Searching for New Physics Through Interference Effects

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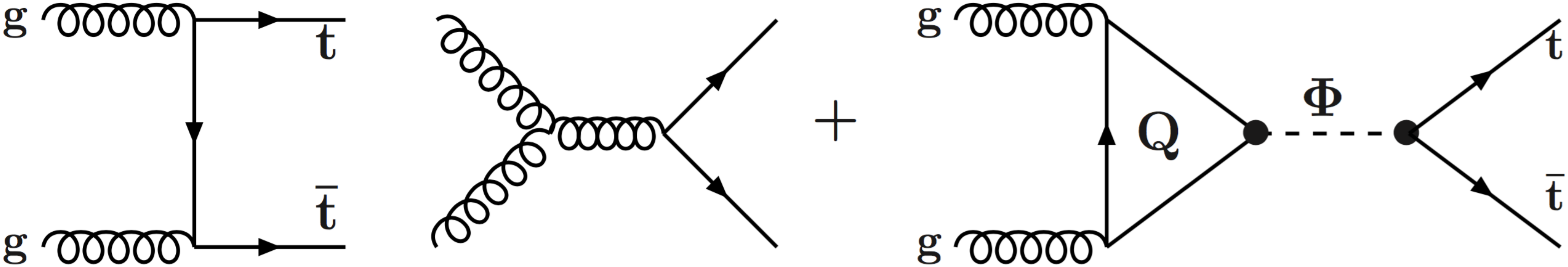
Introduction

- Most of experimental searches interpreted as $\sigma_{\rm signal} \times BR$ so far
- But interferences could be huge and looking at it could shed light on new physics through non-trivial lineshape effects in various distributions
- Most of the extensions of the SM require additional scalar bosons, need to go beyond the usual 5σ bump discovery
- LHC Run II has started to be sensible to such non standard effects

1. Basics of interference effects
2. $t\bar{t}$ production as a window on new physics
3. BSM benchmarks, analysis and sensitivity plots

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



SM continuum

BSM scalar resonance

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

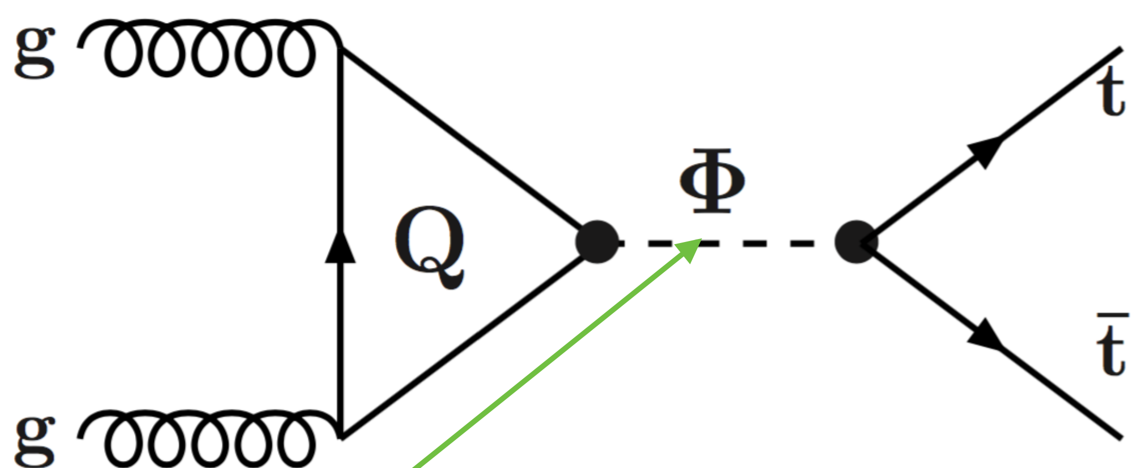
$$|\mathcal{A}_{tot}|^2 = \mathcal{A}_{cont}^2 + |\mathcal{A}_{res}|^2 + \underbrace{\mathcal{A}_{cont} \times (\mathcal{A}_{res} + \mathcal{A}_{res}{}^*)}_{\text{interference}}$$

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

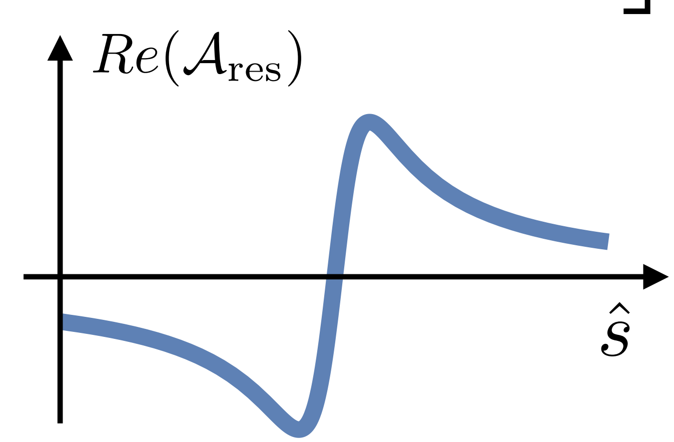
Real part of Interferences

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

usual Breit-Wigner   interference(s)



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



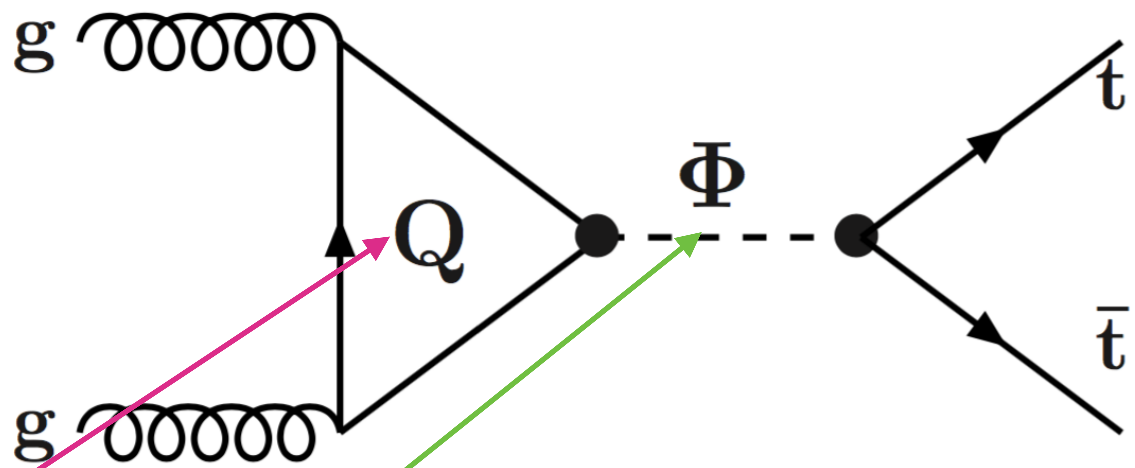
- No interference on shell
- The new contribution is antisymmetric around M

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...

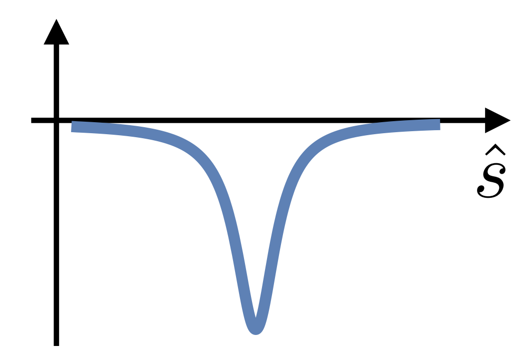
Imaginary part of Interferences

$$|\mathcal{A}_{tot}|^2 = \underbrace{\mathcal{A}^2_{cont} + |\mathcal{A}_{res}|^2}_{\text{usual Breit-Wigner}} + \underbrace{\mathcal{A}_{cont} \times 2Re(\mathcal{A}_{res})}_{\text{interference(s)}}$$



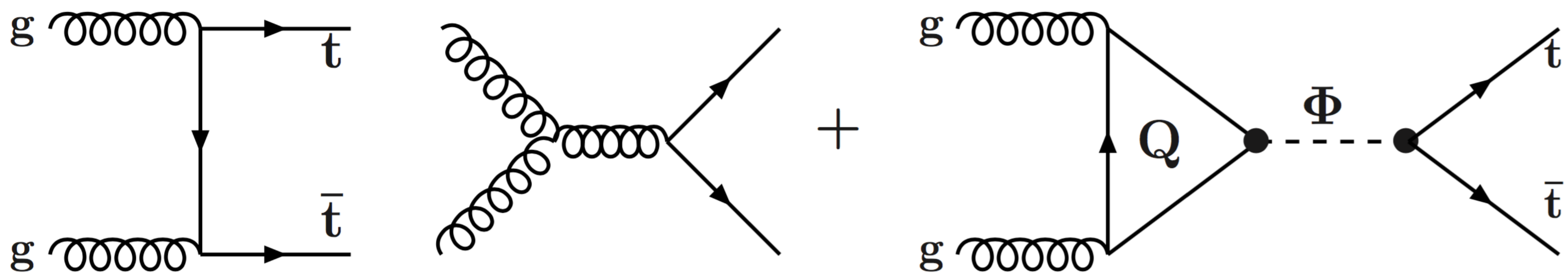
$$\mathcal{A}_{res} = \mathcal{A}e^{i\phi}\boxed{\frac{M^2}{\hat{s} - M^2 + iM\Gamma}} = \mathcal{A}\left[\underbrace{cos\phi\frac{M^2(\hat{s} - M^2)}{(\hat{s} + M^2)^2 + M^2\Gamma^2}}_{\text{as before}} + \underbrace{sin\phi\frac{M\Gamma}{(\hat{s} - M^2)^2 + M^2\Gamma^2}}_{\text{new part}} + i(\ldots)\right]$$

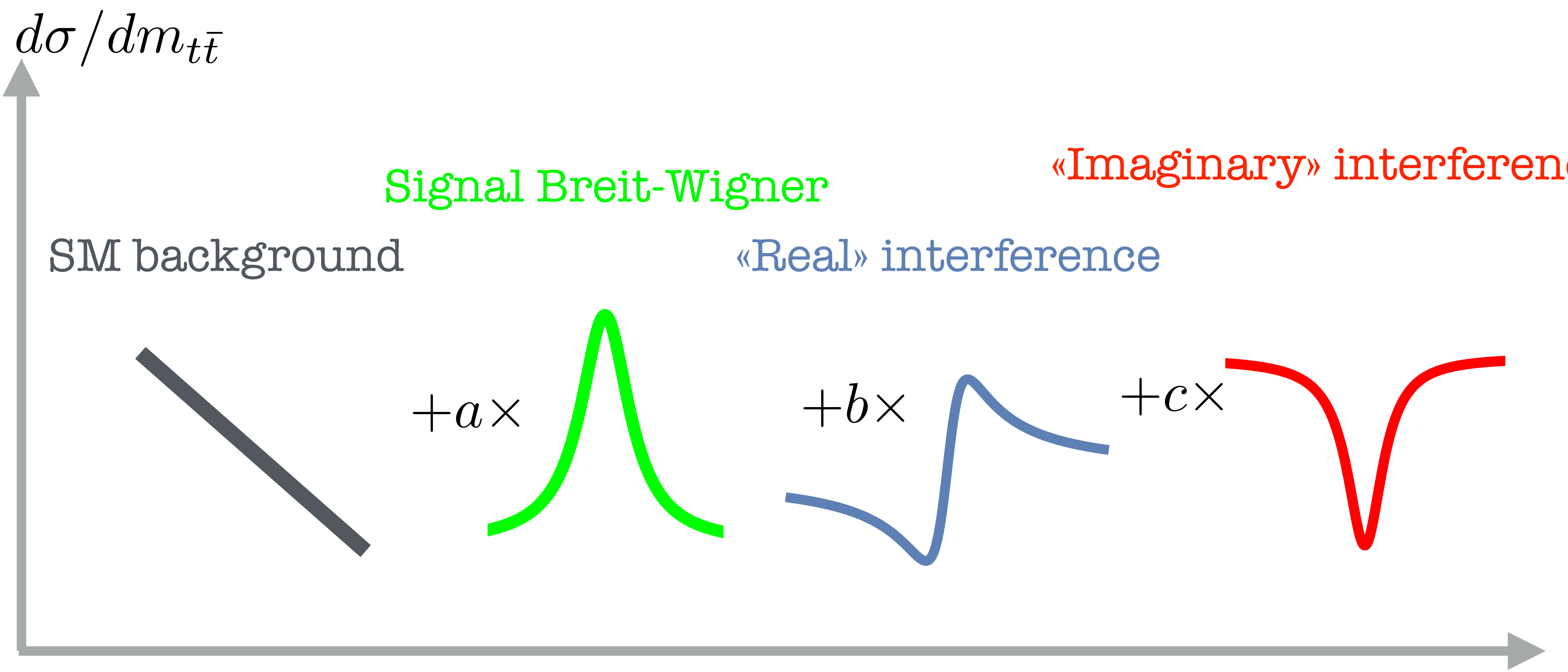
- New interference term does not vanish on shell
- The new contribution does contribute to σ_{tot}



- Interferences are sensible to New Physics through many ways!

Interference lineshapes





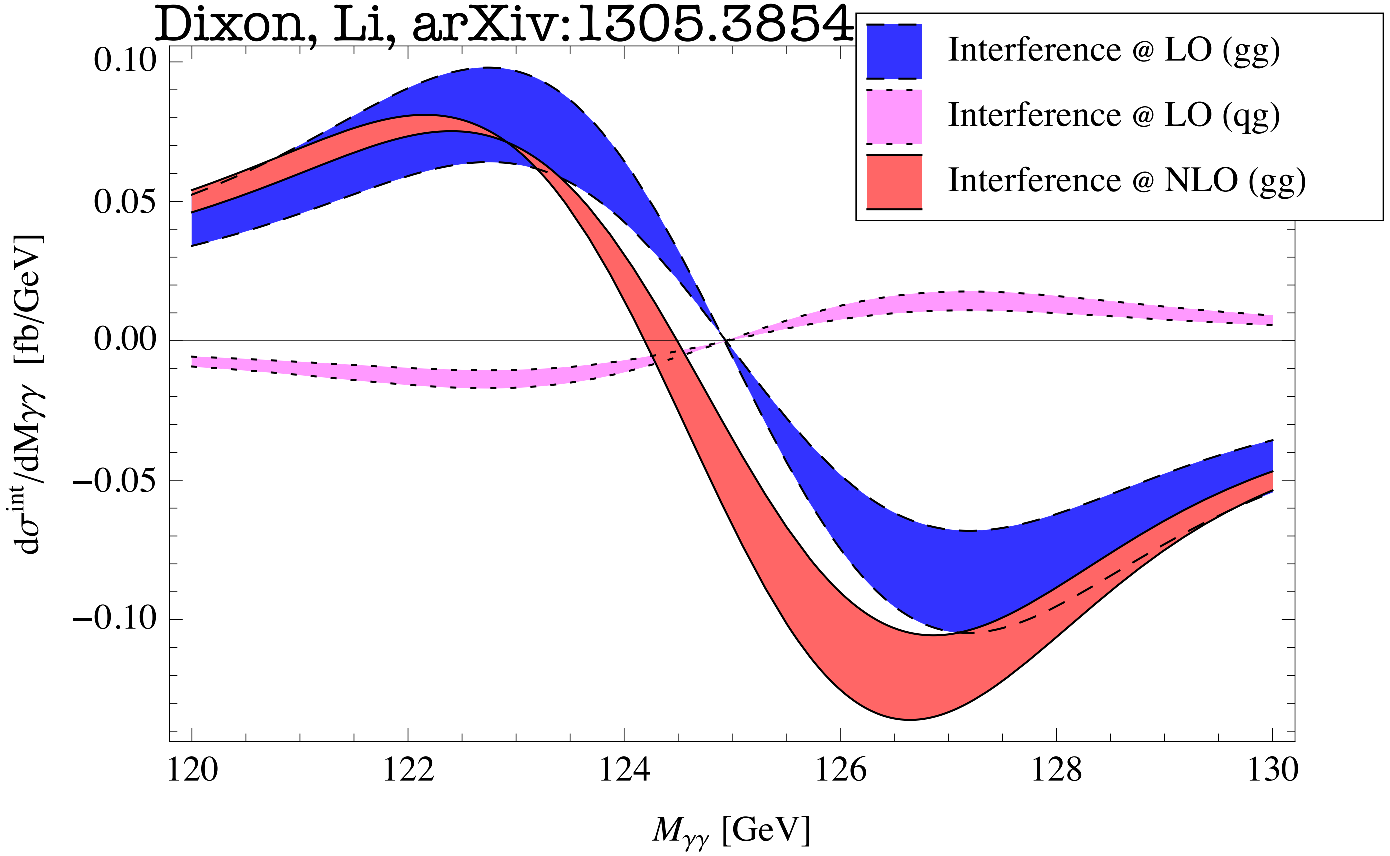
imagine the result with two (non) degenerate resonances as in the (2HDM) MSSM for example, with CP violation ...

SM Application: width measurements of the SM Higgs

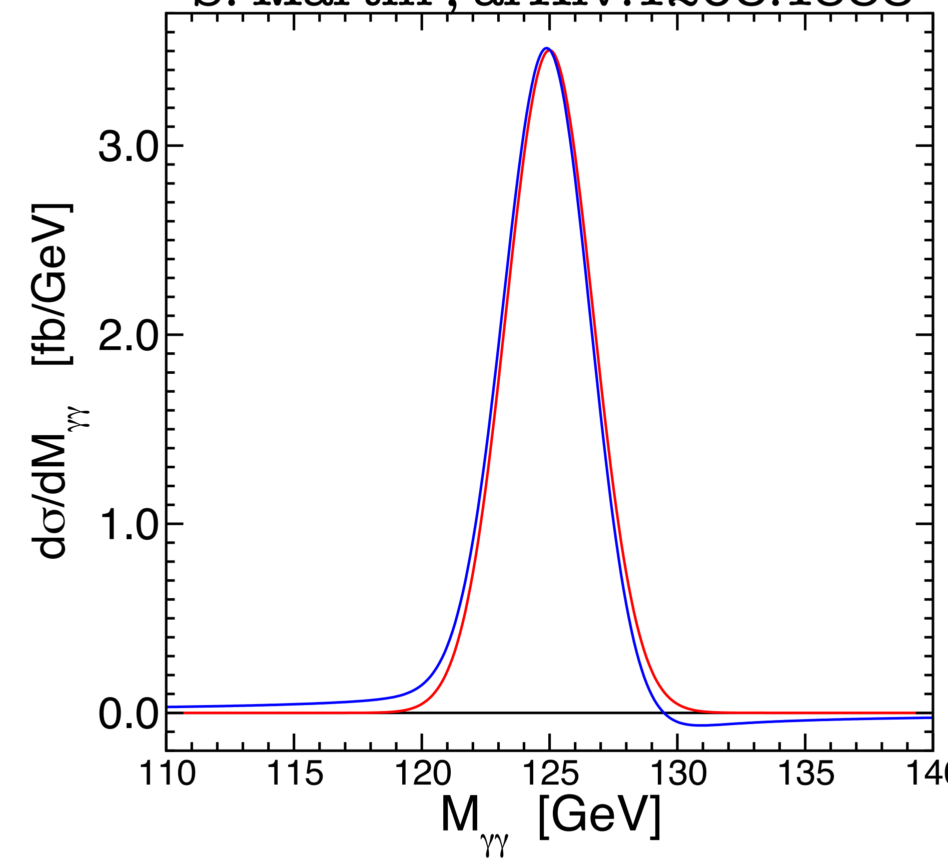
Higgs mass peak shift in $H \to \gamma\gamma$:

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

Dixon, Li, arXiv:1305.3854

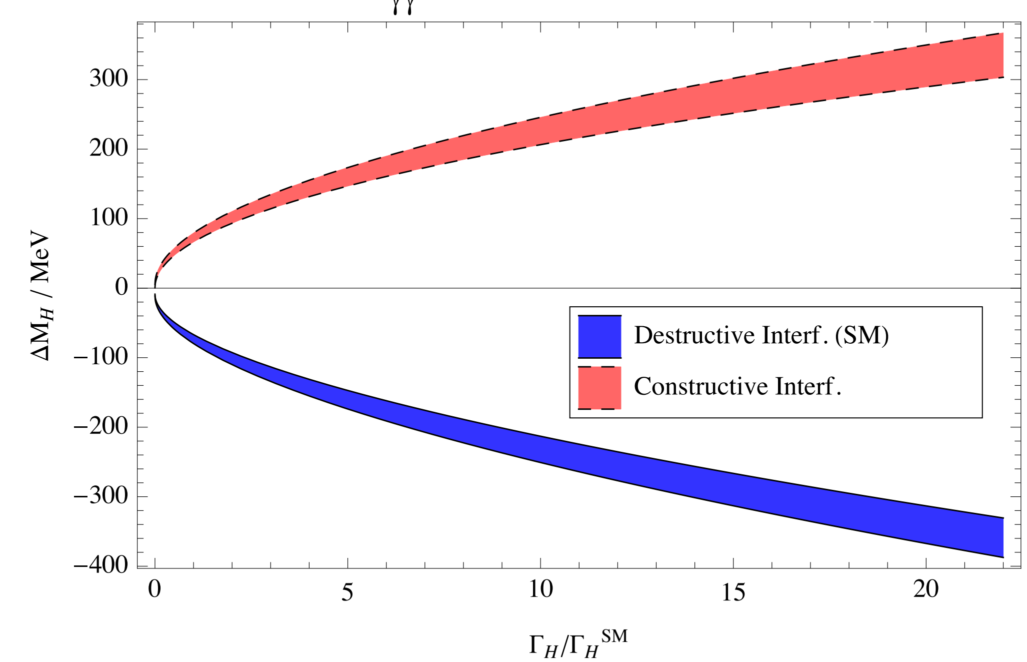


S. Martin , arXiv:1208.1533



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

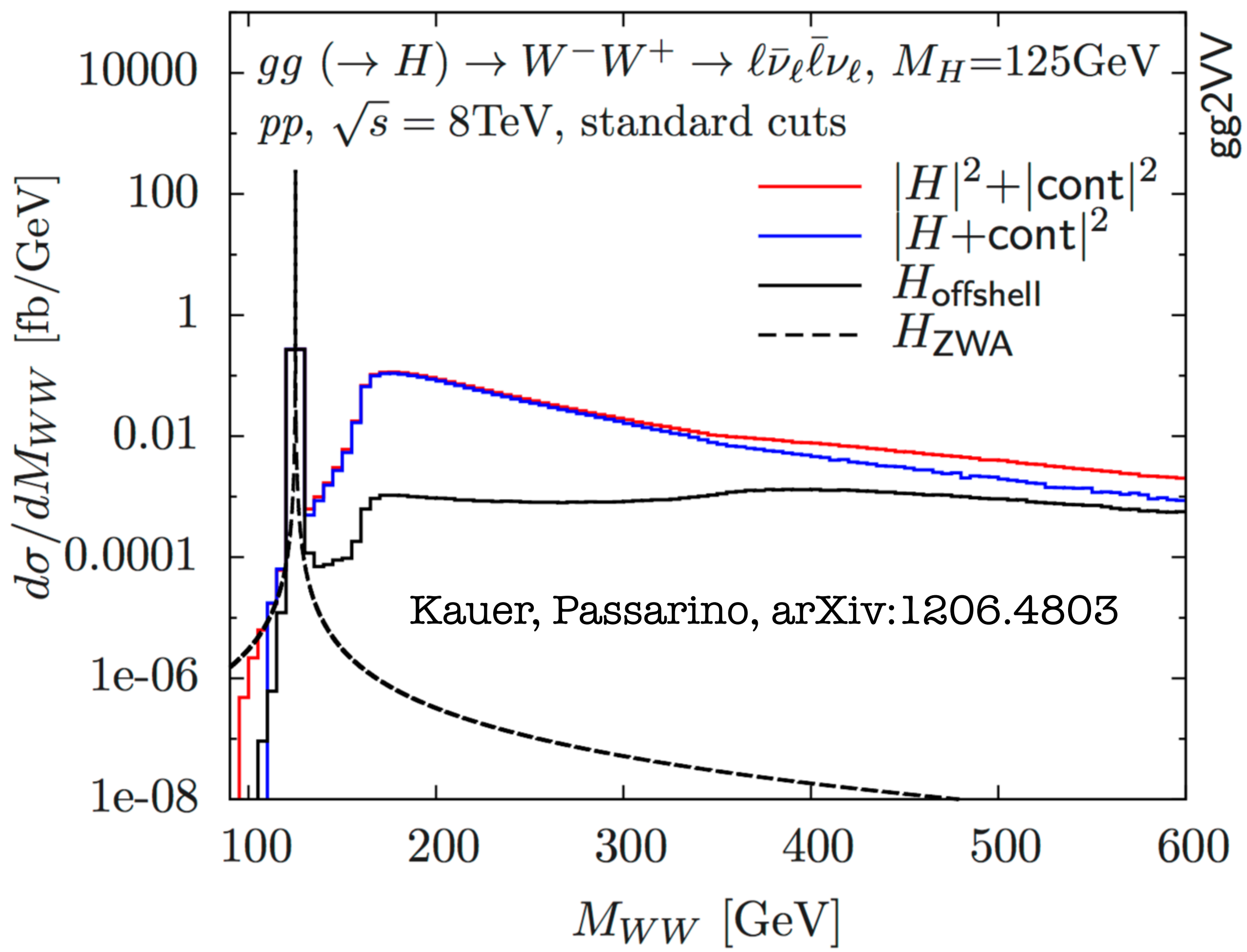
Bigger effect with BSM resonances in $gg \to \Phi \to t\bar{t}$

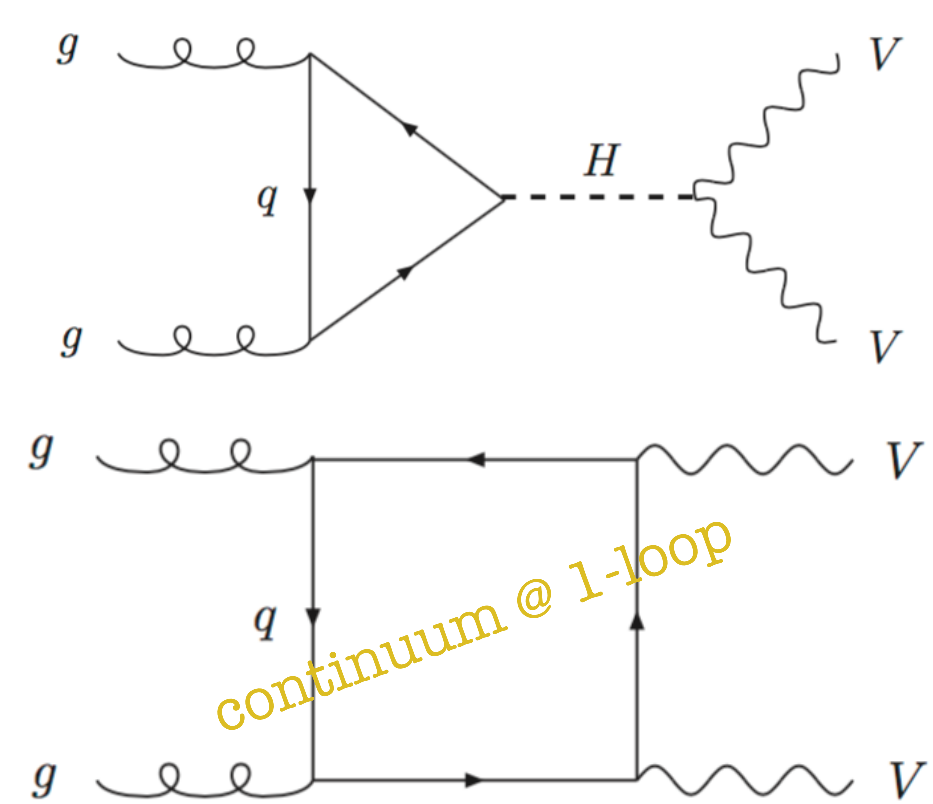


Application: width measurements of the SM Higgs

Higgs mass shift in off-shell regions:

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



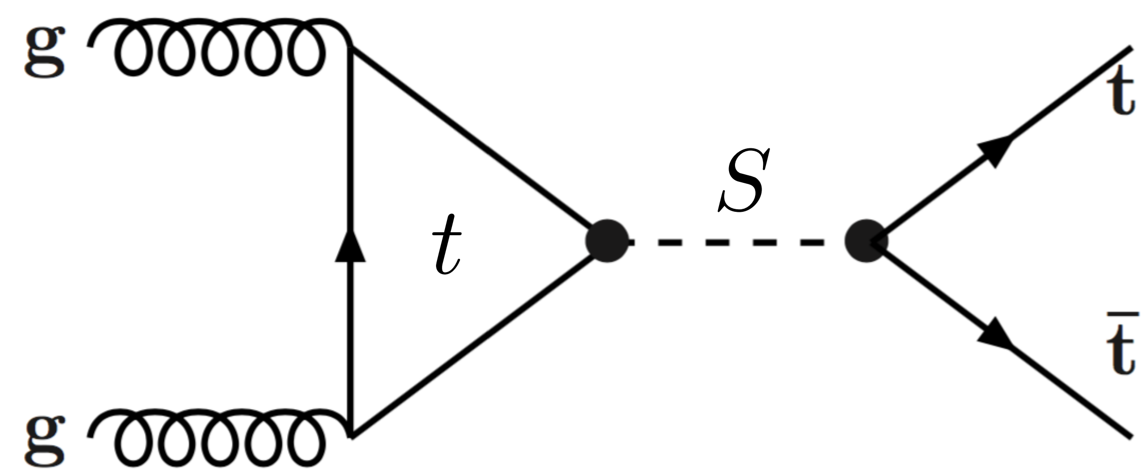


- Large interference effects, O(10%)
- LHC Run 1 data yields a Higgs width constraint of $\frac{\Gamma_H}{\Gamma_H^{SM}} \lesssim 5$

Bigger effects with heavier BSM resonances with large width (ex: $gg \to \Phi \to t\bar{t}$)

BSM generic model

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



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

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

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

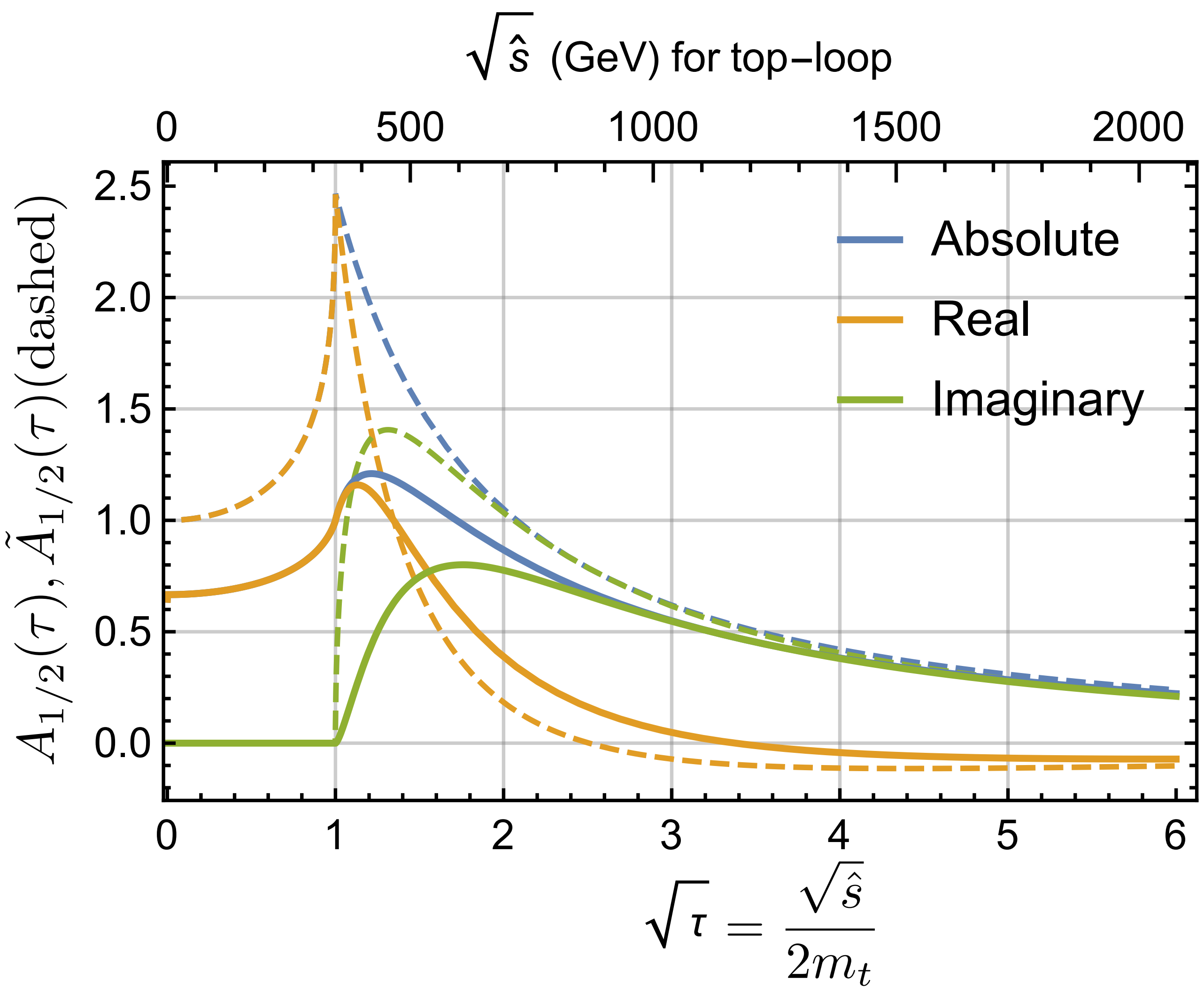
$$\tilde{g}_{sgg}(\hat{s}) = \frac{\alpha_s}{\#} \frac{\tilde{y}_t}{m_t} \tilde{A}_{1/2}(\tau)$$

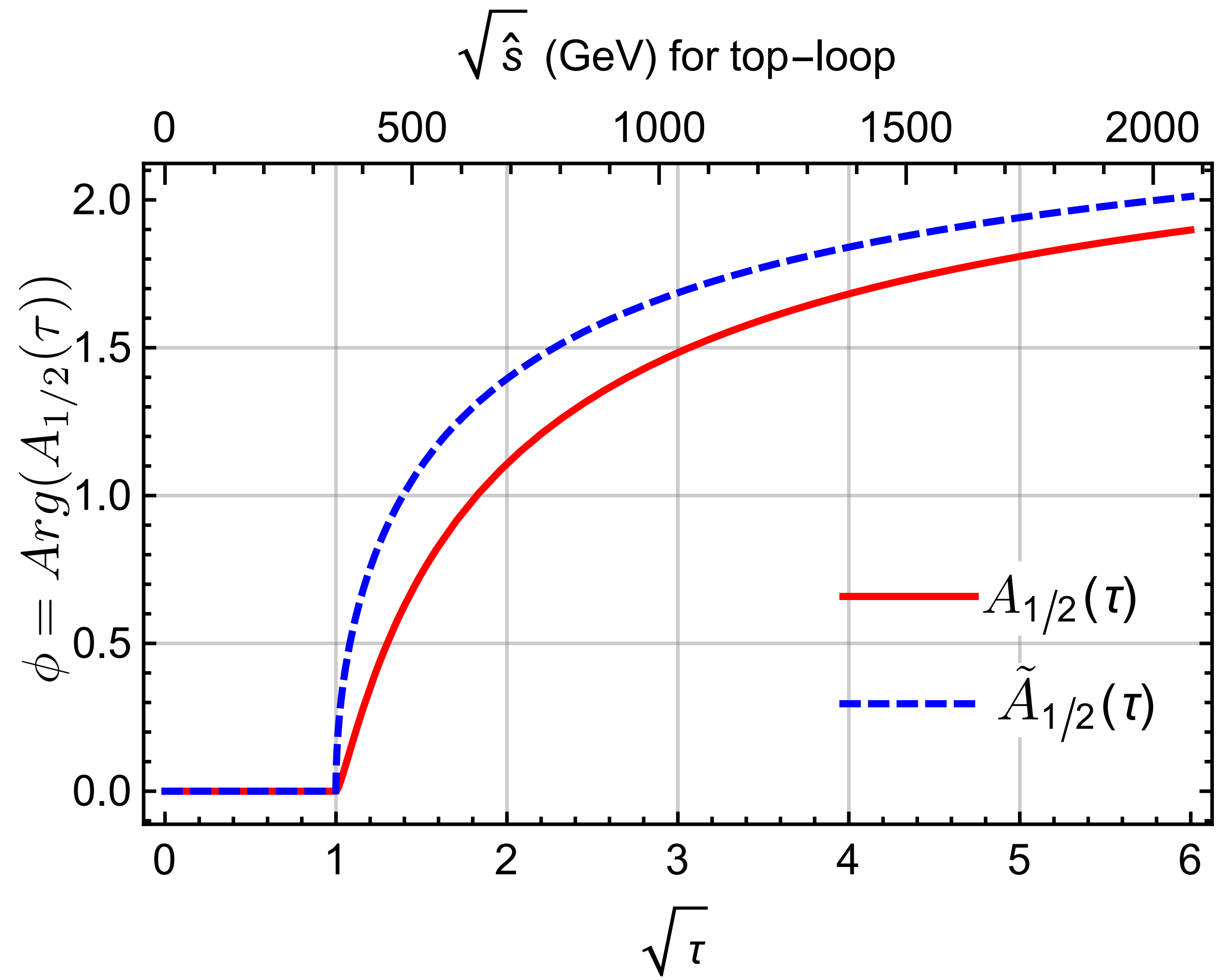
$$\tilde{A}_{1/2}(\tau) = 2\tau^{-1} f(\tau)$$

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

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

The form factors

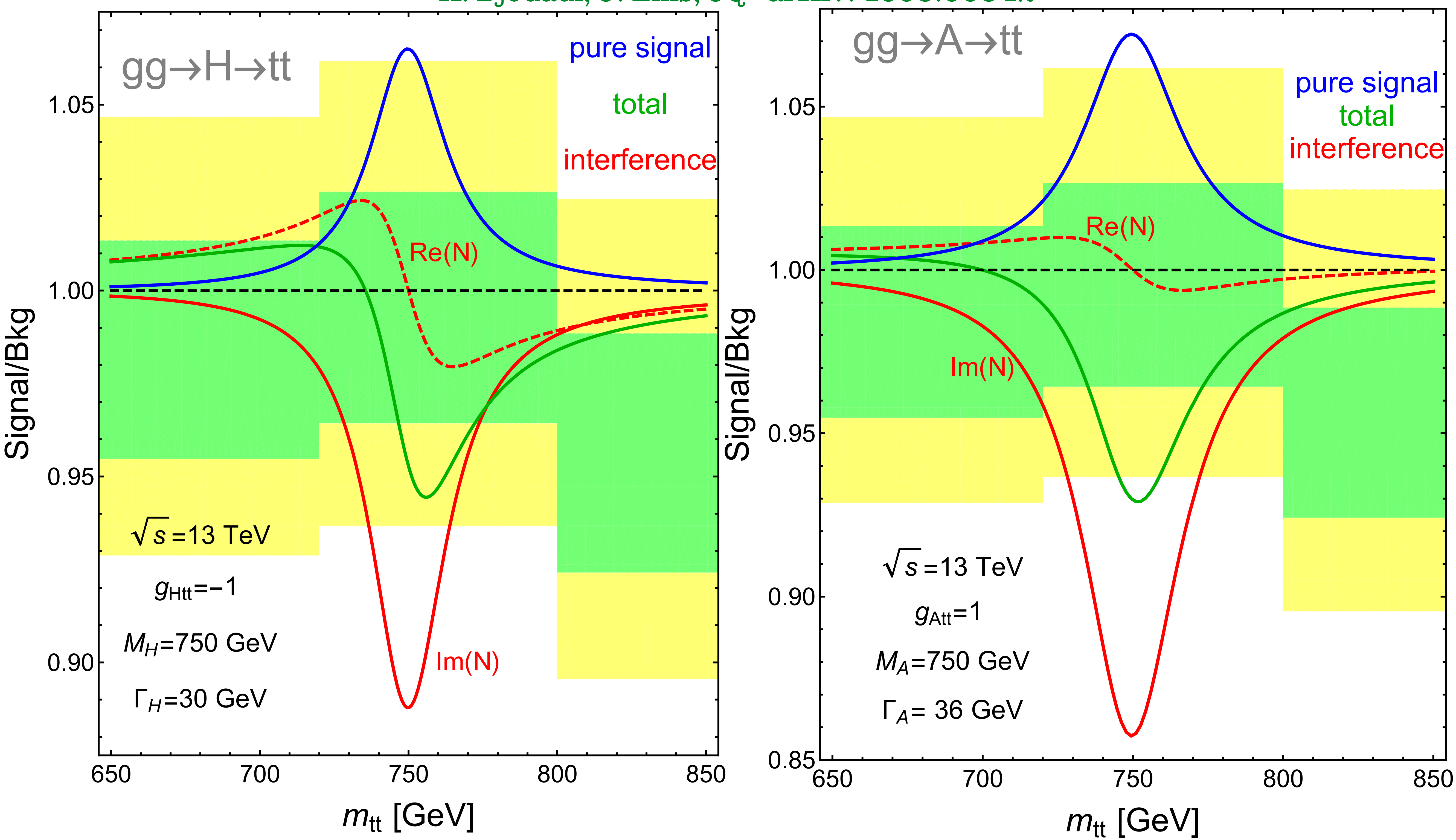




- In the SM, any heavy chiral fermion does not decouple : $g_{hgg}(\hat{s}) = \frac{\alpha_s}{3\pi v} + \mathcal{O}(\tau)$
- ϕ growth quickly and is large $\sim \pi/2 \Rightarrow$ particular BSM phenomenology
- $\phi = \pi/4 \;: Re(A_{1/2}) = Im(A_{1/2}), M_S = 550$ GeV and $M_{PS} = 450$ GeV
- $\phi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

New scalar with the top in the loop

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



2. $t\bar{t}$ production as a window on new physics

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

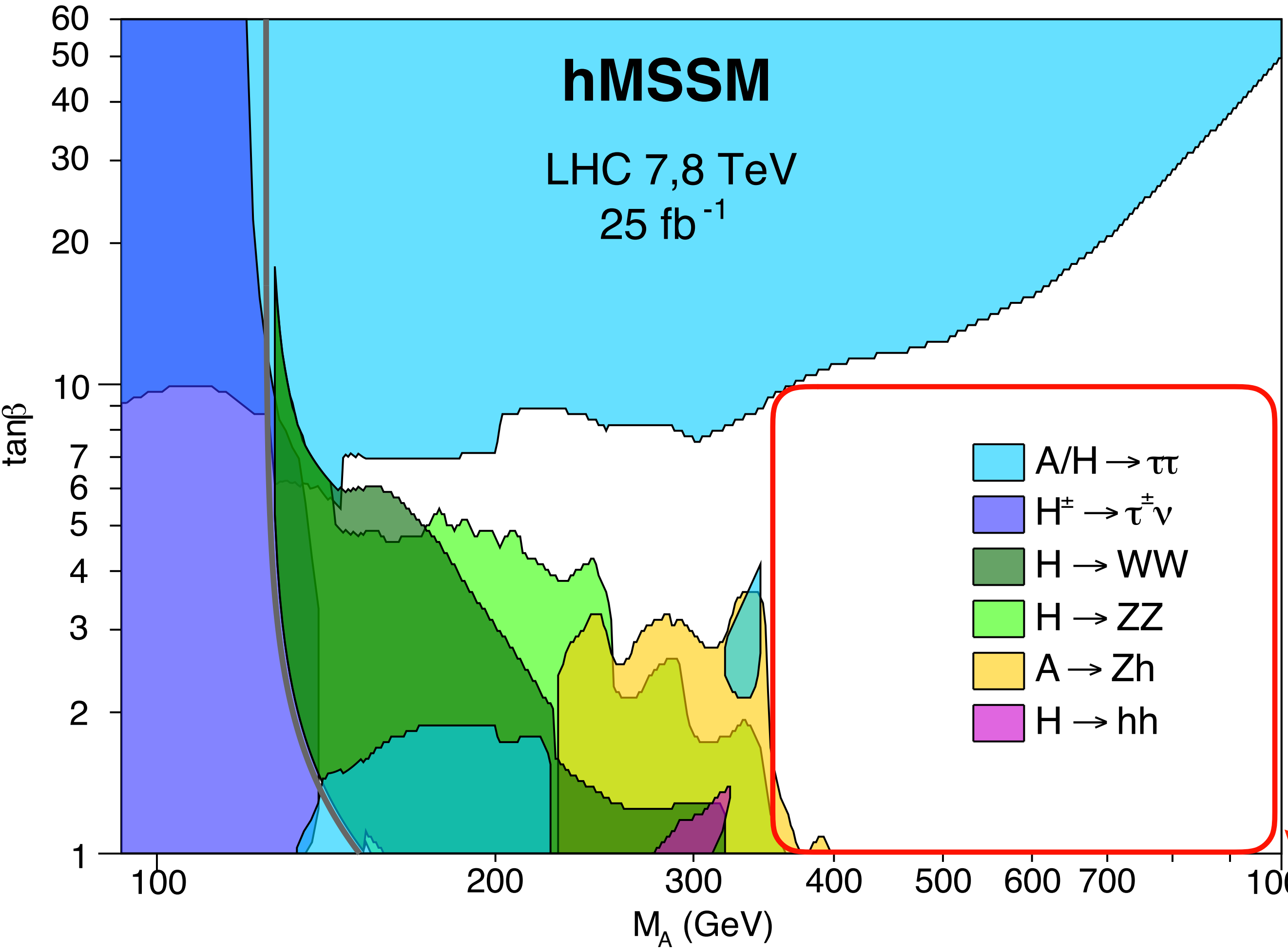
For low $\tan\beta$: H, A couplings to top quark enhanced:

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

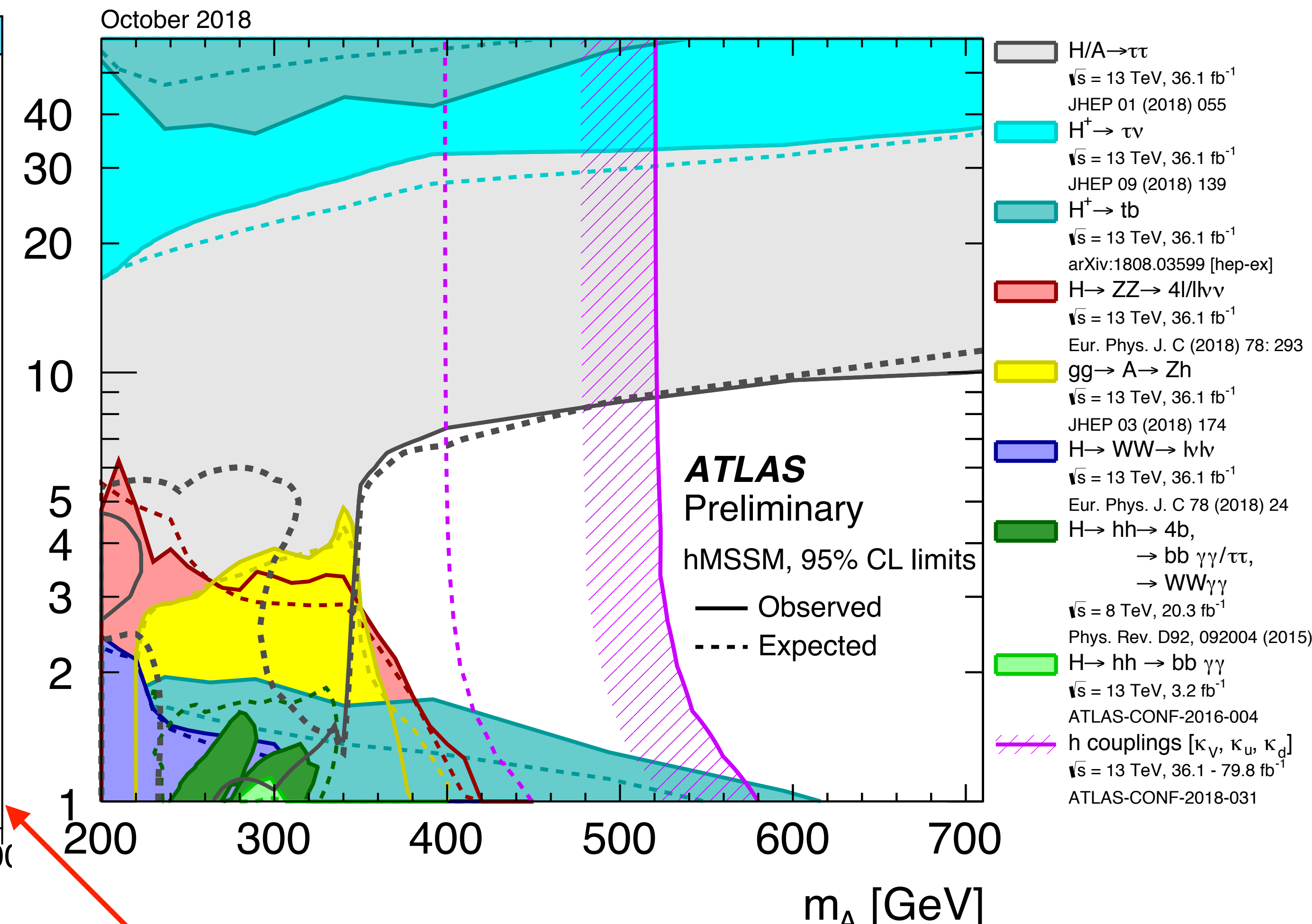
In the decoupling limit: MSSM reduces to SM but with a light SM Higgs

Constraints on the MSSM heavy Higgs bosons

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



Direct searches



Higgs signal strength fits

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

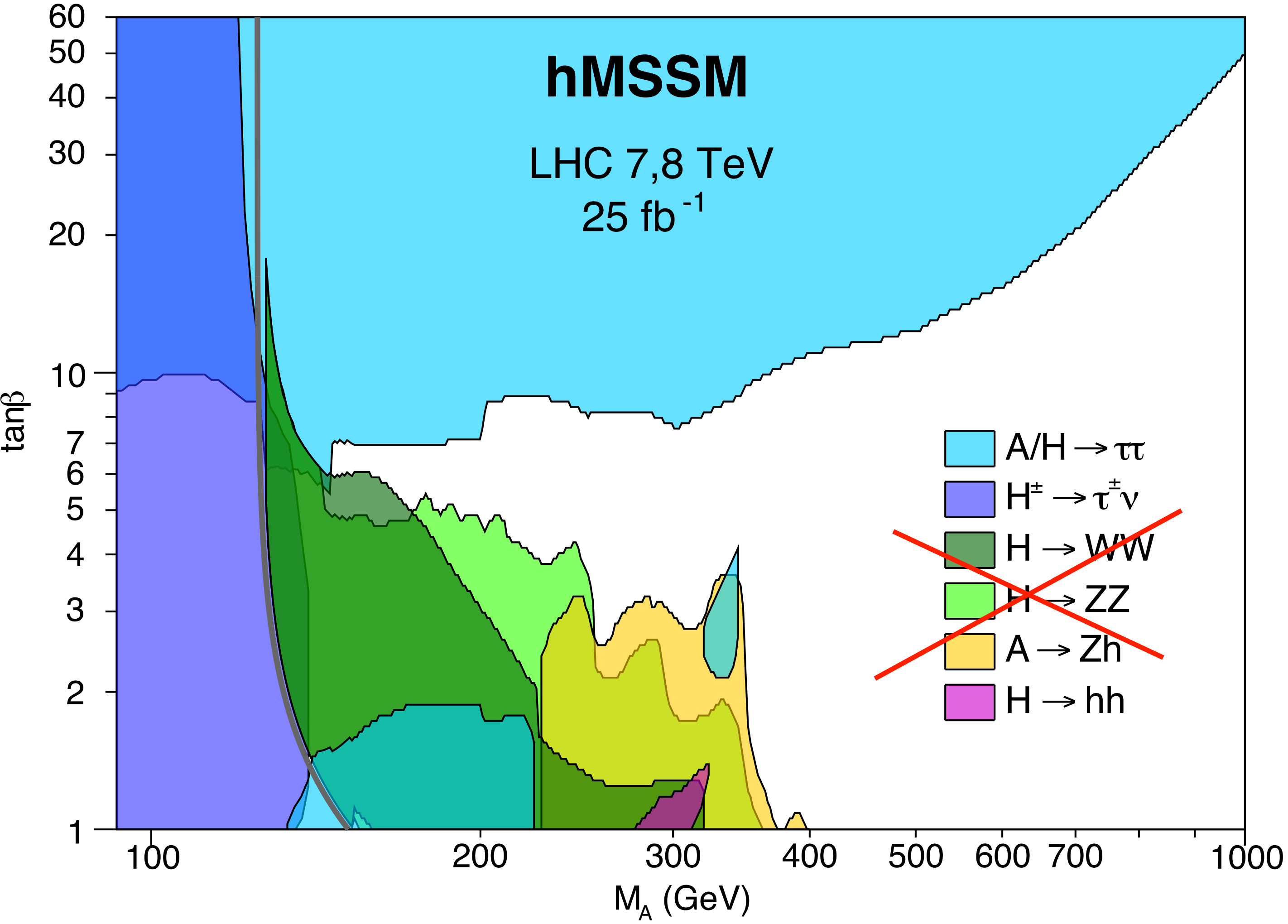
$\Rightarrow$ seem to favor the low $\tan\beta$ region where H, A couplings to top quark are enhanced!

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

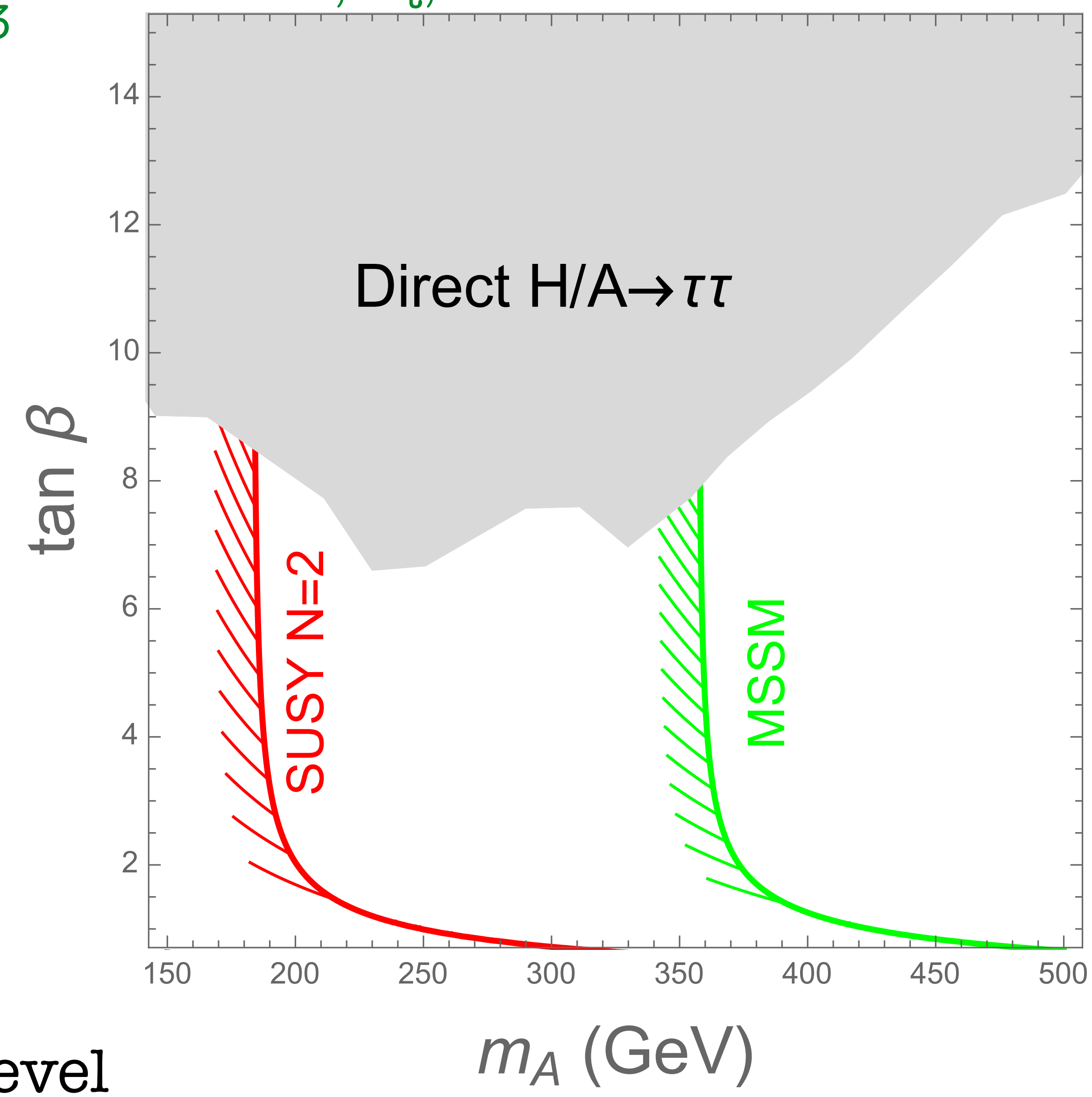
N=2 SUSY ?

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!

3. BSM benchmarks, analysis and sensitivity plots for $t\bar{t}$ production at the LHC

A. Djouadi, J. Ellis, A. Popov, JQ arXiv: 1901.03417

SM with an extra singlet (pseudo)scalar

Type II 2HDM

The hMSSM

Additional Vector-Like Quark in the loop

Simulation of experimental sensitivity

Emulate distribution of reconstructed $m_{t\bar{t}}$ starting from analytical results

- Start from analytical parton-level cross sections : (apply k-factors)

$$\frac{d\hat{\sigma}_{gg\to t\bar{t}}}{d\hat{s}}$$

- Convolute with PDF :

$$\frac{d\sigma_{pp\to t\bar{t}}}{dm_{t\bar{t}}}$$

- Apply event selection efficiency computed as a function of parton-level $m_{t\bar{t}}$:

$$\frac{d\sigma_{pp\to t\bar{t}}}{dm_{t\bar{t}}} \times \epsilon(m_{t\bar{t}})$$

- Convolute with a smearing kernel to emulate reconstruction resolution :

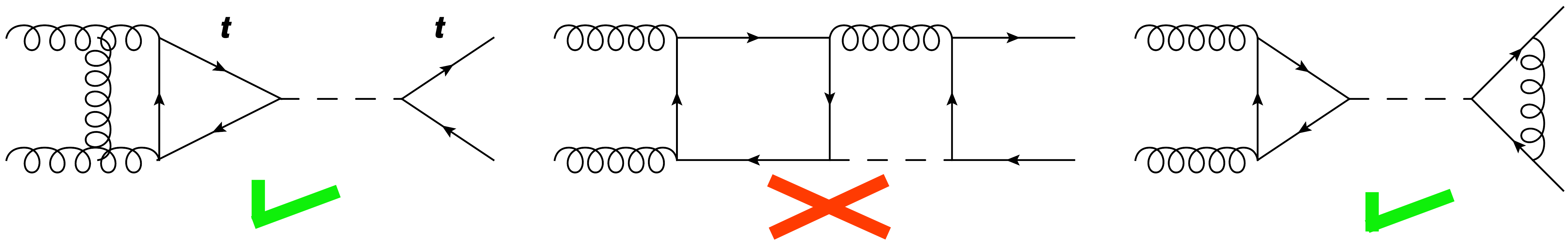
$$\frac{d\sigma_{pp\to t\bar{t}}}{dm_{t\bar{t}}} = \int \frac{d\sigma_{pp\to t\bar{t}}}{dm'_{t\bar{t}}} \times \epsilon(m'_{t\bar{t}}) \times G(m'_{t\bar{t}}, m_{t\bar{t}})\; dm'_{t\bar{t}}$$

Simulation of experimental sensitivity

Emulate distribution of reconstructed $m_{t\bar{t}}$ starting from analytical results

- Start from analytical parton-level cross sections :

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



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

→ 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 »

- Convolute with PDF :
- Apply event selection efficiency computed as a function of parton-level $m_{t\bar{t}}$:
- Convolute with a smearing kernel to emulate reconstruction resolution :

Simulation of experimental sensitivity

Emulate distribution of reconstructed $m_{t\bar{t}}$ starting from analytical results

- Start from analytical parton-level cross sections :
- Convote with PDF :

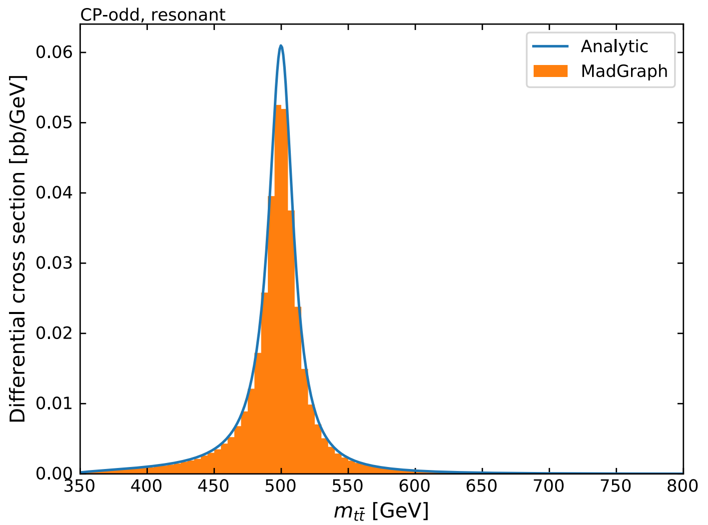
Generating MC samples for each signal hypothesis would not be practical.

Parton-level cross section $\hat{\sigma}$ depends only on $\hat{s} = m_{t\bar{t}}^2$

$$\longrightarrow \frac{\mathrm{d}\sigma}{\mathrm{d}\hat{s}} = \int \hat{\sigma}(\hat{s})\, f_g(x_1) f_g(x_2)\, \delta(x_1 x_2 s - \hat{s})\, \mathrm{d}x_1 \mathrm{d}x_2$$

$$= \frac{\hat{\sigma}(\hat{s})}{s} \int_{\hat{s}/s}^{1} f_g(x_1)\, f_g\left(\frac{\hat{s}}{s x_1}\right) \frac{\mathrm{d}x_1}{x_1} \equiv \hat{\sigma}(\hat{s}) \cdot F(\hat{s}, s)$$

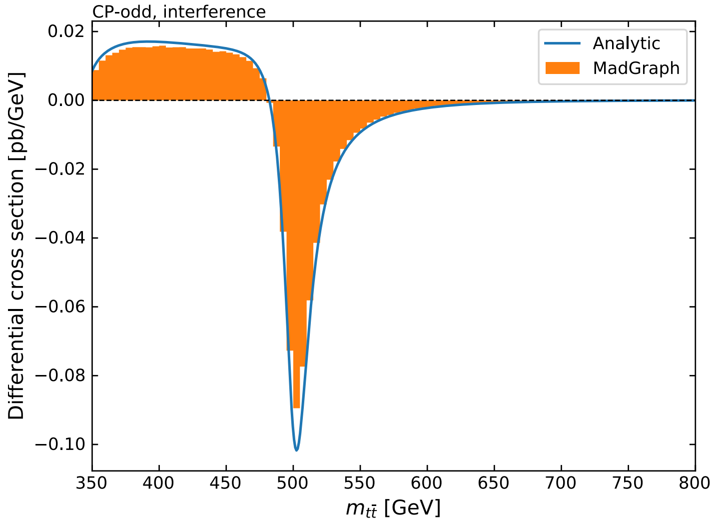
precomputed on a grid of $\hat{s}$ and then interpolated for new $\hat{s}$



Differential cross section in $m_{t\bar{t}}$ is computed fast with :

$$\longrightarrow \frac{\mathrm{d}\sigma}{\mathrm{d}m_{t\bar{t}}} = 2\sqrt{\hat{s}}\, \frac{\mathrm{d}\sigma}{\mathrm{d}\hat{s}}$$

$$= 2\sqrt{\hat{s}}\, F(\hat{s}, s) \cdot \hat{\sigma}(\hat{s})$$



- Apply event selection efficiency computed as a function of parton-level $m_{t\bar{t}}$:
- Convolute with a smearing kernel to emulate reconstruction resolution :

Simulation of experimental sensitivity

Emulate distribution of reconstructed $m_{t\bar{t}}$ starting from analytical results

- Start from analytical parton-level cross sections :
- Convolute with PDF :

- Apply event selection efficiency computed as a function of parton-level $m_{t\bar{t}}$

Event selection « l+jets » :

- Focus on single-lepton channel
  - Exactly one e or μ and no τ in the ME final state
  - The e (μ) must have $p_T > 30$ GeV and $|\eta| < 2.4$
- At least four jets
  - Consider generator-level jets with $p_T > 20$ GeV and $|\eta| < 2.4$
  - Jets that overlap with the lepton (within $\Delta R < 0.4$) are removed
- Two of the jets matched to b quarks within $\Delta R < 0.4$
  - This emulates b-tagging, although false positives are ignored
- Assume a 30% efficient lepton identification and b-tagging (event weights)

- Convolute with a smearing kernel to emulate reconstruction resolution :

Simulation of experimental sensitivity

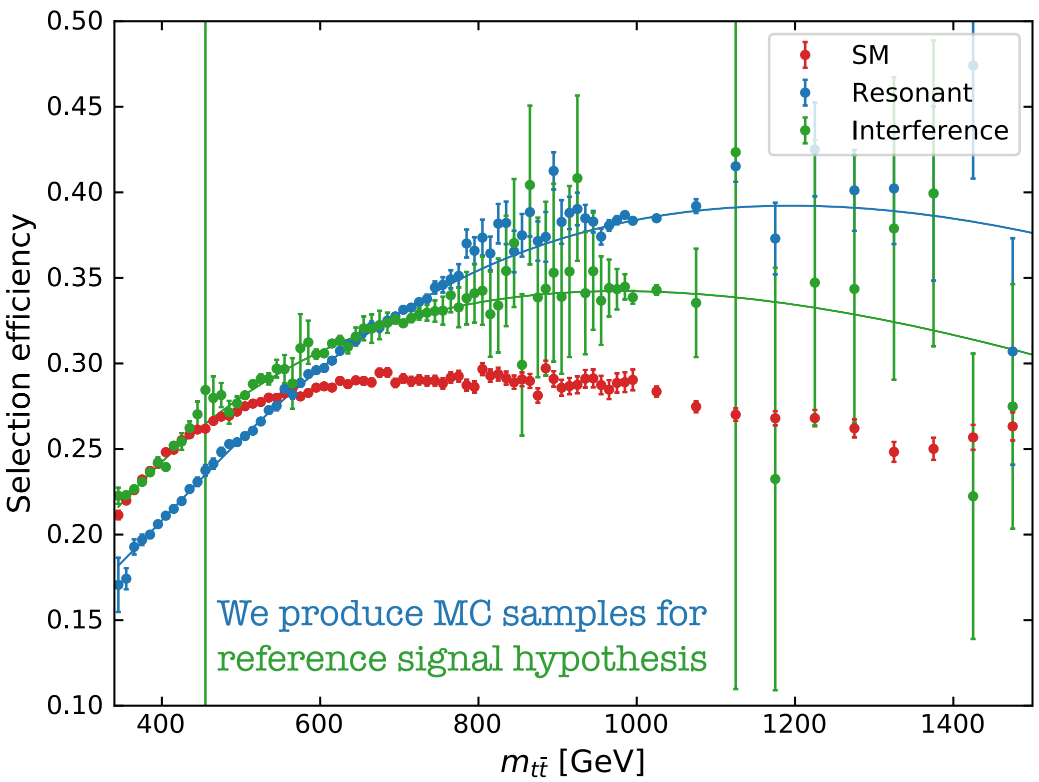
Emulate distribution of reconstructed $m_{t\bar{t}}$ starting from analytical results

- Start from analytical parton-level cross sections :
- Convolute with PDF :

- Apply event selection efficiency computed as a function of parton-level $m_{t\bar{t}}$

Selection efficiency :

- Efficiency of the event selection checked on MC samples for SM $t\bar{t}$, resonant part of the signal, and interference
  - Computed w. r. t. targeted decays
  - In bins of parton-level $m_{t\bar{t}}$
- Efficiencies for the three processes are different
- Fitted $\epsilon(m_{t\bar{t}})$ for signal
  - Described well with $P_3(\ln m_{t\bar{t}})$



- Convolute with a smearing kernel to emulate reconstruction resolution :

Simulation of experimental sensitivity

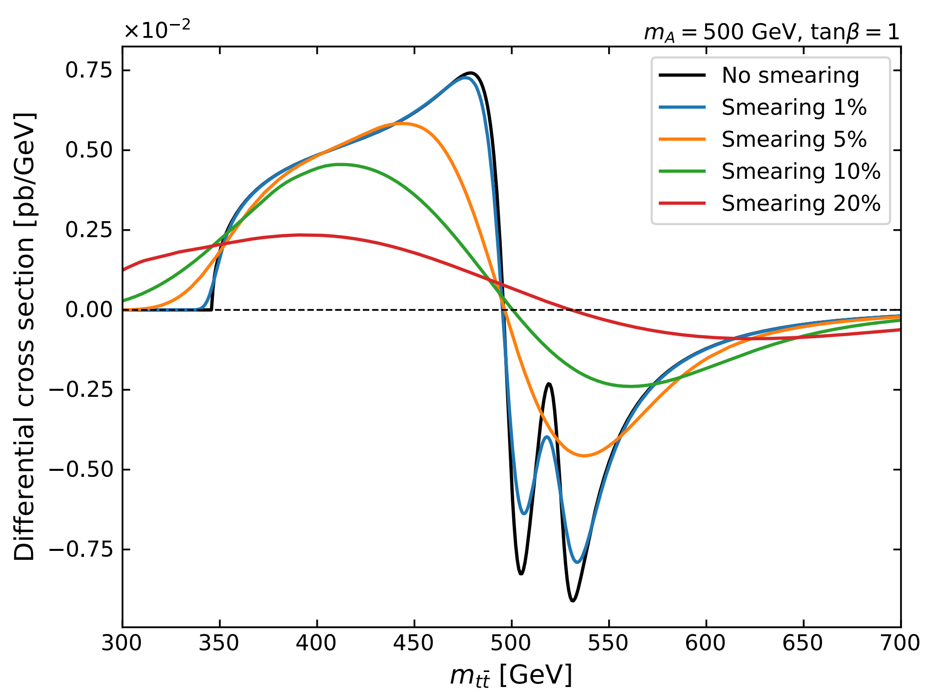
Emulate distribution of reconstructed $m_{t\bar{t}}$ starting from analytical results

- Start from analytical parton-level cross sections :
- Convolute with PDF :
- Apply event selection efficiency computed as a function of parton-level $m_{t\bar{t}}$

- Convolute with a smearing kernel to emulate reconstruction resolution :
  - Apply Gaussian smearing to parton-level $m_{t\bar{t}}$:

$$\frac{\mathrm{d}\tilde{\sigma}}{\mathrm{d}m_{t\bar{t}}} = \int \frac{\mathrm{d}\sigma}{\mathrm{d}m'_{t\bar{t}}} \epsilon(m'_{t\bar{t}}) \cdot \frac{1}{\sqrt{2\pi\left(r \cdot m'_{t\bar{t}}\right)^2}} \exp\left(-\frac{\left(m_{t\bar{t}} - m'_{t\bar{t}}\right)^2}{2\left(r \cdot m'_{t\bar{t}}\right)^2}\right) \mathrm{d}m'_{t\bar{t}}$$

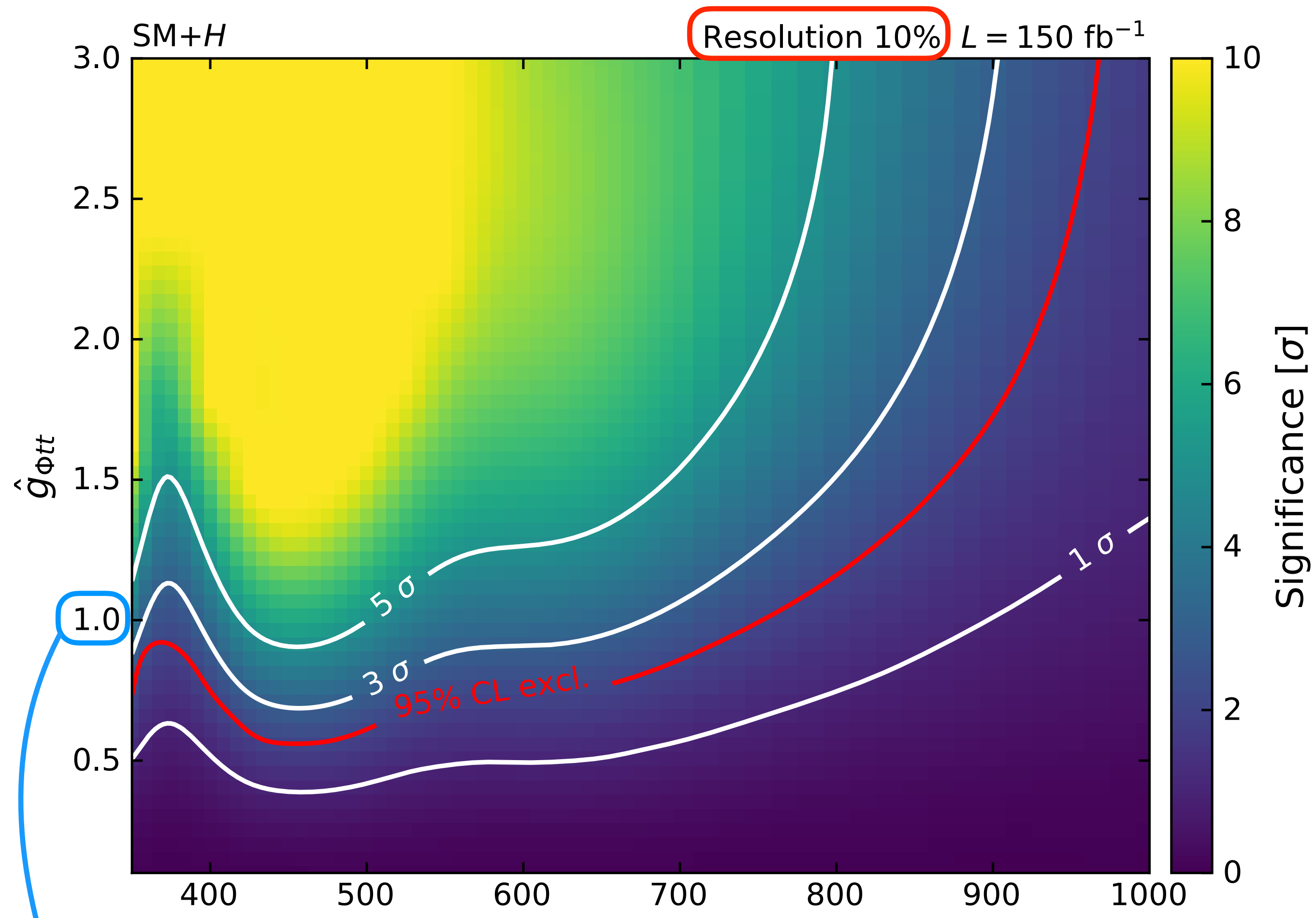
    - r is relative $m_{t\bar{t}}$ resolution
    - Integral is truncated to segment $m_{t\bar{t}} \cdot (1 \pm 3r)$
  - In the following use $r = 20\%$
    - Some results for optimistic scenario $r = 10\%$ will also be shown

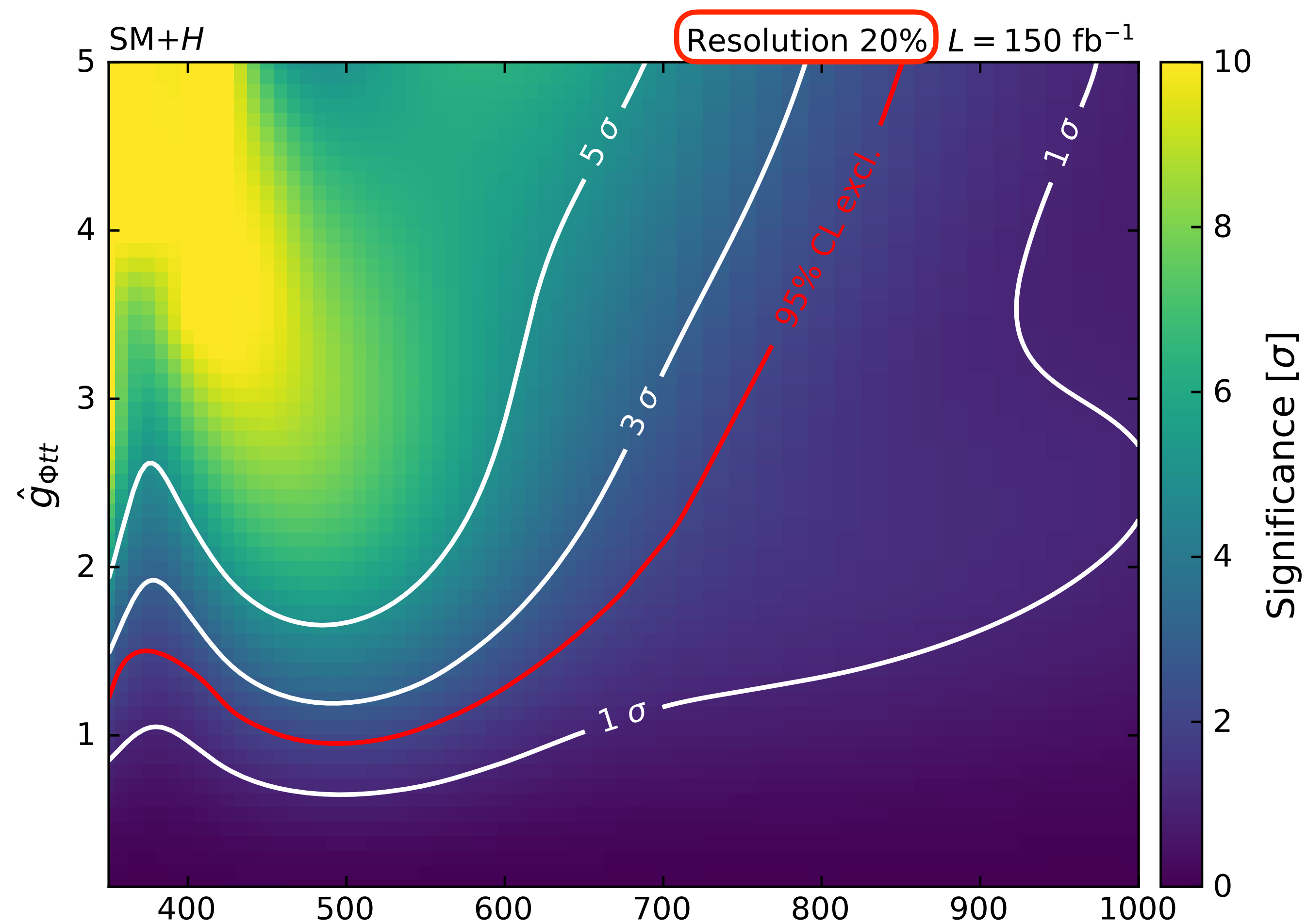


Analysis fully transparent and accessible on GitHub, easily applicable to other BSM models

The SM with an extra singlet

$$\mathcal{L}^{\text{newYukawa}} \supset -g_{Ht\bar{t}}\bar{t}tH \quad \text{or} \quad ig_{At\bar{t}}\bar{t}\gamma_5 tA \qquad \text{with} \qquad g_{\Phi t\bar{t}} = \underbrace{\boxed{\frac{m_t}{v}}}_{g_{ht\bar{t}}} \times \hat{g}_{\Phi t\bar{t}}$$





A. Djouadi, J. Ellis, A. Popov, JQ arXiv: 1901.03417

- boson H, with 10% mass res. & 3/ab: 5σ discovery sensitivity up to $M_H \sim 800\ GeV$
  95% CL exclusion up to $M_H \sim 980\ GeV$
- boson A: exclusion range from 650 GeV (20% res.+ 150 /fb) to over 1 TeV (10% res. & 3 /ab)

Reach of the search for effects in the $m_{t\bar{t}}$ mass spectrum is impressive in the (pseudo) scalar case

Two Higgs doublet models

type II:

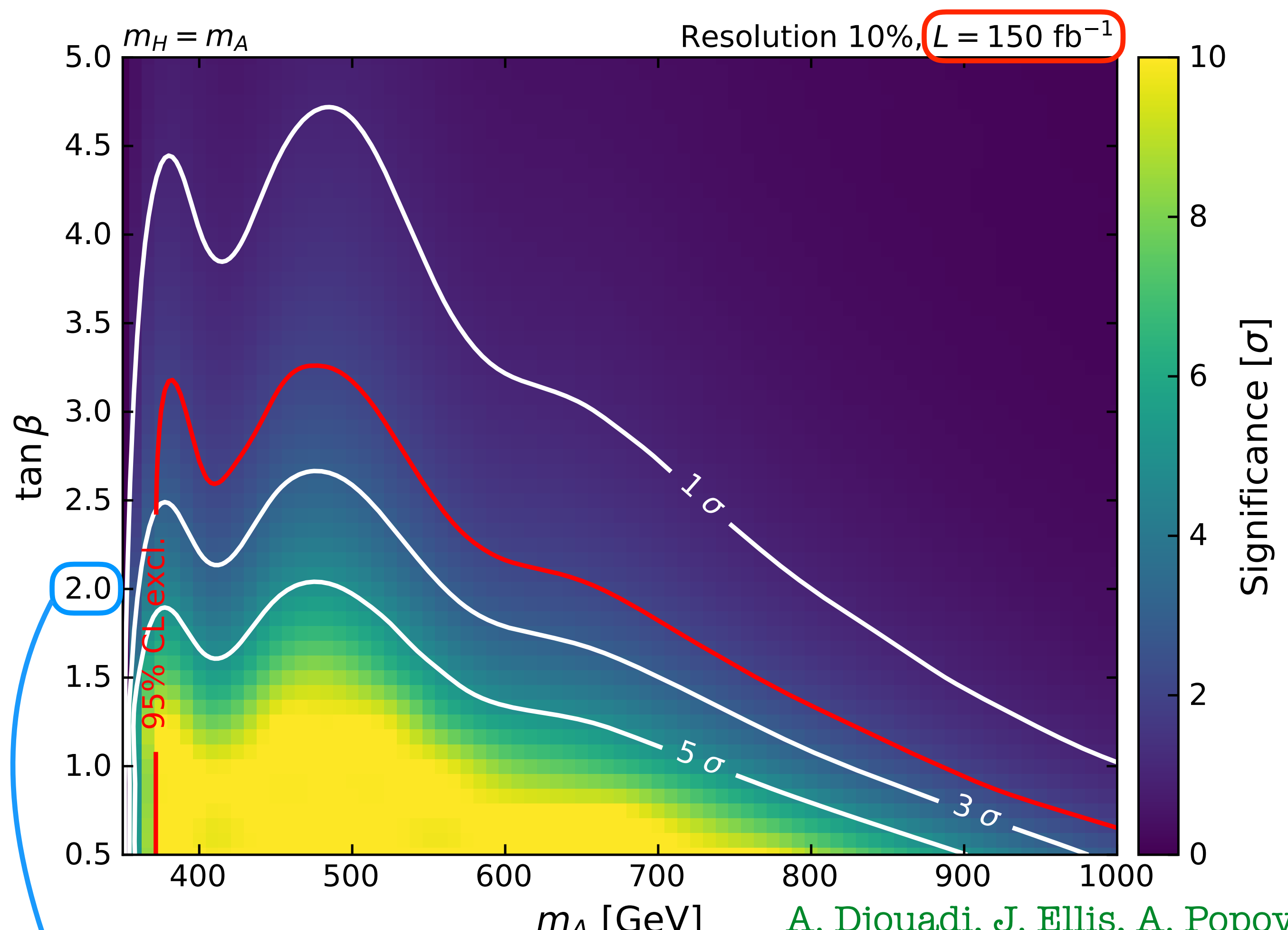
alignement limit : $\alpha = \beta - \frac{\pi}{2}$

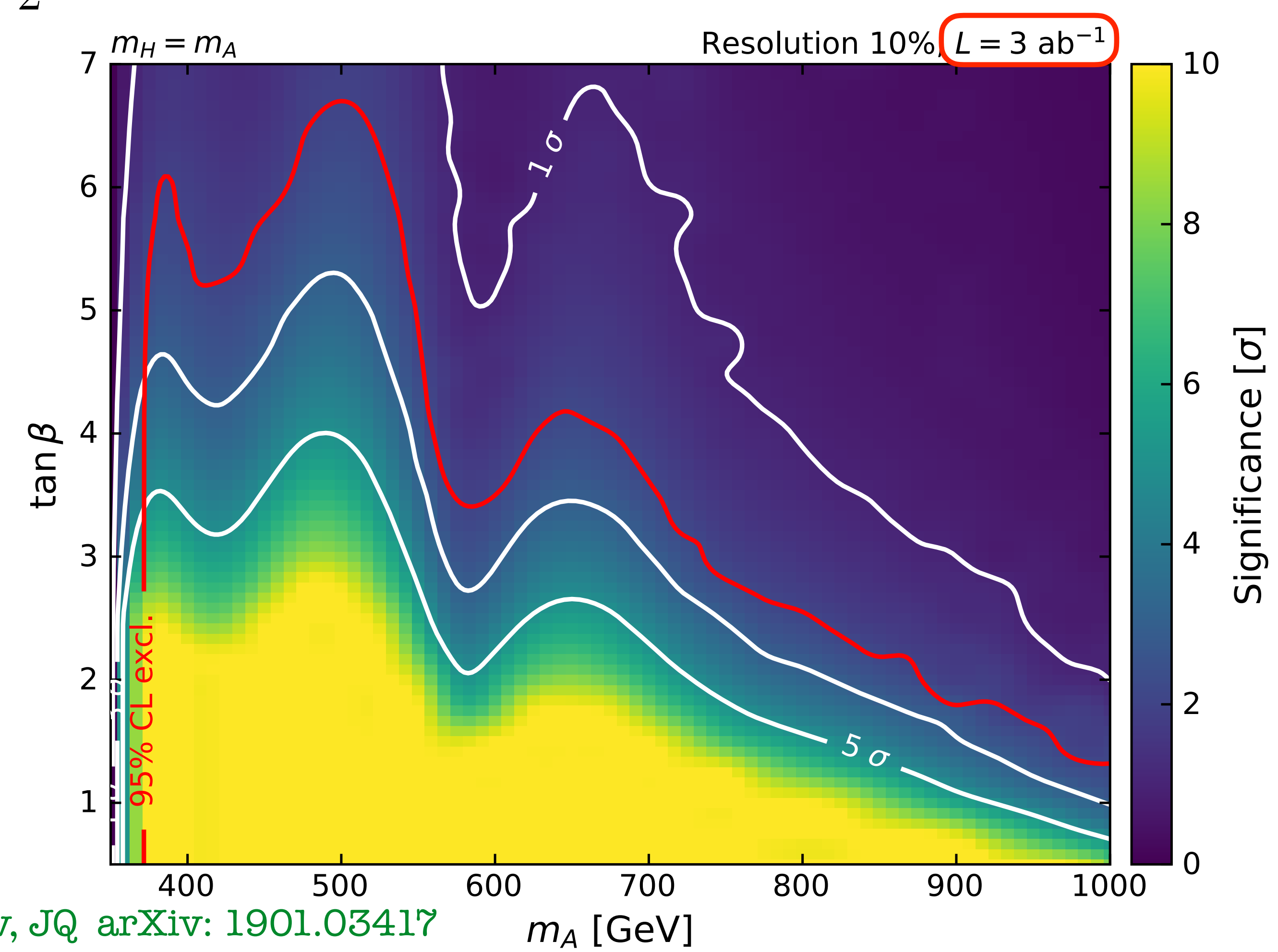
Φ	$g_{\Phi\bar{u}u}$	$g_{\Phi\bar{d}d}$	$g_{\Phi VV}$
h	$\frac{\cos\alpha}{\sin\beta} \to 1$	$\frac{\sin\alpha}{\cos\beta} \to 1$	$\sin(\beta-\alpha) \to 1$
H	$\frac{\sin\alpha}{\sin\beta} \to 1/\tan\beta$	$\frac{\cos\alpha}{\cos\beta} \to \tan\beta$	$\cos(\beta-\alpha) \to 0$
A	$1/\tan\beta$	$\tan\beta$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

SM-like Higgs coupling

Heavy Higgs decouple from the gauge sector

$$2\text{HDM}: M_h = 125\ \text{GeV}\,,\ \alpha = \beta - \frac{\pi}{2}\,,\ M_H \approx M_A\,,\ M_{H^\pm} \geq \max(M_H, M_A)$$





A. Djouadi, J. Ellis, A. Popov, JQ arXiv: 1901.03417

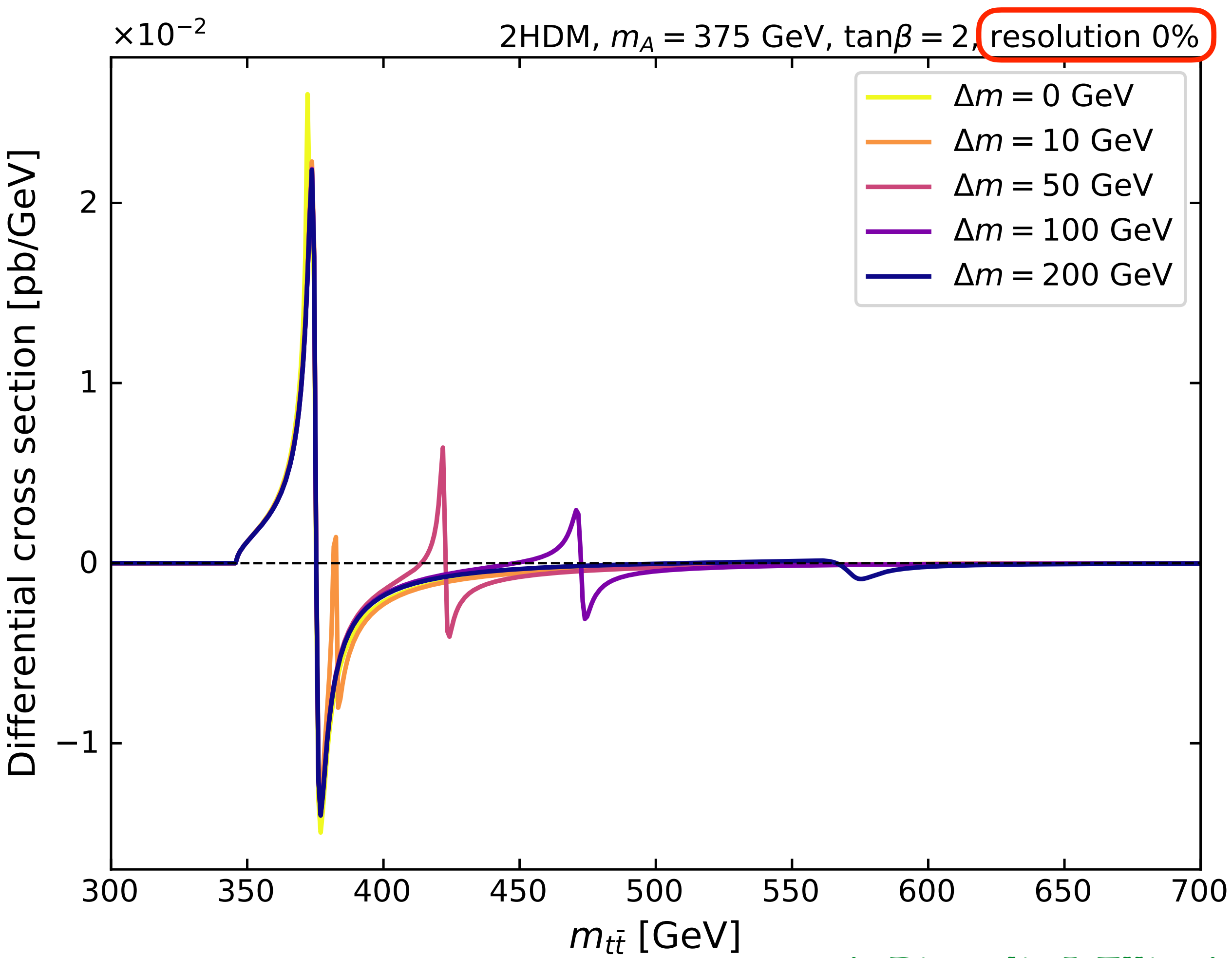
(with 10% mass resolution)	150 /fb	450 /fb	3 /ab
5σ discovery sensitivity up to :	x	540 GeV	730 GeV
95 % CL limit up to :	670 GeV	750 GeV	900 GeV

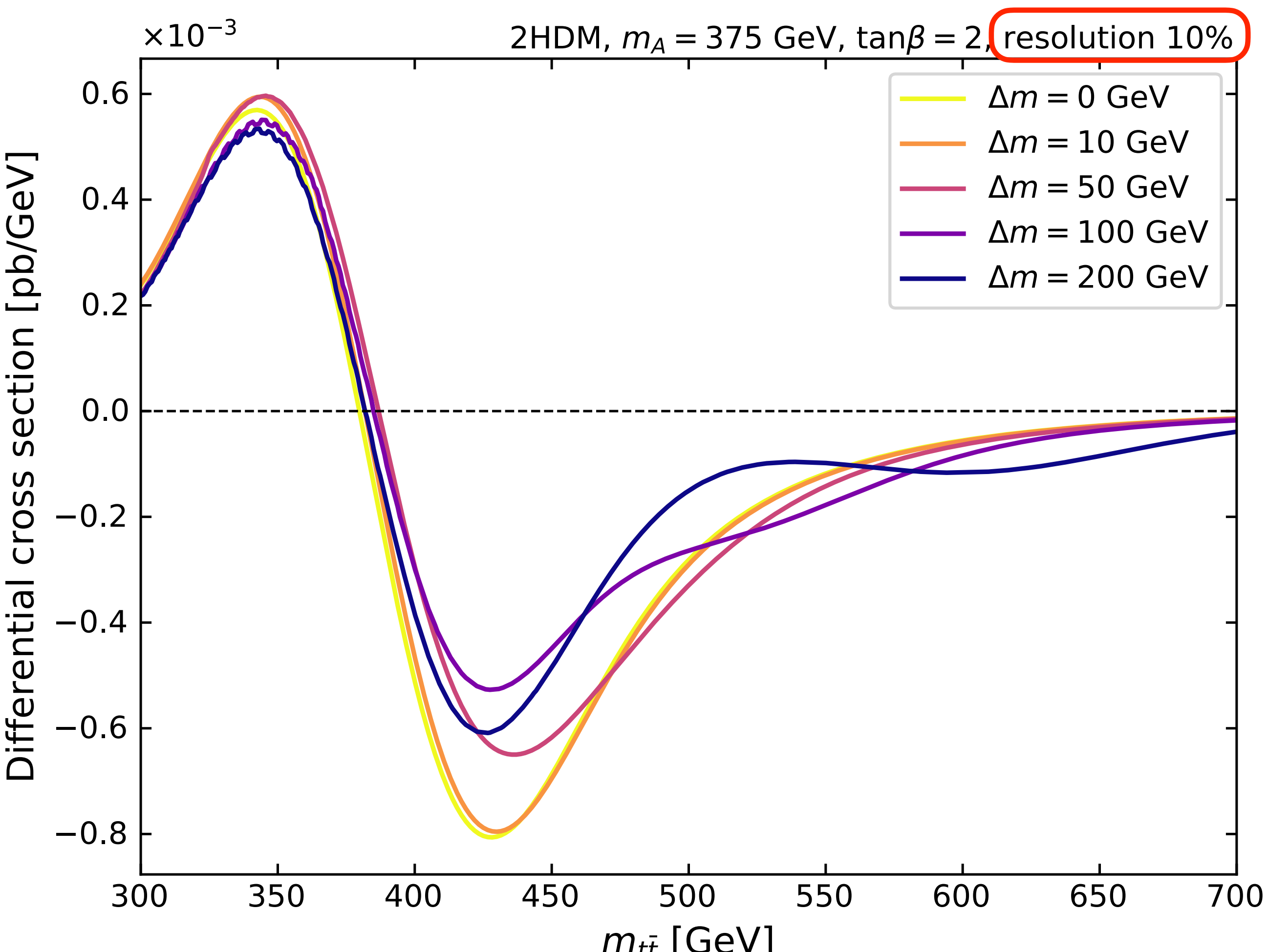
Two Higgs doublet models

effect of the mass splitting $M_H - M_A$

- $M_H - M_A \nearrow$: leads initially to a degradation in the sensitivity (partial cancelation)

- When the mass separation is large enough the structures from the two states do not overlap and the sensitivity increases again





A. Djouadi, J. Ellis, A. Popov, JQ arXiv: 1901.03417

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:

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

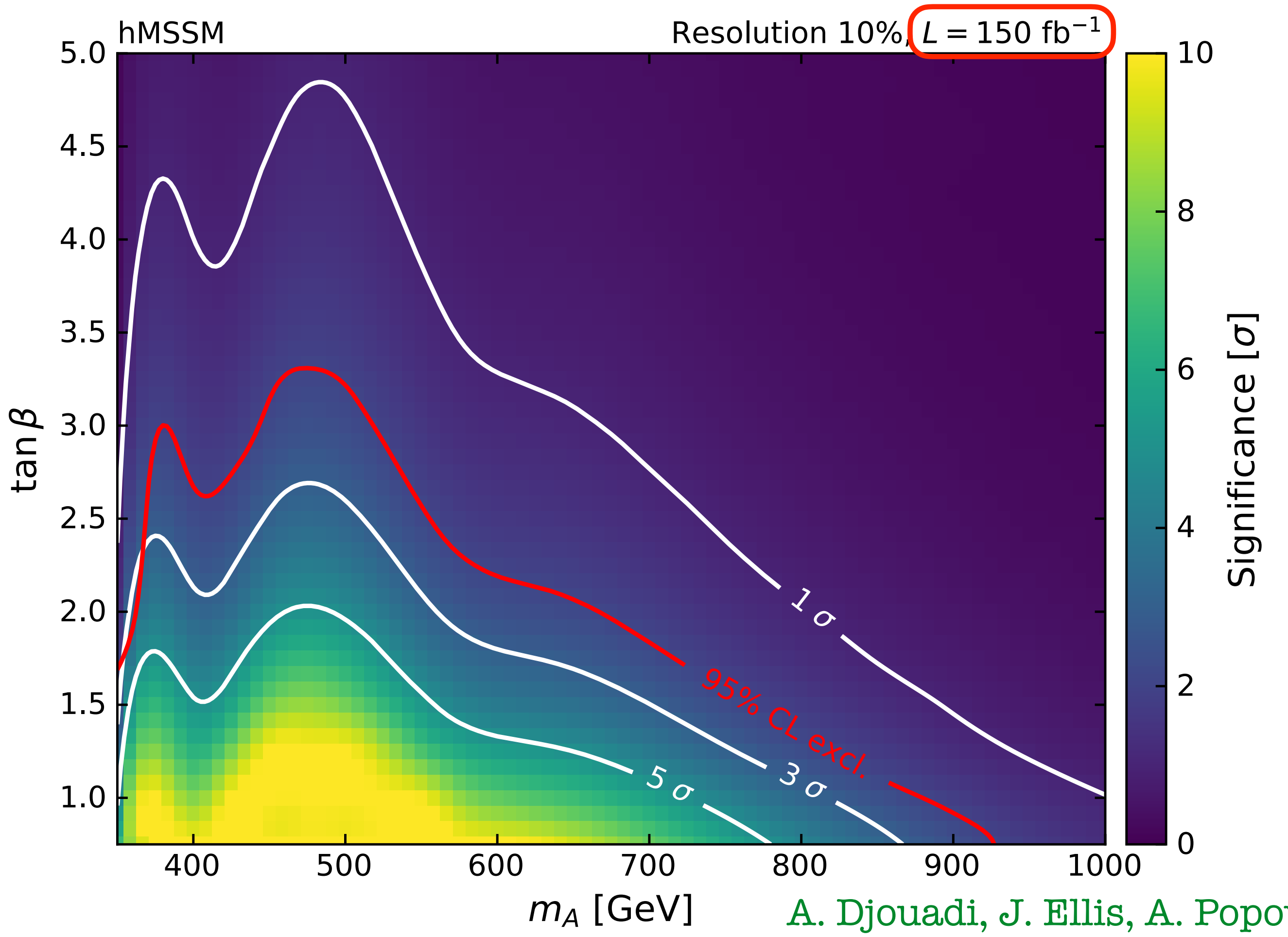
M_h should be an input now...

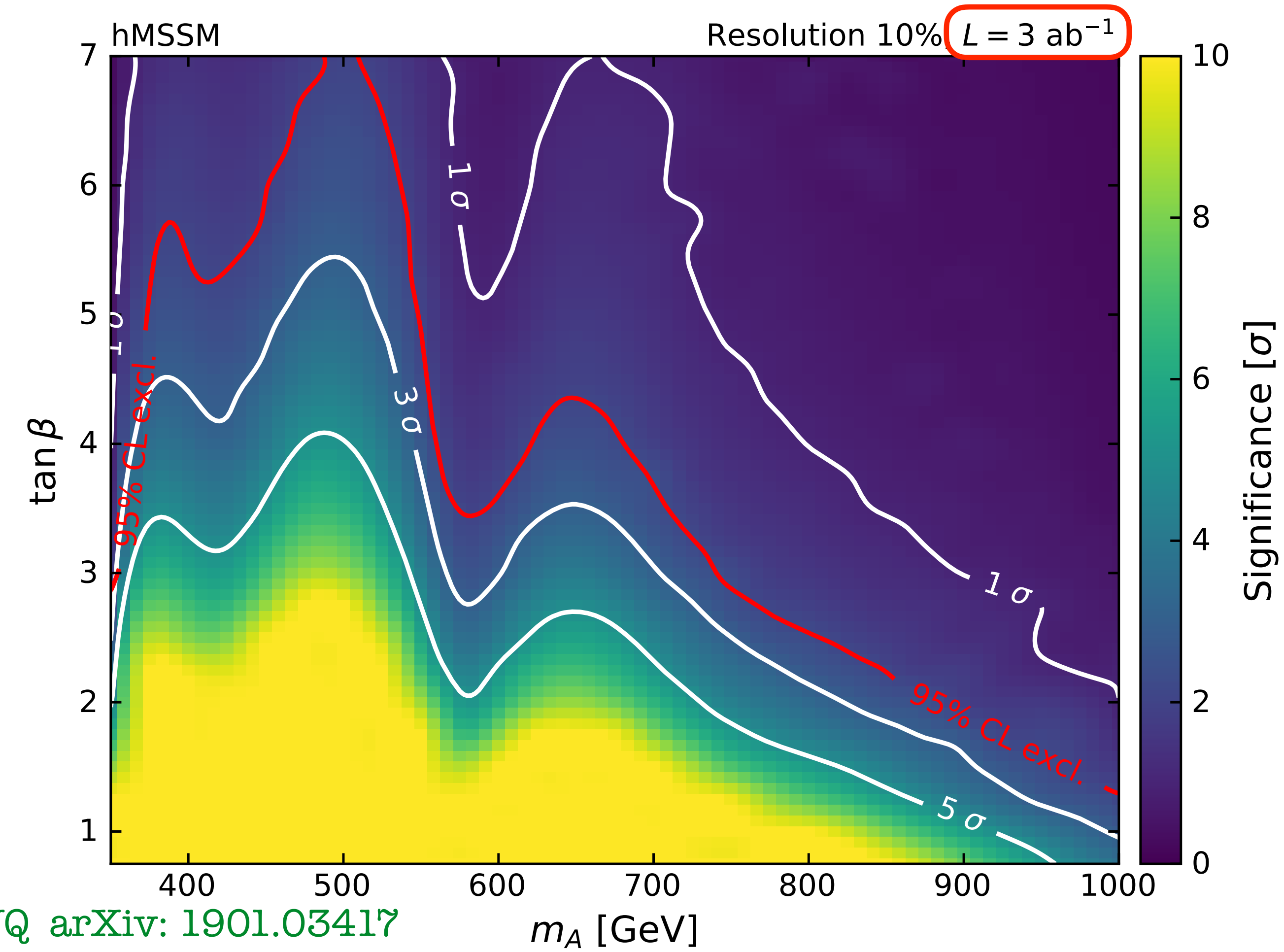
$\Delta\mathcal{M}_{22}^2$ involves the by far dominant stop–top sector correction: $\Delta\mathcal{M}_{22}^2 \gg \Delta\mathcal{M}_{11}^2, \Delta\mathcal{M}_{12}^2$

$\rightarrow$ 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:

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





A. Djouadi, J. Ellis, A. Popov, JQ arXiv: 1901.03417

(with 10% mass resolution)	150 /fb	450 /fb	3 /ab
5σ discovery sensitivity up to :	x	530 GeV	700 GeV
95 % CL limit up to :	660 GeV	740 GeV	870 GeV

very similar to previous 2HDM

If VLQ are also in the loop

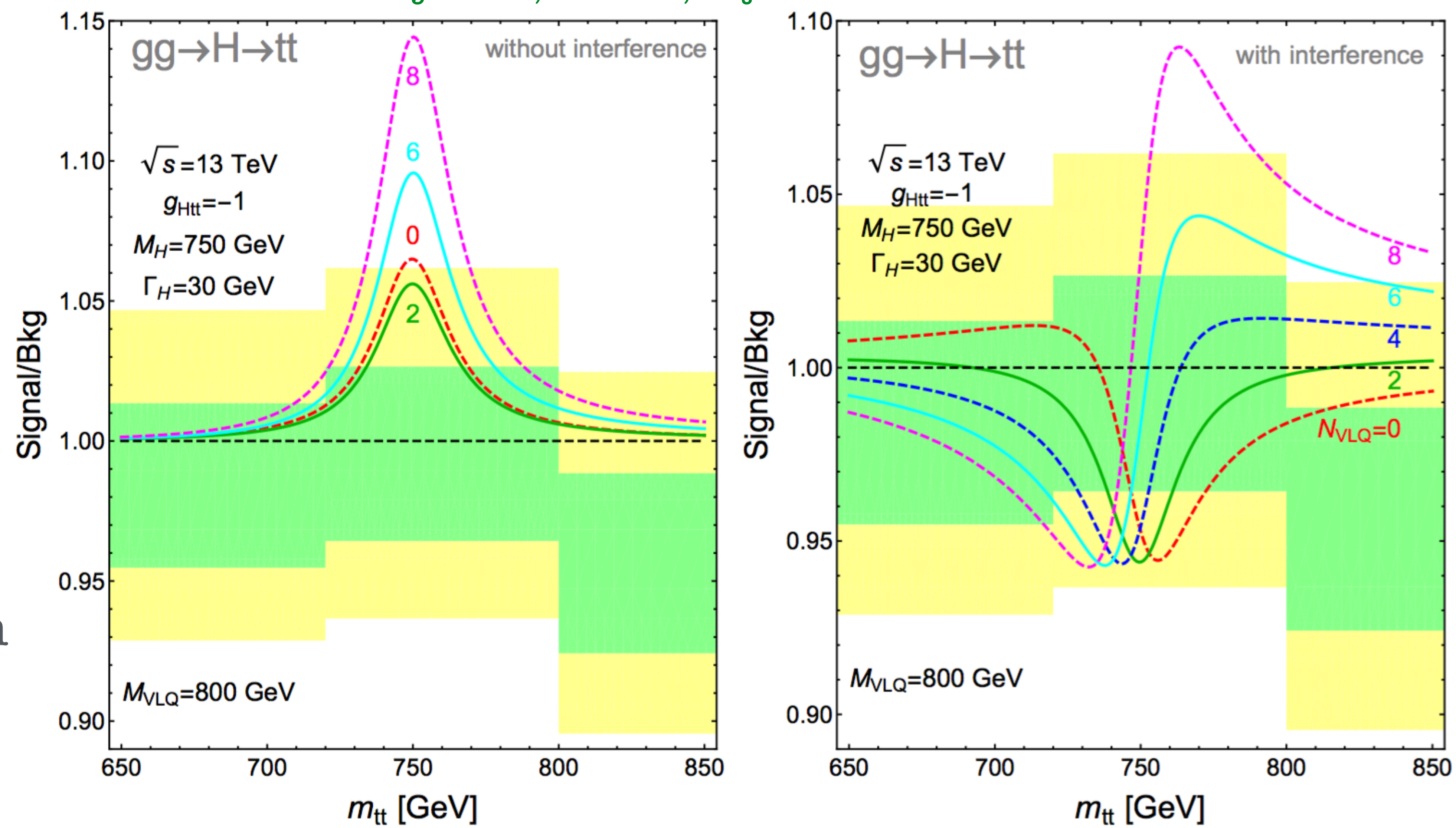
The top quark and VLQ induce the gluon width :

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

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

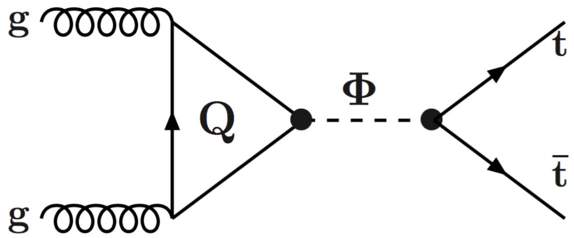
A. Djouadi, J. Ellis, JQ arXiv: 1605.00542

strong exclusion limits



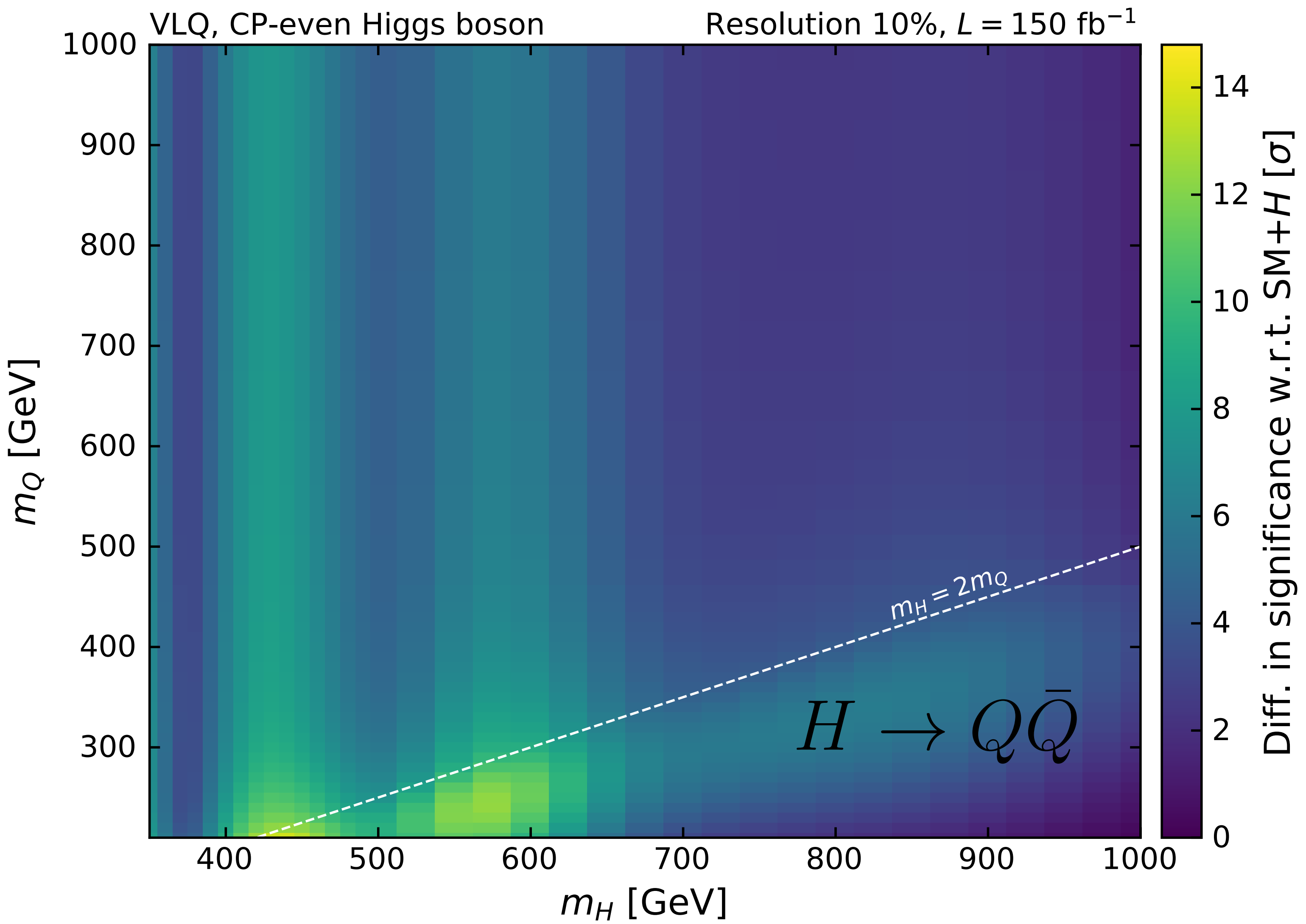
weaker exclusion limits

Additional Vector-Like Quark to



Consider a CP-even heavy Higgs with $\hat{g}_{\Phi Q\bar{Q}} = \hat{g}_{\Phi t\bar{t}} = 1$ and a single VLQ species

compare this model with the SM+H model:



increase in the significance over all the plane

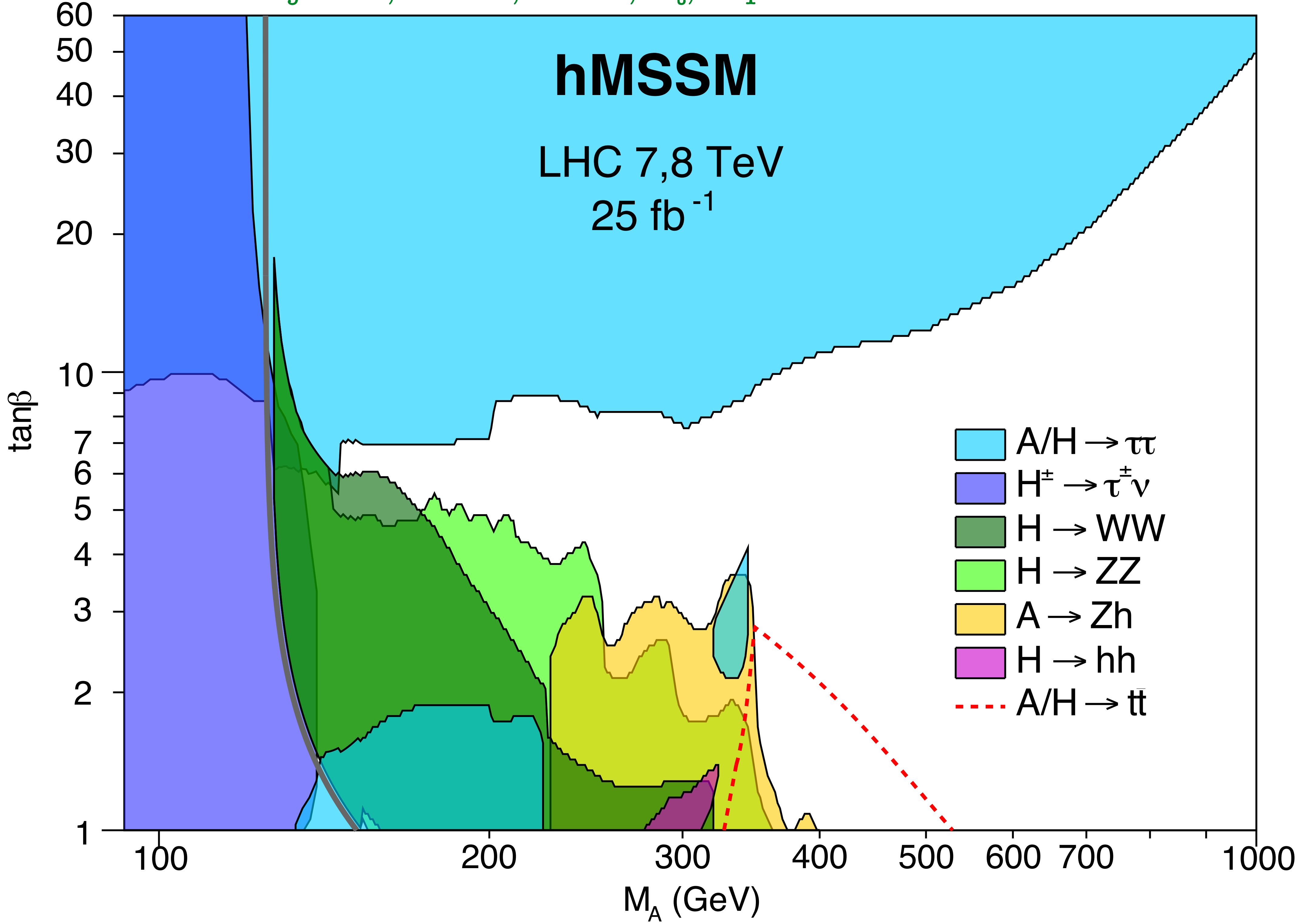
Conclusions

- 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 *** NEW for LHC run II ***
- 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
- the $gg \to t\bar{t}$ process will allow us to test the low $\tan\beta$ region of the MSSM Higgs sector
- A lot still need to be studied regarding BSM interference effects

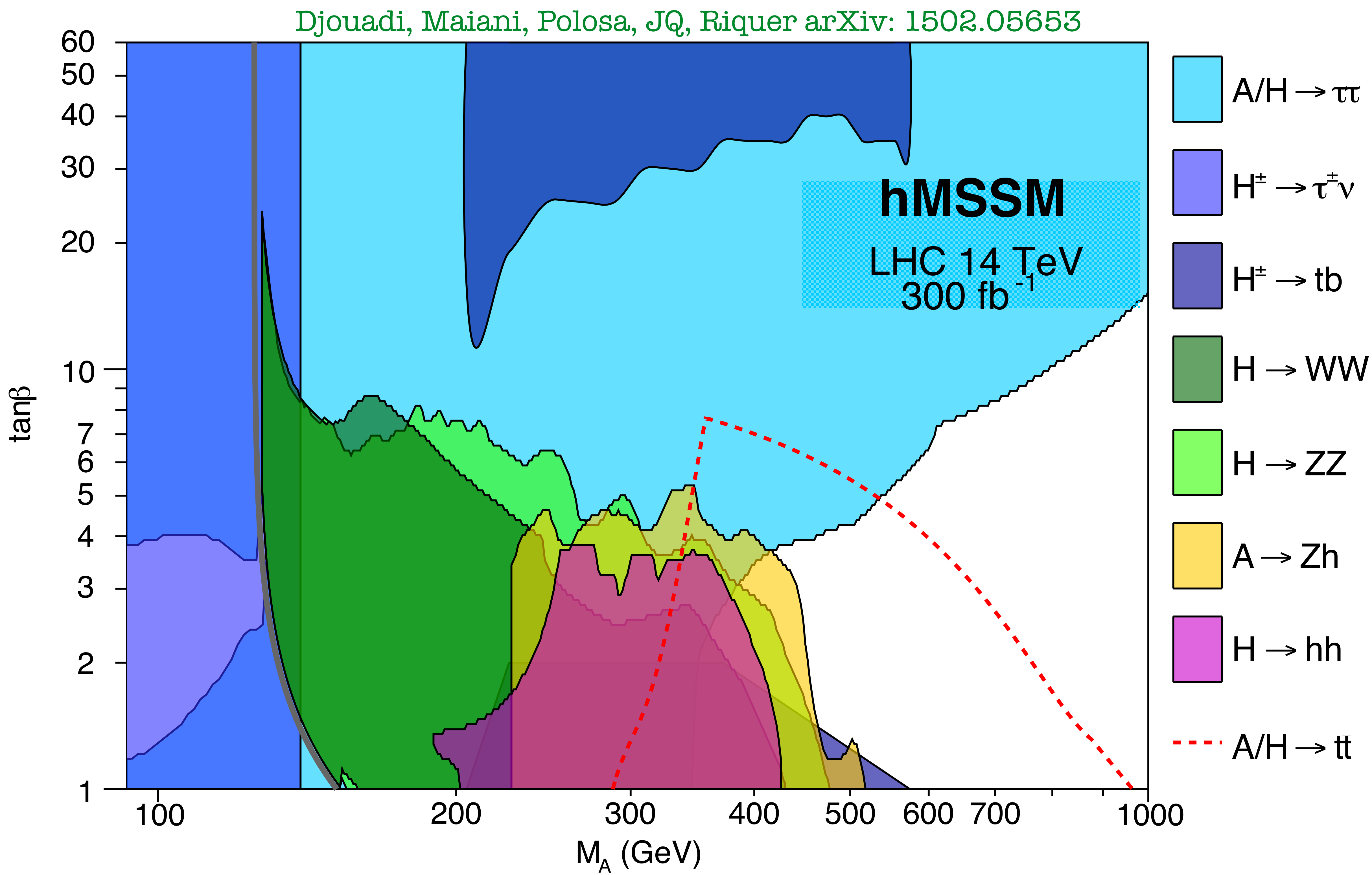
Backup slides

Constraints from LHC run I

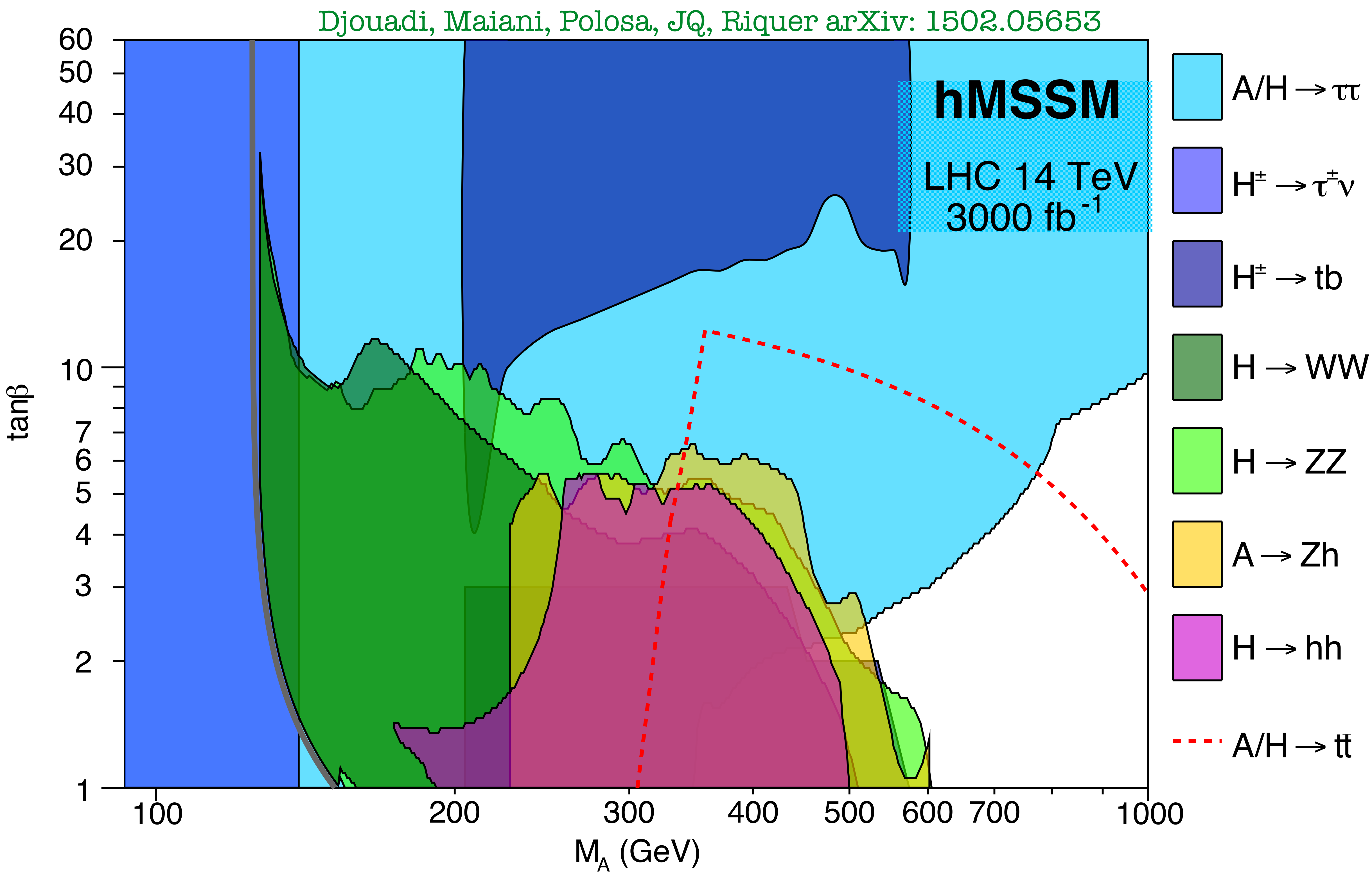
Djouadi, Maiani, Polosa, JQ, Riquer arXiv: 1502.05653



Projected constraints 1



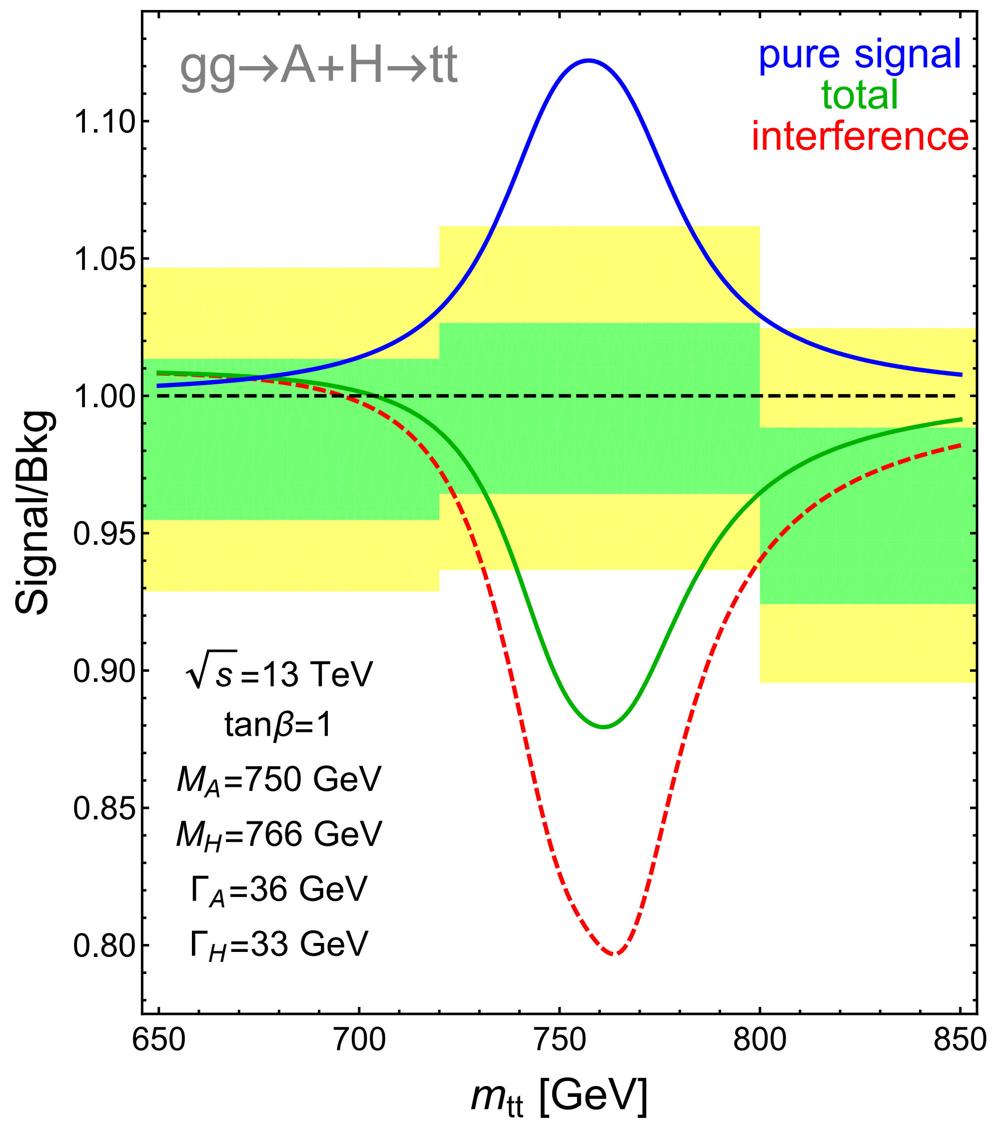
Fully covering the MSSM Higgs sector up to the TeV



If the resonances are the heavy Higgs of the MSSM

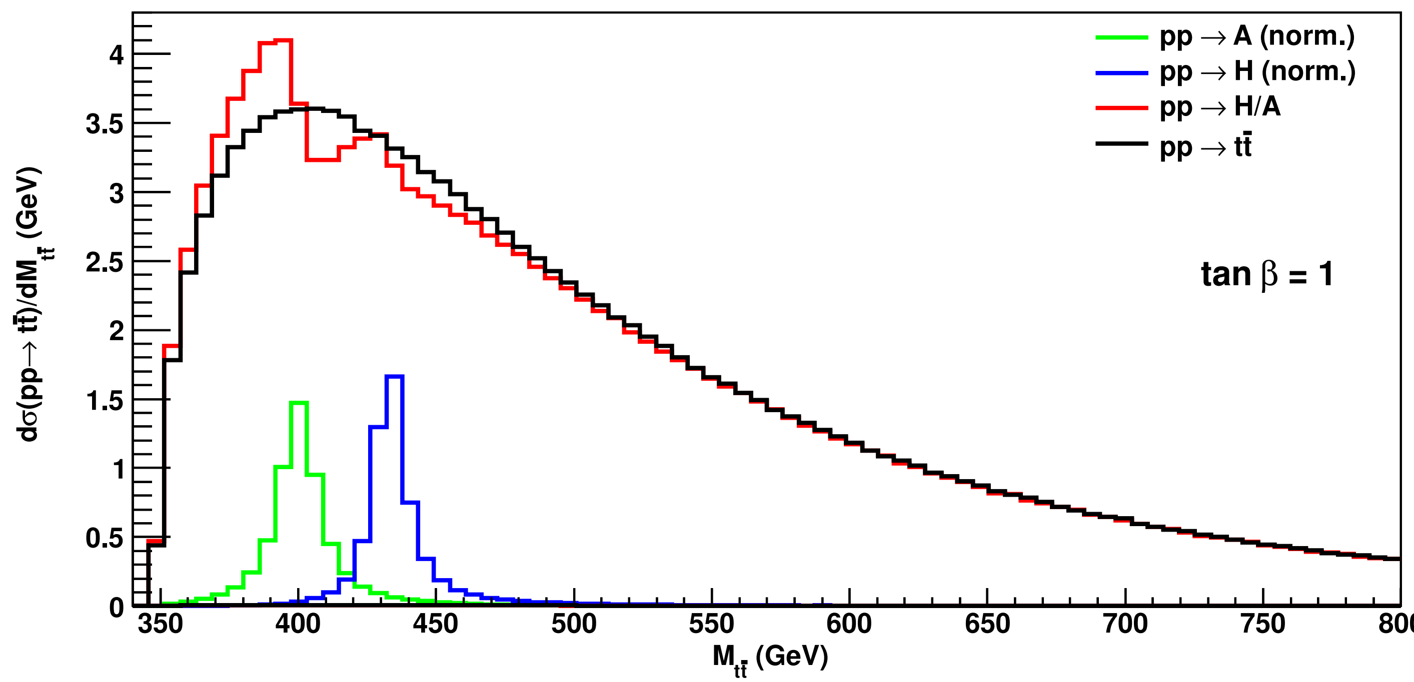
looking for a dip

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 cancelations)

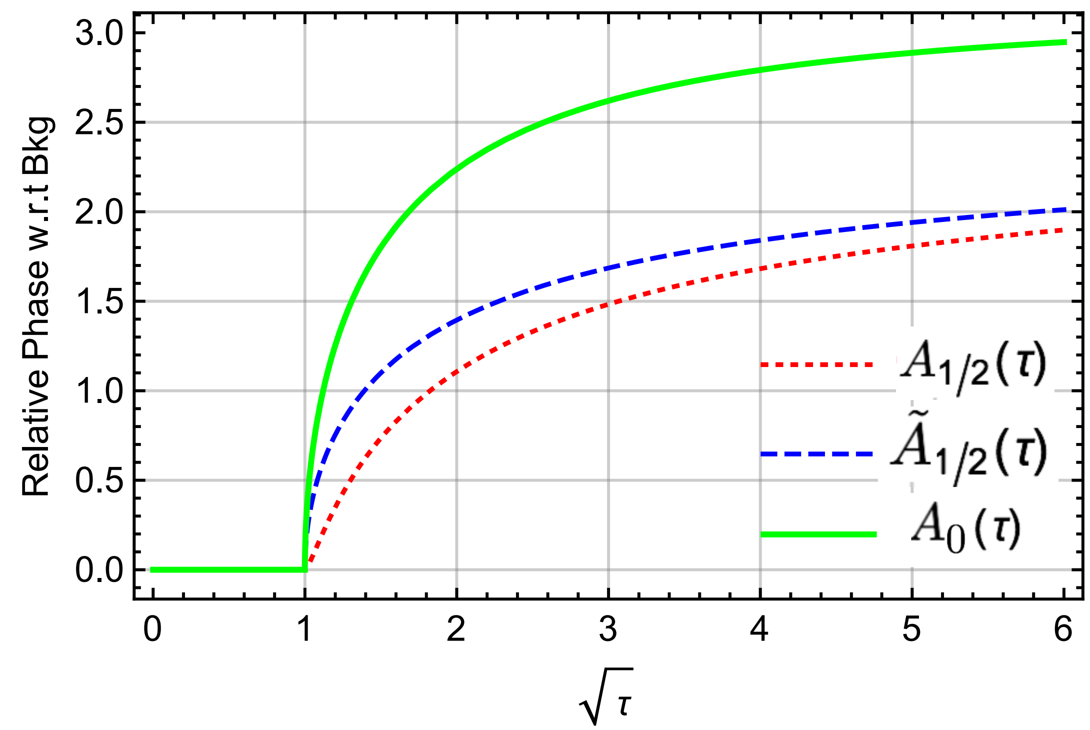
Systematic uncertainties

- Uncertainties in signal
  - Renormalization scale μ_R in ME varied by factor 2
    - Simultaneously in R and I and also SM $t\bar{t}$
- Uncertainties in SM $t\bar{t}$
  - 10% rate variation
    - Represent some experimental uncertainties that affect mostly the rate and also change in cross section due to variations of μ_R and μ_F (see below)
  - Scaling $m_{t\bar{t}} \mapsto (1 \pm \alpha)\, m_{t\bar{t}}$, $\alpha = 0.01$
    - Proxy for the uncertainty in jet p_T scale
  - Renormalization and factorization scales in ME varied by factor 2
    - Variations are rescaled so that they do not change the inclusive cross section
    - Rational: the impact on the rate is huge, and uncertainties would be tightly constrained because of this. Factorizing into rate and shape variations allows to preserve the latter ones
  - Renormalization scale in FSR is varied by factor 2
  - Mass of top quark varied by 0.5 GeV
  - All PDF uncertainties (30 in total) and variation of α_s in PDF

If the stops are also in the loop

$$g_{Sgg}^{\tilde{q}}(\hat{s}) = -\frac{\alpha_s}{8\pi}\sum_{q;i=1,2}\frac{g_i^{\tilde{q}}v}{m_{\tilde{q}_i}^2}\frac{1}{\tau_i^{\tilde{q}}}\left(1-\frac{1}{\tau_i^{\tilde{q}}}f(\tau_i^{\tilde{q}})\right)$$

- Dip structure less prominent for scalars than fermions

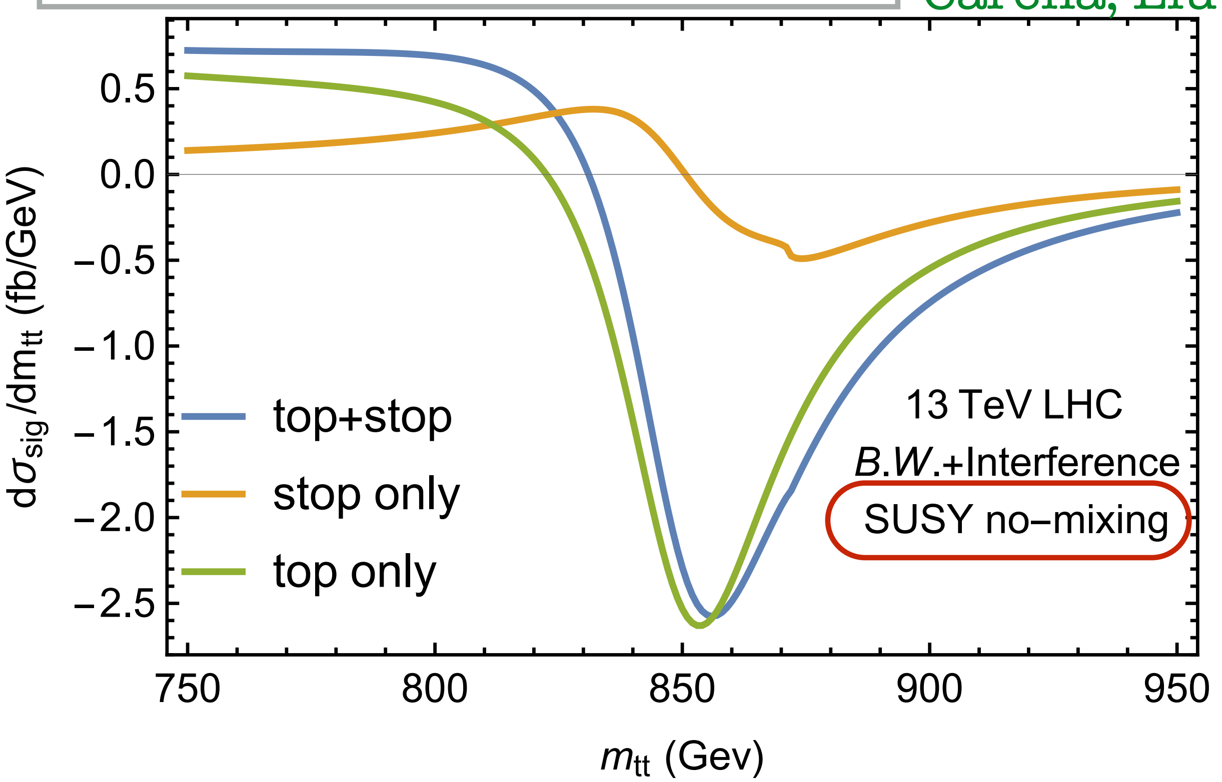


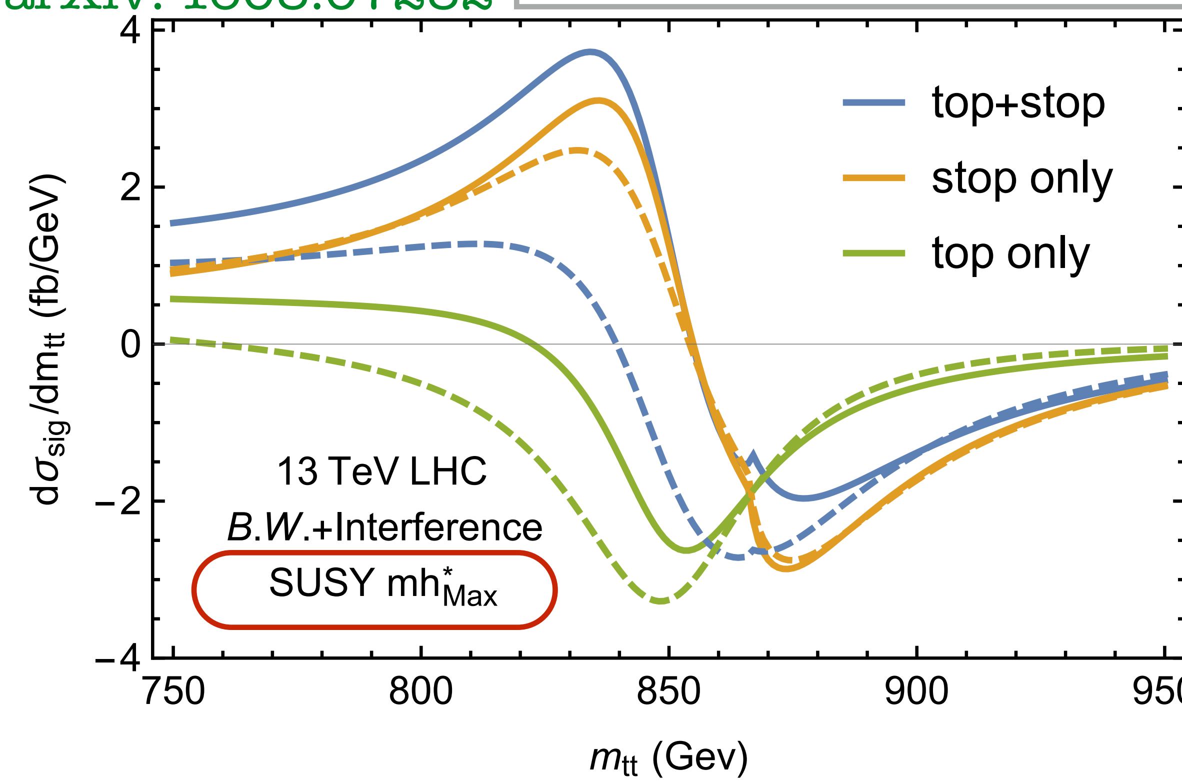
- Stops change the heavy scalar lineshapes in a distinct way depending on the stop mixing.

the top contribution dominates

the stop contribution dominates

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

Non-exhaustive list regarding interferences at the LHC (last 3 years):

▷ Final state $t\bar{t}/gg/\gamma\gamma$:

[1605.00542 Djouadi Ellis Quevillon]: $gg \to \phi \to t\bar{t}$ and $gg \to \phi \to \gamma\gamma$
[1608.07282 Carena Liu]: $gg \to \phi \to t\bar{t}$
[1606.04149 Hespel Maltoni Vryonidou]: $gg \to \phi \to t\bar{t}$ (2HDM, NLO)
[1707.06760 Franzosi Vryonidou Zhang]: $gg \to \phi \to t\bar{t}$ (NLO advanced)
[1606.03026 Martin]: $pp \to \phi \to gg$
[1511.05584 Bernreuther Galler Mellein Si Uwer]: $gg \to \phi \to t\bar{t}$
[1702.06063 Bernreuther Galler Mellein Si Uwer]: $gg \to \phi \to t\bar{t}$ (polarization, spin)
[1505.00291 Jung Song Yoon]: Generic discussion with complex phase (also $b\bar{b}$)

▷ Final state VV: (Consistent model due to unitarity needed!)

[1501.02139 Maina]: $gg \to \phi \to VV$ (SM+singlet)
[1502.04113 Kauer O'Brien]: $gg \to \phi \to VV$ (SM+singlet)
[1506.02257 Ballestrero Maina]: VBF$\to \phi \to VV$ (SM+singlet)
[1506.01694 Kauer O'Brien Vryonidou]: $gg \to \phi \to VV \to 4l$ (SM)
[1510.03450 Jung Song Yoon]: $gg \to \gamma\gamma/ZZ$ (2HDM)
[1512.07232 Greiner SL Weiglein]: $gg \to VV \to 4l$ (2HDM)

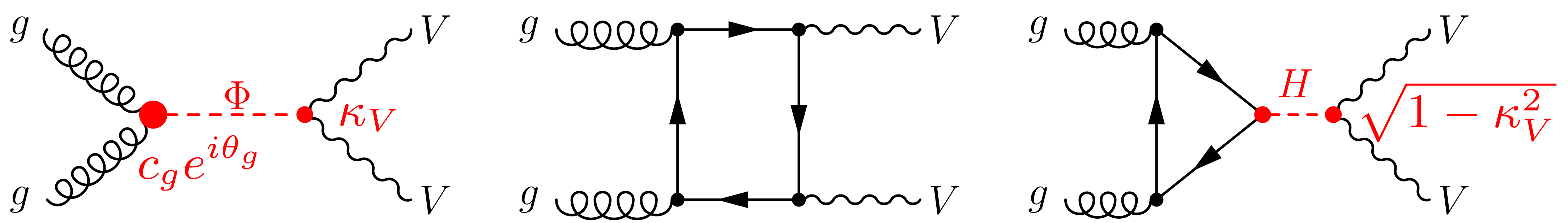
▷ Final state HH:

[1407.0281 Hespel Lopez-Val Vryonidou]: $gg \to \Phi \to HH$ (2HDM, NLO)
[1508.05397 Dawson Lewis]: $gg \to \Phi \to HH$ (SM+singlet, NLO)

▷ Interferences among heavy Higgs bosons:

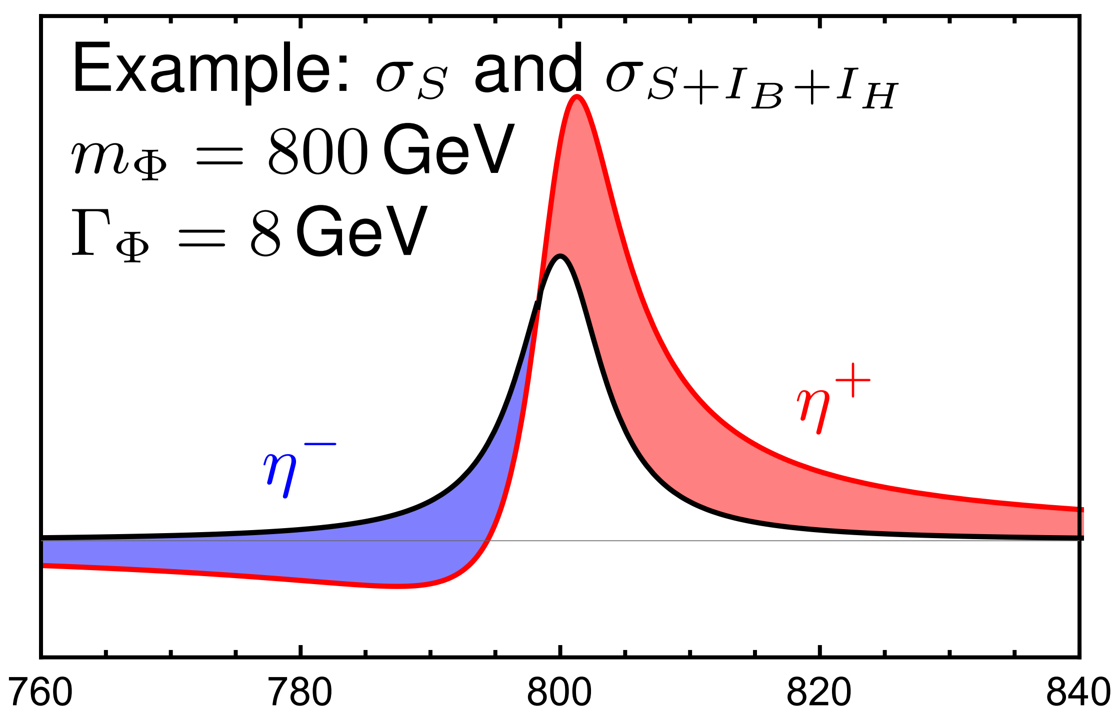
[1411.4652 1705.05757 Fuchs Weiglein]: ϕ's of the MSSM

Idea: Classify relevance of interferences in the VV and HH final states:
Interferences among



Simplified approach with 5 parameters: $c_g e^{i\theta_g}, m_\Phi, \Gamma_\Phi, \kappa_V$
Similar for HH with $\lambda_{\Phi hh}$ and λ_{hhh} instead of κ_V
Quantify interference in terms of:

$$\eta = \sigma_{I_B+I_H}/\sigma_S \quad \text{with} \quad \sigma_X = \int_{m_\Phi - 5\Gamma_\Phi}^{m_\Phi + 5\Gamma_\Phi} dm_{VV} \frac{d\sigma^X}{dm_{VV}}$$



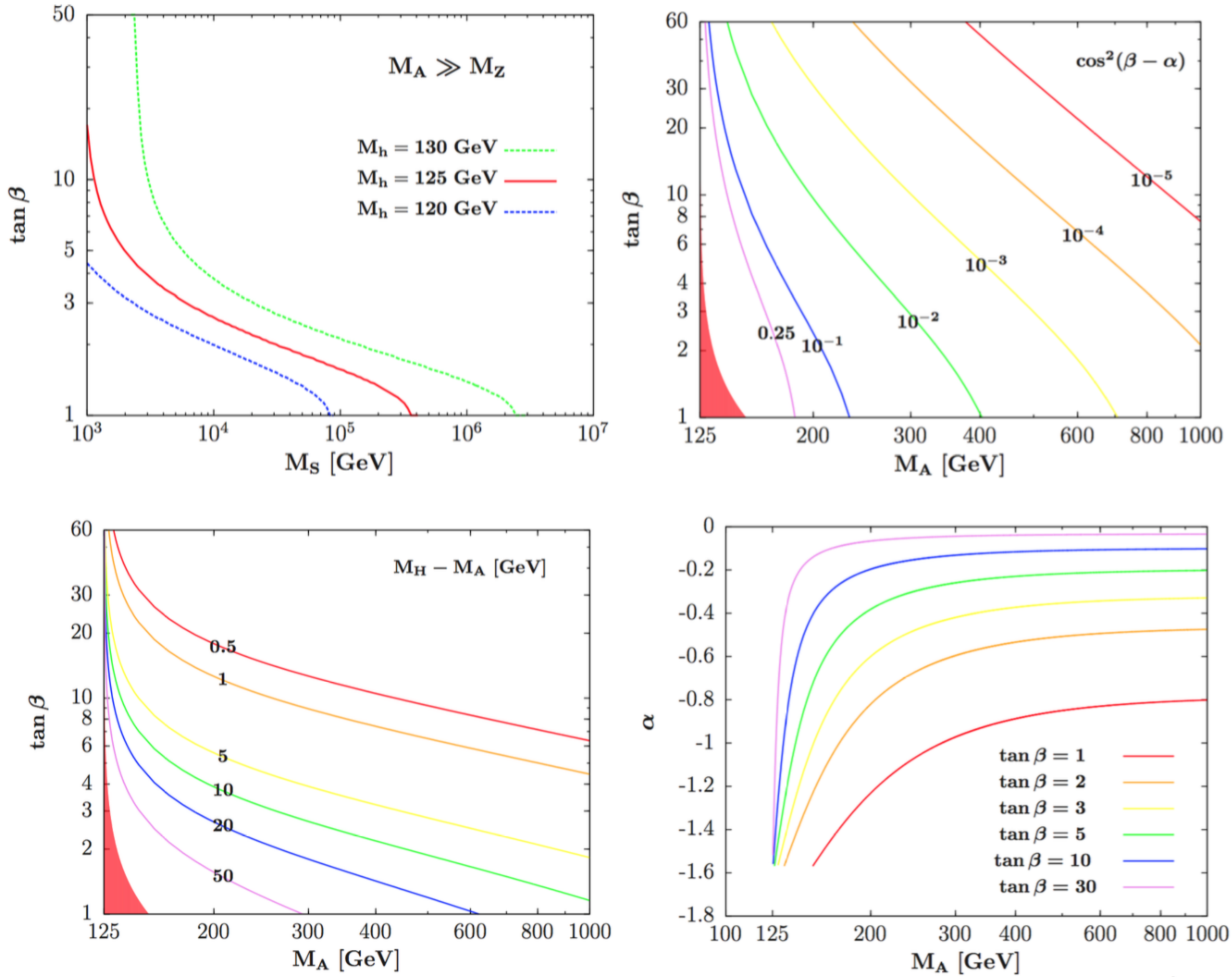
E.g. provide relative corrections:

$$\eta^\mp = \begin{pmatrix} \eta^- \\ \eta^+ \\ \eta \end{pmatrix} = \begin{pmatrix} -165\% \\ +160\% \\ +38\% \end{pmatrix}$$

Make tables, figures as a function of free parameters. Provide guidance.
Check quantity $\Gamma_\Phi/m_\Phi \cdot \sigma_S/\sigma_B$.

The definition of the hMSSM

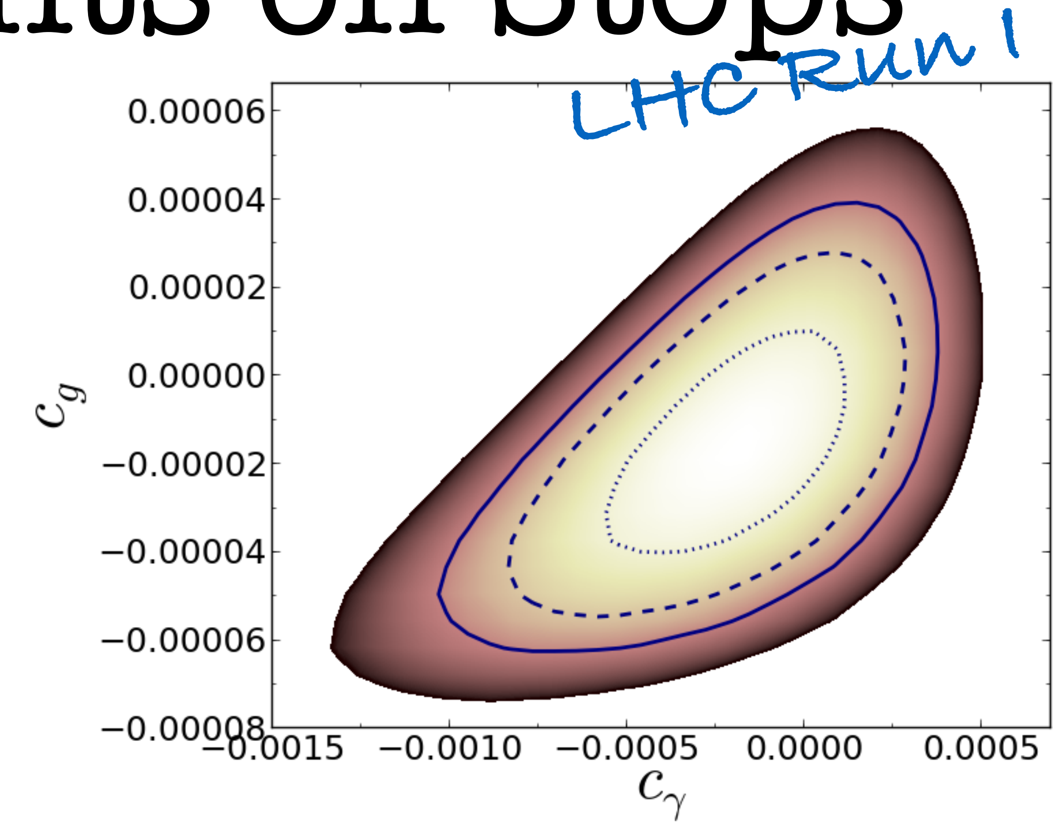
Djouadi, Maiani, Polosa, JQ, Riquer, arXiv:1502.05653

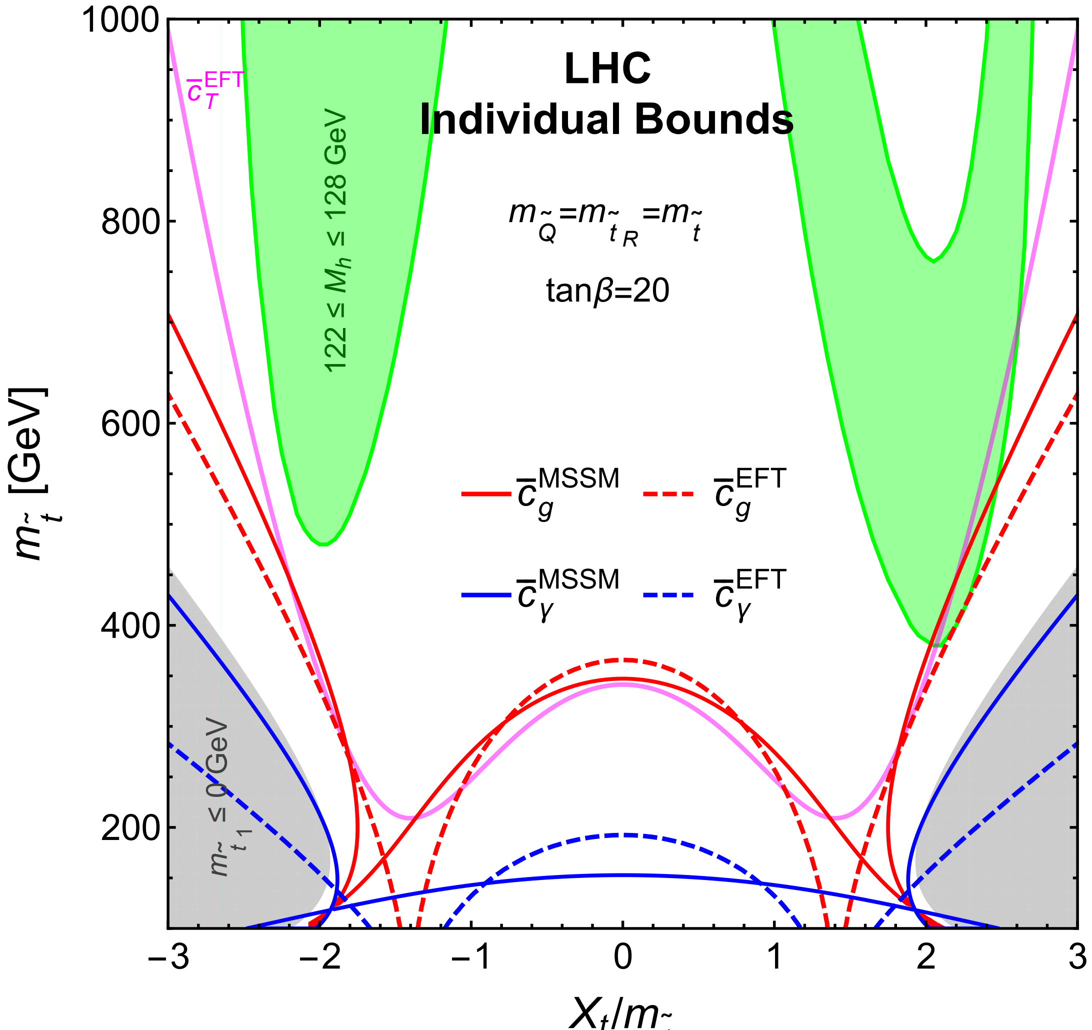


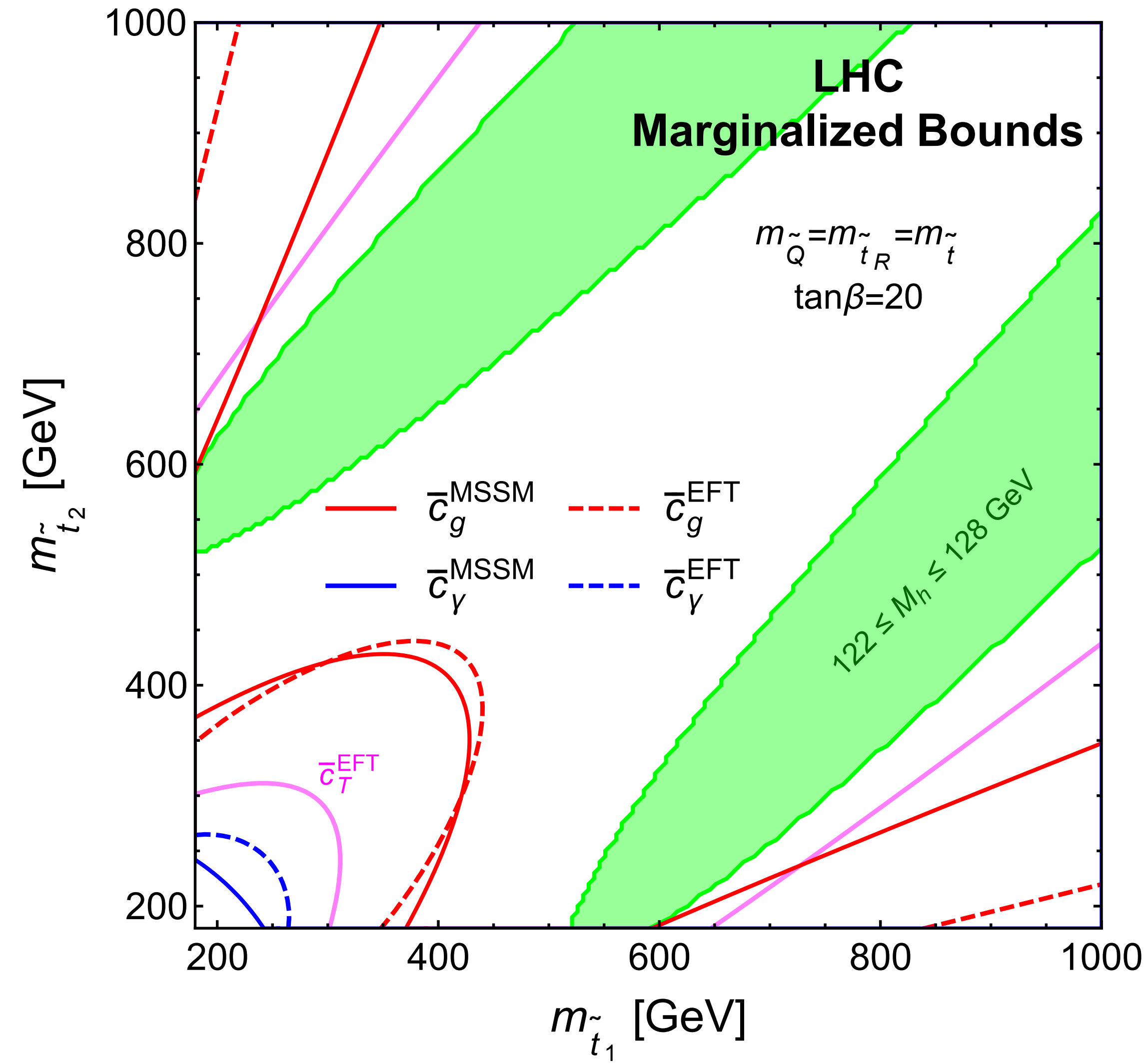
Indirect Constraints on Stops

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

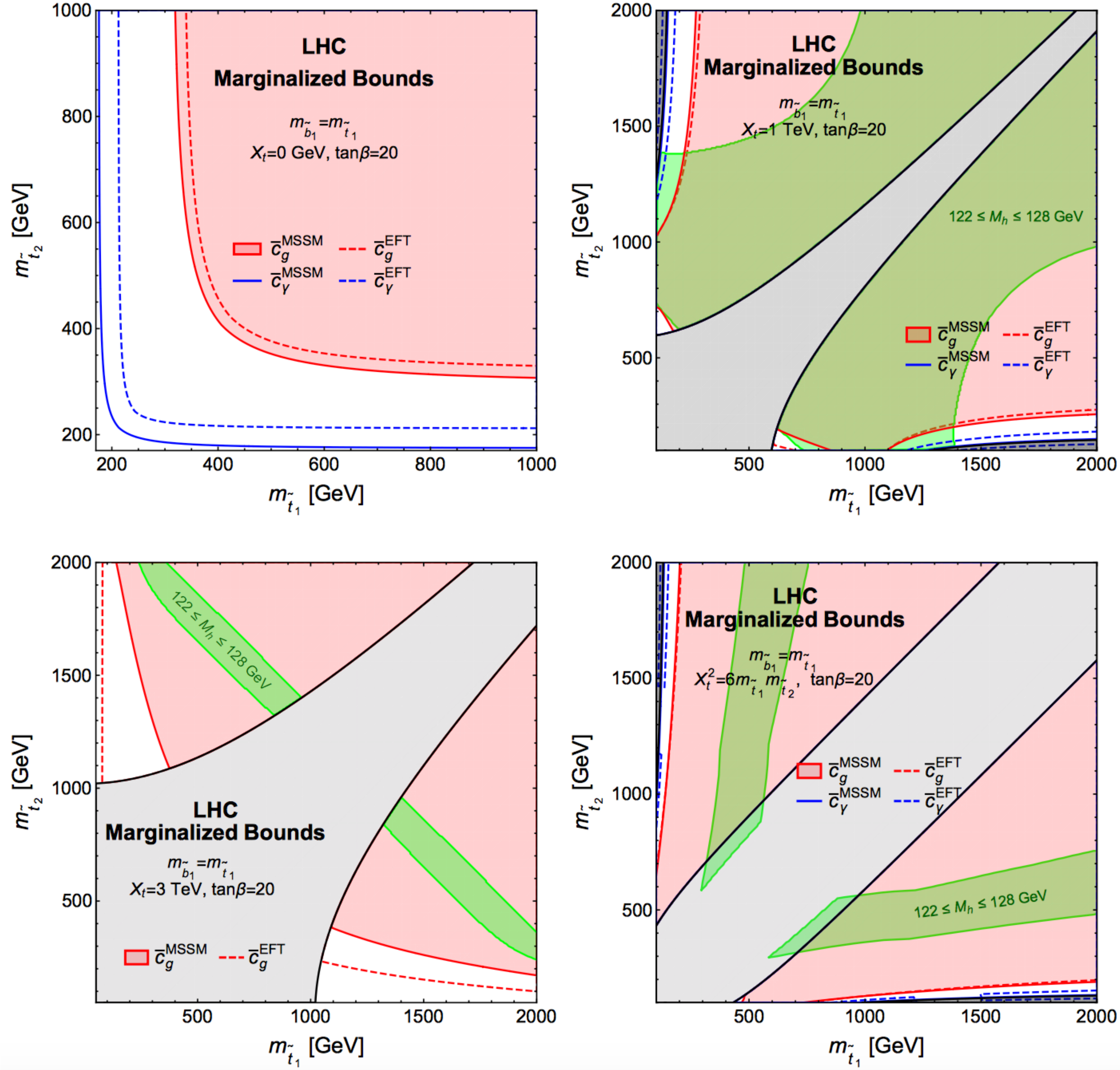






Indirect Constraints on Stops

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