UNIVERSITY OF TORONTO

Higgs Gravitational Interaction and Higgs Self-Couplings

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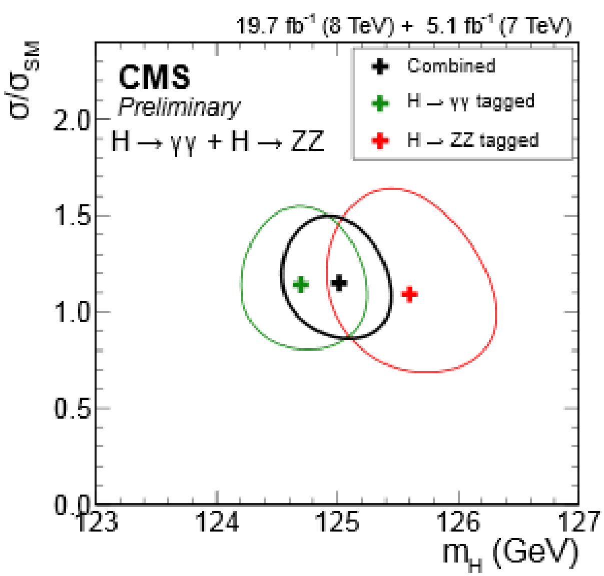
JR, Z. Z. Xianyu, H.J. He, 1404.4627
H.J. He, JR, W. Yao, 1506.03302

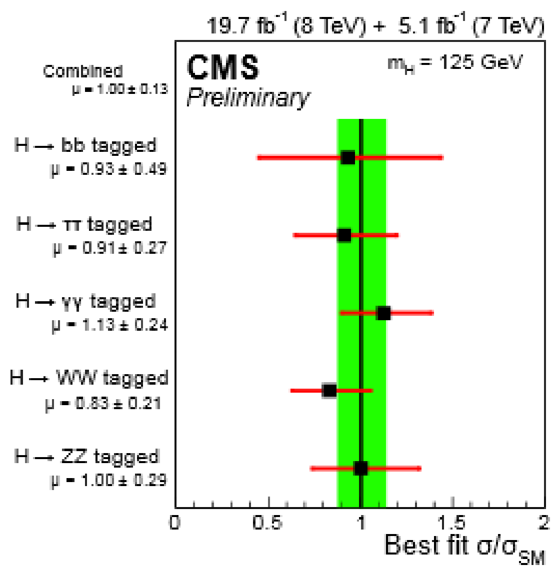
Educational Background

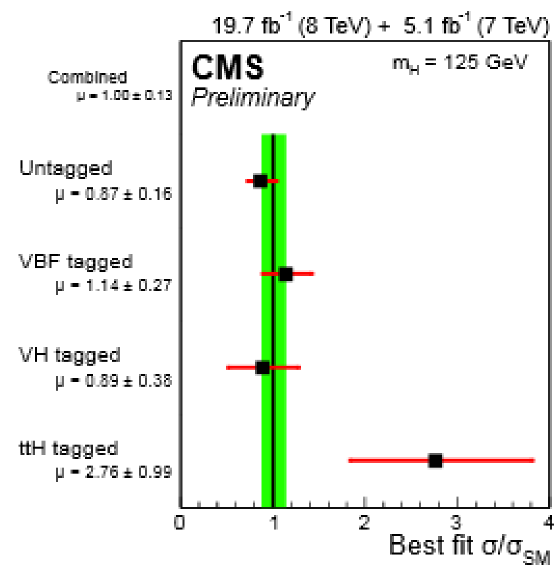
- Postdoc (2014-now)
  - University of Toronto, Canada, work with Prof. Holdom
- Ph.D. (2008-2014)
  - Center for High Energy Physics and Institute of Modern Physics, Tsinghua University. Advisor: Hong-jian He.
  - 2011-2012: Visiting student (Joint Training Program supported by National Scholarship), work with Prof. Chivukula and Prof. Simmons, Michigan State University, USA.
- Bachelor (2004-2008)
  - Department of Physics, Tsinghua University.

Higgs Discovery

- The 125GeV Higgs discovered on LHC in 2012
- Higgs measurement by LHC Run1 7TeV+8TeV data
- So far, couplings, spin and parity compatible with SM!







CMS-PAS-HIG-14-009

Where is New Physics?

- Hint for new physics
  - Neutrino mass
  - Dark matter
  - Baryon asymmetry
  - Fermion mass hierarchy
  - Naturalness problem
  - Quantum Gravity
  - Inflation
  - …

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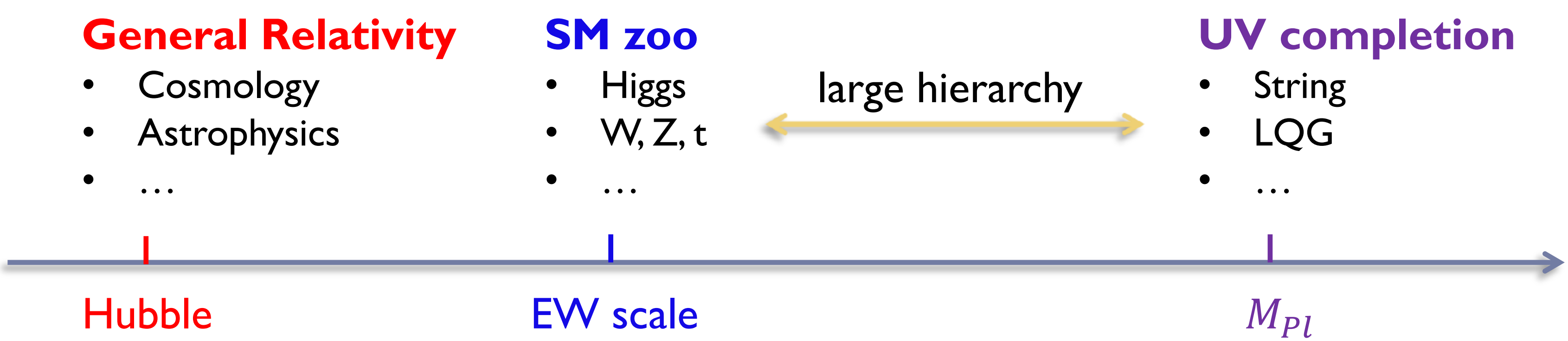

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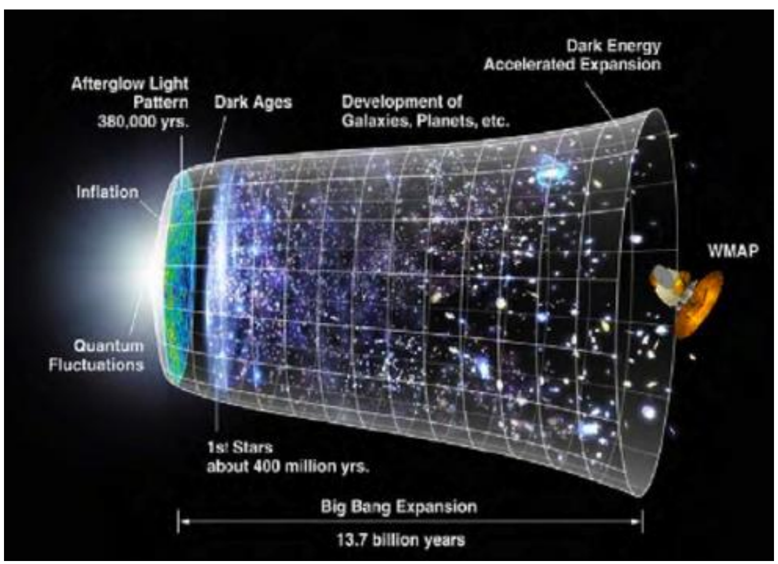

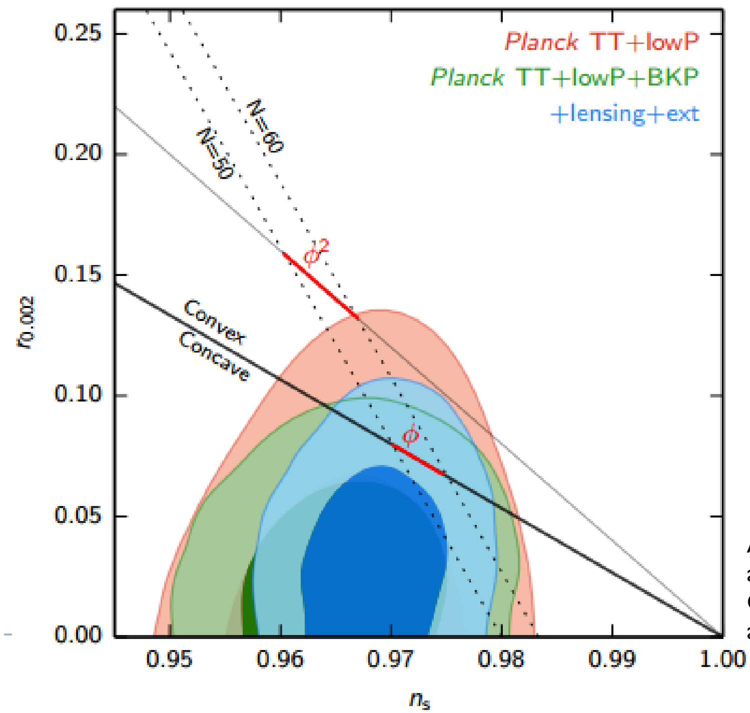

Ade et al. [BICEP2 and Planck Collaborations] arXiv:1502.00612.

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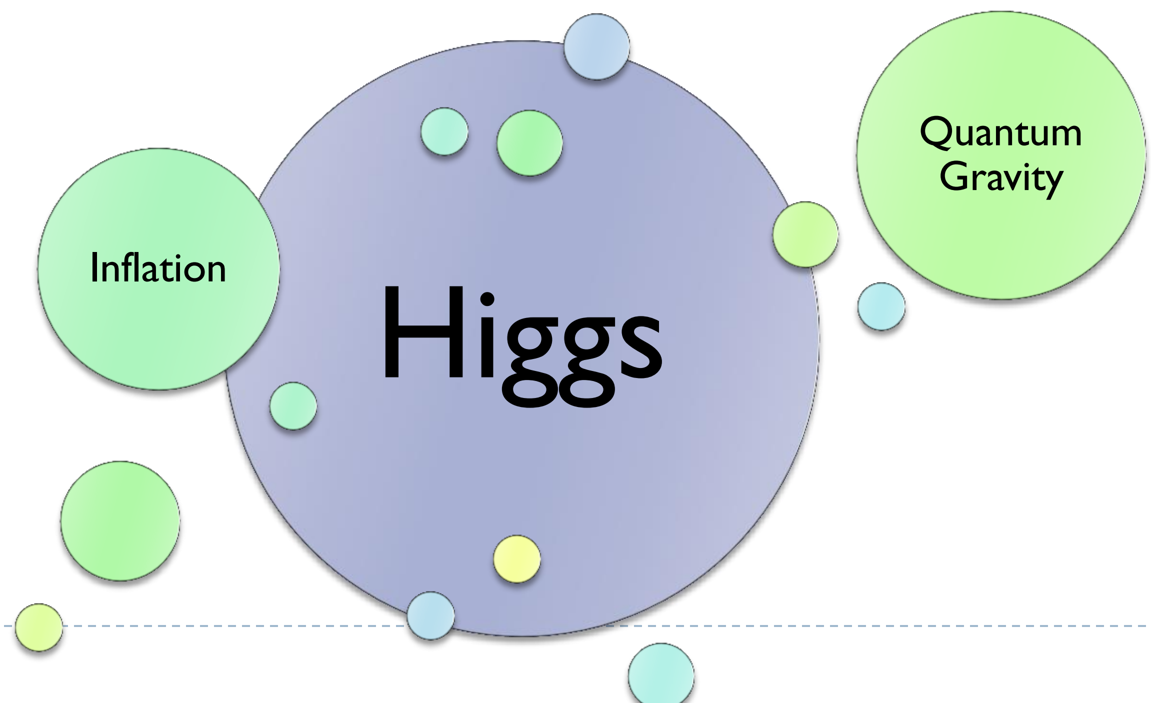

Outline

- Higgs Gravitational Interaction and Higgs Inflation
  - Weak boson scattering and perturbative unitarity
  - Higgs Inflation
- Probing Cubic Higgs Interactions at Hadron Collider
  - New Higgs self-interactions from Dim=6 operators
  - Dihiggs production and full analysis of $gg \to hh \to b\bar{b}\gamma\gamma$
- Summary

Higgs Gravitational Interaction

JR, Z. Z. Xianyu, H.J. He, arXiv: 1404.4627

Effective Field Theory

Quantization of General Relativity (GR)

$$S_{\mathrm{GR}} = \int d^4x \sqrt{-g} \left[M_{\mathrm{Pl}}^2 \left(-\Lambda + \frac{1}{2} R \right) + c_1 R^2 + c_2 R_{\mu\nu} R^{\mu\nu} + \ldots \right]$$

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Joint effective action for the SM and GR

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$$\boxed{S_{\rm NMC} = \int d^4x\sqrt{-g}\,\xi_h R H^\dagger H}$$

- Impact of ξ_h on Higgs physics?
- Impact of ξ_h on gravity and cosmology evolution?

Formalism: Jordan Frame

$$S_J \supset \int d^4x \sqrt{-g^{(J)}} \left[\left(\frac{1}{2} M^2 + \xi_h H^\dagger H \right) R^{(J)} + (D^\mu H)^\dagger (D_\mu H) - V(H) \right]$$

- Perturbation expansion: $M_{\rm Pl}^2 = M^2 + \xi_h v^2$

$$g_{\mu\nu}^{(J)} = \eta_{\mu\nu} + \kappa \hat{h}_{\mu\nu}, \quad H = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & (v + \hat{\phi}) \end{pmatrix}^T \quad (\kappa = \sqrt{2}/M_{\rm Pl})$$

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  - Graviton-Higgs kinetic mixing

$$\begin{aligned} h_{\mu\nu} &= \hat{h}_{\mu\nu} - \eta_{\mu\nu} \xi_h \kappa v \zeta \hat{\phi}, \ \phi = \zeta \hat{\phi} \\ \zeta &= \left(1 + 6\xi_h^2 v^2 / M_{\mathrm{Pl}}^2\right)^{-1/2} < 1 \end{aligned}$$

  - Gravity induced new Higgs-SM $T_{\mu\nu}$ coupling

Formalism: Einstein Frame

- Weyl transformation: $g_{\mu\nu} = \Omega^2 g^{(J)}_{\mu\nu}, \quad \Omega^2 = \frac{M^2 + 2\xi_h H^\dagger H}{M_{\rm Pl}^2}$

$$S_E \supset \int d^4x\sqrt{-g}\left[\frac{1}{2}M_{\rm Pl}^2 R + \frac{3\xi_h^2}{M_{\rm Pl}^2\Omega^4}(\partial_\mu H^\dagger H)^2 + \frac{1}{\Omega^2}(D^\mu H)^\dagger(D_\mu H) - \frac{1}{\Omega^4}V(H)\right]$$

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  - The same Higgs rescaling as in Jordan frame
  - Modified hff, hVV couplings: LHC constraint

$$\frac{6\xi_h^2 v^2}{M_{\rm Pl}^2} \lesssim \mathcal{O}(0.1) \Rightarrow |\xi_h| \lesssim 10^{15}$$

[Atkins, Calmet, Phys. Rev. Lett. 110 (2013) 051301]

  - Derivative Higgs self-couplings

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  - Derivative Higgs self-couplings
- Violation of equivalence principle at short distance

Weak Boson Scattering

Non-renormalizable: low cutoff scale for $|\xi_h| \gg 1$

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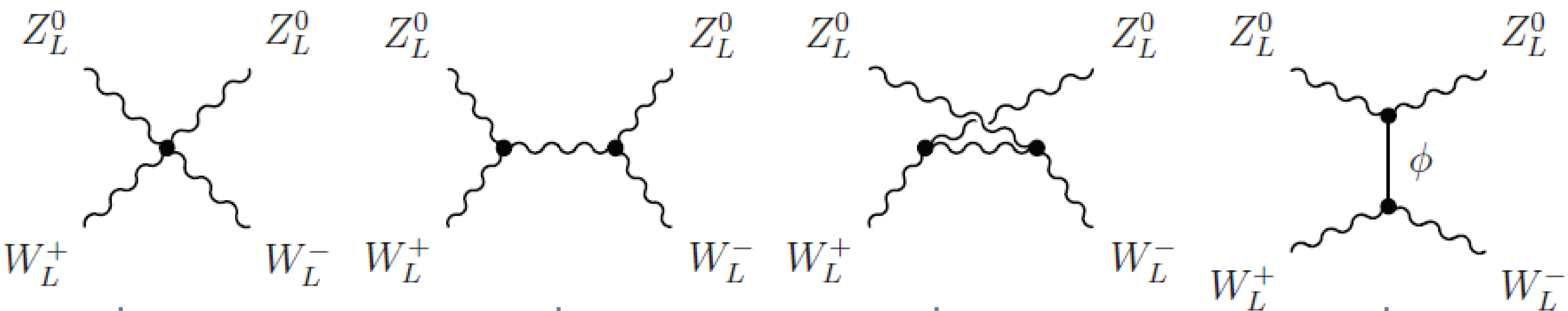

E^4 cancellation (gauge sym)

E^2 cancellation (SM Higgs)

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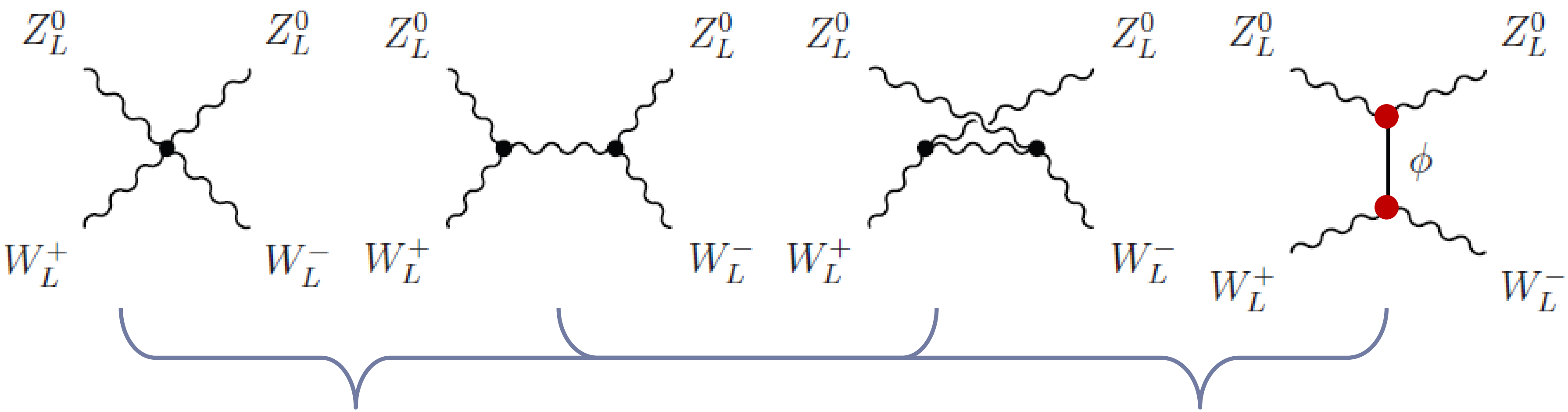


E^4 cancellation (gauge sym) E^2 non-cannellation

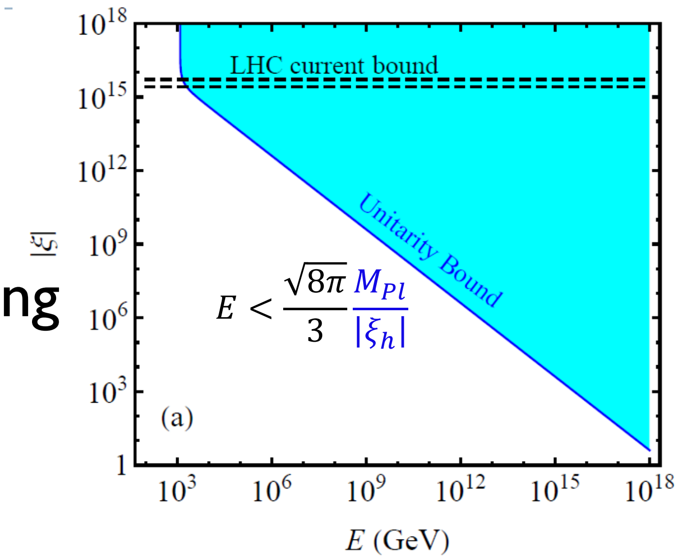
$\xi_h \neq 0$: modified $\phi V_\mu V^\mu$ coupling, perturbative unitarity violation

Perturbative Unitarity Bound

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

- Coupled channel analysis: $2 \to 2$ scattering

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



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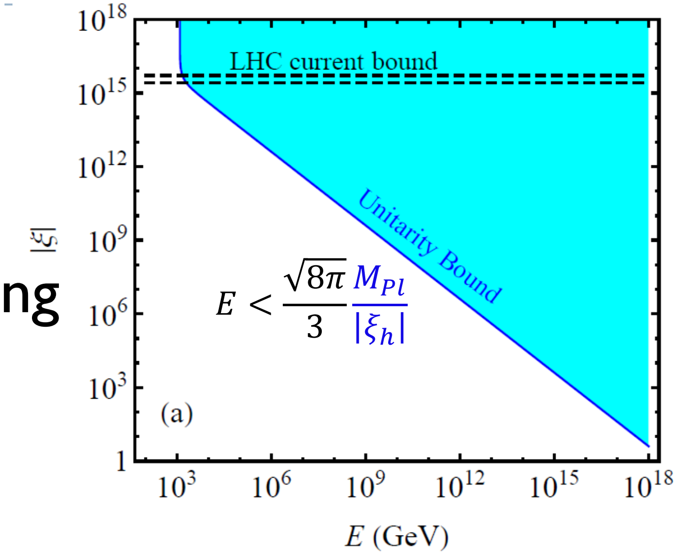

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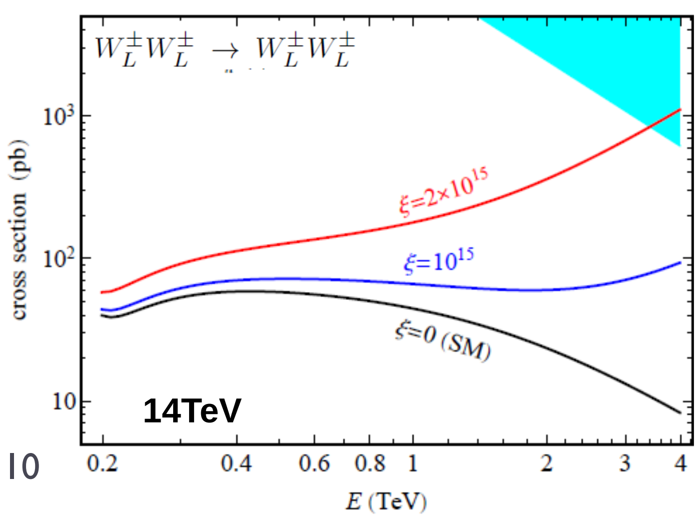
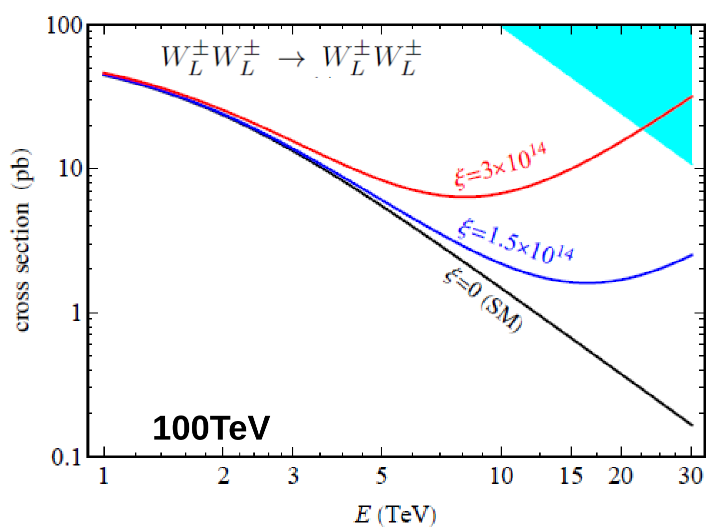
- $W_L W_L \to W_L W_L$ on hadron collider for EFT cutoff $O(10\mathrm{TeV})$





$|\xi_h| \sim 10^{14-15}$

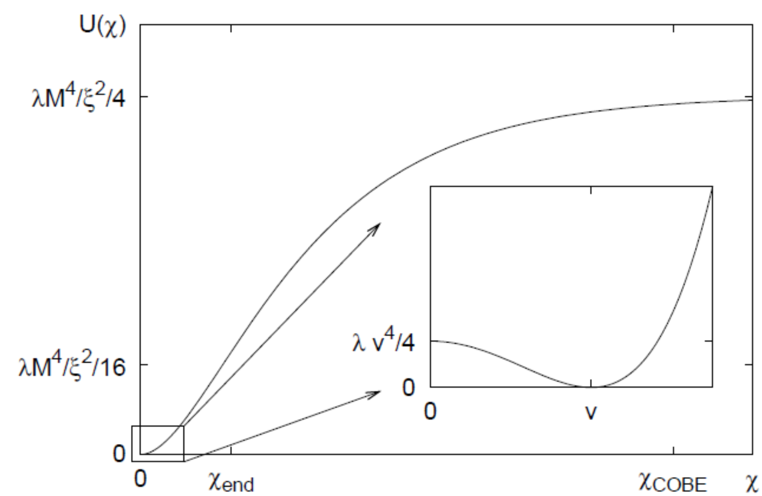
Dileptonic v.s. semileptonic: W-jet

[Cui, Han, PRD 89, 015019 (2014)]

Higgs Inflation

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

$$U = \frac{V(\phi)}{\Omega^4} \xrightarrow{\phi \gg \frac{M_{\rm Pl}}{\sqrt{\xi_h}}} \frac{\lambda M_{\rm Pl}^2}{4\xi_h^2}\left(1 + e^{-\frac{2\chi}{\sqrt{6}M_{\rm Pl}}}\right)^{-2}$$



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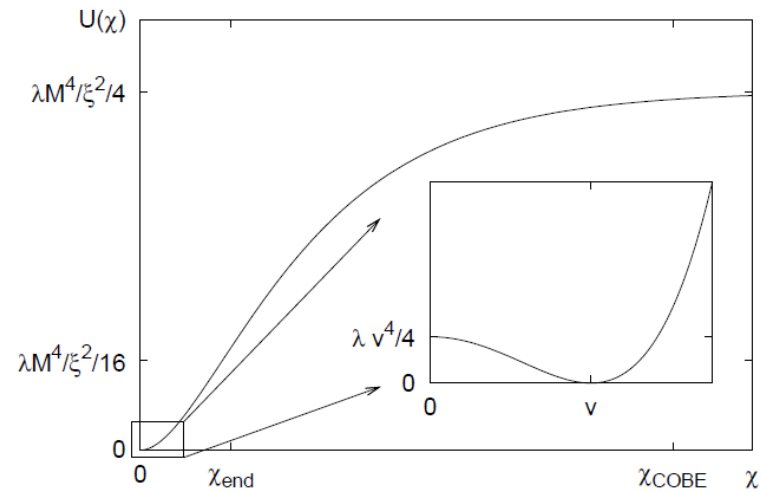
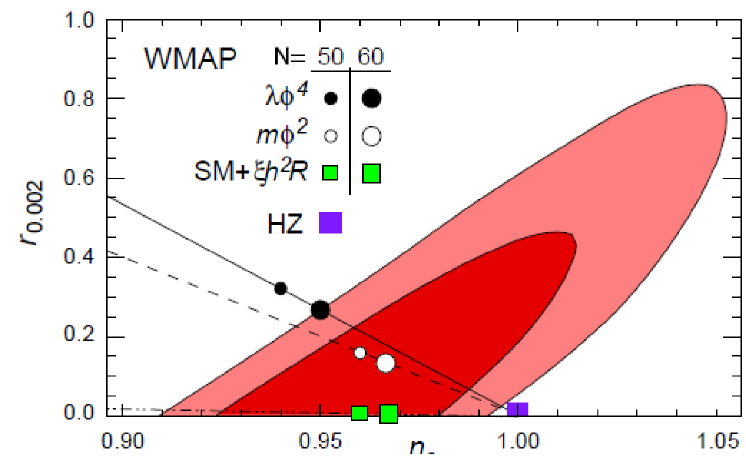


- Starobinsky-like model: $R + R^2$

Slow roll: $n_s \simeq 1 - \frac{2}{N}, \; r \simeq \frac{12}{N^2}$



- Planck normalization

$$(U/\epsilon)^{1/4} = 0.0276 M_{\rm Pl}, \; \Lambda_{\rm INF} = U^{1/4}$$

If $\lambda \sim \mathcal{O}(0.1)$, $|\xi_h| \sim 10^4$,

$$\Lambda_{\rm INF} \sim M_{\rm Pl}/\sqrt{\xi_h} \sim 10^{16}{\rm GeV}$$

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 $|\xi_h| > 1$?

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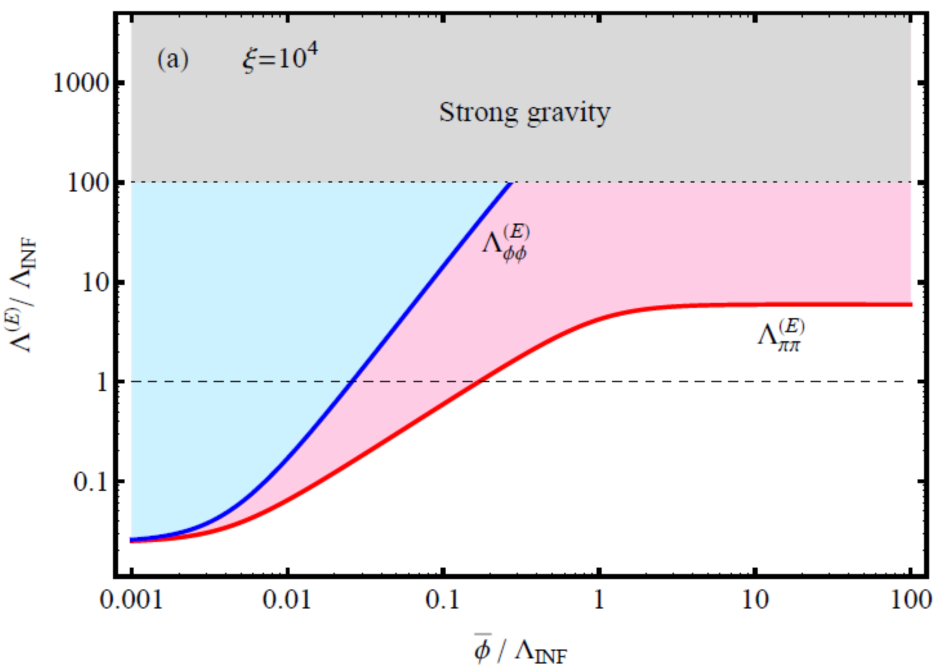
- Unitarity bound depends on background field

Bezrukov, et al.,
JHEP 101, 016 (2011)

  - Generalization to large field background $\bar{\phi} \gg v$
  - $\pi^+\pi^- \to \pi^0\pi^0$ provides the strongest bound



Probing Cubic Higgs Interactions at Hadron Collider

H.J. He, JR, W. Yao, arXiv: 1506. 03302

Motivation

- Higgs gravitational interaction

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- Higgs self-interactions crucial for electroweak symmetry breaking, electroweak phase transition and Higgs inflation…

- Higgs self-interactions difficult to measure
  - Cubic Higgs coupling: 50% accuracy on HL-LHC [Snomass Higgs Working Group Report, arXiv:1310.8361]
  - Quartic Higgs coupling: more challenging [Plehn, Rauch, Phys. Rev. D 72 (2005) 053008]

- Higgs self-interactions as the window to new physics

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)]

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

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- 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 couplings to SM particles rescaled by $\zeta = (1 + x_2)^{-1/2}$
  - Cubic Higgs coupling $h - h - h$:

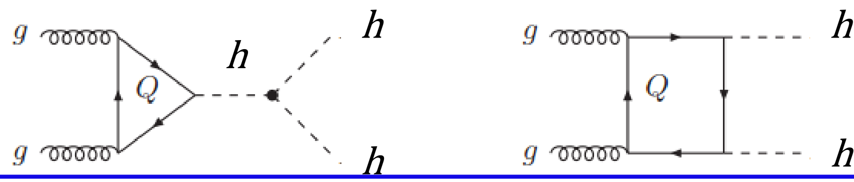
$$-\mathrm{i}\frac{3M_h^2}{v}\zeta\left(1 - x_3\zeta^2\frac{2v^2}{3M_h^2}\right) + \mathrm{i}\frac{x_2}{v}\zeta^3(p_1^2 + p_2^2 + p_3^2) = -\mathrm{i}\frac{\zeta}{v}\left[3\,(1+\widehat{r})\,M_h^2 - \widehat{x}\,(p_1^2 + p_2^2 + p_3^2)\,\right]$$

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

Dihiggs Production on Hadron Collider

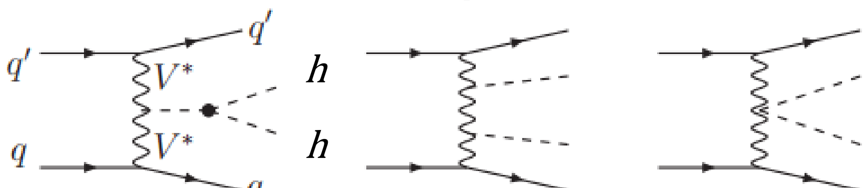
- Gluon fusion production: $gg \to hh$

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



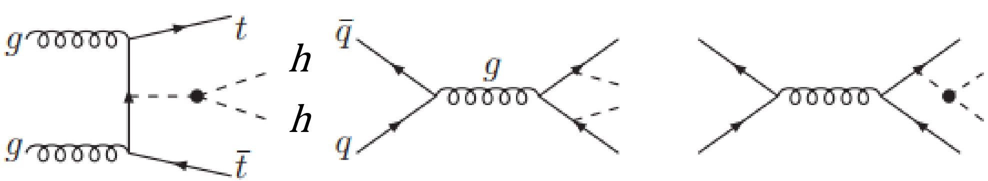
$$\left.\frac{\sigma}{\sigma_{\rm sm}}\right|_{100\rm TeV} = (1-\widehat{x})^2\,(1-0.72\,\widehat{r}+3.6\,\widehat{x}+0.22\,\widehat{r}^2+4.3\,\widehat{x}^2-1.7\,\widehat{r}\,\widehat{x})$$

- Vector boson fusion production: $pp \to hhjj$

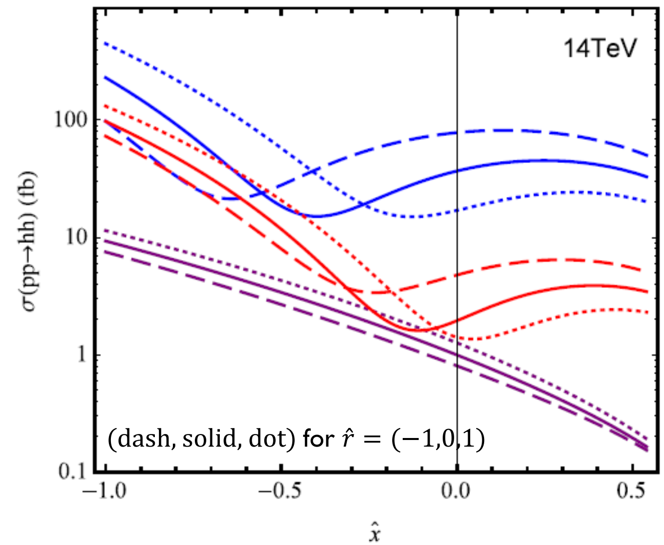


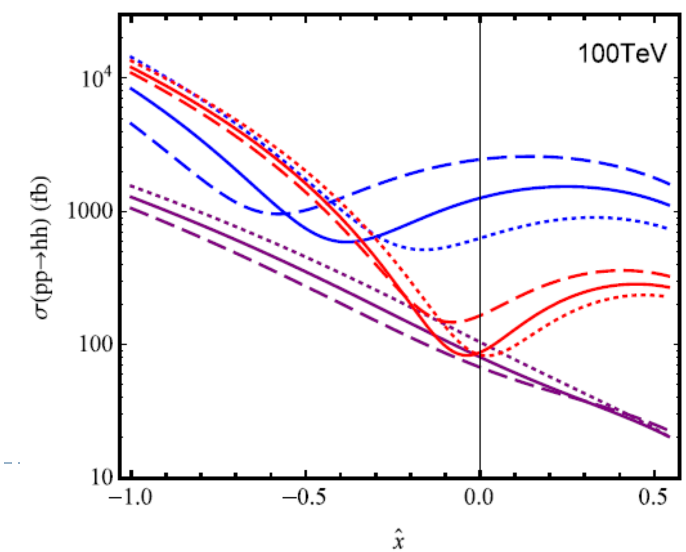
$$\left.\frac{\sigma}{\sigma_{\rm sm}}\right|_{100\rm TeV} = (1-\widehat{x})^2\,(1-0.47\,\widehat{r}+4.6\,\widehat{x}+0.42\,\widehat{r}^2+38\,\widehat{x}^2-4.1\,\widehat{r}\,\widehat{x})$$

- Top-pair associated production: $pp \to t\bar{t}hh$



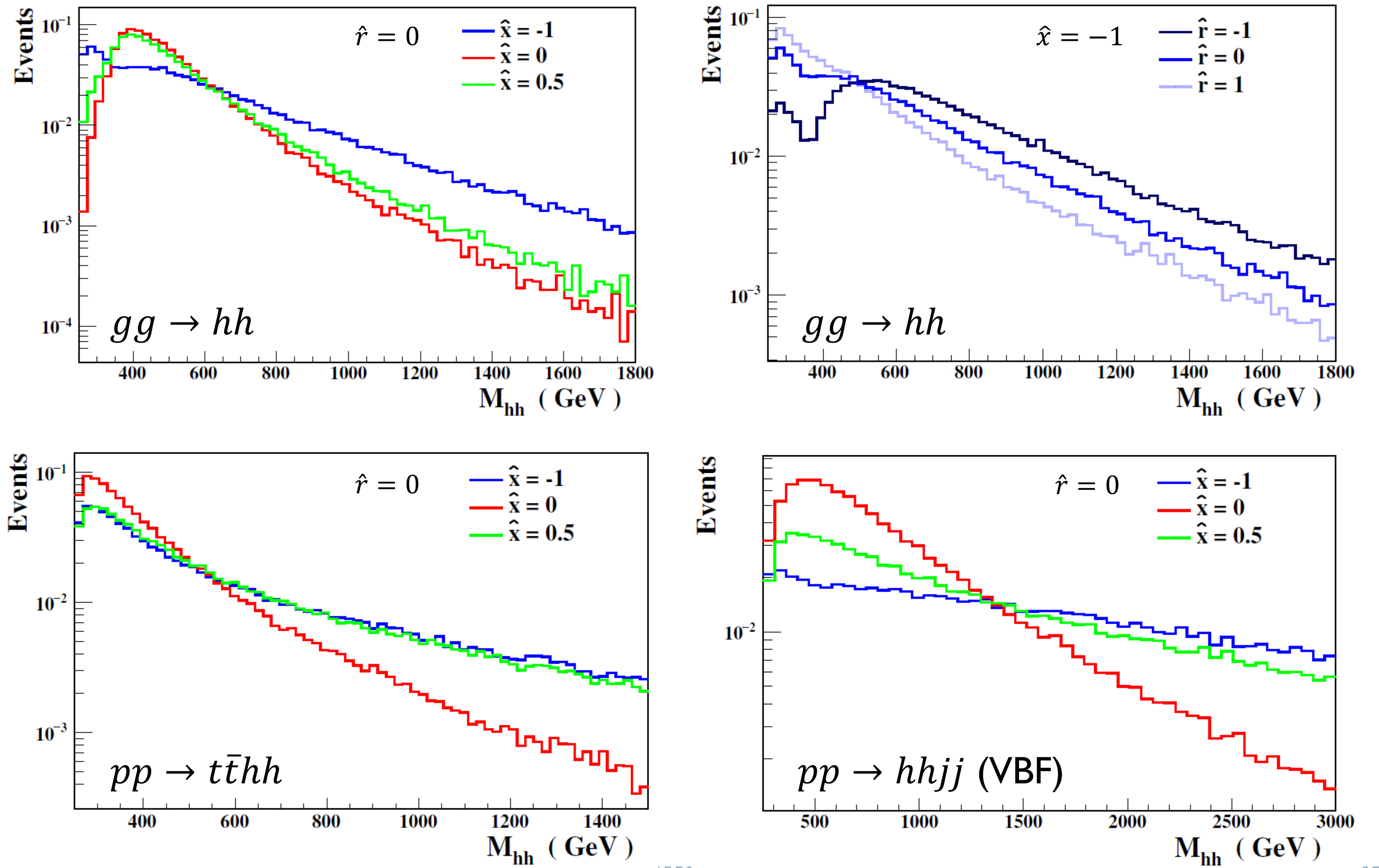
$$\left.\frac{\sigma}{\sigma_{\rm sm}}\right|_{100\rm TeV} = (1-\widehat{x})^2\,(1+0.23\,\widehat{r}-0.80\,\widehat{x}+0.07\,\widehat{r}^2+2.2\,\widehat{x}^2-0.54\,\widehat{r}\,\widehat{x})$$





K-factor: Frederix, et al, Phys. Lett. B 732 (2014) 142

Kinematic distributions @100TeV



Dihiggs Decay Channels

- Gluon fusion production
  - $b\bar{b}\gamma\gamma$: $\mathrm{BR}\sim 10^{-3}$, cleaner background
    - ATLAS at HL-LHC with $3ab^{-1}$: $S/\sqrt{B} = 1.3\sigma$ [ATL-PHYS-PUB-2014-019]
  - $b\bar{b}b\bar{b}$, $b\bar{b}\tau\tau$: larger BR, large background (boosted Higgs)

    [Ferreira de Lima, Papaefstathiou, Spannowsky, JHEP 1408 (2014) 030]

    [Barr, Dolan, Englertt, Spannowsky, Phys. Lett. B 728, 308 (2014)]
  - $b\bar{b}WW^*(b\bar{b}l\upsilon jj), WW^*WW^*(3l3\upsilon jj)$: refined analysis

    [Papaefstathiou, Yang, Zurita, Phys. Rev. D 87 (2013) 011301]

    [Li, Li, Yan, Zhao, arXiv:1503.07611 [hep-ph]]

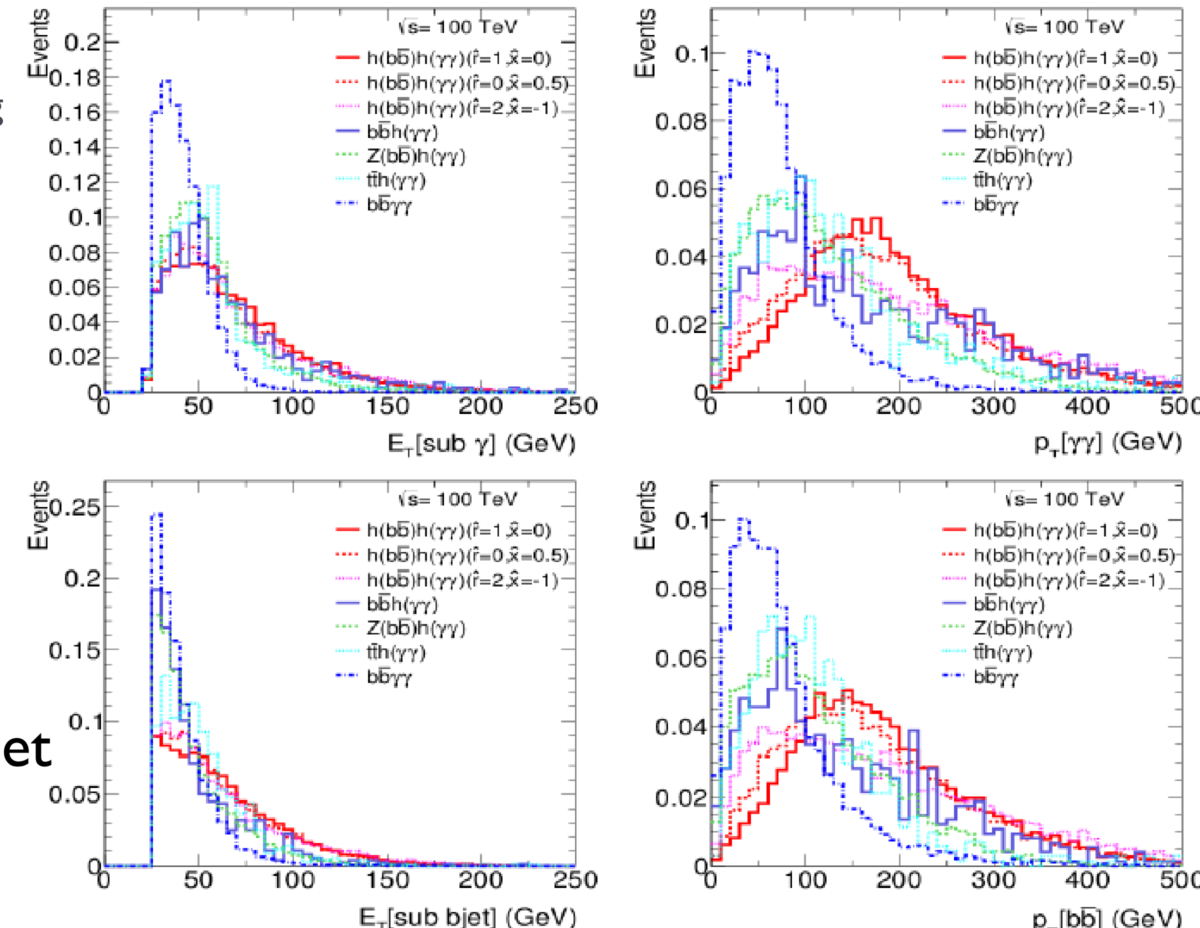
- Top pair associated production
  - $b\bar{b}b\bar{b}$: semileptonic top decay [Englert, Krauss, Spannowsky, Thompson, Phys. Lett. B 743 (2015) 93; Liu, Zhang, arXiv:1410.1855 [hep-ph].]

- Vector boson fusion production: large background from gluon fusion in VBF signal region.

[Dolan, Englert, Greiner, Spannowsky, Phys. Rev. Lett. 112 (2014) 101802; Dolan, Englert, Greiner, Nordstrom. Spannowsky, arXiv:1506.08008v1 [hep-ph]]

Full Analysis of $gg \to hh \to b\bar{b}\gamma\gamma$ @100TeV

- Events generation: Madgraph5, Pythia 6.2, Delphes 3 [W. Yao, arXiv:1308.6302 [hep-ph]]
  - Signal: include finite mt effect
  - Background: include up to one extra parton with MLM matching
  - Detector response based on ATLAS/CMS performance



- Background

  $b\bar{b}\gamma\gamma, b\bar{b}h(\gamma\gamma)$

  $Z(b\bar{b})h(\gamma\gamma), \bar{t}th(\gamma\gamma)$

  $\bar{t}t\gamma\gamma, \bar{t}t\gamma$

  $b\bar{b}j\gamma$ ($b\bar{b}jj$) (jet-faking-photon)

  $jj\gamma\gamma$ (mis-tagging b or $\bar{b}$)

- Selected photon and b-jet

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

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

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

Full Analysis of $gg \to hh \to b\bar{b}\gamma\gamma$ @100TeV

- Selection cuts [W. Yao, arXiv:1308.6302 [hep-ph]]

$$M_{b\bar{b}\gamma\gamma} > 300\,\text{GeV} \quad \Delta R_{\gamma\gamma} < 2.5\,, \quad \Delta R_{b\bar{b}} < 2.0$$

$$p_T^{\gamma},\, p_T^{b} > 35\,\text{GeV}, \quad p_T^{\gamma\gamma},\, p_T^{b\bar{b}} > 100\,\text{GeV} \quad |\cos\theta_h| < 0.8$$ (Higgs decay angle)

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

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

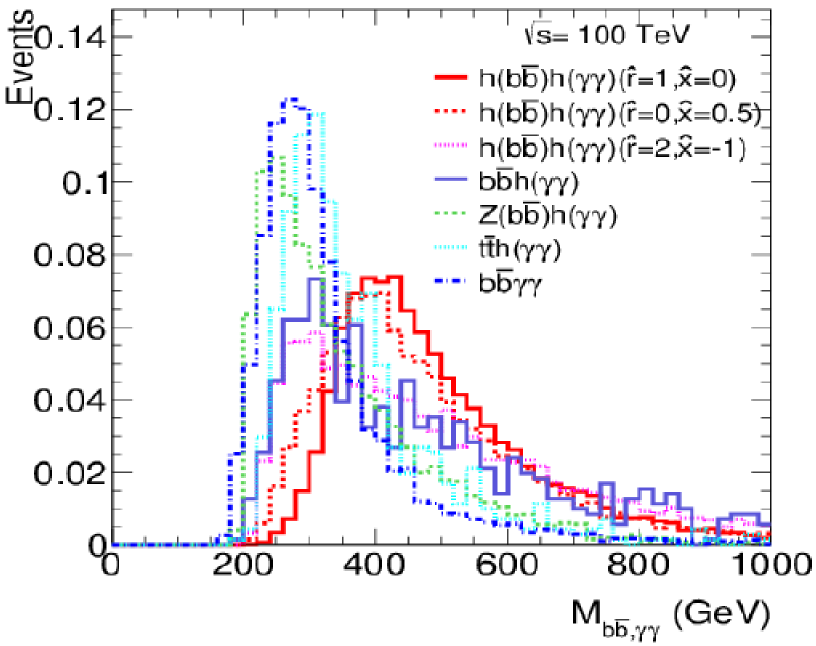
Samples	$\sigma \times$BR (fb)	Generated Evt	Selected Evt	Accept	Expected
$h(b\bar{b})h(\gamma\gamma)$ (SM)	3.53	100000	3955	0.040	418.8 ± 6.6
$\boxed{b\bar{b}h(\gamma\gamma)}$	50.49	99611	78	0.00078	118.6 ± 13.4
$Z(b\bar{b})h(\gamma\gamma)$	0.8756	68585	378	0.0055	14.5 ± 0.7
$\boxed{t\bar{t}h(\gamma\gamma)}$	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
$\boxed{b\bar{b}\gamma\gamma}$	5037	763962	11	1.4e-05	217.6 ± 65.6
$\boxed{b\bar{b}j\gamma}$	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
$S/\sqrt{B}$ ($S/\sqrt{B+S}$)	–	–	–	–	16.5 (12.8)

Barr, Dolan, Englert, Ferreira de Lima, Spannowsky, JHEP 1502 (2015) 016 [arXiv:1412.7154 [hep-ph]]
Azatov, Contino, Panico and Son, arXiv:1502.00539 [hep-ph]

Discrimination of Two Operators

- Utilize distribution in reconstructed M_{hh} bins

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

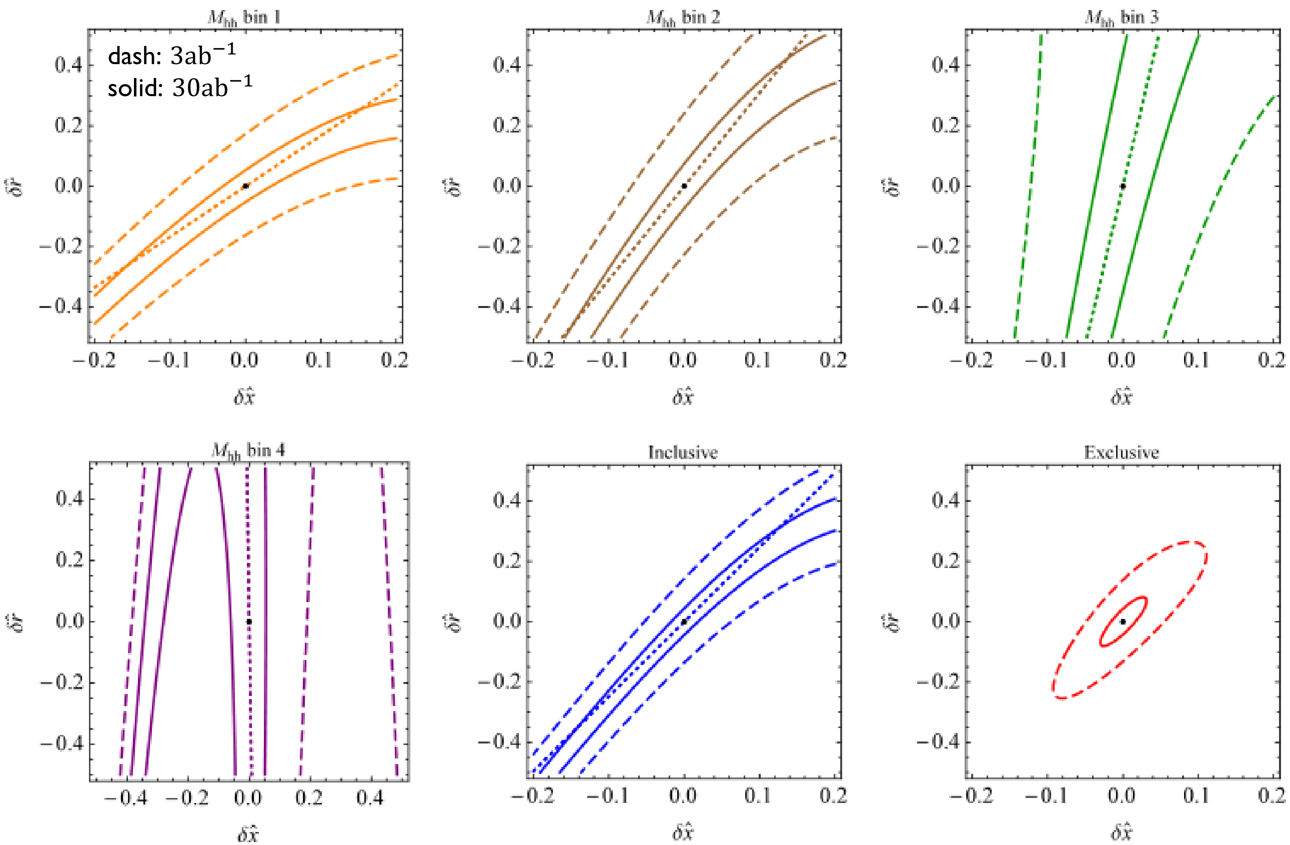


M_{hh} bins (GeV)	[300, 500]	[500, 700]	[700, 900]	[900, 1100]
$h(b\bar{b})h(\gamma\gamma)$ (SM)	200	170	52.5	11.1
$b\bar{b}h(\gamma\gamma)$	67.1	31.9	15.8	3.81
$Z(b\bar{b})h(\gamma\gamma)$	11.2	2.77	0.46	0.04
$t\bar{t}h(\gamma\gamma)$	97.5	15.9	3.22	0.58
$t\bar{t}\gamma\gamma$	5.41	1.1	0.24	0.0
$t\bar{t}\gamma$	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

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

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

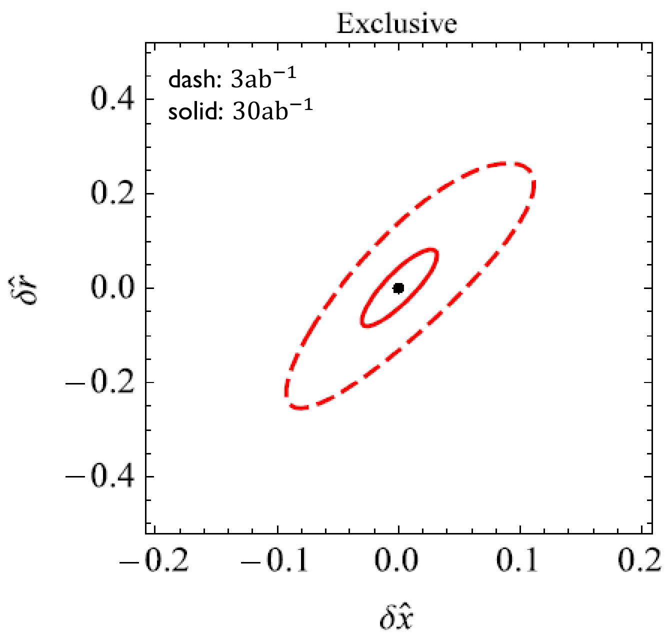
Sensitivity on $(\hat{r}, \hat{x})$ Plane: SM

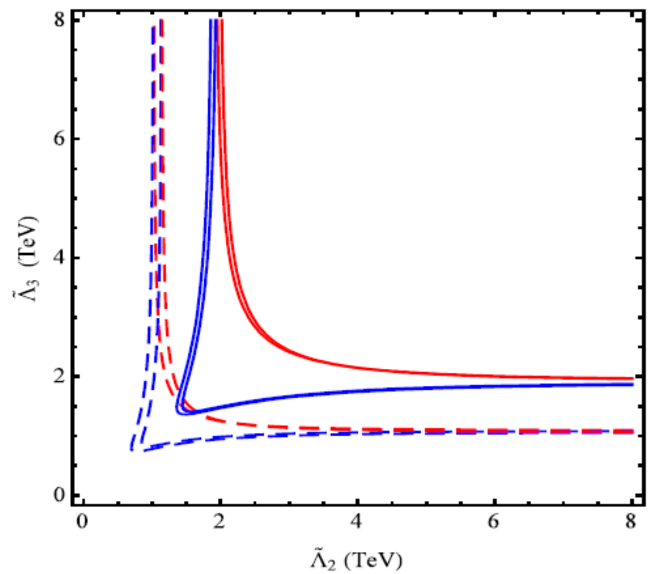


- $(\hat{\boldsymbol{r}}, \hat{\boldsymbol{x}}) = (0,0)$
- Degenerate direction around origin
- Exclusive analysis breaks degenerate direction
- 1d sensitivity: $\delta\hat{r} \sim 13\%(4\%)$, $\delta\hat{x} \sim 5\%(1.6\%)$
- The weakest 2d sensitivity: $\delta\hat{r} \sim 25\%(8\%)$, $\delta\hat{x}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

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

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

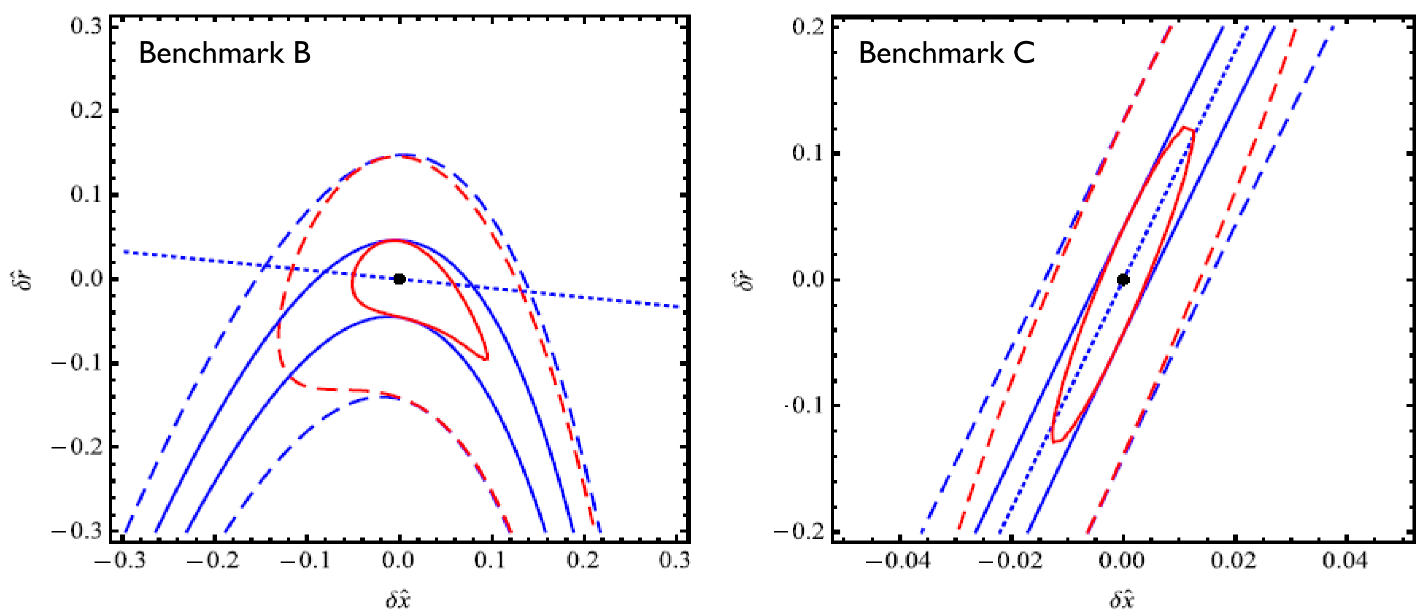




- Exclusive analysis translated as probe of the effective cutoffs
- Tow cases: $x_2 x_3 > 0$ (red), $x_2 x_3 < 0$ (blue)
- 1d sensitivity: $\widetilde{\Lambda}_2, \widetilde{\Lambda}_3 \gtrsim 1(2)$ TeV
- Weakest 2d sensitivity: $\widetilde{\Lambda}_2, \widetilde{\Lambda}_3 \gtrsim 0.75(1.4)$ TeV

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

- Sensitivity contours qualitatively different
  - Benchmark B: $(\hat{r}, \hat{x}) = (-0.5, 0.2)$, low invariant mass bins (dominant) insensitive to $\hat{x}$
  - Benchmark C: $(\hat{r}, \hat{x}) = (1, -0.5)$, all bins sensitive to $\hat{x}$ and similar



Summary

- Studied impact of the unique non-minimal higgs-gravity coupling on Higgs physics and weak boson scattering. The perturbative analysis of slow-roll Higgs inflation is reliable.

- Measurement of derivative cubic Higgs couplings on hadron collider by dihiggs production with distinctive kinematic feature. 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. Sensitivity qualitatively different for various benchmark points.

Thank You!

Higgs Inflation v.s. Electroweak Physics

- Make connection between EW physics and inflation
  - Unitarity problem at (p)reheating
  - Generalization to get rid of the lower cutoff $M_{\rm Pl}/|\xi_h|$, e.g. add a singlet. Giudice, Lee PLB 694, 294 (2011); Barbon, et al. arXiv:1501.02231

- Ambiguity to calculate quantum correction Bezrukov, et al. arXiv:1307.0708
  - EFT at inflation with approximate shift symmetry

$$\mathcal{L} = f^{(1)}(\chi)\frac{(\partial_\mu\chi)^2}{2} - U(\chi) + f^{(2)}(\chi)\frac{(\partial^2\chi)^2}{M^2} + f^{(3)}(\chi)\frac{(\partial\chi)^4}{M^4} + \dots \qquad f^{(i)}(\chi) = \sum_{n=0}^{\infty} f_n^{(i)} e^{-\frac{2n\chi}{\sqrt{6}M}}$$

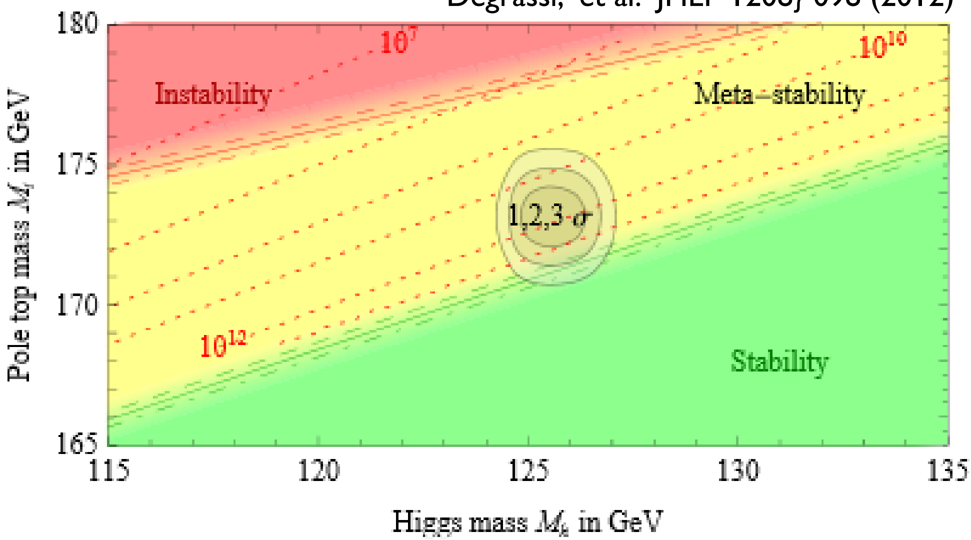
  - Use DREG, but subtraction has arbitrariness

$\mu^2/M_P^2 \propto$	Einstein frame	Jordan frame
Choice I	$F_I^2 = 1$	$F_I^2 = \frac{M_P^2 + \xi h^2}{M_P^2}$
Choice II	$F_{II}^2 = \frac{M_P^2}{M_P^2 + \xi h^2}$	$F_{II}^2 = 1$

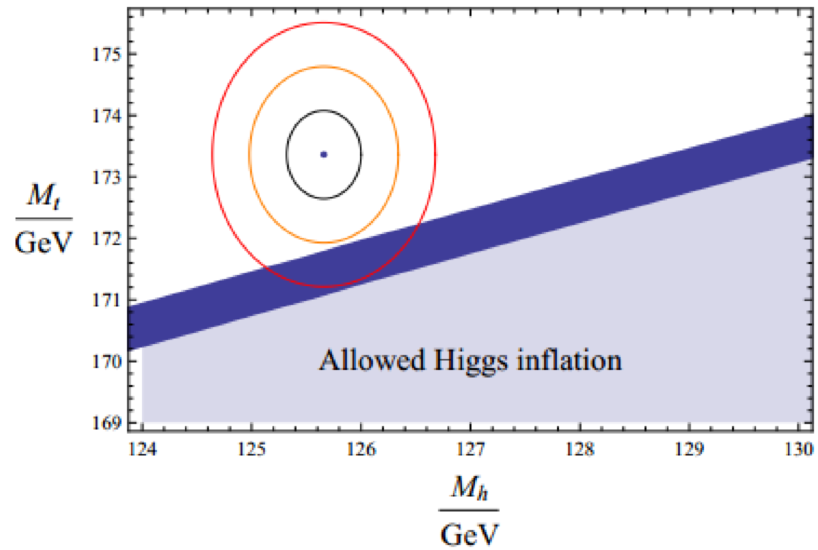
Higgs Inflation v.s. Vacuum Stability

- SM vacuum stability

Degrassi, et al. JHEP 1208} 098 (2012)



Alberto Salvio, Phys. Lett. B 727, 234 (2013)



- Maybe no need of absolute stability
  - Sensitive to higher order terms at $M_{\rm Pl}/|\xi_h|$: effective δy_t in RGE
  - Thermal correction after (p)reheating

Bezrukov, Rubio, Shaposhnikov, arXiv:1412.3811; Rubio, arXiv:1502.07952.

Higgs Inflation with large r

- BICEP2: $r \sim 0.2$ (BKP-joint: $r \lesssim 0.1$)
- Critical regime
  - Flatness due to λ running, $|\xi_h| \sim \mathcal{O}(10-100)$
  - Inflation scale: $\Lambda_{\rm INF} \sim 10^{16}{\rm GeV} \ll M_{\rm Pl}/\sqrt{|\xi_h|}$
- Background dependent unitarity bound

Hamada, Kawai, Oda, Park, arXiv:1403.5043;
Allison, JHEP 02 (2014) 040