Searches for Supersymmetry with heavy object tagging

GIOVANNA SALVI
(RAL & University of Southampton)

On behalf of the CMS collaboration

Introduction:

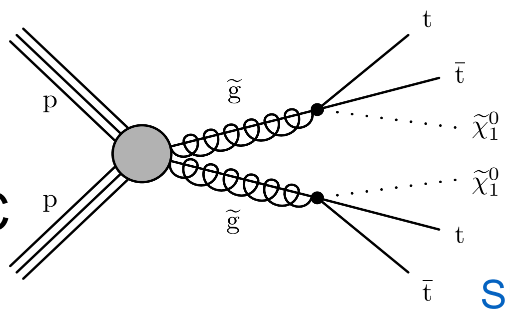
- Heavy objects (W/Z/H/top) are riconstructed with different sized jets (AK8 & AK4)

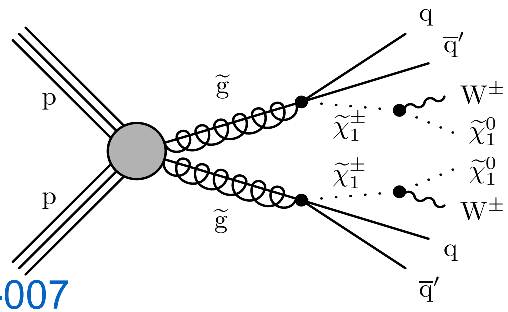
- Different Machine Learning algorithms have been developed in the CMS experiment revolutionizing tagging approaches and searches for SUSY at the LHC

- Heavy objects tagging techniques are widely used in CMS SUS Analyses (SUS-21-007, SUS-21-002, SUS-20-004, SUS-20-003, SUS-19-010 etc)

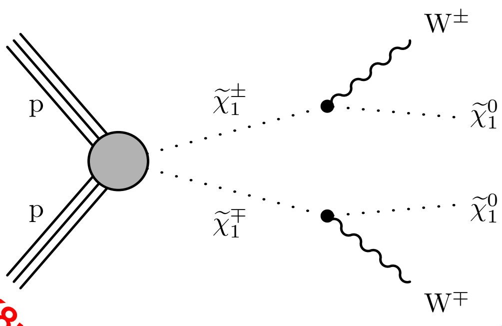
and this talk will focus on 3 recent ones!

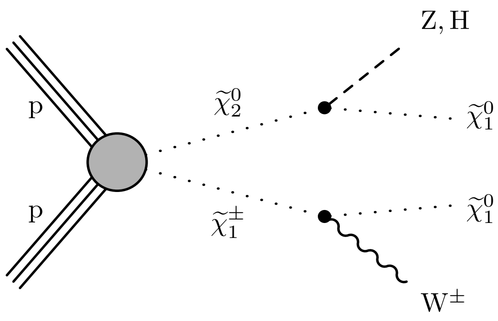
Analysis	$N_{Leptons}$	N_{Jets}	MET
1-Lep ΔΦ SUS-21-007	1 Lepton	>>1 AK4&AK8 Jets	high
NMSSM HIG-20-018	Fully hadronic	2AK8 Jets	NO
WX SUS-21-002	Fully hadronic	2AK8 Jets	high



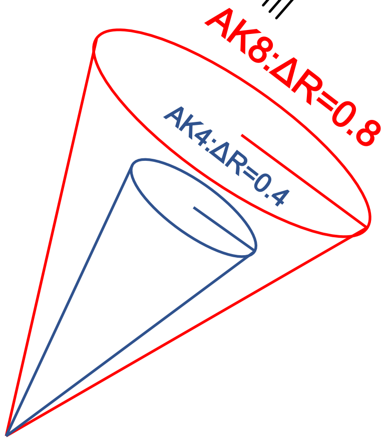


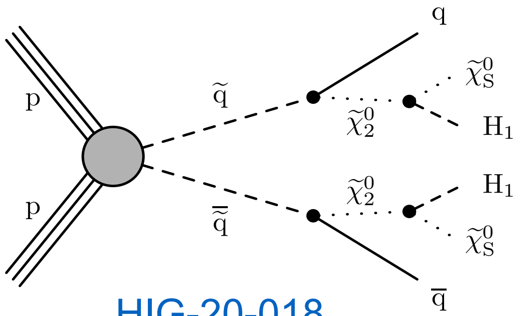
SUS-21-007





SUS-21-002



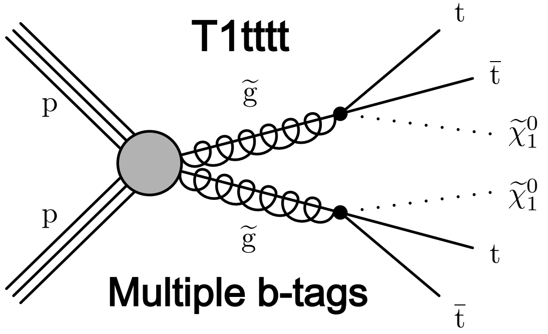


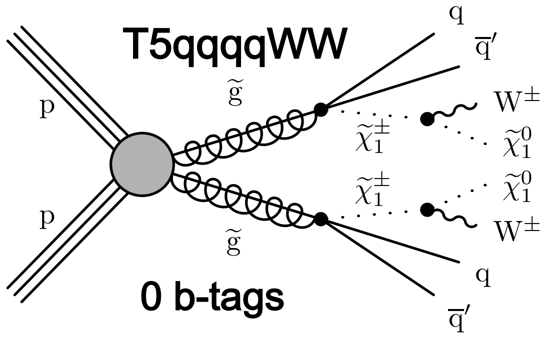
HIG-20-018

1) 1-Lep ΔΦ Analysis (SUS-21-007)

1-Lep ΔΦ Analysis

The analysis targets SUSY in events with **1 lepton, a large number of jets and high MET** in two different signal regions

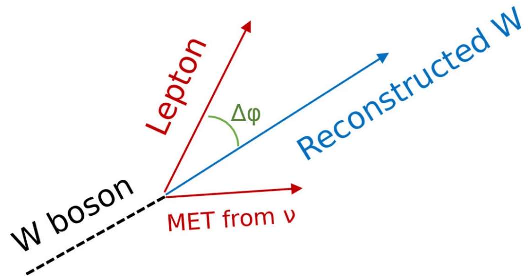




- Two simplified SUSY models with gluino production
- **The 1 lepton is produced in the W boson decay, which originates either from a top decay (multi-b) or chargino decay (0b)**

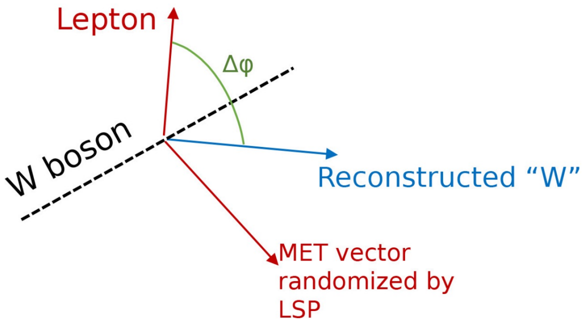
The main discriminating observable to distinguish signal from background is ΔΦ, which is the angle between the lepton and the reconstructed "W boson" (vector sum of the lepton and MET)

SM events

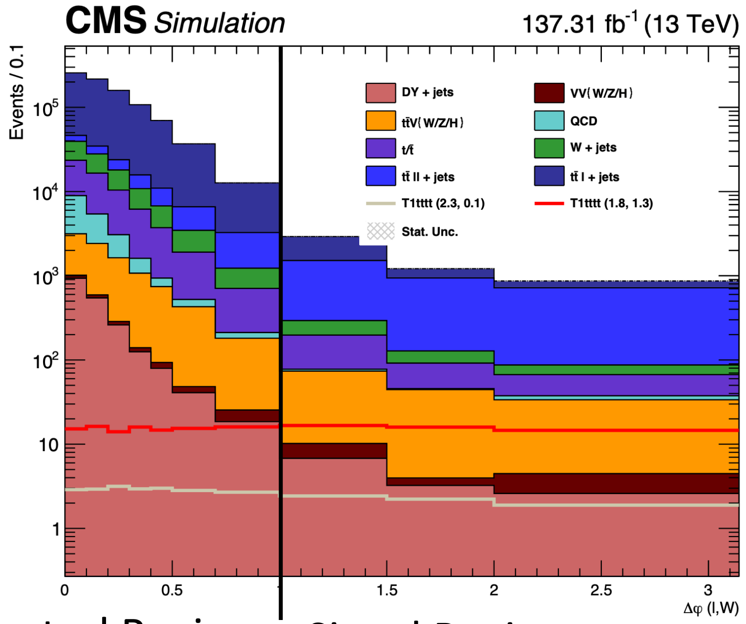


ΔΦ between the lepton and MET is usually small

SUSY events



ΔΦ distribution is flat due to additional MET from two LSPs

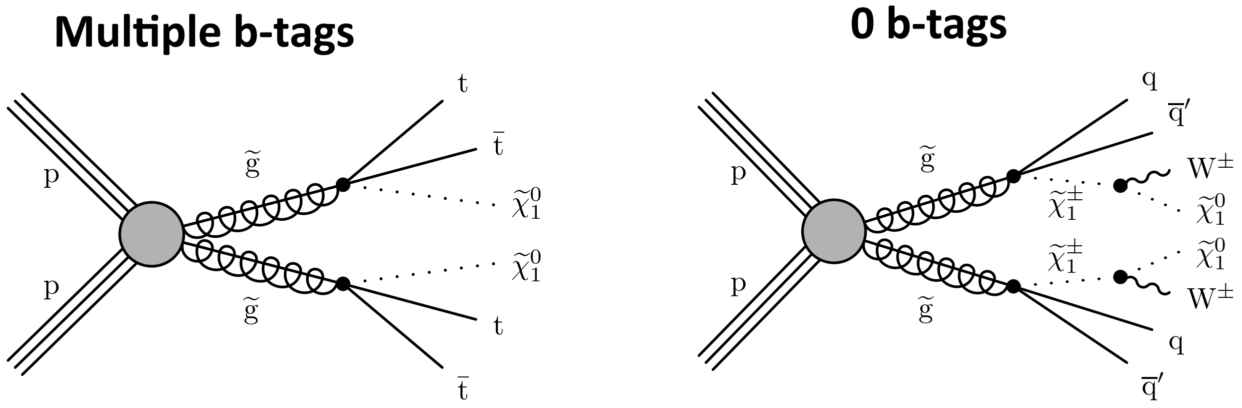


Control Region Signal Region

Event Selection

Analysis regions binned in:

- HT = (∑pT jets)
- LT = |pT(lep)| + |MET|
- N_{jets}
- nb-tag (multi-b), ntop-tag (multi-b)
- nW-tag (0b)



The main backgrounds are:
1) tt → 1 lep (semileptonic ttbar)
2) tt → 2 lep (dileptonic ttbar where one lepton is missing)
3) W+Jets

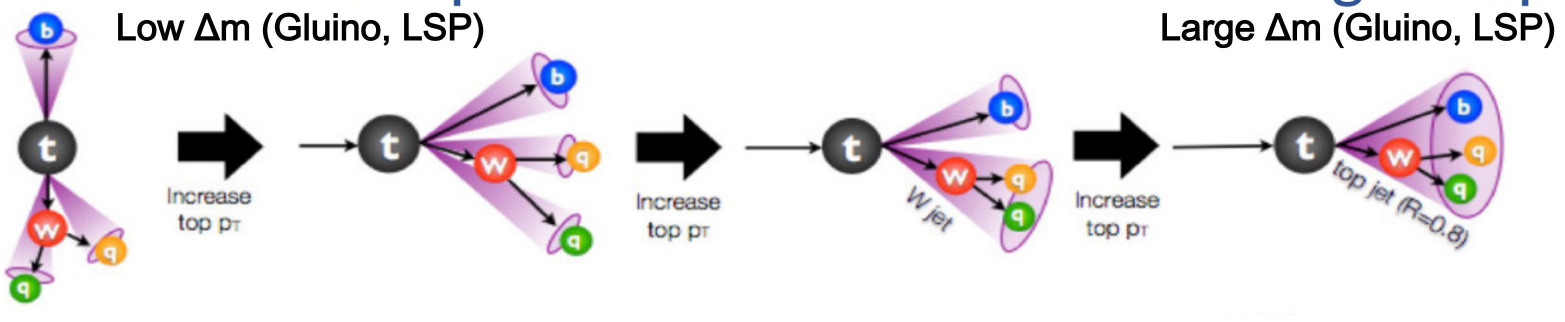
- In the **Search Regions (defined by ΔΦ), the background is dominated by <u>dileptonic ttbar</u> : tt(2lep)**
- By requiring **≥1 hadronic top tag**, we expect significant **suppression of tt(2lep) background** with relatively small decrease in signal efficiency

Multi-b analysis with Top Tagging 0-b Analysis with W Tagging

In the multi-b signal there are 3 hadronic top decays and one semileptonic top decay

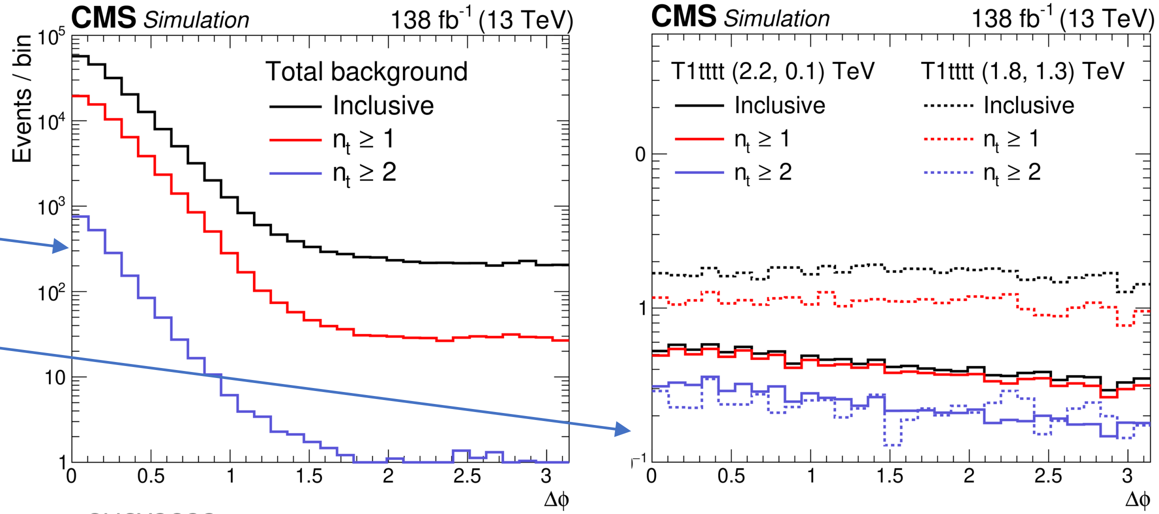
We use a combination of:

- **DeepAK8 top tagger**
  - DNN-based, uses AK8 jets
  - *For merged tops (pT top > 400 GeV)*
- **Resolved top tagger**
  - BDT-based, uses triplets of AK4 jets
  - *For resolved tops (pT top ≤ 400 GeV)*



In Zero-b to identify hadronically decaying W bosons, we employ the **DeepAK8 tagger**

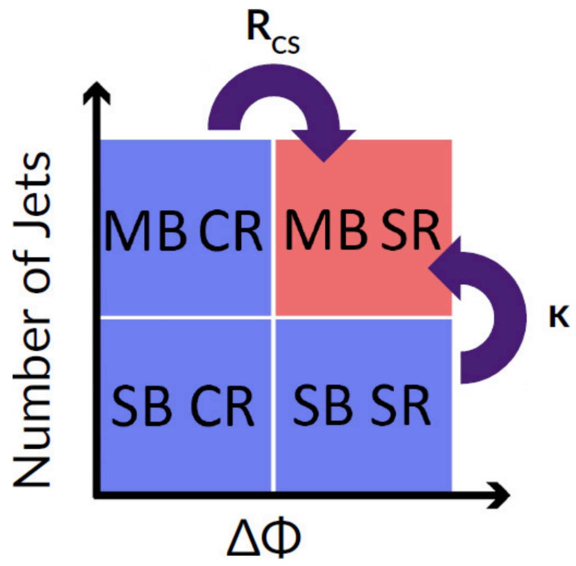
> Applying cuts on ntop-tag
> **reduces significantly background and maintains good signal efficiency**
> for both compressed and uncompressed Signal Regions!



Backgrounds

Multi-b

All backgrounds except QCD are estimated using the data-driven R_{CS} method



- **The phase space is divided in the mainband (MB) and the sideband (SB) based on the N_{jets} and the control region (CR) and the search region (SR) based on the ΔΦ value**

- The RCS factor is determined in the SB in data and defined as the ratio N_{SR} / N_{CR}

$$R^{data}_{CS} = \frac{N^{bkg}_{SB}(SR)}{N^{bkg}_{SB}(CR) - N^{QCD\ pred}_{SB}(CR)}$$

- The predicted bkg yield in the Signal Region is $N^{pred}_{MB}(SR) = R^{data}_{CS} \cdot \kappa_{EW} \cdot \left[N^{data}_{MB}(CR) - N^{QCD\ pred}_{MB}(CR)\right]$

- k is used to correct potential differences in R_{CS} between SB and MB determined in MC, using only the electroweak (EW) backgrounds

$$\kappa_{EW} = \frac{R^{MC}_{CS}(MB, EW)}{R^{MC}_{CS}(SB, EW)}$$

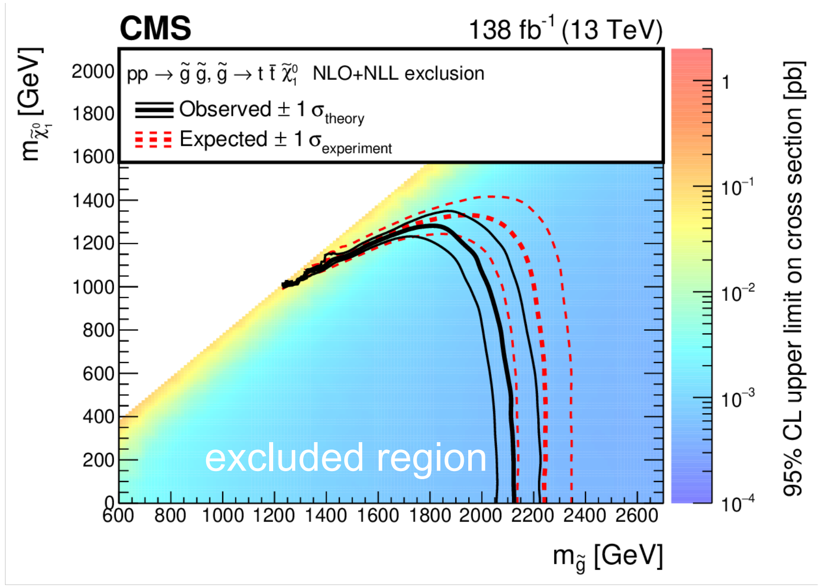
- QCD is calculated with a different data driven prediction method

Zero-b

- Two separate R_{CS} factors are used: one for TTbar and another for W+Jets

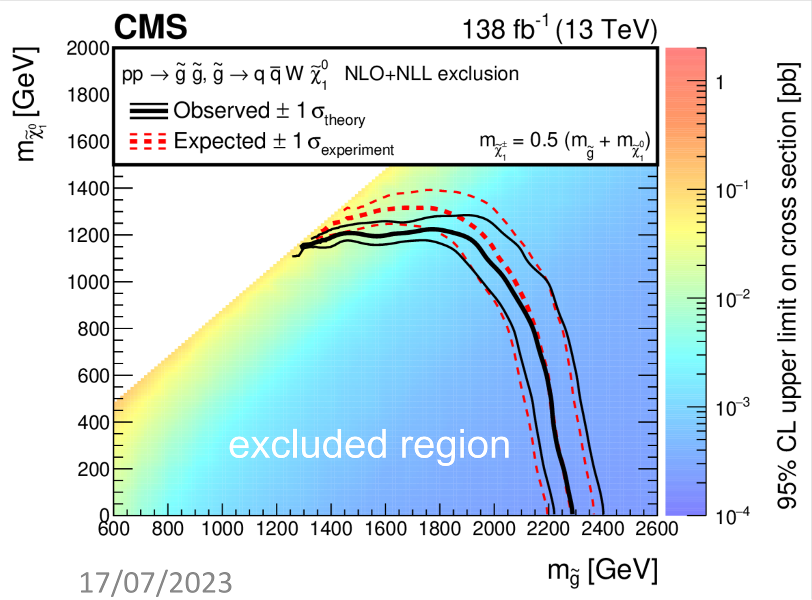
Limits

Limits set using maximum likelihood fit to analysis regions (HT, LT, njet, nb-tag (multi-b), ntop-tag (multi-b), nW-tag (0b))



Limits – Multi-b (T1tttt)

- $m_{\tilde{g}}$< 2130 GeV and
- m_{LSP} < 1270 GeV are excluded



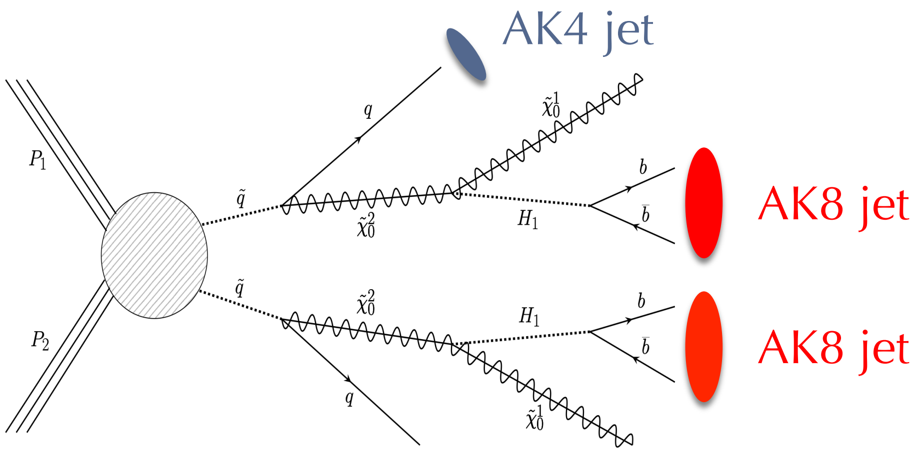
Limits – Zero-b (T5qqqqWW)

- $m_{\tilde{g}}$< 2280 GeV excluded
- m_{LSP} < 1200 GeV excluded

2. NMSSM (HIG-20-018)

NMSSM Signal & Event Selection

- **Search for two light boosted Higgs bosons in all-hadronic events:** $H_1 \rightarrow b\bar{b}$



- **Negligible MET**
  1° time for CMS or ATLAS probing **2 light Higgses and NO MET** analysis
- In the **NMSSM** there are 7 higgses and the lightest higgs can be lighter than the SM higgs!
- **LSP is light** (Singlino-like) and phase space for NLSP decay is small
- **H_1 inherits most of the momentum from the NLSP, so it's highly boosted** (AK8 jets)

Event Selection:

- Two **AK8 jets** (FatJets)
  - pT>300GeV
  - $|\eta|<2.4$
- At least one AK4 jet
  - pT>300GeV
  - $|\eta|<3.0$
  - $\Delta R>1.4$ from selected **AK8jets** to ensure no overlap

- Signal selection based on properties of AK8 jets (Mass reco with softdrop & double-btag-discriminant)
- Use HT bins

Backgrounds

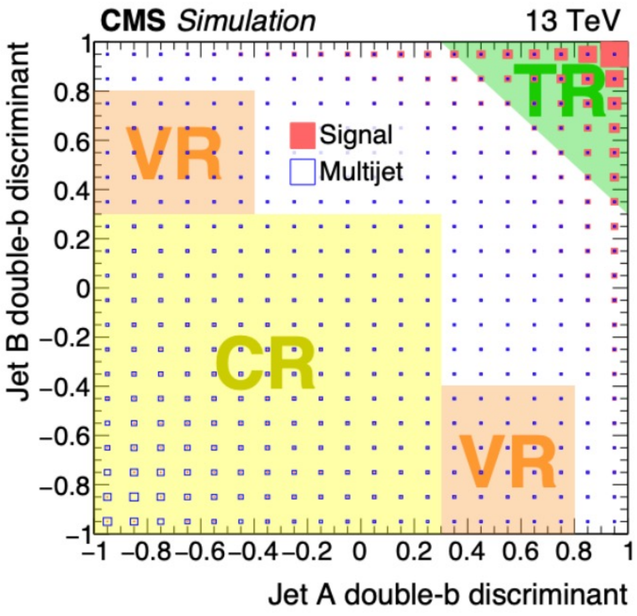
- **Data-driven background estimation method used for QCD (dominant bckg)**
- other backgrounds from MC simulation

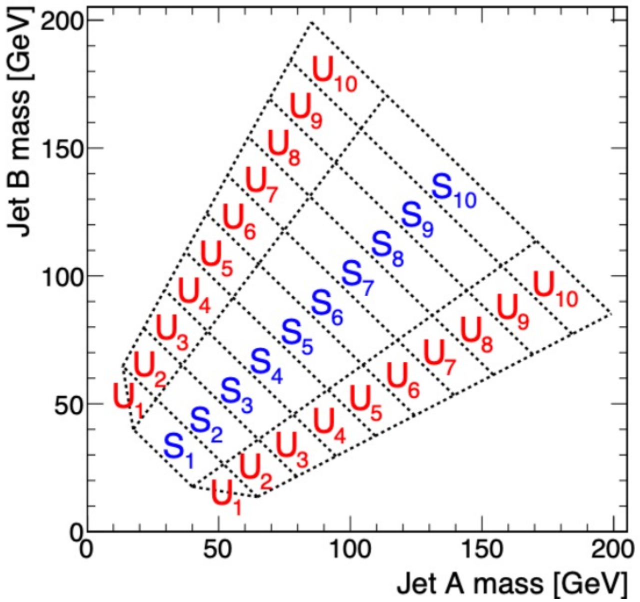
$$\hat{S}_i^{\mathrm{TR}} = \boxed{\frac{\hat{S}_i^{\mathrm{CR}}}{\hat{U}_i^{\mathrm{CR}}}} \hat{U}_i^{\mathrm{TR}}$$

Background-subtracted mass sideband yield in the TR

- For the double-b tag discriminant we define a CR and a Tag Region (TR) and for the mass we define main-bands(S_i) and a side-bands(U_i)

- mass sidebands CRs (U_i) designed to have similar yield as the corresponding SRs (S_i)



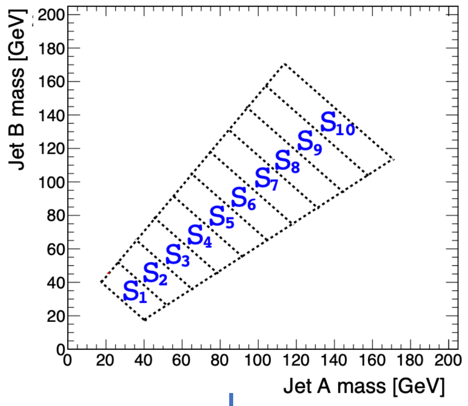


Mass and b-tag discriminant must be **uncorrelated** to apply ABCD method!

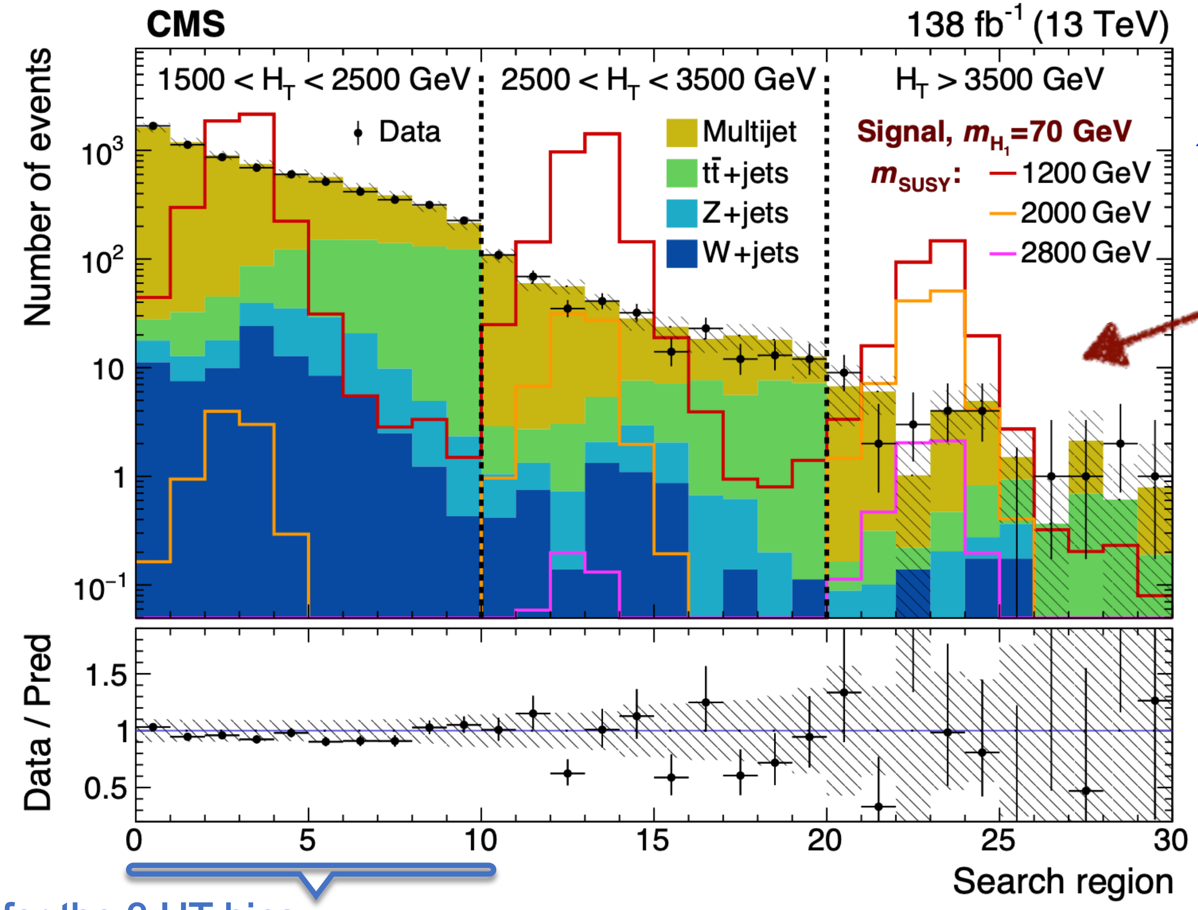
HT Bins

- 3 H_T bins and 10 S_i regions map onto a 30-bin distribution

Backgrounds in solid colours & Signals in coloured lines



Mass SRs repeats 3 times for the 3 HT bins



m_{H1} is fixed at 70 GeV and m_{SUSY} is varying

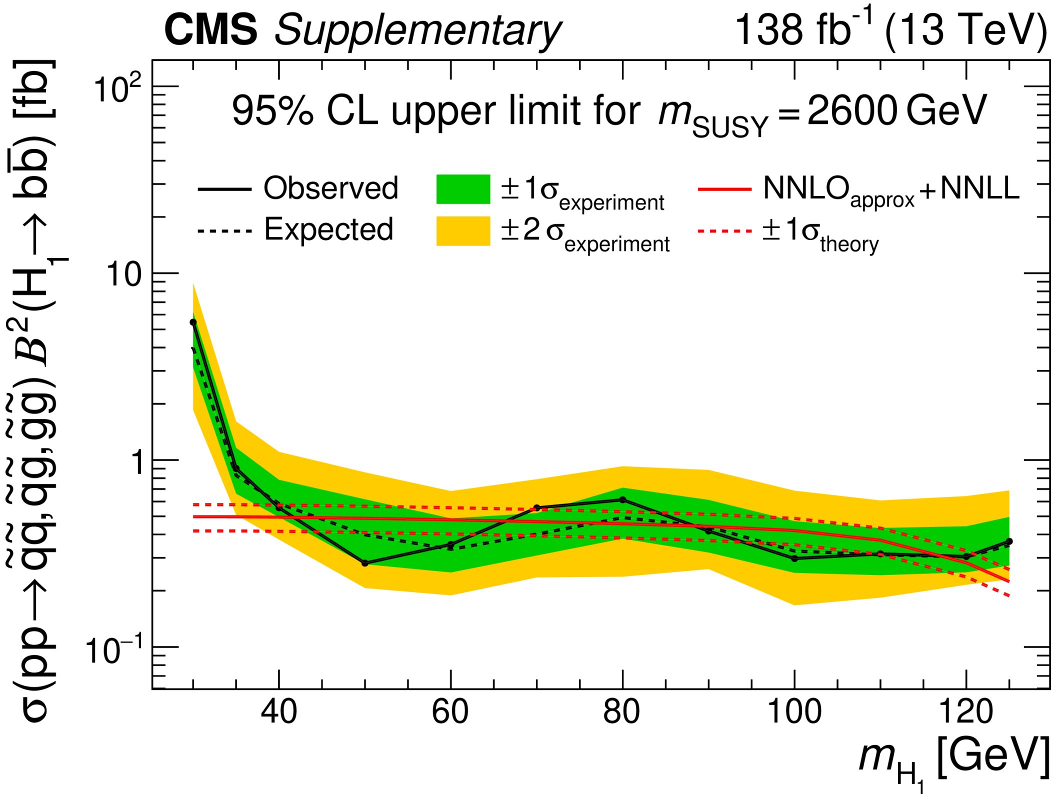
There is greater signal yields at large H_T for large m_{SUSY}

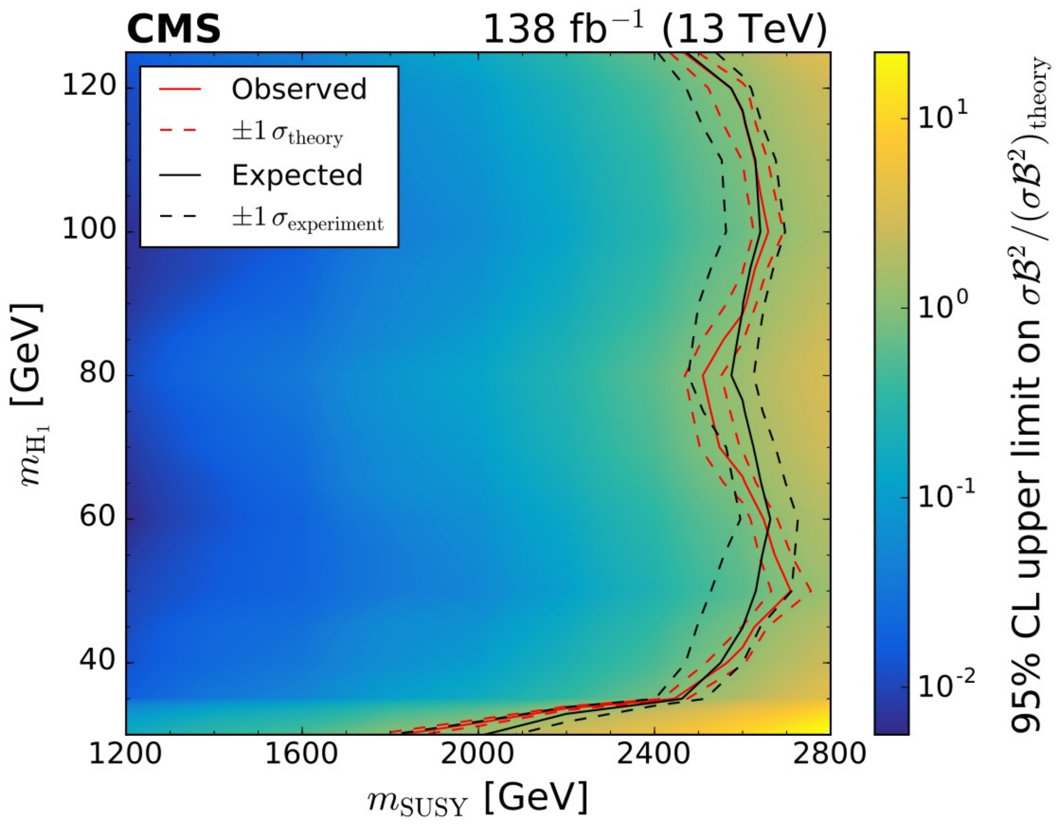
No statistically significant excess observed

Limits

95% CL upper limits on σ × Br^2 are set **as a function of m_{H1} for fixed m_{SUSY}**

- Mass exclusion contours calculated using theoretical xsecs and $H_1 \to bb$ Brs
- H_1 bosons with masses in the range 40-120 GeV arising from the decays of Squarks or Gluinos with a mass of 1200-2500 GeV are excluded at 95% confidence level



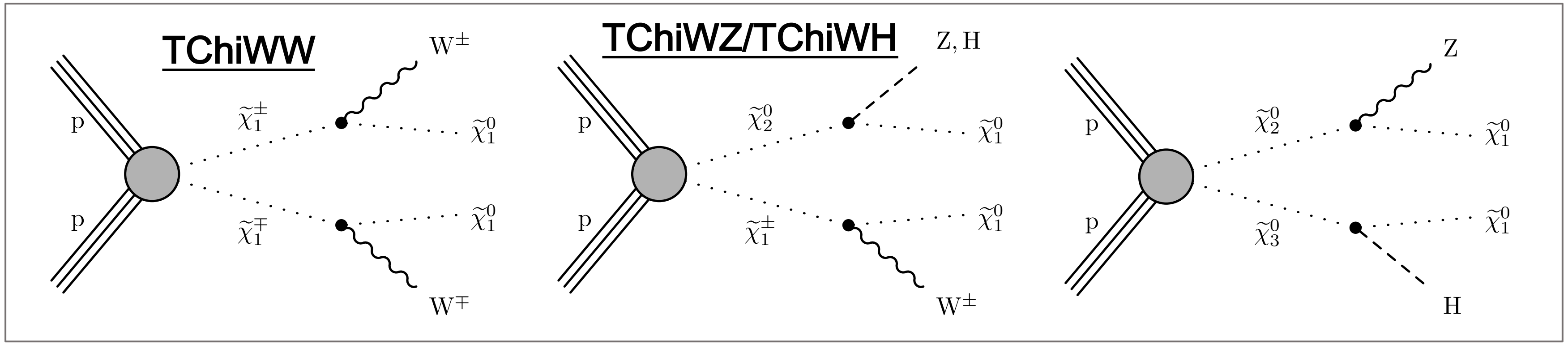


3. WX Search (SUS-21-002)

WX Signal Model

- 3 Simplified models : TChiWW, TChiWZ, TChiWH
- Wino-Like and Higgsino-Like interpretation

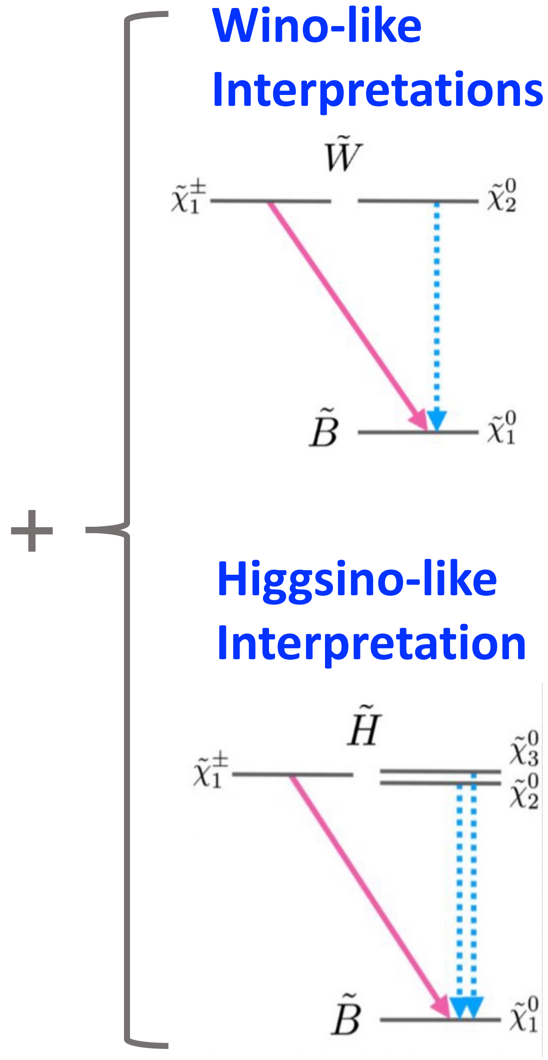
- State of interest: MET from LSP, 0 leptons (fully hadronic), 2 AK8Jets
- Larger NLSP-LSP mass difference ⇒ high p_T LSP ⇒ high p_T^{miss} (MET)
- Larger m_{NLSP} ⇒ high p_T H/W/Z ⇒ taggable boosted AK8 jets



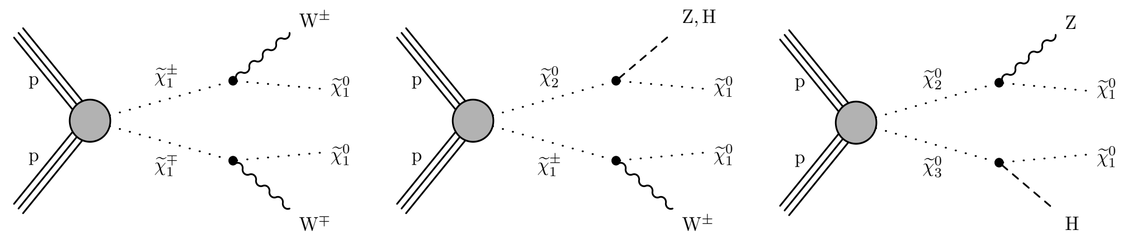
TChiWW: 0 b-tags

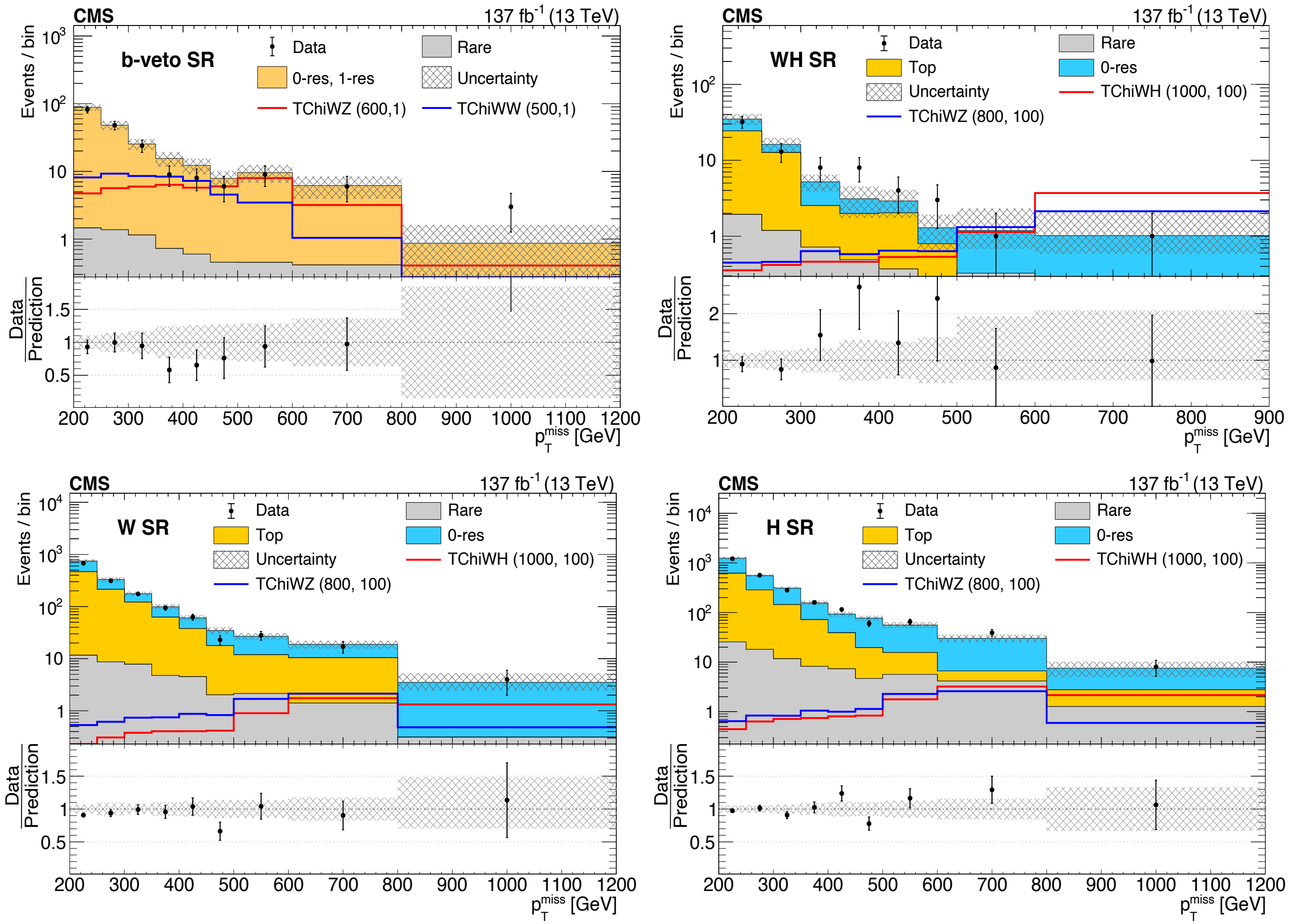
TChiWZ: 0 b-tags when Z → qq
⩾1 b-tags when Z→ bb

TChiWH: ⩾1 b-tags from H→ bb



Event Selection & Signal Regions





- There is a common baseline event selection for every benchmark and there are common signal regions for different models (table)
- Desired phase space requires : Hight p_T^{miss} and H_T
- Lepton vetos rejet major leptonic W decay backgrounds
- DeepAK8 and DeepCSV tagger cuts on AK8 and AK4 jets

Signal Regions	Requirements
b-veto SR (TChiWW & TChiWZ)	$\geq$ 1 V-tagged jet & $\geq$ 1 W-tagged jet & $\geq$ 2 V- or W-tagged jets
b-tag WH SR (TChiWH & TChiWZ)	$\geq$ 1 W-tagged jet & $\geq$ 1 bb-tagged jet
b-tag W SR (TChiWH & TChiWZ)	$\geq$ 1 W-tagged jet & 0 bb-tagged jet
b-tag H SR (TChiWH & TChiWZ)	0 W-tagged jet & $\geq$ 1 bb-tagged jet

Backgrounds

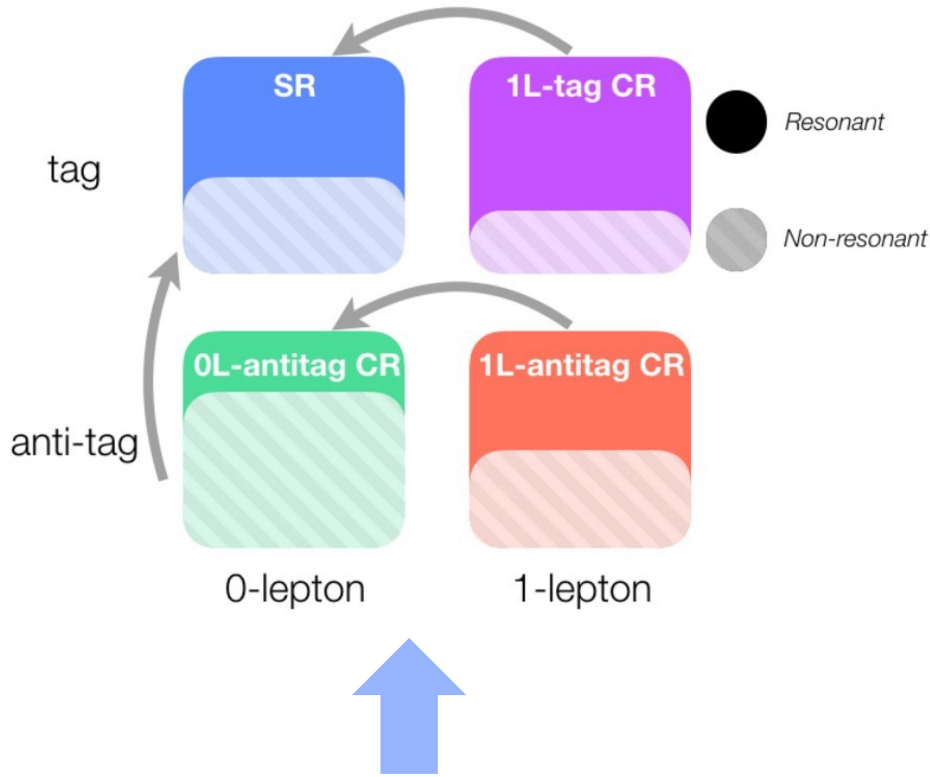
In the b-veto SRs

- **0-resonant bkg** (no W/Z → qq): W(lν)+jets, Z(νν)+jets, QCD [77%]
- **1-resonant bkg** (1 W/Z → qq): ttbar, single top, diboson [20%]

➢ Predictions of 0- and 1-resonant backgrounds are based on two CRs
they are estimated on Montecarlos and normalized to the CRs

$$N_{\mathrm{SR}}^{\mathrm{data}} = \frac{N_{\mathrm{SR,0\&1\text{-}res}}^{\mathrm{MC}}}{N_{\mathrm{CR,0\&1\text{-}res}}^{\mathrm{MC}}}\left(N_{\mathrm{CR}}^{\mathrm{data}} - N_{\mathrm{CR,2\text{-}res}}^{\mathrm{MC}}\right) + N_{\mathrm{SR,2\text{-}res}}^{\mathrm{MC}}$$

- **2-resonant bkg** (2 W/Z → qq): triboson, ttX (X=W,Z,H) [3%] ⟶ taken from MC



In the b-tag SRs

- Top resonant backgrounds: (tt, single t & ttH) are estimated from 1 lepton regions CR (horizontal solid extrapolation)
- Non resonant backgrounds (W→ lν, Z → νν & QCD) are estimated by inverting the tagging requirements-antitag CR (vertical striped extrapolation)
- Other rare backgrounds are taken from MC

Limits

The search is sensitive to a large class of electroweakino models (TChiWW, TChiWZ and TChiWH)

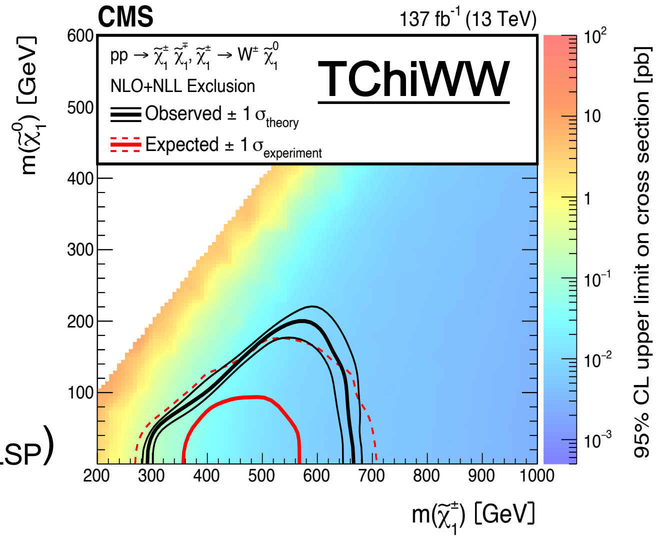
Most stringent limits placed on phase space by CMS

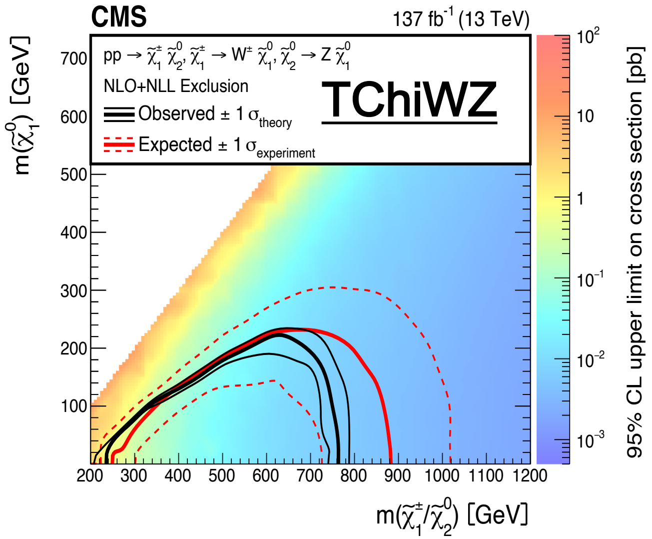
Realistic Wino Interpretations:

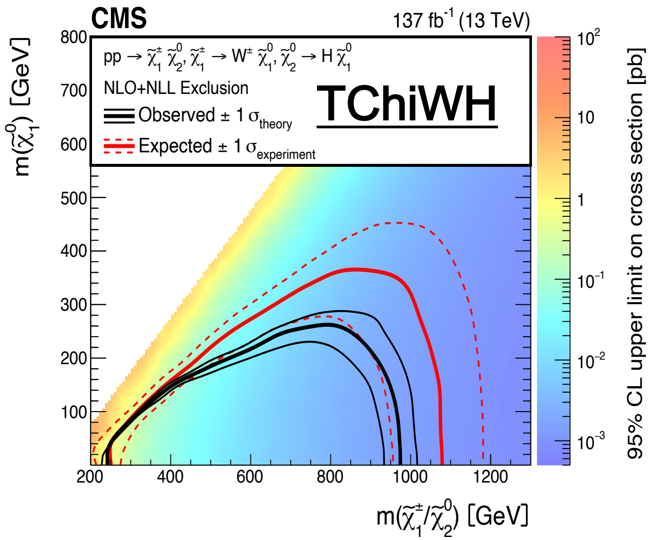
- Assume Br($\tilde{\chi}_2^0 \rightarrow Z\tilde{\chi}_1^0$)=100% or Br($\tilde{\chi}_2^0 \rightarrow H\tilde{\chi}_1^0$)=100%
- Pushes exclusion up to 870 and 960 GeV respectively (m_{NLSP})

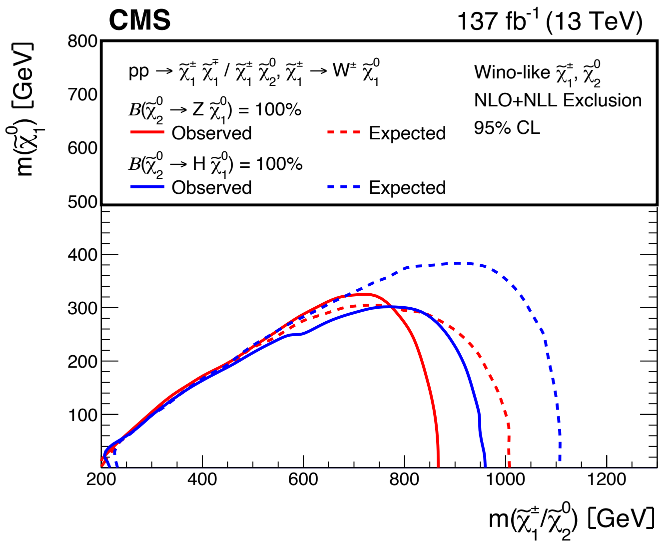
Higgsino-like Interpretation

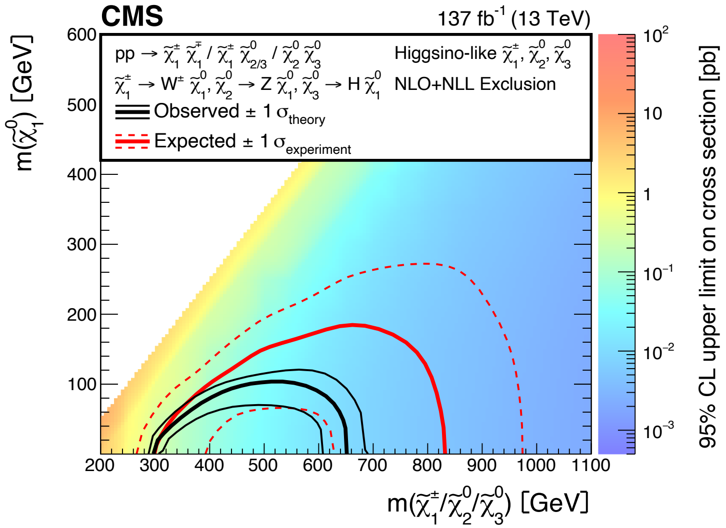
- First significant phase space exclusion of higgsino-bino MSSM scenario for CMS → exclusion of 300-650 GeV (m_{NLSP})





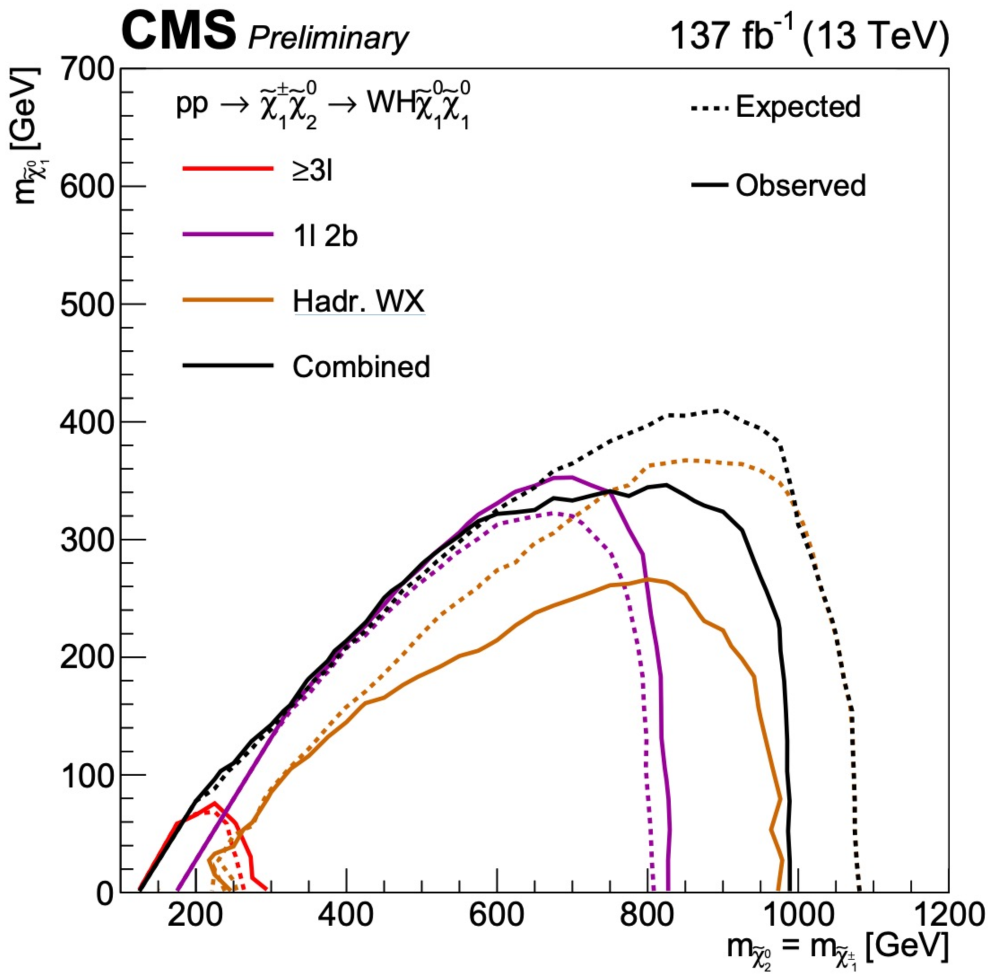






Limits

- SUS-21-008 is a Combination of Analysis with also WX analysis included
- It shows that WX analysis with heavy object tagging really boosts the sensitivity to large deltaM (M_{NLSP}-M_{LSP}) cases
- WX is complementary to other analysis
- The Combination is useful because it merges together complementary analysis improving the observed exclusion limit!



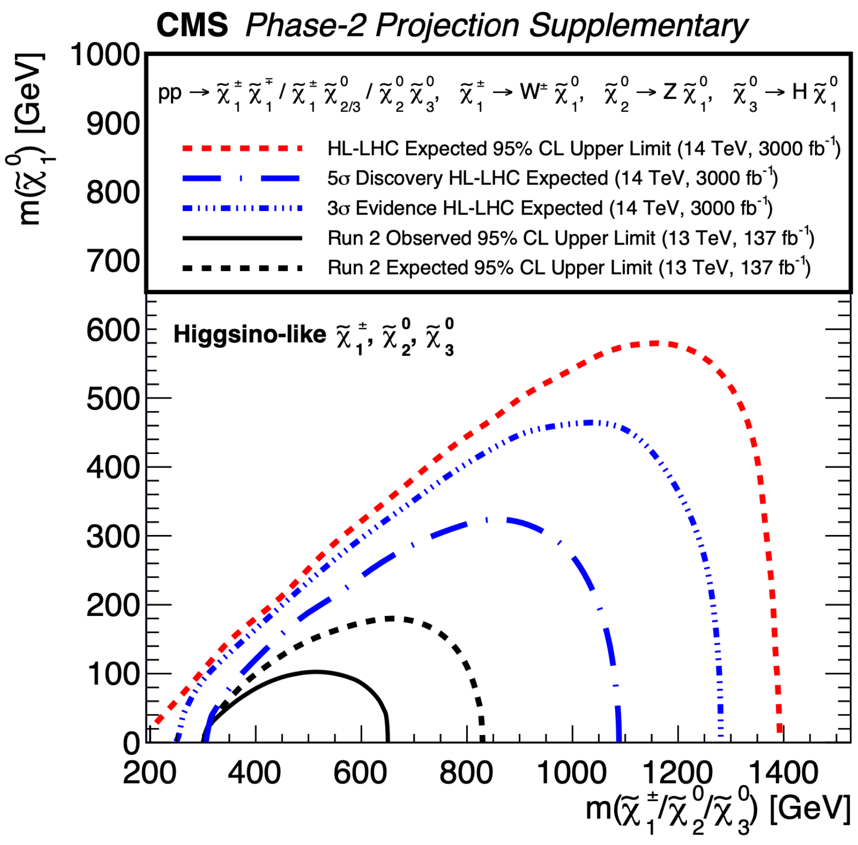
Conclusion

A wide variety of SUSY searches have been performed by CMS with heavy object tagging. This talk mainly presented 3 recent searches from CMS:

1. The new 1 lep Δφ analysis extends both the gluino mass up to 2280 GeV and the LSP mass up to 1220 GeV
2. NMSSM two light Higgses (no MET) puts the 1st limits on this signature at the LHC
3. WX+ p_T^{miss} analysis is sensitive to wide range of pair production of electroweakino models and excludes a significant range of higgsino masses as well

- No signs of BSM physics yet but significant range of phase-space is excluded.
- In the future Run3 analyses, the use of new neural network taggers and ML based analysis techniques would yield much exciting results

- Hadronic analyses **show promise to push discovery reach further in HL-LHC era**



Higgsino-like WX Search reach projected to HL-LHC (ATL-PHYS-PUB-2022-018)

Thank you for your attention!

Backup

Backgrounds

- **Data-driven background estimation method used for QCD (dominant bckg)**
- other backgrounds from MC simulation

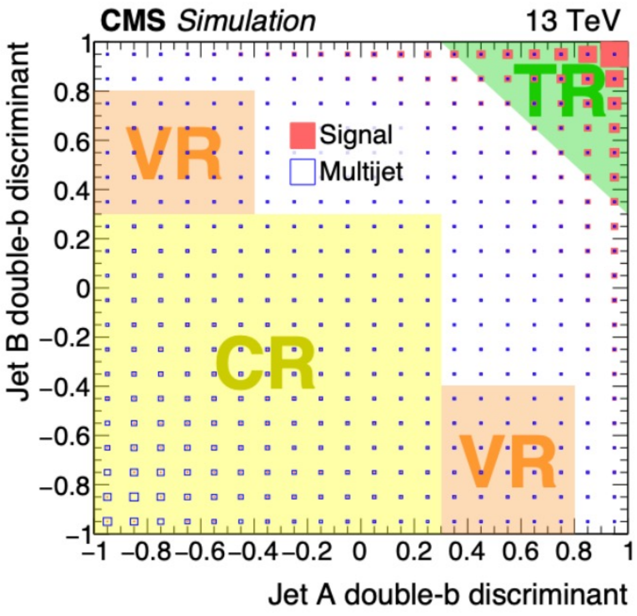
$$\hat{S}_i^{\mathrm{TR}} = \frac{\hat{S}_i^{\mathrm{CR}}}{\hat{U}_i^{\mathrm{CR}}} \hat{U}_i^{\mathrm{TR}}$$

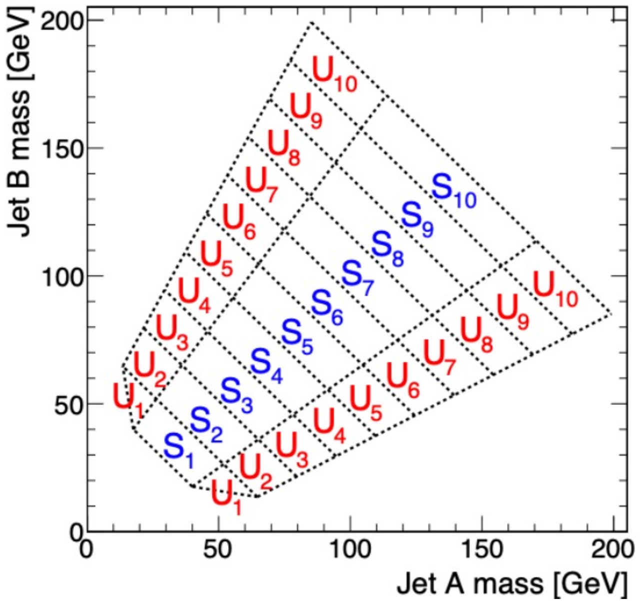
Background-subtracted mass sideband yield in the TR

- For the double-b tag discriminant we define a CR and a Tag Region (TR) and for the mass we define main-bands(S_i) and a side-bands(U_i)

- mass sidebands CRs (U_i) designed to have similar yield as the corresponding SRs (S_i)

AK8 JetA and AK8 JetB are randomly allocated so that the distribution is symmetric

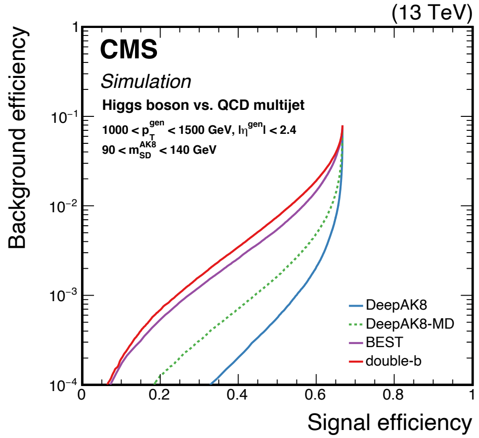


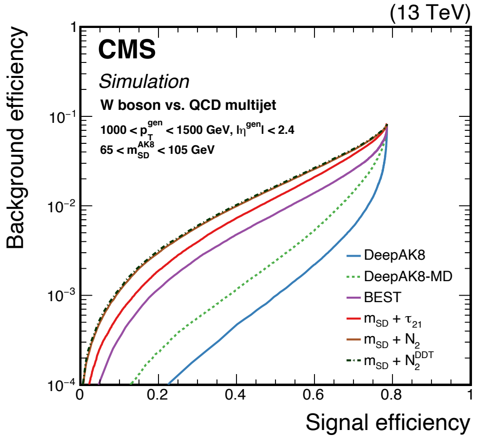


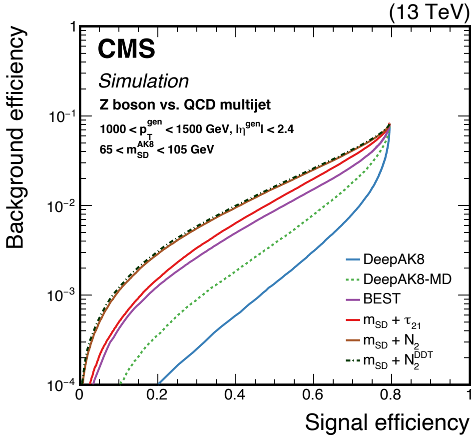
Mass and b-tag discriminant must be **uncorrelated** to apply ABCD method!

Heavy flavour Tagging

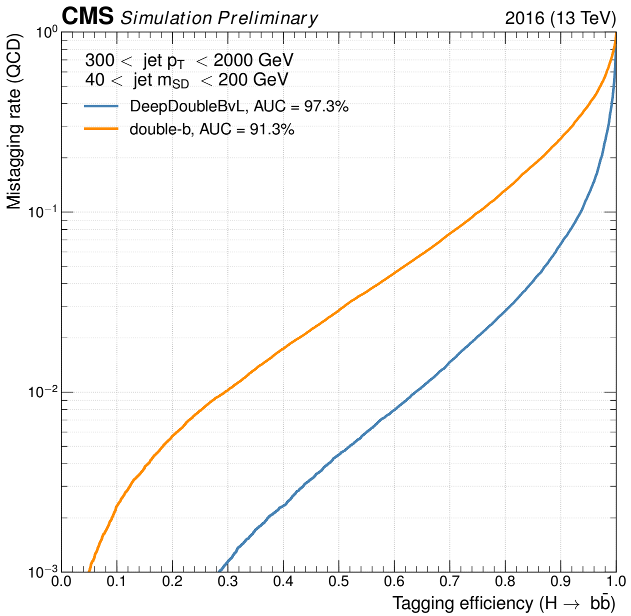
- **DeepAK8** (+MassDecorrelation)–H/W/Z-tagging
  - Use of jet substructure and flavour signatures - NEW
  - Inputs: up to 100 PF candidates + up to 5 SVs
  - PFs and SVs processed in separate 1D CNNs, then combined in fully connected layer
  - Adversarial training used to decorrelate mass



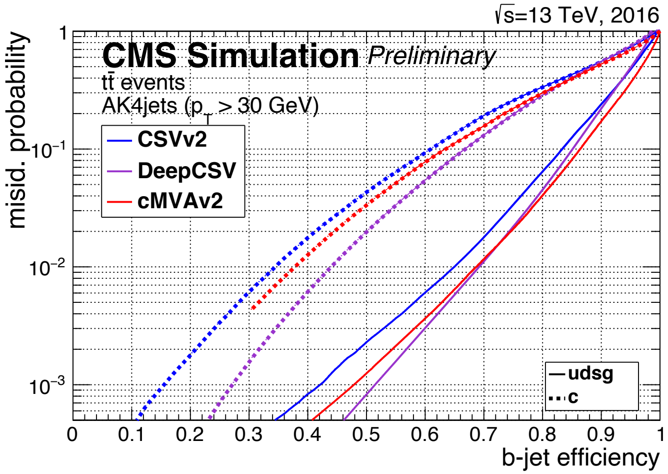




- **DeepDoubleB** (DDBvL)–H-tagging
  - PF and vertex inputs handled separately, then fed through 50 dense layers with track inputs



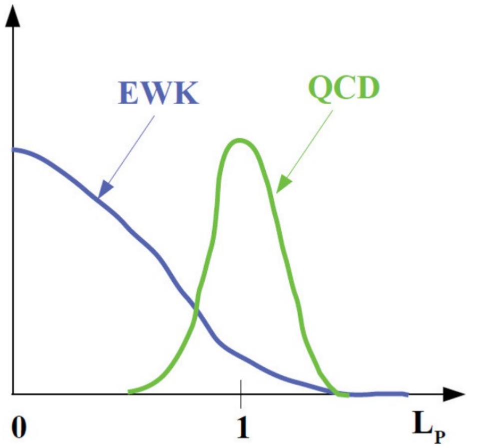
- **DeepCSV** Algorithm–b-tagging
  - 6-layer, 100-node DNN
  - Extension of CSVv2 tagger
  - Additional charged particle tracks - NEW



Backgrounds

- QCD needs to be subtracted (a jet can be misidentified as a prompt lepton)
- We use L_P to separate QCD from other bckg because it reflets lepton polarization in W decays: QCD peaks at 1, EWK falls from 0 to 1

$$L_P = \frac{p_T^l}{p_T^W}\cos(\Delta\phi)$$



Multi-b 0b

Background Estimation of QCD

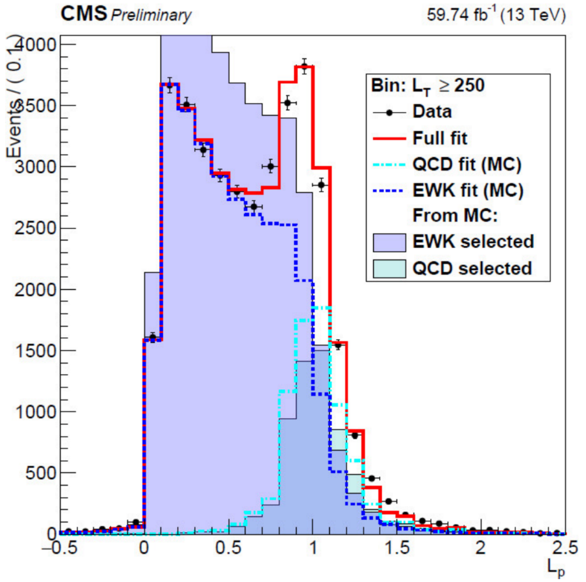
- Estimate QCD by inverting the lepton selection and determining selected to anti-selected ratio in QCD enriched region

$$F_{\text{sel-to-anti}} = \frac{N^{\text{fit}}_{\text{QCD selected}}}{N^{\text{data}}_{\text{QCD anti-selected}}}$$

- To estimate the number of selected QCD events, data is scaled in the anti-selected region (QCD enriched) by the $F_{\text{sel-to-anti}}$ ratio

- For the $F_{\text{sel-to-anti}}$ ratio extraction:
  - Fit on the L_P shape performed in data in n_{jet}=[3,4] $n_{b\text{-}tag}$ = 0 sideband
  - EWK/QCD templates from "selected" MC
  - Determined separately for the different L_T bins used in the analysis

2018



Event Selection 1-Lep ΔΦ Analysis

- Exactly 1 lepton (e or μ)
- HT = ∑pT jets > 500 GeV
- LT = |pT(lep)| + |MET| > 250 GeV
- Sub-leading jet pT > 80 GeV
- njet ≥ 3

For multi-b: nb-tag ≥ 1 and ntop-tag ≥ 1
For 0-b: nb-tag = 0

Analysis regions binned in HT, LT, njet, nb-tag (multi-b), ntop-tag (multi-b), nW-tag (0b).

- Additional MET filters are applied
- Isolated track veto: reduces tt(2lep) background with one missing lepton

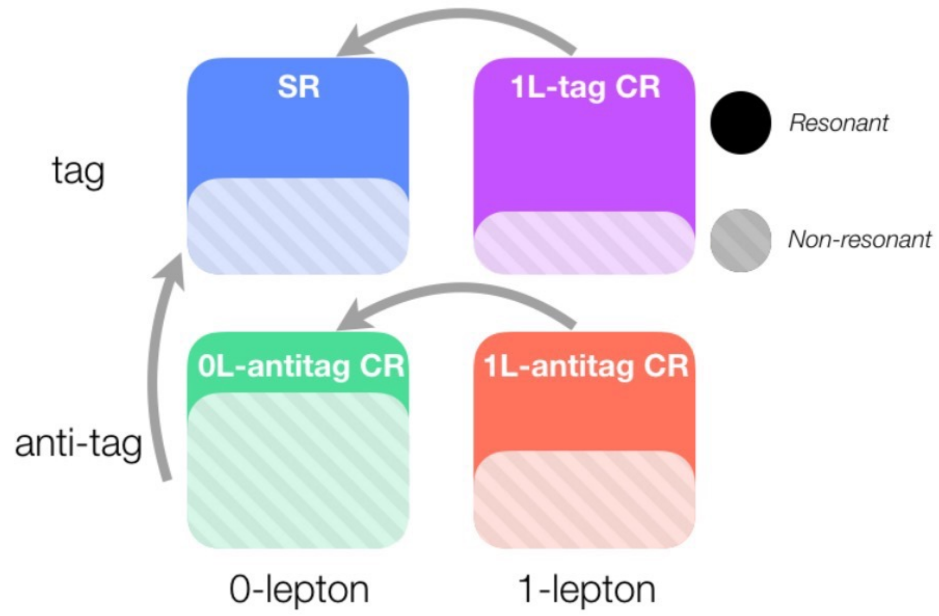
- Electrons: pT > 25 GeV |η| < 2.4 Cut-based ID, tight WP miniIso < 0.1
- Muons: pT > 25 GeV |η| < 2.4 Cut-based ID, medium WP miniIso < 0.2
- Jets: AK4 with |η| < 2.4 Latest JEC applied b-tagging: DeepCSV, medium WP

WX Backgrounds

Data-driven bckg estimation split into:

- ❑ 2 categories for b-veto SR prediction
  - ➢ Resonant Hadronic W bckg
    - o Ttbar, singlet t, ttbarH contain real signal like W peak
    - o Derived in 1l data CR due to missed-l W decays in SR
  - ➢ Non resonant bckg
    - o W➡lv, Z➡vv, and QCD-bckg from fake W-tagged objects
    - o Derived in anti-tag data CR, using known fake W-tag rate

- ❑ 2 categories for b-tag SR prediction
  - ➢ Fake Hadronic W background (0+1resonance) estimated from 0-tag and 1-tag CR
  - ➢ 2 real Hadronic boson background from tri-boson events derived from MC



In b-tag region, resonant BG (solid) in SR estimated from 1l CR,
non-resonant BG (hashed) in SR estimated from 0l anti-tag CR

<u>b-tag SRs</u>

$$N^{\text{data}}_{0\ell,\text{res}} = (N^{\text{MC}}_{0\ell,\text{res}}/N^{\text{MC}}_{1\ell,\text{all}}) \times N^{\text{data}}_{1\ell}$$

$$N^{\text{pred}}_{\text{non-res}} = \frac{N^{\text{MC}}_{\text{tag}}}{N^{\text{MC}}_{\text{!tag}}}\left(N^{\text{data},0\ell}_{\text{!tag}} - N^{\text{pred}}_{\text{!tag,res}} - N^{\text{MC}}_{\text{!tag,rare}}\right) \times \text{SF}_{\text{pass/fail}}$$

<u>b-veto SR</u>

$$N^{\text{data}}_{SR} = \frac{N^{\text{MC}}_{SR,0\&1\text{-res}}}{N^{\text{MC}}_{CR,0\&1\text{-res}}}\left(N^{\text{data}}_{\text{CR}}/N^{\text{MC}}_{\text{CR},2\text{-res}}\right) + N^{\text{MC}}_{\text{SR},2\text{-res}}$$

Antitag (!tag) regions:
All H/W/Z candidates are not tagged

Backgrounds

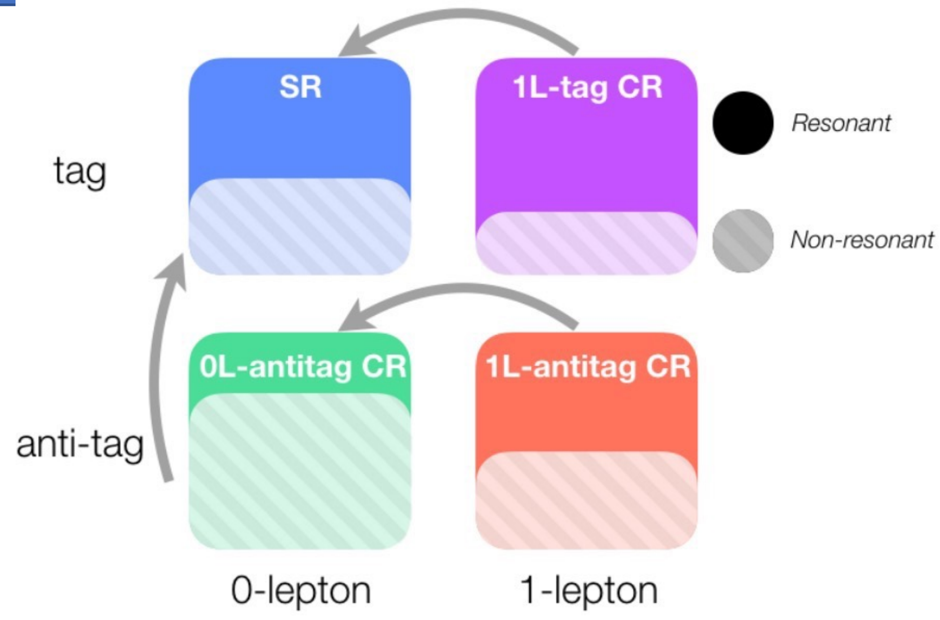
In the b-veto SRs

(~97% of the background is due to at least one mistagged AK8)

- **0-resonant bkg** (no W/Z → qq): W(lν)+jets, Z($\nu\nu$)+jets, QCD [77%]
- **1-resonant bkg** (1 W/Z → qq): ttbar, single top, diboson [20%]
- **2-resonant bkg** (2 W/Z → qq): triboson, ttX (X=W,Z,H) [3%] ⟶ taken from MC

➢ Predictions of 0- and 1-resonant backgrounds are based on two CRs they are estimated on Montecarlos and normalized to the CRs

$$N_{\mathrm{SR}}^{\mathrm{data}} = \frac{N_{\mathrm{SR,0\&1\text{-}res}}^{\mathrm{MC}}}{N_{\mathrm{CR,0\&1\text{-}res}}^{\mathrm{MC}}}\left(N_{\mathrm{CR}}^{\mathrm{data}} - N_{\mathrm{CR,2\text{-}res}}^{\mathrm{MC}}\right) + N_{\mathrm{SR,2\text{-}res}}^{\mathrm{MC}}$$



We use the CR with 1 lepton to predict resonant background in the SR, and the CR with antitag for non-resonant background

In the b-tag SRs

- Top (resonant) backgrounds: (tt, single t & ttH) are estimated from 1 lepton regions
- Non resonant backgrounds (W→ lν, Z → $\nu\nu$ & QCD) are estimated by inverting the tagging requirements
- Other rare backgrounds are taken from MC

Horizontal (solid) extrapolations:

$$N_{0\ell,res}^{\mathrm{data}} = (N_{0\ell,res}^{\mathrm{MC}} / N_{1\ell,all}^{\mathrm{MC}}) \times N_{1\ell}^{\mathrm{data}}$$

Vertical (striped) extrapolations:

$$N_{\mathrm{non-res}}^{\mathrm{pred}} = \frac{N_{\mathrm{tag}}^{\mathrm{MC}}}{N_{\mathrm{!tag}}^{\mathrm{MC}}}\left(N_{\mathrm{!tag}}^{\mathrm{data},0\ell} - N_{\mathrm{!tag,res}}^{\mathrm{pred}} - N_{\mathrm{!tag,rare}}^{\mathrm{MC}}\right)$$

Heavy object tagging evolution