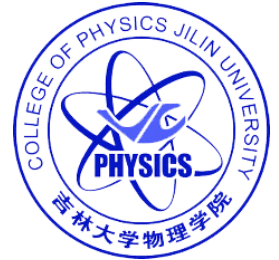


Probing a dynamical scalegenesis via enhanced diHiggs signatures



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references: R. Ouyang (NICPB, Talinn), and S.M., 1809.10009 [hep-ph]
to be published in PRD

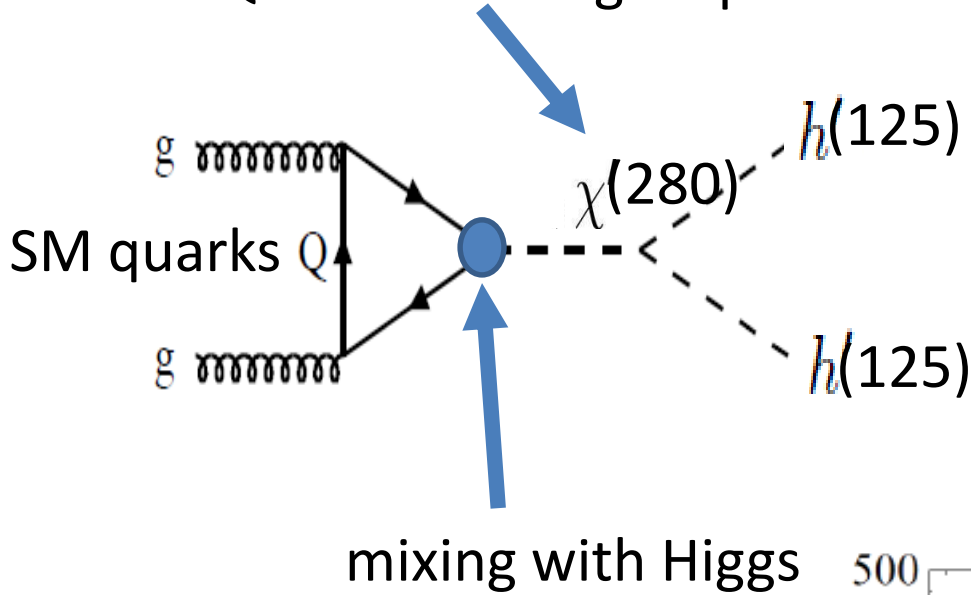
第十四届TeV物理工作组学术研讨会 (14th workshop on TeV Physics)

19-22 April 2019

@ 南京师范大学 (Nanjing Normal University)

Quick view of pheno. consequence

Hidden QCD dilaton: signal particle for origin of mass

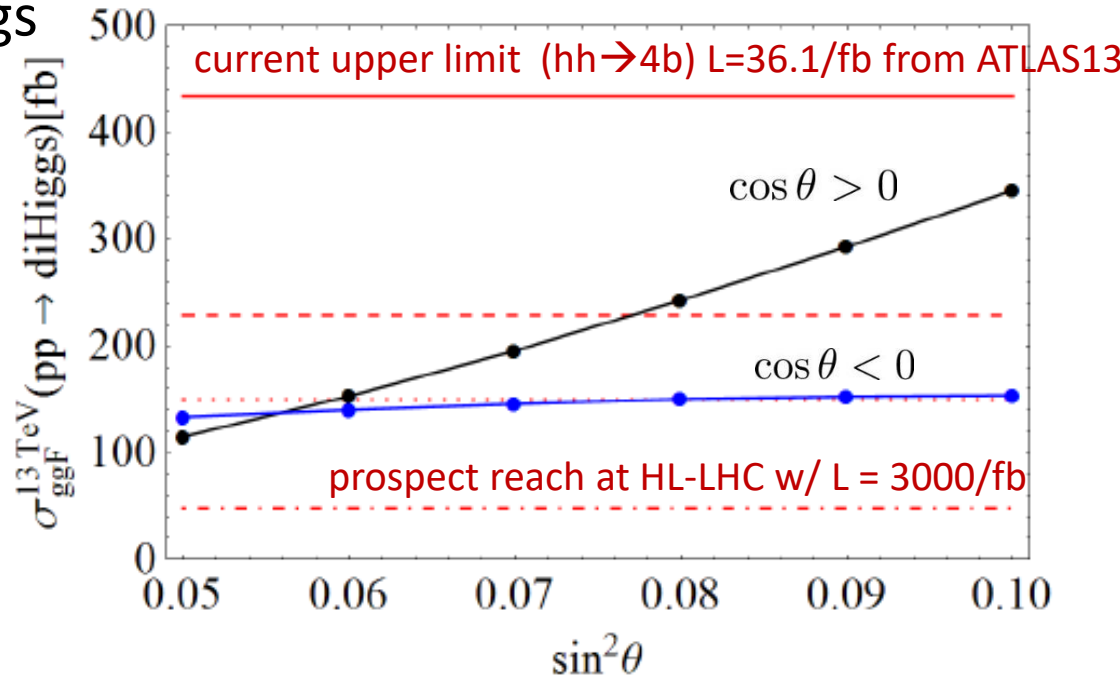


e.g. at the current edge

$$\sin^2 \tilde{\theta} = 0.1.$$

$$\sigma_{ggF}^{13\text{TeV}}(pp \rightarrow h'h') \Big|_{\sin^2 \theta = 0.1} \simeq 346 \text{ fb},$$

About 10 times larger than SM prediction $\sim 34 \text{ fb}$



0. Introduction

☆ Discovery of Higgs boson in 2012

--- last piece of particles predicted in SM

--- very successful SM pheno. so far

--- **but, NOT** the end of the story!

still lots of stuff left needed to account for

{ e.g. neutrino masses (mixing),
dark matter, baryon asymmetry, etc

No clear BSM signal seen yet,
though...
(2012 was already 7 years ago....)

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☆ In particular,

SM involves unsatisfactory stuff on theoretical ground:

--- **origin of mass** is given “**by hand**”

--- **why $m_H^2 < 0$ (dynamical origin?) and $O(100 \text{ GeV})^2$?**
(related to gauge hierarchy problem)

☆ One brave idea to access the origin of mass

= **scale symmetry** (classical scale-inv.(CSI))

Higgs potential: $V = \lambda_H (H^\dagger H)^2 + m_H^2 (H^\dagger H)$

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☆ Then, how to generate “scales”, realize EWSB?

→ **dimensional transmutation** That’s what we call “**scalegenesis**”

☆ “Dynamical scalegenesis” -- one candidate: hsQCD

Extension w/ Higgs portal term $\tilde{V} = \kappa |\phi|^2 (H^\dagger H)$

* $\kappa < O(1)$, and < 0

* Φ = a SM singlet scalar, strongly coupled to hidden/dark QCD

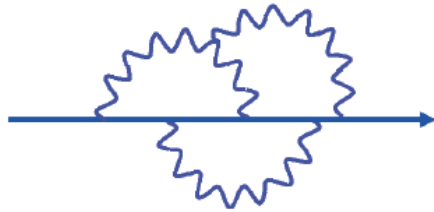
$$\langle \phi^\dagger \phi \rangle \simeq \Lambda_{\text{dQCD}}^2 \quad \longrightarrow \quad V = -|\kappa| \Lambda_{\text{dQCD}}^2 (H^\dagger H)$$

below the dynamical scale, hidden scalar QCD
generates scalar condensation

*F.Wilczek (2008); T.Hur, et al(2011);
M.Holthausen, et al (2013);
J.Kubo, et al(2014); (2015); (2016); (2017); (2018);
R.Ouyang and S.M, (2018)*

BTW.... **what are characteristic features for sQCD dynamics??**

☆ nonperturbative analyses for sQCD with $N_c=3$ & $N_s=1$



Refs.

-- Lattice simulations

H. Iida, et al (2006); (2007); (2008)

-- Schwinger-Dyson analyses

(on diquark mass generation in fermionic QCD)

S. Imai, et al (2014); (2014)

Dynamical mass generation w/o chiral symmetry

* Colored-scalar quarks get the dynamical mass by **nonper. gluon-dressing effects** i.e. **gluon condensate (NP scale anomaly)**

* The estimated size of $m_{\text{dyn}} = \mathcal{O}(\Lambda_{\text{sQCD}})$

as well as mass of the scalar meson bound state $\phi^\dagger \phi$ due to the sizable **gluon condensate** effect (**NP scale anomaly**)

So, NP gluonic scale anomaly is essential for the mass generation!

$$\langle T^\mu_\mu \rangle = \frac{\beta_{\text{sQCD}}(\alpha_{\text{sQCD}})}{4\alpha_{\text{sQCD}}} \langle G^2_{\mu\nu} \rangle$$

disregarded so far in literature...

☆ In this talk, it is shown that

the **significant impact** of the **gluonic-scale anomaly** in s-hQCD
on the Higgs portal physics, **accessible at LHC**

1. Leading order scale symmetry

To access the LHC pheno.,

work in an effective $\phi^\dagger\phi$ meson description

★ Leading order scale symmetry (LOSS)

* Lesson from fermionic QCD

Y.L.Li, et al (2017)

* scale-inv. linear sigma model with the **SI explicitly broken only by the “dilaton” potential**

* dilaton = χ , w/ VEV $\langle\chi\rangle = \eta$

$$V(H, \chi) = -\lambda_{H\chi}(H^\dagger H)\chi^2 + \lambda_H(H^\dagger H)^2 + \lambda_\chi\chi^4 + \lambda_a\eta^4 \left(\frac{\chi}{\eta}\right)^{4+a}$$

breaks SI

* Trace of energy momentum tensor detects the scale-anomaly

$$T_\mu^\mu = \partial_\mu D^\mu = \delta_D \mathcal{L} = -(a \cdot \lambda_a) \cdot \eta^4 \left(\frac{\chi}{\eta}\right)^{4+a}$$

PCDC w/ anomalous dim. “a”

Since χ gets a mass by nonzero “a”

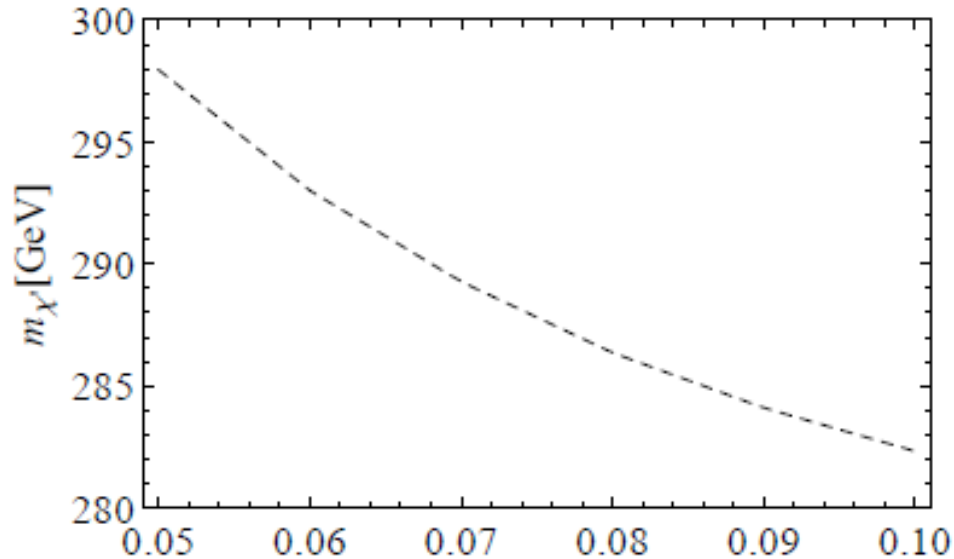
$$m_\chi^2 = (a \cdot \lambda_a)(4+a)\eta^2 \quad \longrightarrow \quad \langle T_\mu^\mu \rangle = -\frac{m_\chi^2 \eta^2}{4+a} \quad d[T_\mu^\mu] = d[(G_{\mu\nu})^2] = 4+a$$

W/ $v = 246 \text{ GeV}$, $m_{h'} = 125 \text{ GeV}$, and

$\eta = m_{\chi'}$: “simple-minded ansatz”

$a = 0.1$: typical small breaking size

Light enough dilaton w/ mass around 280 - 300 GeV

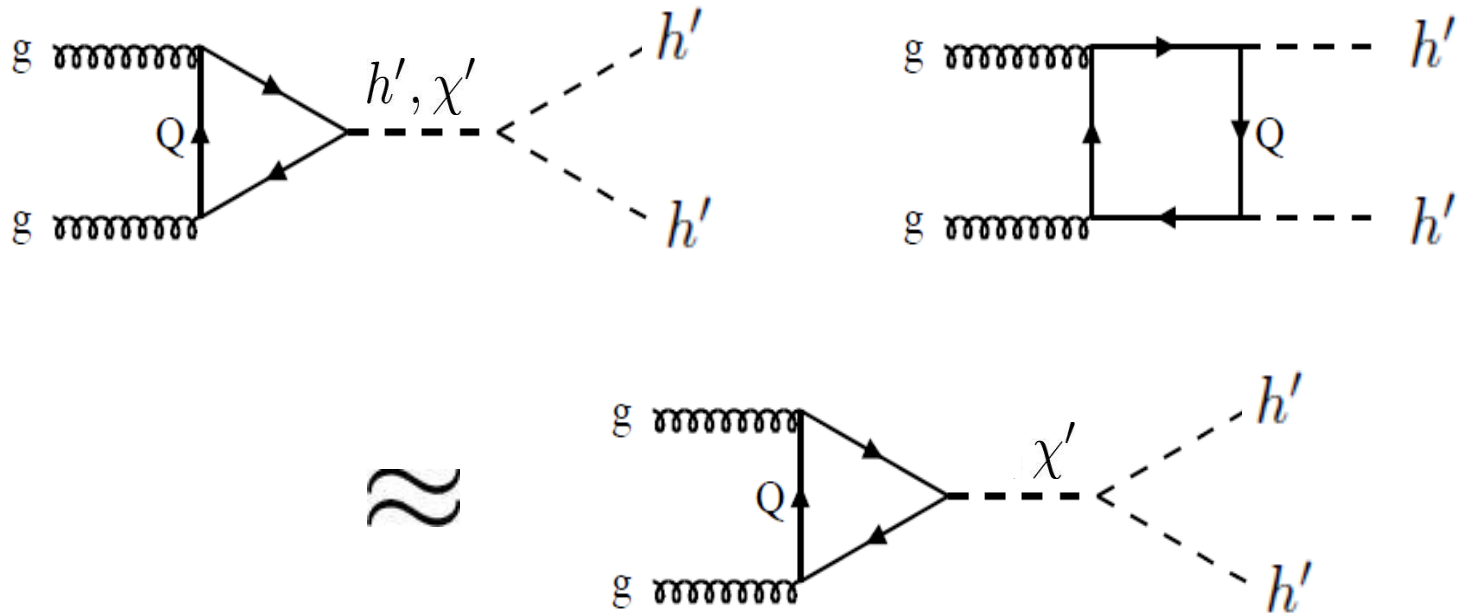


HL-LHC prospect
L=3000/fb

← $\sin^2 \theta$ →
: “mixing strength: h-chi”

current limit
L=36.1/fb

☆ LOSS predictions: **DiHiggs enhancement**



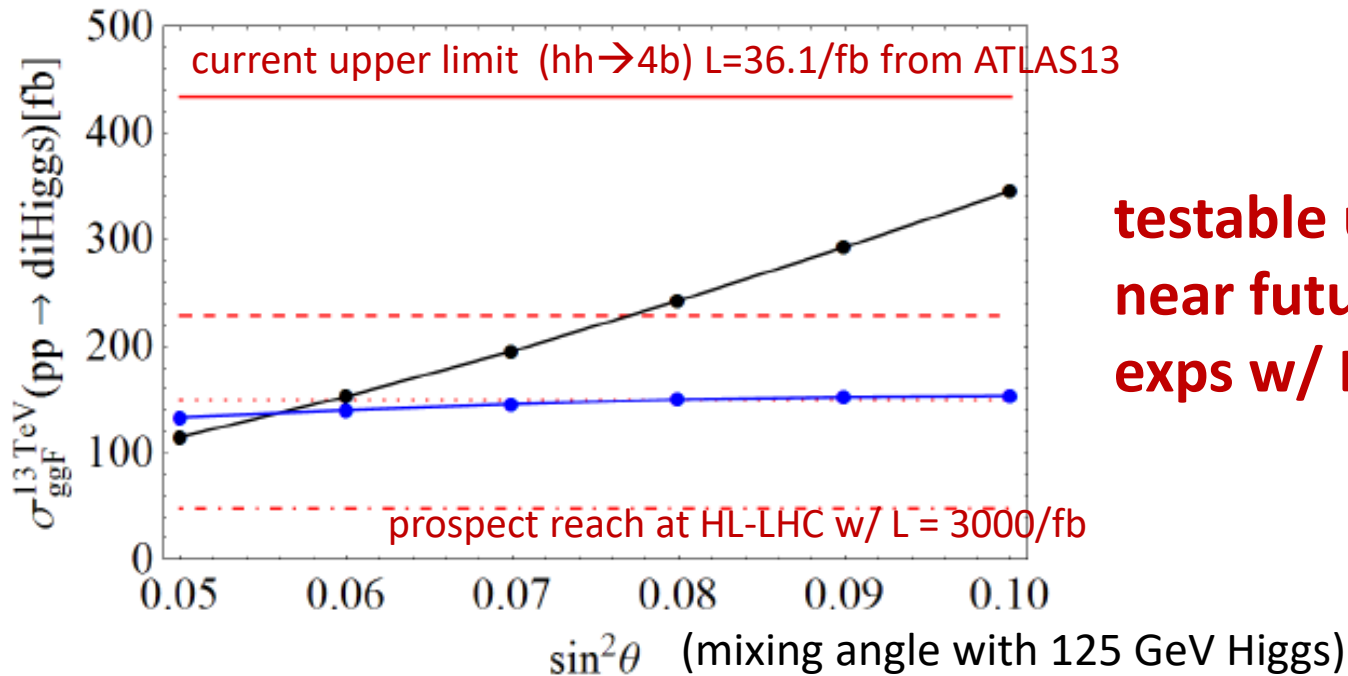
- * Sizable enhancement is expected to happen due to the **narrow on-shell dilaton production** (**$\sim 280 \text{ GeV} - 300 \text{ GeV}$**) near threshold for on-shell diHiggs production ($\sim 250 \text{ GeV}$)

(* w/ QCD-NLO included)

$\cos\theta > 0$ (black) & $\cos\theta < 0$ (blue)

$\mathcal{L}[\text{fb}^{-1}] = 36.1$ (red-solid), 130 (dashed),

300 (dotted), 3000 (dot-dashed)



**testable until
near future high lumi-
exps w/ $L \sim 300/\text{fb}$**

e.g. at the current edge

$$\sin^2 \theta = 0.1$$

$$\left. \sigma_{ggF}^{13\text{TeV}}(pp \rightarrow h'h') \right|_{\sin^2 \theta = 0.1} \simeq 346 \text{ fb}$$

**maximally
about 10 times
larger than SM prediction
($\sim 33\text{-}34 \text{ fb}$)**

2. Summary

- ☆ **Dynamical scalegenesis** gives the elegant explanation for the EW symmetry breaking, in place of the SM
 - candidate scenarios include SI-Hidden scalar QCD:
- ☆ The **LOSS** limit was analyzed, including **crucial gluonic-scale anomaly effect** into a low-energy description
 - **LOSS** predicts light enough (~ 280 GeV), narrow dilaton, at **diboson channels** at LHC
 - remarkably, gives **diHiggs enhancement** to be maximally about 10 times large compared to the SM Higgs, to be tested up until HL-LHC, **w/ significant correlation w/ deviation on Higgs coupling measurements**
- ☆ Applications to other dynamical scalegenesis scenarios easily doable, and LOSS predictions to other physics as well (in progress)

backups

★ Other merits on hsQCD

J.Kubo, et al (2015); (2016); (2017); (2018)

* Predicted hsQCD hadrons (e.g. $\phi_i^\dagger \phi_j$ mesons) = can be stable, to be DM

* Higgs portal coupling $\kappa = \text{nonzero}$, but $< O(1)$;
-- possibly strong 1st order PT;
-- could be linked to a baryo(lepto)genesis
-- sensitive to GWs detections

$$\vec{V} = \kappa |\phi|^2 (H^\dagger H)$$

So, hsQCD provides

- i) the dynamical EW scalegenesis, origin of mass
- ii) rich related phenomenological consequences accessible in future exps.

☆ LOSS predictions: a light dilaton

$$V(H, \chi) = -\lambda_{H\chi}(H^\dagger H)\chi^2 + \lambda_H(H^\dagger H)^2 + \lambda_\chi\chi^4 + \lambda_a\eta^4 \left(\frac{\chi}{\eta}\right)^{4+a}$$

mixing w/ Higgs “h” allowed

Physical χ' dilaton mass

$$\begin{aligned}\chi' &= \chi \cos \theta - h \sin \theta \\ h' &= \chi \sin \theta + h \cos \theta.\end{aligned}$$

$$\begin{aligned}m_{\chi'}^2 &= 2 \left(\frac{\cos^2 \theta}{\cos 2\theta} \lambda_{H\chi} - \frac{\sin^2 \theta}{\cos 2\theta} \lambda_H \right) \cdot v^2 \\ &\quad + 7 \left(\frac{\cos^2 \theta}{\cos 2\theta} (a \cdot \lambda_a) \frac{\lambda_H}{\lambda_{H\chi}} \right) \cdot v^2 \\ &\equiv 2 \left(\frac{\cos^2 \theta}{\cos 2\theta} \lambda_{H\chi} - \frac{\sin^2 \theta}{\cos 2\theta} \lambda_H \right) \cdot v^2 + \underline{\Delta m_{\chi'}^2}\end{aligned}$$

Take $v = 246$ GeV, $m_{h'} = 125$ GeV, and

$\eta = m_{\chi'}$: “simple-minded ansatz”

$\cos^2 \theta = 0.9$: current limit on Higgs coupling measurement

$a = 0.1$: typical small breaking size, controlling scale anomaly

$\eta \equiv m_{\chi'} \simeq 282$ GeV **as low as EW scale v**

$$\begin{aligned}\lambda_{H\chi} &\simeq 0.138, & \lambda_H &\simeq 0.182 \\ \lambda_a &\simeq 1.014, & \lambda_\chi &\simeq -0.987.\end{aligned}$$

$$\frac{\Delta m_{\chi'}^2}{m_{\chi'}^2} \simeq 0.798 \quad \text{NP scale-anomaly dominant}$$

stationary condition

$$\begin{aligned}v^2 &= \frac{\lambda_{H\chi}\eta^2}{\lambda_H} \\ \lambda_a + \lambda_\chi &= \frac{\lambda_{H\chi}^2}{4\lambda_H}.\end{aligned}$$

☆ LOSS predictions: effect on Higgs trilinear coupling

$$\begin{aligned}\lambda_{h'h'h'} &= -4 \sin^3 \theta \left[\lambda_\chi + \left(1 + \frac{13}{12} a \right) \lambda_a \right] \eta \\ &+ \cos^3 \theta \lambda_H v \\ &- \sin \theta \cos \theta \lambda_{H\chi} (v \sin \theta - \eta \cos \theta)\end{aligned}$$

Take $v = 246$ GeV, $m_{h'} = 125$ GeV, and

$\eta = m_{\chi'}$: “simple-minded ansatz”

$\cos^2 \theta = 0.9$: current limit on Higgs
coupling measurement

$a = 0.1$: typical small breaking size

$$\begin{aligned}\frac{\lambda_{h'h'h'}}{v} \Big|_{\text{LOSS}} &\simeq 1.01 \text{ for } \cos \theta > 0 \\ &\simeq -0.702 \text{ for } \cos \theta < 0.\end{aligned}$$

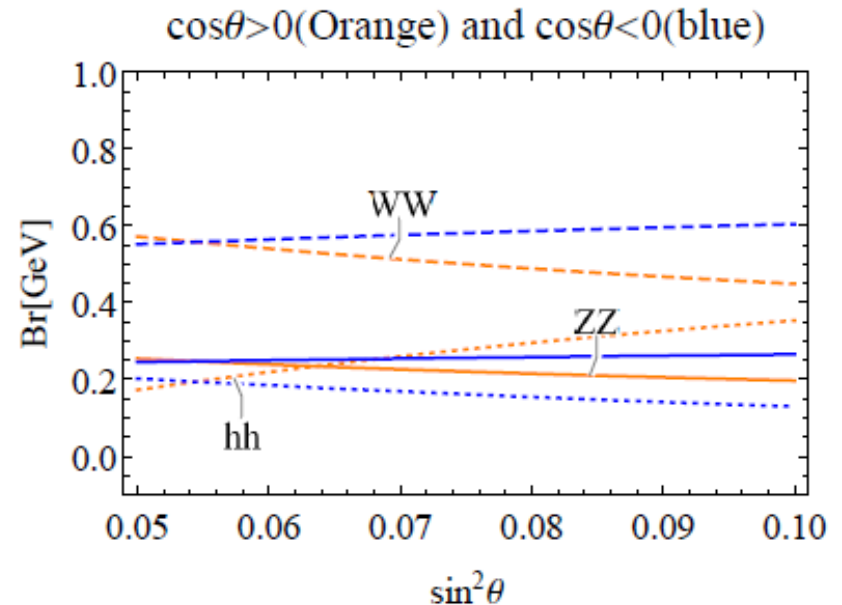
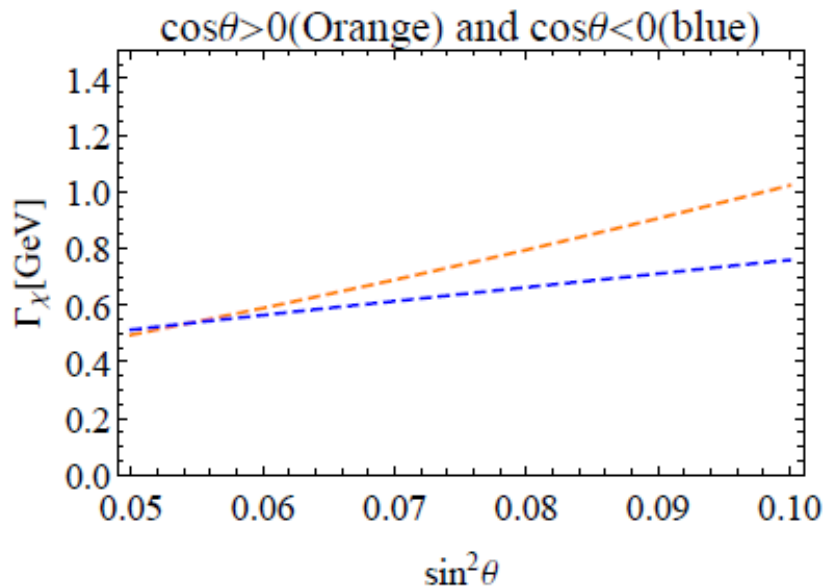
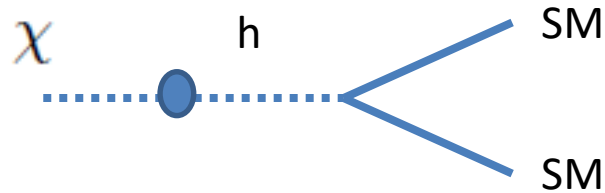
Compared to SM prediction

$$\frac{\lambda_{hhh}}{v} \Big|_{\text{SM}} \simeq 0.75$$

**34% enhancement, or nearly the same,
in magnitude**

☆ LOSS predictions: dilaton decay properties

* Dilaton couples to SM **only through mixing w/ Higgs “h”**



* narrow resonance w/ width-to-mass $\sim 10^{-4} - 10^{-3}$
(around the mass 280 -300 GeV)

* predominantly decays to diboson (WW, ZZ, hh)

☆ LOSS predictions: other dilaton resonance signatures at LHC

Via ggF production

| $\sin^2 \theta$ | $\cos \theta$ | $m_{\chi'} [\text{GeV}]$ | $\sigma(\chi' \rightarrow h'h') [\text{fb}]$ | $\sigma(\chi' \rightarrow \gamma\gamma) [\text{fb}]$ | $\sigma(\chi' \rightarrow ZZ) [\text{fb}]$ | $\sigma(\chi' \rightarrow WW) [\text{fb}]$ | $\sigma(\chi' \rightarrow b\bar{b}b\bar{b}) [\text{fb}]$ |
|-----------------|---------------|--------------------------|--|--|--|--|--|
| 0.1 | + | 282 | 307 | 0.0066 | 158 | 361 | 0.764 |
| 0.1 | - | 282 | 112 | 0.0088 | 213 | 486 | 1.029 |
| 0.05 | + | 298 | 71.9 | 0.0037 | 97.9 | 220 | 0.400 |
| 0.05 | - | 298 | 84.2 | 0.0035 | 94.4 | 213 | 0.385 |

Current bound on di-EW boson (ATLAS13 w/ L=36.1/fb; arXiv:1808.02380)

$\sigma[\text{WW or ZZ}] \sim 300\text{fb}$ @ resonant mass = 300 GeV

--- close to the LOSS predictions

--- **probed by upcoming data in near future,
in significant correlation w/ deviation on Higgs coupling,
and excessive diHiggs signal**