Signal-background interference effects in heavy scalar production and decay to a top–anti-top pair

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2) Interference features
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5) 750 GeV diphoton excess

1) Introduction

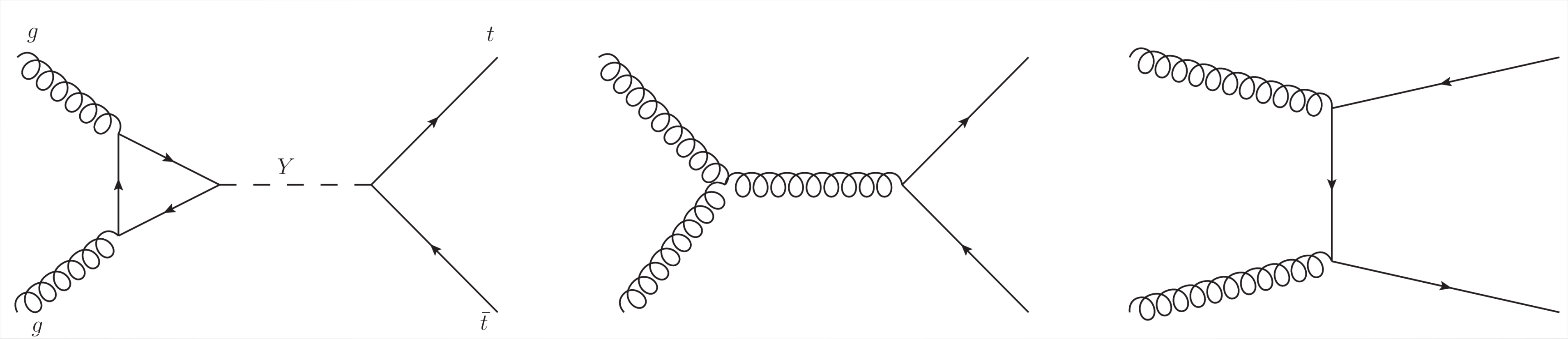
- Top quark: a interesting possibly window on new physics (Bargen et al hep-ph/0612016)
- Main production mode is gg → tt
- Many experimental searches interpreted as σ_{signal}*BR (CMS arXiv:1309.2030, ATLAS arXiv:1505.07018)
- However interference should be taken into account:
  - Heavy state resonance bump in the mtt distribution can be turned into a peak-dip structure instead (Dicus, Stange, Willenbrock hep-ph/9404359)
- Interference between signal/background is colour suppressed @LO in QCD
- But maybe this is no longer the case @NLO QCD due to gluons exchange

1) Models under consideration

$$\mathcal{L} = \bar{t}\frac{y^t}{\sqrt{2}}(g_t^S + i g_t^P \gamma^5) t\, Y,$$

- 1) First step: generic simplified model
  - 1 Generic top-philic state Y (pure scalar, pseudo or mixed)
  - 4 params: m_Y, Γ_Y ,g_t^S,g_t^P
- 2) Second step: UV complete model: 2HDM
  - CP-conserving
    - 5 physical states: h, H, A(,H+,H-)
    - 7 params: m_h,m_H,m_A,m_{H+},tan(β), sin(β-α),(m_{12}^2)
  - 4 still-alive-benchmarks considered and detailed later

1) Top pair production with heavy scalars



- Very large QCD background (pp → tt) known at NNLO QCD and NLO EW
- Signal amplitude (gg → Y → tt) is proportional to $(g_t y_t)^2$

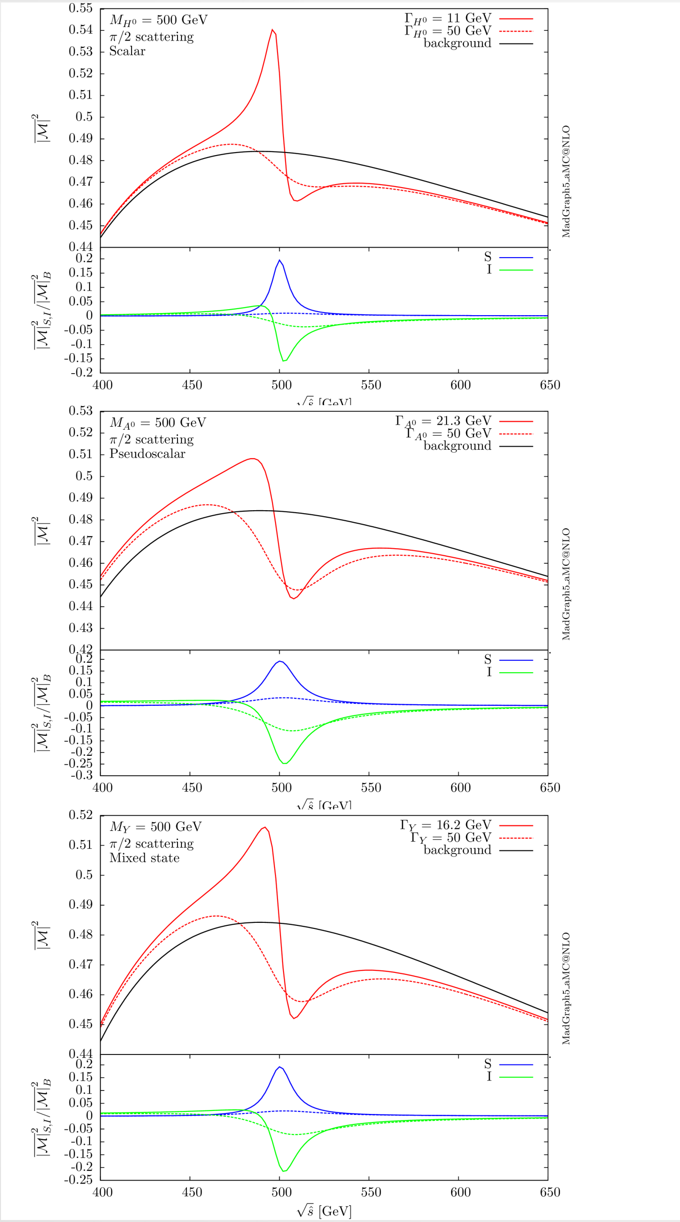
  → insensitive to sign of g_t if no additional particle in the loop
- Large signal if $m_Y > 2m_t$ and $g_t > 1$ will drive our benchmark design

2) Amplitude squared level

Scalar

Pseudo

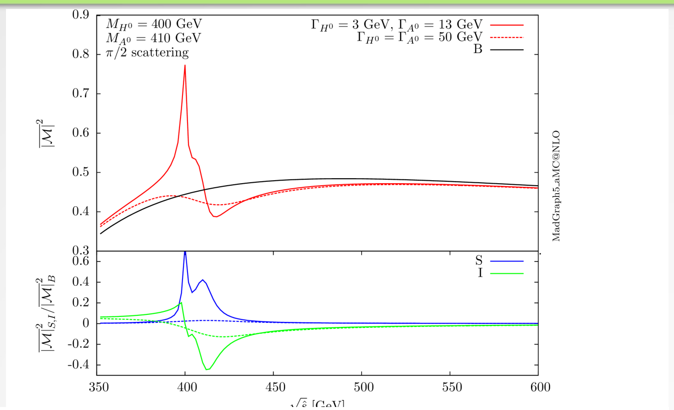
Mixed



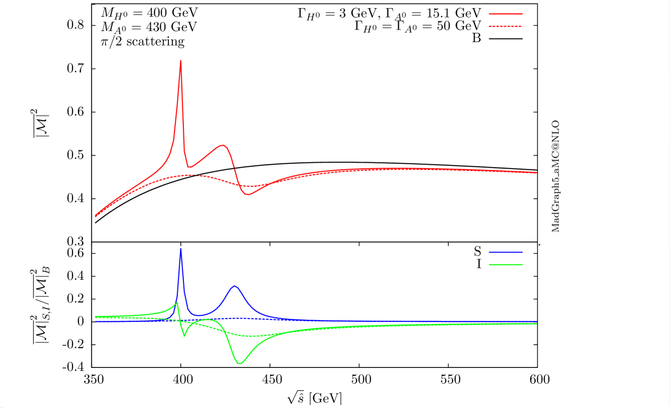
- 90° scattering
- 2 widths:
  - *Minimal one* (computed @LO)
  - *Larger one* fixed to 50 GeV to allow Y to couple to additional unknown particles (DM, ...)
- Interference can be as large as signal but negative
- When Γ_Y increases → peak-dip becomes a global wide dip
- Pseudoscalar peak is bigger than scalar one

2) Amplitude squared level – 2 states

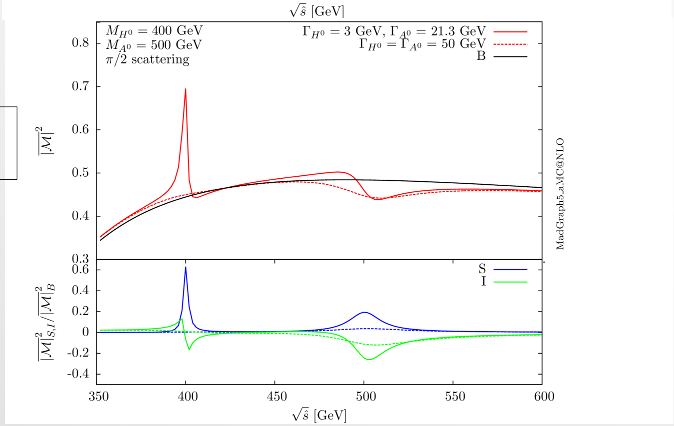
Δm=10 GeV



Δm=30 GeV

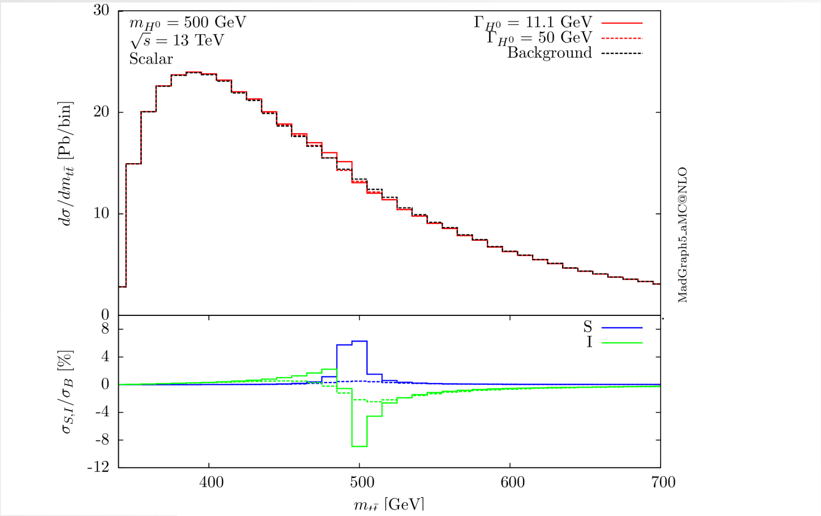


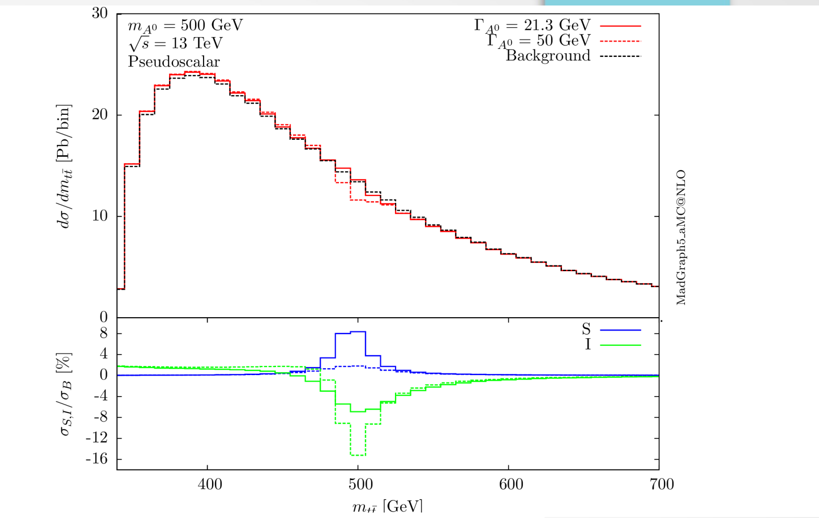
Δm=100 GeV



- 90° scattering
- 2 widths:
  - *Minimal one* (computed @LO)
  - *Larger one* fixed to 50 GeV to allow Y to couple to additional unknown particles
- 2HDM-like scenarios: 1 pure scalar H, 1 pure pseudo A
- For Δm =10 GeV → impossible to disentangle between the 2 states
- In practice this is driven by experimental resolution

2) Leading order differential results





	Scalar		Pseudoscalar	
Width	$\Gamma_{min} = 11.1$ GeV	$\Gamma = 50$ GeV	$\Gamma_{min} = 21.3$ GeV	$\Gamma = 50$ GeV
Signal	2.38	0.47	4.54	1.81
Interference	-1.27	-1.25	-2.19	-2.50

- For comparison:
  - σ_{QCD} = 498.1 pb
  - $\sigma_{h\text{-}QCD}$=- 0.90 pb
  - σ_{Higgs}=0.022 pb

- Large widths → interference dominates over signal
- Dip instead of peak

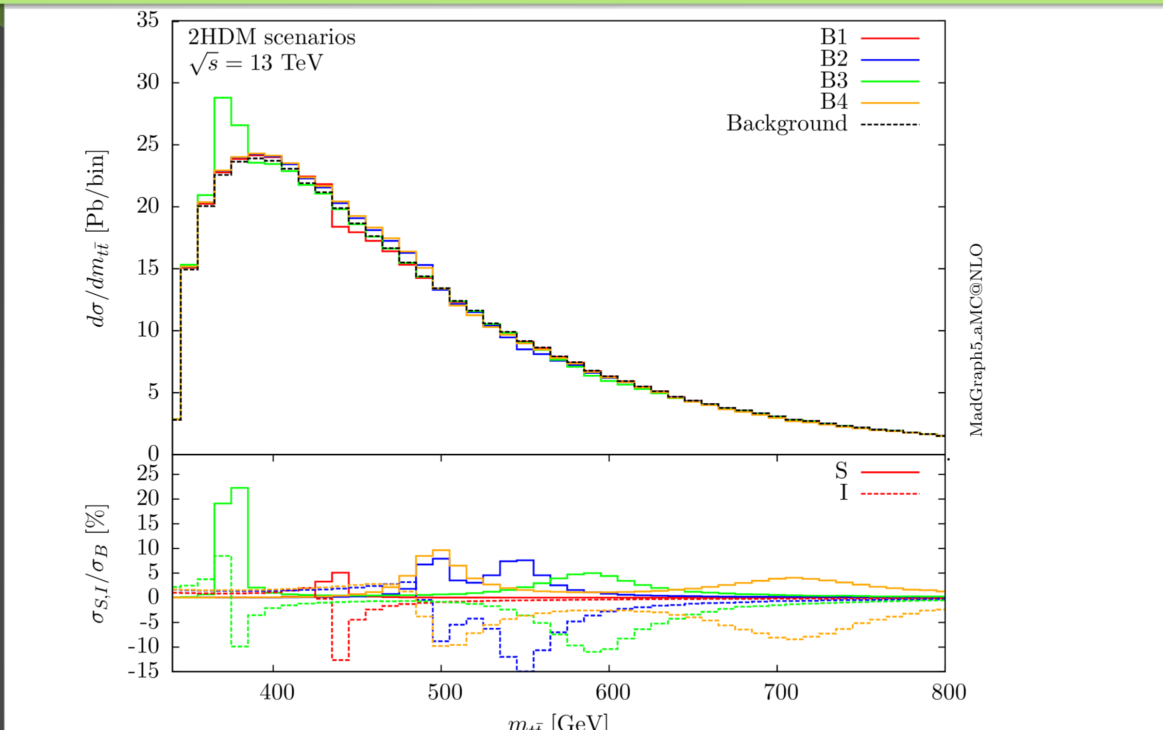
2) 2HDM benchmarks

	$\tan\beta$	α/π	m_{H^0}	m_{A^0}	$m_{H^\pm}$	m_{12}^2
B1	1.75	-0.1872	300	441	442	38300
B2	0.9	-0.267	500	550	620	10000
B3	0.7	-0.306	380	590	610	10000
B4	0.6	-0.328	500	710	720	10000

	$\hat{g}_{h^0tt}$	$\hat{g}_{H^0tt}$	$\hat{g}_{A^0tt}$	Γ_{H^0} (GeV)	$BR(H^0 \to t\bar{t})$	Γ_{A^0} (GeV)	$BR(A^0 \to t\bar{t})$
B1	0.96	-0.64	0.57	0.138	0.0	7.20	0.723
B2	1.00	-1.11	1.11	13.75	0.9997	29.97	0.9997
B3	1.00	-1.43	1.43	3.39	0.9989	64.57	0.849
B4	1.00	-1.67	1.67	30.93	0.9998	105.23	0.896

- Type II 2HDM considered (because tan(β) < 1 discarded for type I)
- g_t increases when tan(β) decreases
- Viability checked via 2HDMC, SuperIso, HiggsSignals, HiggsBounds
- B1: only non-resonant scalar

2) 2HDM LO results

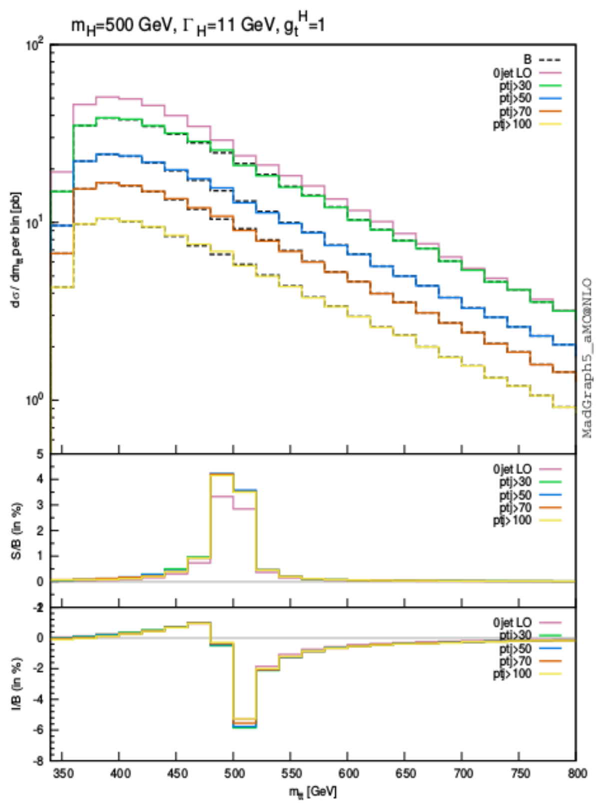


- B1: dip only
- B2: wide peak for scalar, wide dip for pseudo
- B3: large peak due to narrow width H resonance
- B4 mild deviation due to very large widths

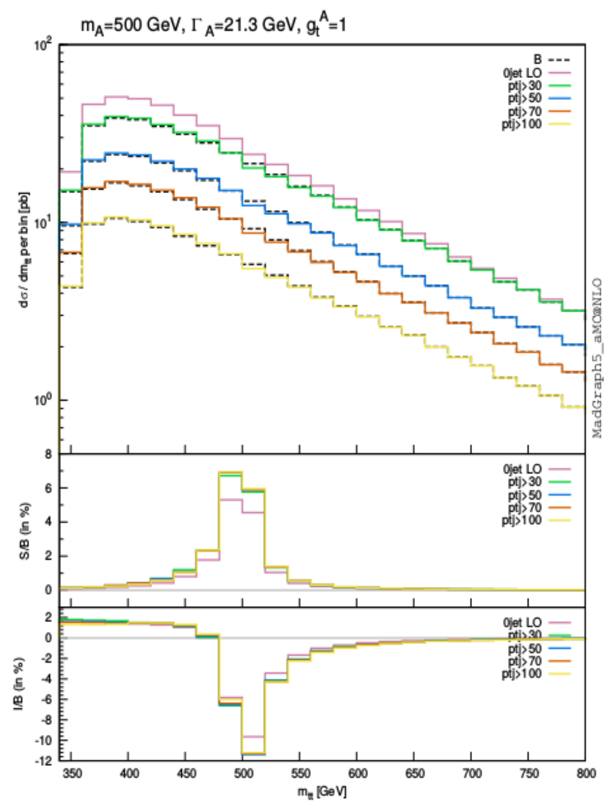
Benchmarks	Total	Signal		Interference	
		Scalar	Pseudoscalar	Scalar	Pseudoscalar
B1	$497.05^{+31.7\%}_{-22.7\%}$	$0.01^{+32.7\%}_{-23.1\%}$	$2.13^{+32.2\%}_{-22.8\%}$	$-0.62^{+32.4\%}_{-23.0\%}$	$-1.78^{+33.7\%}_{-23.6\%}$
B2	$501.01^{+31.8\%}_{-22.7\%}$	$2.90^{+33.0\%}_{-23.3\%}$	$3.51^{+33.5\%}_{-23.5\%}$	$-1.55^{+34.9\%}_{-24.3\%}$	$-1.09^{+40.6\%}_{-27.1\%}$
B3	$503.96^{+32.3\%}_{-23.2\%}$	$10.86^{+31.3\%}_{-22.4\%}$	$3.35^{+33.8\%}_{-23.7\%}$	$-6.56^{+32.2\%}_{-22.9\%}$	$-1.15^{+42.4\%}_{-28.0\%}$
B4	$502.06^{+31.9\%}_{-22.8\%}$	$6.19^{+33.0\%}_{-23.3\%}$	$1.85^{+34.6\%}_{-24.1\%}$	$-3.53^{+34.7\%}_{-24.1\%}$	$0.30^{+67.6\%}_{-56.0\%}$

3) Higher-order QCD effects: 1 jet distribution

Scalar

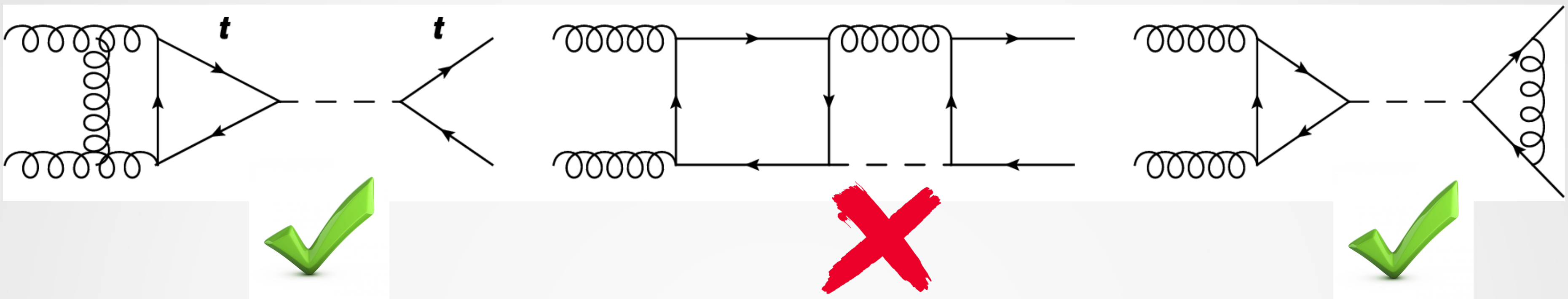


Pseudo



- Could color suppression be lifted by additional radiation?
  - No significant increase is found
  - Whatever jet cut
- → ISR dominates

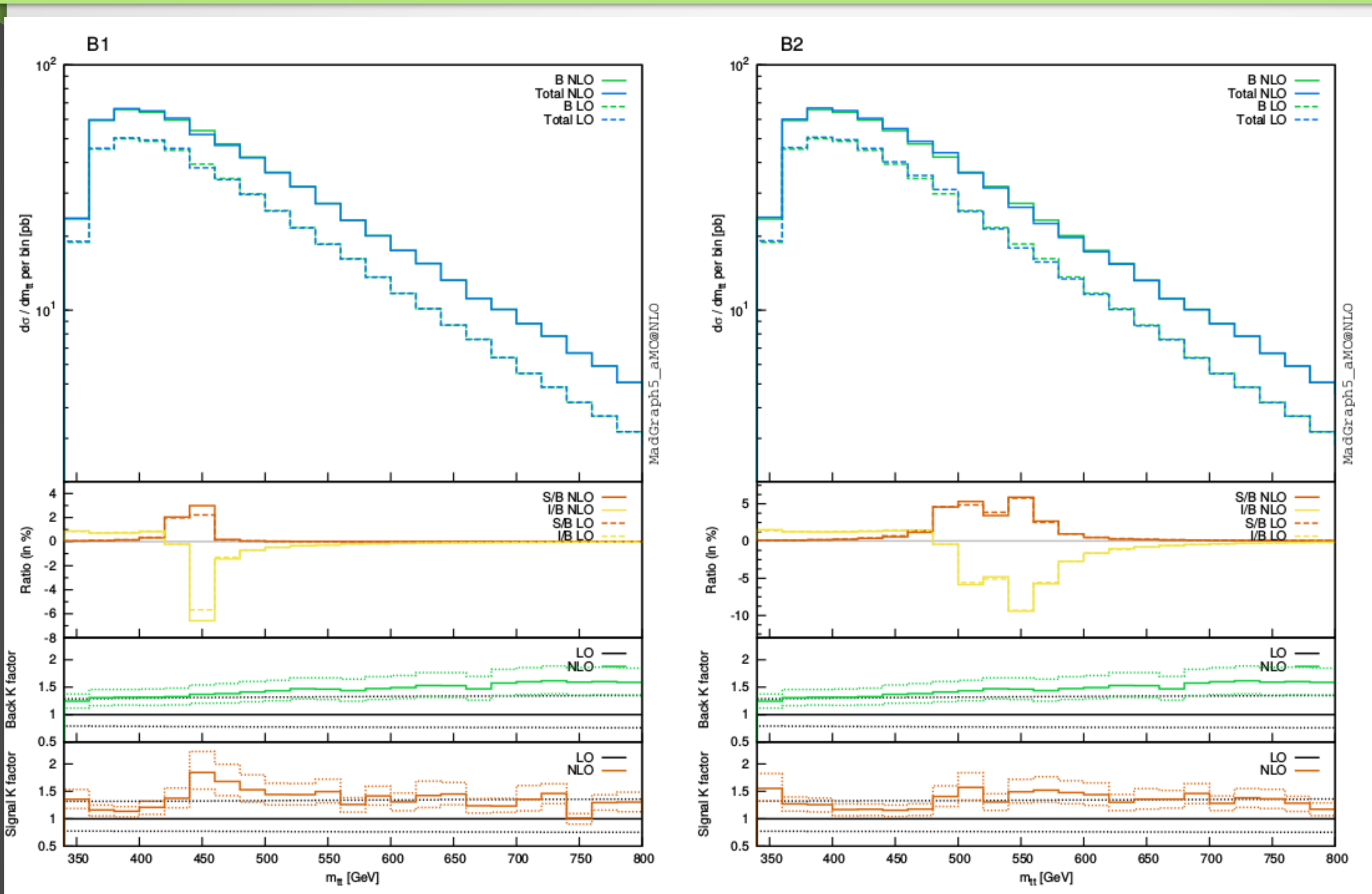
3) NLO results



- Virtual NLO corrections to signal in the initial (extracted from SusHi [Harlander, Liebler, Mantler arXiv:1212.3249], aMCSusHi [Mantler, Wiesemann arXiv:1504.0662] and final states ([Djouadi, Spira et al hep-ph/9504378]) are well known.
- BUT The corrections connecting initial and final states are **NOT** → impossible to have full NLO interference
  - We will use LO interference * $(K_s K_B)^{1/2}$

$$\sigma_{NLO} = \sigma_{NLO}^{back} + \sigma_{NLO}^{signal} + \sigma_{LO}^{inter}\sqrt{K_S K_B}\,,$$

3) 2HDM NLO results



Benchmark	Signal	K_S	Interference: $\sqrt{K_S K_B}\,\sigma_{LO}^{inter}$
B1	$3.31^{+16.8\%}_{-14.3}$	1.55	$-3.00^{+30.7\%}_{-22.4\%}$
B2	$9.02^{+13.7\%}_{-13.0}$	1.41	$-3.53^{+34.3\%}_{-24.1\%}$
B3	$25.37^{+20.0\%}_{-16.0}$	1.79	$-9.32^{+32.6\%}_{-24.1\%}$
B4	$11.51^{+14.3\%}_{-13.3\%}$	1.43	$-4.23^{+38.8\%}_{-30.1\%}$

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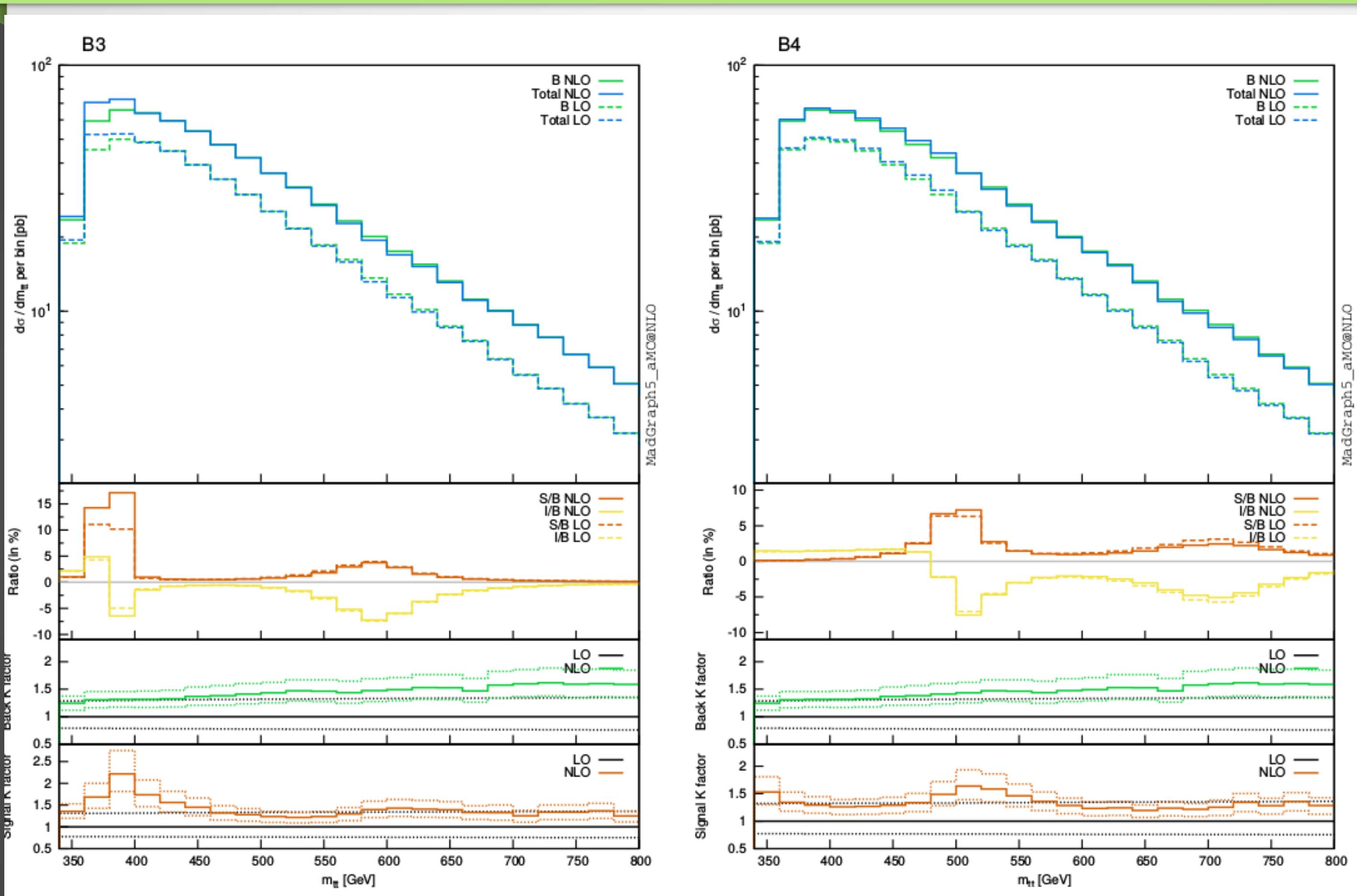

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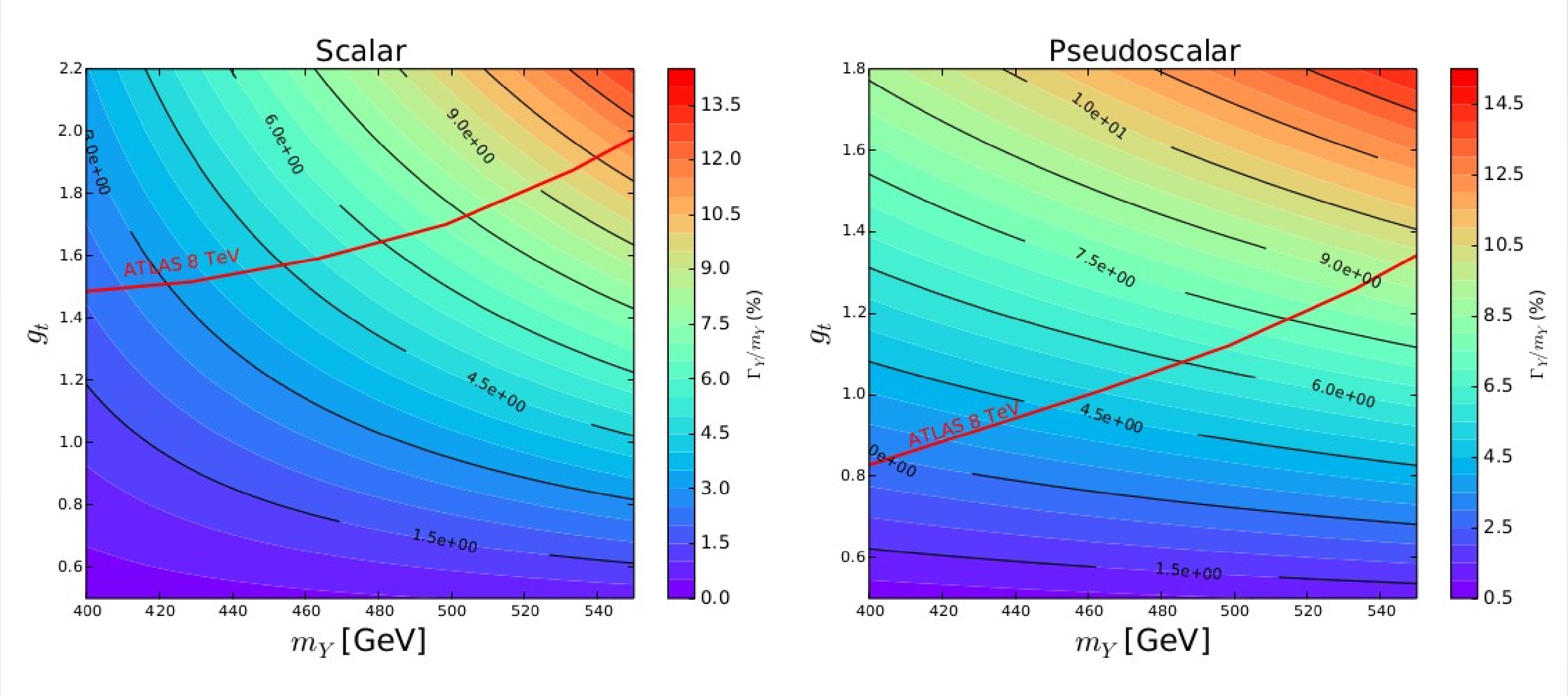
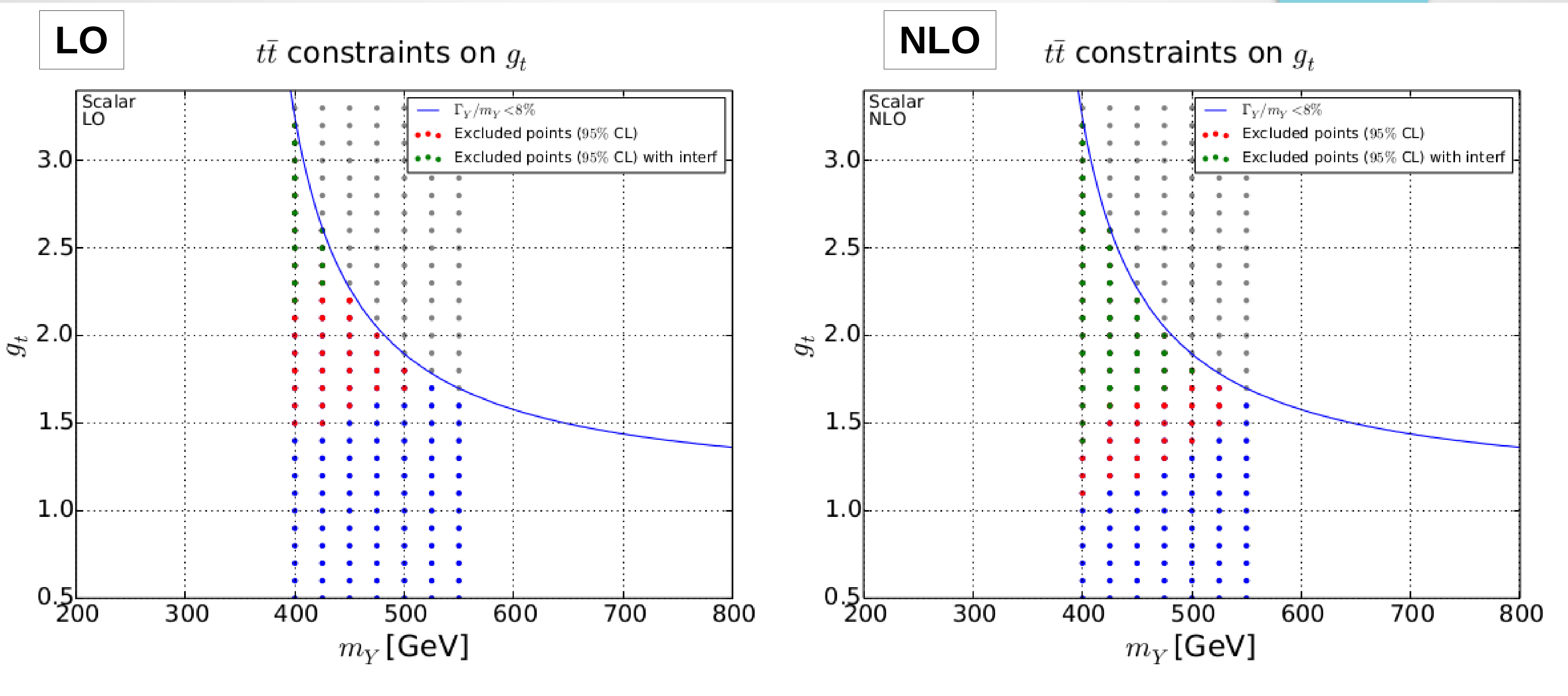
4) Comparison with ATLAS tt results



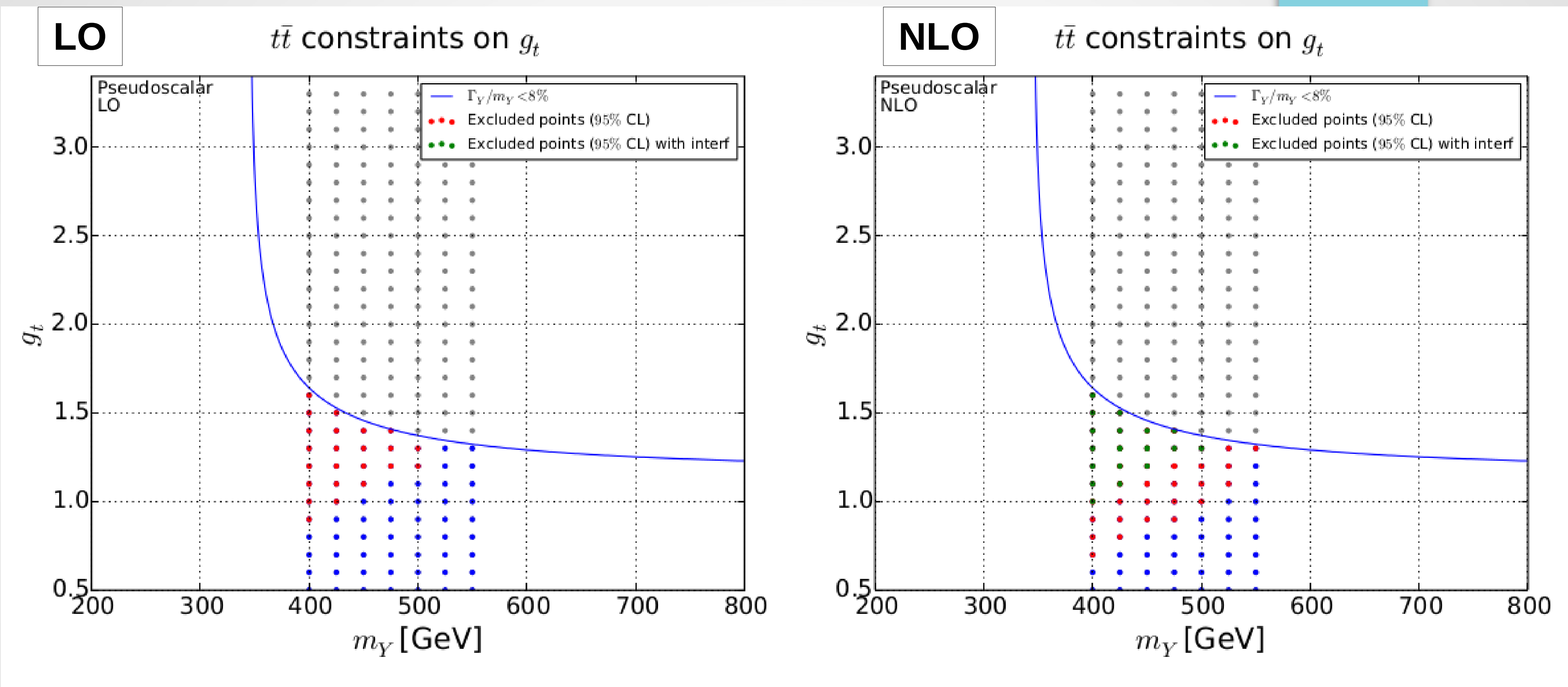
- 8 TeV resonant search (ATLAS arXiv:1505.07018) in narrow width approximation (Γ<3%) but we allow up to 8%
- ATLAS exclusion curve is lower as production cross section is bigger

4) Comparison with ATLAS tt results – scalar case



- Taking into account the interference reduces number of excluded points by a factor ~3 @LO and factor ~2 @NLO
- $g_t > 1.6$ for $400 < m_y < 550$ GeV can be excluded even with interference

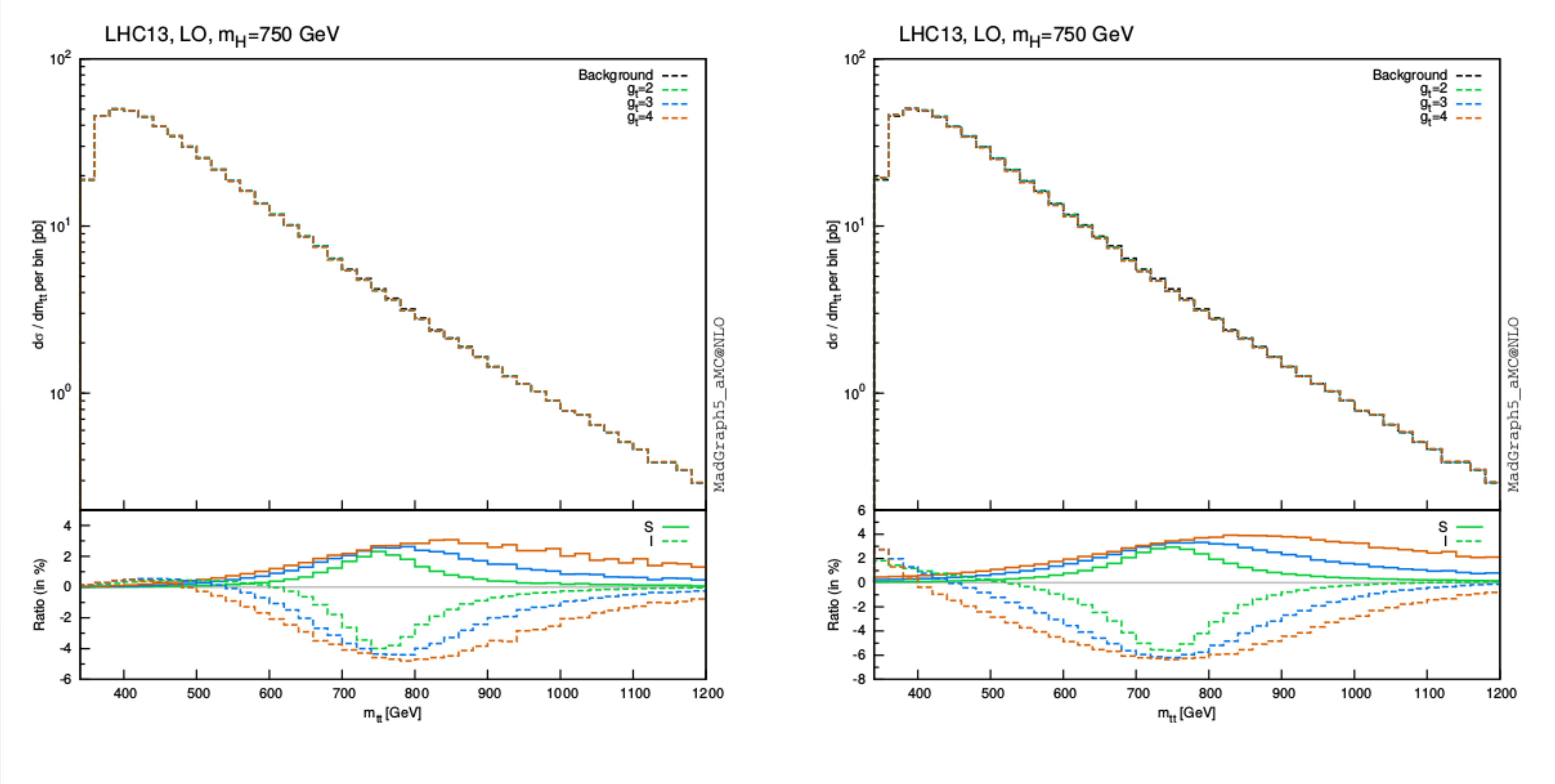
4) Comparison with ATLAS tt results – pseudo case



- The is no point excluded anymore when taking into account the interference @LO → Huge impact
- $g_t > 1.2$ for $400 < m_y < 550$ GeV can be excluded even with interference

5) The 750 GeV diphoton excess

- Characterised by
  – m_Y ~ 750 GeV, $\Gamma_Y/m_Y < 6\%$, σ ~ 1-10 fb
- Cannot be accounted for with our model (would require $g_t > 4\pi$)



5) The 750 GeV diphoton excess – new attempt

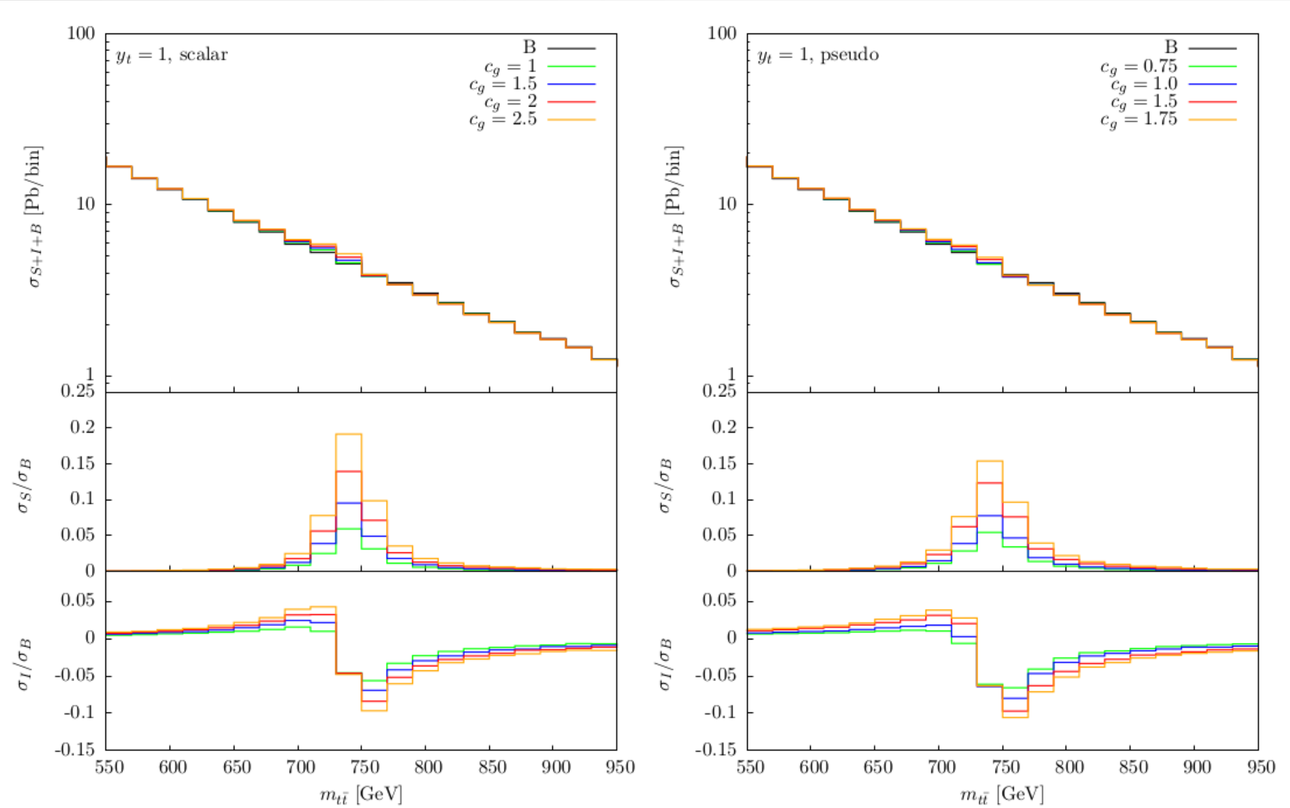
- To enhance the cross section without increasing the width we can employ dim-5 operators:

$$L_g = \frac{\alpha_s c_g^S}{12\pi v} G_{\mu\nu} G^{\mu\nu} H^0 - \frac{\alpha_s c_g^P}{8\pi v} G_{\mu\nu} \tilde{G}^{\mu\nu} A^0.$$

- However a very large c_g coupling would be needed to satisfy the signal which would be ruled out by the tt ATLAS search
- We need to introduce an effective coupling to the photon too:

$$L_\gamma = -\frac{2\alpha_{EM} c_\gamma^S}{9\pi v} F_{\mu\nu} F^{\mu\nu} H^0 - \frac{\alpha_{EM} c_\gamma^P}{3\pi v} F_{\mu\nu} \tilde{F}^{\mu\nu} A^0,$$

5) The 750 GeV diphoton excess – new attempt



	g_t	c_g	c_γ	Γ_{tot}	$\sigma(pp \to Y \to \gamma\gamma)$	$\sigma(pp \to Y \to t\bar{t})$
Scalar	1	1.0	100	32.8	9.4 fb	0.2 pb
	1	1.5	55	31.7	6.7 fb	0.4 pb
	1	2.0	30	31.4	3.6 fb	0.7 pb
	1	2.5	20	31.4	2.5 fb	1.1 pb
Pseudoscalar	1	0.75	65	41.1	9.0 fb	0.2 pb
	1	1.0	45	40.3	7.8 fb	0.4 pb
	1	1.5	20	39.8	3.6 fb	0.9 pb
	1	1.75	10	39.7	1.2 fb	1.2 pb

- Selection of possible setups in agreement with observation
- ATLAS @8Tev impose σ<0.8 pb. We extrapolate this limit @13Tev

Conclusion

- Interference needs to be taken into account to reliably predict the line-shape of additional scalar and exclusion limits
- We found that the interference impact become important as soon as the width is large.
- $2 \rightarrow 3$ doesn't change the shape and size of the interference with respect to $2 \rightarrow 2$
- Any differential distribution can be obtained for the signal @NLO with full top mass dependance.
- We showed that in order to interpret the 750 diphoton excess, new effective couplings have to be considered.

Thanks for your attention