Probing New Physics of Cubic Higgs Interaction

Jing Ren
University of Toronto

ACFI Workhop

September 19, 2015

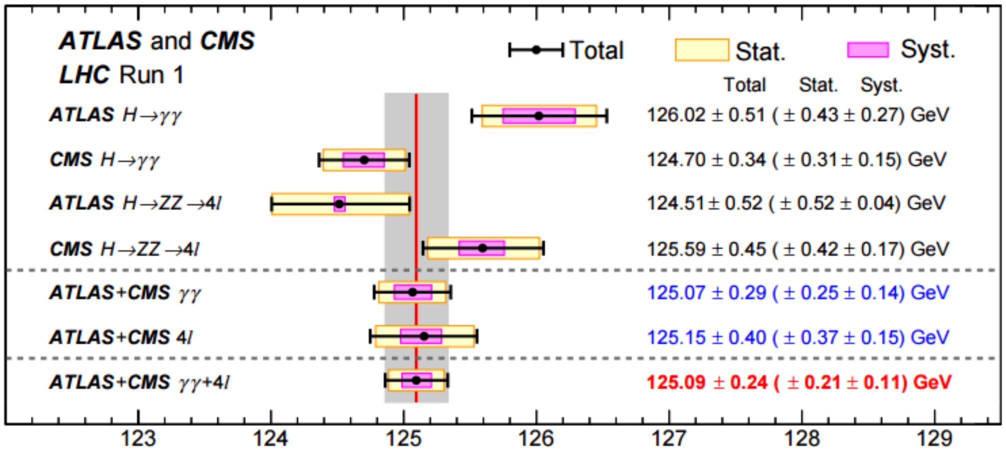
Based on H.J. He (Tsinghua), JR, W. Yao (LBNL), 1506.03302

Outline

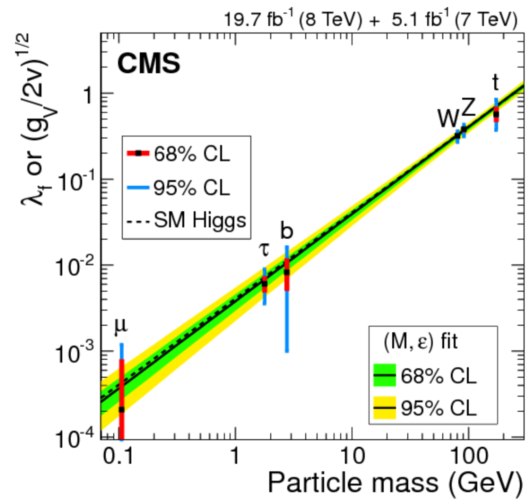
- Motivation
- New physics v.s. Higgs self-interactions
  - Strong first order electroweak phase transition (SFOEWPT)
  - Higgs non-minimal gravitational interaction
- Probing new cubic Higgs interactions on hadron collider
  - Effective theory with dim=6 operators
  - Higgs pair production on hadron collider

Higgs Discovery

- We now have the 125GeV SM-like Higgs with LHC Run1



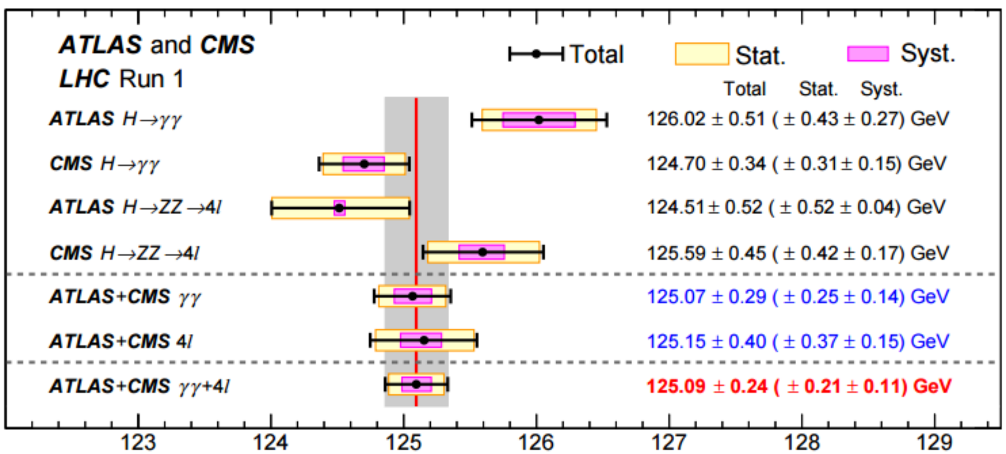
ATLAS and CMS Collaborations RRL 114, 191803 (2015)



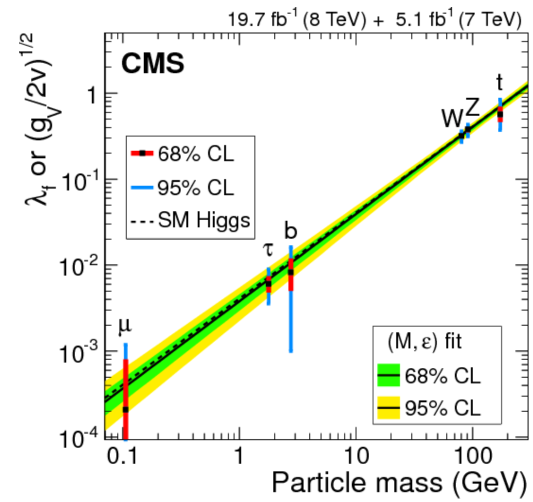
- But no convincing evidence from new physics search

Higgs Discovery

- We now have the 125GeV SM-like Higgs with LHC Run1

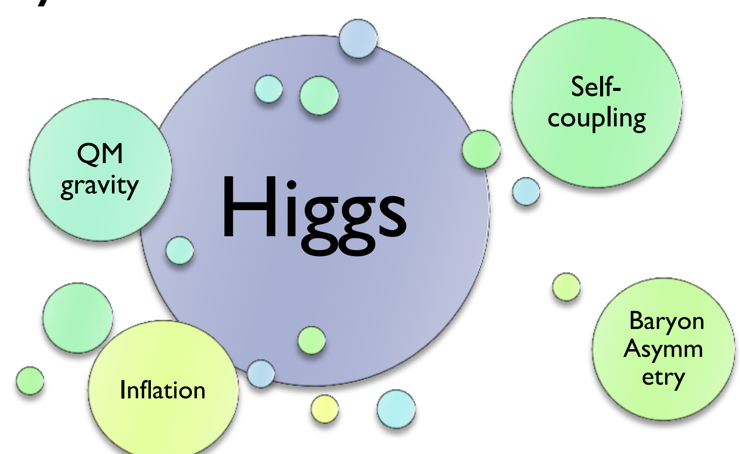


ATLAS and CMS Collaborations RRL 114, 191803 (2015)



- But no convincing evidence from new physics search

- Higgs as the window for new physics



Less Known Higgs Potential

SM Higgs potential $V(H) = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2$

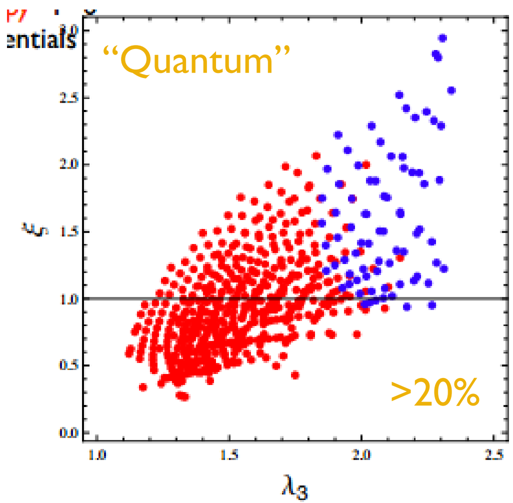
- EWSB: μ^2, λ fixed by $v = 246\text{GeV}, M_h = 125\text{GeV}$
- EWPT: far from first order, (~cross-over)
- Self-couplings: $\lambda_3 = 3M_h^2/v, \lambda_4 = 3M_h^2/v^2$

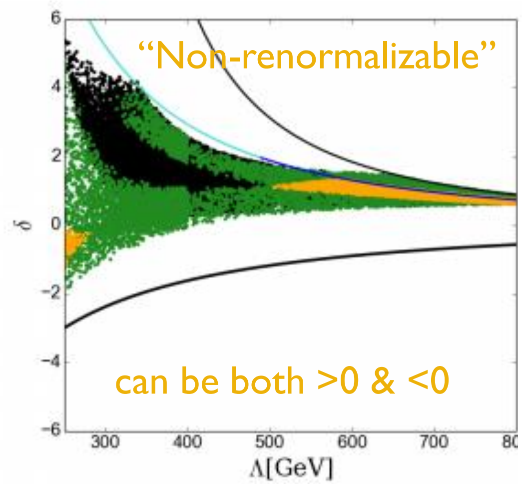
- Higgs self-couplings measurement
  - Dihiggs production to probe λ_3
    - ~ 50% accuracy on HL-LHC [Snomass Higgs Working Group Report, arXiv:1310.8361]
    - ~ 27% accuracy on ILC @500GeV [arXiv:1506.05992] [See Jianming Qian's talk]
    - ~ 35% accuracy on CEPC5 (careful!) [McCullough, arXiv:1312.3322]
  - TriHiggs production to probe λ_4: much more challenging [Plehn, Rauch, PRD 72 (2005) 053008]
- Higgs self-interactions as the window to new physics

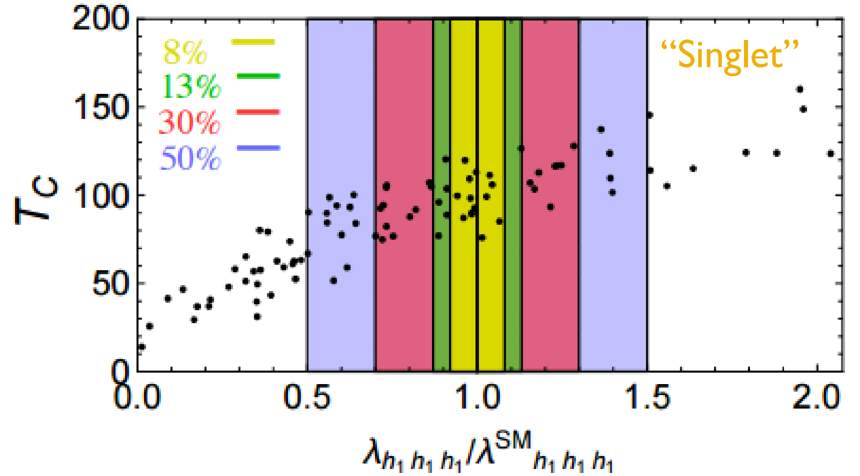
New Physics v.s. Higgs Self-Interactions

Strong first order EWPT (SFOEWPT)

- Correlation between SFOEWPT and cubic Higgs coupling







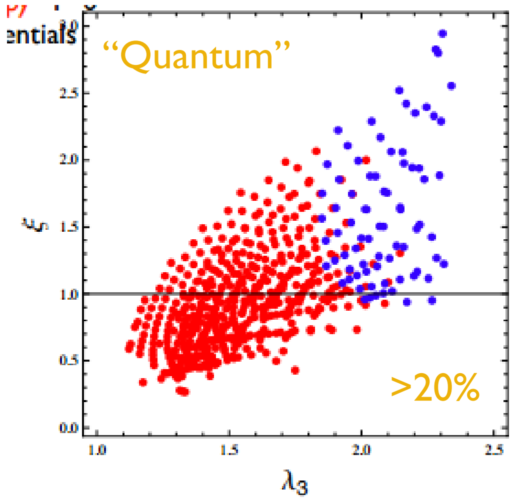
[See M. Perelstein's talk]

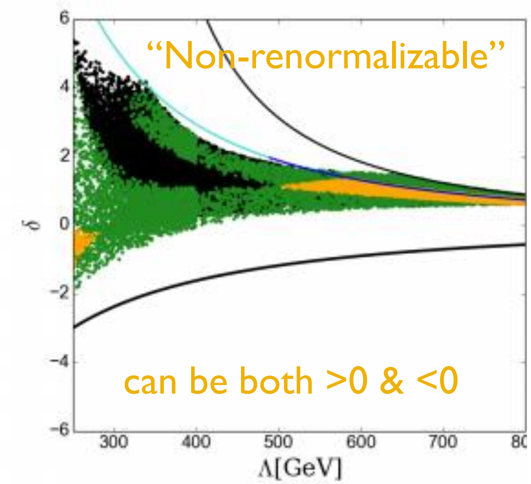
[See C. Wagner's talk]

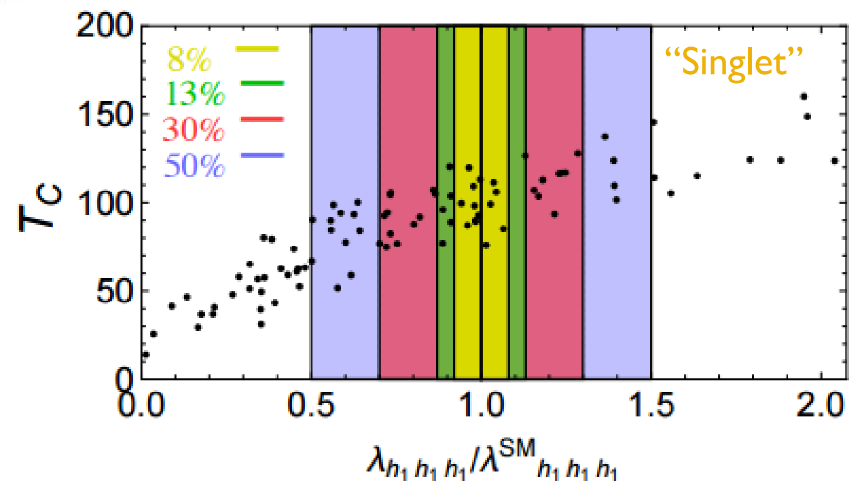
[See P. Winslow's talk]

Strong first order EWPT (SFOEWPT)

- Correlation between SFOEWPT and cubic Higgs coupling





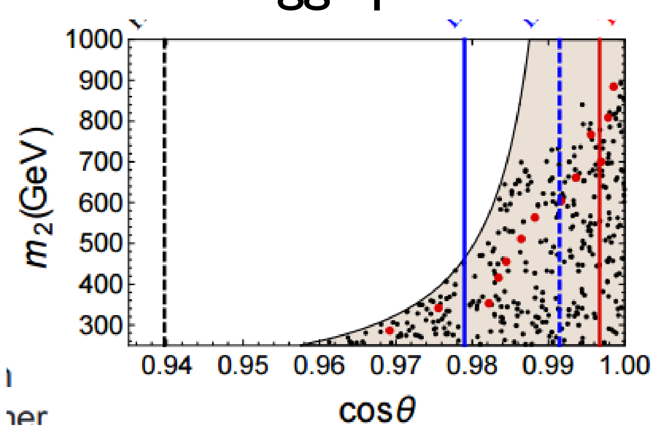


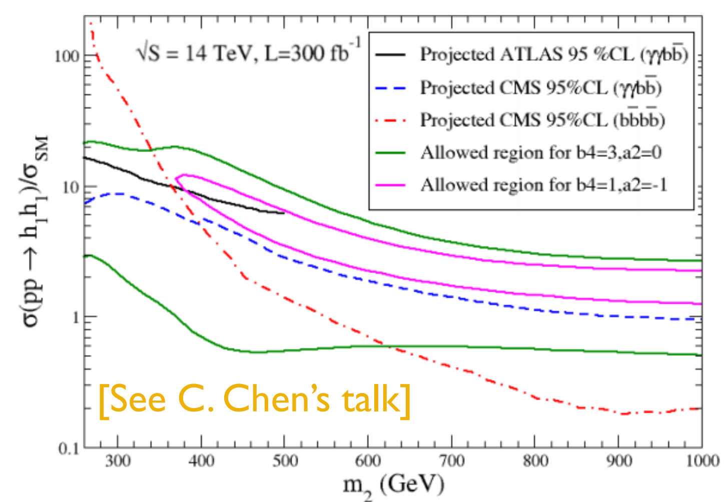
[See M. Perelstein's talk]

[See C. Wagner's talk]

[See P. Winslow's talk]

- Resonance dihiggs production





Higgs non-minimal gravitational interaction

Joint effective action for SM and GR: $S = S_{\mathrm{GR}} + S_{\mathrm{SM}} + S_{\mathrm{NMC}}$

Higgs non-minimal gravitational interaction

Joint effective action for SM and GR: $S = S_{\mathrm{GR}} + S_{\mathrm{SM}} + \xi_h R H^\dagger H$

$$L \xrightarrow[\text{transformation}]{\text{Einstein frame}} \frac{3\xi_h^2}{M_{\mathrm{Pl}}^2\Omega^4}(\partial_\mu H^\dagger H)^2 + \frac{1}{\Omega^2}(D^\mu H)^\dagger(D_\mu H) - \frac{1}{\Omega^4}V(H) \qquad \Omega^2 = 1 + \frac{2\xi_h H^\dagger H}{M_{Pl}^2}$$

$$\boxed{\Delta L_6 = \frac{3\lambda}{\Lambda_{\xi 1}^2}(\partial_\mu H^\dagger H)^2 + \frac{4}{\Lambda_{\xi 2}^2}\left[\lambda\left(H^\dagger H\right)^3 + \cdots\right], \quad \Lambda_{\xi 1} = \frac{M_{Pl}}{\xi_h} \ll \Lambda_{\xi 2} = \frac{M_{Pl}}{\sqrt{\xi_h}}, \quad \text{if } \xi_h \gg 1}$$

Higgs non-minimal gravitational interaction

Joint effective action for SM and GR: $S = S_{\rm GR} + S_{\rm SM} + \xi_h R H^\dagger H$

$$L \xrightarrow[\text{transformation}]{\text{Einstein frame}} \frac{3\xi_h^2}{M_{\rm Pl}^2\Omega^4}(\partial_\mu H^\dagger H)^2 + \frac{1}{\Omega^2}(D^\mu H)^\dagger(D_\mu H) - \frac{1}{\Omega^4}V(H) \qquad \Omega^2 = 1 + \frac{2\xi_h H^\dagger H}{M_{Pl}^2}$$

$$\boxed{\Delta L_6 = \frac{3\lambda}{\Lambda_{\xi 1}^2}(\partial_\mu H^\dagger H)^2 + \frac{4}{\Lambda_{\xi 2}^2}\left[\lambda\left(H^\dagger H\right)^3 + \cdots\right],\ \Lambda_{\xi 1} = \frac{M_{Pl}}{\xi_h} \ll \Lambda_{\xi 2} = \frac{M_{Pl}}{\sqrt{\xi_h}},\ \text{if } \xi_h \gg 1}$$

- Higgs rescaling induced by graviton-Higgs kinetic mixing

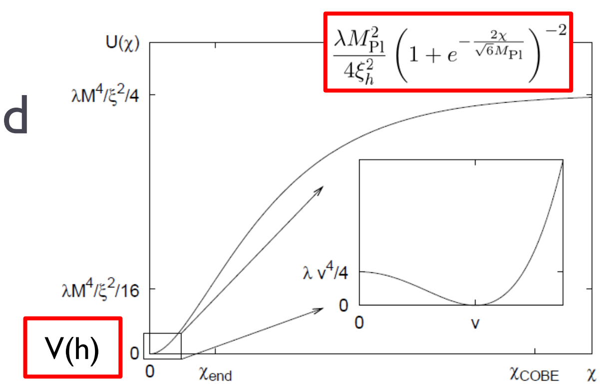
  $\frac{6v^2}{\Lambda_{\xi 1}^2} \lesssim O(0.1) \Rightarrow |\xi_h| \lesssim 10^{15}$ (LHC bound) $\quad \Lambda_{UV} \lesssim \Lambda_{\xi 1}$ (Unitarity bound)

- New derivative Higgs self-couplings: $h\partial_\mu h \partial^\mu h$

- Higgs inflation: extreme flat potential at large field

  Slow roll: $n_s \simeq 1 - 2/N, r_s \simeq 12/N^2$

  If $\lambda \sim \mathcal{O}(0.1)$, $|\xi_h| \sim 10^4$, $\Lambda_{\rm INF} \sim M_{\rm Pl}/\sqrt{\xi_h} \sim 10^{16}{\rm GeV}$



[Bezrukov, Shaposhnikov, Phys.Lett. B 659 (2008) 703]

Probing New Cubic Higgs Interactions

EFT: Dim=6 Operators

- Dim=6 operators for Higgs self-interactions: $\mathcal{L}_{\text{eff}} = \sum_n \frac{f_n}{\Lambda^2}\mathcal{O}_n$

[Corbett, Eboli, Gonzalez-Fraile, Gonzalez-Garcia, Phys. Rev. D 87, 015022 (2013)]

$$\mathcal{O}_{\Phi,1} = (D^\mu H)^\dagger H H^\dagger (D_\mu H)\,, \qquad \mathcal{O}_{\Phi,2} = \frac{1}{2}\partial^\mu (H^\dagger H)\partial_\mu (H^\dagger H)\,,$$

$$\mathcal{O}_{\Phi,3} = \frac{1}{3}(H^\dagger H)^3, \qquad \mathcal{O}_{\Phi,4} = (D^\mu H)^\dagger (D_\mu H)(H^\dagger H)\,.$$

EFT: Dim=6 Operators

- Dim=6 operators for Higgs self-interactions: $\mathcal{L}_{\rm eff} = \sum_n \frac{f_n}{\Lambda^2}\mathcal{O}_n$

[Corbett, Eboli, Gonzalez-Fraile, Gonzalez-Garcia, Phys. Rev. D 87, 015022 (2013)]

$$\cancel{\mathcal{O}_{\Phi,1} = (D^\mu H)^\dagger H H^\dagger (D_\mu H)},\qquad \mathcal{O}_{\Phi,2} = \frac{1}{2}\partial^\mu(H^\dagger H)\partial_\mu(H^\dagger H)\,,$$

$$\mathcal{O}_{\Phi,3} = \frac{1}{3}(H^\dagger H)^3,\qquad \mathcal{O}_{\Phi,4} = (D^\mu H)^\dagger(D_\mu H)(H^\dagger H)\,.$$

Violate custodial symmetry,
negligible for collider study

EFT: Dim=6 Operators

- Dim=6 operators for Higgs self-interactions: $\mathcal{L}_{\rm eff} = \sum_n \frac{f_n}{\Lambda^2}\mathcal{O}_n$

[Corbett, Eboli, Gonzalez-Fraile, Gonzalez-Garcia, Phys. Rev. D 87, 015022 (2013)]

$$\cancel{\mathcal{O}_{\Phi,1} = (D^\mu H)^\dagger H H^\dagger (D_\mu H)}, \qquad \mathcal{O}_{\Phi,2} = \frac{1}{2}\partial^\mu (H^\dagger H)\partial_\mu (H^\dagger H)\,,$$

$$\mathcal{O}_{\Phi,3} = \frac{1}{3}(H^\dagger H)^3, \qquad \cancel{\mathcal{O}_{\Phi,4} = (D^\mu H)^\dagger (D_\mu H)(H^\dagger H)}.$$

Violate custodial symmetry, negligible for collider study

Eliminated by EOM

EFT: Dim=6 Operators

- Dim=6 operators for Higgs self-interactions: $\mathcal{L}_{\text{eff}} = \sum_n \frac{f_n}{\Lambda^2}\mathcal{O}_n$

[Corbett, Eboli, Gonzalez-Fraile, Gonzalez-Garcia, Phys. Rev. D 87, 015022 (2013)]

$$\cancel{\mathcal{O}_{\Phi,1} = (D^\mu H)^\dagger H H^\dagger (D_\mu H)}, \qquad \mathcal{O}_{\Phi,2} = \frac{1}{2}\partial^\mu (H^\dagger H)\partial_\mu (H^\dagger H),$$

$$\mathcal{O}_{\Phi,3} = \frac{1}{3}(H^\dagger H)^3, \qquad \cancel{\mathcal{O}_{\Phi,4} = (D^\mu H)^\dagger (D_\mu H)(H^\dagger H)}.$$

Violate custodial symmetry, negligible for collider study

Eliminated by EOM

- The 2d Parameter Space: (x_2, x_3) $x_j \equiv \frac{f_{\Phi,j} v^2}{\Lambda^2} \equiv \text{sign}(f_{\Phi,j})\frac{v^2}{\tilde{\Lambda}_j^2}$ ← Effective cutoff
  - Higgs-SM couplings rescaled by $\zeta = (1+x_2)^{-1/2}$
  - Cubic Higgs coupling $\lambda_3 = -\mathrm{i}\frac{\zeta}{v}\left[3\,(1+\widehat{r})\,M_h^2 - \widehat{x}\,(p_1^2+p_2^2+p_3^2)\,\right]$

$$\boxed{\widehat{r} \equiv -x_3\,\zeta^2 \frac{2v^2}{3M_h^2}\,, \qquad \widehat{x} \equiv x_2\,\zeta^2}$$

EFT: Dim=6 Operators

- Dim=6 operators for Higgs self-interactions: $\mathcal{L}_{\rm eff} = \sum_n \frac{f_n}{\Lambda^2}\mathcal{O}_n$

[Corbett, Eboli, Gonzalez-Fraile, Gonzalez-Garcia, Phys. Rev. D 87, 015022 (2013)]

$$\cancel{\mathcal{O}_{\Phi,1} = (D^\mu H)^\dagger H H^\dagger (D_\mu H)}\,, \qquad \mathcal{O}_{\Phi,2} = \frac{1}{2}\partial^\mu (H^\dagger H)\partial_\mu (H^\dagger H)\,,$$

$$\mathcal{O}_{\Phi,3} = \frac{1}{3}(H^\dagger H)^3\,, \qquad \cancel{\mathcal{O}_{\Phi,4} = (D^\mu H)^\dagger (D_\mu H)(H^\dagger H)}\,.$$

Violate custodial symmetry, negligible for collider study

Eliminated by EOM

- The 2d Parameter Space: (x_2, x_3) $\quad x_j \equiv \frac{f_{\Phi,j} v^2}{\Lambda^2} \equiv \mathrm{sign}(f_{\Phi,j})\frac{v^2}{\tilde{\Lambda}_j^2}$ $\longleftarrow$ Effective cutoff
  - Higgs-SM couplings rescaled by $\zeta = (1 + x_2)^{-1/2}$
  - Cubic Higgs coupling $\lambda_3 = -\mathrm{i}\frac{\zeta}{v}\left[3\,(1+\widehat{r})\,M_h^2 - \widehat{x}\,(p_1^2 + p_2^2 + p_3^2)\,\right]$

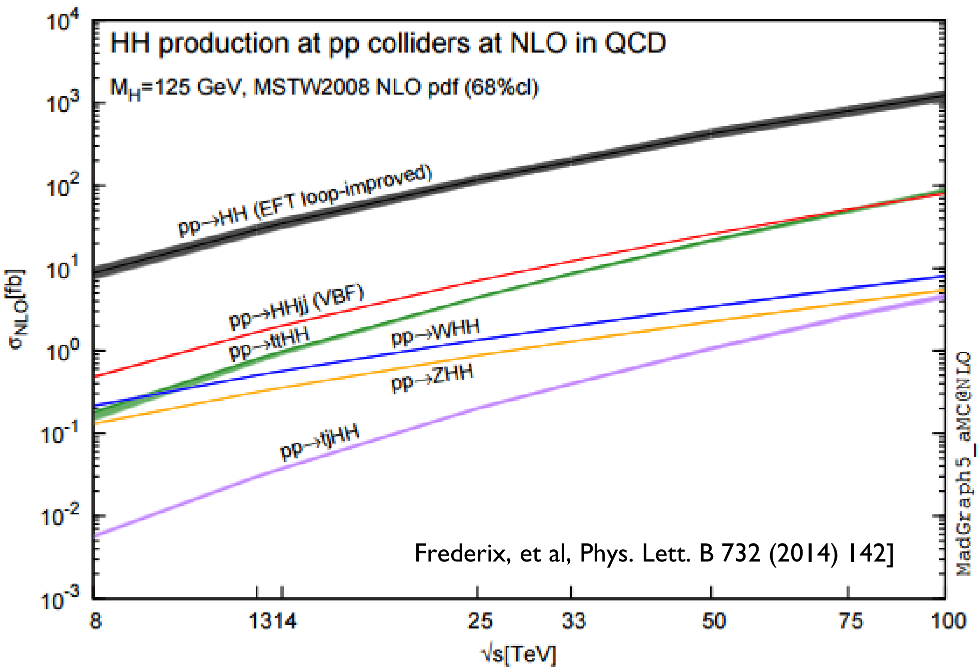
$$\boxed{\widehat{r} \equiv -x_3\,\zeta^2 \frac{2v^2}{3M_h^2}\,, \qquad \widehat{x} \equiv x_2\,\zeta^2}$$

Treat $\hat{r}, \hat{x}$ as two free inputs

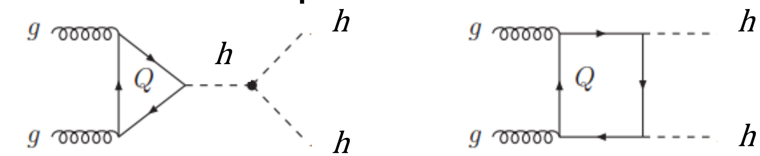
- Accidental cancelation with other operators in single higgs measurement
- Nonlinear realization: "quadratic" & "cubic" correlation broken down

Dihiggs Production on Hadron Collider

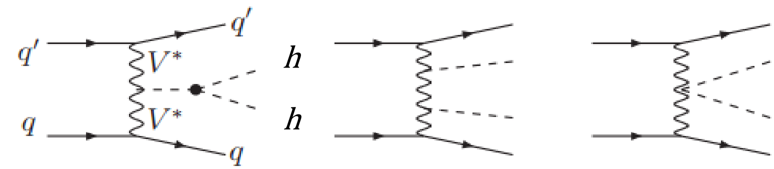
A. Djouadi, Phys. Rept. 457 (2008) 1 [arXiv:hep-ph/0503172]



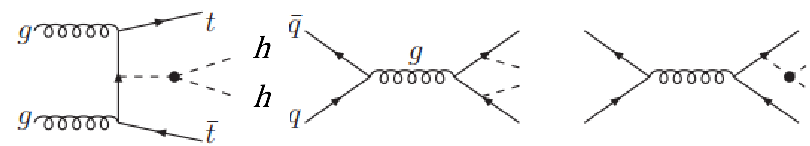
- Gluon fusion production



- Vector boson fusion production



- Top-pair associated production



NLO cross section in unit of fb

$\sqrt{s}$ (TeV)	$pp \to HH$	$pp \to HHjj$	$pp \to \bar{t}tHH$	$pp \to WHH$	$pp \to ZHH$
8	8.73	0.479	0.177	0.214	0.130
14	34.8	2.017	0.981	0.565	0.356
100	1186	79.6	87.8	7.90	5.18

Dihiggs Production on Hadron Collider

- $gg \to hh$

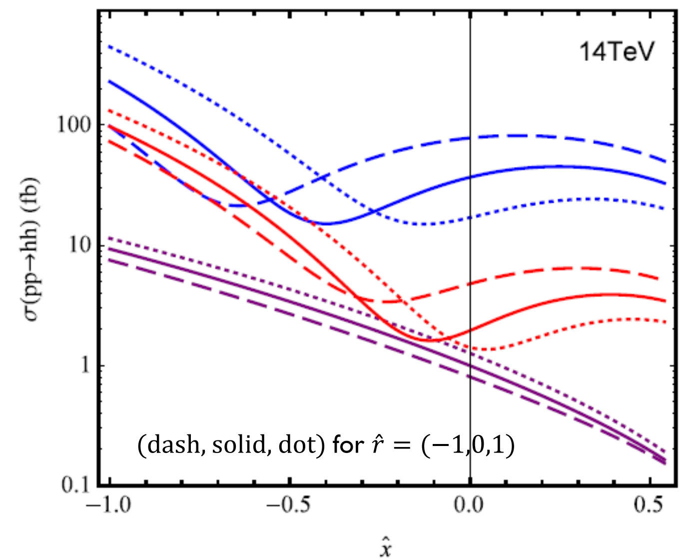
$$\boxed{\left.\frac{\sigma}{\sigma_{\rm sm}}\right|_{100\rm TeV} = (1-\hat{x})^2\left(1 - 0.72\,\hat{r} + 3.6\,\hat{x} + 0.22\,\hat{r}^2 + 4.3\,\hat{x}^2 - 1.7\,\hat{r}\,\hat{x}\right)}$$

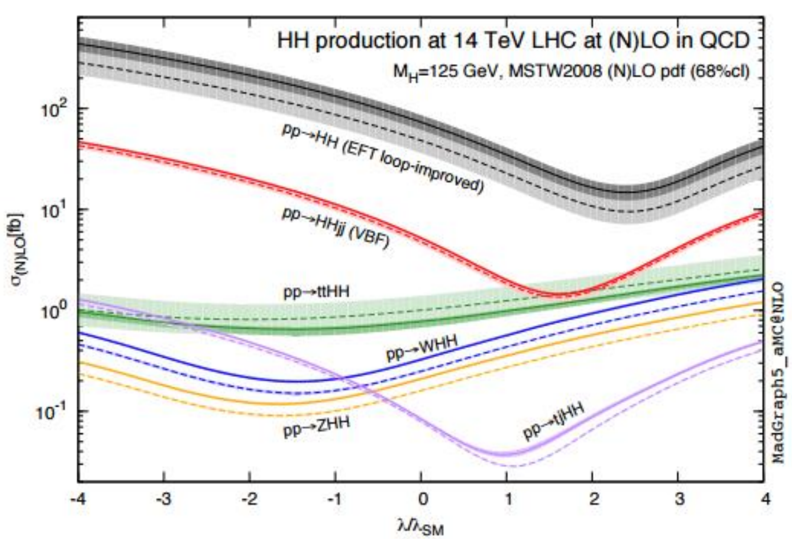
- $pp \to hhjj$

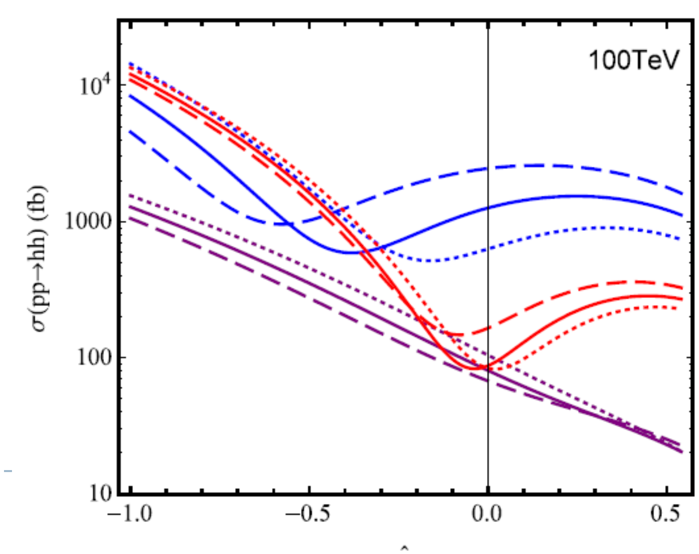
$$\boxed{\left.\frac{\sigma}{\sigma_{\rm sm}}\right|_{100\rm TeV} = (1-\hat{x})^2\left(1 - 0.47\,\hat{r} + 4.6\,\hat{x} + 0.42\,\hat{r}^2 + 38\,\hat{x}^2 - 4.1\,\hat{r}\,\hat{x}\right)}$$

- $pp \to t\bar{t}hh$

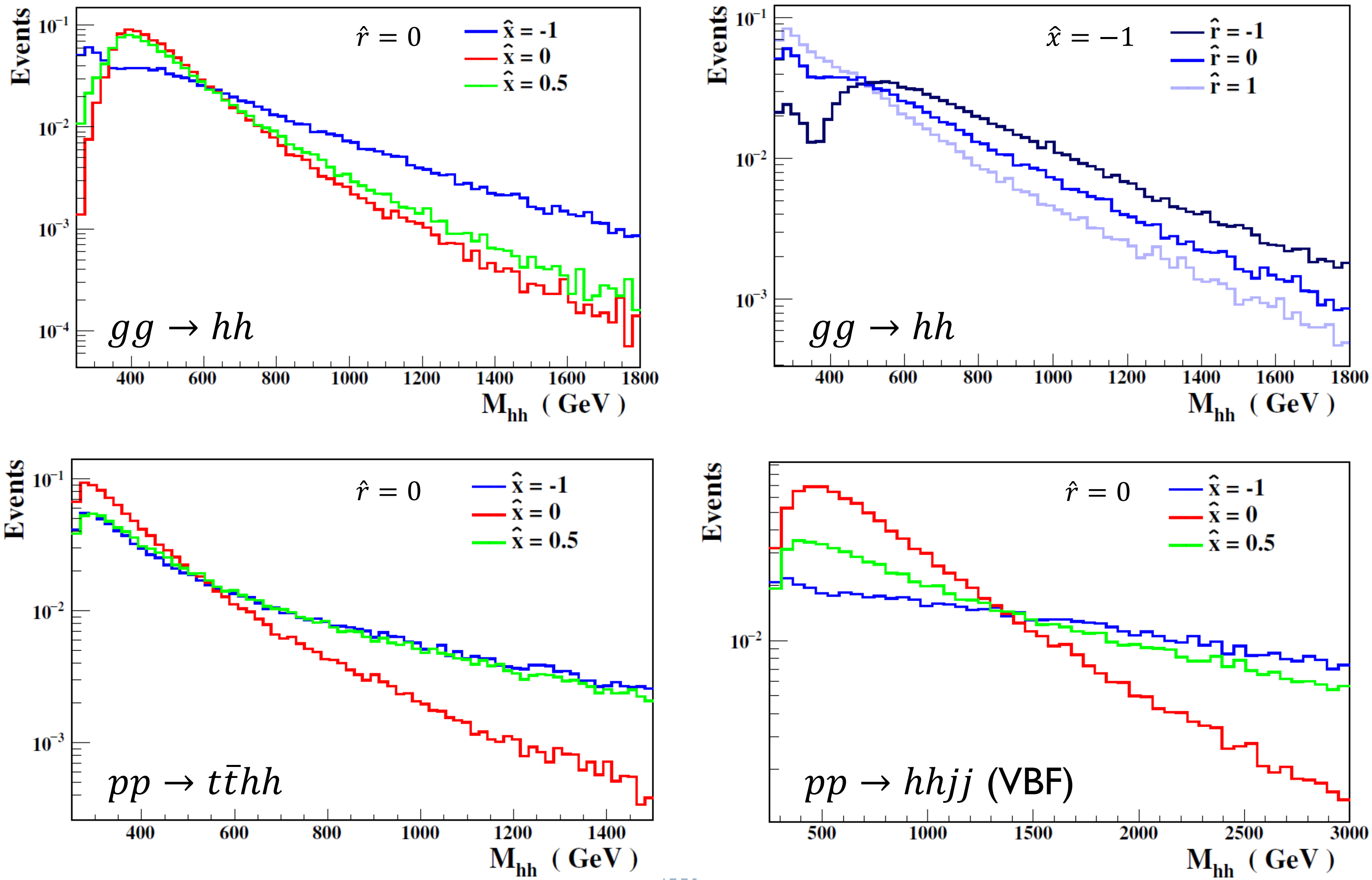
$$\boxed{\left.\frac{\sigma}{\sigma_{\rm sm}}\right|_{100\rm TeV} = (1-\hat{x})^2\left(1 + 0.23\,\hat{r} - 0.80\,\hat{x} + 0.07\,\hat{r}^2 + 2.2\,\hat{x}^2 - 0.54\,\hat{r}\,\hat{x}\right)}$$







Kinematic distributions @100TeV



Dihiggs Decay Channels

Decay	Issues	Expectation 3000 ifb	References
$b\bar{b}\gamma\gamma$ (0.26%)	• Signal small • BKG large & difficult to asses • Simple reconst.	$S/B \simeq 1/3$ $S/\sqrt{B} \simeq 2.5$	[Baur, Plehn, Rainwater] [Yao 1308.6302] [Baglio et al. JHEP 1304]
$b\bar{b}\tau^+\tau^-$ (7.3%)	• tau rec tough • largest bkg tt • Boost+MT2 might help	**differ a lot** $S/B \simeq 1/5$ $S/\sqrt{B} \simeq 5$	[Dolan, Englert, MS] [Barr, Dolan, Englert, MS] [Baglio et al. JHEP 1304]
$b\bar{b}W^+W^-$ (25%)	• looks like tt • Need semilep. W to rec. two H • Boost + BDT proposed	**differ a lot** best case: $S/B \simeq 1.5$ $S/\sqrt{B} \simeq 8.2$	[Dolan, Englert, MS] [Baglio et al. JHEP 1304] [Papaefstathiou, Yang, Zurita 1209.1489]
$b\bar{b}b\bar{b}$ (33%)	• Trigger issue (high pT kill signal) • 4b background large difficult with MC • Subjets might help	$S/B \simeq 0.02$ $S/\sqrt{B} \lesssim 2.0$	[Dolan, Englert, MS] [Ferreira de Lima, Papaefstathiou, MS] [Wardrope et al, 1410.2794]
WW^*WW^* $(3l3\upsilon jj, 2l^{\pm}2\upsilon 4j)$ (4.7%)	• Many taus/W not clear if 2 Higgs • Zs, photons no rate	$S/\sqrt{B} \sim 1.5\sigma$ $(3l3\upsilon jj)$	[Li, Li, Yan, Zhao, 1503.07611] [Baur, Plehn, Rainwater, PRL 89, 151801 (2002)]

HL-LHC with $3ab^{-1}$
$S/\sqrt{B} = 1.3\sigma$

[ATL-PHYS-PUB-2014-019]

Search in **tthh** and **VBF** channel,
[Liu, Zhang, 1410.1855]
[Dolan et al,, 1506.08008]

Fast Simulation of $b\bar{b}\gamma\gamma$ @100TeV

Events generation: Madgraph5, Pythia 6.2, Delphes 3

- Signal: include finite mt effect
- Background: include up to one extra parton with MLM matching
- Detector simulation based on ATLAS responses
  - Use anti-kT for jets with $\Delta R = 0.5$
  - b-tagging efficiency: 75%, 18.8%, and 1% for bottom, charm, and light favor jets in the central region
  - Photon identification efficiency: roughly 80% for photons with $E_T > 50\text{GeV}$ and $|\eta| < 2.5$ (HL-LHC: $E_T > 80\text{GeV}$)
  - Jet-faking-photon background: a faking probability of $f_j = 0.0093\exp(-E_T/27)$ as a function of jet E_T in GeV, and scale the jet energy by 0.75 ± 0.12 as the photon energy

Fast Simulation of $b\bar{b}\gamma\gamma$ @100TeV

- Background: $b\bar{b}\gamma\gamma,\ b\bar{b}h(\gamma\gamma),\ Z(b\bar{b})h(\gamma\gamma),\ \bar{t}th(\gamma\gamma), jj\gamma\gamma$ (mis-tagging b or $\bar{b}$)
  $\bar{t}t\gamma\gamma,\ b\bar{b}j\gamma,\ b\bar{b}jj,\ \bar{t}t\gamma$ (jet-faking-photon)
- Events selection [W. Yao, arXiv:1308.6302 [hep-ph]]
  - 2 bjets and b photon

    $E_T > 25\,\mathrm{GeV} \quad |\eta| < 2.5$

    $\boxed{122\,\mathrm{GeV} < M_{\gamma\gamma} < 128\,\mathrm{GeV}}$

    $85\,\mathrm{GeV} < M_{b\bar{b}} < 135\,\mathrm{GeV}$

  - Kinematic cuts

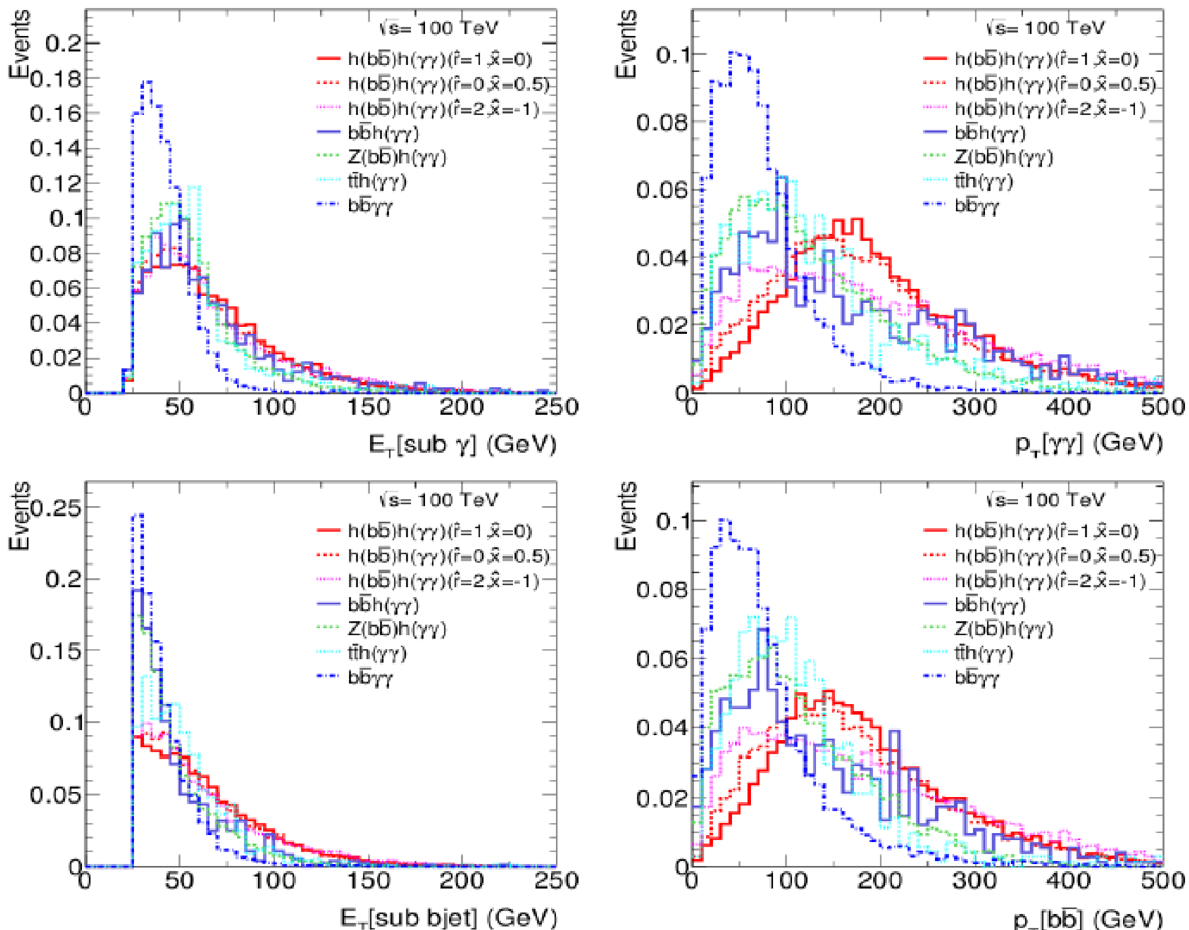
    $M_{b\bar{b}\gamma\gamma} > 300\,\mathrm{GeV}$

    $\Delta R_{\gamma\gamma} < 2.5\,, \quad \Delta R_{b\bar{b}} < 2.0$

    $p_T^{\gamma}, p_T^{b} > 35\,\mathrm{GeV}, \quad p_T^{\gamma\gamma}, p_T^{b\bar{b}} > 100\,\mathrm{GeV}$

    $|\cos\theta_h| < 0.8$ (Higgs decay angle)

    $\Sigma(njets + nphos + nleps + nmet) < 7$



Results

Signal and background at pp(100TeV) with $L = 3ab^{-1}$

Samples	$\sigma \times$BR (fb)	Generated Evt	Selected Evt	Accept	Expected
$h(b\bar{b})h(\gamma\gamma)$ (SM)	3.53	100000	3955	0.040	418.8 ± 6.6
$b\bar{b}h(\gamma\gamma)$	50.49	99611	78	0.00078	118.6 ± 13.4
$Z(b\bar{b})h(\gamma\gamma)$	0.8756	68585	378	0.0055	14.5 ± 0.7
$t\bar{t}h(\gamma\gamma)$	37.26	63904	67	0.0010	117.2 ± 14.3
$t\bar{t}\gamma\gamma$	335.8	150654	1	6.6e-06	6.75 ± 6.7
$t\bar{t}\gamma$	108400	285787	0.013	4.7e-08	15.2 ± 3.2
$b\bar{b}\gamma\gamma$	5037	763962	11	1.4e-05	217.6 ± 65.6
$b\bar{b}j\gamma$	8960000	1119406	0.0051	4.6e-09	123.6 ± 31.9
$jj\gamma\gamma$	164200	813797	0.056	6.9e-08	33.9 ± 3.8
Total background	–	–	–	–	647.3 ± 76.0
$S/\sqrt{B}$	–	–	–	–	16.5

Comparison:

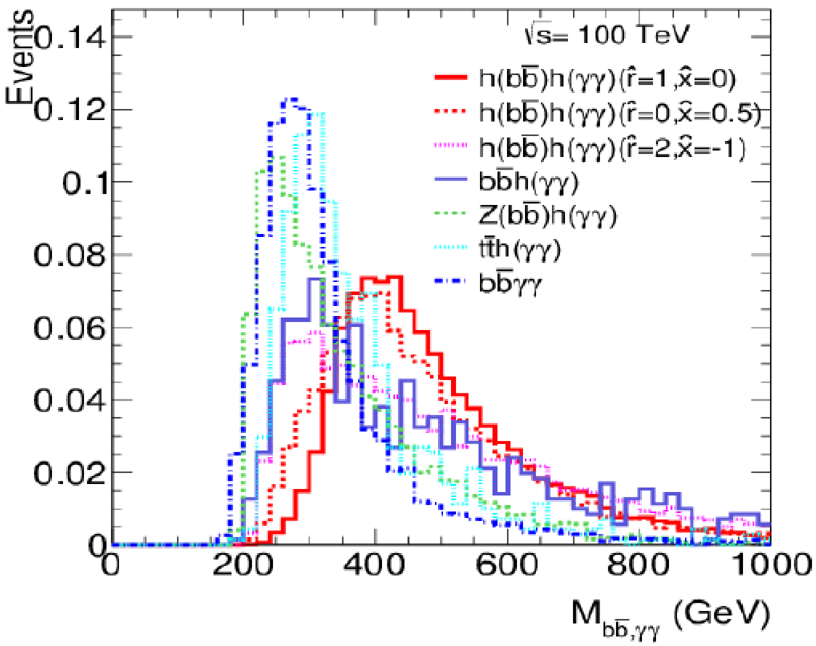
-- $S/\sqrt{B} = 8.4$, conservative (photon identification) efficiency [Bar et al, JHEP 1502 (2015) 016, arXiv:1412.7154]

-- $S/\sqrt{B} = 15.2$, comparable efficiency [Azatov et al, arXiv:1502.00539]

Discrimination of Two Operators

- Utilize distribution in reconstructed M_{hh} bins

$$M_{hh} \text{ bins (GeV):} \quad [300, 500],\ [500, 700],\ [700, 900],\ [900, 1100]$$

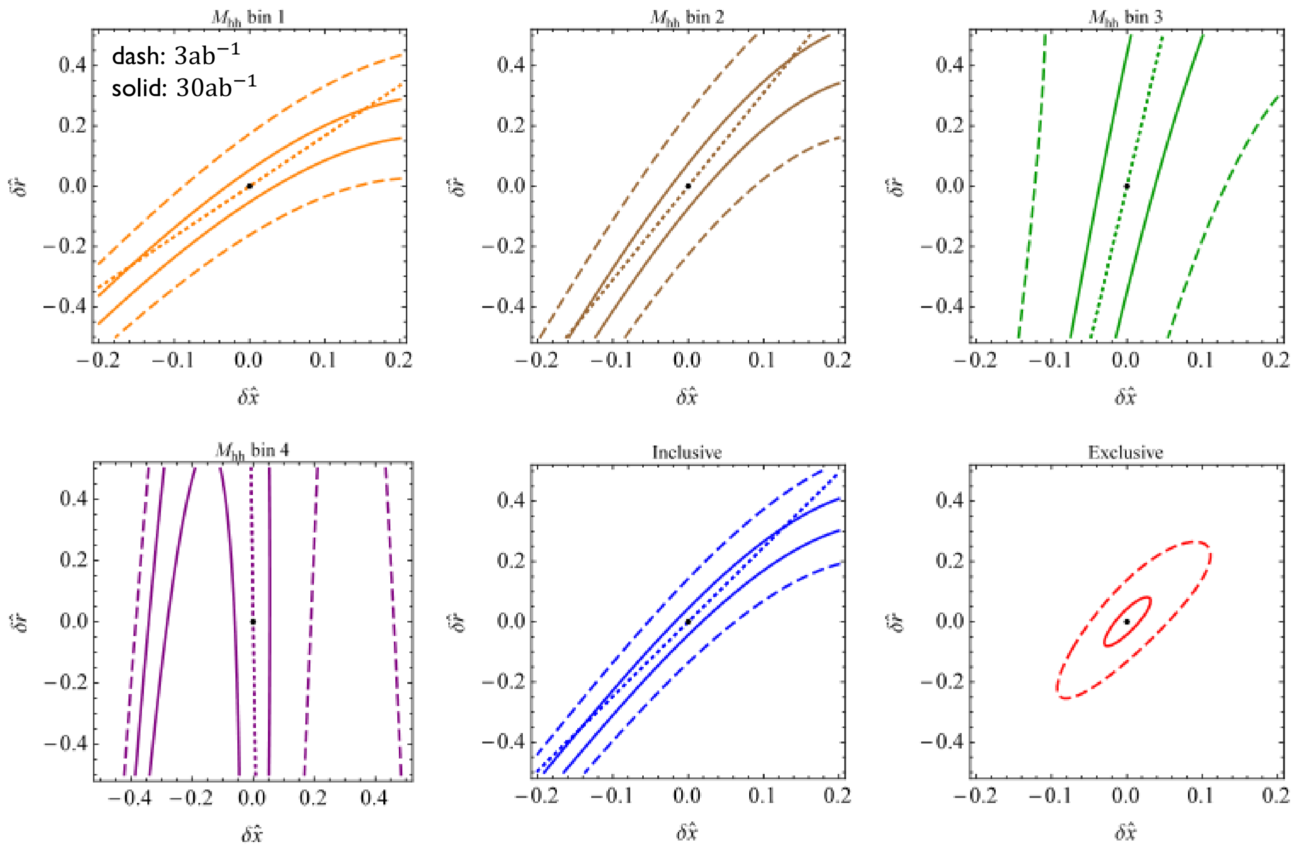


M_{hh} bins (GeV)	[300, 500]	[500, 700]	[700, 900]	[900, 1100]
$h(b\bar{b})h(\gamma\gamma)$ (SM)	200	170	52.5	11.1
$b\bar{b}h(\gamma\gamma)$	67.1	31.9	15.8	3.81
$Z(b\bar{b})h(\gamma\gamma)$	11.2	2.77	0.46	0.04
$t\bar{t}h(\gamma\gamma)$	97.5	15.9	3.22	0.58
$t\bar{t}\gamma\gamma$	5.41	1.1	0.24	0.0
$t\bar{t}\gamma$	13.9	1.09	0.16	0.05
$b\bar{b}\gamma\gamma$	188	23.7	5.25	0.32
$b\bar{b}j\gamma$	107	11.8	3.44	1.32
$jj\gamma\gamma$	30.3	2.58	0.82	0.24
Total Backgrounds	521	90.8	29.4	6.37

$$\left.\frac{\sigma}{\sigma_{\rm sm}}\right|_{\rm bin\,1} = (1-\widehat{x})^2(1-0.82\,\widehat{r}+3.4\,\widehat{x}+0.17\,\widehat{r}^2+3.3\,\widehat{x}^2-1.5\,\widehat{r}\widehat{x})\,, \quad \left.\frac{\sigma}{\sigma_{\rm sm}}\right|_{\rm bin\,3} = (1-\widehat{x})^2(1-0.14\,\widehat{r}+3.5\,\widehat{x}+0.04\,\widehat{r}^2+5.6\,\widehat{x}^2-0.85\widehat{r}\widehat{x})$$

$$\left.\frac{\sigma}{\sigma_{\rm sm}}\right|_{\rm bin\,2} = (1-\widehat{x})^2(1-0.42\,\widehat{r}+3.3\,\widehat{x}+0.06\,\widehat{r}^2+3.8\,\widehat{x}^2-0.95\,\widehat{r}\widehat{x})\,, \quad \left.\frac{\sigma}{\sigma_{\rm sm}}\right|_{\rm bin\,4} = (1-\widehat{x})^2(1-0.03\,\widehat{r}+4.0\,\widehat{x}+0.03\,\widehat{r}^2+8.6\,\widehat{x}^2-0.65\,\widehat{r}\widehat{x})$$

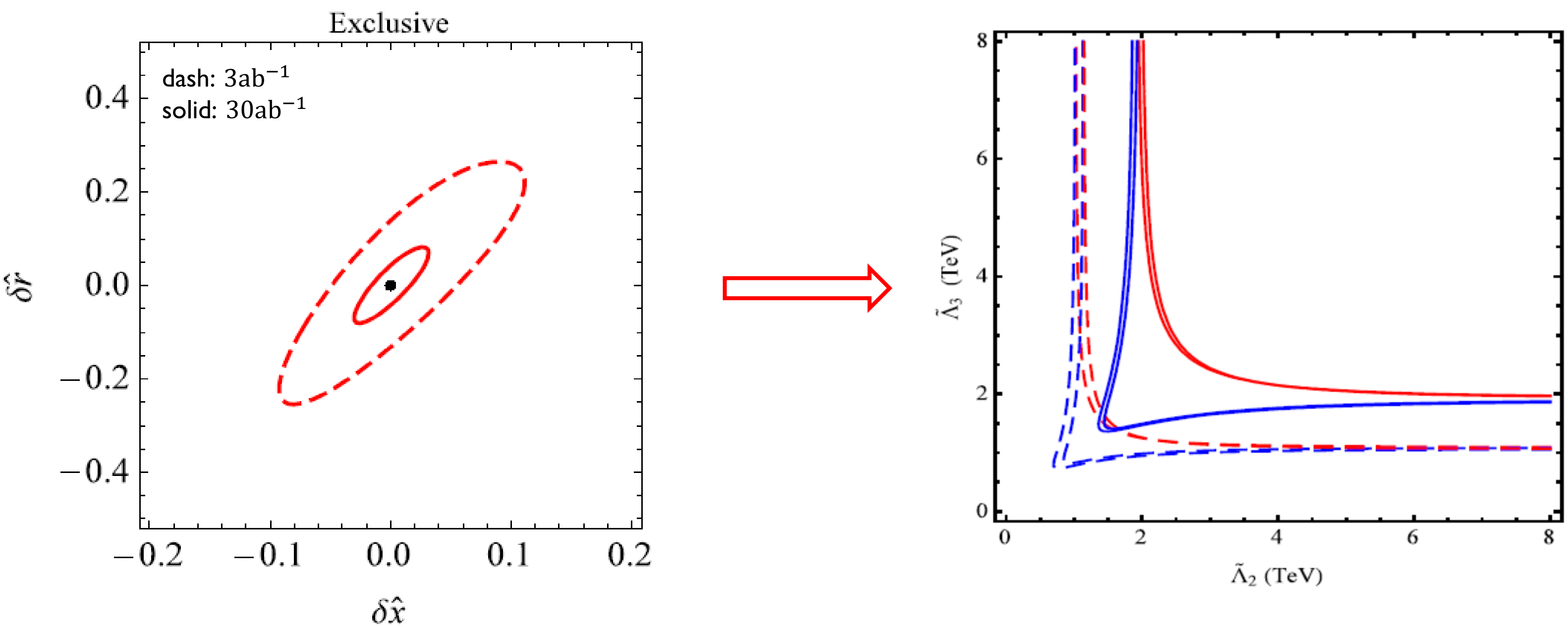
Sensitivity on $(\hat{r}, \hat{x})$ Plane: SM



- $(\hat{\boldsymbol{r}}, \hat{\boldsymbol{x}}) = (0,0)$
- Degenerate direction around origin
- Exclusive analysis breaks degenerate direction
- 1d sensitivity: $\delta\hat{r}\sim 13\%(4\%)$, $\delta\hat{x}\sim 5\%(1.6\%)$
- The weakest 2d sensitivity: $\delta\hat{r}\sim 25\%(8\%)$, $\delta\hat{x}\sim 10\%(3\%)$

Dihiggs measurements alone can probe both $(\hat{\boldsymbol{r}}, \hat{\boldsymbol{x}})$ to a good accuracy

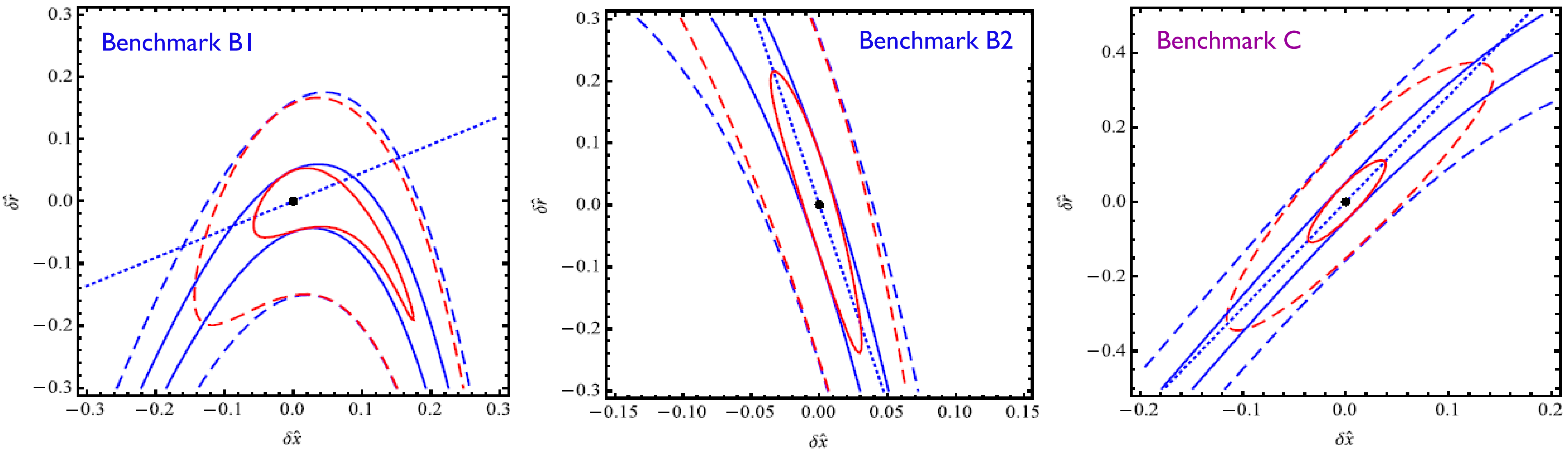
Sensitivity on $(\hat{r}, \hat{x})$ Plane: SM



- Exclusive analysis translated as probe of the effective cutoffs
- Tow cases: $x_2 x_3 > 0$ (red), $x_2 x_3 < 0$ (blue)
- 1d sensitivity: $\widetilde{\Lambda}_2, \widetilde{\Lambda}_3 \gtrsim 1(2)$ TeV
- Weakest 2d sensitivity: $\widetilde{\Lambda}_2, \widetilde{\Lambda}_3 \gtrsim 0.75(1.4)$ TeV

Sensitivity for Generic $(\hat{r}, \hat{x})$

- Sensitivity contours qualitatively different
  - Benchmark B: non-minimal gravitational coupling.
    $(\hat{r}, \hat{x}) = (0, 0.2)$ (B1), $(\hat{r}, \hat{x}) = (0, 0.5)$ (B2), sensitivity contour and degenerate direction strongly depend on the explicit $\hat{x}$.
  - Benchmark C: CW potential in classical scale invariant model.
    $(\hat{r}, \hat{x}) = (2/3, 0)$, similar to the SM.



Summary

- Higgs self-interactions as the window for new physics, important for big questions: EWPT, EWSB, Higgs gravitational interaction…

- Probing new physics of Higgs self-couplings based on effective theory with dim=6 operators. For dihiggs production on hadron collider, discriminate deviation couplings from the SM one by using M_{hh} bins.

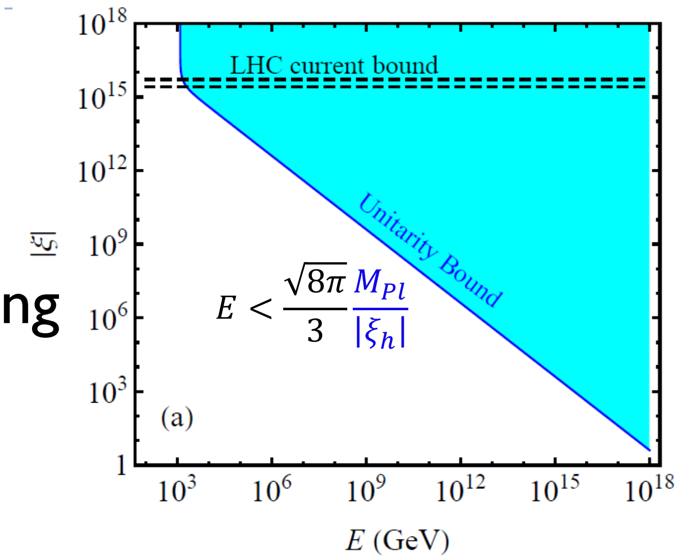
- Dihiggs production alone can probe both cubic Higgs couplings to a good accuracy on 100TeV. Sensitivity qualitatively different for various benchmark points.

Thank You!

Perturbative Unitarity Bound

[JR, Z. Z. Xianyu, H.J. He, 1404.4627]

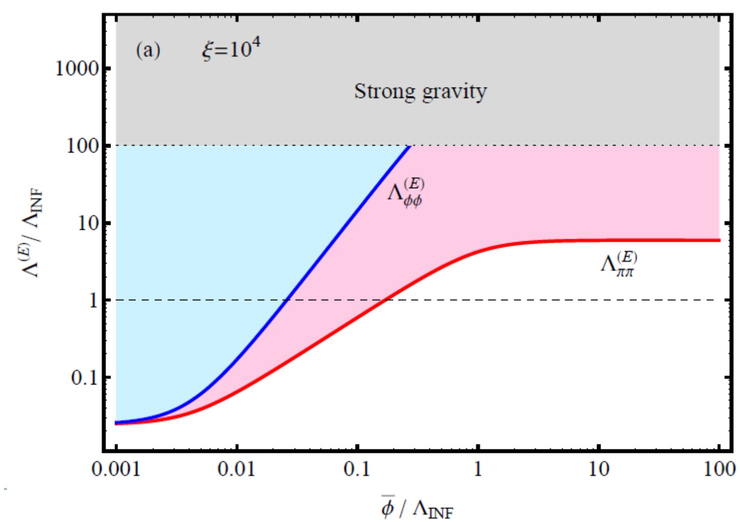
- Goldstone boson equivalence theorem: $\xi_h R H^\dagger H$ is gauge invariant



- Coupled channel analysis: 2 → 2 scattering

$$E^2 < \frac{16\pi v^2}{(1-\zeta^2)\left(1+\sqrt{1+3\zeta^4}\right)}$$

- Unitarity analysis for Higgs inflation
  - Puzzle: $\Lambda_{\rm INF} \sim M_{\rm Pl}/\sqrt{|\xi_h|}$ go beyond cutoff $M_{\rm Pl}/|\xi_h|$ for $|\xi_h| > 1$
  - Unitarity bound depends on background field
  - The strongest bound from $\pi^+\pi^- \to \pi^0\pi^0$



Other Dim=6 Operators

For different dihiggs production, some other operators contribute as well

- Top-pair associated production

  dim=6: $H^\dagger H \, \overline{q}_L H^c t_R + \mathrm{h.c.}$

- Gluon fusion production

  dim=6: $H^\dagger H G^a_{\mu\nu} G^{a\,\mu\nu}$

- Vector fusion production

  dim=6: $H^\dagger H W^{a\mu\nu} W^a_{\mu\nu}$, $H^\dagger H (D^\mu H)^\dagger (D_\mu H)$

Higgs Mass Reconstruction

When one of the reconstructed mass consistent with the Higgs mass