What can we learn from the current Higgs data?

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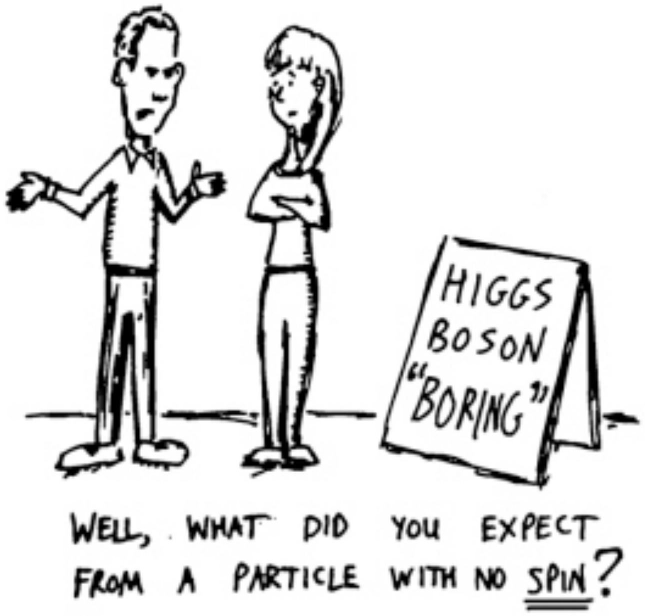
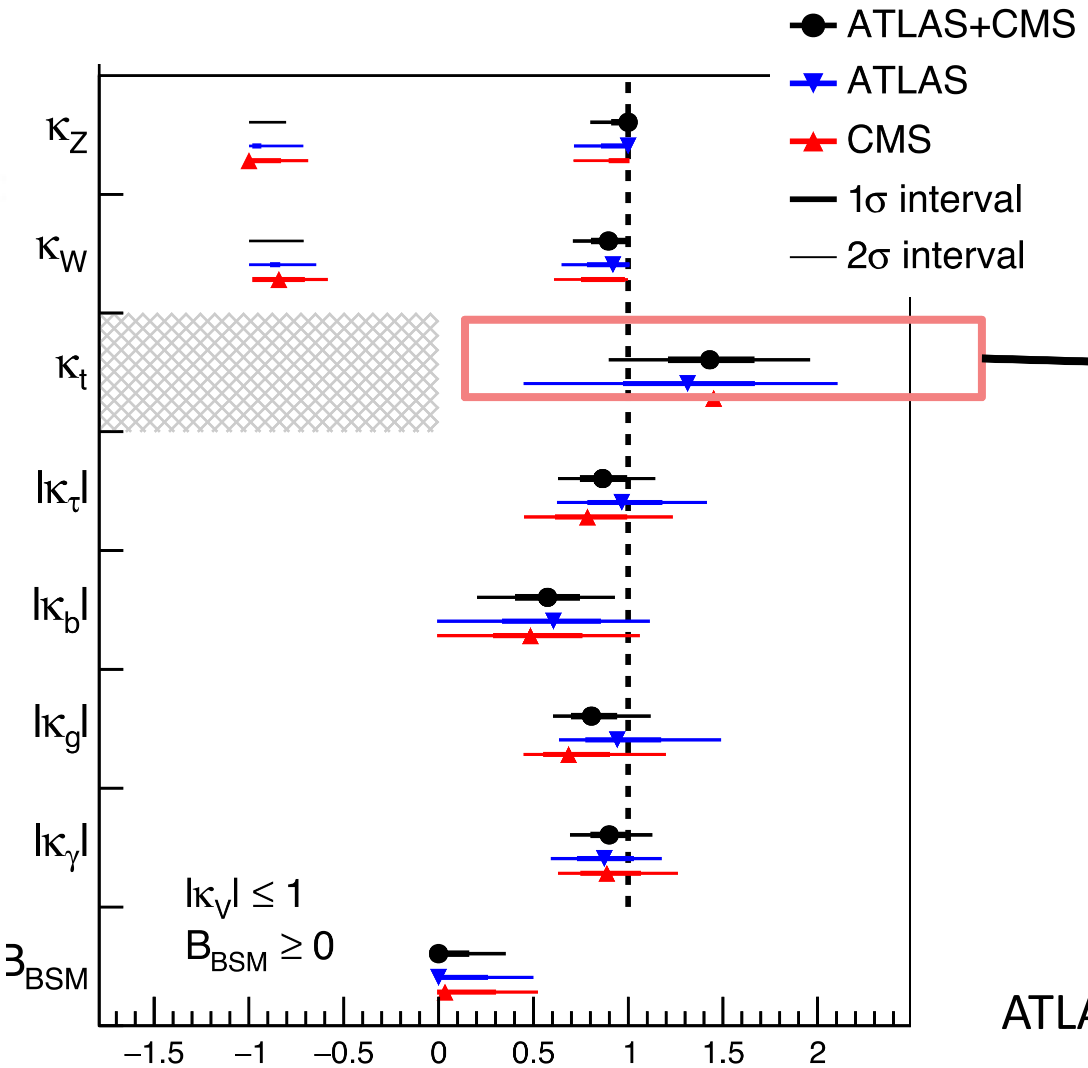
Theory seminar, UW-Madison
04/25/2017



Current Higgs Profile

7+8 TeV data



~40% higher than SM

Driven by the excess in tth, h->W^+W^- multi-lepton

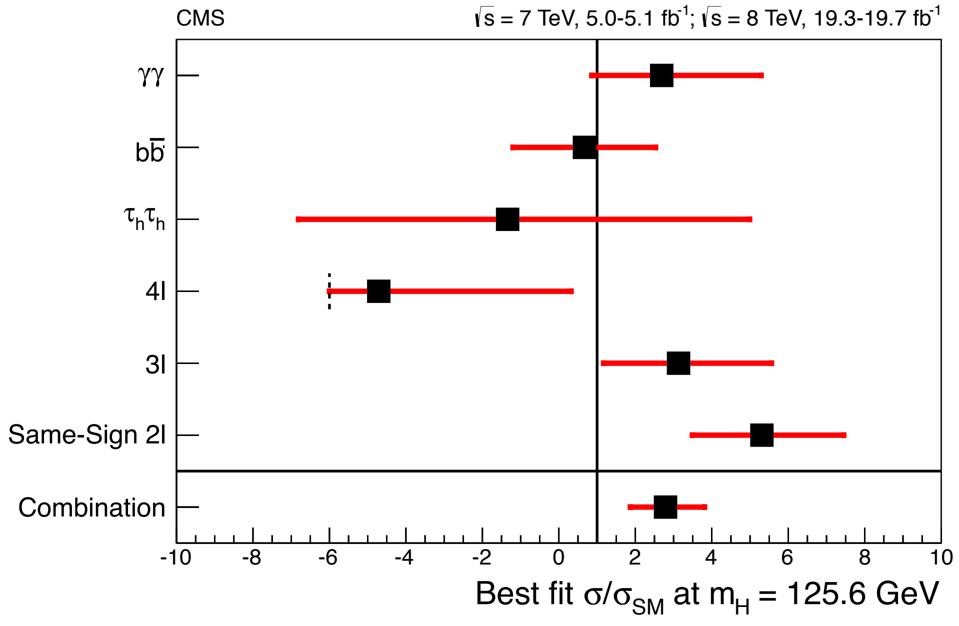
ATLAS and CMS, 1606.02266

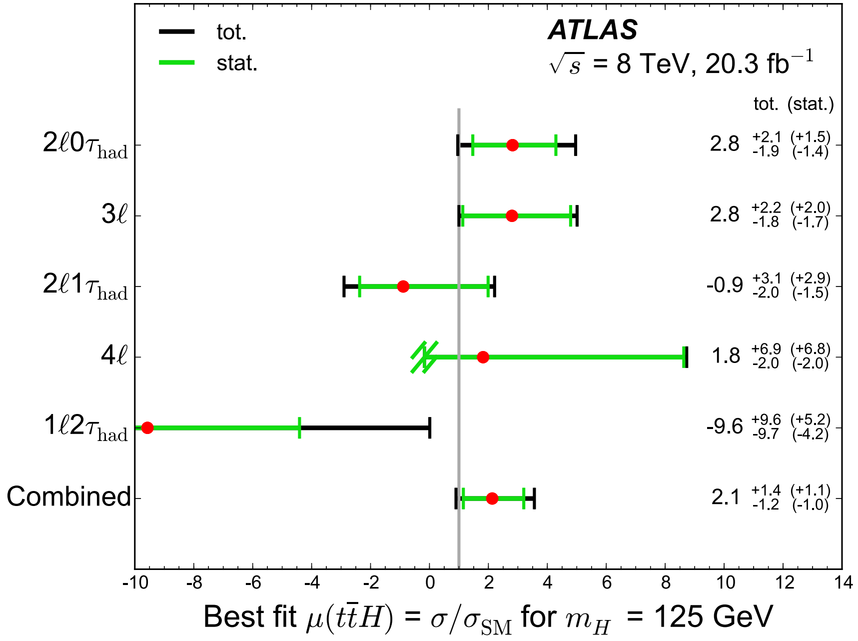
Interesting Excess: Excess at Both Experiments

ttH, H->W$^+$W$^-$, multi-lepton

$$\boxed{\mu = 2.8^{+1}_{-0.9}}$$

$$\boxed{\mu = 2.1^{+1.4}_{-1.2}}$$



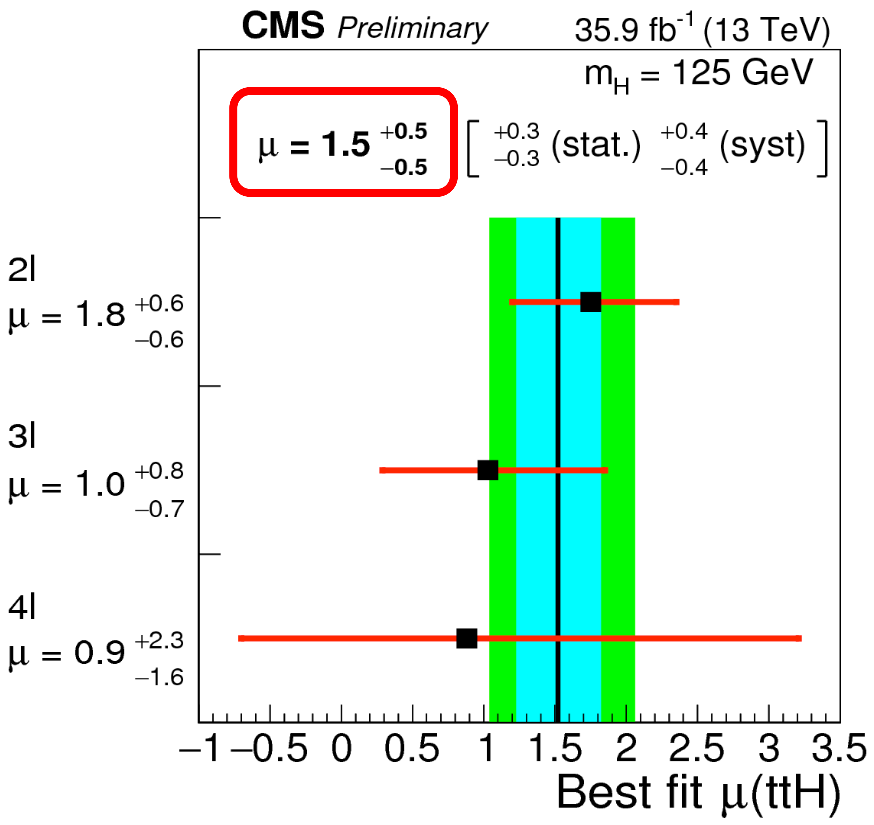


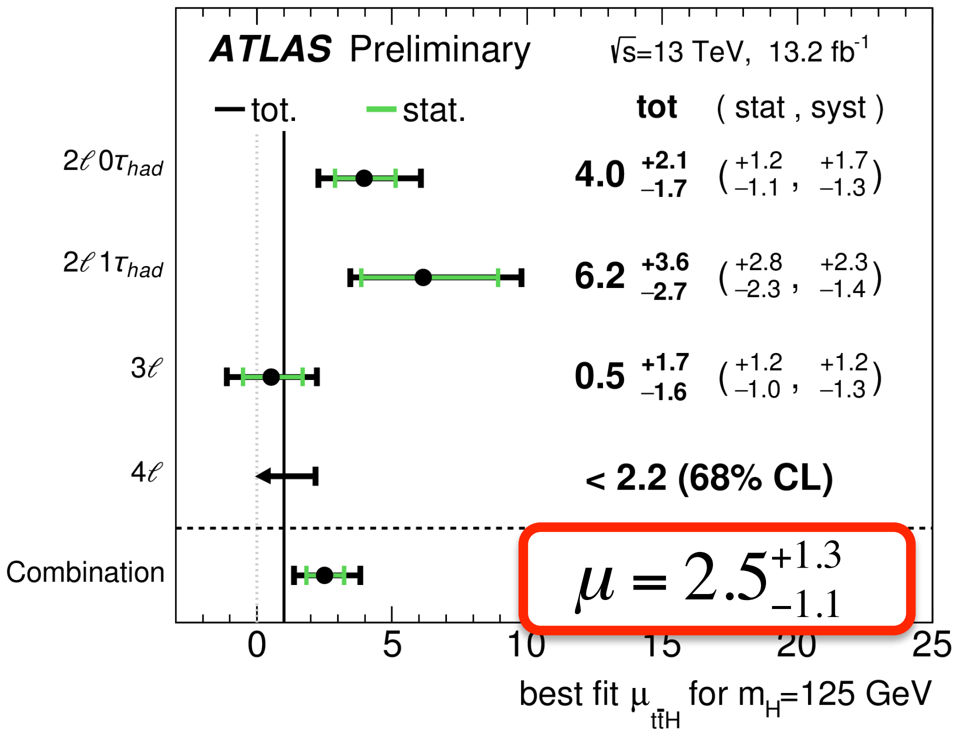
CMS 1408.1682, local significance 2.6σ

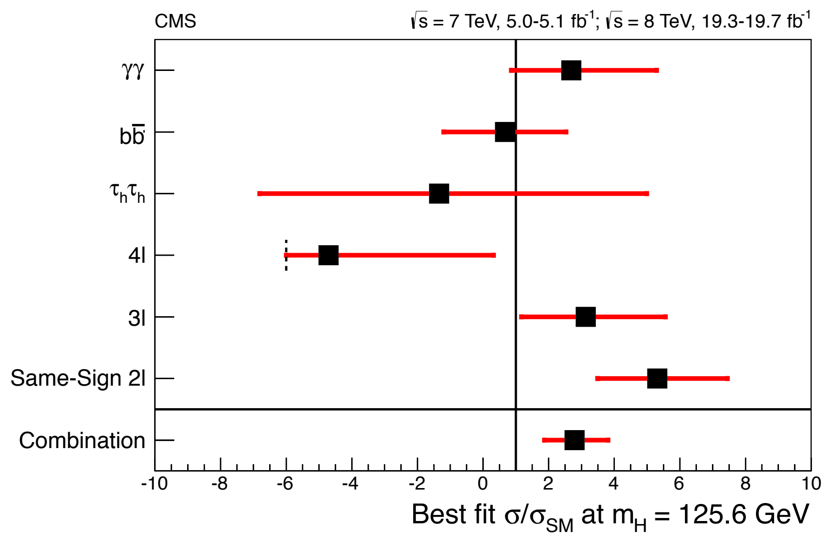
ATLAS 1506.05988

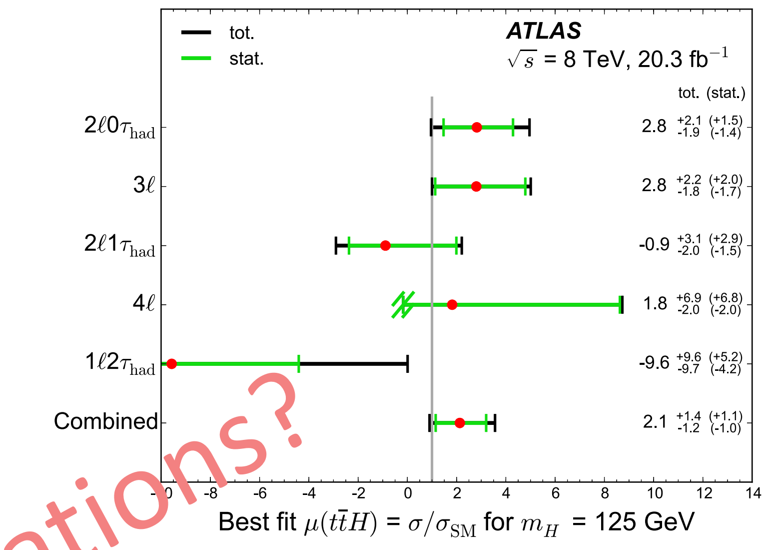
Excess at Both Runs

Moriond 2017

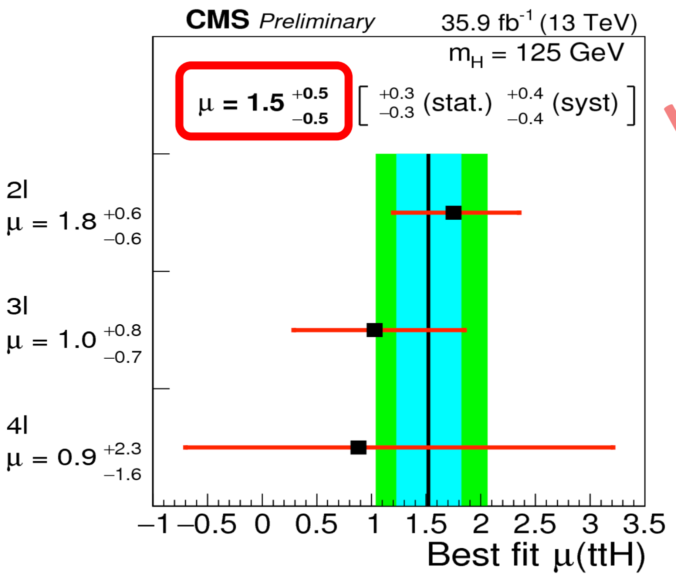




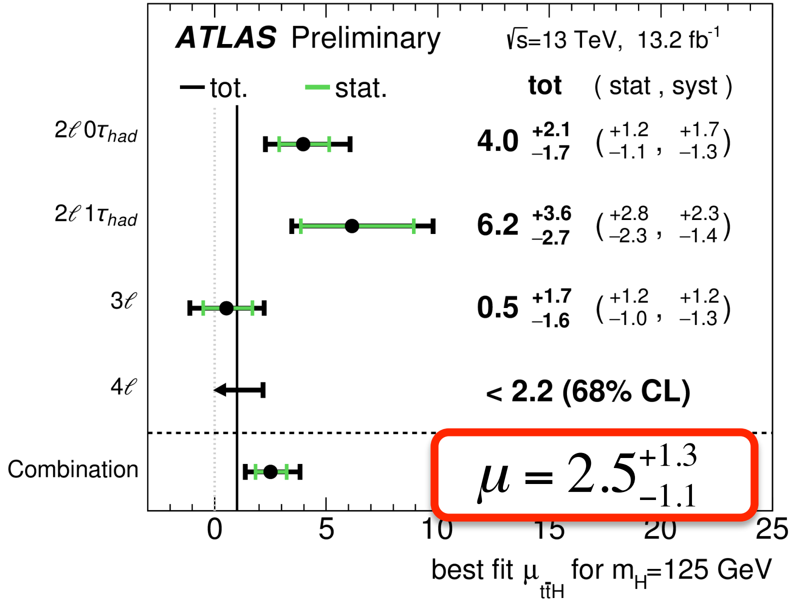




Interpretations?



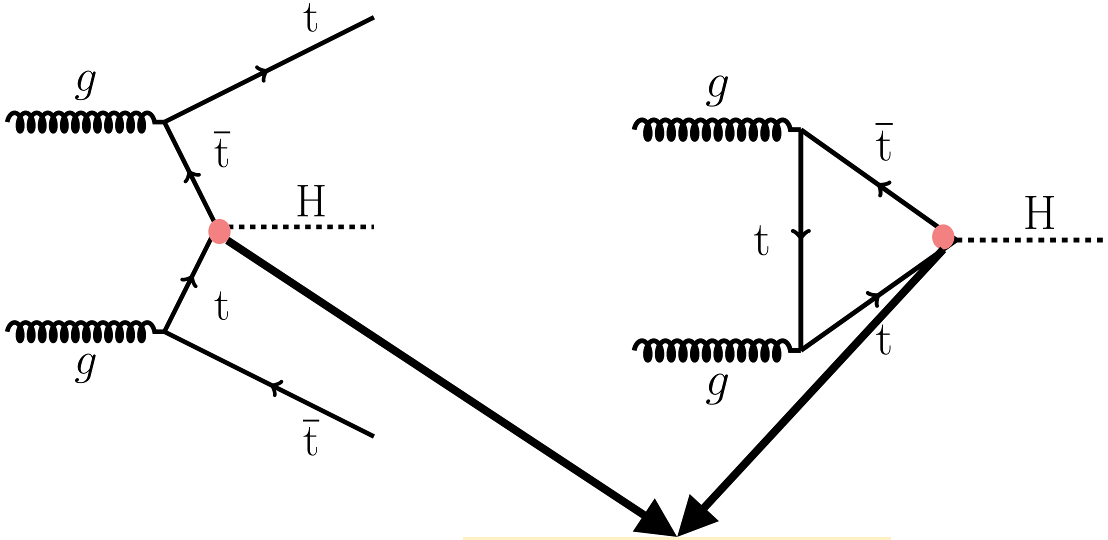
$\mu = 1.5^{+0.5}_{-0.5}$



$\mu = 2.5^{+1.3}_{-1.1}$

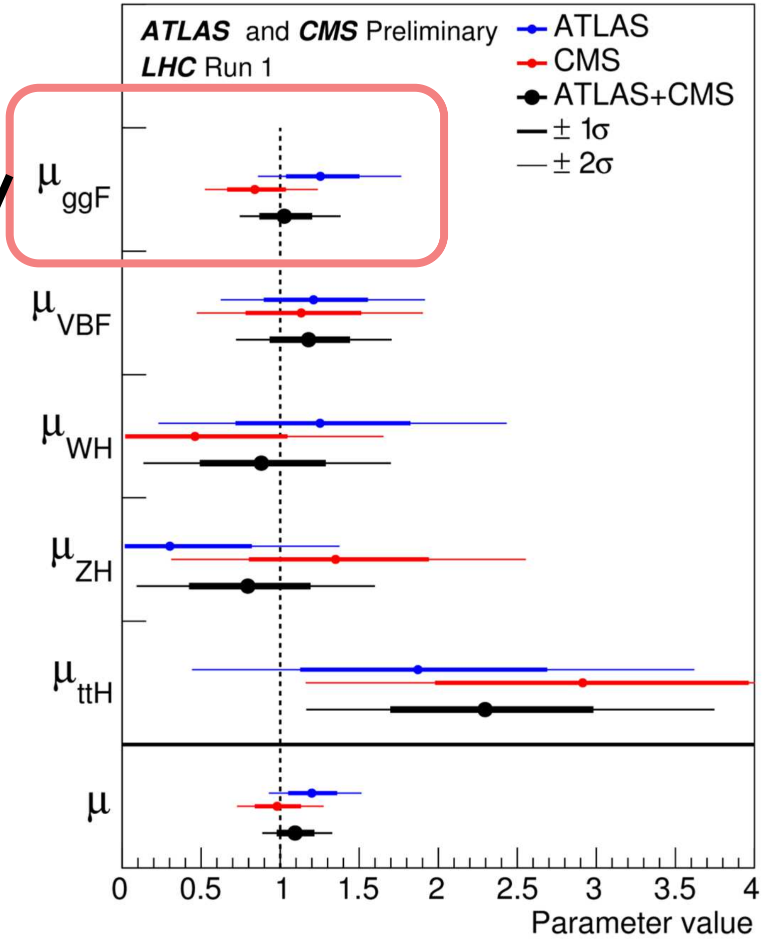
SM + An Enhanced Top Yukawa Coupling

SM+ a enhanced top Yukawa coupling?



Same Coupling

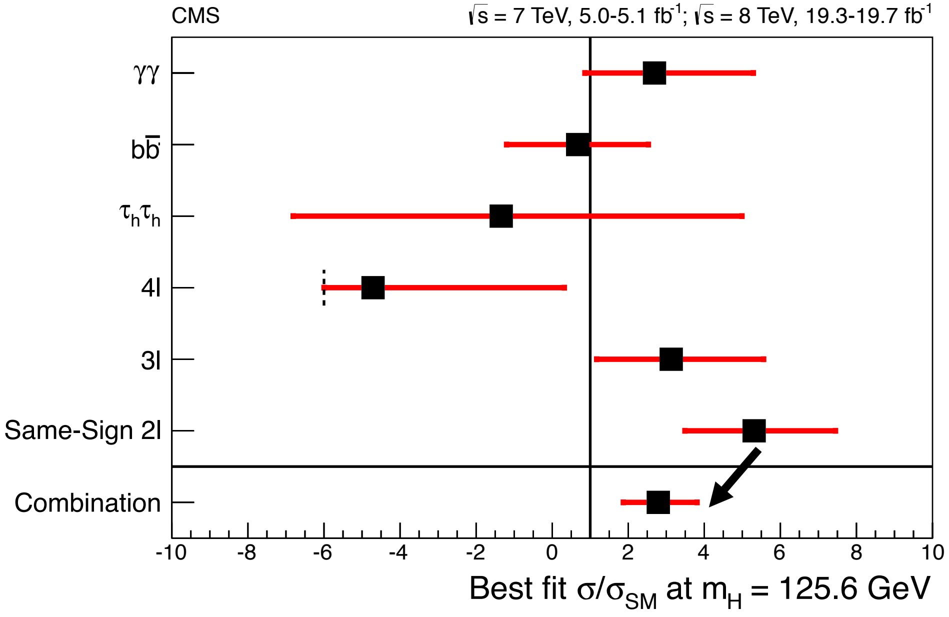
Very SM-like

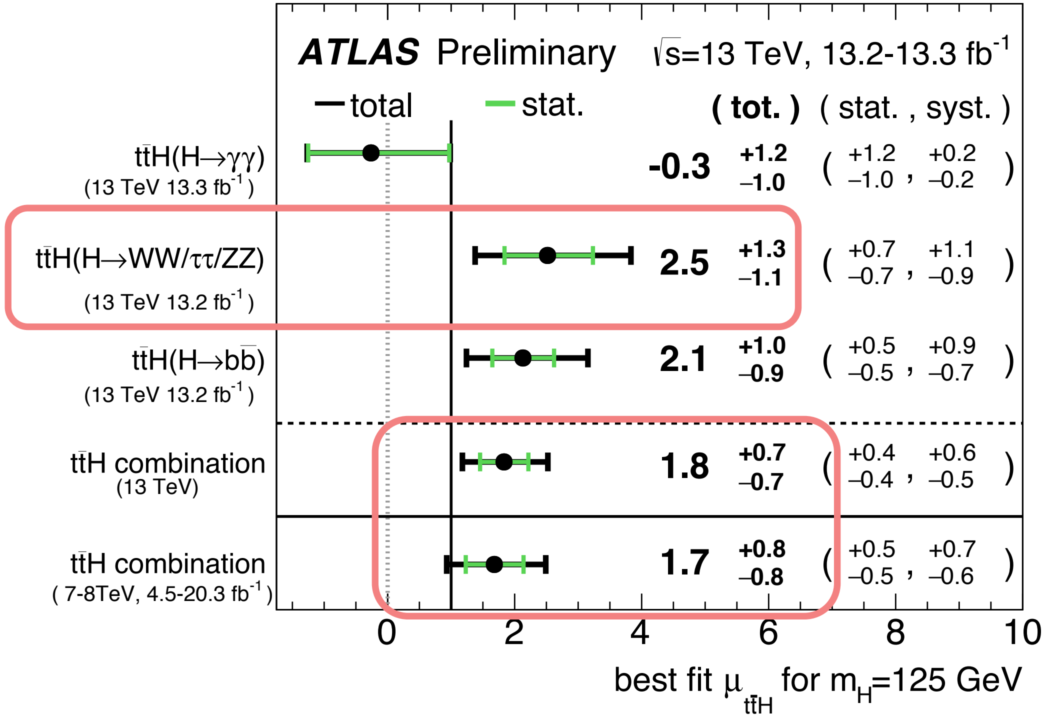


Would expect gluon fusion to be high as well

Combine with other channels

If combine all channels in tth searches,



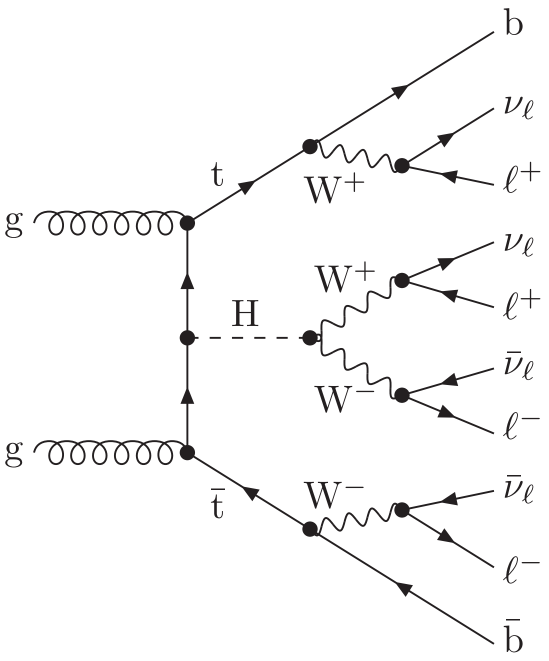


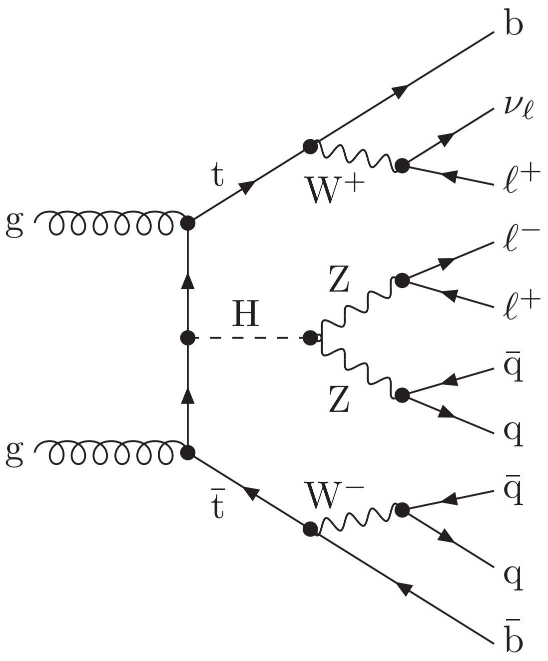
The excess becomes less significant, or the signal strength is more SM-like

is the excess really about tth?

Take a Closer Look at the Signature

- What are we seeing exactly?
  tth, h->W^+W^-
- It is really a search for 2t + 2W, or equivalently 2b + 4W final states
- 2b + 4W gives rise to the multi-lepton + multi-(b)jets + MET signatures
- tth, h->W+W- is really not about tth, but about new physics!

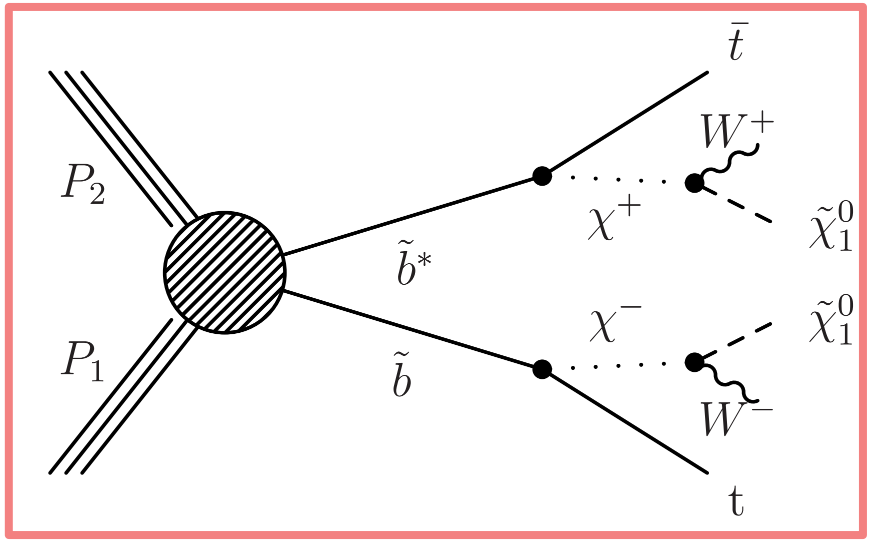


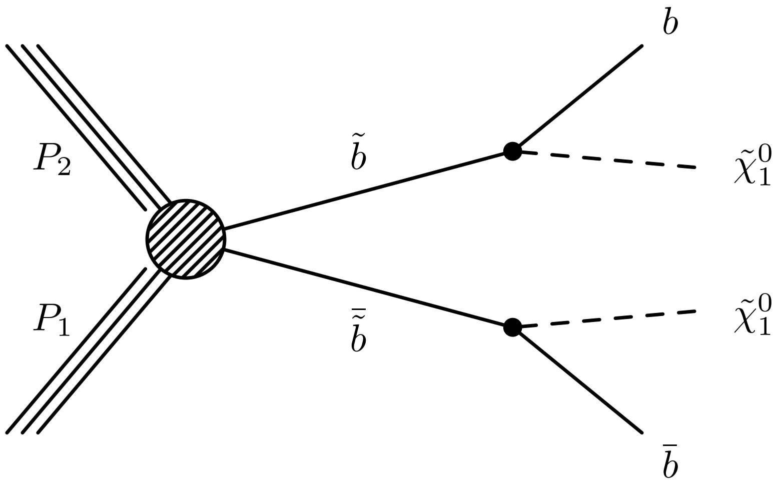


Excesses in Multi-lepton + b-jets + MET

2t + 2W final states,
exactly what you would do
when you search for sbottoms

Caveat in the simplified model:
can not have 100% Branching
ratio, some BR goes to

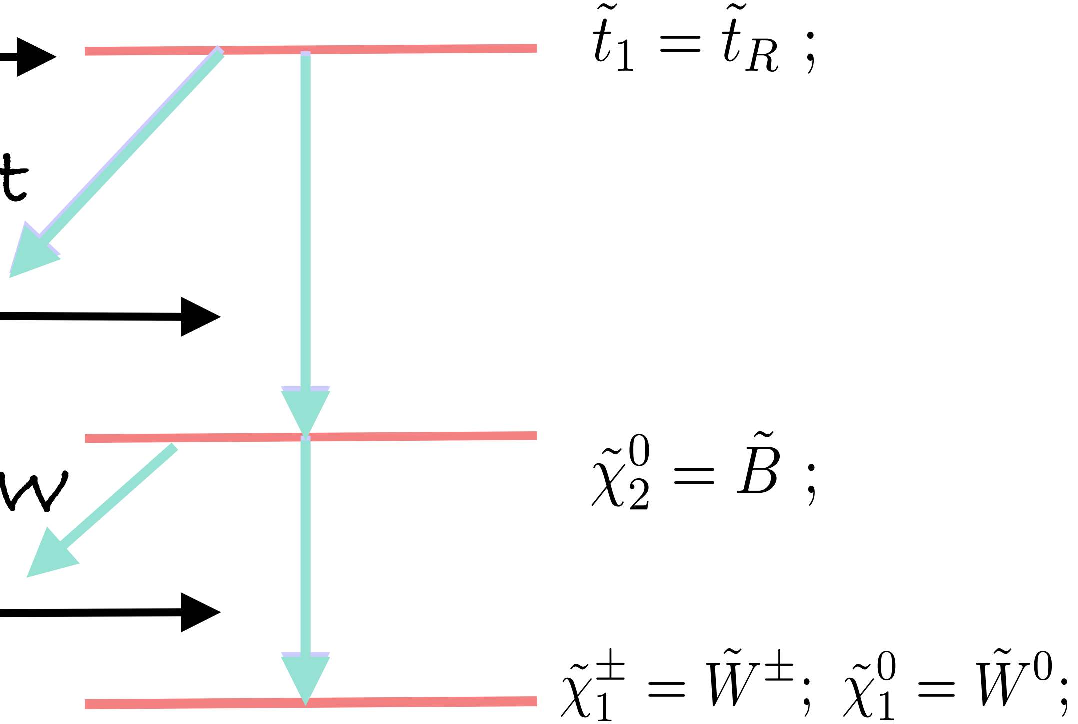




CMS-SUS-13-008

Just an Example: A Right-handed Stop

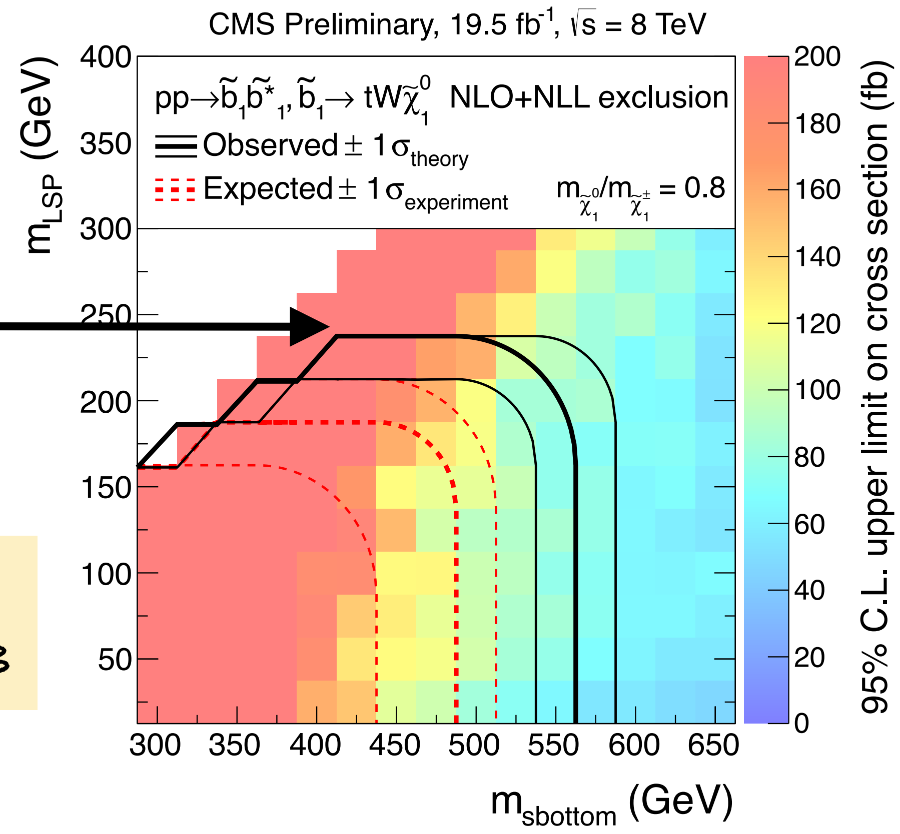
- Stops are pair produced, 2t + 2W →
- A pure right-handed stop does not couple to winos, 100% BR →
- The neutralino mass difference is smaller than the Higgs mass, 100% BR →

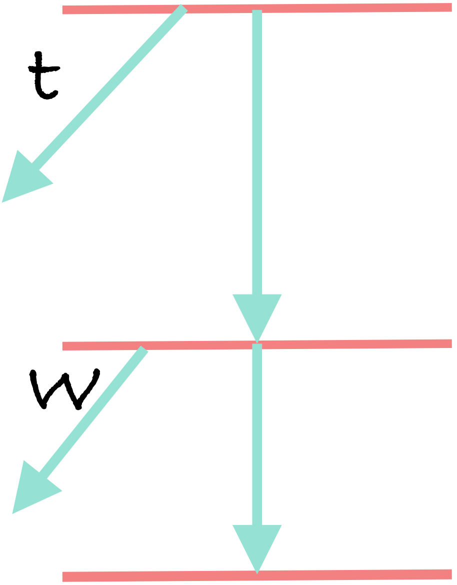


PH, A. Ismail, I. Low, C. Wagner, 1507.01601

A Spectrum

Bounds disappear
once the LSP is heavier than 240 GeV





$\tilde{t}_1 = \tilde{t}_R$;

550 GeV, a signal
strength for ss2l ~ 2.83

$\tilde{\chi}^0_2 = \tilde{B}$;

No decay through a higgs
< 260 + 125, call it 340 GeV

$\tilde{\chi}^\pm_1 = \tilde{W}^\pm$; $\tilde{\chi}^0_1 = \tilde{W}^0$;

260 GeV

$$\text{ATLAS} : \mu = 2.8^{+2.1}_{-1.9}$$

$$\text{CMS} : \mu = 5.3^{+2.1}_{-1.8}$$

PH, A. Ismail, I. Low, C. Wagner, 1507.01601

Distinguishing Stops from Enhanced Top Yukawa?

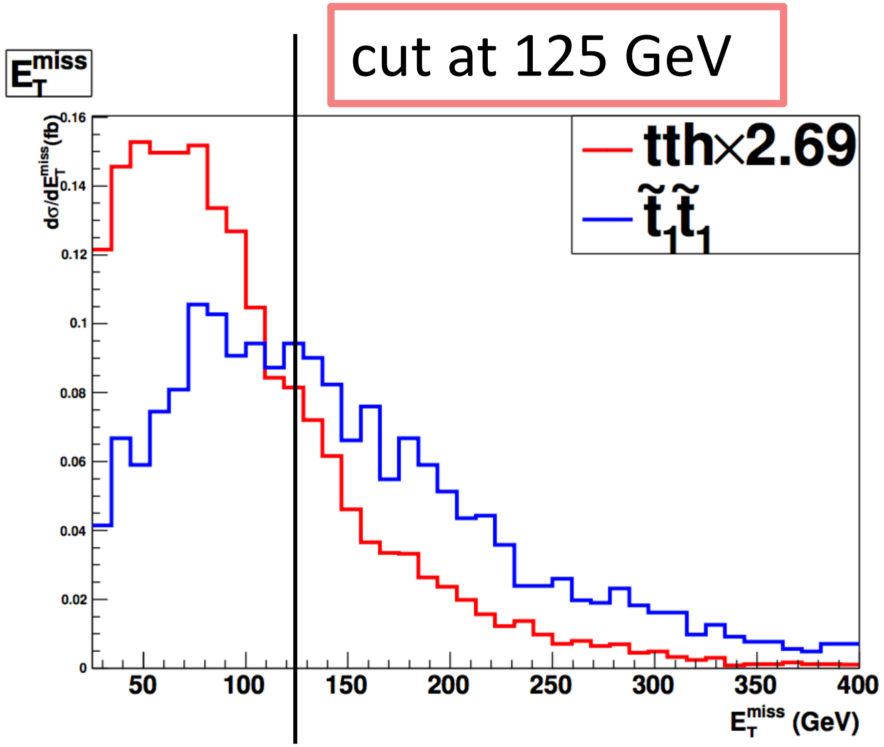
Stops are heavier, cross section increases faster from the pdf

	σ(8 TeV)	σ(13 TeV)	Ratio(13 TeV/8 TeV)
$\sigma(pp \to \mathrm{ttH})$	129 fb	509 fb	3.9
$\sigma(pp \to \tilde{t}_1\tilde{t}_1^*)$	45 fb	296 fb	6.6

Expect a signal strength ~ 3.69 at 13 TeV

PH, A. Ismail, I. Low, C. Wagner, 1507.01601

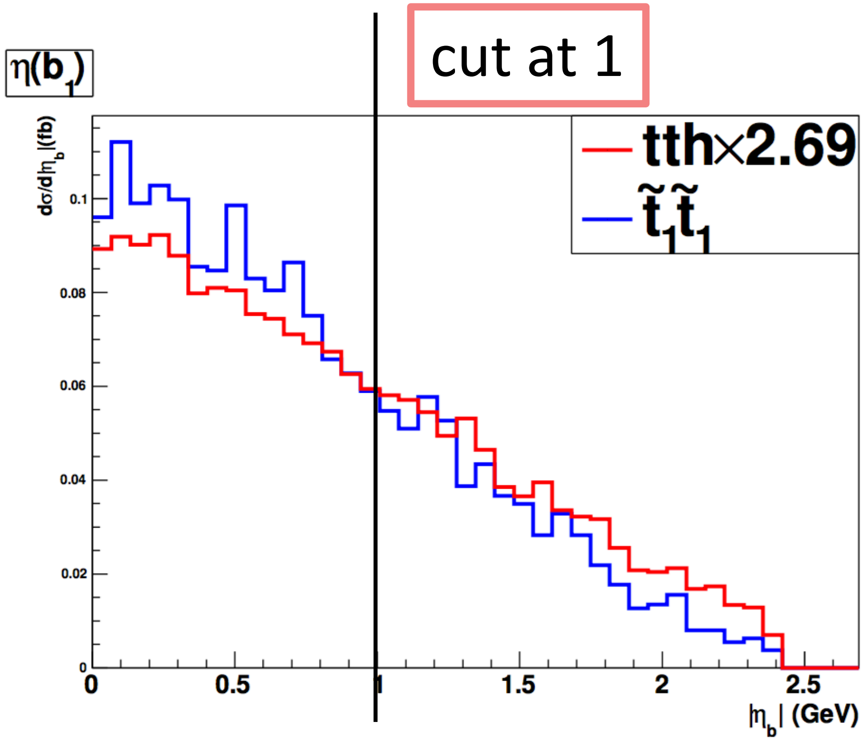
Distinguishing Stops from Enhanced Top Yukawa?



cut at 125 GeV

More missing energy from stop than tth

μ (13 TeV) ~ 6.94
reach 5 σ with about 40 fb^{-1}



cut at 1

In the stop events, b-jets are more centrally produced, while the b-jets from ttH tend to be more forward, from the t-channel kinematics

PH, A. Ismail, I. Low, C. Wagner, 1507.01601

Other Signatures

Charged Wino: Disappearing Tracks

- For a 260 GeV pure wino, the mass splitting between the neutral wino and the charge wino ~ 160 MeV (about the CMS limit)
- A small amount of higgsino mixing, would significantly increase the mass splitting
- A 1 TeV higgsino, the mass splitting is ~ 240 MeV

Same Sign Trilepton

$$\tilde{t}_R \to t + \tilde{B} \to t + (\tilde{W}^{\pm} + W^{\mp})$$

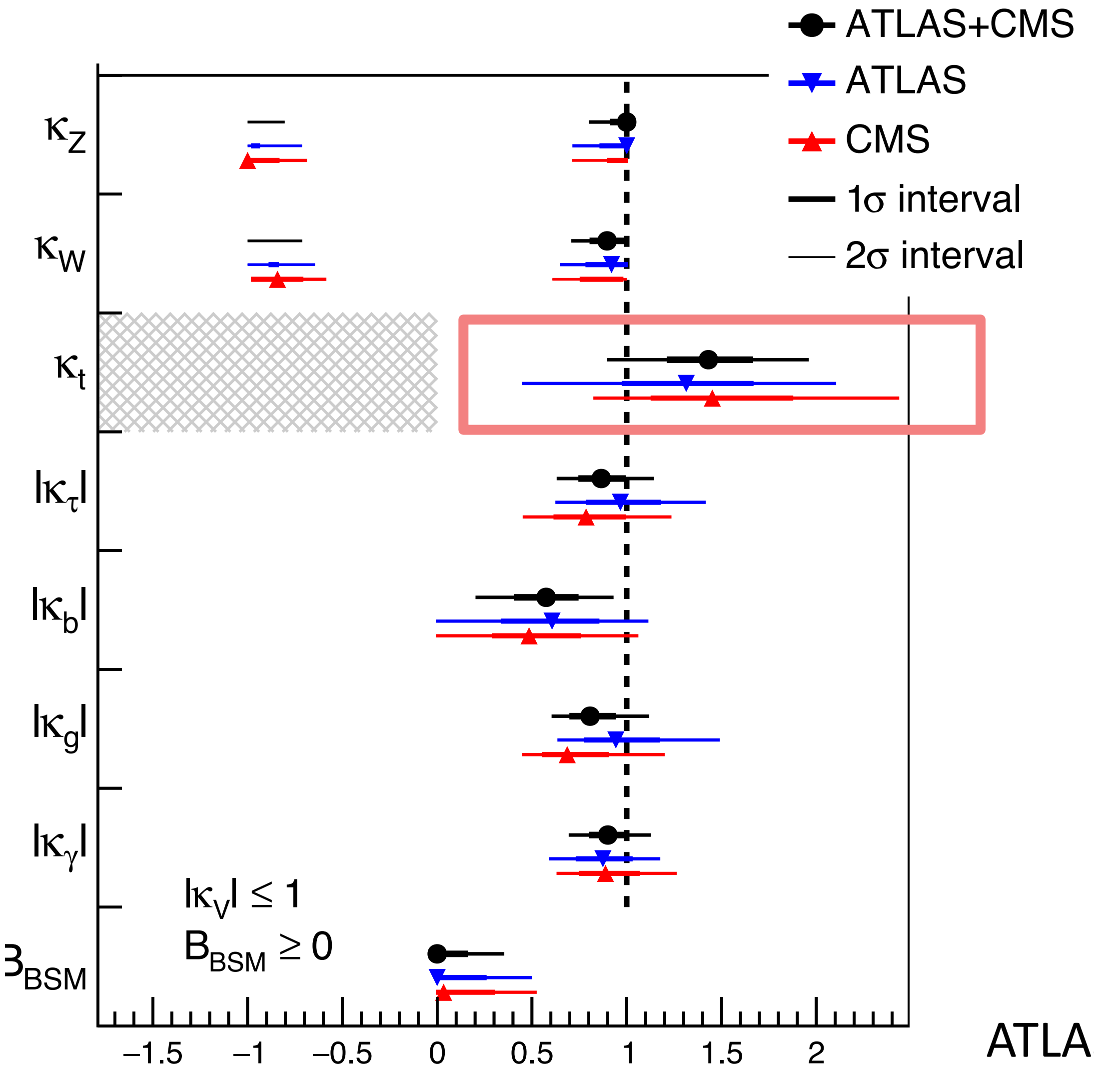
- Ws from the bino decay are charge symmetric
- Expect same sign trileptons
- With 40 fb^{-1}, expect about 5 same sign trilepton events

Confronting the current data

- The multi-lepton + bjets + missing energy search should place a further limit on this scenario
- The sbottom->t chargino search with a wino-like LSP is not updated
- SUSY-AI claims the Benchmark point is consistent with 13 TeV 3.2 fb^{-1}
- 610 GeV stops(winos ~ 320 GeV) will lead to a signal strength about 2 at 13 TeV
- 640 GeV stops will lead to a signal strength about 1.5 at 13 TeV

Enough room for this scenario

Current Higgs Profile



ATLAS and CMS, 1606.02266

Interpretations

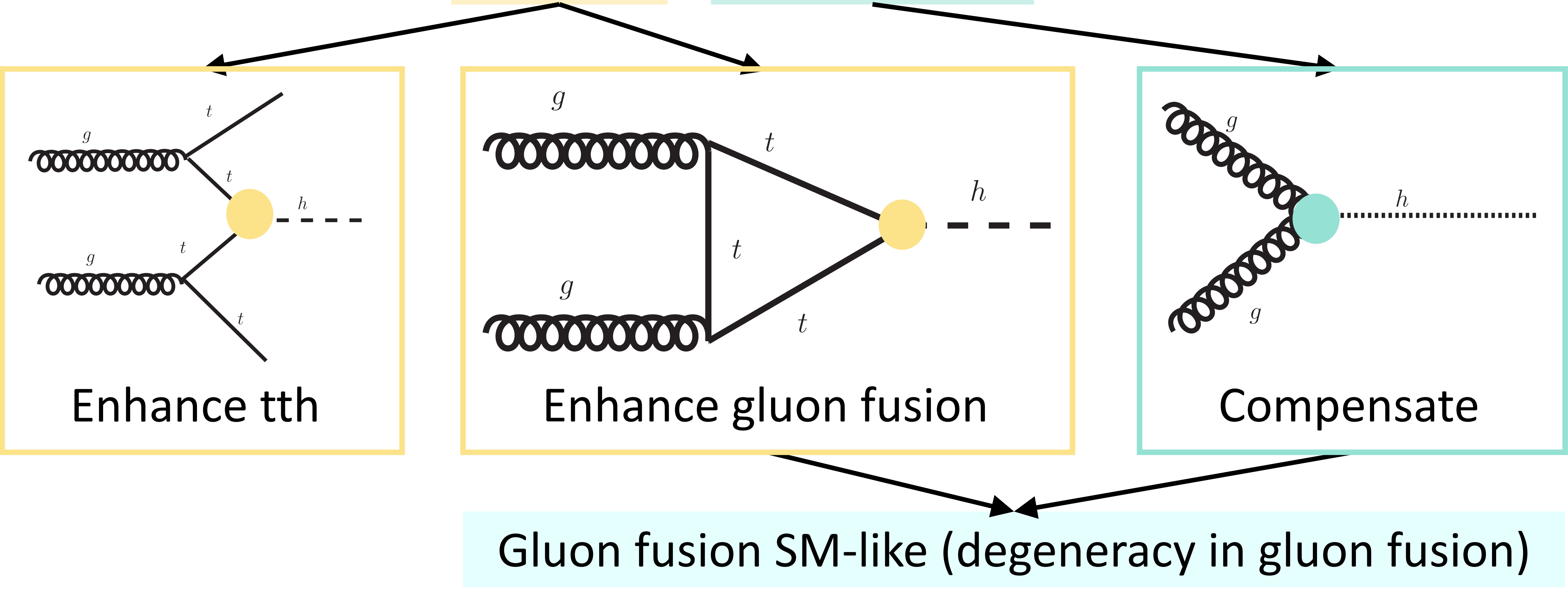
- tth coupling is SM like. The excess is from stop pair production
- The signal strength will be higher at 13 TeV
- Will see it in same sign trilepton, or disappearing tracks

PH, A. Ismail, I. Low, C. Wagner, 1507.01601

Other possibilities?

Enhanced Top Yukawa + New Physics

$$\mathcal{L}_6 = -c_t \frac{m_t}{v} \bar{t} t h + \frac{c_g g_s^2}{48\pi^2} \frac{h}{v} G_{\mu\nu} G^{\mu\nu}$$



Enhance tth

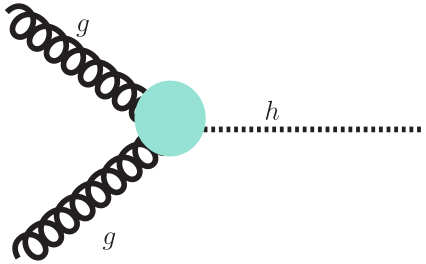
Enhance gluon fusion

Compensate

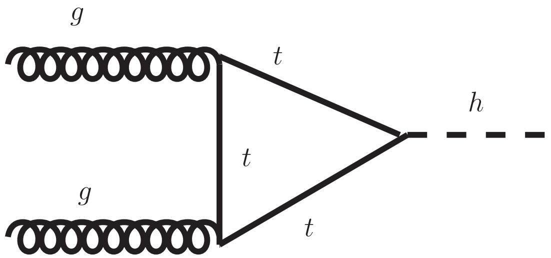
Gluon fusion SM-like (degeneracy in gluon fusion)

Enhanced Top Yukawa + New Physics

Modified

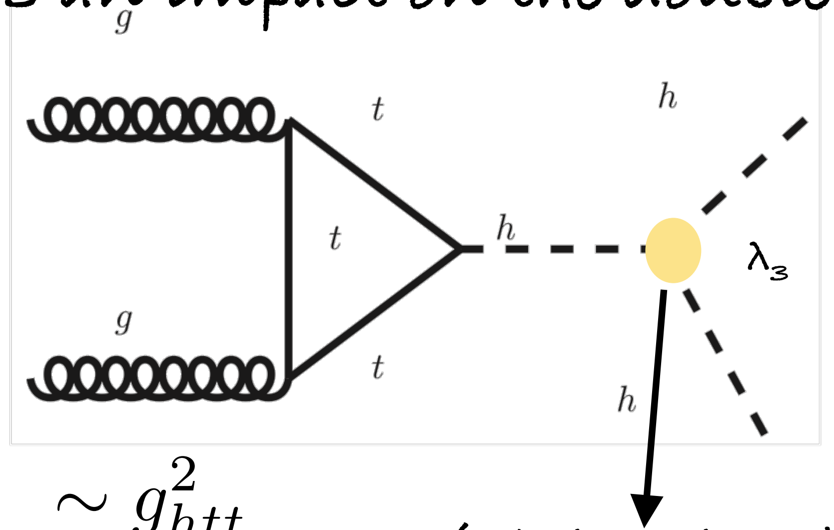


Modified



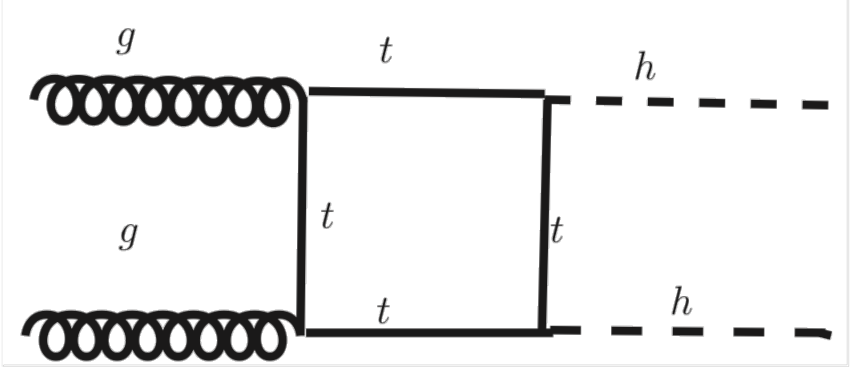
New particle(s) in the loop

Has an impact on the double Higgs production



$\sim g_{htt}^2$

tightly related to EWPT

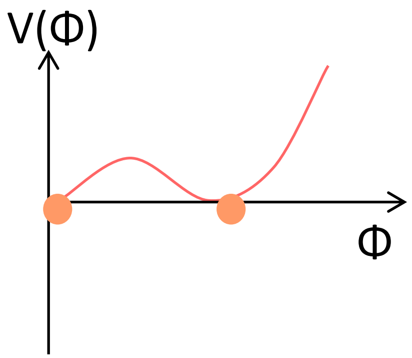


$\sim g_{htt}^4$

Electroweak Baryogenesis – Sakharov Conditions

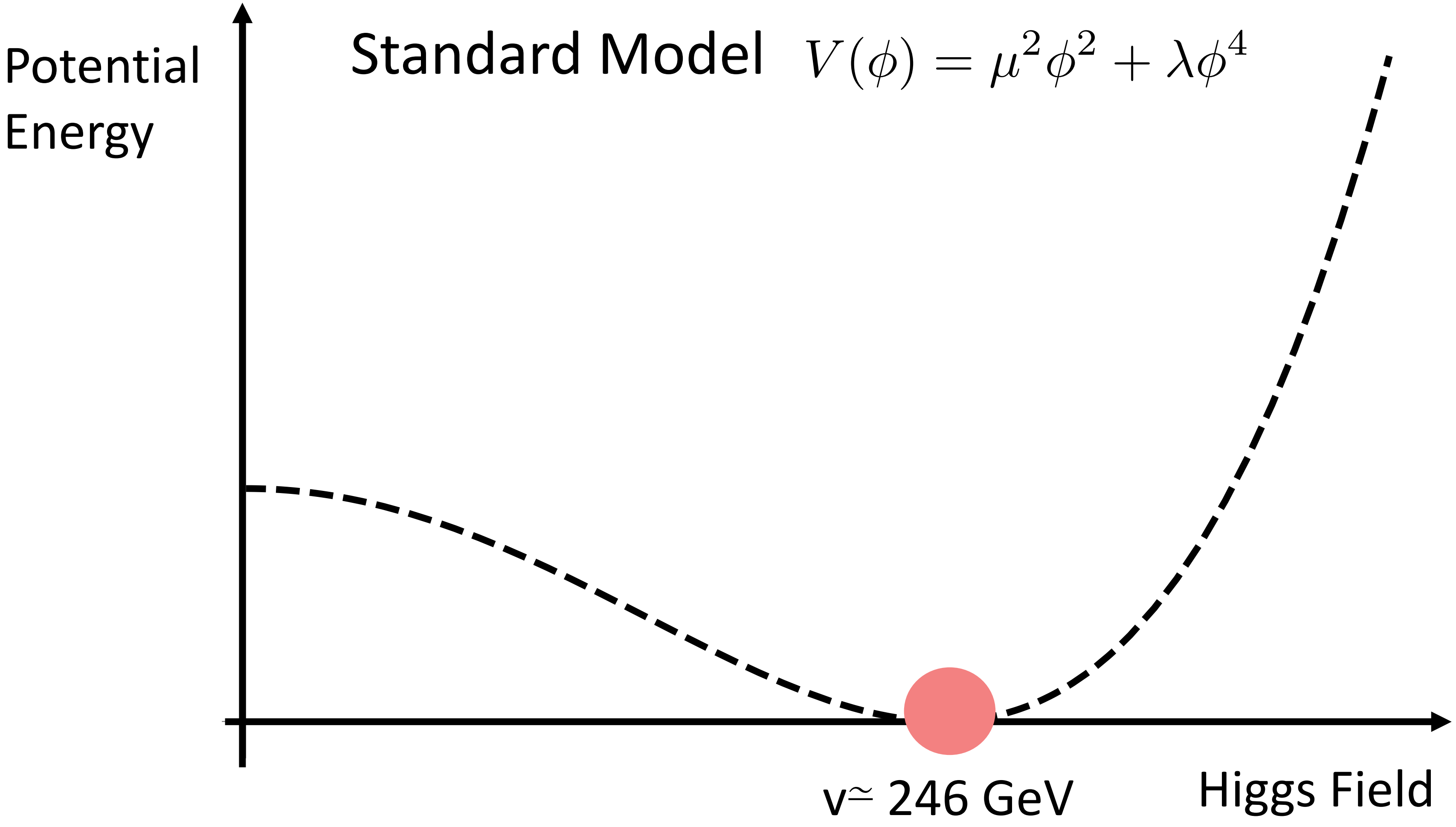
- Generates Extra Baryons
  - Baryon number violation
- Prefers Matter Over Anti-matter
  - CP violation
  - Or else, for each process creating matter at the cost of anti-matter, the CP-mirrored, inverse process would take place with equal probability
- Irreversible Process
  - Departure from thermal equilibrium – A first order phase transition
  - Or else, for each process creating matter at the cost of anti-matter, the inverse process would take place with equal probability

Electroweak Phase Transition



- EWPT is difficult to study from cosmology
- EWPT in the SM is not first order (unless the $m_h < 40$ GeV)
- New physics is required for a strongly first-order phase transition
- The new physics will alter the finite-temperature Higgs potential
- We can measure the zero temperature Higgs potential at the LHC!

Measure the Higgs Potential

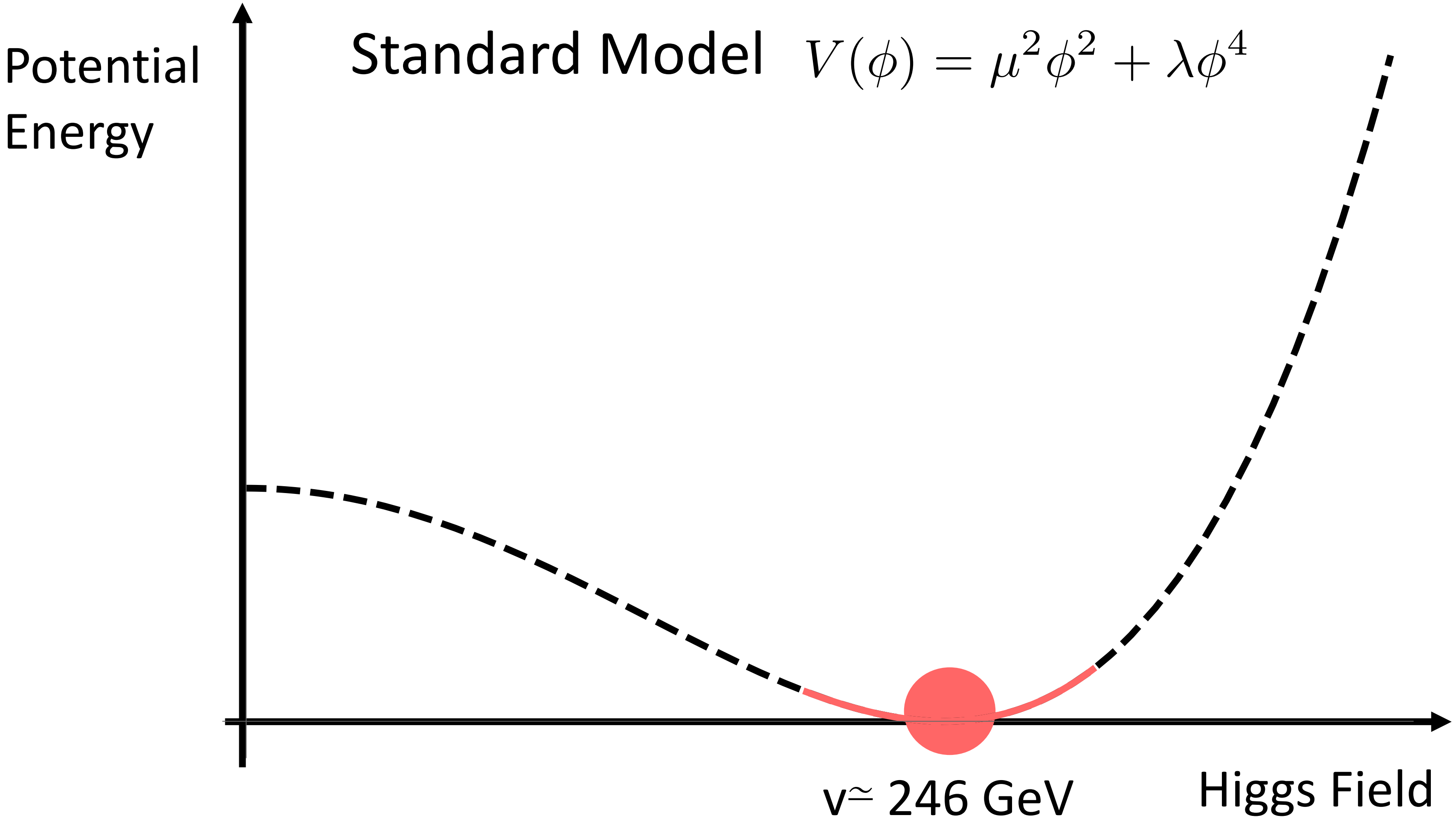


$V(\phi) = \mu^2\phi^2 + \lambda\phi^4$

$$\left.\frac{\partial V}{\partial \phi}\right|_{\phi=v}$$

Higgs vev measured from G_F

Measure the Higgs Potential



Standard Model $V(\phi) = \mu^2\phi^2 + \lambda\phi^4$

$$\left.\frac{\partial V}{\partial \phi}\right|_{\phi=v}$$

Higgs vev measured from G_F

$$\left.\frac{\partial^2 V}{\partial^2 \phi}\right|_{\phi=v} = m_h^2$$

Higgs mass measured at the LHC

$$\left.\frac{\partial^3 V}{\partial^3 \phi}\right|_{\phi=v} = \lambda_3$$

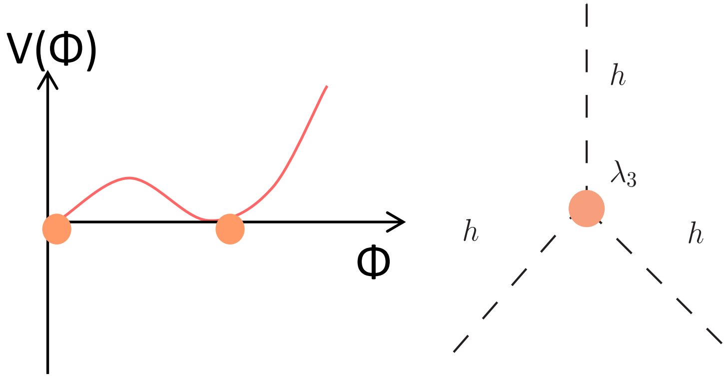
Next Measurement:
Higgs Trilinear Coupling

Relate the Trilinear Coupling with the EWPT

A lot of models can be consistent with a first order EWPT

SM + singlet
SM + scaler doublet (like MSSM stops)
SM + chiral fermion (like MSSM gauginos)
SM + varying Yukawas (like flavons)
…

Calculate

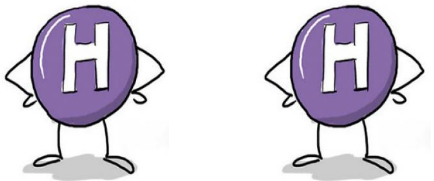


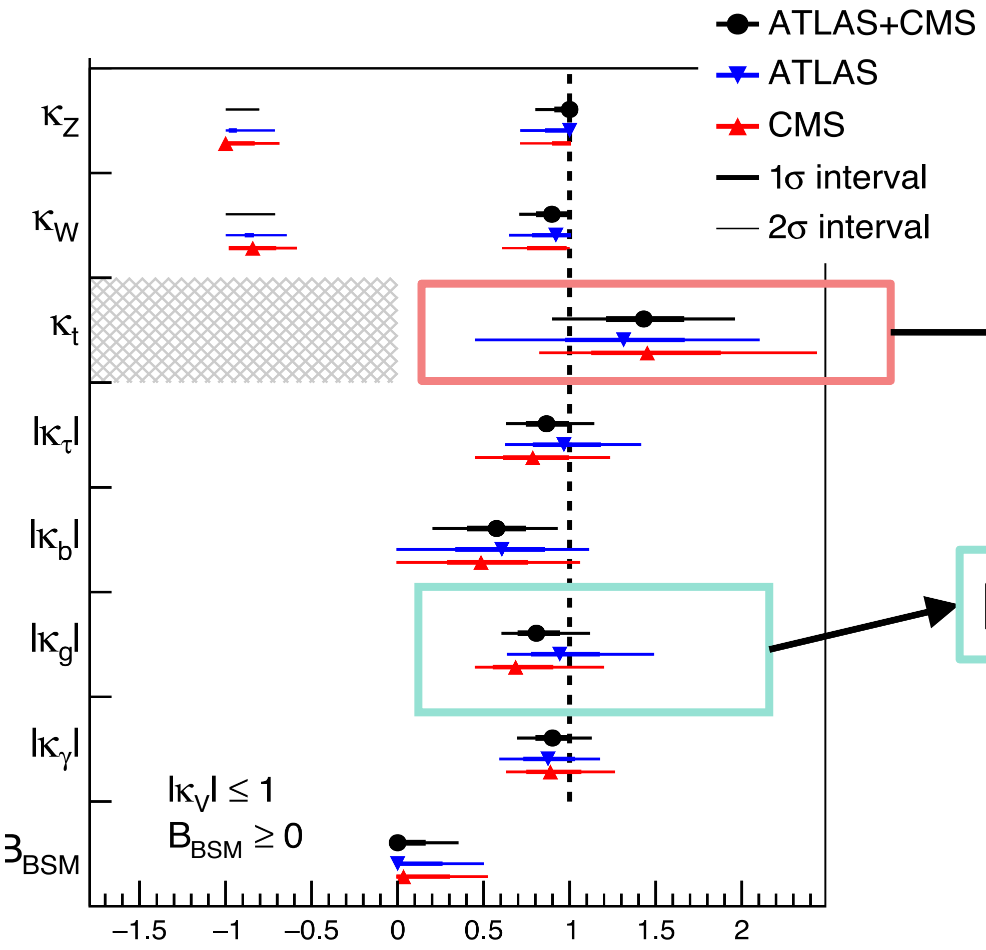
The trilinear coupling could deviate significantly from its SM value in the region consistent with a first order EWPT

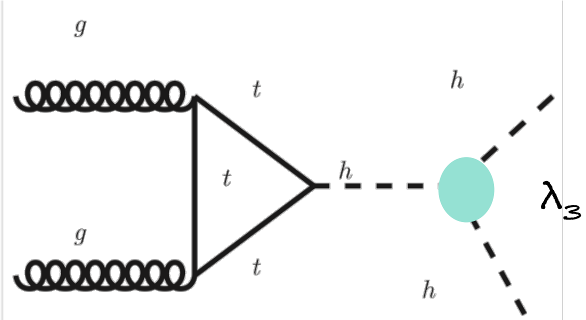
$O(1)$ deviation is typical can go up to $7\lambda_3^{SM}$

PH, A. Joglekar, B. Li, and C. Wagner, arxiv:1512:00068; PH, A. Long, and L.T. Wang, arxiv:1608.06619

Double Higgs







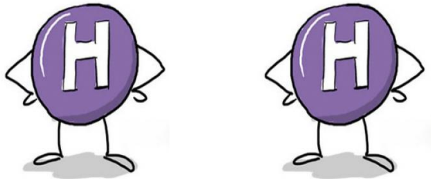
g_{htt}

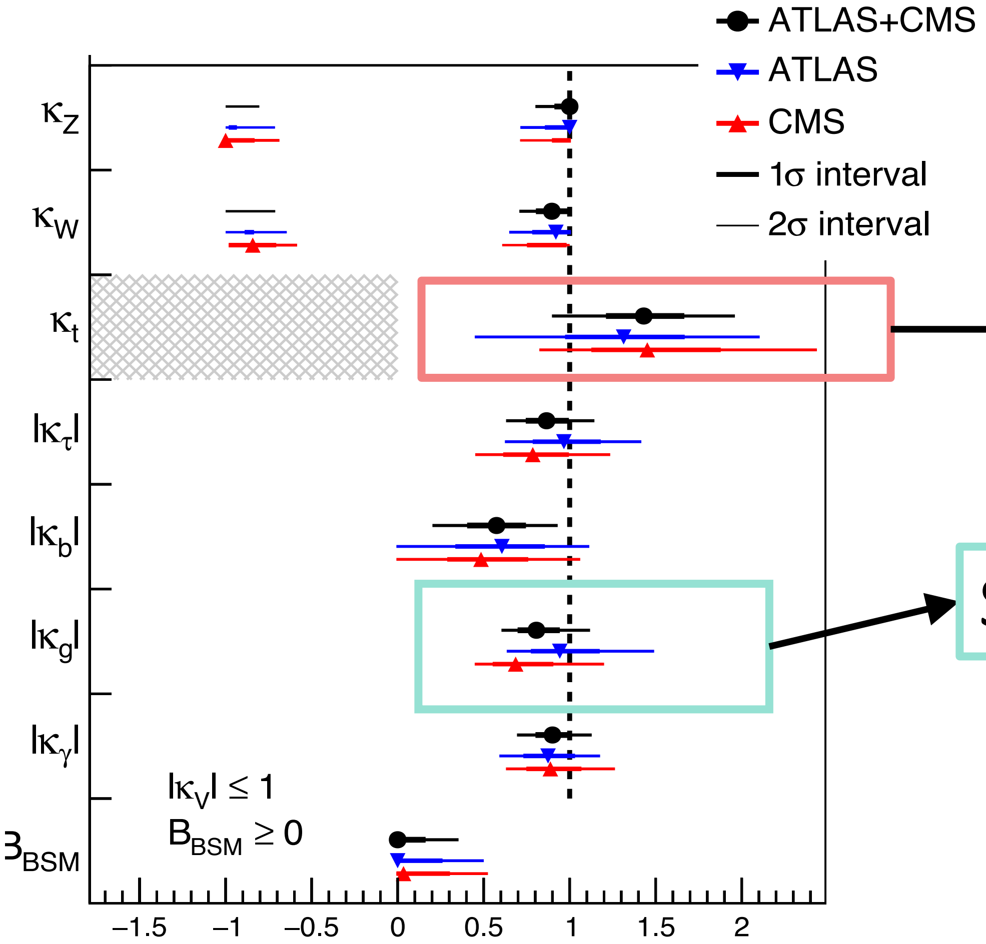
Possible modifications in λ_3

New Particles

Implication for Double Higgs?

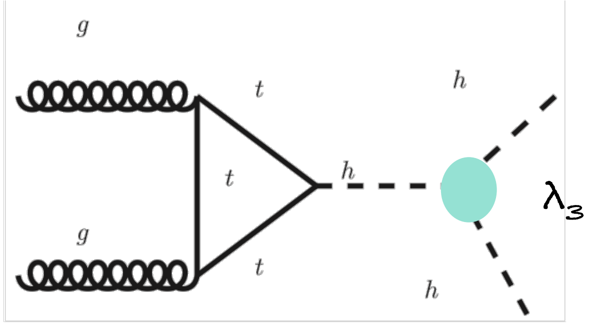
Double Higgs





g_{htt}

Stops



Possible modifications in λ_3

Implication for Double Higgs?

Constraints

- modification in gluon fusion

compensated by the mixing between the two stops

$$\frac{c_g}{c_g^{\mathrm{SM}}} = \frac{c_\gamma}{c_\gamma^{\mathrm{SM}}} = c_t + \frac{m_t^2}{4}\left[c_t\left(\frac{1}{m_{\tilde{t}_1}^2} + \frac{1}{m_{\tilde{t}_2}^2}\right) - \frac{\tilde{X}_t^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}\right]$$

enhanced from an enhanced tth coupling

- Vacuum stability

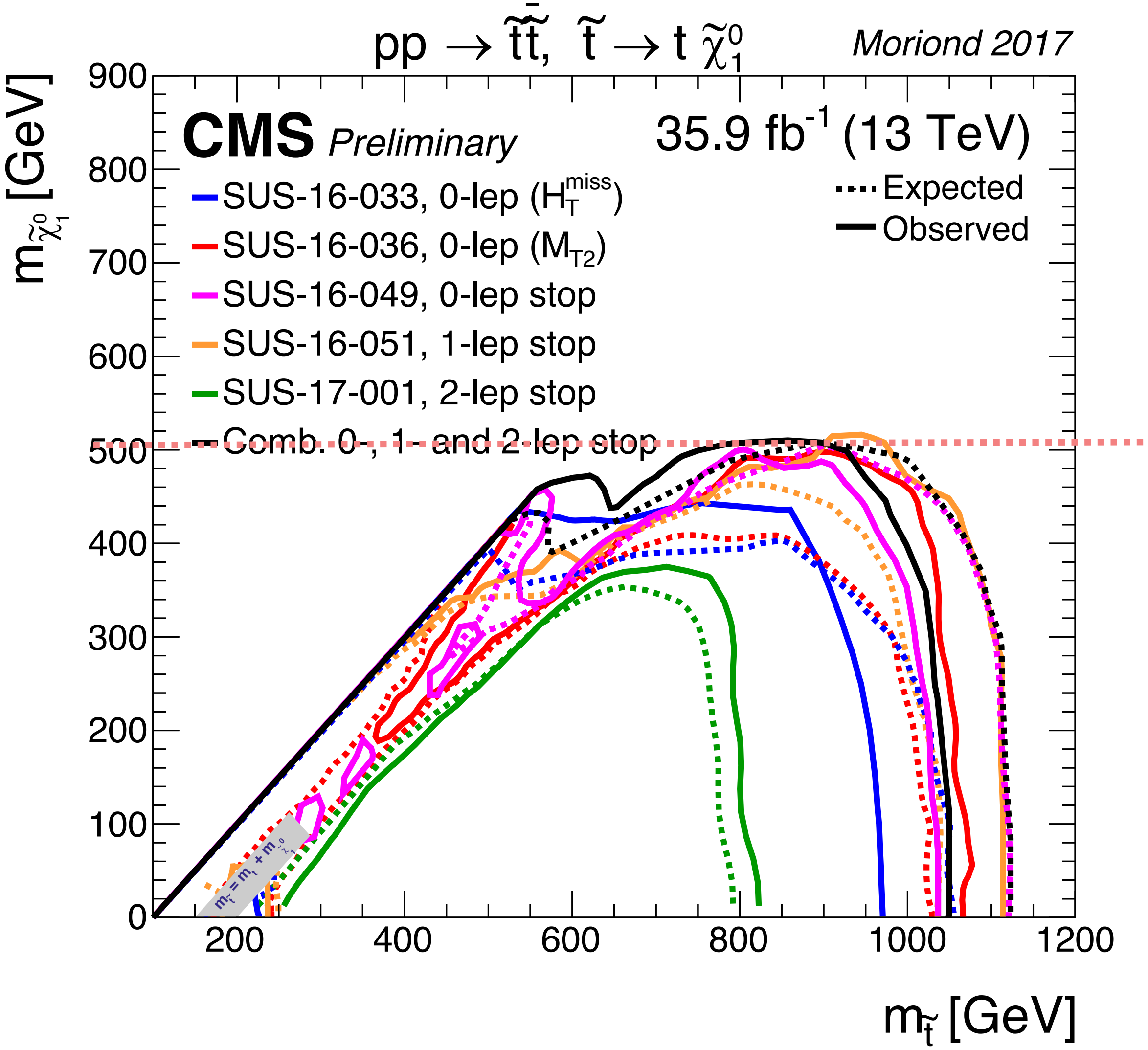
$$A_t^2 \lesssim \left(3.4 + 0.5\frac{|1-r|}{1+r}\right) m_T^2 + 60\, m_2^2$$

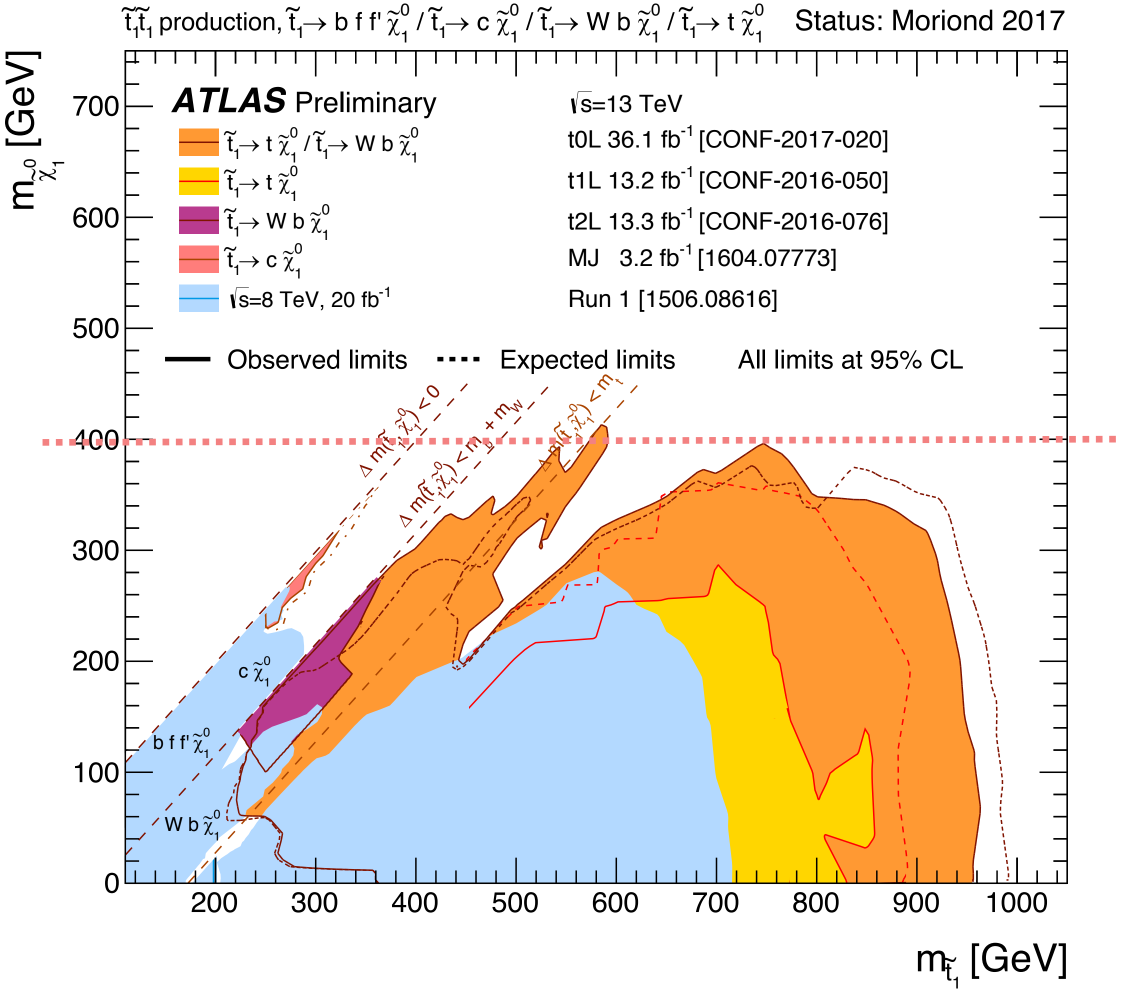
$$m_T^2 = (m_{Q_3}^2 + m_{U_3}^2),\ m_2^2 = (m_{H_u}^2 + \mu^2),\ \text{and}\ r = m_{U_3}^2/m_{Q_3}^2$$

Blinov, and Morrissey, 2014

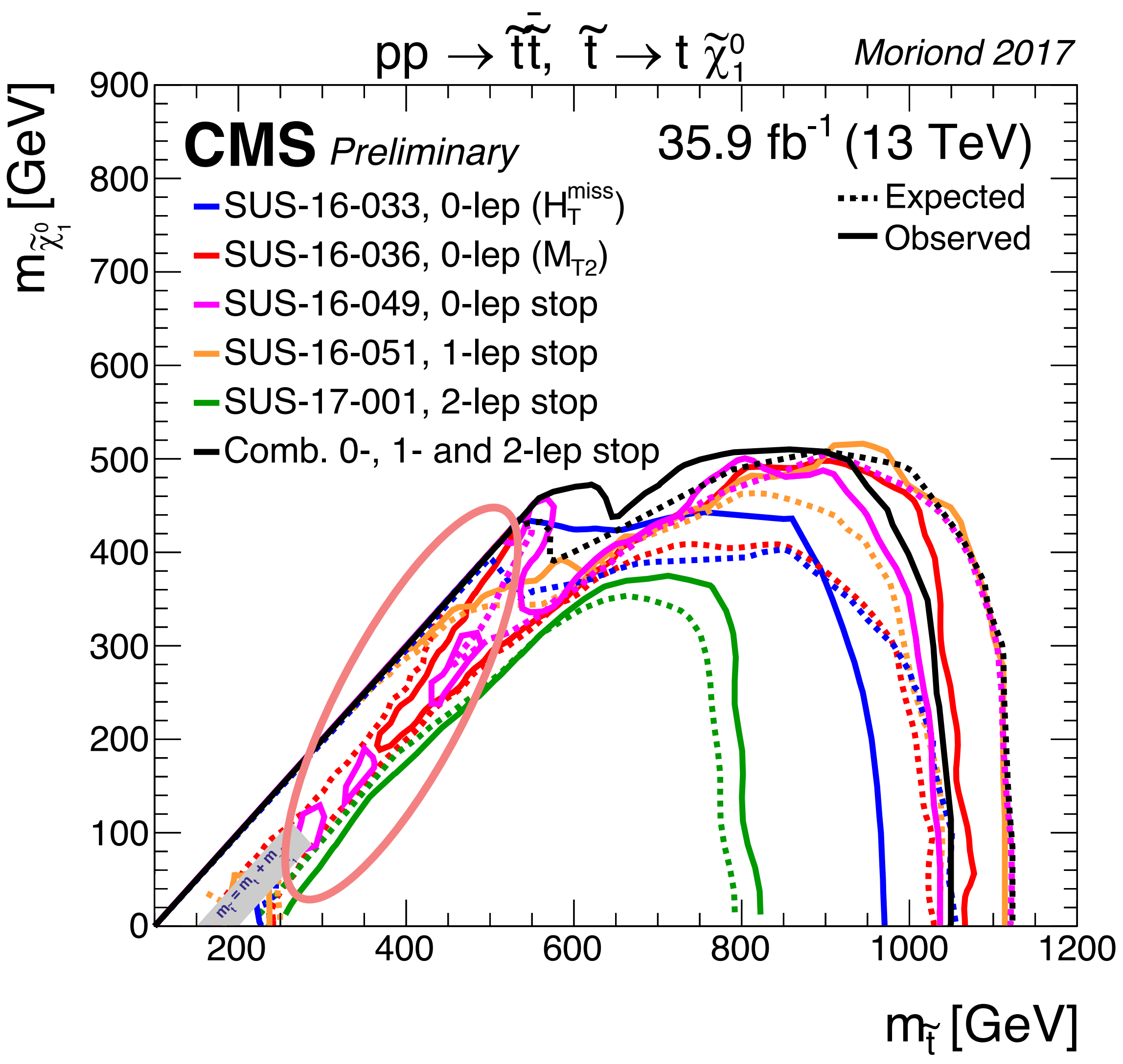
Stops – current limit

Weak constraints when stops are heavier than 500 GeV





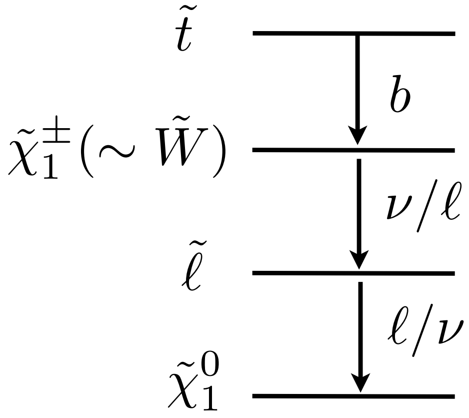
How to hide the light stops?



Compressed region

small islands, stops can hide in the holes

Weak constraints for di-lepton channel, make that channel dominant



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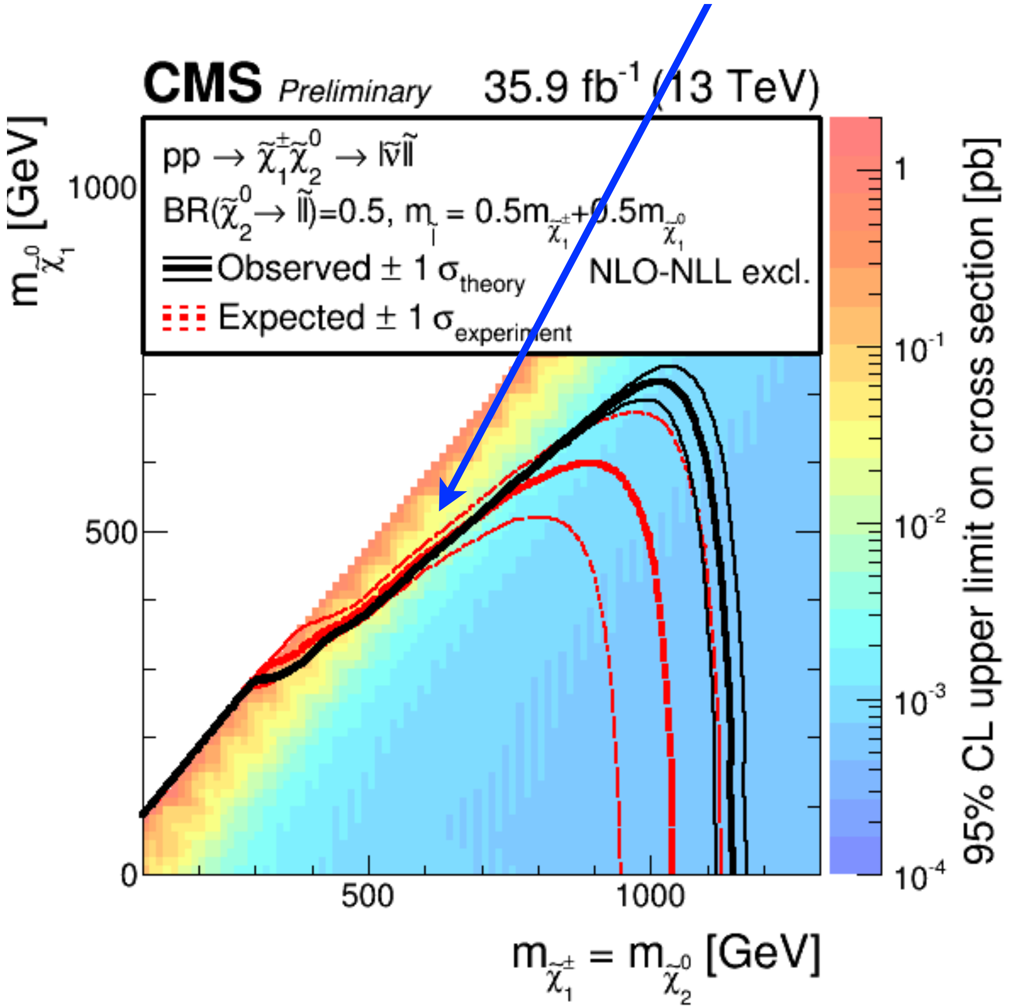
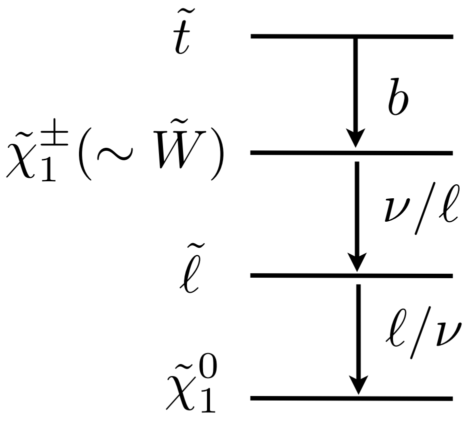
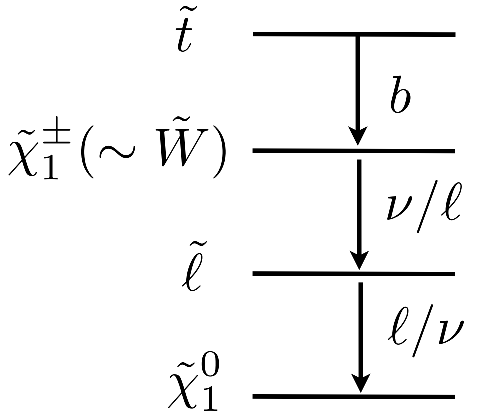


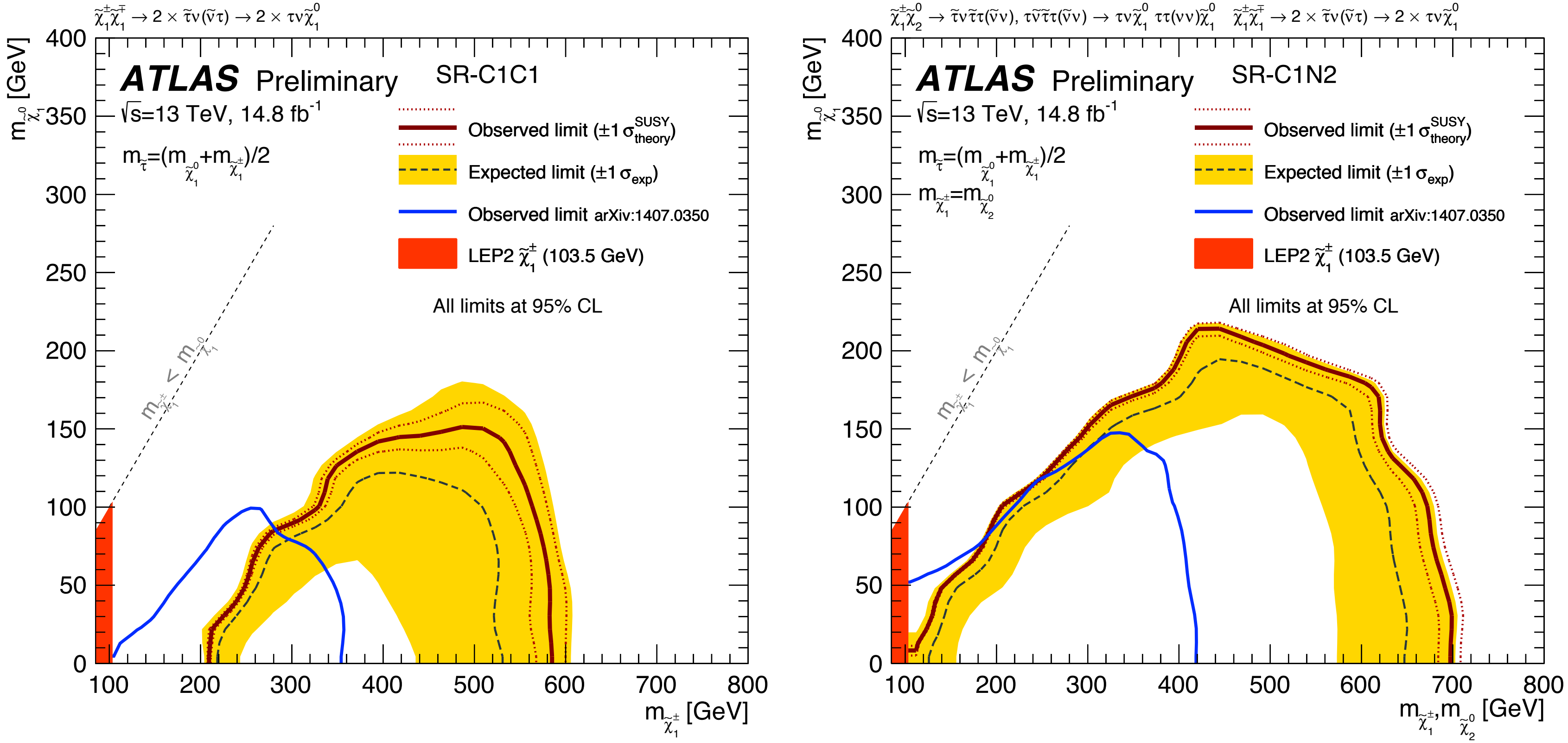
Weak constraints for di-lepton channel, make that channel dominant



Main constraint: trilepton search for EW-ino compressed region, winos around 300 GeV can be allowed

How to hide the light stops?





Constraints can be further lowered with a light stau

~ 200 GeV possible

Implications on Double Higgs – Decay channels

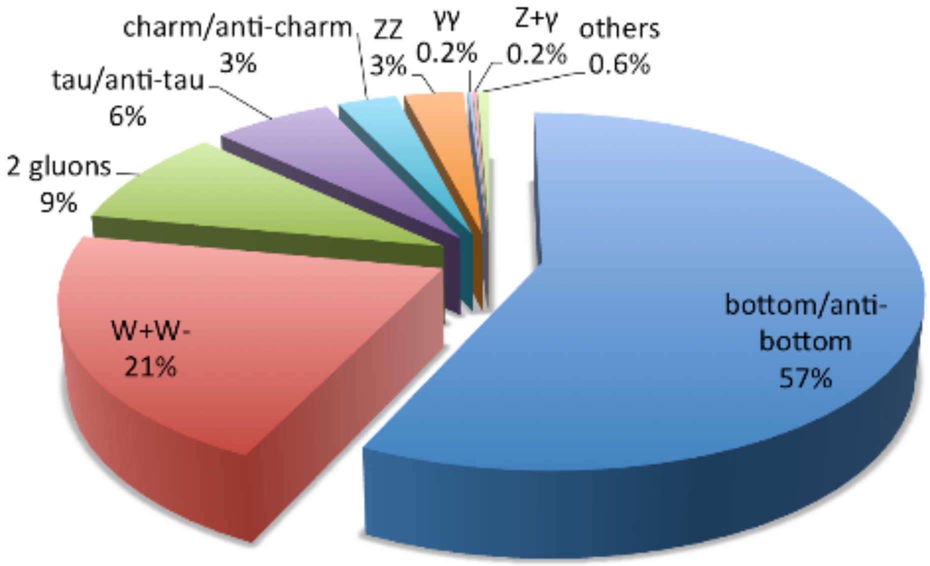
- Decay of one 

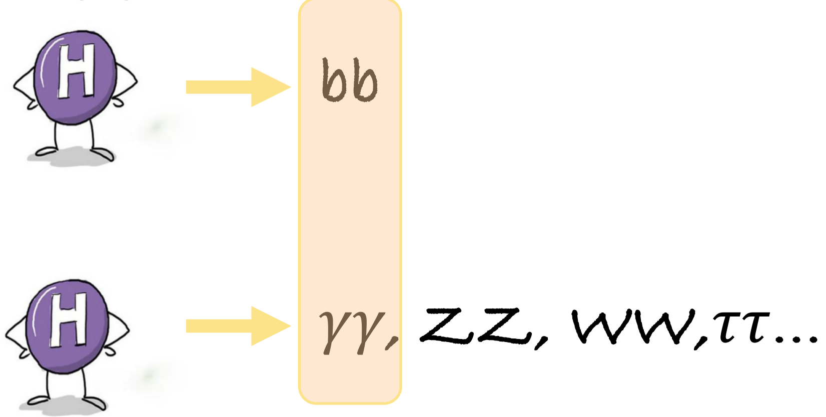
bb : large branching ratio, large background

ZZ->4l, $\gamma\gamma$: clean, low branching ratio

WW, $\tau\tau$: hard, missing energy, measured for a single Higgs

Decays of a 125 GeV Standard-Model Higgs boson

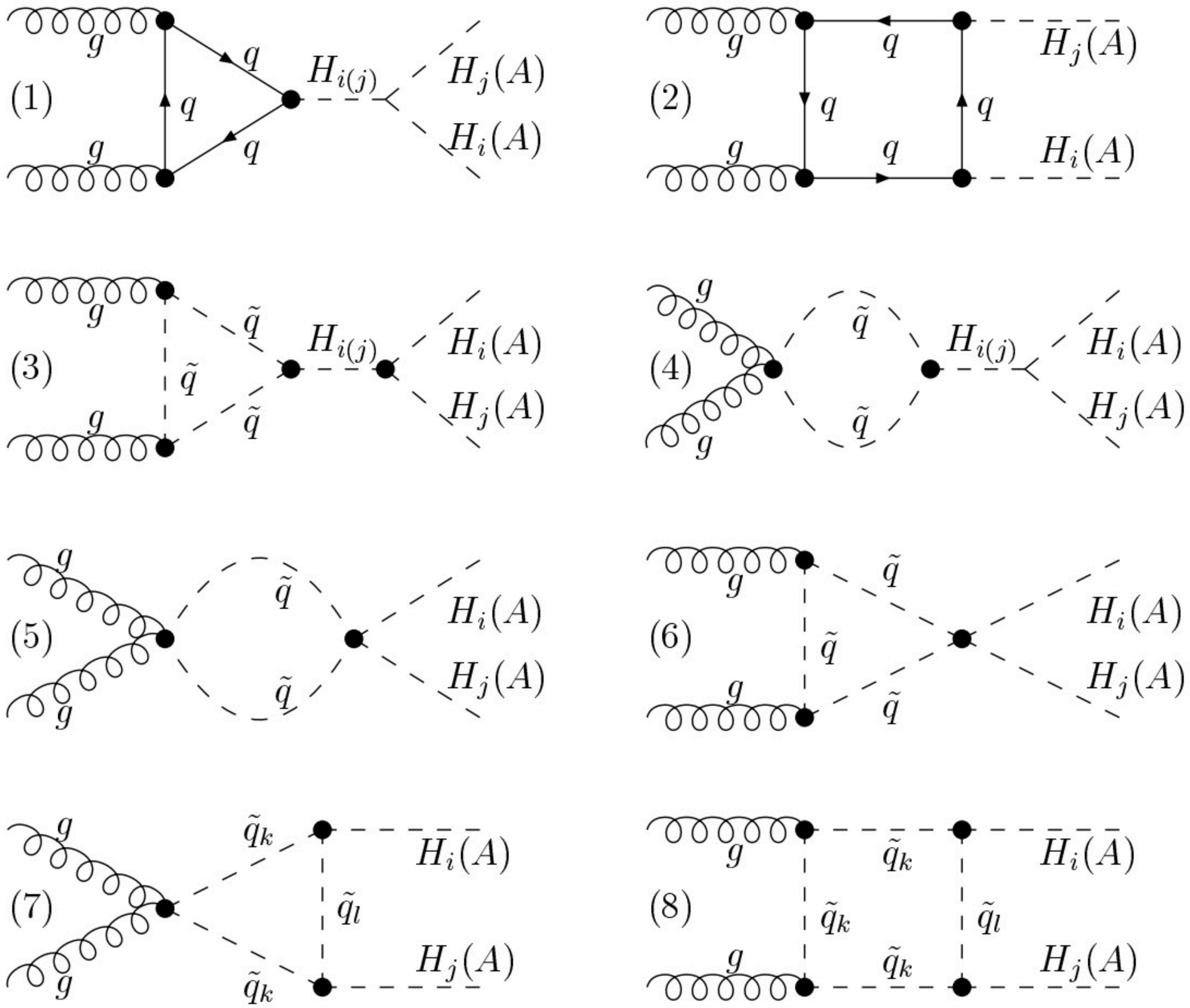




bb

$\gamma\gamma$, ZZ, WW,$\tau\tau$...

Double Higgs : production



Sum of the two diagrams on each line is gauge invariant

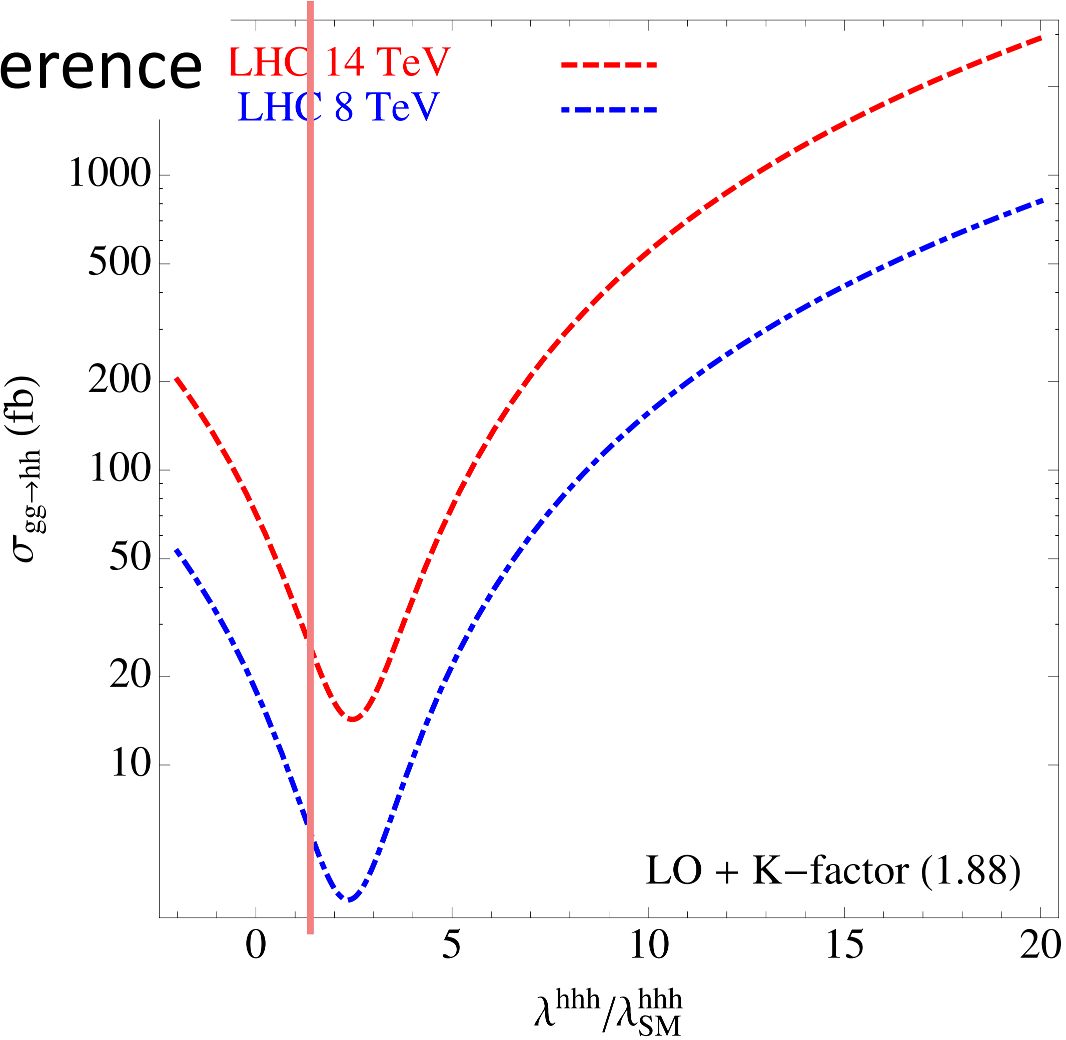
SM, interface with each other destructively

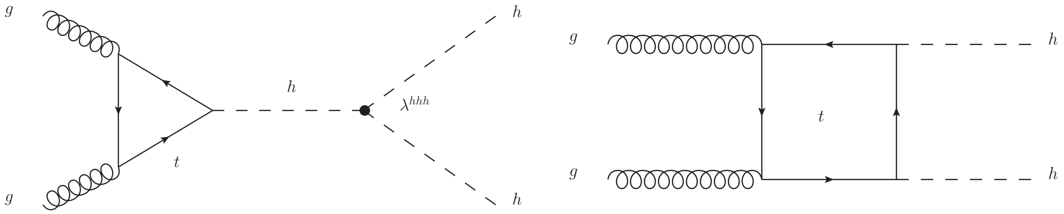
- Stop contribution without mixing is small enough in the current stop limit
- (7)+(8) dominates the stop contribution

Double Higgs : production

constructive interference

destructive interference



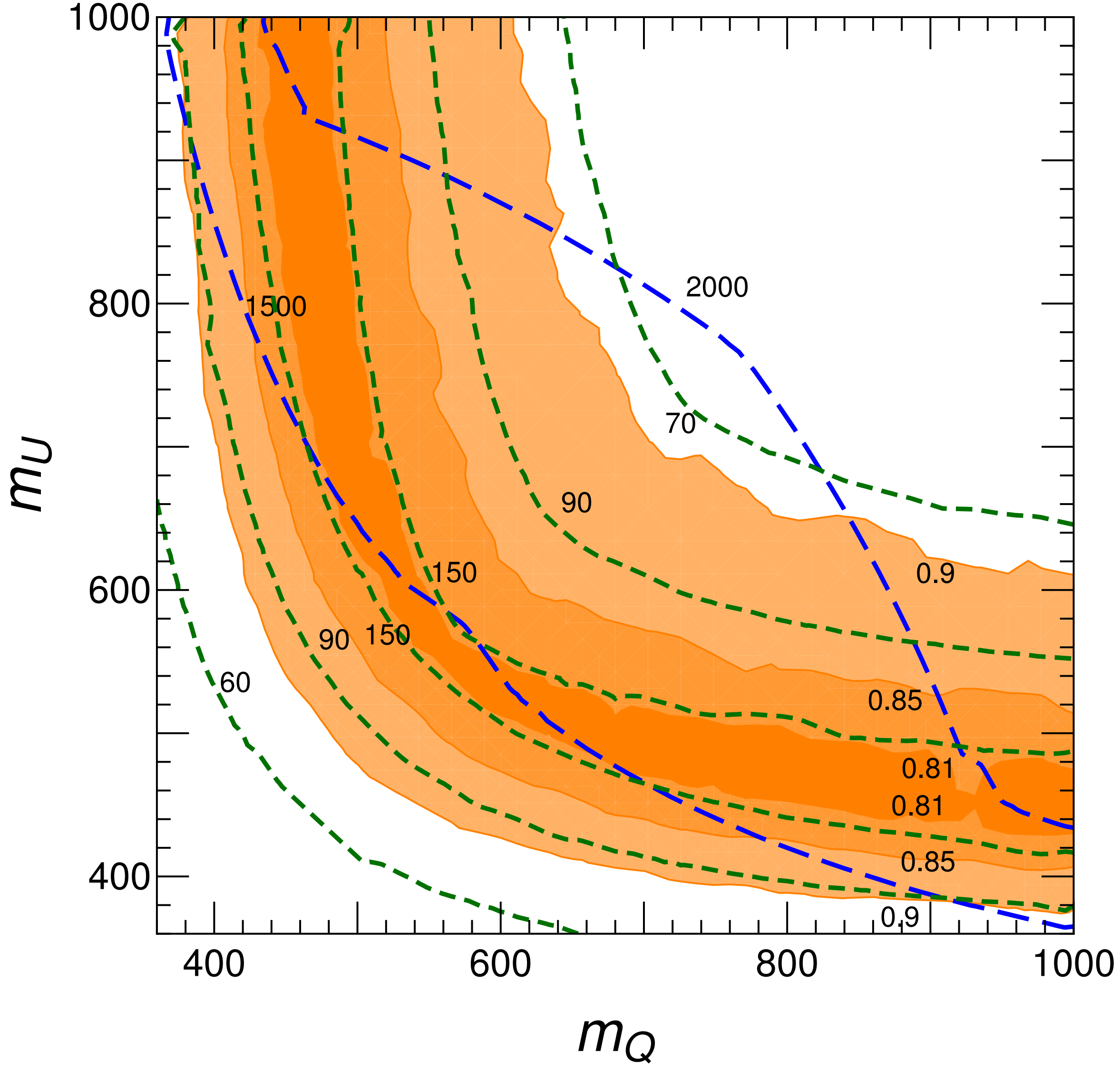


$\lambda_3 < 2\,\lambda_3^{SM}$ box diagram dominates

$\lambda_3 \sim 2\text{-}3\,\lambda_3^{SM}$ box and triangle diagram are comparable

$\lambda_3 > 3\,\lambda_3^{SM}$ triangle diagram dominates

large modification in double Higgs

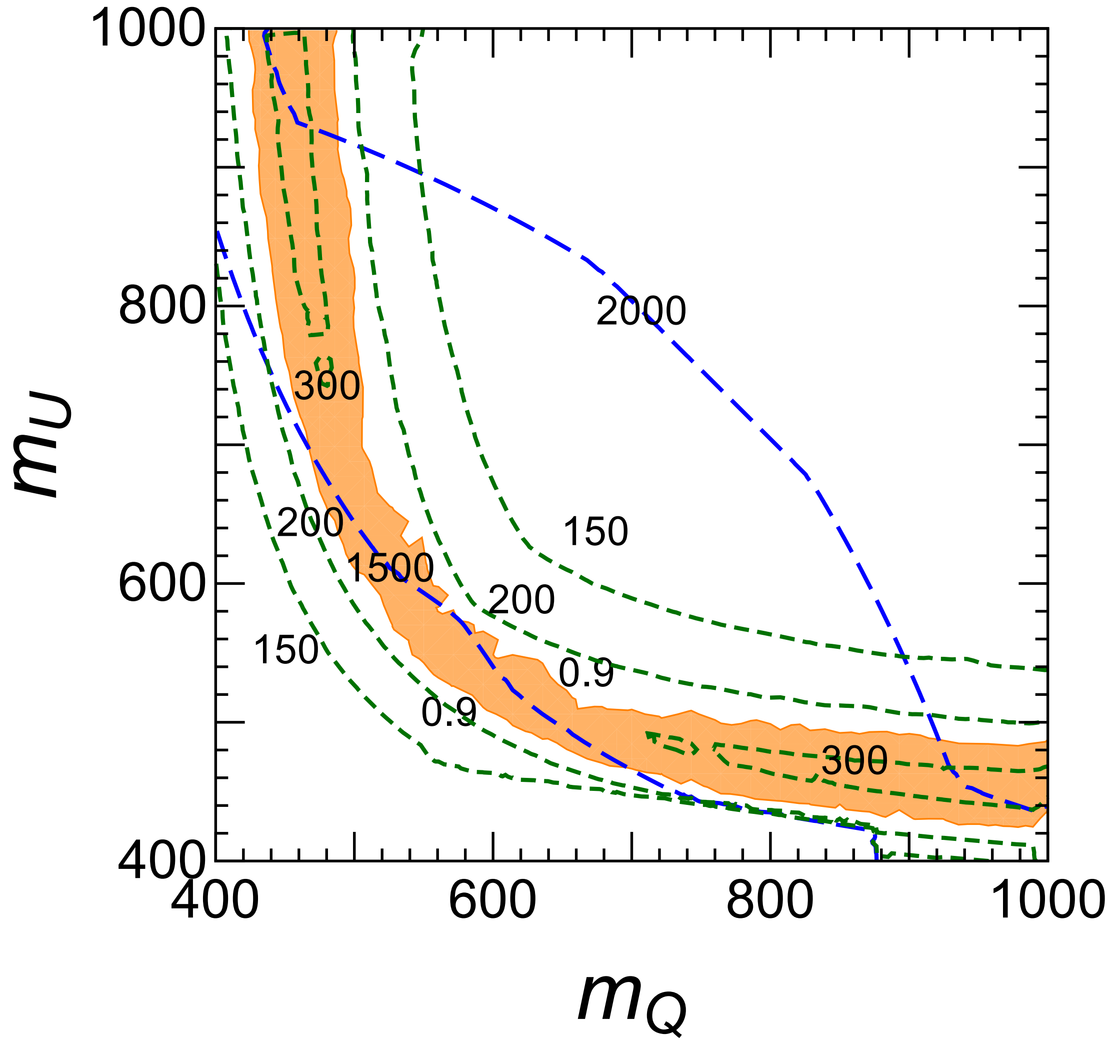


- Without enhanced top coupling
- dark orange, effective gluon Higgs coupling is consistent with current best fit within 1σ
- light orange, consistent with the current best fit within 2σ
- Maximum Xt allowed
- cross section for pp->hh->bb$\gamma\gamma$ (SM value 60ab)

Double Higgs can be at least twice the SM value

work in progress with Joglekar, Li, and Wagner

large modification in double Higgs

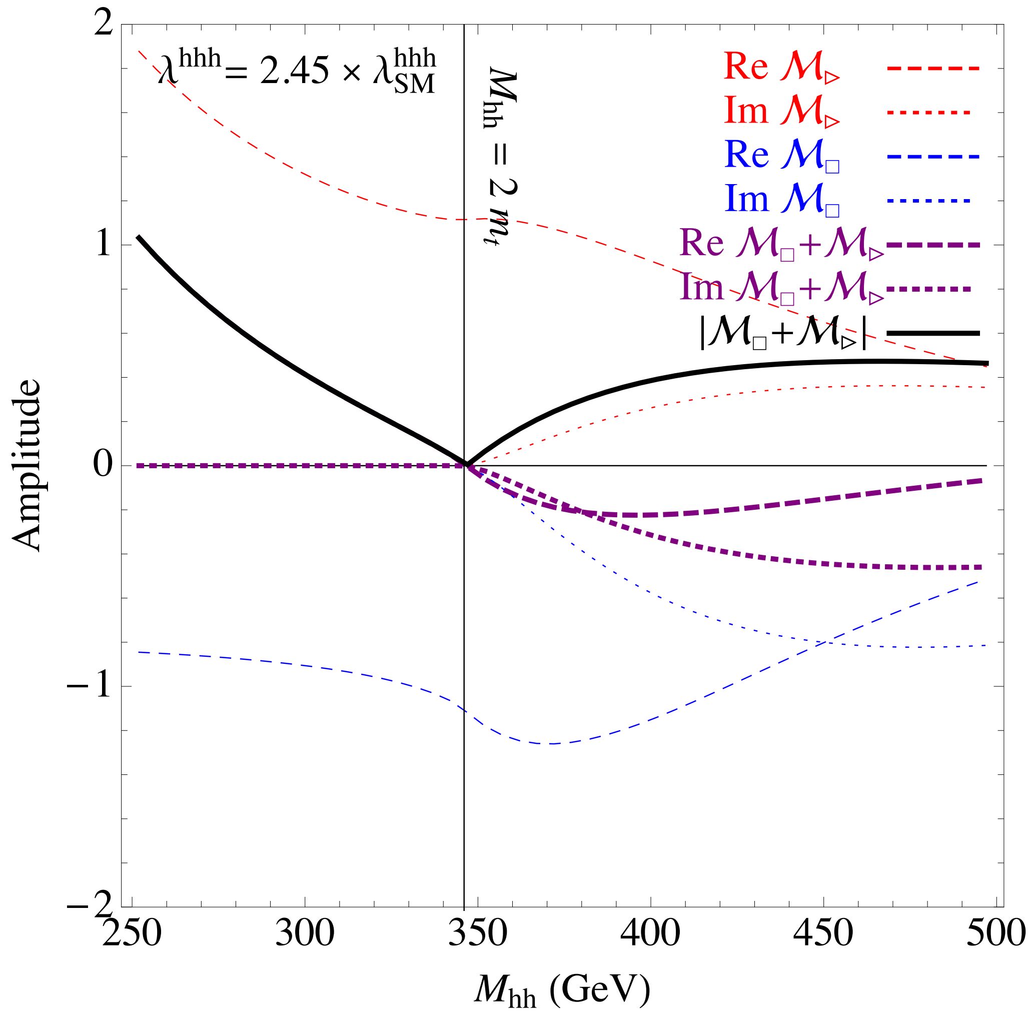


- $\kappa_t = 1.1$
- orange, consistent with current best fit within 2σ
- cross section for pp->hh->bb$\gamma\gamma$ (SM value 60ab)
- Maximum Xt allowed

Double Higgs can be about five times the SM value

work in progress with Joglekar, Li, and Wagner

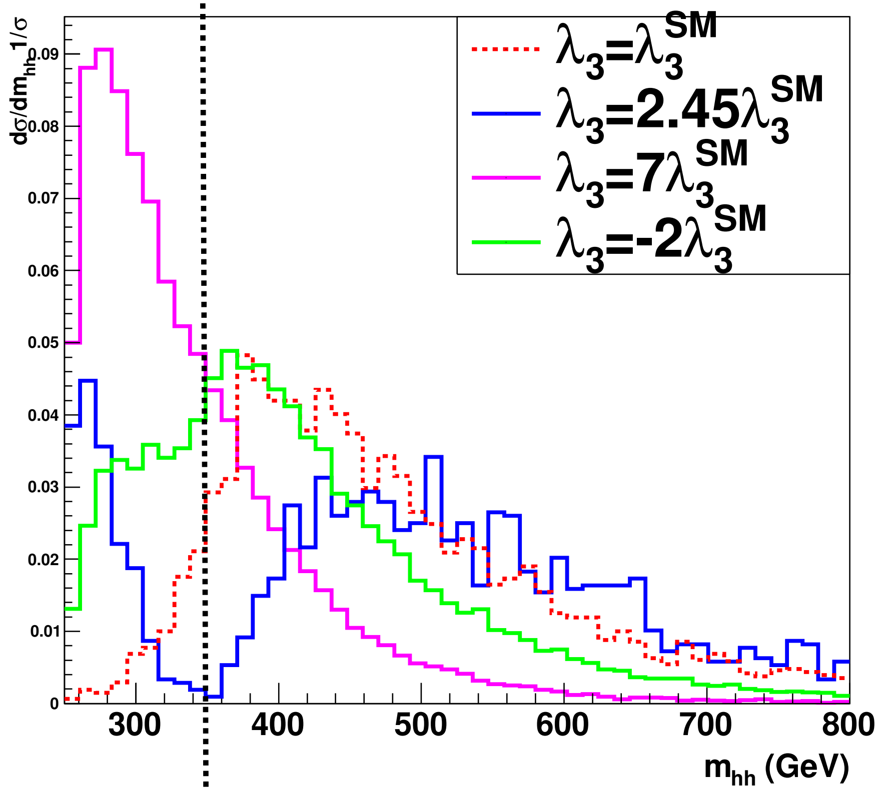
Kinematic Distributions : λ_3



- The destructive interference occurs between the real part of the triangle and the box diagrams
- Above the tt threshold, the amplitudes develop imaginary parts, the cancellation does not occur
- When λ_3 increases, the amplitudes increases more below the tt threshold than above the threshold
- m_{hh} shifts to smaller value for large λ_3

Barger, Everett, Jackson, and Shaughnessy

Kinematic Distributions : λ_3

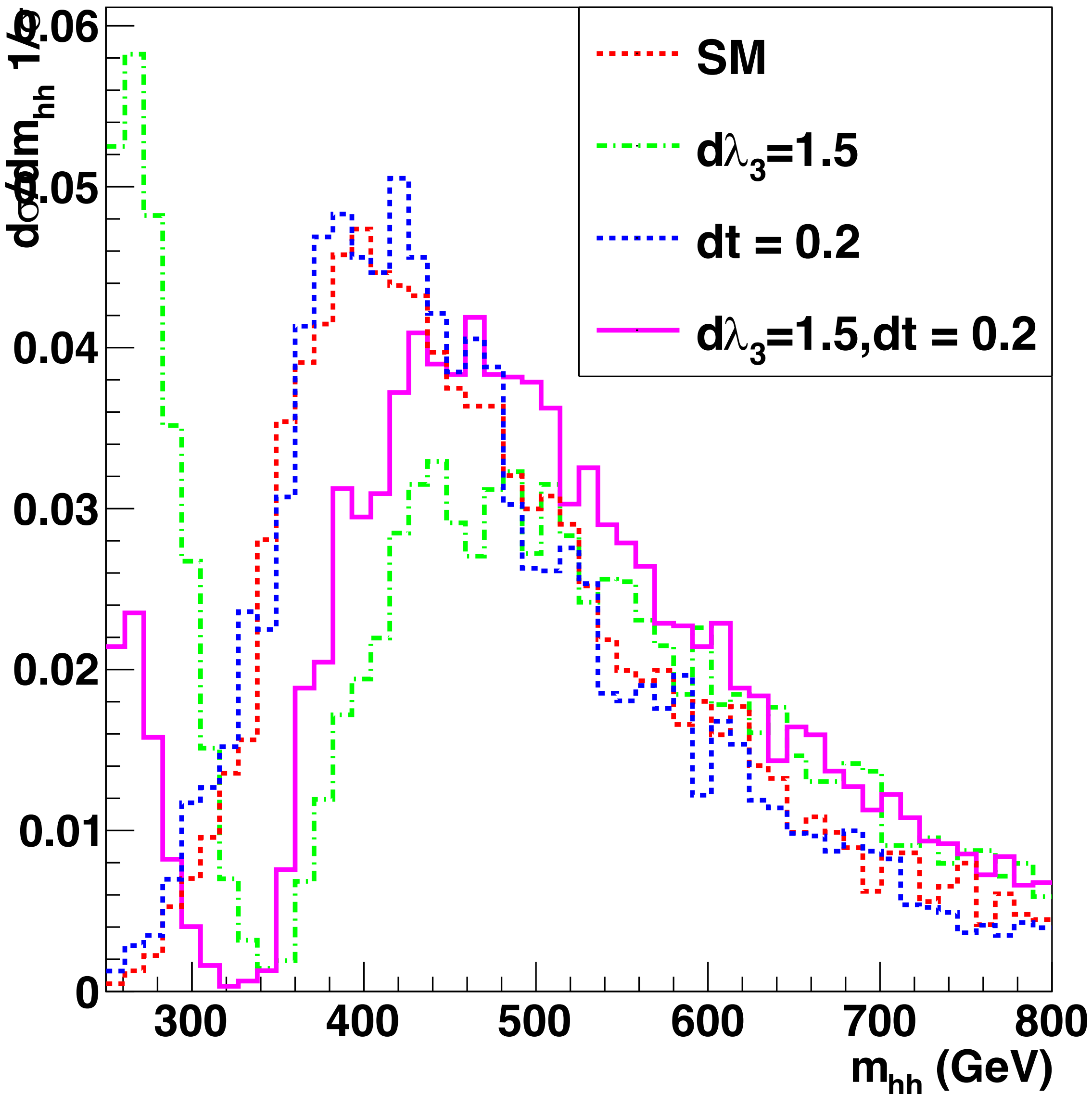


$\lambda_3 > 3\lambda_3^{SM}$, m_{hh} distribution is much softer than the SM case

- Re-design the cuts for large λ^3
- The distribution can be used to distinguish λ^3 that have the same production cross sections (maybe for future colliders).

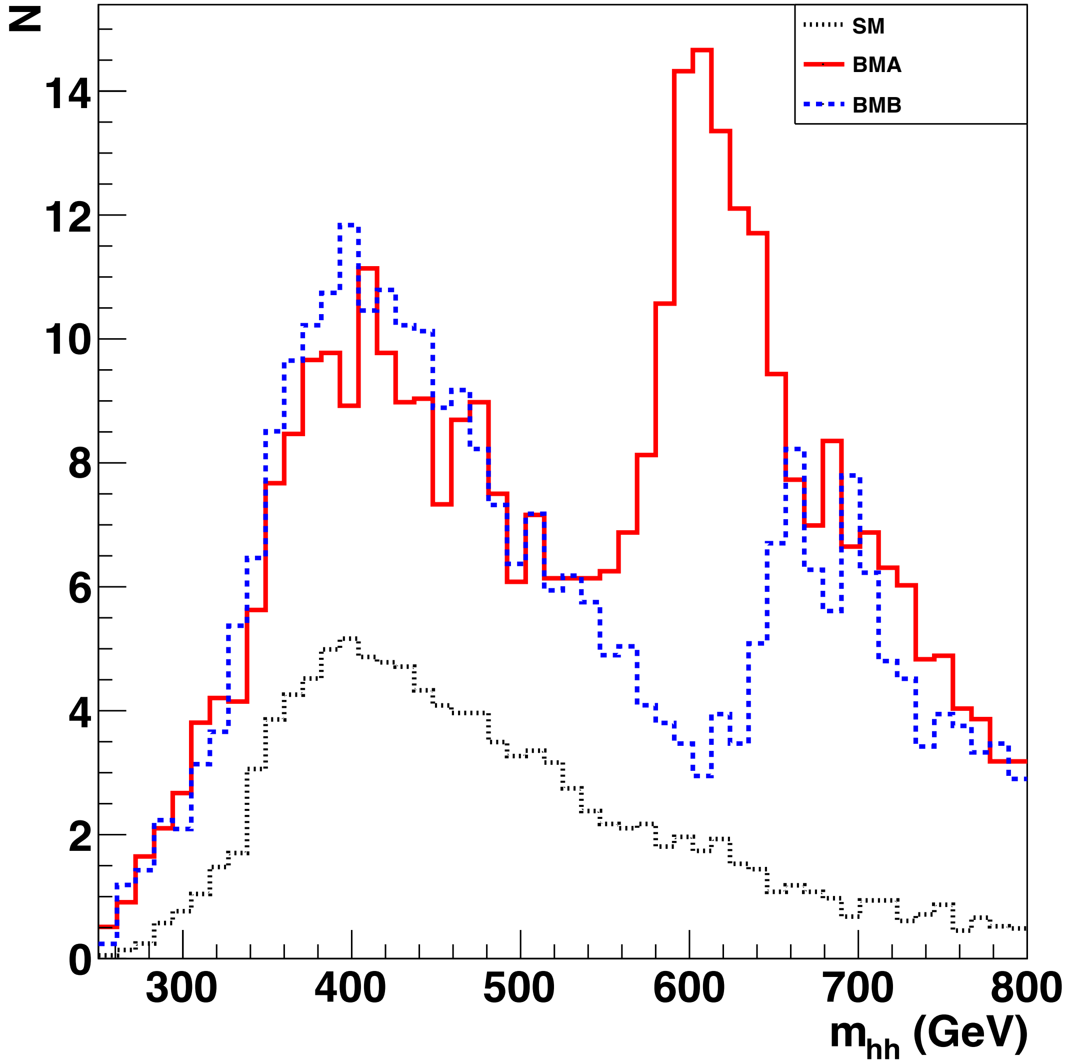
PH, A. Joglekar, B. Li, and C. Wagner, arxiv:1512.00068

Kinematic Distributions : λ_3, κ_t



- κ_t does not change the distribution for the SM
- When the triangle diagram and the box diagram are comparable ($\lambda_3 \sim 3\,\lambda_3^{SM}$), κ_t changes the location of the complete cancellation

Kinematic Distributions : stops



BMA:

$m_{\tilde{t}_1} = 300$ GeV, $m_{\tilde{t}_2} = 1$ TeV
$X_t = 1.5$ TeV, $\kappa_t = 1$, $\kappa_g = 0.8$
$\sigma_{hh \to bb\gamma\gamma} = 0.19$ fb

BMB, same as BMA, but

$\kappa_t = 1.1$, $\kappa_g = 0.9$
$\sigma_{hh \to bb\gamma\gamma} = 0.16$ fb

Collider study

$$p_t(b) > 30\text{ GeV}, |\eta(b)| < 2.5,\ p_t(\gamma) > 30\text{ GeV}, |\eta(\gamma)| < 2.5$$

$$112.5\text{ GeV} < m_{bb} < 137.5\text{ GeV},\ 120\text{ GeV} < m_{\gamma\gamma} < 130\text{ GeV}.$$

$$n_{lep} + n_{jet} < 4$$

$\lambda^3 < 3\lambda^3_{SM}$, $m_{hh} > 350$ GeV

$\lambda^3 > 3\lambda^3_{SM}$, 250 GeV < m_{hh} < 350 GeV

λ_3	λ_3^{SM}	$5\lambda_3^{SM}$	$7\lambda_3^{SM}$	$9\lambda_3^{SM}$	0	-λ_3^{SM}	-2 λ_3^{SM}
$S/\sqrt{B}$	3.3	2.1	6.0	11	4.4	7.5	9.8

14 TeV and 3000 fb $^{-1}$

0.7 σ for $\lambda^3 \sim 5\lambda^3_{SM}$ if using the cut m_{hh} > 350 GeV

5 σ for $\lambda^3 \sim 6.5\lambda^3_{SM}$, or $\lambda^3 \sim -0.2\ \lambda^3_{SM}$

arxiv:1512.00068 PH, A. Joglekar, B. Li, and C. Wagner

Collider study

$$p_t(b) > 30\ \mathrm{GeV}, |\eta(b)| < 2.5,\ p_t(\gamma) > 30\ \mathrm{GeV}, |\eta(\gamma)| < 2.5$$

$$112.5\ \mathrm{GeV} < m_{bb} < 137.5\ \mathrm{GeV},\ 120\ \mathrm{GeV} < m_{\gamma\gamma} < 130\ \mathrm{GeV}.$$

$$n_{lep} + n_{jet} < 4$$

$\lambda^3 < 3\lambda^3_{SM}$, $m_{hh} > 350$ GeV

$\lambda^3 > 3\lambda^3_{SM}$, 250 GeV < m_{hh} < 350 GeV

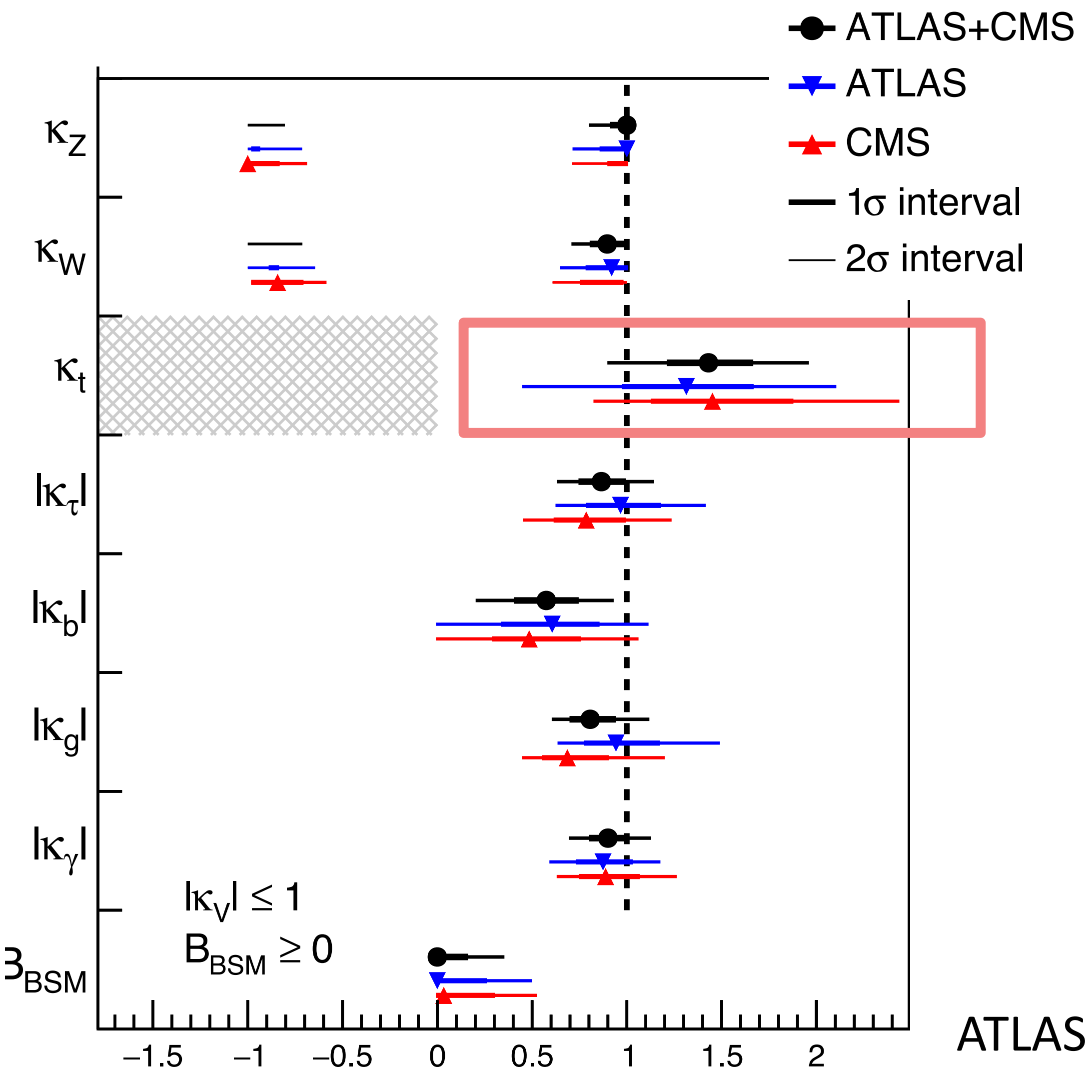
λ_3	λ_3^{SM}	$3\ \lambda_3^{SM}$	$5\ \lambda_3^{SM}$
$S/\sqrt{B}$	11	4.5	5.3

100 TeV, 3000 fb^{-1}

5 σ for $\lambda^3 \sim 5\lambda^3_{SM}$, or $\lambda^3 \sim 1.6\ \lambda^3_{SM}$

arxiv:1512.00068 PH, A. Joglekar, B. Li, and C. Wagner

Current Higgs Profile



ATLAS and CMS, 1606.02266

Interpretations

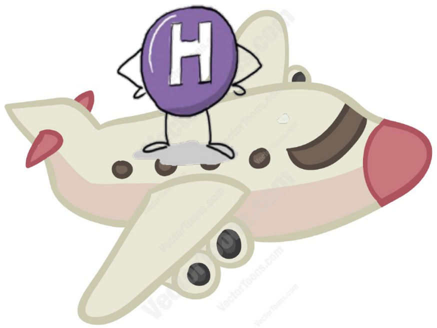
- Stop pair production

PH, A. Ismail, I. Low, C. Wagner, 1507.01601

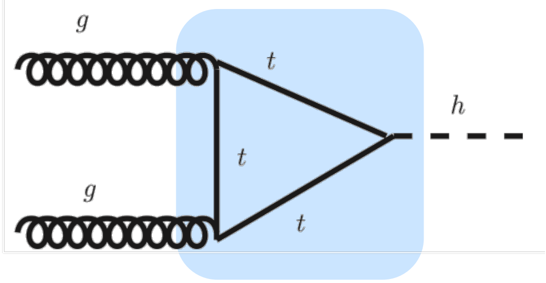
- Enhanced htt coupling + new physics. The new loop particles compensate the enhanced htt coupling to keep gluon fusion SM-like
- The new physics will show up in double Higgs production.

backup

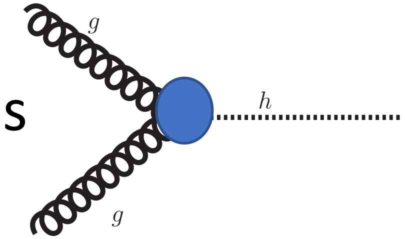
Boosted Higgs



In the boosted region

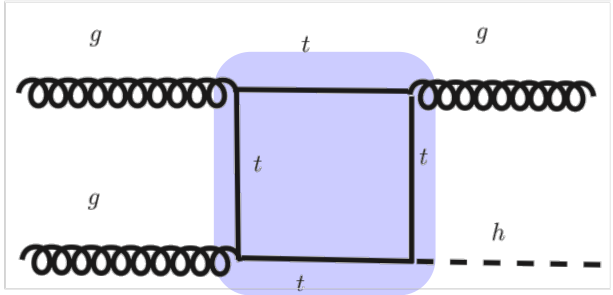


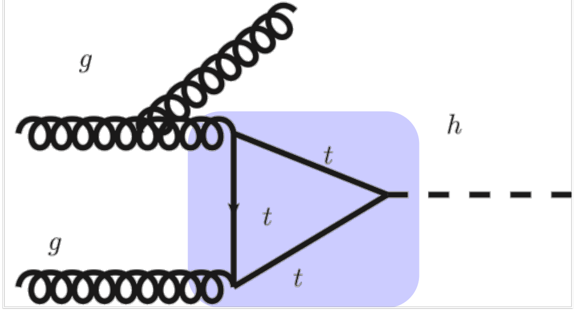
can not be treated as



Above $p_T(h) \sim m_t$, expect full theory and EFT diverge

Sensitive to possible new loop particles





Expect that the p_T distributions change for different loop particles, helps to resolve the degeneracy in gluon fusion

Current signal strength on gluon fusion

Inclusive: $\mu = 1.13^{+0.18}_{-0.17}$