Anatomy of tthh Physics

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

June 26, 2019

Opportunities at Future High Energy Colliders

Outline

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

Higgs Trilinear Coupling Measurement

Contact Interaction Measurement

Resonance Search

heavy fermions, heavy scalars in turtling models/MSSM

BDT analysis and Results

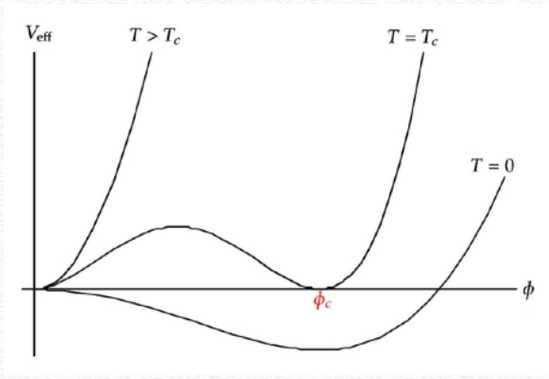
Conclusion and Outlook

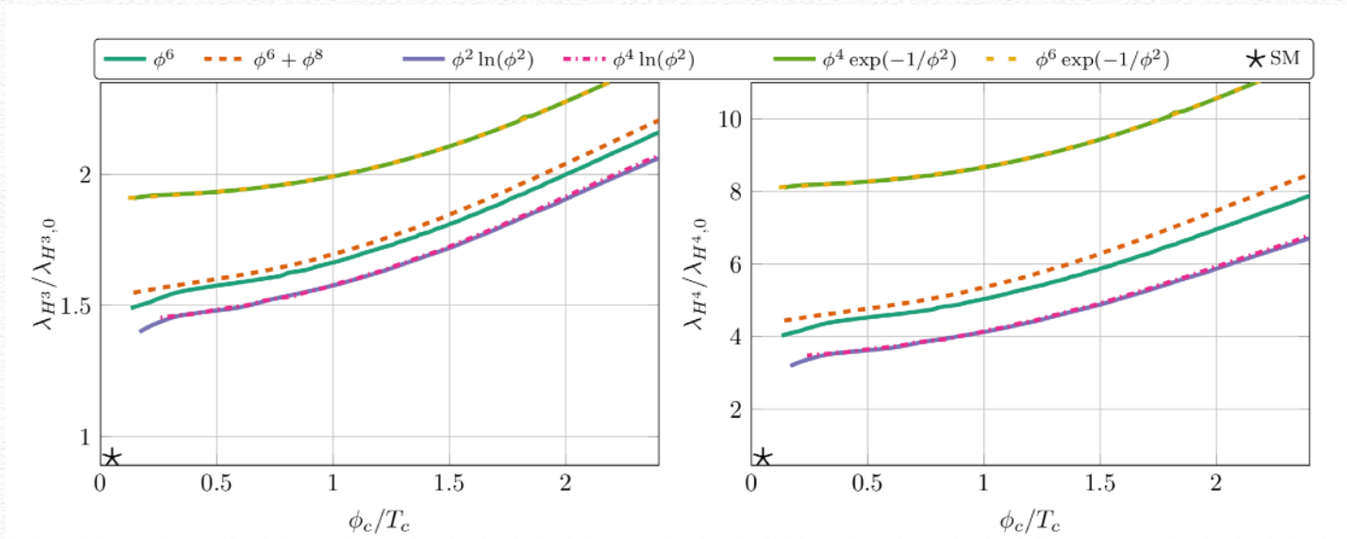
Higgs Trilinear Coupling

1, Electroweak baryongenesis: out of equilibrium

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

baryon asymmetry preserved





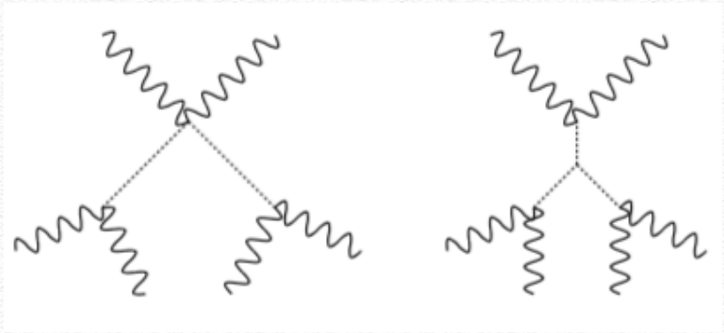
[M. Reichert, et al. arXiv:1711.00019]

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

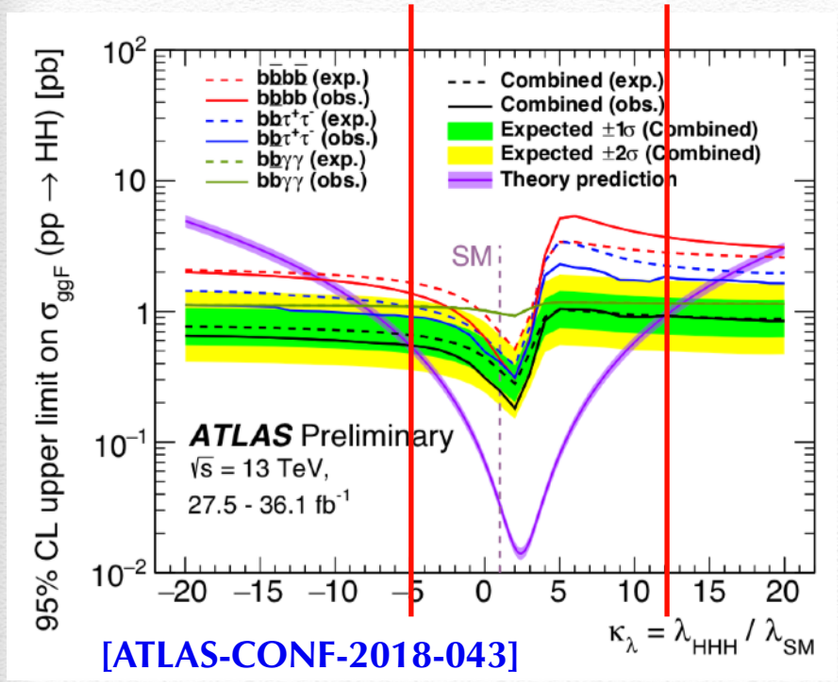
[S. Chang, et al. arXiv:1902.05556]

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

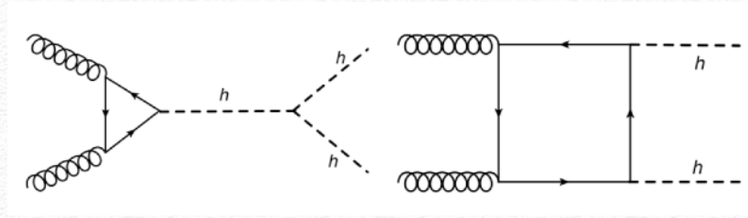
Z_{L}^{6}

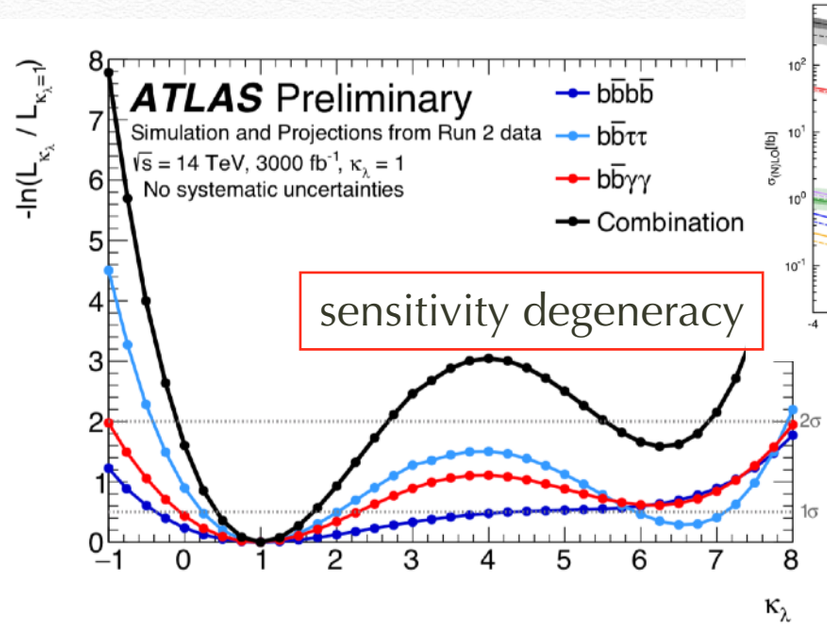


Higgs Trilinear Coupling

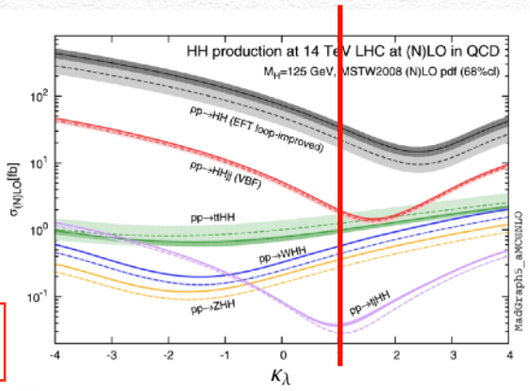


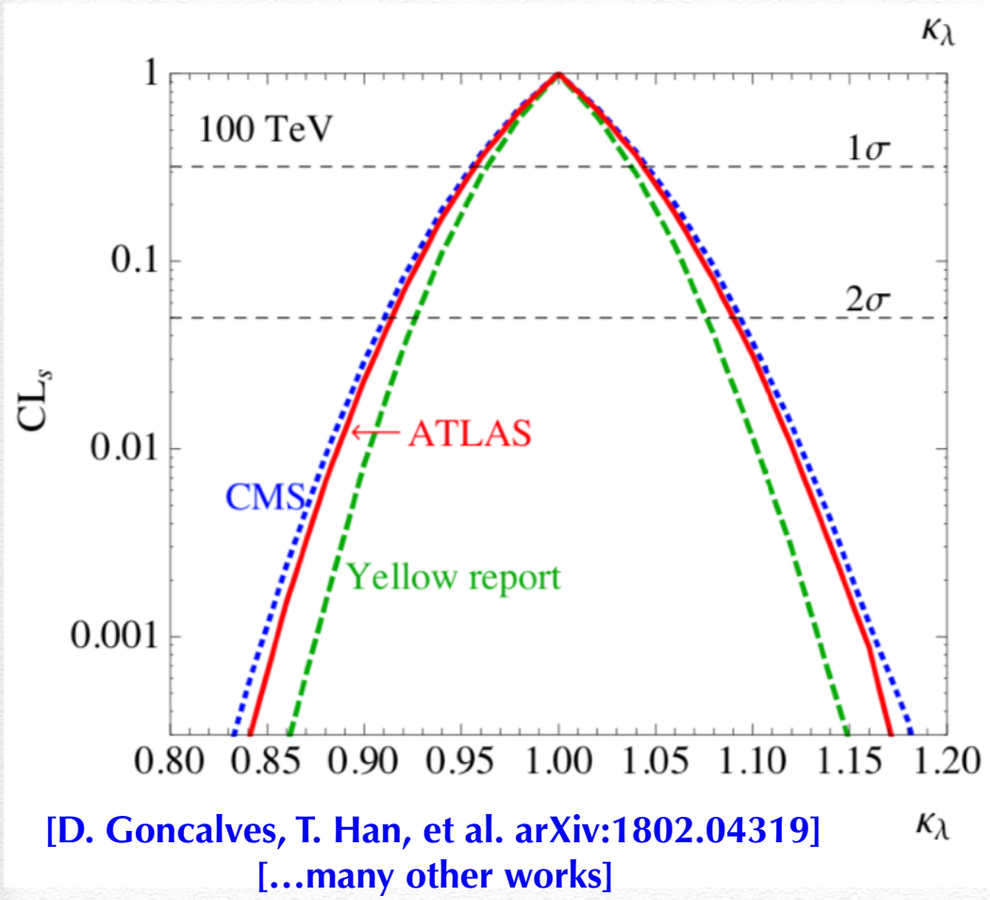
[ATLAS-CONF-2018-043]



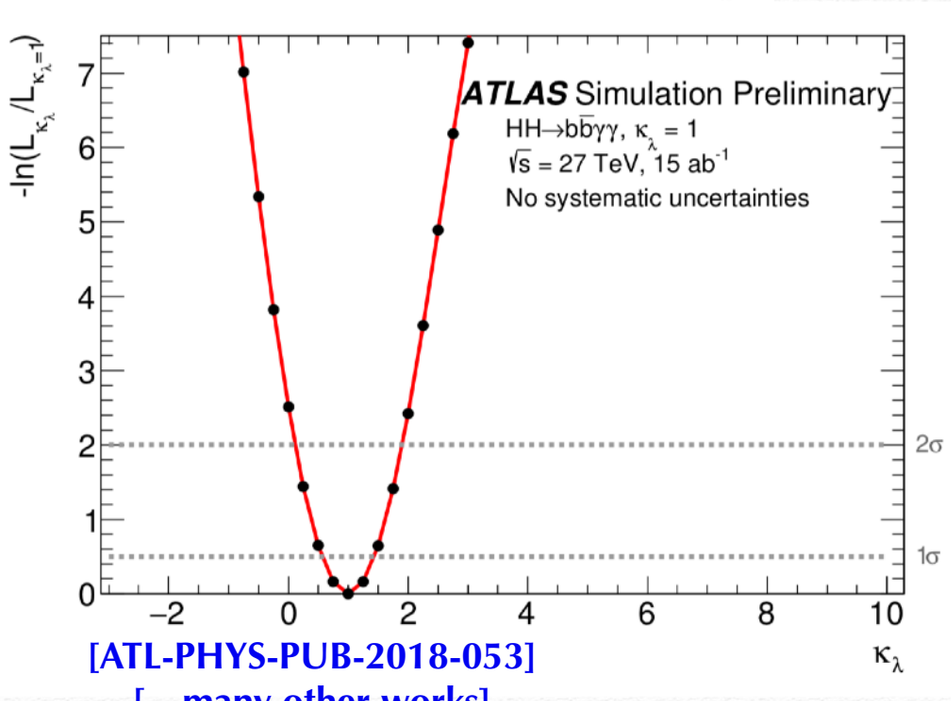


sensitivity degeneracy





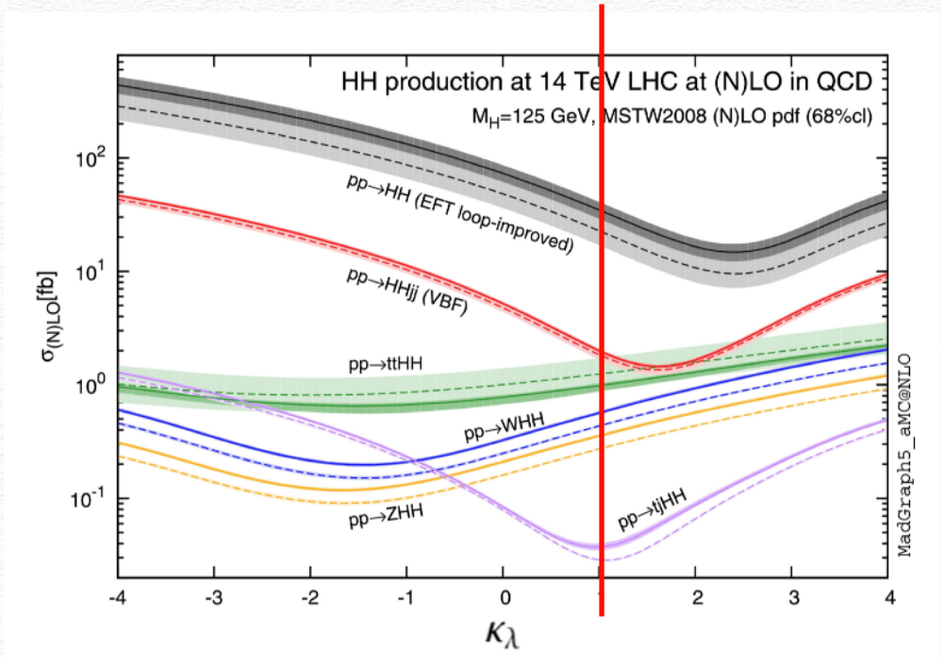
[D. Goncalves, T. Han, et al. arXiv:1802.04319]
[…many other works]

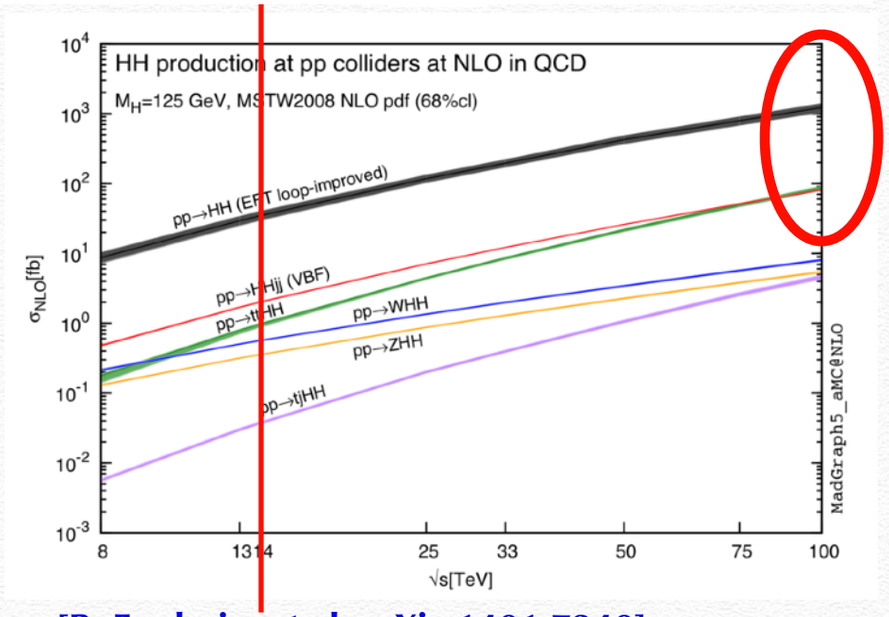


[ATL-PHYS-PUB-2018-053]
[…many other works]

tthh—Higgs trilinear coupling

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

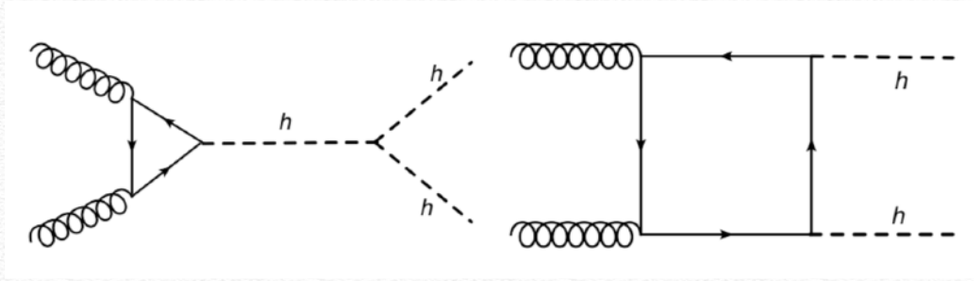




[R. Frederix, et al. arXiv:1401.7340]

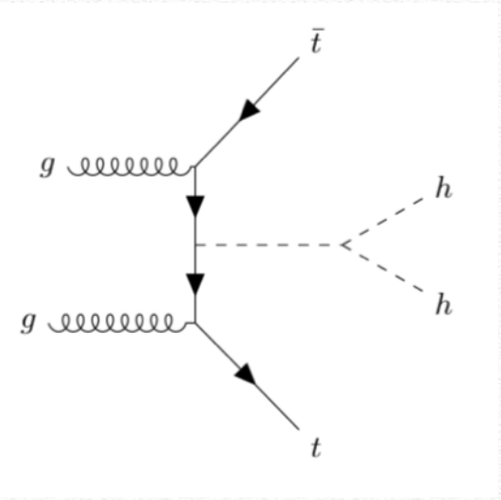
tthh could play a complementary role!

destructive interference



sensitivity degeneracy for gluon fusion di-Higgs production;

tthh channel: constructive interference for enhanced trilinear coupling; smaller bg



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

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

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

tthh could play a complementary role

tthh channel: constructive interference for enhanced trilinear coupling and positive 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

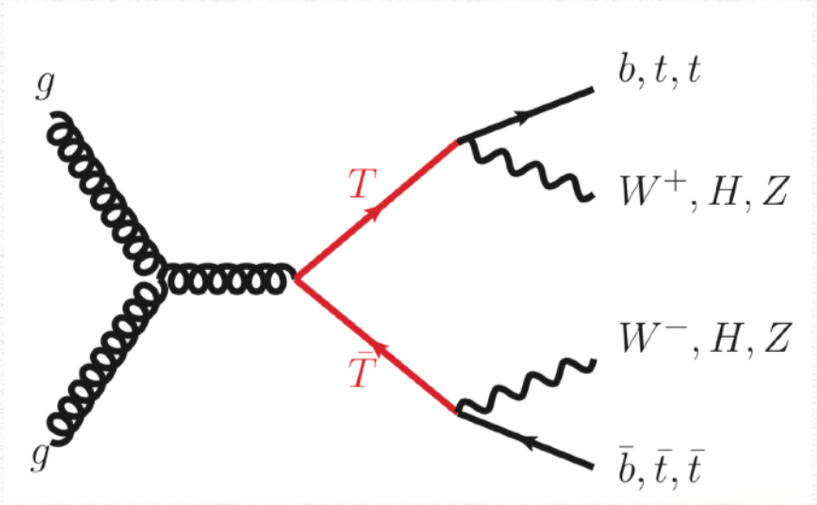
$$BR(T \to th) \sim BR(T \to tZ) \sim \frac{1}{2} BR(T \to Wb) \sim 25\%$$

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

$$BR(T \to th) \sim BR(T \to tZ) \sim 50\%$$

tthh could play an important role!

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



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

twin Higgs model need to be further extended!

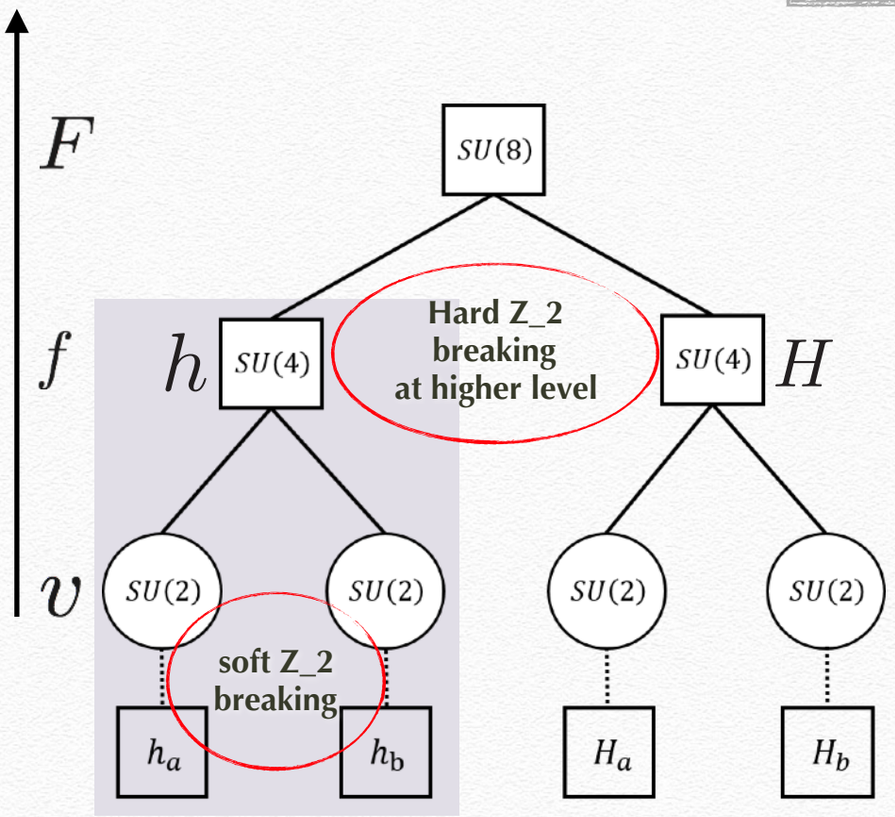
Precision may not be enough

tthh—Resonance Search—scalars

direct search for new states, highly motivated by naturalness

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

Twin Turtles



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

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

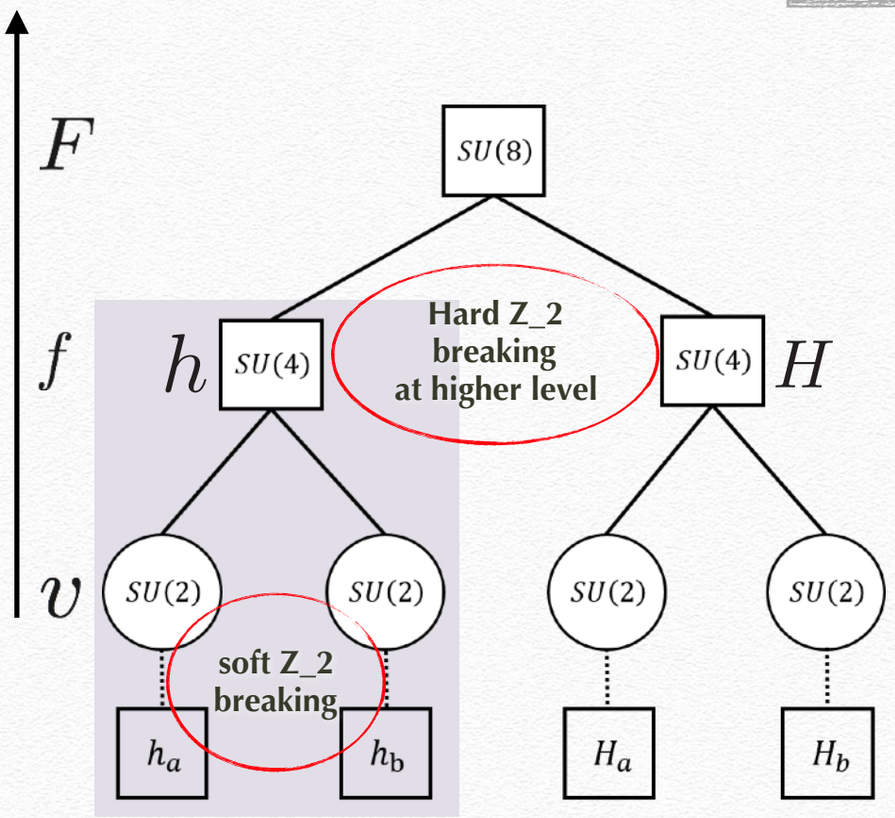
$$\begin{aligned} V \supset\ & \bar\lambda(|h|^2+|H|^2)^2+m^2(|h|^2+|H|^2)+\bar\kappa(|h|^4+|H|^4)+\bar\rho|h|^4+m_h'^2|h|^2 \\ +\ & \rho''(|h_a|^2+|H|^2)^2+\kappa''(|h_a|^4+|h_b|^4+|H_a|^4+|H_b|^4) \\ +\ & \kappa'(|h_a|^4+|h_b|^4)+\rho'|h_a|^4+\mu'^2|h_a|^2. \end{aligned}$$

tthh—Resonance Search—scalars

direct search for new states, highly motivated by naturalness

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

Twin Turtles



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

Precision measurement?

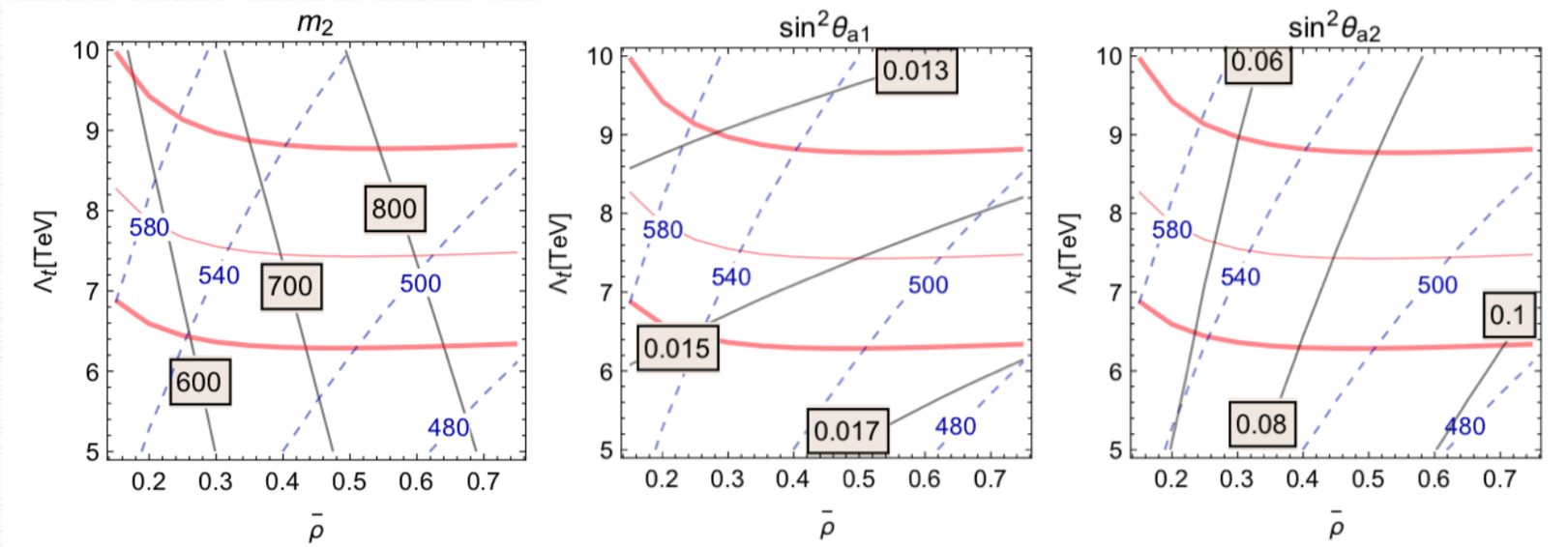
$$g_{hii} \sim g_{h_{SM}ii}\left(1-\frac{1}{2}(\sin^2\theta_{a1}+\sin^2\theta_{a2})\right) \sim g_{h_{SM}ii}(1-\frac{v^2}{2f^2})$$

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!

tthh—Resonance Search—scalars

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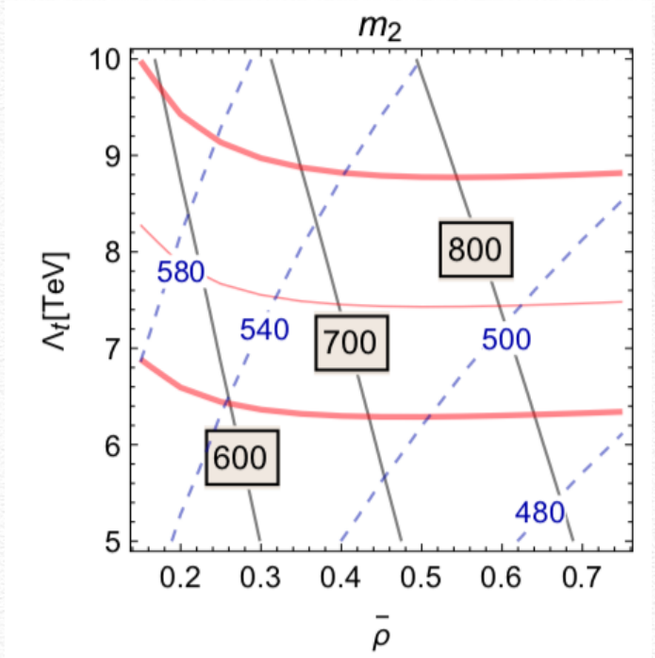
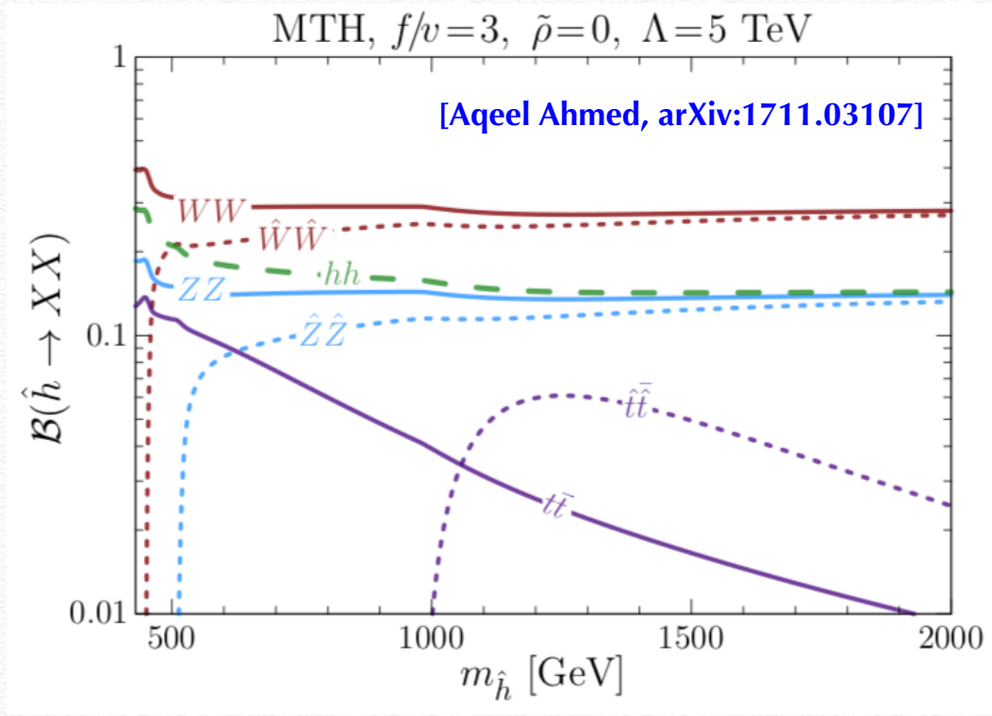


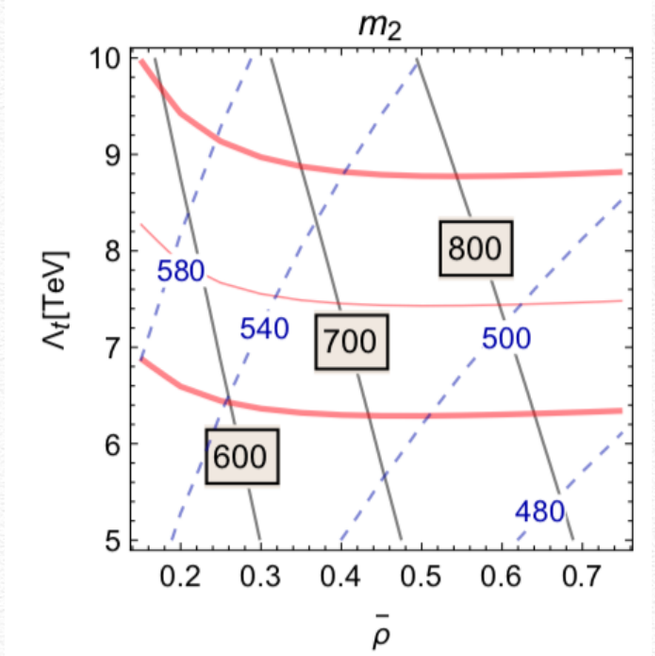


large Br(h2-> hh);

rich signatures from di-Higgs decay.

Direct production of heavy scalars (h2) becomes crucial!

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



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.

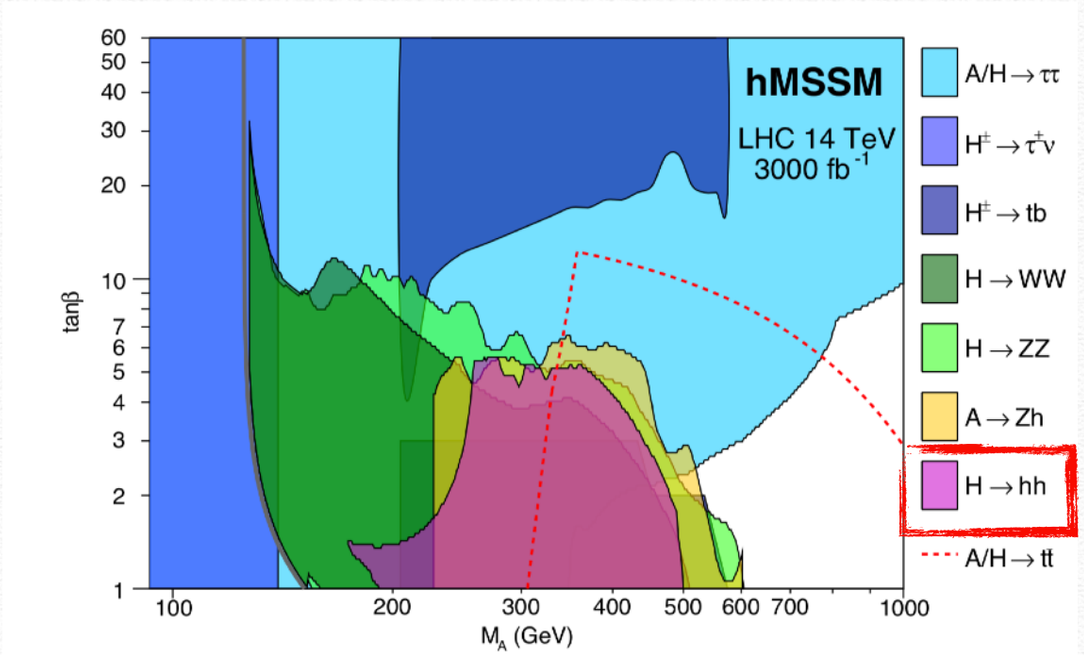
tthh could play an important role!

tthh—Resonance Search—scalars

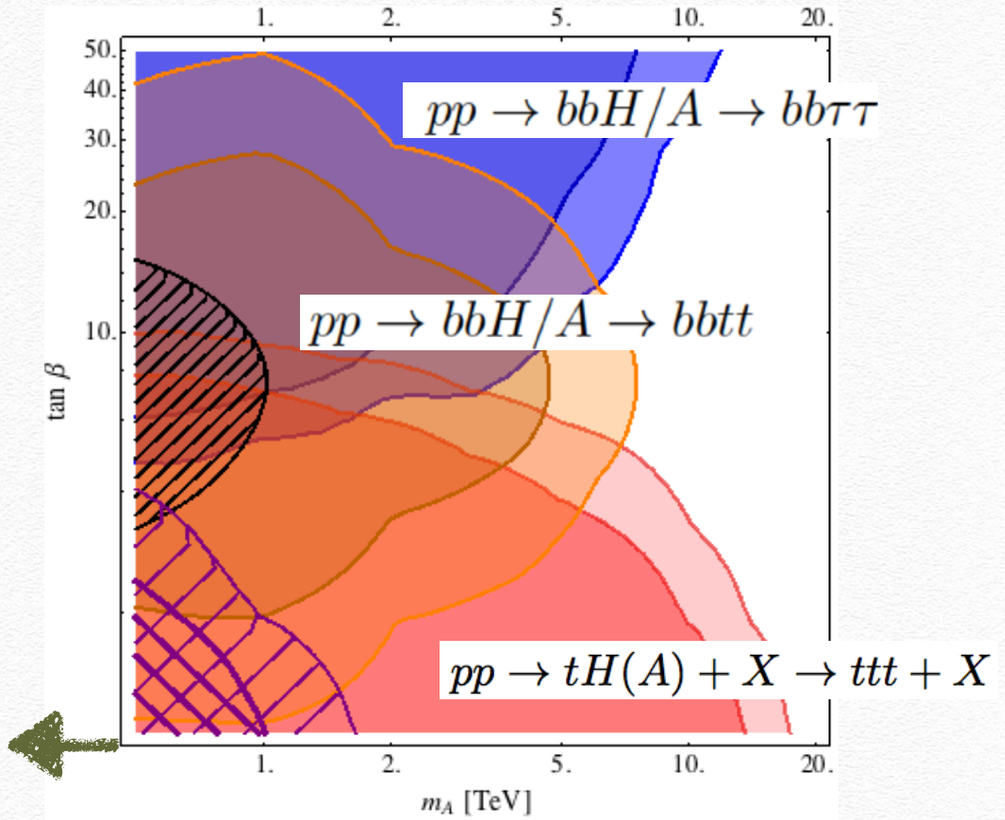
MSSM Higgs bosons(no CP-violation):H,A,Hc

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]



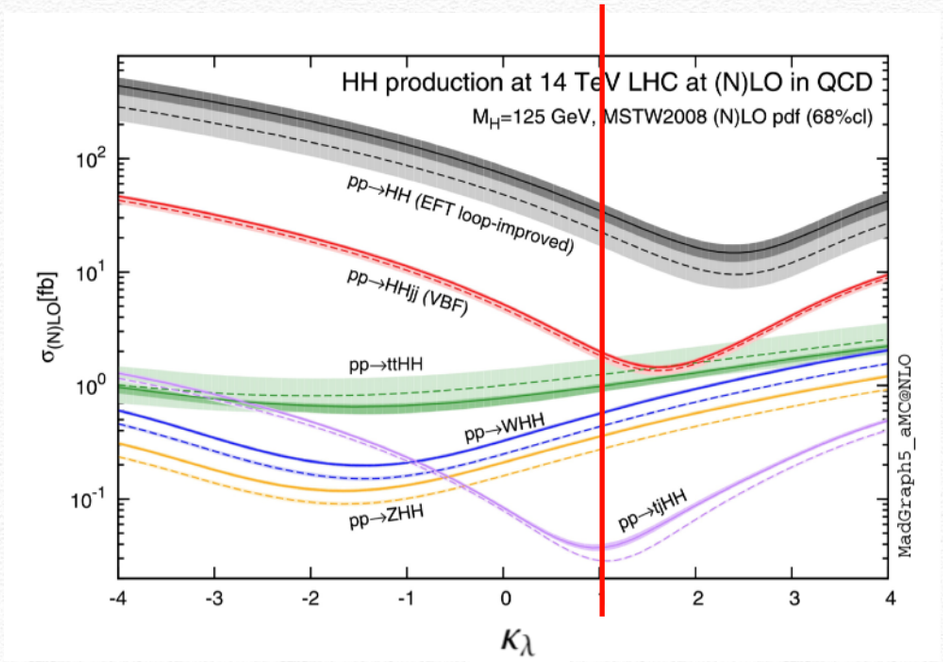
[N. Craig, J. Hajer, YYL, T. Liu, H. Zhang, arXiv:1605.08744]

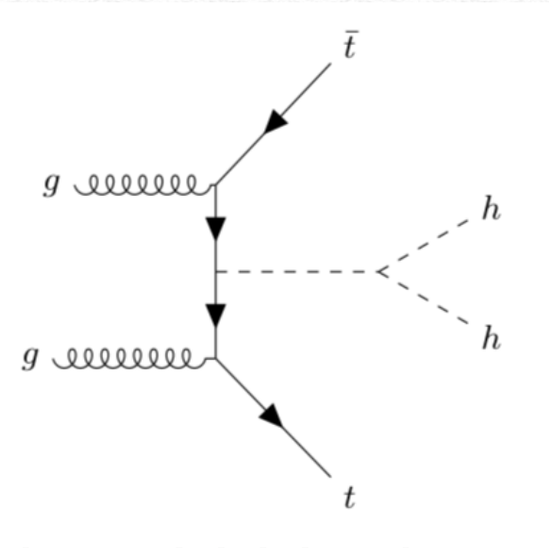


tthh could play an important role!

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

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

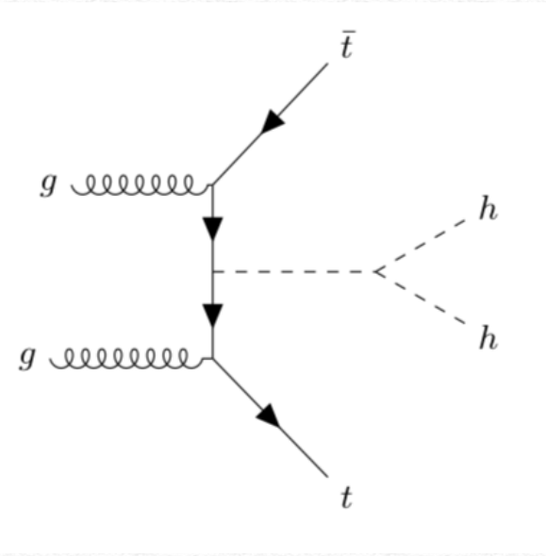
complicated topologies, BDT method?

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

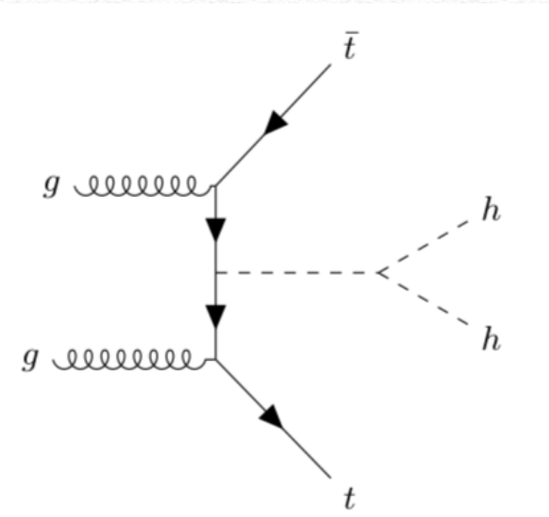
	No cut	Preselection	$5b1\ell$	$5b2\ell$	SS2ℓ	Multi-ℓ	$\tau\tau$
$tthh$	2.9e3	7.37e2	50.9 (97.2)	6.1 (12.0)	14.6 (15.7)	8.6 (9.2)	3.6 (3.8)
$tt4b$	1.1e6	1.79e5	6.56e3 (1.31e4)	664 (1.30e3)	212 (223)	115 (121)	94.1 (95.1)
$tt2b2c$	3.1e5	4.28e4	621 (1.73e3)	59.4 (163)	38.0 (42.4)	24.1(26.8)	43.6 (48.6)
$ttVV$	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)

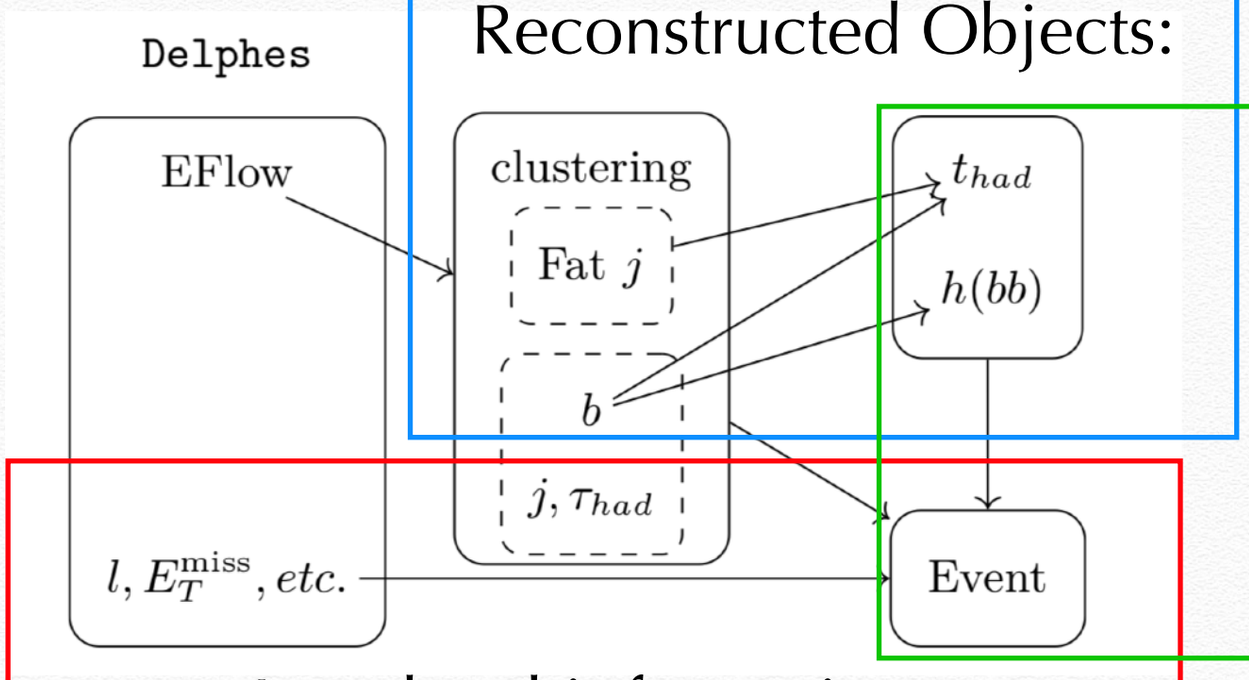
tthh channel analysis

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

@HL-LHC

$5b1\ell$	$5b2\ell$	SS2ℓ	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

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@HL-LHC

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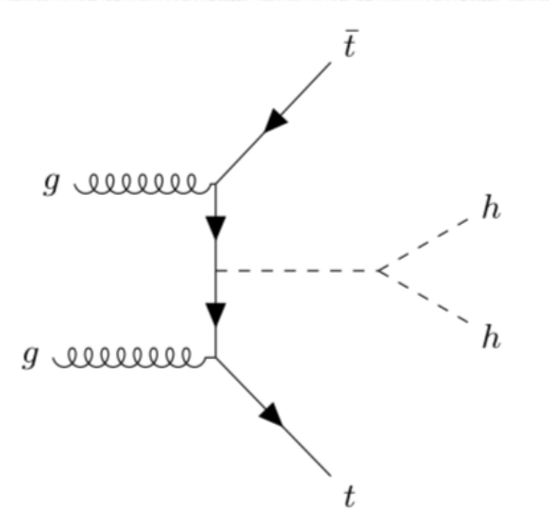

$-10 < \kappa\lambda < 6.9$@95%C.L.

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$(S/B)_{\rm cut}(\%)$			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]

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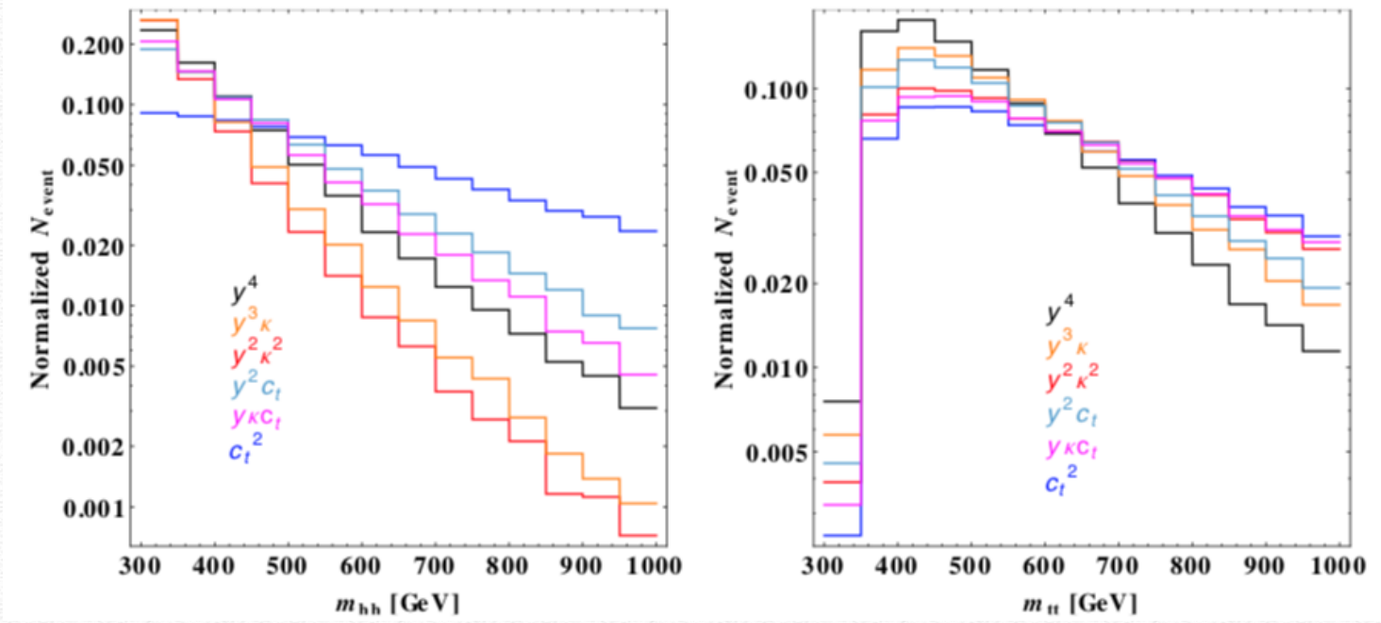

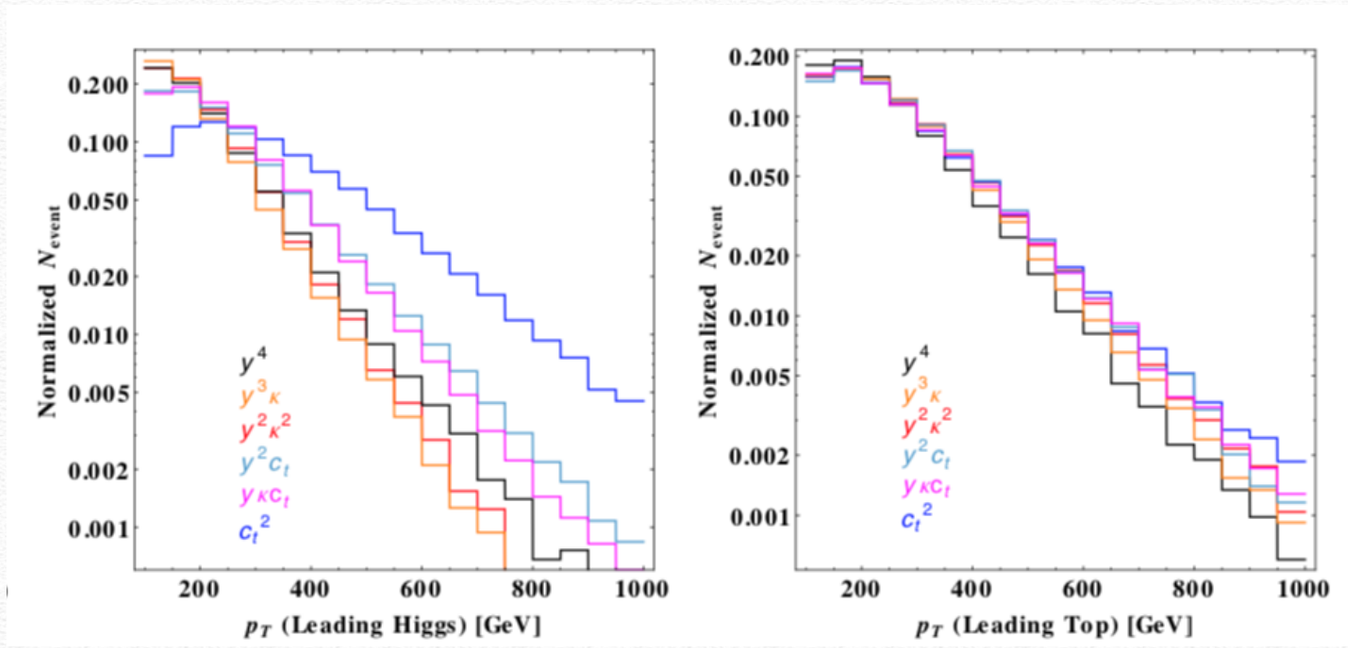

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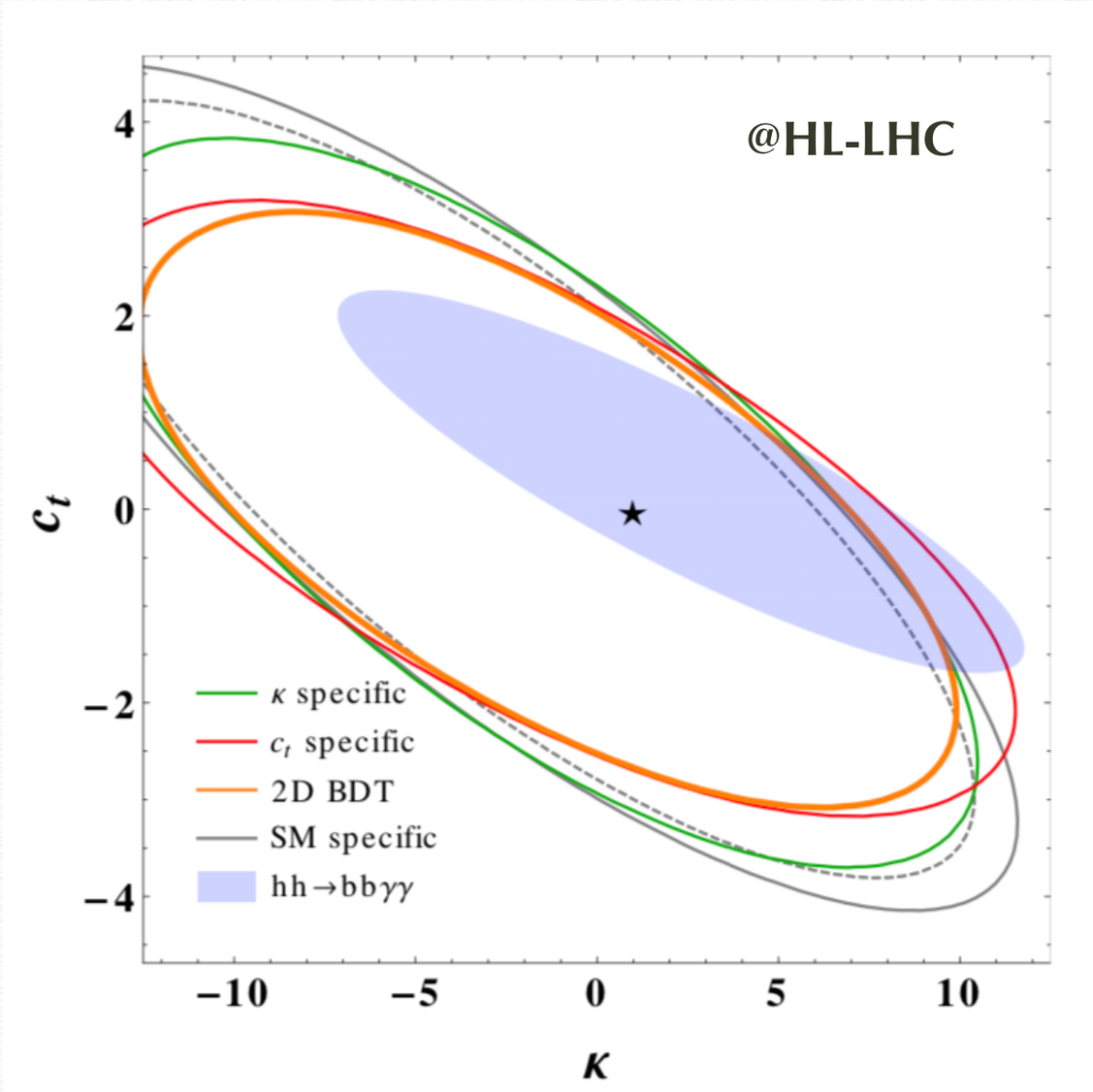
Assuming SM top Yukawa coupling

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



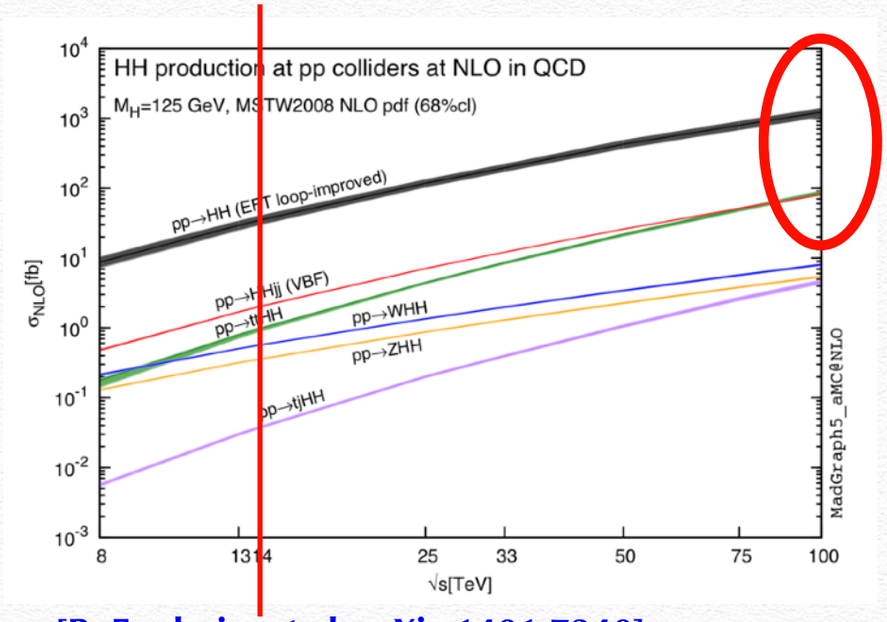
Blue region is the exclusion limit based on gluon fusion channel projected from [ATL-PHYS-PUB-2018-053]

Partially breaks the degeneracy in the gg → hh → bbγγ

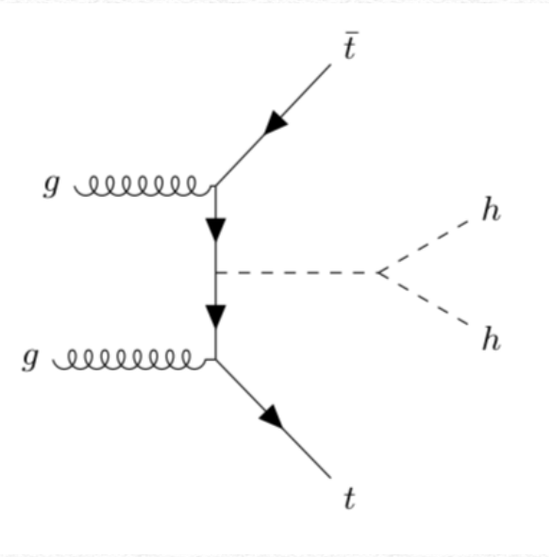
Kappa specific BDT help to improve the c_t direction.

Kinematics help to further improve the sensitivity.

tthh—Higgs self coupling measurement



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



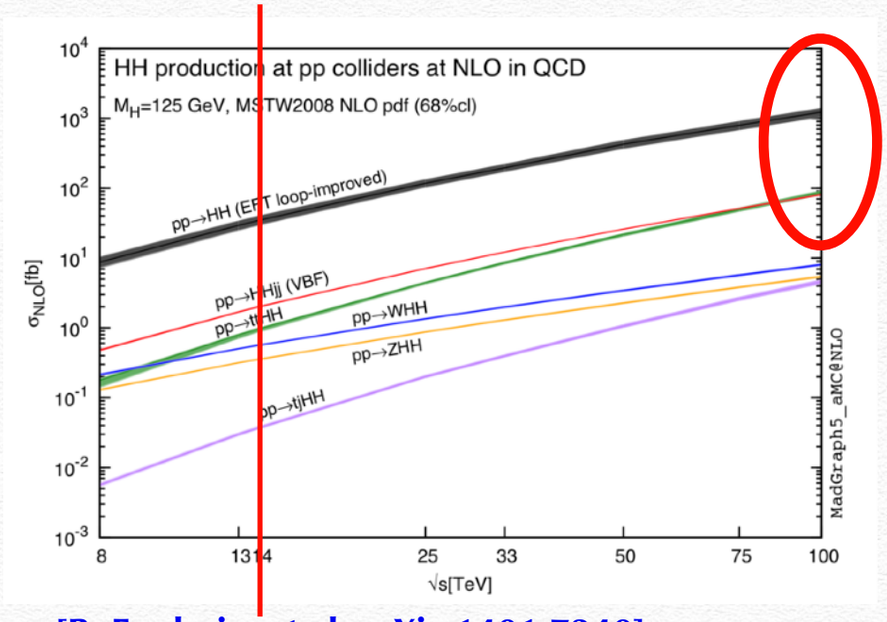
$$\frac{\sigma(gg \to hh \to bb\gamma\gamma)_{14}}{\sigma(gg \to hh \to bb\gamma\gamma)^{\rm SM}_{14}} = 1.70 - 0.82\kappa + 0.12\kappa^2 - 3.79c_t + 0.98c_t\kappa + 2.68c_t^2$$

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

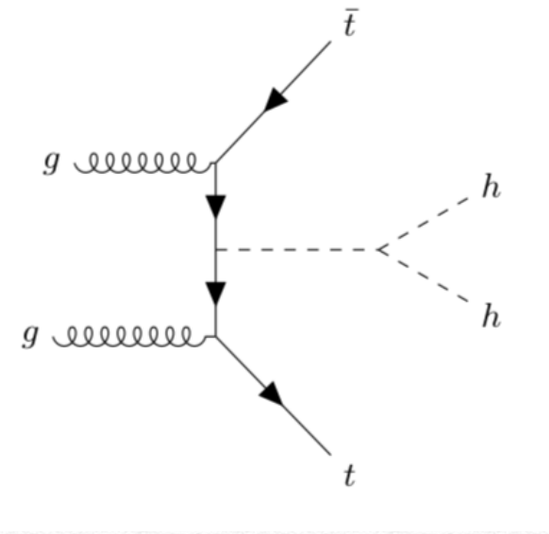
$$\frac{\sigma(tthh)_{14}}{\sigma(tthh)^{\rm SM}_{14}} = 0.82 + 0.14\kappa + 0.04\kappa^2 + 0.28c_t + 0.21\kappa c_t + 0.44c_t^2$$

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

tthh—Higgs self coupling measurement



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



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

~5.9σ @100TeV 30/ab

−3.01 < κλ < 1.65@68%C.L.

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

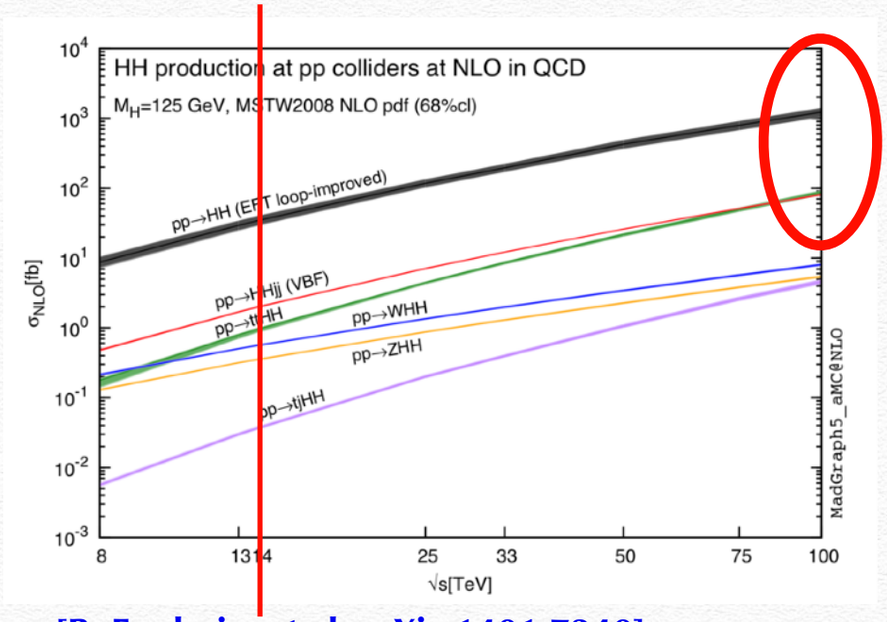
Projected @ 100TeV 30/ab

~14.3σ

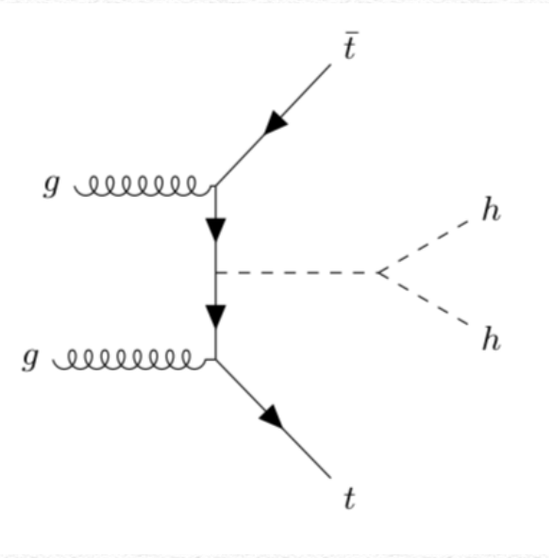
−2.6 < κλ < -1.6 U 0.2 < κλ < 1.6@95%C.L.

gain mainly from combing all decay channels

tthh—Higgs self coupling measurement



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

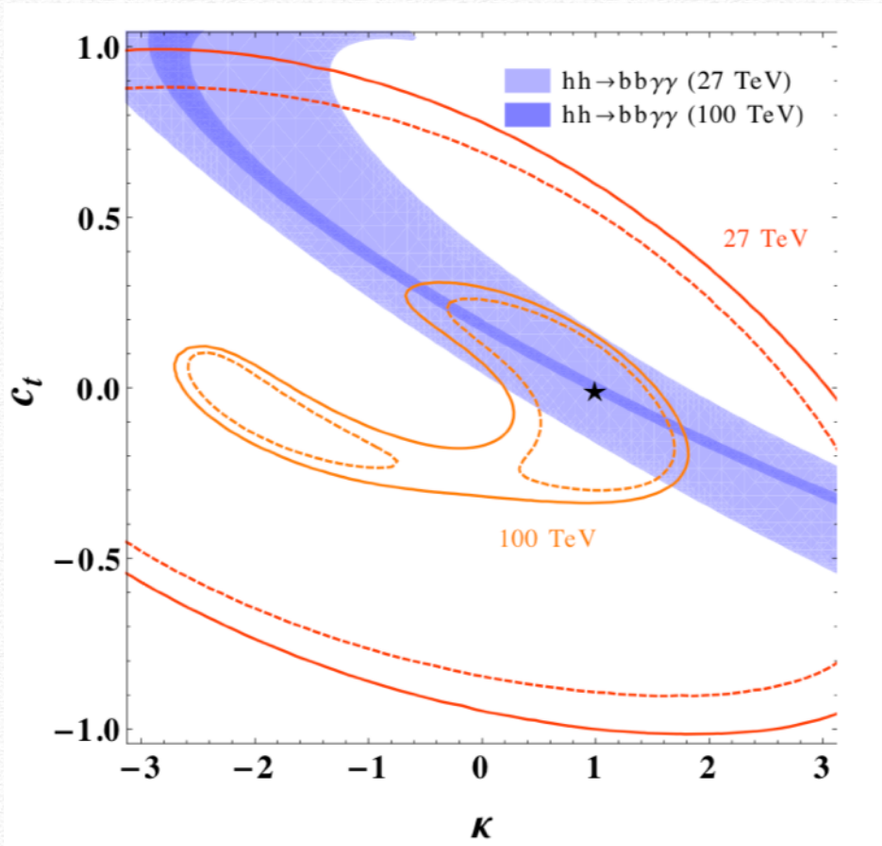


[L. Li, YYL, T. Liu, arXiv:1905.03772]

fitting to {κ,ct} = {1,0}

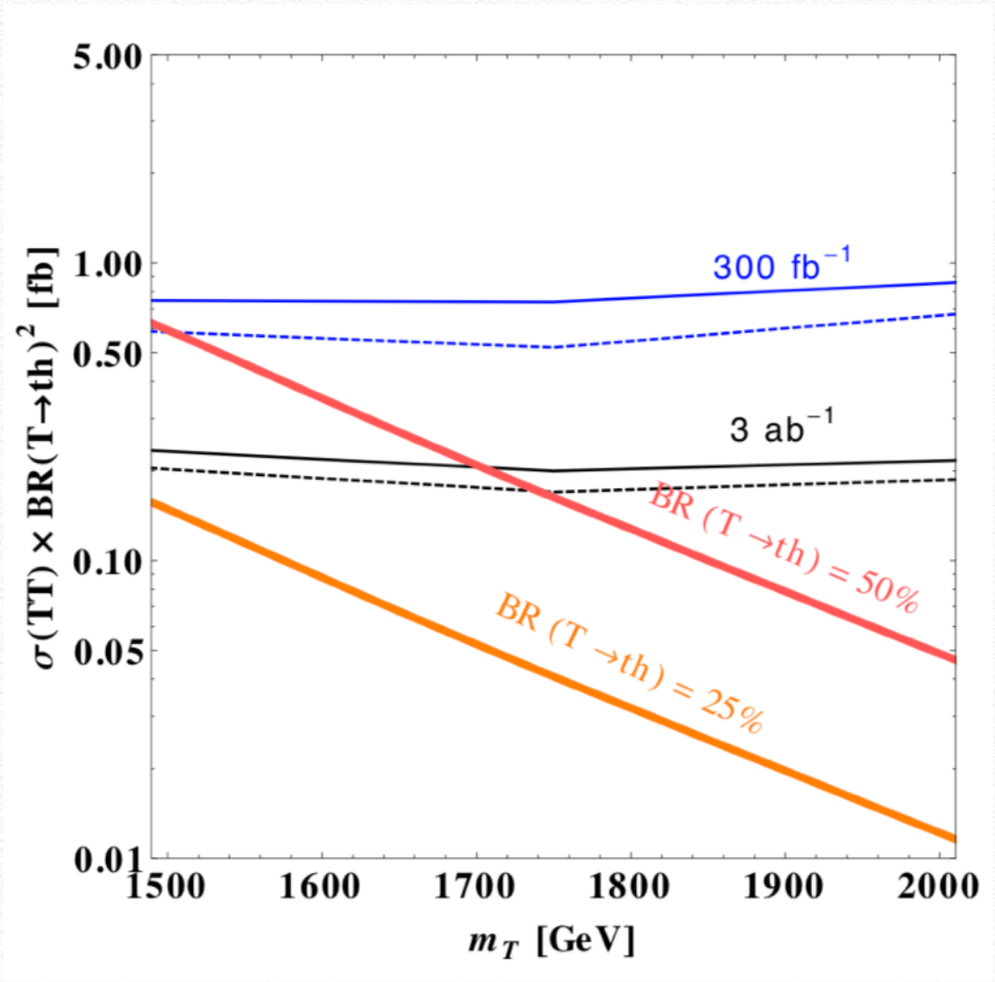
cross section contour centre around {κ,ct} = {0,0}

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



Coloured vector-like top partners

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

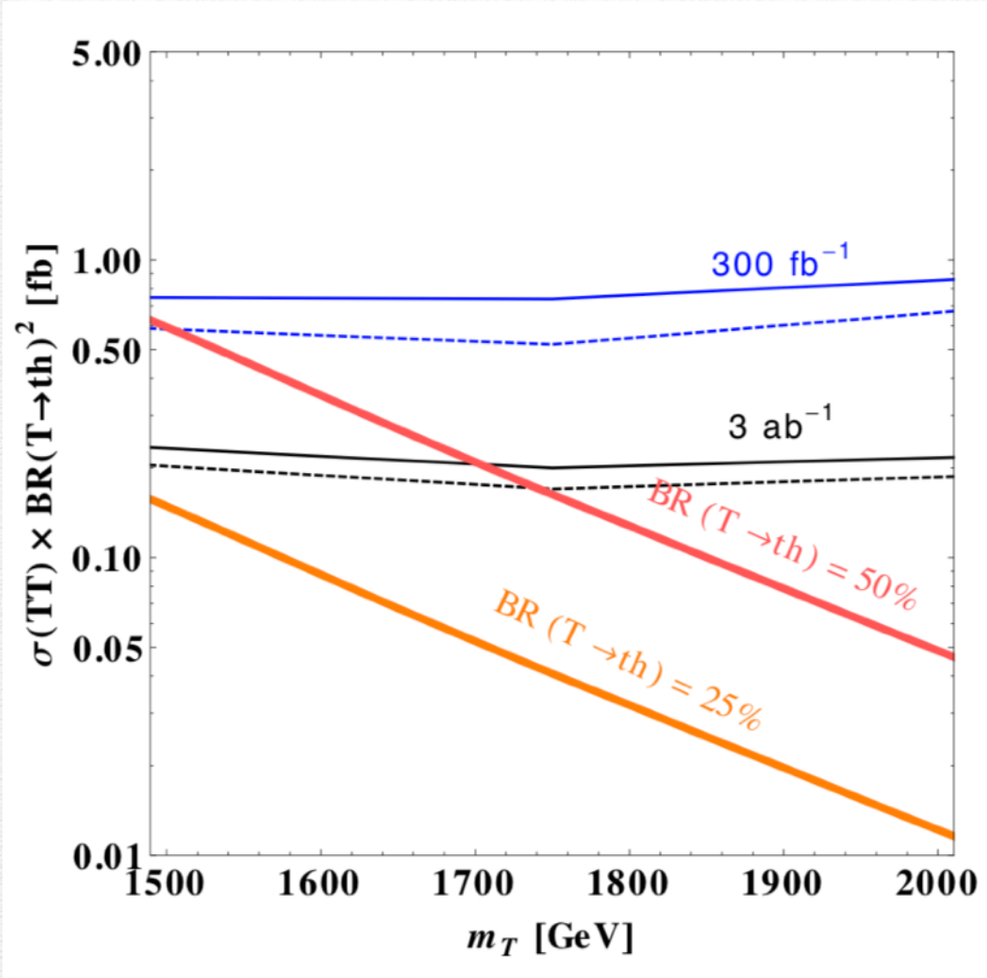


Limit is improved by combining all decay channels compared with that in **[ATLAS, arXiv:1808.02343]**

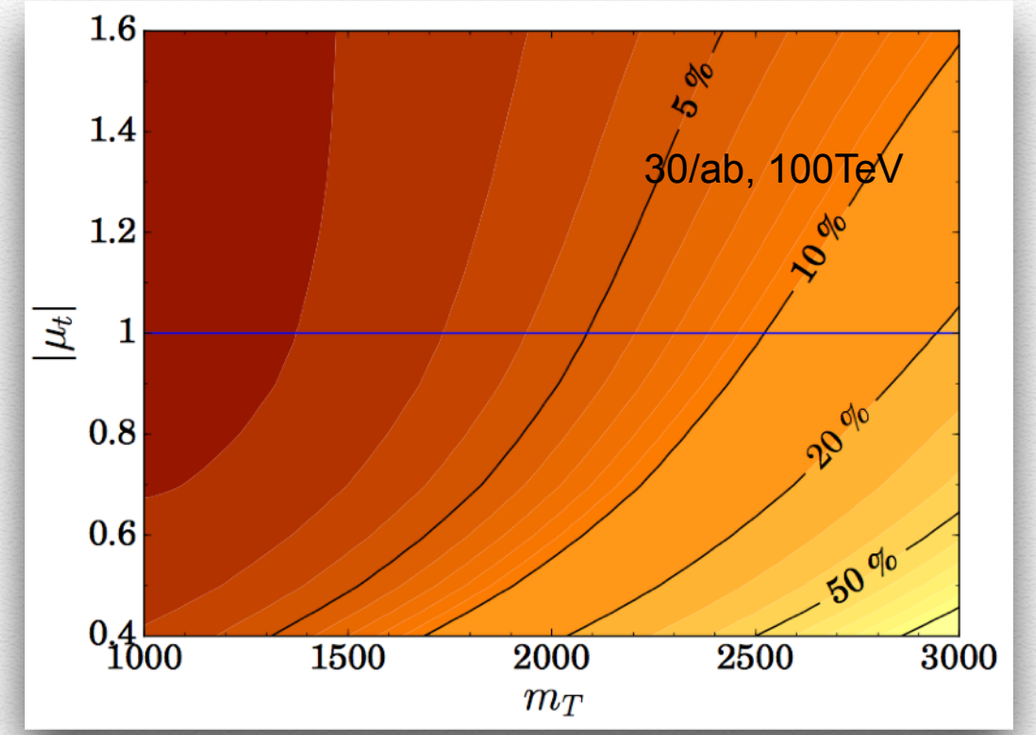
tthh—Resonance Search—fermions

Coloured vector-like top partners

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



[C. Chen, J. Hajer, TL, I. Low and H. Zhang, arXiv: 1705.07743]



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)

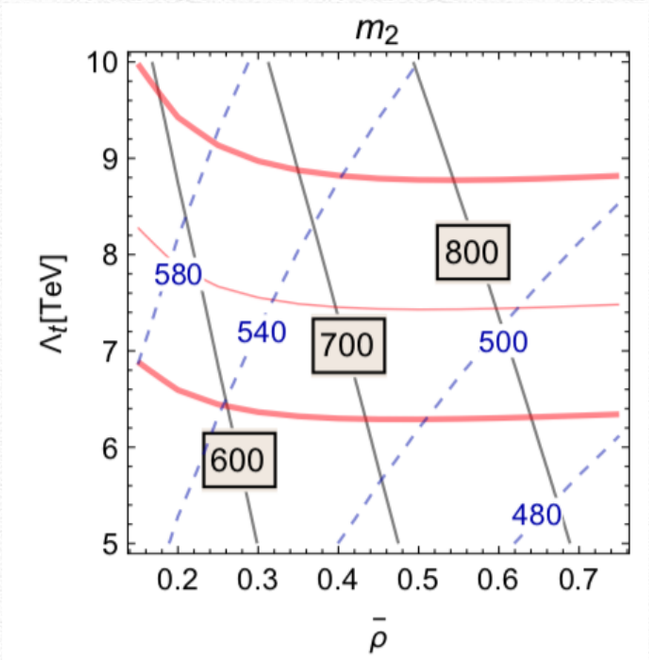
ttH, mH=600GeV 1.8

@100TeV 30/ab

	Combined (fb)
$ttH,\ m_H = 500$ GeV	6.6(5.3)

ttH, mH=600GeV 5.8

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



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

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

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

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

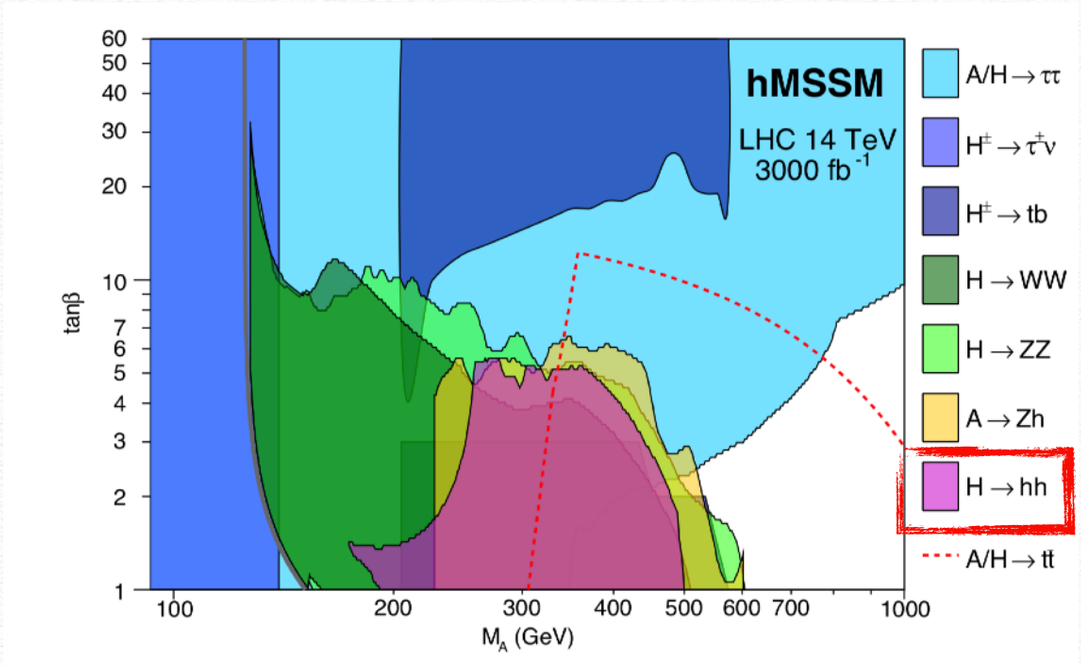
able to probe the turtling structure@100TeV!

tthh—Resonance Search—scalars

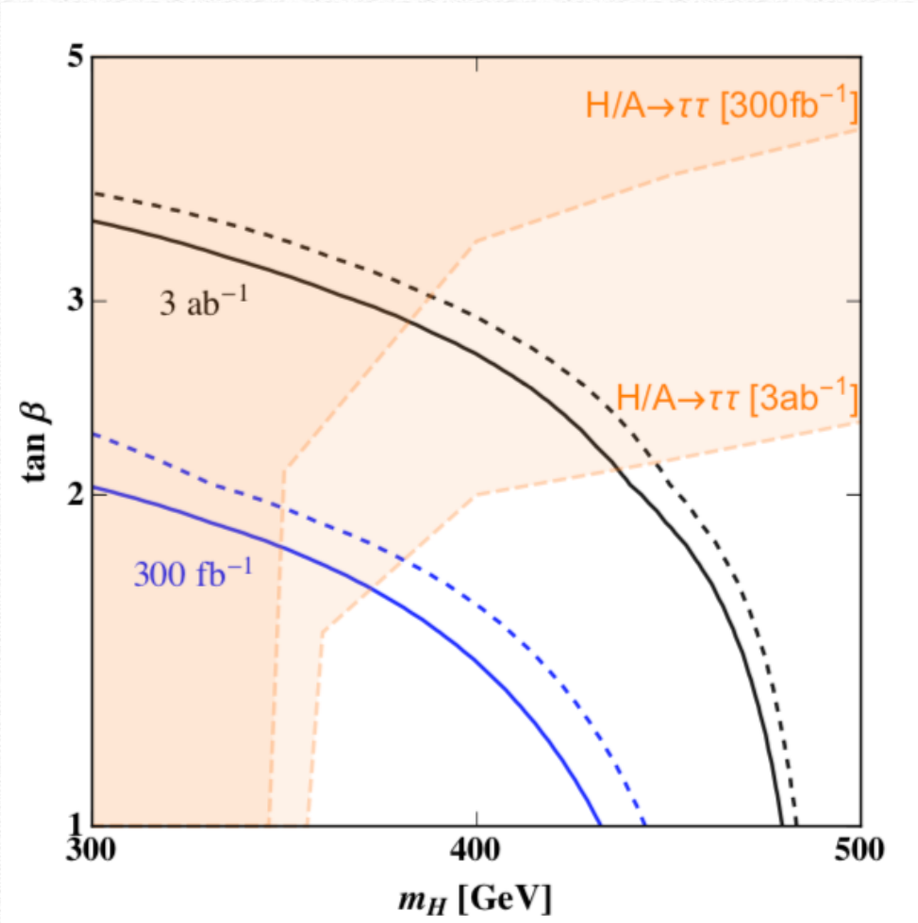
MSSM Higgs bosons(no CP-violation):H,A,Hc

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 turtling structure at 100TeV colliders.

Outlook

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

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

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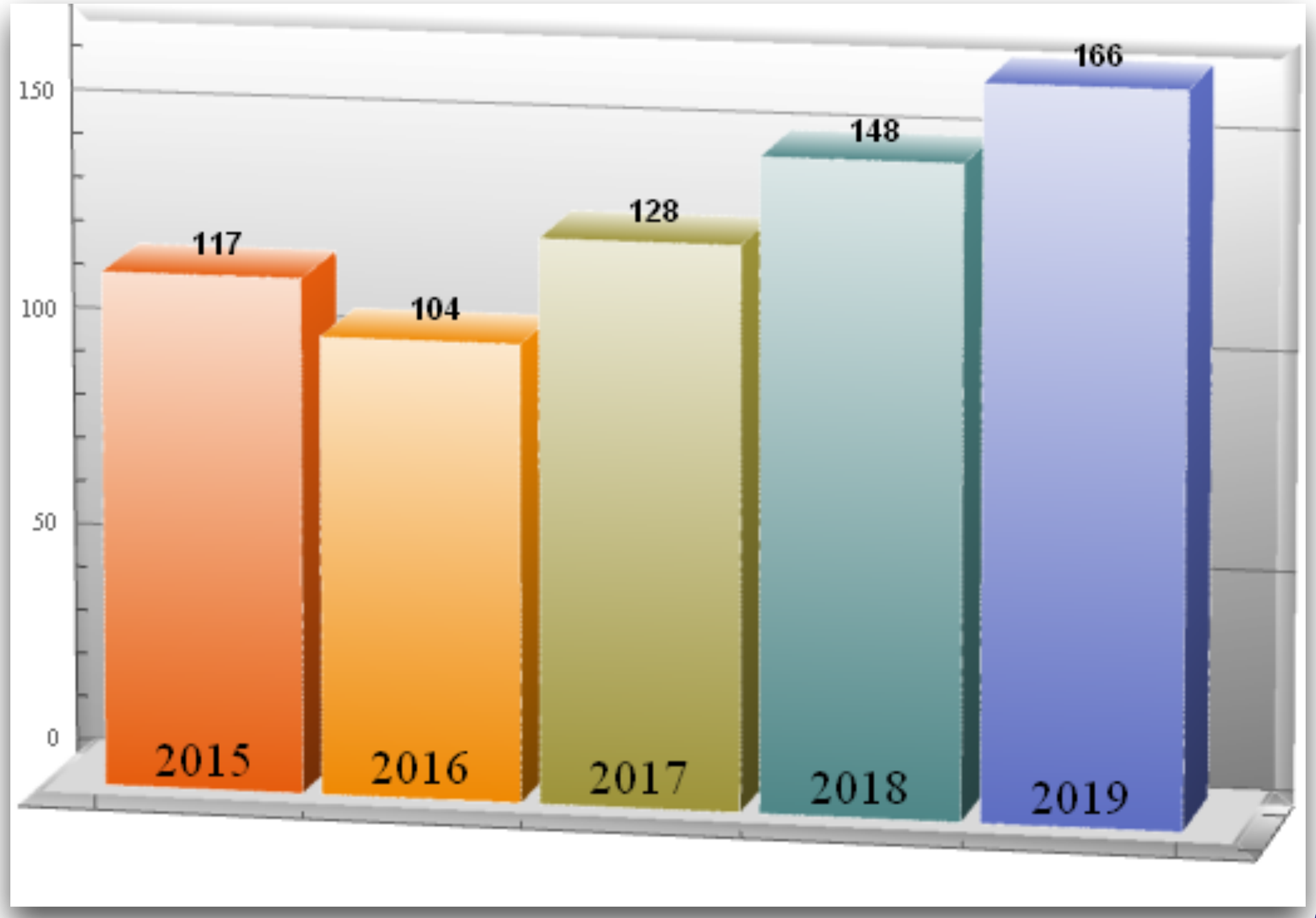

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Thank you and Welcome to HK!