Searches for heavy scalars decaying to $t\bar{t}$ and ZZ in the CMS experiment

Andrey Popov

Université Libre de Bruxelles

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beyond The H boson gateway to new physics

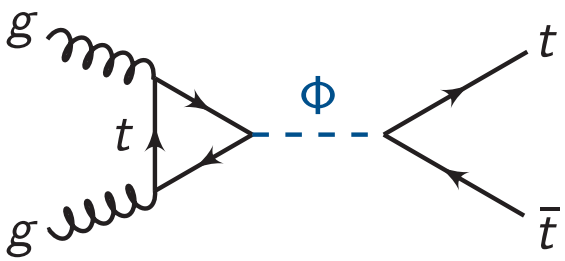
More scalars?

- SM contains only one $SU(2)_L$ doublet of scalar fields
- A number of models extend the scalar sector of the SM, predicting additional Higgs bosons
  - SM+S, which contains an additional EW singlet
    - Additional Higgs-like scalar
    - Connection to dark matter ('Higgs portal')
  - 2HDM
    - h, H, A, $H^{\pm}$
    - Concrete example: MSSM
  - 2HDM+S
    - Three CP-even states, two CP-odd, two charged
    - Concrete example: NMSSM
  - Models with $SU(2)_L$ triplet
    - Contain doubly charged states $H^{\pm\pm}$
    - Concrete example: type II seesaw

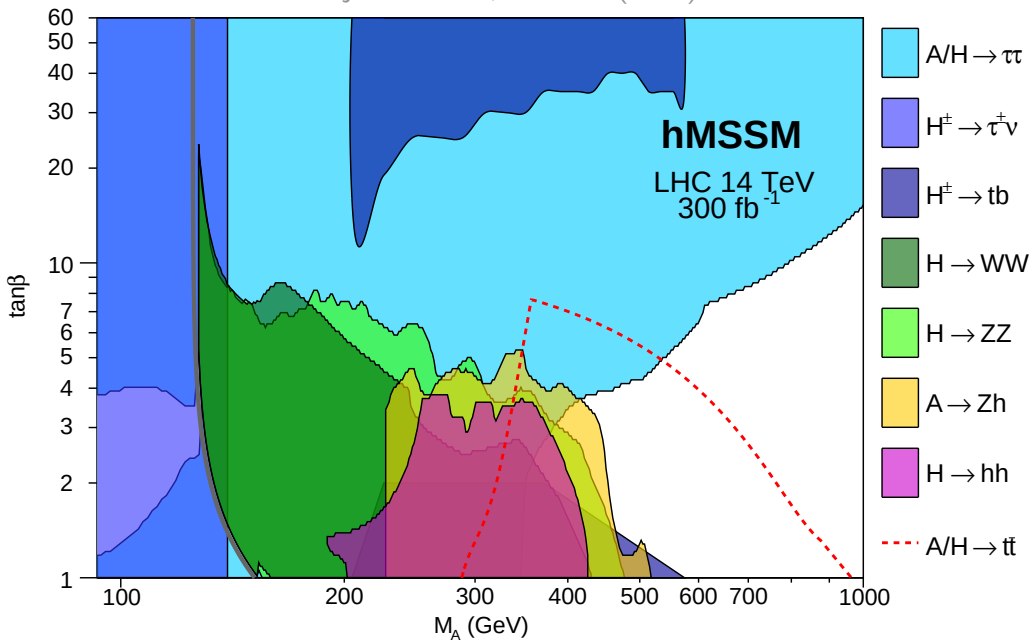
$$\Phi \longrightarrow t\bar{t}$$

$\Phi \to t\bar{t}$

- Special interest to $\Phi \to t\bar{t}$ in 2HDM
  - $A \to VV$ forbidden by CP conservation
  - $H \to VV$ vanishes in the alignment limit
  - For $m_\Phi \gtrsim 2m_t$, $\tan\beta \lesssim 5$ in type II 2HDM
    $t\bar{t}$ is *the* decay channel to search for Φ



Djouadi et al., JHEP 06 (2015) 168



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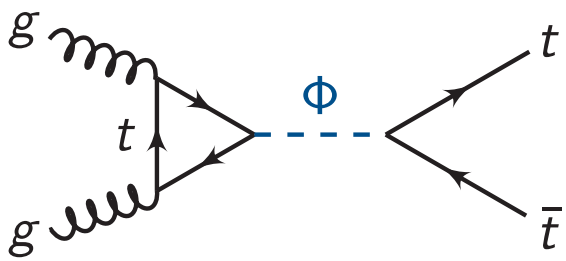
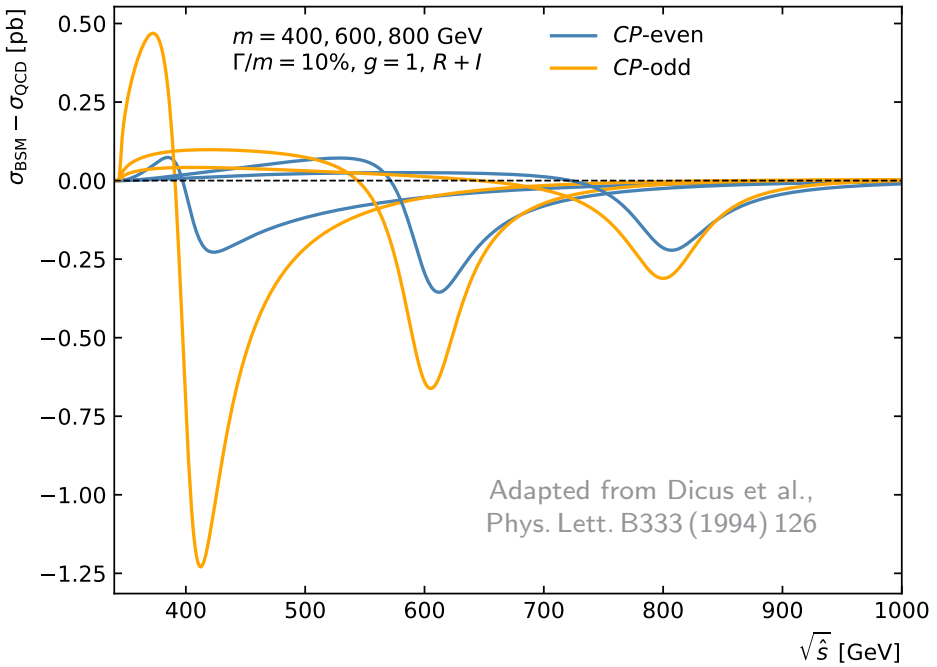


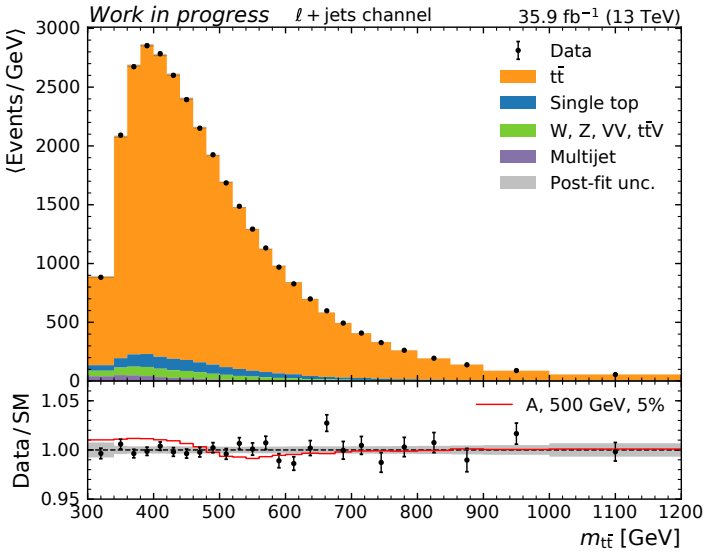
- Interference with SM $t\bar{t}$ distorts $m_{t\bar{t}}$ lineshape drastically
  - Results in a peak–dip or even dip–only structure
  - 'Bump hunting' searches are not appropriate

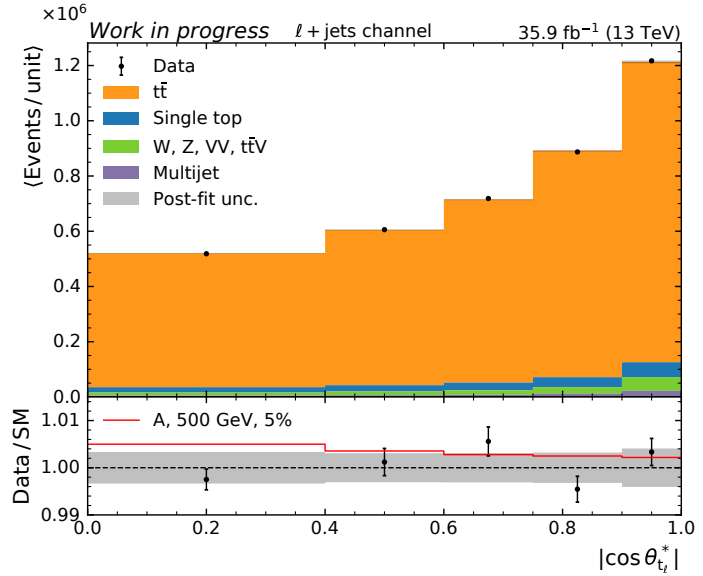


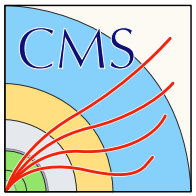
Search for $\Phi \to t\bar{t}$

Work in progress

- There is an on-going search in CMS
  - $35.9\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 13\,\mathrm{TeV}$
- Interference taken into account explicitly
- Resolved topology
- ℓ + jets channel $(\ell = e, \mu)$
  - Reconstruct ν from $t \to b\ell\nu$ by minimizing $D_\nu = \|\vec{p}_\mathrm{T}^{\,\nu} - \vec{p}_\mathrm{T}^{\,\mathrm{miss}}\|$ respecting constraints from m_W and m_t [1]
  - Reconstruct $t\bar{t}$ by maximizing product of likelihood for D_ν and 2D likelihood for $m_{t\to\mathrm{had}}$ and $m_{W\to\mathrm{had}}$
  - Utilize $m_{t\bar{t}}$ and decay angle of $t_{b\ell\nu}$
    - Angle between $\vec{p}_{t\to b\ell\nu}$ in $t\bar{t}$ rest frame and $\vec{p}_{t\bar{t}}$ in lab frame
    - Reflects the spin of the resonance





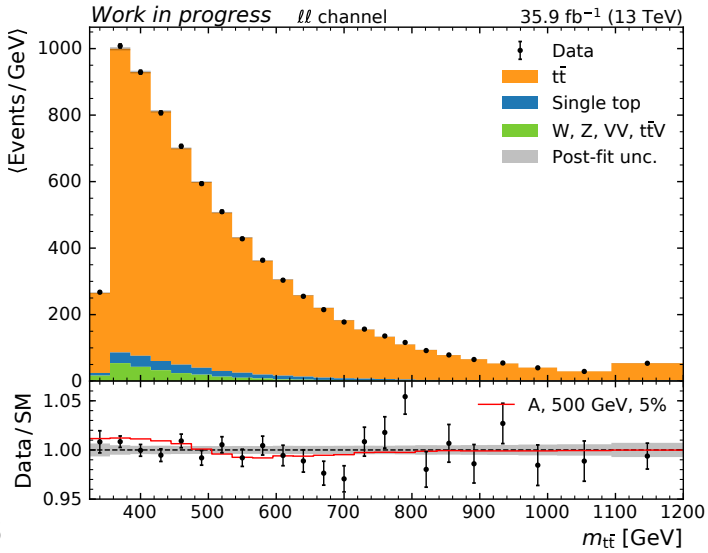


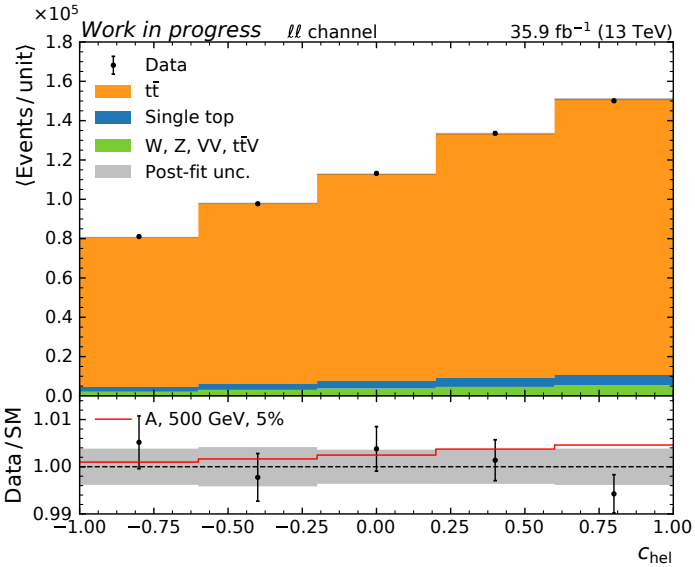
[1] Betchart et al., NIM A 736 (2014) 169

Search for $\Phi \to t\bar{t}$

Work in progress

- $\ell\ell$ channel $(\ell = e, \mu)$
  - Reconstruct neutrinos[1] using constraints from $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$, m_t $(\times 2)$, m_W $(\times 2)$
    - Out of multiple solutions, choose one with smallest $m_{t\bar{t}}$
  - Reconstruct momenta of top quarks by weighting all permutations according to product of likelihoods for $m_{\ell-\bar{b}}$ and $m_{\ell+b}$
    - Smear input momenta within the resolutions
  - Utilize $m_{t\bar{t}}$ and angle between $\vec{p}_{\ell+}$ and $\vec{p}_{\ell-}$ in their respective helicity frames
    - Top quarks are boosted into $t\bar{t}$ rest frame, each lepton is then boosted to rest frame of its parent top quark
    - Sensitive to spin and CP state of the resonance





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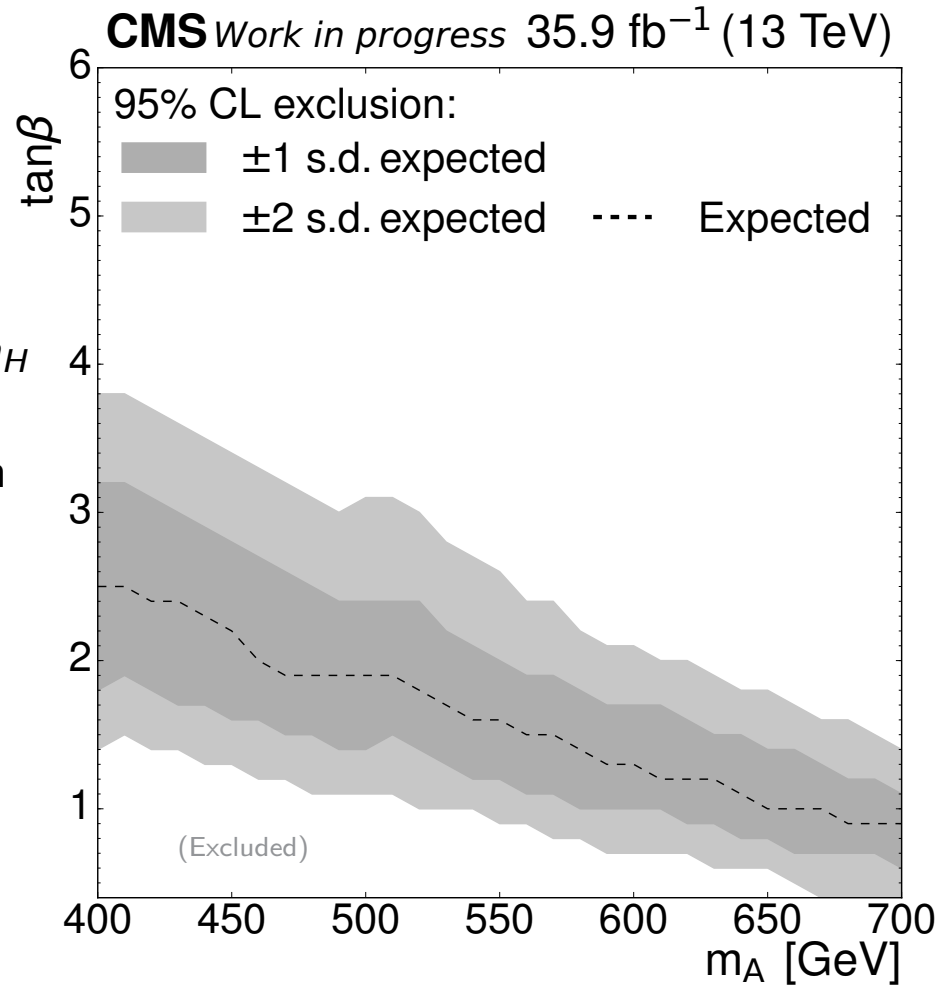
Search for $\Phi \to t\bar{t}$

Work in progress

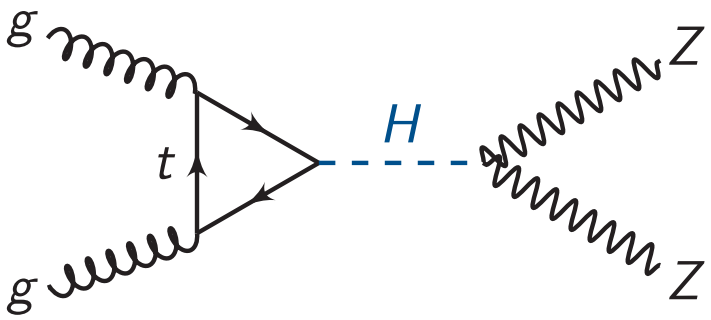
- Search for signal using 2D distributions of $m_{t\bar{t}}$ and the angles
- Dominant $t\bar{t}$ bkg described by MC
- Set constraints in hMSSM
  - Take into account dependence of m_H and $\Gamma_{A/H}$ on m_A and $\tan\beta$
  - Shown is blinded expected exclusion
- Will also report model-independent exclusion for Φtt couplings

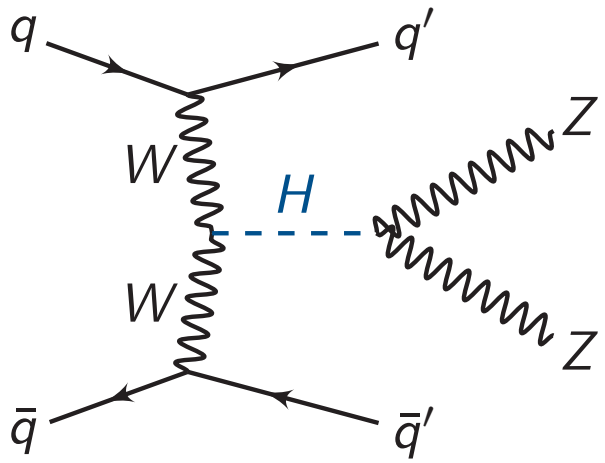


$$H \to ZZ \to 2\ell 2\nu$$

$H \to ZZ$

- Beyond 2HDM, heavy *CP*-even states decaying to ZZ appear





- Search performed at CMS with 2016 data
  - $35.9\,\text{fb}^{-1}$ at $\sqrt{s} = 13\,\text{TeV}$
- Agnostic about production mode
  - Fraction of VBF f_{VBF} is a free parameter
  - VX production is scaled with VBF
- Three final states: 4ℓ, $2\ell 2q$, $2\ell 2\nu$, $\ell = e, \mu$
  - Here focus on $2\ell 2\nu$, to which ULB and UCL contributed

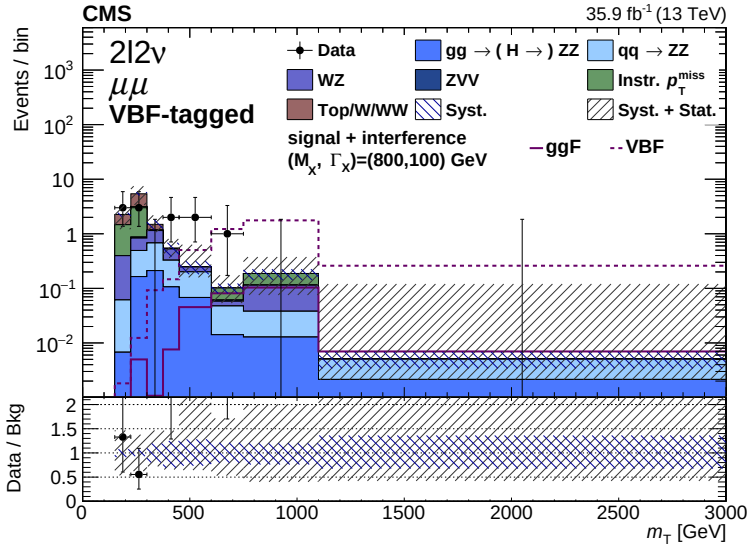
$H \to ZZ \to 2\ell 2\nu$

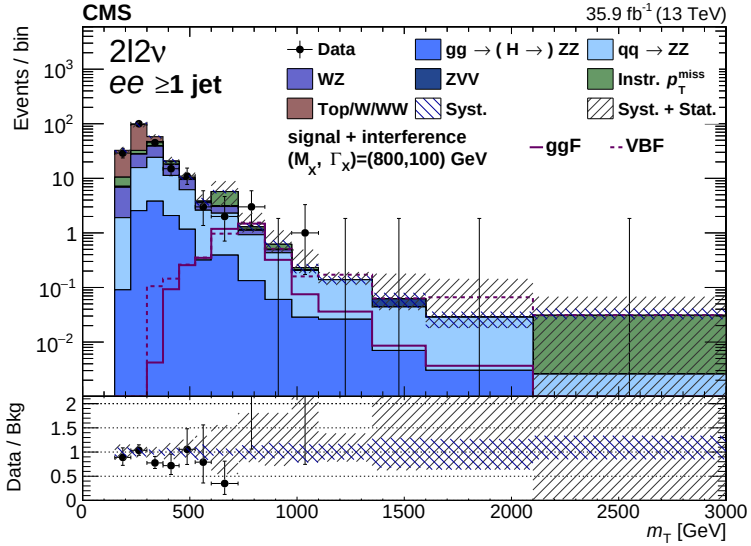
JHEP 06 (2018) 127

- $m_H > 300\,\text{GeV}$, $p_\text{T}^\text{miss} > 125\,\text{GeV}$
  - Suppresses Z + jets
- Categories (further split by flavour):
  - VBF-tagged
  - $\geqslant 1$ jet (but not VBF) and 0 jet
- Cannot reconstruct $Z \to \nu\nu \Rightarrow$ Fit m_T

$$m_\text{T}^2 = \left(\sqrt{p_\text{T}^{\ell\ell\,2} + m_{\ell\ell}^2} + \sqrt{p_\text{T}^{\text{miss}\,2} + m_Z^2} \right)^2 - \left(\vec{p}_\text{T}^{\,\ell\ell} + \vec{p}_\text{T}^{\,\text{miss}} \right)^2$$

- Irreducible SM ZZ bkg taken from MC
- Other important bkgs are data-driven:
  - Z + jets modelled with γ + jets
    - Reweighted by boson's p_T
    - Similar sources of p_T^miss
  - Non-resonant bkgs from $e^\pm\mu^\mp$ region





$H \to ZZ$: Limits

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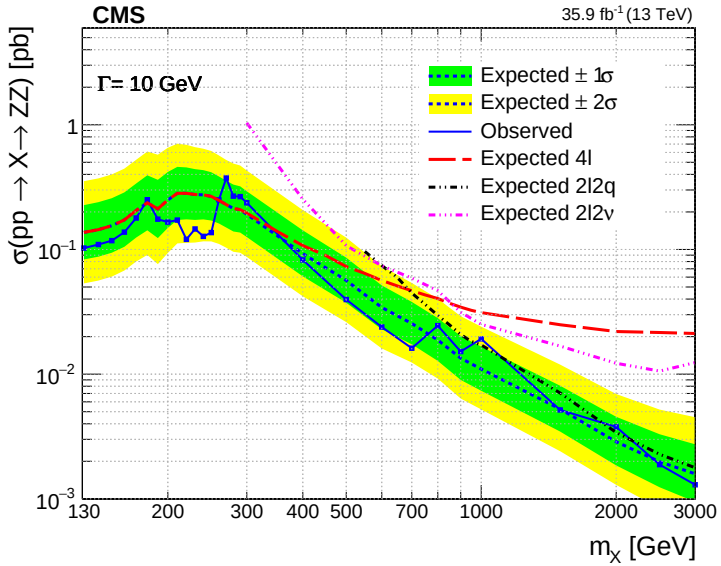
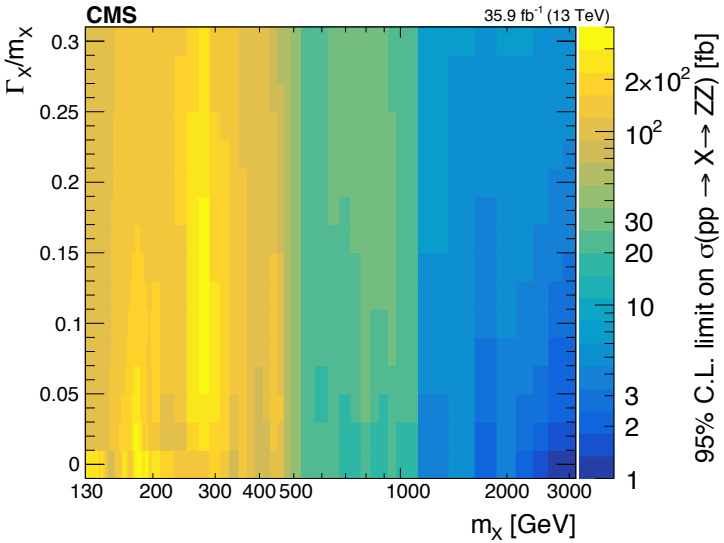
- Confidence intervals on $\sigma_{\text{tot}}\mathcal{B}_{H\to ZZ}$ from a scan over (m_H, Γ_H)
  - f_{VBF} is floating or set to 1
- Interference with SM bkg (including h_{125}) taken into account explicitly
  - Contribution is not negligible, but the effect is not as drastic as in $\Phi \to t\bar{t}$
- Upper limits on $\sigma_{\text{tot}}\mathcal{B}_{H\to ZZ}$ are set





$Z(\to \ell\ell) + \Phi(\to \text{invisible})$

- In the context of the $H \to ZZ$ search, $2\ell 2\nu$ final state mostly provides a complementary experimental signature to 4ℓ and $2\ell 2q$
  - But drives the combination for a wide H with $300 \lesssim m_H \lesssim 700\,\text{GeV}$

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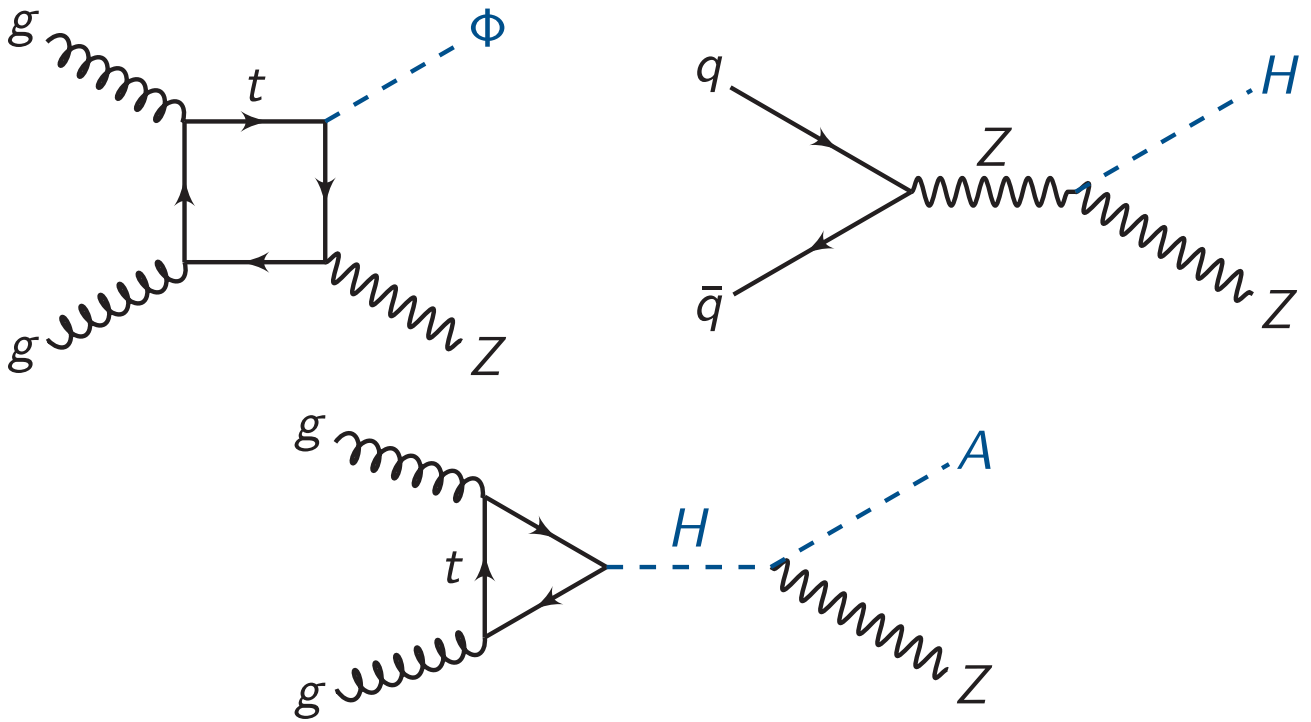
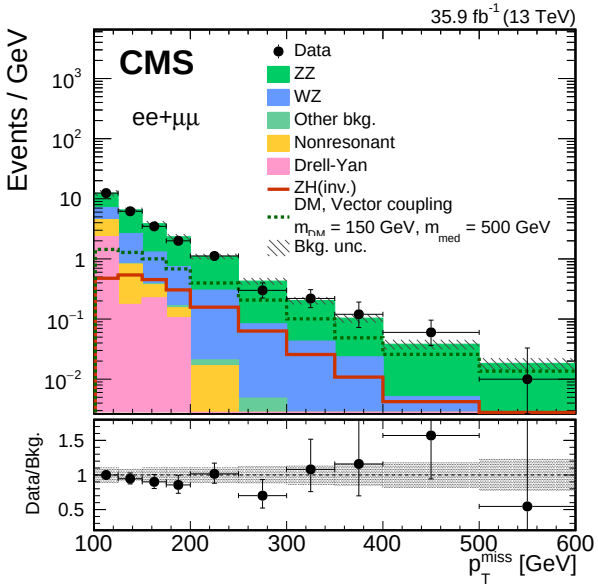
  - But drives the combination for a wide H with $300 \lesssim m_H \lesssim 700\,\text{GeV}$
- Becomes especially interesting for $Z\Phi$ with Φ decaying to invisible BSM
  - Dark matter portals in SM+S or 2HDM+S

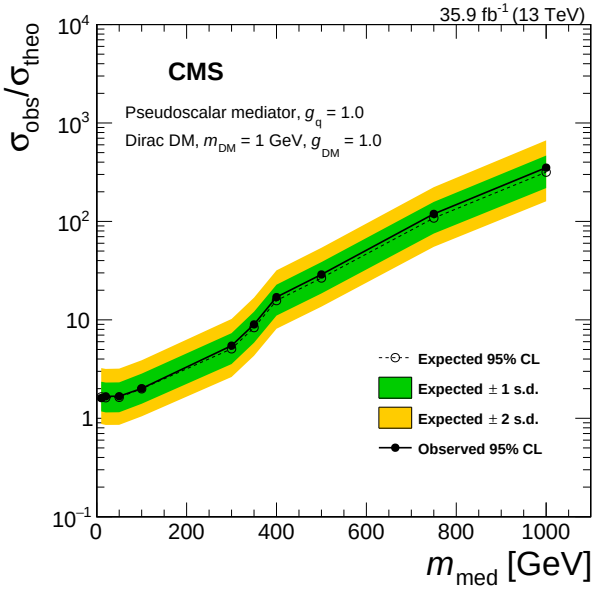


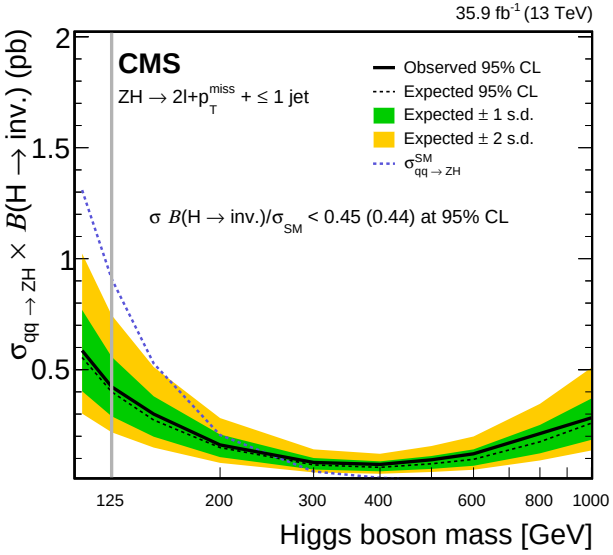
Search for mono-Z

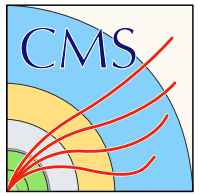
Eur. Phys. J. C78 (2018) 291

- Search for mono-Z in CMS with 2016 data
  - $\ell^{\pm}\ell^{\mp}$ pair compatible with Z
  - $p_{\mathrm{T}}^{\mathrm{miss}} > 100\,\mathrm{GeV}$
  - Balance between $\vec{p}_{\mathrm{T}}^{\,\ell\ell}$ and $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$
- Extract signal from distribution of $p_{\mathrm{T}}^{\mathrm{miss}}$
- Many interpretations; relevant here are in SM+S
  - Single additional scalar that couples either to quarks or to Z and decays to dark matter







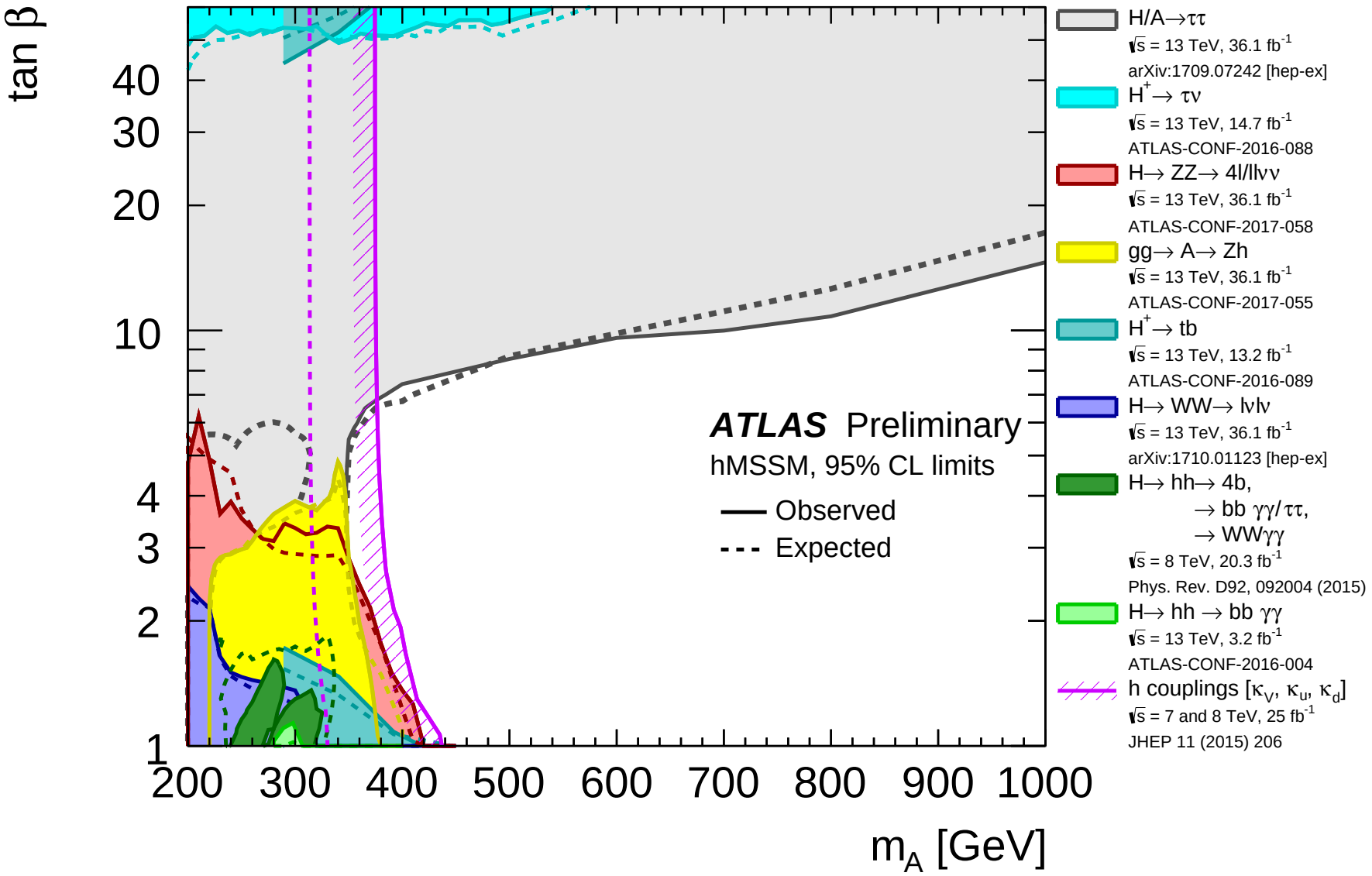


Summary

- With one Higgs boson discovered, experiments are looking for its counterparts
- Search for $\Phi \to t\bar{t}$ starts to probe low-tan β, $m_\Phi > 2m_t$ region of 2HDM
- Scalar sectors of other structures are put under test with searches such as $H \to ZZ$
- Connection to dark matter is being investigated via $\Phi \to$ invisible
- Expect new results with full Run 2 data set

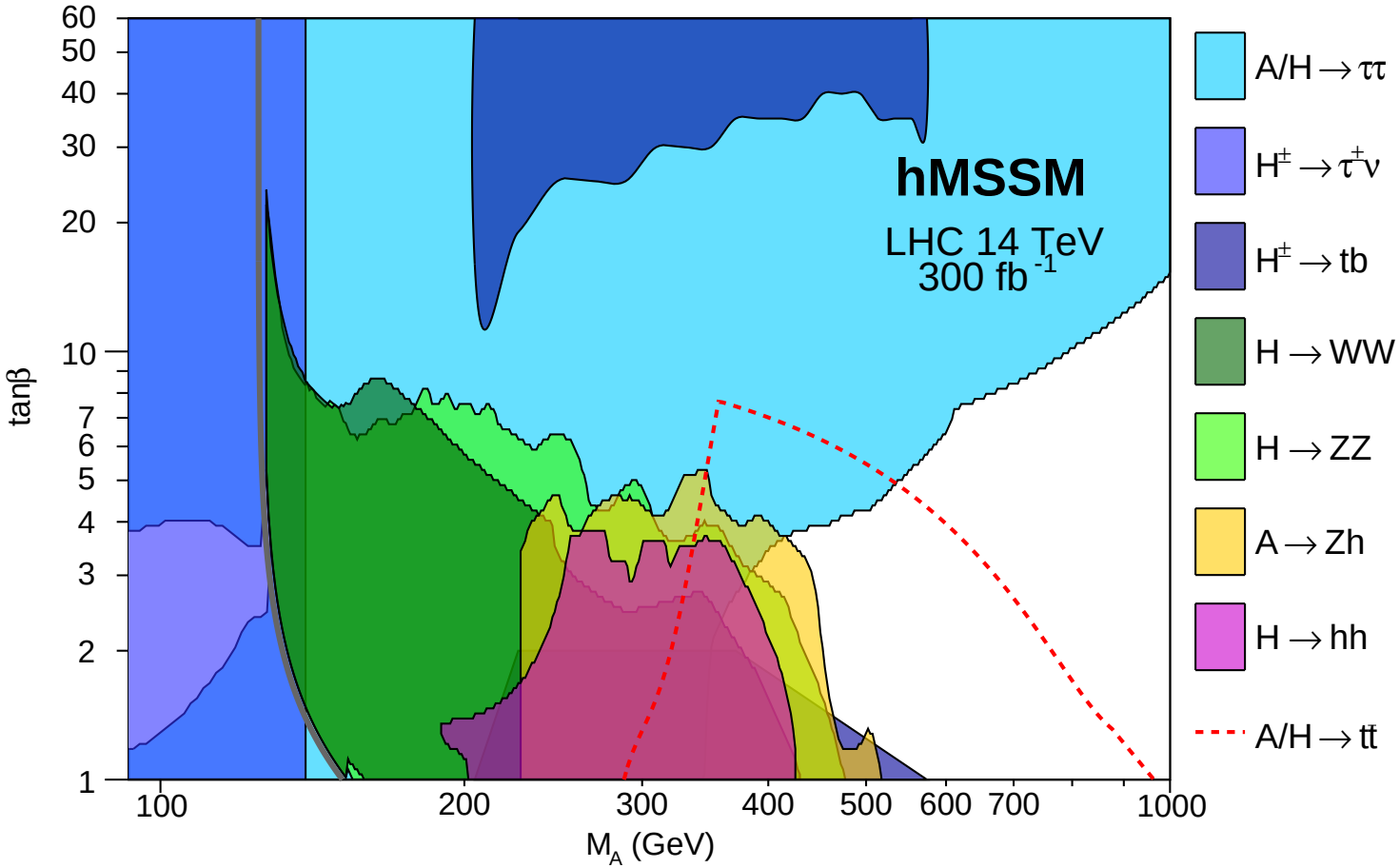
Additional slides

ATLAS hMSSM exclusion



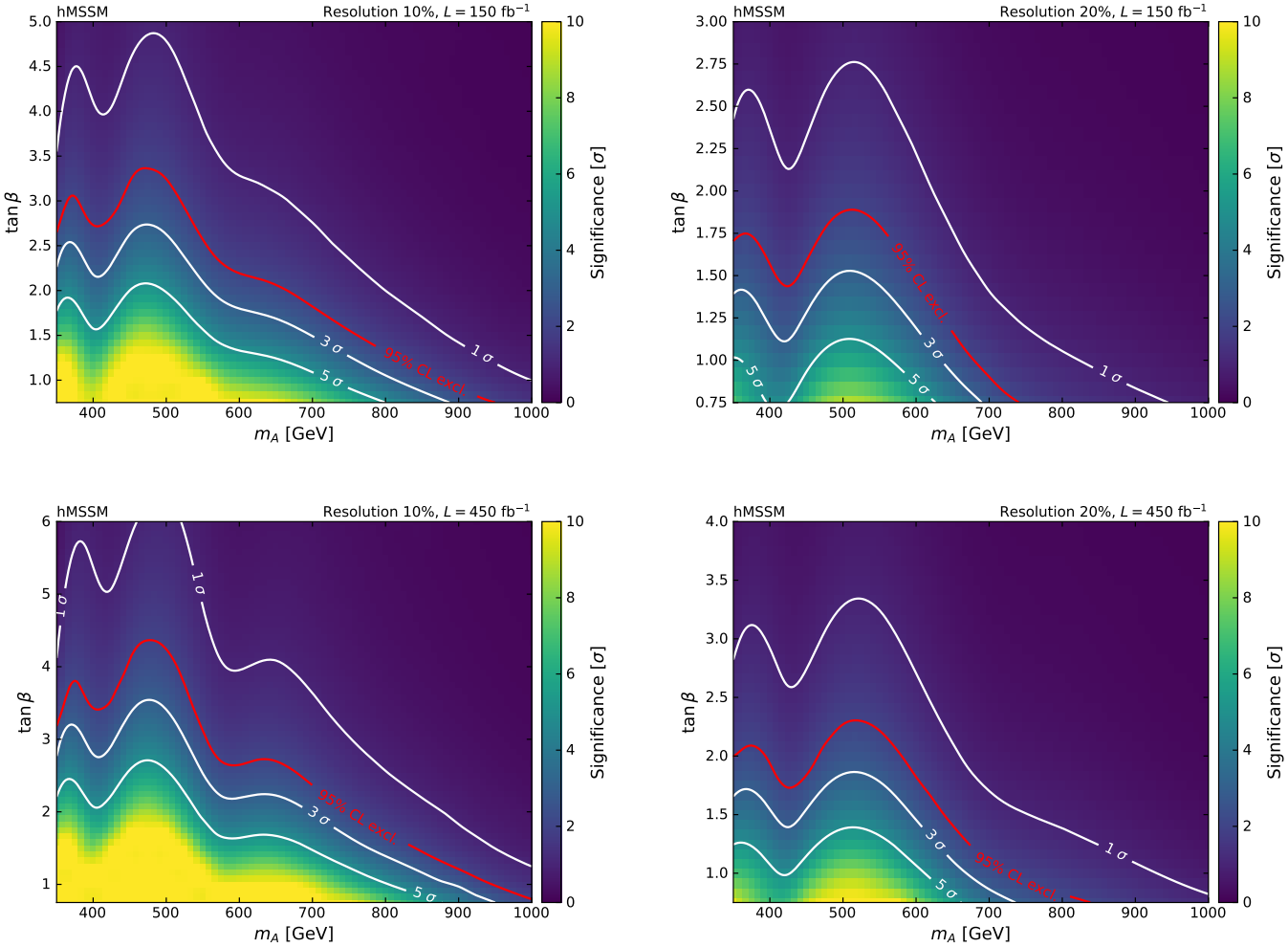
Projected constraints in hMSSM

- Constraints in hMSSM from phenomenological studies [Djouadi et al., JHEP 06 (2015) 168]



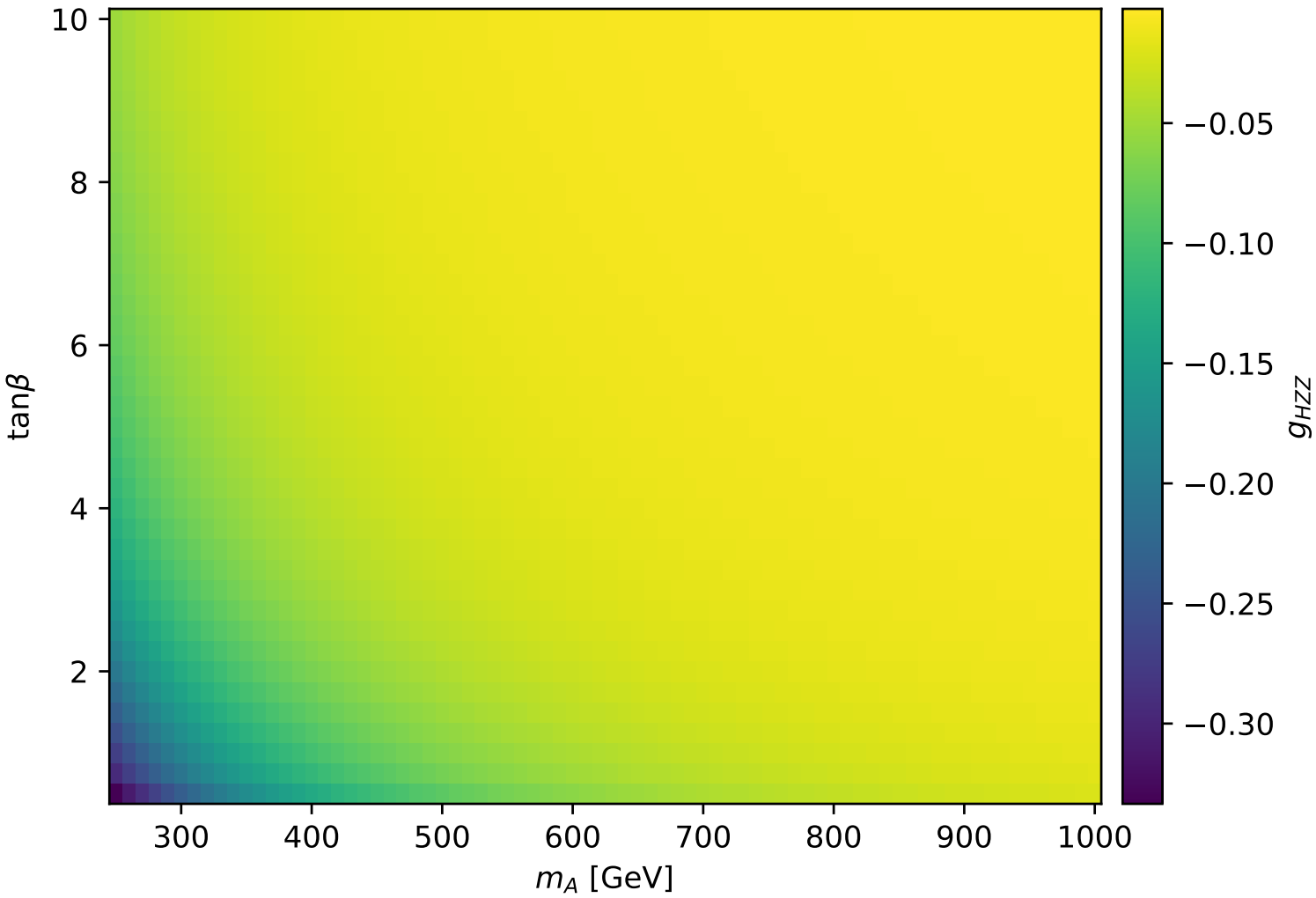
Projected constraints in hMSSM

- Projections for $t\bar{t} \to \ell +$ jets with somewhat realistic uncertainties
- A. Djouadi, J. Ellis, A. P., J. Quevillon, in preparation



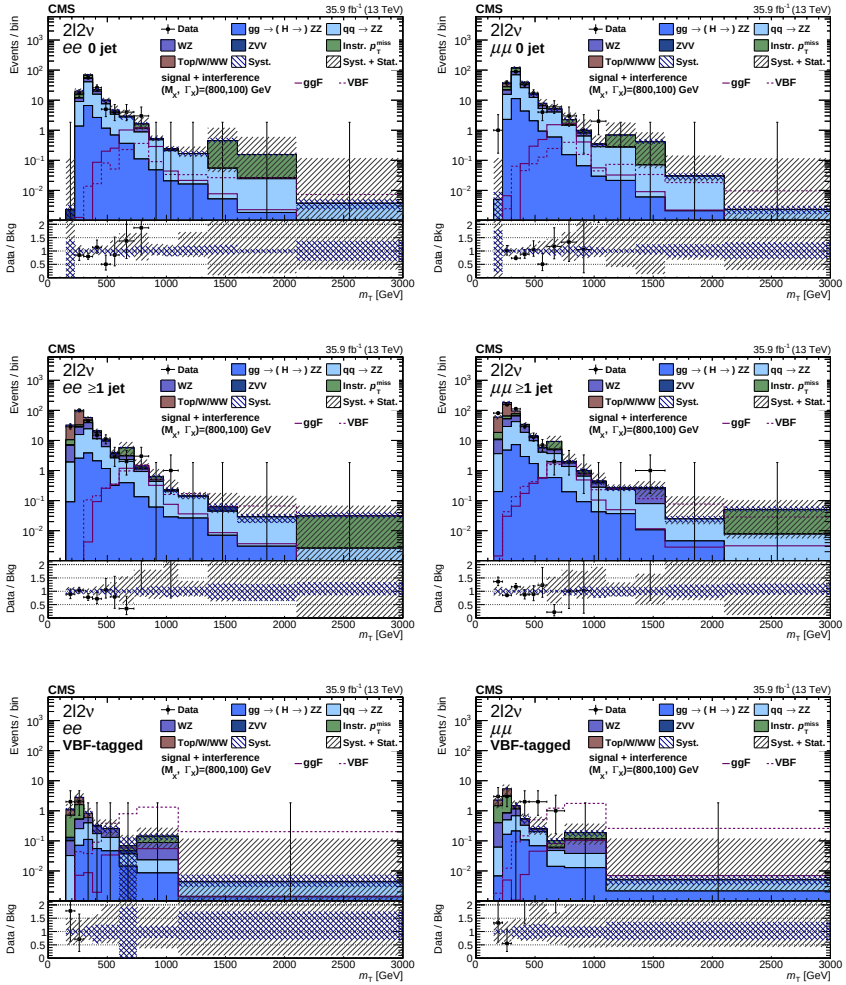
HZZ coupling in hMSSM

- Couping of the heavier CP-even state to weak bosons



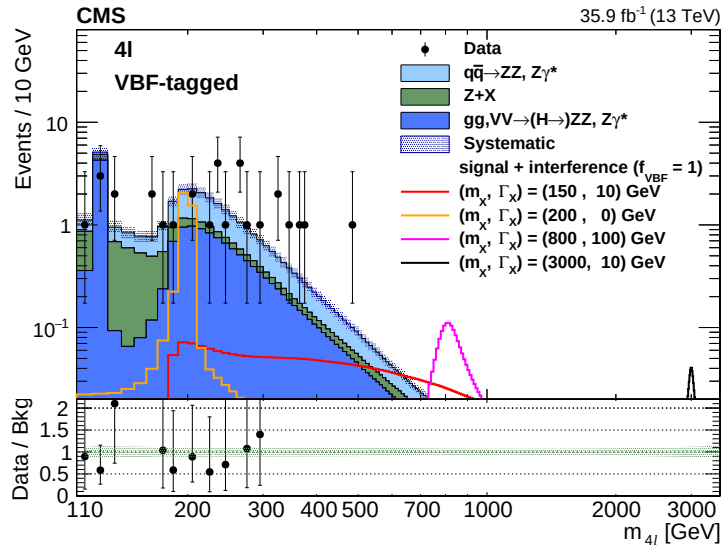
$H \to ZZ \to 2\ell 2\nu$

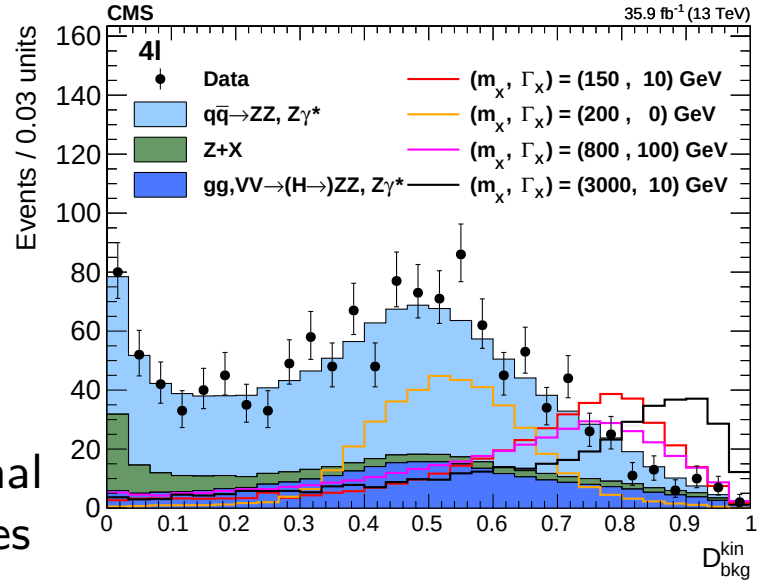
- Distributions of m_{T} in all channels:



$H \to ZZ \to 4\ell$

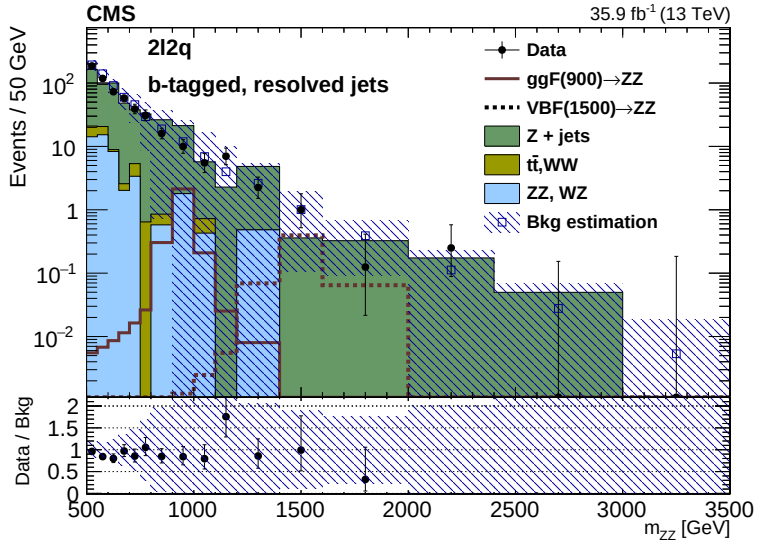
- Reconstruct Z from $\ell^{\pm}\ell^{\mp}$ pairs respecting mass constraints
- Multiple categories:
  - VBF-tagged
    - Additional jets and $\mathcal{D}^{\text{VBF}}_{\text{2jet}}$ passes mass-dependent selection
  - Untagged
    - Remaining events with standard lepton ID
  - Events with relaxed electron selection
    - Recover efficiency for $m_{4\ell} > 300\,\text{GeV}$
  - Further split by lepton flavour
- Two observables: $m_{4\ell}$ and $\mathcal{D}^{\text{kin}}_{\text{bkg}}$
  - $\mathcal{D}^{\text{kin}}_{\text{bkg}}$ is MEM discriminator between $X \to 4\ell$ and SM $q\bar{q} \to 4\ell$
- Data-driven bkg with fake leptons
  - $Z + 2\ell$ region with relaxed ID for additional leptons, opposite- and same-sign categories

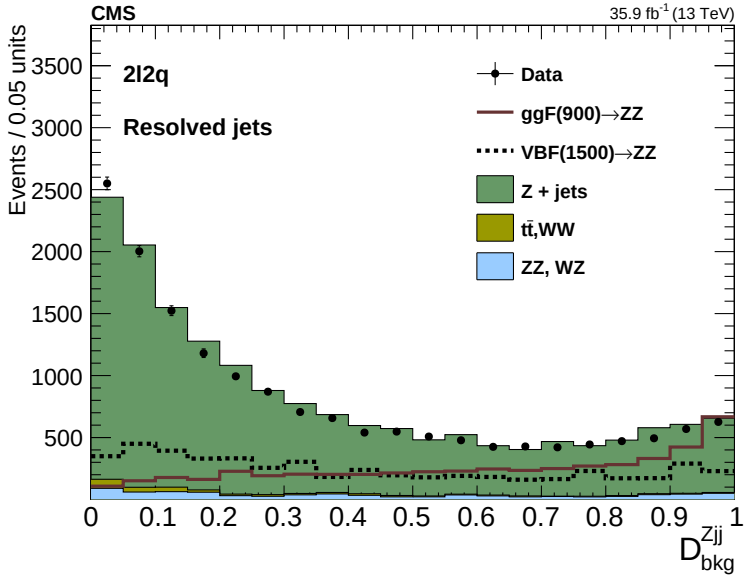




$H \to ZZ \to 2\ell 2q$

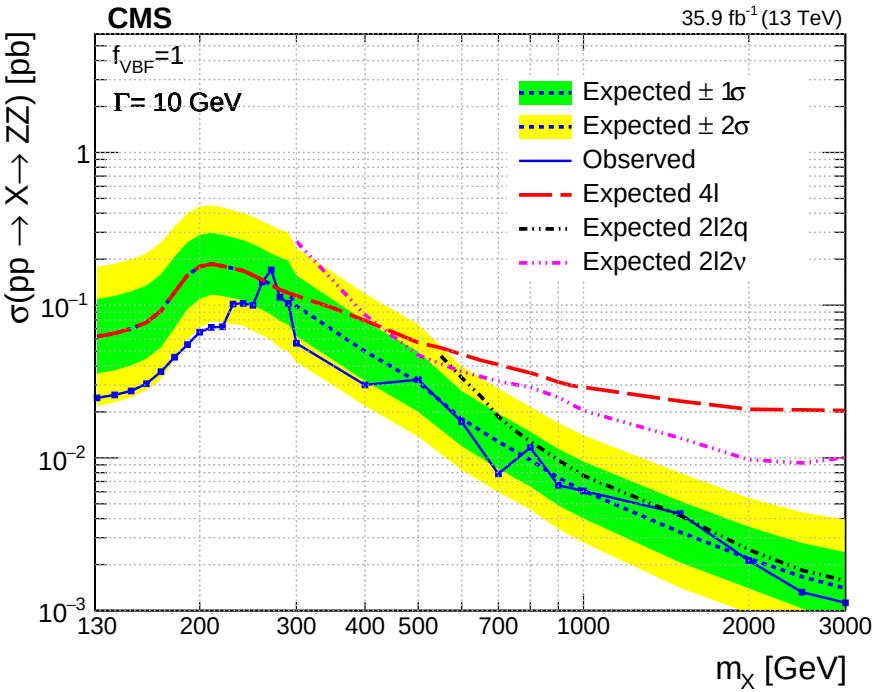
- Target $m_{ZZ} > 500\,\text{GeV}$
  - Suppress $Z + \text{jets}$ bkg
- Resolved and boosted $Z \to q\bar{q}$
  - Kinematic fit based on $m_{Z_{\text{had}}}$
- Categories (further split by flavour):
  - VBF-tagged
    - Additional jets and selection on $\mathcal{D}^{\text{VBF}}_{\text{2jet}}$
  - b-tagged, which targets $Z \to b\bar{b}$
  - Untagged (remaining events)
- Two observables: m_{ZZ} and $\mathcal{D}^{Zjj}_{\text{bkg}}$
  - $\mathcal{D}^{Zjj}_{\text{bkg}}$ is MEM discriminator from $Z + 2j$
- Data-driven bkgs:
  - $Z + \text{jets}$ scaled using $m_{Z_{\text{had}}}$ sideband
  - Rate of $t\bar{t}$ from $e^{\pm}\mu^{\mp}$ control region

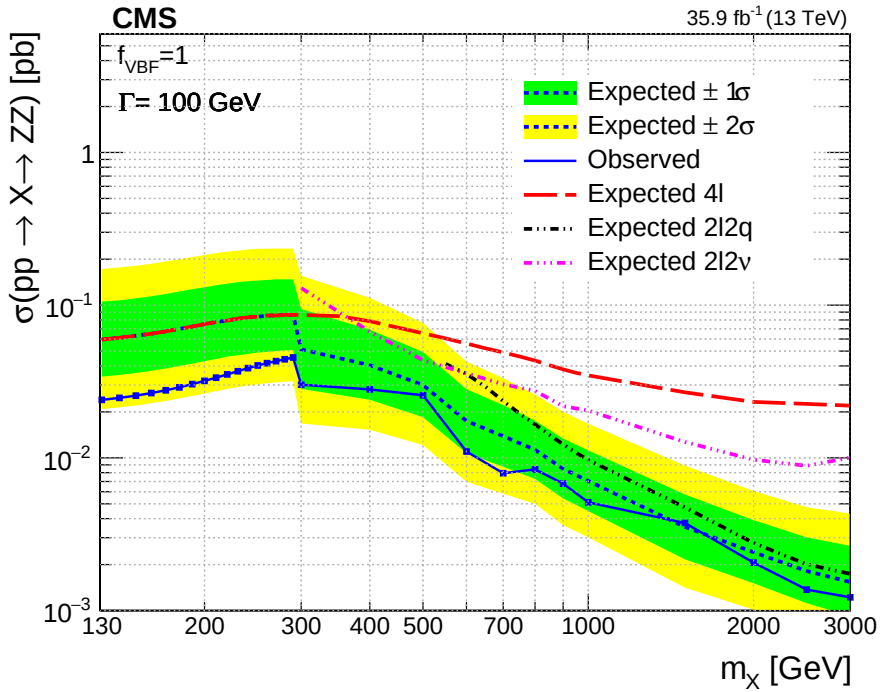




Contribution from $H \to ZZ \to 2\ell 2\nu$ in combination

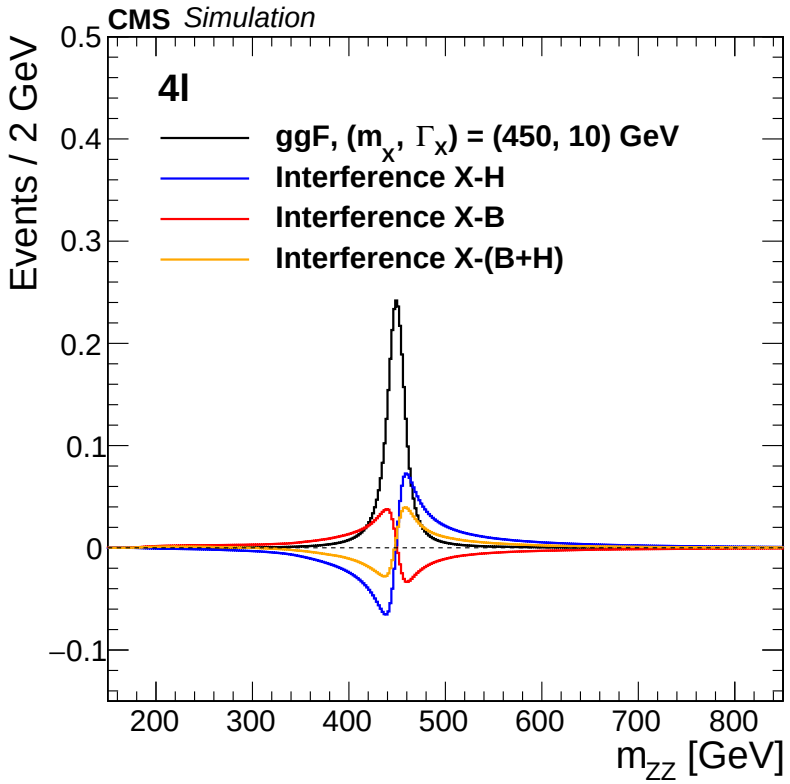
- $2\ell 2\nu$ final state is competitive for large Γ_H and m_H around 500 GeV
  - Especially for $f_{\mathrm{VBF}} = 1$, when H is produced exclusively in VBF and VH

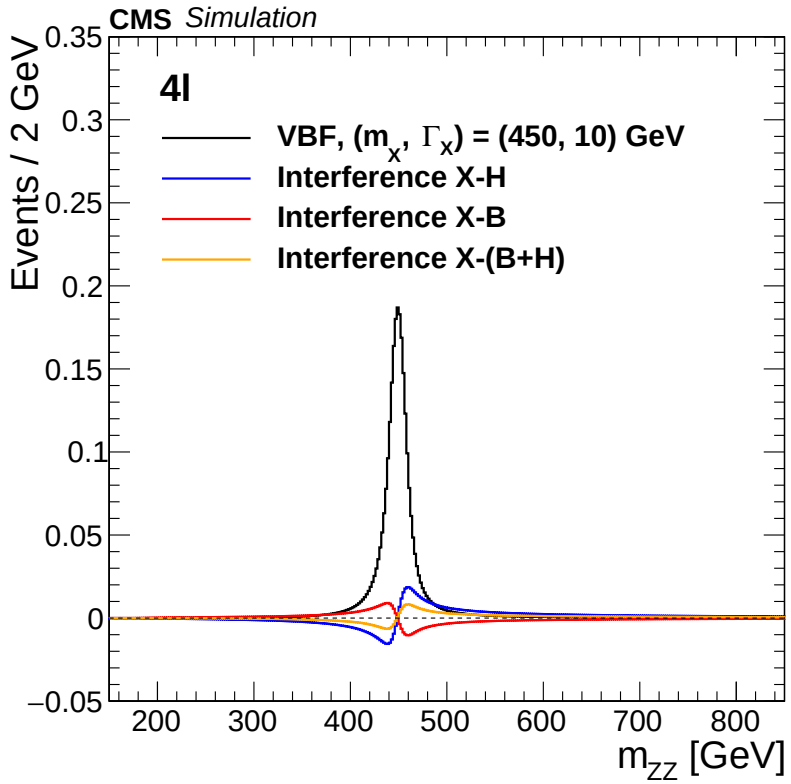




Interference in $H \to ZZ \to 4\ell$

- Signal is scaled to limits obtained in 4ℓ channel





Systematic uncertainties in CMS $H \to ZZ$

Source of uncertainty [%]	$X \to ZZ \to 4\ell$	$X \to ZZ \to 2\ell 2q$	$X \to ZZ \to 2\ell 2\nu$
Experimental sources			
Integrated luminosity	2.5	2.5	2.5
ℓ trigger and selection efficiency	2.5–9	4–8	6–8
ℓ momentum/energy scale (*)	0.04–0.3	0.1–0.3	0.01–0.3
ℓ resolution (*)	20	20	—
JES, JER, p_T^{miss} (*)	1–30	1–10	1–30
b tagging/mistag	—	5–7	2–4
Background estimates			
$Z + jets$	36–43	10–50	20–50
top quark, WW	—	15	10
$W\gamma^*$, WZ	—	3–10	15
Theoretical sources			
Renorm./factor. scales	3–10	3–10	5–10
PDF set	3–4	3–5	1–4
EW corrections ($q\bar{q} \to ZZ$) (*)	1	1	2
NNLO ($gg \to ZZ$) K factor	10	10	10

Search for VBF $H \rightarrow$ invisible

arXiv:1809.05937, submitted to PLB

- Search for $H \rightarrow$ invisible in VBF topology
  - SM-like Higgs boson
  - VBF topology with $p_T^{miss} > 250\,GeV$
  - Fit m_{jj} distribution
- Tighter limits than in mono-Z $qq \rightarrow ZH$