CP violation in radiative Higgs decays

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THE GOAL

- show that there are observables in $h \to \gamma\gamma$ linear in CPV parameter
- the effects can be *O(1)*
- warning: the measurement is challenging
  - LHC upgrade? Only Higgs factory?

MOTIVATION

- NP could modify higgs couplings
  - most of the studies on CP conserving case
  - how about CPV?

see Roni's talk on 7/1/13

- e.g., one could have NP generate $i\bar{\tau}\gamma_5\tau h$
- here will focus on Higgs decays to vectors
  - in particular on $h\to\gamma\gamma$

MOTIVATION

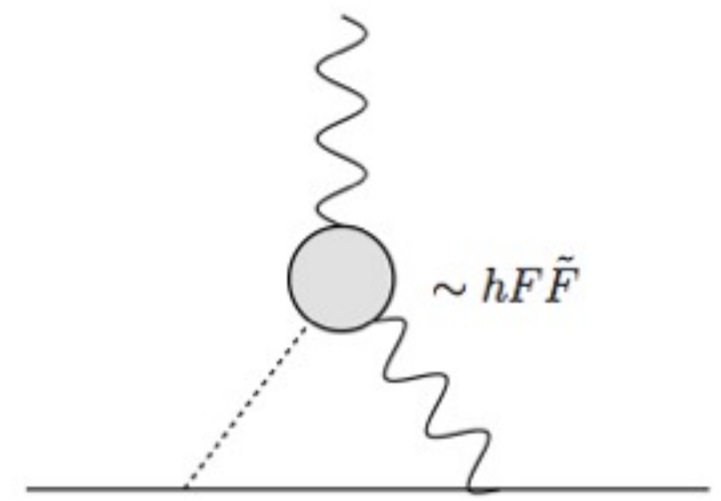
- compare NP contribs. to $h \to \gamma\gamma$ and $h \to ZZ$

$$\mathcal{L}_{\rm eff} \supset c_V \frac{m_Z^2}{v} h Z^\mu Z_\mu + \hat{c}\frac{\alpha}{\pi v} h F_{\mu\nu}F^{\mu\nu} + \hat{c}_{ZZ}\frac{\alpha}{\pi v} h Z^{\mu\nu}Z_{\mu\nu} + \tilde{c}_{ZZ}\frac{\alpha}{2\pi v} h Z_{\mu\nu}\tilde{Z}^{\mu\nu} + \tilde{c}\frac{\alpha}{2\pi v} h F_{\mu\nu}\tilde{F}^{\mu\nu},$$

- *0*$^+$ Higgs experimentally preferred at more than 3σ
  - $\tilde{c}$ and $\tilde{c}_{ZZ}$ ops. are P and CP violating
- CPV only in dim 5 ops., generated at 1-loop from NP
- in $h \to \gamma\gamma$ also the CP conserving (SM) at 1-loop
  - large *O(1)* CPV effects possible
- unlike $h \to ZZ$ which has a tree level c_V
  - to see CPV in $h \to ZZ$ need a measurement at *O(0.001)*

EDM CONSTRAINTS

- constraint on $y_e\tilde{c}$ from electron EDM



McKeen, Pospelov, Ritz, 1208.4597

- gives $\tilde{c} \lesssim 10^{-2}$ for SM electron yukawa
  - vanishes if the Higgs does not couple to e^-
  - or if coupling to e^- is purely CPV
- important to have an independent measurement of $\tilde{c}$

CPV IN DIPHOTON HIGGS DECAYS

- from now on focus on $h \to \gamma\gamma$

$$\mathcal{H}_{\rm eff} = -\hat{c}\frac{\alpha}{\pi v} h F_{\mu\nu} F^{\mu\nu} - \frac{\tilde{c}}{2}\frac{\alpha}{\pi v} h F_{\mu\nu} \tilde{F}^{\mu\nu}$$

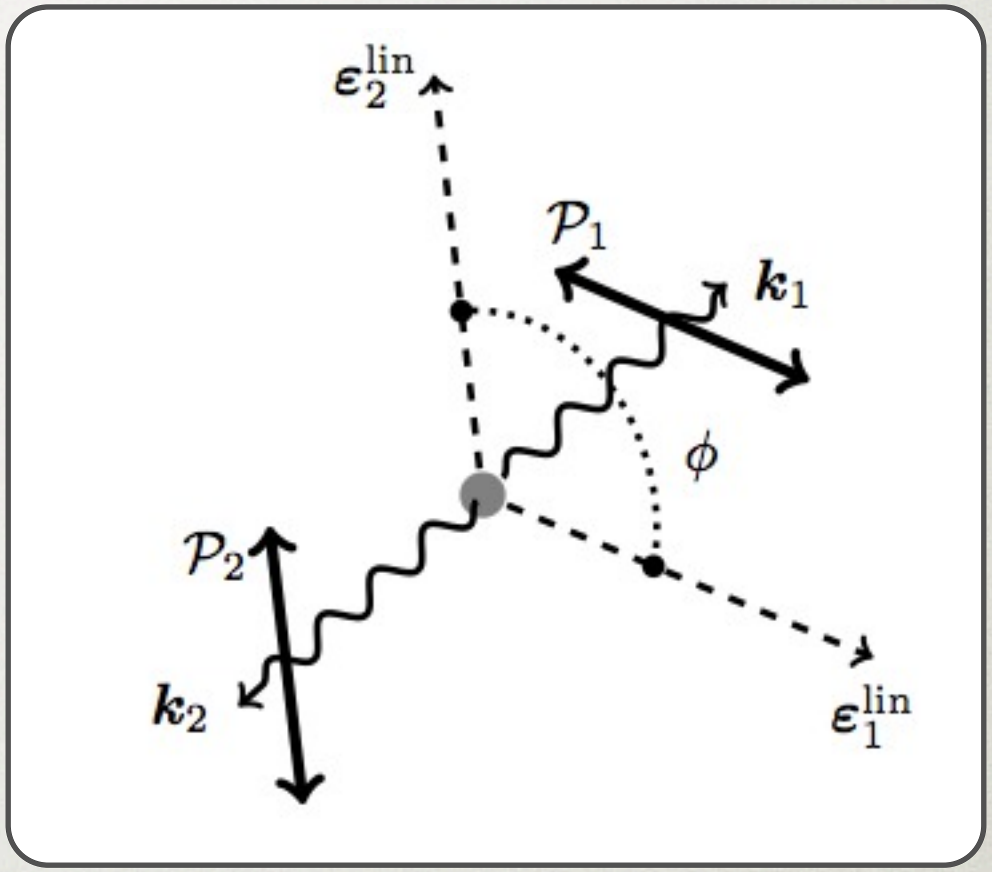
- how to measure CPV coupl. ?
- in the rate quadratic sensitivity

$$\mu_{\gamma\gamma} \equiv \frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)_{\rm SM}} = \frac{\hat{c}^2 + \tilde{c}^2}{\hat{c}^2_{\rm SM}}$$

  - here c_{SM}=-0.81
  - CP conserving and CPV always add up
- how about differential $h \to \gamma\gamma$ rate?

MEASURING CPV

- Higgs is a scalar ⇒ no information on $\tilde{c}$ from angular distributions of photons
- need to measure photon polarizations
- if perfect linear polarization analyzers



$$\frac{d\Gamma}{d\phi} = \frac{2}{\pi}\Gamma_{h\to\gamma\gamma}\cos^2(\phi+\xi)$$

  - where $\xi \equiv \tan^{-1}(\tilde{c}/\hat{c})$
- CPV causes a shift in the modulation of the rate
  - the shift is linear in CPV ξ
  - more sensitive than the total rate $\Gamma_{h\to\gamma\gamma} = \frac{\alpha^2}{4\pi^3}\frac{m_h^3}{v^2}(\hat{c}^2+\tilde{c}^2)$

LINEAR SENSITIVITY

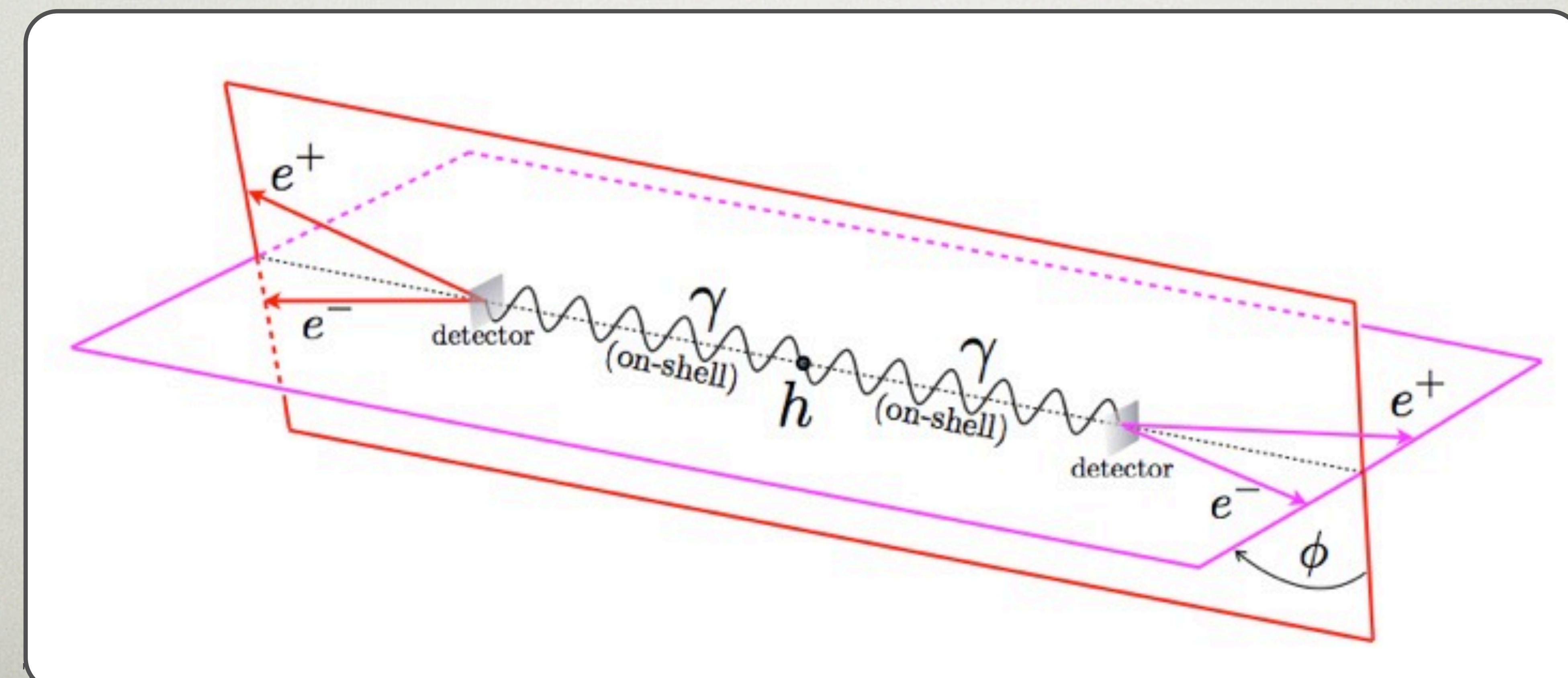
- linear sensitivity comes from helicity interference

$$\mathcal{H}_{\rm eff}|h\rangle \propto \sqrt{\hat{c}^2 + \tilde{c}^2}\left(e^{-i\xi}\,|{+}{+}\rangle + e^{i\xi}\,|{-}{-}\rangle\right)$$

  - to be sensitive to CPV phase ξ need interference between ++ and -- helicity states
  - interference term then linear in $\tilde{c}$

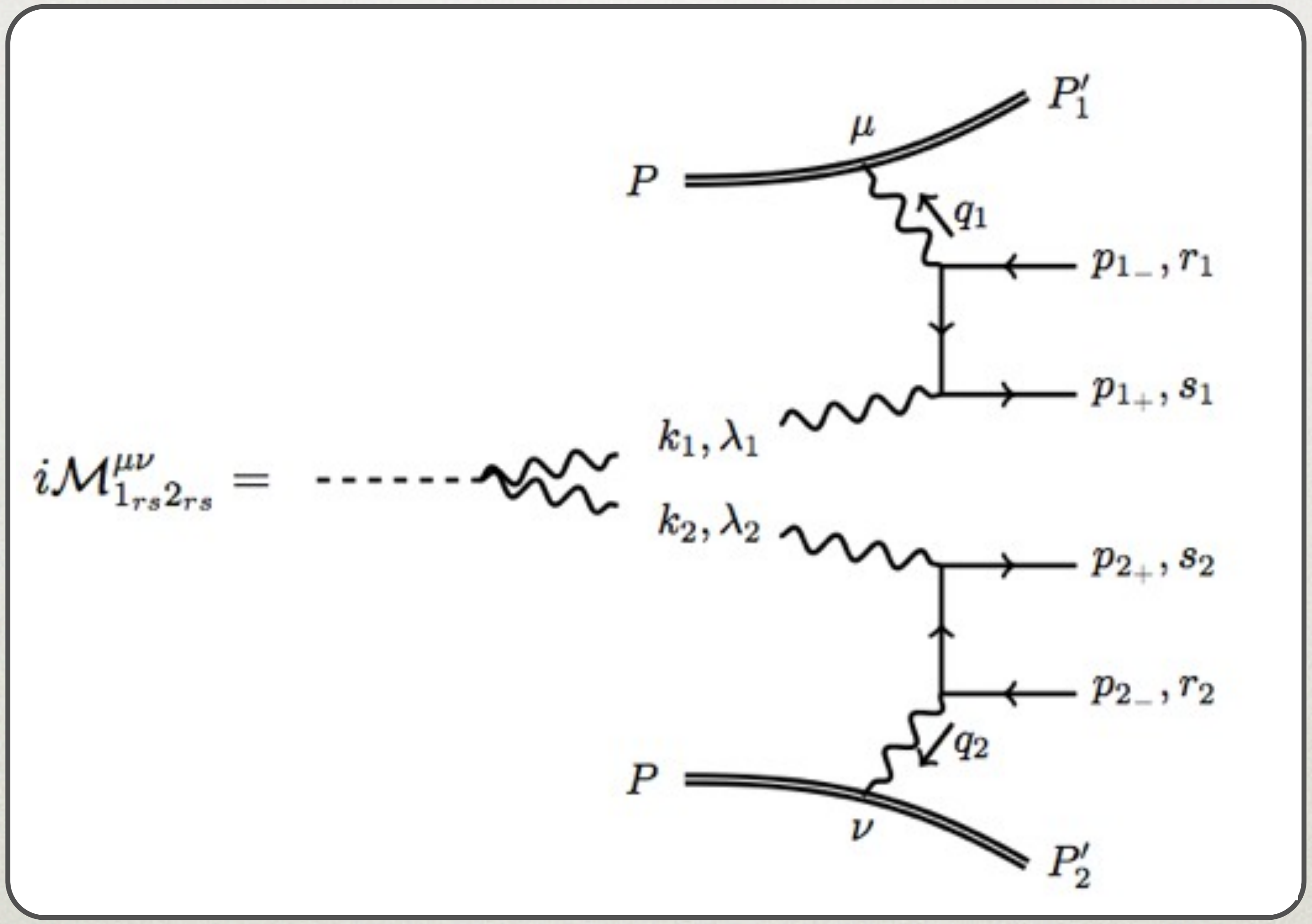
MEASURING CPV

- how to measure a polarization of a ~60 GeV photon?
  - ~50% of the photons convert in Si tracker
  - can one use these?



HIGGS-BETHE-HEITLER

- the photons are on-shell and convert to e^+e^- after traveling macroscopic distance



- it is a 3→6 process
  - relatively involved kinematics

HOW EXPERIMENTALLY CHALLENGING

- how experimentally difficult?
  - should one worry about decoherence?
    - no! $\Leftarrow$ γ+Si xsec is dominated by Bethe-Heitler conversion
    - so that essentially no interactions with material before conversion
  - to determine e^+e^- orientation need to measure their opening angle
    - roughly half event have opening angles larger then 10^{-4}
    - need to measure opening angles of $O(10^{-4})$ to $O(10^{-3})$
    - angle of 10^{-4} corresponds to 50μm over lever arm of 0.5m
    - at the limit of present ATLAS silicon detector

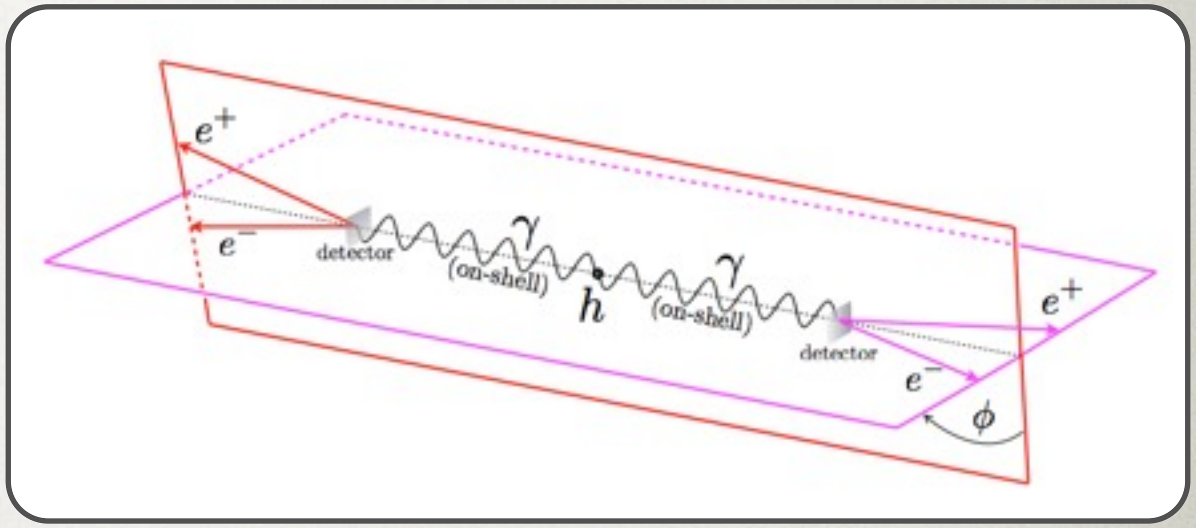
HOW EXPERIMENTALLY CHALLENGING

- another exp. challenge: multiple scattering of outgoing electrons
- after traversing 0.01 radiation length of material
  - typical scattering angle $\sim 10^{-4}$ for 10 GeV electron and $\sim 10^{-3}$ for 1 GeV electron
- **challenging but maybe not impossible**
  - could potentially determine the e^+e^- orientation on a statistical basis
- a more realistic detector study needed
  - this is just the first step $\Rightarrow$ we are mostly dealing with theory aspects

WHAT WE HAVE DONE

- what we have done
  - analytical results for HBH using Feynman diagrams and spin-helicity formalism
  - built a Monte Carlo program for HBH
    - uses Mathematica to have enough precision
    - eventually C++ code or interface with MadGraph (but needs quadruple precision)
- the goal is to understand where the sensitivity to CPV comes from/how large it is
  - for now leave backgrounds aside

CPV sensitive observables

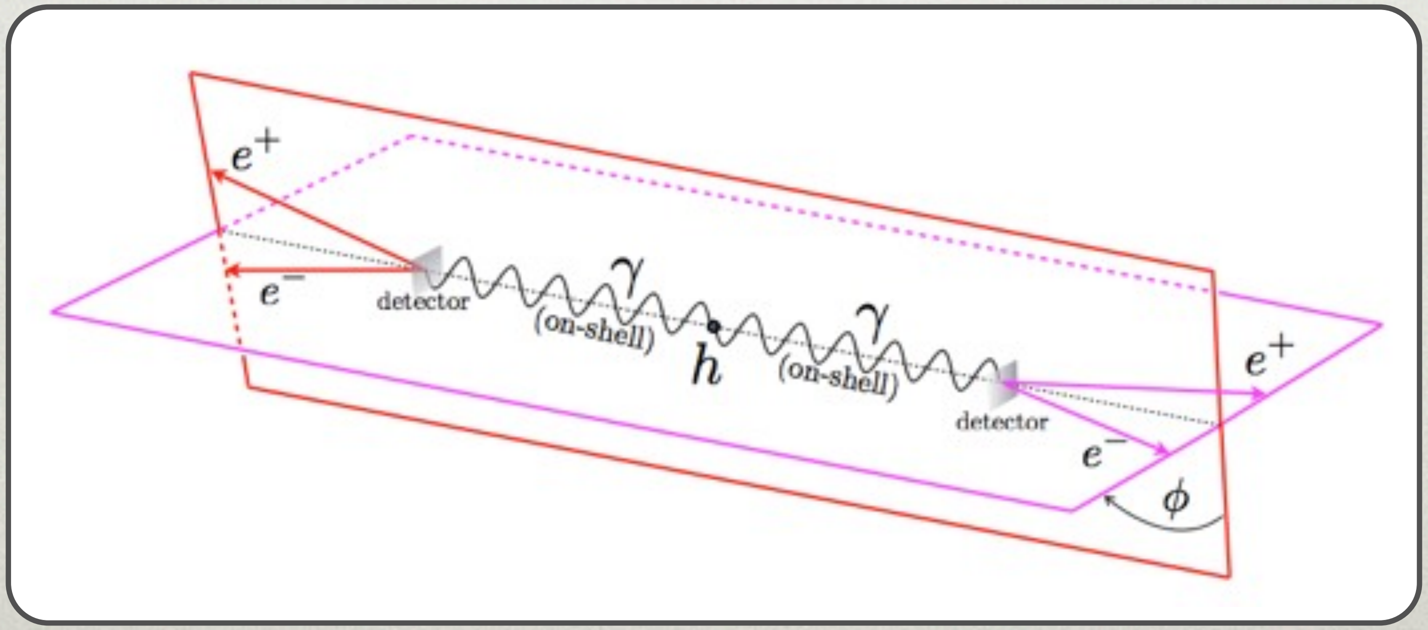


- what are CPV sensitive observables?
- counting the parameters describing leptonic config.
  - 8 angular variables+4energies
  - 3 angles are just global rotations
  - of the remaining 5
    - two are opening angles between e^+e^- on the same branch
    - two measure acoplanarity between e^+e^- and photon on the same branch
    - cannot be sensitive to CPV
- this leaves us with a <u>single angle</u> that carries info about CPV

CPV sensitive observables

- there is just one angle that carries information about CPV phase ξ
  - can be taken to be the angle between e^+e^- planes

$$\cos\phi = \frac{\boldsymbol{p}_{1_+} \times \boldsymbol{p}_{1_-}}{\|\boldsymbol{p}_{1_+} \times \boldsymbol{p}_{1_-}\|} \cdot \frac{\boldsymbol{p}_{2_+} \times \boldsymbol{p}_{2_-}}{\|\boldsymbol{p}_{2_+} \times \boldsymbol{p}_{2_-}\|}$$



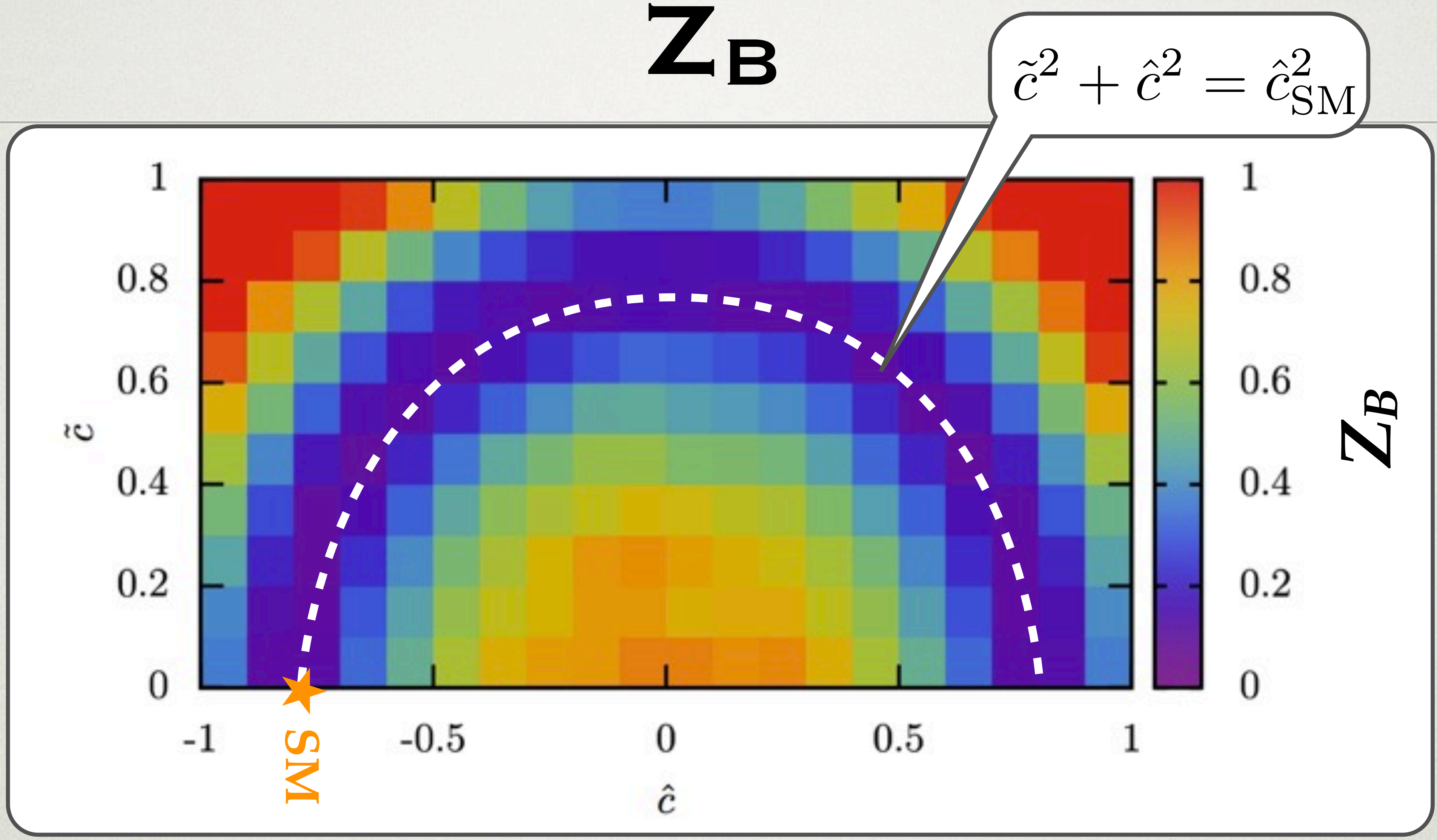
THE SIZE OF CPV

- how big of an effect should we expect from $\tilde{c}$~*O(1)*?
- first look at an integrated effect
  - define Z_B global variable

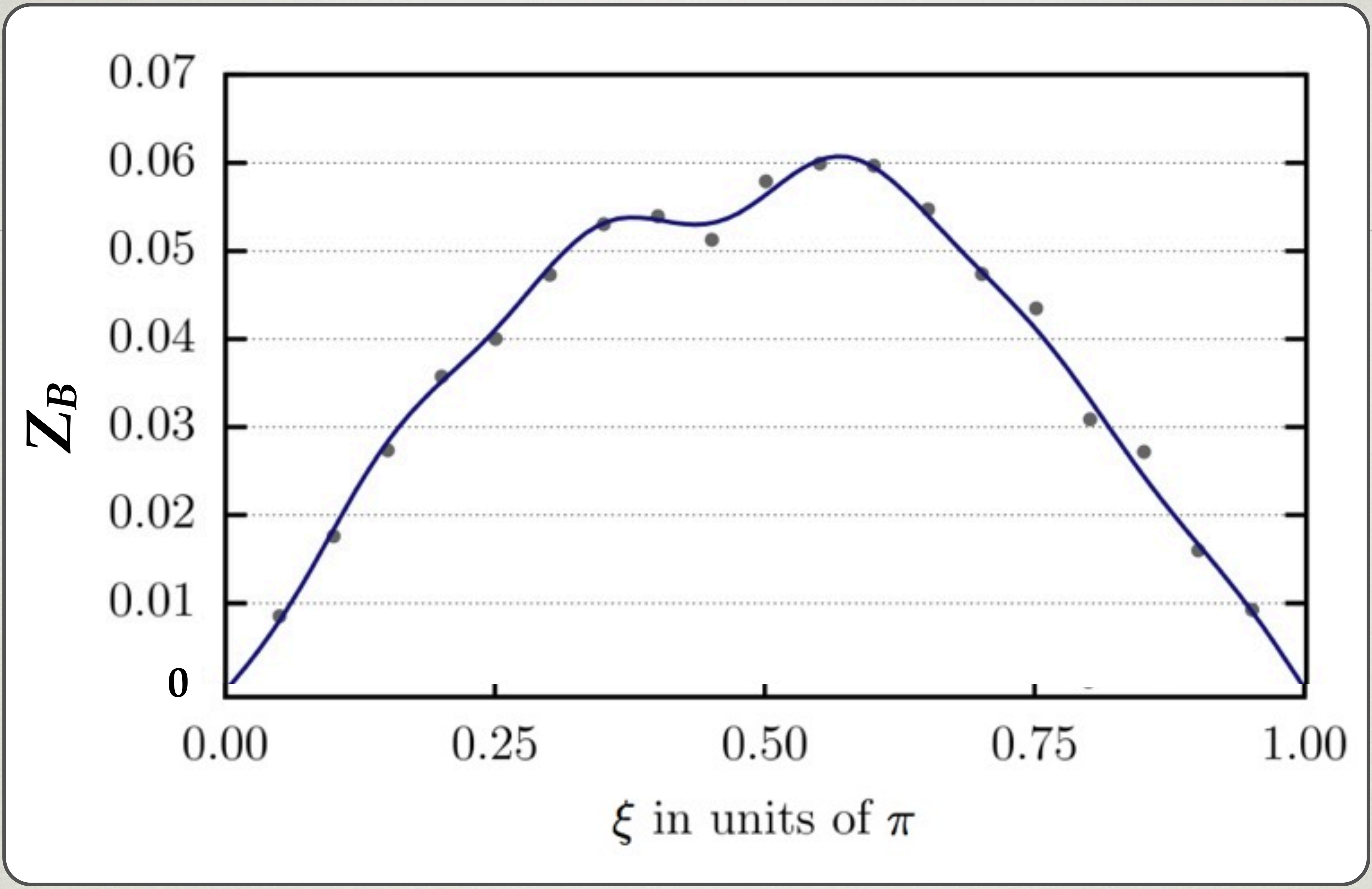
$$Z_B(\hat{c},\tilde{c}) = \frac{\int |d\Gamma(\textsc{sm})/d\textsc{ps} - d\Gamma(\hat{c},\tilde{c})/d\textsc{ps}|\, d\textsc{ps}}{\int [d\Gamma(\textsc{sm})/d\textsc{ps}]\, d\textsc{ps}}$$

  - a proxy for integrated matrix element method sensitivity

Z_B



$\tilde{c}^2 + \hat{c}^2 = \hat{c}_{\rm SM}^2$
1
0.8
0.6
0.4
0.2
0
$\tilde{c}$
-1
-0.5
0
0.5
1
$\hat{c}$
SM
Z_B



- the integrated effect (for the conservative case) ~O(5%)
- is this O(5%) everywhere?
- or O(5%) phase space has O(1) effect?
    - second possibility much better experimentally

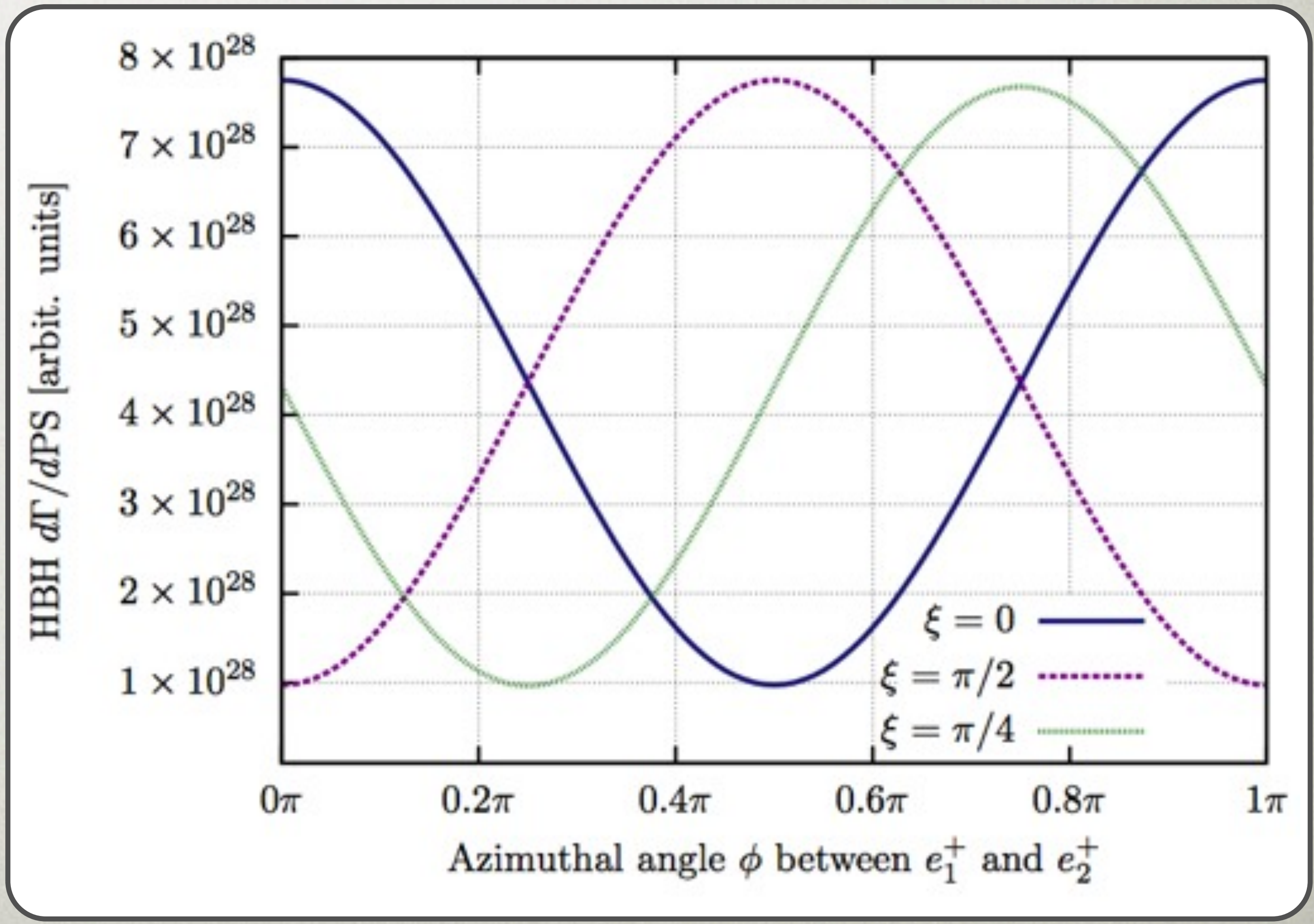
LARGE EFFECTS?

- differential spectrum has the following form

$$\frac{d\Gamma_{\mathrm{BHB}}}{d\phi} = \mathcal{A} + \mathcal{B}\cos(2\xi + 2\phi)$$

- sensitivity to $\xi \Leftrightarrow$ how large is $\mathcal{B}/\mathcal{A}$?

- are there slices in phase space where $\mathcal{B}/\mathcal{A} \sim O(1)$?
    - yes! $\Rightarrow$ an example: $E_{i+} = E_{i-} = m_h/4$, $\theta_{i+} = 10^{-4}$, $\theta_{i-} = 2\theta_{i+}$



INCREASING SENSITIVITY TO CPV

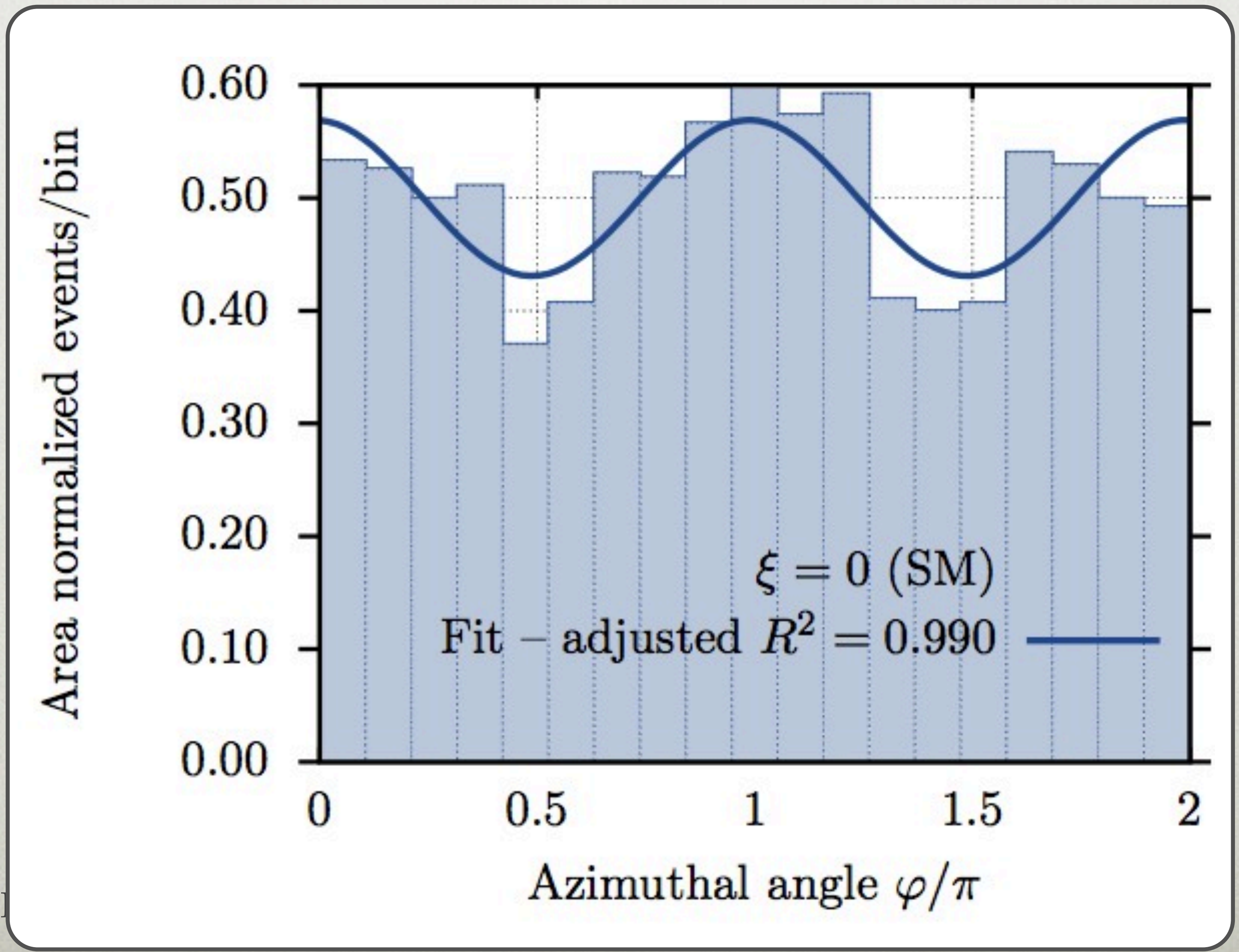
- want to select regions in phase space most sensitive to CPV phase ξ
- sensitivity to ξ from helicity interference
- can use variable

$$\mathcal{T} \sim \frac{\text{interf. term in } |\mathcal{M}|^2}{\text{total } |\mathcal{M}|^2}$$

- cut on $\mathcal{T}$ selects large $\mathcal{B}/\mathcal{A}$ regions

AN EXAMPLE

- a cut of $\mathcal{T}$>0.7: oscillation amplitude is enhanced
  - this cut keeps 2% of events
  - visible shift due to nonzero ξ



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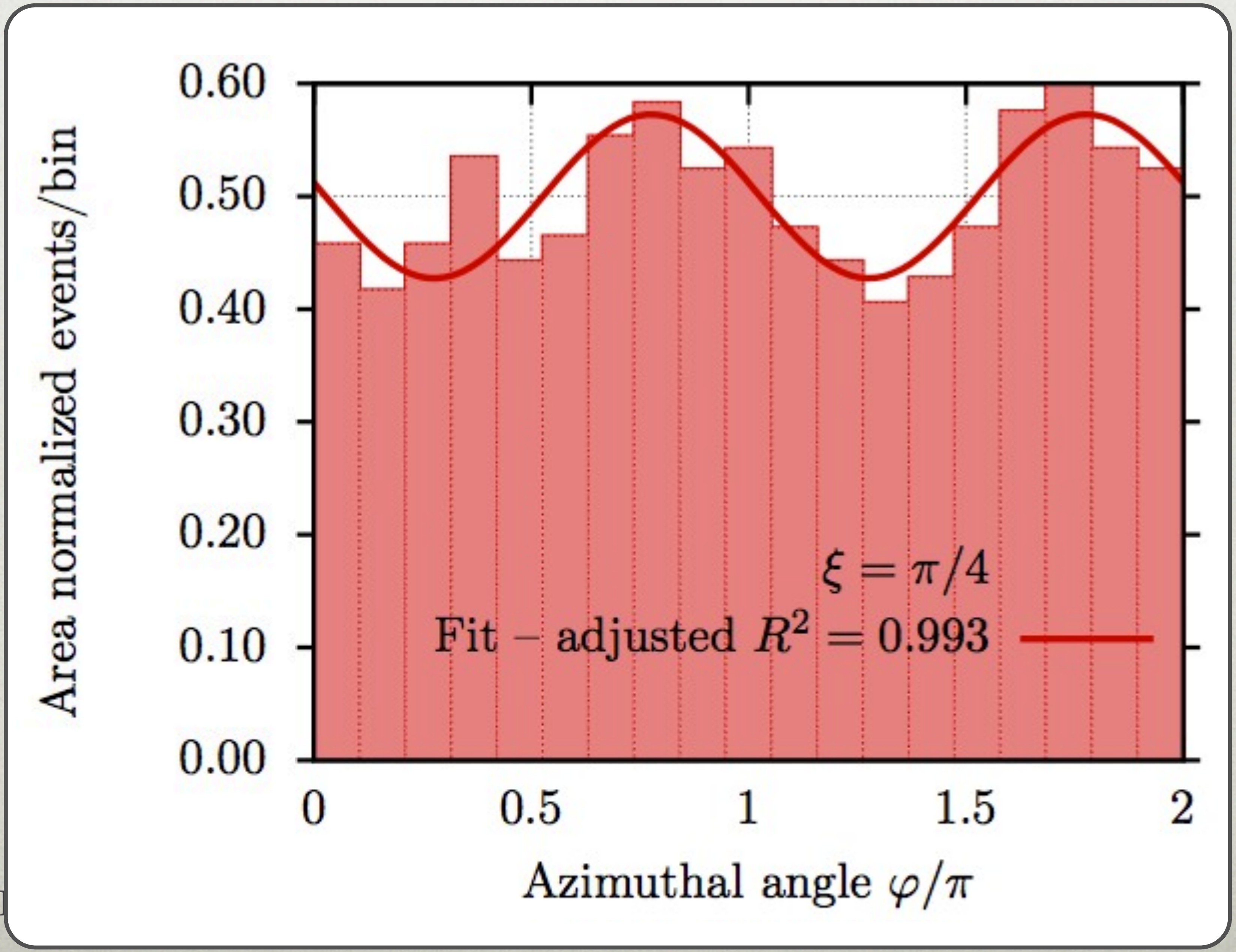


TRIPLE PRODUCTS

- triple product - a classic CPV observable

$$\tau_1 = \epsilon^{p_{1-} p_{1+} p_{2-} p_{2+}}$$

- a challenge is that for coplanar configs. $<\tau_1>=0$
- solution: do not integrate over whole phase space
- still work in progress
  - right now looks like a promising observable

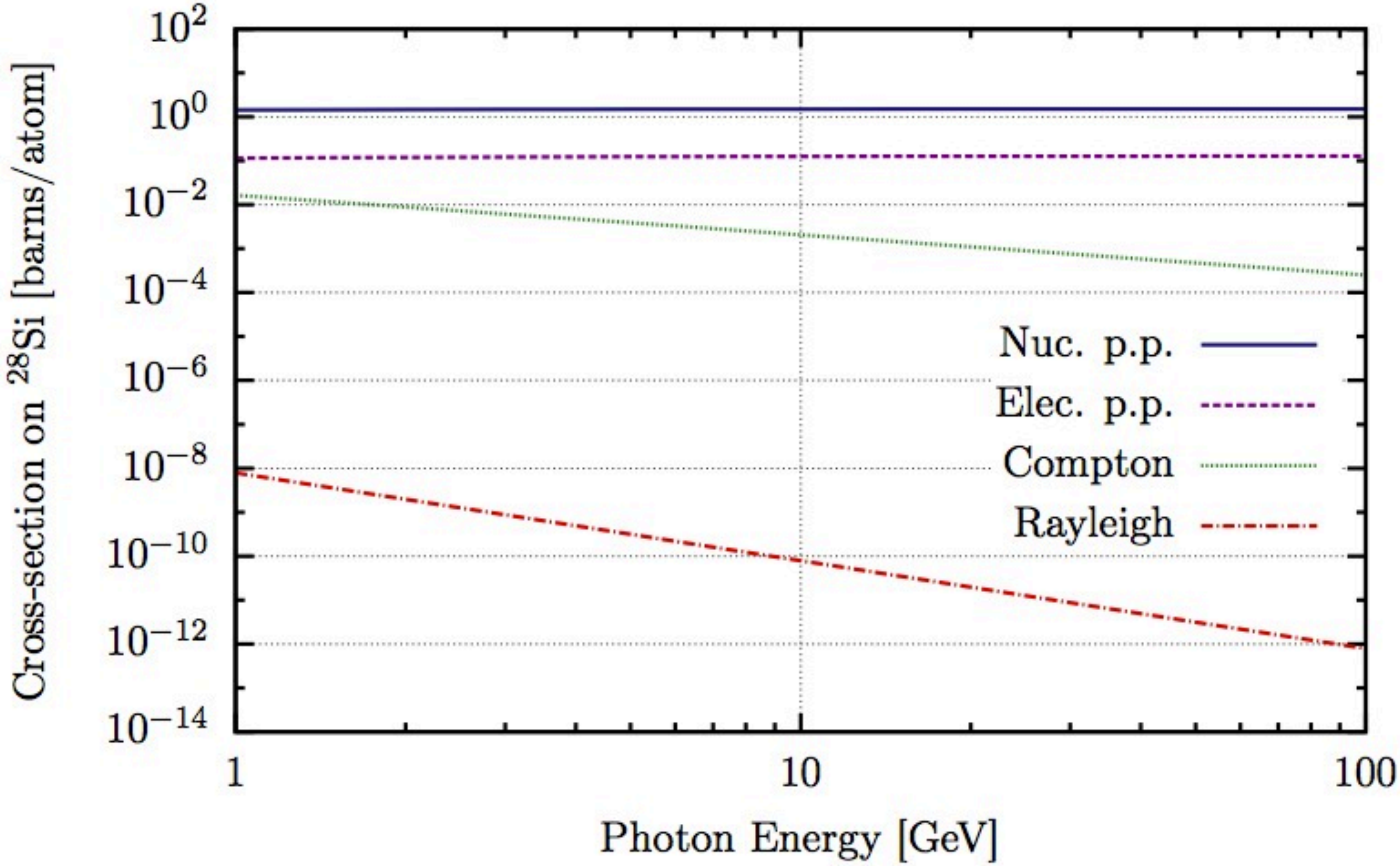
CONCLUSIONS

- converted photons can be used to probe CPV $h \to \gamma\gamma$ couplings
- proposed measurmnts. challenging but maybe not impossible

BACKUP SLIDES

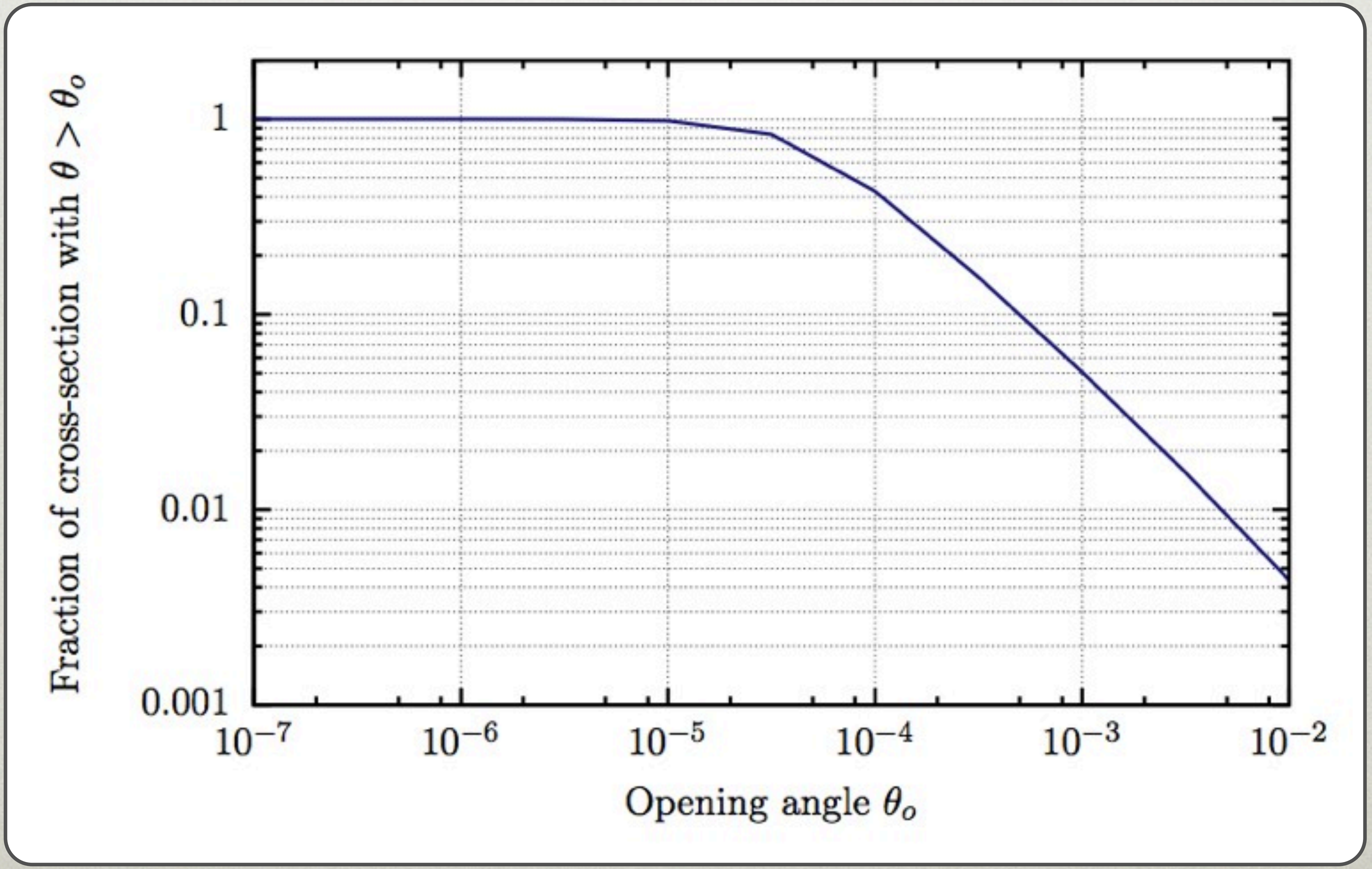
SCATTERING XSEC

- cross sections for $\gamma + {}^{28}Si$ interaction



OPENING ANGLE

- BH conversion of 50 Gev photon on ^{28}Si



CONCLUSIONS

- converted photons can be used to probe CPV $h \to \gamma\gamma$ couplings
- proposed measurmnts. challenging but maybe not impossible
    - would break the degeneracy between CPC and CPV $h \to \gamma\gamma$ couplings present in the rate