Off-shell Higgs effects ~~(propagation)~~ of a classically scale invariant model in e^+e^- processes ~~(ee->Ztt)~~

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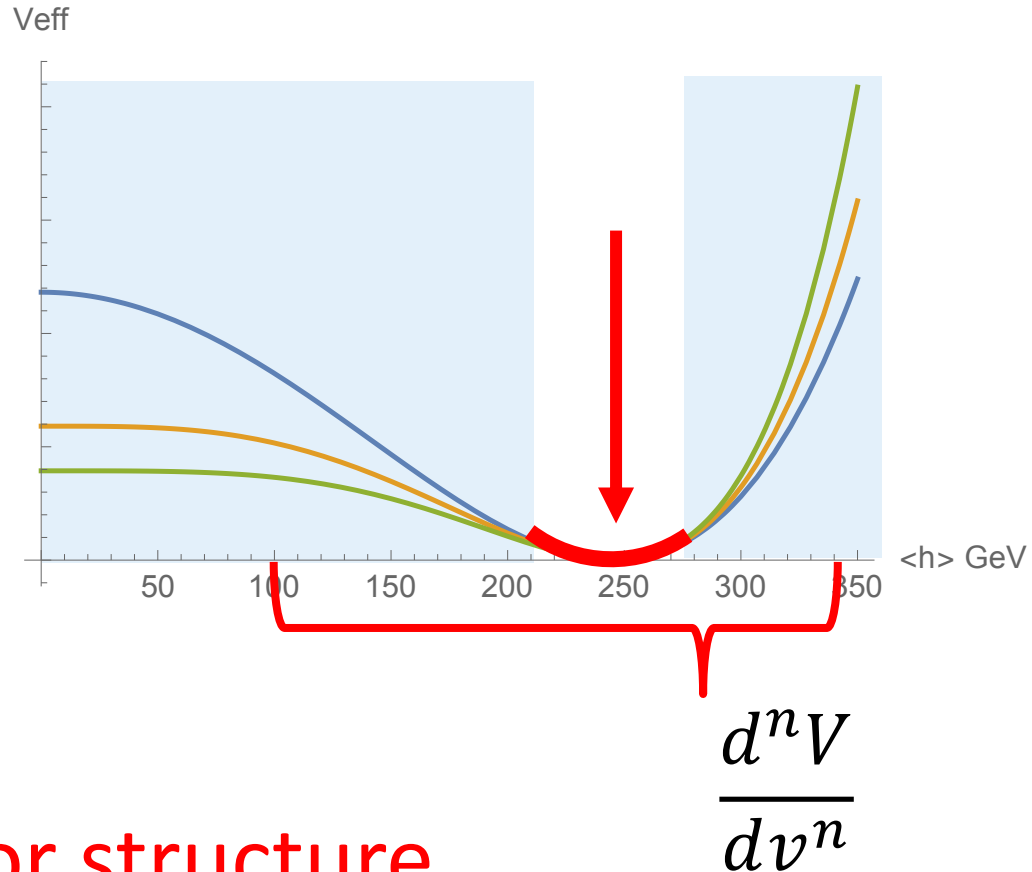
Higgs and vacuum structure

After Higgs boson discovery, we know

$$\text{VEV} \leftrightarrow 0 = \frac{dV}{dv} \qquad m_h^2 \leftrightarrow \frac{d^2V}{dv^2}$$

Global Shape of pot. is unknown

Higgs self interaction $\lambda_{hhh} \leftrightarrow \frac{d^3V}{dv^3}$



We don't know Higgs sector structure.

Classically Scale Invariant (CSI)-model

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}\ \mu^2 \to 0} + \frac{1}{2}\left(\partial_\mu \vec{S}\right)^2 - \lambda_{\mathrm{HS}}\left(H^\dagger H\right)\left(\vec{S}\cdot\vec{S}\right) - \frac{\lambda_{\mathrm{S}}}{4}\left(\vec{S}\cdot\vec{S}\right)^2$$

Foot et.al.,2007; Endo,Sumino 2015

$\mu^2 H^\dagger H - \lambda_{\mathrm{H}}\left(H^\dagger H\right)^2$

SM singlet scalar w/ $O(N)$ sym.

Higgs portal coupling

- EWSB → Radiative Breaking (tree + 1 loop at Leading Order(LO))
- Log-like potential (non-SM-like) → Large deviation
- Parameters $\lambda_{\mathrm{H,HS}}$ are fixed at LO.

Order counting: ξ-expansion

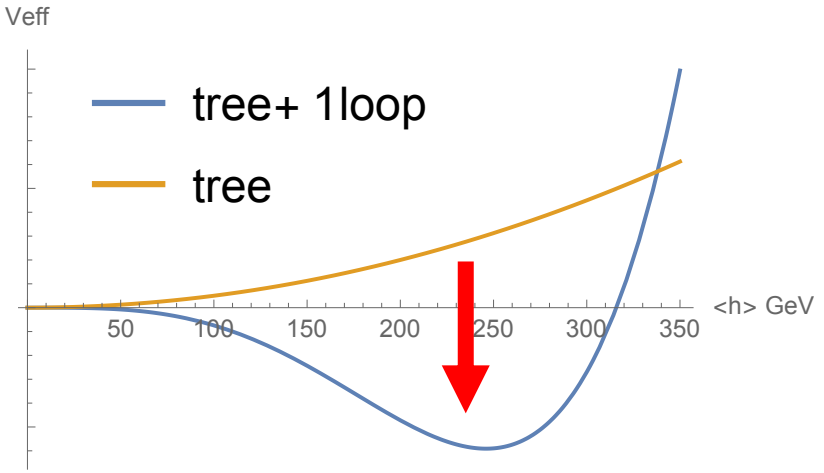
The eff. pot. has VEV($\neq 0$)

at tree + (parts of) 1 loop order.

$$0 = \frac{d}{d\varphi}V = \varphi^3\left[\cancel{-\frac{\mu^2}{\varphi^2}} + \lambda_{\mathrm{H}} - \frac{\lambda_{\mathrm{HS}}^2}{(4\pi)^2}(\dots) + \frac{3y_t^4}{(4\pi)^2}(\dots) + \cdots\right]$$

$$= 0$$

$$\lambda_{\mathrm{H}} \to \xi^2\lambda_{\mathrm{H}}, \lambda_{\mathrm{HS}} \to \xi\lambda_{\mathrm{HS}}, y_t \to \xi^{1/2}y_t, \text{others} \to O(\xi^2)$$



LO (ξ-expansion) $\leftrightarrow$ tree + singlet loop + top loop

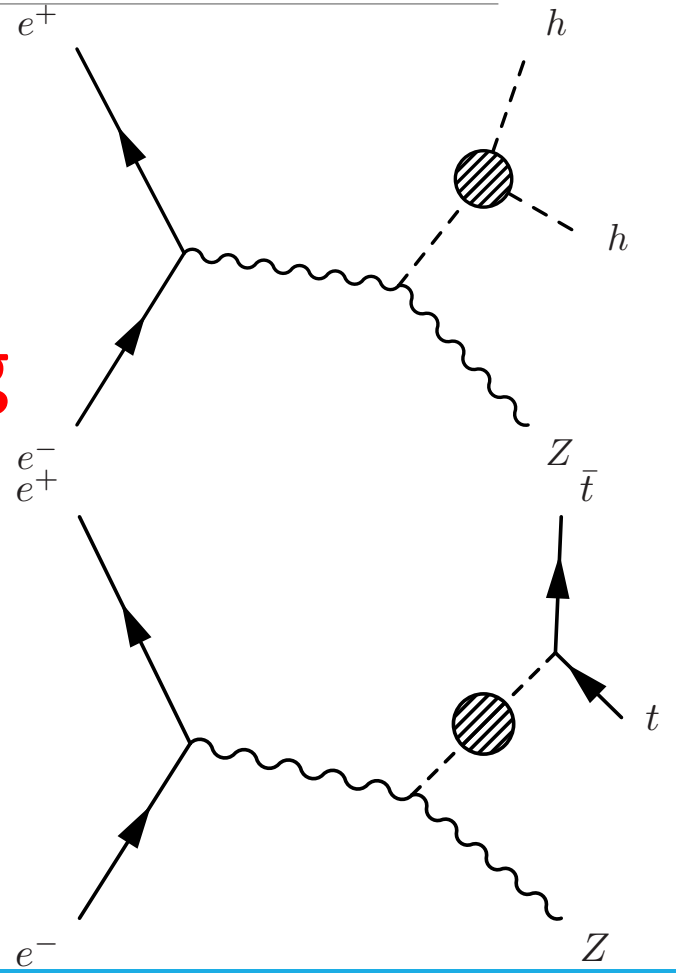
Observables in Higgs portal model

Additional Scalar with SM charge or mixing

-> See EW coupling

In CSI model, S has no SM charge and mixing

- EW coupling at $\mathrm{N^nLO}$
- Off-shell effects of h
  - Higgs self coupling $h^* \to hh$
  - Off-shell Higgs propagation $h^* \to t\bar{t}$

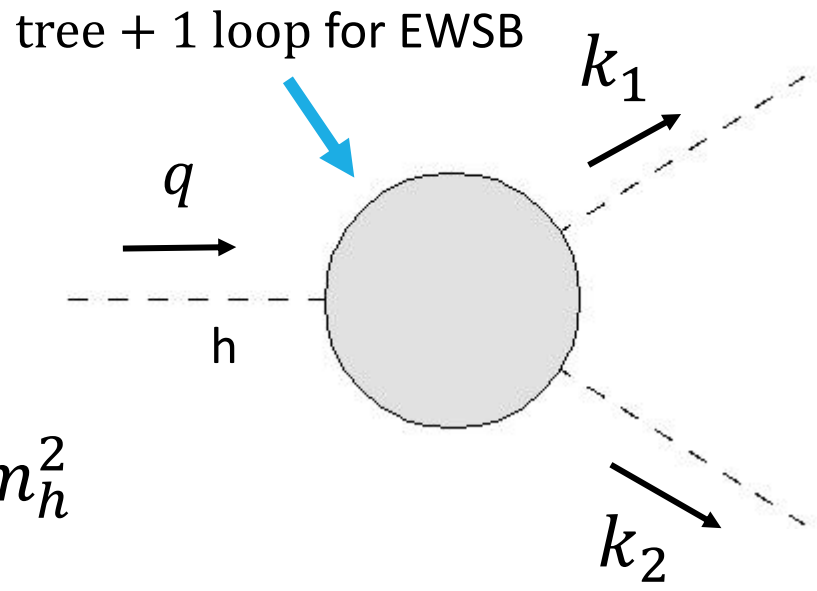


Higgs triple coupling of CSI-model

From the effective potential, the Higgs triple coupling is

$$\lambda_{hhh}^{\mathrm{CSI}} = \frac{1}{v}\frac{d^3V}{dv^3} = \frac{5m_h^2}{v^2} = \frac{5}{3}\lambda_{hhh}^{\mathrm{SM}} \rightarrow +67\%$$

Chway, et.al. 2013; Endo,Sumino 2015;
Hashino,Kanemura,Orikasa,2015



$$\lambda_{hhh} = \frac{1}{v}\frac{d^3V}{dv^3} + f(q^2)\ ,\ q^2 \sim O(m_h^2),\ \ k_{1,2}^2 = m_h^2$$

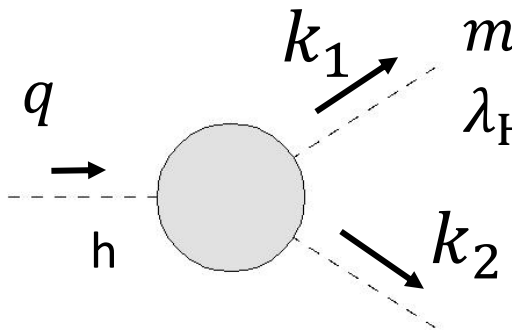
can be same order (1 loop)

We have to compare them in physical process.

λ_{hhh} w/ momentum dependence

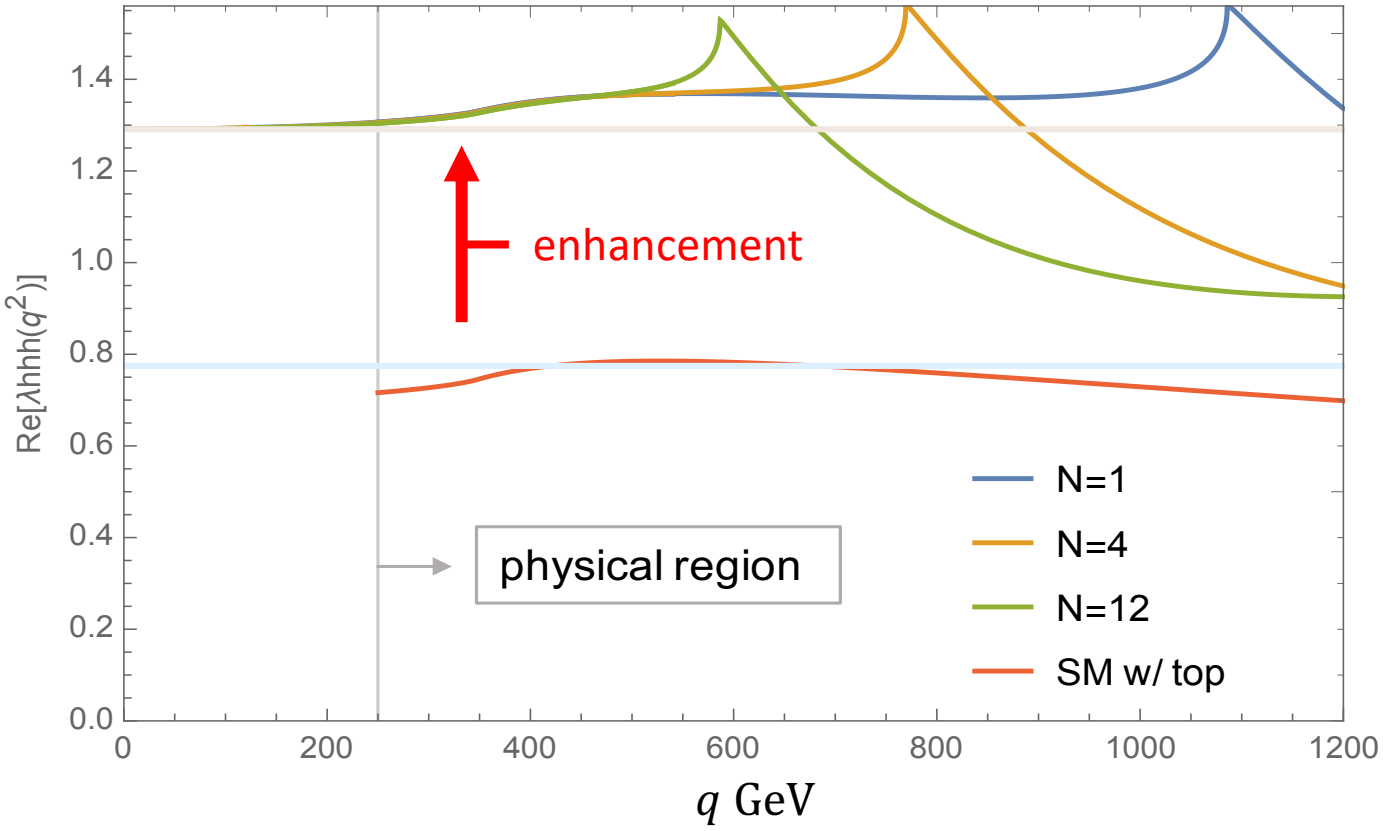
$v = 246$ GeV
$m_h = 125$ GeV
$m_t = 173$ GeV

N	m_s GeV	λ_{HS}
1	543	4.87
4	385	2.45
12	293	1.42



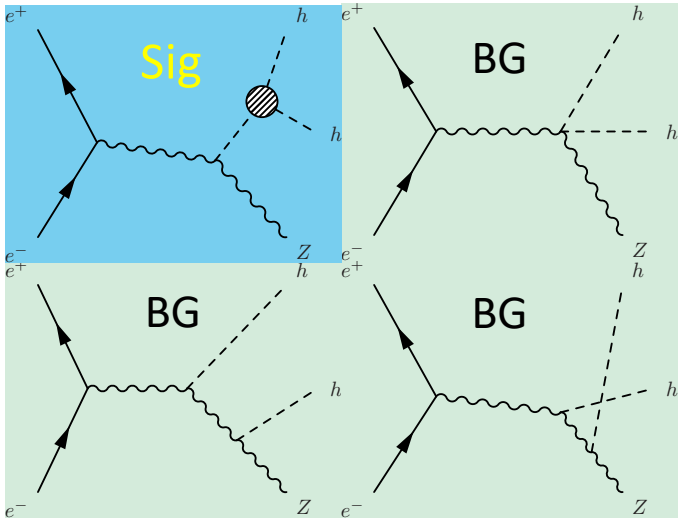
$m_s = \lambda_{\mathrm{HS}}^{1/2} v$
$\lambda_{\mathrm{H}} = \lambda_{\mathrm{H}}(\lambda_{\mathrm{HS}}, m_t, v; \mu)$

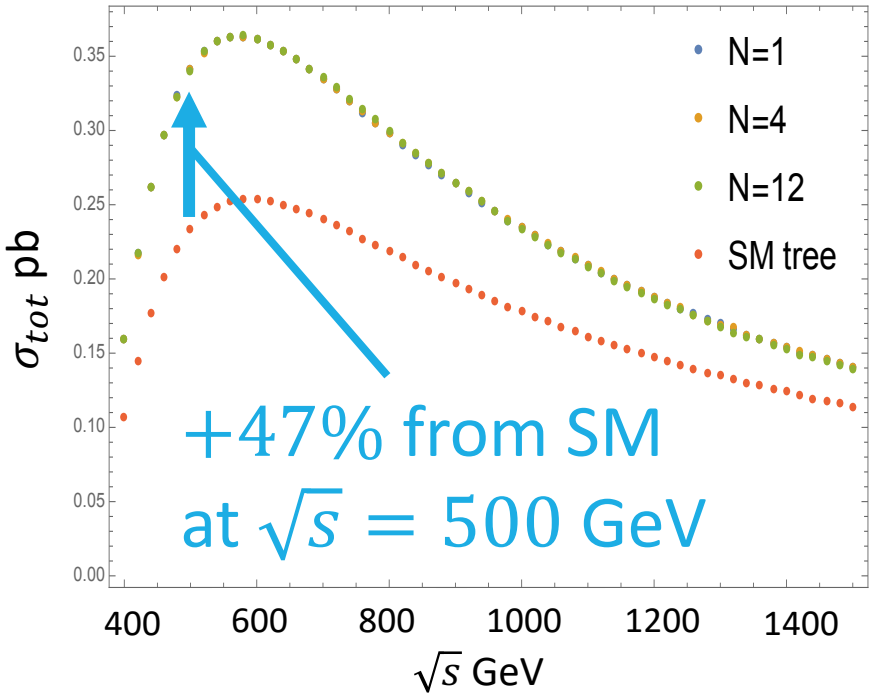
$\lambda_{hhh}(q^2)$ =tree+(singlet, top loop) at LO $O(\xi^2)$

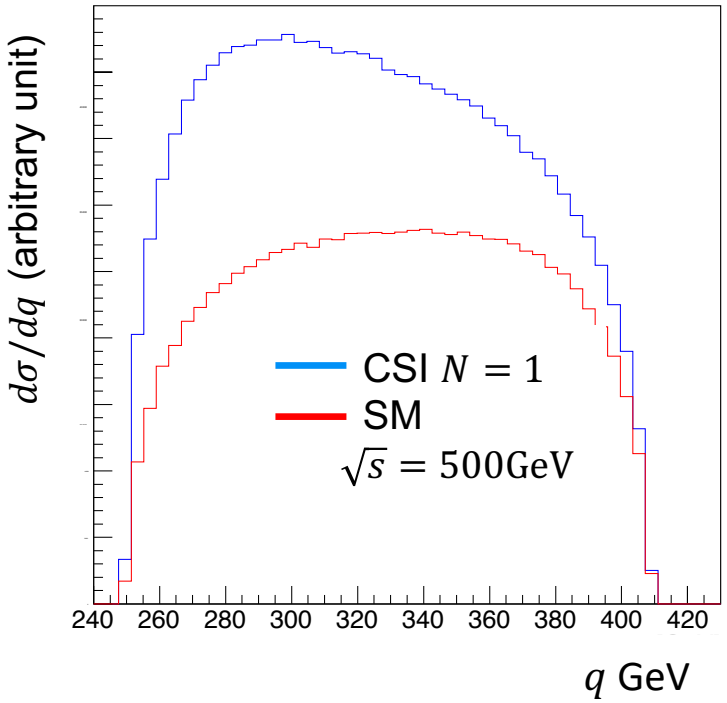


$e^+e^- \to Zhh$ total and diff. cross section

$P(e^+, e^-) = (0.3, -0.8)$





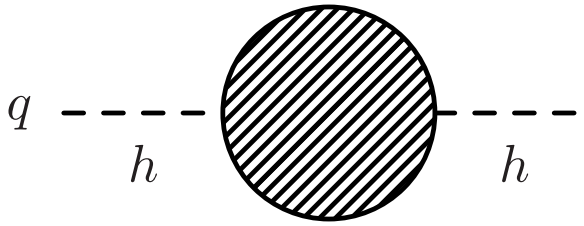


$\lambda_{hhh}^{\mathrm{CSI}}$ can be tested!

Integrated Luminosity to discover 5σ/exclude 3σ
$710/260\mathrm{fb}^{-1}$ Based on LC-REP-2013-003, $1\sigma \simeq N_{sig}/\sqrt{N_{BG}}$

Off-shell Higgs propagation

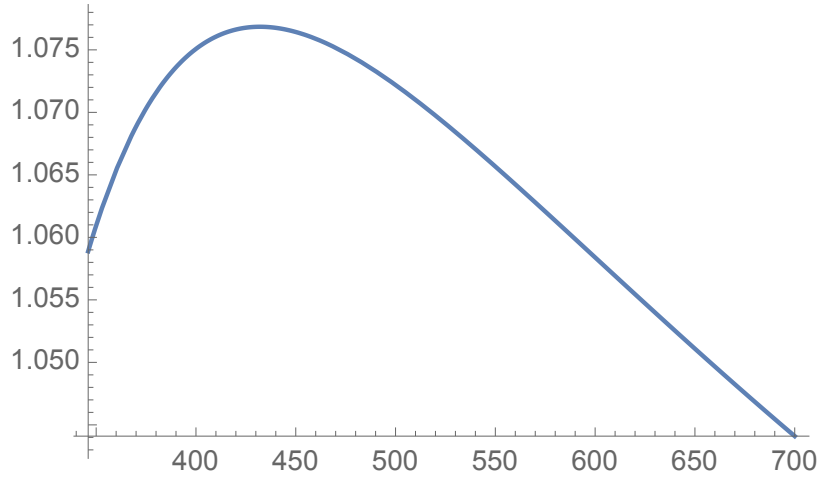
In CSI model, off-shell effect exists at LO



$$= m_h^2 + \Sigma(q^2)$$

1 loop contribution

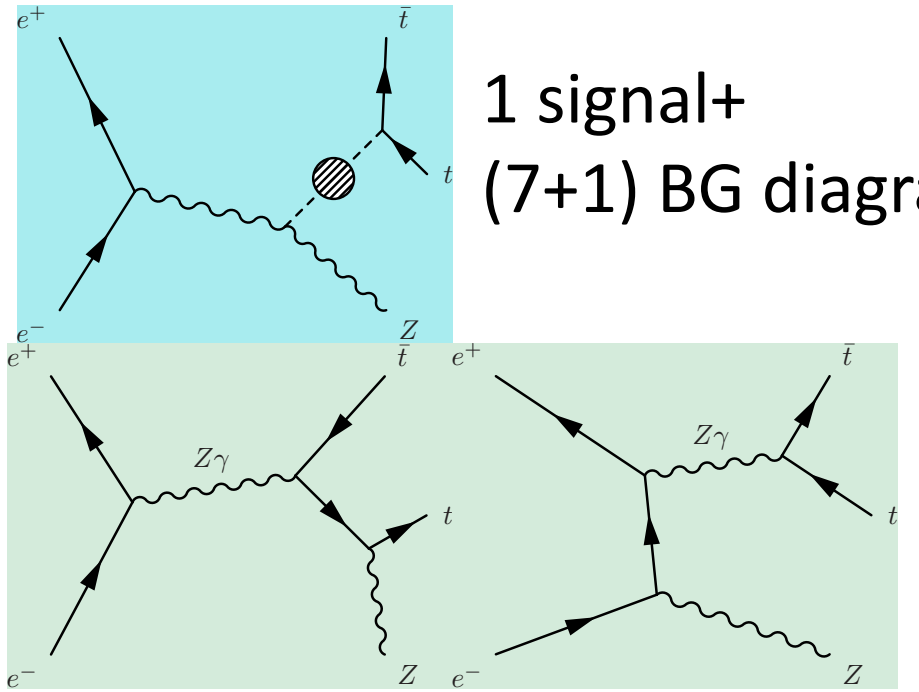
$$\left| \frac{q^2 - m_h^2}{q^2 - m_h^2 - \Sigma} \right|$$



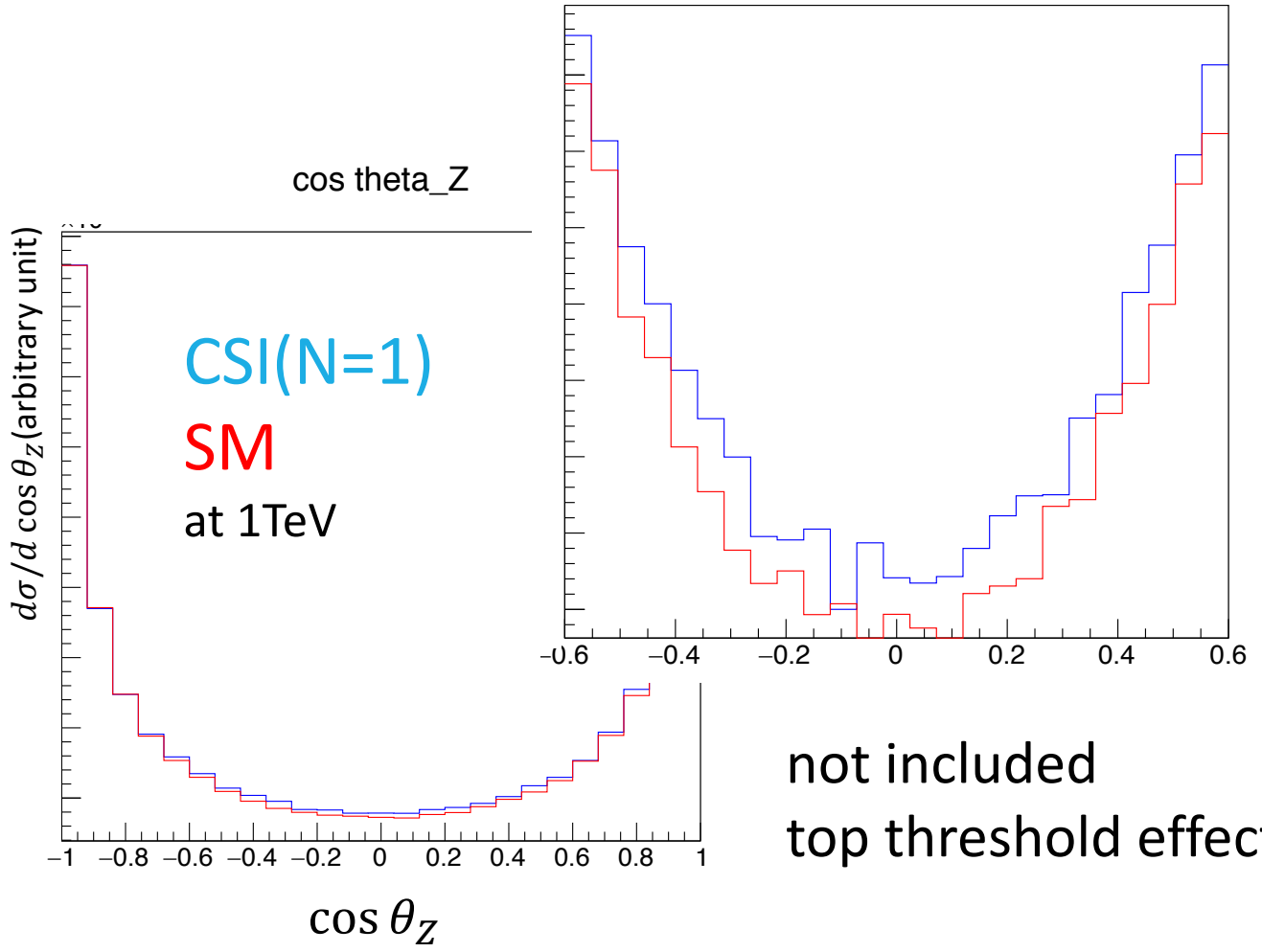
$\Sigma(q^2) \neq 0$ and can be measurable at $q^2 \gg m_h^2$

$e^+e^- \to Zt\bar{t}$

$P(e^+, e^-) = (0.3, -0.8)$



1 signal+
(7+1) BG diagrams



not included
top threshold effect

$\sigma^{e^+e^-\to Zt\bar{t}}_{|\cos\theta_Z|<0.6} = 3.922$fb, +3.4% from SM tree at 1TeV

Summary

- CSI-model breaks EW sym. by radiatively and has large deviation in physical processes.
- $\sigma_{\mathrm{tot}}^{e^+e^-\to Zhh}$ is $+47\%$ from SM at $\sqrt{s} = 500$ GeV
- $\sigma_{\mathrm{tot}}^{e^+e^-\to Zt\bar{t}}$ has $O(1)\%$ enhancement at $\sqrt{s} = 1$ TeV w/cut
- CSI model can be tested in future ee-collider.