Higgs Properties at A γγ Collider

Xiao-Gang He

SJTU/NCTS

Windows on the Universe, 12-17/8/2013, Quy-Nhon, Vietnam

arXiv: 1302,6302 (with Siao-Fong Li, Hsiu-Hsien Lin)
arXiv:1211.5528 (with Gang Guo, Guan-nan Li, Bo Ren, Ya-Juan Zheng)

Higgs h → γγ and γγ → h

LHC has discovered a SM Higgs-like h. h → γγ has been observed but larger than SM prediction by a factor of 1.65 (ATLAS), and 1.11(0.78) (CMS)

This process is crucial in identifying h with the SM Higgs.

LHC will have more data, it may have conclusive information soon.

Still it is important whatever LHC finds, can be confirmed at other facilities.

A γ γ collider to produce a on-shell h would be an idea place for such a purpose.

arXiv:1302.6302

A possible way of building a a γγ collider

Realistically a $\gamma\gamma$ collider can be constructed by using the laser backscattering technique on the electron and positron beams in an e^+e^- collider. For example the e^+e^- ILC collider. Such a collider has been shown to be useful to study beyond SM physics [8]. In this case the energy E_γ of the photons are not monochromatic, but have a distribution $F(x)$ for a given electron/positron energy E_e [9]

$$F(x) = \frac{1}{D(\xi)}(1 - x + \frac{1}{1-x} - \frac{4x}{\xi(1-x)} + \frac{4x^2}{\xi^2(1-x)^2} ,$$

$$D(\xi) = (1 - \frac{4}{\xi} - \frac{8}{\xi^2}) \ln(1+\xi) + \frac{1}{2} + \frac{8}{\xi} - \frac{1}{2(1+\xi)^2} . \qquad (4)$$

Here $x = E_\gamma/E_e$, and $\xi = 2(1+\sqrt{2})$.

γγ collision producing a on-shell h

$$\sigma(s)_{0,\gamma\gamma} = \Gamma^2_{0,\gamma\gamma}\frac{8\pi^2}{m_h\Gamma_{total}}\delta(s-m_h^2)$$

for $\gamma\gamma \to h \to \gamma\gamma$ cross section $\sigma^L_{0,\gamma\gamma}(s)$

$$\sigma(s)^L_{0,\gamma\gamma} = \int_{x_{min}}^{x_{max}} dx_1 \int_{x_{min}}^{x_{max}} dx_2 \sigma(s)_{0,\gamma\gamma}(x_1 x_2 s)F(x_1)F(x_2) = I(m_h^2/s)\frac{8\pi^2}{m_h^3}\Gamma_{0,\gamma\gamma}B_{0,\gamma\gamma} \ ,$$

where, $B_{0,\gamma\gamma} = \Gamma_{0,\gamma\gamma}/\Gamma_{0,total}$. In the SM $B_{\gamma\gamma} = 2.28\times 10^{-3}$ [10]. The function $I(y)$ is [8]

$$I(y) = \int_{y/x_{max}}^{x_{max}} dx \frac{y}{x}F(x)F(y/x) \ ,$$

with $y = m_h^2/s$, $x_{max} = \xi/(1+\xi)$, and $x_{min} = y/x_{max}$. Note that the function $I(y)$

SM prediction for Higgs h → γ γ

Assuming that the h boson discovered at the LHC is a spin-0 scalar particle, the matrix element $M(J=0,\gamma\gamma)$ of a spin-0 scalar coupling to $\gamma\gamma$ has the form

$$M(0,\gamma\gamma) = A(k_{2\mu}k_{1\nu} - g_{\mu\nu}k_1\cdot k_2)\varepsilon^{\mu *}(k_1)\varepsilon^{\nu *}(k_2). \tag{1}$$

The decay width for $h\to\gamma\gamma$ is given by, $\Gamma_{0,\gamma\gamma} = A^2 m_h^3/64\pi$.

If h is the SM Higgs boson [6],

$$\begin{aligned} A &= \frac{ie^2}{8\pi^2}(\sqrt{2}G_\mu)^{\frac{1}{2}}[\Sigma_f N_c Q_f^2 A_{1/2}^H(\tau_f) + A_1^H(\tau_W)]\ , \\ A_{1/2}^H(x) &= 2[x+(x-1)f(x)]x^{-2}\ , \\ A_1^H(x) &= -[2x^2+3x+3(2x-1)f(x)]x^{-2}\ , \end{aligned} \tag{2}$$

where N_c is the number of color, $\tau_i = m_h^2/4m_i^2$. The definition of loop function $f(x)$ is

$$f(x) = \begin{cases} \arcsin^2\sqrt{x} & \text{if } x\le 1; \\ \frac{-1}{4}[\ln(\frac{1+\sqrt{1-x^{-1}}}{1-\sqrt{1-x^{-1}}}) - i\pi]^2 & \text{if } x>1. \end{cases}$$

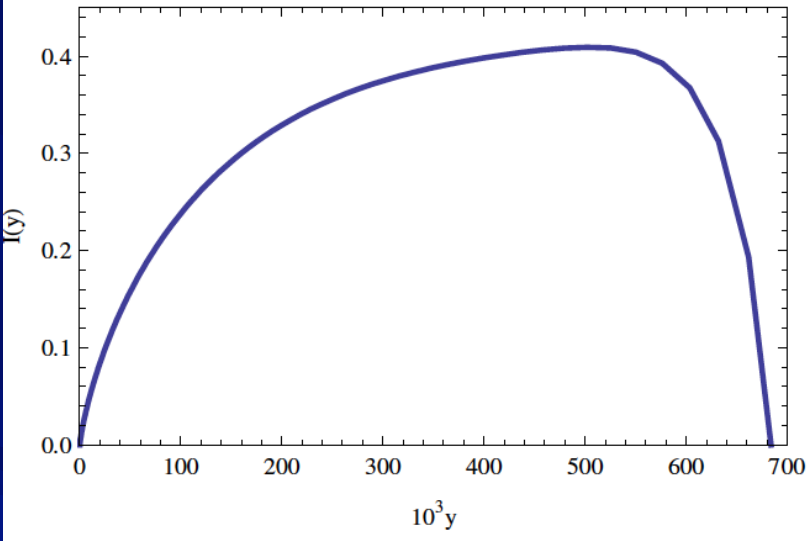

FIG. 1: $I(y)$ as a function of y.

With integrated luminosity of 500 fb^{-1}, can have about 60 events.

Can confirm LHC h → $\gamma\gamma$ measurement.

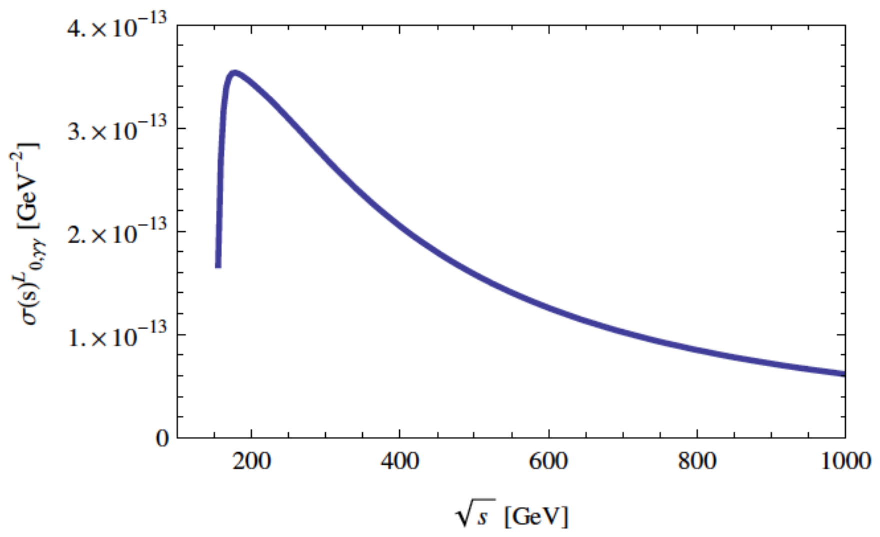

FIG. 2: $\sigma(s)^L_{0,\gamma\gamma}$ (in unit of GeV^{-2}) as a function of $\sqrt{s}$ in the SM.

If the current LHC data for enhanced $h \to \gamma\gamma$ hold, one would obtain a $\sigma^L_{0,\gamma\gamma}(s)$ which is larger than SM prediction by a factor $R^2_{\gamma\gamma}$ if the total decay width is the same as that of SM prediction. If the branching ratio is kept the same as that of SM, then the enhancement for $\sigma(s)^L_{0,\gamma\gamma}$ is $R_{0,\gamma\gamma}$. If $\Gamma_{0,\gamma\gamma} B_{0,\gamma\gamma}$ turns out to be the same as that of SM prediction, but $\Gamma_{0,\gamma\gamma}$ and $B_{0,\gamma\gamma}$ are different from those of SM predictions, information from other modes is needed to see whether there is new physics beyond the SM.

To see how information from additional decay modes can help to distinguish different models, let us take $h \to \gamma Z$ for example. In this case, one obtains the cross section $\sigma(s)^L_{0,\gamma Z}$ for $\gamma\gamma \to h \to \gamma Z$ as

$$\sigma(s)^L_{0,\gamma Z} = I(m_h^2/s)\frac{8\pi^2}{m_h^3}\Gamma_{0,\gamma\gamma} B_{0,\gamma Z} \ , \tag{7}$$

where $B_{0,\gamma Z}$ is the branching ratio for $h \to \gamma Z$.

Taking the ratio of $\sigma(s)^L_{0,\gamma\gamma}$ and $\sigma(s)^L_{0,\gamma Z}$, we have

$$S_{0,\gamma Z/\gamma\gamma} = \frac{\sigma(s)^L_{0,\gamma Z}}{\sigma(s)^L_{0,\gamma\gamma}} = \frac{\Gamma_{0,\gamma Z}}{\Gamma_{0,\gamma\gamma}} \ . \tag{8}$$

In the SM, $\Gamma_{\gamma Z}/\Gamma_{\gamma\gamma} = 0.7$

An example: A dark matter model with triplet arXiv:1212.5528

The couplings of h to $\Delta^{-,--}$ come from $\lambda^{1,2}_{\Delta H}(\Delta^\dagger \Delta H^\dagger H)_{1,2}$ after H develops vev. The $h\bar{\Delta}\Delta$ couplings are given by

$$L \sim -[\lambda^1_{\Delta H}(\Delta^+\Delta^- + \Delta^{++}\Delta^{--}) + \lambda^2_{\Delta H}(\Delta^{++}\Delta^{--} + \frac{1}{2}\Delta^+\Delta^-)]vh\ . \quad (16)$$

Combined with contributions from W and top in the loop, the $h \to \gamma\gamma$ rate is modified by a factor $R_{\gamma\gamma} = \Gamma(h \to \gamma\gamma)_{U(1)_D}/\Gamma(h \to \gamma\gamma)_{\rm SM}$ given by

$$R_{\gamma\gamma} = |1 + \frac{v^2}{2}\frac{1}{A_1(\tau_W) + N_c Q_t^2 A_{1/2}(\tau_t)}\{\frac{\lambda^1_{H\Delta} + \frac{1}{2}\lambda^2_{H\Delta}}{m^2_{\Delta^-}}A_0(\tau_{\Delta^-}) + \frac{4(\lambda^1_{H\Delta} + \lambda^2_{H\Delta})}{m^2_{\Delta^{--}}}A_0(\tau_{\Delta^{--}})\}|^2 \quad (17)$$

$$R_{Z\gamma} = |1 - \frac{2v}{A^{Z\gamma}_{SM}}\{\frac{g_{Z\Delta^-\Delta^-}(\lambda^1_{H\Delta} + \frac{1}{2}\lambda^2_{H\Delta})}{m^2_{\Delta^-}}A_0(z_{\Delta^-}, \lambda_{\Delta^-}) + \frac{2g_{Z\Delta^{--}\Delta^{--}}(\lambda^1_{H\Delta} + \lambda^2_{H\Delta})}{m^2_{\Delta^{--}}}A_0(z_{\Delta^{--}}, \lambda_{\Delta^{--}})\}|^2 \tag{20}$$

where $z_i = 4m_i^2/m_h^2$, $\lambda_i \equiv 4m_i^2/m_Z^2$ and $g_{Z\Delta\Delta} \equiv (T^3_\Delta - Q_\Delta s_W^2)/s_W c_W$. $A^{Z\gamma}_{SM}$ comes from SM W boson and top quark contributions and A_0 comes from new charged scalars in this model. They are given by

$$A_{SM} = \frac{2}{v}\Big[\cot\theta_W A_1(z_W, \lambda_W) + N_c\frac{2Q_t(T^t_3 - 2Q_t s_W^2)}{s_W c_W}A_{1/2}(z_t, \lambda_t)\Big],$$
$$A_0(x, y) = I_1(x, y),$$
$$A_{1/2}(x, y) = I_1(x, y) - I_2(x, y),$$
$$A_1(x, y) = 4(3 - \tan^2\theta_W)I_2(x, y) + [(1 + 2x^{-1})\tan^2\theta_W - (5 + 2x^{-1})]I_1(x, y),$$

where T^t_3 is the third component of isospin of top quark, and I_1, I_2 are given by

$$I_1(x, y) = \frac{xy}{2(x-y)} + \frac{x^2y^2}{2(x-y)^2}[f(x^{-1}) - f(y^{-1})] + \frac{x^2y}{(x-y)^2}[g(x^{-1}) - g(y^{-1})],$$
$$I_2(x, y) = -\frac{xy}{2(x-y)}[f(x^{-1}) - f(y^{-1})],$$
$$g(x) = \sqrt{x^{-1} - 1}\arcsin\sqrt{x}.$$

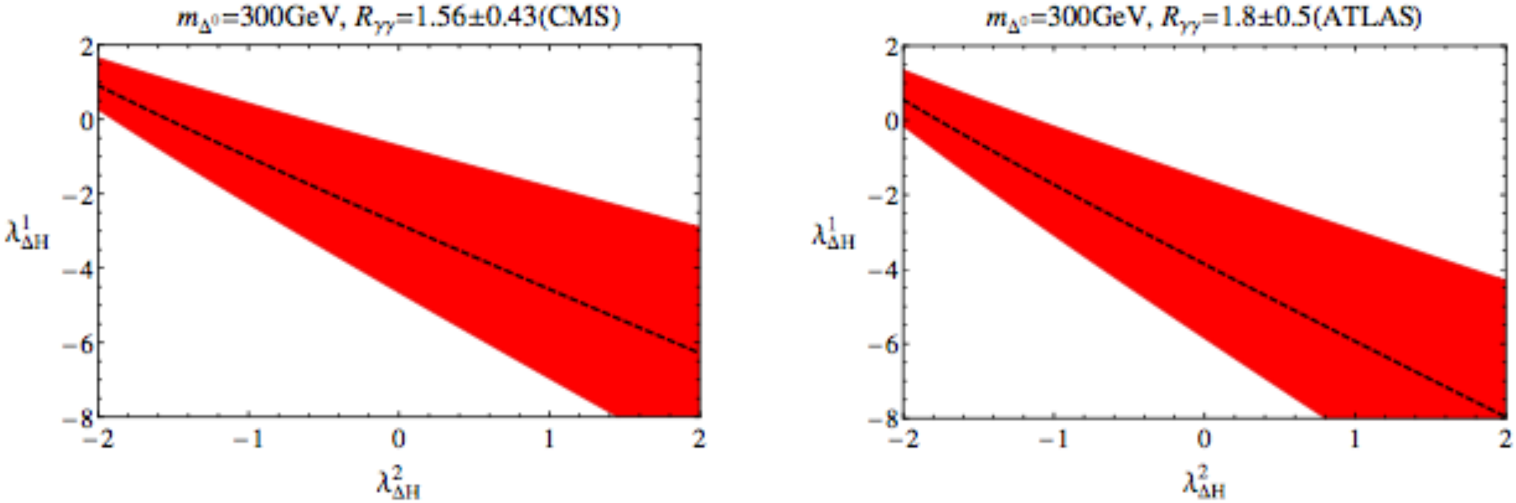

FIG. 5: Constraints on $\lambda^1_{H\Delta}$ and $\lambda^2_{H\Delta}$ with $m_{\Delta^0} = 300$GeV.

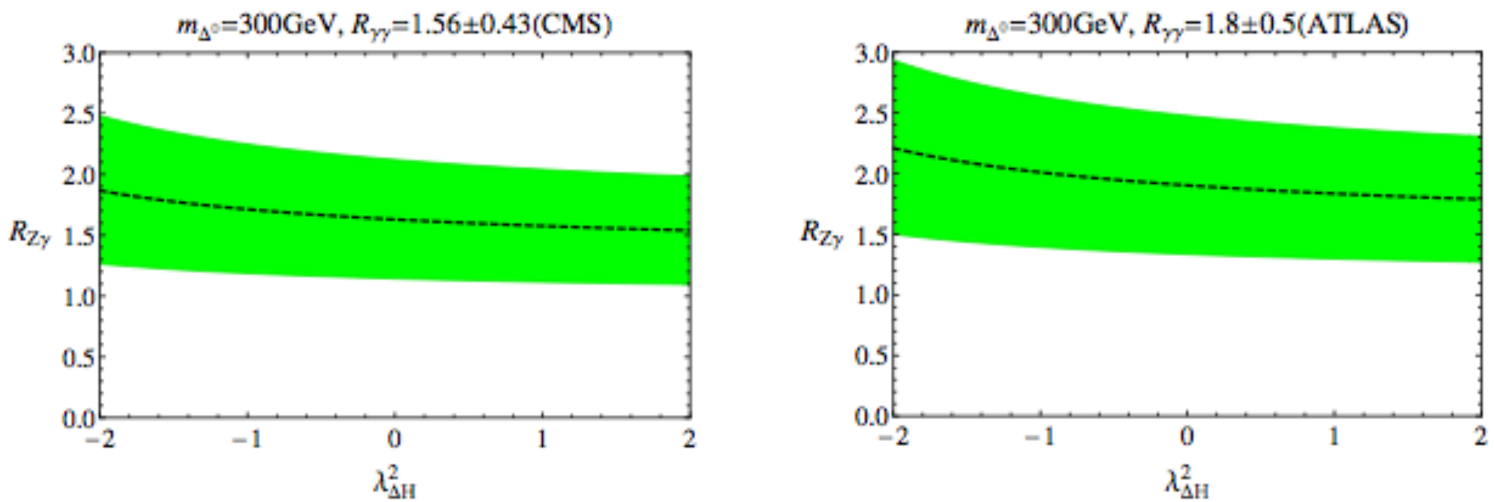

FIG. 7: Scaling factor for $h \to Z\gamma$ with the same parameters for $h \to \gamma\gamma$.

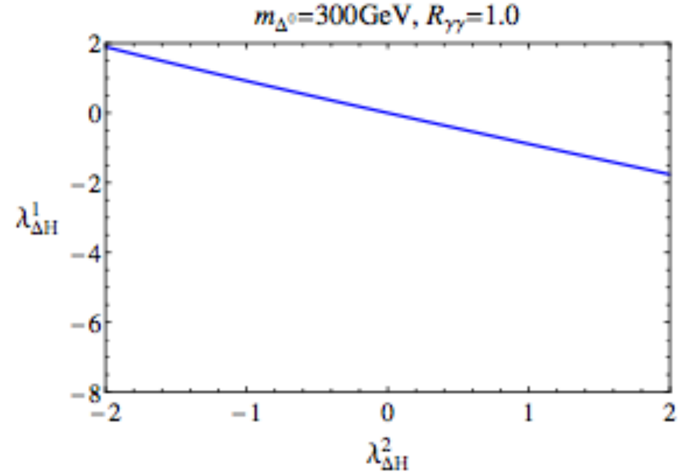

FIG. 6: Constraints on $\lambda^1_{H\Delta}$ and $\lambda^2_{H\Delta}$ with $R_{\gamma\gamma} = 1$ for $m_{\Delta^0} = 300$GeV.

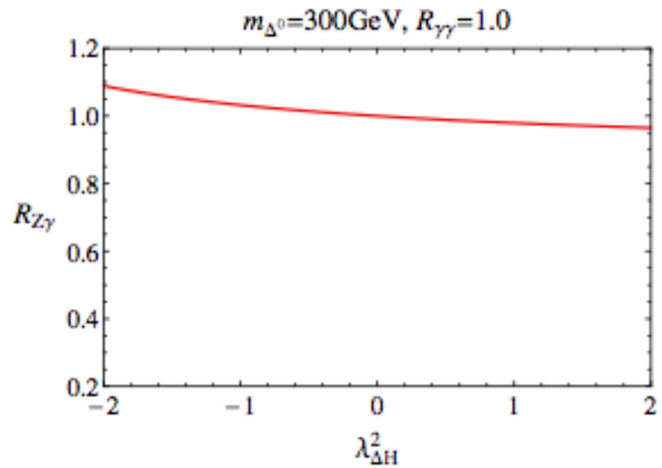

FIG. 8: Scaling factor for $h \to Z\gamma$ with the same parameters for $R_{\gamma\gamma} = 1$.

Final γ angular distribution determine h spin
arXiv:1302.6302

In the γγ CM frame
In the SM

$$\frac{1}{\sigma(s)_{0,\gamma\gamma}} \frac{d\sigma(s)_{0,\gamma\gamma}}{d\cos\theta} = 1\,.$$

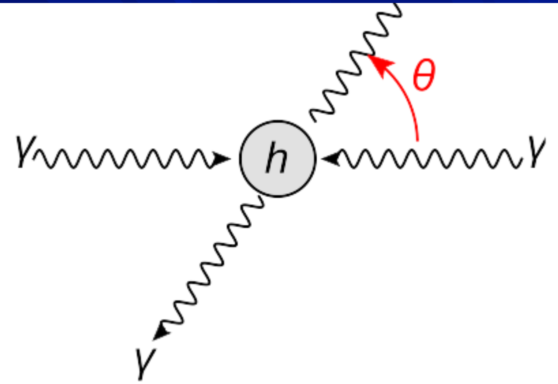

FIG. 3: The angle θ of a final photon in $\gamma\gamma \to \gamma\gamma$.

In the e^+e^- CM frame (laboratory frame), collision of the two photons is not in the $\gamma\gamma$ CM frame and therefore the distribution of the photons is not the same as that predicted by eq. (9). In the laboratory frame, depending on the values of x_1 and x_2, the two photons may have different energy. The h produced will be boosted to the direction of the photon with a larger x_i. The angle θ when seeing from laboratory frame will be changed to θ_L. The relation between θ and θ_L can be easily shown to be

$$\cos\theta = \frac{\cos\theta_L + \beta}{\beta\cos\theta_L + 1}\,,\quad \frac{d\cos\theta}{d\cos\theta_L} = \frac{1-\beta^2}{(\beta\cos\theta_L + 1)^2}\,,\quad \beta = \frac{x_1 - x_2}{x_1 + x_2}\,. \qquad (10)$$

An interesting observable

$$A(0,\theta_L) = \frac{1}{\sigma(s)^L_{0,\gamma\gamma}} \int_{x_{min}}^{x_{max}} dx_1 \int_{x_{min}}^{x_{max}} dx_2 F(x_1) F(x_2) \frac{d\sigma(s)_{0,\gamma\gamma}}{d\cos\theta}$$

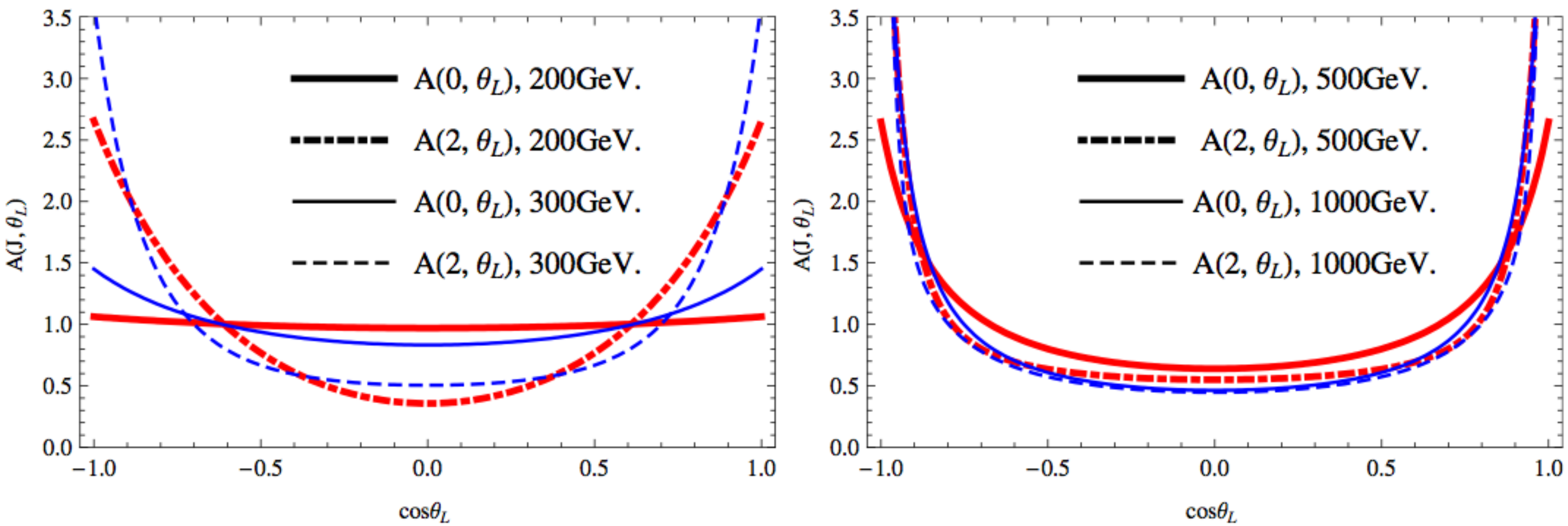

FIG. 4: Angular distribution $A(J=0,2,\gamma\gamma)$ in $\gamma\gamma \to h \to \gamma\gamma$

What if h has spin 2

$$M(2,\gamma\gamma) = \frac{\kappa}{2}[(k_1 \cdot k_2)C_{\mu\nu,\varrho\sigma} + D_{\mu\nu,\varrho\sigma}(k_1,k_2)]\varepsilon^{\rho *}(k_1)\varepsilon^{\sigma *}(k_2)\epsilon^{\mu\nu *} \ ,$$

$$C_{\mu\nu,\varrho\sigma} = \eta_{\mu\varrho}\eta_{\nu\sigma} + \eta_{\mu\sigma}\eta_{\nu\rho} - \eta_{\mu\nu}\eta_{\rho\sigma} \ ,$$

$$D_{\mu\nu,\varrho\sigma}(k_1,k_2) = \eta_{\mu\nu}k_{1\sigma}k_{2\rho} - [\eta_{\mu\sigma}k_{1\nu}k_{2\rho} + \eta_{\mu\rho}k_{1\sigma}k_{2\nu} - \eta_{\rho\sigma}k_{1\mu}k_{2\nu} + (\mu \leftrightarrow \nu)] \ .$$

$$\frac{d\sigma(s)_{2,\gamma\gamma}}{d\cos\theta} = \frac{25\pi^2}{2m_h}(\cos^4\theta + 6\cos^2\theta + 1)\Gamma_{2,\gamma\gamma}B_{2,\gamma\gamma}\delta(s - m_h^2) \ ,$$

$$\Gamma_{2,\gamma\gamma} = \frac{\kappa^2 m_h^3}{320\pi} \ .$$

Different angular distribution compared with spin 0

In the lab frame, also different!

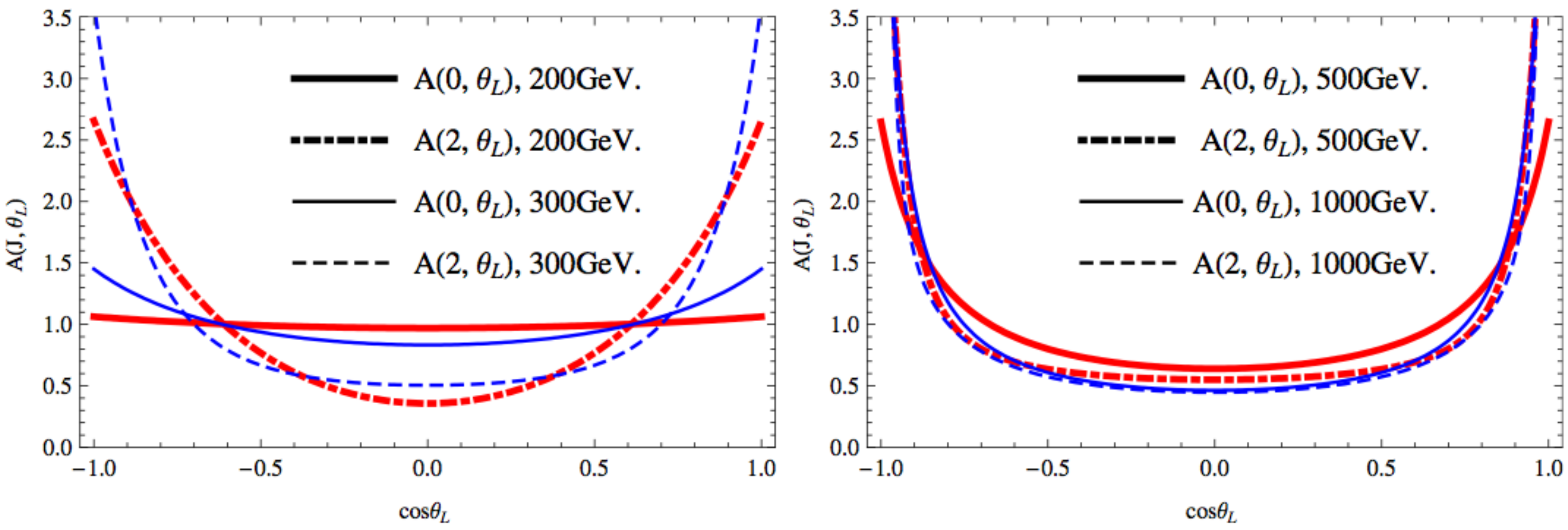

FIG. 4: Angular distribution $A(J = 0, 2, \gamma\gamma)$ in $\gamma\gamma \to h \to \gamma\gamma$

Things under Studying

Non-resonant background, non-resonant contributions

Polarized γγ beams to study more properties of h boson, CP property of h…

Other Higgs decay modes, choose a optimal mode, best signal/bacgrund ratio, may be h to b anti-b.