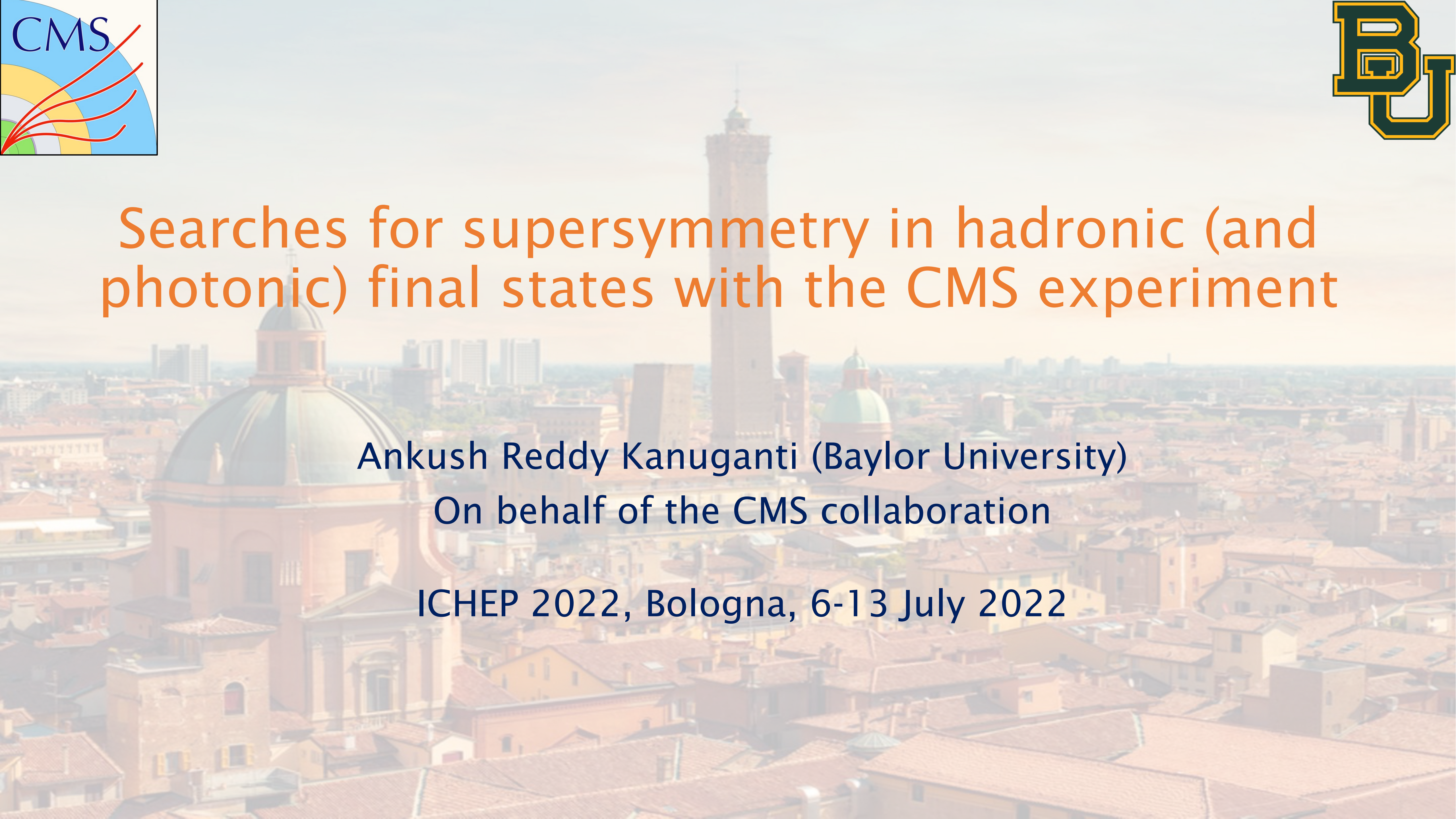


Searches for supersymmetry in hadronic (and photonic) final states with the CMS experiment

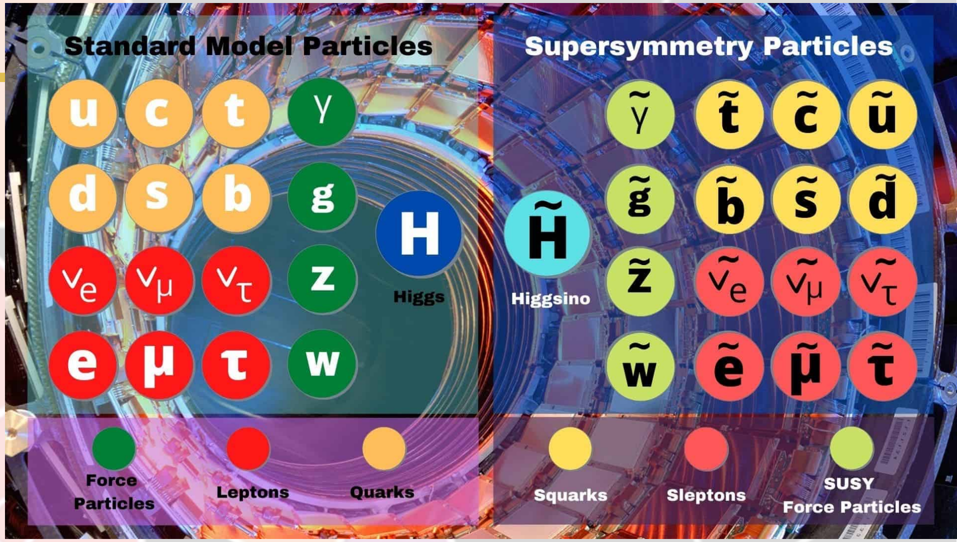
Ankush Reddy Kanuganti (Baylor University)
On behalf of the CMS collaboration

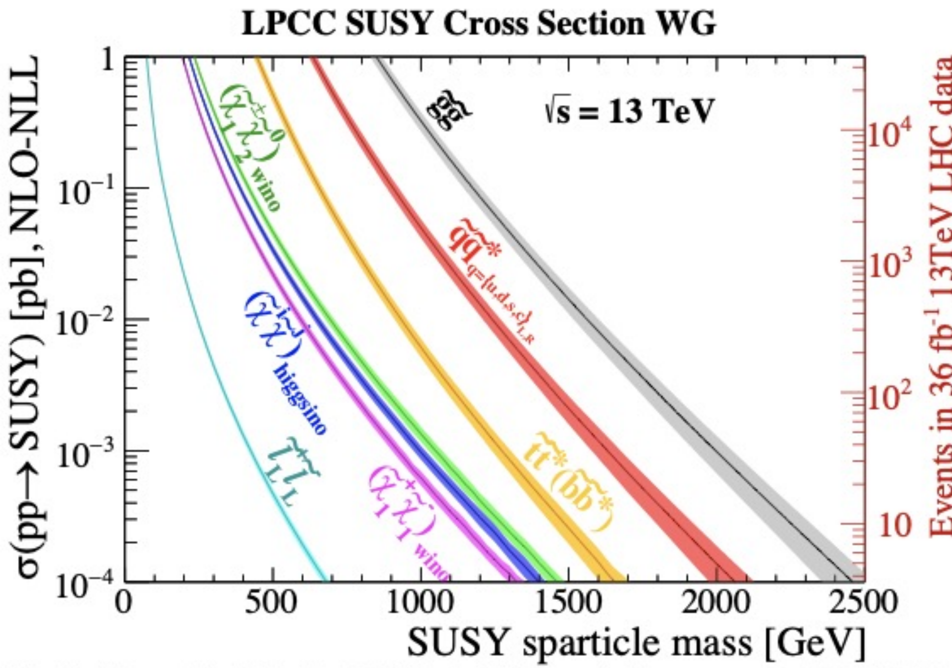
ICHEP 2022, Bologna, 6-13 July 2022

Motivation and challenges

- Supersymmetry (SUSY) proposes super partners with a spin difference of ½
- SUSY can answer many questions about the hierarchy problem and the lightest supersymmetric candidate could be DM candidate.
- R-parity conserving SUSY with p_T^{miss} searches:
  - Strong
  - Electroweak

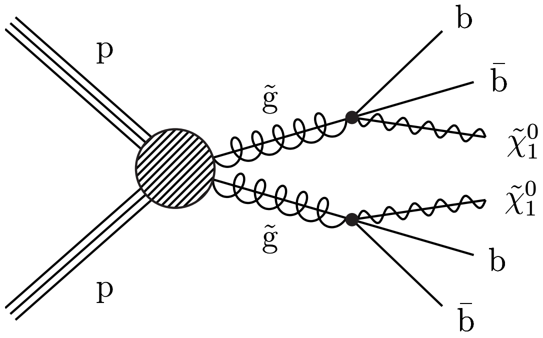
  In this talk
  - 3rd generation (squarks/sleptons) (more in Pablo's talk later)
- Searches in hadronic final states provide good sensitivities to strong SUSY particle production (gluinos, squarks)
- While the **electroweak SUSY** are critical for testing natural SUSY and extremely challenging due to their smaller cross-sections.

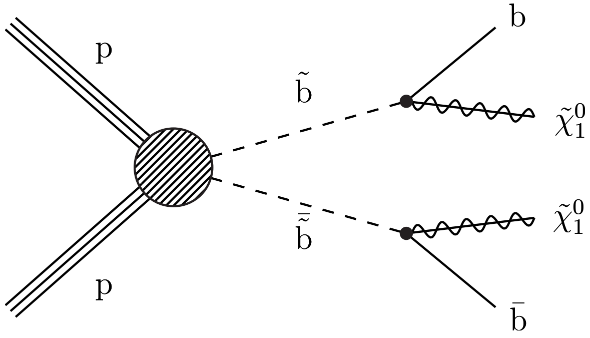


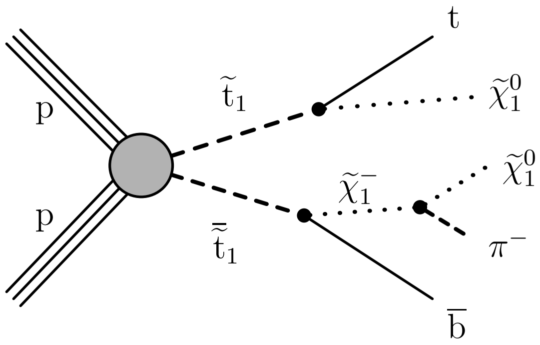


https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections arXiv:1407.5066

Strong SUSY searches

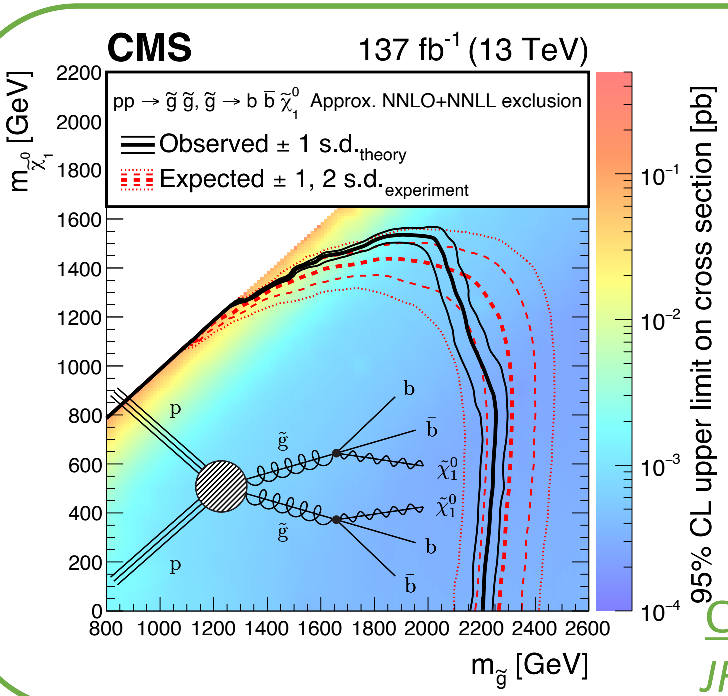


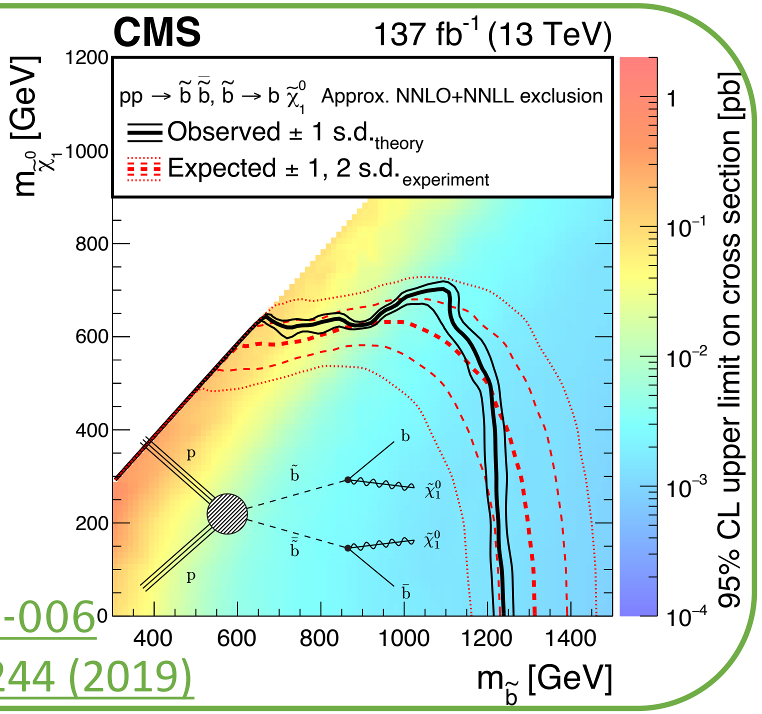




Inclusive SUSY searches in hadronic final states

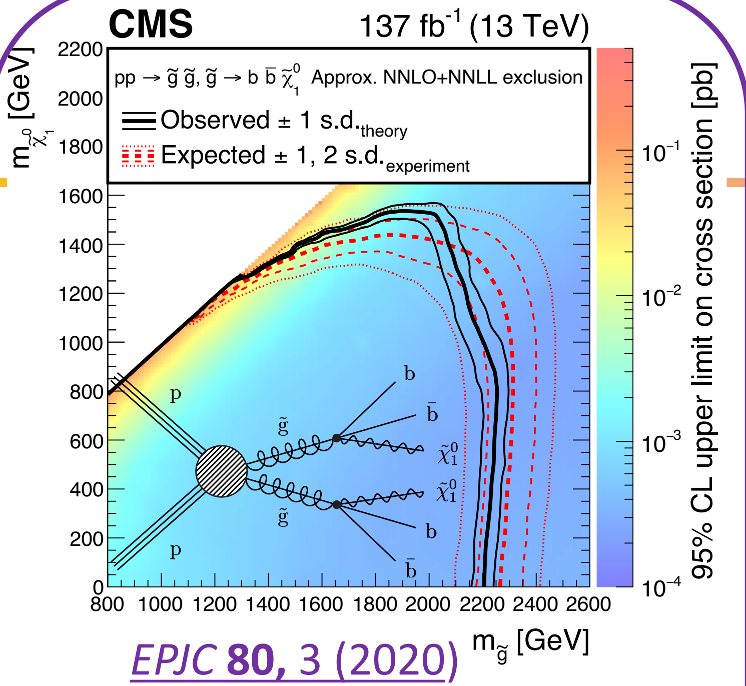
- The analysis using the M_{T2} variable established a baseline for the Run2 analyses. Gluino masses up to 2250 GeV and 1250 GeV for squark masses are excluded.
- Better reduction of background using the M_{T2} variable
- In compliment, other analysis (SUS-19-006) looks for direct production of gluinos and squarks using N_{jets}, N_{bjets}, HT and MHT.
  Gluino masses up to 2310 GeV and Sbottom up to 1230 GeV are excluded.





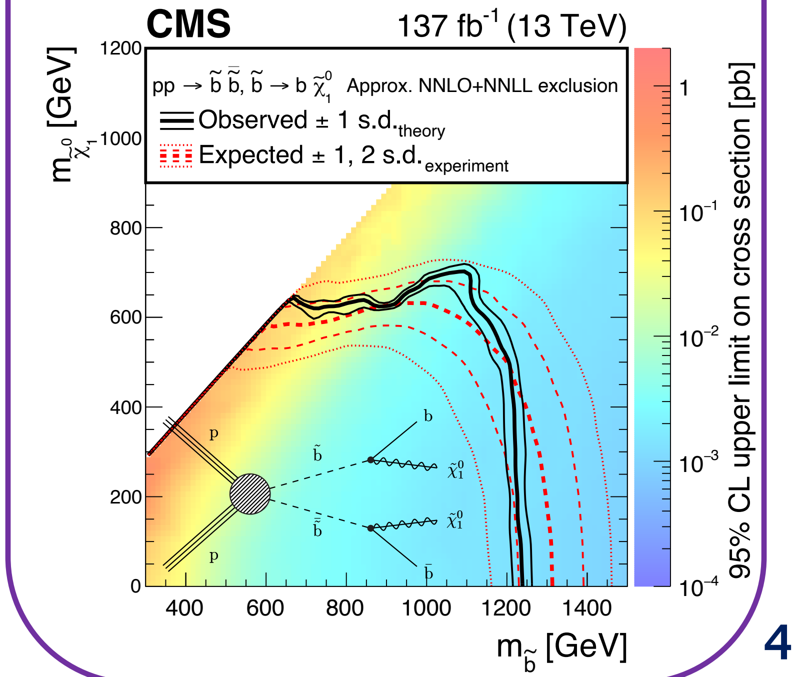
CMS-SUS-19-006

JHEP. **2019,** 244 (2019)



EPJC **80,** 3 (2020)

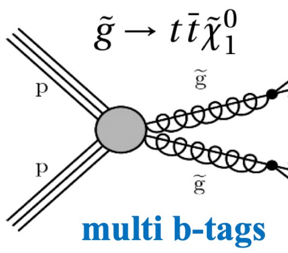
CMS-SUS-19-005



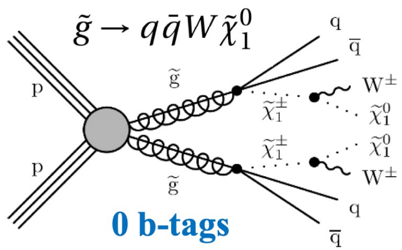
NEW

1 lep Δφ search

CMS-SUS-21-007

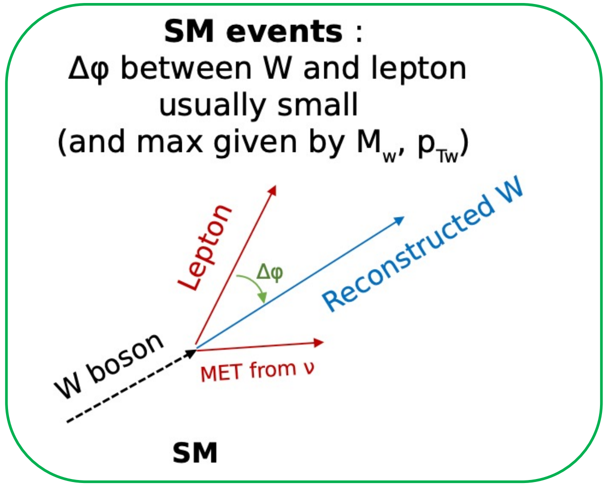


multi b-tags

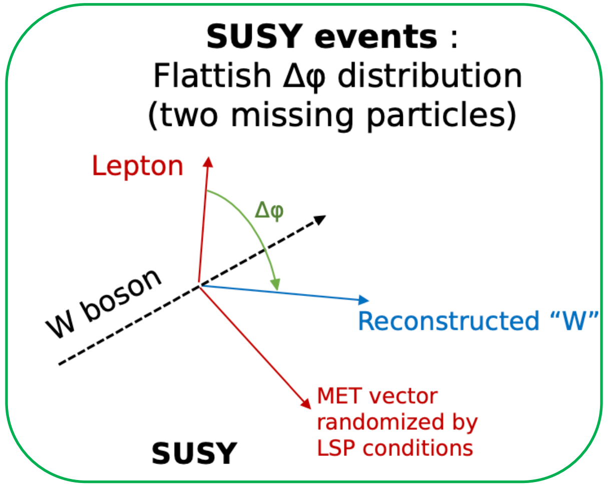


0 b-tags

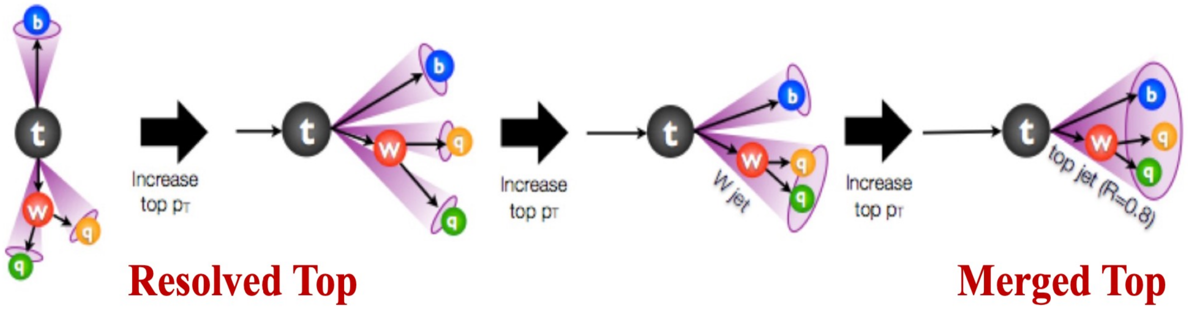
- SUSY search with 1 lepton, jets and p_T^{miss} in the final state.
- Signal regions are classified based on the **b-tag requirement**.
- Signal-rich region: Defined by large Δϕ and high nJet
- low Δm (Gluino, LSP) ⟹ Resolved top → tagged using Resolved top tagger
- high Δm (Gluino, LSP) ⟹ Merged top → tagged using DeepAK8 top tagger



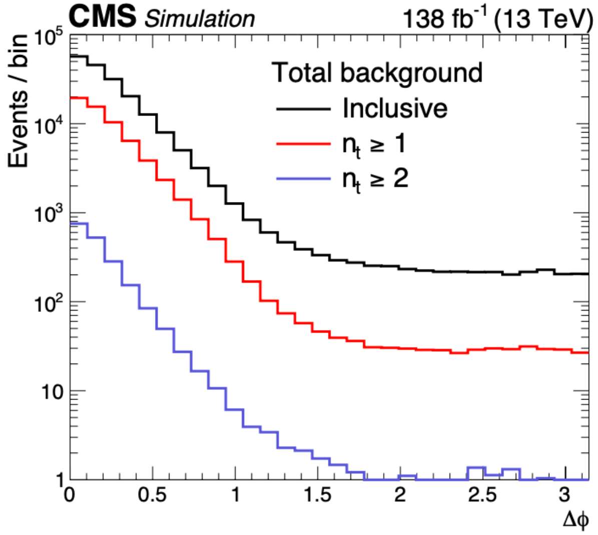
SM events :
Δφ between W and lepton usually small
(and max given by M_W, p_{TW})

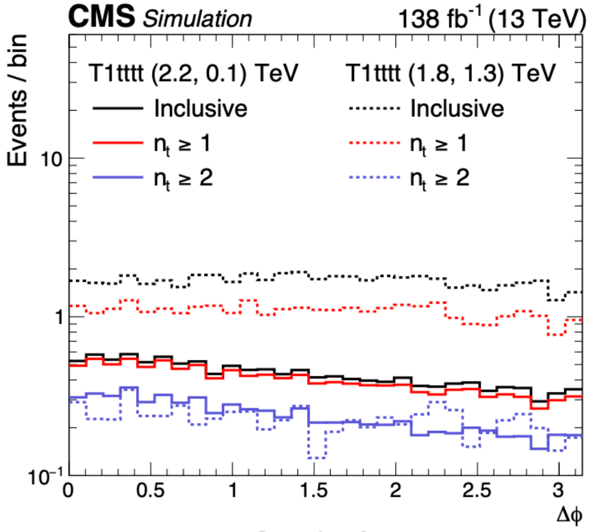


SUSY events :
Flattish Δφ distribution
(two missing particles)



- Better suppression of backgrounds while still achieving high signal sensitivity.

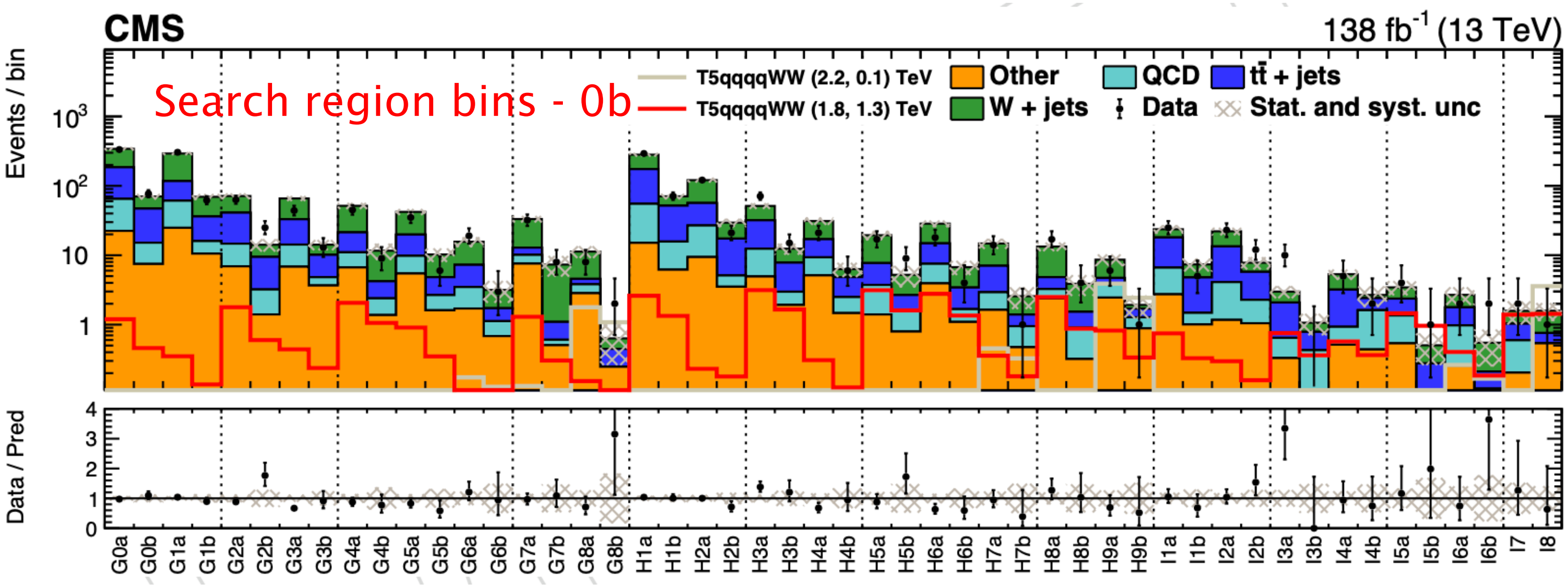




NEW

1 lep $\Delta\varphi$ search results

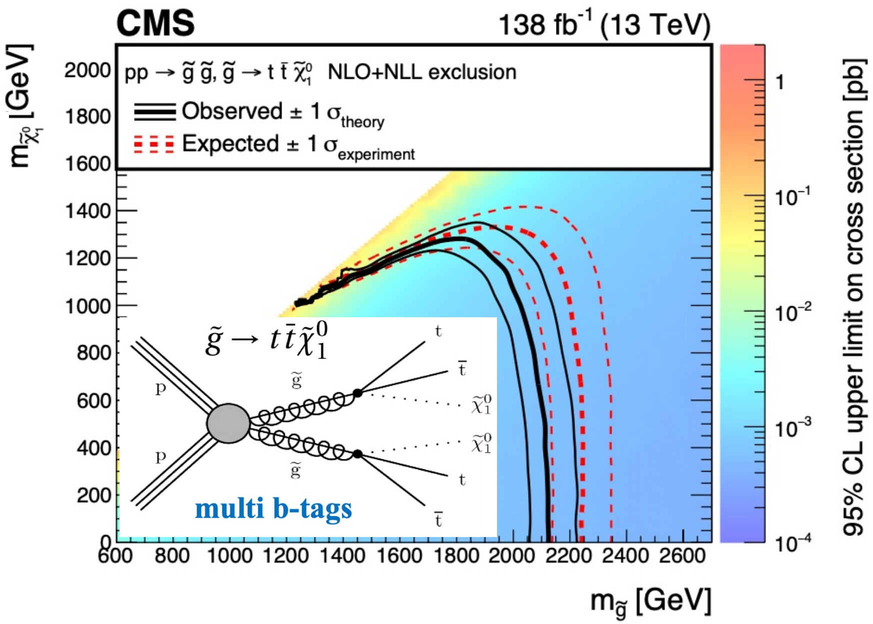
CMS-SUS-21-007

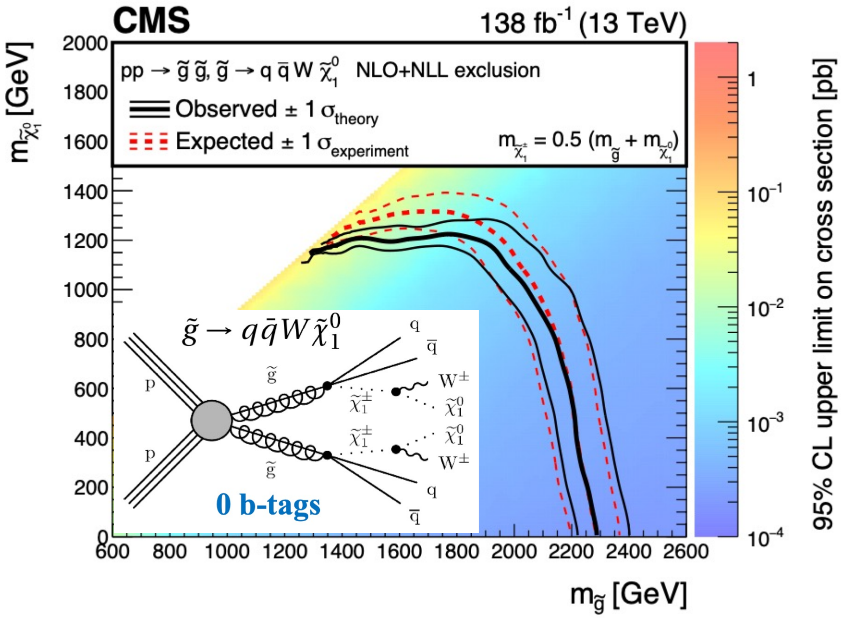


- Good agreement between the data and the prediction is observed.

- Multi-b analysis: m($\tilde{g}$) < 2120 GeV & m($\tilde{\chi}_1^0$) < 1270 GeV are excluded.
  - Improvement of about 320 (170) GeV on the gluino (neutralino) masses

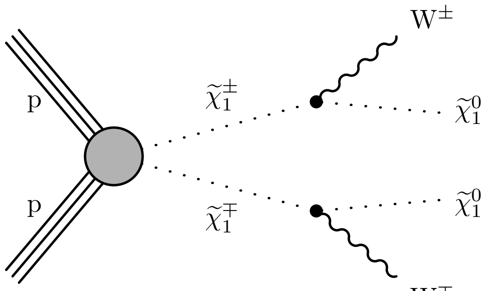
- 0b analysis: m($\tilde{g}$) < 2280 GeV & m($\tilde{\chi}_1^0$) < 1220 GeV are excluded.
  - Improvement of about 380 (270) GeV on the gluino (neutralino) masses



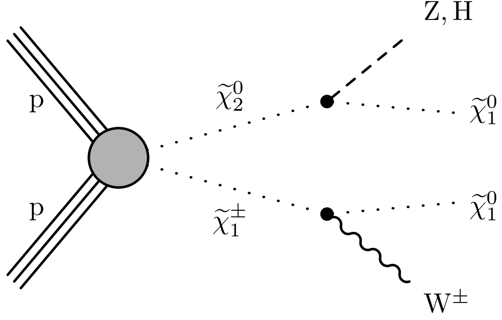


Electroweak SUSY searches

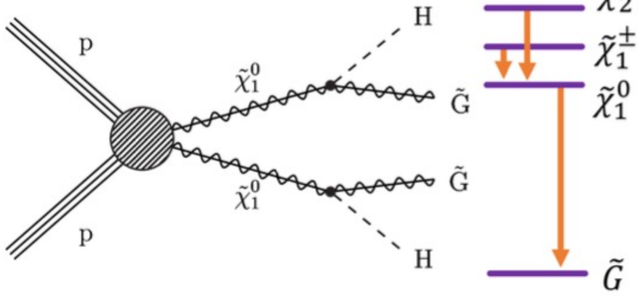
TChiWW



TChiWZ / TChiWH



TChiHH-G



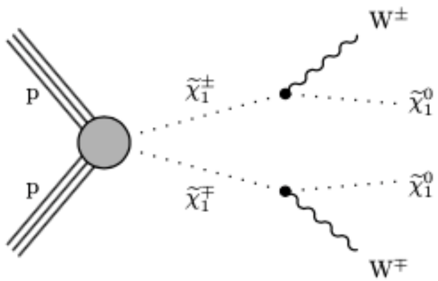
WX + p_T^{miss} search

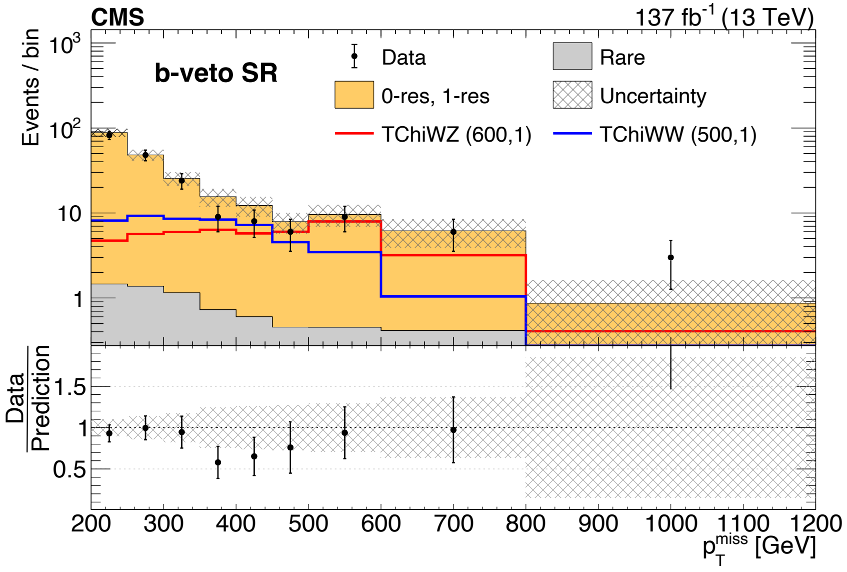
arxiv 2205.09597

CMS-SUS-21-002

- Targets electroweakino pair production in high p_T^{miss} regions.
- Baseline selections includes:
  - Lepton veto
  - High p_T^{miss} and H_T
  - Use of DeepAK8 boson taggers to tag each of the W/Z/H decays

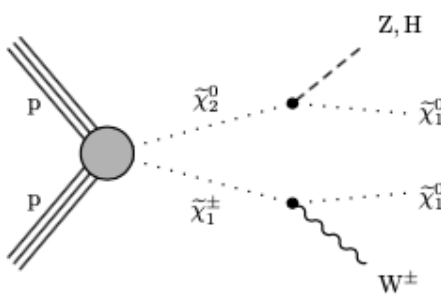
TChiWW

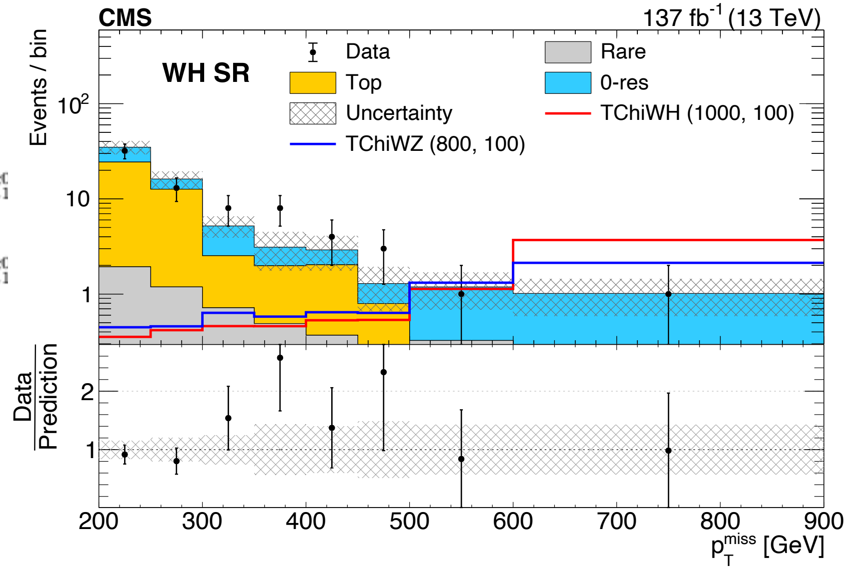




- **b-veto signal region (TChiWW + TChiWZ):**
  - ≥ 2 AK8 jets with WZ-mass (65-105 GeV), use of dedicated neural network taggers to tag W/Z bosonic decays.
- **b-tag signal region (TChiWZ + TChiWH):**
  - The signal region with highest sensitivity is WHTag SR
  - WHTag SR: ≥ 1 AK8 jets with WZ-mass (65-105 GeV),
    ≥ 1 AK8 jets with ZH-mass (75-140 GeV),
    use of Z / H neural network taggers.
- All SRs are binned in p_T^{miss}.

TChiWZ, TChiWH





WX + p_T^{miss} search strategy

arxiv 2205.09597

CMS-SUS-21-002

- For b-veto SR, predictions for the 0 and 1-resonant backgrounds are made using the transfer factor method as shown and the 2 resonant background is taken directly from simulation.

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

- For the b-tag SR, the top background is predicted using the

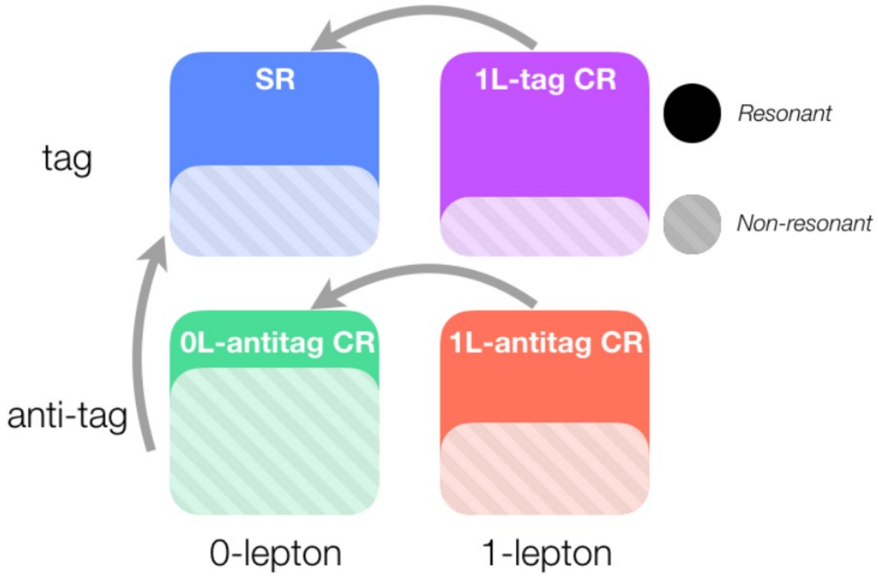
$$N^{\mathrm{data}}_{0\ell,\mathrm{res}} = \boxed{(N^{\mathrm{MC}}_{0\ell,\mathrm{res}}/N^{\mathrm{MC}}_{1\ell,all})} \times N^{\mathrm{data}}_{1\ell}$$

Transfer factor from
1-lepton control region

- The non-resonant background is predicted using anti-tag data control regions.

$$N^{\mathrm{pred},0\ell}_{\mathrm{0\text{-}res}} = \boxed{\mathcal{R}_{\mathrm{p/f}}}(N^{\mathrm{data},0\ell}_{\mathrm{!tag}} - N^{\mathrm{pred},0\ell}_{\mathrm{!tag,1\text{-}res}} - N^{\mathrm{MC},0\ell}_{\mathrm{!tag,rare}})$$

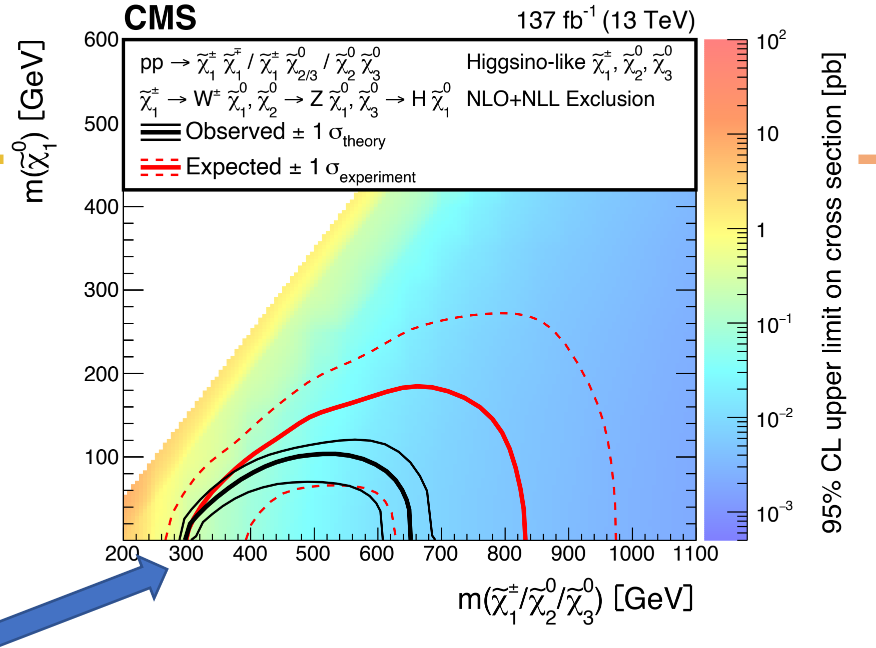
pass/fail ratio
pass = tag regions
fail – anti-tag regions



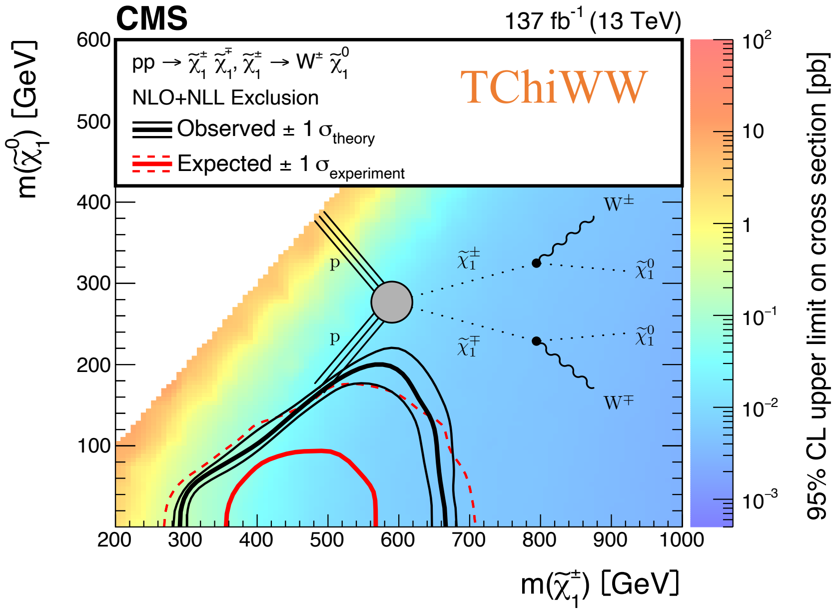
WX + p_T^{miss} search results

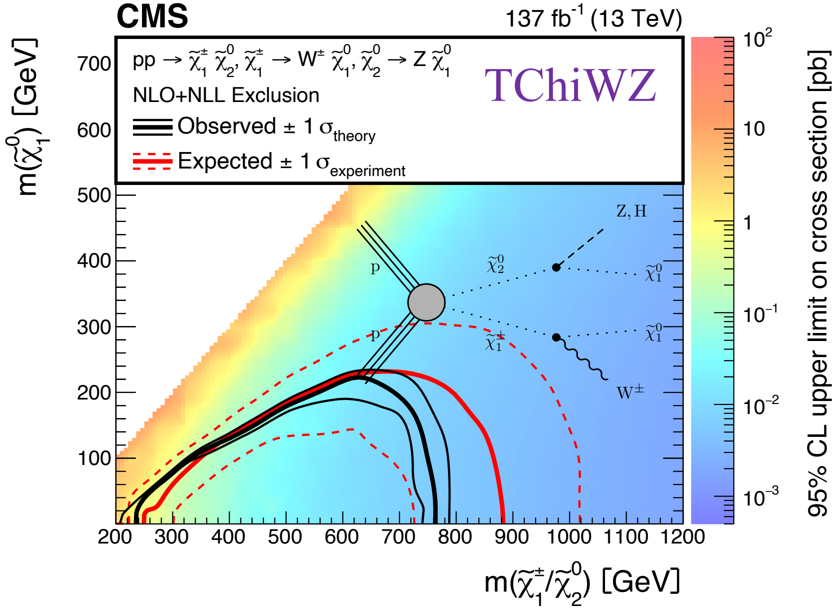
arxiv 2205.09597

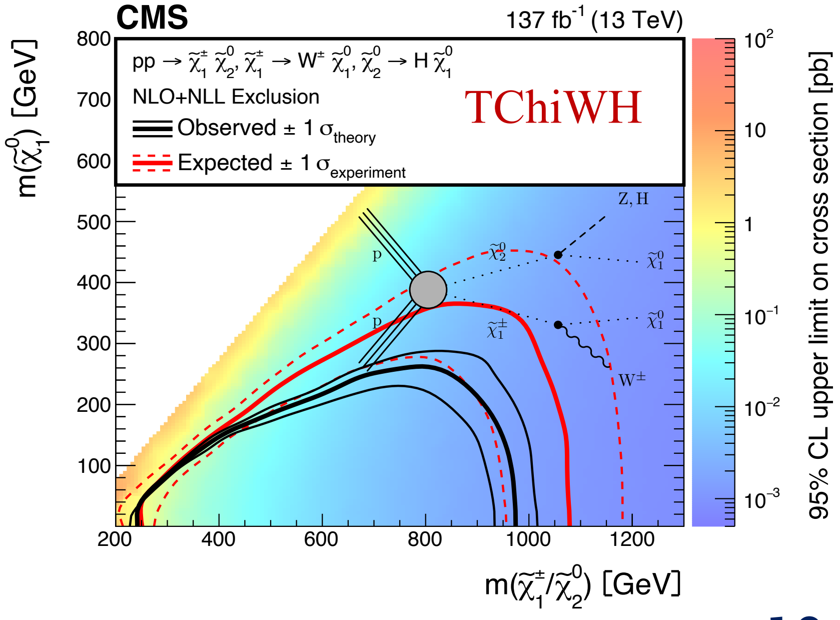
CMS-SUS-21-002



- It's challenging to probe the hadronic phase-space, but the deep NN taggers and robust SR selections bolstered to exclude higher NLSP masses than the counter leptonic searches.
- A more realistic interpretation for the Wino – bino doublet scenario where $\chi_2^0 \rightarrow$ Z/H + χ_1^0
- The search is sensitive to a large class of electroweakino models (TChiWW, TChiWZ and TChiWH)
- This is the first time that we exclude a significant phase space (300 – 650 GeV) of higgsino - bino scenarios of MSSM in CMS analyses.



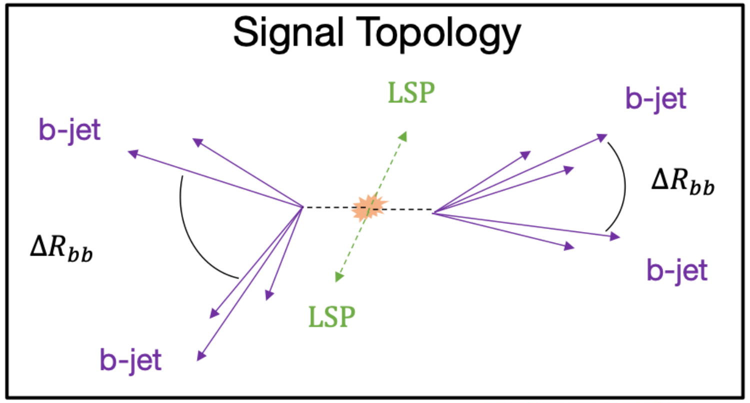




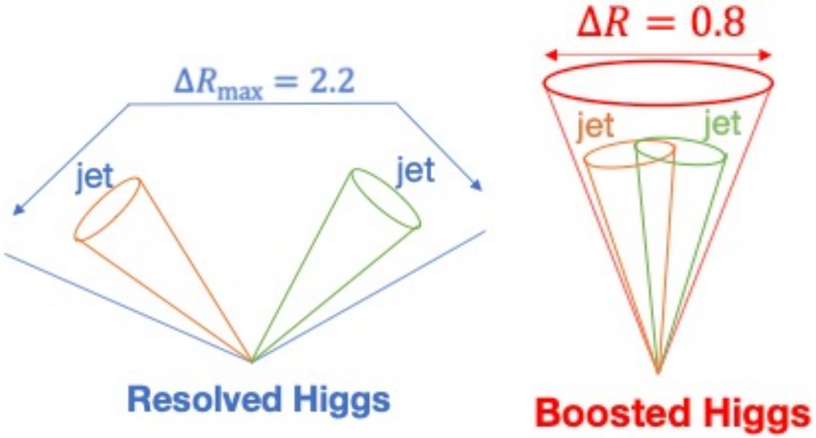
HH + p_T^{miss} search

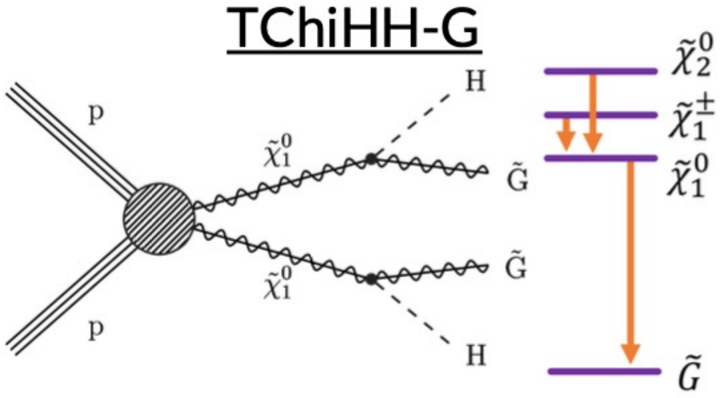
[*JHEP* **2022,** 14 (2022)](#)

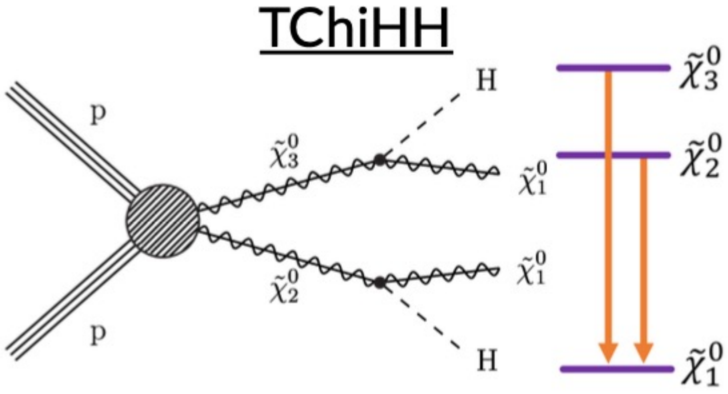
[CMS-SUS-20-004](#)

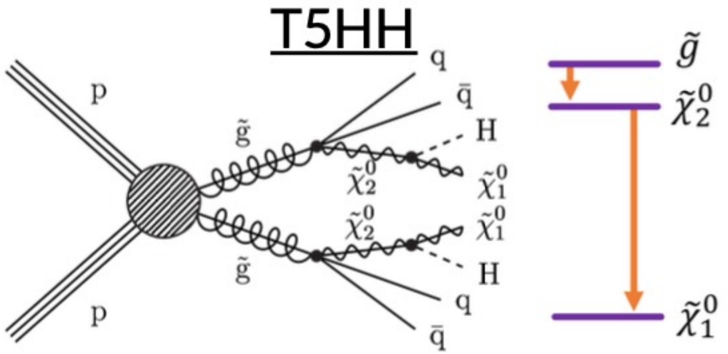


- This search targets simplified SUSY Model
  - $\tilde{\chi}_1^0$ LSP, $\tilde{\chi}_2^0/\tilde{\chi}_3^0$ NLSP
  - Only $\tilde{\chi}_2^0/\tilde{\chi}_3^0$ (nearlymass-degenerate)may decay to LSP
- Final states are HH + p_T^{miss} classified broadly into:
  - Resolved: 2 b-jets from H are reconstructed
  - Boosted: The b-jets from H are reconstructed by a fat jet
- GMSB scenario assuming: $\tilde{G}$ (LSP), $\tilde{\chi}_1^0$ (NLSP) → H $\tilde{G}$ (100%)
- T5HH model gains edge over high H production from gluino cascades.









HH + p_T^{miss} search strategy

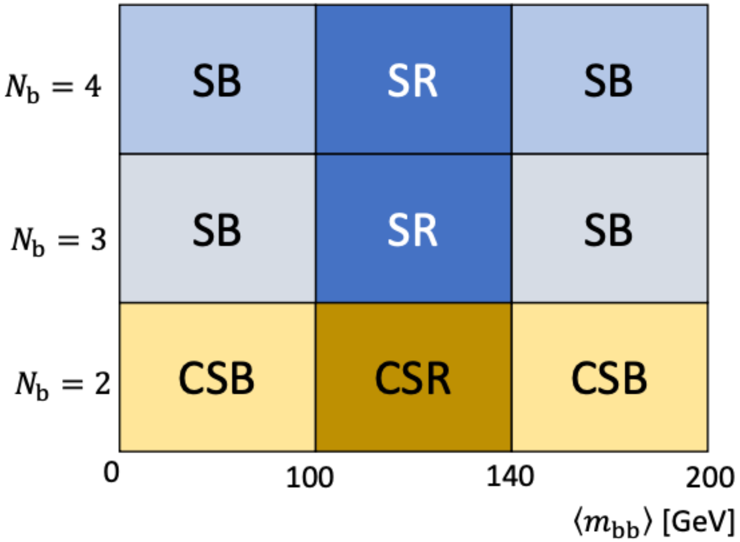
JHEP **2022,** 14 (2022)
CMS-SUS-20-004

- Resolved analysis: Binned in H mass and # b-jets (N_b)
  - Search bins are based on ΔR_{max} , p_T^{miss} and N_b
  - Background is predicted using the control signal regions and side bands.
  - $\mathcal{K}$ is derived from MC and validated in data CR

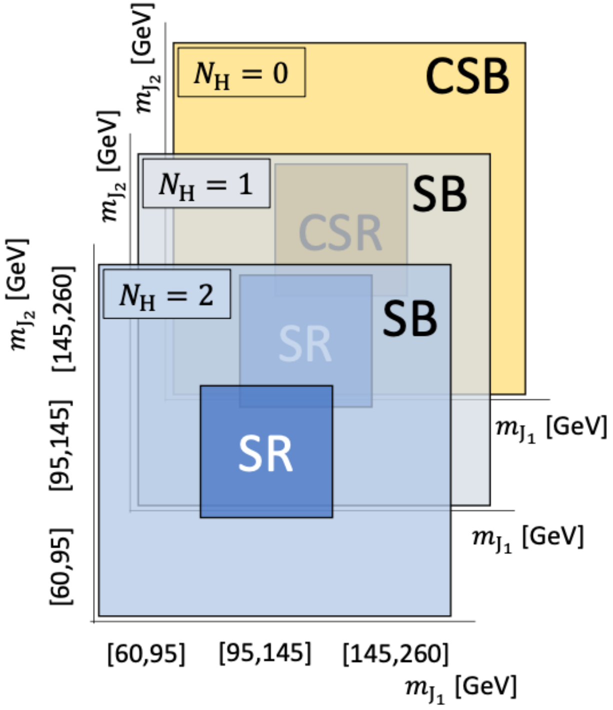
$$N_{SR}^{pred} = \kappa \frac{N_{CSR}}{N_{CSB}} N_{SB}, \quad \kappa = \left. \frac{N_{SR}/N_{SB}}{N_{CSR}/N_{CSB}} \right|_{MC}$$

- Boosted analysis: Binned in p_T^{miss} and N_H (1-2)
  - Background normalization factor derived using the ABCD method.
  - β_{norm} = SB * CSR/CSB
  - f_{bkg} is the shape derived form SR / “0H + b”
  - Both the factors are derived for each SR (binned in p_T^{miss})

$$N_{bkg}(p_T^{miss}) = \beta_{norm} \cdot f_{bkg}(p_T^{miss})$$



resolved



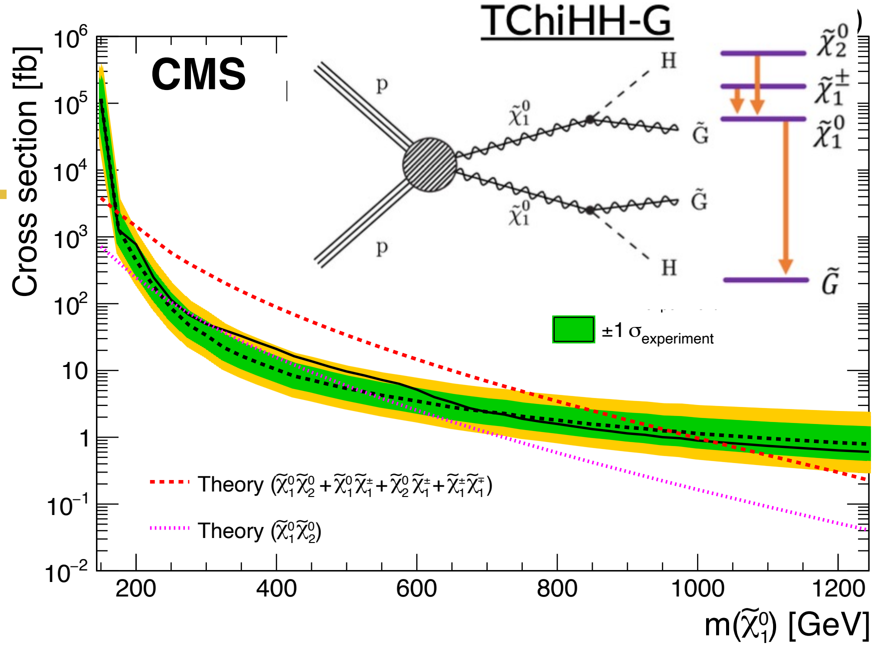
boosted

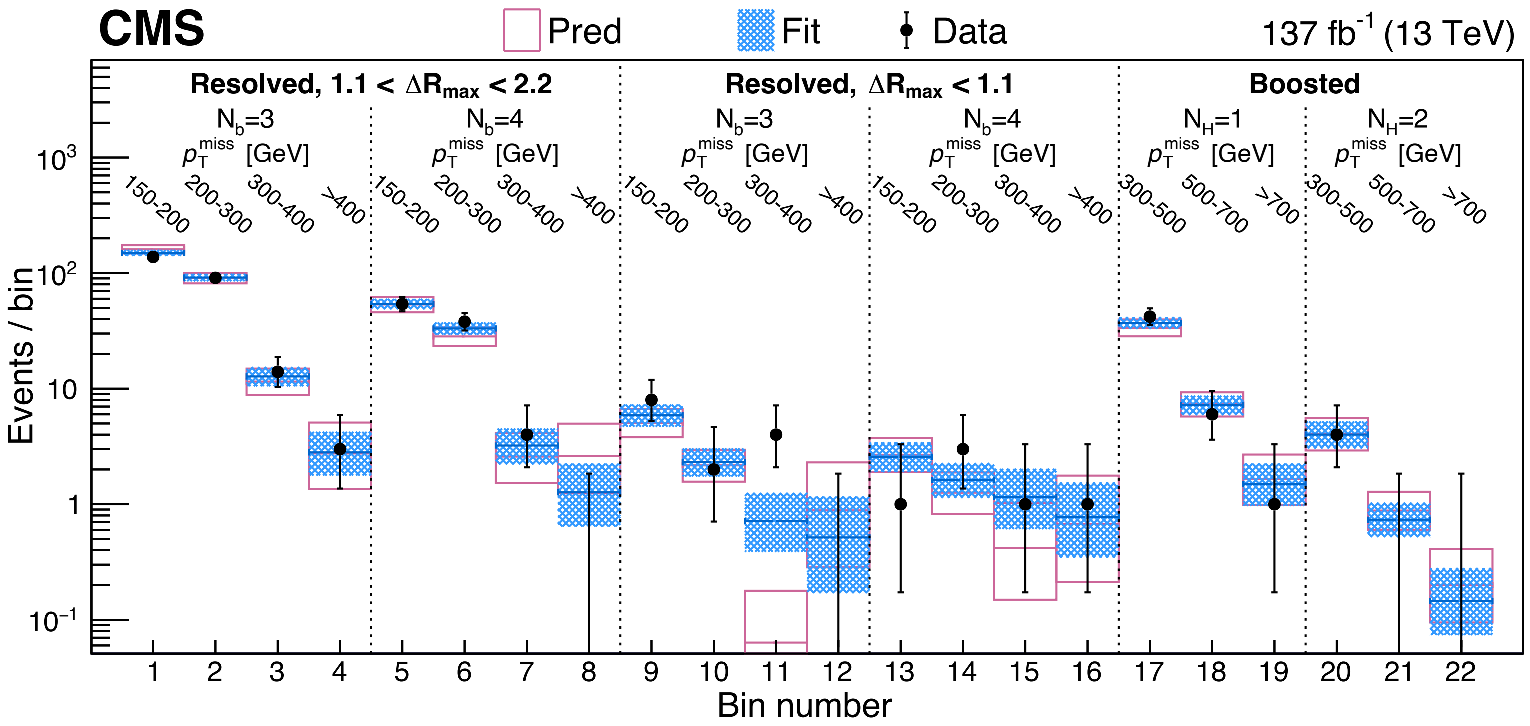
HH + p_T^{miss} results

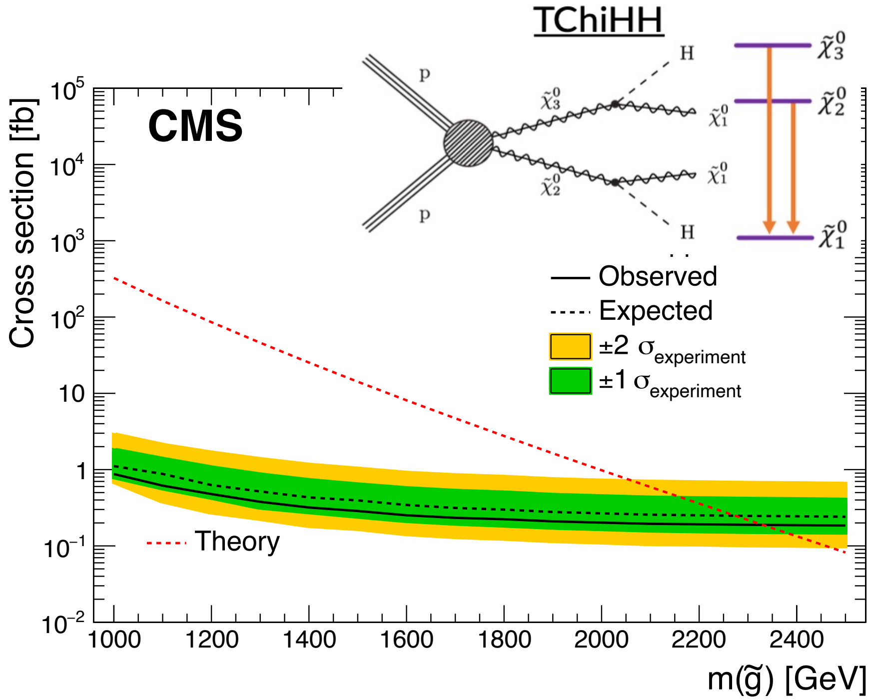
JHEP **2022,** 14 (2022)

CMS-SUS-20-004

- In all of the SR, the predictions are consistent with observed except bin 11 which has a 3.2 σ excess (1.9 σ global)
- Excludes m($\tilde{g}$) up to 2330 GeV (T5HH)
- Excludes $\tilde{\chi}_1^0$ from [175,1025] GeV for Higgsino model w/ $\tilde{G}$ (TChiHH-GMSB)



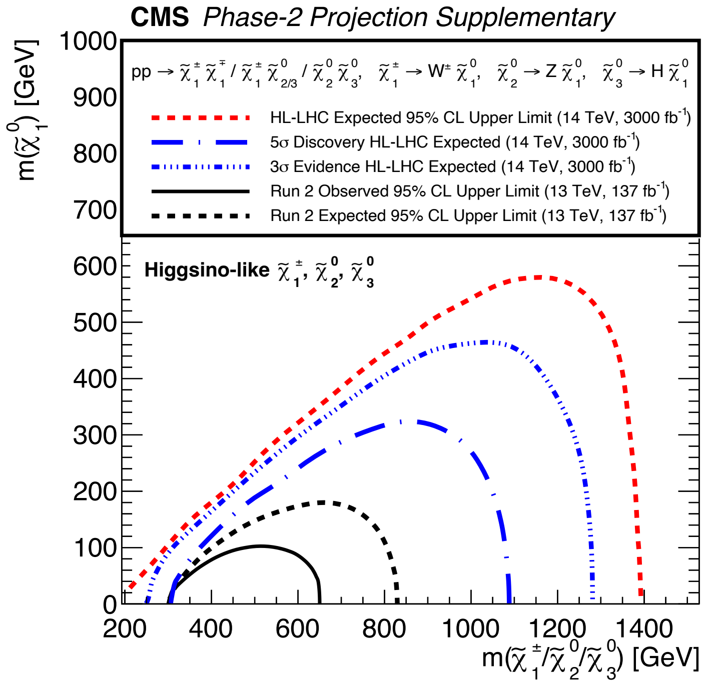




Summary & Outlook

- A wide variety of SUSY searches have been performed by CMS in hadronic final states.
- This talk mainly presented three recent searches from CMS.
    - WX+ p_T^{miss} analysis is sensitive to wide range of pair production of electroweakino models and also excludes a significant range of higgsino masses as well.
        - Complement searches in leptonic final states, in particular at high NSLP masses
    - HH+ p_T^{miss} search significantly pushes the gluino mass boundary up to 2330 GeV
    - The new 1 lep $\Delta\phi$ analysis also extends both the gluino mass upto 2280 GeV and the $\tilde{\chi}_1^0$ mass up to 1220 GeV.
- No signs of BSM physics yet but significant range of phase-space is excluded.
- In the future Run3 analyses, use of new neural network taggers and ML based analysis techniques would yield much exciting results.

Snowmass 2022



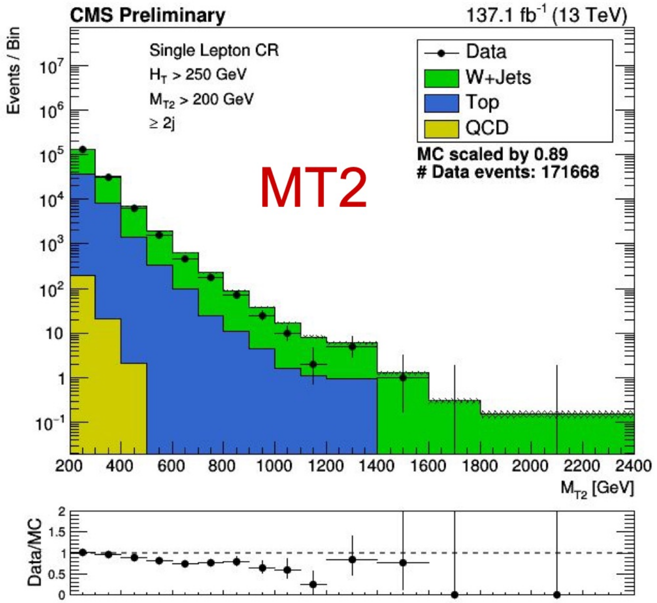
Backup

M_{T2} search

CMS-SUS-19-005

- $M_{T2} = \min_{\vec{p}_T^{X(1)}+\vec{p}_T^{X(2)}=\vec{p}_T^{\text{miss}}} \left[\max\left(M_T^{(1)}, M_T^{(2)}\right)\right]$
- Better background suppression using M_{T2} variable.

Trigger	2016:
	$p_T^{\text{miss}} > 120\,\text{GeV}$ and $H_T^{\text{miss}} > 120\,\text{GeV}$, or
	$H_T > 300\,\text{GeV}$ and $p_T^{\text{miss}} > 110\,\text{GeV}$, or
	$H_T > 900\,\text{GeV}$, or jet $p_T > 450\,\text{GeV}$
	2017 and 2018:
	$p_T^{\text{miss}} > 120\,\text{GeV}$ and $H_T^{\text{miss}} > 120\,\text{GeV}$, or
	$H_T > 60\,\text{GeV}$ and $p_T^{\text{miss}} > 120\,\text{GeV}$ and $H_T^{\text{miss}} > 120\,\text{GeV}$, or
	$H_T > 500\,\text{GeV}$ and $p_T^{\text{miss}} > 100\,\text{GeV}$ and $H_T^{\text{miss}} > 100\,\text{GeV}$, or
	$H_T > 800\,\text{GeV}$ and $p_T^{\text{miss}} > 75\,\text{GeV}$ and $H_T^{\text{miss}} > 75\,\text{GeV}$, or
	$H_T > 1050\,\text{GeV}$, or jet $p_T > 500\,\text{GeV}$
Jet selection	$R = 0.4$, $p_T > 30\,\text{GeV}$, $\lvert\eta\rvert < 2.4$
b-tagged jet selection	$p_T > 20\,\text{GeV}$, $\lvert\eta\rvert < 2.4$ and b tag
H_T	$H_T > 250\,\text{GeV}$
p_T^{miss}	$p_T^{\text{miss}} > 250\,\text{GeV}$ for $H_T < 1200\,\text{GeV}$ or $N_j = 1$, else $p_T^{\text{miss}} > 30\,\text{GeV}$
	$\Delta\phi_{\min} = \Delta\phi\left(\vec{p}_T^{\text{miss}}, j_{1,2,3,4}\right) > 0.3$
	$\lvert\vec{p}_T^{\text{miss}} - \vec{H}_T^{\text{miss}}\rvert / p_T^{\text{miss}} < 0.5$
M_{T2} (if $N_j \geq 2$)	Inclusive M_{T2} search:
	$M_{T2} > 200\,\text{GeV}$ for $H_T < 1500\,\text{GeV}$, else $M_{T2} > 400\,\text{GeV}$
	Disappearing tracks search:
	$M_{T2} > 200\,\text{GeV}$
p_T^{sum} cone (isolation)	Veto eor μ: $\Delta R = \min(0.2, \max(10\,\text{GeV}/p_T^{\text{lep}}, 0.05))$
	Veto track: $\Delta R = 0.3$
Veto electron	$p_T > 10\,\text{GeV}$, $\lvert\eta\rvert < 2.4$, $p_T^{\text{sum}} < 0.1\,p_T^{\text{lep}}$
Veto electron track	$p_T > 5\,\text{GeV}$, $\lvert\eta\rvert < 2.4$, $M_T < 100\,\text{GeV}$, $p_T^{\text{sum}} < 0.2\,p_T^{\text{lep}}$
Veto muon	$p_T > 10\,\text{GeV}$, $\lvert\eta\rvert < 2.4$, $p_T^{\text{sum}} < 0.2\,p_T^{\text{lep}}$
Veto muon track	$p_T > 5\,\text{GeV}$, $\lvert\eta\rvert < 2.4$, $M_T < 100\,\text{GeV}$, $p_T^{\text{sum}} < 0.2\,p_T^{\text{lep}}$
Veto track	$p_T > 10\,\text{GeV}$, $\lvert\eta\rvert < 2.4$, $M_T < 100\,\text{GeV}$, $p_T^{\text{sum}} < 0.1\,p_T^{\text{track}}$

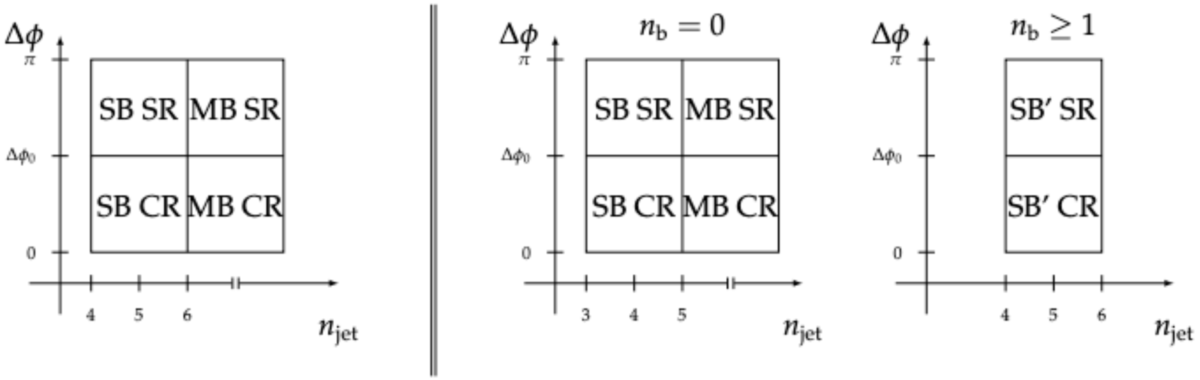


NEW

1 lep Δφ search backup

CMS-SUS-21-007

- Overview of SR definitions
- Multi-b analysis (left); 0-b analysis (middle, right)



- Major background is estimated using the ABCD method.

$$R^{CS}_{data}\left(n_{jet} \in [4,5]\,, n_b \text{ as in MB}\right) = \frac{N^{SB,SR}_{data} - N^{SB,SR}_{Pred,QCD}}{N^{SB,CR}_{data} - N^{SB,CR}_{Pred,QCD}}$$

- The prediction is done by scaling the low Δϕ region by SB R^{CS} from data and $\mathcal{K}_{EW}$

$$\kappa_{EW} = \frac{R^{CS}_{MC,EW}\left(n_{jet} \text{ as in MB}\right)}{R^{CS}_{MC,EW}\left(n_{jet} \in [4,5]\right)}$$

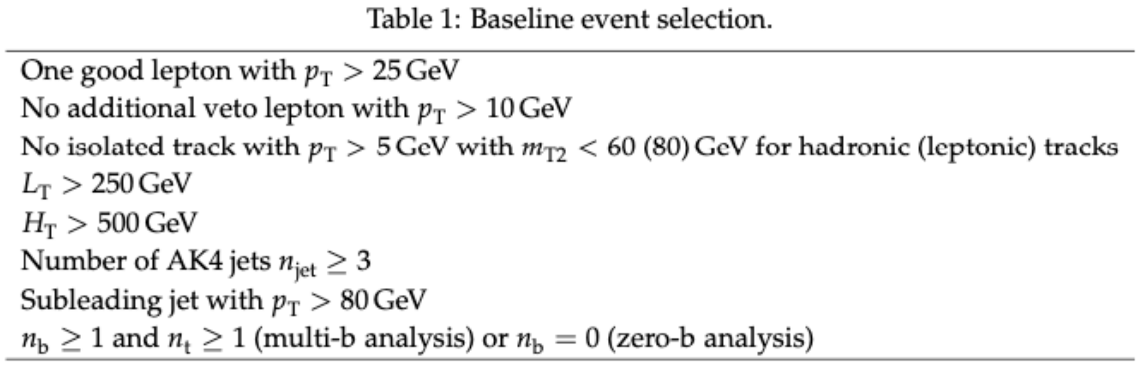
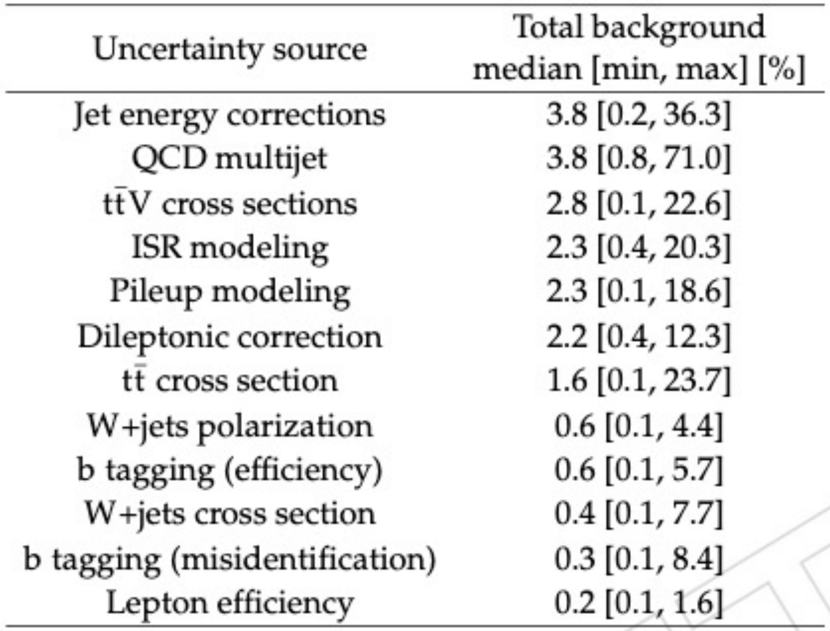


Table 1: Baseline event selection.

One good lepton with $p_T > 25$ GeV
No additional veto lepton with $p_T > 10$ GeV
No isolated track with $p_T > 5$ GeV with $m_{T2} < 60$ (80) GeV for hadronic (leptonic) tracks
$L_T > 250$ GeV
$H_T > 500$ GeV
Number of AK4 jets $n_{jet} \geq 3$
Subleading jet with $p_T > 80$ GeV
$n_b \geq 1$ and $n_t \geq 1$ (multi-b analysis) or $n_b = 0$ (zero-b analysis)

- Multi-b analysis systematic uncertainties



Uncertainty source	Total background median [min, max] [%]
Jet energy corrections	3.8 [0.2, 36.3]
QCD multijet	3.8 [0.8, 71.0]
$t\bar{t}V$ cross sections	2.8 [0.1, 22.6]
ISR modeling	2.3 [0.4, 20.3]
Pileup modeling	2.3 [0.1, 18.6]
Dileptonic correction	2.2 [0.4, 12.3]
$t\bar{t}$ cross section	1.6 [0.1, 23.7]
W+jets polarization	0.6 [0.1, 4.4]
b tagging (efficiency)	0.6 [0.1, 5.7]
W+jets cross section	0.4 [0.1, 7.7]
b tagging (misidentification)	0.3 [0.1, 8.4]
Lepton efficiency	0.2 [0.1, 1.6]

CMS-SUS-21-002

WX + p_T^{miss} search backup

- b-veto signal region

Region	Requirements
b-veto SR	≥1 V-tagged jet ≥1 W-tagged jet ≥2 V- or W-tagged jets
b-veto 0-tag CR	0 V-tagged jets 0 W-tagged jets
b-veto 1-tag CR	1 V-tagged jet 0 other W-tagged jets

- b-tag signal region

	Wboson candidate		Higgs boson candidate	
	Wtagged	not Wtagged	$b\bar{b}$ tagged	not $b\bar{b}$ tagged
WH SR	≥1	—	≥1	—
WSR	≥1	—	0	—
H SR	0	—	≥1	—
WH antitag CR	0	≥1	0	≥1
Wantitag CR	0	≥1	0	0
H antitag CR	0	0	0	≥1

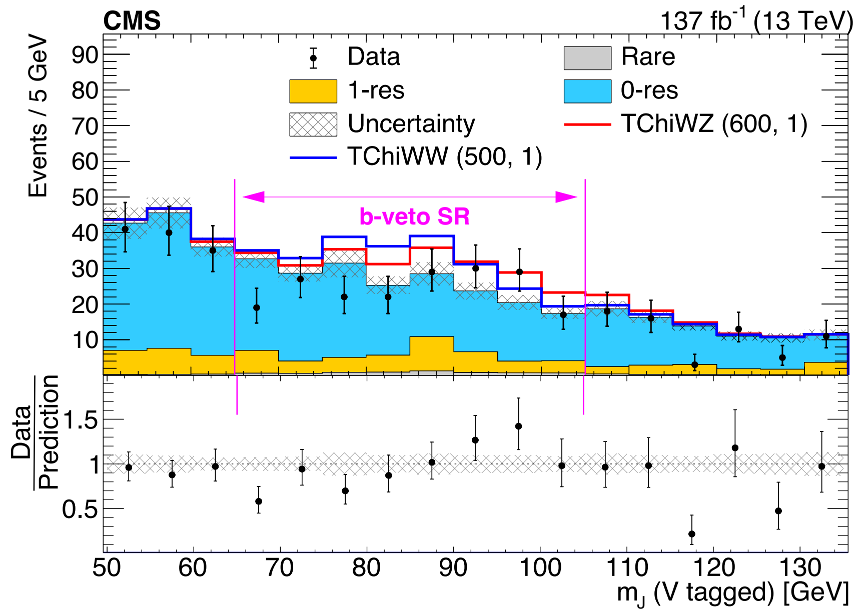
- Systematic uncertainties

	b veto				b tag			
Source	0- and 1-res bkg.		Rare	Signal	Top quark	0-res	Rare	Signal
	0-tag CR	1-tag CR						
Integr. luminosity	—	—	1.6	1.6	—	—	1.6	1.6
CR data size	6–71	5–50	—	—	3–100	2–35	—	—
MC sample size	8–25	8–30	14–24	2–5	2–28	3–40	4–27	2–5
μ_R and μ_F	1.2	0.4	8	<5	2–10	0.5	11	<5
Trigger efficiency	—	—	2–3	2–3	—	—	2–3	2–3
b-tag correction	<1	<1	<1	1	1	<3	<3	2–3
$b\bar{b}$-tag correction	—	—	—	—	—	4	2–7	4
W-tag correction	12–28	6–22	11–15	15	1	9	7	9
V-tag correction	7–15	2–10	1–4	2	—	—	—	—
W-tag nonclosure	3–48	3–48	—	—	—	—	—	—
V-tag nonclosure	1–27	—	—	—	—	—	—	—
Fast simulation	—	—	—	5	—	—	—	8

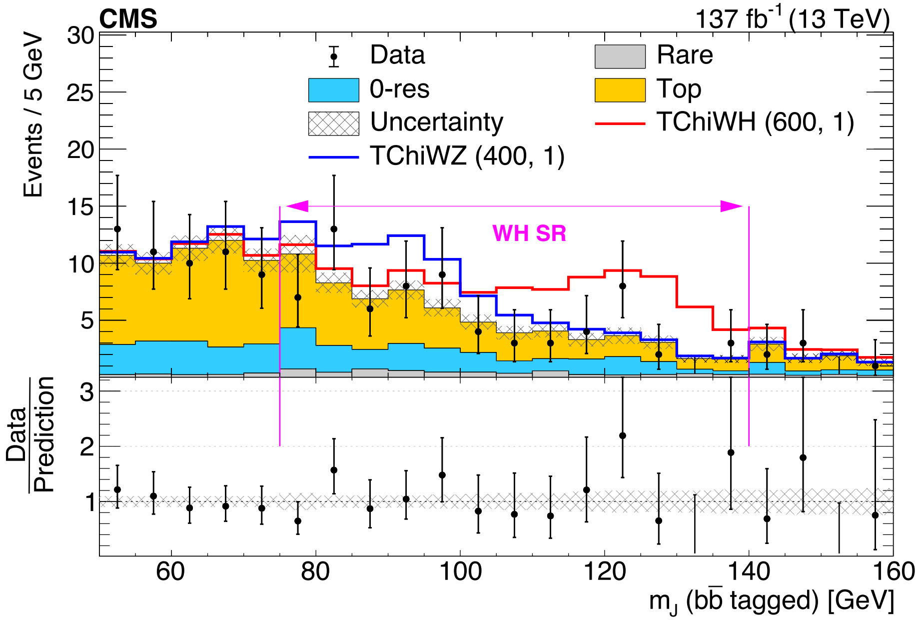
WX + p_T^{miss} search backup

CMS-SUS-21-002

- Mainly classified into b-Veto SR (top) and b-Tag SR (bottom)
- The common baseline selections include: ≥ 2 AK8 jets, $p_T^{miss} \geq 200$ GeV, no leptons.
- The b-Veto SR targets W/Z → qq (q ≠ b) decays, additionally requires:
  - AK8 jets mass window for W/Z: 65-105 GeV
  - Deep AK8 taggers used: deep-W tagger and deep W mass-decorrelated (WMD) tagger.
  - The WMD tagger, agnostic to jet mass, captures hadronic decays of both W and Z and is calibrated with W → qq decays.
- The b-Tag SR targets Z/H → bb decays, additionally requires:
  - AK8 jets mass window for Z/H: 75-140 GeV
  - Deep AK8 taggers used: deep-W tagger and deep-bb tagger.
  - Taking advantage of the Z/H → bb branching ratio, we optimize this SR using deep-bb tagger.



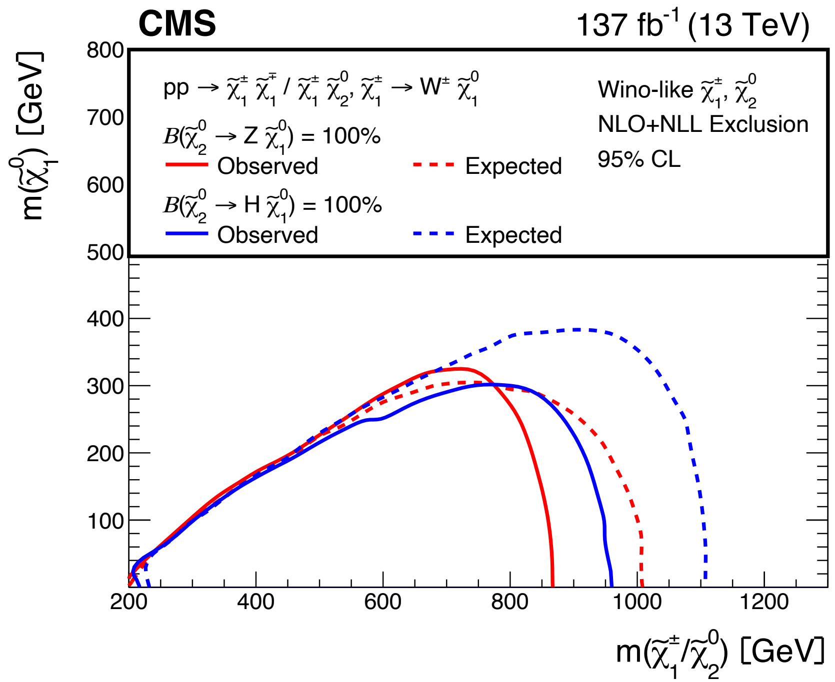
Mass of the deep-WMD tagged jet in b-Veto SR

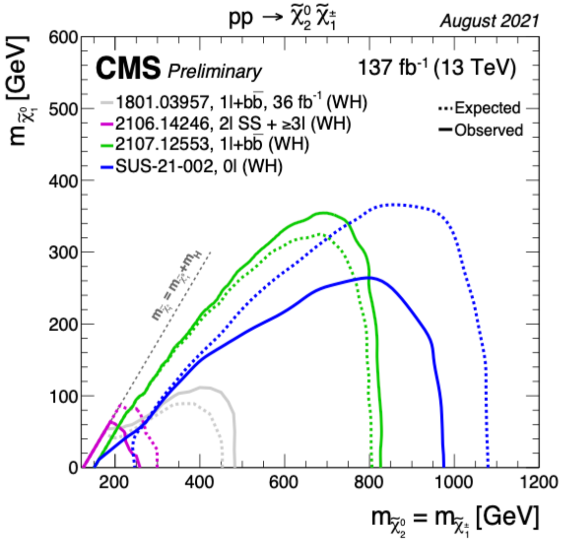


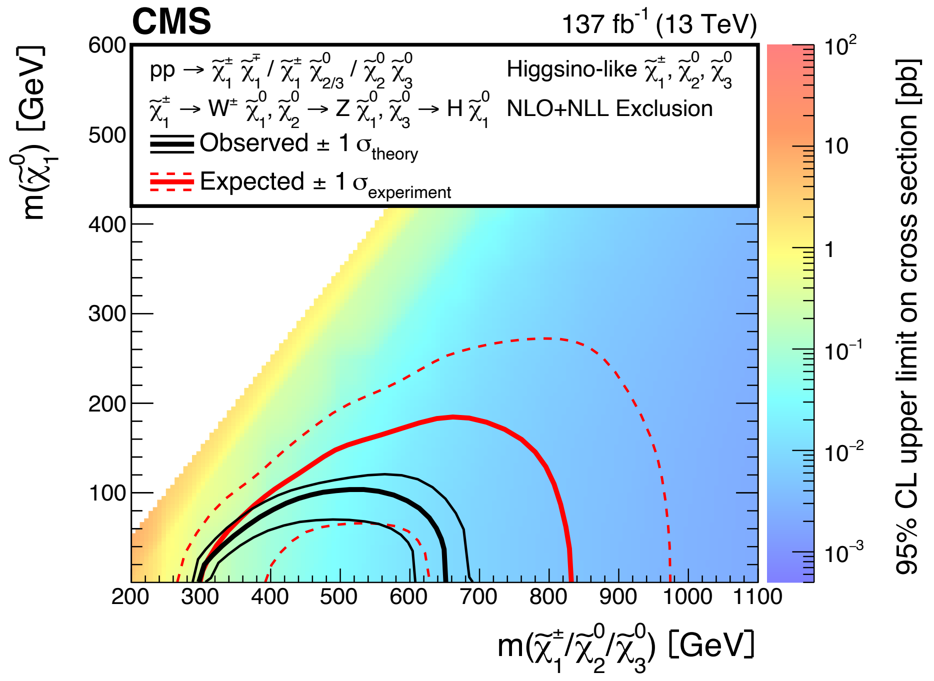
Mass of the bb-tagged jet in b-Tag SR

WX + p_T^{miss} search backup

- No significant deviations from SM predictions are observed.
- A more realistic interpretation for the Wino – bino doublet scenario where $\chi_2^0 \rightarrow$ Z/H + χ_1^0
- This is the <u>first time</u> that we exclude a significant phase space of <u>higgsino - bino scenarios</u> of MSSM in CMS analyses.
- These mass exclusions significantly improve on those achieved by searches using leptonic probes of SUSY for high NLSP masses







HH + p_T^{miss} search backup

JHEP **2022,** 14 (2022)
CMS-SUS-20-004

- Resolved signal regions

Bin	ΔR_{max}	N_b	p_T^{miss} [GeV]	κ	N_{SR}^{pred}	N_{SR}^{fit}	N_{SR}^{obs}
1	1.1–2.2	3	150–200	$1.09 \pm 0.04 \pm 0.02$	161^{+14}_{-13}	$149.7^{+8.9}_{-8.5}$	138
2			200–300	$0.92 \pm 0.04 \pm 0.02$	$90.4^{+9.7}_{-9.0}$	$91.5^{+6.9}_{-6.5}$	91
3			300–400	$0.94 \pm 0.09 \pm 0.01$	$11.5^{+3.4}_{-2.7}$	$12.8^{+2.6}_{-2.2}$	14
4			>400	$0.98^{+0.19}_{-0.16} \pm 0.02$	$2.8^{+2.3}_{-1.4}$	$2.8^{+1.4}_{-1.0}$	3
5		4	150–200	$1.13 \pm 0.09 \pm 0.08$	$53.5^{+8.8}_{-7.8}$	$54.1^{+5.6}_{-5.2}$	54
6			200–300	$0.96 \pm 0.07 \pm 0.07$	$28.3^{+5.6}_{-4.8}$	$33.2^{+4.2}_{-3.9}$	38
7			300–400	$0.89^{+0.16}_{-0.15} \pm 0.05$	$2.6^{+1.5}_{-1.1}$	$3.2^{+1.3}_{-1.0}$	4
8			>400	$0.92^{+0.27}_{-0.22} \pm 0.07$	$2.6^{+2.4}_{-1.4}$	$1.27^{+0.98}_{-0.63}$	0
9	<1.1	3	150–200	$1.05^{+0.18}_{-0.15} \pm 0.12$	$5.1^{+1.6}_{-1.3}$	$5.9^{+1.4}_{-1.2}$	8
10			200–300	$1.04^{+0.14}_{-0.13} \pm 0.11$	$2.17^{+0.79}_{-0.60}$	$2.31^{+0.73}_{-0.57}$	2
11			300–400	$0.72^{+0.33}_{-0.22} \pm 0.08$	$0.06^{+0.11}_{-0.04}$	$0.72^{+0.53}_{-0.33}$	4
12			>400	$1.24^{+0.67}_{-0.45} \pm 0.10$	$0.89^{+1.42}_{-0.60}$	$0.52^{+0.65}_{-0.35}$	0
13		4	150–200	$1.26^{+0.21}_{-0.20} \pm 0.23$	$2.68^{+1.06}_{-0.79}$	$2.58^{+0.85}_{-0.67}$	1
14			200–300	$1.21^{+0.22}_{-0.21} \pm 0.22$	$1.26^{+0.62}_{-0.44}$	$1.62^{+0.65}_{-0.48}$	3
15			300–400	$2.35^{+0.88}_{-0.72} \pm 0.34$	$0.42^{+0.61}_{-0.27}$	$1.16^{+0.87}_{-0.55}$	1
16			>400	$0.94^{+0.53}_{-0.36} \pm 0.13$	$0.67^{+1.10}_{-0.46}$	$0.78^{+0.76}_{-0.43}$	1

- Boosted signal regions

Bin	N_H	p_T^{miss} [GeV]	$N_{SR, tot}^{pred}$	f_{pTmiss}	N_{SR}^{pred}	N_{SR}^{fit}	N_{SR}^{obs}
17	1	300–500	42.6 ± 4.2	0.789 ± 0.030	$33.6^{+6.1}_{-5.2}$	$37.0^{+4.2}_{-4.0}$	42
18		500–700		0.172 ± 0.028	$7.3^{+2.0}_{-1.6}$	$7.2^{+1.5}_{-1.3}$	6
19		>700		0.039 ± 0.014	$1.65^{+1.04}_{-0.66}$	$1.50^{+0.75}_{-0.53}$	1
20	2	300–500	5.1 ± 1.0	0.789 ± 0.030	$4.0^{+1.5}_{-1.1}$	$4.0^{+1.2}_{-1.0}$	4
21		500–700		0.172 ± 0.028	$0.88^{+0.40}_{-0.28}$	$0.74^{+0.29}_{-0.21}$	0
22		>700		0.039 ± 0.014	$0.20^{+0.21}_{-0.10}$	$0.14^{+0.13}_{-0.07}$	0

- Systematic uncertainties

Source	Relative uncertainty [%]	
	Resolved	Boosted
MC sample size	0–18	1–15
ISR modeling	0–2	0–18
Renormalization and factorization scales μ_R and μ_F	0–2	0–7
Pileup corrections	0–3	0–9
Integrated luminosity	1.6	
Jet energy scale	0–7	0–12
Jet energy resolution	0–7	0–7
Isolated track veto	2–9	1–8
Trigger efficiency	1–12	0–4
m_J resolution	—	0–9
b tagging efficiency	2–6	—
b mistagging	0–1	—
bb tagging efficiency	—	6–15
Uncertainties attributable to the fast simulation		
Jet quality requirements	1	
p_T^{miss} modeling	0–14	0–12
m_J resolution	—	2–4
b tagging efficiency	0–1	—
b mistagging	0–1	—
bb tagging efficiency	—	0–1