Anatomy of tthh Physics

Ying-Ying Li
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[L. Li, YYL, T. Liu, arXiv:1905.03772]

[P. Asadi, N. Craig, YYL, arXiv:1810.09467]

June 05, 2019
43rd Johns Hopkins Workshop

Outline

I will focus on tthh channel, talk about its potential in

Higgs Trilinear Coupling Measurement

Contact Interaction Measurement

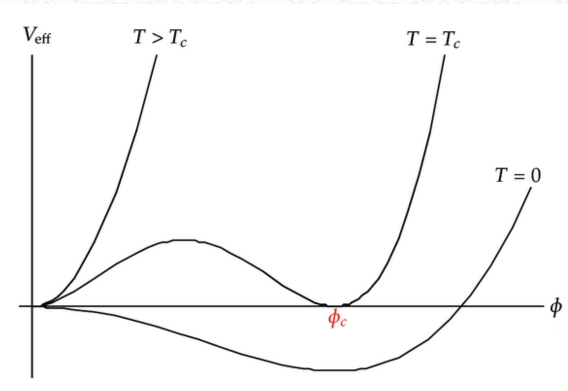
Resonant Search

heavy fermions, heavy scalars in turtling models/MSSM

BDT analysis and Results

Conclusion and Outlook

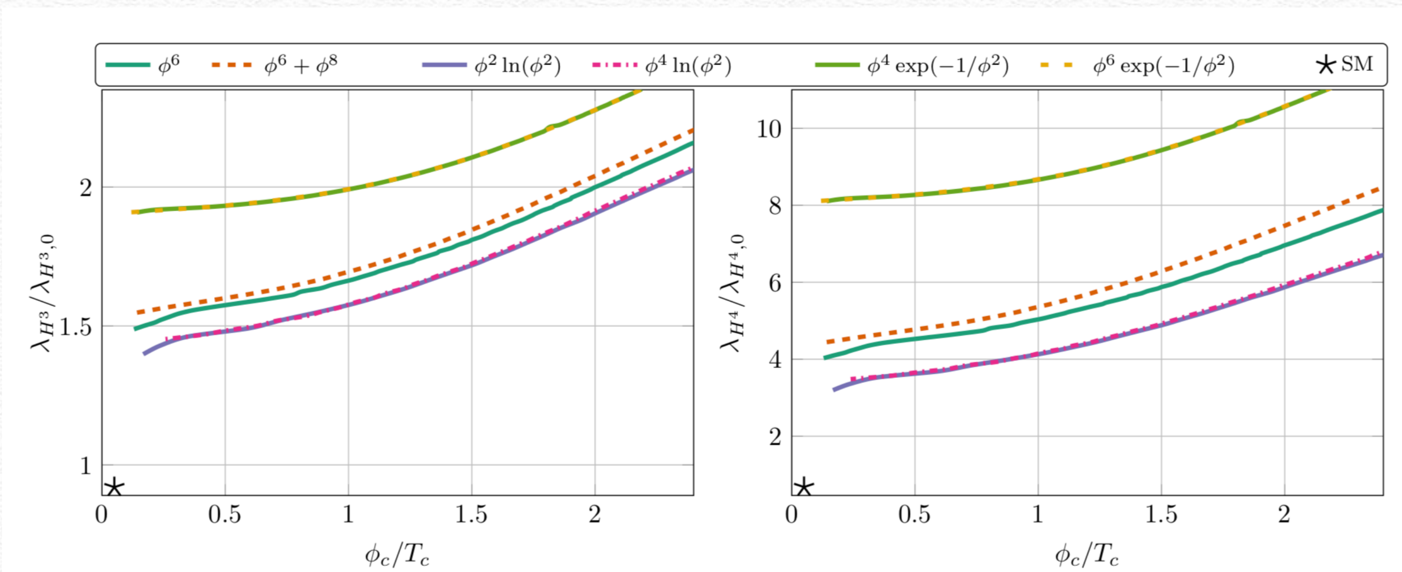
Higgs trilinear Coupling



1, Electroweak baryongenesis: out of equilibrium

strong first order phase transition
$\phi_c/T_c \gtrsim 1$

baryon asymmetry preserved



[M. Reichert, et al. arXiv:1711.00019]

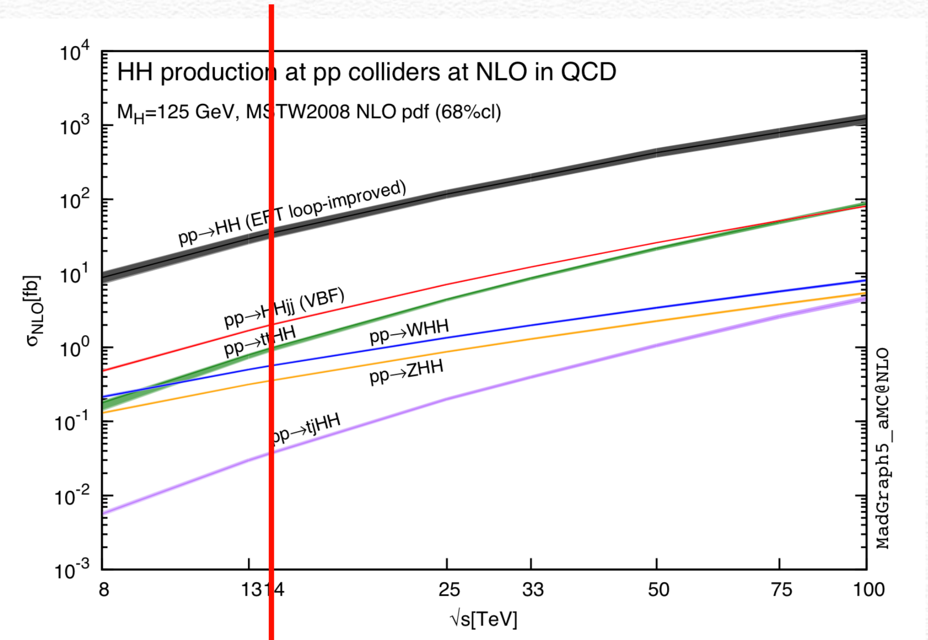
2, deviation of trilinear coupling -> unitarity bound of scale of new physics

[S. Chang, et al. arXiv:1902.05556]

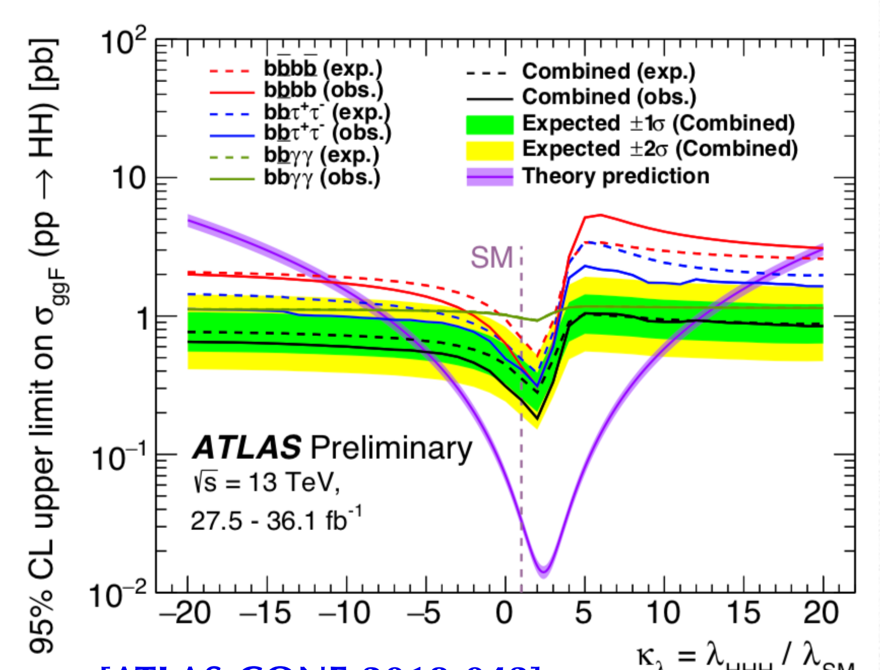
[A. Falkowski, et al. arXiv:1902.05936]

[see Spencer's talk tomorrow]

Higgs trilinear Coupling

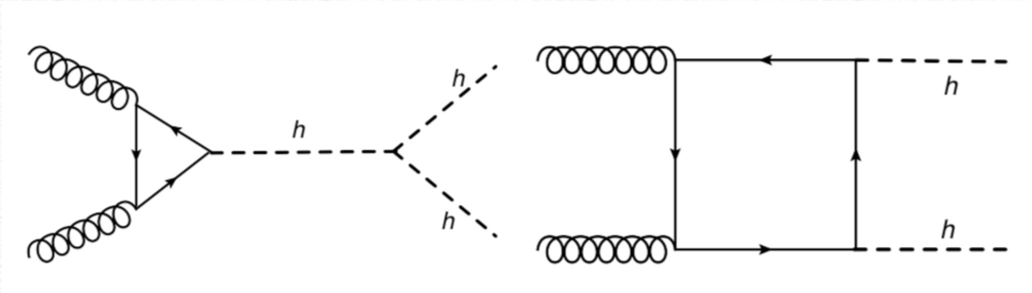


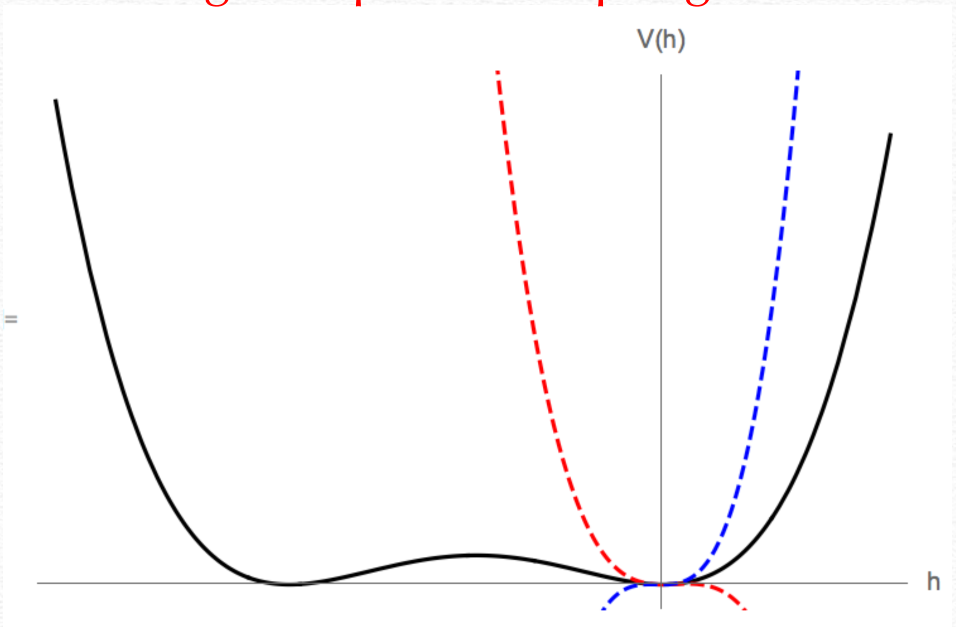
[R. Frederix, et al. arXiv:1401.7340]



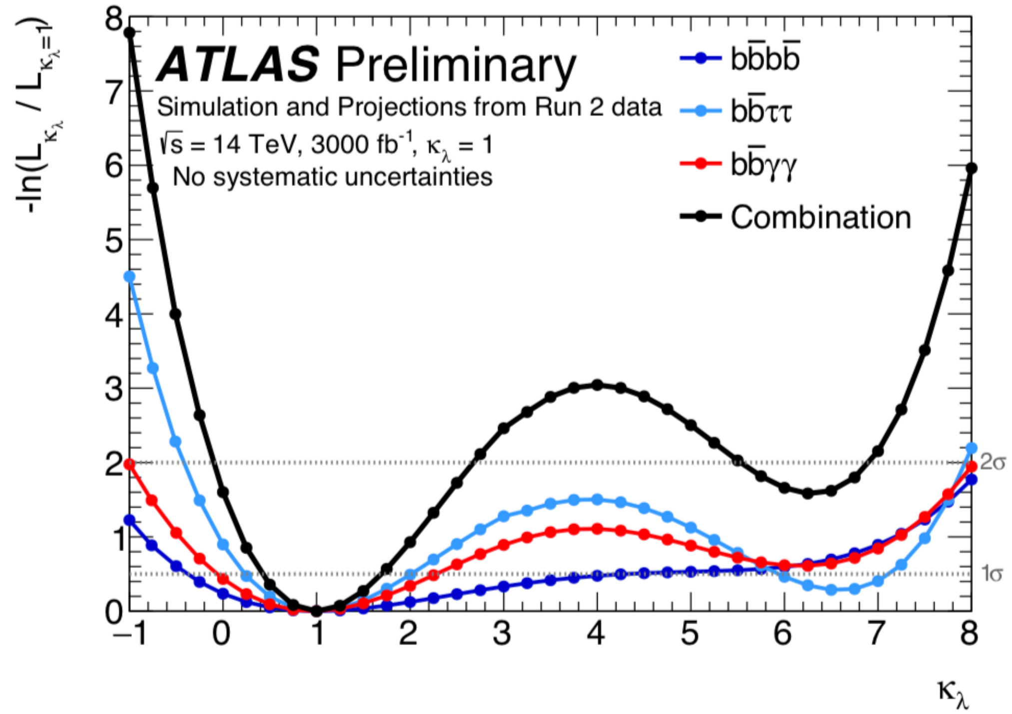
[ATLAS-CONF-2018-043]

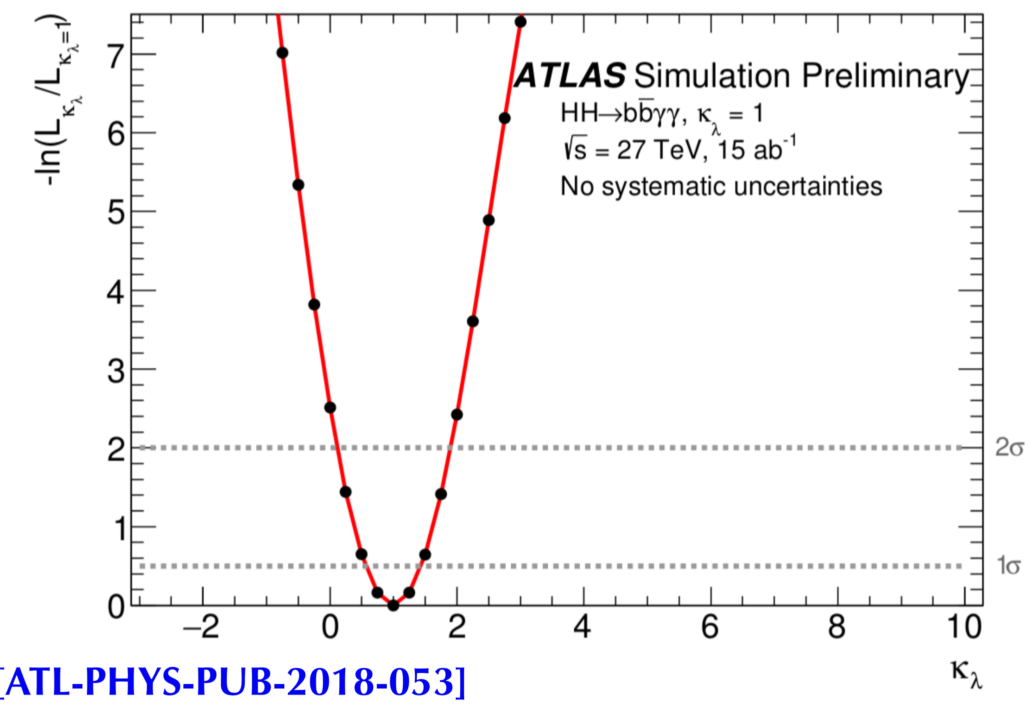
Assuming SM quartic coupling



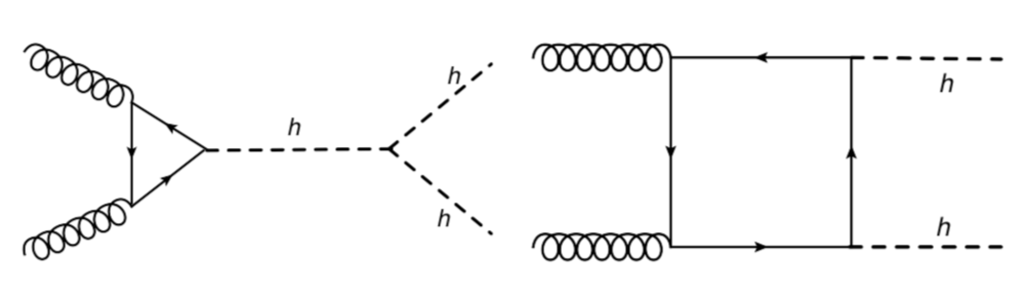


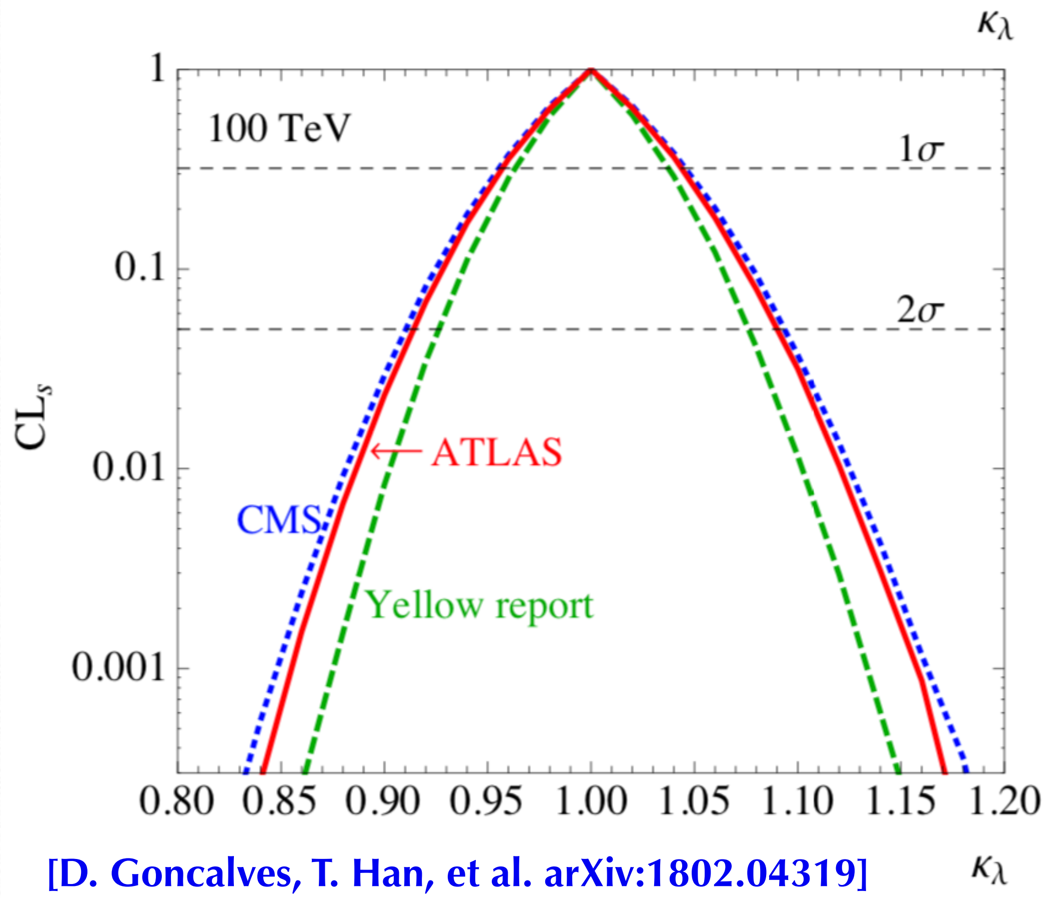
Higgs trilinear Coupling





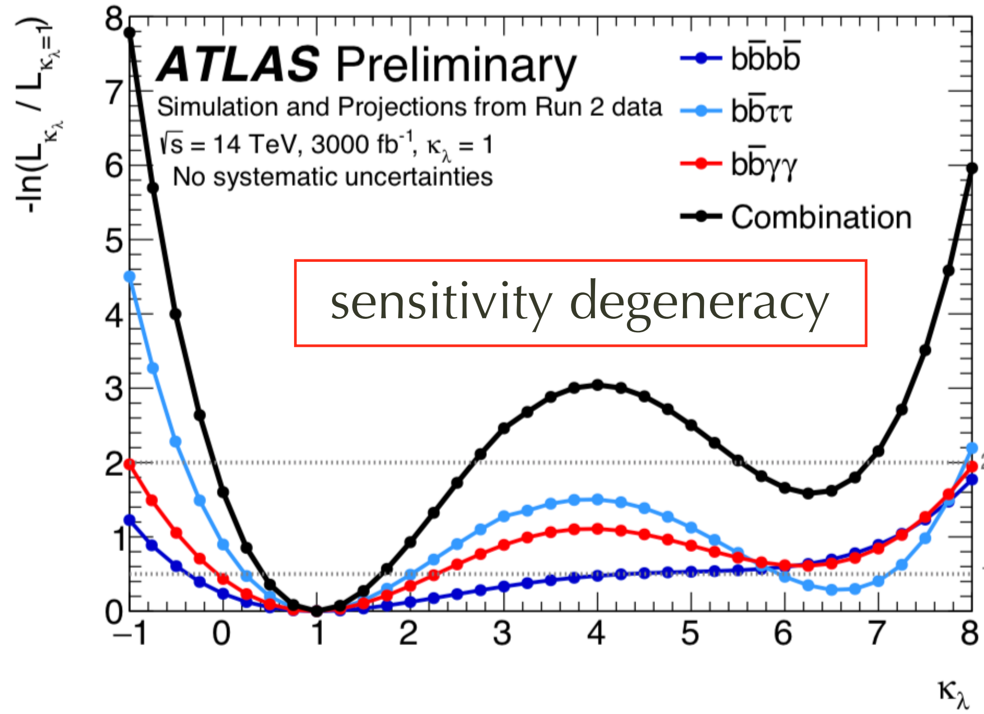
[ATL-PHYS-PUB-2018-053]
[…many other works]

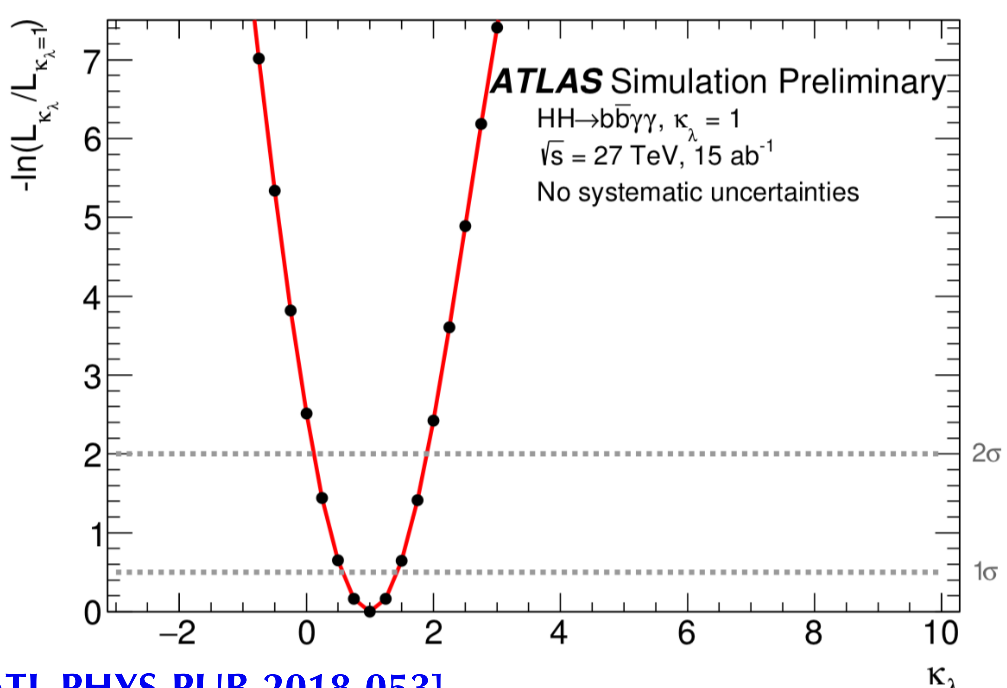




[D. Goncalves, T. Han, et al. arXiv:1802.04319]
[…many other works]

Higgs trilinear Coupling





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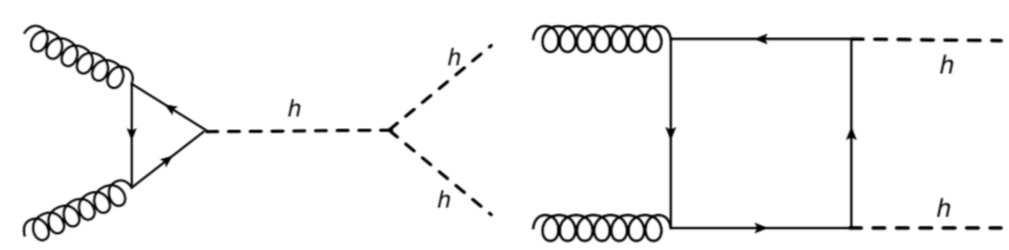

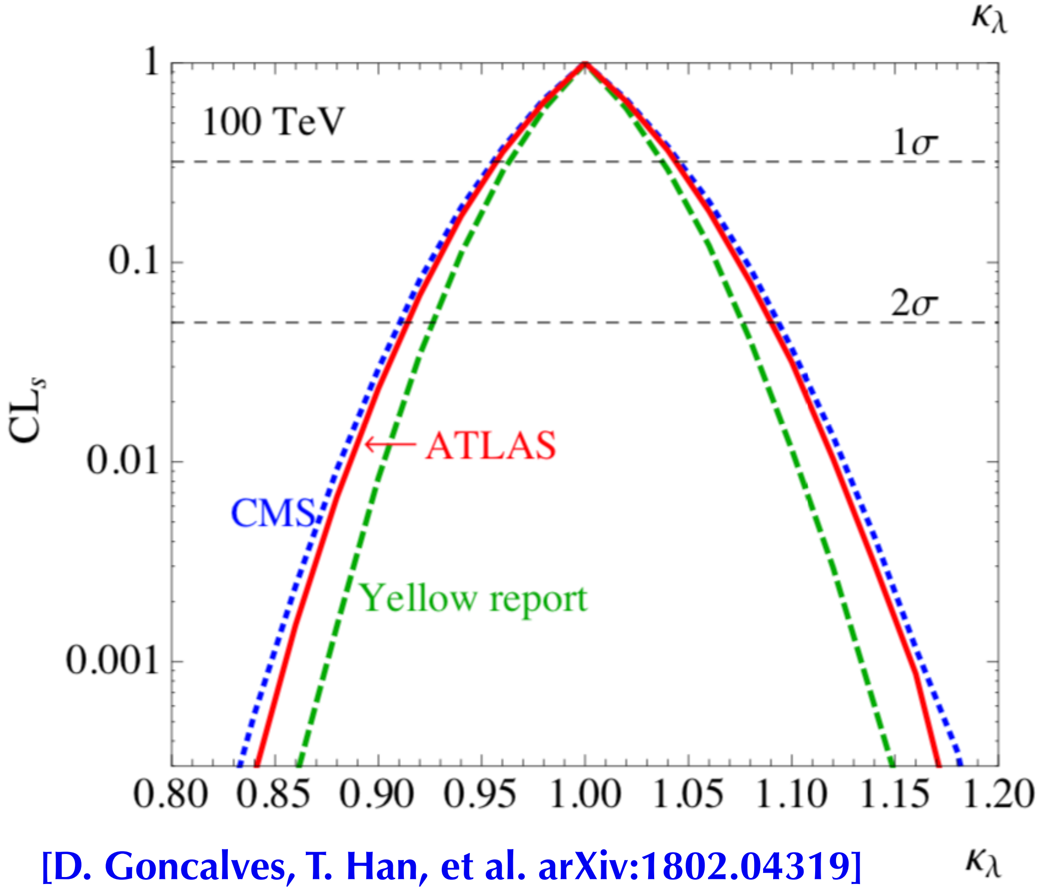

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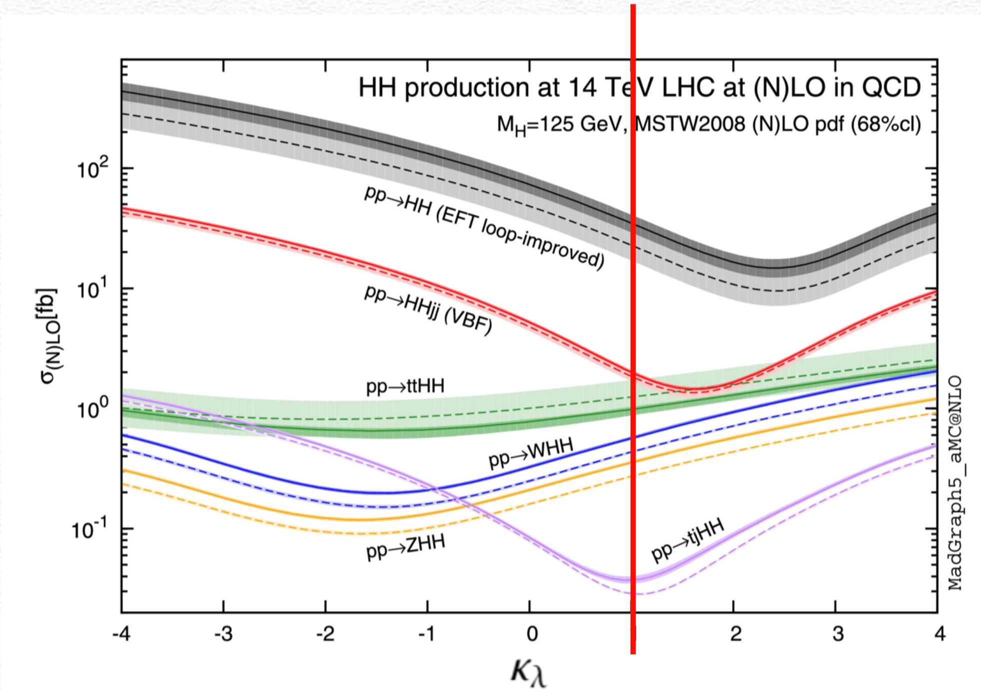
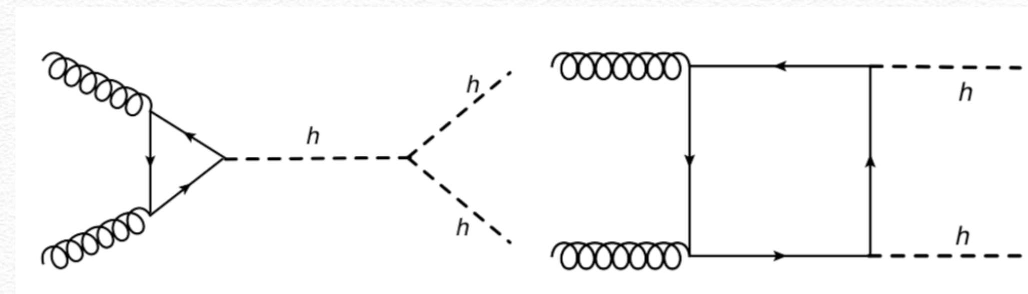
Higgs trilinear Coupling

[R. Frederix, et al. arXiv:1401.7340]

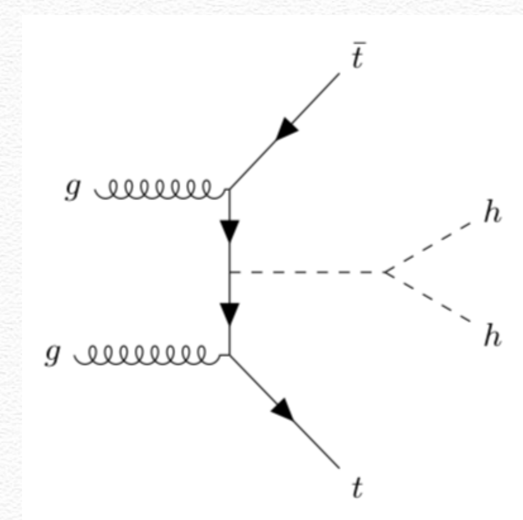


destructive interference



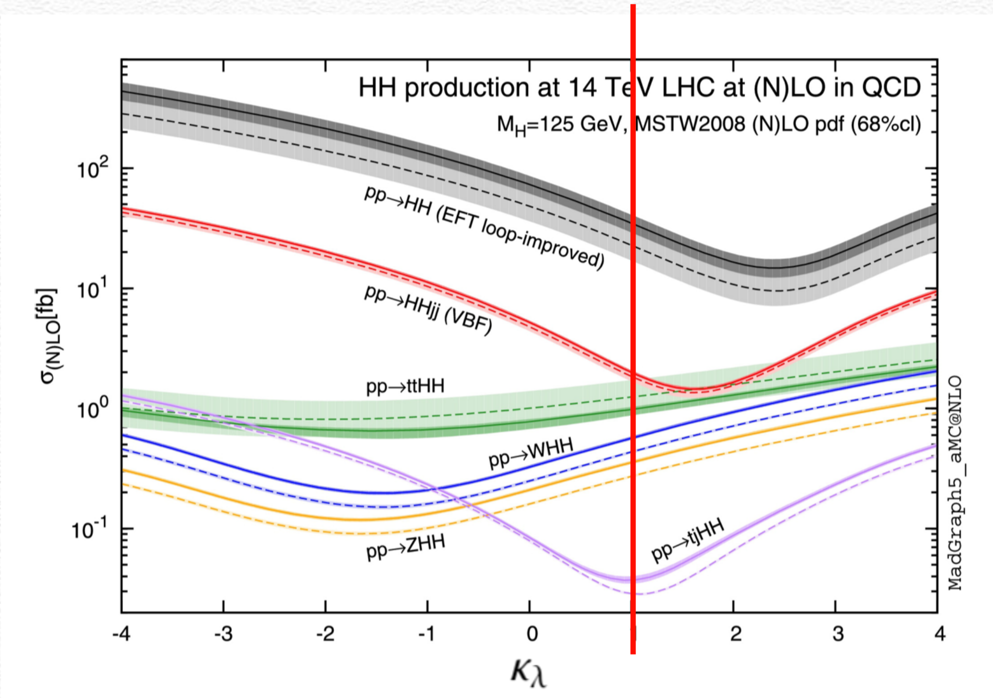
sensitivity degeneracy for gluon fusion di-Higgs production;

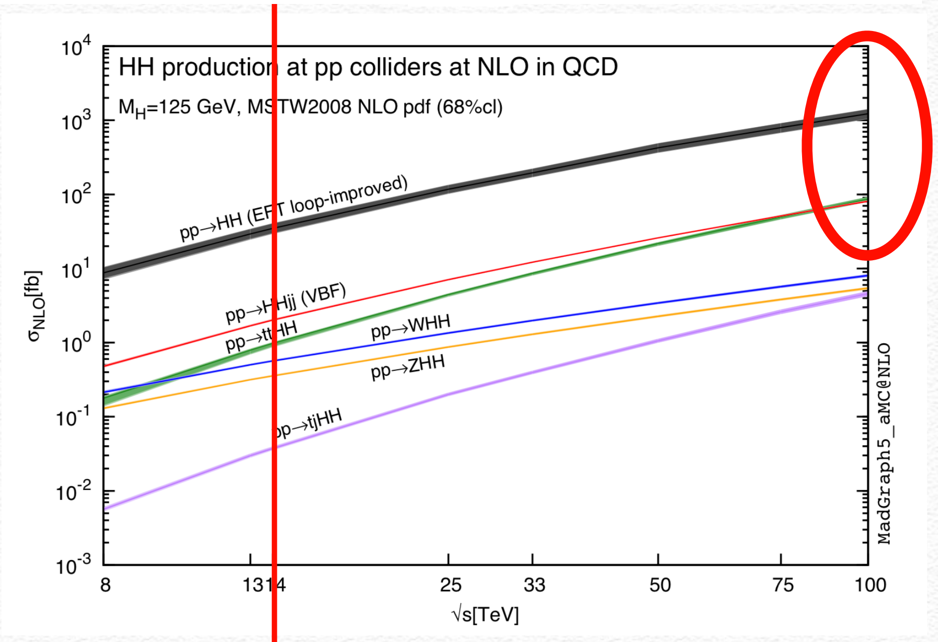
tthh channel: constructive interference for enhanced trilinear coupling;



tthh—Higgs trilinear coupling

[R. Frederix, et al. arXiv:1401.7340]





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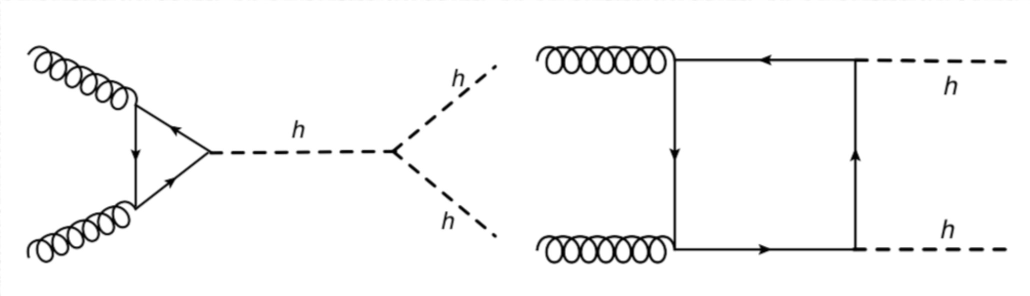
destructive interference



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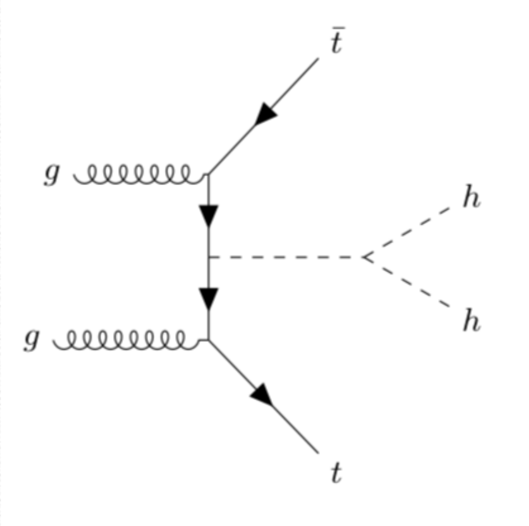

tthh could play a complementary role!

tthh—contact interactions

[L. Li, YYL, T. Liu, arXiv:1905.03772]

$$\mathcal{L} \supset -y\frac{m_t}{v}t\bar{t}h - \kappa\frac{1}{3!}\frac{3m_h^2}{v}h^3 - c_t\frac{1}{2!}\frac{m_t}{v^2}t\bar{t}hh$$

Assuming SM top Yukawa coupling

$$\frac{\sigma(gg \to hh \to bb\gamma\gamma)_{14}}{\sigma(gg \to hh \to bb\gamma\gamma)_{14}^{\rm SM}} = 1.70 - 0.82\kappa + 0.12\kappa^2 - 3.79c_t + 0.98c_t\kappa + 2.68c_t^2$$

$$\frac{\sigma(tthh)_{14}}{\sigma(tthh)_{14}^{\rm SM}} = 0.82 + 0.14\kappa + 0.04\kappa^2 + 0.28c_t + 0.21\kappa c_t + 0.44c_t^2$$

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tthh channel: constructive interference for enhanced trilinear coupling and enhanced contact interactions;

tthh—Resonance Search—fermions

direct search for new states, highly motivated by naturalness

Coloured vector-like top partners are predicted in natural models, e.g. Composite Higgs

[R. Contino, et al. arXiv:hep-ph/0612190]

Singlet, e.g. little higgs,
decay via its mixing with SM top quark

$$BR(T \to th) \sim BR(T \to tZ) \sim \frac{1}{2} BR(T \to Wb) \sim 25\%$$

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Doublet, top quark mixes more with its partner than bottom quark

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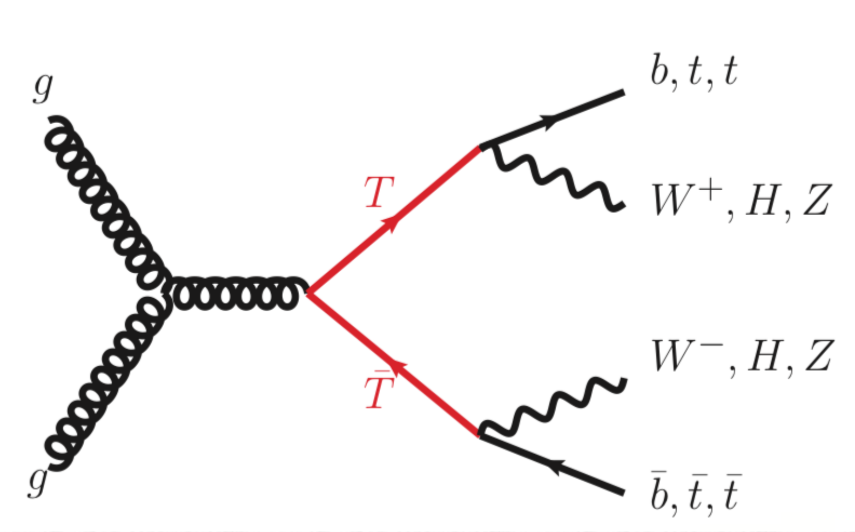

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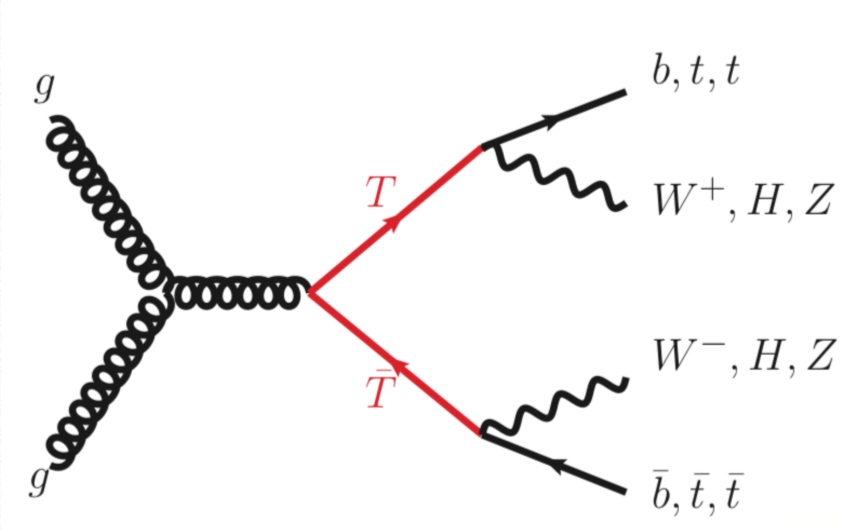
Current bound: 1.3TeV [ATLAS, arXiv:1808.02343]



Re-introduce tuning:
neutral naturalness model,
e.g. twin Higgs model

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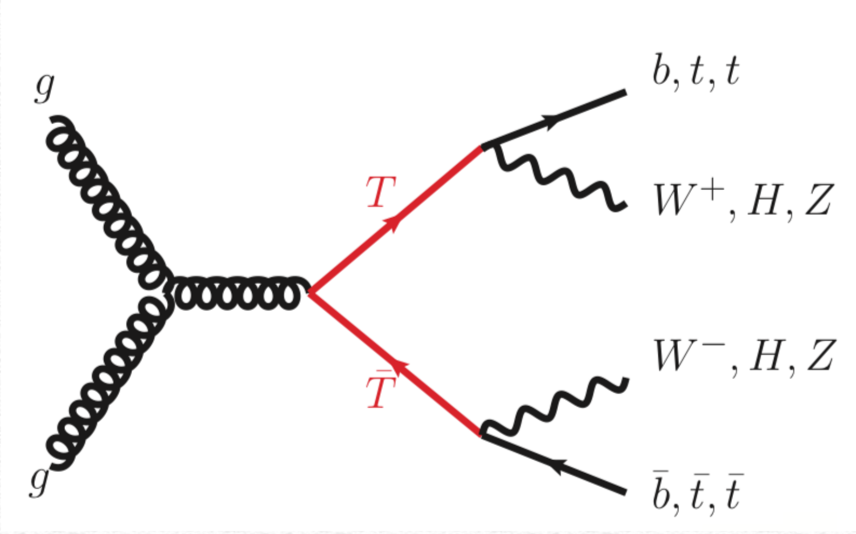

Re-introduce tuning:
neutral naturalness model,
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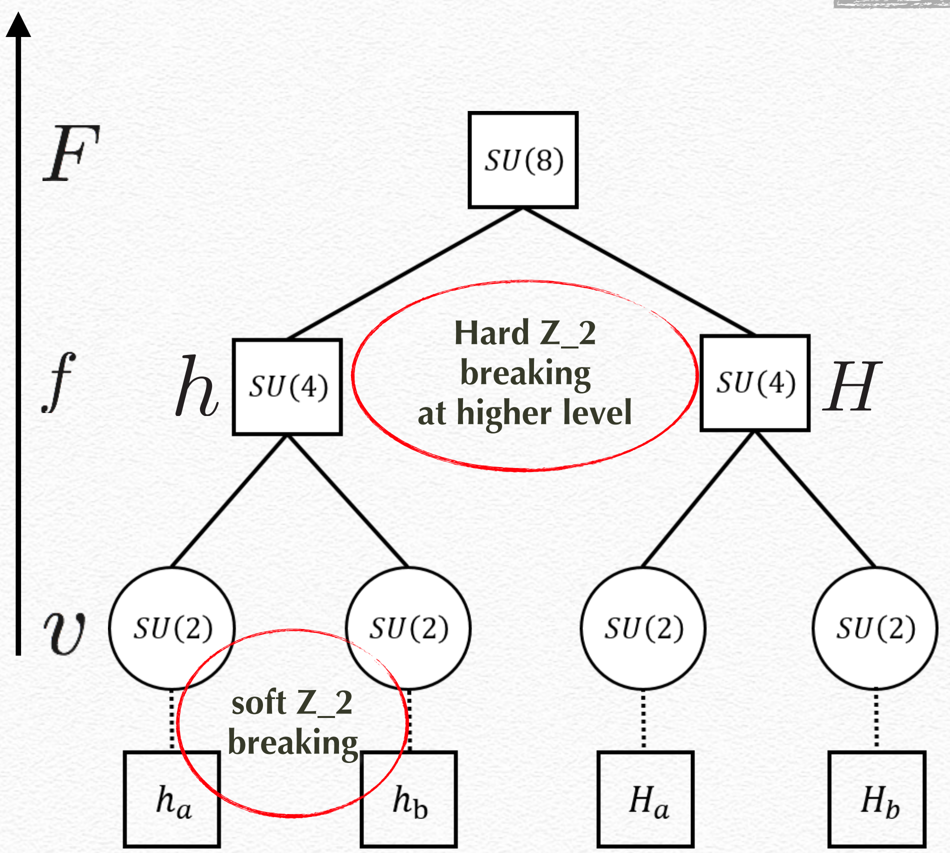
twin Higgs model need to be further extended to push the coloured top partner out of reach.

tthh—Resonance Search—scalars

direct search for new states, highly motivated by naturalness

[P. Asadi, N. Craig, YYL, arXiv:1810.09467]

Twin Turtles



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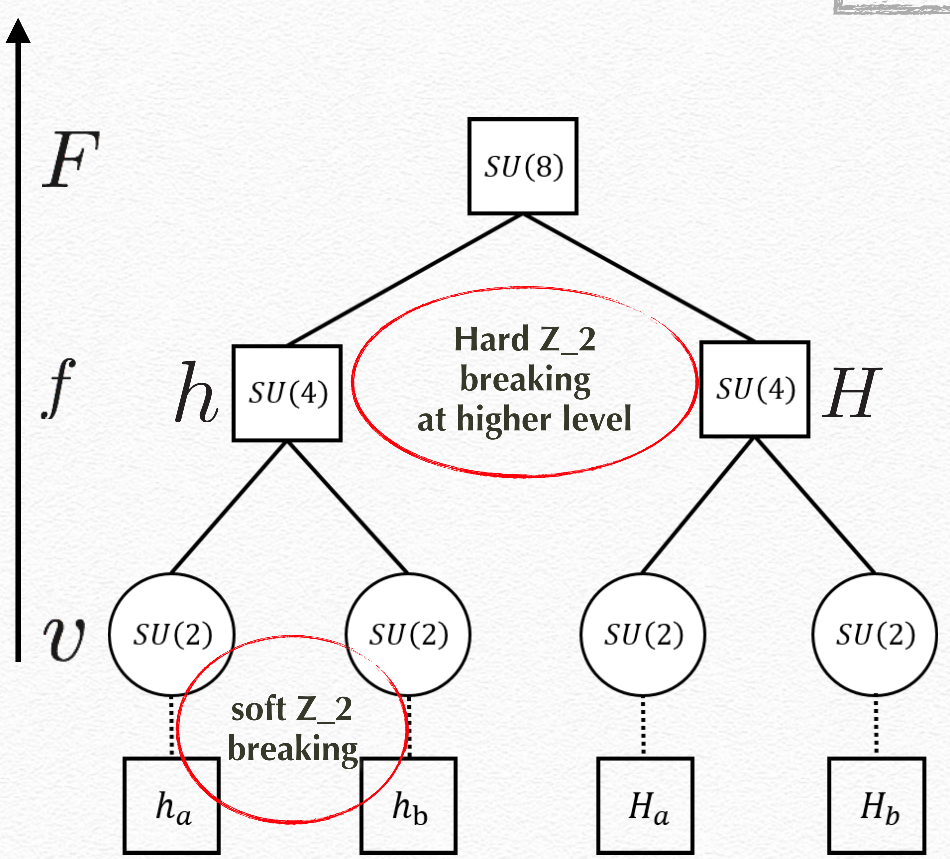

$$\Delta^{\rm TMNT}_{v/\Lambda} \approx \frac{1}{64\pi^2}\frac{\bar\kappa}{2\bar\kappa+\bar\rho}\left(\frac{3y_t^2}{\bar\lambda}\frac{\Lambda_t^2}{v^2} - \left(9+5\epsilon_\pm\frac{\bar\rho}{\bar\kappa}\right)\frac{\Lambda_\rho^2}{v^2}\right)$$

$$\Delta^{\rm SM}_{v/\Lambda} \approx \frac{1}{32\pi^2}\left(\frac{3y_t^2}{\lambda_{\rm SM}}\frac{\Lambda_t^2}{v^2} - 3\frac{\Lambda_\rho^2}{v^2}\right)$$

$$\begin{aligned} V \supset\ & \bar\lambda(|h|^2+|H|^2)^2 + m^2(|h|^2+|H|^2) + \bar\kappa(|h|^4+|H|^4) + \bar\rho|h|^4 + m_h'^2|h|^2 \\ +\ & \rho''(|h_a|^2+|H|^2)^2 + \kappa''(|h_a|^4+|h_b|^4+|H_a|^4+|H_b|^4) \\ +\ & \kappa'(|h_a|^4+|h_b|^4) + \rho'|h_a|^4 + \mu'^2|h_a|^2. \end{aligned}$$

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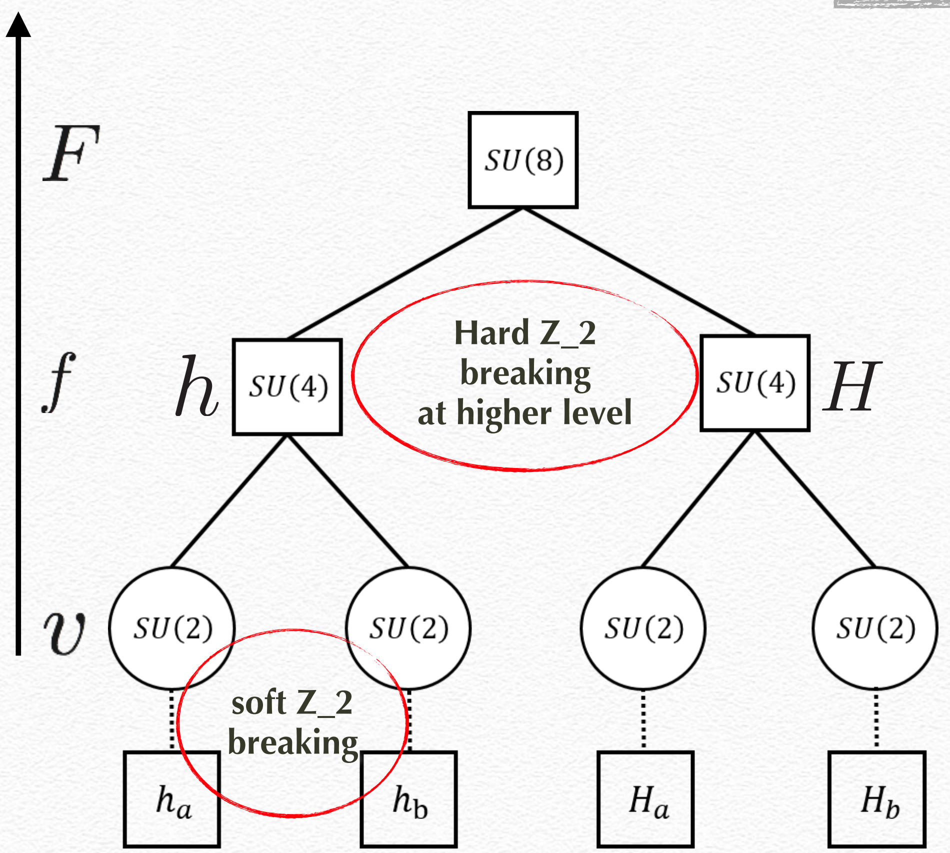

More scalars are introduced to push up the scale of coloured states!

Higgs like scalars -> definite signature of naturalness

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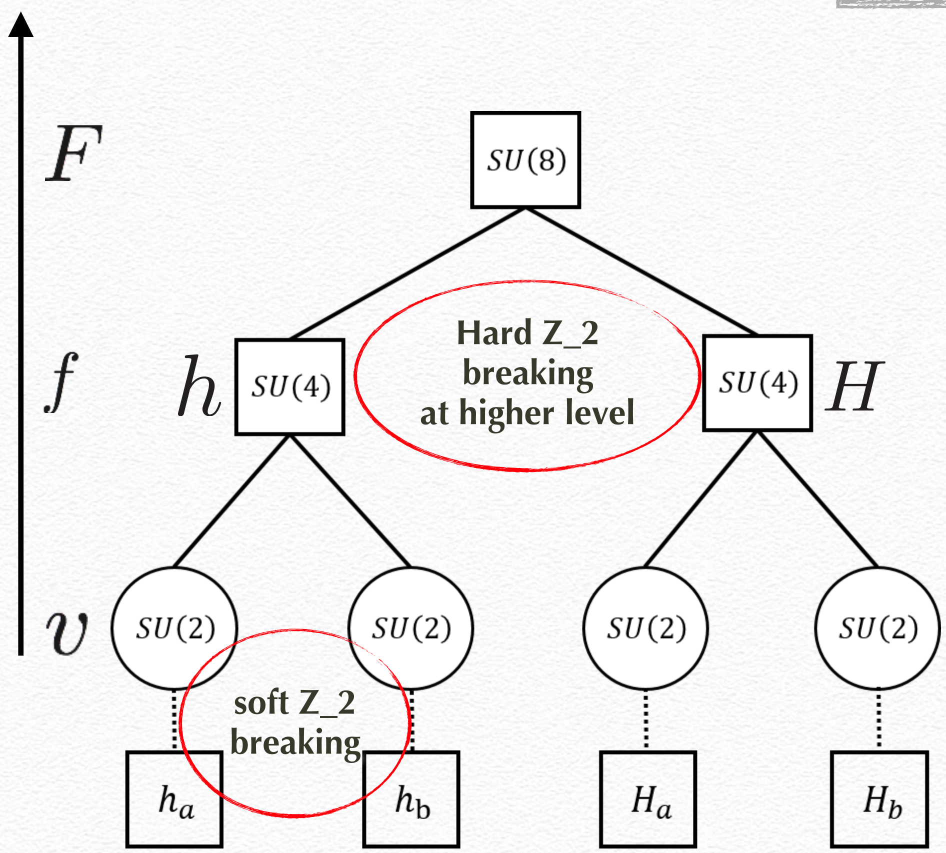


More scalars are introduced to push up the scale of coloured states!
Higgs like scalars -> definite signature of naturalness

Precision measurement?

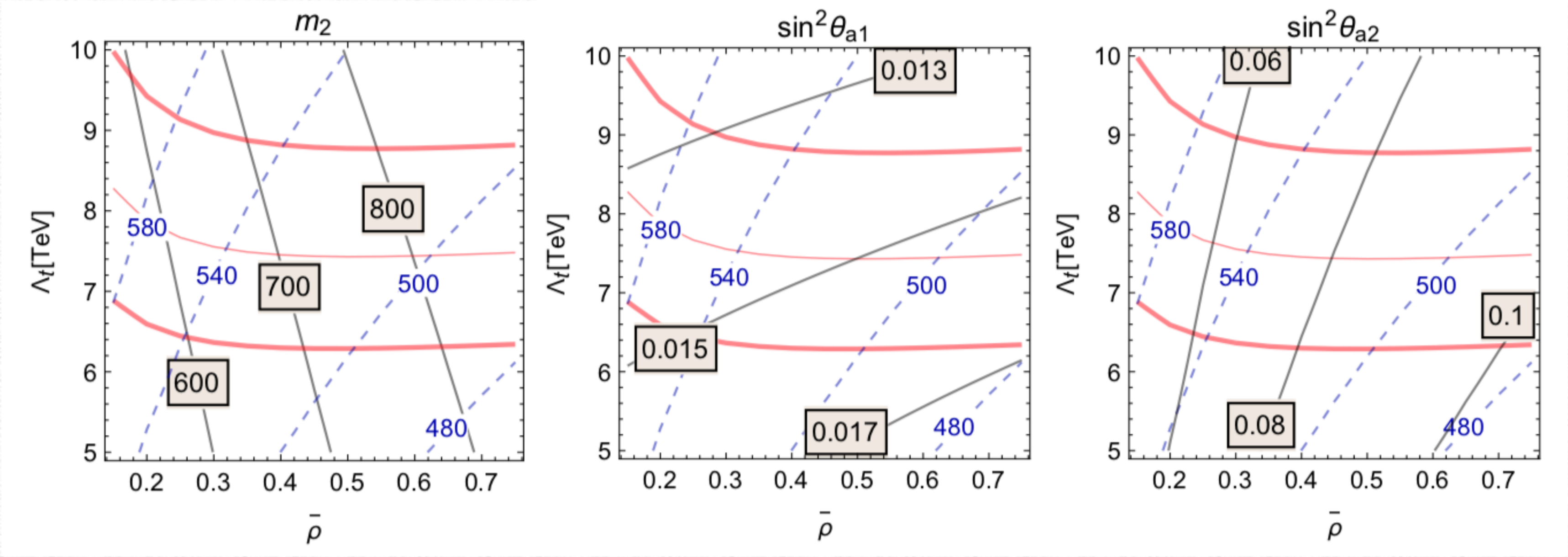
$$g_{hii} \sim g_{h_{SM}ii}\left(1 - \frac{1}{2}(\sin^2\theta_{a1} + \sin^2\theta_{a2})\right) \sim g_{h_{SM}ii}(1 - \frac{v^2}{2f^2})$$

Precision could not distinguish twin from turtles.

tthh—Resonance Search—scalars

[P. Asadi, N. Craig, YYL, arXiv:1810.09467]

More scalars mix with the SM-like Higgs states



Direct production of heavy scalars (h2) becomes crucial!

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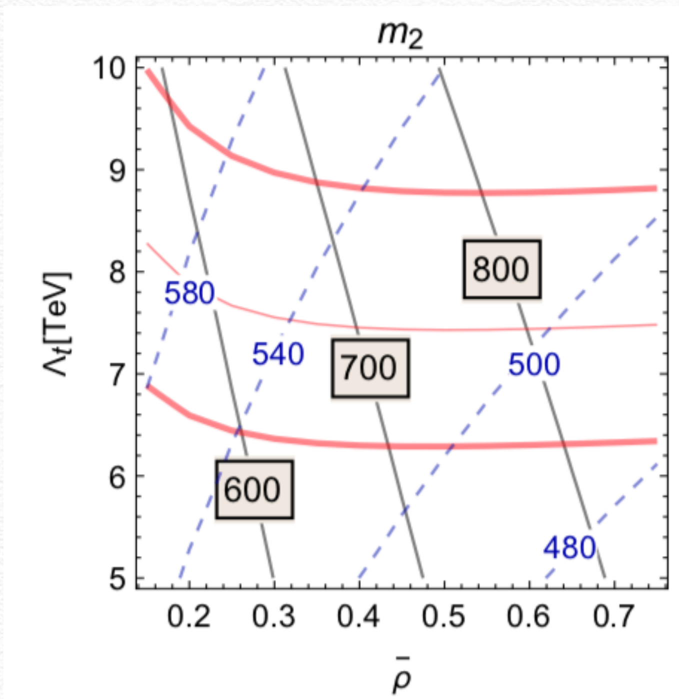

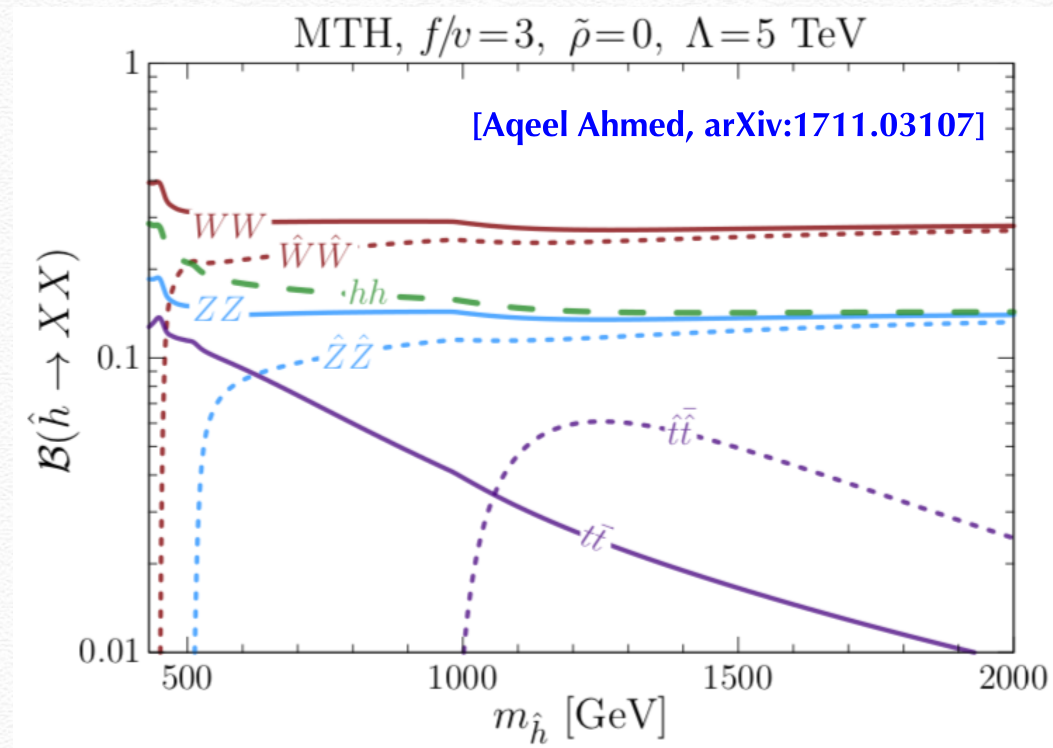

large Br(h2-> hh);

rich signatures from di-Higgs decay.

Direct production of heavy scalars (h2) becomes crucial!

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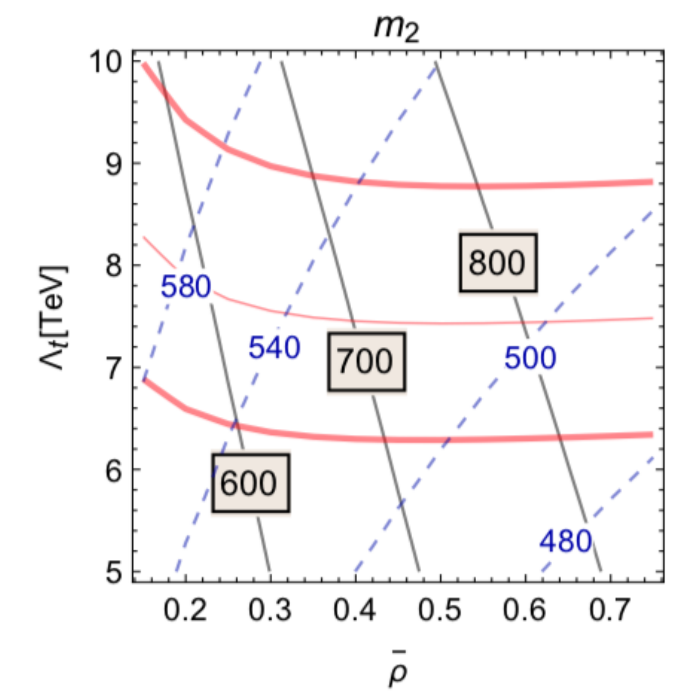


gluon fusion:
500GeV(mh2)@14/100TeV =2.13/102.7pb;
600GeV(mh2)@14/100TeV =0.968/55.2pb;

tth2:
500GeV(mh2)@14/100TeV =0.013/2.17pb;
600GeV(mh2)@14/100TeV =0.0083/1.63pb;

decay products from associated top could help to suppress background;

production cross section increases faster at 100TeV.

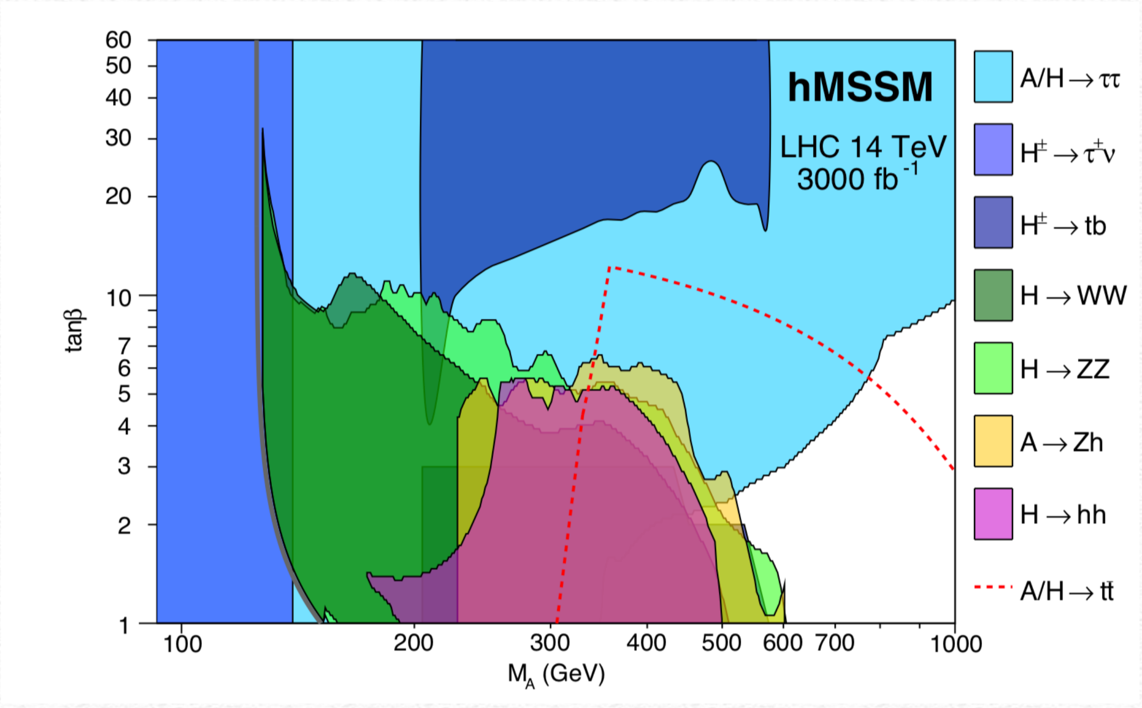
tthh could play an important role!

tthh—Resonance Search—scalars

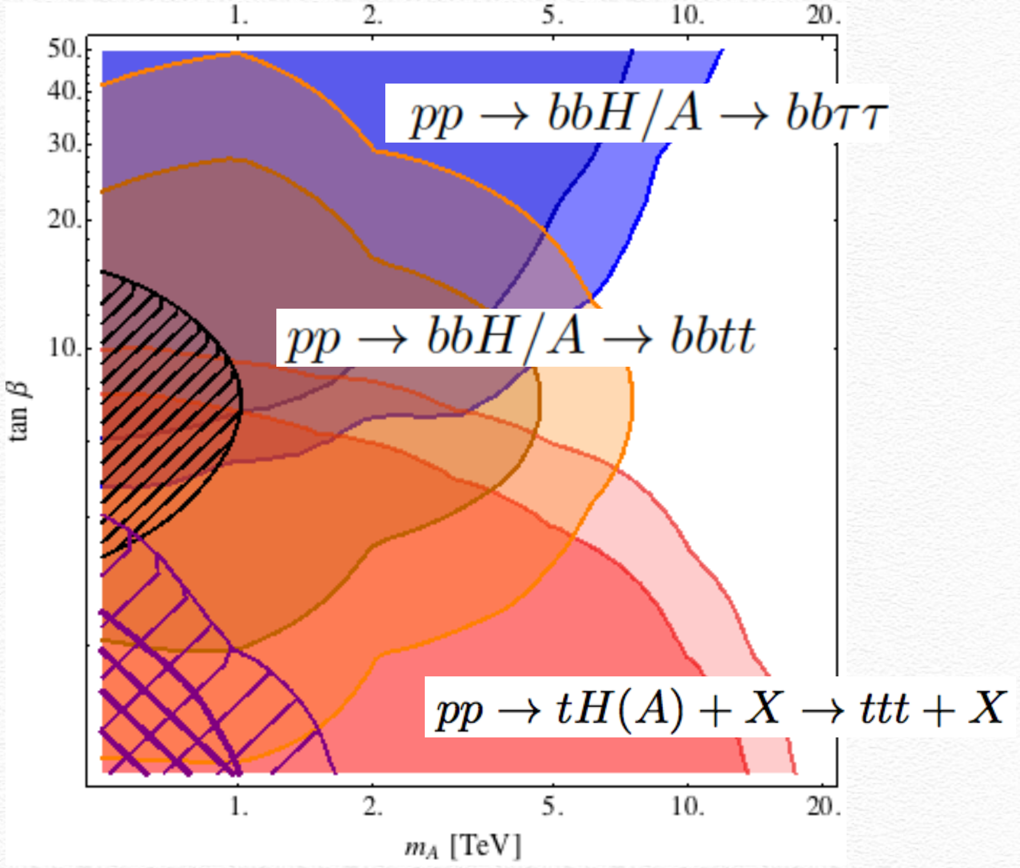
MSSM Higgs bosons(no CP-violation):H,A,Hc

Higgs mass spectrum and couplings only depend on two parameters (in additional to the SM ones) at tree-level: tan_beta, mA/mHc;

[A. Djouadi, et al. arXiv:1502.05653]



[N. Craig, J. Hajer, YYL, T. Liu, H. Zhang, arXiv:1605.08744]



Neutral Higgs Exclusion limit

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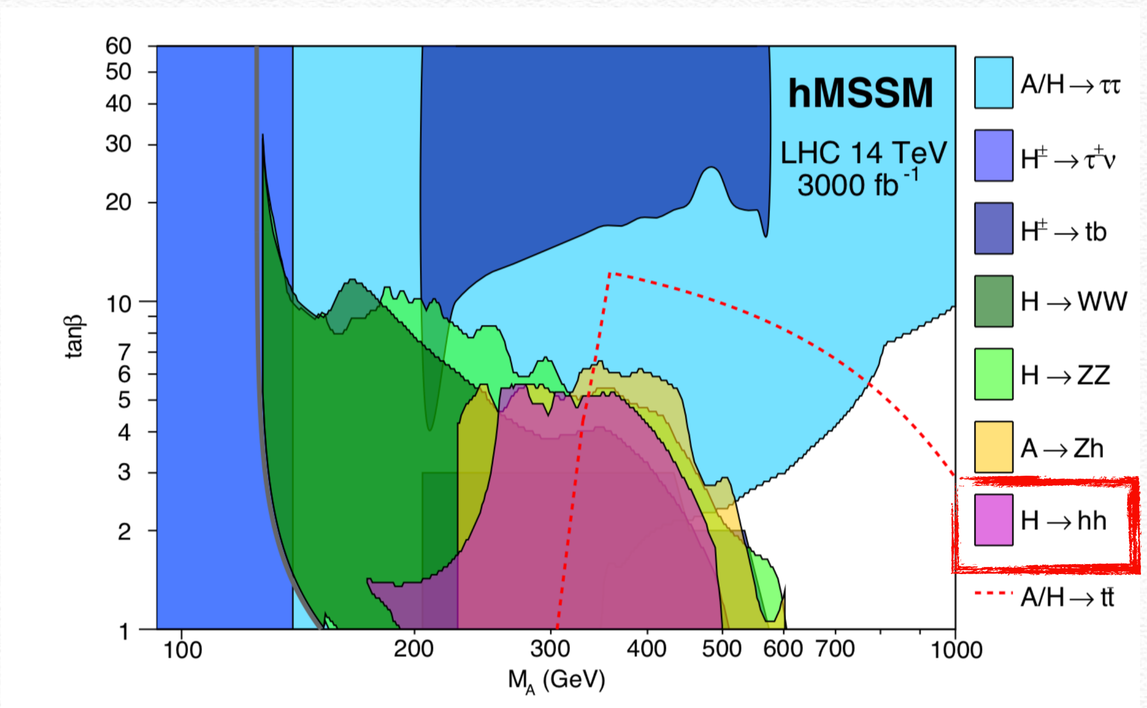

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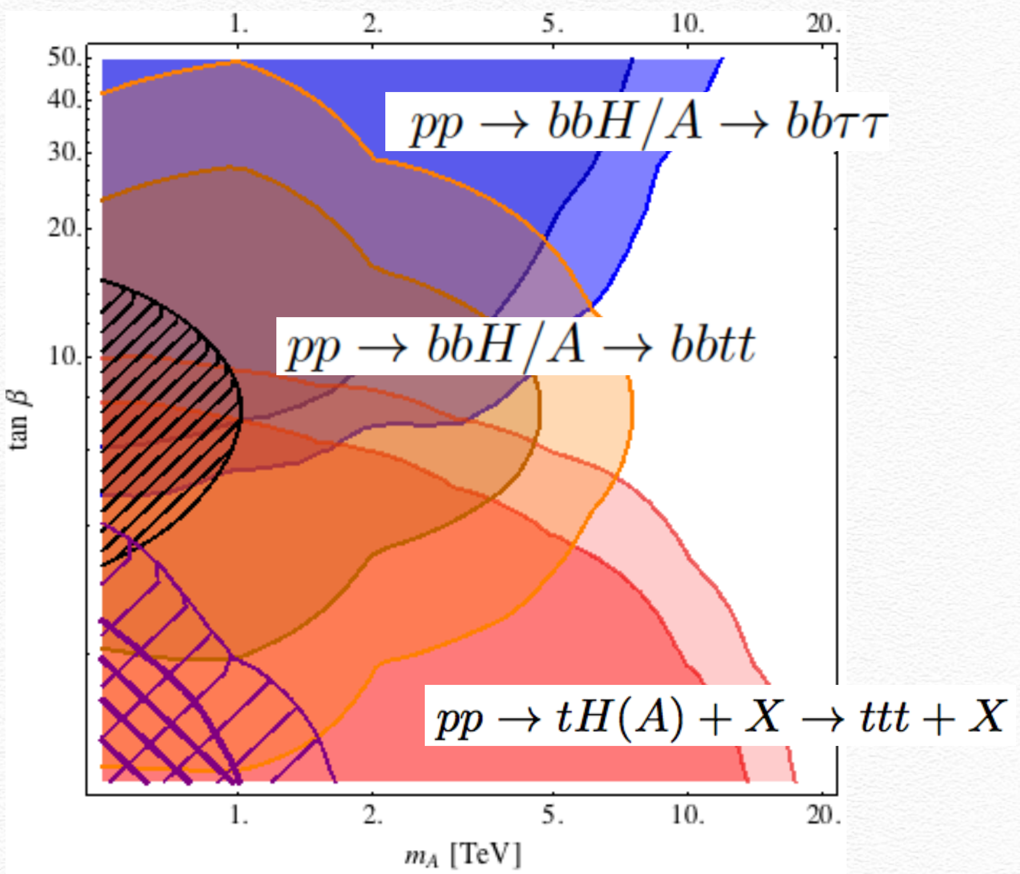

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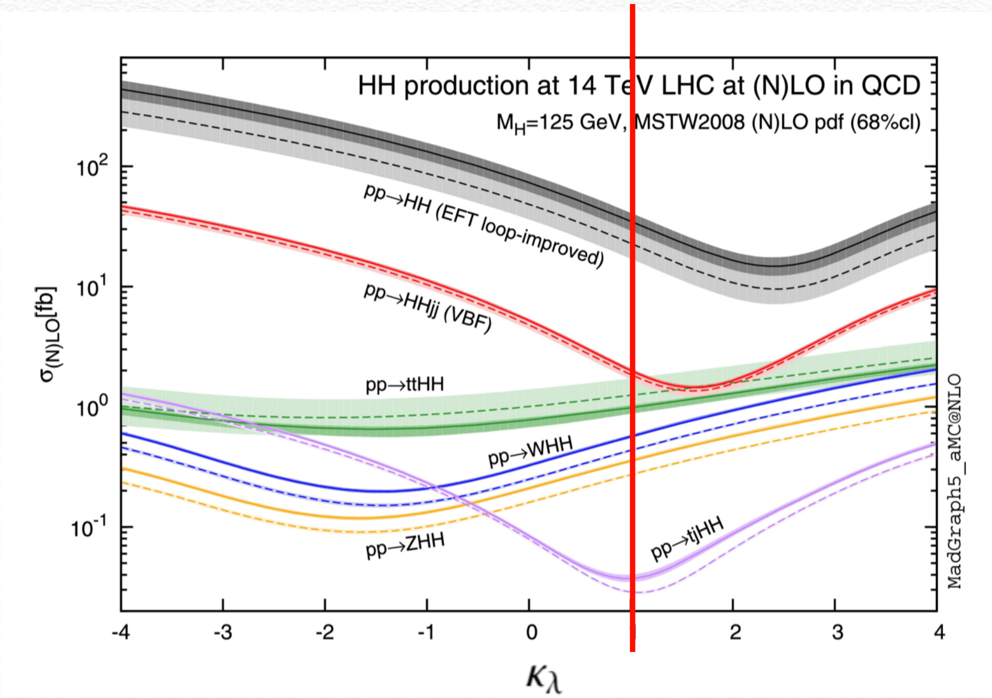
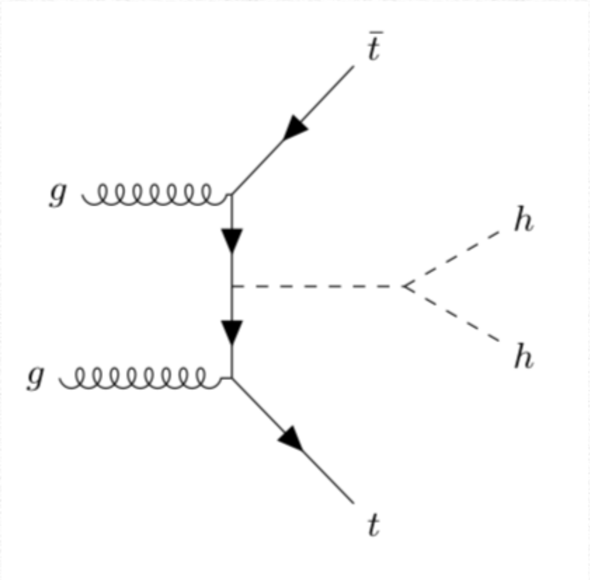
Neutral Higgs Exclusion limit

tthh channel analysis

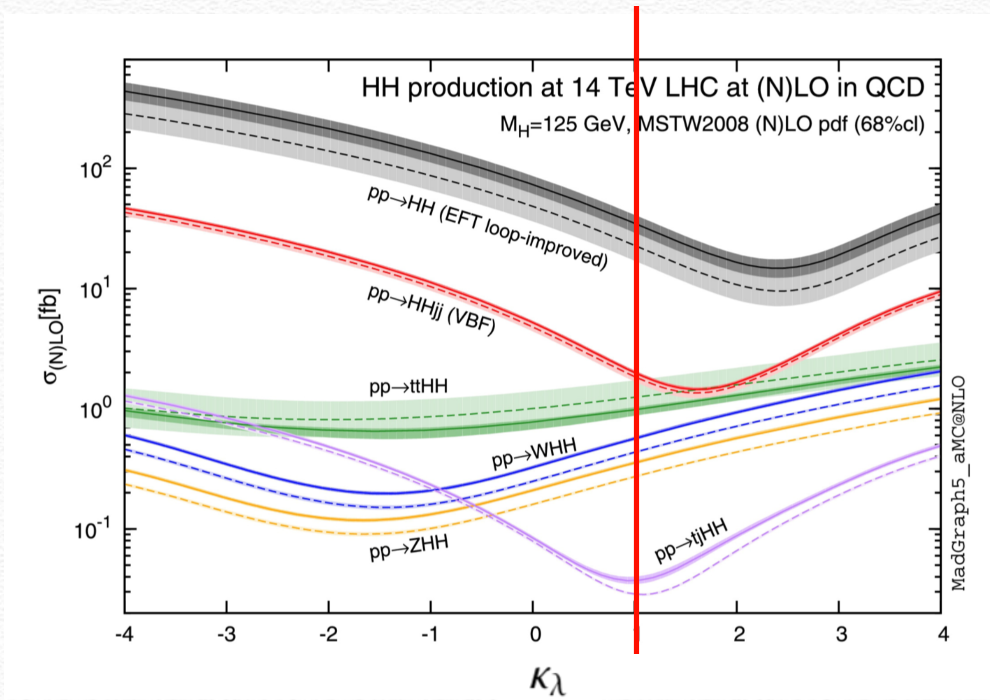


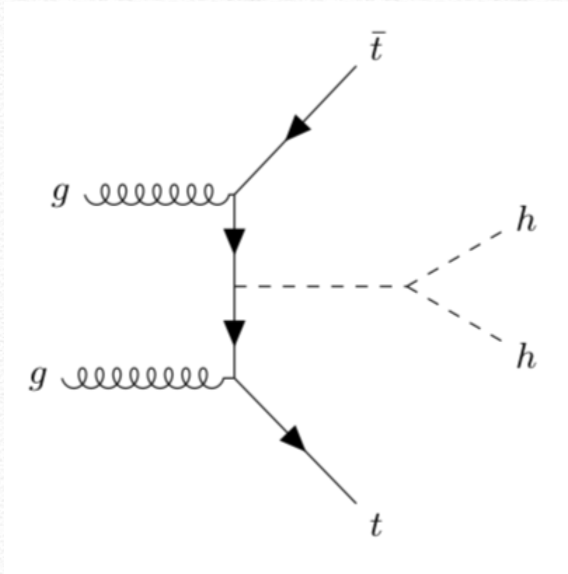


tthh->ttbbbb channel

[T. Liu, H. Zhang, arXiv:1410.1855]
[C. Englert,et al. arXiv:1409.8074]
[ATL-PHYS-PUB-2016-023] with aggressive cut

tthh channel analysis





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different decay channels with very rich kinematics, combining all channels?

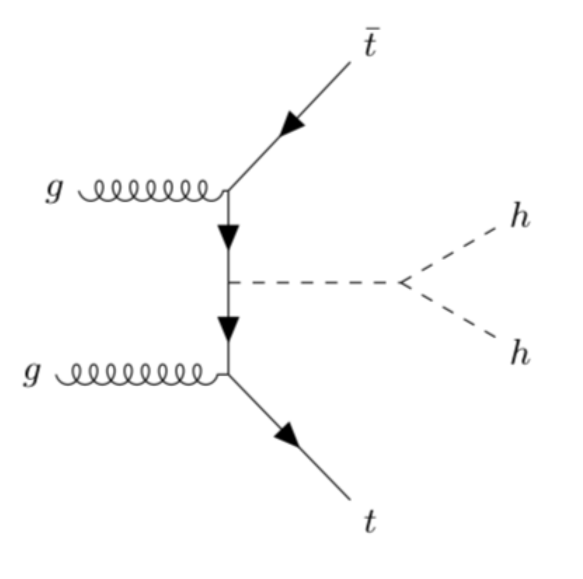
complicated topologies, BDT method?

tthh channel analysis

[L. Li, YYL, T. Liu, arXiv:1905.03772]

@HL-LHC

$5b1\ell$	$5b2\ell$	SS2ℓ	Multi-ℓ	$\tau\tau$



5(or more)b+1 lepton	tt(semi-leptonic)bbbb
5(or more)b + OS dilepton	tt(leptonic)bbbb
SS dilepton (w/ >=4 b jets)	tt(semi)VV*bb
Multi-lepton (w/ >=4 b jets)	tt(semi)VV*bb
2τ jets (w/ >=4b jets & 1 lepton)	tt(semi)bbττ

tthh channel analysis

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@HL-LHC

$5b1\ell$	$5b2\ell$	SS2ℓ	Multi-ℓ	$\tau\tau$

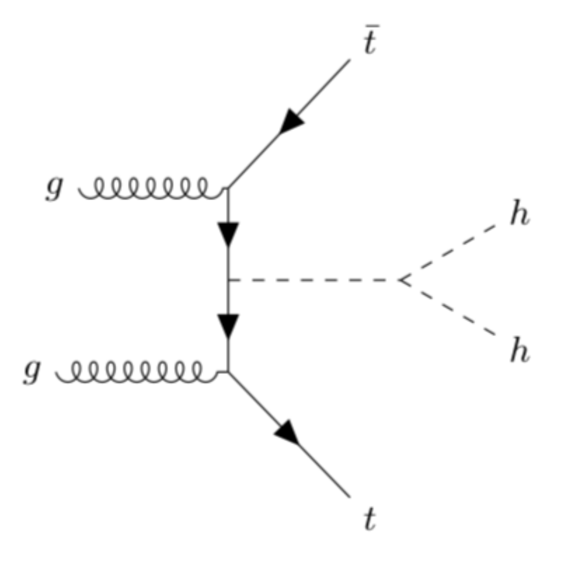
5(or more)b+1 lepton — tt(semi-leptonic)bbbb

5(or more)b + OS dilepton — tt(leptonic)bbbb

SS dilepton (w/ >=4 b jets) — tt(semi)VV*bb

Multi-lepton (w/ >=4 b jets) — tt(semi)VV*bb

2τ jets (w/ >=4b jets & 1 lepton) — tt(semi)bbττ



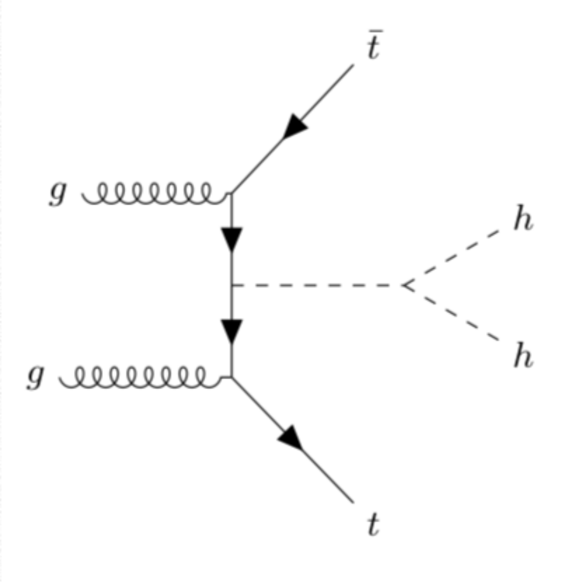
	No cut	Preselection	$5b1\ell$	$5b2\ell$	SS2ℓ	Multi-ℓ	$\tau\tau$
$tthh$	2.9e3	7.37e2	50.9 (97.2)	6.1 (12.0)	14.6 (15.7)	8.6 (9.2)	3.6 (3.8)
$tt4b$	1.1e6	1.79e5	6.56e3 (1.31e4)	664 (1.30e3)	212 (223)	115 (121)	94.1 (95.1)
$tt2b2c$	3.1e5	4.28e4	621 (1.73e3)	59.4 (163)	38.0 (42.4)	24.1(26.8)	43.6 (48.6)
$ttVV$	4.4e4	3.64e3	20.7 (52.7)	3.5 (6.4)	51.8(60.9)	32.4 (36.5)	3.1 (3.9)
$4t$	3.54e4	1.30e4	350 (804)	68.3 (152)	592 (635)	307 (324)	59.8 (64.2)
$ttbbV$	8.29e4	1.54e4	353 (765)	47.8 (105)	114 (124)	203 (221)	22.2 (24.2)
$ttbbh$	4.68e4	1.04e4	608 (1.15e3)	69.0 (136)	91.0 (98.0)	53.4 (56.2)	24.2 (25.9)
$tthZ$	4.65e3	881	28.1 (58.5)	4.1 (9.1)	8.8 (9.5)	18.5 (19.9)	2.3 (2.5)
Total	1.6e6	2.65e5	8.53e3 (1.76e4)	918 (1.88e3)	1.11e3 (1.19e3)	753 (806)	249 (265)
σ_{cut}			0.46 (0.62)	0.17 (0.23)	0.39 (0.40)	0.28 (0.29)	0.20 (0.20)
$(S/B)_{\text{cut}}(\%)$			0.42 (0.40)	0.47 (0.55)	1.1 (1.1)	0.9 (0.9)	1.1 (1.1)

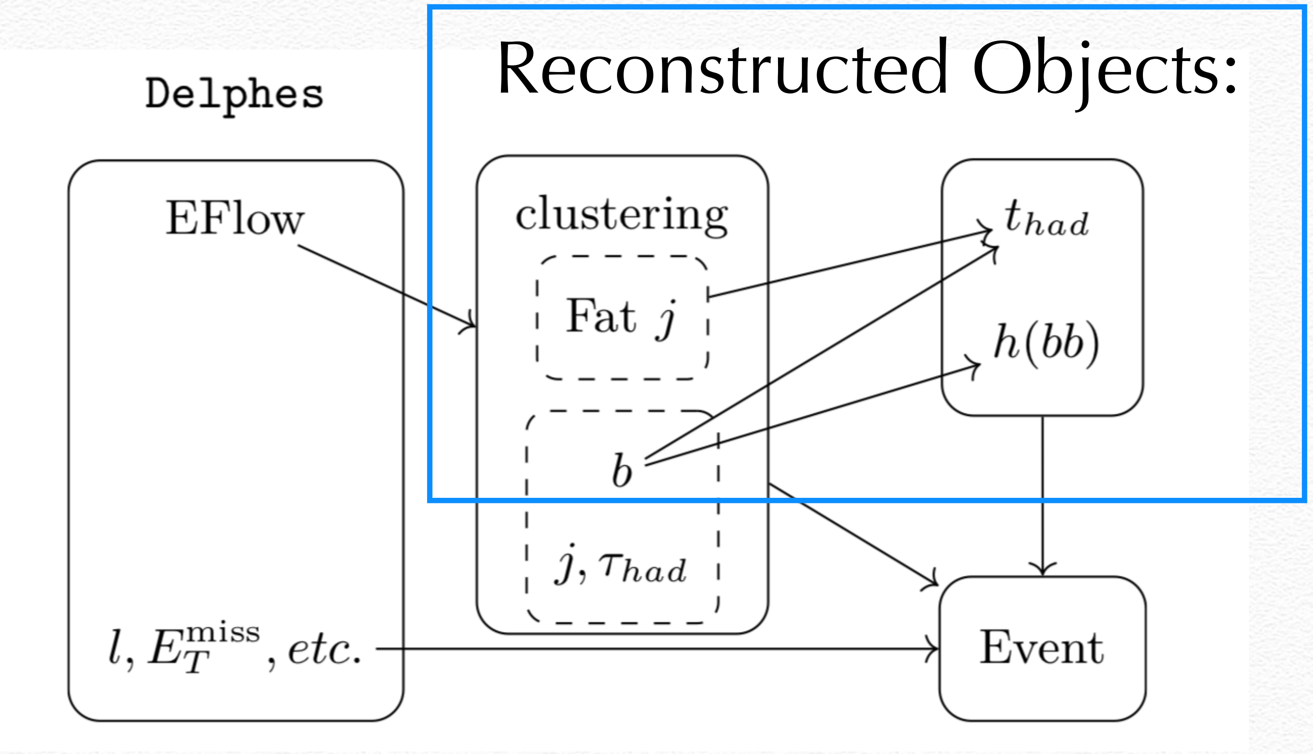
tthh channel analysis

[L. Li, YYL, T. Liu, arXiv:1905.03772]

@HL-LHC

$5b1\ell$	$5b2\ell$	$SS2\ell$	Multi-ℓ	$\tau\tau$



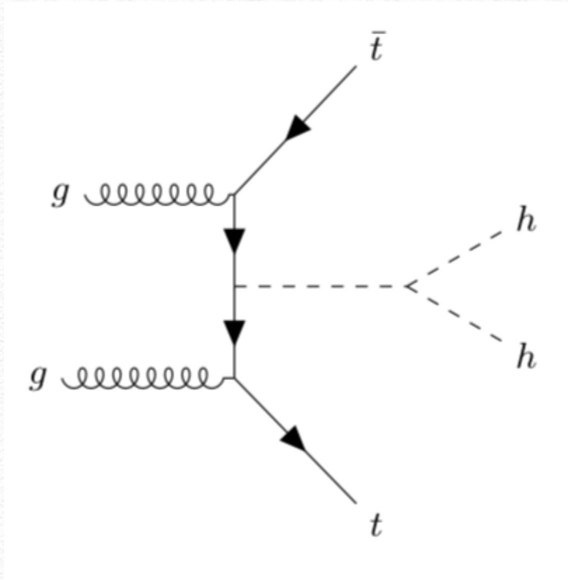


tthh channel analysis

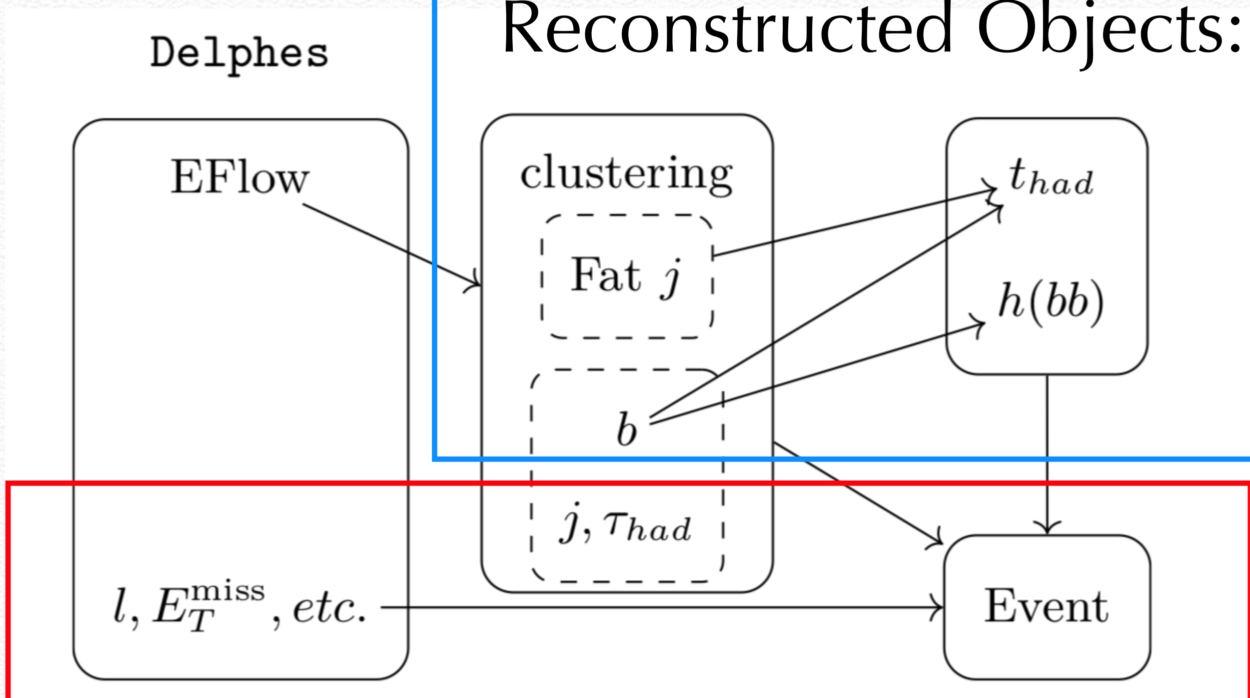
[L. Li, YYL, T. Liu, arXiv:1905.03772]

@HL-LHC

$5b1\ell$	$5b2\ell$	SS2ℓ	Multi-ℓ	$\tau\tau$



Reconstructed Objects:



Low level information:

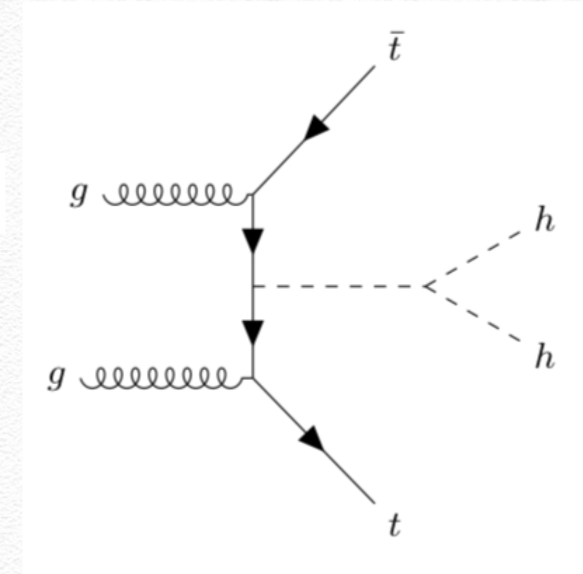
pt of leptons/ H_t/N_jet

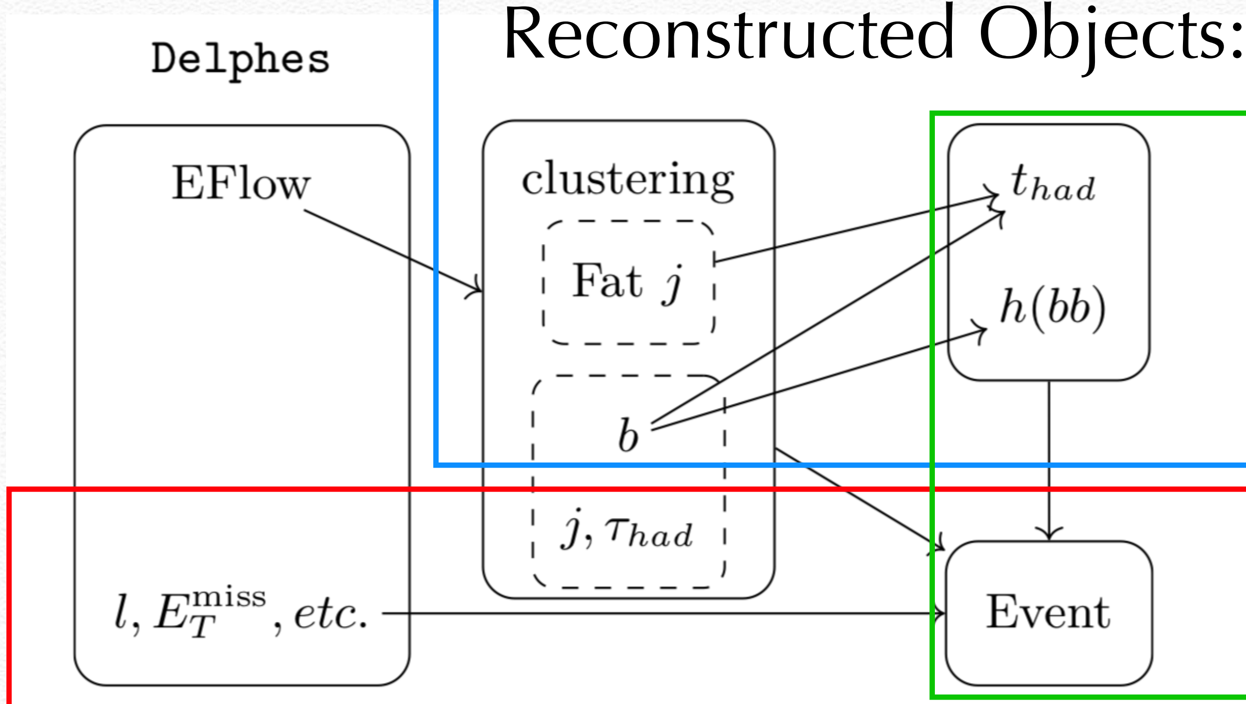
tthh channel analysis

[L. Li, YYL, T. Liu, arXiv:1905.03772]

@HL-LHC

$5b1\ell$	$5b2\ell$	$SS2\ell$	Multi-ℓ	$\tau\tau$





Reconstructed Objects:

Correlations between different objects: deltaR, delta_eta, invariant mass …

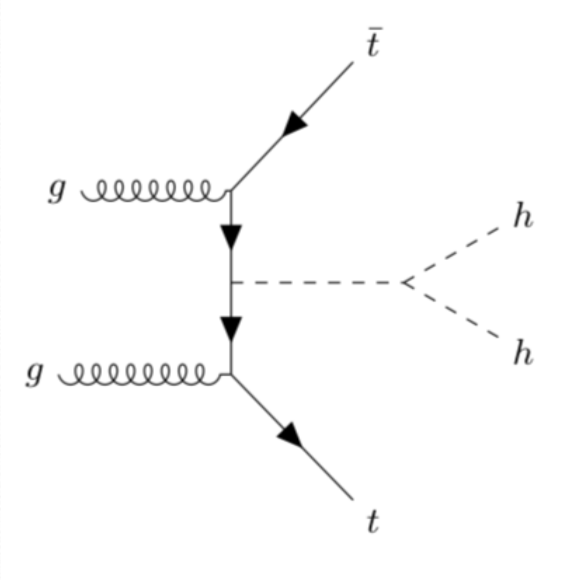
Low level information: pt of leptons/ H_t/N_jet

tthh channel analysis

[L. Li, YYL, T. Liu, arXiv:1905.03772]

@HL-LHC

$5b1\ell$	$5b2\ell$	SS2ℓ	Multi-ℓ	$\tau\tau$



$-10 < \kappa\lambda < 6.9$@95%C.L.

	No cut	Preselection	$5b1\ell$	$5b2\ell$	SS2ℓ	Multi-ℓ	$\tau\tau$
$tthh$	2.9e3	7.37e2	50.9 (97.2)	6.1 (12.0)	14.6 (15.7)	8.6 (9.2)	3.6 (3.8)
$tt4b$	1.1e6	1.79e5	6.56e3 (1.31e4)	664 (1.30e3)	212 (223)	115 (121)	94.1 (95.1)
$tt2b2c$	3.1e5	4.28e4	621 (1.73e3)	59.4 (163)	38.0 (42.4)	24.1(26.8)	43.6 (48.6)
$ttVV$	4.4e4	3.64e3	20.7 (52.7)	3.5 (6.4)	51.8(60.9)	32.4 (36.5)	3.1 (3.9)
$4t$	3.54e4	1.30e4	350 (804)	68.3 (152)	592 (635)	307 (324)	59.8 (64.2)
$ttbbV$	8.29e4	1.54e4	353 (765)	47.8 (105)	114 (124)	203 (221)	22.2 (24.2)
$ttbbh$	4.68e4	1.04e4	608 (1.15e3)	69.0 (136)	91.0 (98.0)	53.4 (56.2)	24.2 (25.9)
$tthZ$	4.65e3	881	28.1 (58.5)	4.1 (9.1)	8.8 (9.5)	18.5 (19.9)	2.3 (2.5)
Total	1.6e6	2.65e5	8.53e3 (1.76e4)	918 (1.88e3)	1.11e3 (1.19e3)	753 (806)	249 (265)
$\sigma_{\rm cut}$			0.46 (0.62)	0.17 (0.23)	0.39 (0.40)	0.28 (0.29)	0.20 (0.20)
$(S/B)_{\rm cut}(\%)$			0.42 (0.40)	0.47 (0.55)	1.1 (1.1)	0.9 (0.9)	1.1 (1.1)
$\sigma_{\rm BDT}$			0.59 (0.79)	0.21 (0.30)	0.45 (0.46)	0.33 (0.35)	0.21 (0.21)
$(S/B)_{\rm BDT}(\%)$			1.2 (1.0)	1.3 (1.6)	1.6 (1.6)	1.6 (1.9)	1.6 (1.6)
$\sigma_{\rm com}$			0.86 (1.04)				

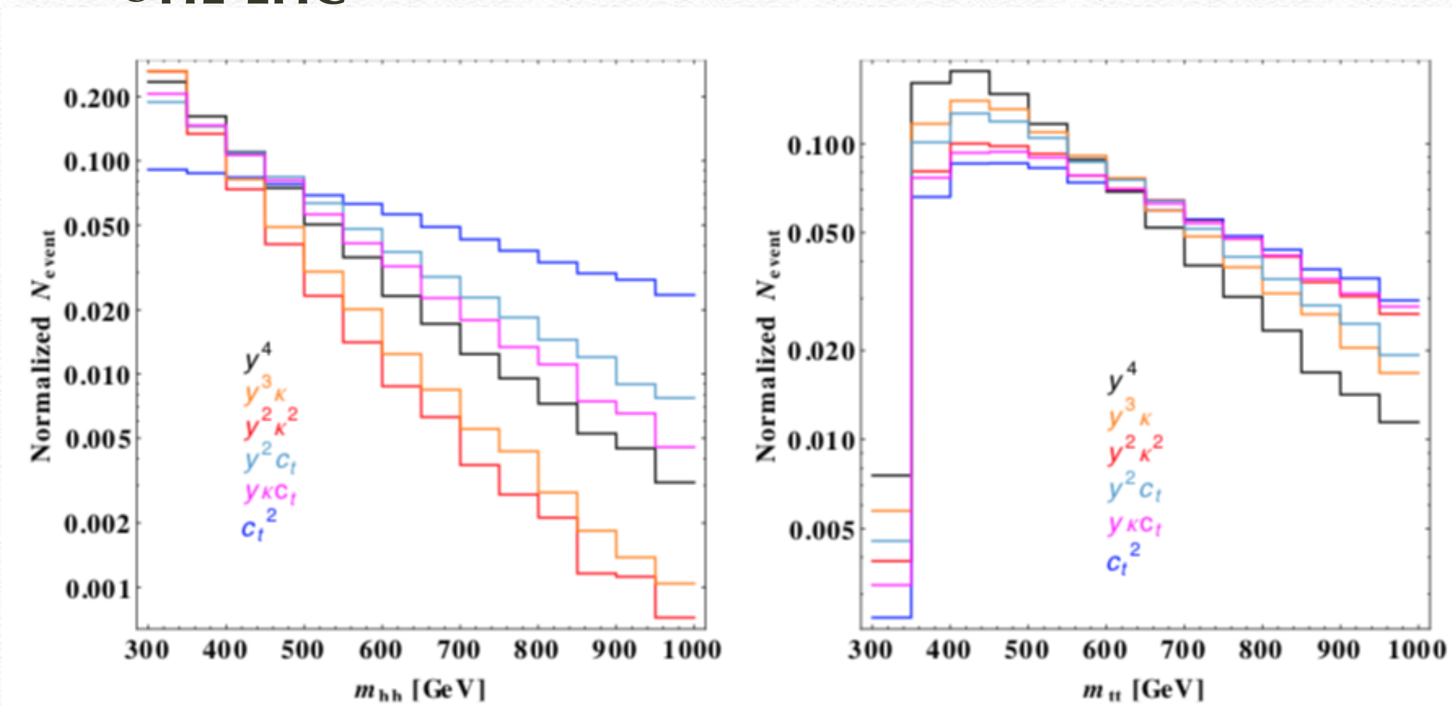
tthh—contact interactions

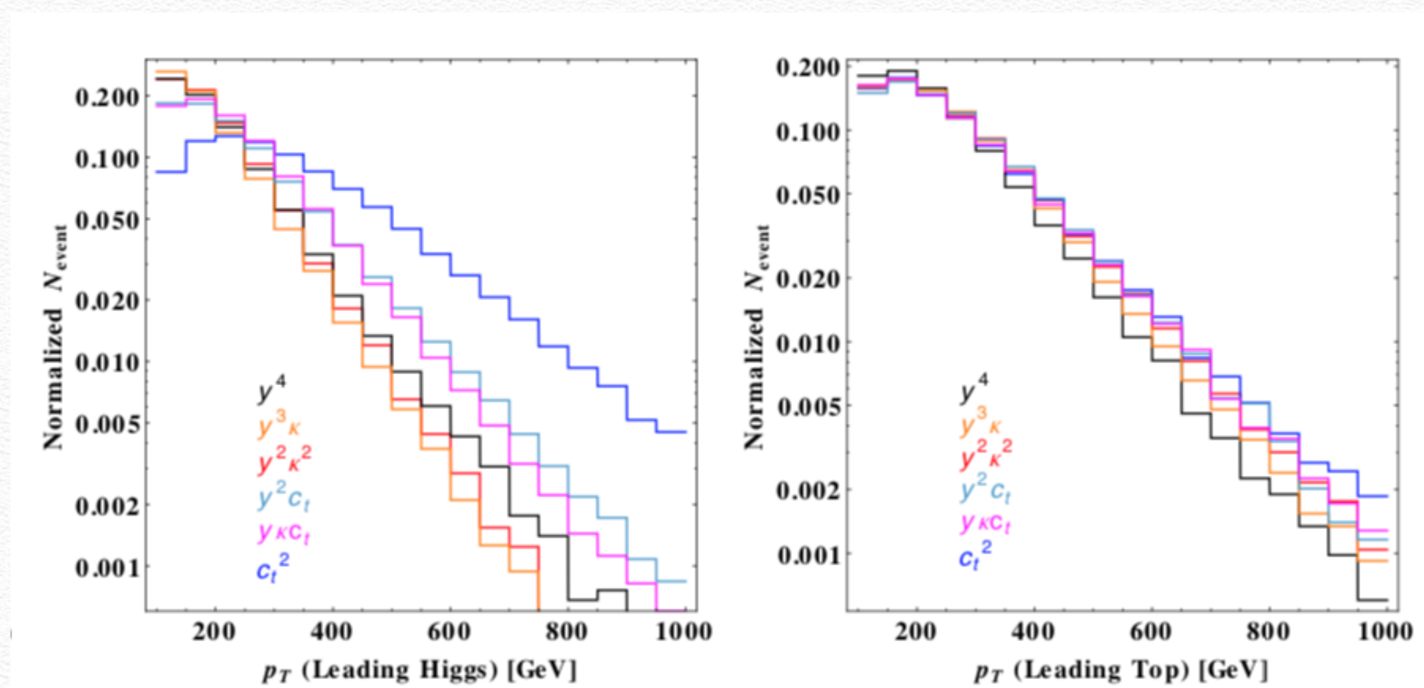
$$\mathcal{L} \supset -y\frac{m_t}{v}t\bar{t}h - \kappa\frac{1}{3!}\frac{3m_h^2}{v}h^3 - c_t\frac{1}{2!}\frac{m_t}{v^2}t\bar{t}hh$$

Assuming SM top Yukawa coupling

[L. Li, YYL, T. Liu, arXvi:1905.03772]

@HL-LHC



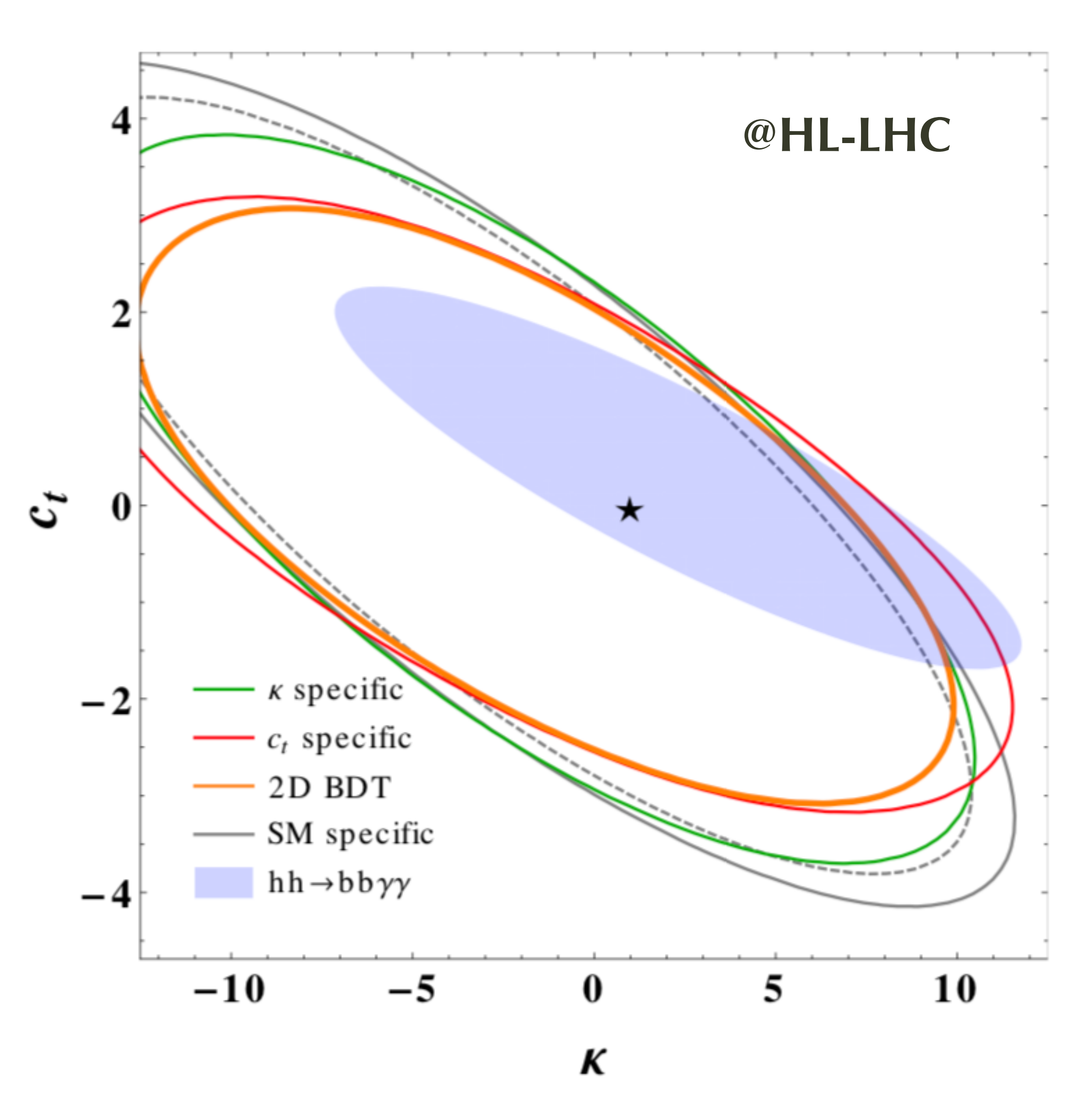


tthh—contact interactions

$$\mathcal{L} \supset -y\frac{m_t}{v}t\bar{t}h - \kappa\frac{1}{3!}\frac{3m_h^2}{v}h^3 - c_t\frac{1}{2!}\frac{m_t}{v^2}t\bar{t}hh$$

Assuming SM top Yukawa coupling

[L. Li, YYL, T. Liu, arXvi:1905.03772]



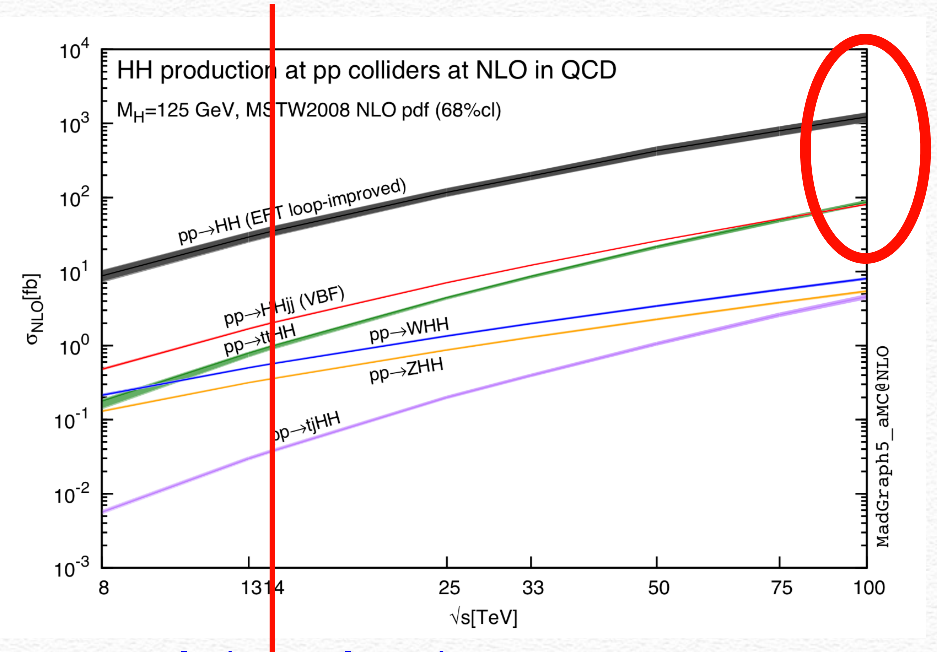
Blue region is the exclusion limit based on gluon fusion channel projected from [ATL-PHYS-PUB-2018-053]

Partially breaks the degeneracy in the $gg \to hh \to bb\gamma\gamma$

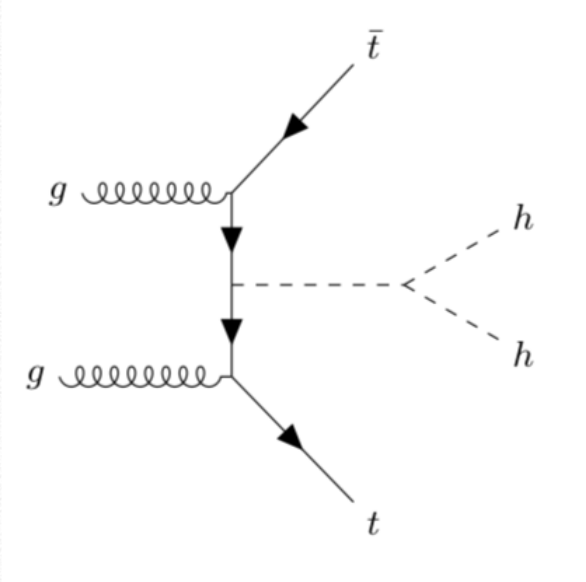
Kappa specific BDT help to improve the c_t direction.

Kinematics help to further improve the sensitivity.

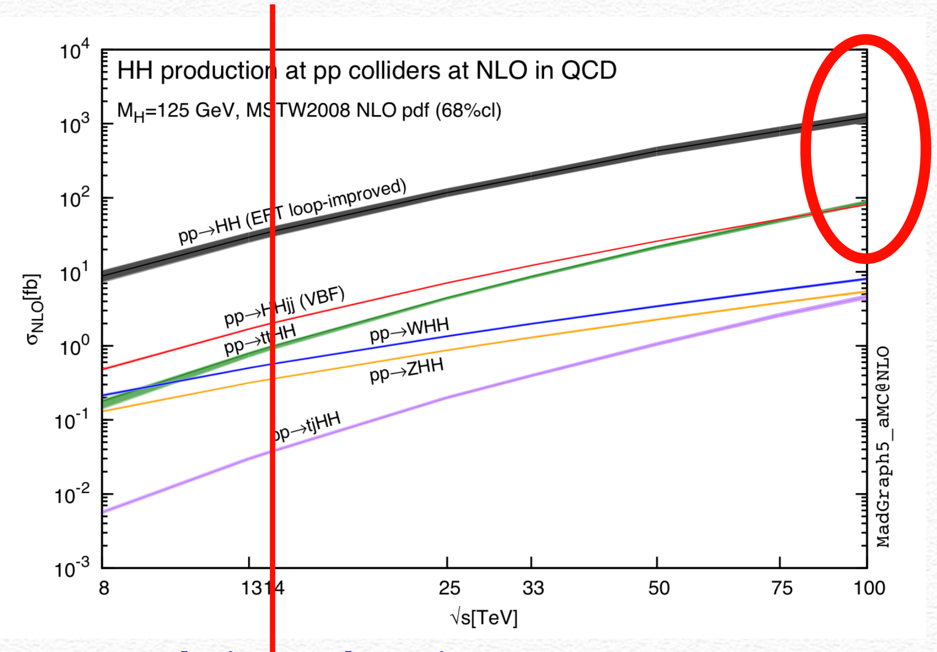
tthh—Higgs self coupling measurement



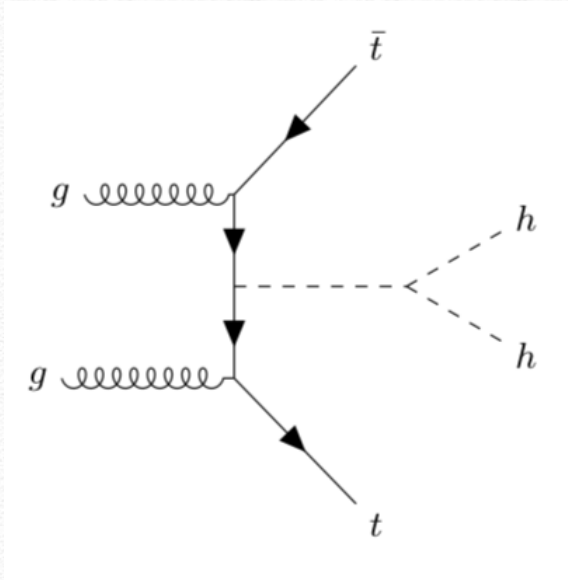
[R. Frederix, et al. arXiv:1401.7340]



tthh—Higgs self coupling measurement



[R. Frederix, et al. arXiv:1401.7340]



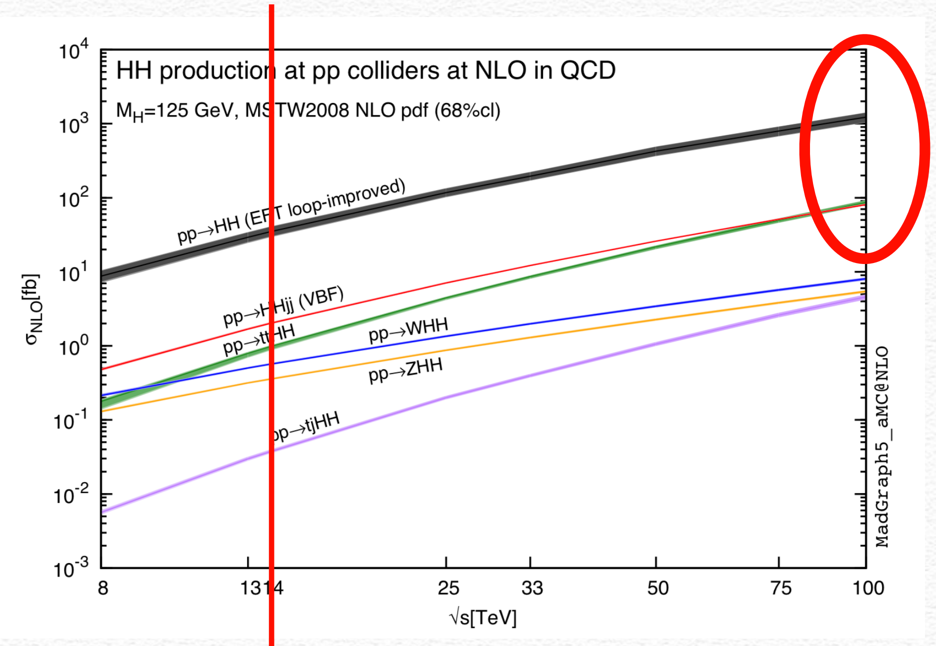
$$\frac{\sigma(gg \to hh \to bb\gamma\gamma)_{14}}{\sigma(gg \to hh \to bb\gamma\gamma)_{14}^{\rm SM}} = 1.70 - 0.82\kappa + 0.12\kappa^2 - 3.79c_t + 0.98c_t\kappa + 2.68c_t^2$$

$$\frac{\sigma(gg \to hh \to bb\gamma\gamma)_{100}}{\sigma(gg \to hh \to bb\gamma\gamma)_{100}^{\rm SM}} = 1.59 - 0.68\kappa + 0.09\kappa^2 - 3.83c_t + 0.92c_t\kappa + 3.20c_t^2$$

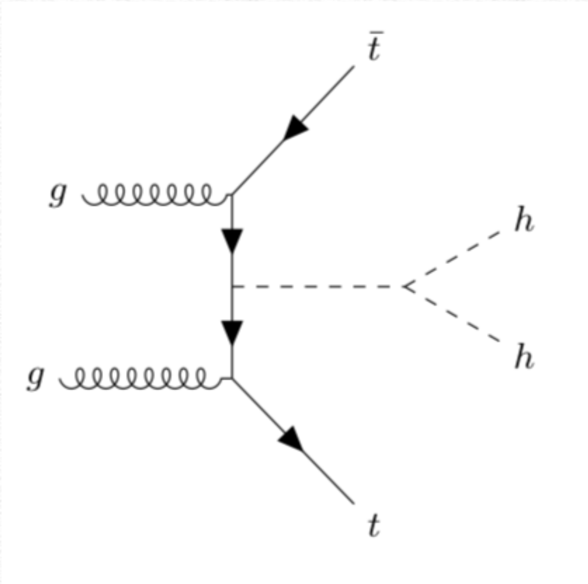
$$\frac{\sigma(tthh)_{14}}{\sigma(tthh)_{14}^{\rm SM}} = 0.82 + 0.14\kappa + 0.04\kappa^2 + 0.28c_t + 0.21\kappa c_t + 0.44c_t^2$$

$$\frac{\sigma(tthh)_{100}}{\sigma(tthh)_{100}^{\rm SM}} = 0.84 + 0.07\kappa + 0.09\kappa^2 + 0.15c_t + 0.41\kappa c_t + 1.73c_t^2$$

tthh—Higgs self coupling measurement



[R. Frederix, et al. arXiv:1401.7340]



[L. Li, YYL, T. Liu, arXiv:1905.03772]

Projected @ 100TeV 30/ab
∼14.3σ

−2.6 < κλ < -1.6 U 0.2 < κλ < 1.6@95%C.L.

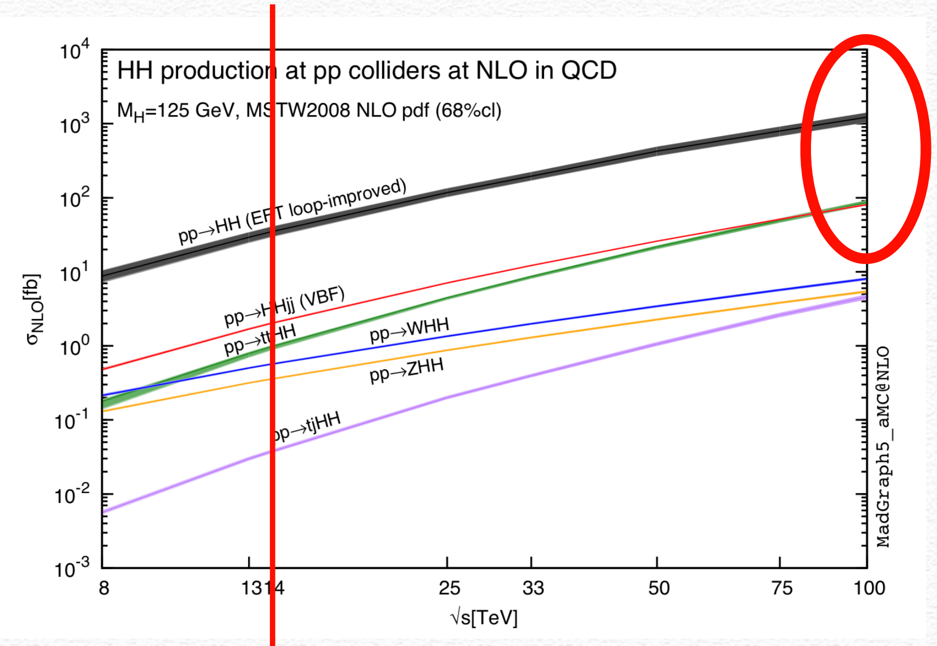
gain mainly from combing all decay channels

[S. Banerjee, et al. arXiv:1904. 07886]

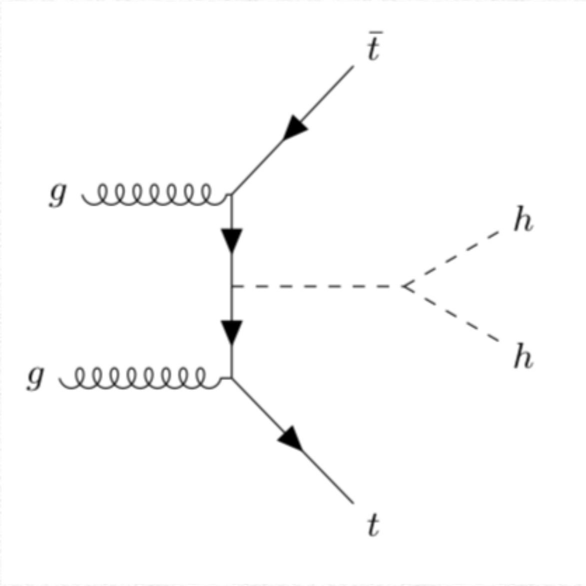
~5.9σ @100TeV 30/ab

−3.01 < κλ < 1.65@68%C.L.

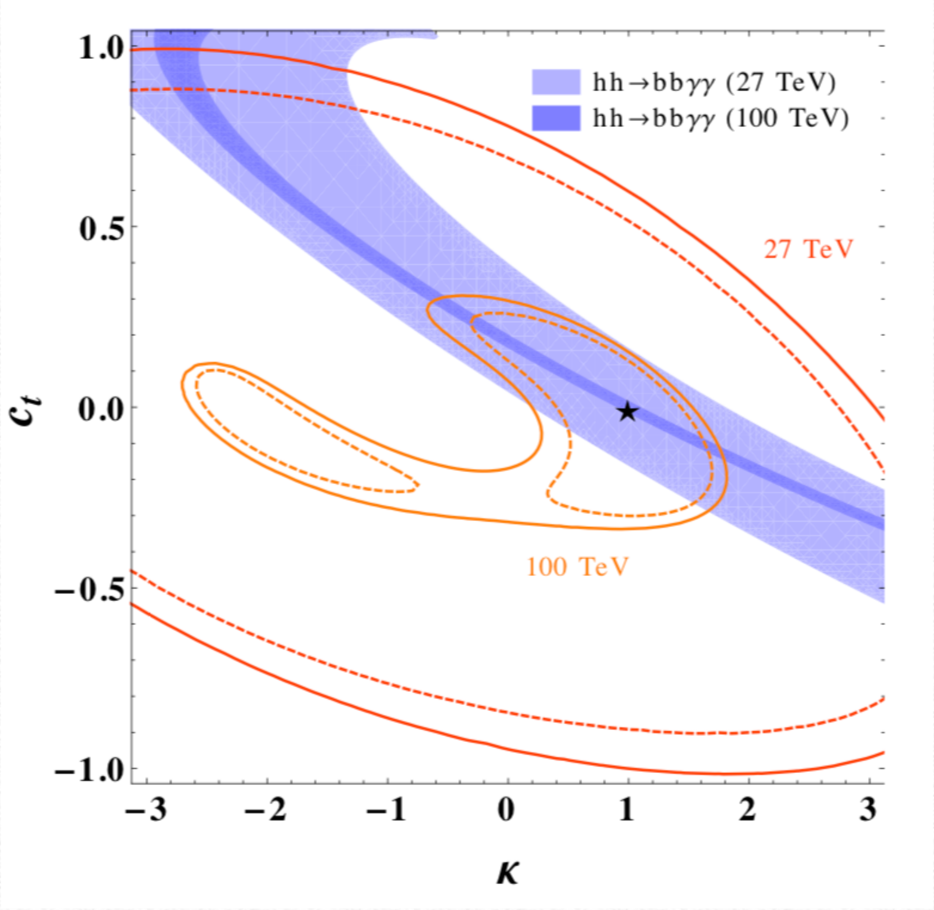
tthh—Higgs self coupling measurement



[R. Frederix, et al. arXiv:1401.7340]



[L. Li, YYL, T. Liu, arXiv:1905.03772]



fitting to {κ,ct} = {1,0}

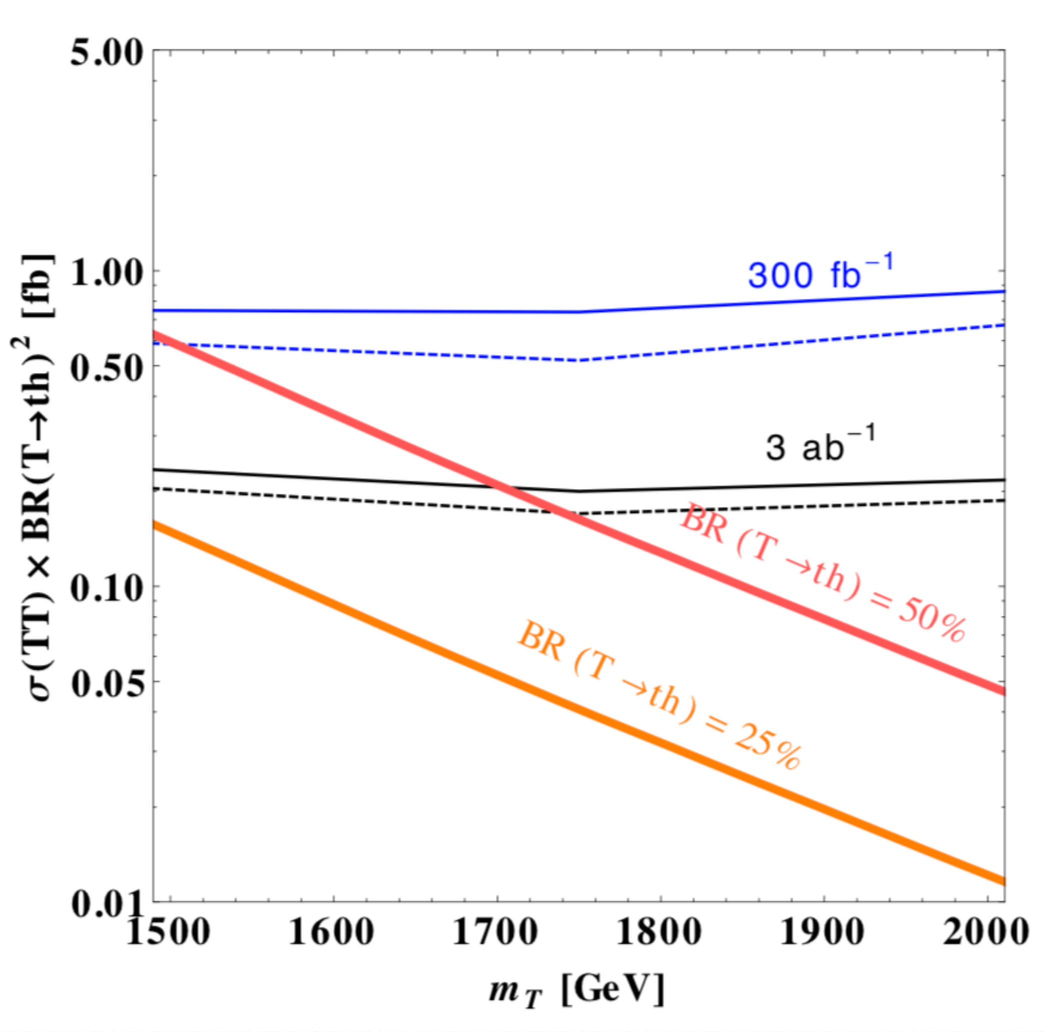
cross section contour centre around {κ,ct} = {0,0}

Encouraging from comparison with blue region, could be further improved by utilising kinematics.

tthh—Resonance Search—fermions

Coloured vector-like top partners

[L. Li, YYL, T. Liu, arXiv:1905.03772]



Limit is improved by combining all decay channels compared with that in [ATLAS, arXiv:1808.02343]

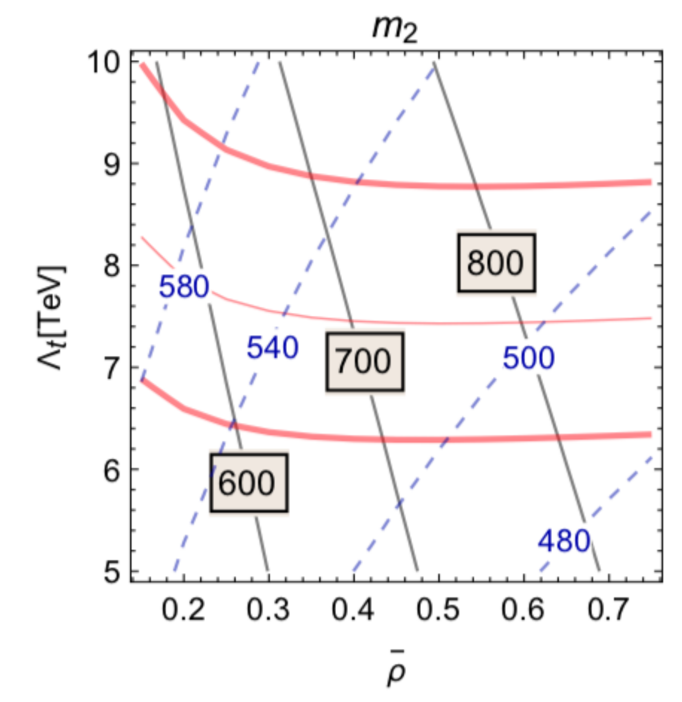
tthh—Resonance Search—scalars

[L. Li, YYL, T. Liu, arXiv:1905.03772]

@HL-LHC

	$5b1\ell$ (fb)	$5b2\ell$ (fb)	SS2ℓ (fb)	Multi-ℓ (fb)	$\tau\tau$ (fb)	Combined (fb)
$ttH,\ m_H = 300$ GeV	3.6 (2.4)	10 (7.4)	6.8 (6.5)	9.2 (8.9)	12 (11)	2.5 (2.2)
$ttH,\ m_H = 500$ GeV	2.6 (2.0)	7.6 (5.7)	5.3 (5.1)	7.4 (7.2)	8.0 (7.7)	2.0 (1.6)
ttH, mH=600GeV						1.8

[P. Asadi, N. Craig, YYL, arXiv:1810.09467]



@HL-LHC with f/v~3, mh2 = 600GeV,

$$\sigma(tth_2 \to tthh) \sim 0.1 fb$$

tthh—Resonance Search—scalars

[L. Li, YYL, T. Liu, arXiv:1905.03772]

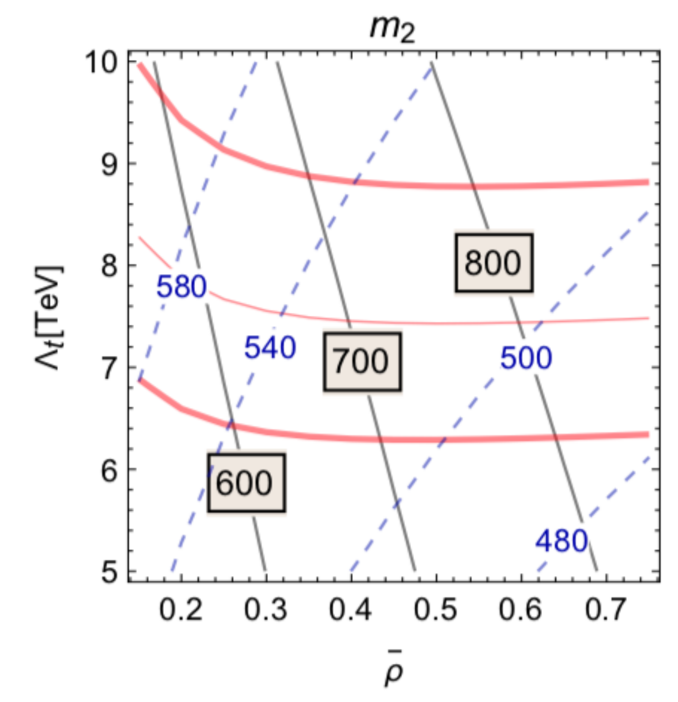
@HL-LHC

	$5b1\ell$ (fb)	$5b2\ell$ (fb)	$SS2\ell$ (fb)	Multi-ℓ (fb)	$\tau\tau$ (fb)	Combined (fb)
$ttH,\ m_H = 300$ GeV	3.6 (2.4)	10 (7.4)	6.8 (6.5)	9.2 (8.9)	12 (11)	2.5 (2.2)
$ttH,\ m_H = 500$ GeV	2.6 (2.0)	7.6 (5.7)	5.3 (5.1)	7.4 (7.2)	8.0 (7.7)	2.0 (1.6)
ttH, mH=600GeV						1.8

@100TeV 30/ab

	Combined (fb)
$ttH,\ m_H = 500$ GeV	6.6(5.3)
ttH, mH=600GeV	5.8
ttH, mH=800GeV	3.2

[P. Asadi, N. Craig, YYL, arXiv:1810.09467]



@HL-LHC with f/v~3, mh2 = 600GeV,

$$\sigma(tth_2 \to tthh) \sim 0.1 fb$$

@100TeV with f/v~3, mh2 = 600GeV,

$$\sigma(tth_2 \to tthh) \sim 21 fb$$

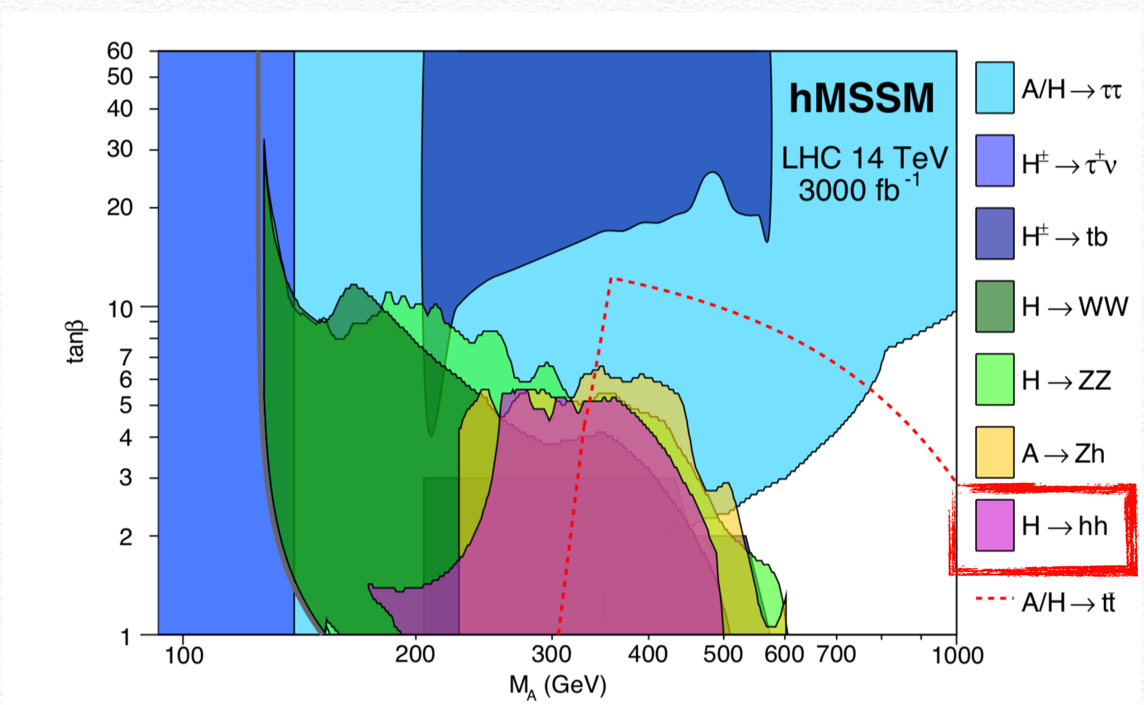
able to discover the turtling structure@100TeV!

tthh—Resonance Search—scalars

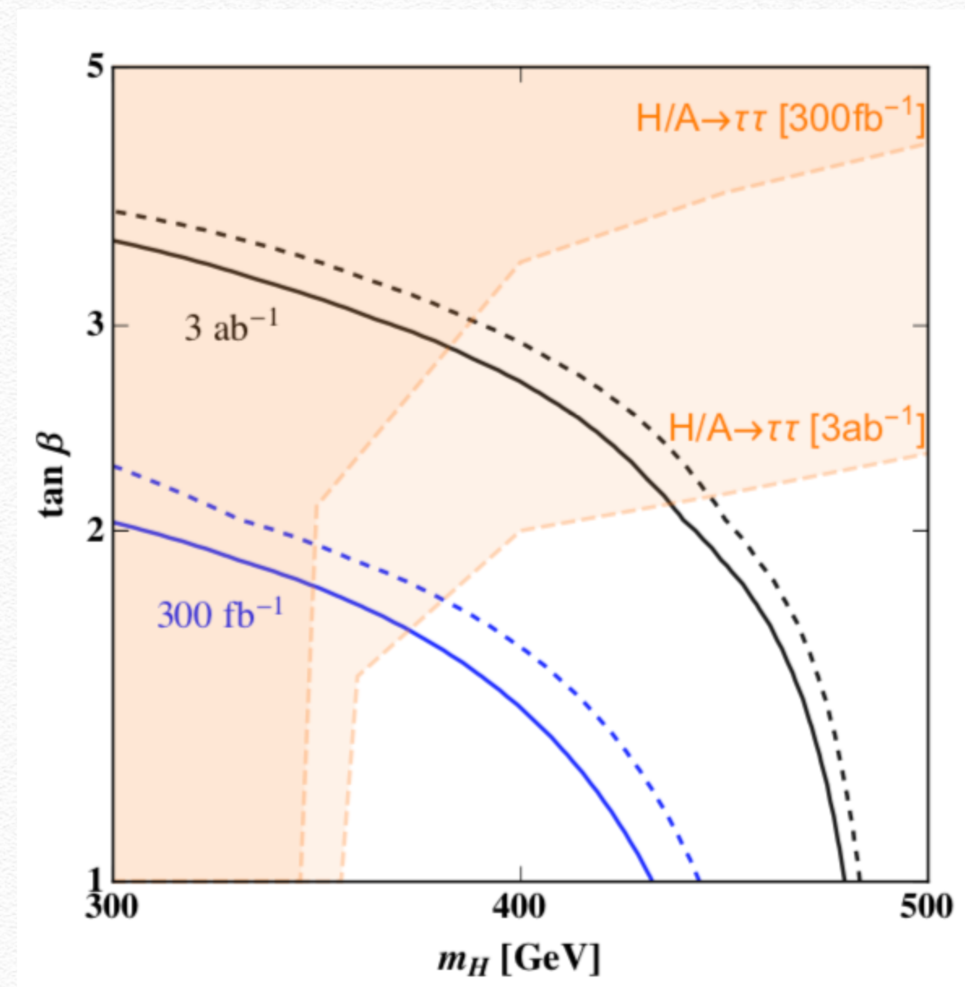
MSSM Higgs bosons(no CP-violation):H,A,Hc

Higgs mass spectrum and couplings only depend on two parameters (in additional to the SM ones) at tree-level: tan_beta, mA/mHc;

[A. Djouadi, et al. arXiv:1502.05653]



[L. Li, YYL, T. Liu, arXiv:1905.03772]



not bad compared with gg->H->hh channel

Decay products from associated top help!

tthh—Conclusion and Outlook

I have talked about tthh potential in

Higgs Self Coupling Measurement

Contact Interaction Measurement

Complementary to gluon fusion channel because of constructive interference;

combining all decay channels to further improve the sensitivety;

gain at 100TeV collider from kinematics potential ;

Resonant Search

heavy fermions, heavy scalars in turtling models/MSSM;

able to probe the turnling structure at 100TeV colliders.

Outlook

including kinematics at 100TeV?? way to simulate the bg

tthh potential with hh->bbaa at 100TeV??

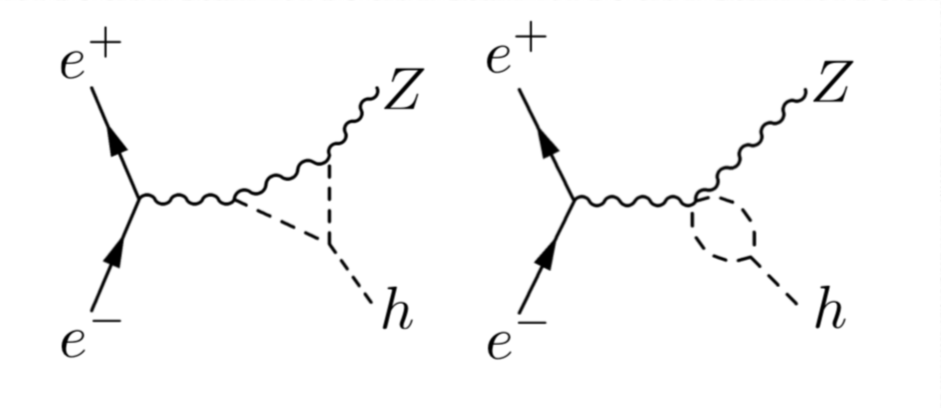
We are heading forward to the truth of our nature

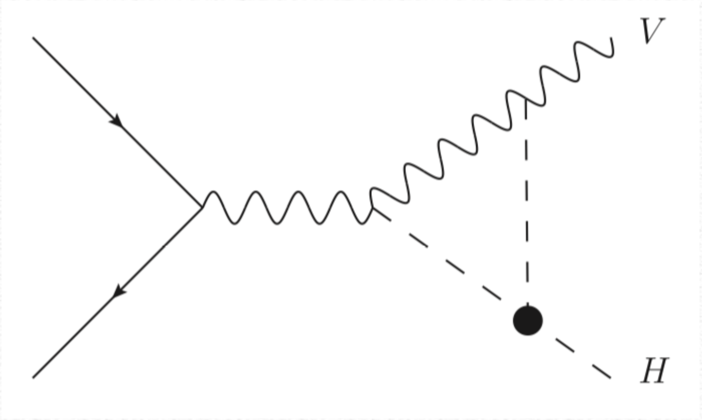
gradually and passionately

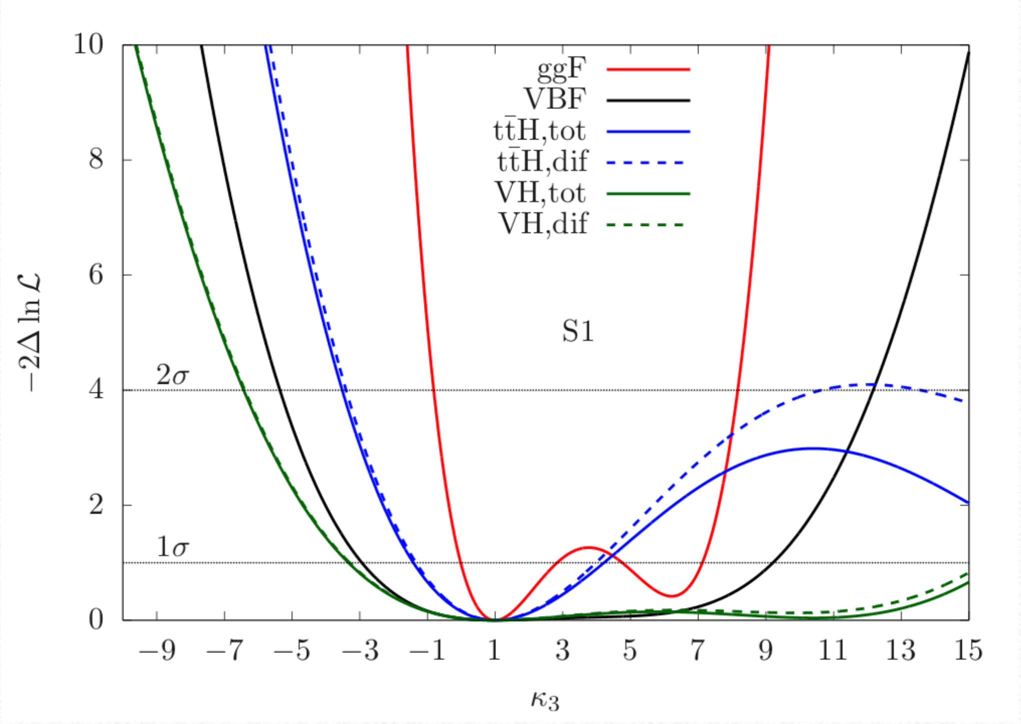
Thank YOU!

Higgs Self Coupling — indirect measurement

[Matthew McCullough arXiv:1312.3322]



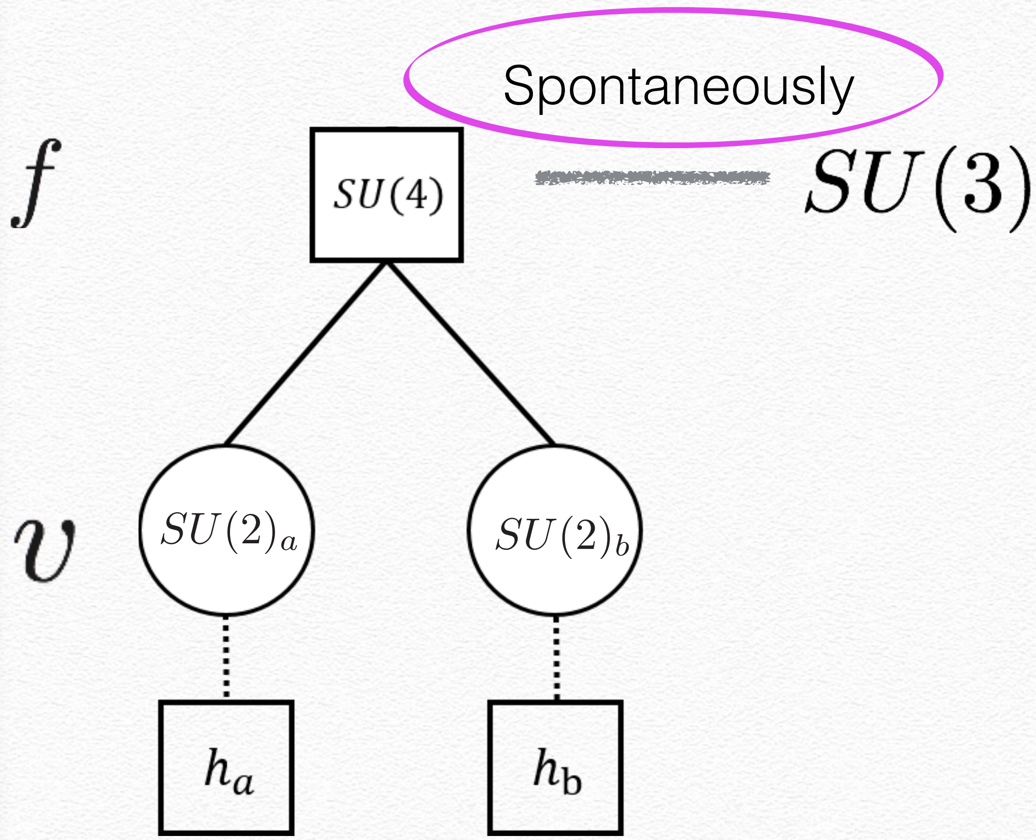




[F. Maltoni, et al. arXiv:1709.08649]

tthh—Resonance Search—scalars

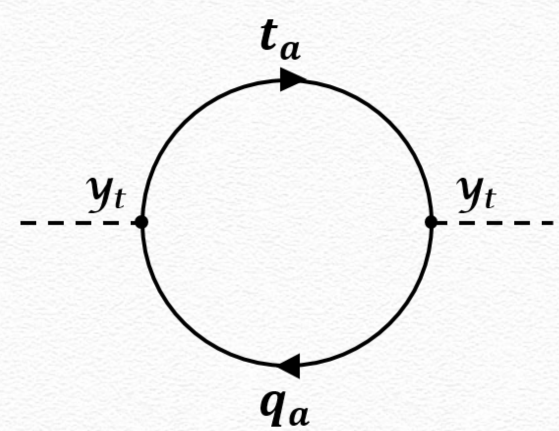
[Z.Chacko, Hock-Seng Goh and Roni Harnik] (2005)

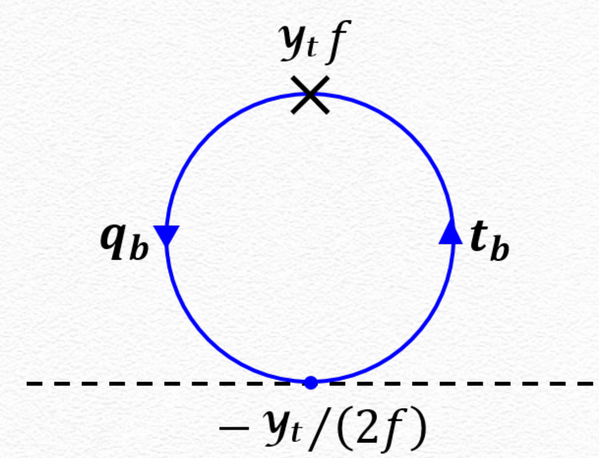


$$[SU(3) \times SU(2) \times U(1)]_{a,b}$$

SM(a)	SM′(b)
q_a, t_a	q_b, t_b

Z_2





tthh—Resonance Search—scalars

[Z.Chacko, Hock-Seng Goh and Roni Harnik] (2005)

$$v = \langle \mathbf{h} \rangle \ll f$$

$$V = \lambda(|h_a|^2 + |h_b|^2)^2 + m_h^2(|h_a|^2 + |h_b|^2) + \kappa(|h_a|^4 + |h_b|^4) + \rho|h_a|^4 + \mu^2|h_a|^2$$

- $\rho|_{tree} = 0$

$$\Delta_{v/\Lambda}^{\mathrm{TH}} \equiv \frac{d\log v^2}{d\log \Lambda^2} = \frac{\partial \log v^2}{\partial \log f^2}\frac{d\log f^2}{d\log \Lambda^2} + \frac{\partial \log v^2}{\partial \log \Lambda^2}$$

[Barbieri-Giudice measure](1988)

$$\Delta_{v/\Lambda}^{\mathrm{TH,soft}} \approx \frac{1}{64\pi^2}\left(\frac{3y_t^2}{\lambda}\frac{\Lambda_t^2}{v^2} - 5\frac{\Lambda_\rho^2}{v^2}\right)$$

$$\Delta_{v/\Lambda}^{\mathrm{SM}} \approx \frac{1}{32\pi^2}\left(\frac{3y_t^2}{\lambda_{\mathrm{SM}}}\frac{\Lambda_t^2}{v^2} - 3\frac{\Lambda_\rho^2}{v^2}\right)$$

Tuning improvement: $\frac{\lambda_{SM}}{2\lambda}$, UV-extension is needed

tthh—Resonance Search—scalars

[P. Asadi, N. Craig, YYL, arXiv:1810.09467]

- *Turtling structure for twin Higgs*

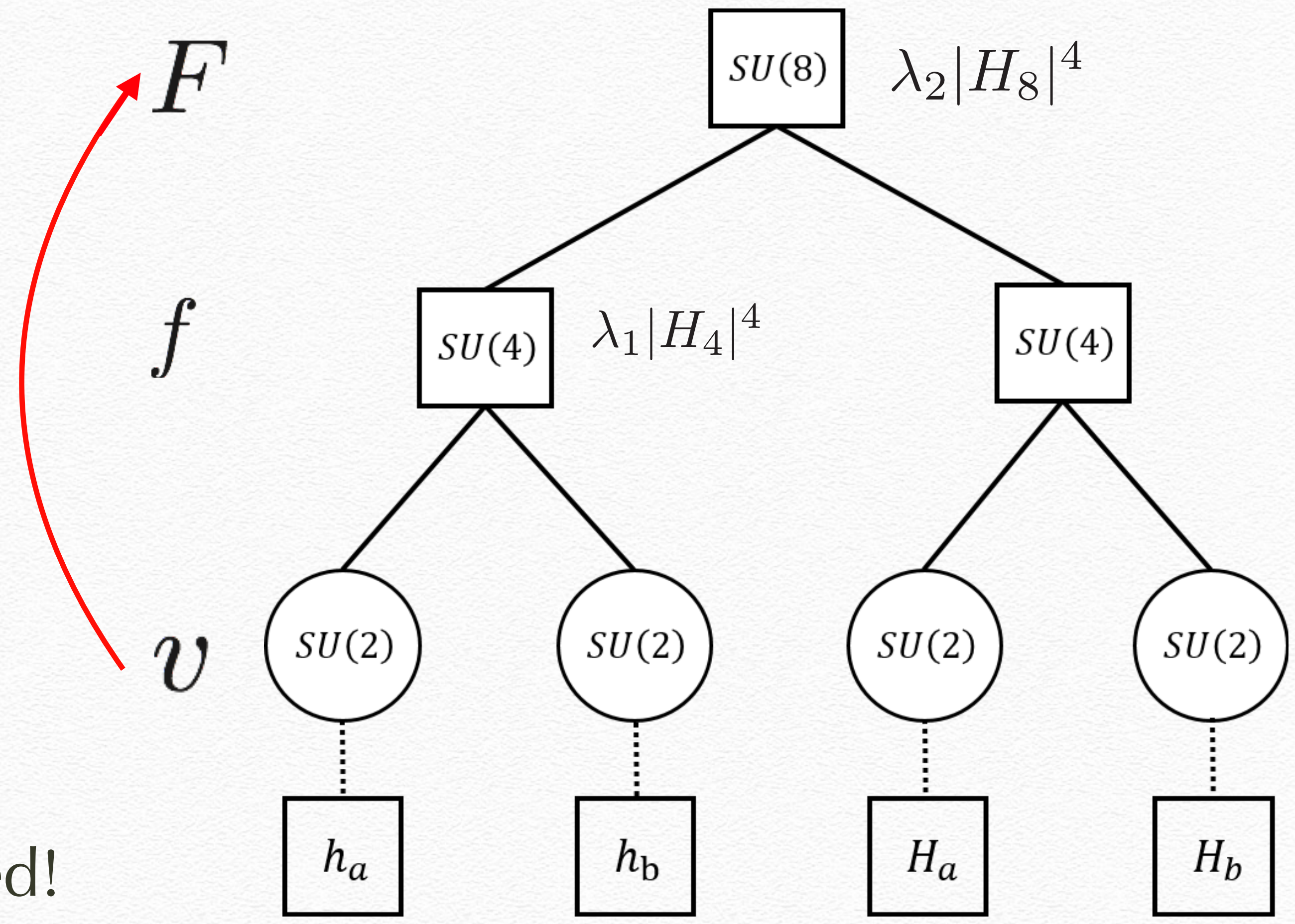
  Symmetry breaking scale protected by another breaking of global symmetry

$$\frac{\lambda_{SM}}{2\lambda} \to \frac{\lambda_{SM}}{2\lambda_1} \times \frac{\lambda_1}{2\lambda_2} \times \ldots \times \frac{\lambda_{n-1}}{2\lambda_n}$$

Landau pole scale not too low=>

NEED $\lambda_i < \lambda_{i-1}$

the tuning is not really improved!



tthh—Resonance Search—scalars

$$V = \lambda(|h_a|^2 + |h_b|^2)^2 + m_h^2(|h_a|^2 + |h_b|^2) + \kappa(|h_a|^4 + |h_b|^4) + \rho|h_a|^4 + \mu^2|h_a|^2$$

- $\rho|_{tree} \neq 0$ [A.Katz, et al. arXiv:1611.08615]

$$\Delta_{v/\Lambda}^{\text{TH,hard}} = \frac{1}{64\pi^2}\frac{2\kappa}{2\kappa+\rho}\left(\frac{3y_t^2}{\lambda}\frac{\Lambda_t^2}{v^2} - \left(5 + 3\epsilon_\pm\frac{\rho}{\kappa}\right)\frac{\Lambda_\rho^2}{v^2}\right)$$

$$m_{SM}^2 = 4v^2(2\kappa+\rho)(1-\frac{v^2}{f^2}) \qquad 2\kappa + \rho \sim \lambda_{SM}$$

tthh—Resonance Search—scalars

$$V = \lambda(|h_a|^2 + |h_b|^2)^2 + m_h^2(|h_a|^2 + |h_b|^2) + \kappa(|h_a|^4 + |h_b|^4) + \rho|h_a|^4 + \mu^2|h_a|^2$$

- $\rho|_{tree} \neq 0$ [A.Katz, et al. arXiv:1611.08615]

$$\Delta_{v/\Lambda}^{\mathrm{TH,hard}} = \frac{1}{64\pi^2}\frac{2\kappa}{2\kappa+\rho}\left(\frac{3y_t^2}{\lambda}\frac{\Lambda_t^2}{v^2} - \left(5 + 3\epsilon_\pm\frac{\rho}{\kappa}\right)\frac{\Lambda_\rho^2}{v^2}\right)$$

$$m_{SM}^2 = 4v^2(2\kappa+\rho)(1-\frac{v^2}{f^2}) \qquad 2\kappa + \rho \sim \lambda_{SM}$$

tthh—Resonance Search—scalars

$$V = \lambda(|h_a|^2 + |h_b|^2)^2 + m_h^2(|h_a|^2 + |h_b|^2) + \kappa(|h_a|^4 + |h_b|^4) + \rho|h_a|^4 + \mu^2|h_a|^2$$

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$$\Lambda_t \sim 5\mathrm{TeV} \mapsto 2\kappa|_{loop} \sim \lambda_{SM}$$

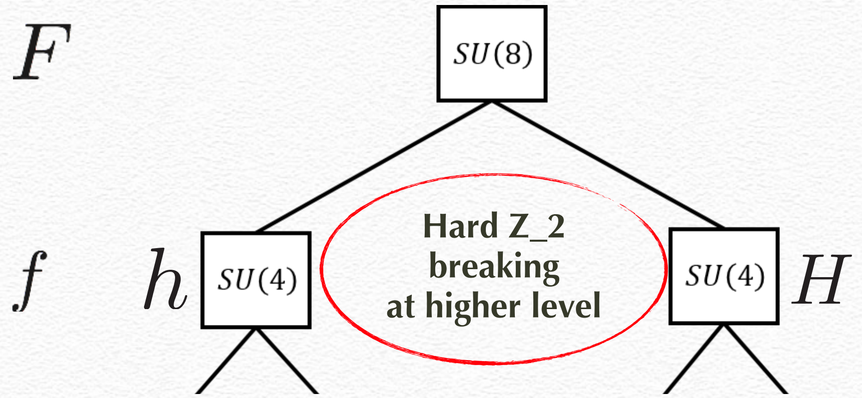
Tuning cannot be improved by much!

tthh—Resonance Search—scalars

[P. Asadi, N. Craig, YYL, arXiv:1810.09467]

Turtling structure for twin Higgs

Symmetry breaking scale protected by another breaking of global symmetry
With hard breaking in the higher level
To reduce tuning and push the cutoff to a higher scale



$$V \supset \bar{\lambda}(|h|^2+|H|^2)^2 + m^2(|h|^2+|H|^2) + \bar{\kappa}(|h|^4+|H|^4) + \bar{\rho}|h|^4 + m_h'^2|h|^2$$

tthh—Resonance Search—scalars

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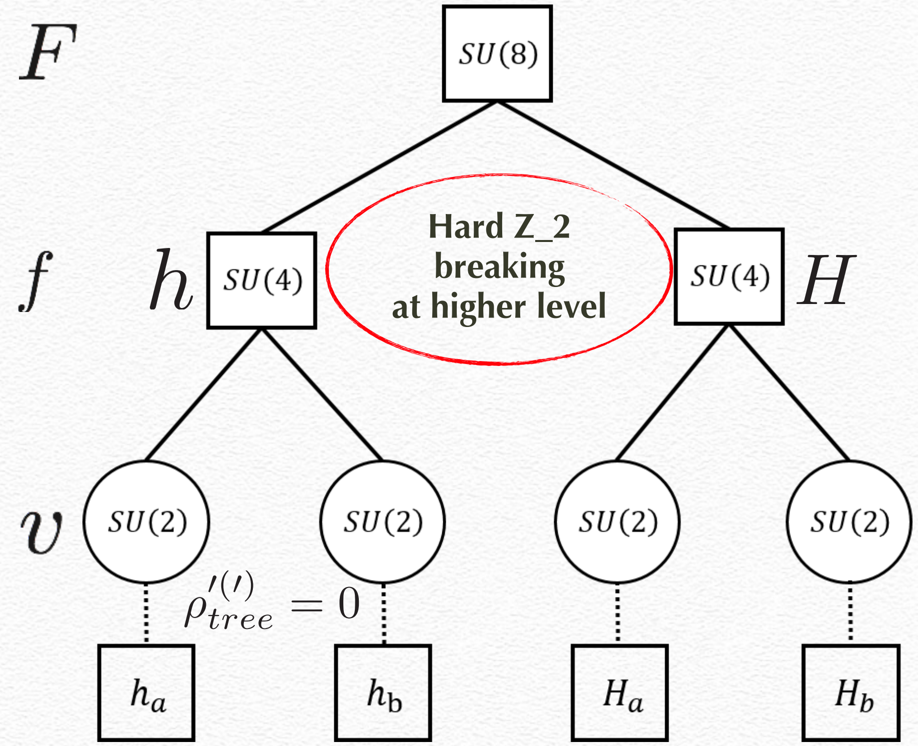

$$
\begin{aligned}
V \supset\ & \bar{\lambda}(|h|^2 + |H|^2)^2 + m^2(|h|^2 + |H|^2) + \bar{\kappa}(|h|^4 + |H|^4) + \bar{\rho}|h|^4 + m_h'^2|h|^2 \\
+\ & \rho''(|h_a|^2 + |H|^2)^2 + \kappa''(|h_a|^4 + |h_b|^4 + |H_a|^4 + |H_b|^4) \\
+\ & \kappa'(|h_a|^4 + |h_b|^4) + \rho'|h_a|^4 + \mu'^2|h_a|^2.
\end{aligned}
$$

tthh—Resonance Search—scalars

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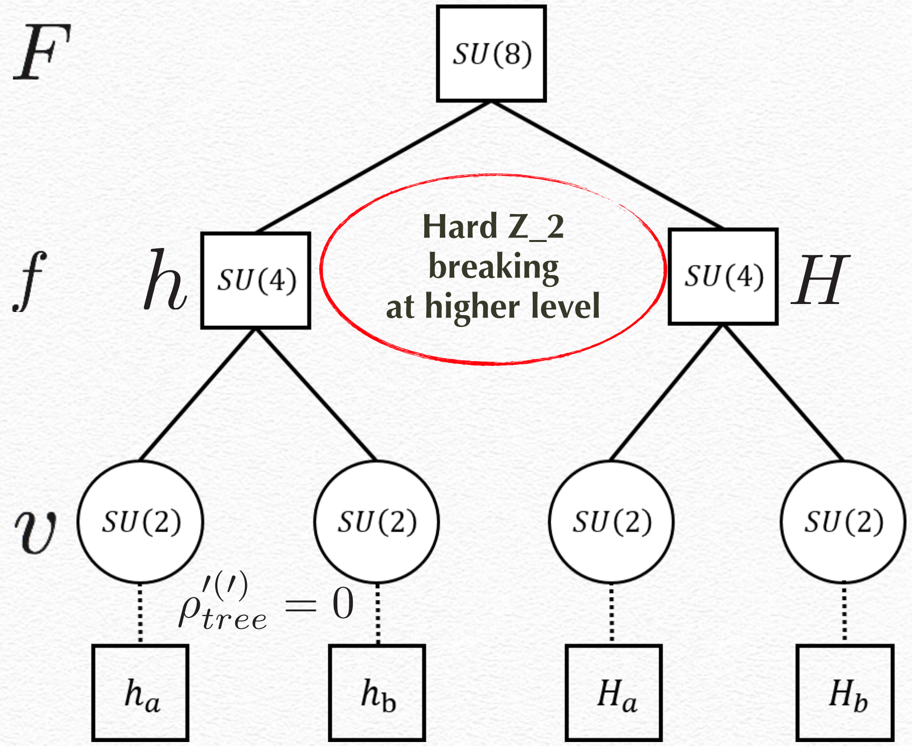

$$
\begin{aligned}
V \supset\ & \bar{\lambda}(|h|^2 + |H|^2)^2 + m^2(|h|^2 + |H|^2) + \bar{\kappa}(|h|^4 + |H|^4) + \bar{\rho}|h|^4 + m_h'^2|h|^2 \\
+\ & \rho''(|h_a|^2 + |H|^2)^2 + \kappa''(|h_a|^4 + |h_b|^4 + |H_a|^4 + |H_b|^4) \\
+\ & \kappa'(|h_a|^4 + |h_b|^4) + \rho'|h_a|^4 + \mu'^2|h_a|^2 .
\end{aligned}
$$

$$m_{SM}^2 \sim 4v^2(2\kappa_1)(1 - \frac{v^2}{f^2})$$

$$\kappa_1 = \kappa'' + \kappa'$$

$$\Delta_{v/\Lambda}^{\text{TMNT}} \approx \frac{1}{64\pi^2}\frac{\bar{\kappa}}{2\bar{\kappa} + \bar{\rho}}\left(\frac{3y_t^2}{\bar{\lambda}}\frac{\Lambda_t^2}{v^2} - \left(9 + 5\epsilon_\pm \frac{\bar{\rho}}{\bar{\kappa}}\right)\frac{\Lambda_\rho^2}{v^2}\right)$$

tthh—Resonance Search—scalars

[P. Asadi, N. Craig, YYL, arXiv:1810.09467]

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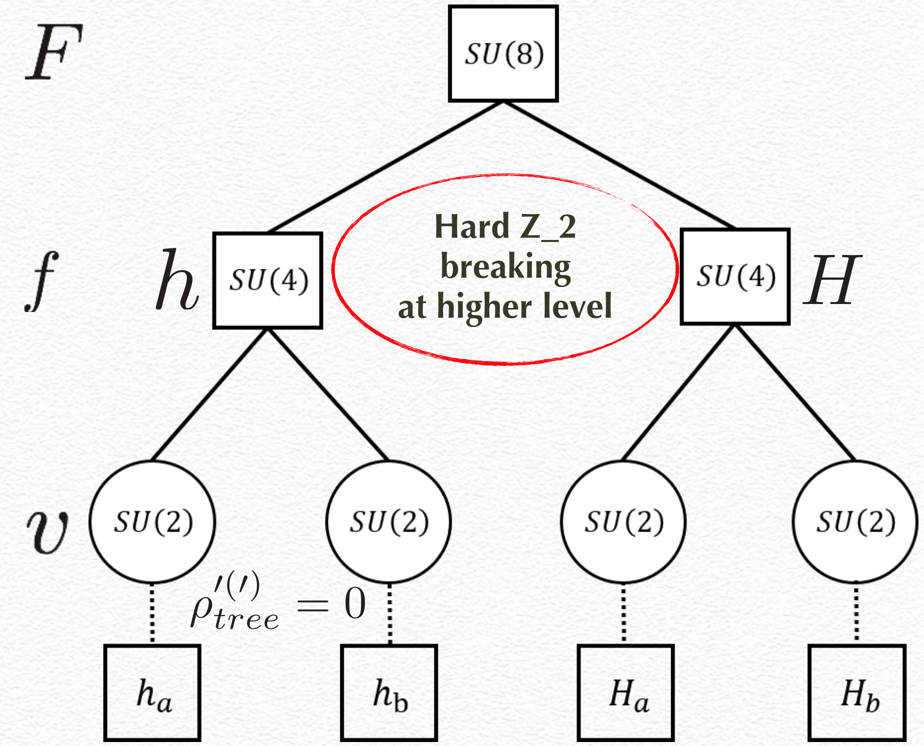


$$
\begin{aligned}
V \supset\ & \bar\lambda(|h|^2+|H|^2)^2 + m^2(|h|^2+|H|^2) + \bar\kappa(|h|^4+|H|^4) + \bar\rho|h|^4 + m_h'^2|h|^2 \\
+\ & \rho''(|h_a|^2+|H|^2)^2 + \kappa''(|h_a|^4+|h_b|^4+|H_a|^4+|H_b|^4) \\
+\ & \kappa'(|h_a|^4+|h_b|^4) + \rho'|h_a|^4 + \mu'^2|h_a|^2 .
\end{aligned}
$$

$$m_{SM}^2 \sim 4v^2(2\kappa_1)(1-\frac{v^2}{f^2})$$

$$\kappa_1 = \kappa'' + \kappa'$$

$$\Delta_{v/\Lambda}^{\rm TMNT} \approx \frac{1}{64\pi^2}\frac{\bar\kappa}{2\bar\kappa+\bar\rho}\left(\frac{3y_t^2}{\bar\lambda}\frac{\Lambda_t^2}{v^2} - \left(9+5\epsilon_\pm\frac{\bar\rho}{\bar\kappa}\right)\frac{\Lambda_\rho^2}{v^2}\right)$$

$$\Delta_{v/\Lambda}^{\rm TH,soft} \approx \frac{1}{64\pi^2}\left(\frac{3y_t^2}{\lambda}\frac{\Lambda_t^2}{v^2} - 5\frac{\Lambda_\rho^2}{v^2}\right)$$

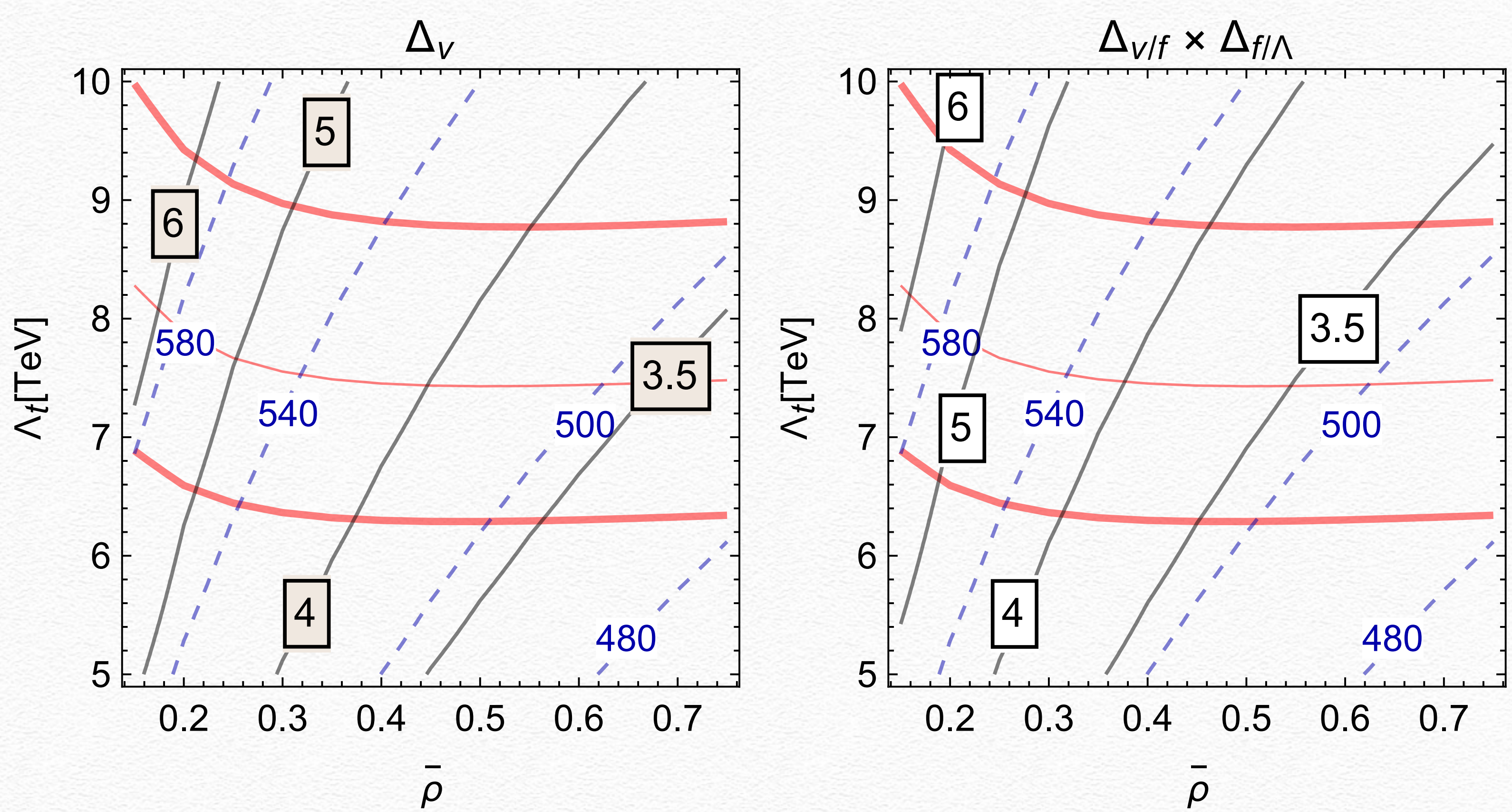
$$\Delta_{v/\Lambda}^{\rm SM} \approx \frac{1}{32\pi^2}\left(\frac{3y_t^2}{\lambda_{\rm SM}}\frac{\Lambda_t^2}{v^2} - 3\frac{\Lambda_\rho^2}{v^2}\right)$$

tthh—Resonance Search

[P. Asadi, N. Craig, YYL, arXiv:1810.09467]

m [TeV]	Λ_ρ [TeV]	$\bar{\lambda}$	$\bar{\kappa}$	κ''	κ'	ρ'	m_h^2	ρ''
1.8	3.0	0.8	0.0(0.15)	0.0	0.005	0.0	0.0	0.0

$$
\begin{aligned}
\delta m^2 &= -\frac{3y_t^2}{16\pi^2}\Lambda_t^2 + \frac{9\bar{\lambda}}{16\pi^2}\Lambda_\rho^2, \\
\delta\bar{\kappa} &= \frac{5\bar{\rho}\bar{\lambda}}{32\pi^2}\log\frac{\Lambda_\rho^2}{m_2^2}, \\
\delta\kappa'' &= \frac{3y_t^4}{16\pi^2}\log\frac{\Lambda_t^2}{m_{T_a}^2}, \\
\delta\kappa' &= \frac{3y_t^4}{16\pi^2}\log\frac{m_{T_a}^2}{m_{t_b}^2}, \\
\delta\rho' &= \frac{3y_t^4}{16\pi^2}\log\frac{m_{t_b}^2}{m_{t_a}^2}, \\
\delta m_h'^2 &= \epsilon_\pm\frac{5\bar{\rho}}{16\pi^2}\Lambda_\rho^2,
\end{aligned}
$$



a factor of 8-15 improvement on tuning!

tthh—Resonance Search—scalars

[P. Asadi, N. Craig, YYL, arXiv:1810.09467]

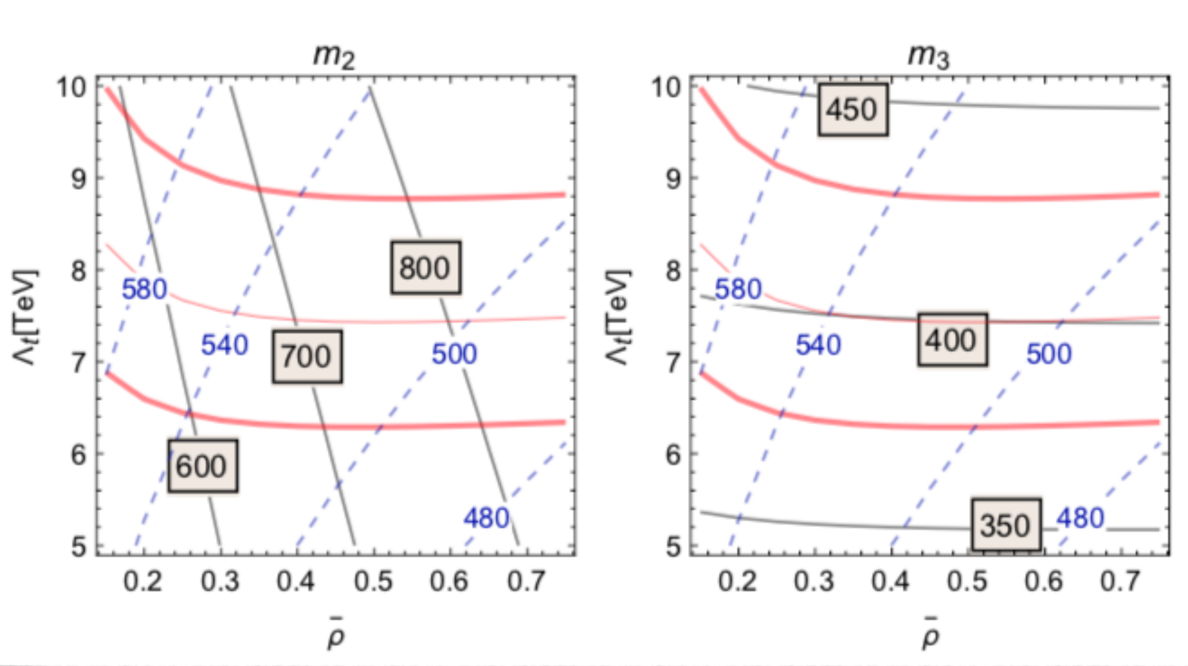
$$\delta m_{SM}^2 \sim -\frac{3y_t^2\Lambda^2}{16\pi^2} + \frac{g^2\Lambda^2}{32\pi^2} + \frac{\lambda_{SM}\Lambda^2}{32\pi^2}$$

$$\delta m_{SM}^2 = \frac{\kappa_1}{\bar\lambda}\frac{\bar\kappa}{2\bar\kappa+\bar\rho}\left(m^2 - \frac{3y_t^2}{16\pi^2}\Lambda_t^2 + \frac{9\bar\lambda}{16\pi^2}\Lambda_\rho^2\right) + \frac{\epsilon\pm\bar\rho}{2\bar\kappa+\bar\rho}\frac{5\kappa_1\Lambda_\rho^2}{16\pi^2} + \mu'^2$$

direct quadratic sensitivity to scalar cutoff

$\Lambda_\rho \sim 2\text{TeV}$ roughly the same cutoff scale as SM, at which new electroweak scalars appear

But stops us from turtling up



more light scalars (radial mode) are below TeV scale, almost not couples to our EW sector, safe from data

More scalars-> Higher colored states scale

scalars are definite signature of naturalness!