Let's Interfere with New Physics

Jérémie Quevillon

King's College London

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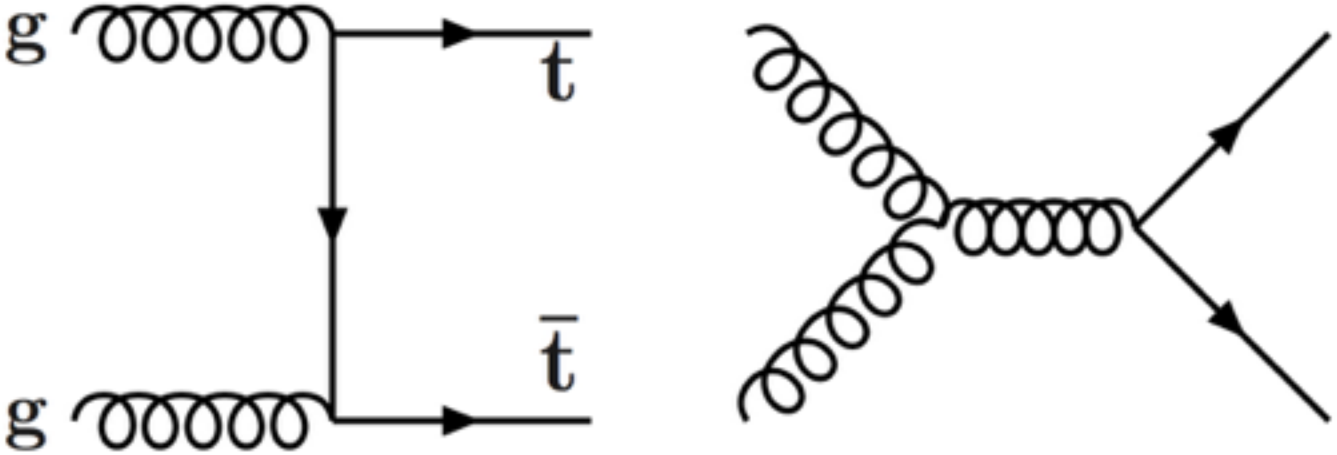
Introduction

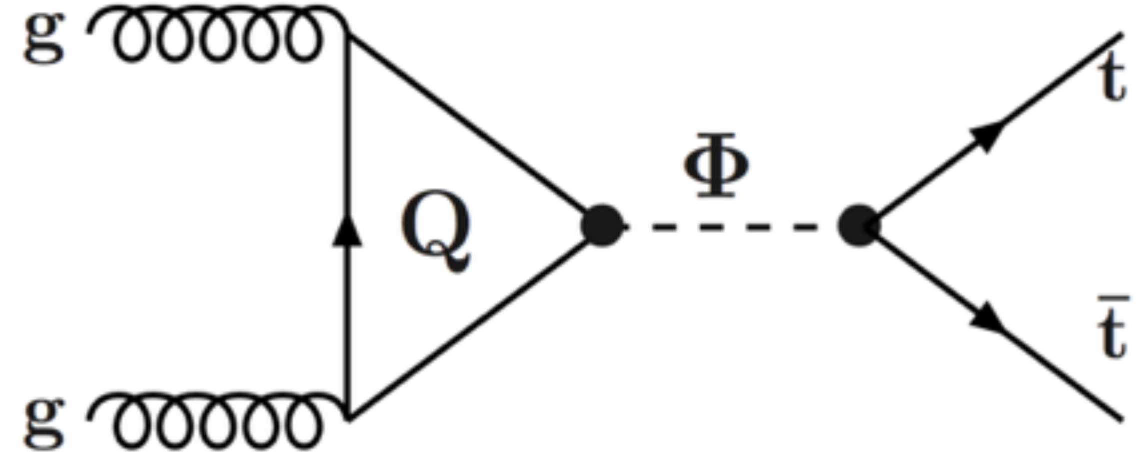
- The top quark is an interesting window on new physics
- Main production mode is initiated by gluons, $gg \to t\bar{t}$
- All experimental searches interpreted as $\sigma_{\text{signal}} \times BR$ so far
- But interferences could be huge and looking at it could shed light on new physics through non-trivial lineshape effects
- Most of the extensions of the SM require additional scalar bosons, need to go beyond the usual 5σ bump discovery.

When $(a+b)^2$ is not a^2+b^2



SM continuum

+



BSM scalar resonance

$$|\mathcal{A}_{tot}|^2 = |\mathcal{A}_{cont} + \mathcal{A}_{res}|^2$$

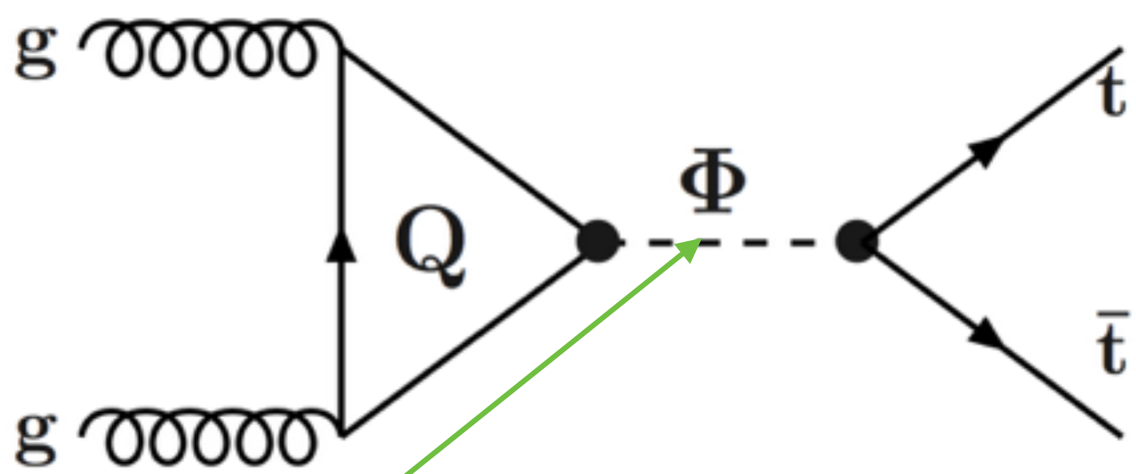
$$|\mathcal{A}_{tot}|^2 = \mathcal{A}^2_{cont} + |\mathcal{A}_{res}|^2 + \underbrace{\mathcal{A}_{cont} \times (\mathcal{A}_{res} + \mathcal{A}_{res}{}^*)}_{\text{interference}}$$

- In BSM analyses interferences are usually neglected
- They affect or not the total cross section
- But they always affect the invariant mass differential distribution

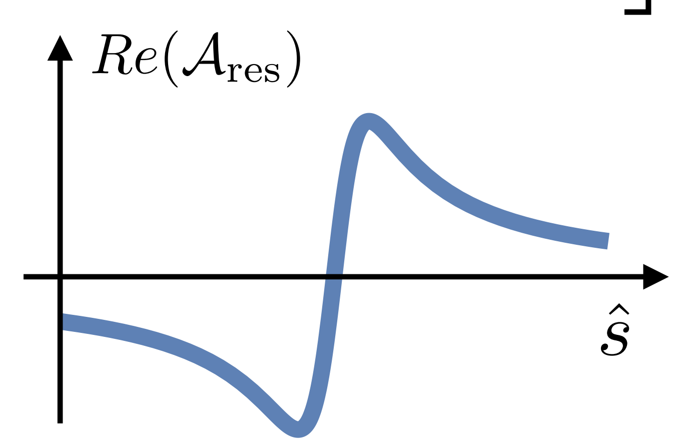
Real part of Interferences

$$|\mathcal{A}_{tot}|^2 = \mathcal{A}_{cont}^2 + |\mathcal{A}_{res}|^2 + \mathcal{A}_{cont} \times 2Re(\mathcal{A}_{res})$$

usual Breit-Wigner   interference(s)



$$\mathcal{A}_{res} = \mathcal{A}\frac{M^2}{\hat{s} - M^2 + iM\Gamma} = \mathcal{A}\left[\underbrace{\frac{M^2(\hat{s}-M^2)}{(\hat{s}-M^2)^2 + M^2\Gamma^2}}_{\text{Real part}} - i\frac{M\Gamma}{(\hat{s}-M^2)^2 + M^2\Gamma^2}\right]$$



- No interference on shell
- The new contribution is antisymmetric around M

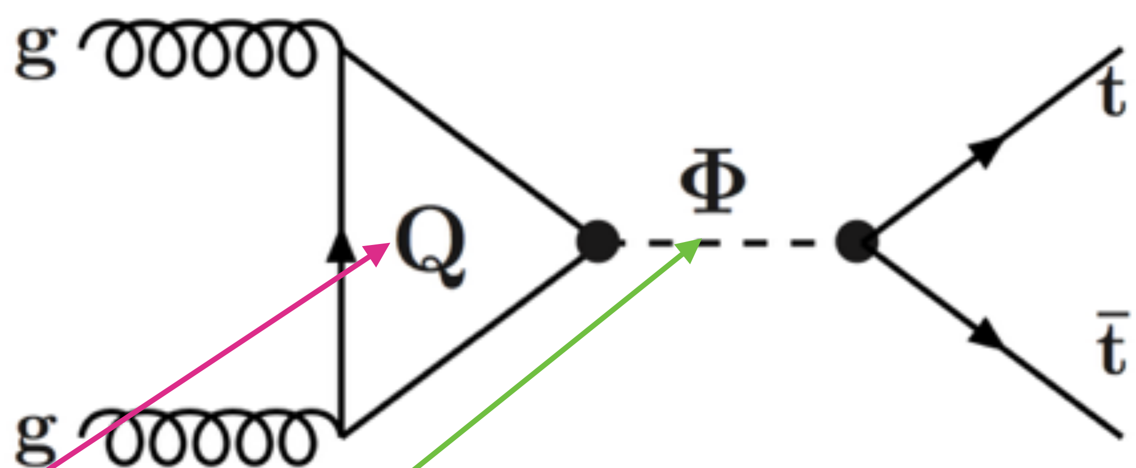
so does not contribute to $\sigma_{\rm tot} \propto \int d\hat{s}|\mathcal{A}_{\rm tot}|^2$

- But the amplitude could develop an imaginary part due to the loop...

Imaginary part of Interferences

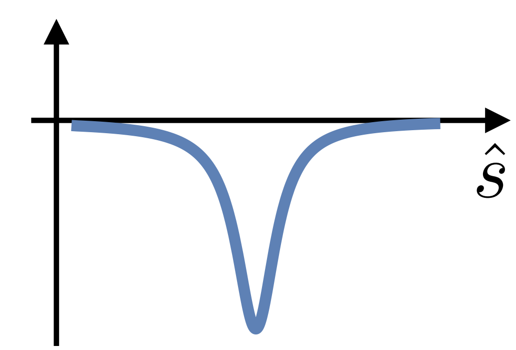
$$|\mathcal{A}_{tot}|^2 = \mathcal{A}_{cont}^2 + |\mathcal{A}_{res}|^2 + \mathcal{A}_{cont} \times 2Re(\mathcal{A}_{res})$$

usual Breit-Wigner interference(s)



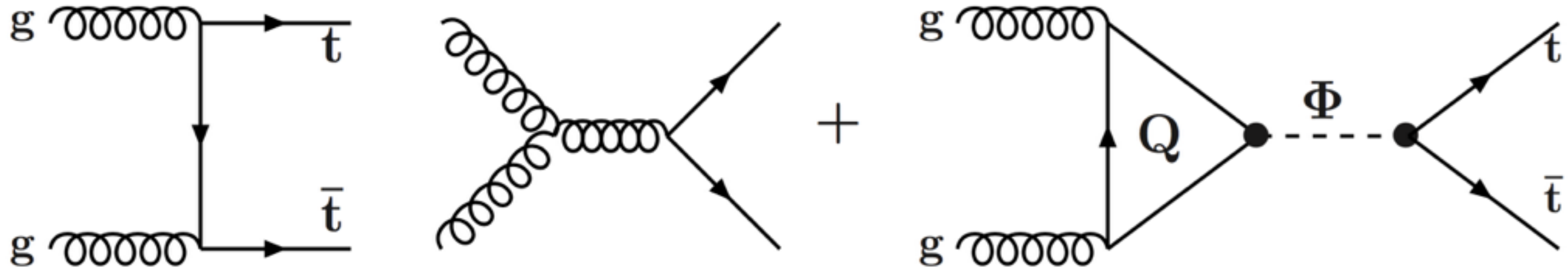
$$\mathcal{A}_{res} = \mathcal{A}e^{i\phi}\frac{M^2}{\hat{s} - M^2 + iM\Gamma} = \mathcal{A}\left[\underbrace{cos\phi\frac{M^2(\hat{s} - M^2)}{(\hat{s} + M^2)^2 + M^2\Gamma^2}}_{\text{as before}} + \underbrace{sin\phi\frac{M\Gamma}{(\hat{s} - M^2)^2 + M^2\Gamma^2}}_{\text{new part}} + i(...)\right]$$

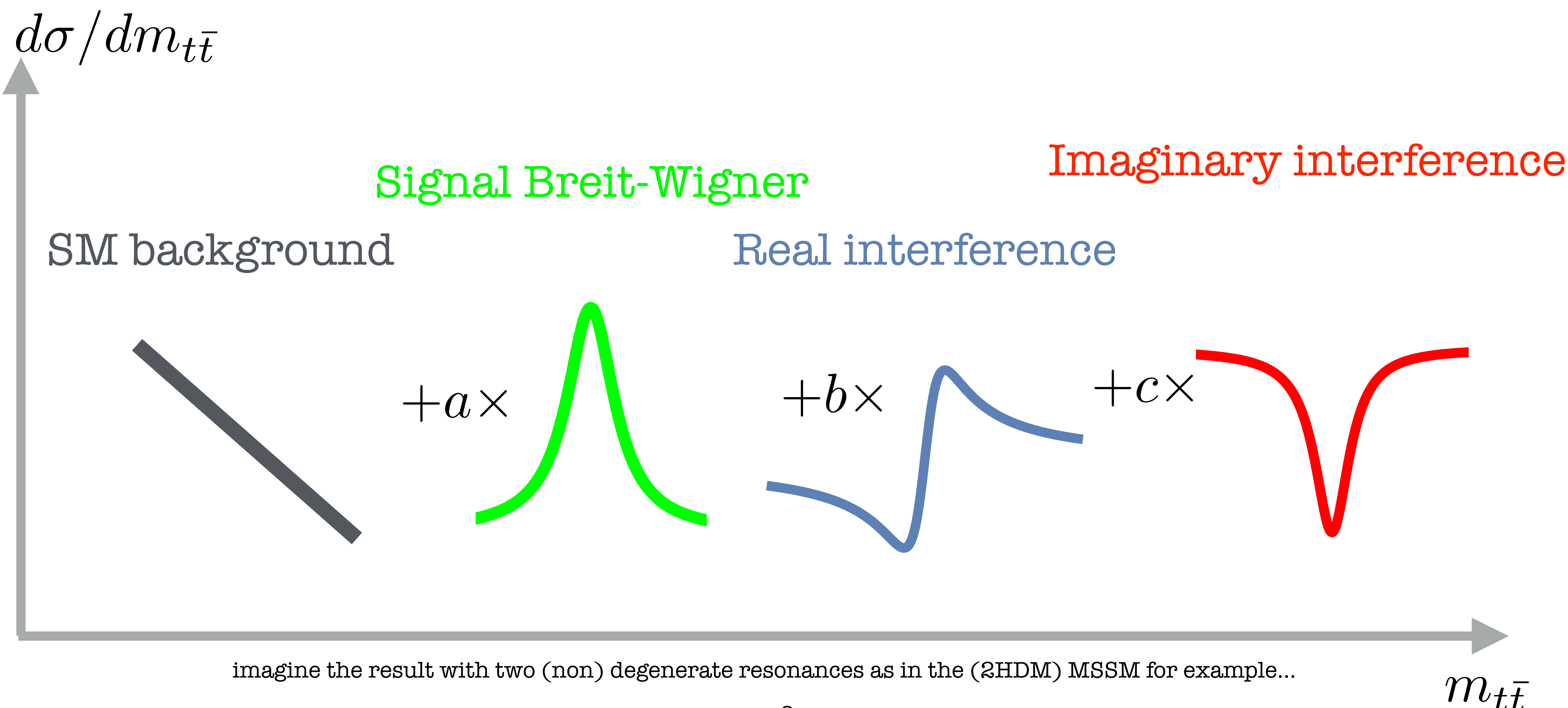
- New interference term does not vanish on shell
- The new contribution does contribute to σ_{tot}



- Interferences are sensible to New Physics through many ways!

Interference lineshapes





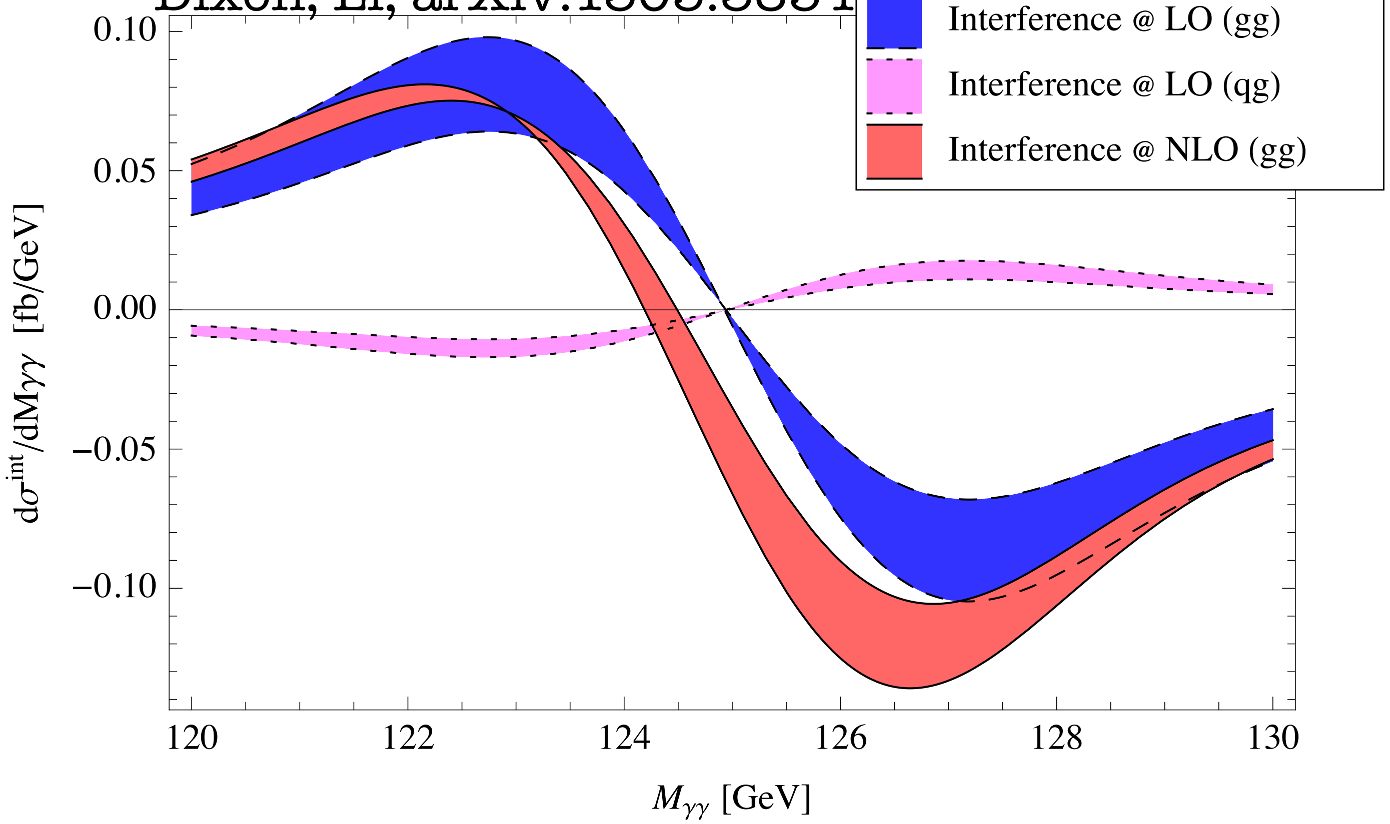
imagine the result with two (non) degenerate resonances as in the (2HDM) MSSM for example...

SM Application: width measurements of the SM Higgs

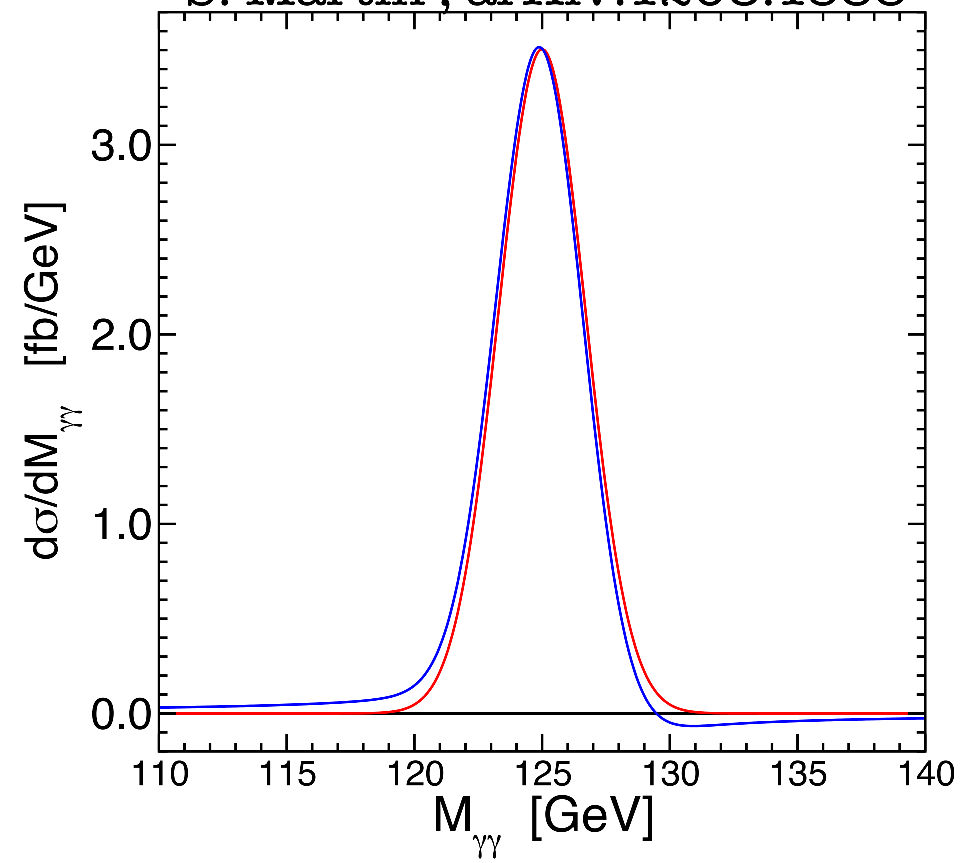
Higgs mass peak shift in $H \to \gamma\gamma$:

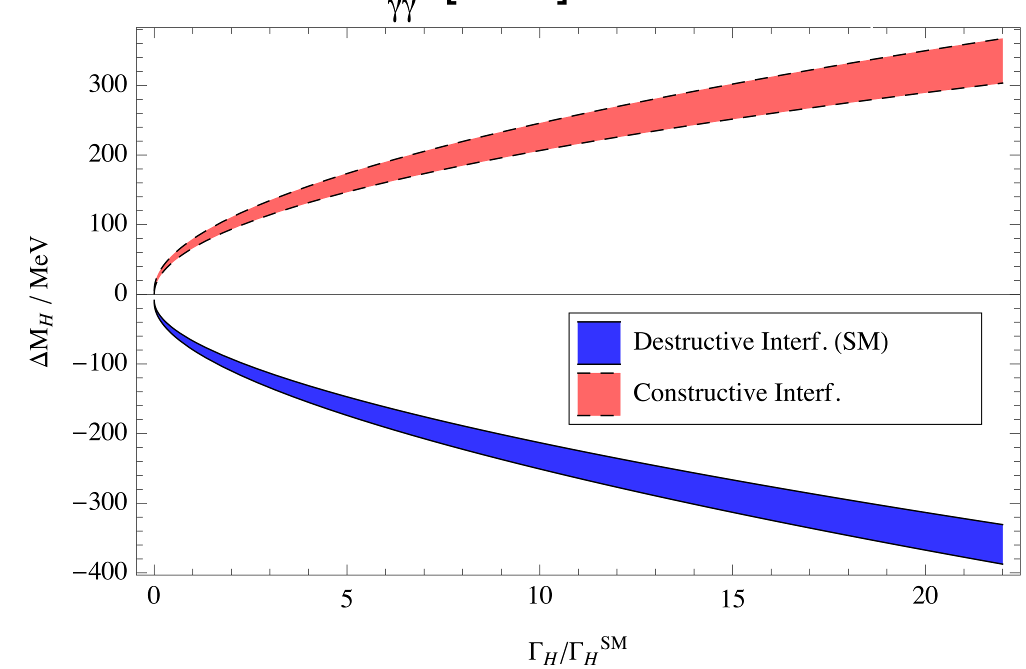
$$\frac{d\sigma^{\rm inter}}{dM_{\gamma\gamma}} = \frac{(M_{\gamma\gamma}^2 - m_H^2)R + \cancel{m_H \Gamma_H I}}{(M_{\gamma\gamma}^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}$$ $\sim 1\%$, negligeable

Dixon, Li, arXiv:1305.3854



S. Martin , arXiv:1208.1533





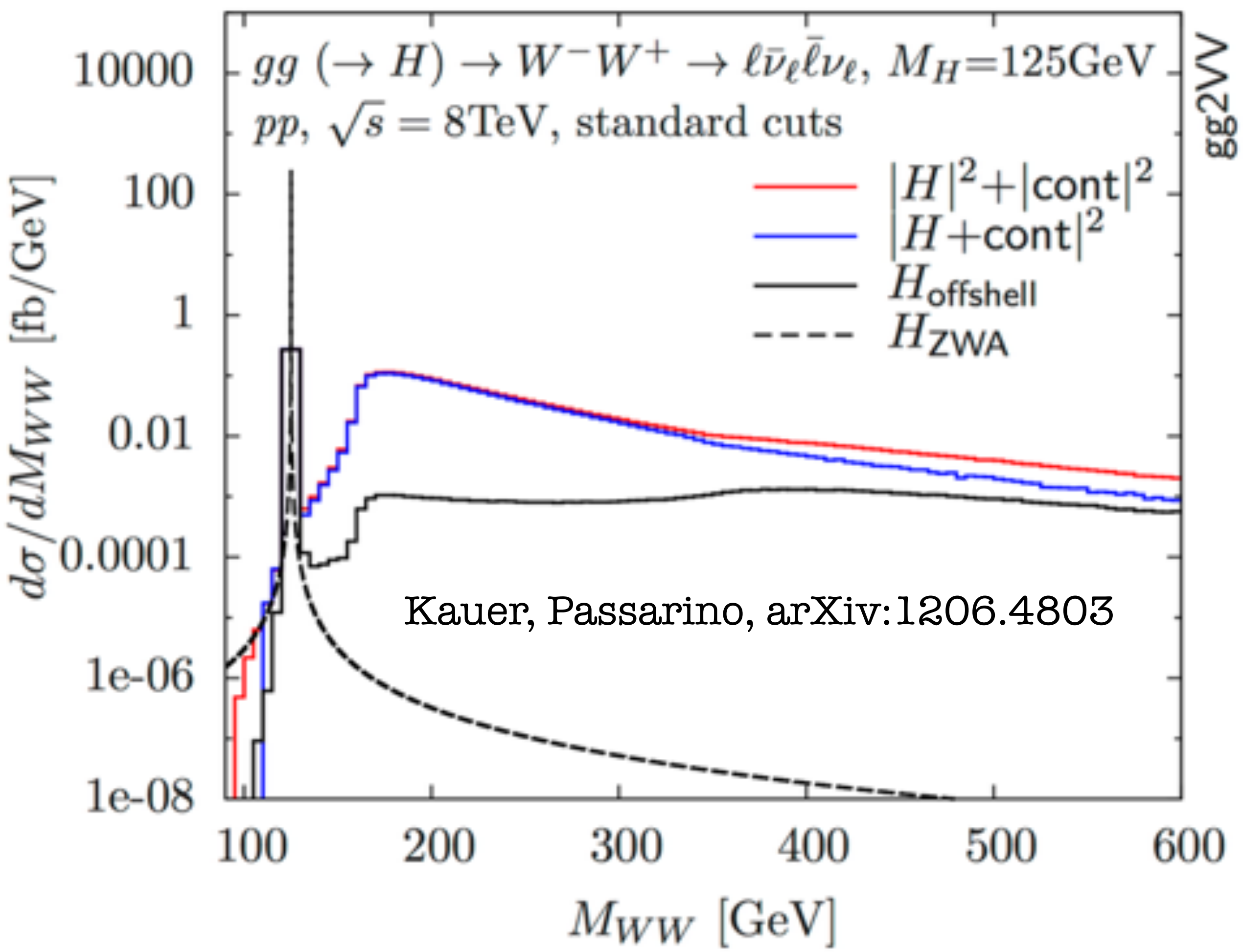
- **Mass shift** R-term related to the **Higgs width**
- Current data indicates $\frac{\Gamma_H}{\Gamma_H^{SM}} \lesssim 200$
- With 3ab^-1, $\frac{\Gamma_H}{\Gamma_H^{SM}} \lesssim 15$

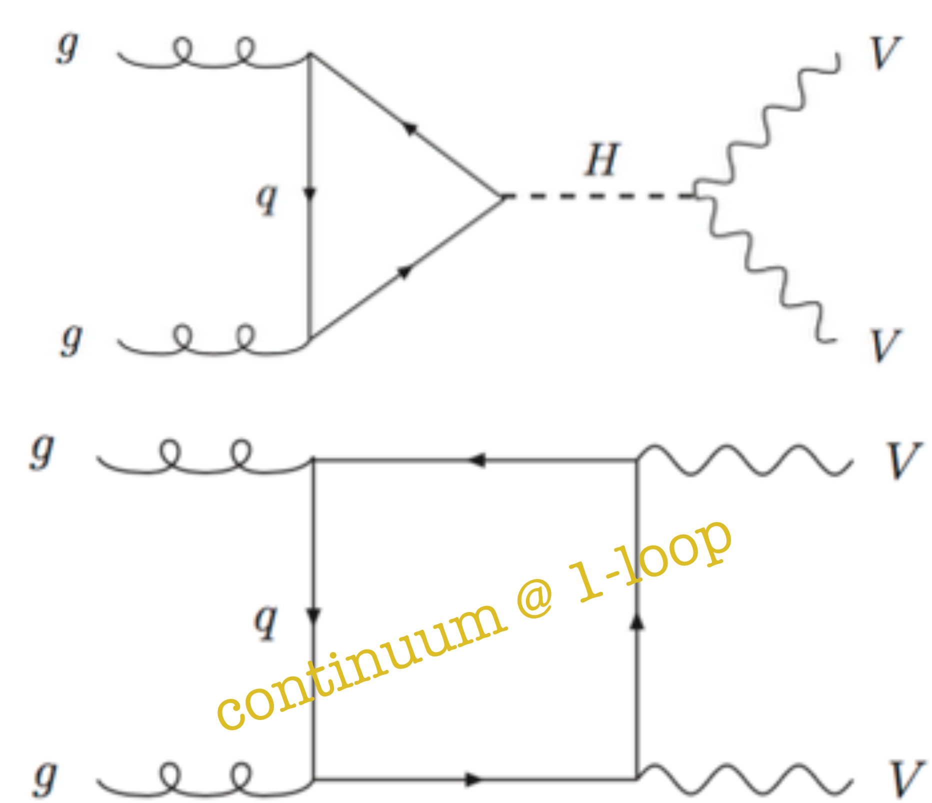
Bigger effect with BSM resonances in $gg \to \Phi \to t\bar{t}$

Application: width measurements of the SM Higgs

Higgs mass shift in off-shell regions:

$$\frac{d\sigma^{\text{inter}}}{dM_{VV}} = \frac{(M_{VV}^2 - m_H^2) R + m_H \Gamma_H I}{(M_{VV}^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}$$



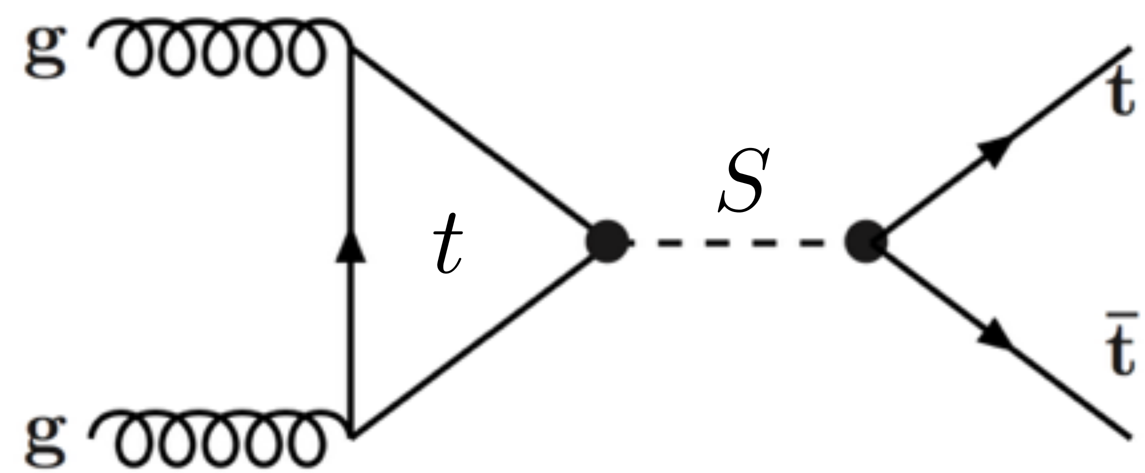


- Large interference effects, O(10%)
- LHC Run 1 data yields a Higgs width constraint of $\frac{\Gamma_H}{\Gamma_H^{SM}} \lesssim 5$

Bigger effect with BSM resonances in $gg \to \Phi \to t\bar{t}$

BSM generic model

$$\mathcal{L}_{top} = y_t \bar{t} t S + i\tilde{y}_t \bar{t}\gamma_5 t S$$



$$\mathcal{L}_{top}^{\text{loop-induced}} = -g_{sgg}(\hat{s}) G_{\mu\nu} G^{\mu\nu} S - i\tilde{g}_{sgg}(\hat{s}) \tilde{G}_{\mu\nu} G^{\mu\nu} S$$

$$g_{sgg}(\hat{s}) = \frac{\alpha_s}{\#}\frac{y_t}{m_t} A_{1/2}(\tau)$$

$$A_{1/2}(\tau) = 2\left[\tau + (\tau - 1) f(\tau)\right]\tau^{-2}$$

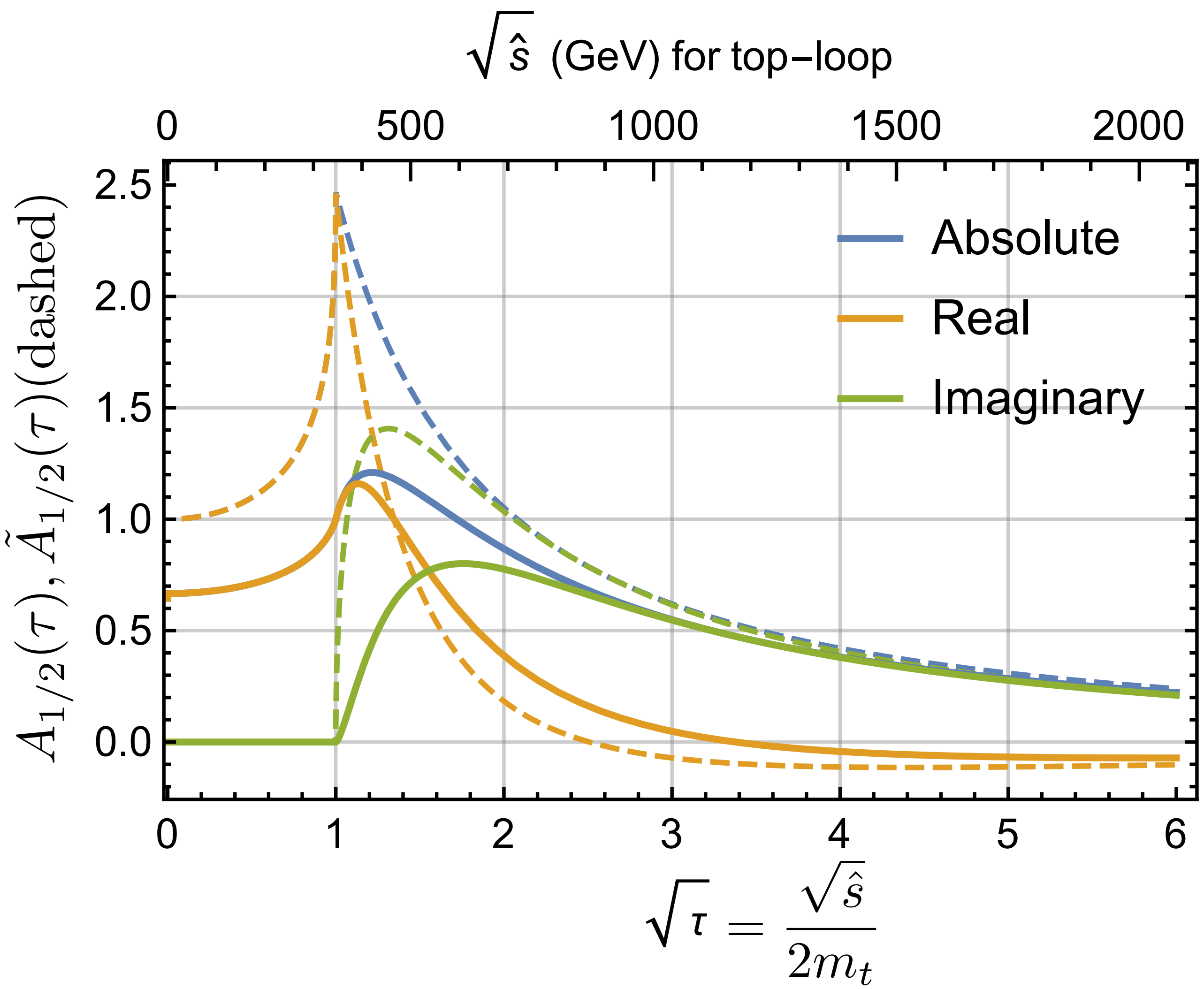
$$\tilde{g}_{sgg}(\hat{s}) = \frac{\alpha_s}{\#}\frac{\tilde{y}_t}{m_t} \tilde{A}_{1/2}(\tau)$$

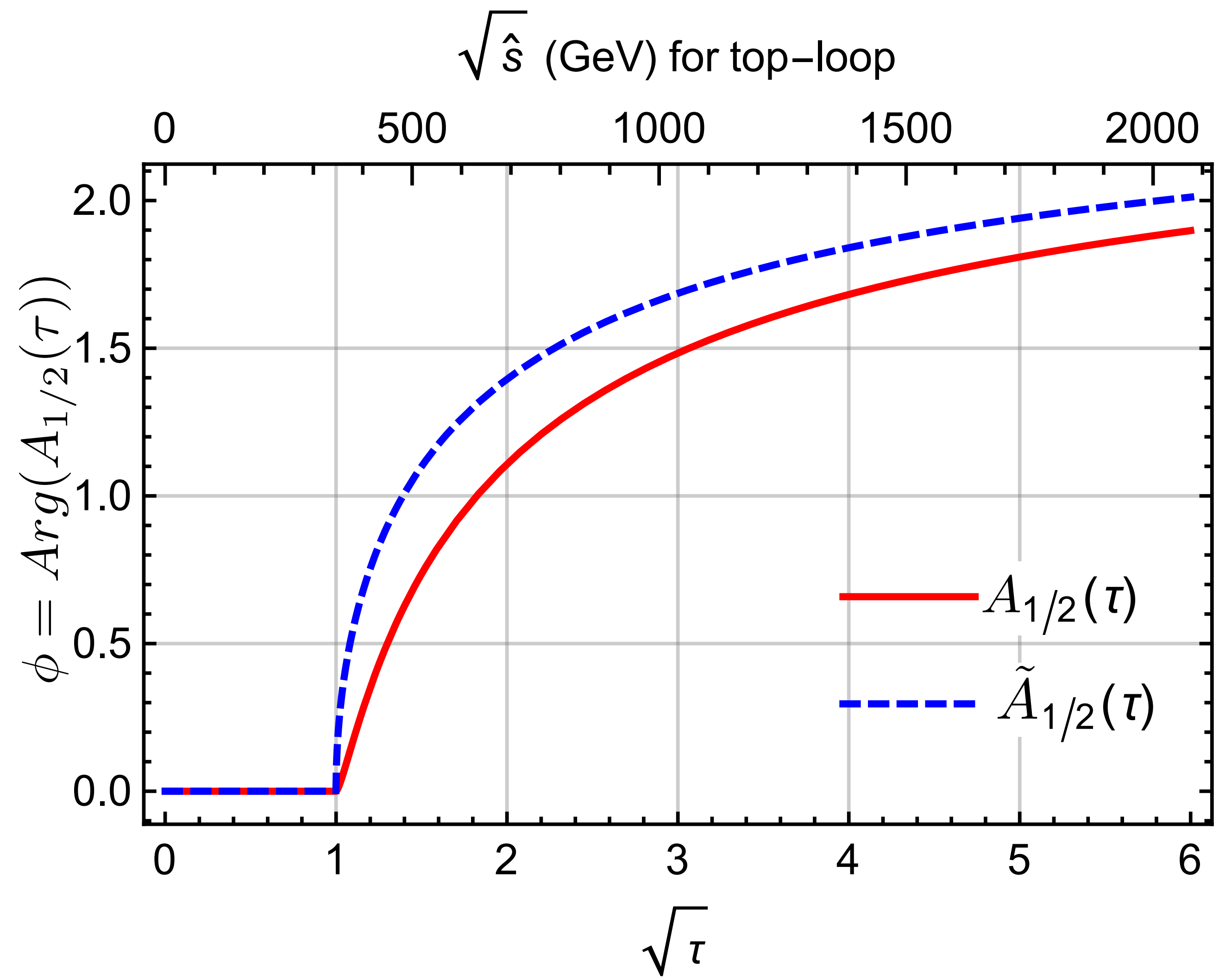
$$\tilde{A}_{1/2}(\tau) = 2\tau^{-1} f(\tau)$$

$$f(\tau) = \begin{cases} \arcsin^2 \sqrt{\tau} & \text{for } \tau \le 1\,, \\ -\frac{1}{4}\left[\log \frac{1+\sqrt{1-\tau^{-1}}}{1-\sqrt{1-\tau^{-1}}} - i\pi\right]^2 & \text{for } \tau > 1 \end{cases}$$

$$\tau = \frac{\hat{s}}{4m_t^2}$$

The form factors

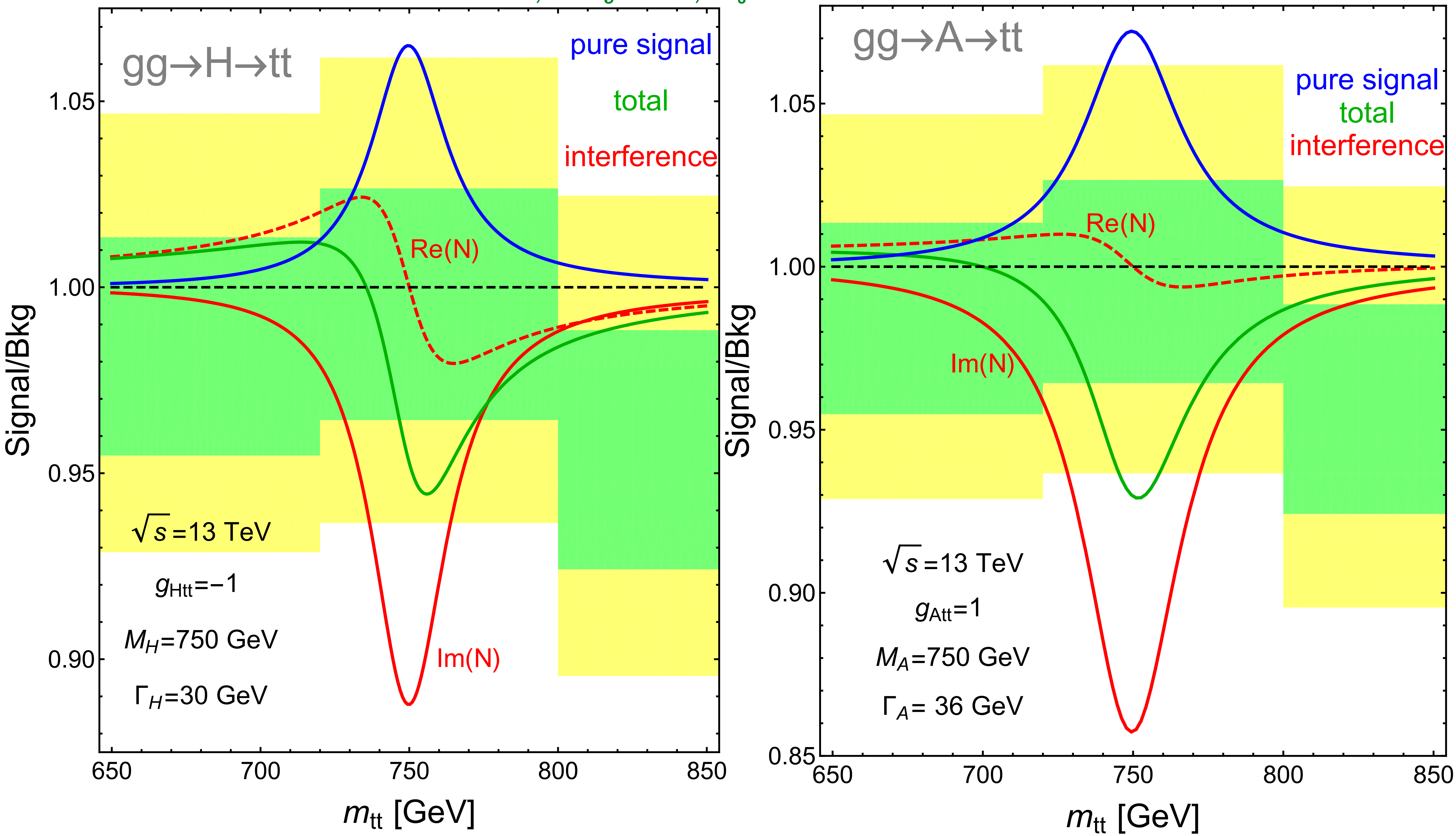




- In the SM, any heavy chiral fermion does not decouple : $g_{hgg}(\hat{s}) = \frac{\alpha_s}{3\pi v} + \mathcal{O}(\tau)$
- ϕ growth quickly and is large $\sim \pi/2 \Rightarrow$ particular BSM phenomenology
- $\phi = \pi/4 \;\; : Re(A_{1/2}) = Im(A_{1/2}), M_S = 550$ GeV and $M_{PS} = 450$ GeV
- $\phi = \pi/2 \;\; : Re(A_{1/2}) = 0, M_S = 1.2$ TeV and $M_{PS} = 850$ GeV

New scalar with the top in the loop

J. Ellis, A. Djouadi, JQ arXiv: 1605.00542



What else is there?

Supersymmetry

- Successful prediction for Higgs mass
  - Should be < 130 GeV in simple models
- Successful predictions for Higgs couplings
  - Should be within few % of SM values
- Could explain the dark matter
- Naturalness, GUTs, string, … (???)

The MSSM

In the MSSM: two Higgs doublets: $H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}$ and $H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}$

After EWSB (which can be made radiative: more elegant than in the SM):

Three d.o.f. to make $W_L^\pm, Z_L \Rightarrow 5$ physical states left out: $h, H, A, H^\pm$

Only two free parameters at tree-level: $\tan\beta, M_A$ but important rad. corr. :

$$M_h \xrightarrow{M_A \gg M_Z} M_Z|\cos 2\beta| + \frac{3\bar{m}_t^4}{2\pi^2 v^2 \sin^2\beta}\left[\ln\frac{M_S^2}{\bar{m}_t^2} + \frac{X_t^2}{2M_S^2}\left(1 - \frac{X_t^2}{6M_S^2}\right)\right]$$

[Okada+Yamaguchi+Yanagida, Ellis+Ridolfi+Zwirner, Haber+Hempfling (1991)]

depending on $\tan\beta$, $M_S = \sqrt{\tilde{m}_{t_1}\tilde{m}_{t_2}}$, $X_t = A_t - \frac{\mu}{\tan\beta}$: $M_h^{max} \to M_Z + 30 - 50$ GeV

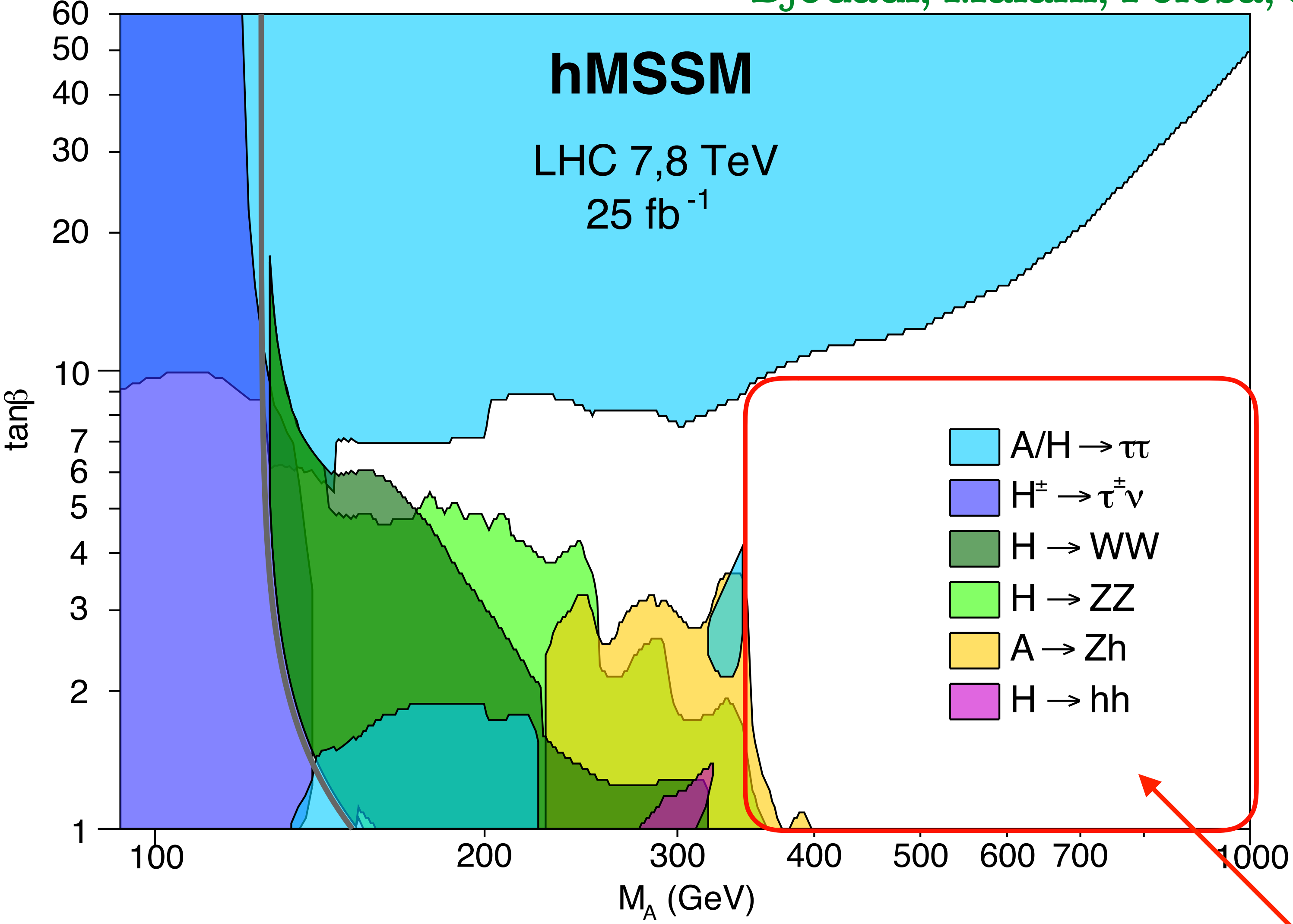
For low $\tan\beta$: H, A couplings to top quark enhanced:

Φ	$g_{\Phi\bar{u}u}$	$g_{\Phi\bar{d}d}$	$g_{\Phi VV}$
h	$\frac{\cos\alpha}{\sin\beta} \to 1$	$\frac{\sin\alpha}{\cos\beta} \to 1$	$\sin(\beta-\alpha) \to 1$
H	$\frac{\sin\alpha}{\sin\beta} \to 1/\tan\beta$	$\frac{\cos\alpha}{\cos\beta} \to \tan\beta$	$\cos(\beta-\alpha) \to 0$
A	$1/\tan\beta$	$\tan\beta$	0

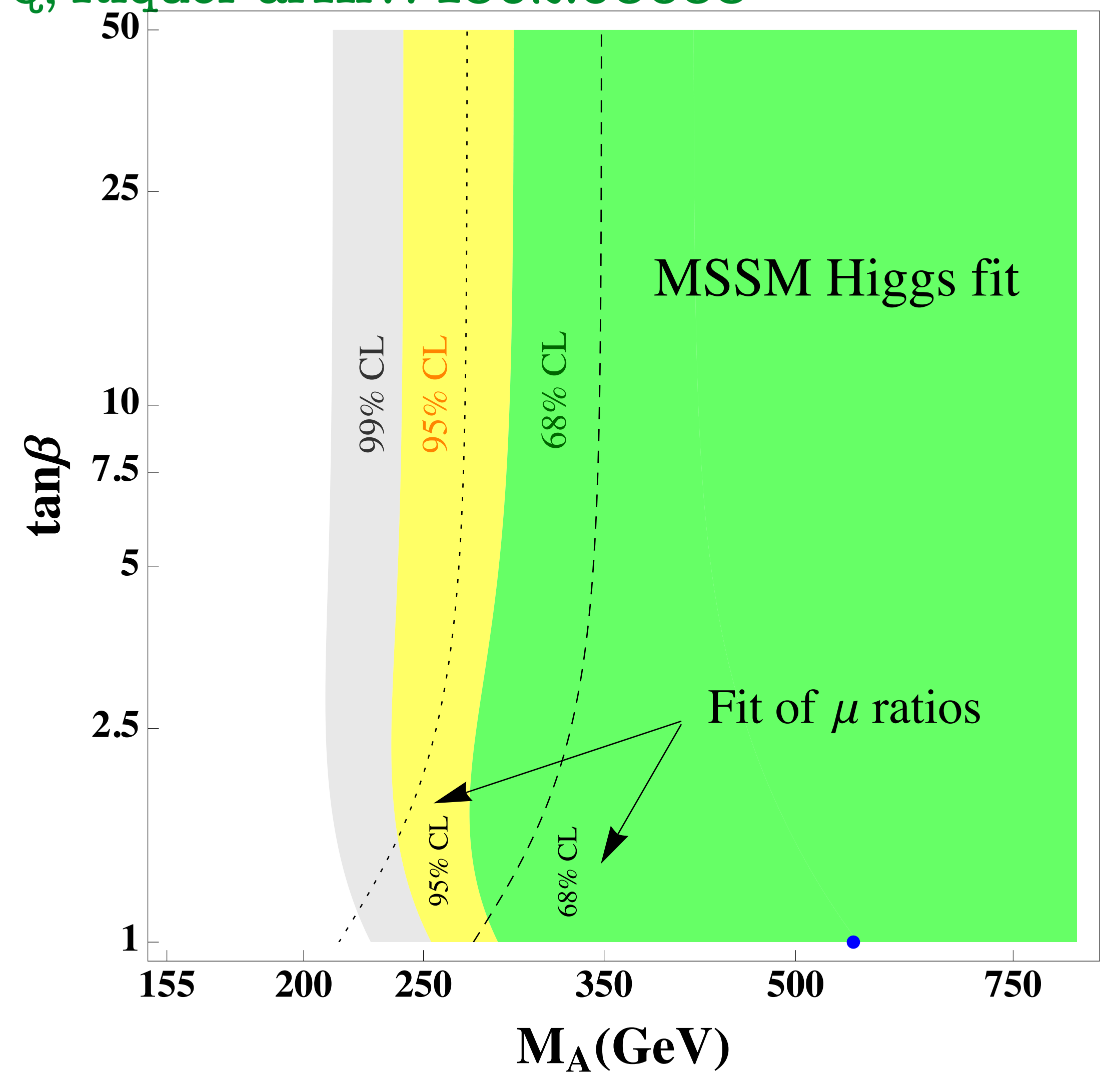
In the decoupling limit: MSSM reduces to SM but with a light SM Higgs

Constraints on the MSSM heavy Higgs bosons

Djouadi, Maiani, Polosa, JQ, Riquer arXiv: 1502.05653



Direct searches



Higgs signal strength fits

$M_h = 125$ GeV
+ no light stops
+ $H, A \to \tau\tau$

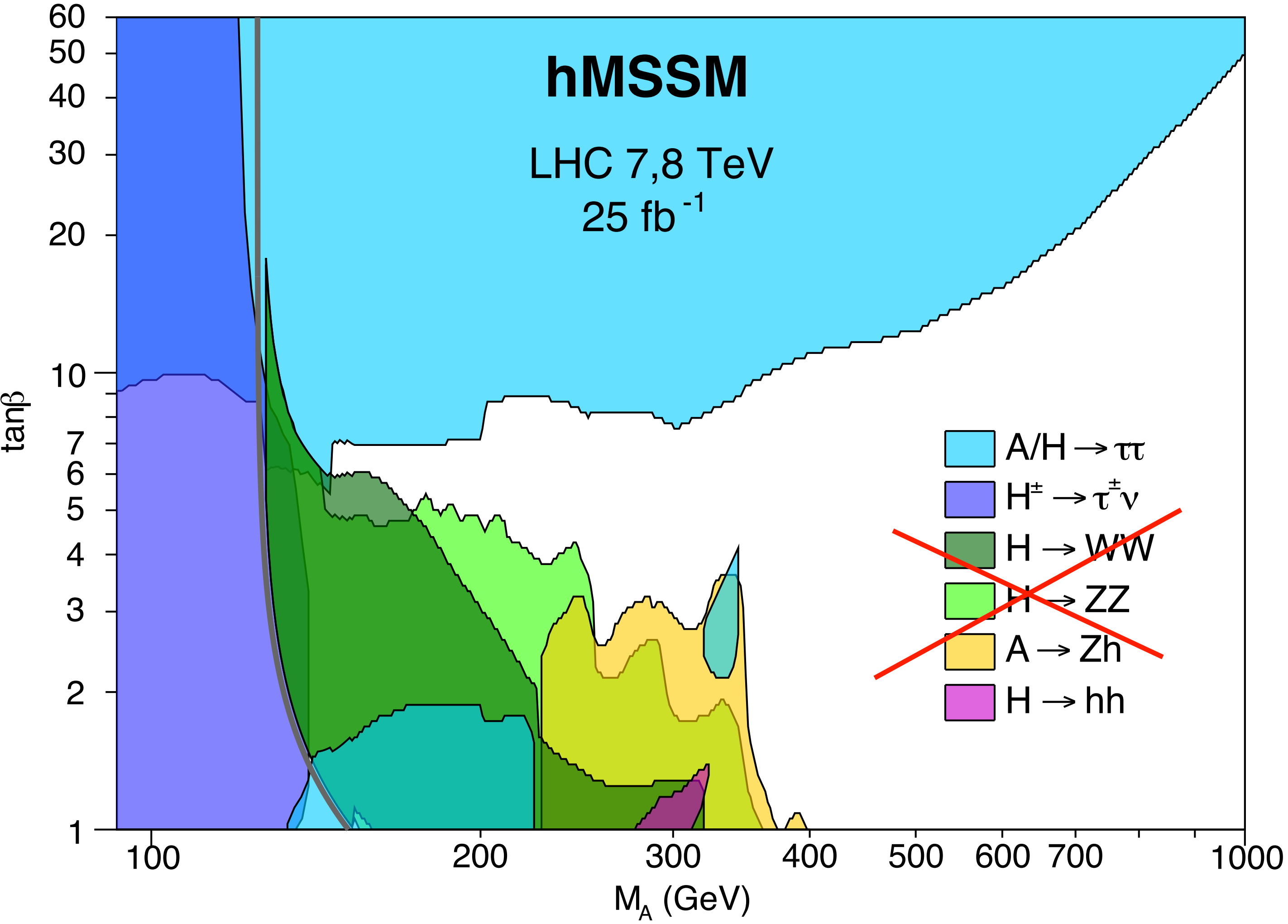
$\Rightarrow$ seem to favor the low $\tan\beta$ region where H, A couplings to top quark are enhanced!

$\Rightarrow H, A \to t\bar{t}$

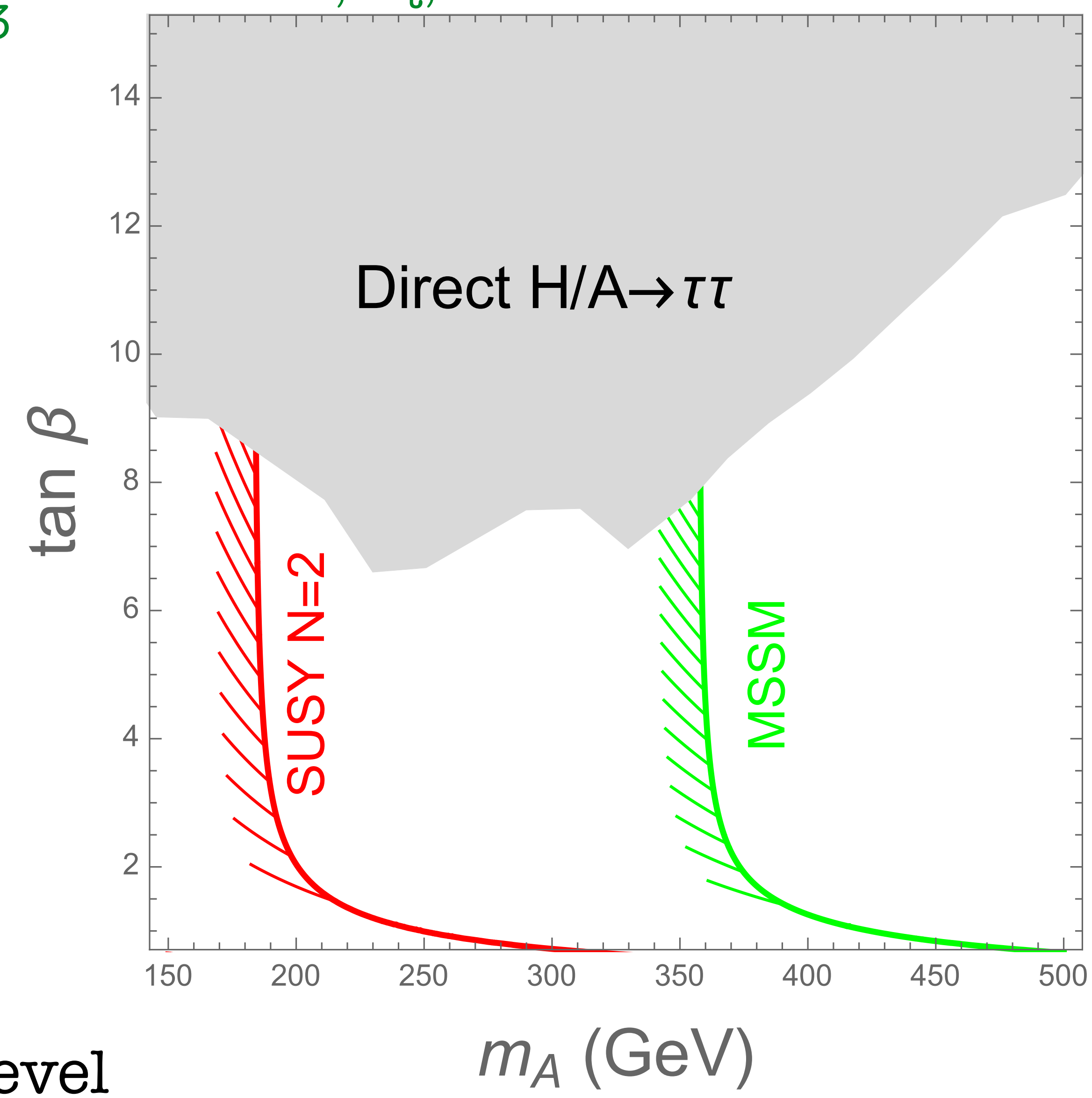
N=2 SUSY ?

the MSSM is the « easiest » realization of SUSY, what if SUSY is non minimal?

Djouadi,Maiani, Polosa, JQ, Riquer arXiv: 1502.05653



J. Ellis, JQ, V. Sanz arXiv:1607.05541



the N=2 scalar potential is modified at tree-level

⟶ theory realizes automatically the alignment limit: | h is SM-like & H doesn't couple to W/Z

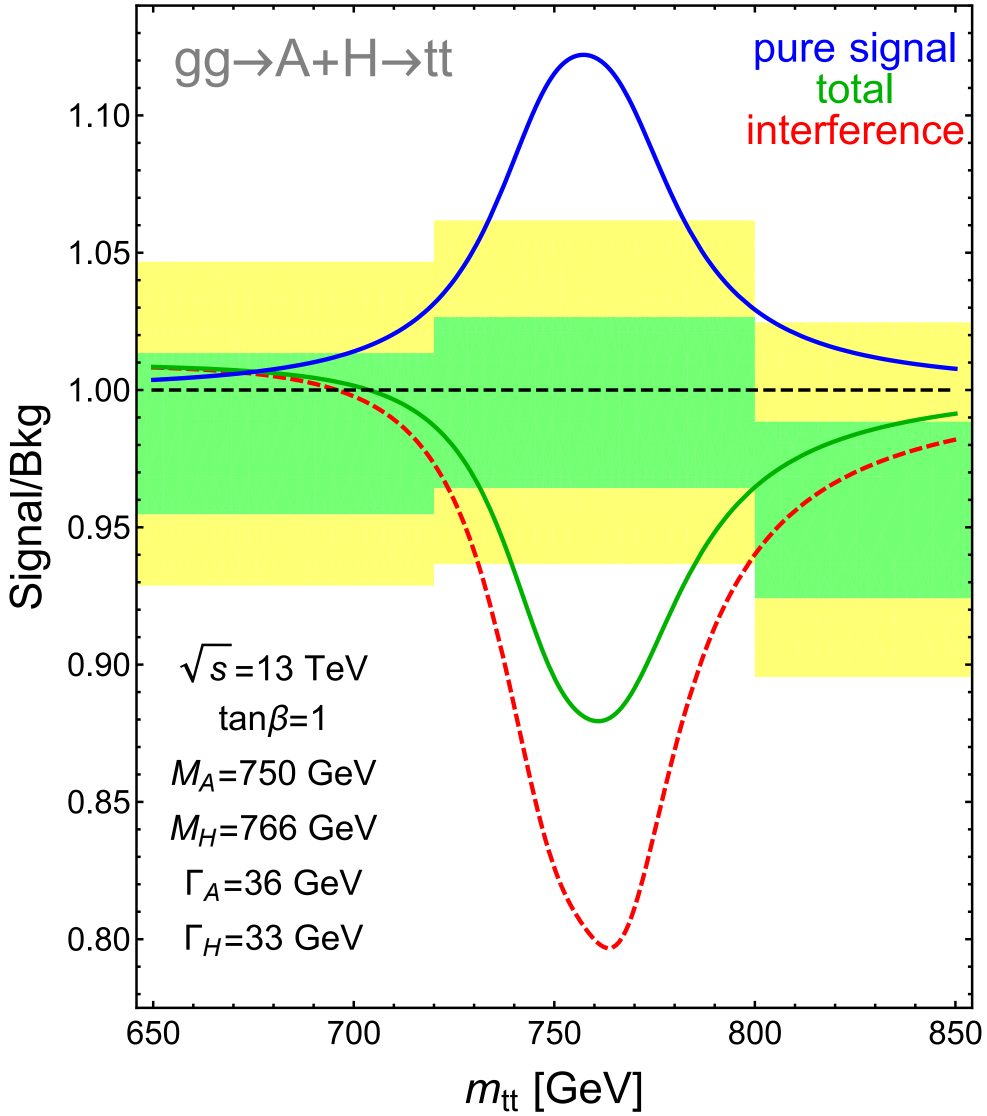
SUSY Higgs as light as 200 GeV are allowed

$H, A \to t\bar{t}$: the channel to test directly the low $\tan\beta$ region!

If the resonances are the heavy Higgs of the MSSM

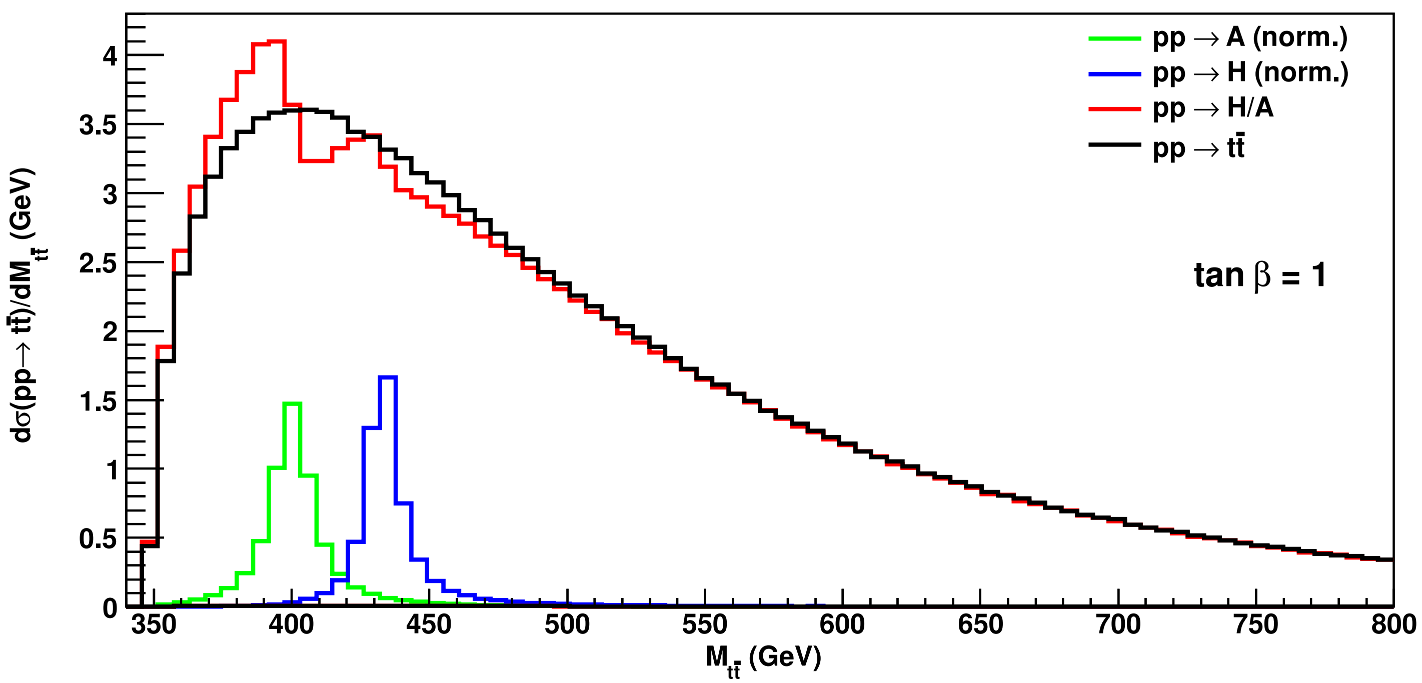
looking for a dip

J. Ellis, A. Djouadi, JQ   arXiv: 1605.00542



nearly degenerate H,A

looking for a peak & dip

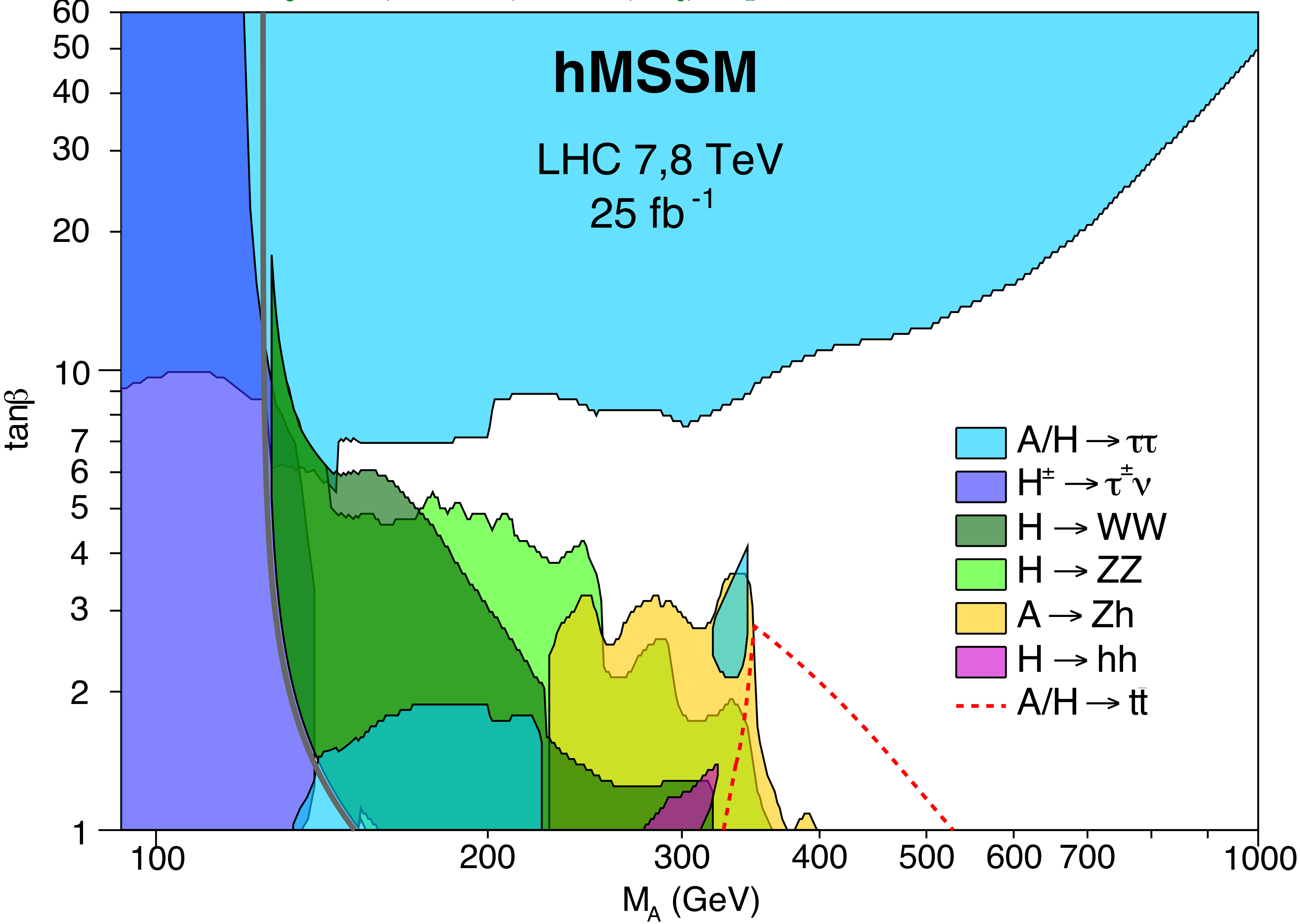


non degenerate H,A

- In the high mass region, the two resonances would mimic a single broad resonance
- In a 2HDM, the signal could be anything (including nothing due to cancelation)

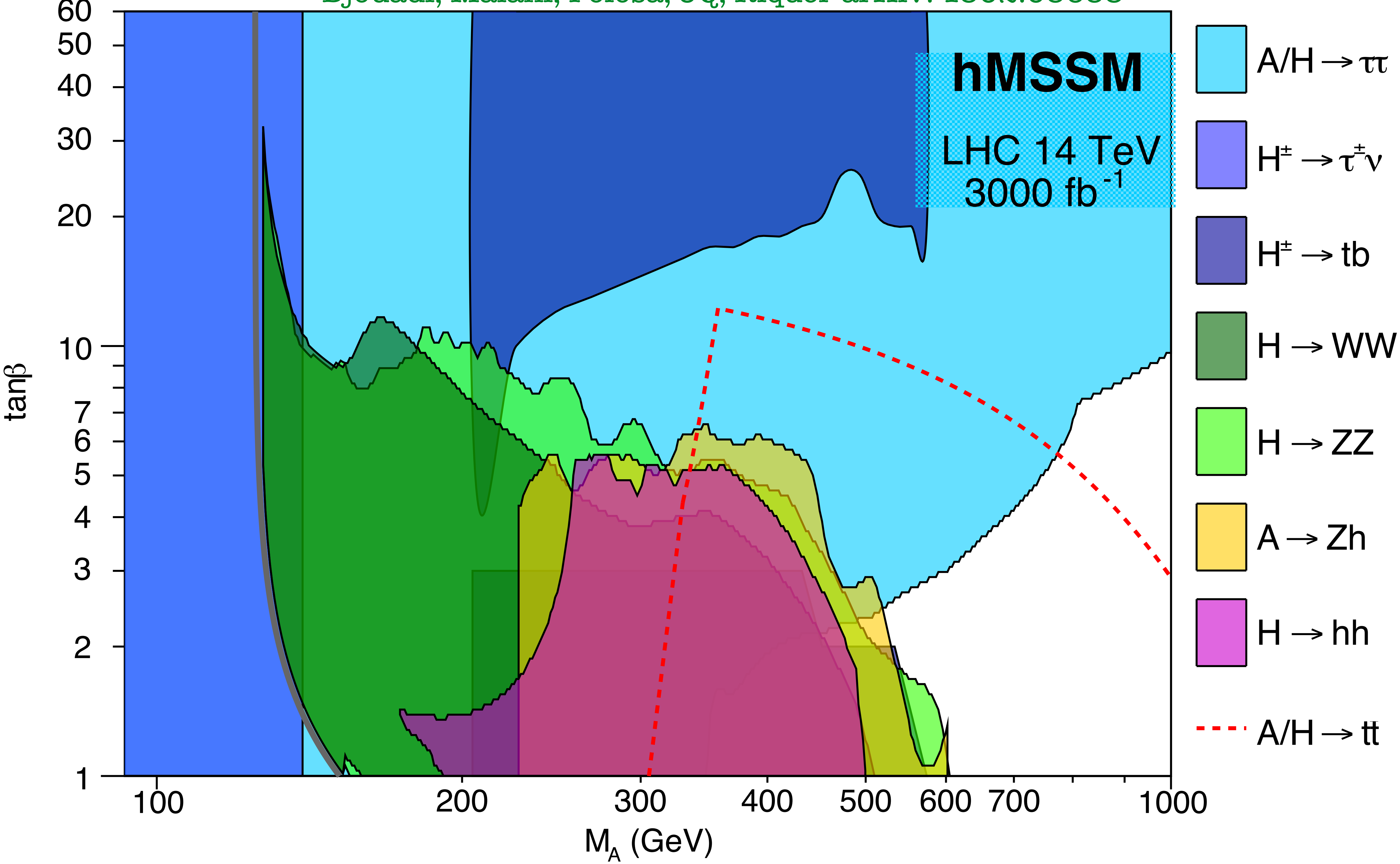
Constraints from LHC run I

Djouadi, Maiani, Polosa, JQ, Riquer arXiv: 1502.05653



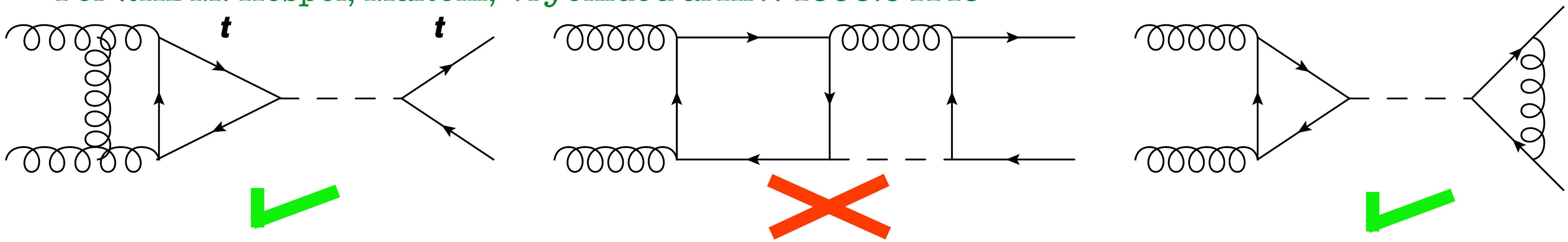
Fully covering the MSSM Higgs sector up to the TeV

Djouadi, Maiani, Polosa, JQ, Riquer arXiv: 1502.05653



Towards interferences at NLO

For 2HDM: Hespel, Maltoni, Vryonidou arXiv: 1606.04149



- Virtual NLO corrections to signal in the initial and final states are well know.
- But the corrections connecting initial and final states are NOT know.

  ->Impossible to have the full NLO interferences

  ->use LO interferences scaled by K-factors

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

Interferences still important at « NLO »

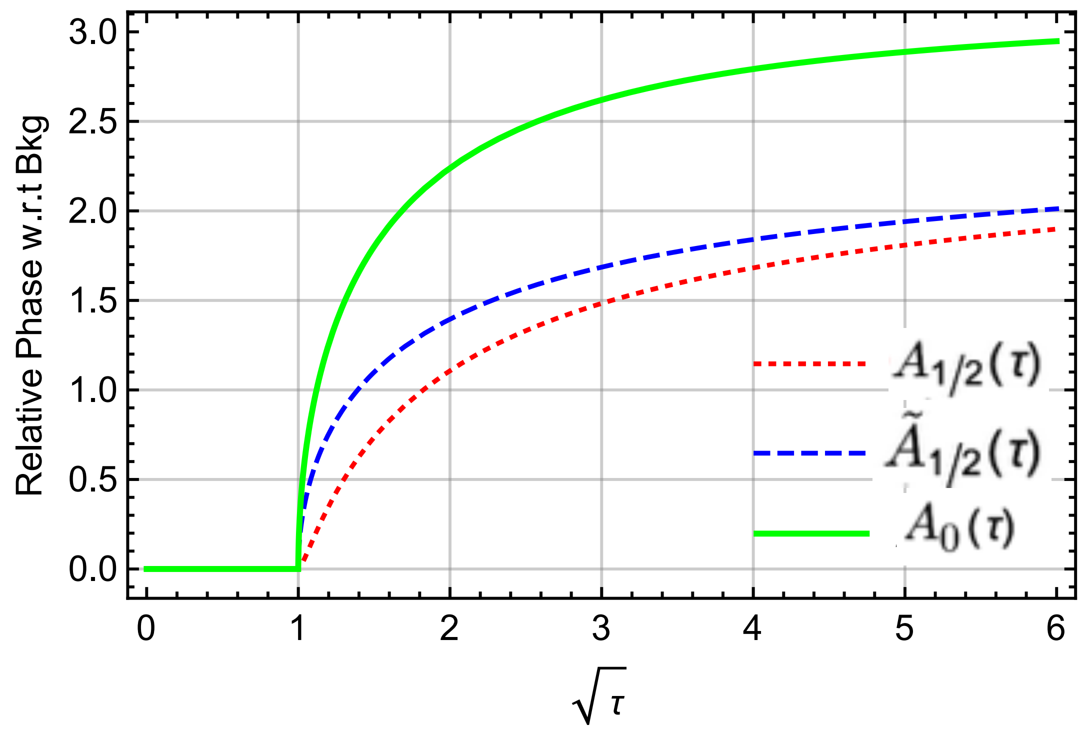
For SM: Czakon, Heymes, Mitov arXiv: 1608.00765

- $m_{t\bar{t}}$ spectra, computed at NNLO QCD, have small associated theoretical error and should be used as an efficient tool for bump-hunting in $t\bar{t}$ events

If the stops are also in the loop

$$g^{\tilde{q}}_{Sgg}(\hat{s}) = -\frac{\alpha_s}{8\pi} \sum_{q;i=1,2} \frac{g^{\tilde{q}}_i v}{m^2_{\tilde{q}_i}} \frac{1}{\tau^{\tilde{q}}_i} \left(1 - \frac{1}{\tau^{\tilde{q}}_i} f(\tau^{\tilde{q}}_i)\right)$$

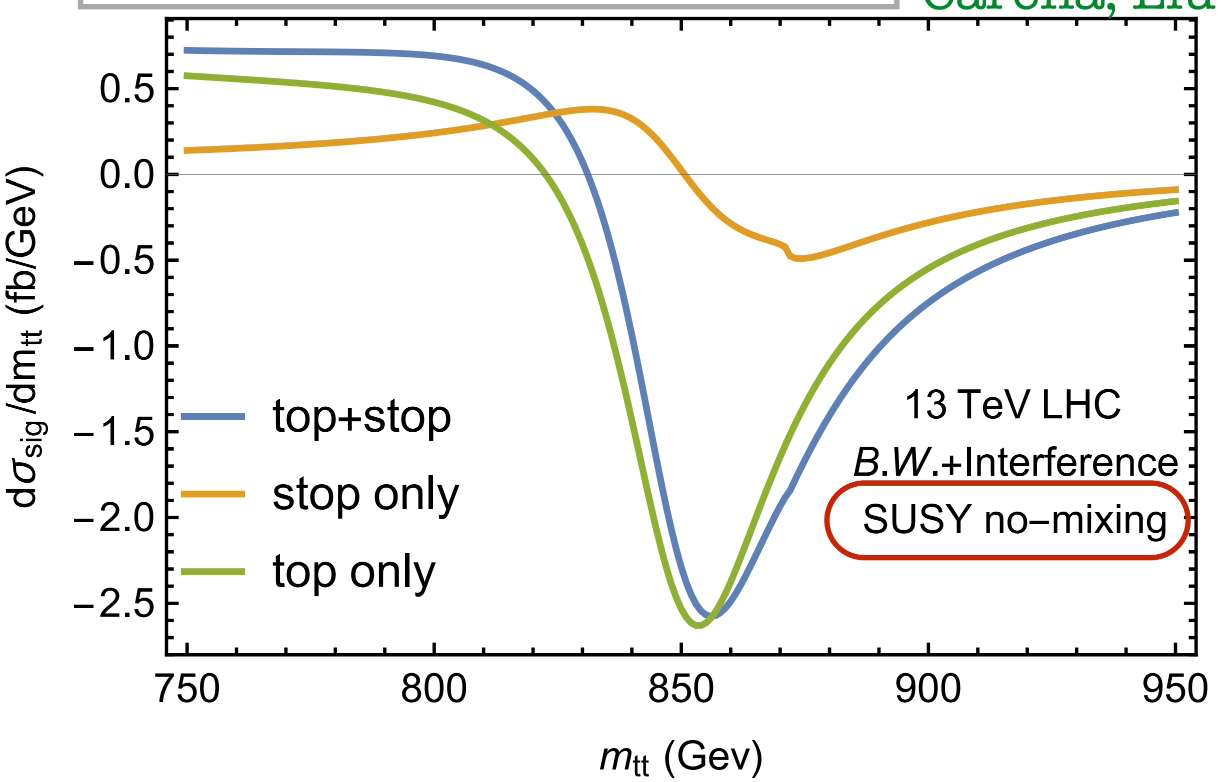
- Dip structure less prominent for scalars than fermions
- Stops change the heavy scalar lineshapes in a distinct way depending on the stop mixing.

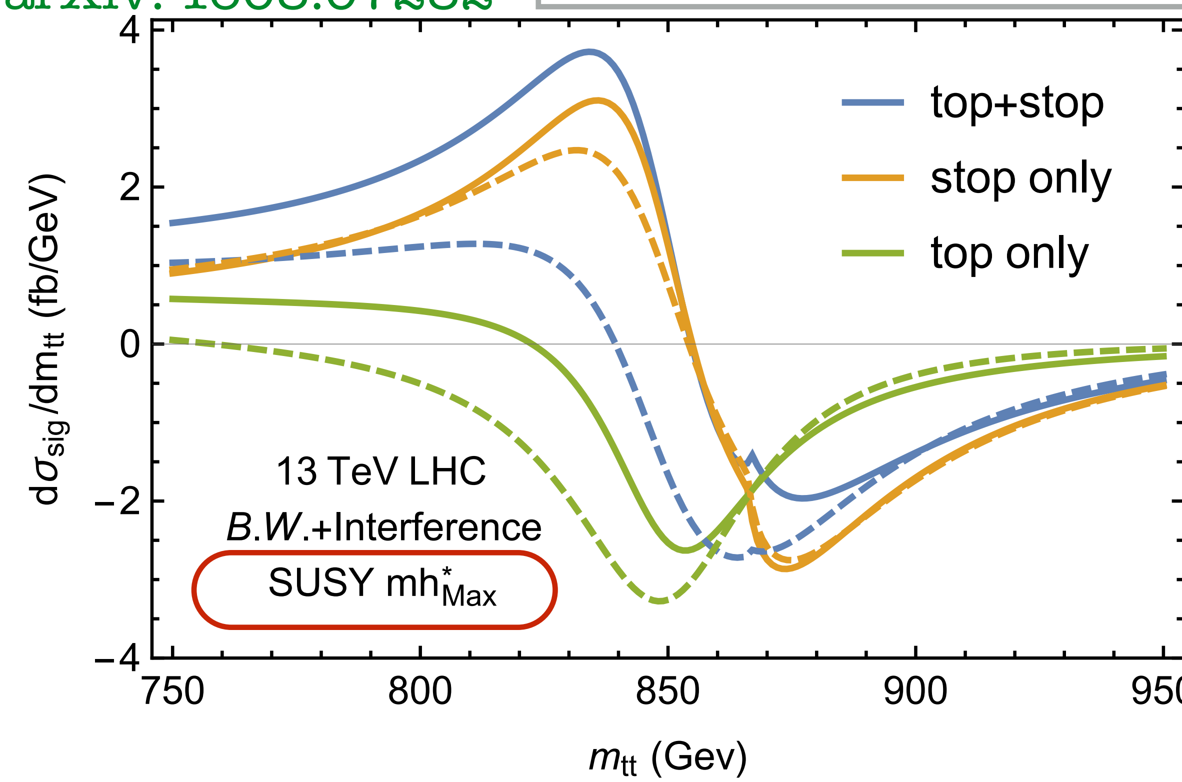


the top contribution dominate

the stop contribution dominate

Carena, Liu arXiv: 1608.07282





Vector Like Fermions

What are Vector-Like fermions?

The left-handed and right-handed chiralities of a Vector-Like fermion transform in the same way under the SM gauge groups $SU(3)_c \times SU(2)_L \times U(1)_Y$

Why are they called « vector-like »?

$$\mathcal{L}_W = \frac{g}{\sqrt{2}}(J^{\mu+}W^+_\mu + J^{\mu-}W^-_\mu)$$ Charged current

- SM chiral quarks: only left-handed charged currents

$$J^{\mu+} = J_L^{\mu+} + J_R^{\mu+} \quad \text{with} \begin{cases} J_L^{\mu+} = \bar{u}_L\gamma^\mu d_L = \bar{u}\gamma^\mu(1-\gamma^5)d = V - A \\ J_R^{\mu+} = 0 \end{cases}$$

- Vector-Like quarks: both left-handed and right-handed charged currents

$$J^{\mu+} = J_L^{\mu+} + J_R^{\mu+} = \bar{u}_L\gamma^\mu d_L + \bar{u}_R\gamma^\mu d_R = \bar{u}\gamma^\mu d = V$$

New type of gauge invariant mass term (without the Higgs)

$$\mathcal{L}_M = -M\bar{\psi}\psi$$ ex: the MSSM higgsino is a VL-Fermion

Vector Like Fermions

What are Vector-Like fermions?

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Why are they called « vector-like »?

$\mathcal{L}_W$ ... $J^{\mu-}W^-_\mu)$ Charged current

Vector-Like quarks play an important rôle in BSM physics :

- **Warped extra-dimensions**: KK excitations of bulk fields
- **Composite Higgs** models: excited resonances of the bounded states which form SM particles
- **Little Higgs** models: partners of SM fermions in larger group representations which ensure the cancellation of divergent loops
- **Gauged flavour group** with low scale gauge flavor bosons: required to cancel anomalies in the gauged flavor symmetry
- **N>1 SUSY**: super-partners of gauge fields

- SM ... $V - A$

- Vector-Like quarks: both left-handed ... rents

$$J^{\mu+} = J^{\mu+}_L + J^{\mu+}_R = \bar{u}_L\gamma^\mu d_L + \bar{u}_R\gamma^\mu d_R = \bar{u}\gamma^\mu d = V$$

New type of gauge invariant mass term (without the Higgs)

$\mathcal{L}_M = -M\bar{\psi}\psi$ ex: the MSSM higgsino is a VL-Lepton

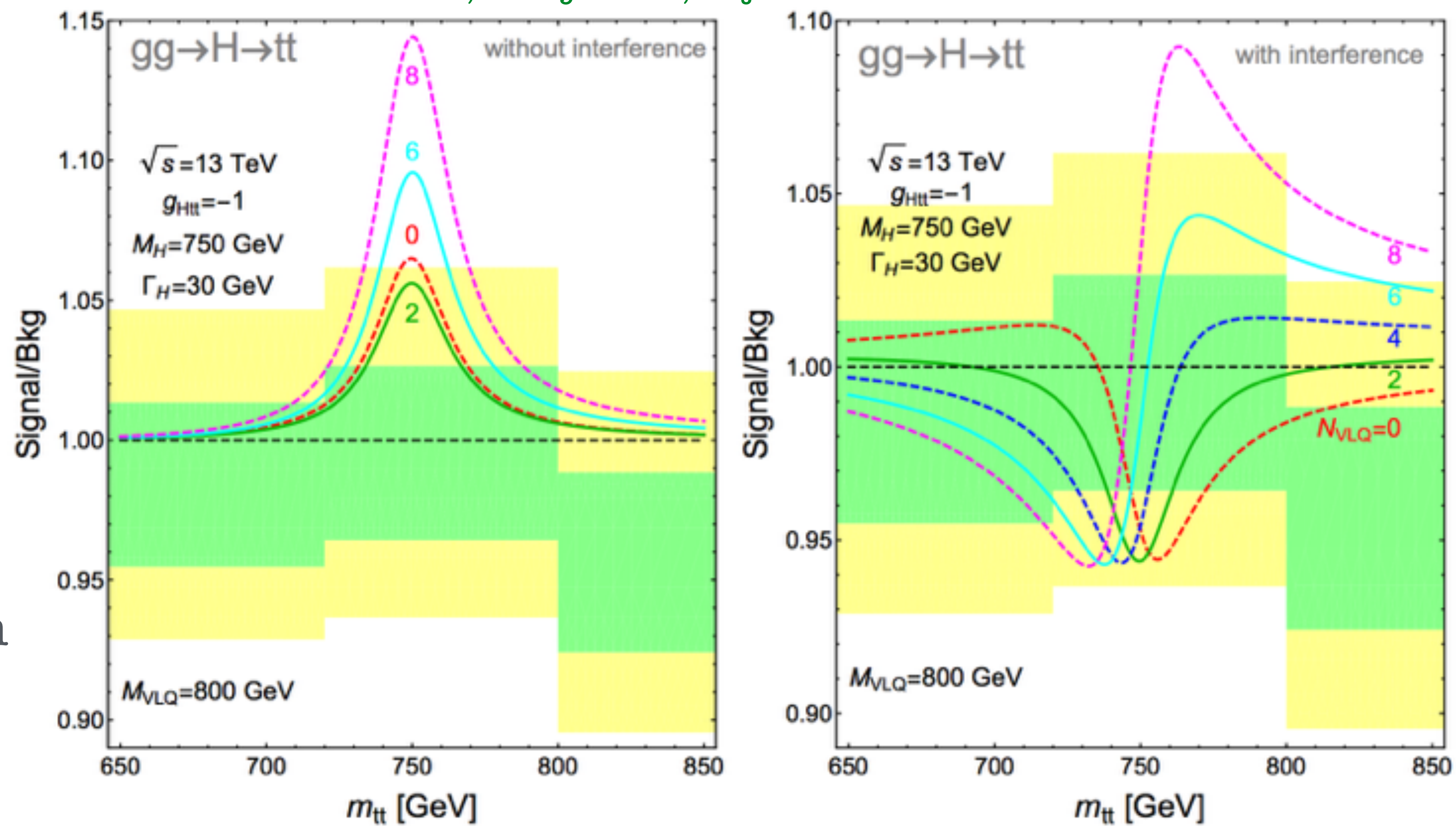
If VLQ are also in the loop

The top quark and VLQ induce the gluon width :

$$\Gamma(\Phi \to gg) = \frac{G_\mu \alpha_s^2 M_\Phi^3}{64\sqrt{2}\pi^3} \left| \sum_Q \hat{g}_{\Phi QQ} A_{1/2}^{\Phi}(\tau_Q) \right|^2 \quad \text{with} \quad \hat{g}_{\Phi QQ} = \frac{v}{m_Q} \hat{y}_Q$$

note that heavy VLQ decouple $\neq$ heavy chiral fermion regarding $\Gamma(h_{\rm SM} \to gg)$

J. Ellis, A. Djouadi, JQ arXiv: 1605.00542

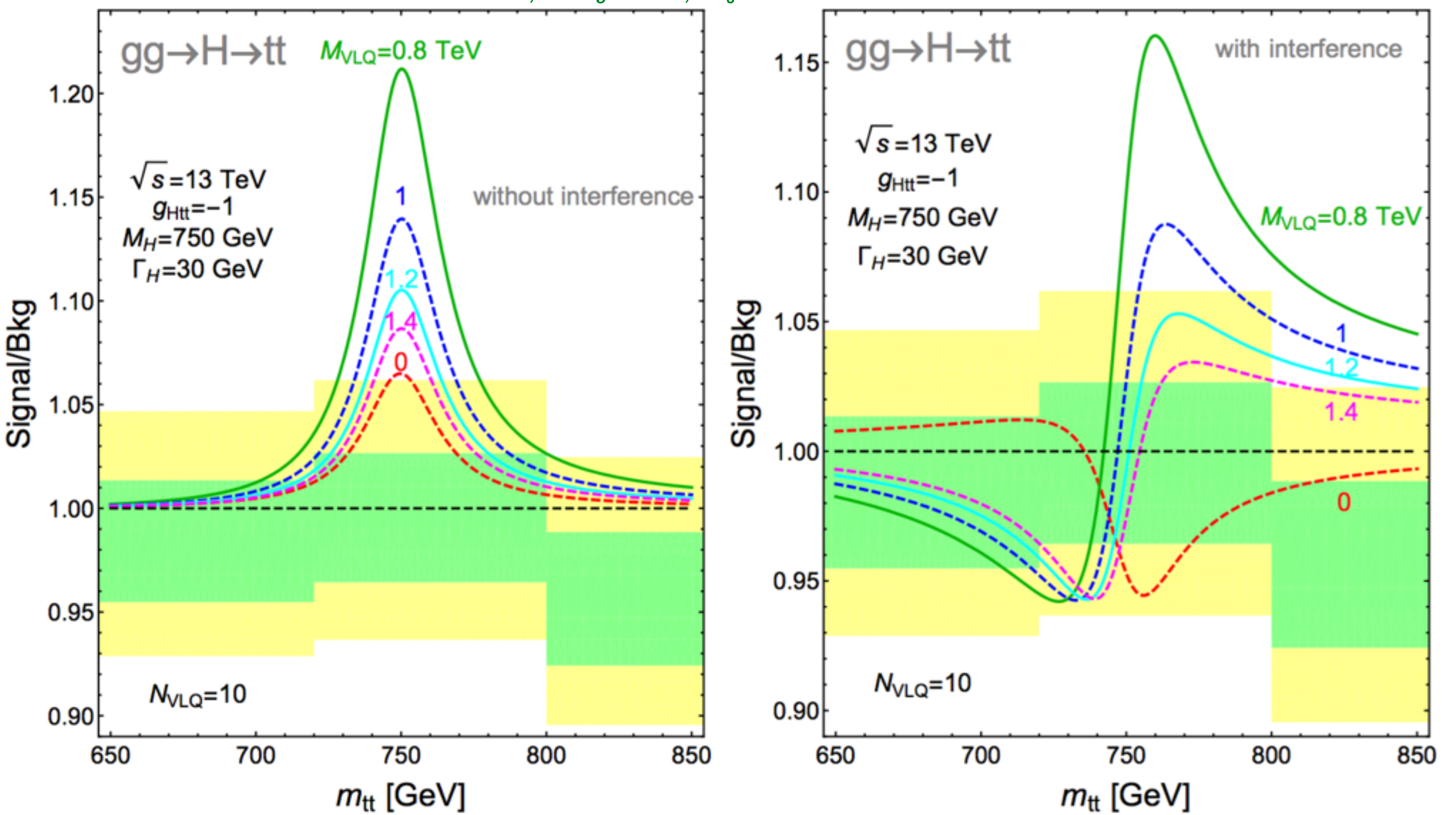


strong exclusion limits

weaker exclusion limits

If VLQ are also in the loop

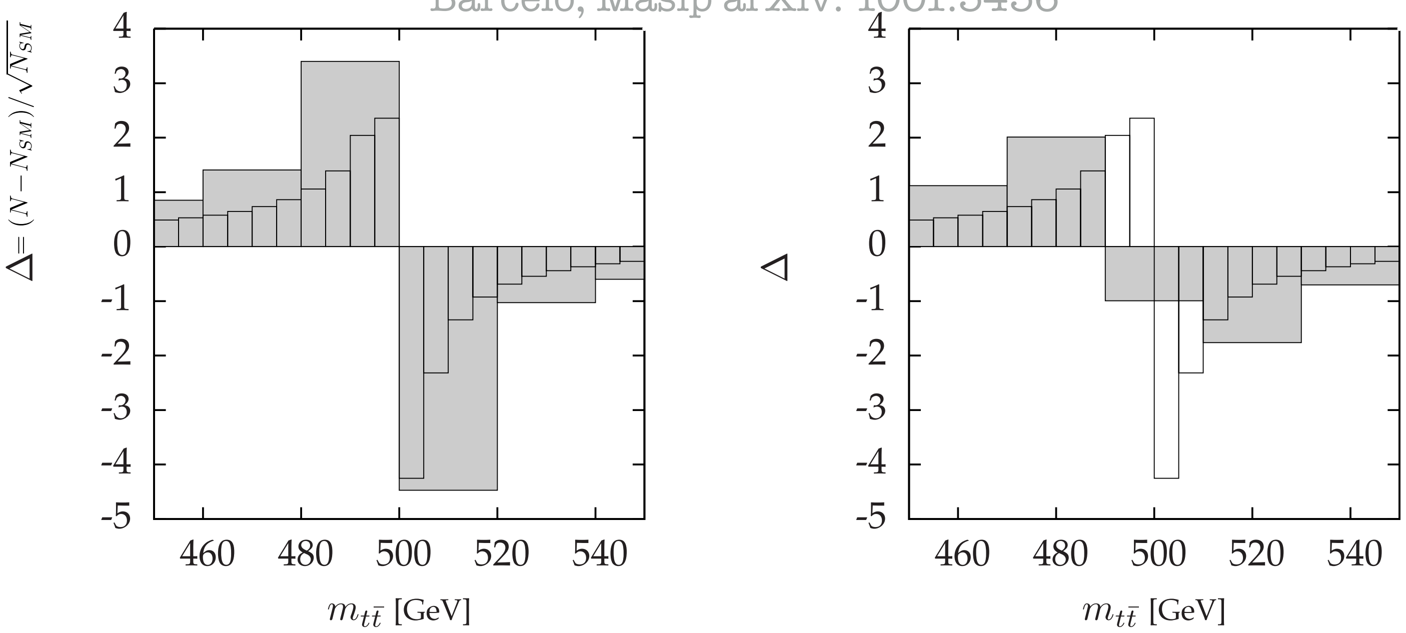
J. Ellis, A. Djouadi, JQ   arXiv: 1605.00542



Challenging the SM background

- First challenge: search for non-conventional peak-dip, dip-peak, dip structures
- By mis-reconstruction: events in the peak could populate the dip (& vice versa)
  ⟶ smearing effect reduces the significance of the lineshape analysis
- statistical uncertainty << systematic uncertainty (key point to achieve sensitivity in this channel)
  ⟶ Thanks to the large data set one can afford a lower signal efficiency with higher quality in $m_{t\bar{t}}$ reconstruction accuracies?
  ⟶ new analysis technics to reduce the systematics?
- changing the binning is important in order to optimize the effect

Barcelo, Masip arXiv: 1001.5456



the most sensitive way to search for such effects would be to use off-centre bins

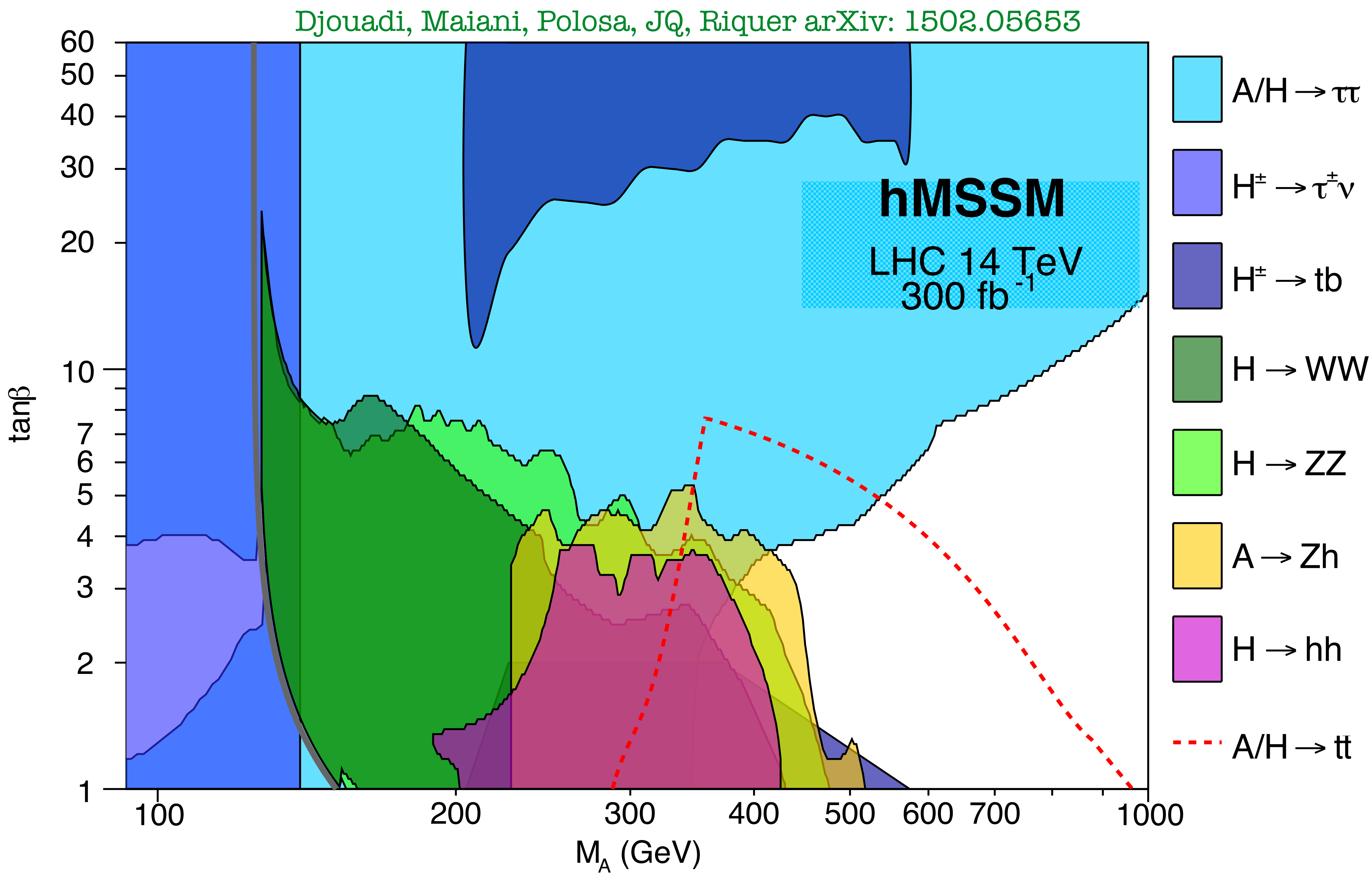
-> 2 binning sets for 1 analysis ?

Conclusions

- Searching for a top quark pair resonance is promising for new physics
- Interference effects are crucial: need to go beyond a parametrization in terms of the total rate
- Interference effects contain information on new resonances and also new particles in the loop inducing coupling to gluons
- Develop procedure to analyse carefully lineshapes looking for bump, peak-dip,dip-peak and simple deep
- Important challenge concerning the systematic uncertainty of the $t\bar{t}$ SM background
- the $gg \to t\bar{t}$ process will allow us to test the low $\tan\beta$ region of the MSSM Higgs sector

Thank You !

Projected constraints 1



The hMSSM

In the basis (H_d, H_u), the CP–even Higgs mass matrix can be written as:

$$M_S^2 = M_Z^2 \begin{pmatrix} c_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & s_\beta^2 \end{pmatrix} + M_A^2 \begin{pmatrix} s_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & c_\beta^2 \end{pmatrix} + \begin{pmatrix} \Delta\mathcal{M}_{11}^2 & \Delta\mathcal{M}_{12}^2 \\ \Delta\mathcal{M}_{12}^2 & \Delta\mathcal{M}_{22}^2 \end{pmatrix}$$

$\Delta\mathcal{M}_{ij}^2$: radiative corrections

One derives the neutral CP-even Higgs boson masses and the mixing angle α:

$$\begin{aligned} M_{h/H}^2 &= f_{h/H}(M_A, \tan\beta, \Delta\mathcal{M}_{11}, \Delta\mathcal{M}_{12}, \Delta\mathcal{M}_{22}) \\ \tan\alpha &= f_\alpha(M_A, \tan\beta, \Delta\mathcal{M}_{11}, \Delta\mathcal{M}_{12}, \Delta\mathcal{M}_{22}) \end{aligned}$$

M_h should be an input now...

The post-Higgs MSSM scenario:

- observation of the lighter h boson at a mass of $\approx 125\ GeV$
- non-observation of superparticles at the LHC

MSSM $\Rightarrow$ SUSY–breaking scale rather high, $M_S \gtrsim 1$ TeV.

$\Delta\mathcal{M}_{22}^2$ involves the by far dominant stop–top sector correction: $\Delta\mathcal{M}_{22}^2 \gg \Delta\mathcal{M}_{11}^2, \Delta\mathcal{M}_{12}^2$

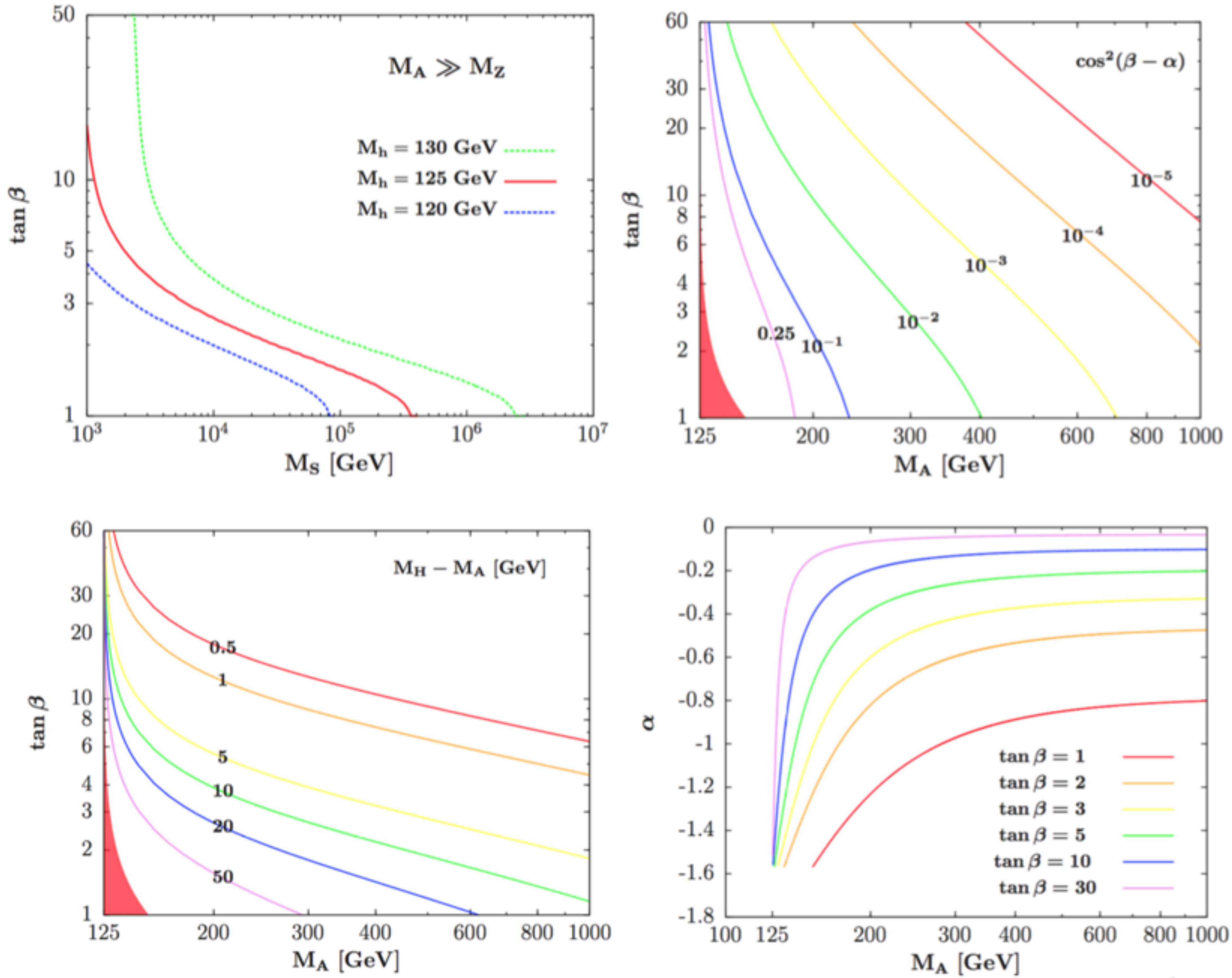
$\rightarrow$ One can trade $\Delta\mathcal{M}_{22}^2$ (M_S) for the by now known M_h

In this case, one can simply describe the Higgs sector in terms of $M_A, \tan\beta$ and M_h:

$$\text{hMSSM}: \quad \begin{aligned} M_H^2 &= \frac{(M_A^2+M_Z^2-M_h^2)(M_Z^2 c_\beta^2+M_A^2 s_\beta^2)-M_A^2 M_Z^2 c_{2\beta}^2}{M_Z^2 c_\beta^2+M_A^2 s_\beta^2-M_h^2} \\ \alpha &= -\arctan\left(\frac{(M_Z^2+M_A^2)c_\beta s_\beta}{M_Z^2 c_\beta^2+M_A^2 s_\beta^2-M_h^2}\right) \end{aligned}$$

The definition of the hMSSM

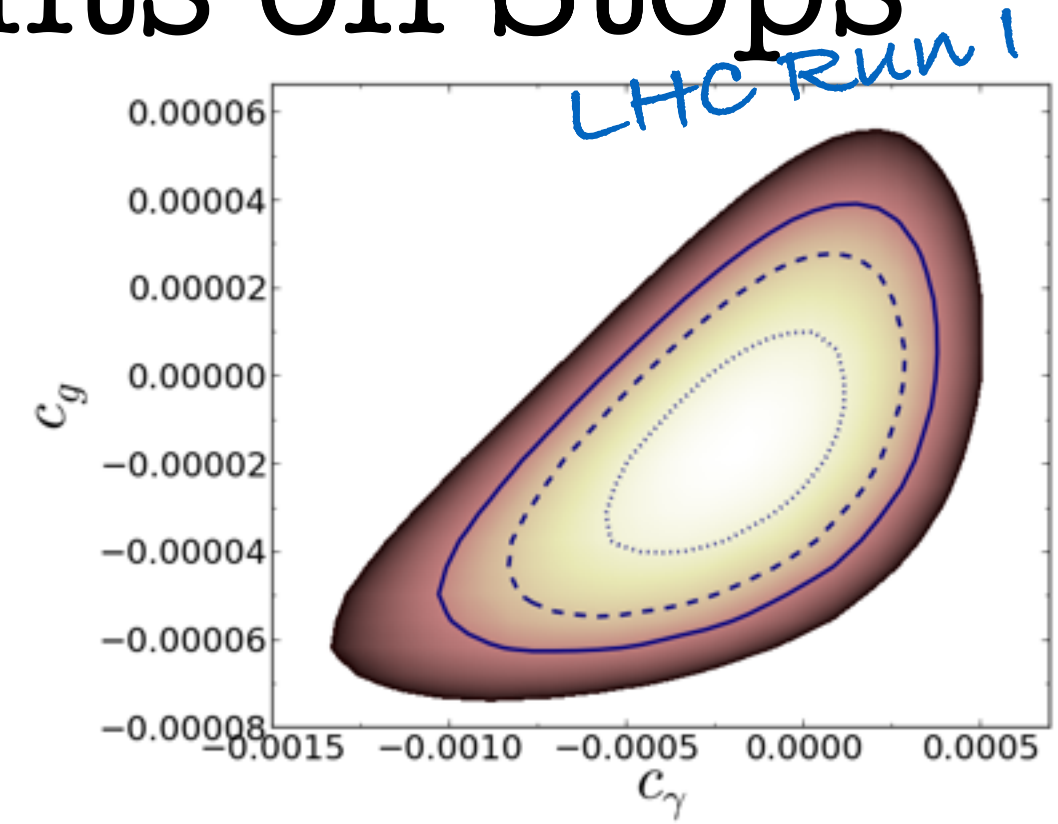
Djouadi, Maiani, Polosa, JQ, Riquer, arXiv:1502.05653

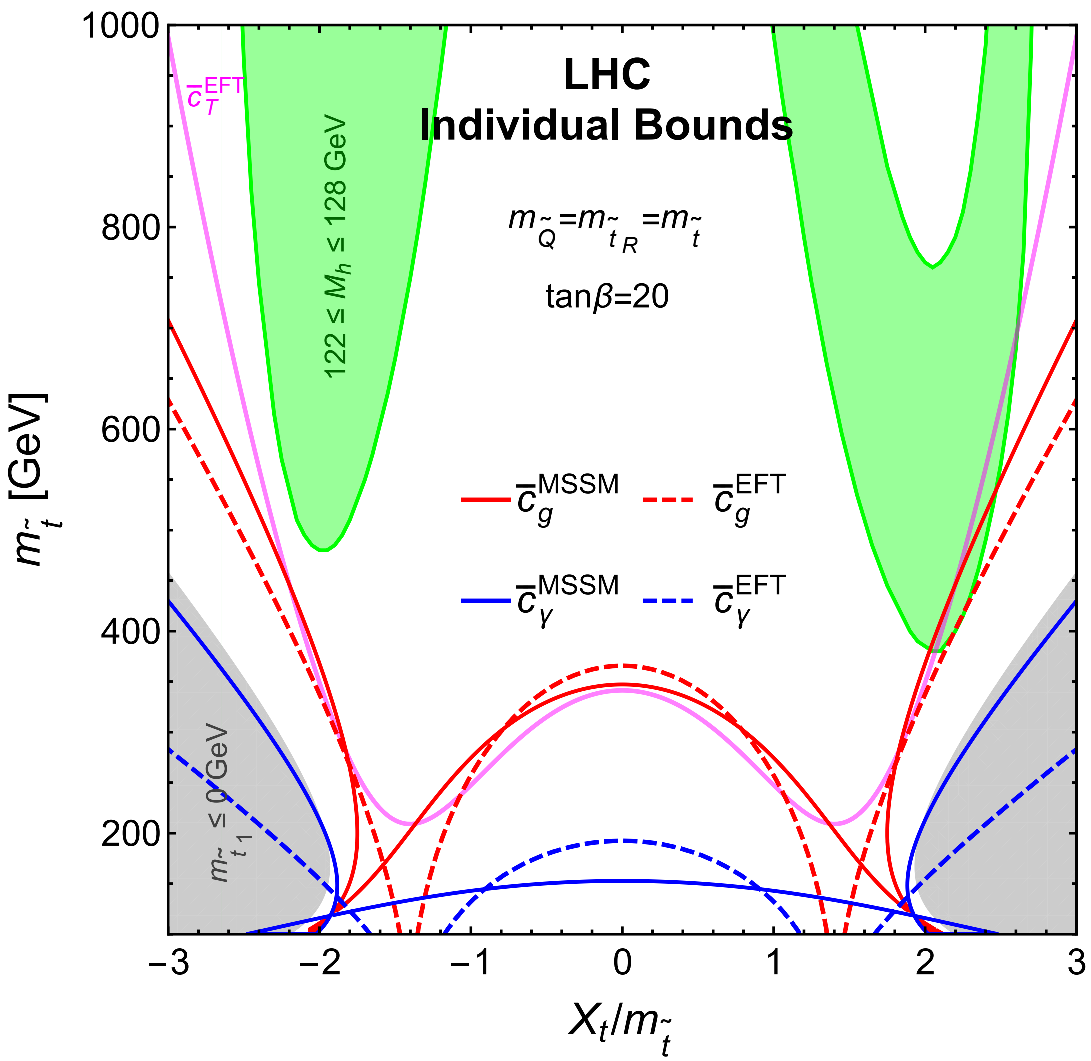


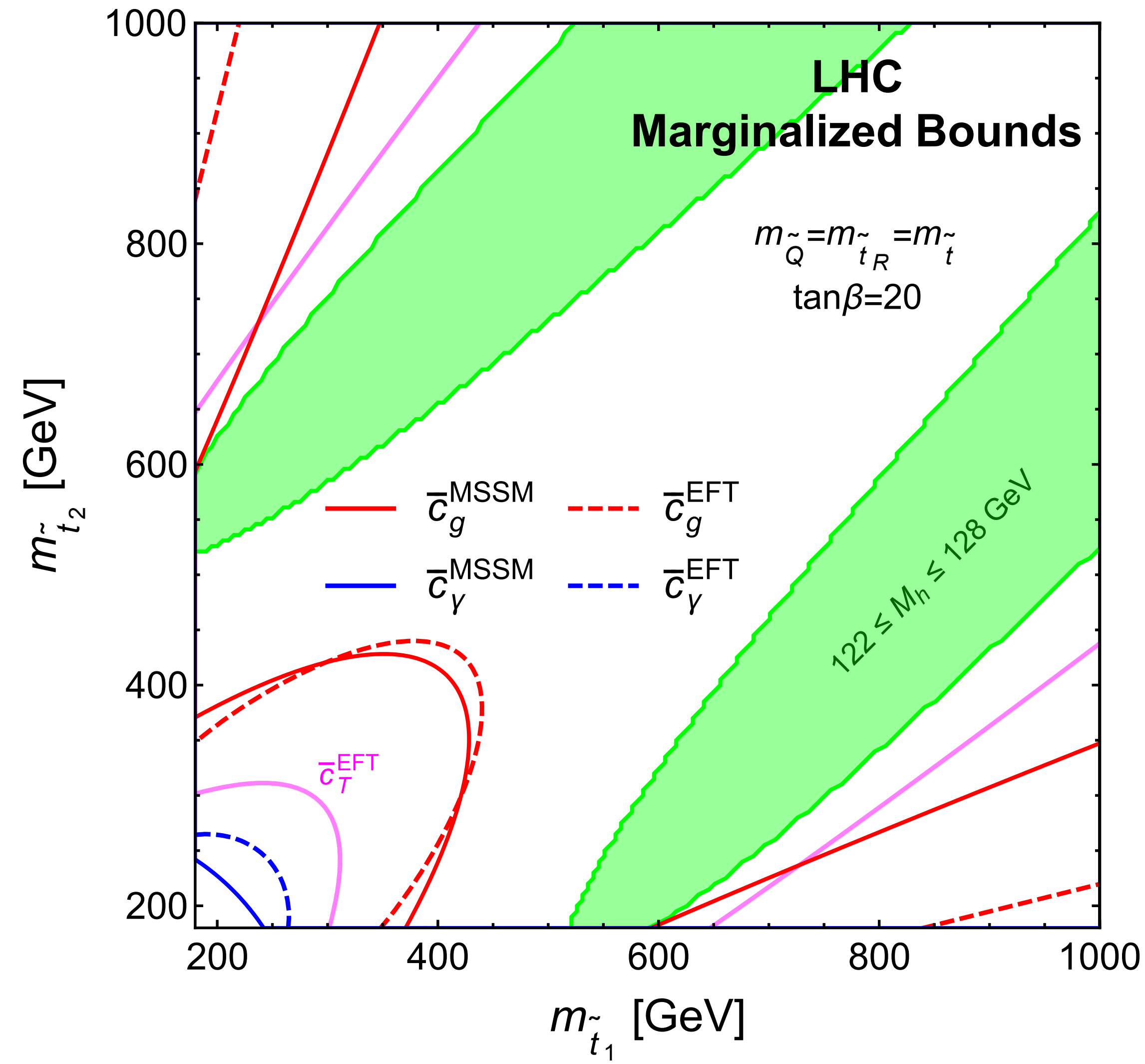
Indirect Constraints on Stops

A. Drozd, J. Ellis, JQ and T. You arXiv:1504.02409

Coeff.	Experimental constraints		95 % CL limit	deg. $m_{\tilde{t}_1}$, $X_t = 0$
$\bar{c}_g$	LHC	marginalized	$[-4.5, 2.2] \times 10^{-5}$	~ 410 GeV
		individual	$[-3.0, 2.5] \times 10^{-5}$	~ 390 GeV
$\bar{c}_\gamma$	LHC	marginalized	$[-6.5, 2.7] \times 10^{-4}$	~ 215 GeV
		individual	$[-4.0, 2.3] \times 10^{-4}$	~ 230 GeV
$\bar{c}_T$	LEP	marginalized	$[-10, 10] \times 10^{-4}$	~ 290 GeV
		individual	$[-5, 5] \times 10^{-4}$	~ 380 GeV
$\bar{c}_W + \bar{c}_B$	LEP	marginalized	$[-7, 7] \times 10^{-4}$	~ 185 GeV
		individual	$[-5, 5] \times 10^{-4}$	~ 195 GeV

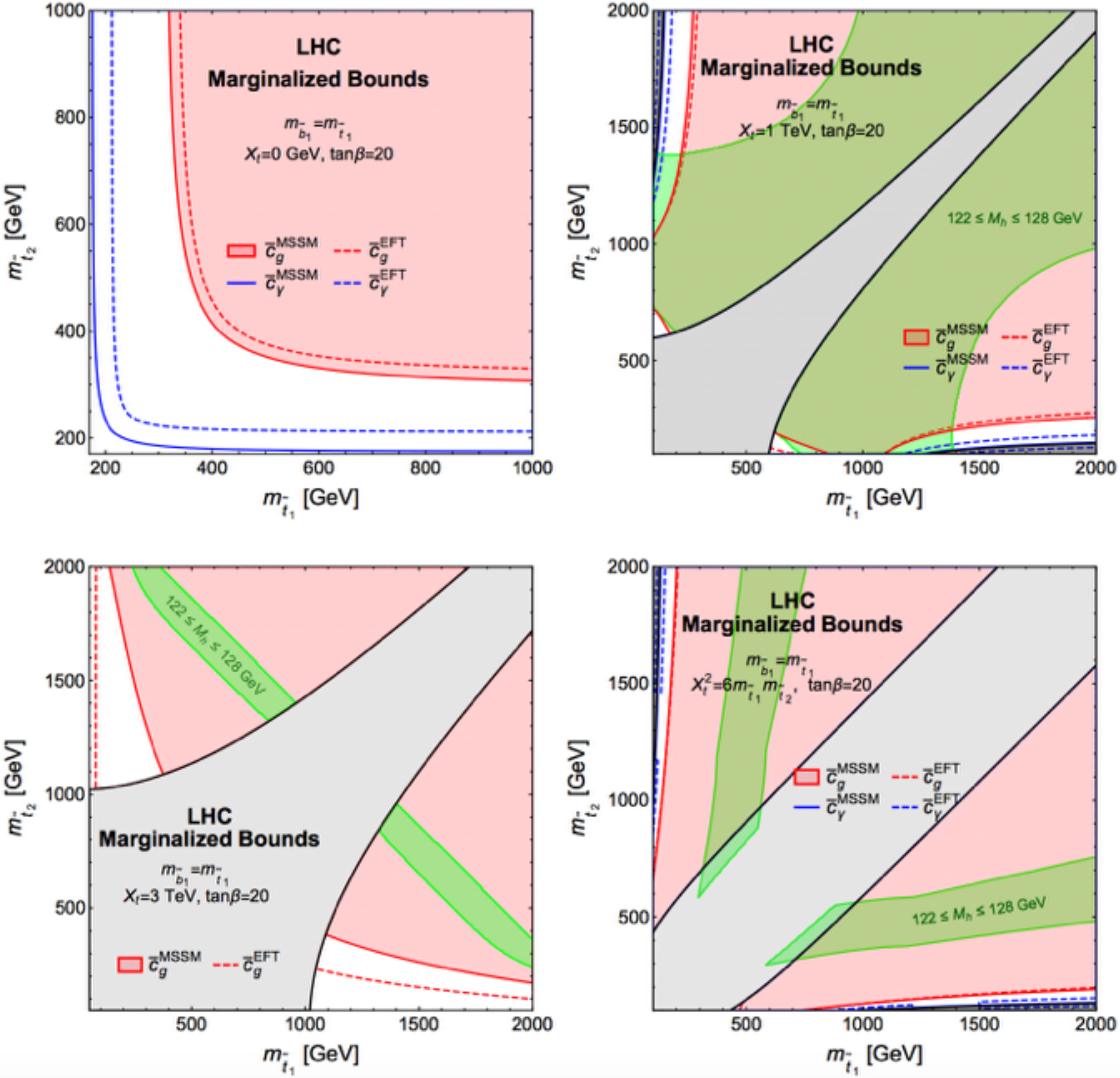






Indirect Constraints on Stops

LHC Run I



A. Drozd, J. Ellis, JQ and T. You arXiv:1504.02409

The current sensitivity is already comparable to that of direct LHC searches