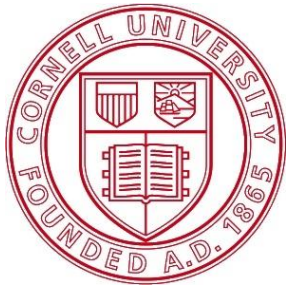
CP violation in $h \to Z\gamma$

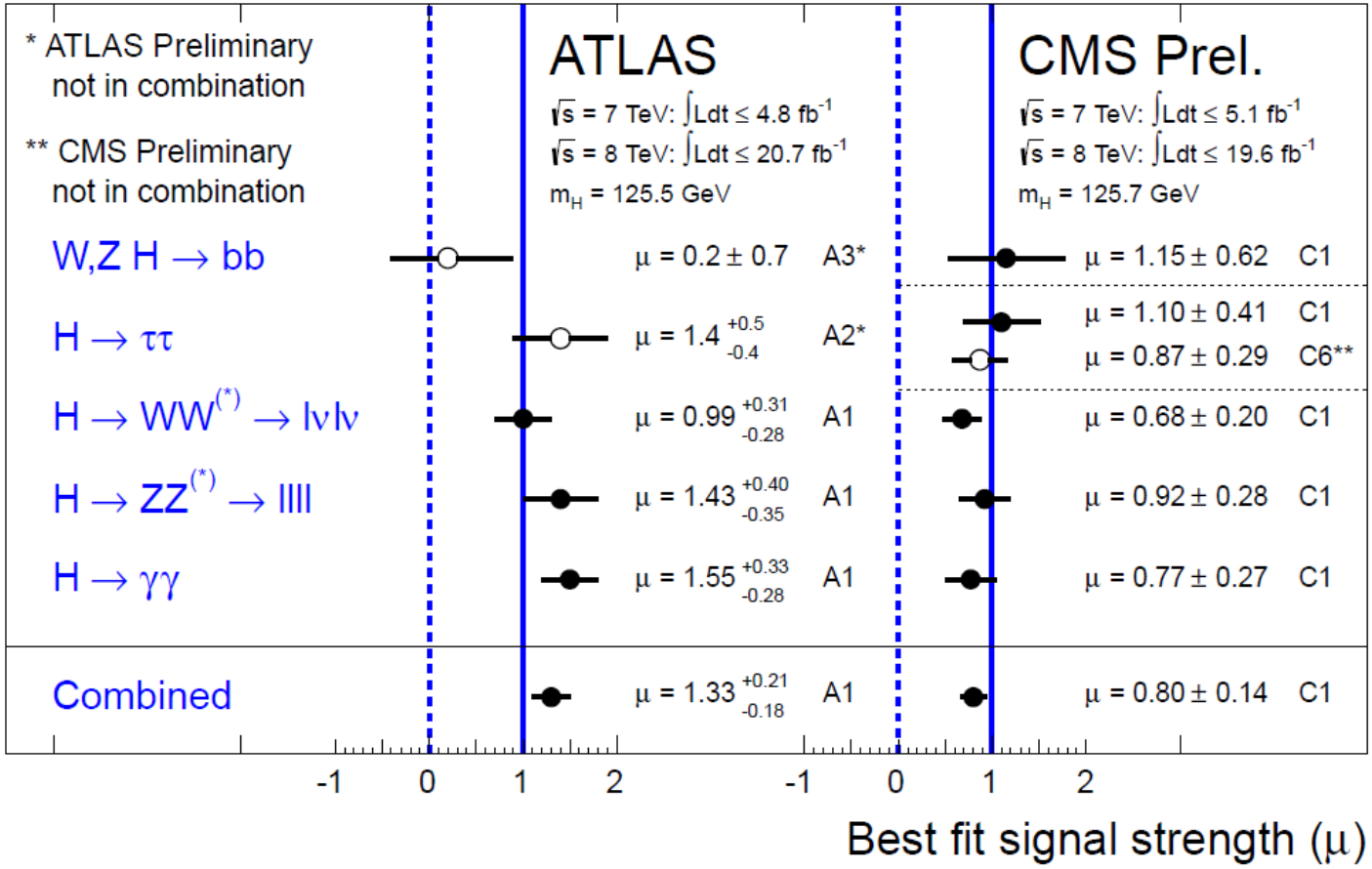
UMass Amherst
May 2, 2015

Marco Farina
Cornell University



First look

The Higgs looks quite SM like



PDG Review (Nov 2013)

Introduction

How well at the end of LHC?

Luminosity	300 fb^{-1}	3000 fb^{-1}
Coupling parameter	7-parameter fit	
κ_γ	$5-7\%$	$2-5\%$
κ_g	$6-8\%$	$3-5\%$
κ_W	$4-6\%$	$2-5\%$
κ_Z	$4-6\%$	$2-4\%$
κ_u	$14-15\%$	$7-10\%$
κ_d	$10-13\%$	$4-7\%$
κ_ℓ	$6-8\%$	$2-5\%$
Γ_H	$12-15\%$	$5-8\%$
	additional parameters (see text)	
$\kappa_{Z\gamma}$	$41-41\%$	$10-12\%$
κ_μ	$23-23\%$	$8-8\%$
$\mathrm{BR}_{\mathrm{BSM}}$	$< 14-18\%$	$< 7-11\%$

Snowmass Higgs Working Group Report 1310.8361

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$h\, F_{\mu\nu} \tilde{Z}^{\mu\nu}$?

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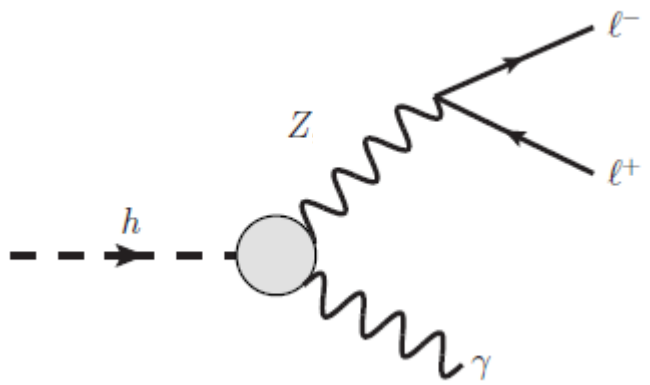
FB asymmetry

- Only one angle.
  Claim: you can construct a FB asymmetry



- Just Zɣ itself?

A. K orchin, V. Kovalchuk 1303.0365

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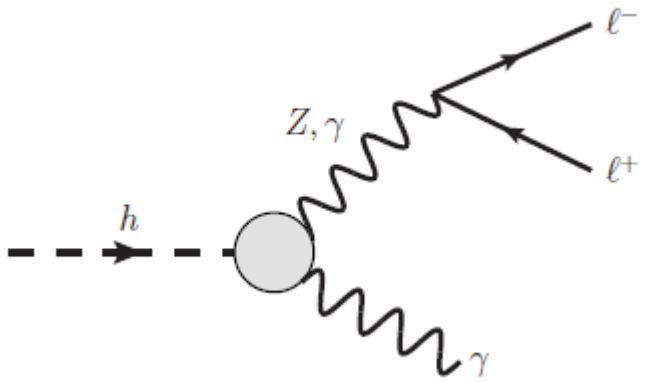


- Just Zɣ itself?

  A. K orchin, V. Kovalchuk 1303.0365

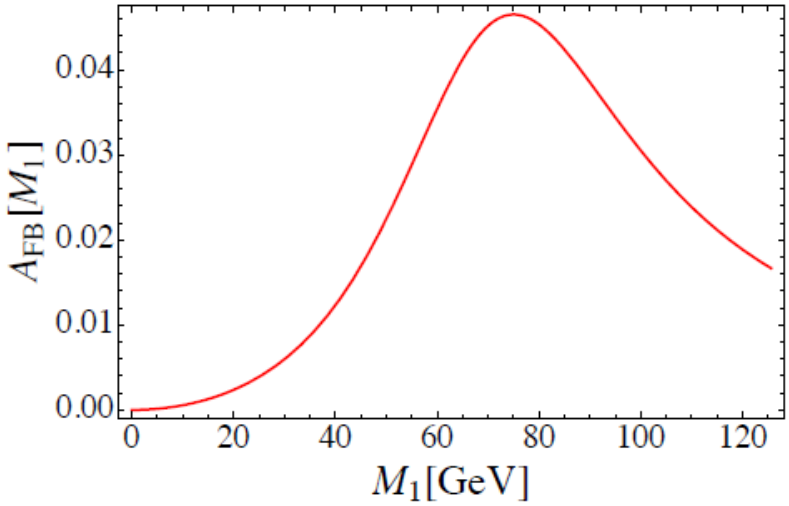
$$\bar{A}_{\rm FB} \approx \frac{\Gamma_Z}{m_Z} \frac{A_2^{Z\gamma} A_3^{\gamma\gamma} - A_2^{\gamma\gamma} A_3^{Z\gamma}}{(A_2^{Z\gamma})^2 + (A_3^{Z\gamma})^2}$$

- Interference with ɣɣ

  Y Chen et al. 1405.6723

- HL-LHC might not be enough

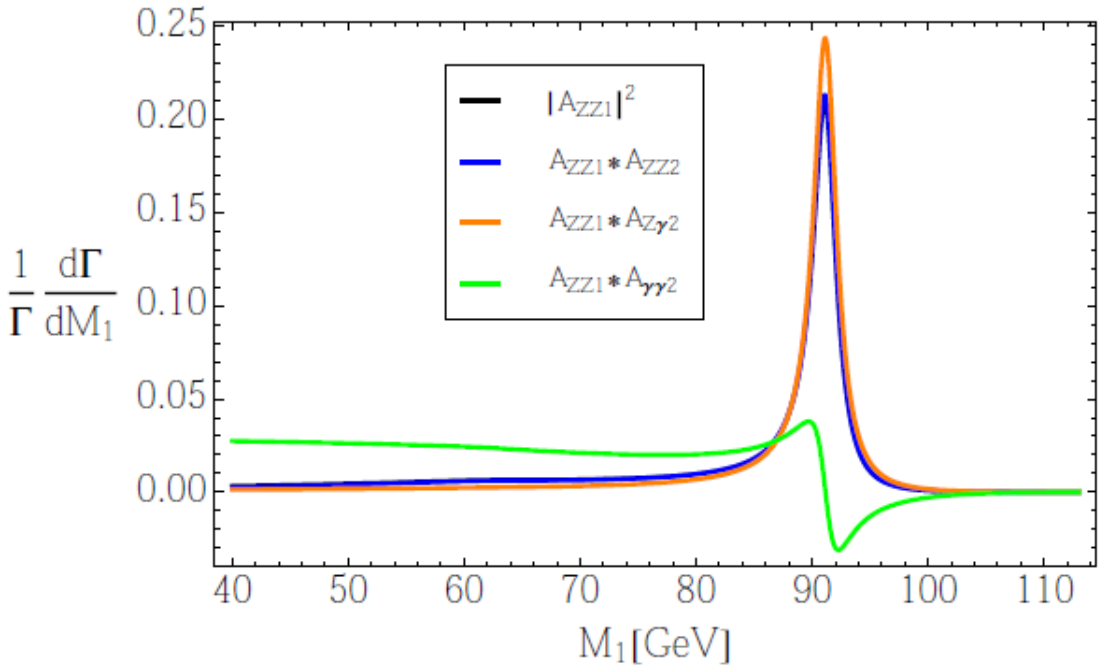
$$\frac{S}{\sqrt{B}} \sim \left(\frac{A_{\rm FB}}{0.1}\right) \sqrt{\frac{L}{3000\ {\rm fb}^{-1}}}$$



4 leptons

- Intereference with ZZ

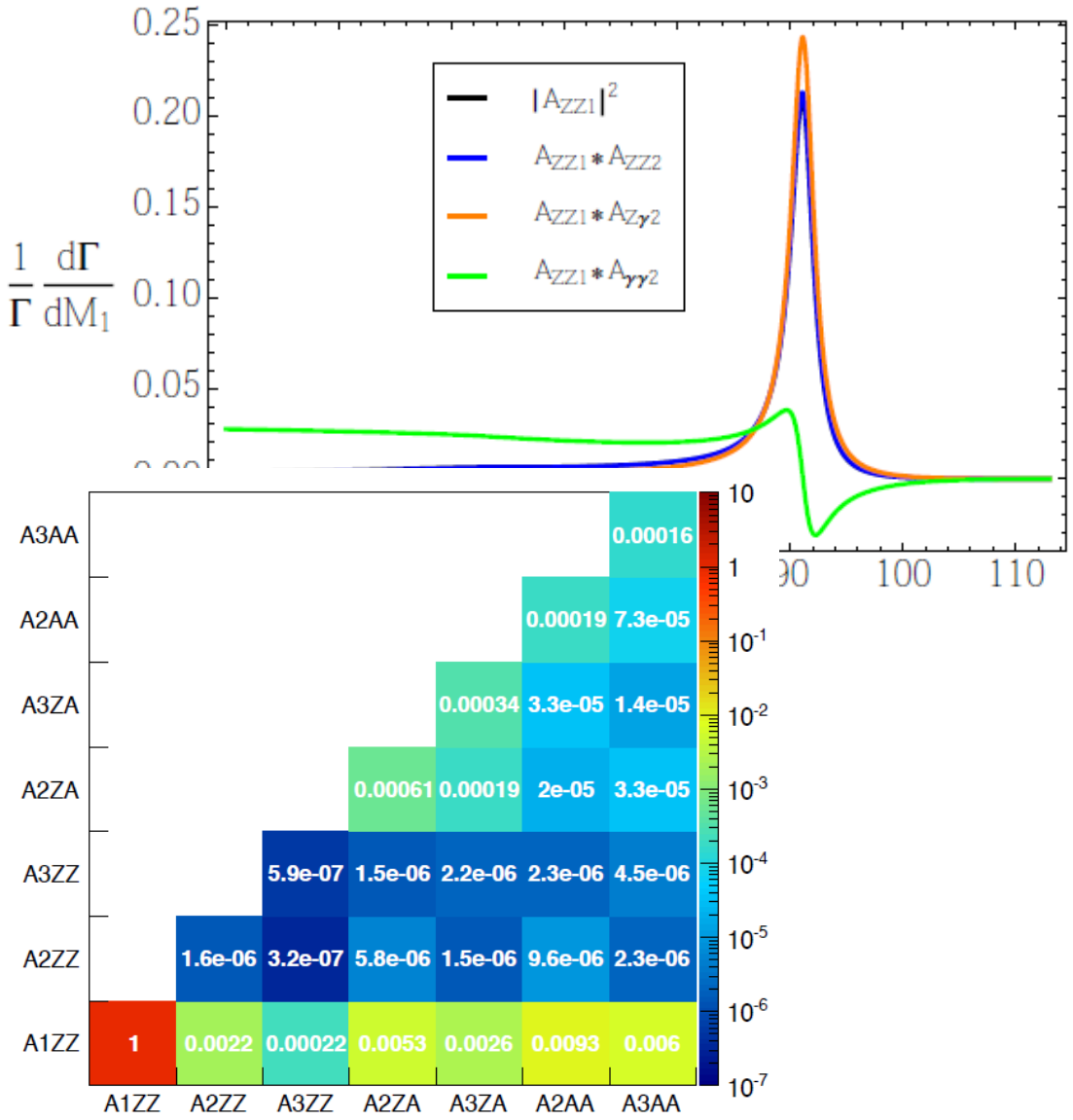
Y. Chen, R. Harnik, R. Vega-Morales 1404.1336



4 leptons

- Intereference with ZZ
- HL-LHC necessary (few % precision)
- How to disentangle different effects? (not a smoking gun)

Y. Chen, R. Harnik, R. Vega-Morales 1404.1336

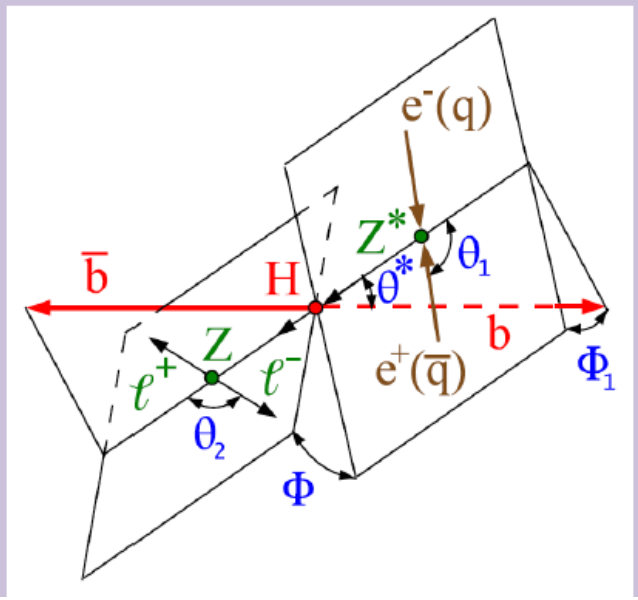


Lepton colliders?

Felix's Presentation

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]

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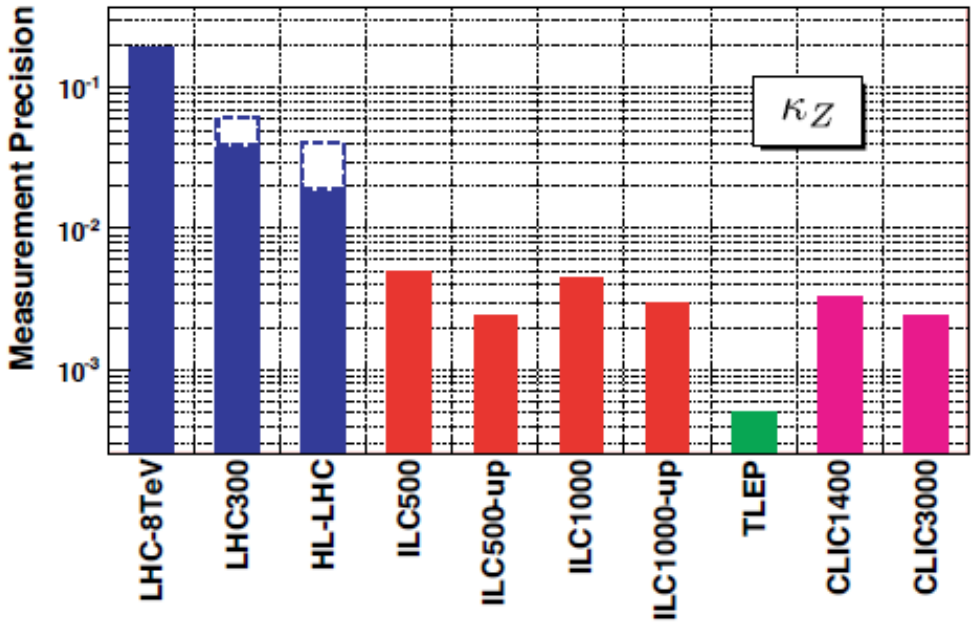


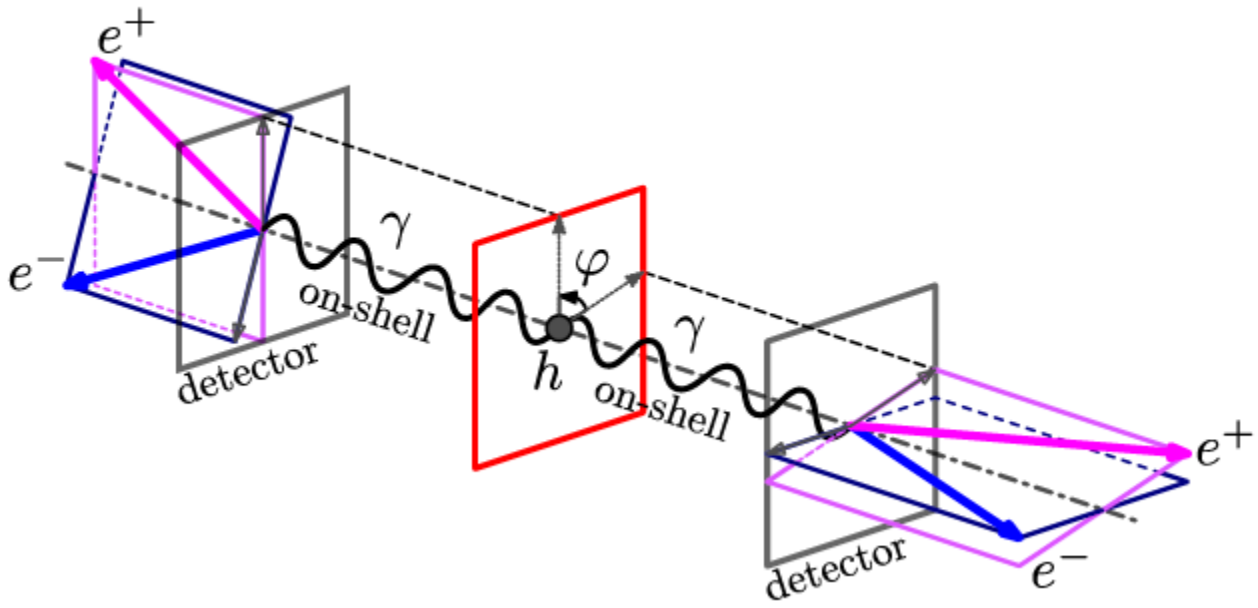
Anderson, *et. al.* [1309.4819]

Converted photons?

- Same idea of γγ, photons converting to e+e- pairs

F. Bishara et al. 1312.2955

- Even more challenging



Our proposal

$$gg \to h \to \gamma Z \to \gamma \ell^+ \ell^-$$

- What else can you interefere with?
- “QCD” Background!
- Different set of Higgs couplings involved

$$\mathcal{L}_{\rm h} = \frac{c}{v}\, h\, F_{\mu\nu} Z^{\mu\nu} + \frac{\tilde{c}}{2v}\, h\, F_{\mu\nu} \tilde{Z}^{\mu\nu} + \frac{c_g}{v}\, h\, G^a_{\mu\nu} G^{a\mu\nu}$$

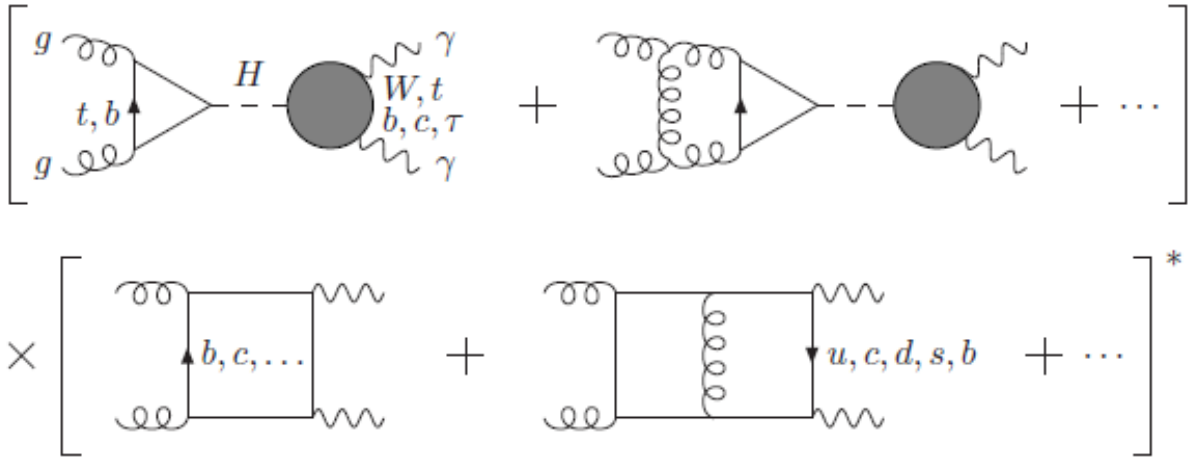
MF, Y. Grossman, D. Robinson 1503.06470

Interlude

It is a well known effect in the γγ case

L. Dixon, MS. Siu hep-ph(0302233

S. Martin 1303.3342



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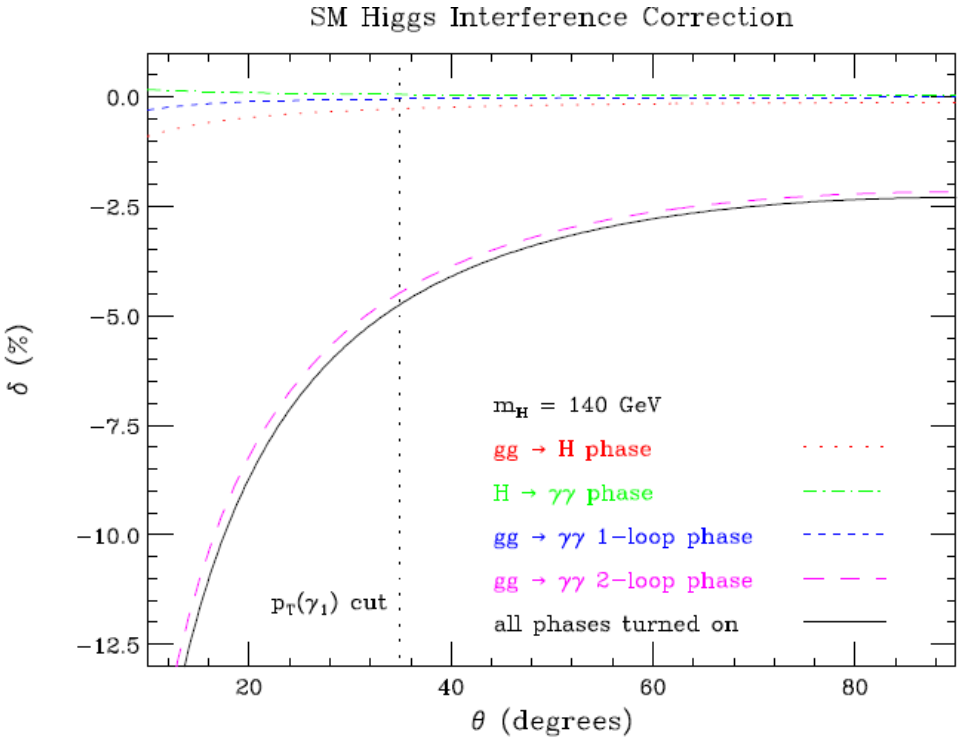
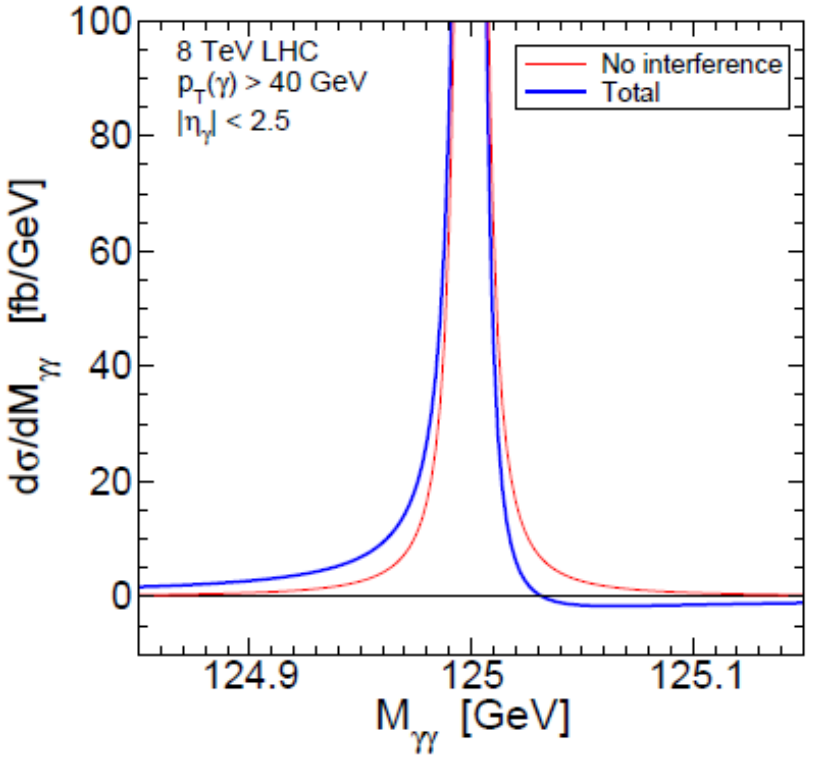


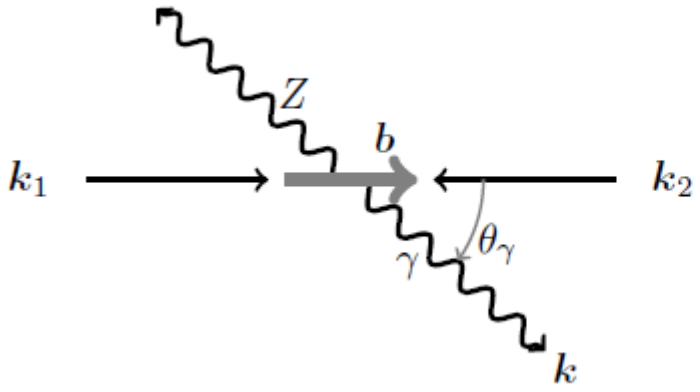


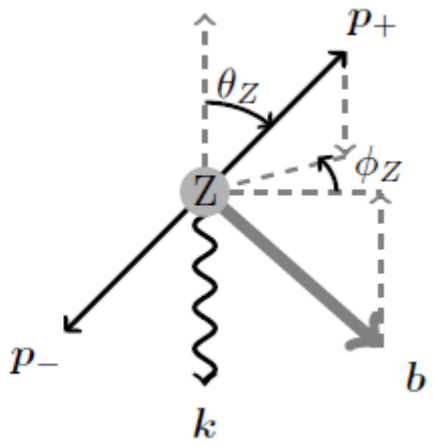
Kinematics

Back to Zɣ:

5 independent variables in a 2 → 3 process.

4 in our narrow width, on shell Z approximation





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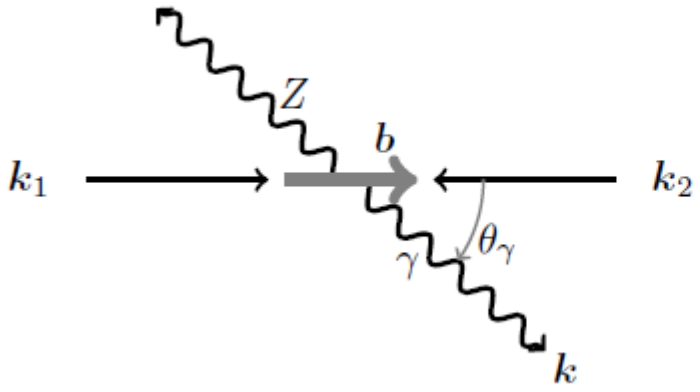

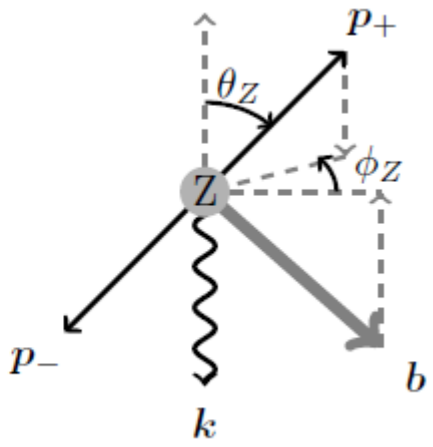

$$\frac{d\sigma(s,\theta_\gamma;\theta_Z,\phi_Z)}{d(\cos\theta_\gamma)d(\cos\theta_Z)d\phi_Z} = \frac{(s-m_Z^2)}{2^{11}\pi^3 s^2}\frac{\left|\mathcal{M}(s,\theta_\gamma;\theta_Z,\phi_Z)\right|^2}{m_Z\Gamma_Z}$$

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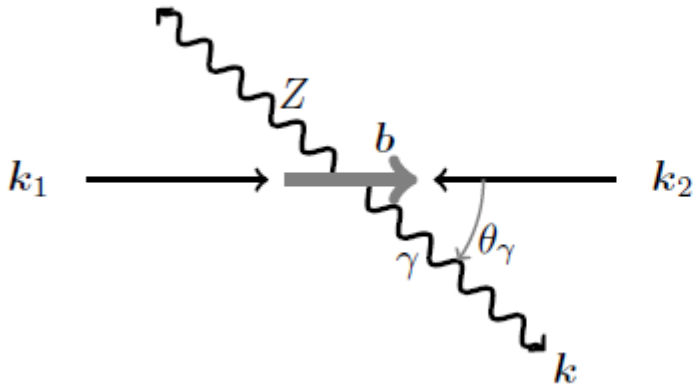

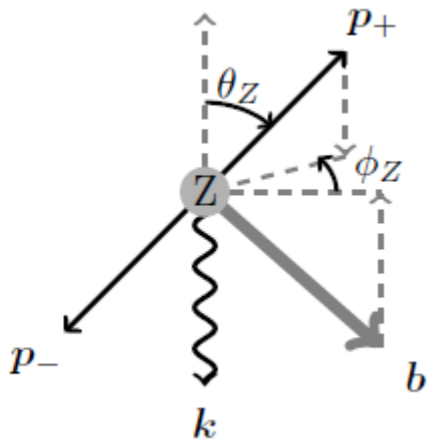

Under CP

$$\frac{d\sigma(s,\theta_\gamma;\phi_Z)}{d\cos\theta_\gamma d\phi_Z} = \left.\frac{d\sigma(s,\theta_\gamma;-\phi_Z)}{d\cos\theta_\gamma d\phi_Z}\right|_{\xi\to-\xi}$$

$$\xi \equiv \tan^{-1}(\tilde{c}/c)$$

Massaging

...

Massaging

...

$$\frac{d\sigma^I}{d\phi_Z} = \frac{\sigma^I_{\mathrm{SM}}}{2\pi}\frac{1}{1+b_0/a_0}\left[1 + a_2/a_0\cos(2\phi_Z) + b_0/a_0\cos(\xi) + b_2/a_0\cos(2\phi_Z+\xi)\right]$$

Main result

$$\frac{d\sigma^I}{d\phi_Z} = \frac{\sigma^I_{\rm SM}}{2\pi}\frac{1}{1+b_0/a_0}\left[1 + a_2/a_0\cos(2\phi_Z) + b_0/a_0\cos(\xi) + b_2/a_0\cos(2\phi_Z+\xi)\right]$$

How can we get the coefficients?

$$\xi \equiv \tan^{-1}(\tilde{c}/c)$$

- Do the full computation
- Quick and painless: MCFM (custom)

Fitting main result

$$\frac{d\sigma^I}{d\phi_Z} = \frac{\sigma^I_{\rm SM}}{2\pi}\frac{1}{1+b_0/a_0}\left[1 + a_2/a_0\cos(2\phi_Z) + b_0/a_0\cos(\xi) + b_2/a_0\cos(2\phi_Z+\xi)\right]$$

How can we get the coefficients?

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$$a_2/a_0 \equiv \frac{\mathcal{C}^I_{+-} + \mathcal{C}^I_{-+}}{\sum_k \mathcal{C}^I_{kk}} = 0.143 \pm 0.001$$

$$b_0/a_0 \equiv \frac{\mathcal{C}^I_{h_{++}} + \mathcal{C}^I_{h_{--}}}{\sum_k \mathcal{C}^I_{kk}} = (6.61 \pm 0.08) \times 10^{-3}$$

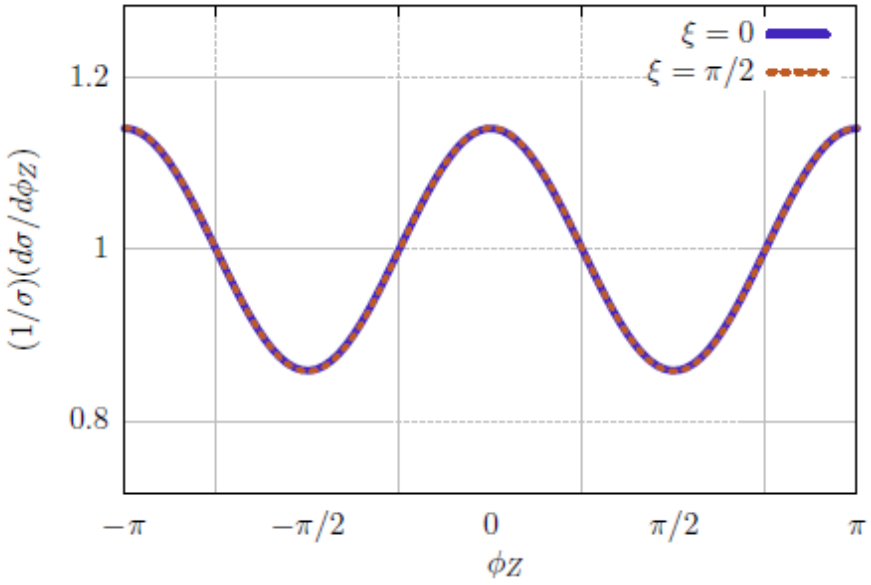
$$b_2/a_0 \equiv \frac{\mathcal{C}^I_{h_{+-}} + \mathcal{C}^I_{h_{-+}}}{\sum_k \mathcal{C}^I_{kk}} = -(0.92 \pm 0.08) \times 10^{-3}$$

Doomed?

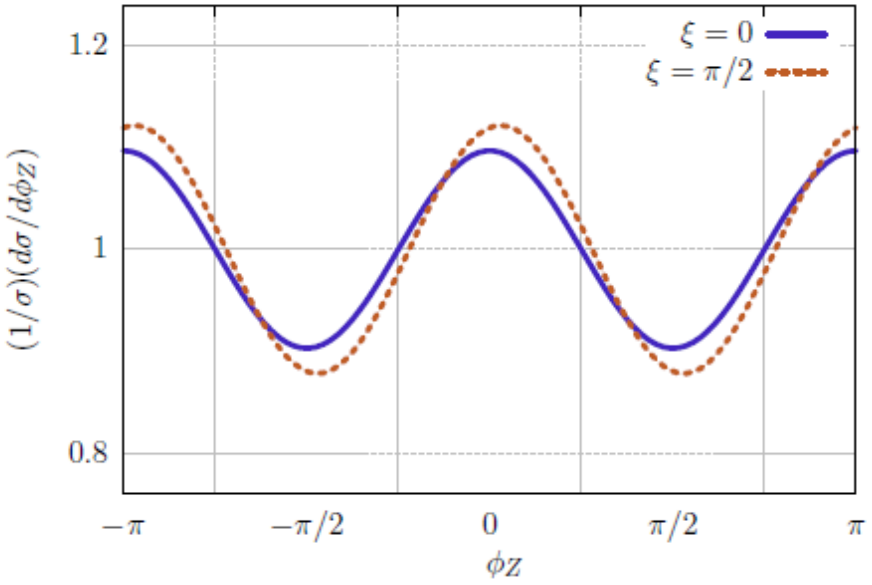
$$\frac{d\sigma^I}{d\phi_Z} = \frac{\sigma^I_{\rm SM}}{2\pi}\frac{1}{1+b_0/a_0}\left[1 + a_2/a_0\cos(2\phi_Z) + b_0/a_0\cos(\xi) + b_2/a_0\cos(2\phi_Z+\xi)\right]$$

Very small effect O(1%)

$$\xi \equiv \tan^{-1}(\tilde{c}/c)$$



x 1

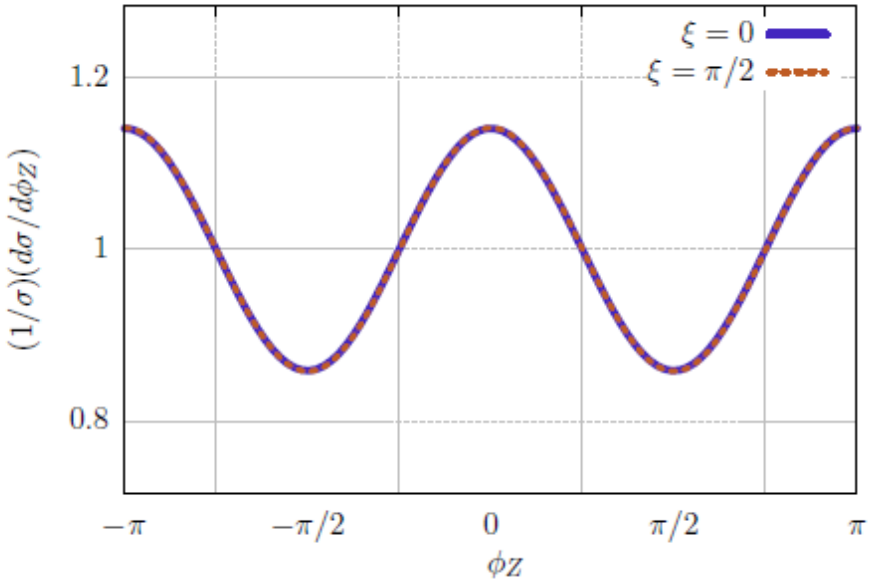


x 30

Doomed!

"Easy" observable $\Sigma_{\phi_Z} \equiv \frac{1}{\sigma} \int_{-\mathrm{I}+\mathrm{II}-\mathrm{III}+\mathrm{IV}} \left(\frac{d\sigma^I}{d\phi_Z} \right) d\phi_Z$

SM (ξ=0) hypothesis rejection at 95% C.L. requires $10^8\ \mathrm{fb}^{-1}$



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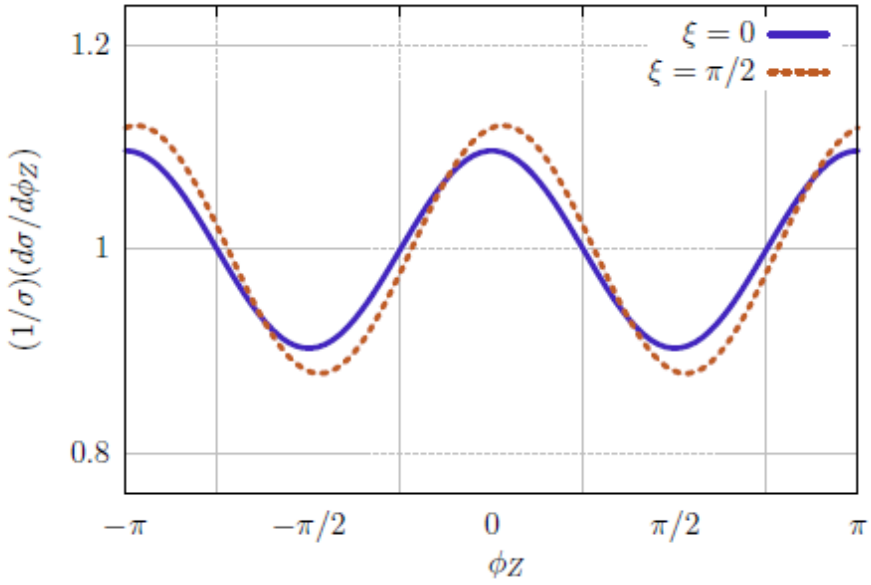
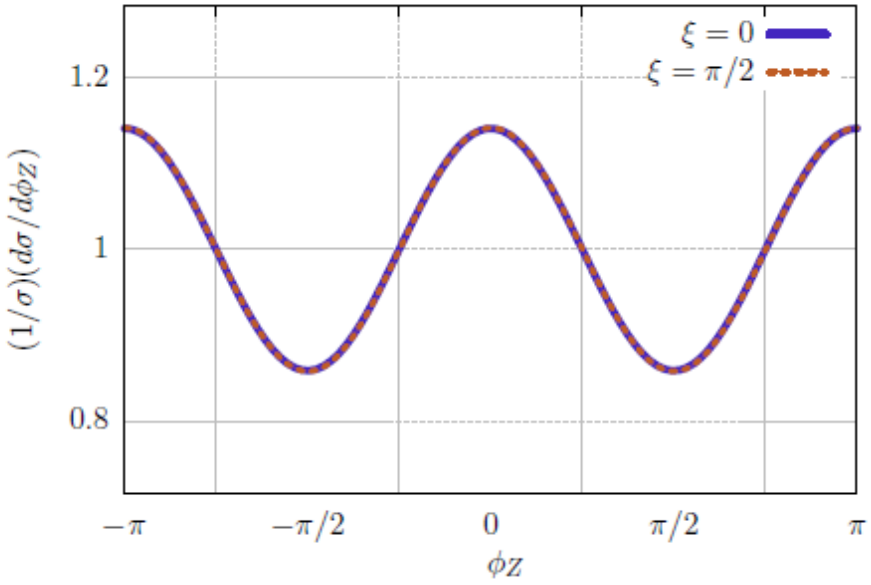


x 30

Future colliders?

- One could use VBF at lepton colliders (not competitive?)
- What about a 100TeV collider?



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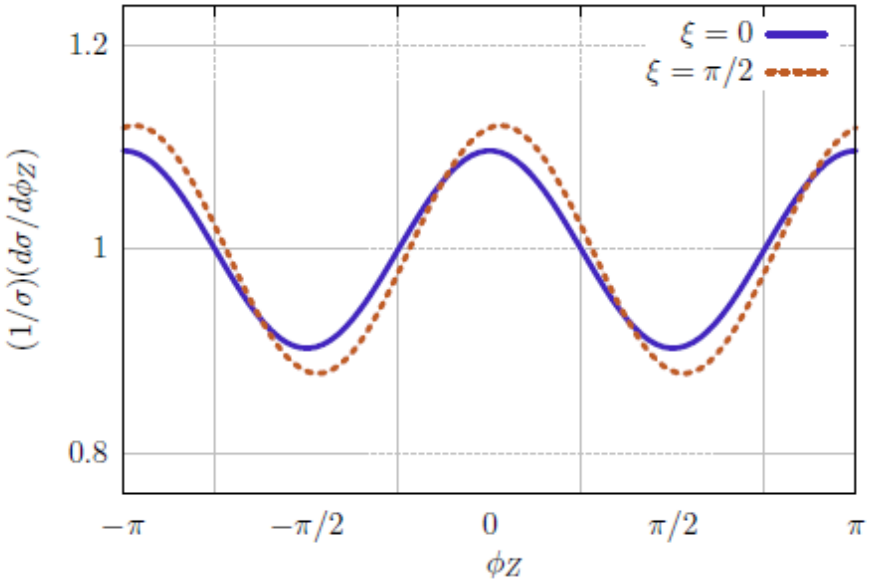

x 30

Conclusions

- **$H \rightarrow Z\gamma$ is hard!**
- **At least HL-LHC is mandatory:** yet very challenging measurements
- **Do we need better ideas?**