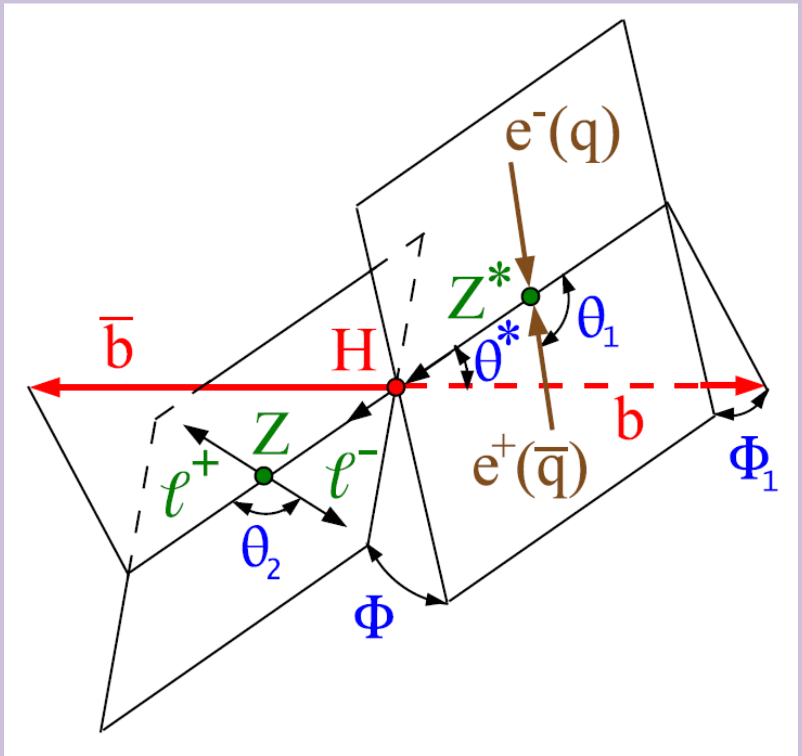
- VBF production
  - CP even is pure $W_{\mu\nu}W^{\mu\nu}$
  - CP odd is pure $W_{\mu\nu}\tilde{W}^{\mu\nu}$
  - Shape is influenced by VBF cuts



Plehn, Rainwater, Zeppenfeld [hep-ph/0105325]

Testing CPV in Higgs production

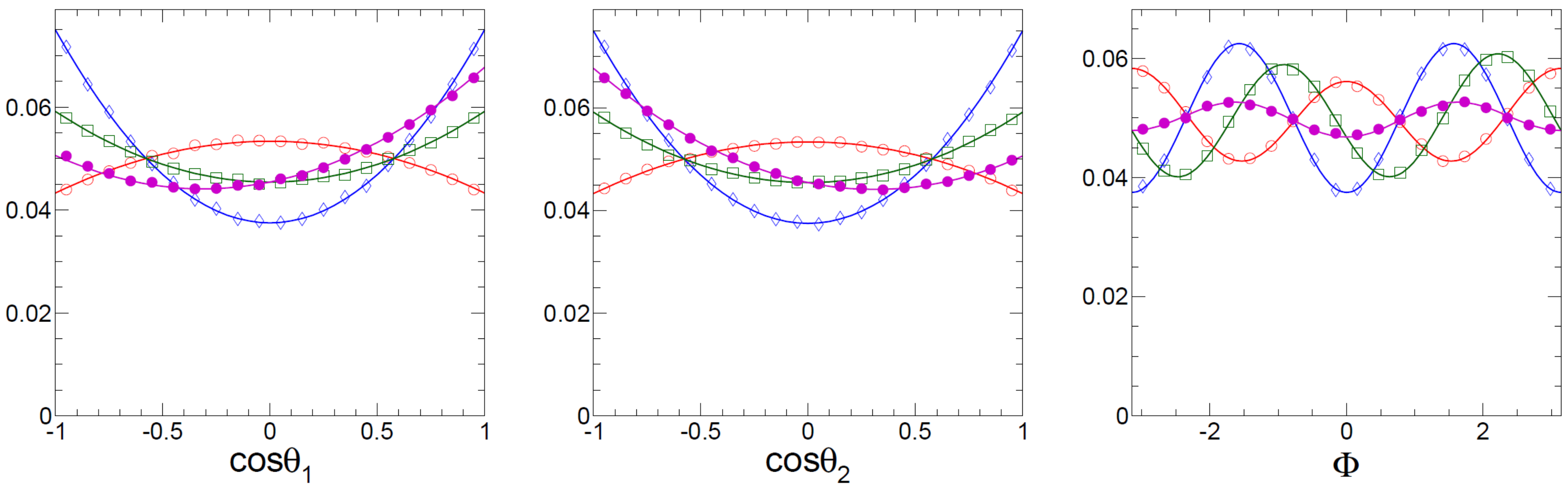
- VH Production is equivalent physics to decay because of crossing symmetry
  - More sensitive to momentum form factors
  - Use ZH production, Z to leptons, Higgs to bottoms



Anderson, *et. al.* [1309.4819]

Testing CPV in Higgs production

- VH Production is equivalent physics to decay because of crossing symmetry
  - At lepton collider



Red: SM

Blue: pseudoscalar

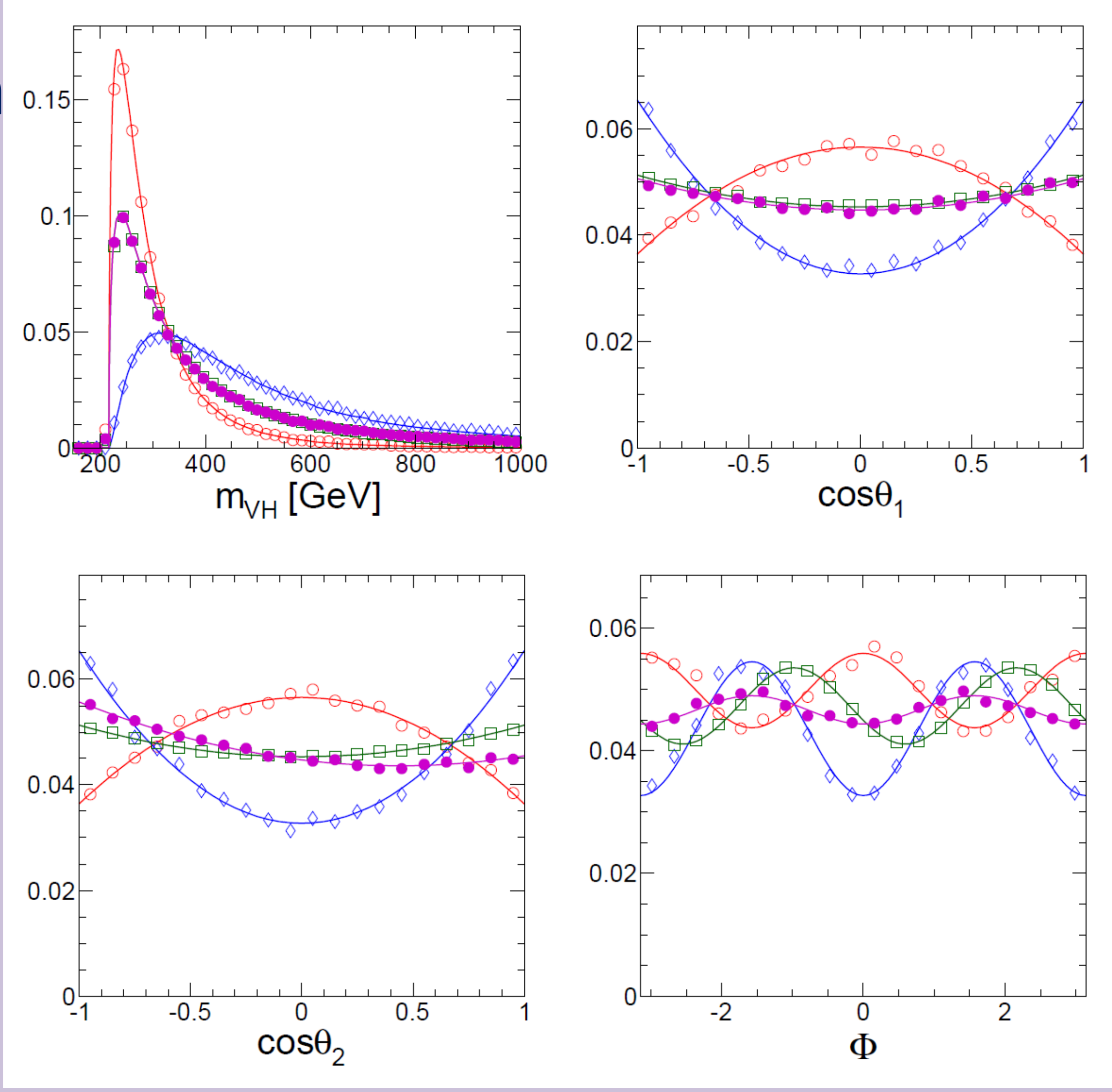
Green: $f_{a3} = 0.5$, $\phi_{a3} = 0$

Magenta: $f_{a3} = 0.5$, $\phi_{a3} = \pi/2$

Anderson, *et. al.* [1309.4819]

Testing CPV in Higgs production

- LHC ZH production



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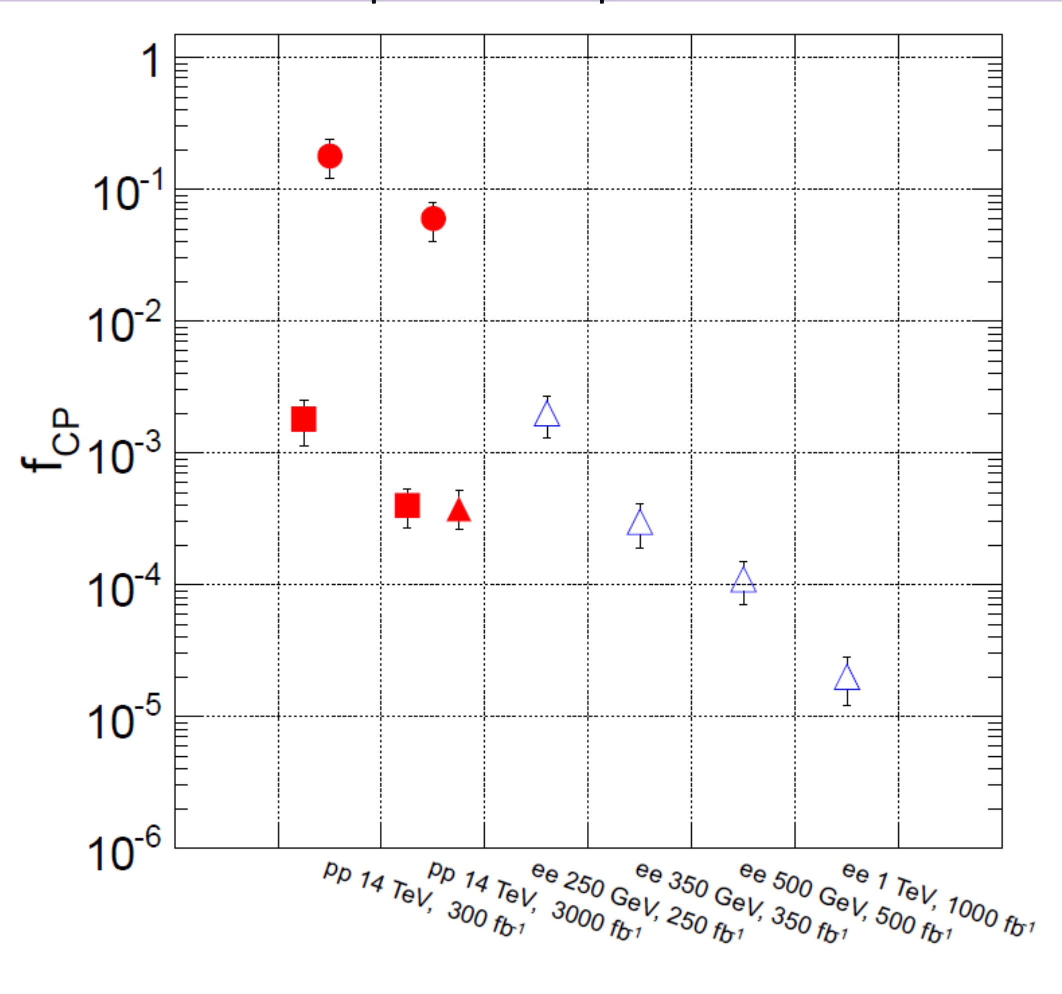
Anderson, *et. al.* [1309.4819]

CPV in HVV interactions

- Build kinematic discriminant and extrapolate sensitivity
  - Extrapolation will be systematics limited
  - Form factors in production also change kinematics (interpretation is not model independent)

Circles: HVV decay
Triangles: VH production
Squares: VBF production



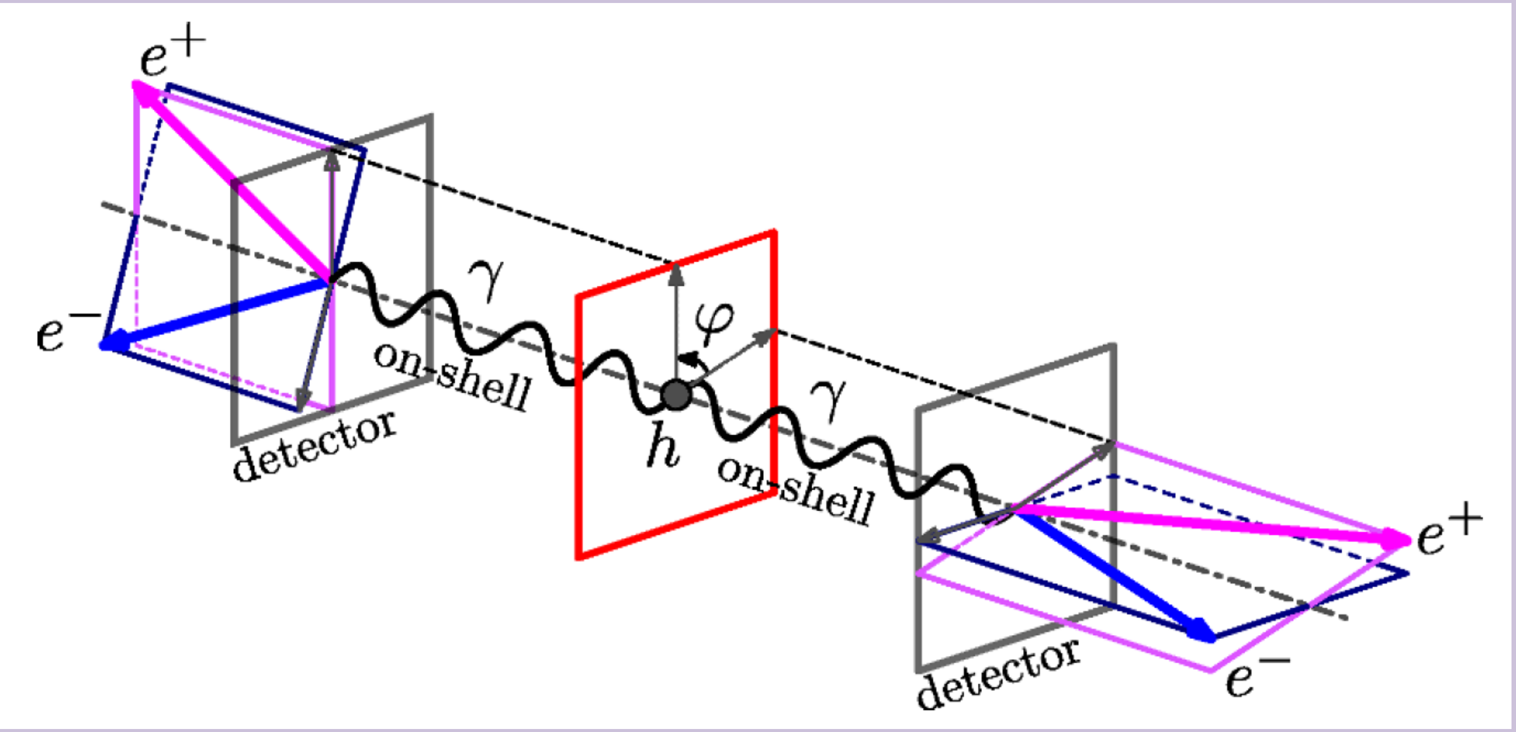
Anderson, *et. al.* [1309.4819]

Other channels and representative work

- $Z\gamma$, $Z \to l^+l^-$ (M. Farina and collaborators, 1503.06470)
  - Take advantage of interference between continuum background and signal from gluon initiated events
- gg (M. Dolan and collaborators, 1406.3322)
  - Use associated jets for angular analysis
- $\tau\tau$ (FY and collaborators, 1308.1094)
  - At LHC or other proton machines, reconstruct acoplanarity from rho meson decays
  - At lepton colliders, can fully reconstruct Higgs rest frame and neutrino momenta (up to two-fold ambiguity)
    - See also Berge, *et. al.* [1308.2674] and refs. therein

Other channels

- γγ (F. Bishara, *et. al.*, 1312.2955)
  - Require converted photons (detector material) and angular resolution on leptonic opening angles



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- γγ (F. Bishara, *et. al.*, 1312.2955)
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$\sqrt{s}$	$\mathcal{L}$ [fb^{-1}]	$\sigma \times \mathrm{BR}(h \to \gamma\gamma)$ [fb]	Events
8	20	47	0.24
14	3000	125	94
33	3000	444	333
100	3000	1875	1406

Table 1. Expected number of events after the application of $\mathcal{S}$ or $\mathcal{T}$ cuts with $\theta_{\ell\ell} > 10^{-4}$ to obtain $\langle\mathcal{B}\rangle/\langle\mathcal{A}\rangle \sim 20\%$. The Higgs production cross section includes the gluon fusion and VBF channels only and is taken from [55].

  - Would be trivial (!) at γγ collider

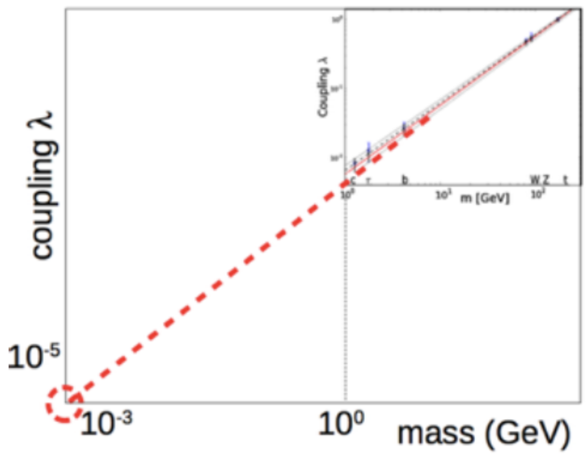
Other channels

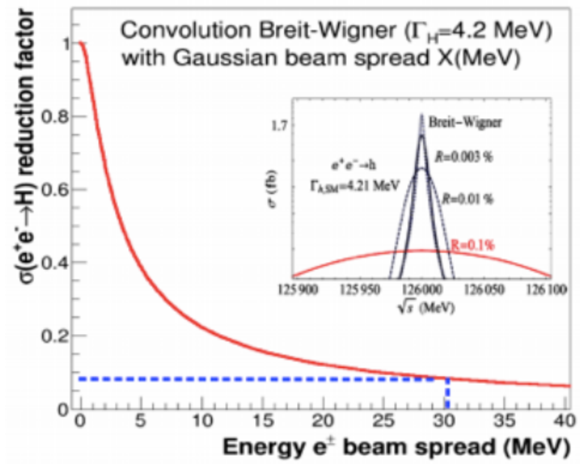
- μμ
  - Not possible in Higgs decay
  - Polarize beams at muon collider
- ee
  - Not possible in Higgs decay
  - Polarize beams at electron collider, push energy resolution to R = 0.01% or less

First generation couplings

➡ **s-channel Higgs production**

- Unique opportunity for measurement close to SM sensitivity
- Highly challenging; σ(ee→H) = 1.6fb; 7 Higgs decay channels studied





Preliminary Results

L = 10 ab^{-1}

κ_e < 2.2 at 3σ

➡ **Work in progress**

- How large are loop induced corrections? How large are BSM effects?
- Do we need an energy scan to find the Higgs?
- How much luminosity will be available for this measurement? By how much is the luminosity reduced by monochromators?
- Can polarization increase sensitivity? 20

Slide from M. Klute, FCC Week 2015

Other channels

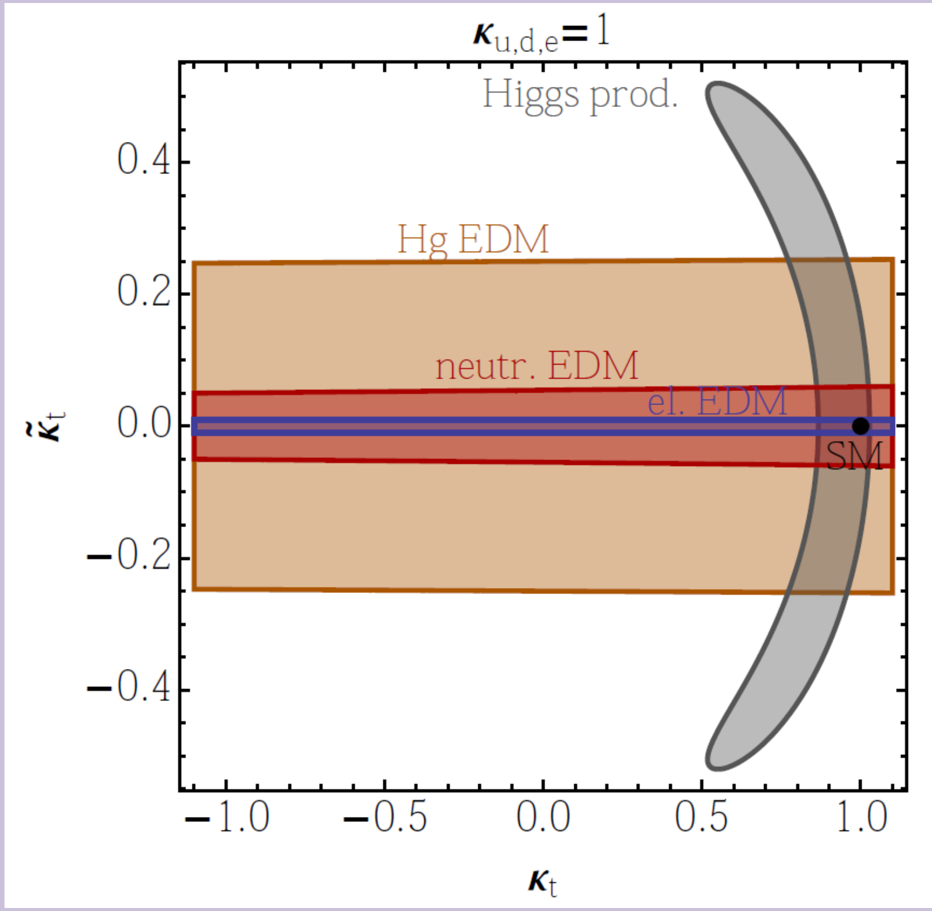
- μμ
  - Not possible in Higgs decay
  - Polarize beams at muon collider
- ee
  - Not possible in Higgs decay
  - Polarize beams at electron collider, push energy resolution to R = 0.01% or less
- qq (q = u, d, s, c)
  - Only recent work addressed extracting second generation Yukawas from $h \to J/\Psi\ \gamma$
    - See Kagan, et. al. (1406.1722), Grossman, et. al. (1501.06569)
    - Needs full luminosity HL-LHC
    - No study of CPV prospects in these decays
    - May have complentarity with meson CPV probes

Other channels

- bb
  - Without 2HDM tan β enhancement, could only use Higgs decay and not bbH production
  - Some work in progress by Yevgeny Kats and collaborators about how bottom spin is retained in hadronization and subsequent decay
    - See Y. Kats, "b polarization as a probe of new physics", 2^{nd} NPKI Workshop, Physics from Run 2 of the LHC
  - Would require dedicated analysis for constructing appropriate CPV observable in bb decay channel

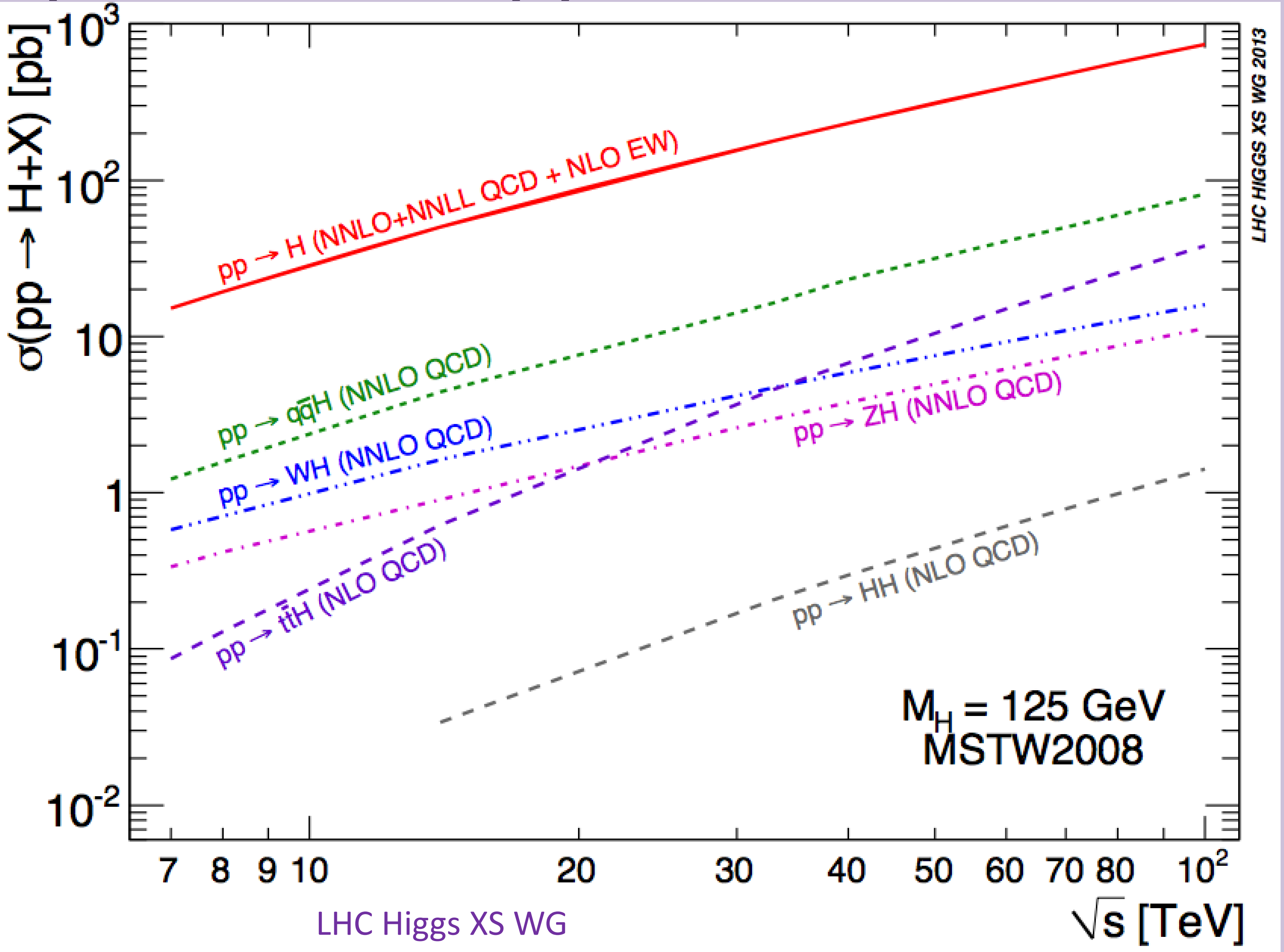
Other channels

- tt (see talk by T. Liu)
  - Independent measurement from gg production, γZ and γγ decay
  - Probed via ttH production
  - EDM constraints require non-trivial flavor construction if we have positive signal in ttH and null results in EDM



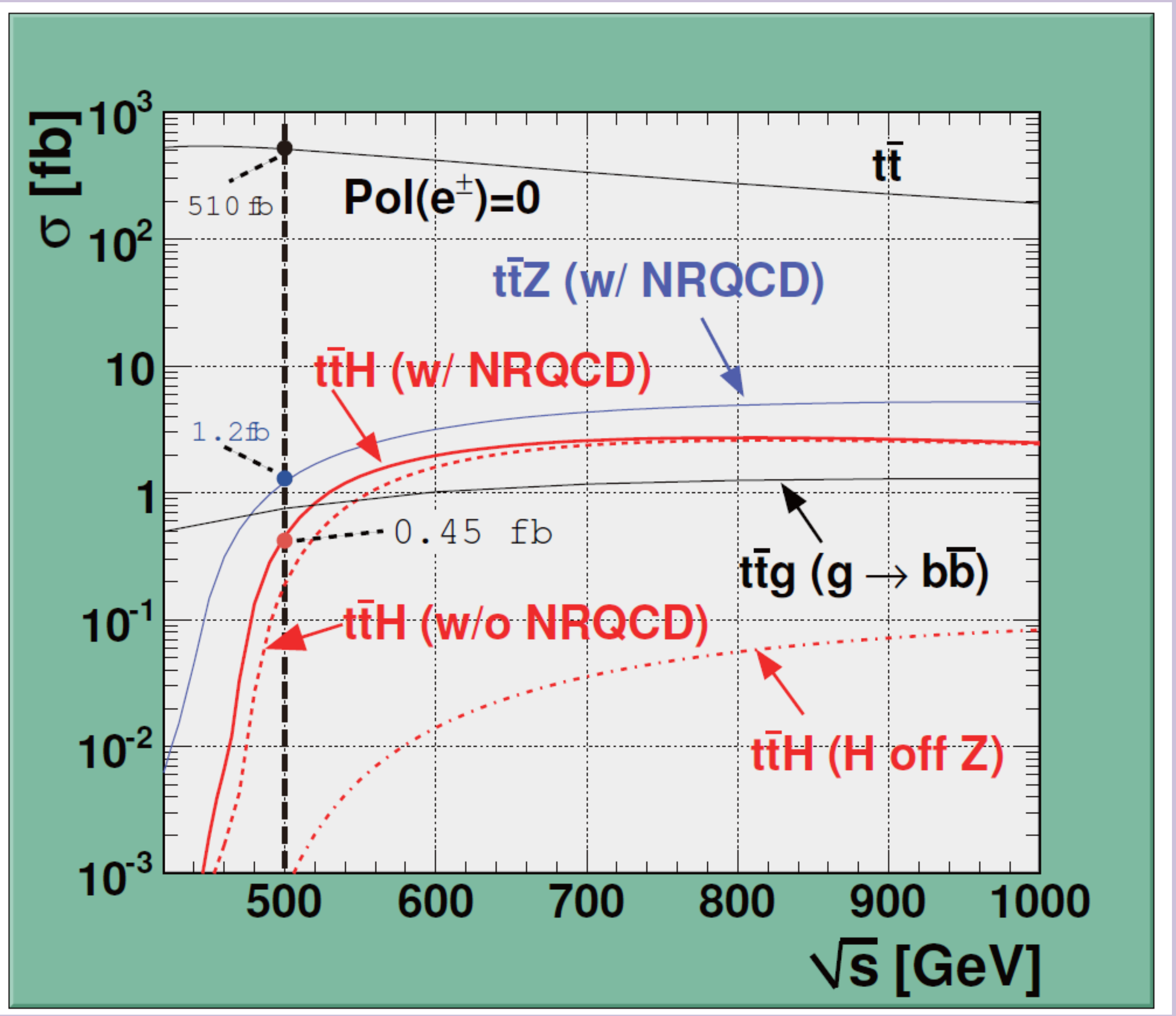
Brod, Haisch, Zupan [1310.1385]

ttH production – pp collider



LHC Higgs XS WG

ttH production – (high energy) e^+e^- collider



ttH production at lepton collider

- Need to capture top polarization
- No modern complete pheno studies

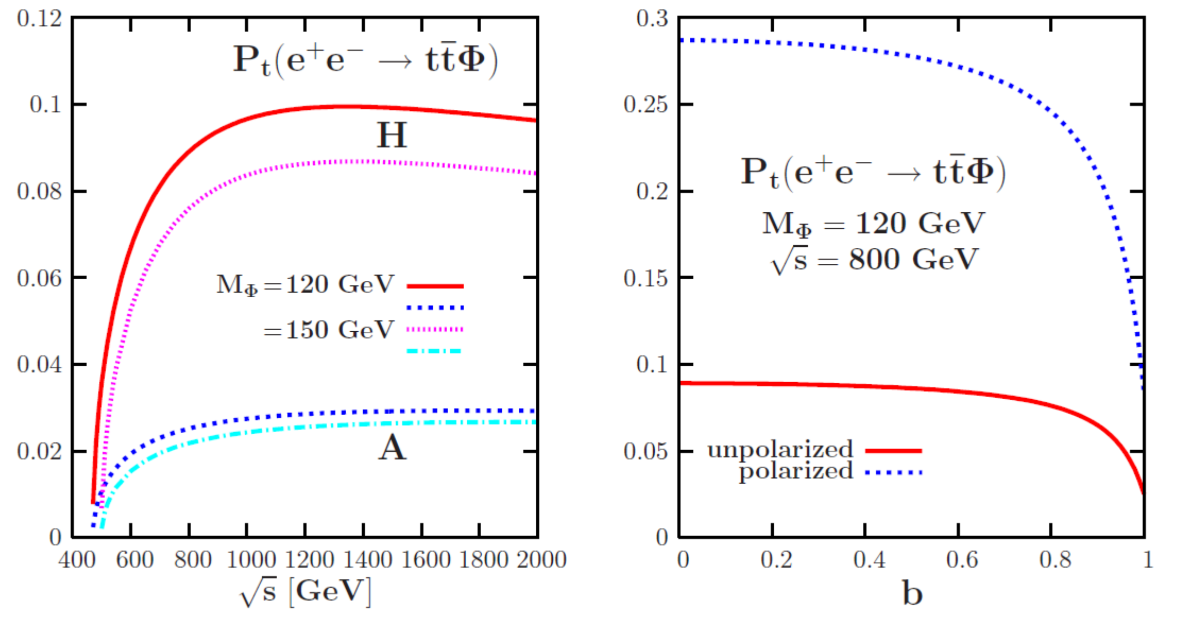


FIG. 3: The top quark polarization in the process $e^+e^- \to t\bar{t}\Phi$ for a scalar and a pseudoscalar Higgs boson as a function of $\sqrt{s}$ for two masses $M_\Phi = 120$ and 150 GeV (left) and with unpolarized and polarized $e^\pm$ beams as a function of the parameter b at $\sqrt{s} = 800$ GeV for $M_\Phi = 120$ GeV (right).

Dev, *et. al.* [0707.2878]

ttH production at lepton collider

- Sensitivity to pseudoscalar coupling

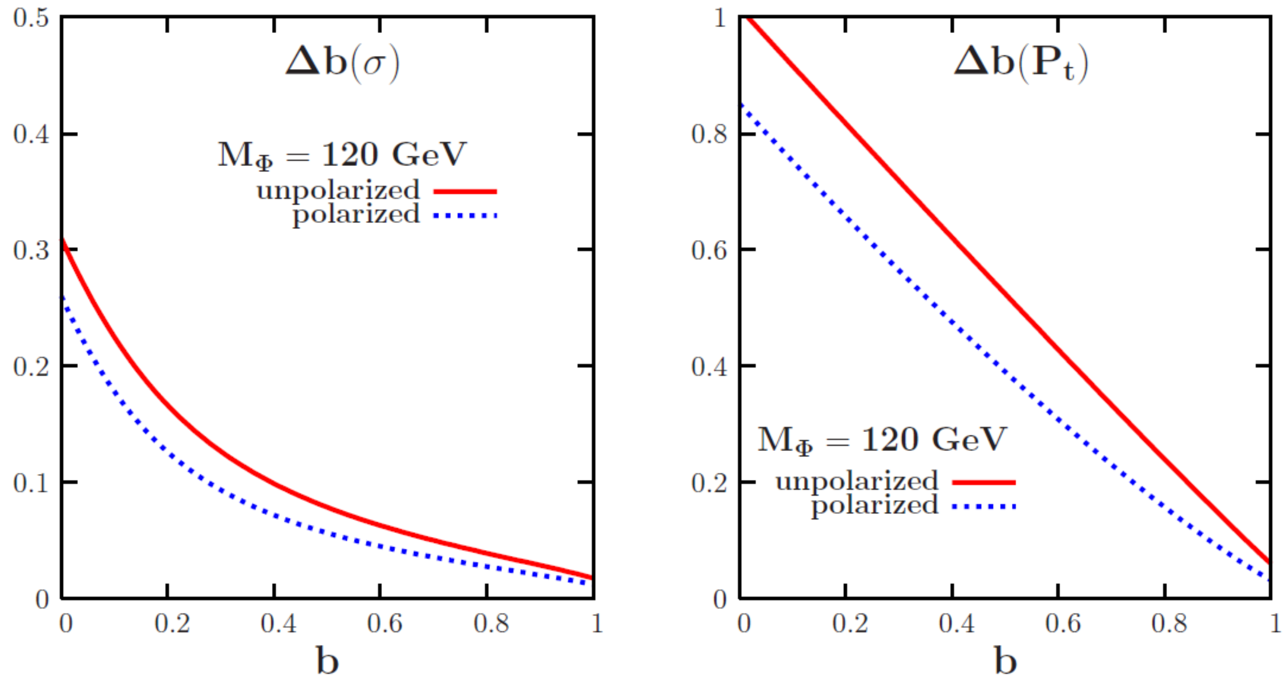


FIG. 4: The sensitivity of the cross section (left) and the top quark polarization (right) on the parameter b for $M_\Phi = 120$ at $\sqrt{s} = 800$ with $\mathcal{L} = 500$ fb^{-1}.

$$g_{\Phi tt} = -i \frac{e}{s_W} \frac{m_t}{2M_W}(a + ib\gamma_5)$$

Dev, *et. al.* [0707.2878]

Open issues

- Post-discovery: what Lagrangian CPV source is responsible in the case of a positive measurement?
- Targets for CPV sensitivity
  - Tree-level operator (Yukawa) vs. loop-induced
  - How to include rate effects
- Precision Higgs physics NP models
  - Real coefficients induce unitarity violation in scattering
    - Imply a NP scale for UV completion
  - Imaginary coefficients – any guiding principle for size of effects?

Summary

- New CP phases are motivated from general baryogenesis arguments
- Many physics studies are needed to motivate the physics case of future machines
- Each measured Higgs coupling can be a test bed for CPV
  - New dimension 4 couplings (for example, FV couplings) are also possible and immediately go beyond SM

CPV in HVV interactions

- Comparison for e^+e^- and pp

TABLE III: List of f_{CP} values in HVV couplings expected to be observed with 3σ significance and the corresponding uncertainties δf_{CP} for several collider scenarios, with the exception of $V^* \to VH$ mode at pp 300 fb^{-1} where the simulated measurement does not quite reach 3σ. Numerical estimates are given for the effective couplings Hgg, $H\gamma\gamma$, $HZ\gamma$, HZZ/HWW, assuming custodial Z/W symmetry and using HZZ couplings as the reference. The ✓ mark indicates that a measurement is in principle possible but is not covered in this study.

			HZZ/HWW						Hgg		$HZ\gamma$	$H\gamma\gamma$	
collider	energy	$\mathcal{L}$	$H \to VV^*$		$V^* \to VH$		$V^*V^* \to H$		$gg \to H$		$H \to Z\gamma$	$\gamma\gamma \to H$	$H \to \gamma\gamma$
	GeV	fb^{-1}	f_{CP}	δf_{CP}	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}	–	0.50			
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}	0.50	0.16	✓		✓
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		✓									✓	

Anderson, *et. al.* [1309.4819]