# New physics searches in Higgs final states at ATLAS and CMS

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for the ATLAS & CMS collaborations

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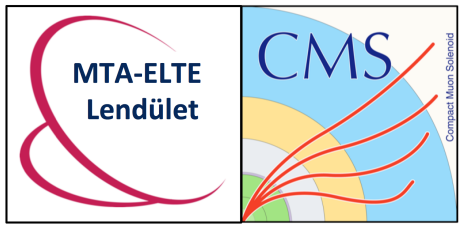

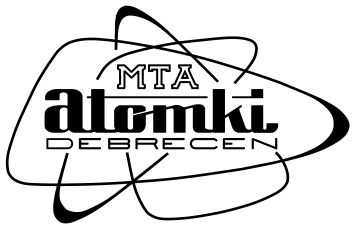


QCD@LHC 2017
Debrecen

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- Searches for BSM with SM Higgs at LHC
  - SUSY
  - Baryonic (leptophobic) Z' model
  - Heavy Vector Triplet (HVT)
  - two-Higgs-Doublet (2HDM), *see Tom's talk*

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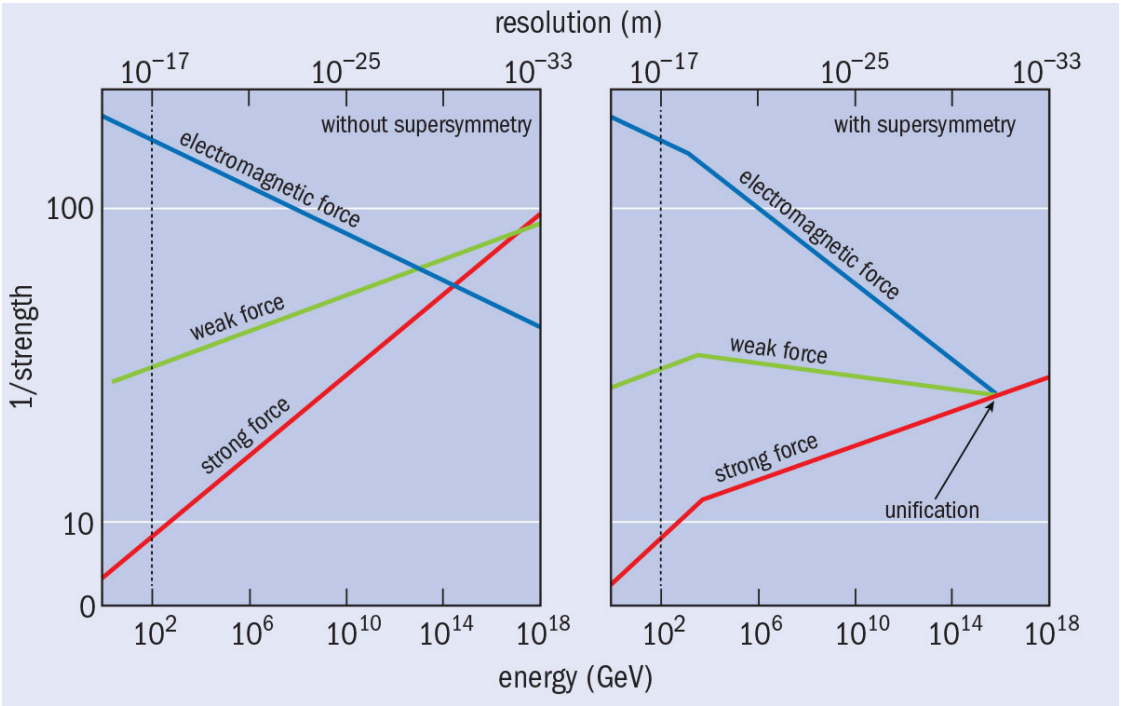

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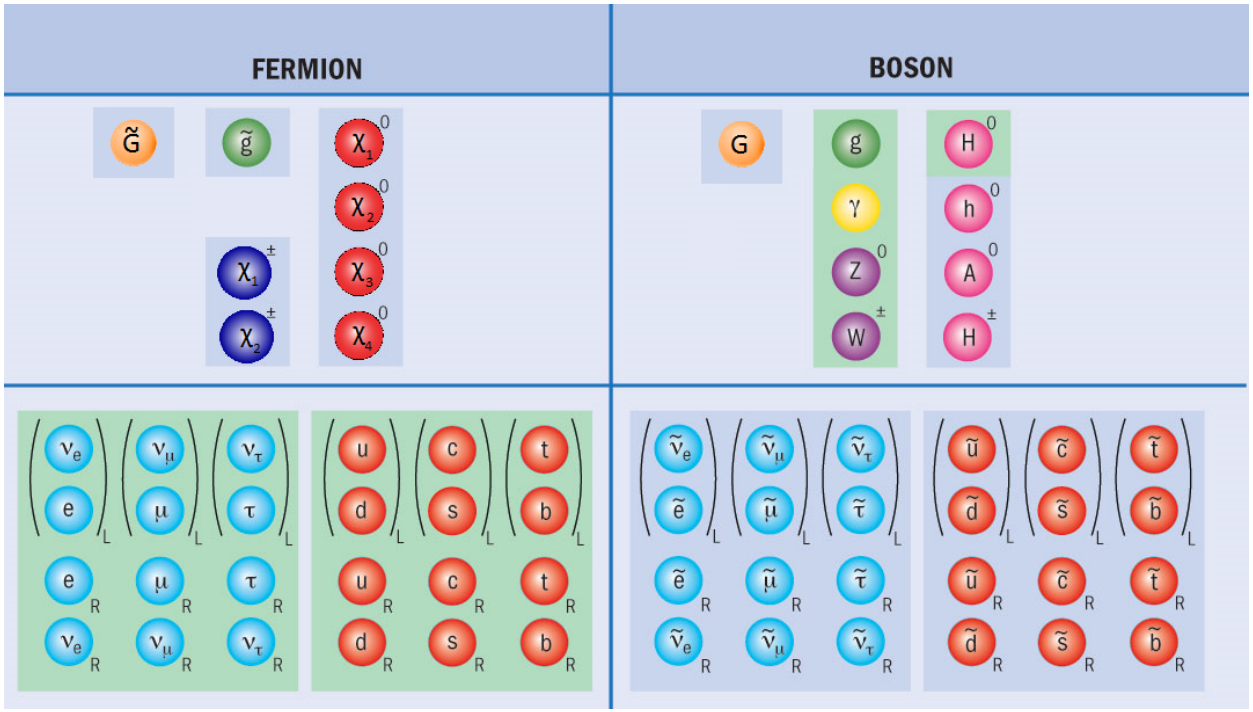
**Higgs** in SUSY models

- Minimum 2 Higgs doublets
- Considering models where lightest CP-even boson SM-like



SUSY particles not seen at low energy $\rightarrow$ supersymmetry **broken**
How does SUSY break? – *Several ideas!*

- Minimal Supergravity (mSUGRA)
- Gauge Mediated Supersymmetry Breaking (GMSB)
- etc. . .

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- **Multiplicative quantum number**, **+1** for **SM**, **-1** for **SUSY**
- R-parity conserved $\rightarrow$ SUSY particles pair-produced, **LSP stable**

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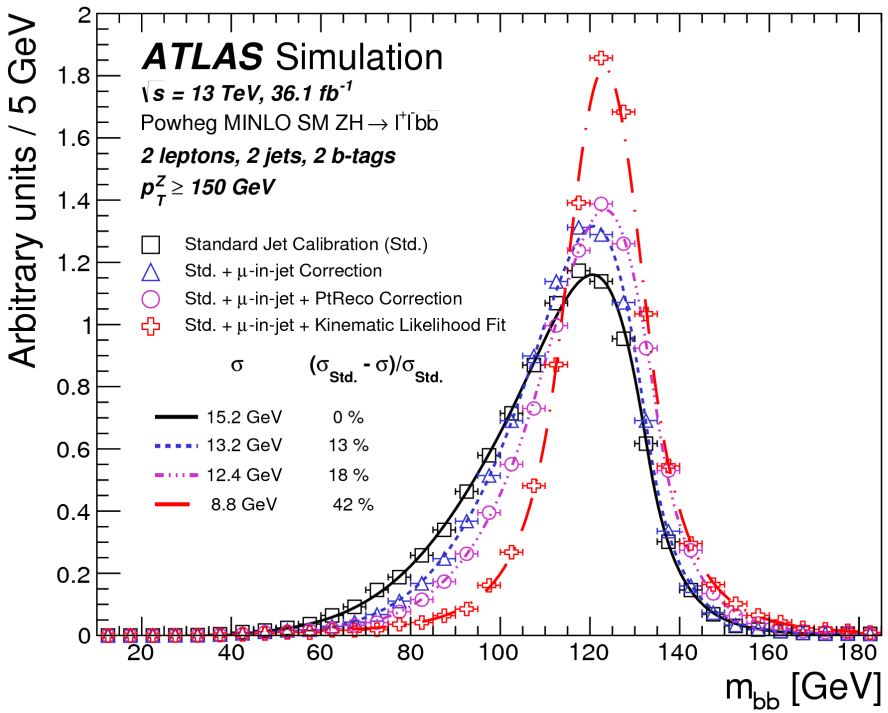
**Neutralinos** ($\widetilde{\chi}_i^0$) & **charginos** ($\widetilde{\chi}_i^\pm$)

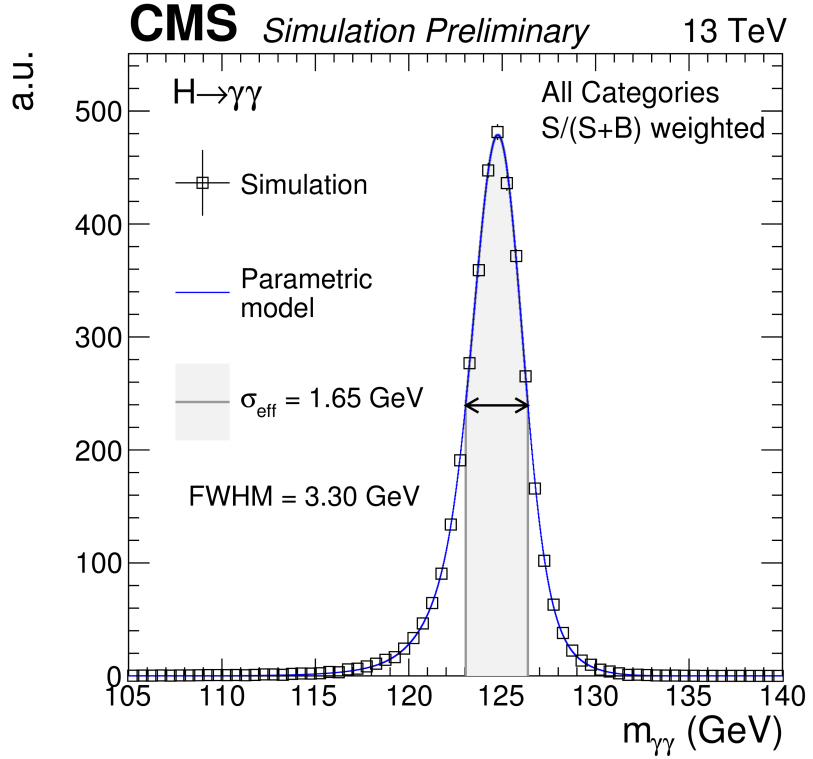
- Superpartners of EW bosons: Higgsinos ($\widetilde{H}_i$), winos ($\widetilde{W}_i$) and bino ($\widetilde{B}$)
- Symmetry breaking→these mix together to form mass eigenstates: neutralinos ($\widetilde{\chi}_1^0, \widetilde{\chi}_2^0, \widetilde{\chi}_3^0, \widetilde{\chi}_4^0$) and charginos ($\widetilde{\chi}_1^\pm$, $\widetilde{\chi}_2^\pm$)

Lightest **neutralino** ($\widetilde{\chi}_1^0$) LSP in most models
GMSB: **gravitino** ($\widetilde{G}$) LSP, **neutralino** ($\widetilde{\chi}_1^0$) Next-to-LSP (NLSP)

Higgs reconstruction

- $H \to bb$: high cross-section, lower resolution
  - resolved: 2 b-tagged jets
  - boosted: 1 large jet, b-tagging in jet sub-structure
- $H \to \gamma\gamma$: lower cross-section, higher resolution

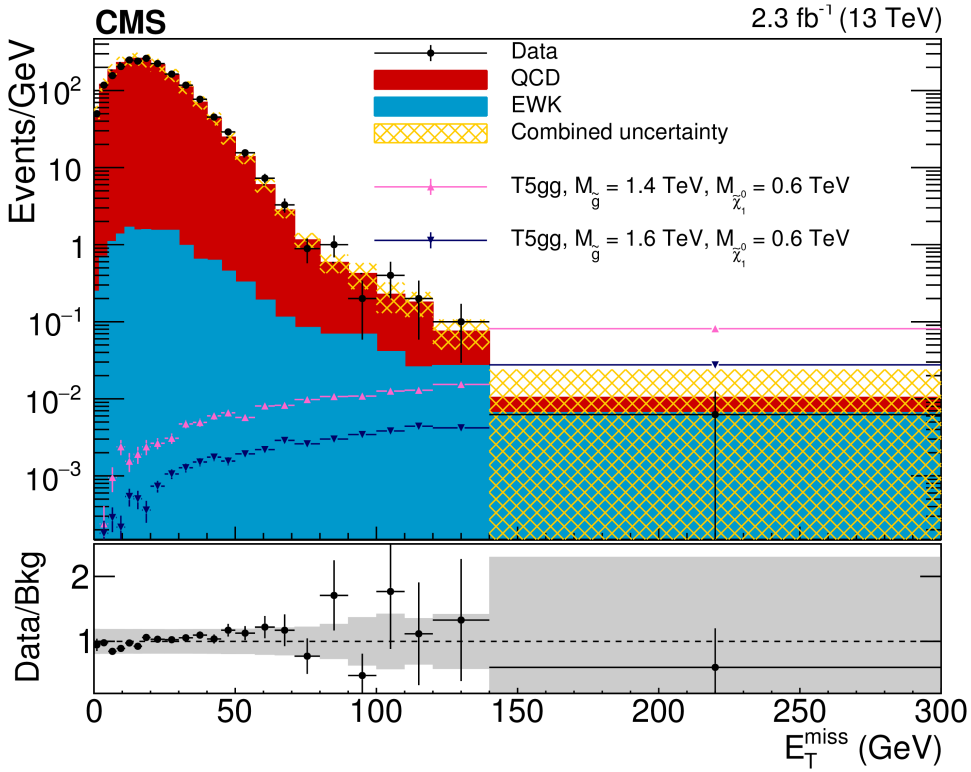


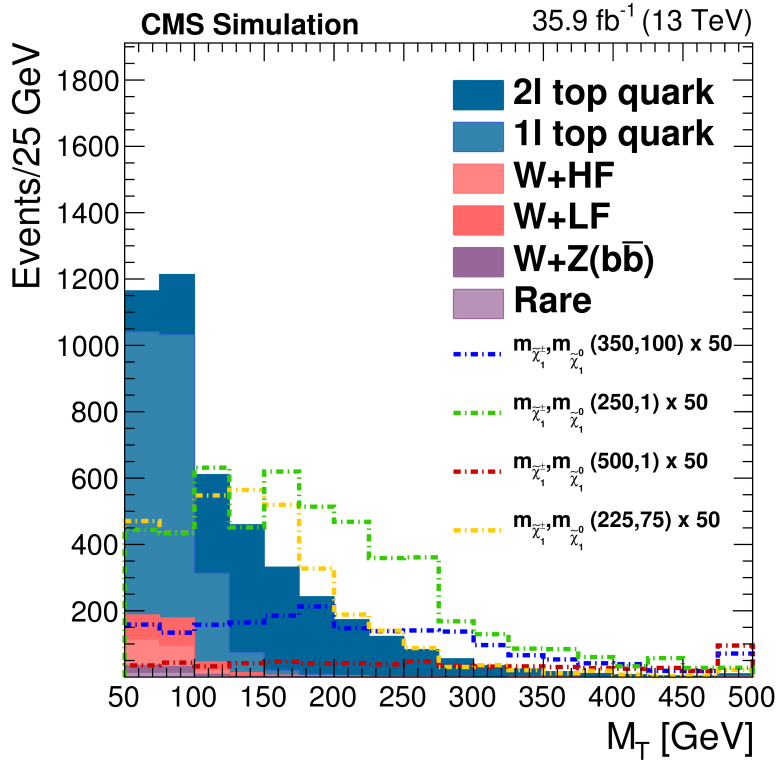




Ref.: ATLAS-HIGG-2016-29 CMS-PAS-HIG-16-040

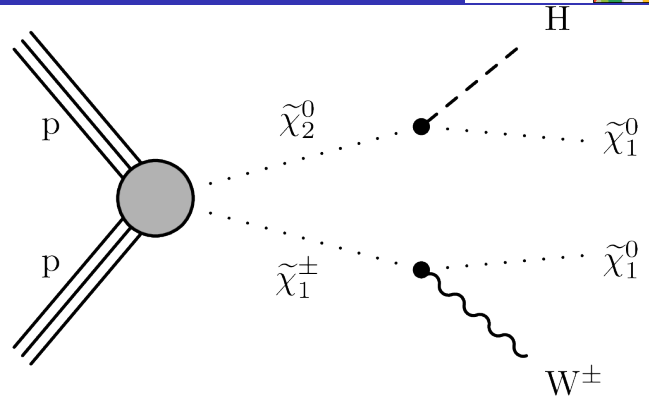
Important variables

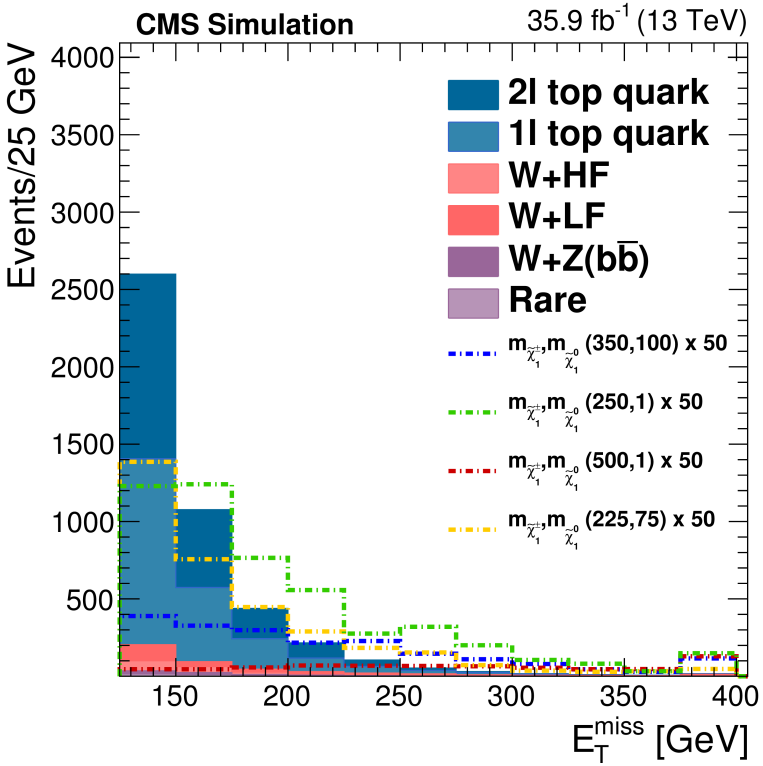
- Missing $E_T$ (MET): $E_T^{miss} = |\vec{p}_T^{miss}| = |-\sum_i \vec{p}_T(i)|$, $i$ =all objects
  - Important signal of LSP/DM
- Transverse mass ($M_T$): $M_T^2(l, E_T^{miss}) = 2E_T^{miss} p_T^l [1 - \cos\Delta\phi(\vec{p}_T^{miss}, l)]$
  - Reduce process $W \to l\nu$

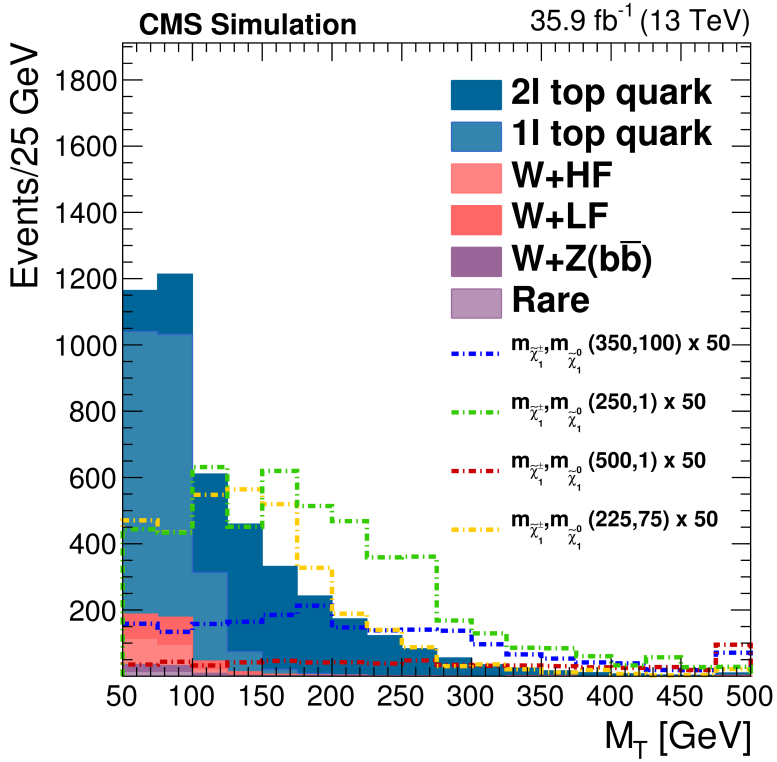


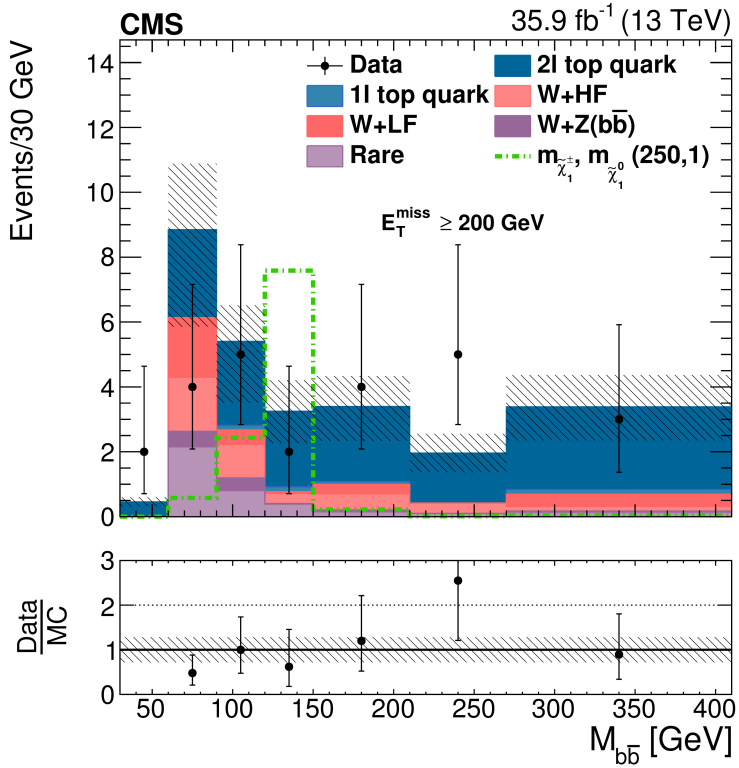
- 1 charged lepton
  2 b-jets $\rightarrow m_{bb} \approx 125$ GeV
  large $E_T^{miss}$
- Dominant background: dileptonic tt production
- Kinematic cuts ($M_T(l, E_T^{miss})$)
  to reduce tt, W+jets
- Prediction by MC, validated in data control regions

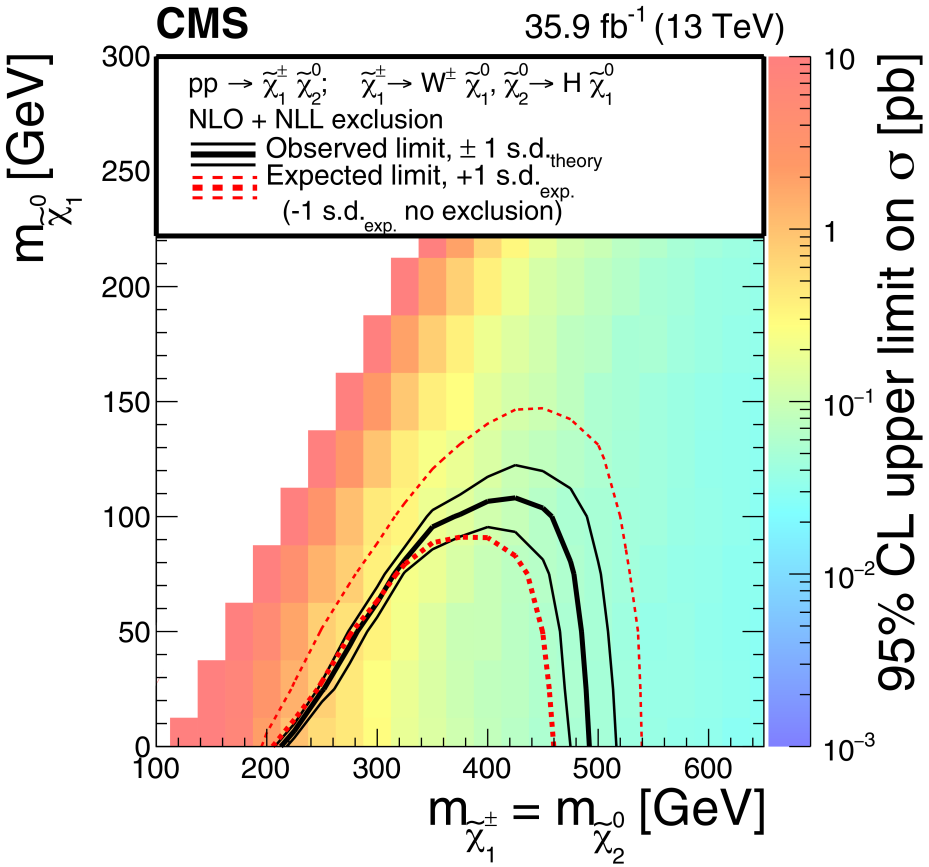


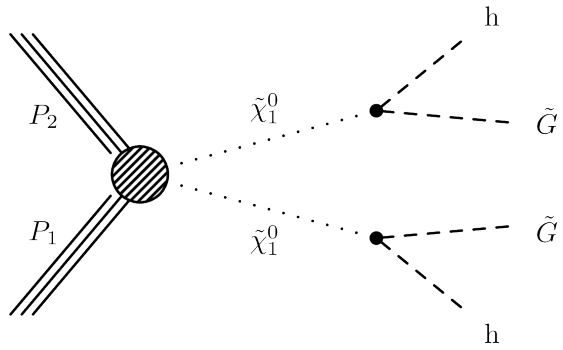



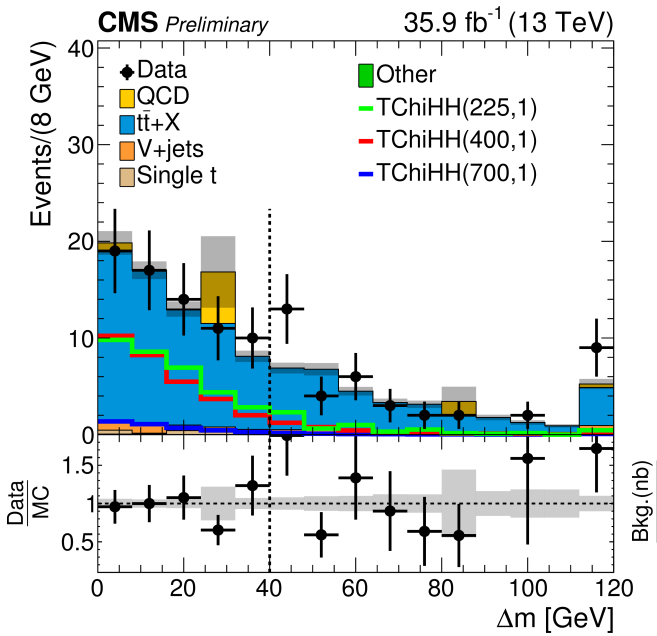
- 2 SR: $125 \leq E_T^{miss} < 200$, $E_T^{miss} \geq 200$
- Exclusion: $m_{\tilde{\chi}_1^\pm} \notin (220, 490)$ GeV when $m_{\tilde{\chi}_1^0} \approx 0$
  $m_{\tilde{\chi}_1^0} > 110$ GeV when $m_{\tilde{\chi}_1^\pm} \approx 450$ GeV

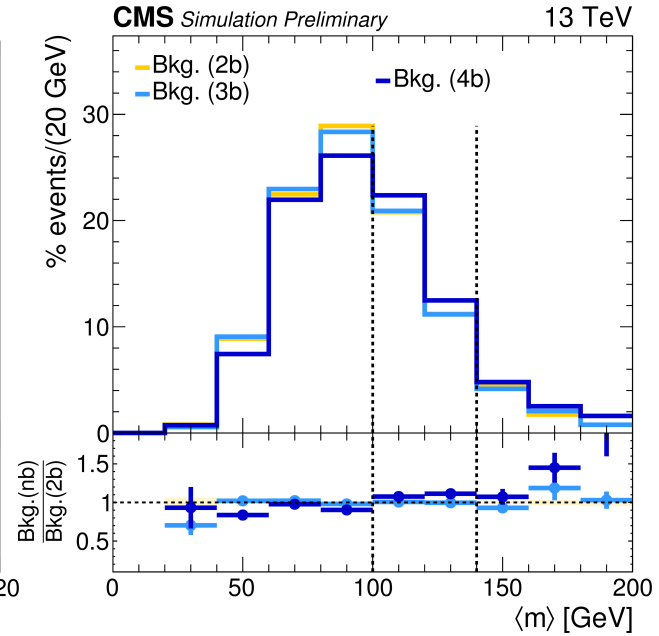


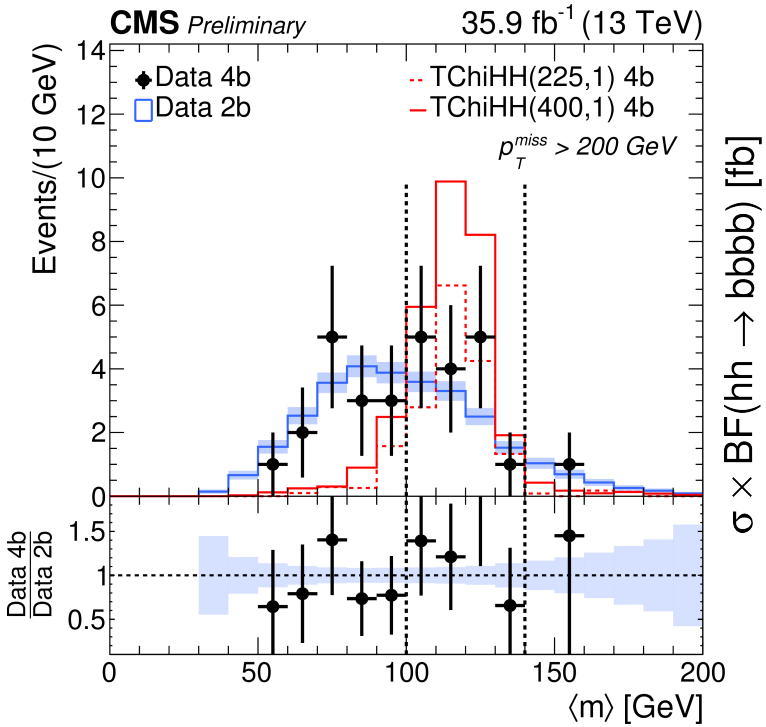


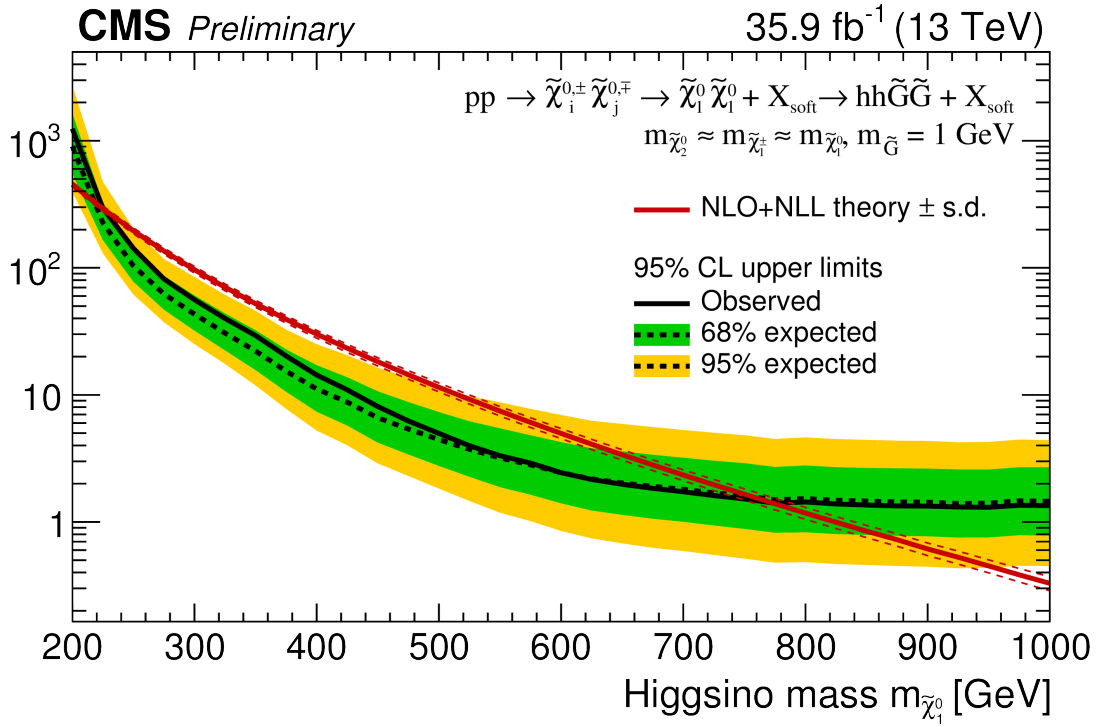

- 3 or $\geq 4$ b-jets
  lepton veto
  large $E_T^{miss}$
- Reconstruct Higgs mass:
  2-2 highest b-tagged jets, choose pairs with $\Delta m$ minimised, $100 < \langle m \rangle \leq 140$ GeV
- Dominant background: semi-leptonic tt production
- Prediction by ABCD method, $N_{b-jets}$ and $\langle m \rangle$ as independent variables



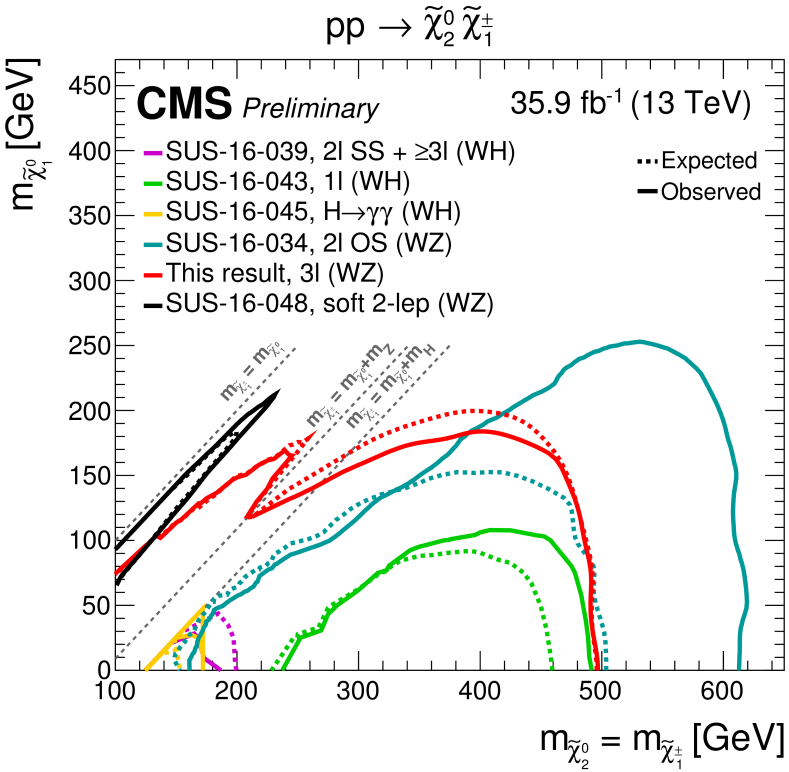
- SR: 4 bins in $E_T^{miss}$ from 150 to 450 GeV, 2 bins in # of b-jets: 3 b-jets, 4 b-jets
- Exclusion: $m_{\tilde{\chi}_1^0} \notin (225, 770)$ GeV

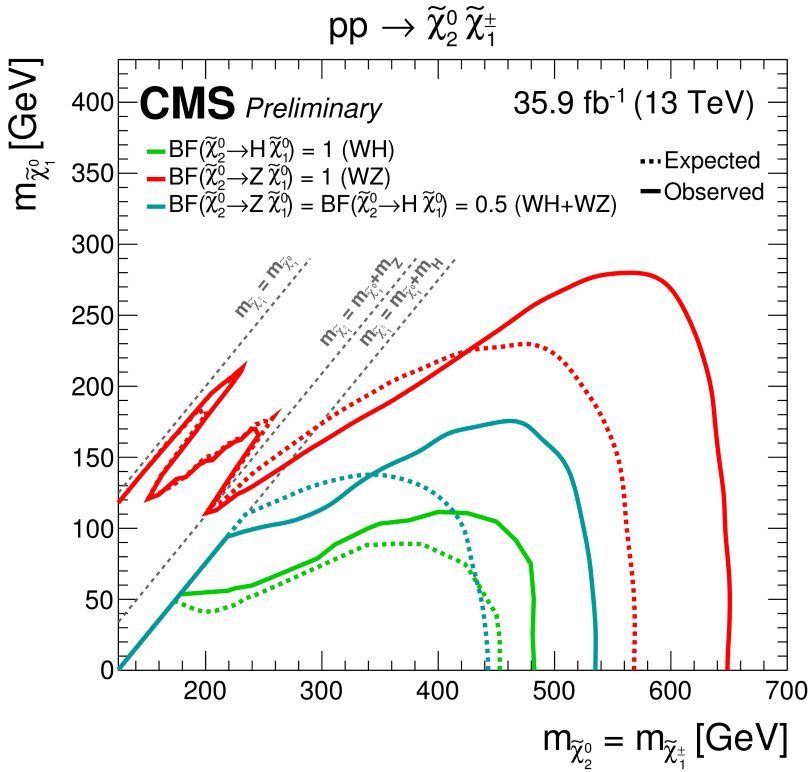


- Statistical combination of several searches
  - Wino $\widetilde{\chi}_1^{\pm}$, $\widetilde{\chi}_2^0 \rightarrow$ WZ, WH
  - Higgsino $\widetilde{\chi}_1^0$, $\widetilde{\chi}_1^0 \rightarrow$ ZZ, ZH, HH
- New search: $\geq 3$ leptons when $m_{\widetilde{\chi}_2^0} - m_{\widetilde{\chi}_1^0} \approx m_Z$
- Improves WZ topology
- Combined results also improve WH topology

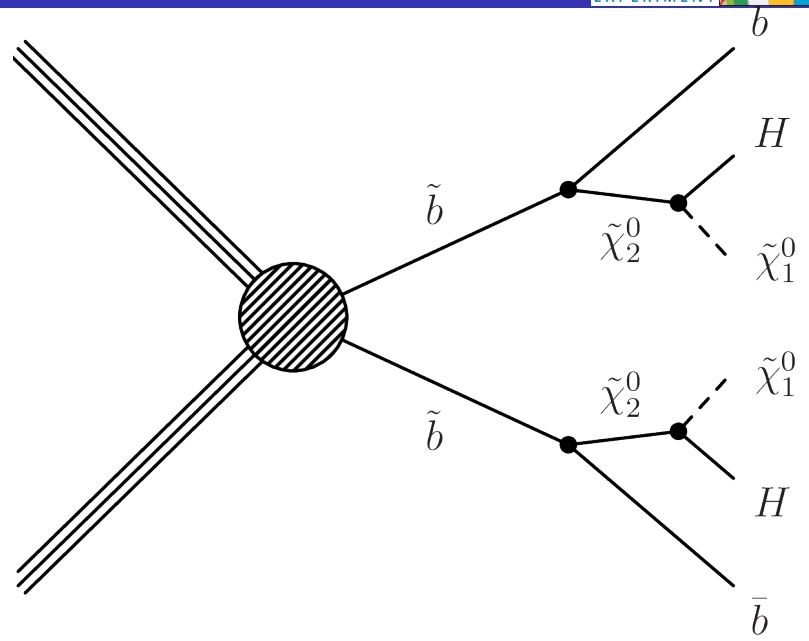
| Search | Signal topology WZ | WH | ZZ | ZH | HH |
|---|---|---|---|---|---|
| $1\ell$ 2b | | ✓ | | | |
| 4b | | | | | ✓ |
| $2\ell$ on-Z | ✓ | | ✓ | ✓ | |
| $2\ell$ soft | ✓ | | | | |
| $2\ell$ SS, $\geq 3\ell$ | ✓ | ✓ | ✓ | ✓ | ✓ |
| H($\gamma\gamma$) | | ✓ | | ✓ | ✓ |

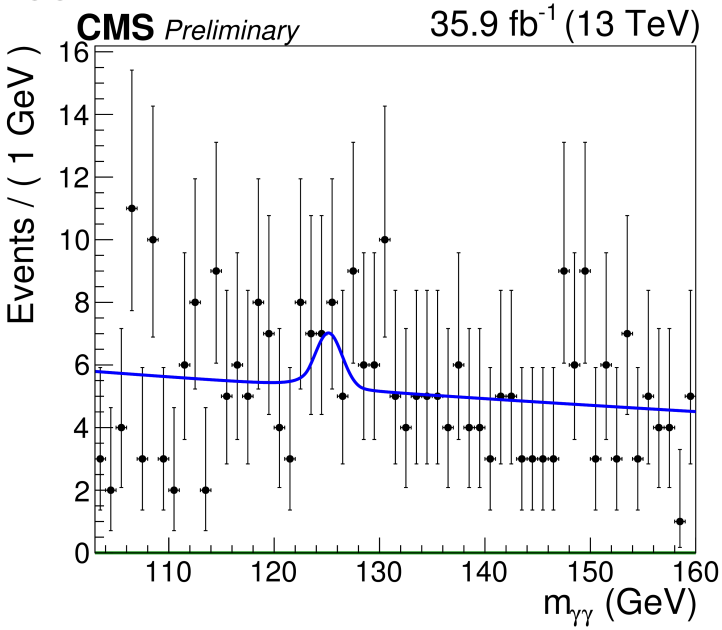


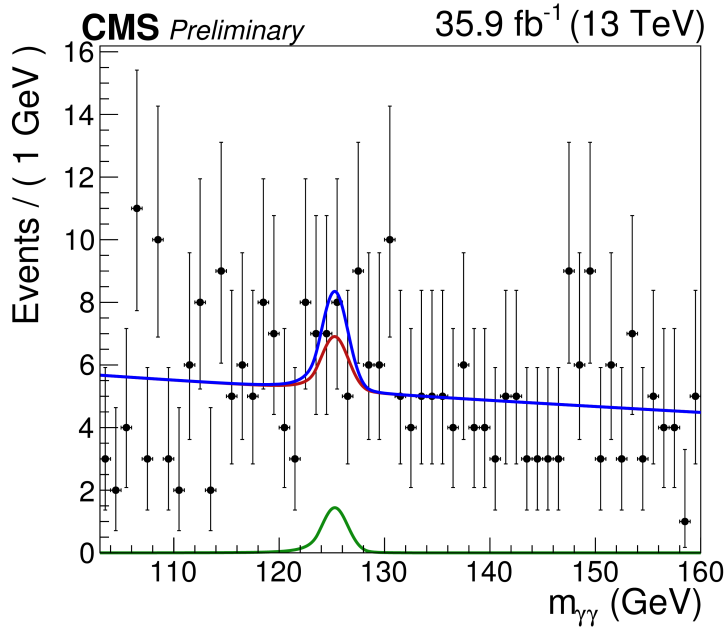



# Higgs→ $\gamma\gamma$+X with razor variables CMS-PAS-SUS-16-045

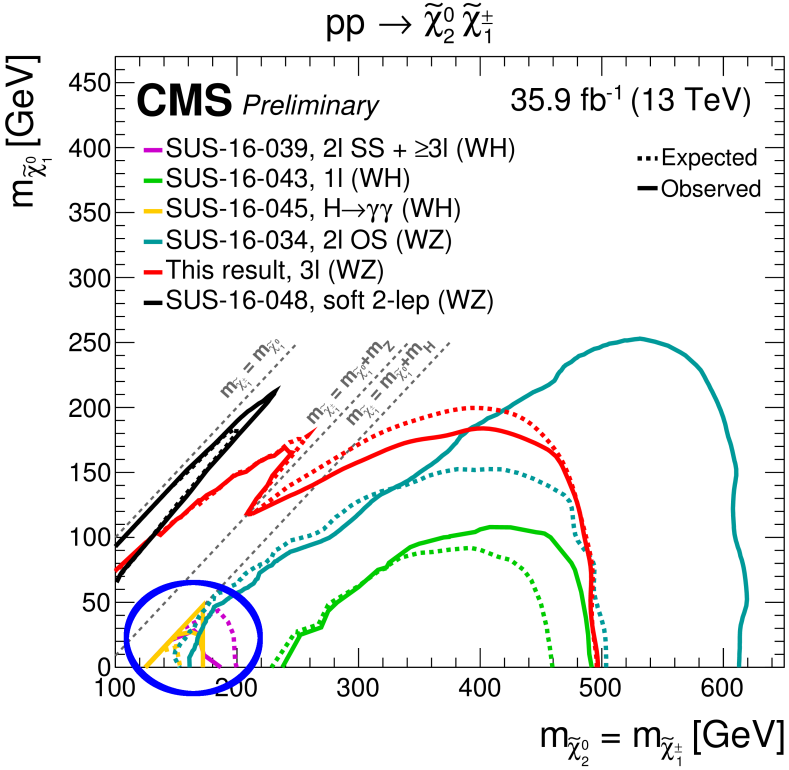
- 2 photons $m_{\gamma\gamma} \approx 125$ GeV
  $\geq$ 1jets
  large $E_T^{miss}$
- Razor variables $M_R$, $R^2$ (definition in backup)
  to suppress SM background
- Dominant background:
  $\gamma\gamma$+jets, $\gamma$+jets, SM Higgs boson
- Background prediction:
  QCD: fit $m_{\gamma\gamma}$ spectrum
  SM Higgs: MC prediction



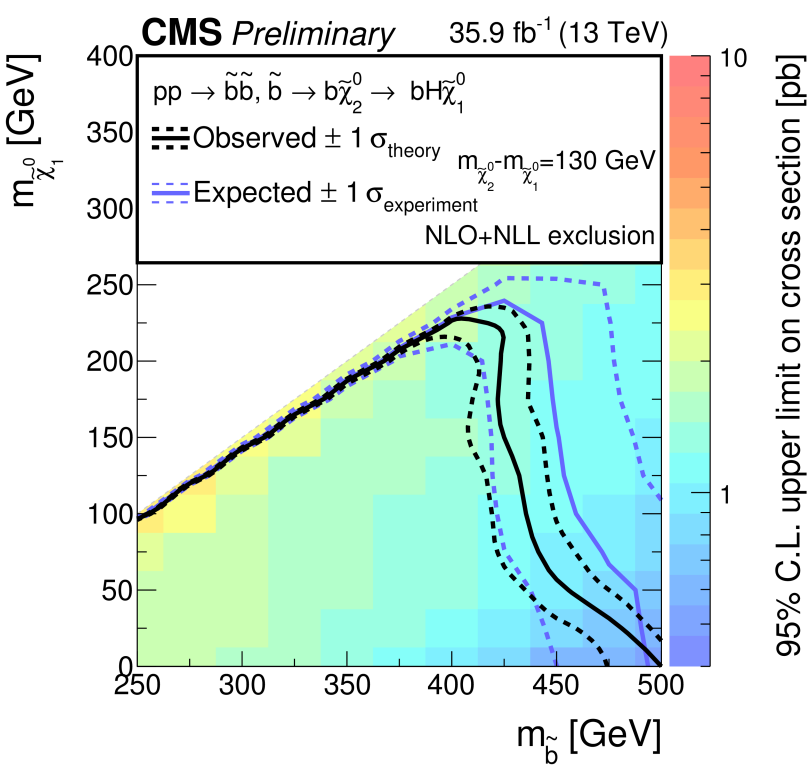



- EWK WH, ZH, HH interpretation in combined EWK search
- Exclusion: $\widetilde{\chi}_1^{\pm} > 170$ GeV for $m_{\widetilde{\chi}_1^0} < 25$ GeV

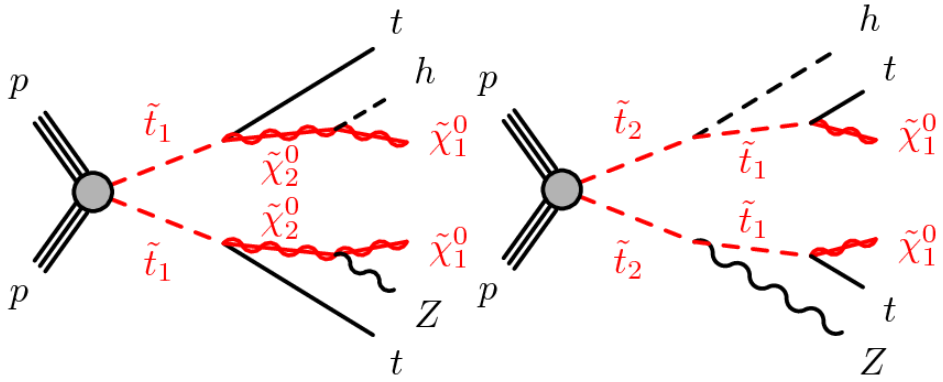


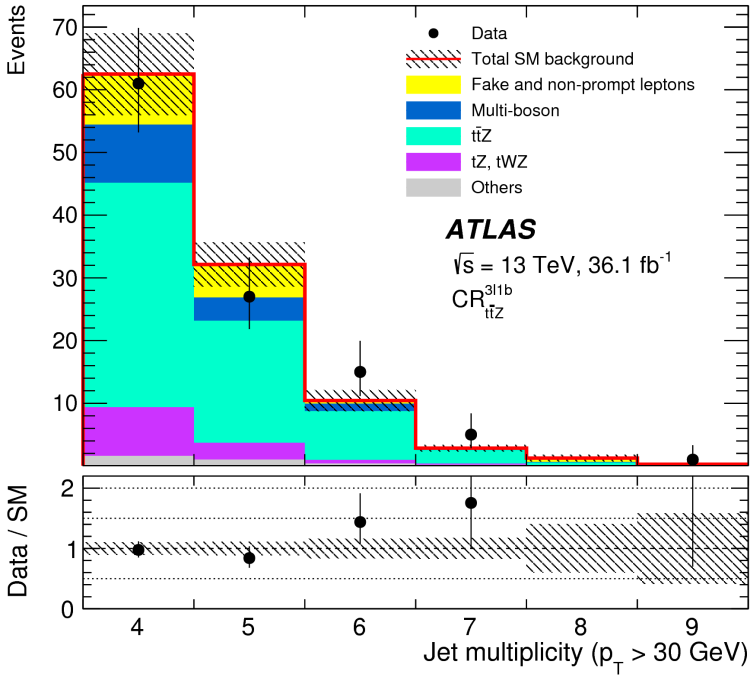

- Results interpreted also in bottom squark pair production
- Exclusion: $m_{\widetilde{b}} > 450$ GeV for $m_{\widetilde{\chi}_1^0} < 250$ GeV

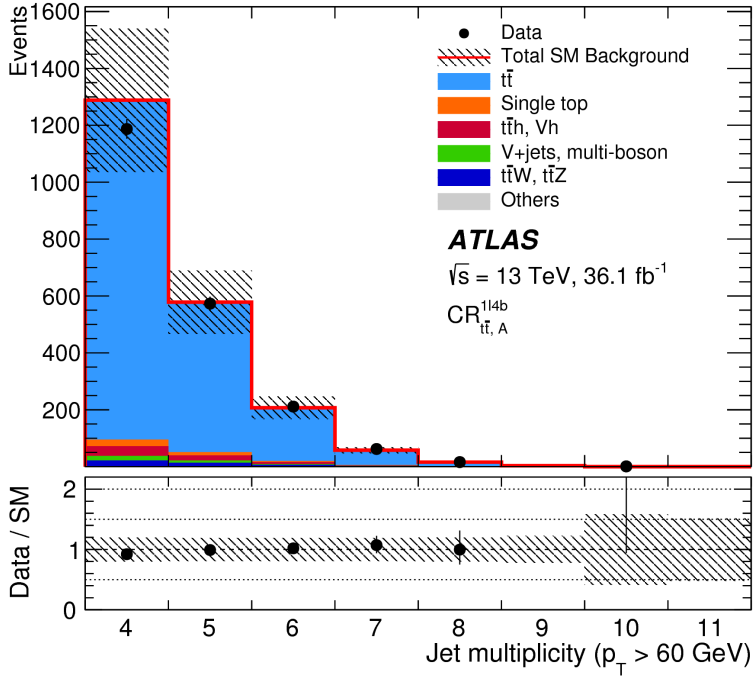


# Stop pairs in ZH + tt + MET ATLAS-SUSY-2016-20

- 2 main SR:
  reconstruct Z with leptons
  reconstruct Higgs with b-jets
- Z: $\geq 3$ leptons, $\geq 1$ b-jets + $E_T^{miss}$
- H: 1–2 leptons, $\geq 4$ b-jets + $E_T^{miss}$
- Dominant background: ttZ, tt
- Prediction:
  from MC, verified with data in Control Regions

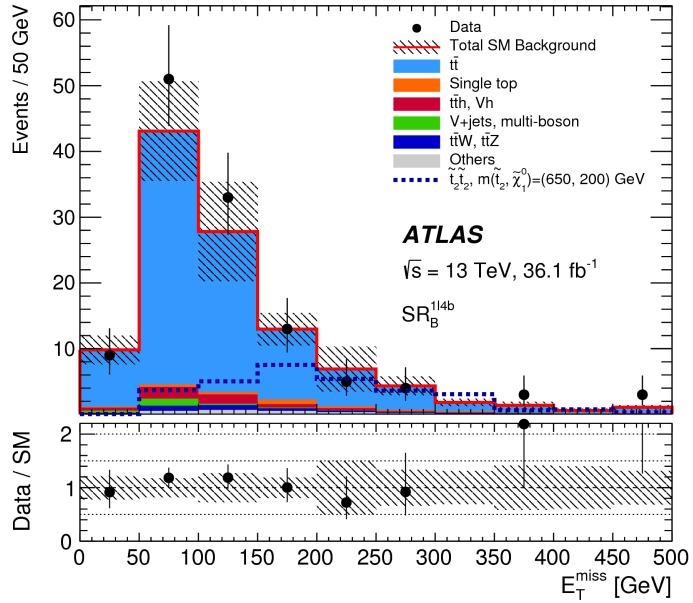


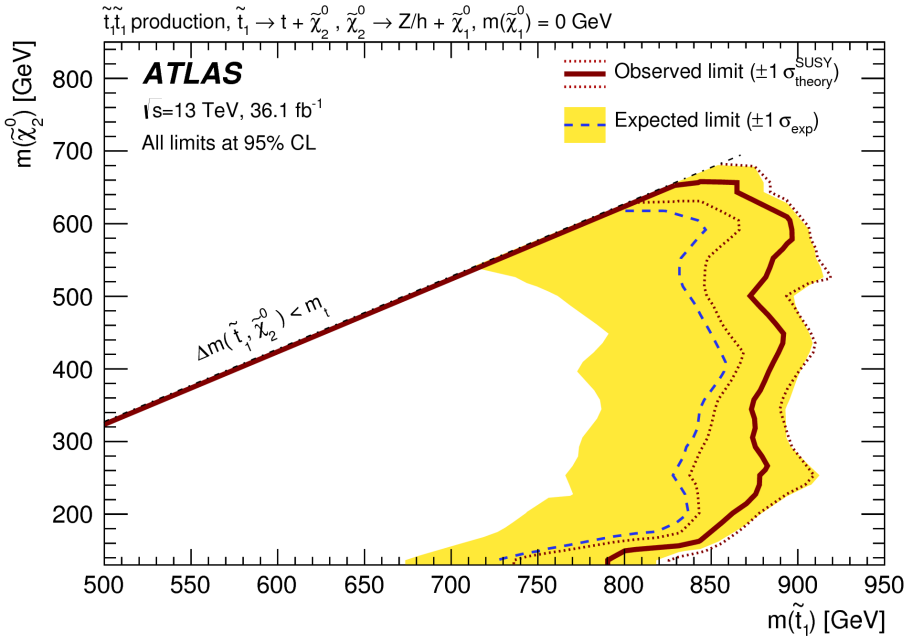



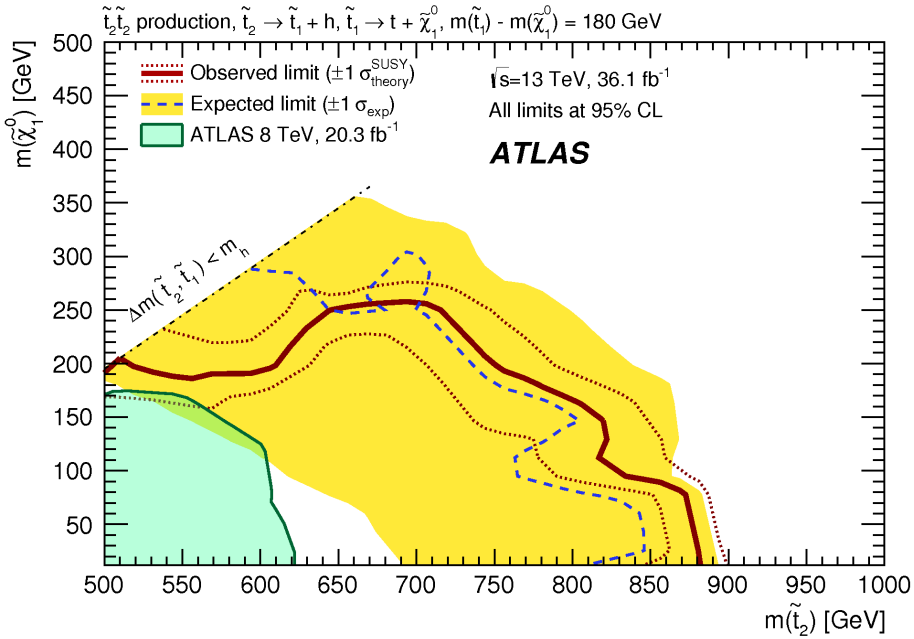



# Stop pairs in ZH + tt + MET ATLAS-SUSY-2016-20

- 3-3 search bins:
  from boosted to resolved case of Z/H
  $p_T^{ll} > 150, > 80$ GeV
  $p_T^{bb} > 300, > 0$ GeV
- Exclusion: $m_{\tilde{t}} > 800$ GeV



# Baryonic Z' model

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$\rightarrow$ new heavy neutral **Z' boson**

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Z' not couples to leptons?

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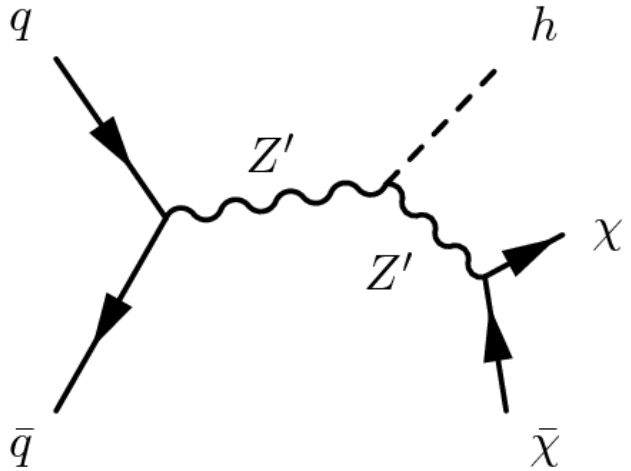
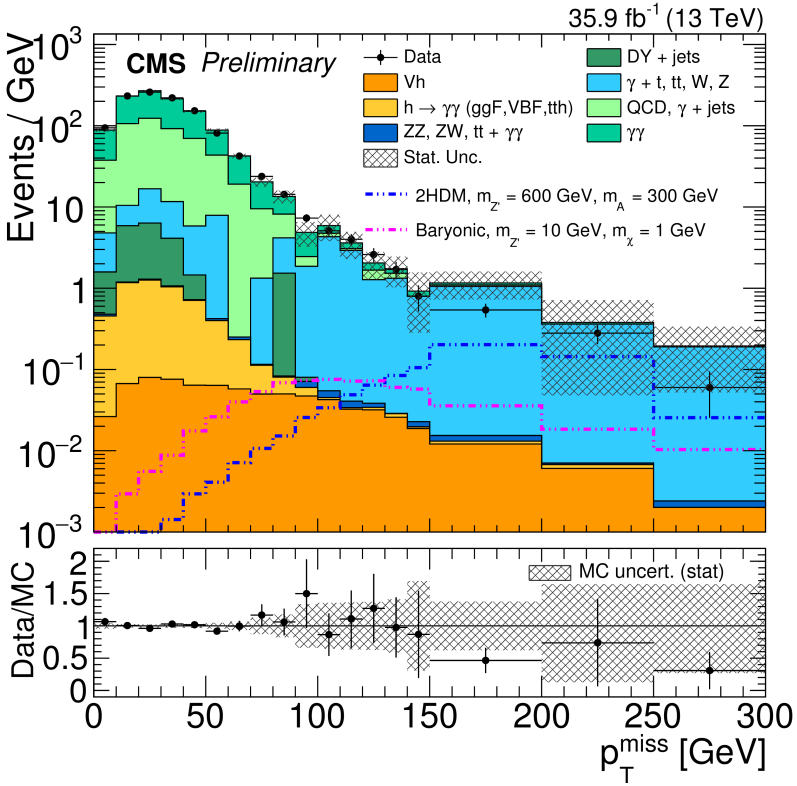
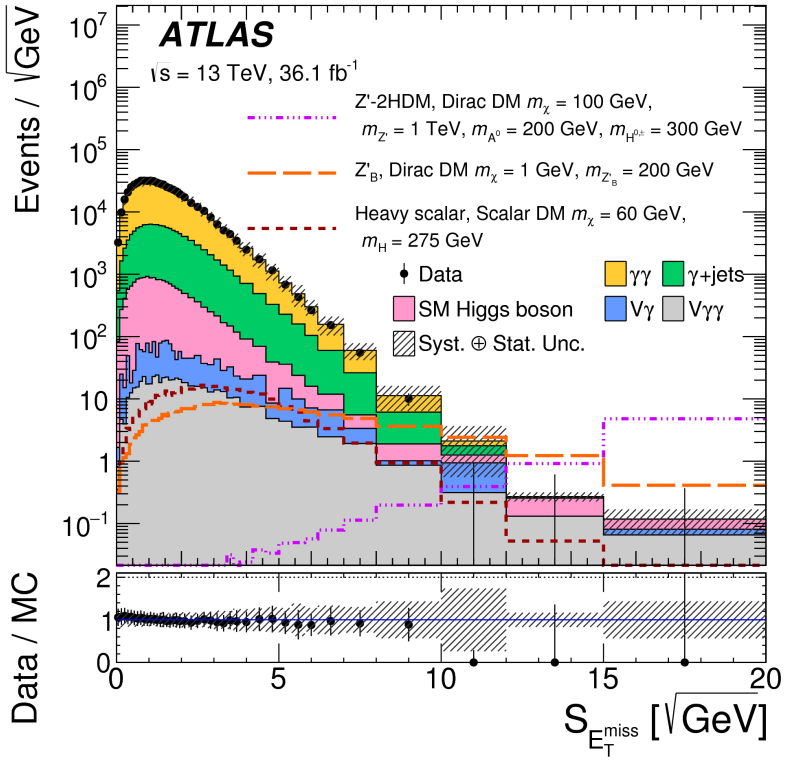
In certain models Z' linking dark and visible sectors – dark **Z' "portal"**

- DM search: $Z' \rightarrow$ SM particle(s) $+E_T^{miss}$

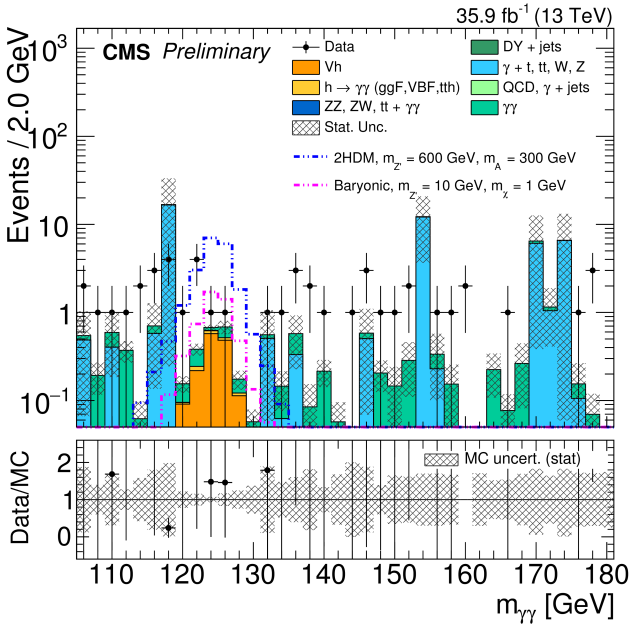
- 2 photons
  $E_T^{miss}$
- Dominant background: SM $\gamma\gamma$, $\gamma$+X
  h$\rightarrow \gamma\gamma$ (Vh)
- Prediction:
  data-driven methods by fitting $m_{\gamma\gamma}$ spectum

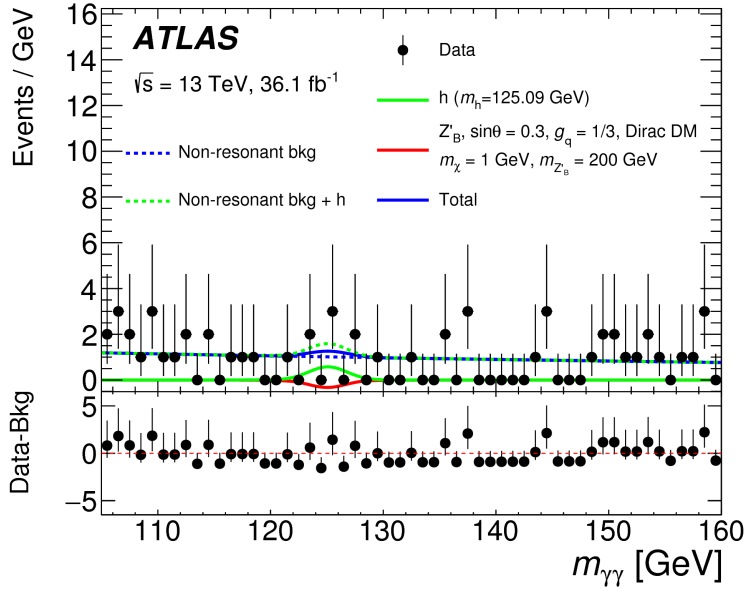


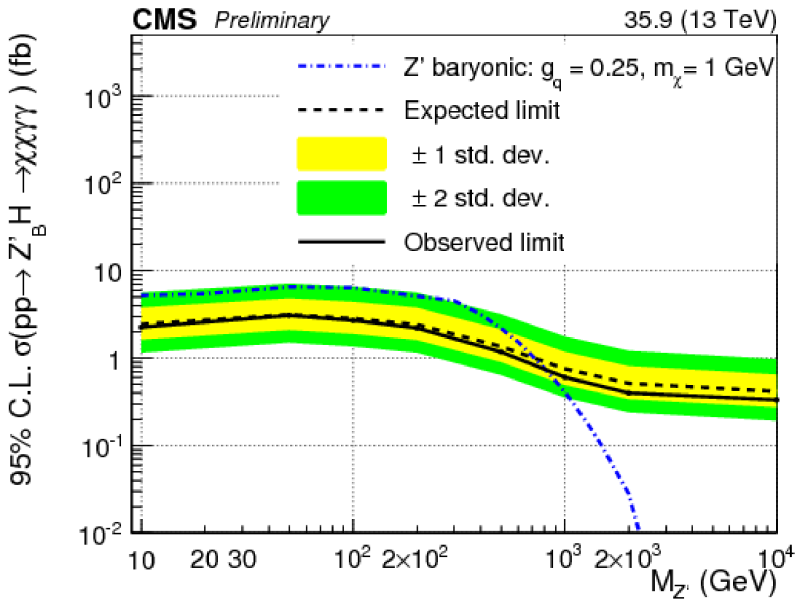



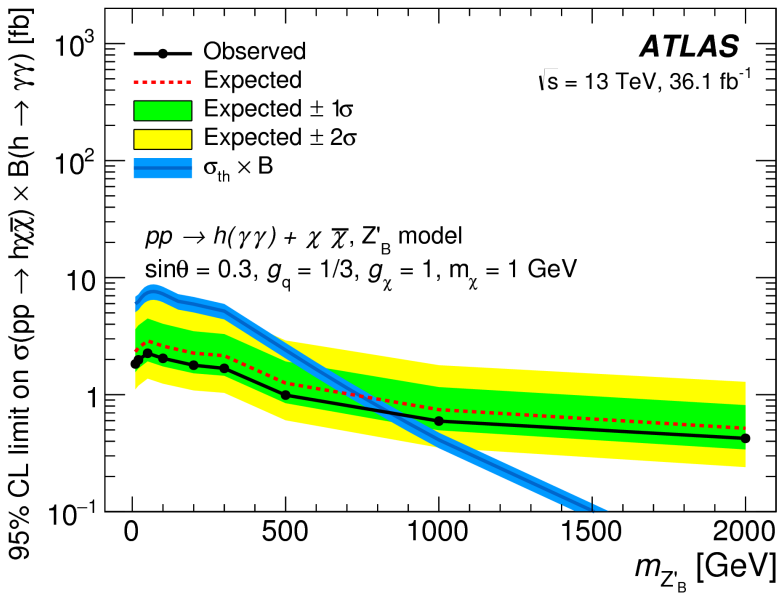



- Several SR in $E_T^{miss}$ & $p_T^{\gamma\gamma}$
- Exclusion: $m_{Z'_B} > 800$ GeV
- CMS & ATLAS results consistent



# Heavy Vector Triplet model (HVT)

Many BSM theories predict **heavy** spin-1 vector particles: **V'**

- Minimal Walking Technicolor, Little Higgs, composite Higgs ...

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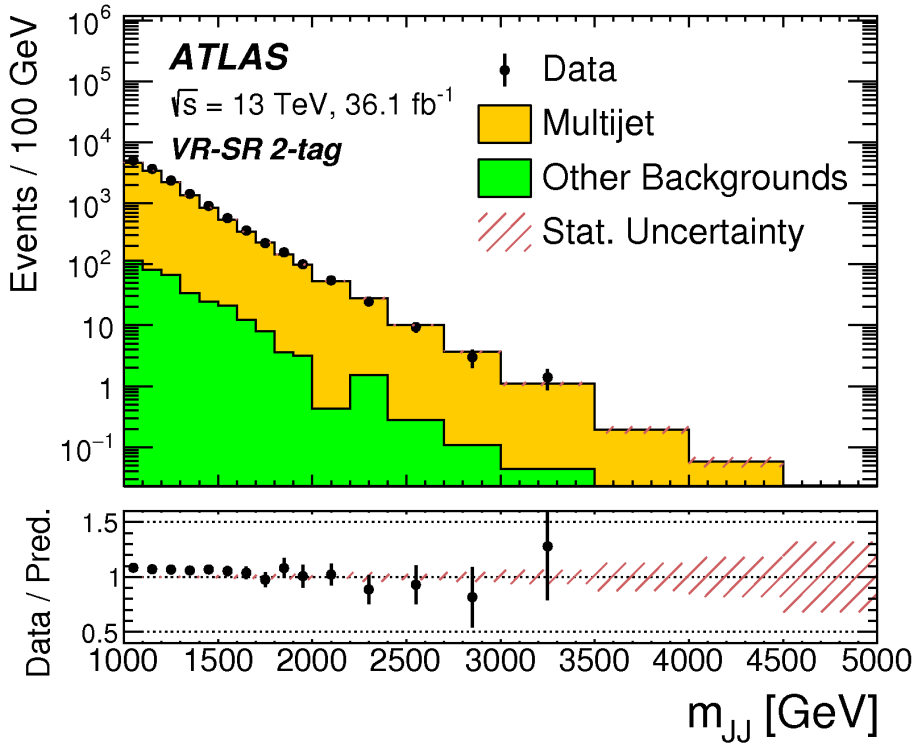
**HVT** simplified model with effective Lagrangian
$\rightarrow$ experimental and theoretical results comparison easier

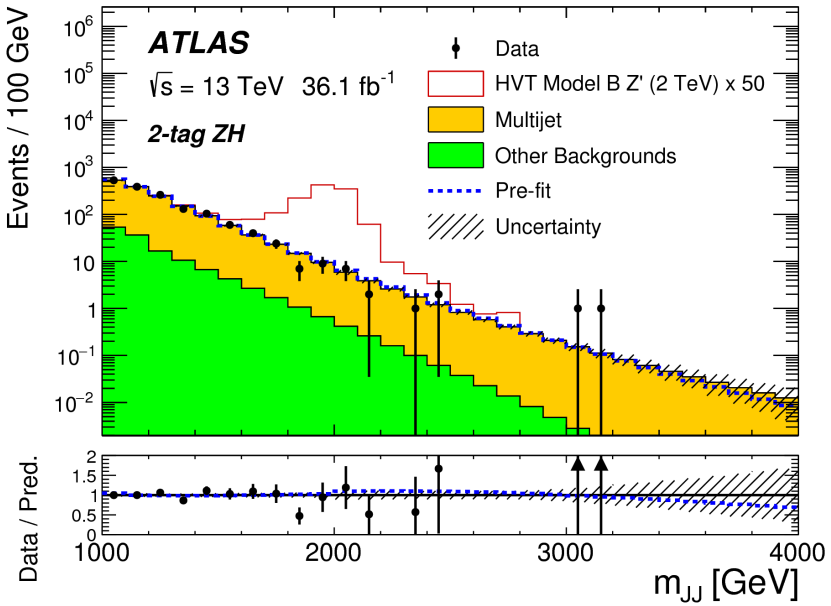
New heavy boson produced $\rightarrow$ **resonance** in decay products

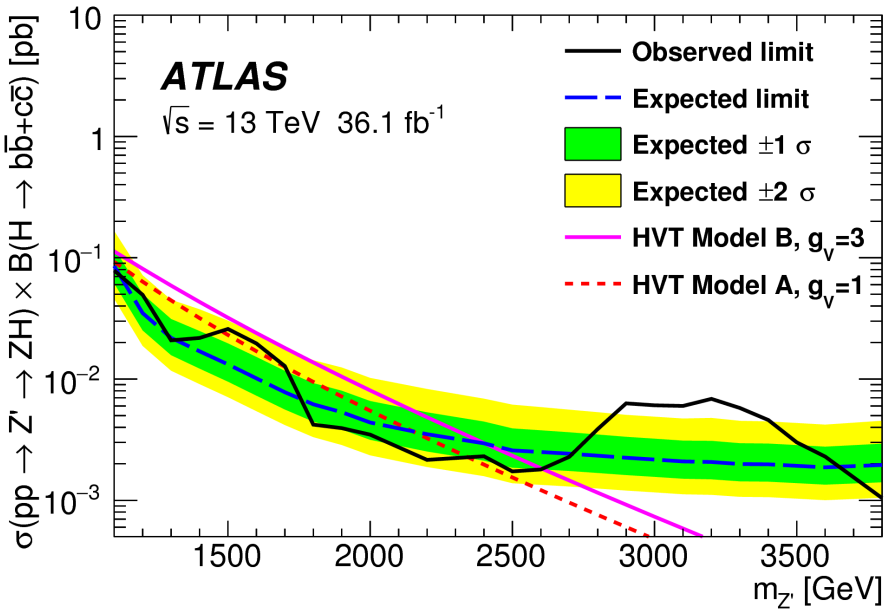
- Generally V'$\rightarrow$ SM vector boson + h is possible
- $V' = W'^{\pm}, Z'$

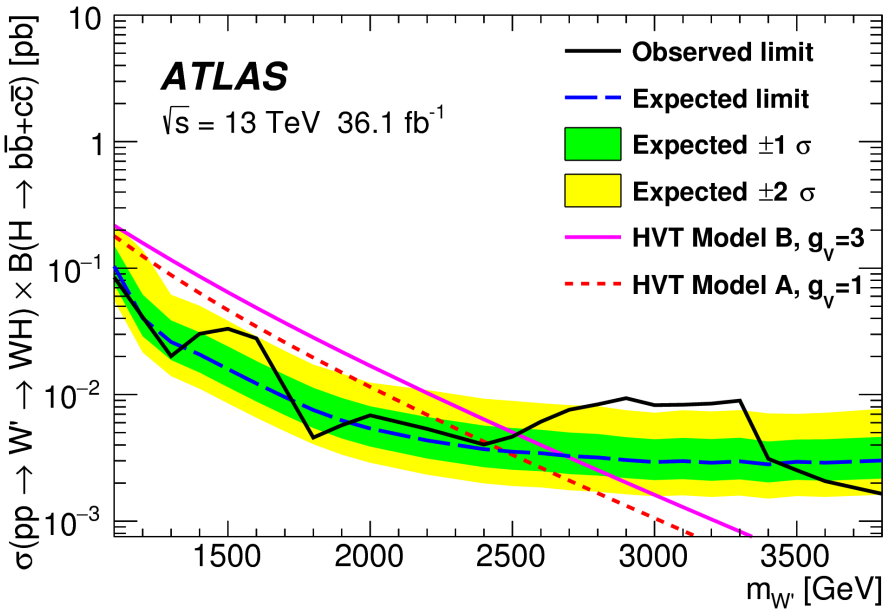
- $W'/Z' \to W^{\pm}/Z + h \to q\bar{q} + b\bar{b}$
- $\geq$ 2 large jets (R=1.0) with large $p_T$, lepton veto, $E_T^{miss}$ veto
- H-jet b-tagged, $m_{H-jet} \approx$ 125Gev
- V-jet W-tagged or Z-tagged
- Dominant background: QCD multijet
- Prediction from 0-btag CR



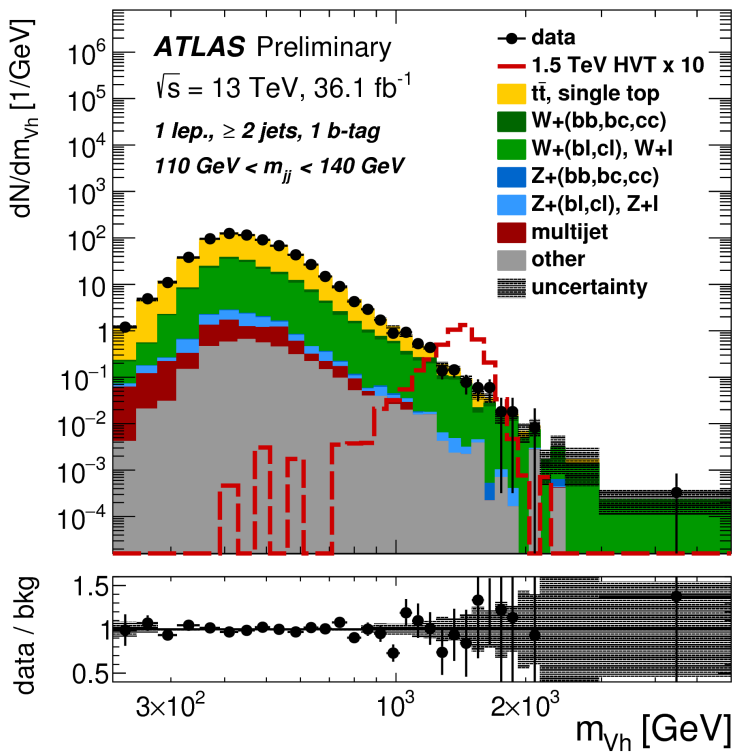
- 4 SR: 2 in btag, 2 in W/Z tag
- Exclusion:
  $m_{W'} \notin (1.1, 2.5)$ TeV
  $m_{Z'} \notin (1.1, 2.6)$ TeV
- Small excess in ZH
  $m_{JJ} \approx 3$ TeV, $3.3\sigma$ local, $2.1\sigma$ global

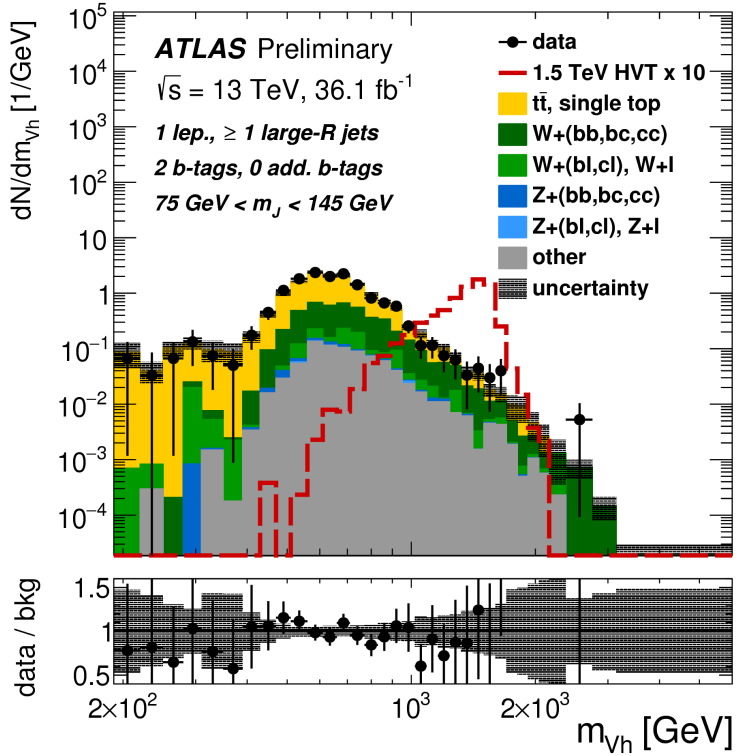


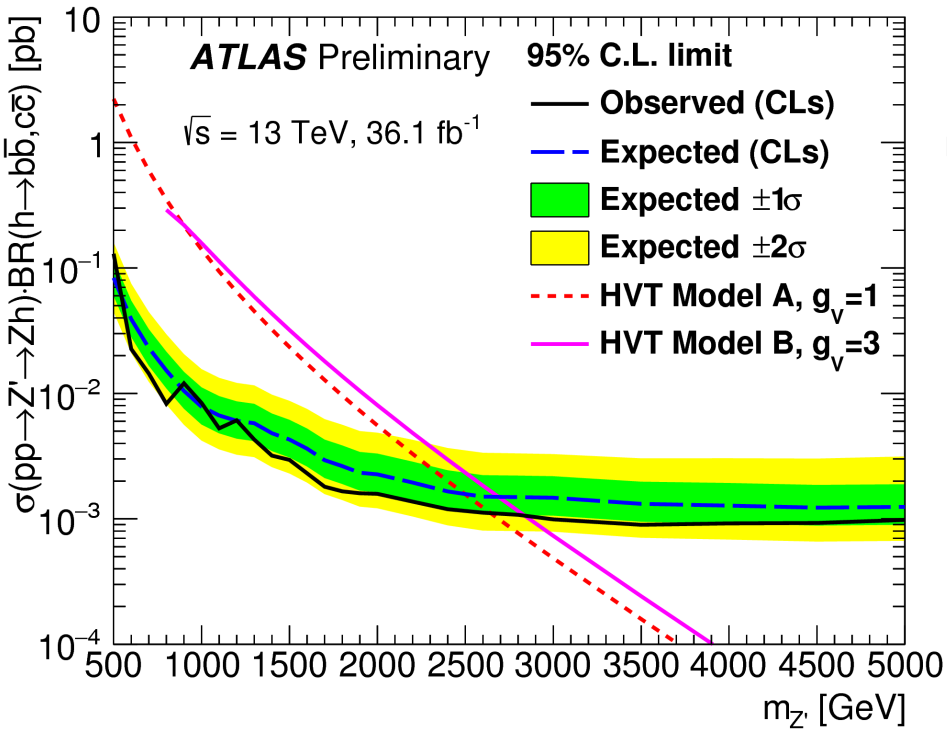



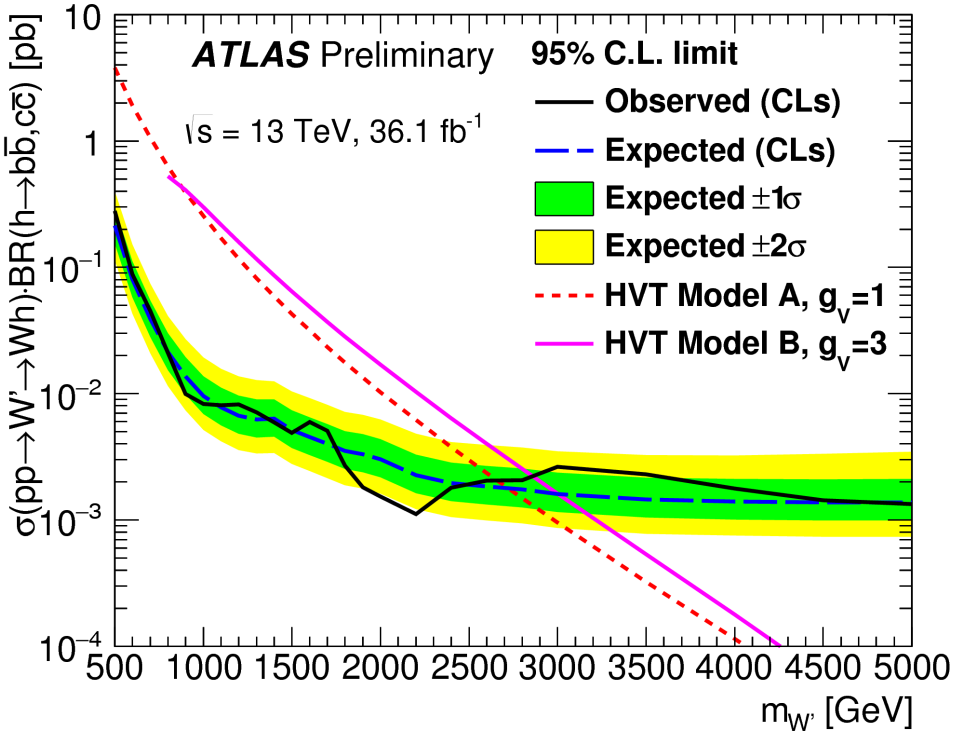
- $W'/Z' \to W^{\pm}/Z + h \to l^{\pm}\nu/l^{+}l^{-}/\nu\bar{\nu} + b\bar{b}$
- 0, 1 or 2 leptons
- Resolved: 2 small jets ($\geq$ 1b-tag), Merged: 1 large jet
- Dominant backgrounds: tt, W/Z+jets
- Prediction: from MC, rescaled using control region



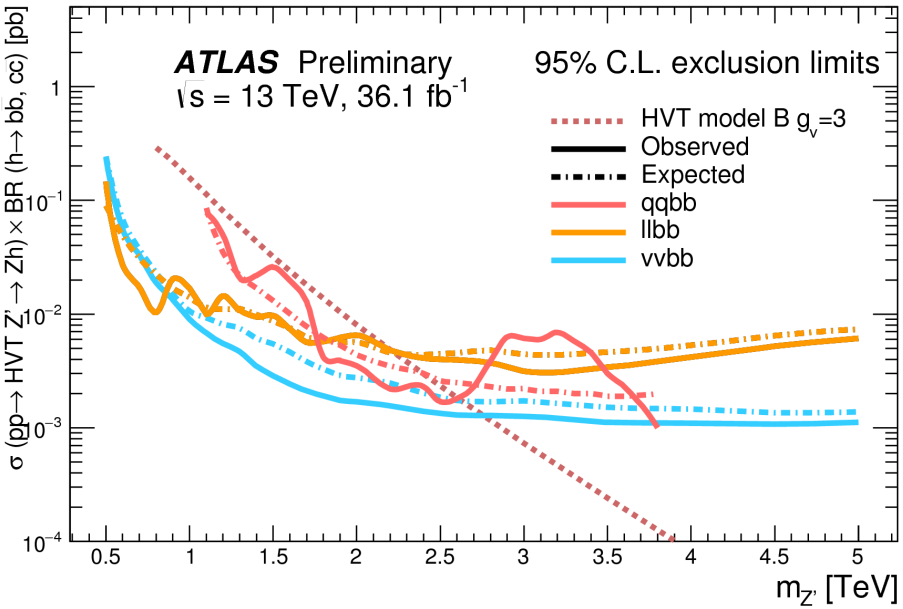
- Results interpreted in 2 HVT models
  $g_V$: strength of new interaction
- Exclusion:
  $m_{Z'} > 2.7$ TeV
  $m_{W'} > 2.7$ TeV
- 2HDM interpretation *see Tom's talk*

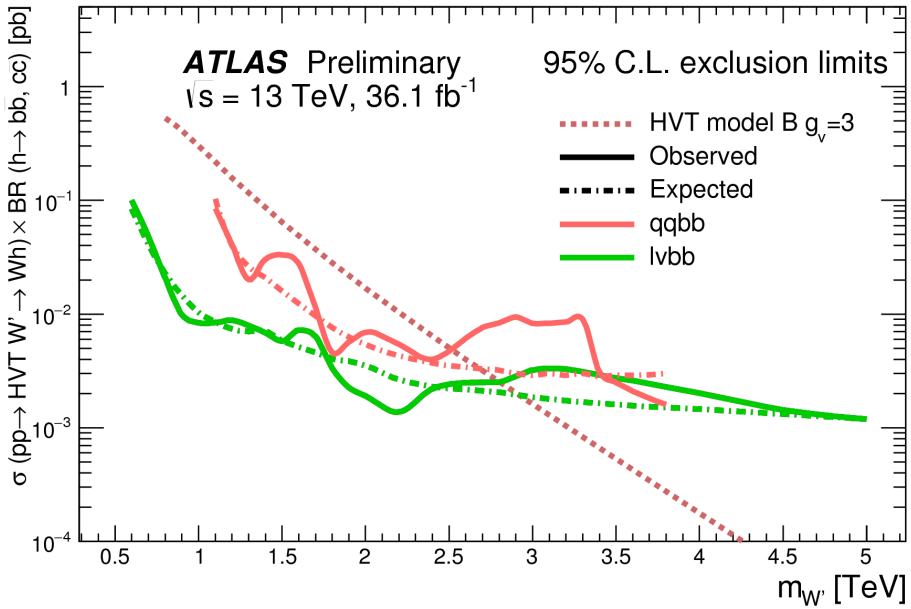


# Summary of ATLAS HVT results

- Similar exclusion limits from both analyses



# Summary

- Several analyses shown for BSM searches with Higgs boson
  - SUSY, Baryonic Z', HVT
  - Final states: $H \to bb$, $H \to \gamma\gamma$, $E_T^{miss}$, leptons ...
- No significant excess observed
- Many ongoing analyses for further searches

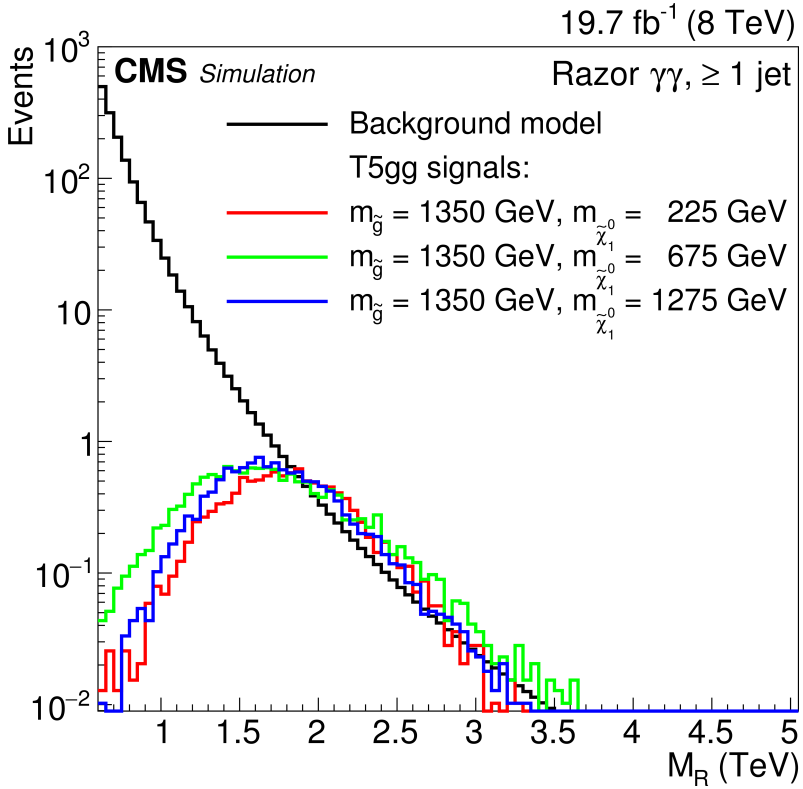
Backup

# Razor variables

- Based on pair production of two heavy particles
- Decaying to undetected particle + visible products
- All events treated like di-jet event
- Reconstructed objects $\rightarrow$ two megajets $j_1$, $j_2$

$$M_R = \sqrt{(|\vec{p}^{j_1}| + |\vec{p}^{j_2}|)^2 - (p_z^{j_1} + p_z^{j_2})^2}$$

$$M_T^R = \sqrt{\frac{E_T^{miss}(p_T^{j_1} + p_T^{j_2}) - \vec{p}_T^{miss}(\vec{p}_T^{j_1} + \vec{p}_T^{j_2})}{2}}$$

$$R^2 = (\frac{M_T^R}{M_R})^2$$

- SM background exponentially falling
- SUSY signals large values of $M_R$, $R^2$