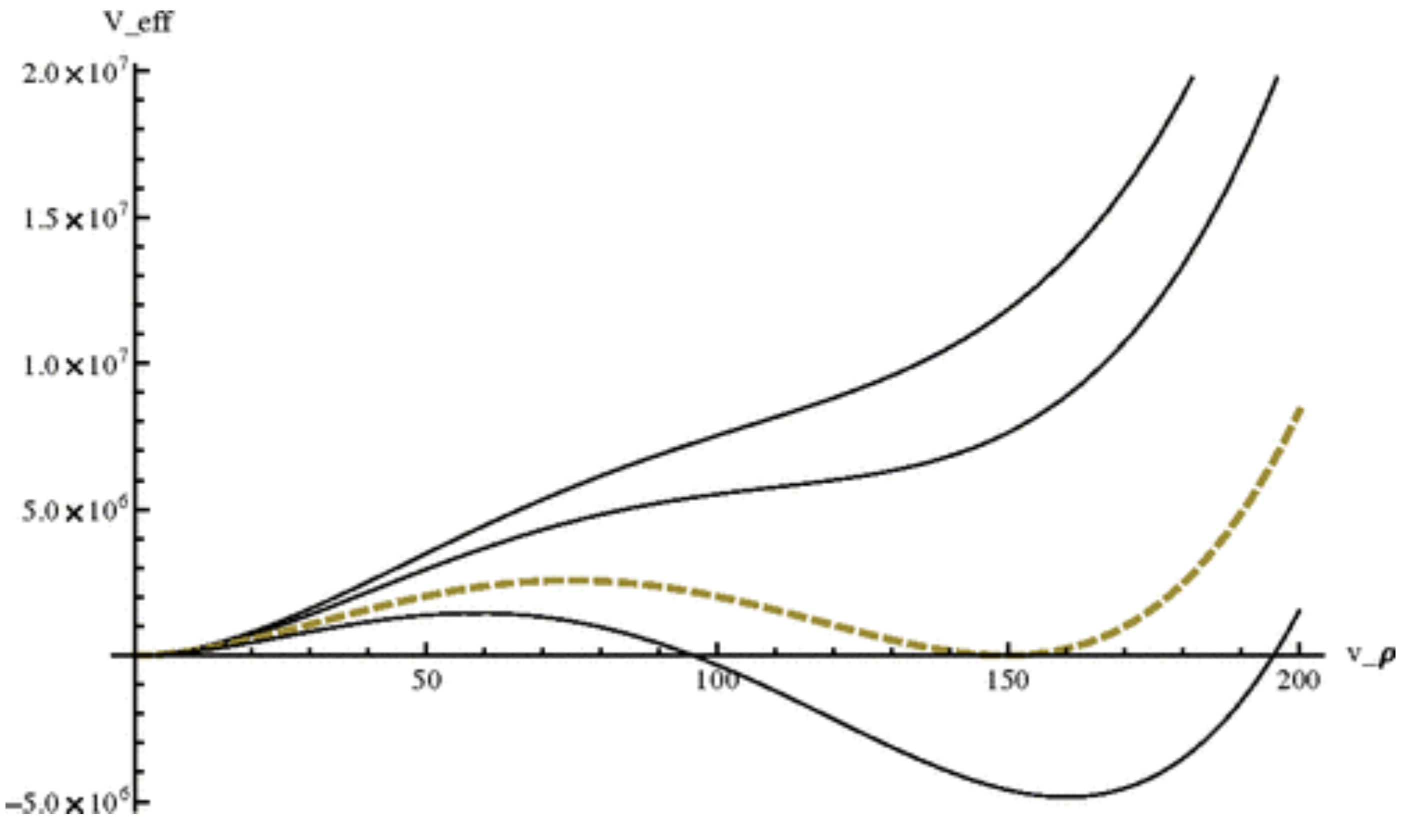
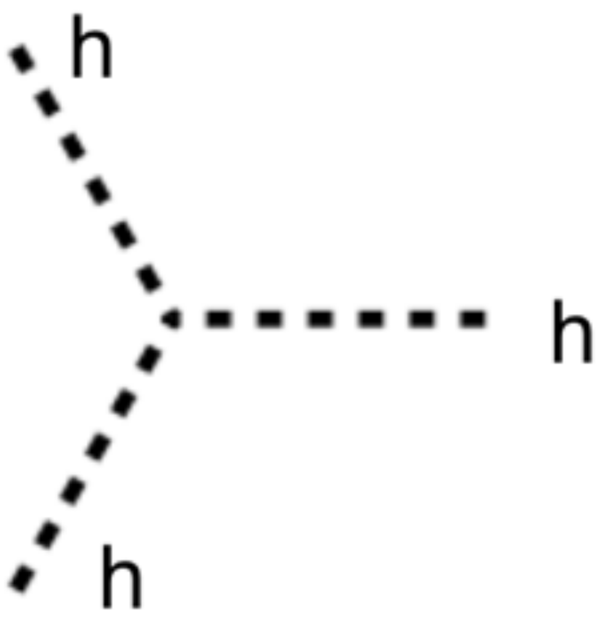
ANATOMY OF THE TTHH PHYSICS AT HL-LHC

Tao Liu
The Hong Kong University of Science and Technology

Based on arXiv:1905.03772
in collaboration with Lingfeng Li and Ying-Ying Li

Non-Resonant tthh - Cubic Higgs Coupling

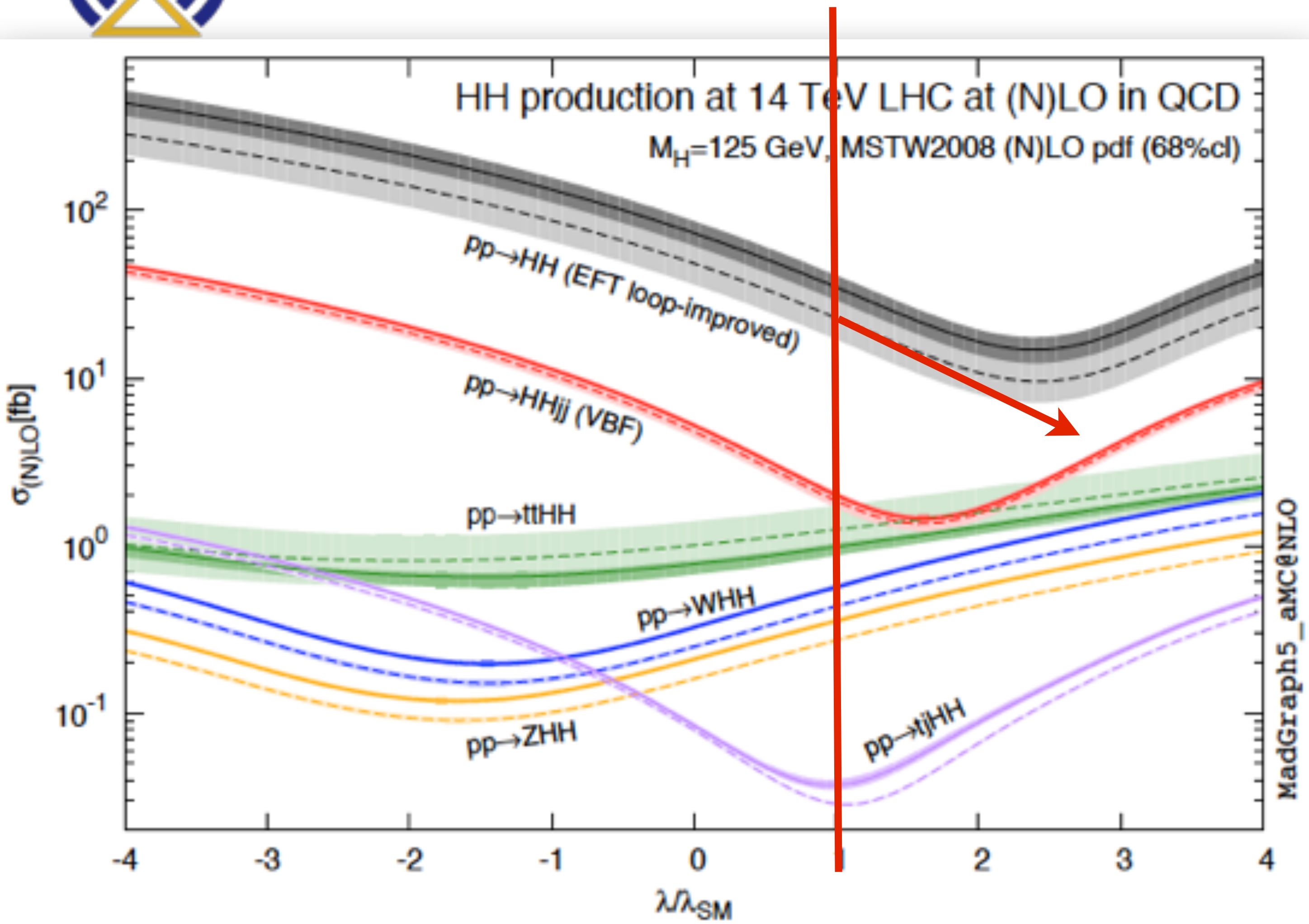




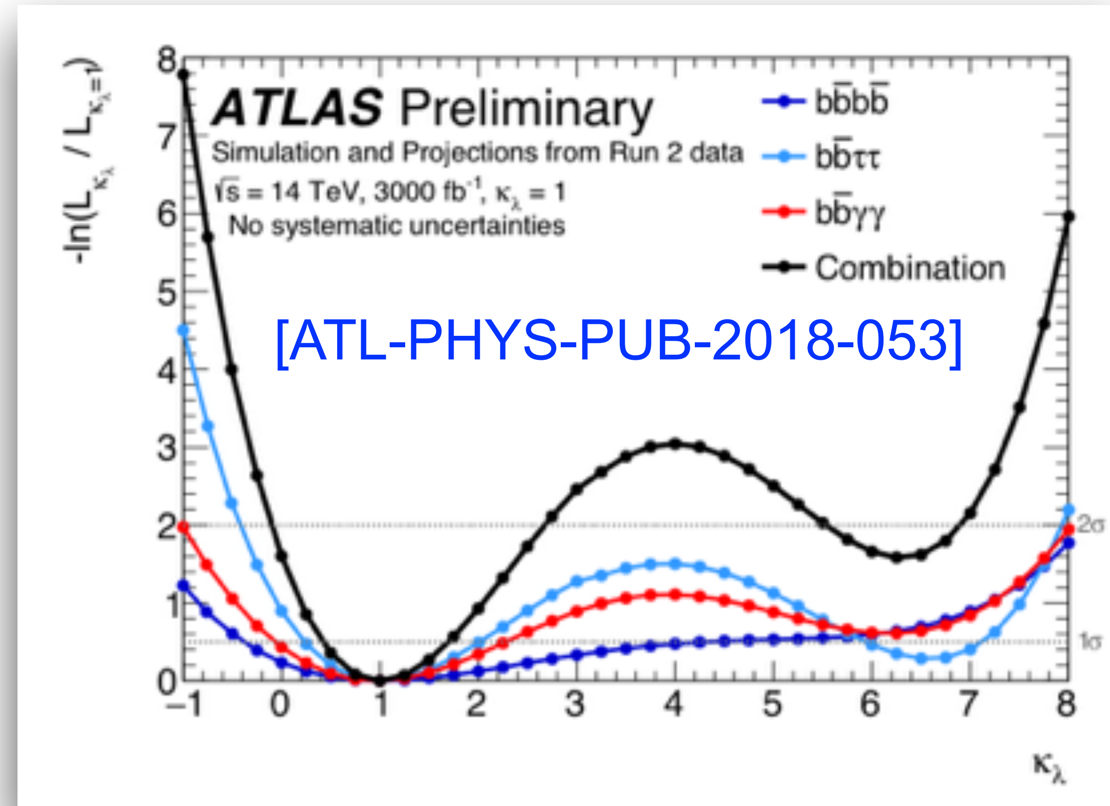
Known for some time that there exists a correlation between the nature of electroweak phase transition and the cubic Higgs coupling.

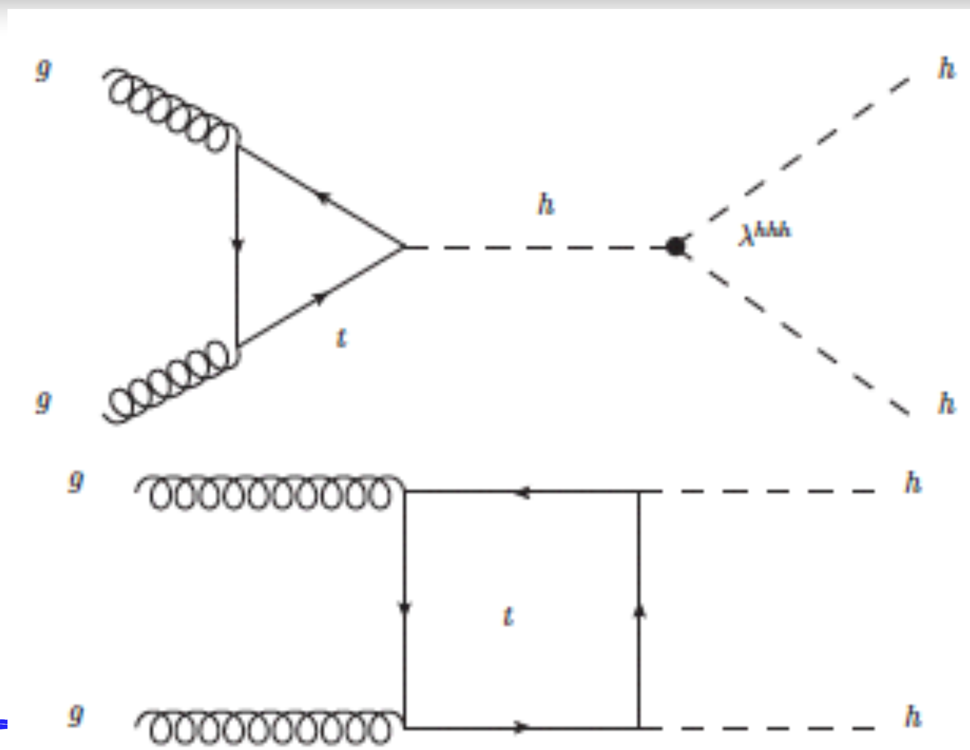
[A. Noble and M. Perelstein, '07]

Non-Resonant tthh - Cubic Higgs Coupling



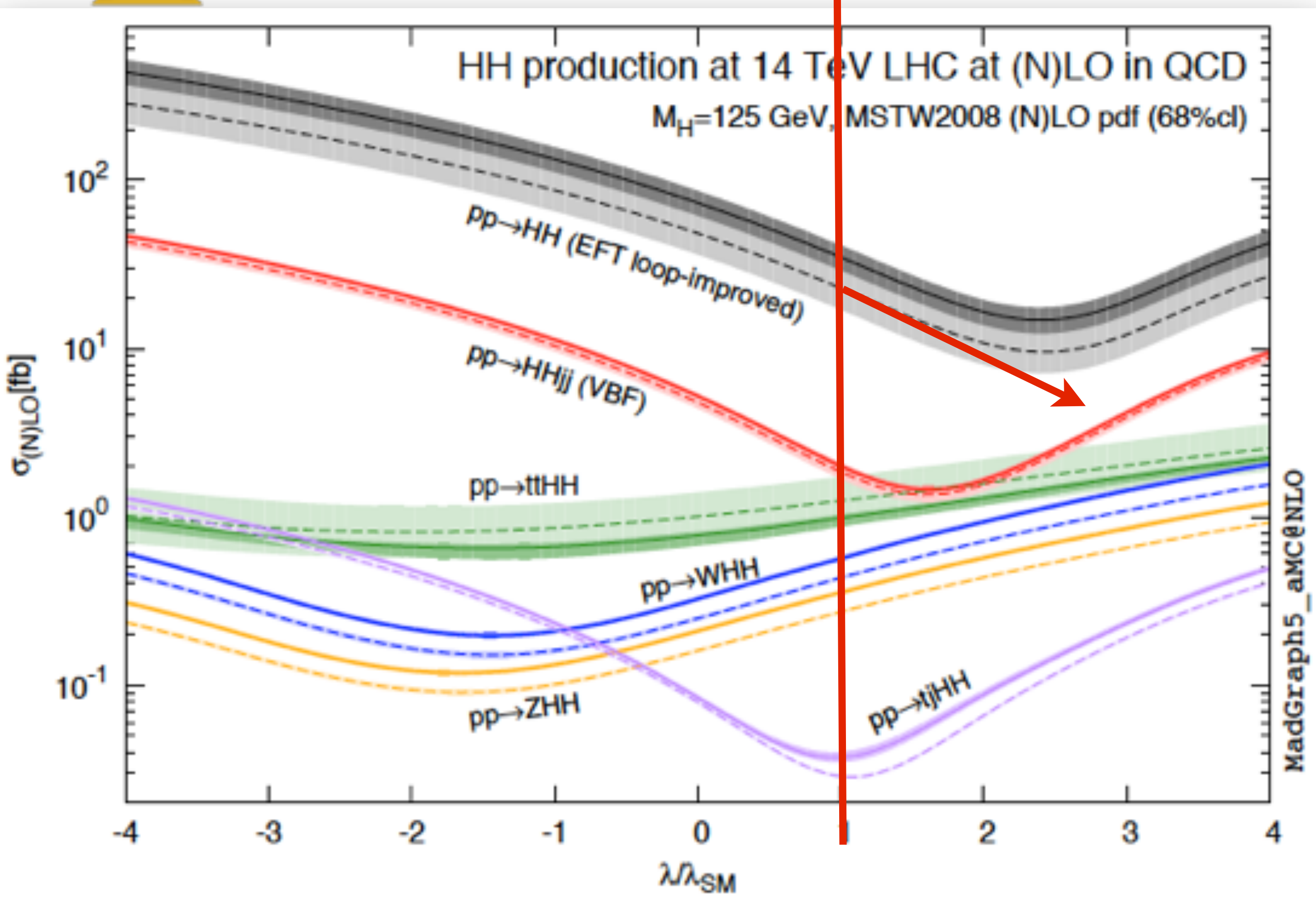
[R. Frederix et. al., arXiv:1401.7340]

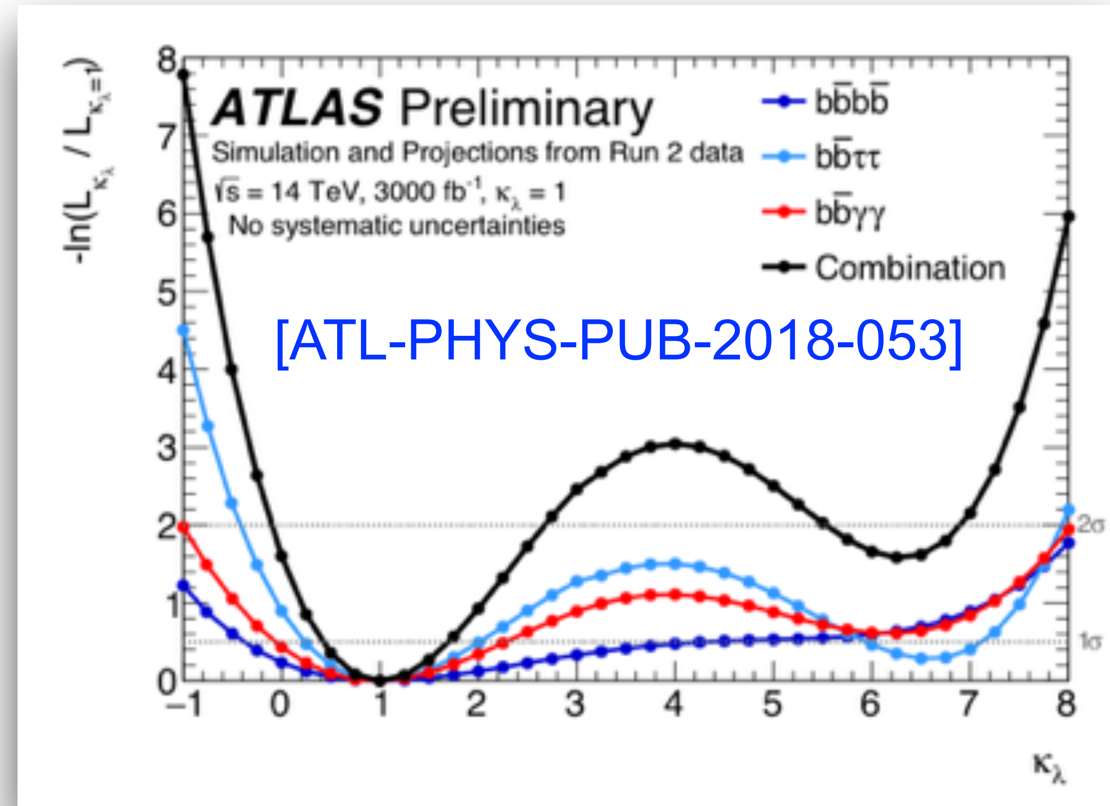




- Most studies so far were focused on gluon fusion di-Higgs production
- Destructive interference => Sensitivity degeneracy w.r.t. kappa = lambda/lambda_SM at HL-LHC

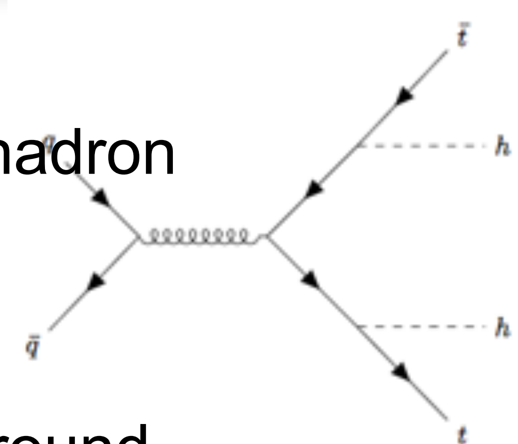
Non-Resonant tthh - Cubic Higgs Coupling

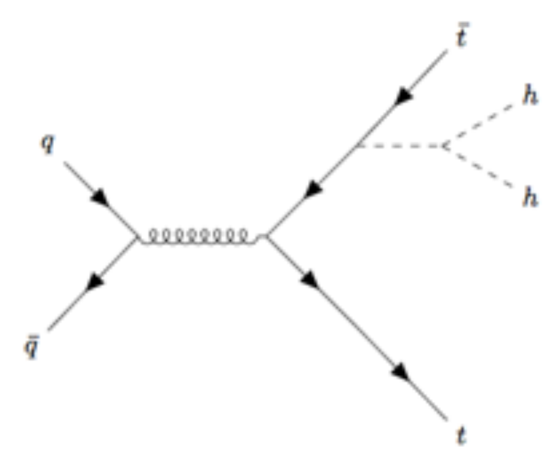




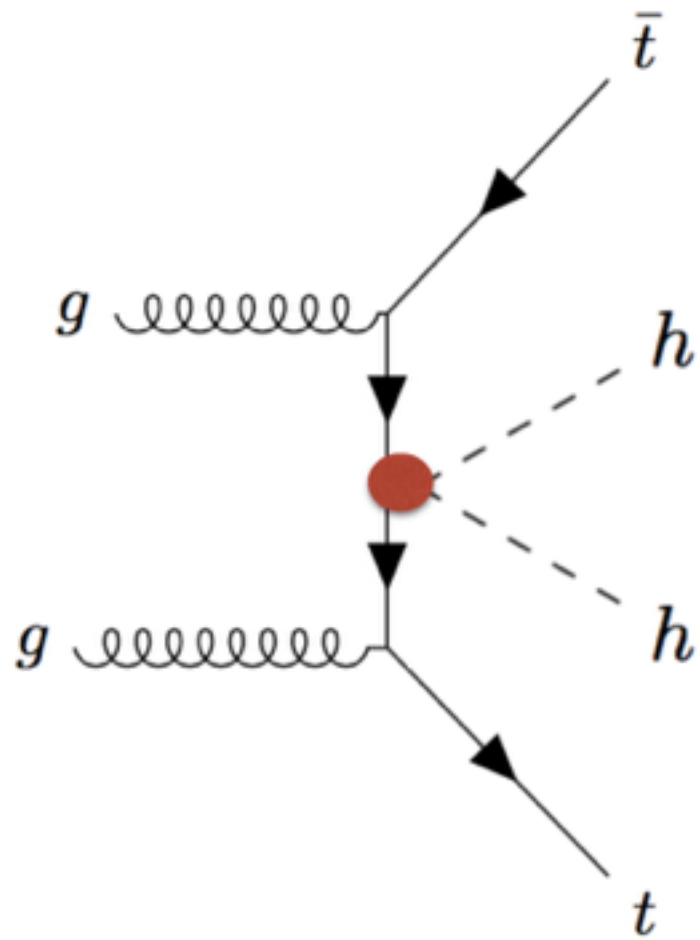
[R. Frederix et. al., arXiv:1401.7340]

- Can be broken using kinematics at future hadron colliders
- Alternatively, tthh could help at HL-LHC: constructive interference + reduced background



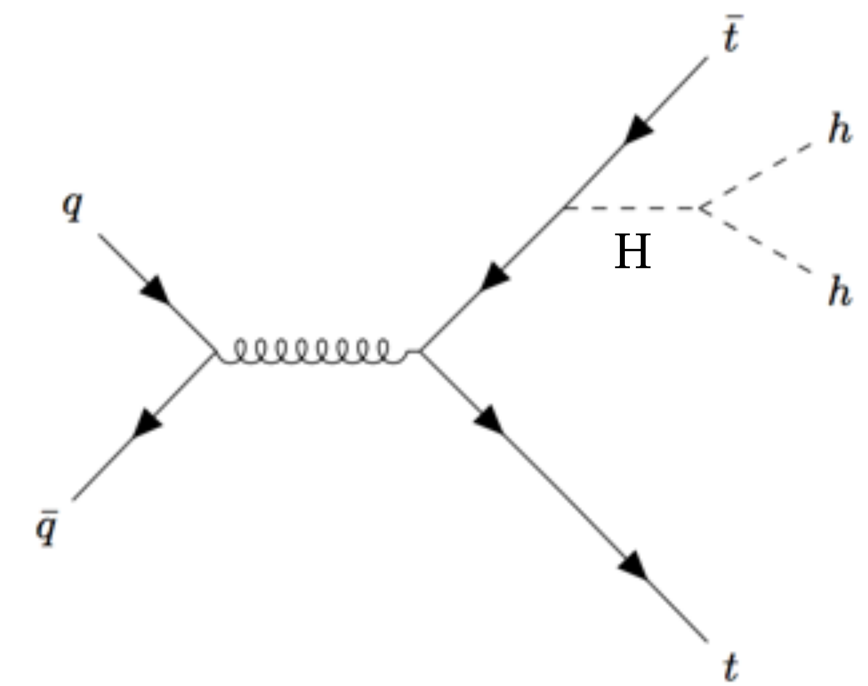


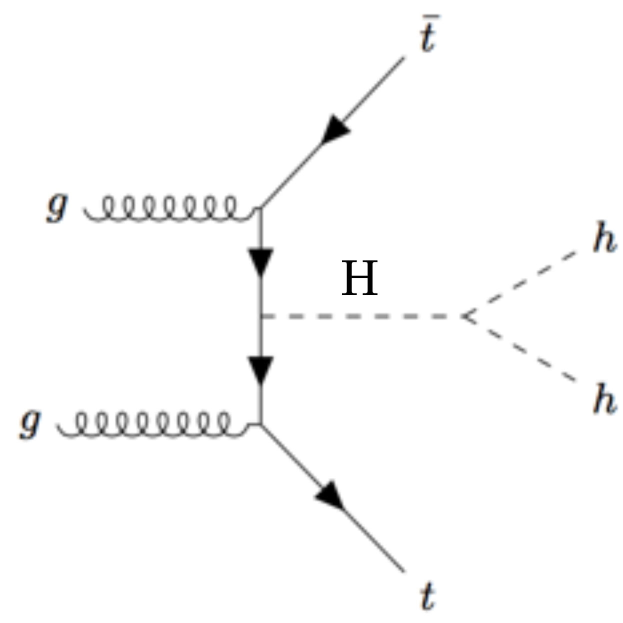
Non-Resonant tthh - Contact Interaction

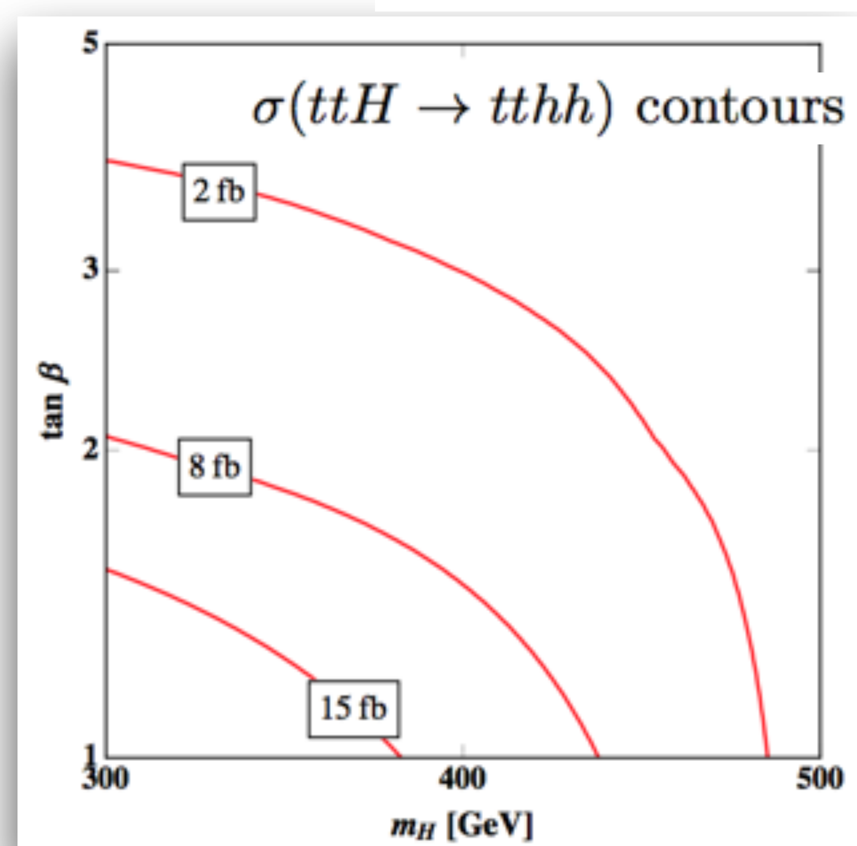


- tthh contact interaction may arise from, e.g., 6D operator in CHM: $\frac{H^\dagger H Q_L H t_R}{\Lambda^2}$
- Been applied for electroweak baryogenesis (EWBG), as new CP-violating source - minimal EWBG [S. Huber, M. Pospelov and A. Ritz, arXiv:hep-ph/0610003]

Resonant tthh - Heavy Higgs Siblings

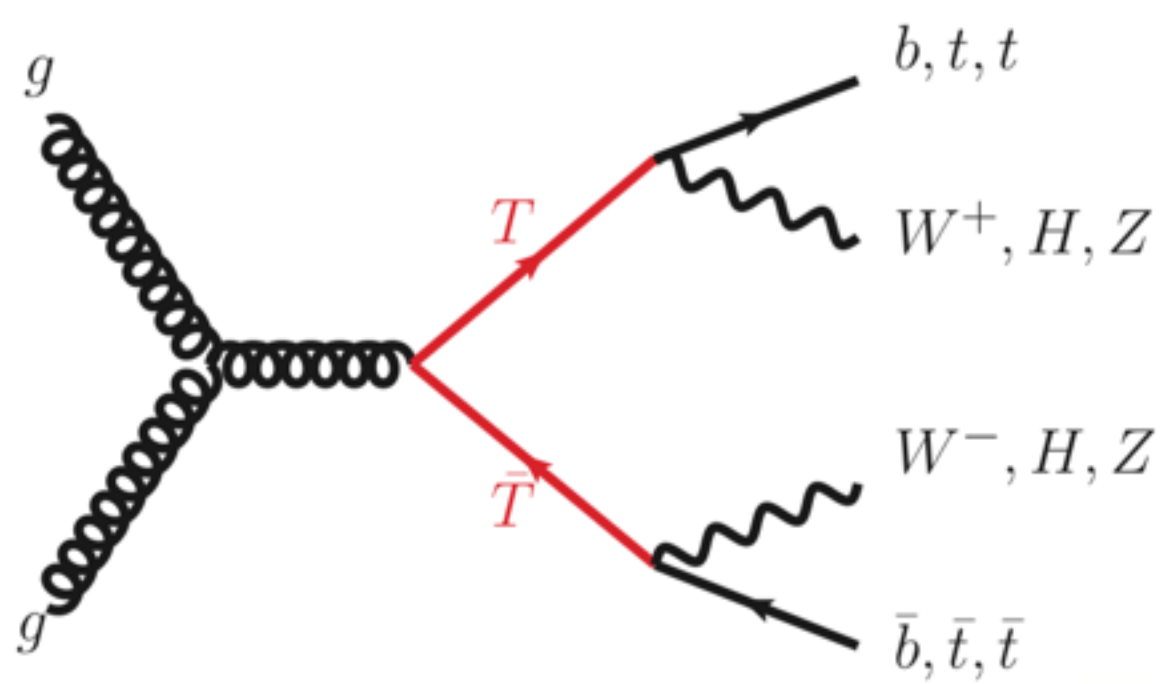






- BSM physics with extended Higgs sector such as two Higgs doublet model (THDM)
- Especially important for Higgs sibling search, e.g., in the nearly decoupling limit $2m_h < m_H < 2m_t$ with low tan_beta in type II THDM or MSSM:
  - On-shell H -> tt turned off
  - H coupling to gauge bosons suppressed

Resonant tthh - Fermionic Top Partners



- One of the most important modes for searching pair production of top partners in CHMs. Br(T-> th) typically varies from 25% to 50%, depending on the EW charge carried by T

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

Early Sensitivity Analyses

	signal		backgrounds					
	$\xi=1$	$\xi=4$	$t\bar{t}bbbb$	$t\bar{t}hbb$	$t\bar{t}hZ$	$t\bar{t}Zbb$	$t\bar{t}ZZ$	$Wbbbb$
trigger	0.10	0.23	4.75	1.38	0.64	1.37	1.36×10^{-2}	1.33
jet cuts	7.40×10^{-2}	0.17	1.44	0.76	0.40	0.65	8.74×10^{-3}	7.46×10^{-2}
5 b tags	1.23×10^{-2}	2.83×10^{-2}	4.46×10^{-2}	6.19×10^{-2}	7.24×10^{-3}	4.43×10^{-2}	1.25×10^{-3}	5.35×10^{-4}
$2\times h\to b\bar{b}$	7.33×10^{-3}	1.69×10^{-2}	1.59×10^{-2}	2.71×10^{-2}	3.41×10^{-3}	1.56×10^{-2}	4.28×10^{-4}	$<1\times10^{-4}$
lep./had. t	5.04×10^{-3}	1.12×10^{-2}	9.50×10^{-3}	1.66×10^{-2}	2.29×10^{-3}	9.42×10^{-3}	2.69×10^{-4}	$<1\times10^{-4}$
lep. t only	2.33×10^{-3}	5.29×10^{-3}	5.03×10^{-3}	9.36×10^{-3}	1.14×10^{-3}	4.90×10^{-3}	1.39×10^{-4}	$<1\times10^{-4}$
had. t only	2.71×10^{-3}	5.93×10^{-3}	4.47×10^{-3}	7.20×10^{-3}	1.16×10^{-3}	4.44×10^{-3}	1.30×10^{-4}	$<1\times10^{-4}$
6 b tags	2.21×10^{-3}	4.97×10^{-3}	3.80 [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
$2\times h\to b\bar{b}$	1.81×10^{-3}	5.94×10^{-3}	2.01 [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

[C. Englert, F. Krauss, M. Spannowsky, J. Thompson, arXiv:1409.8074]

$\sqrt{s}=14$ TeV	$t\bar{t}hh$	$t\bar{t}b\bar{b}b\bar{b}$	$t\bar{t}b\bar{b}c\bar{c}$	$t\bar{t}hb\bar{b}$	$t\bar{t}Zb\bar{b}$	$t\bar{t}hc\bar{c}$
Preselection	39.0	390.6	353.1	222.7	126.8	98.2
Di-Higgs rec.	33.0	269.3	242.1	171.0	93.5	76.8
Top rec.	19.5	160.7	149.0	102.8	54.6	47.1

[TL, H. Zhang, arXiv:1410.1855]

- Luminosity of 3/ab => $S/\sqrt{B}\sim 1-2\sigma$
- A subsequent analysis [ATL-PHYS-PUB-2016-023] => $S/\sqrt{B}\sim 0.35\sigma$

[TL, talk in TOP2018]

Early Sensitivity Analyses

[C. Englert, F. Krauss, M. Spannowsky, J. Thompson, arXiv:1409.8074]

[TL, H. Zhang, arXiv:1410.1855]

- [ATL-PHYS-PUB-2016-023]

Yet, these analyses were not optimized.

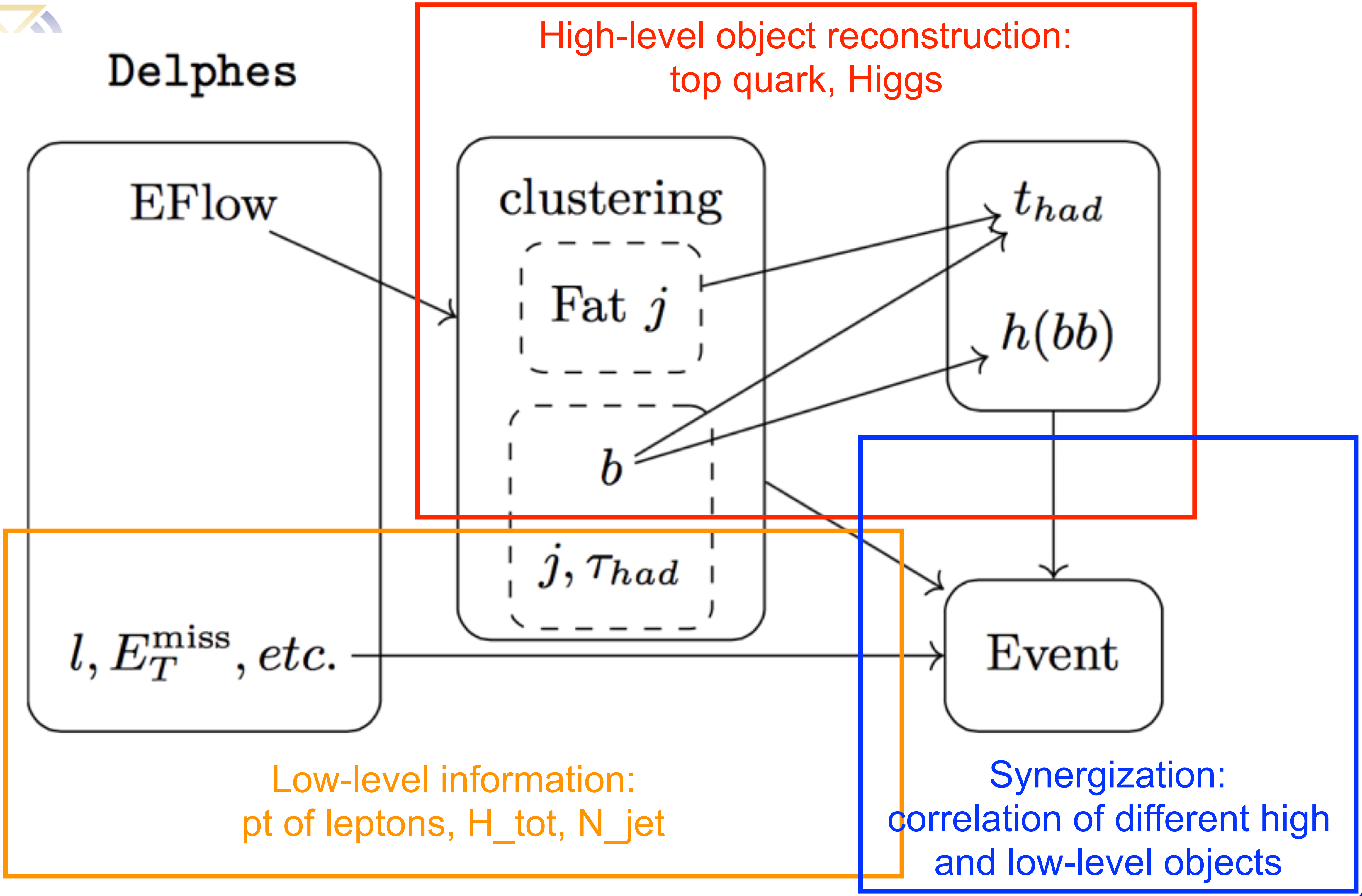
- Handle I: clean channels such as same-sign di-lepton and multiple leptons, etc.
- Handle II: advanced tools such as BDT
  - All of these analyses were cut-based
  - Incapable for addressing complicated topology and kinematics: jet multiplicity, combinatorial backgrounds, etc.
- Most importantly, BSM physics may significantly modify the kinematics and signal rates of the SM tthh, yielding valuable sensitivities at HL-LHC

Strategies of New Analysis

Analysis	$5b1\ell$	$5b2\ell$	$SS2\ell$	Multi-ℓ	$\tau\tau$
Triggers	$\cup\{1,4,5\}$	$\cup\{1,2,4,5\}$	$\cup\{2\}$	$\cup\{1,2,3,4,5\}$	$\cup\{1,4,5,6,7\}$

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

Strategies for New Analysis



Strategies for New Analysis

- Analysis I: non-resonant tthh (SM)
- Analysis II: non-resonant tthh with anomalous cubic Higgs coupling and tthh contact interaction

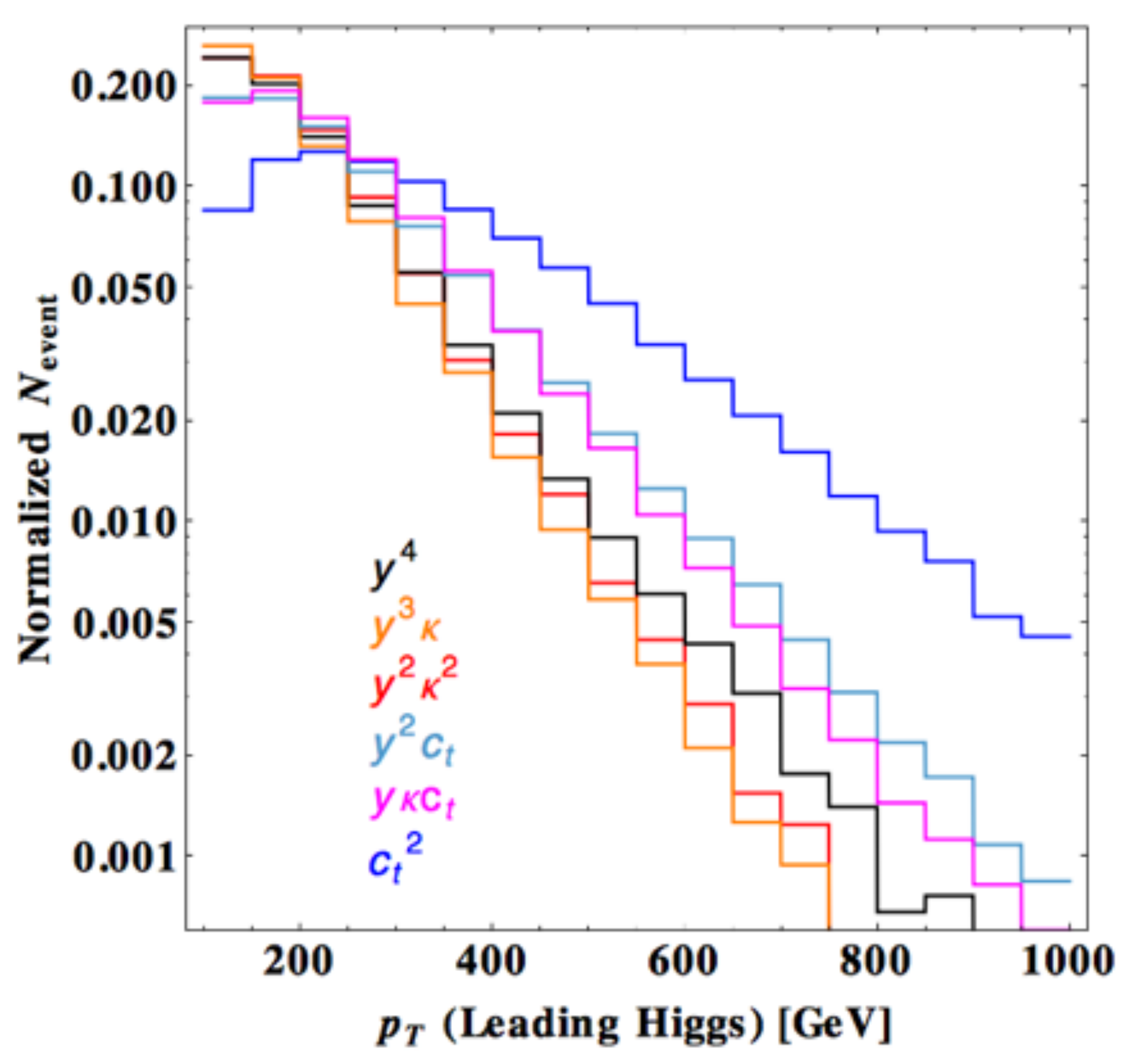
$$\mathcal{L} \supset -y\frac{m_t}{v}t\bar{t}h - \kappa\frac{1}{3!}\frac{3m_h^2}{v}h^3 - c_t\frac{1}{2!}\frac{m_t}{v^2}t\bar{t}hh$$

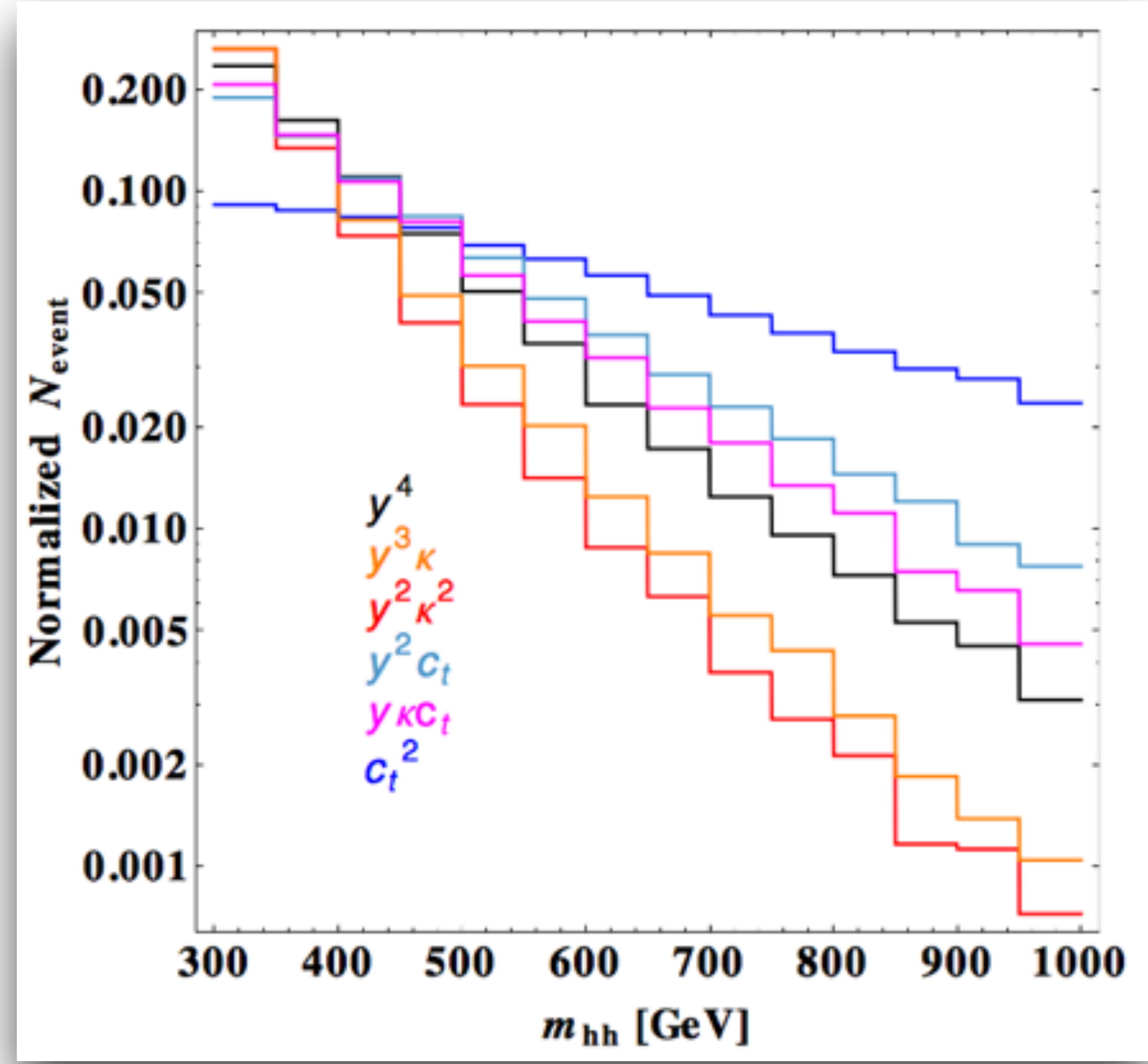
- Analysis III: resonant tthh with heavy Higgs boson
- Analysis IV: resonant tthh with fermionic top partners

Analysis I: The SM tthh Production

	No cut	Preselection	$5b1\ell$	$5b2\ell$	$SS2\ell$	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)
$(S/B)_{\mathrm{cut}}(\%)$			0.42 (0.40)	0.47 (0.55)	1.1 (1.1)	0.9 (0.9)	1.1 (1.1)
σ_{BDT}			0.59 (0.79)	0.21 (0.30)	0.45 (0.46)	0.33 (0.35)	0.21 (0.21)
$(S/B)_{\mathrm{BDT}}(\%)$			1.2 (1.0)	1.3 (1.6)	1.6 (1.6)	1.6 (1.9)	1.6 (1.6)
σ_{com}			0.86 (1.04)				

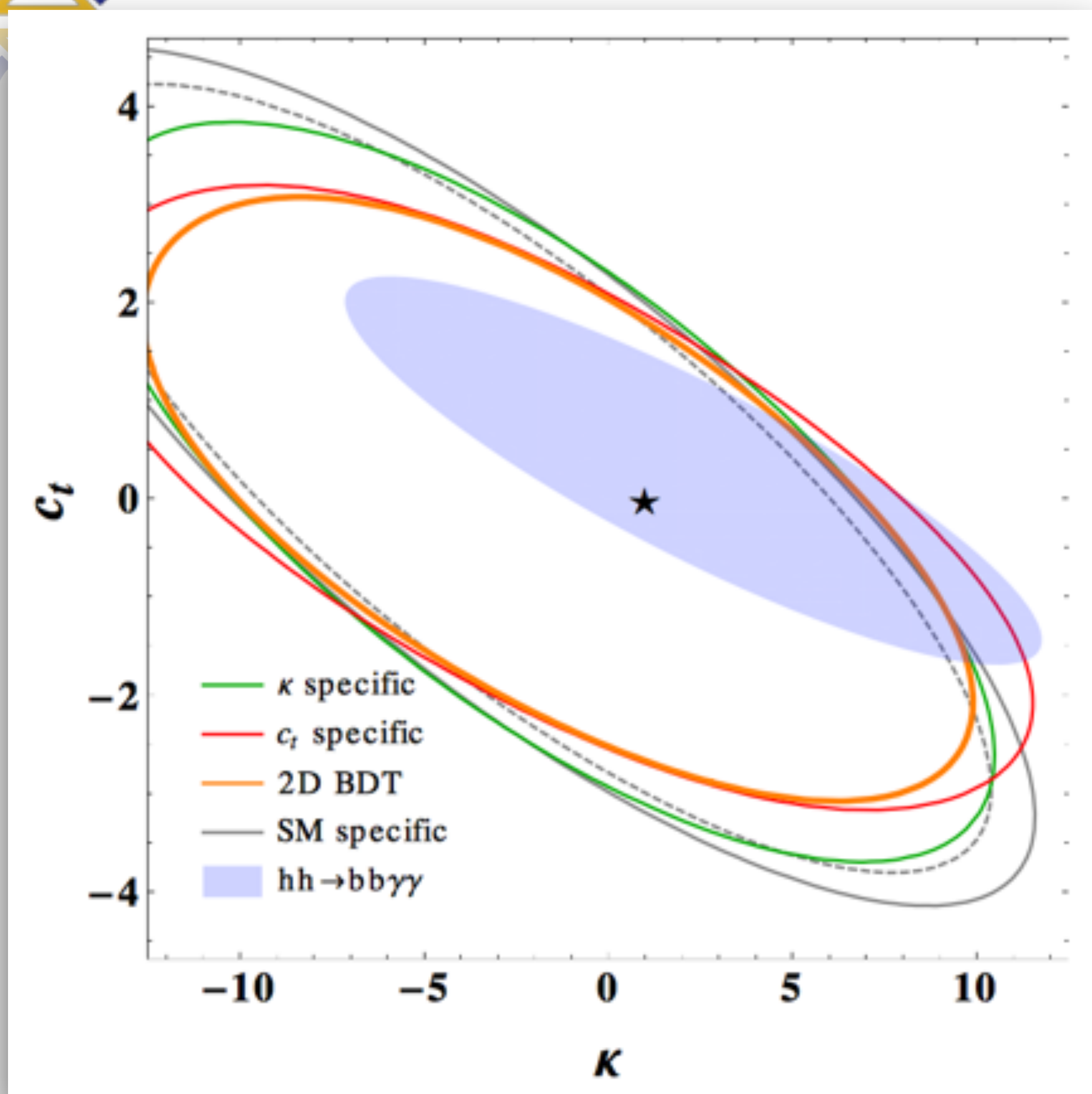
- 5b1l and SS2l + multi-l provide comparable sensitivities
- 5b1l gains more from BDT, in both statistical significance and S/B
- A combination yields ~ 0.9 sigma against background-only hypothesis

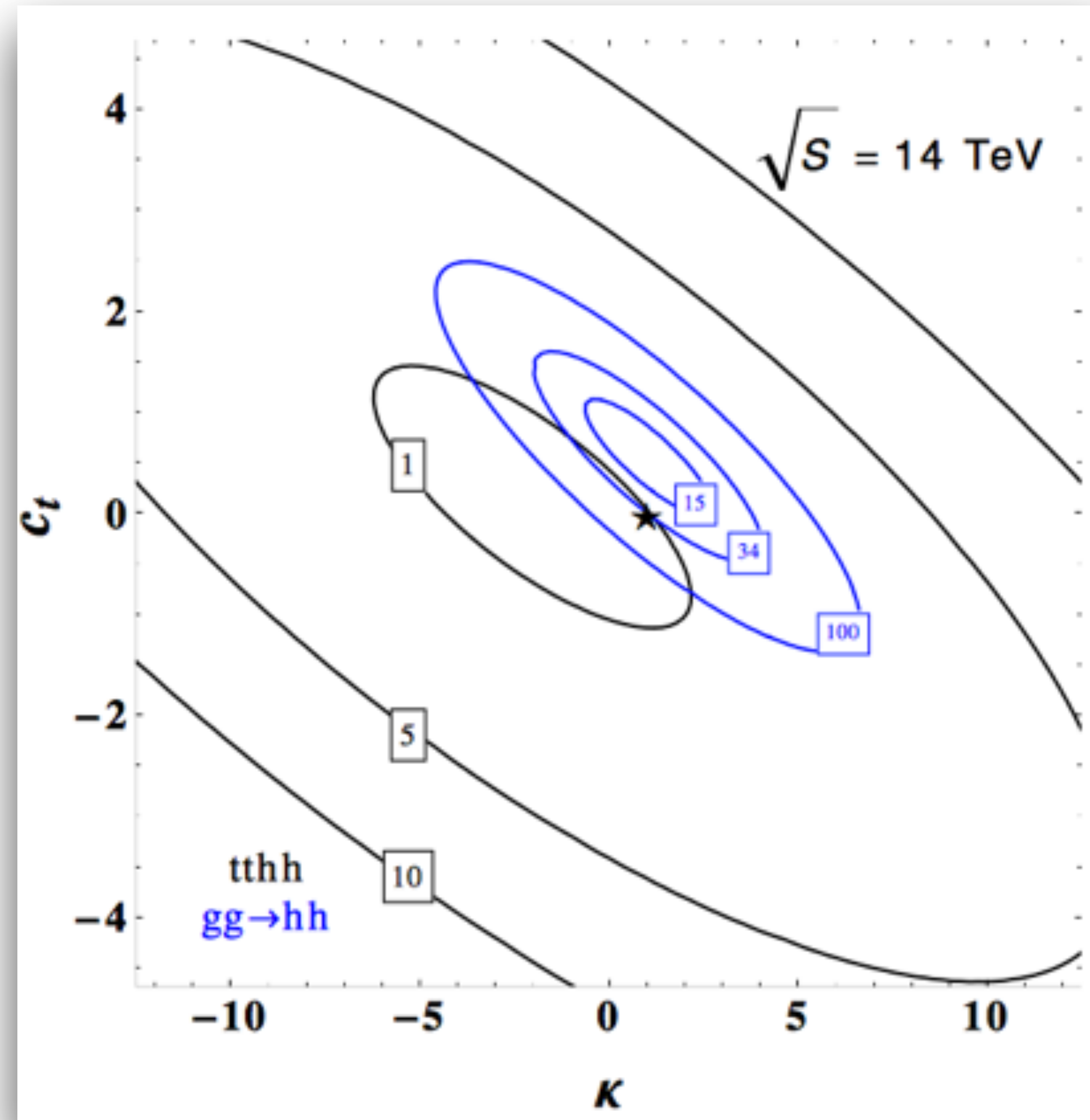




- Kinematics in opposite directions: soft (kappa) vs. hard (ct)
- 2-dim BDT, with $y^2\kappa^2$ and c_t^2 kinematics being favored respectively by the two dimensions.

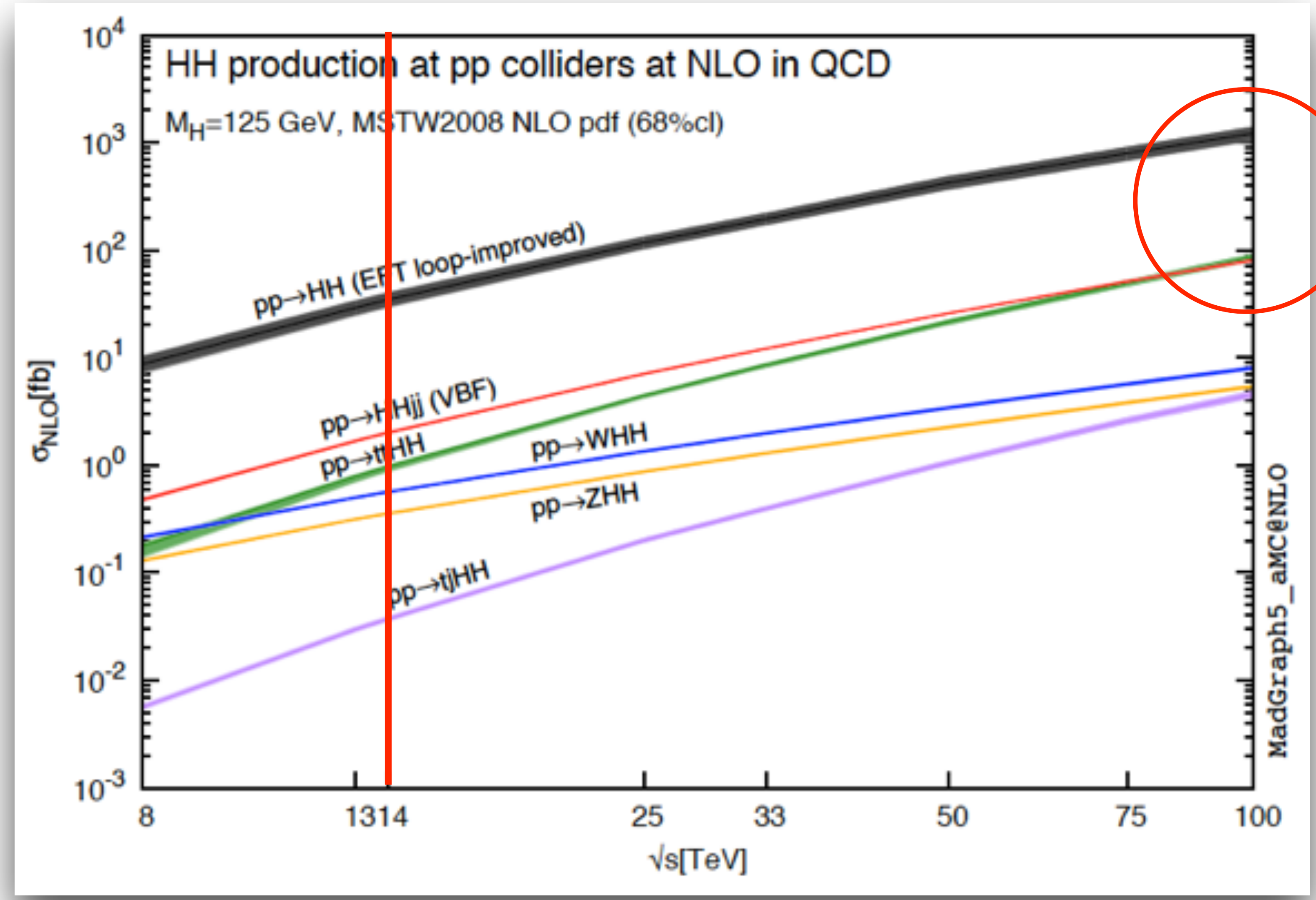
Analysis II: Anomalous $\kappa + c_t$





- Constrain κ to $\{6.9, -10\}$ for $c_t = 0$, and c_t to $\{-2.7, 1.8\}$ for $\kappa = 1$
- Partly breaks the sensitivity degeneracy w.r.t. the cubic Higgs self-coupling usually thought to exit in the gluon-fusion di-Higgs analysis at HL-LHC

Potential Gains at 100 TeV: Cross Section



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

Cross section ratio (tthh/gluon fusion)

35 (14 TeV) vs. 14 (100 TeV)

Potential Gains at 100 TeV: Kinematics

The tthh production becomes more sensitive to kappa and ct at non-linear level at 100 TeV

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

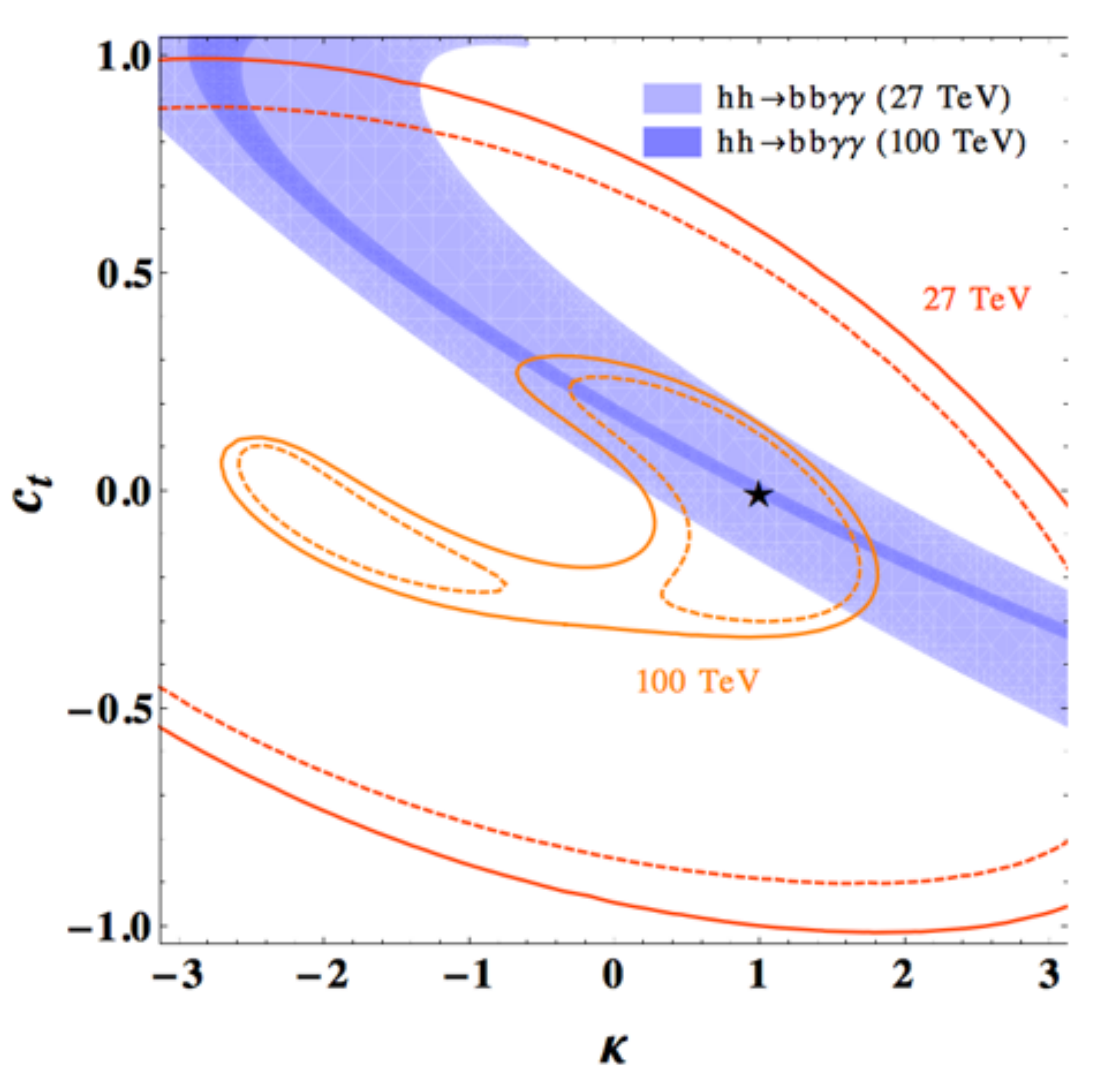
[A. Azatov et. al. arXiv:1502.00539]

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

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

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

Sensitivity Projection at 100 TeV

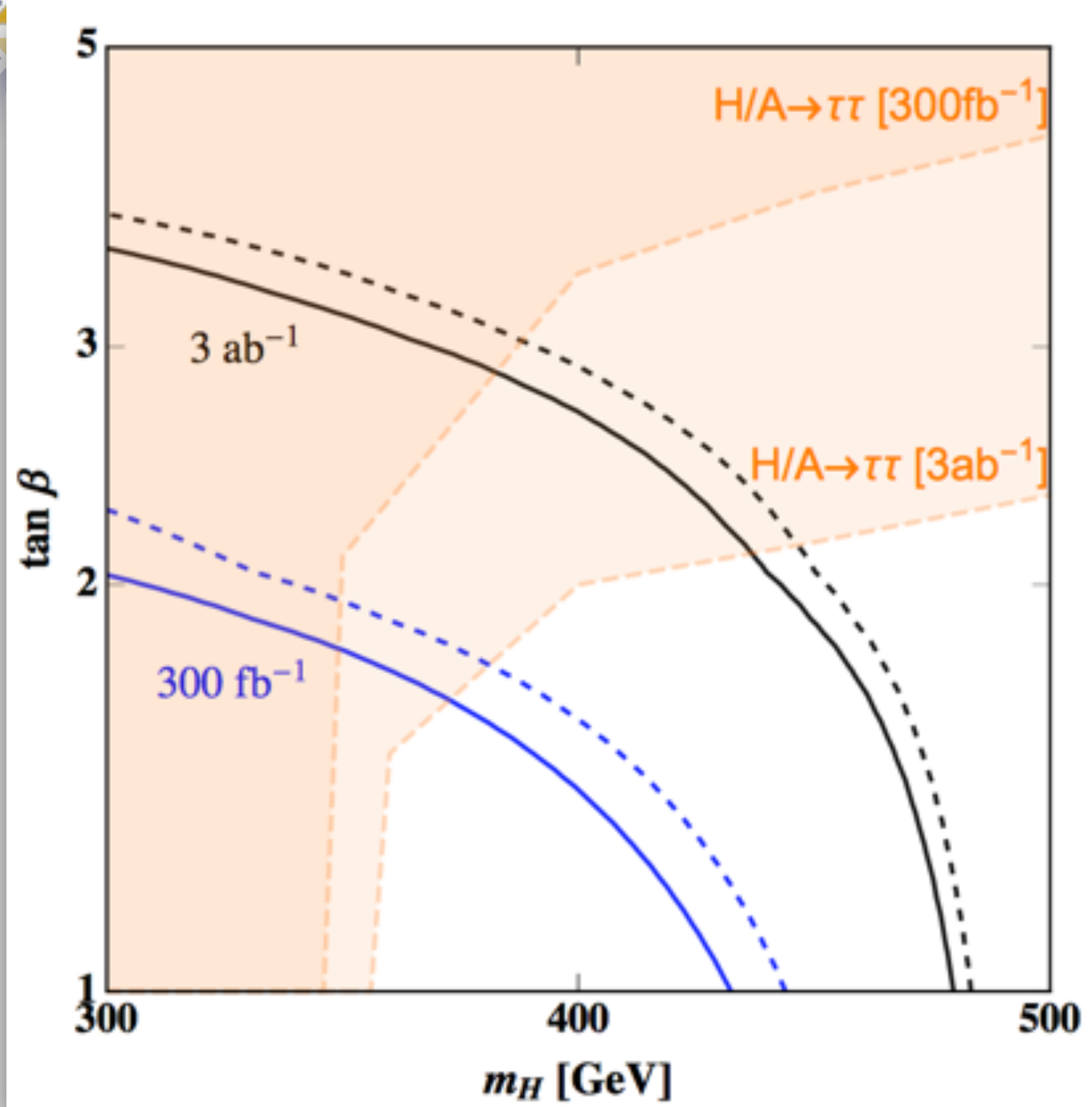


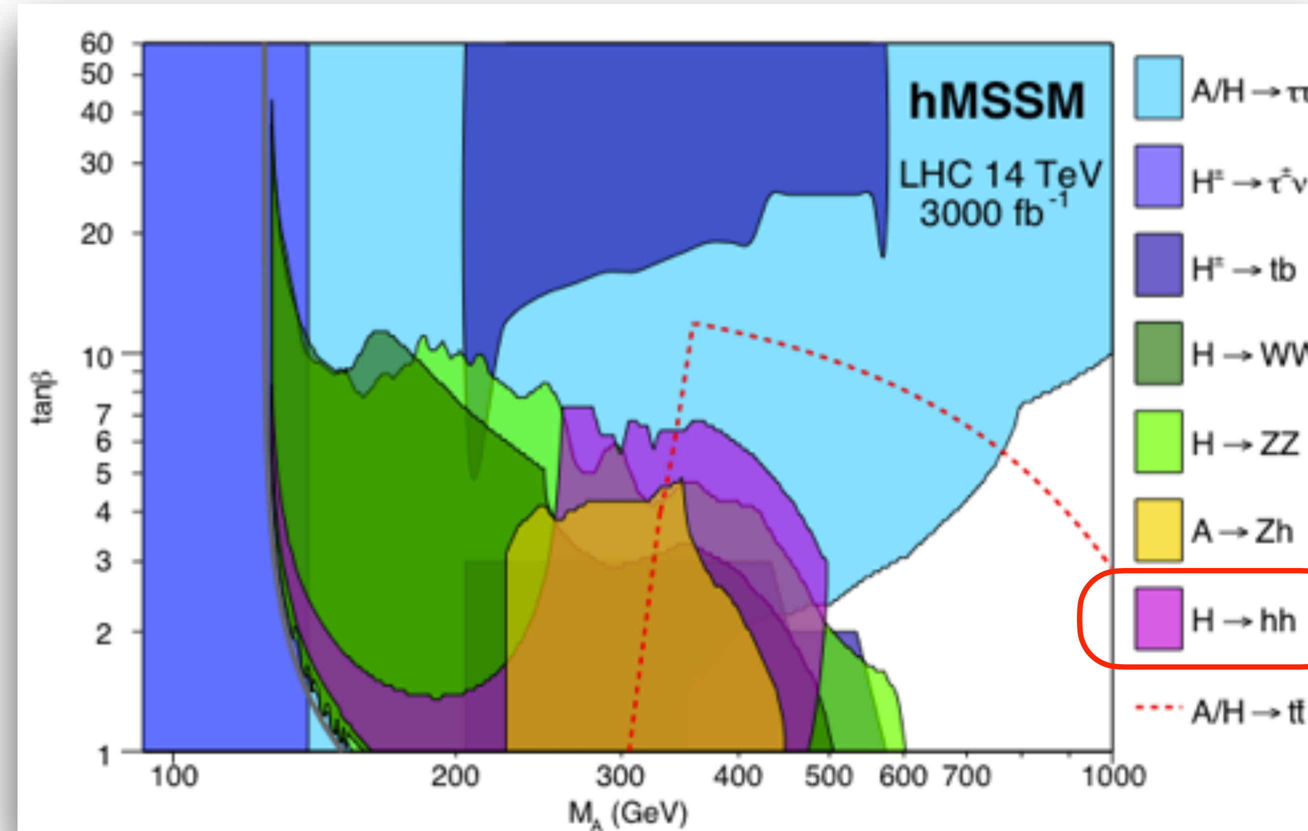
- Assuming the signal efficiency and background rejection at HL-LHC to be unchanged
- tthh in SM: ~ 14 sigma with 30/ab@100 TeV
- Constrain κ to

  $\{-2.6, -1.6\} \cup \{0.2, 1.6\}$ for $c_t = 0$,

  and c_t to $\{-0.34, 0.16\}$ for $\kappa = 1$
- Note, the reference sensitivity of hh->bb gamma gamma was not optimized using kinematics

Analysis III: Heavy Higgs Bosons

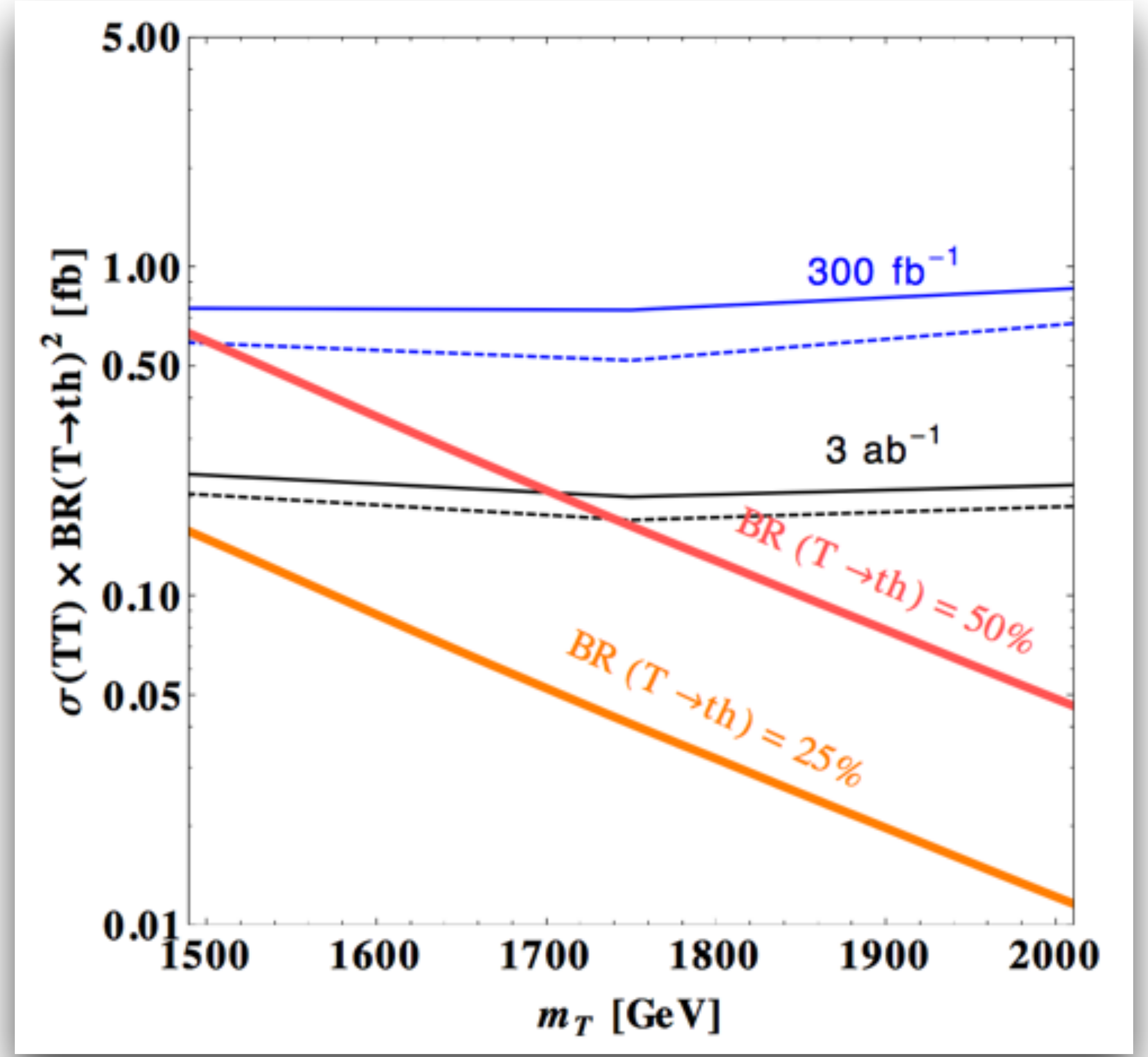




[Djouadi et. al.'arXiv:1502.05653]

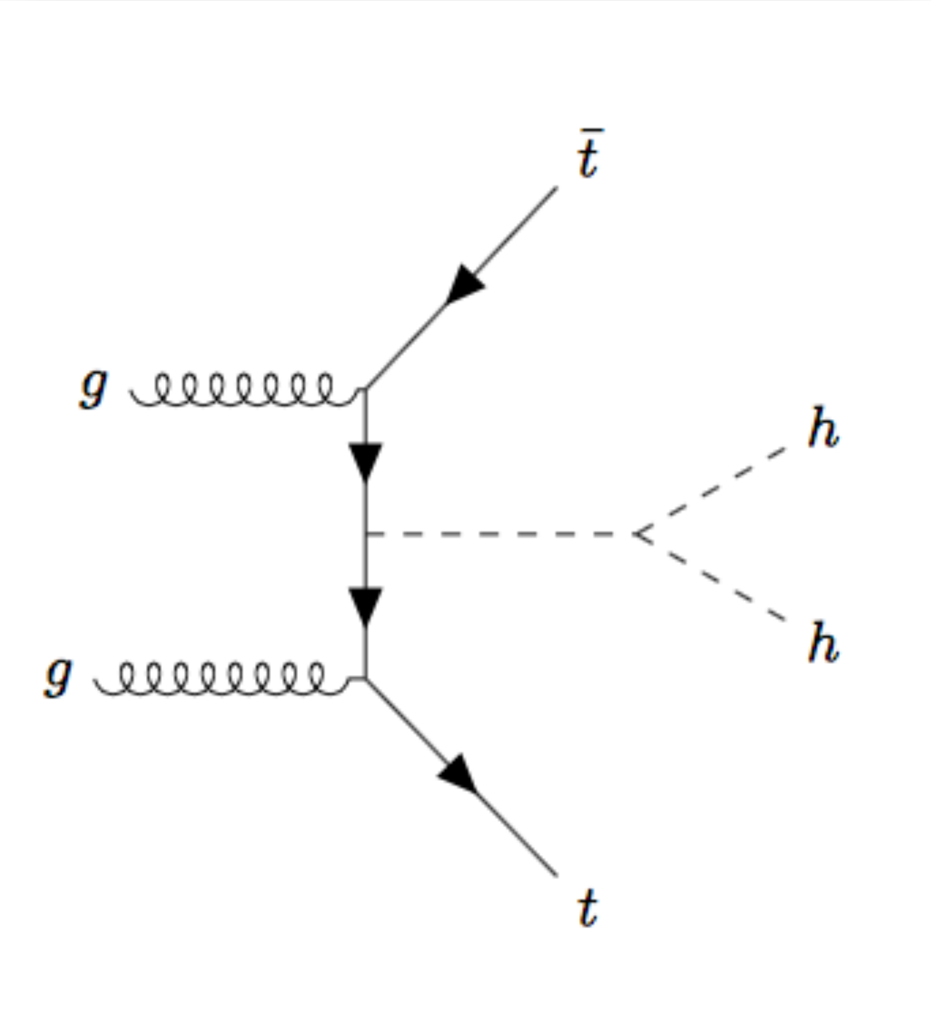
- Complement the tan_beta favored channels well for $2m_h < m_H < 2m_t$ and even beyond
- Sensitivity is not bad compared to gg -> H -> hh: associated top pair (ttH -> tthh) compensates for relative smallness of the tthh cross section

Analysis IV: Pair Production of Top Partners



Excludes the scenarios with Br(T → th) = 25% and 50% up to 1.5 TeV and 1.7 TeV, respectively, at HL-LHC

Summary



- The tthh production can couple with BSM physics in multiple ways (deformed Higgs self-interaction, tthh contact interaction, new heavy resonances, etc.)
- Though its cross section in the SM is relatively low, the kinematics (e.g., resonance) and signal rate of the tthh could be significantly modified by the BSM physics, yielding valuable sensitivities at HL-LHC
- Given its potential role in probing BSM physics, a full exploration of its sensitivity at 100 TeV is important: still ongoing; will be presented somewhere else

Thank you!

UGC 大學教育資助委員會 University Grants Committee

Under Grant No. 16312716