Search for $A/H \to t\bar{t}$ at CMS 13 TeV

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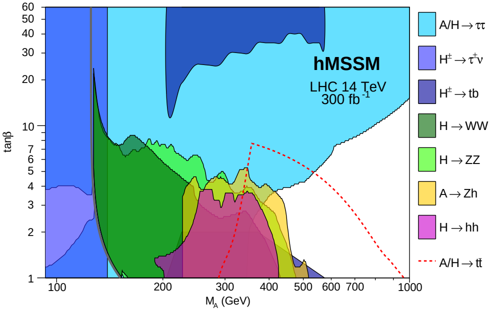
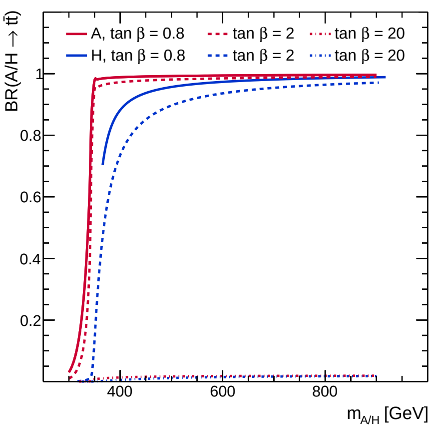
Motivation

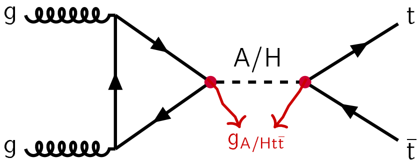
- Extended Higgs sector is predicted by many models
  2HDM, (h)MSSM, composite Higgs…
  - With 2 doublets we have 5 scalars: A, h, H and $H^{\pm}$
  - Identify h = h(125) → alignment limit
  - May also be the link to the dark matter sector
- Yukawa-like coupling means large top contributions
  - Dominating also the decay if $m_{A/H} \gtrsim 2m_t$
  - Especially for A: direct A → VV is forbidden
    (H → VV is also suppressed)
- $A/H \to t\bar{t}$ may be the only viable channel
  - Specific models have ways to dodge this
    e.g. large $\tan\beta$ in Type-II 2HDM





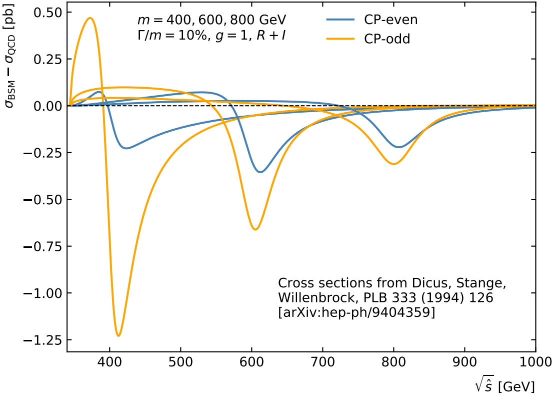
arXiv 1502.05653

Overview



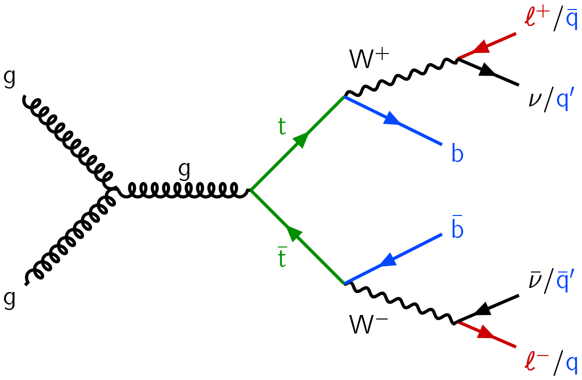
- Search for $A/H \to t\bar{t}$ produced through gluon fusion
  - MG5_aMC@NLO at LO scaled to N^{3}LO
  - Assume CP conservation

    i.e. signal is pure A and/or pure H
- Set limits on coupling strength modifier $g_{A/Ht\bar{t}}$ and perform a hMSSM interpretation
- Search conducted in the ℓj and $\ell\ell$ channels
  - Talk is based on arXiv:1908.01115



Dataset, event selection and corrections

- Used CMS 2016 data, 35.9 /fb in total
- SM simulation: $t\bar{t}$ (POWHEGV2), single top, DY, $t\bar{t}V$, VV, W and multijet QCD



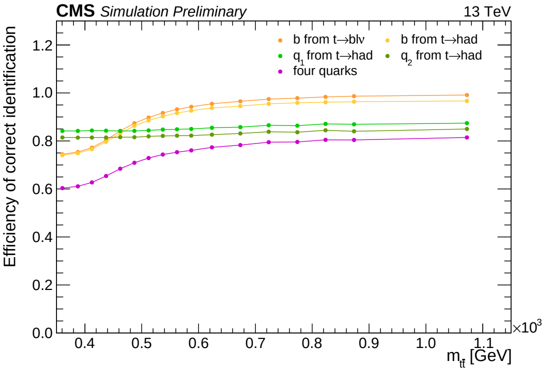
- ℓj channel:
  - Single lepton triggers
  - Exactly 1 tight e or μ
  - ≥ 4 jets, ≥ 2 b-tagged
  - $m_T^W > 50$ GeV
  - Data-driven multijet QCD background
- $\ell\ell$ channel:
  - Double + single lepton triggers
  - Exactly 2 e or μ
  - ≥ 2 jets, ≥ 1 jet b-tagged
  - Same-flavor $\ell\ell$: Z-veto cuts
  - Data-driven DY estimation

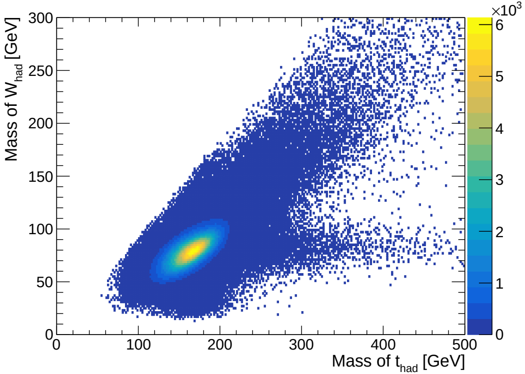
- $t\bar{t}$ kinematic reconstruction employed in both analyses
- Apply the empirical top p_T reweighting on SM $t\bar{t}$ events

ℓj kinematic reconstruction

- Reconstruct neutrino by minimizing $D_\nu = \left\|\vec{p}_T^{\,\nu} - \not{p}_T\right\|$ while respecting constraints on m_W and m_t
- Solution obtained by maximizing the likelihood constructed from:
  - Distribution of minimum D_ν values
  - Distribution of reconstructed m_t and m_W in the hadronic branch
  - Only correctly matched SM $t\bar{t}$ events are used in the distributions
- Only allow b-tagged jets to be matched to the b quarks

- Efficiency to solve is ∼85% regardless of matching
- $m_{t\bar{t}}$ resolution is ∼14% for events with solution
- Correct matching eff is ∼70% within the 'target topology'

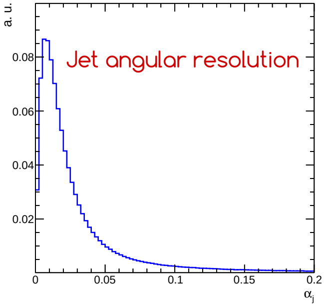


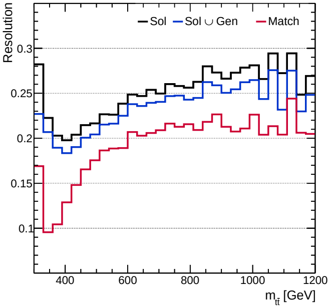


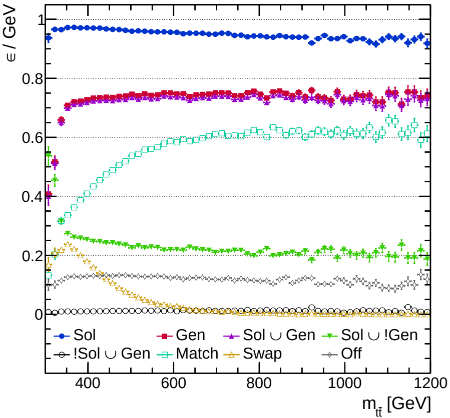
$\ell\ell$ kinematic reconstruction

- Analytical neutrino solver
  - Constraints from $\not{p}_T$, m_t and m_W lead to 4th-order polynomial
  - Solution with the smallest $m_{t\bar{t}}$ is chosen
- Solve for all ℓ-jet combinations prioritizing b-tagged jets
  - Each combination is solved 100 times with smeared measured momenta and assigned weights based on gen $m_{\ell b}$ distribution
  - Pick the combination with highest sum of weights
  - Obtain t and $\bar{t}$ momenta from the average of the highest combination

- Efficiency to solve is ∼95% regardless of matching
- $m_{t\bar{t}}$ resolution is ∼25% for events with solution
- Correct matching eff is ∼60% within the 'target topology'



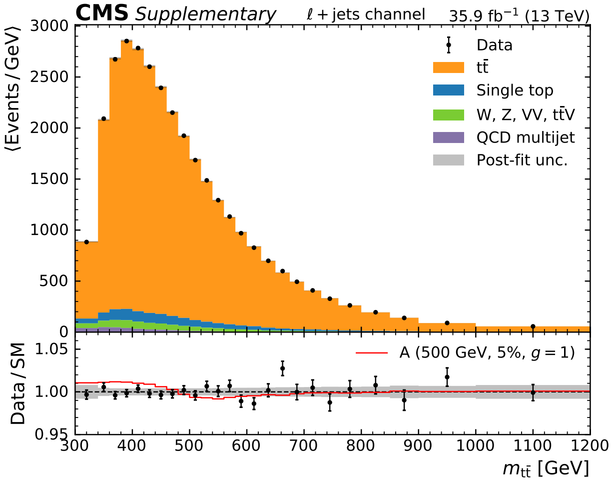




arXiv 0603011, DESY-THESIS-2016-011

Analysis strategy

- Use the 2D templates of
  $m_{t\bar{t}} \times$ a spin-sensitive angular observable



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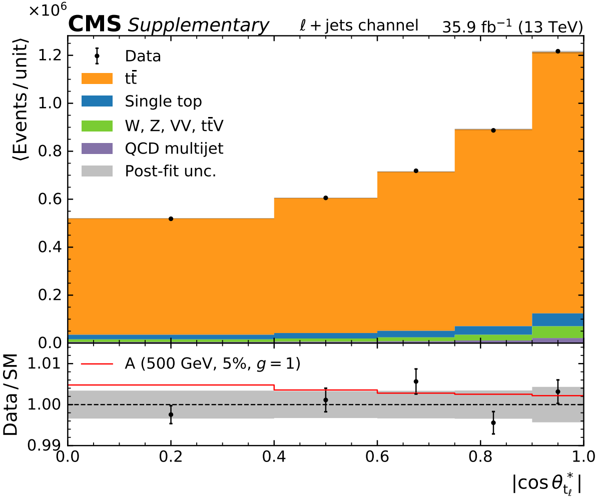
  - ℓj: $\cos\theta^*_{t\ell}$ exploiting isotropic emission of tops by a scalar resonance



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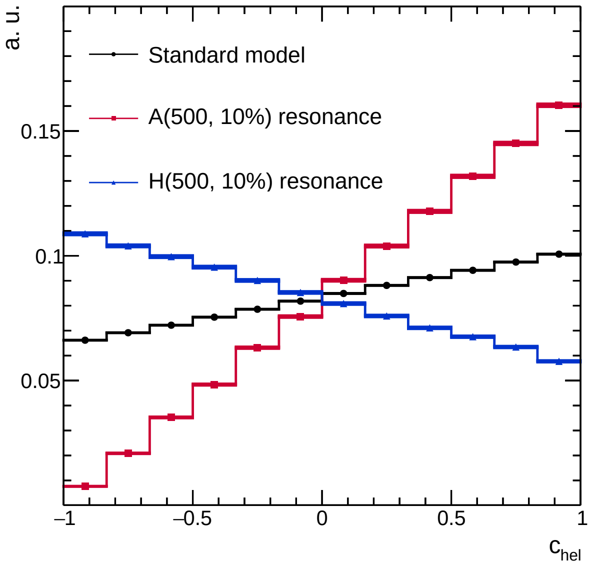

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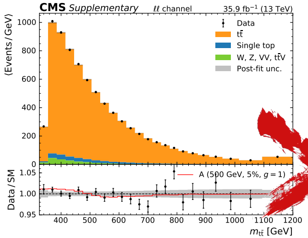
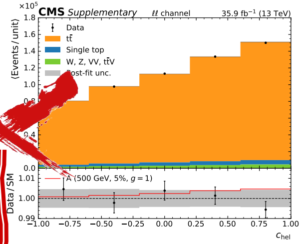
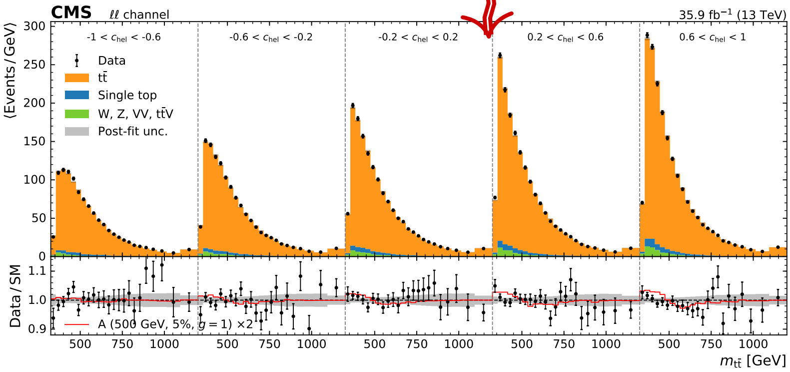
- Sensitive to resonances of various masses and spins







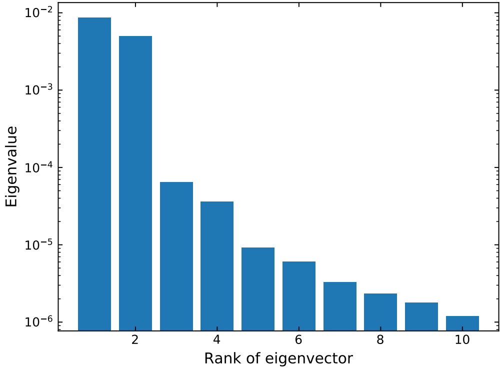
Systematic uncertainty sources

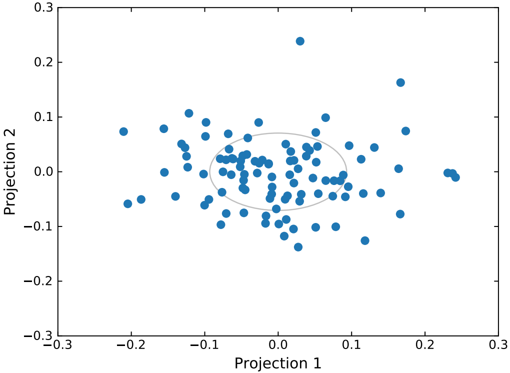
Analysis-specific treatment to be discussed

Uncertainty (# of parameters)	Type	Affected process	Correlation
Jet p_T scale (19)	shape	All	All
Jet p_T resolution	shape	All	All
Unclustered p_T^{miss}	shape	All	All
btagging heavy-flavor jets	shape	All	All
btagging light-flavor jets	shape	All	All
Pileup	shape	All	All
Electron identification	shape	All	All
Muon identification	shape	All	All
Single-electron trigger	shape	All	e, $\ell\ell$
Single-muon trigger	shape	All	μ, $\ell\ell$
Luminosity calibration	norm.	All	All
Renorm. scale SM $t\bar{t}$	shape	SM $t\bar{t}$	All
Fact. scale SM $t\bar{t}$	shape	SM $t\bar{t}$	All
Parton shower FSR $t\bar{t}$	shape	SM $t\bar{t}$	All
h_{damp}	shape	SM $t\bar{t}$	All
Top quark mass	shape	SM $t\bar{t}$	All
Top quark p_T (2)	shape	SM $t\bar{t}$	All
PDF (3)	shape	SM $t\bar{t}$	All
Renorm. scale res. signal	shape	Resonant signal	All
Renorm. scale int. signal	shape	Interference signal	All
Fact. scale res. signal	shape	Resonant signal	All
Fact. scale int. signal	shape	Interference signal	All
SM $t\bar{t}$ norm.	norm.	SM $t\bar{t}$	All
Single top t channel norm.	norm.	Single top t channel	ℓ
Single top s channel norm.	norm.	Single top s channel	ℓ
Single top tW channel norm.	norm.	Single top tW channel	All
W + jets norm.	norm.	W + jets	ℓ
Z/γ^* + jets norm.	norm.	Z/γ^* + jets	ℓ
Z/γ^* + jets norm. from data	norm.	Z/γ^* + jets	$\ell\ell$
Diboson norm.	norm.	Diboson	All
$t\bar{t}V$ norm.	norm.	$t\bar{t}V$	All
QCD multijet norm. from data, e	norm.	QCD multijet	e
QCD multijet norm. from data, μ	norm.	QCD multijet	μ
MC statistical uncertainty (365)	shape	All	No

PDF principal component analysis

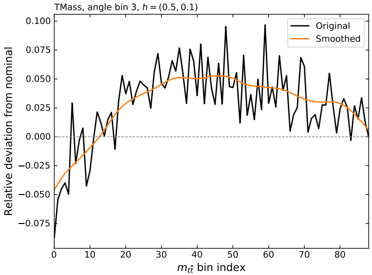
- Apply PCA to relative deviations from nominal distribution
  - Each of the 100 MC replicas is treated as a "measurement"
  - Each measurement is comprised of the deviations in 2D distributions in both channels
    - $25 \times 5 + 23 \times 5 = 240$ "features" per measurement
    - Perform an eigenvalue decomposition of the 240×240 covariance matrix to obtain the basis variations
- Deviations for each MC replica are then approximated as a linear combination of the dominating 2 basis variations

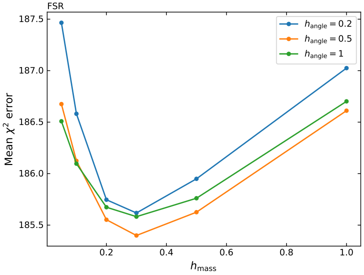


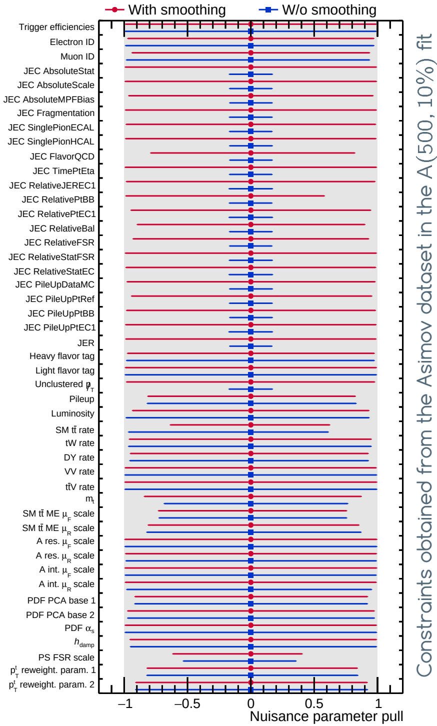


Template smoothing

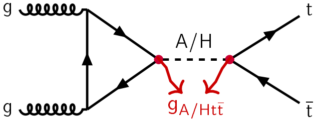
- Some systematic sources are constrained
  - Spurious in that the fit is constraining statistical fluctuations
- Eliminate by a smoothing procedure
  - Based on a local regression over a sliding plane
- Remaining constraints are in line with expectations



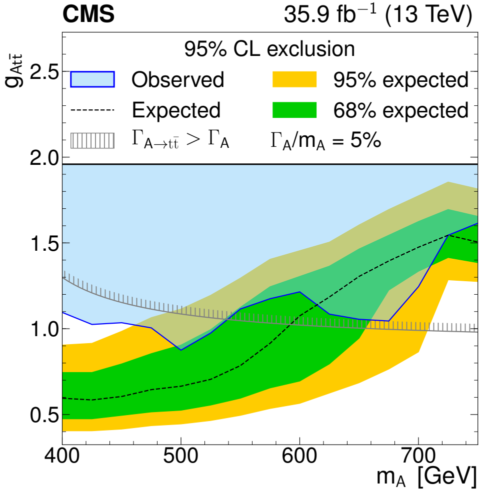


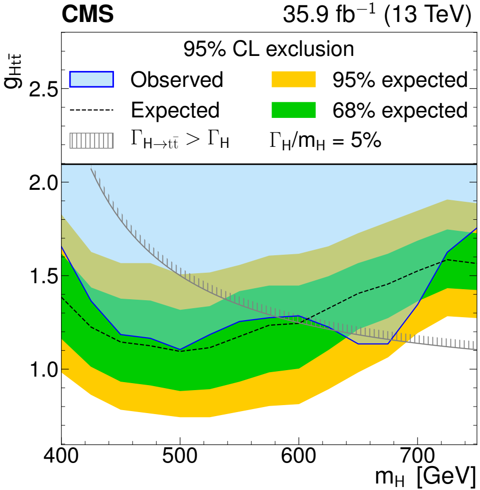


Model-independent interpretation



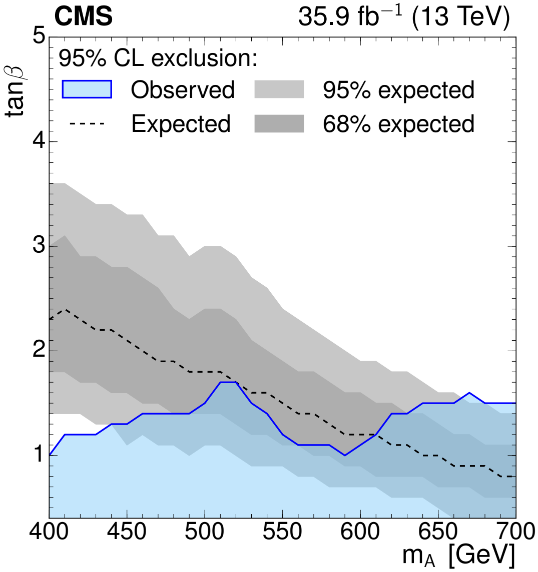
- Exclusion regions on $g_{A/Ht\bar{t}}$ are set for each signal point
  - Based on the maximum likelihood estimation and CL_s method
- Observed exclusion is weaker than expected at low m_A, indicative of an excess
  - Most significant for $A(400, 4\%)$ at 3.5σ, 1.9σ after LEE





hMSSM interpretation

- Analysis also interpreted in the hMSSM context
  - ...in which case A and H are related
  - Set exclusion on $g_{A/Ht\bar{t}}$ as before, convert to a $(m_A, \tan\beta)$ point using hMSSM relations
  - No A/H mass degeneracy assumed
    invalid at low $\tan\beta$
- Exclude the $\tan\beta$ range of 1 to 1.5 from m_A of 400 GeV to 700 GeV



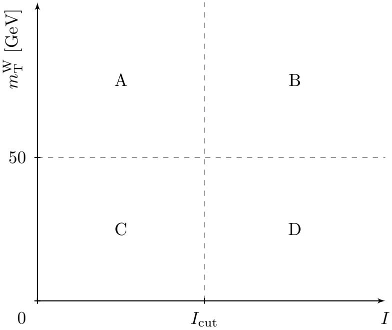
Afterword

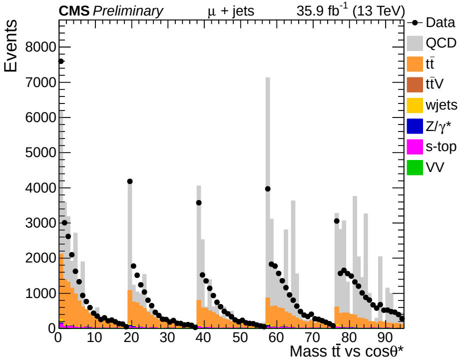
- Presented the search for $A/H \to t\bar{t}$ at CMS 13 TeV
- This is the first such search by CMS
- Set limits on the coupling modifiers $g_{A/Ht\bar{t}}$ and the hMSSM $(m_A, \tan\beta)$ space
- Strong DESY involvement in the analysis
  - Solely responsible for the $\ell\ell$ channel
  - Leading the effort of the full Run 2 analysis
- Fluctuation or a hint of BSM? We will see…

Backup

Data-driven multijet background

- Multijet background is hard to model with MC
- Normalization estimated with a variant of ABCD method
  - Based on isolation and m_T^W
  - Assume factorization for multijet
  - ML fit to event counts in the four regions while taking other background from MC
- Conservative uncertainty of $^{+100}_{-50}$%
- Shape is taken from region with inverted isolation
  - Backgrounds with prompt leptons are modelled with MC and subtracted from data
  - Statistical uncertainties in the template are included into systematics



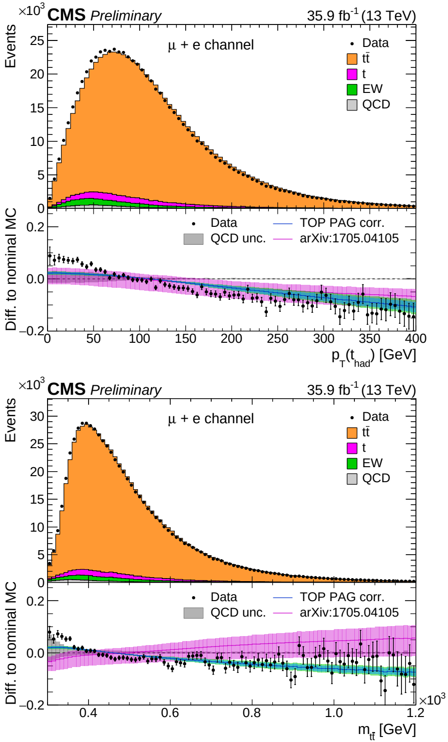


Data-driven DY background

- Estimate the data DY yield outside Z window as $Z^{out}_{\ell\ell} = R^{\ell\ell}_{out/in}(N^{in}_{\ell\ell} - 0.5 N^{in}_{e\mu} k_{\ell\ell})$
  - $N_{\ell\ell}$ ($Z_{\ell\ell}$) is the data yield (estimated DY yield)
  - $R^{\ell\ell}_{out/in}$ is the ratio between
    simulated DY yields outside and inside the Z window
  - $k_{\ell\ell}$ accounts for different e and μ efficiencies: $k^2_{ee} = N^{in}_{ee}/N^{in}_{\mu\mu}$
- Reweight MC by SF $s^{\ell\ell} = Z^{out}_{\ell\ell}/N^{out}_{\ell\ell,\mathrm{DY\ MC}}$; $s^{e\mu} = \sqrt{s^{ee}s^{\mu\mu}}$
  - All SFs are around 1.2
  - Assign 30% systematic on the SFs
    i.e. the variation between the SFs derived at the 2 jet cut and the full selection

Top p_T reweighting

- Tried to mitigate the top p_T mismodelling by reweighting to theory predictions
- Worsens description of $m_{t\bar{t}}$
- Adopted empirical reweighting
  - $SF = e^{p_0 + p_1 \cdot p_T^t}$, $p_0 = 0.0615$, $p_1 = -0.0005$
  - Event weight is the geom. mean of the generator t and $\bar{t}$ SFs
- Uncertainty from covariance matrix of the fit for corrections
- A/H signal manifests itself as a feature in $m_{t\bar{t}}$ spectrum, not trends
  - Reweighting might be hiding new physics but not the one we are looking for
- No impact on the results by replacing the uncertainties with a conservative approach (no- and double-reweighting)



$\ell\ell$ event yields

Process	Event yield
Observed	230 233
Signal $\mathrm{A} \to \mathrm{t\bar{t}}$ $(m_{\mathrm{A}} = 500\,\mathrm{GeV}, \Gamma_{\mathrm{A}}/m_{\mathrm{A}} = 5\%)$	$(0.7^{+0.5}_{-0.4}) \times 10^3$
Total background	$(231.1 \pm 0.8) \times 10^3$

	Fraction w. r. t. total background
$\mathrm{t\bar{t}}$	93.3%
Single top quark	3.3%
$\mathrm{Z}/\gamma^* + \mathrm{jets}$	2.9%
$\mathrm{t\bar{t}}V$	0.3%
Diboson	0.1%

ℓj event yields

Process	Electron channel	Muon channel
	Event yield	
Observed	274 821	416 254
Signal A $\rightarrow$ t$\bar{\text{t}}$ ($m_\text{A} = 500\,\text{GeV}, \Gamma_\text{A}/m_\text{A} = 5\%$)	$\left(0.9^{+0.6}_{-0.5}\right) \times 10^3$	$\left(1.5^{+0.9}_{-0.8}\right) \times 10^3$
Total background	$\left(274.8^{+0.8}_{-0.9}\right) \times 10^3$	$\left(416.3^{+1.1}_{-1.2}\right) \times 10^3$
	Fraction w. r. t. total background	
t$\bar{\text{t}}$	91.9%	92.1%
Single top quark	3.9%	4.0%
W + jets	1.9%	2.1%
Z/γ^* + jets	0.4%	0.3%
t$\bar{\text{t}}V$	0.2%	0.2%
Diboson	0.1%	0.1%
QCD multijet	1.5%	1.0%

A/H statistical analysis

- Establish presence of A/H signal through the following likelihood function:

$$L(\mu, \vec{p}_{A/H}, \vec{\nu}) = \prod_i \frac{\lambda_i^{N_i}(\mu, \vec{p}_{A/H}, \vec{\nu})}{N_i!} e^{-\lambda_i(\mu, \vec{p}_{A/H}, \vec{\nu})} \times G(\vec{\nu})$$

- μ: signal strength parameter, $\vec{p}_{A/H} = (m_{A/H}, \Gamma_{A/H}, g_{A/H})$
- $\lambda_i(\mu, \vec{p}_{A/H}, \vec{\nu})$, N_i: expected, observed event yield in bin i
- $\vec{\nu}$: set of nuisance parameters, $G(\vec{\nu})$ encode the external constraints on them
- Test statistic $\tilde{q}_\mu$ given by:

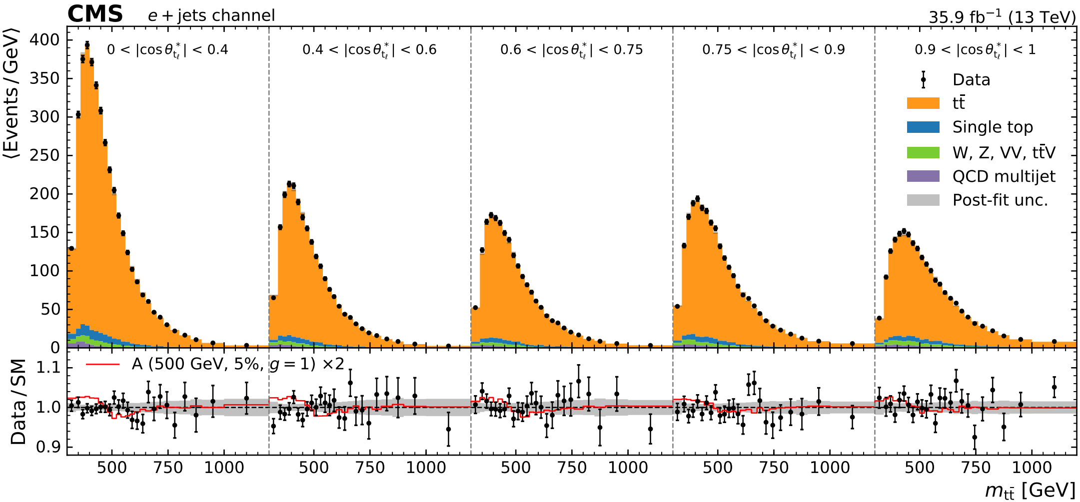
  (suppressing the fixed arguments of L, $\mu = 1$, $g_{A/H}$ to value being probed)

$$\tilde{q}_\mu = -2 \ln \frac{L(\vec{\nu})}{L(\mu, \vec{\nu})}, \ \mu \in [0, 1]$$

- Compute $\tilde{q}_\mu$ for $g_{A/H} \in [0, 3]$, exclude a given $g_{A/H}$ if the corresponding $CL_s < 0.05$

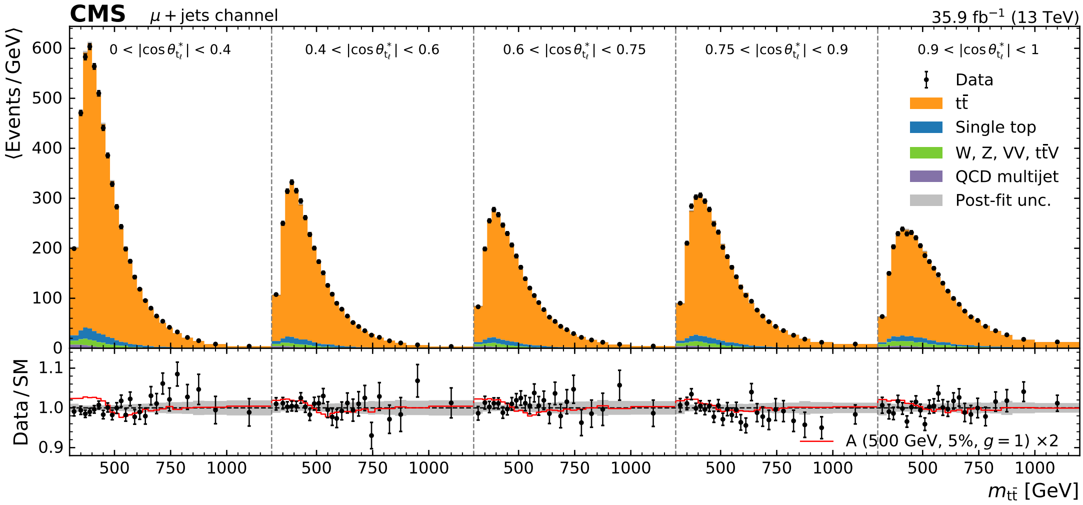
arXiv 1007.1727, 9902006; J. Phys. G 28 (10)

Post-fit ej search template



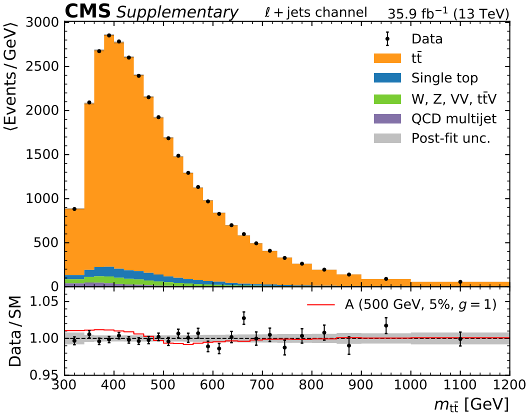
…in a background-only fit to the real data in the $\ell\ell + \ell j$ channels

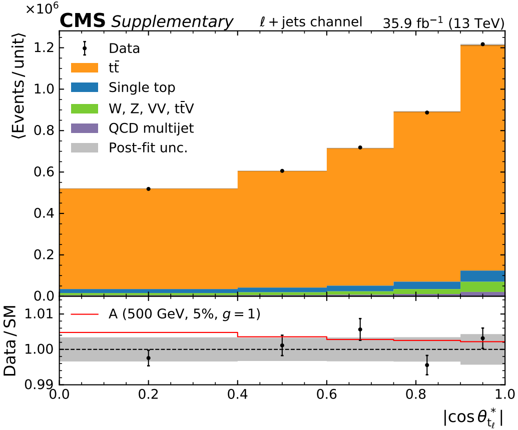
Post-fit μj search template



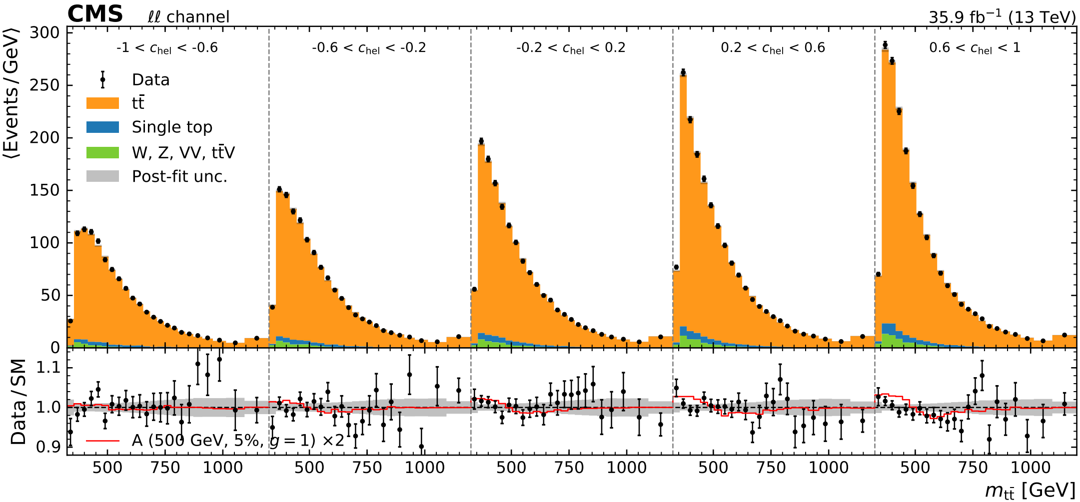
…in a background-only fit to the real data in the $\ell\ell$ + ℓj channels

Projected post-fit ℓj search template



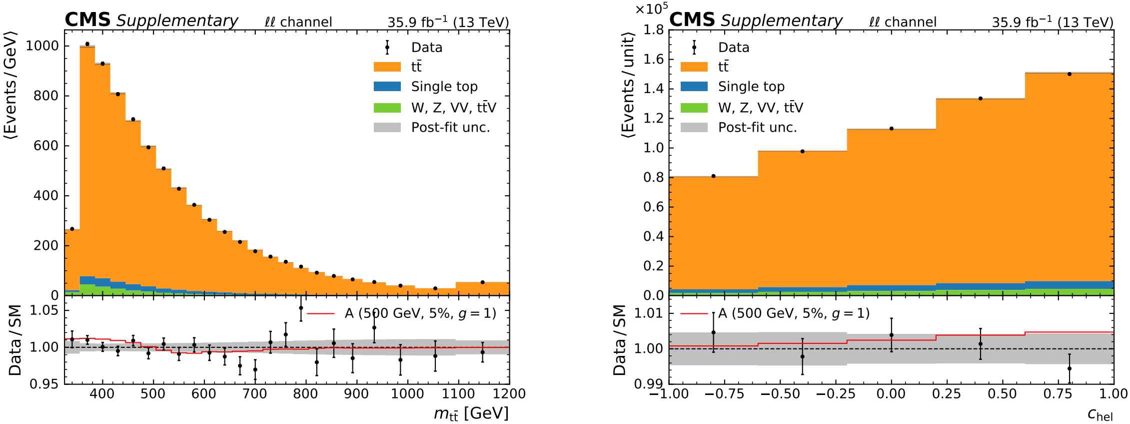


Post-fit $\ell\ell$ search template

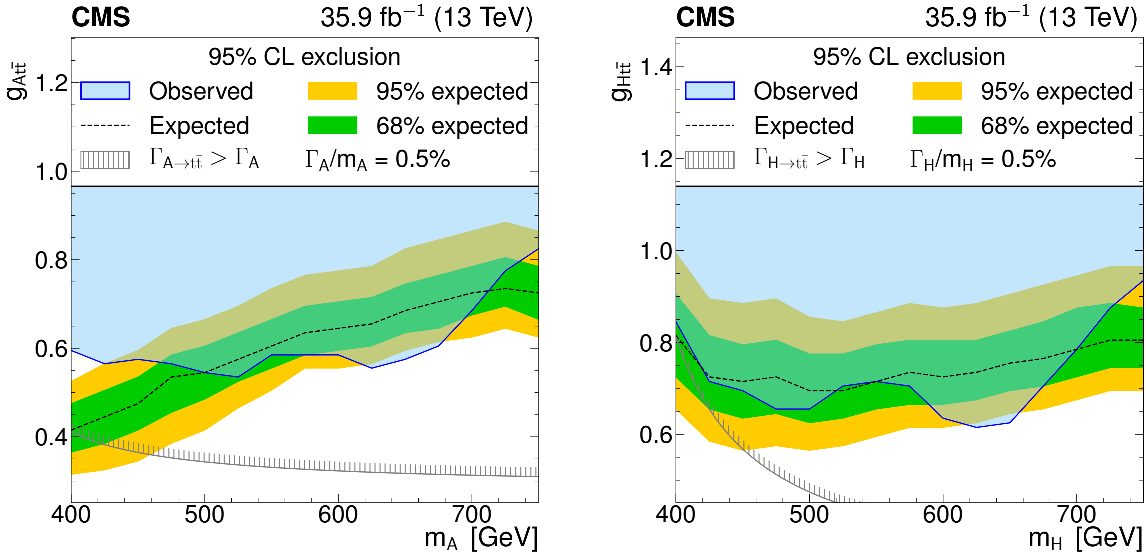


…in a background-only fit to the real data in the $\ell\ell$ + ℓj channels

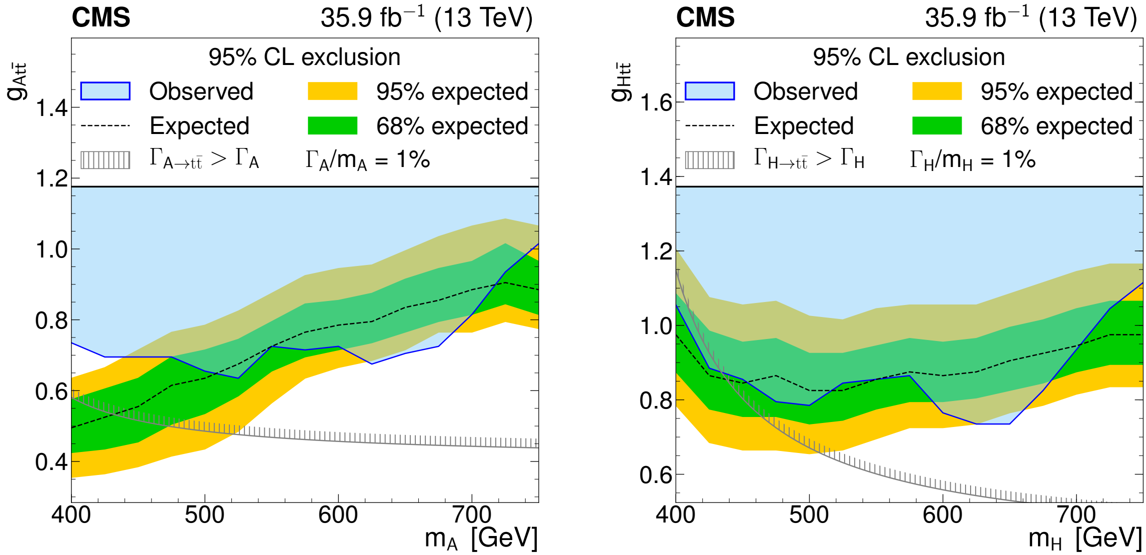
Projected post-fit $\ell\ell$ search template



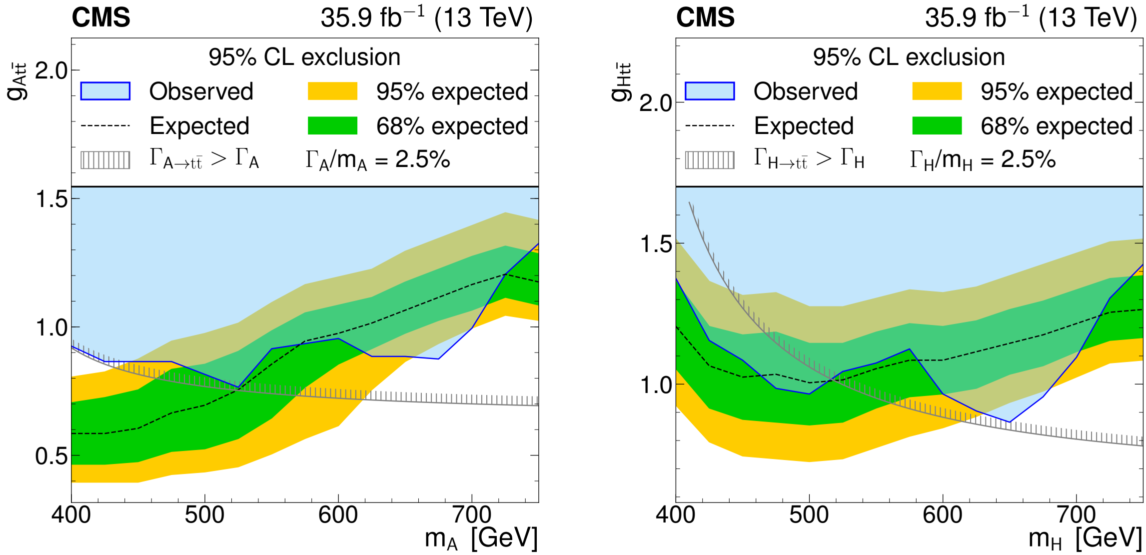
A/H(0.5%) model-independent exclusion



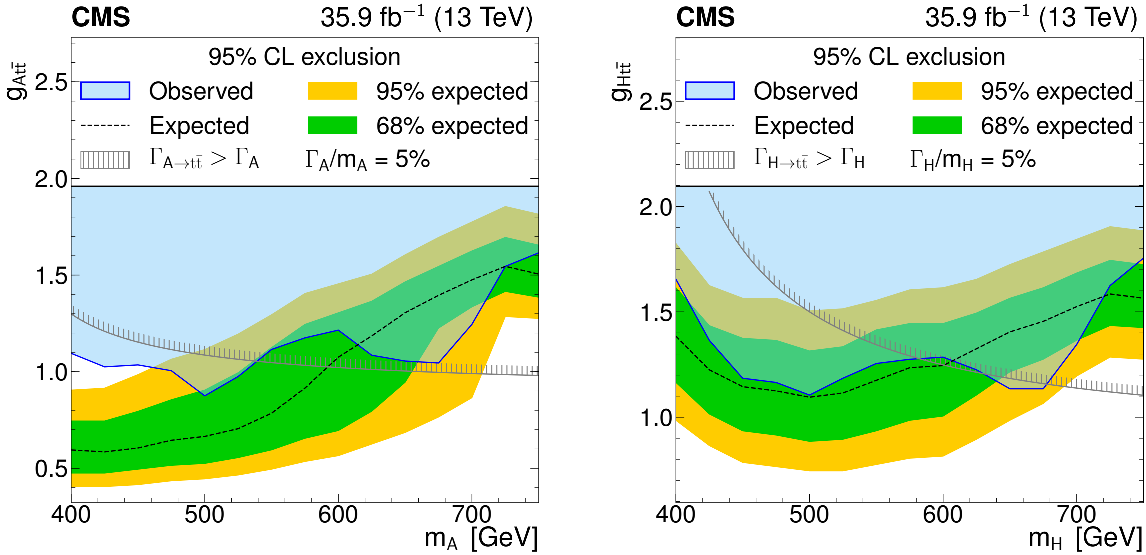
A/H(1%) model-independent exclusion



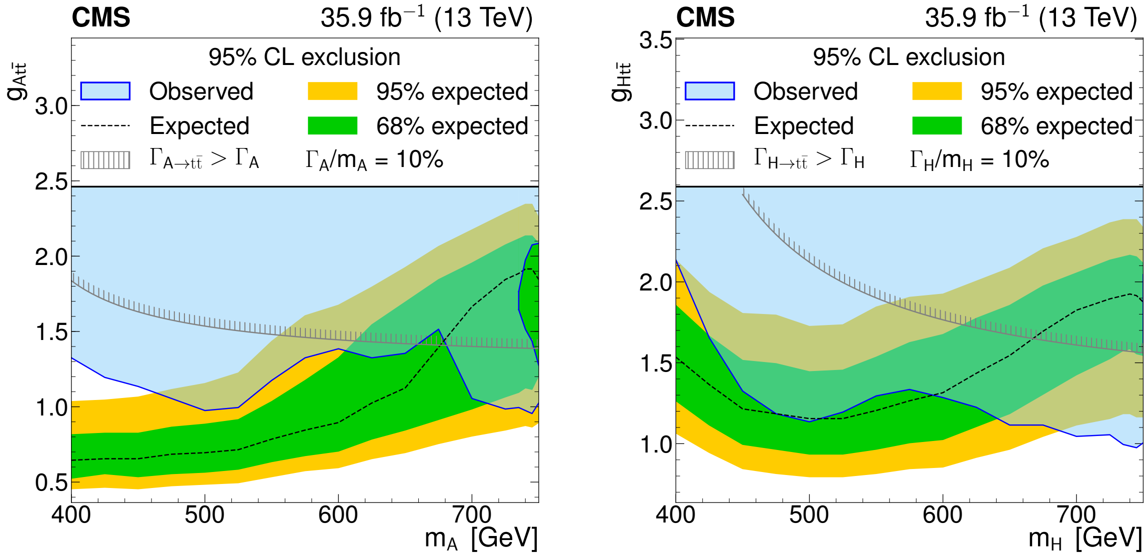
A/H(2.5%) model-independent exclusion



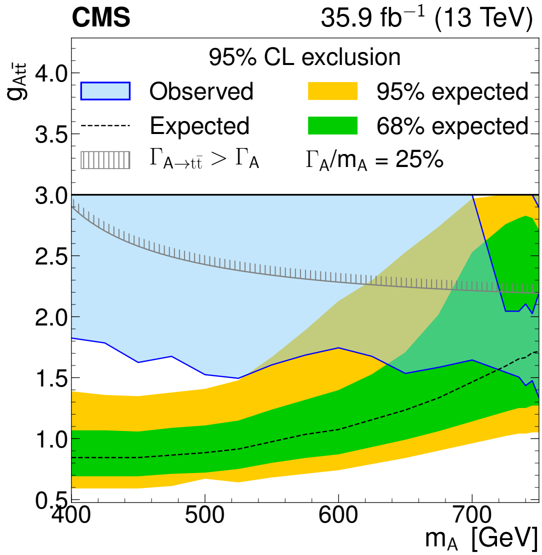
A/H(5%) model-independent exclusion

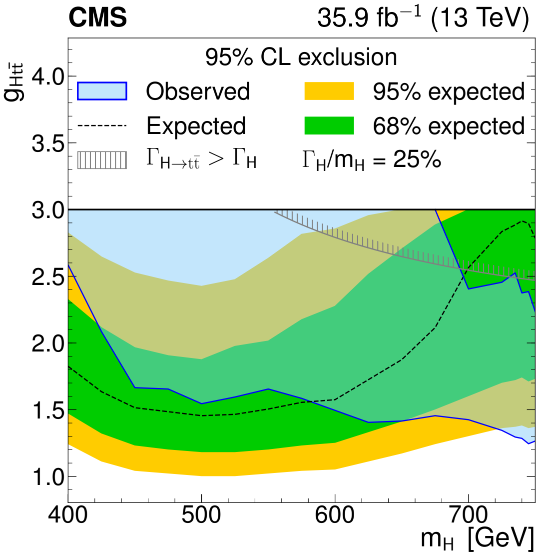


A/H(10%) model-independent exclusion



A/H(25%) model-independent exclusion



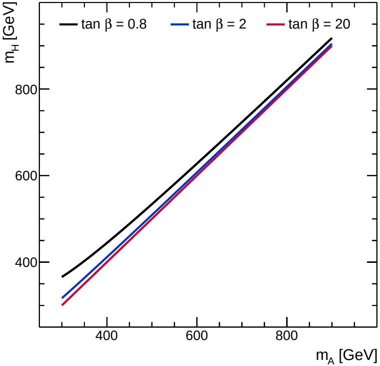


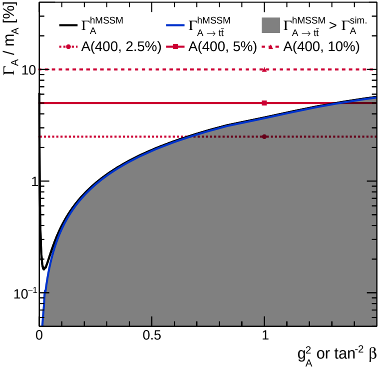
Type II 2HDM coupling modifiers

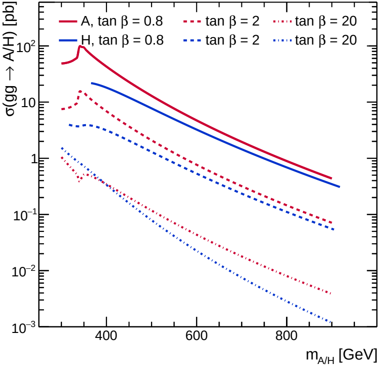
Φ	$g_{\Phi u\bar{u}}$	$g_{\Phi d\bar{d}}$	$g_{\Phi VV}$
A	$\cot\beta$	$\tan\beta$	0
h	$\cos\alpha\,/\,\sin\beta$	$-\sin\alpha\,/\,\cos\beta$	$\sin(\beta-\alpha)$
H	$\sin\alpha\,/\,\sin\beta$	$\cos\alpha\,/\,\cos\beta$	$\cos(\beta-\alpha)$

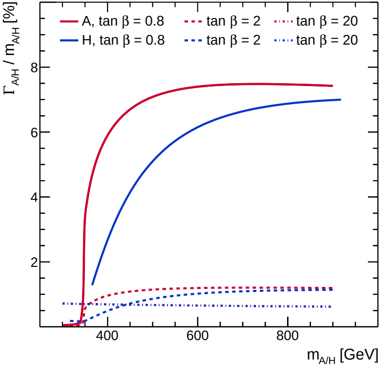
hMSSM A/H: additional info

- Top right: $m_H(m_A)$
- Bottom left: $(m_A, \tan\beta)$ exclusion setting procedure
- Bottom middle: $\sigma_{A/H}(m_{A/H})$
- Bottom right: $\frac{\Gamma_{A/H}}{m_{A/H}}(m_{A/H})$









Per-channel hMSSM