Search for Electroweak SUSY in Leptonic Final States With the CMS Detector

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THE UNIVERSITY OF KANSAS

Introduction

- Searches for chargino and neutralino production with 2 or more leptons, jets and large p_T^{miss}.

- Strategies and results from three published papers:

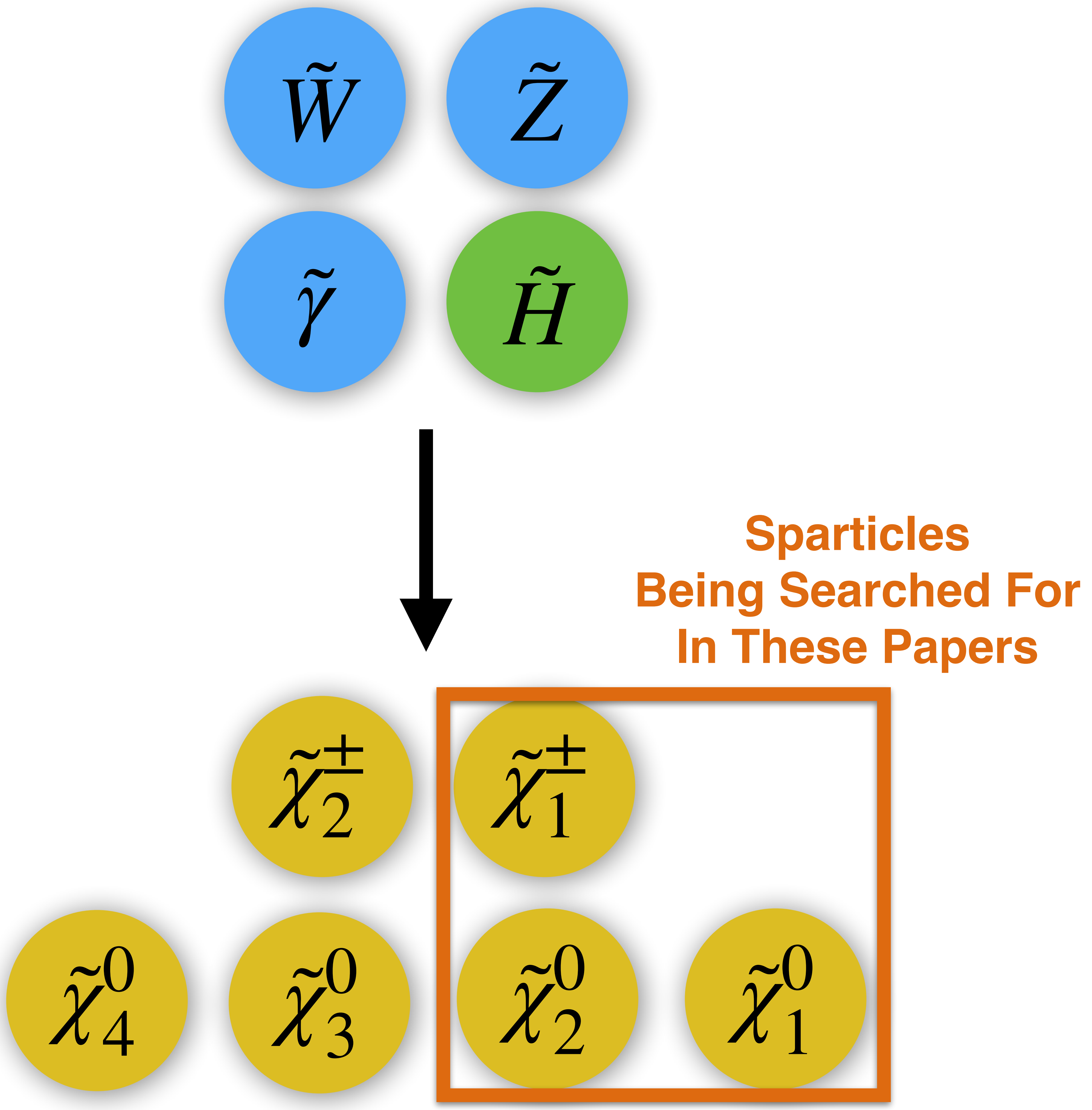
  - SUS-18-004 (arXiv:2111.06296) - **Compressed SUSY with 2 and 3 leptons in the final state.**

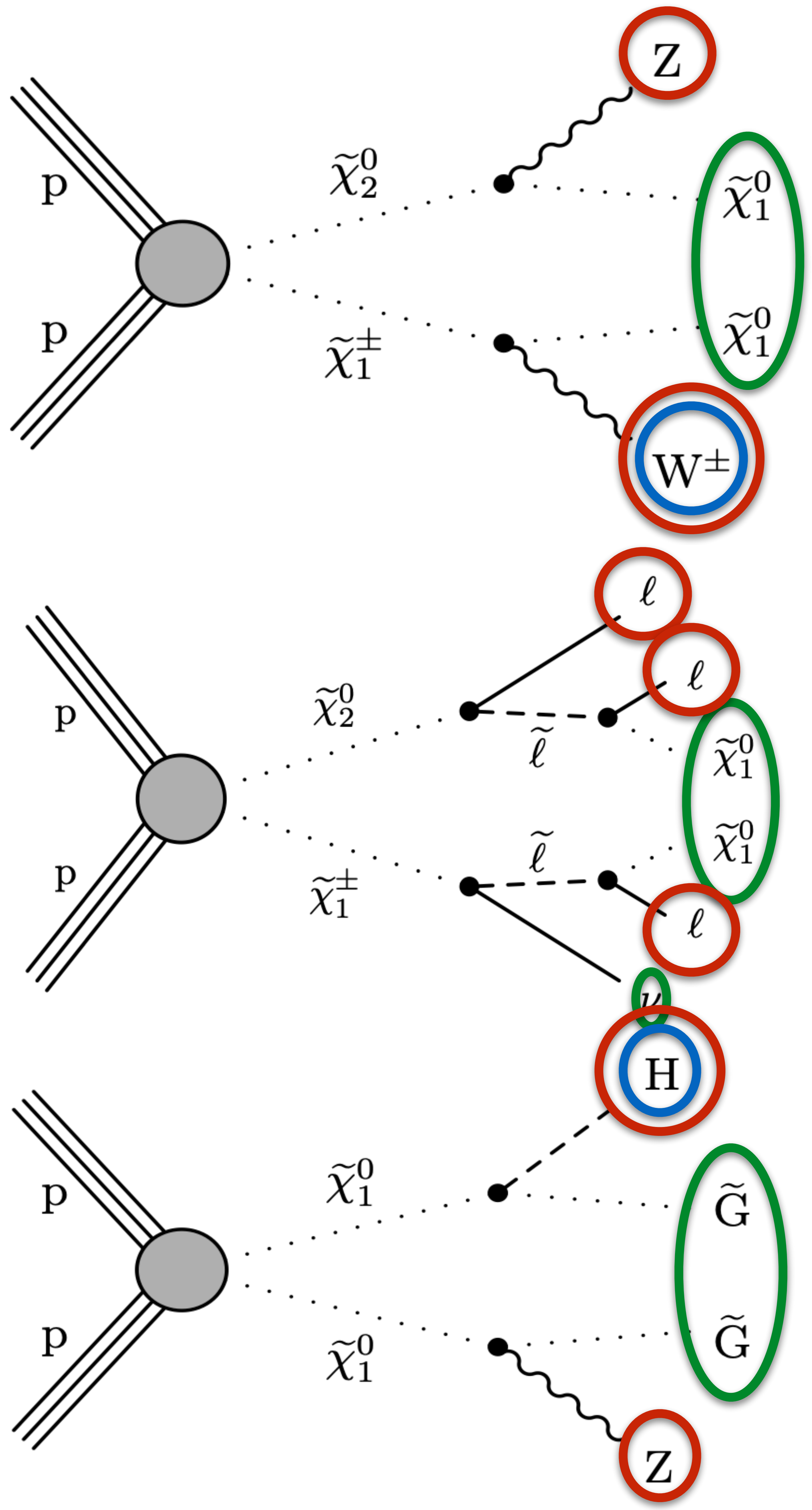
  - SUS-19-012 (arXiv:2106.14246) - **Final states with 3 or more leptons.**

  - SUS-20-001 (arXiv:2012.08600) - **Final states with 2 OSSF leptons.**

Electroweak SUSY

- **Electroweakinos** - mixed states of $\tilde{W}, \tilde{Z}, \tilde{\gamma}, \tilde{H}$ sparticles:
  - 4 charged ($\tilde{\chi}_2^{\pm}, \tilde{\chi}_1^{\pm}$) and 4 neutral ($\tilde{\chi}_4^0, \tilde{\chi}_3^0, \tilde{\chi}_2^0, \tilde{\chi}_1^0$).
- Why are they relevant?
  - Contribute to **large corrections in Higgs mass**.
  - Viable candidates for **dark matter**.
  - Near electroweak (TeV) scale - **Accessible at current LHC energies**.
  - **Enough data** to probe the phase space.



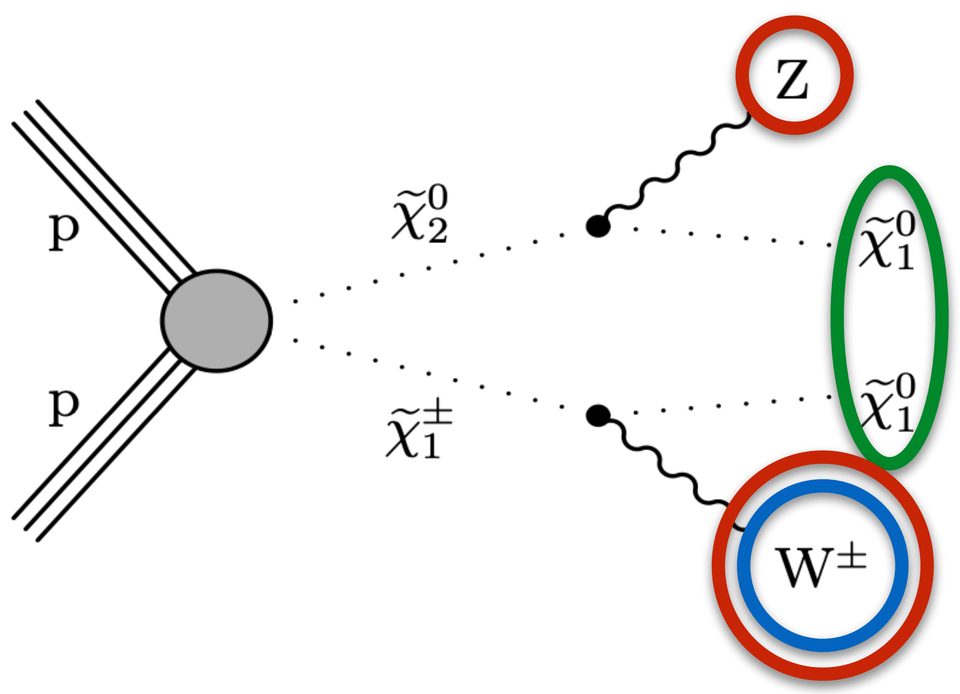


- Production of Charginos ($\tilde{\chi}_1^\pm$) and Neutralinos ($\tilde{\chi}_2^0/\tilde{\chi}_1^0$) with 2 or more leptons in the final state.

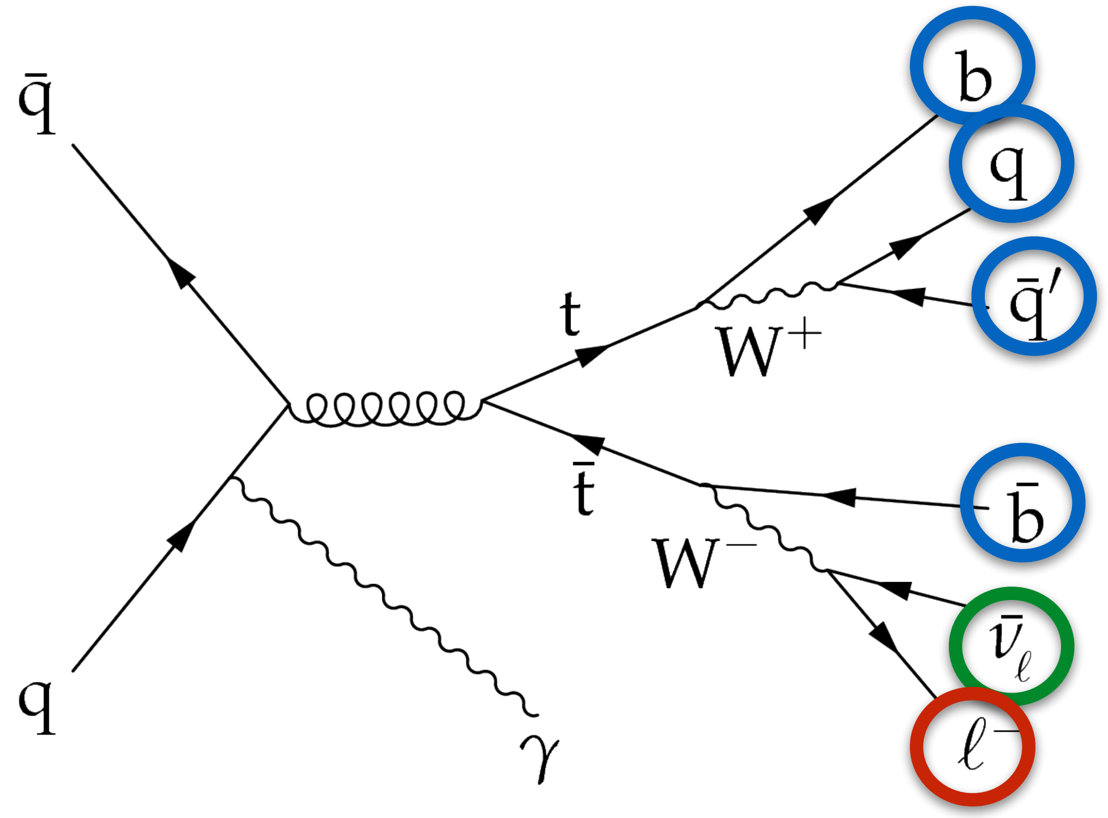
- **Common characteristics**:
  - Multiple leptons produced **promptly** from SUSY particles or SM processes.
  - Large p_T^{miss} from pair-produced lightest SUSY particles (LSPs), either neutralinos ($\tilde{\chi}_1^0$) or gravitinos ($\tilde{G}$).
  - Jets from ISR or SM boson decays.

SM Backgrounds

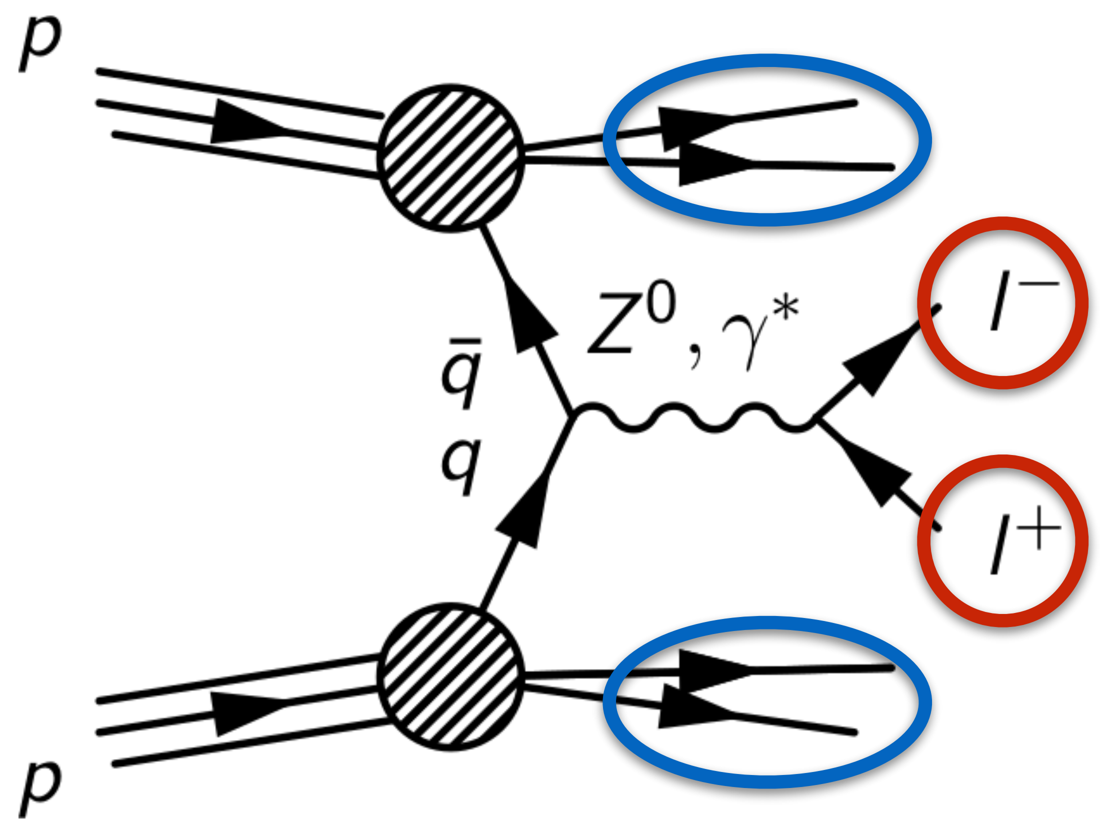
Signal



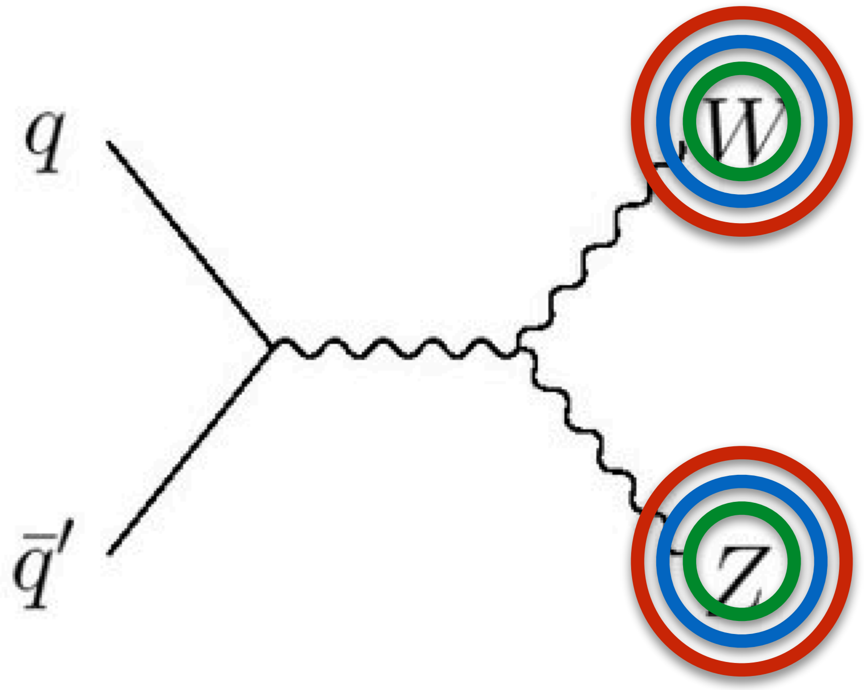
$t\bar{t} + Jets$



$Z/\gamma * + Jets$

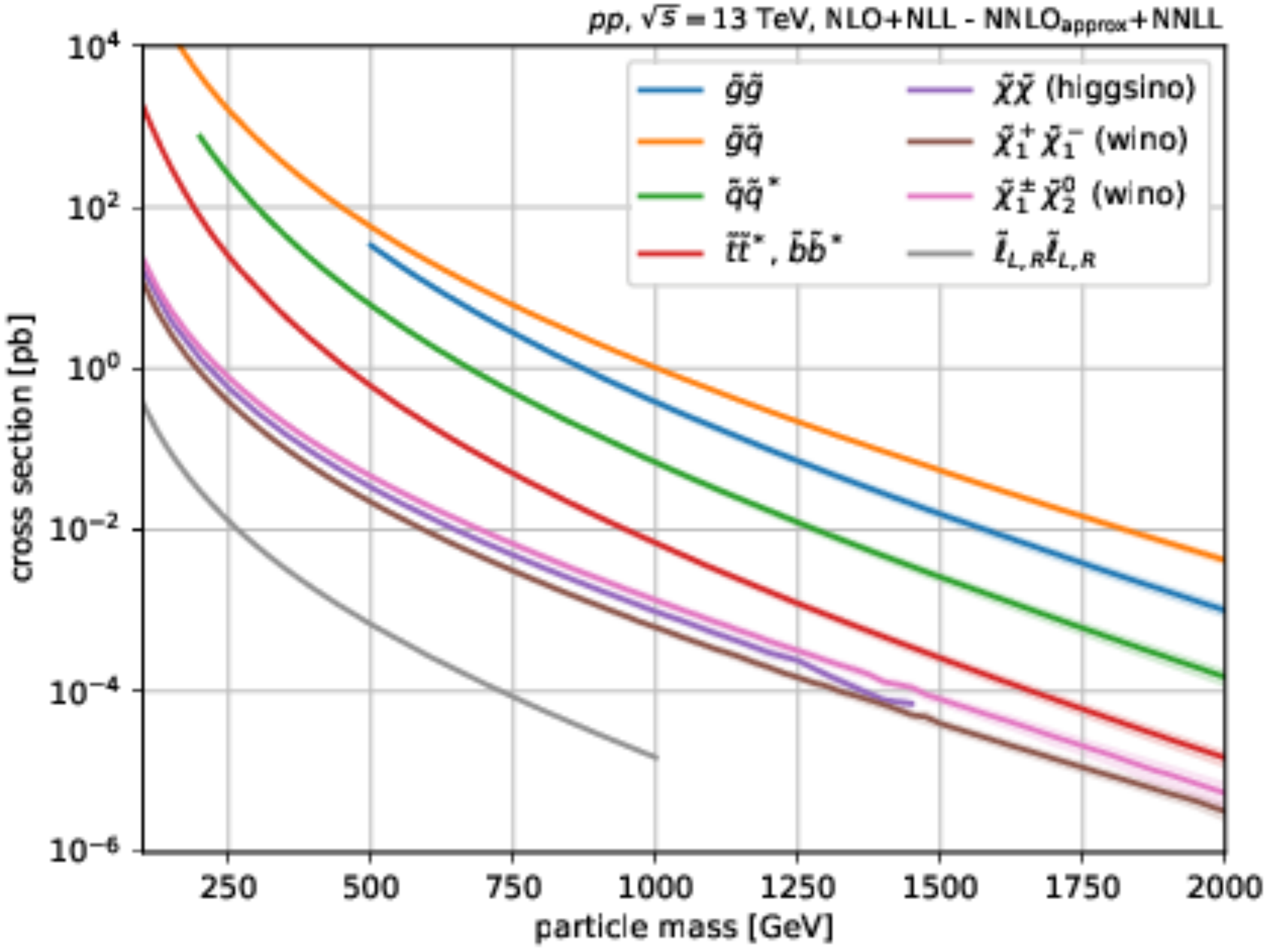


Diboson



- Several SM processes with multiple prompt leptons and large cross-sections.
- Main backgrounds:
  - $\mathbf{t\bar{t} + Jets}$ - two prompt **leptons** from $W^{\pm}$ and multiple **jets**.
  - $\mathbf{Z/\gamma * + Jets}$ - two OSSF **leptons** from Z_0 and multiple **jets**.
  - **Diboson** - up to 4 prompt **leptons** from various processes (WW, ZZ, WZ, etc.) with p_T^{miss} and **jets**.
  - Other sources include **rare SM processes and events with misidentified leptons**.
- **Background mitigation strategies contingent on signal model being studied.**

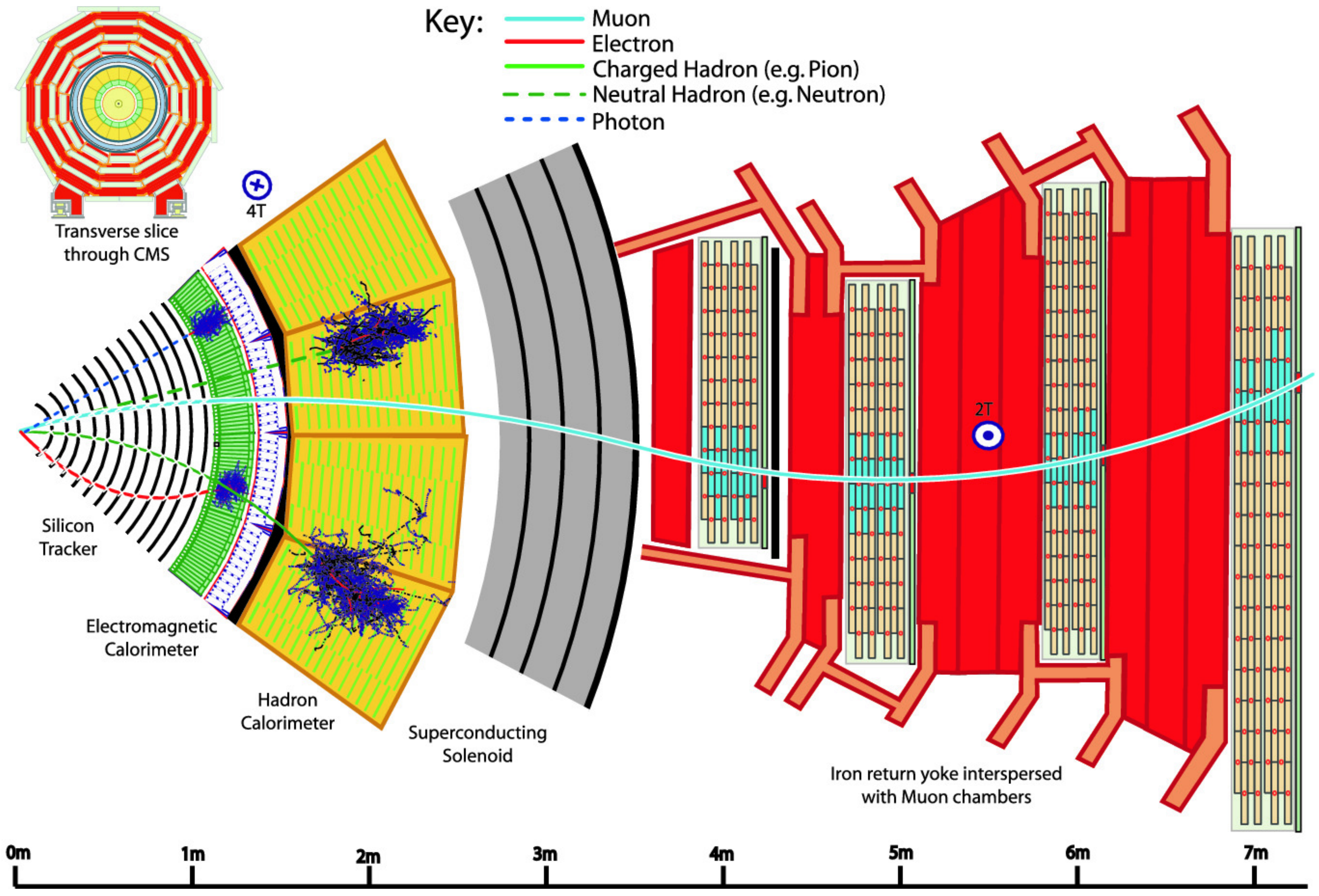
Additional Challenges



- Masses of SUSY particles **unknown**.
- **Large parameter space to cover**:
  - Complicated with models that have multiple SUSY decay chains.
  - "**Compressed**" scenarios notoriously difficult.
  - Particles with heavier masses might still be out of reach at the LHC.

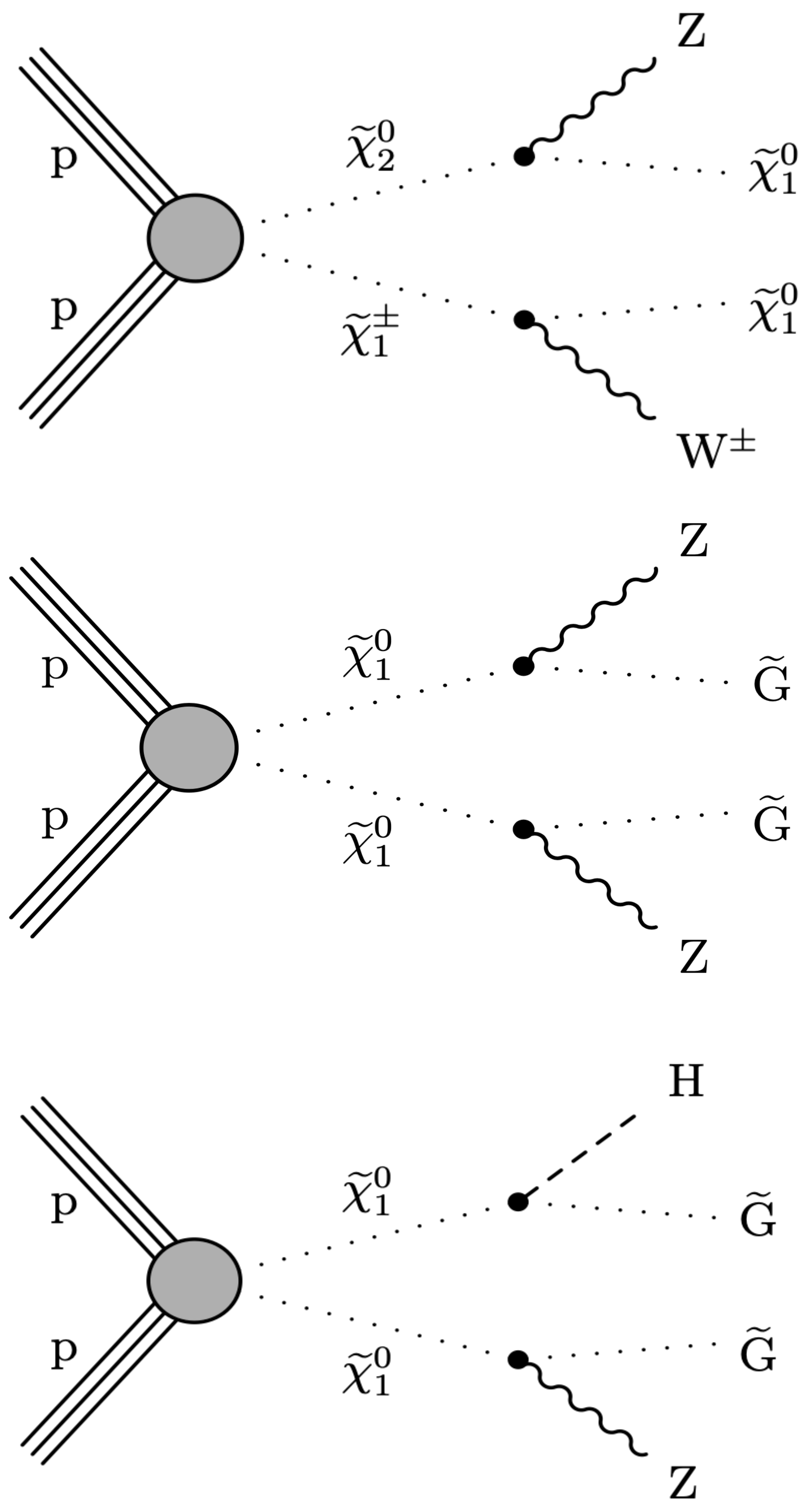
Lepton Reconstruction

- Objects reconstructed from combined readings of multiple subsystems (PF candidates):
  - **Electrons**: tracks + ECAL.
  - **Muons**: global fit combining tracker, muon spectrometer and calorimeters.
- Leptons required to be **prompt** and **isolated**:
  - **Prompt**: cuts on transverse and longitudinal impact parameter.
  - **Isolation**: restriction on scalar p_T sum of all PF candidates in a cone around lepton.



Transverse Slice of CMS Detector

2 OSSF Leptons - Search Regions

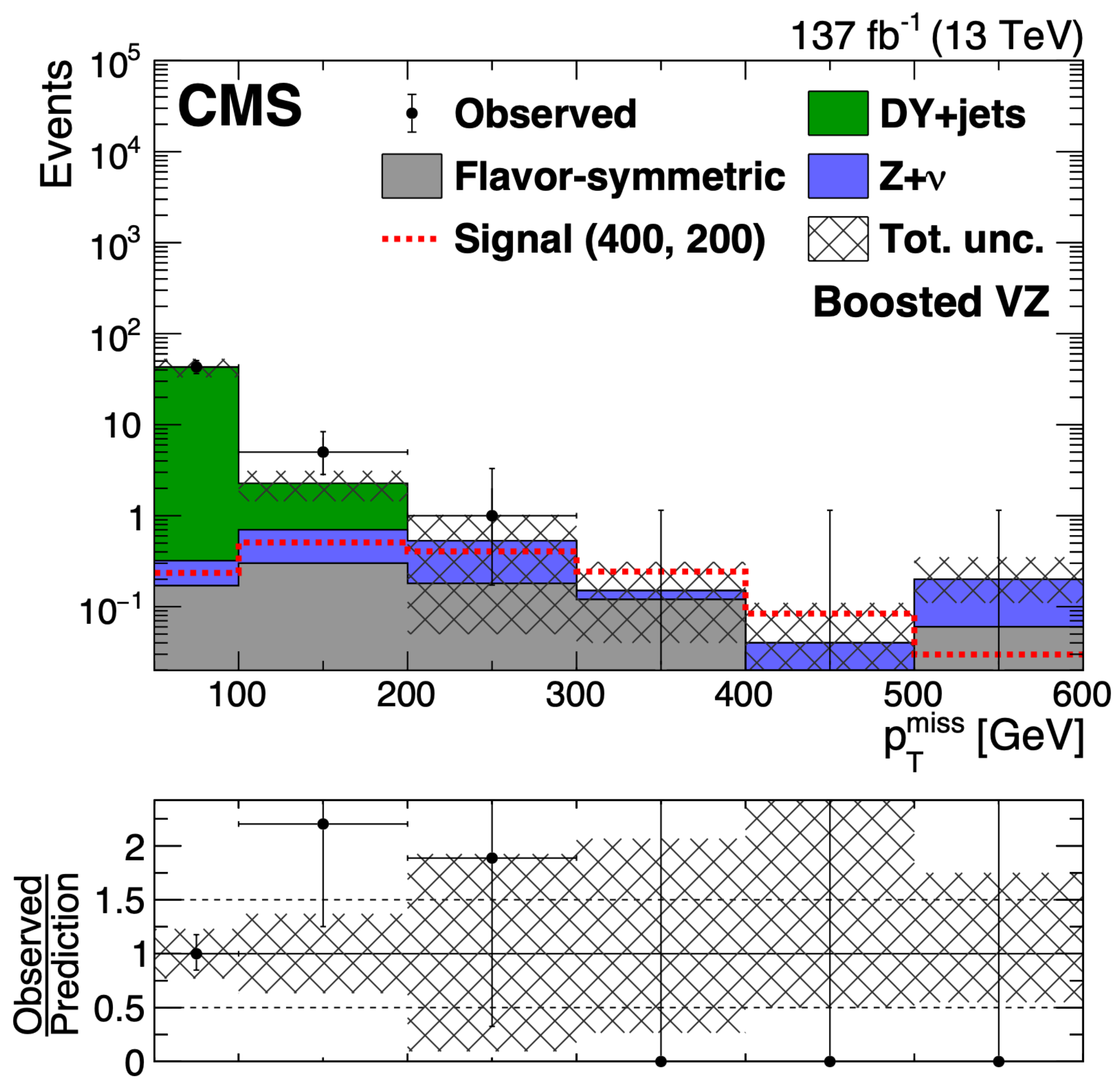


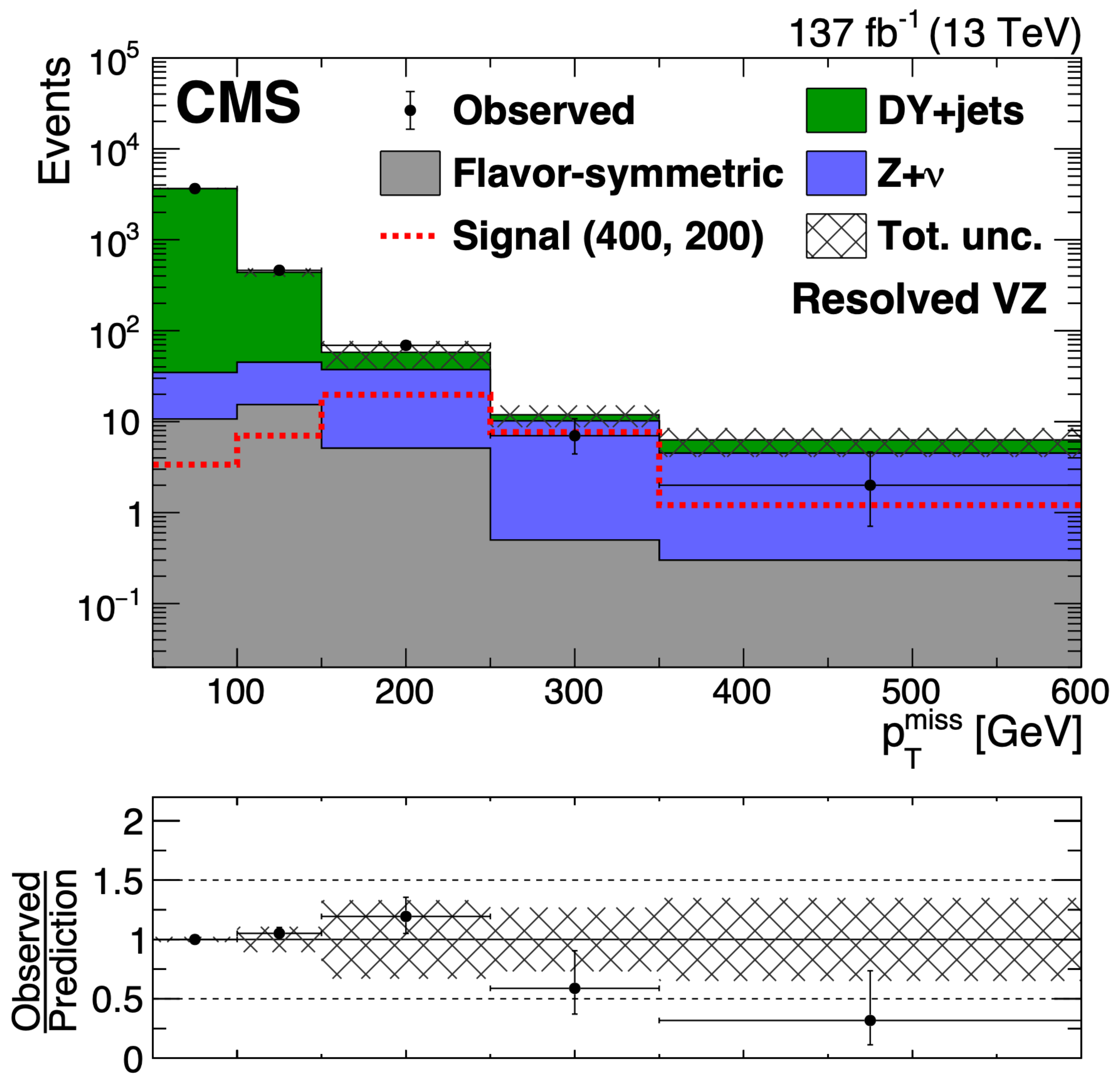
- WZ, ZZ or HZ production with **one Z always decaying leptonically** and the **second boson decaying hadronically**.
- **Three categories binned in p_T^{miss}**: Boosted VZ, Resolved VZ and HZ.
- Resolved VZ and HZ categories:
  - M_{T2} variable to constrain $t\bar{t}$ background.
  - Dijet mass cut to restrict mass window within W, Z and H masses.

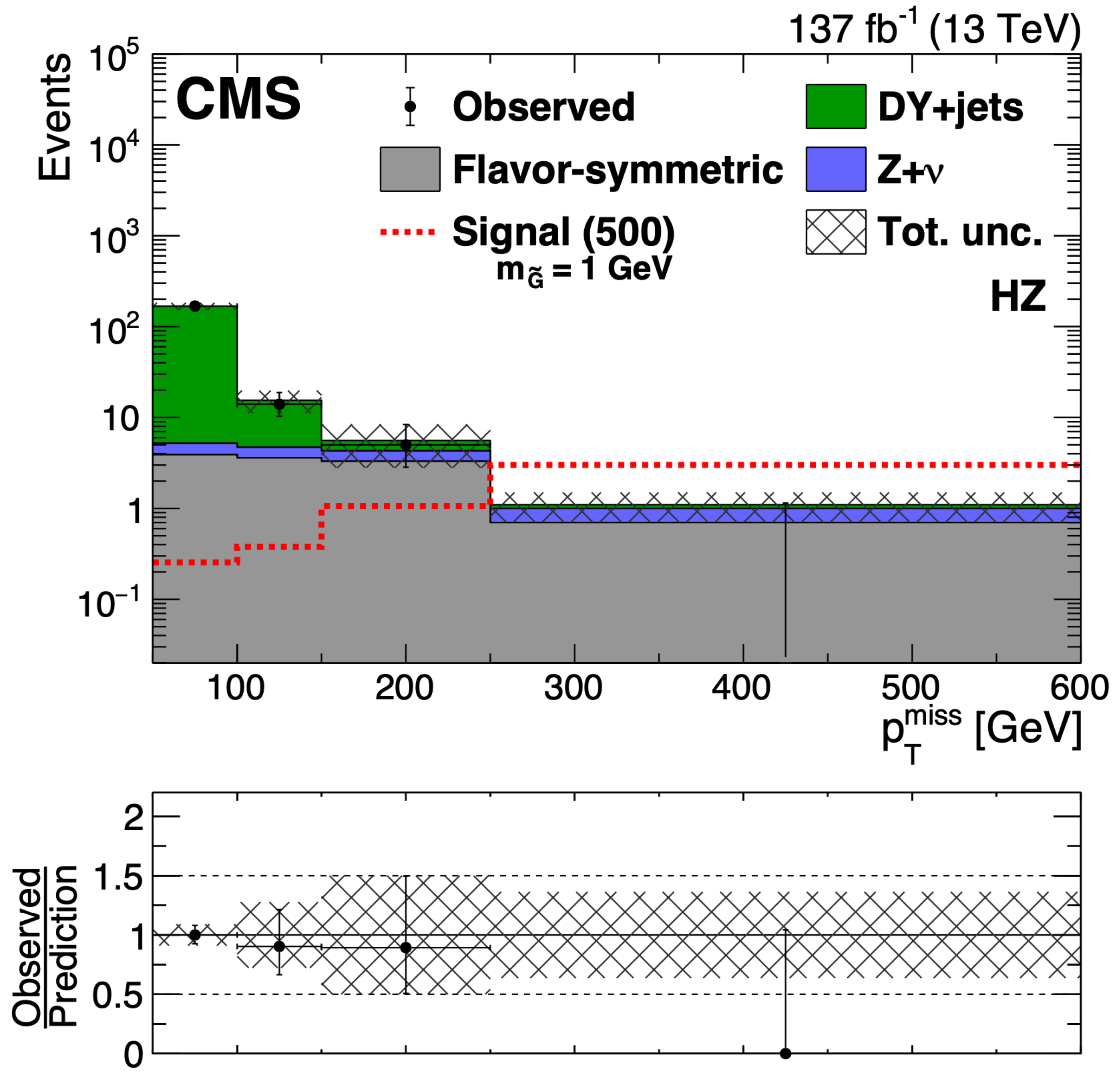
SUS-20-001
arXiv:2012.08600

Region	n_j ($n_V^{boosted}$)	n_b	Dijet mass [GeV]	M_{T2} [GeV]	p_T^{miss} bins [GeV]
Boosted VZ	<2 (>0)	=0	—	—	[100, 200, 300, 400, 500, ∞)
Resolved VZ	>1	=0	$m_{jj} < 110$	$M_{T2}(\ell\ell) > 80$	[100, 150, 250, 350, ∞)
HZ	>1	=2	$m_{bb} < 150$	$M_{T2}(\ell b \ell b) > 200$	[100, 150, 250, ∞)

2 OSSF Leptons - SRs and Background

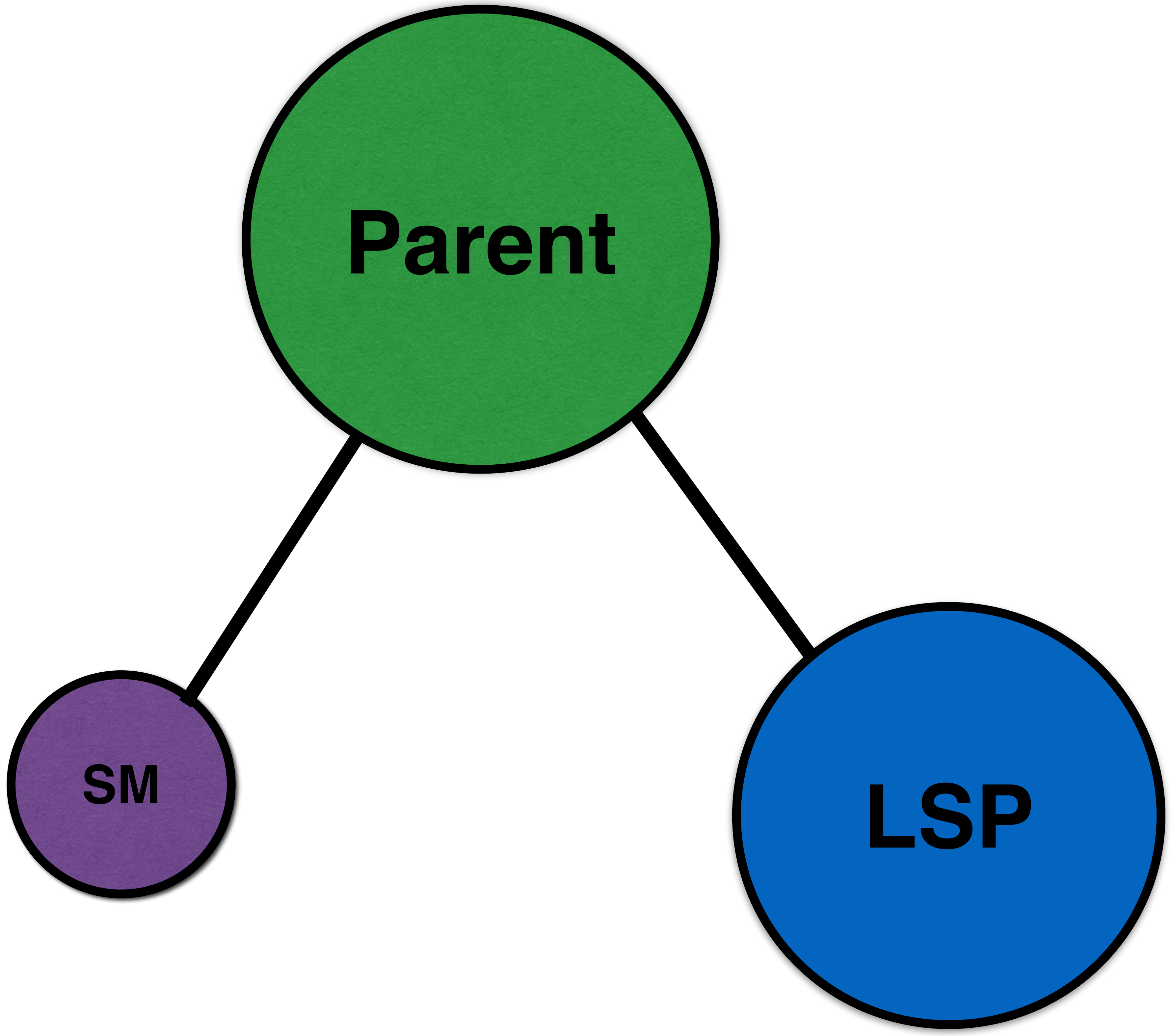






- **Flavor-symmetric**: backgrounds with equal production rates of same flavor (SF) and different flavor (DF) leptons.
  - Transfer factor determined to account for differences in reconstruction, ID and trigger efficiencies between DF and SF.
- **Drell-Yan + Jets**: Corrections to mis-measured p_T^{miss} determined from $\gamma + Jets$ data.
- **Z bosons with genuine p_T^{miss}**: Determined from simulation.

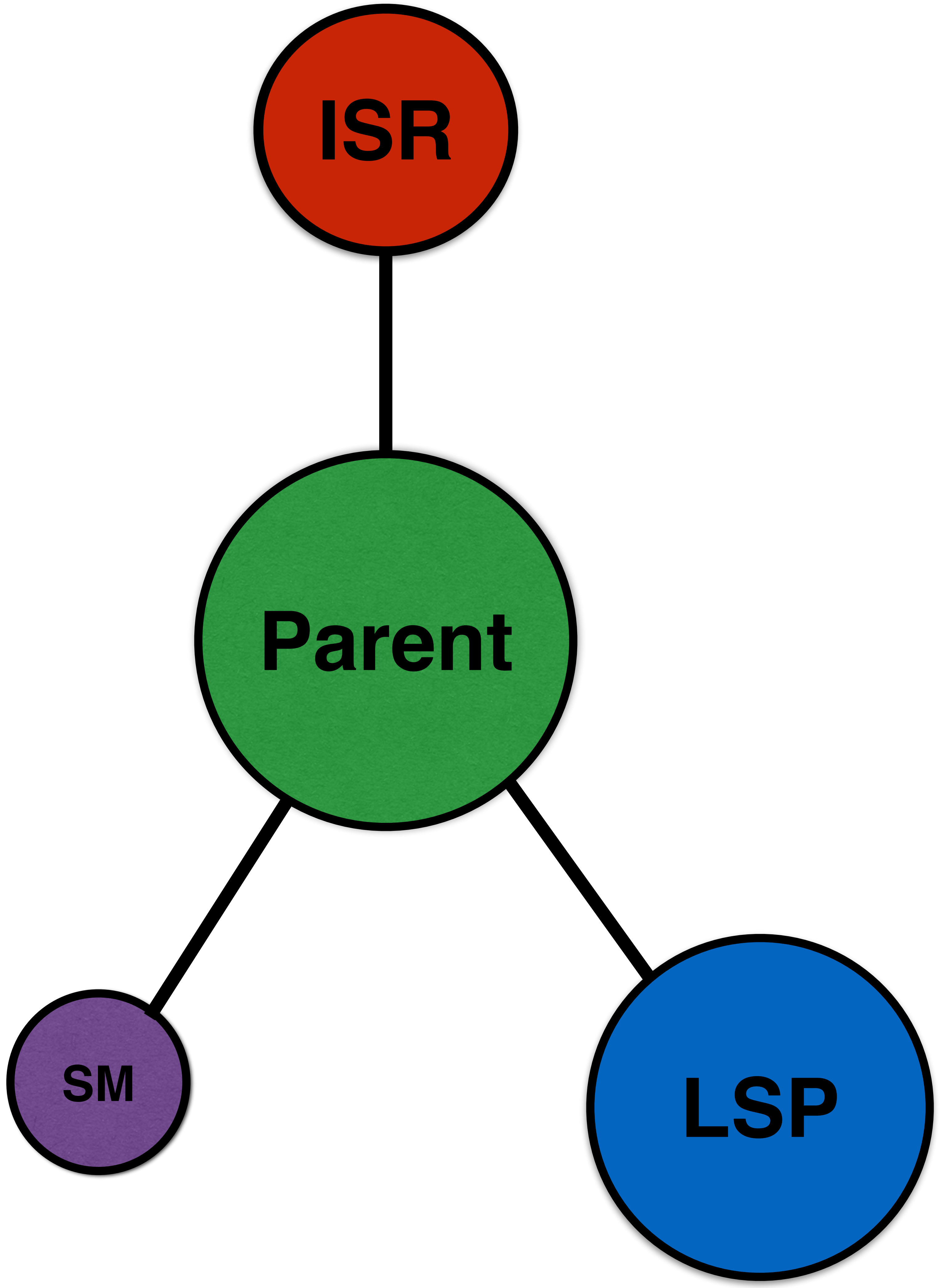
Compressed SUSY



$$M_P \sim M_{LSP}$$

- SUSY decay where **parent** and **child** sparticles are **nearly degenerate in mass**.
- **Low-momentum** decay products:
  - Hard to detect.
  - Blends in with **SM background**.
- We can take advantage of naturally-occurring **ISR** to “kick” decay products.

Compressed SUSY



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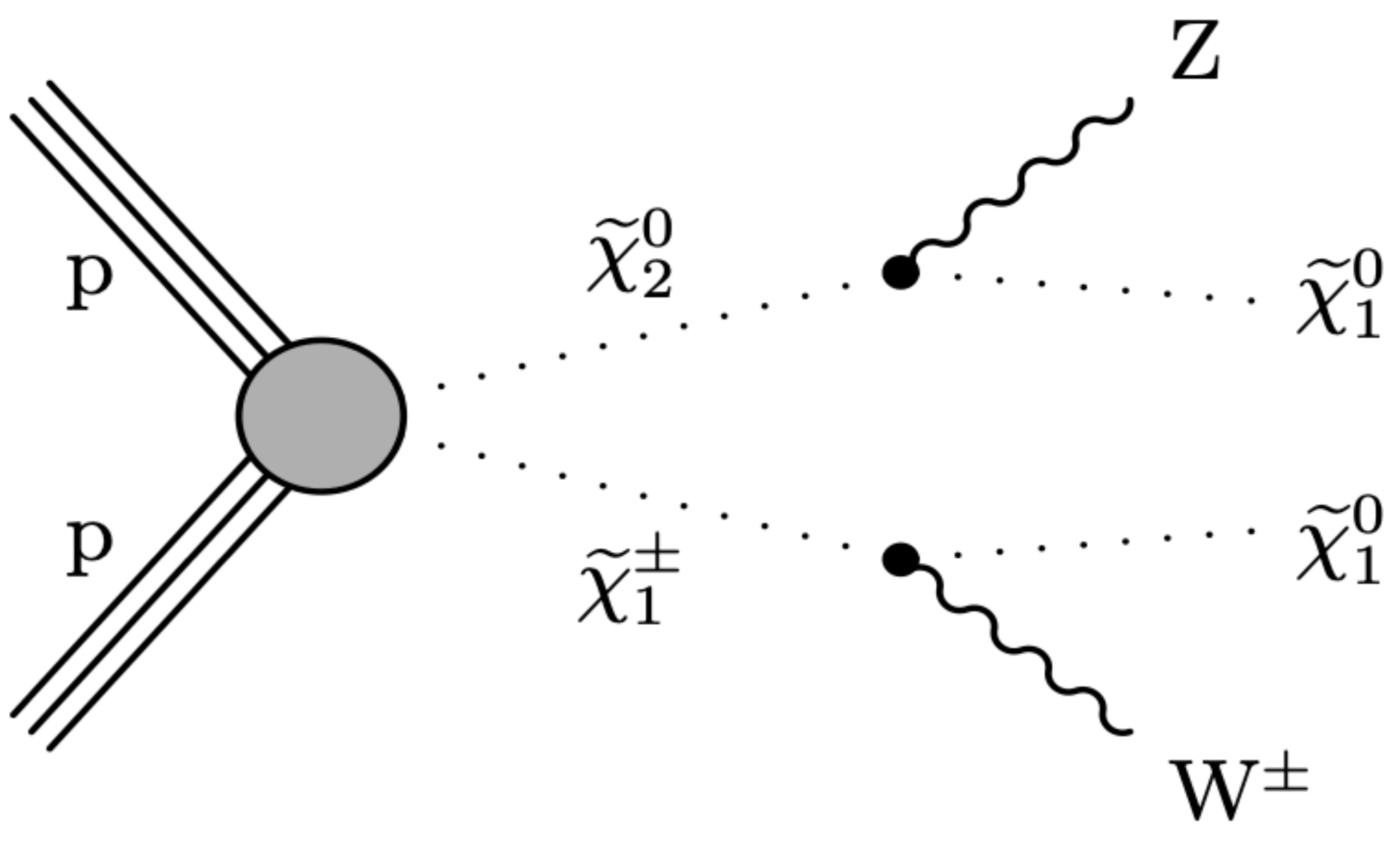
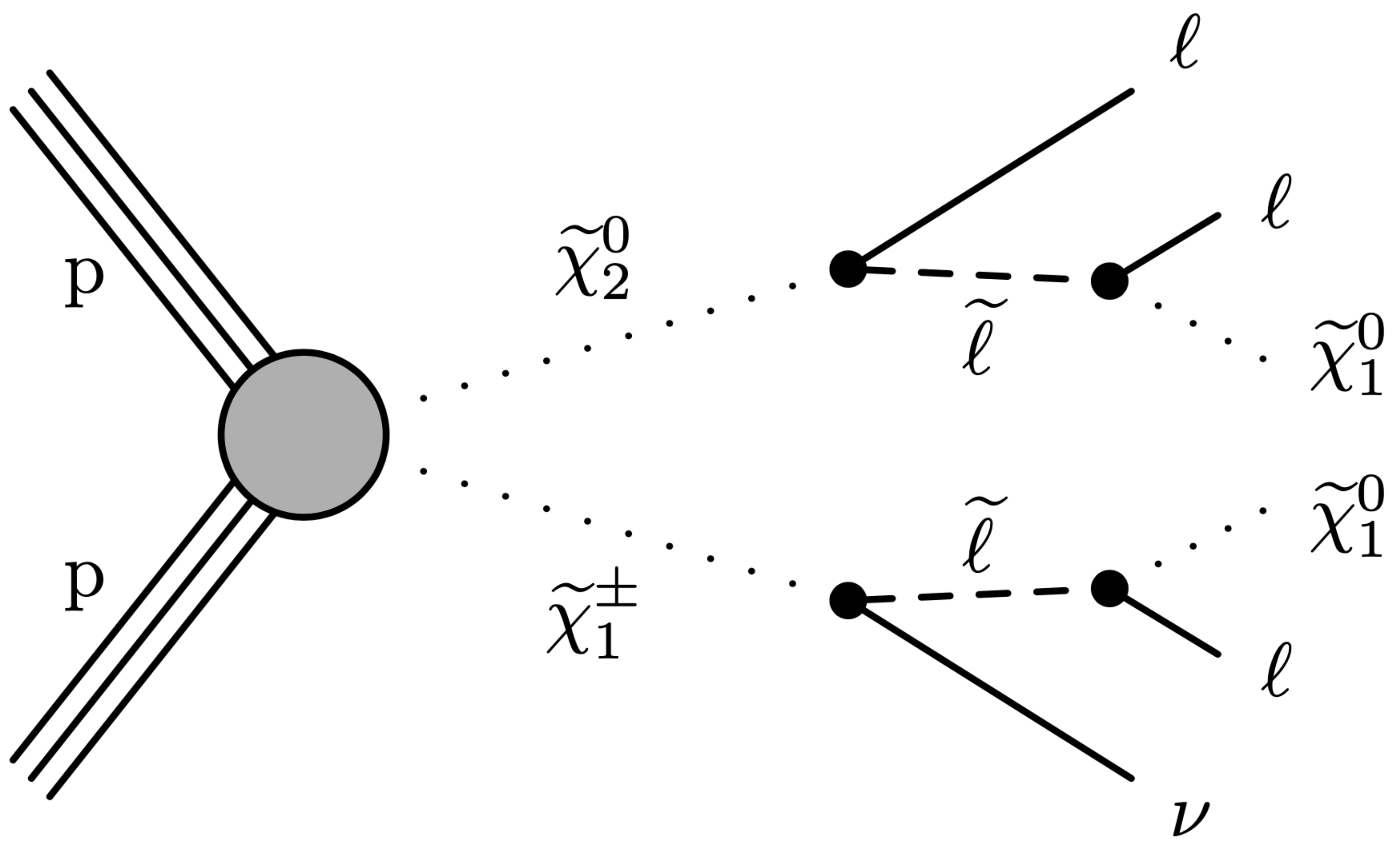
3 Leptons With Parametric NN





SUS-19-012
arXiv:2106.14246

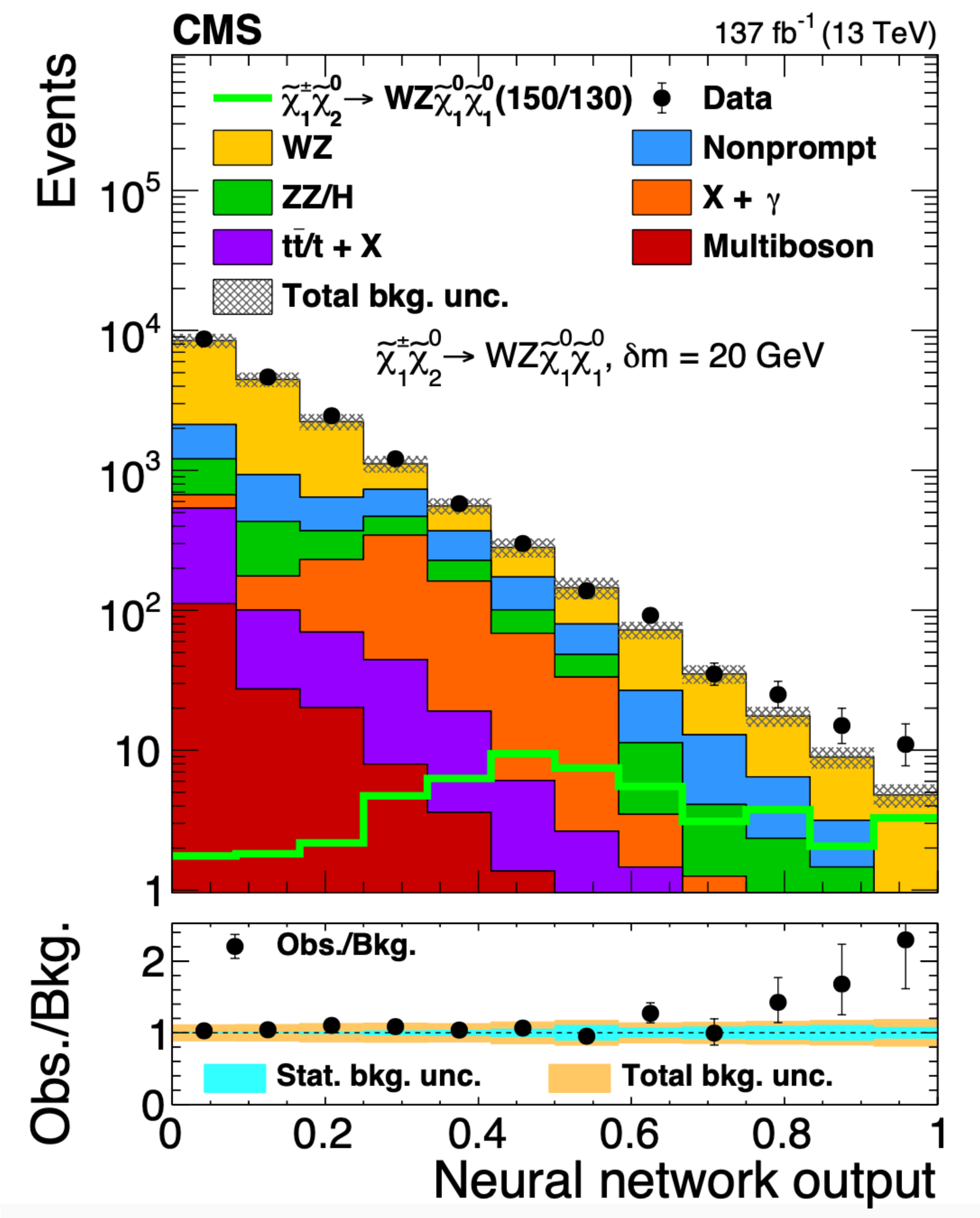
- Final state with three leptons including a OSSF pair.
- **Mass of slepton** (bottom diagram) assumed to be (where $x = 0.05,\ 0.5,\ 0.95$):

$$m_{\tilde{\ell}} = x m_{\tilde{\chi}_2^0} - (1 - x) m_{\tilde{\chi}_1^0}$$

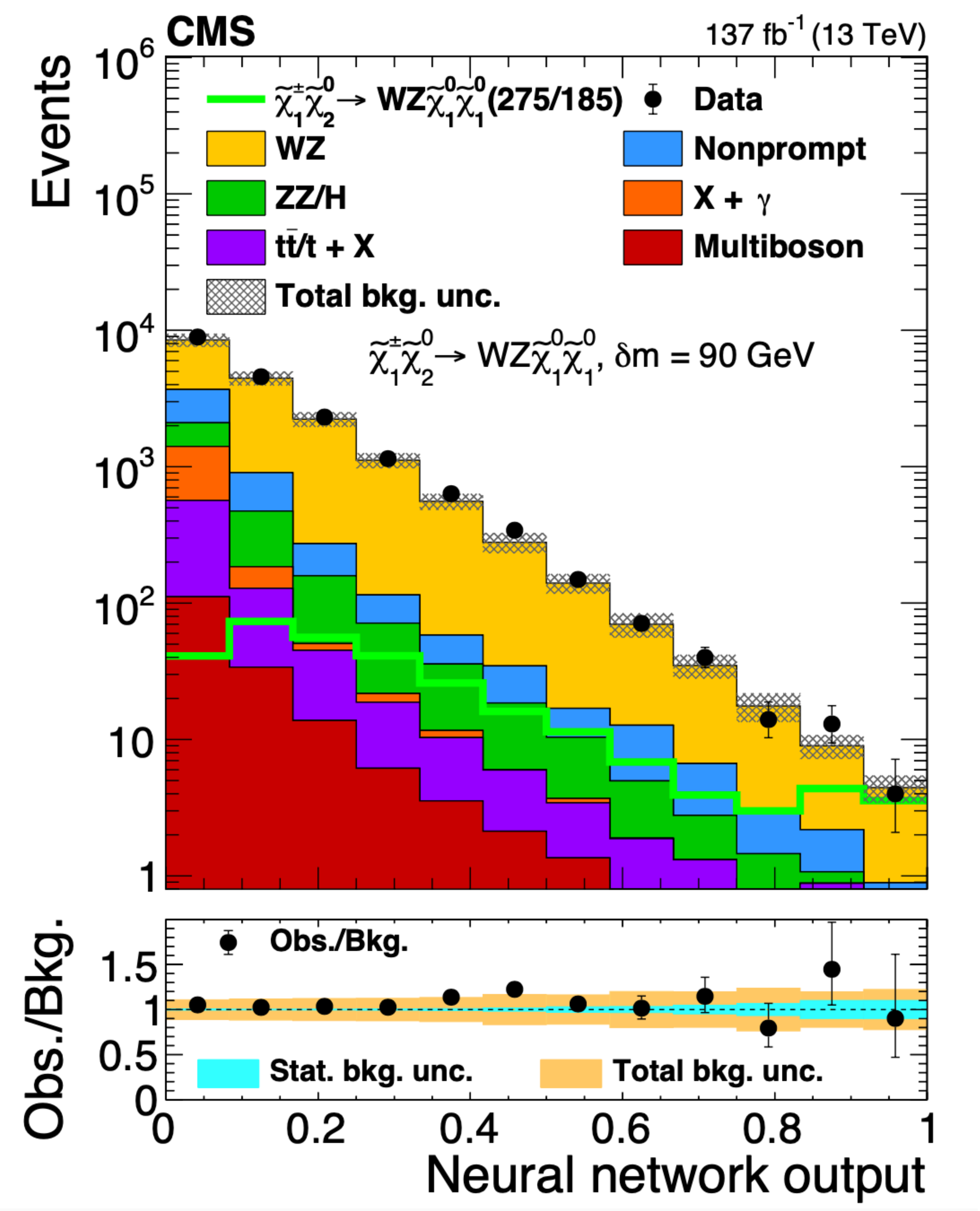
- Neural network trained parametric in $\delta m = m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$ to distinguish signal from background:
  - **Input variables**: $M_{\ell\ell}^{OSSF}$, $M_T^{\ell,3}$, $M_T^{3\ell}$, $M_{3\ell}$, p_T^{miss}, $L_T + p_T^{miss}$ and H_T.
  - **Three representative signal points**: uncompressed, compressed and $\delta m = 90$ GeV (Z boson mass).

3 Leptons With Parametric NN - Results

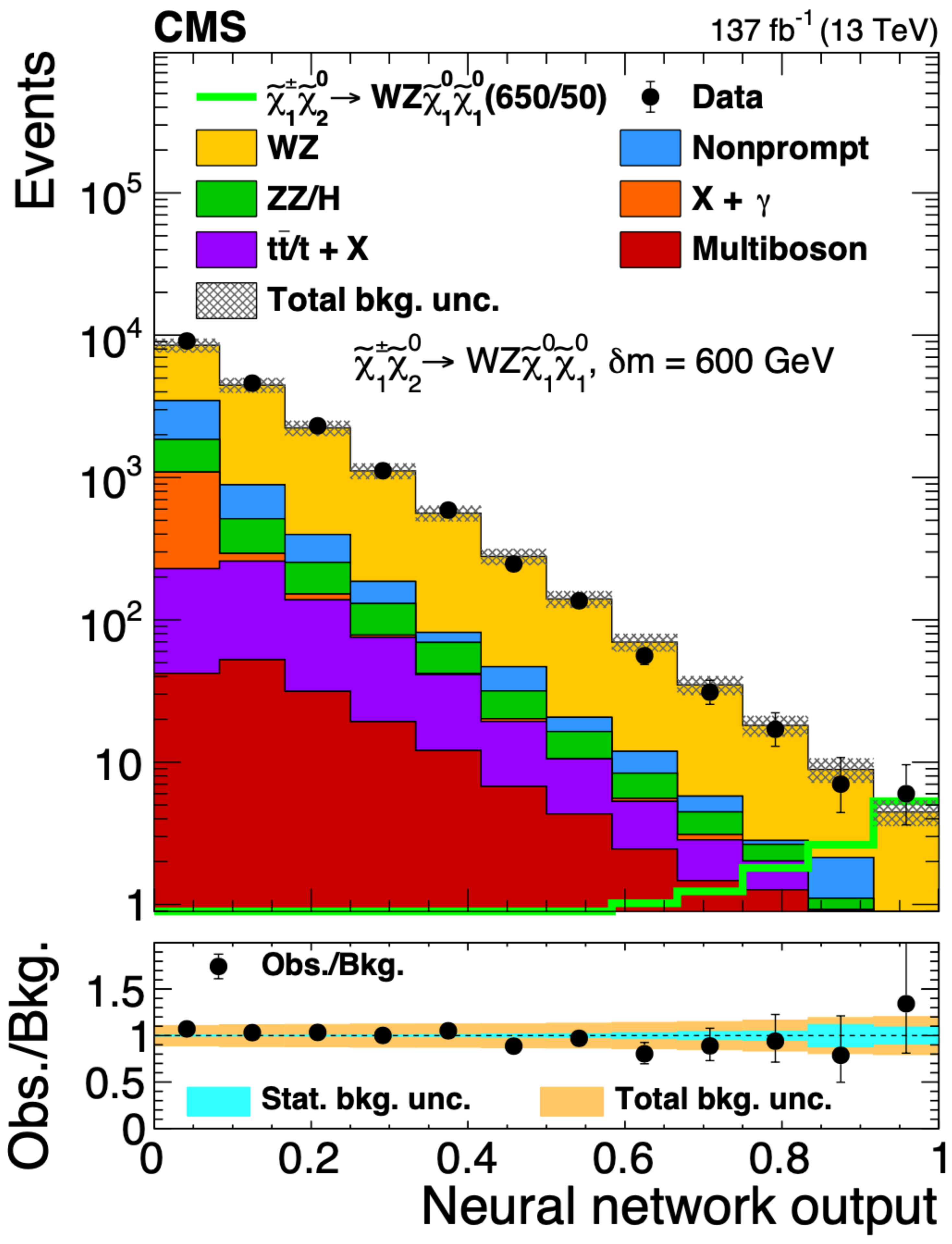
Compressed



Z Mass



Uncompressed



Compressed Search With 2 or 3 Leptons

- 2 or 3 soft leptons ($p_T < 30$ GeV) with at least one OS pair and significant p_T^{miss} induced by an ISR Jet.

- Search regions defined in terms of $\mathbf{p_T^{miss}}$ and **lepton multiplicity**:
  - Binned in OSSF dilepton invariant mass ($\mathbf{M_{OSSF}}(\ell\ell)$ or $\mathbf{M_{OSSF}^{min}}(\ell\ell)$ in the case of 3ℓ).

- **Cut-based selection** for constraining the different SM backgrounds at different ranges of p_T^{miss} (table on the next slide).

SUS-18-004
arXiv:2111.06296

Search region	Low-MET		Med-MET	High-MET	Ultra-MET
	Raw p_T^{miss}	p_T^{miss}	p_T^{miss}	p_T^{miss}	p_T^{miss}
2ℓ-Ewk	> 125	$(125, 200]$	$(200, 240]$	$(240, 290]$	> 290
2ℓ-Stop	> 125	$(125, 200]$	$(200, 290]$	$(290, 340]$	> 340
3ℓ-Ewk	> 125	$(125, 200]$		> 200	

Compressed Search With 2 or 3 Leptons

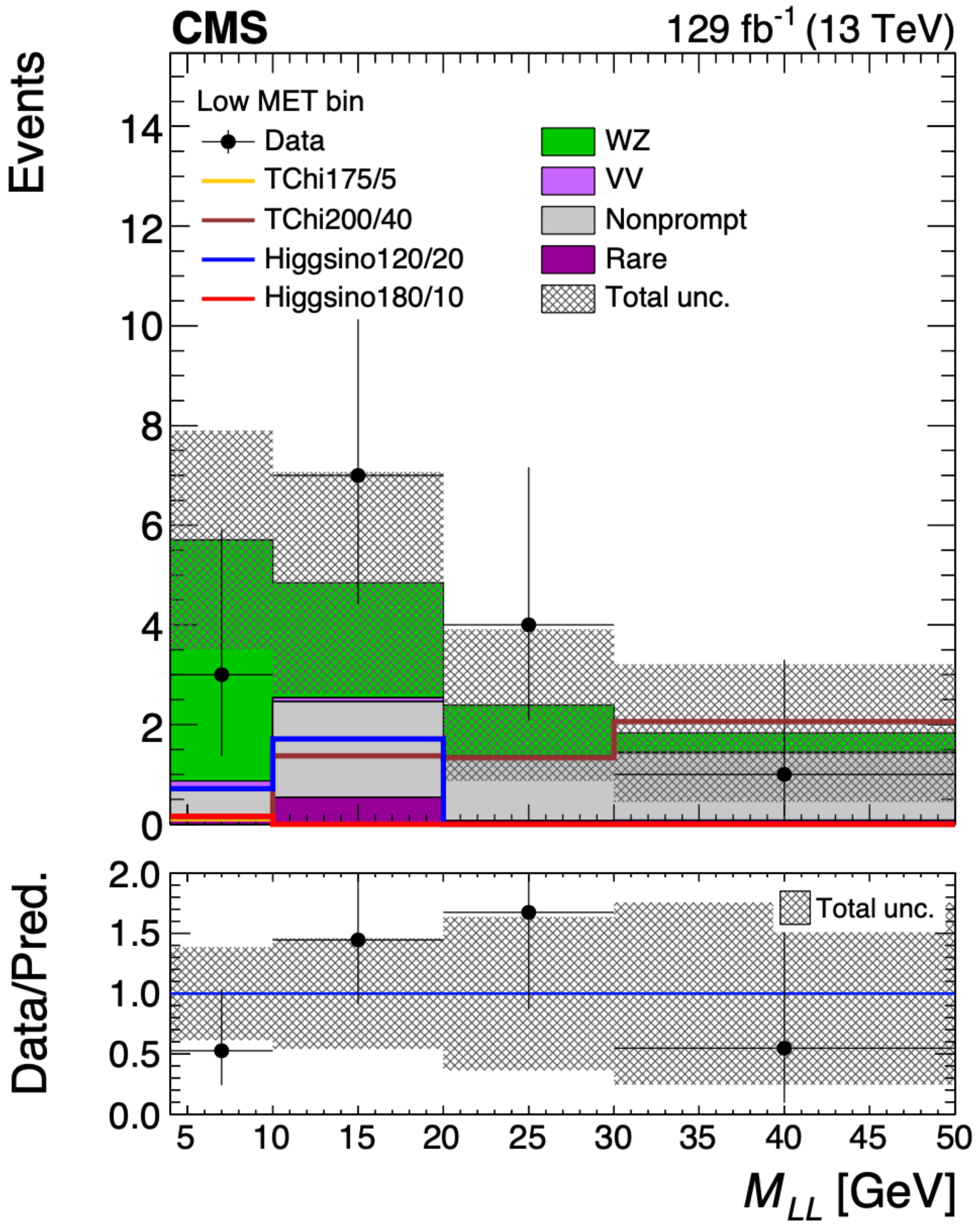
Discussed Next Slide

Variable	2ℓ-Ewk		2ℓ-Stop		3ℓ-Ewk	
	Low-MET	Higher-MET	Low-MET	Higher-MET	Low-MET	Higher-MET
N_{lep}	2	2	2	2	3	3
$p_{\text{T}}(\ell_1)$ [GeV] for e(μ)	(5, 30)	(5(3.5), 30)	(5, 30)	(5(3.5), 30)	(5, 30)	(5(3.5), 30)
$p_{\text{T}}(\ell_2)$ [GeV] for e(μ)	(5, 30)	(5(3.5), 30)	(5, 30)	(5(3.5), 30)	(5, 30)	(5(3.5), 30)
$p_{\text{T}}(\ell_3)$ [GeV] for e(μ)	—	—	—	—	(5, 30)	(5(3.5), 30)
1 OS pair	✓	✓	✓	✓	✓	✓
1 OSSF pair	✓	✓	✓	—	✓	✓
$\Delta R(\ell_i \ell_j)$ ($i, j = 1, 2, 3, i \neq j$)	—	> 0.3	—	> 0.3	—	> 0.3
$M_{\text{SFOS}}(\ell\ell)$ ($M^{\text{min}}_{\text{SFOS}}(\ell\ell)$ in 3ℓ) [GeV]	(4, 50)	(1, 50)	(4, 50)	(1, 50)	(4, 50)	(1, 50)
$M^{\text{max}}_{\text{SFAS}}(\ell\ell)$ (AS=any sign) [GeV]	—	—	—	—	< 60	—
$M_{\text{SFOS}}(\ell\ell)$ ($M^{\text{min}}_{\text{SFOS}}(\ell\ell)$ in 3ℓ) [GeV]			veto (3, 3.2) and (9, 10.5)			
$p_{\text{T}}(\ell\ell)$ [GeV]	> 3		> 3		—	
Leading jet "Tight lepton veto"	✓		✓		—	
$m_{\text{T}}(\ell_i, p_{\text{T}}^{\text{miss}})$ [GeV] ($i = 1, 2$)	< 70		—		—	
H_{T} [GeV]			> 100			
$p_{\text{T}}^{\text{miss}} / H_{\text{T}}$	(2/3, 1.4)		(2/3, 1.4)		—	
$\text{N}_b(p_{\text{T}} > 25\,\text{GeV})$			$= 0$			
$M_{\tau\tau}$ [GeV]	veto (0, 160)		veto (0, 160)		—	

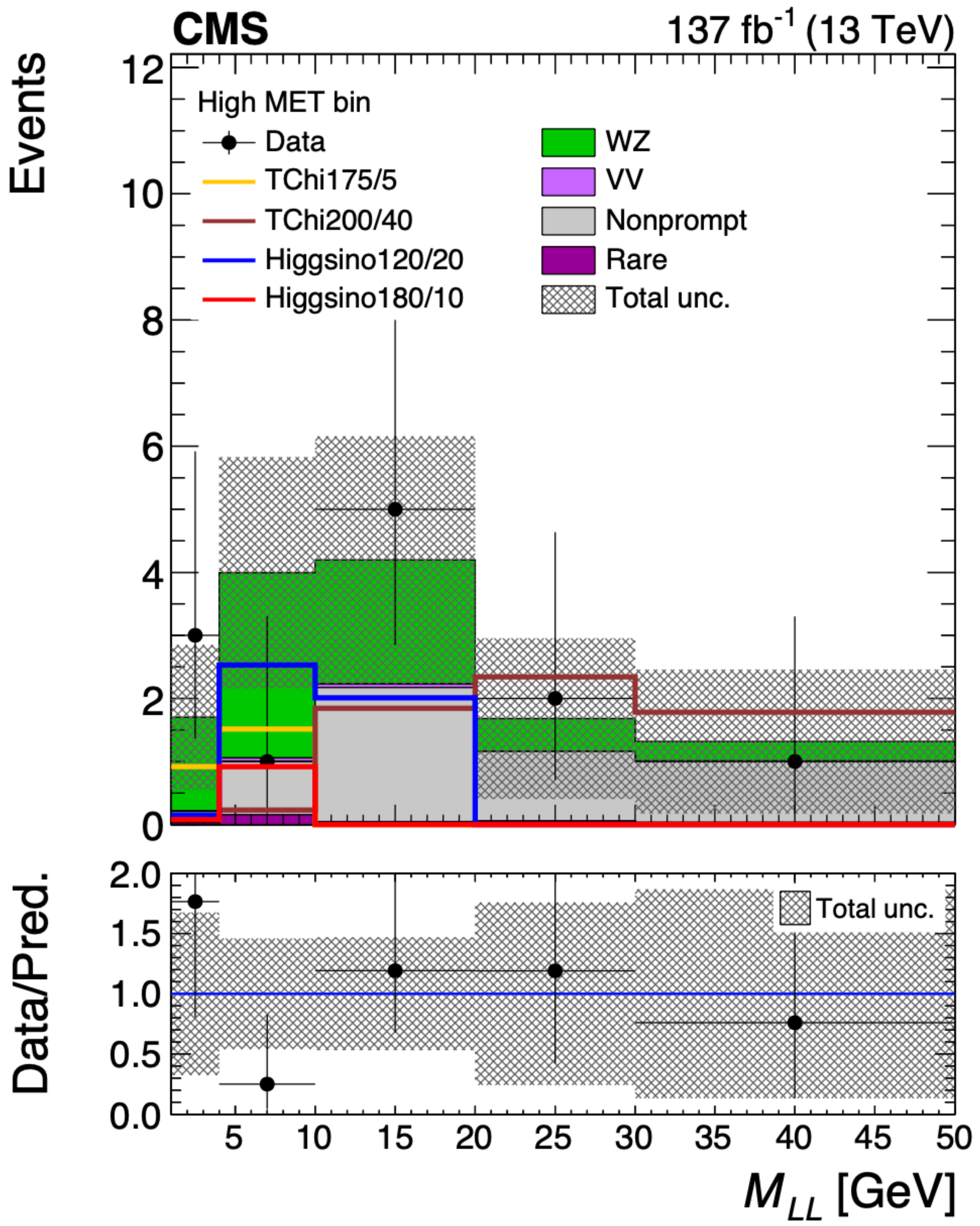
ISR Jets

Compressed Search - Signal Regions and Background

Low MET

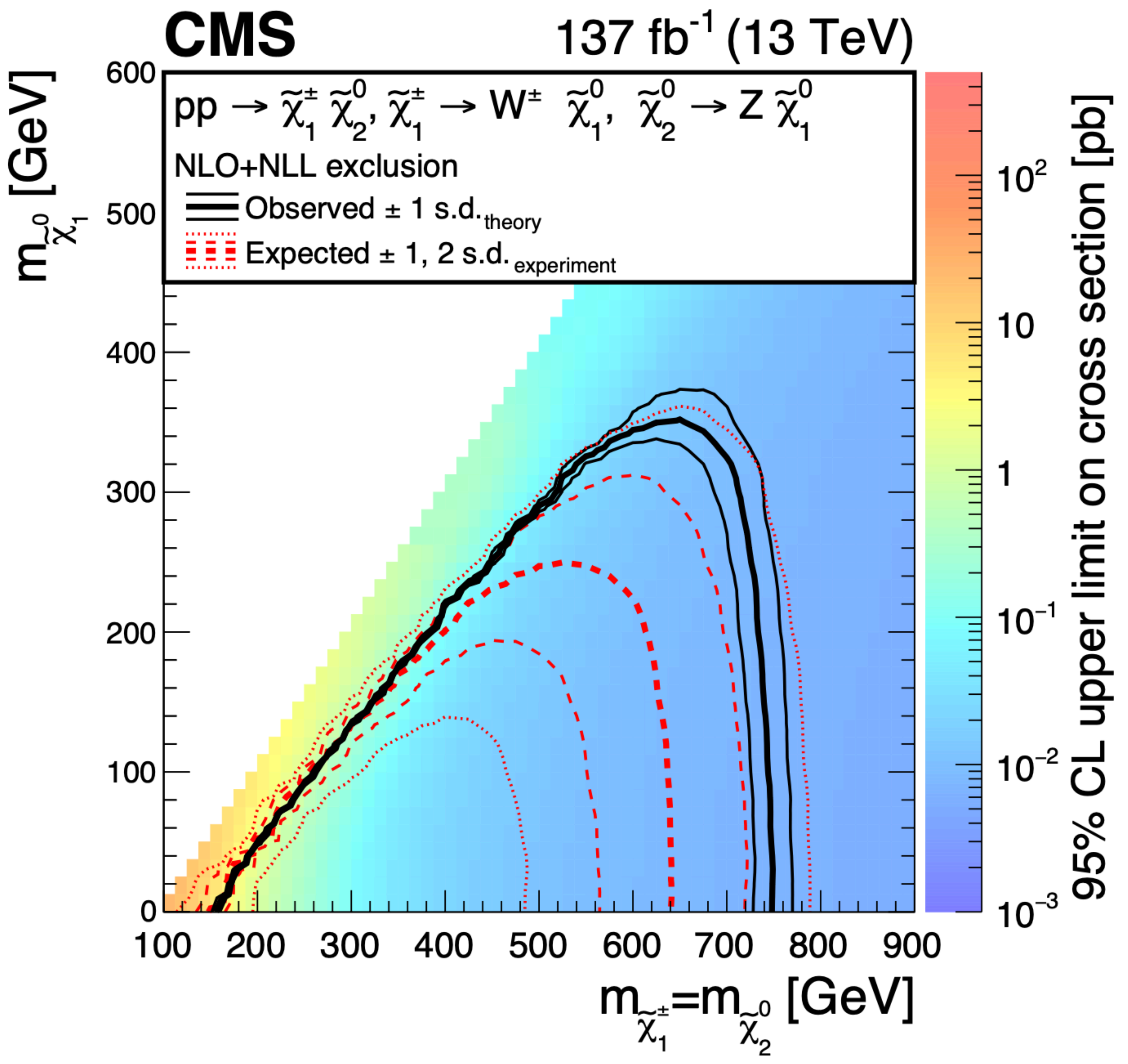


High MET



3ℓ Ewk Category

- Control regions with Leading lepton $p_T > 30$ GeV.
- **WZ-enriched control region**:
  - At least one μ with $p_T > 20$ GeV.
  - No $M_{OSSF}^{min}(\ell\ell)$ upper requirement and no $M_{ASSF}^{max}(\ell\ell)$ requirement.
- **VV validation region**:
  - Invert $m_T(\ell_i, p_t^{miss})$ requirement (2ℓ only).
- **Rare** - Determined from MC simulation.
- **Non-prompt** - "Tight-to-loose" method.



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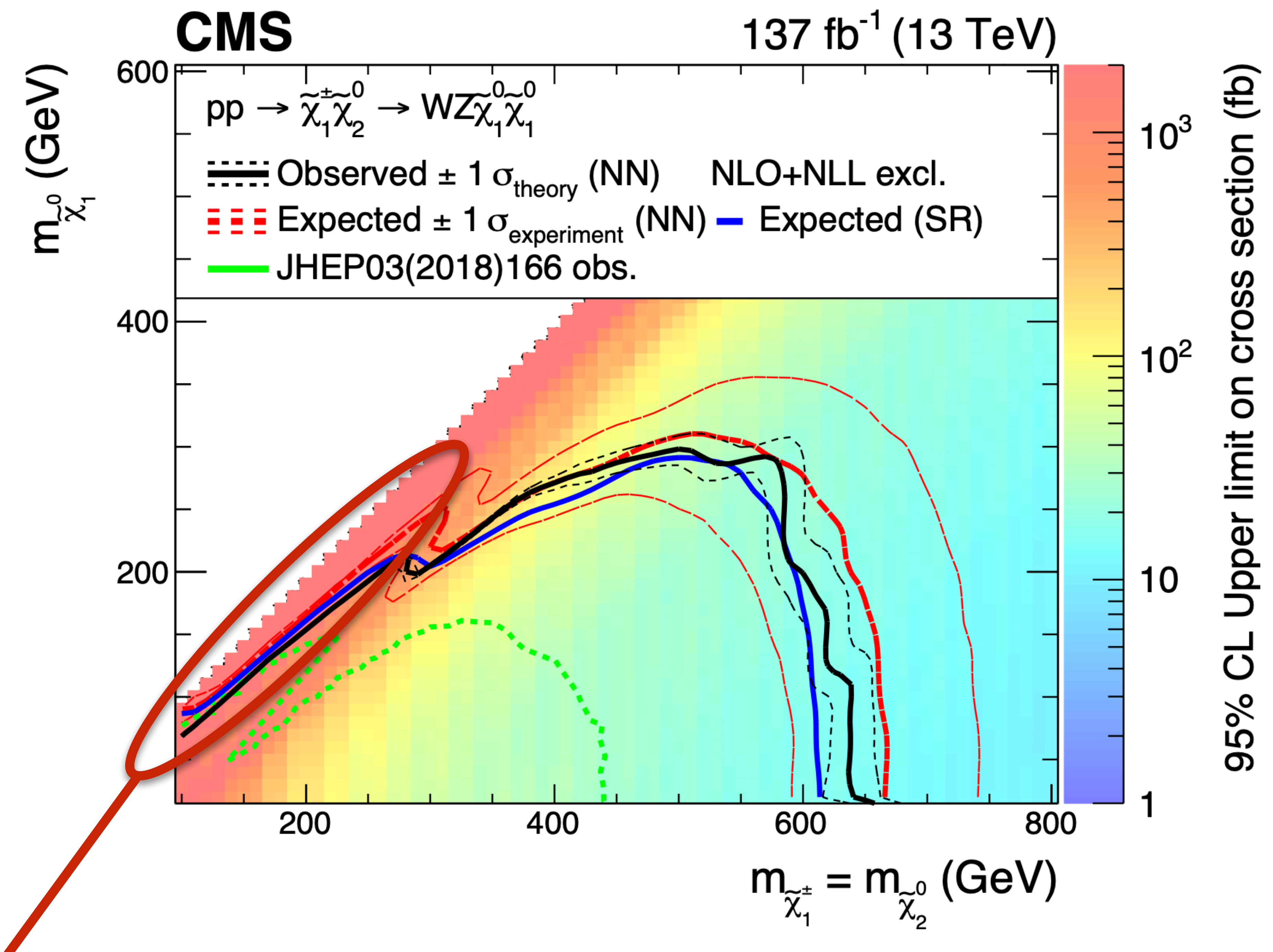

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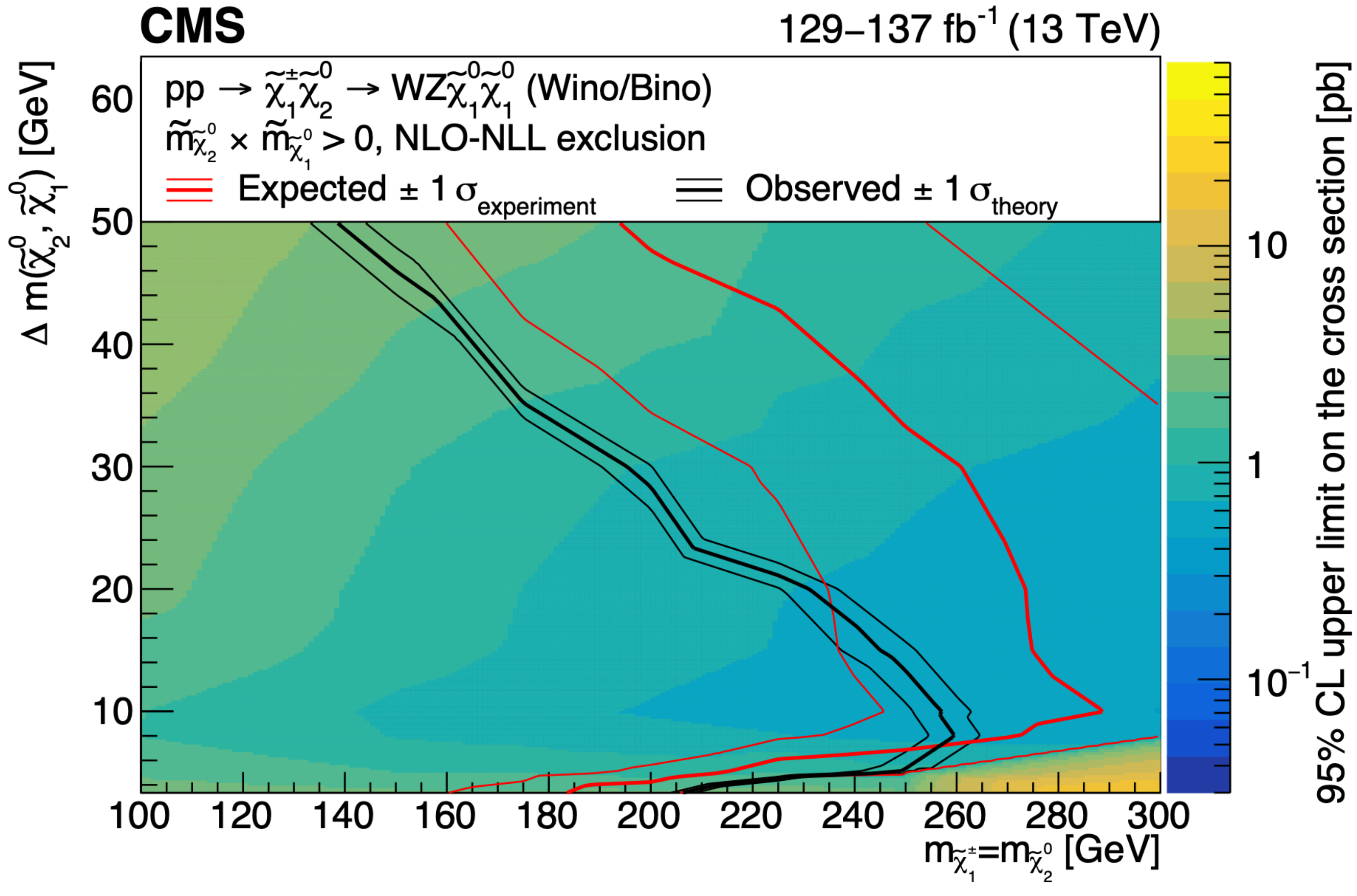

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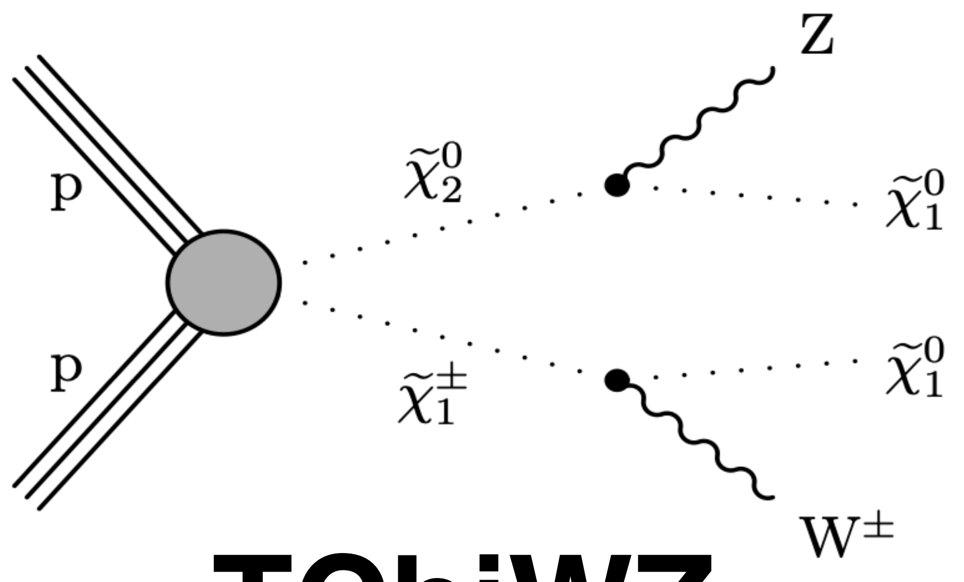
Compressed



TChiWZ

Summary and Outlook

- **Good reason to believe electroweak SUSY is within reach at the LHC**.
- Three recent analysis techniques shown for electroweak SUSY with leptonic final states:
  - **No significant excesses** observed for SUSY signal models studied.
  - **Mass exclusions extended** from previous similar searches.
- Stay tuned:
  - **New analysis techniques** to improve sensitivities to various SUSY signals.
  - **Run 3 data taking is starting with improved CMS detector!**

Backup

SUS-20-001

Flavor-Symmetric Background Estimation

$$r_{\mu/\mathrm{e}}(p_{\mathrm{T}},\eta) = r^{0}_{\mu/\mathrm{e}}\, f(p_{\mathrm{T}})\, g(\eta),$$

where

$$f(p_{\mathrm{T}}) = (a_1 + b_1/p_{\mathrm{T}}),$$

and

$$g(\eta) = a_2 + \begin{cases} 0 & |\eta| < 1.6 \\ c_1(\eta - 1.6)^2 & \eta > 1.6 \\ c_2(\eta + 1.6)^2 & \eta < -1.6 \end{cases}.$$

Year	$r^{0}_{\mu/e}$	a_1	b_1	a_2	c_1	c_2
2016	1.277 ± 0.001	1.493 ± 0.008	6.135 ± 0.364	0.600 ± 0.001	0.356 ± 0.022	0.476 ± 0.024
2017	1.226 ± 0.001	1.356 ± 0.008	6.665 ± 0.325	0.647 ± 0.002	0.462 ± 0.024	0.690 ± 0.027
2018	1.234 ± 0.001	1.437 ± 0.006	3.870 ± 0.266	0.653 ± 0.001	0.097 ± 0.015	0.099 ± 0.015

$$R_{\mathrm{SF/DF}} = (1/2)(r_{\mu/\mathrm{e}}(\mu) + r_{\mu/\mathrm{e}}(\mathrm{e})^{-1})R_{\mathrm{T}}.$$

Transfer Factor For Estimating SF from DF

- Difference in reconstruction from residual differences in the efficiencies between e and μ.
- Same selection as SR but requiring DF instead of SF.
- Constants extracted from fit of $r_{\mu/e}$ in data over η and p_T.

Drell-Yan+Jets Background

- Mis-measurements of momenta of reconstructed objects affecting $\vec{p}_T^{miss}$:
  - Jet energy mis-measurement.
  - Estimated from p_T^{miss} "templates" method.
- p_T^{miss} distribution estimated from $\gamma + jets$ data:
  - Identical jet requirements in SRs.
  - M_{T2} emulated from photon decaying into 2 leptons.
  - Weights determined from the SRs to account for differences in masses between Z and γ.

Yields

Category	SM processes						
Boosted VZ	$p_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	50–100	100–200	200–300	300–400	400–500	>500
	DY+jets	42.7 ± 9.9	1.6 ± 0.8	0.0 ± 0.5	$0.0^{+0.1}_{-0.0}$	$0.0^{+0.1}_{-0.0}$	$0.0^{+0.1}_{-0.0}$
	Flavor-symmetric	$0.2^{+0.2}_{-0.1}$	0.3 ± 0.2	$0.2^{+0.2}_{-0.1}$	0.1 ± 0.1	$0.0^{+0.1}_{-0.0}$	0.1 ± 0.1
	Z+ν	0.2 ± 0.2	0.4 ± 0.2	0.3 ± 0.1	$0.0^{+0.1}_{-0.0}$	$0.0^{+0.1}_{-0.0}$	0.1 ± 0.1
	Total background	43.0 ± 9.9	2.3 ± 0.8	0.5 ± 0.5	$0.2^{+0.2}_{-0.1}$	$0.0^{+0.1}_{-0.0}$	0.2 ± 0.1
	Observed	43	5	1	0	0	0
Resolved VZ	$p_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	50–100	100–150	150–250	250–350	>350	
	DY+jets	3613 ± 80	394 ± 46	21 ± 18	1.7 ± 2.4	1.8 ± 1.9	
	Flavor-symmetric	$10.7^{+3.0}_{-2.9}$	15.4 ± 4.2	5.1 ± 1.5	0.5 ± 0.2	0.3 ± 0.2	
	Z+ν	24.0 ± 4.1	29.5 ± 5.6	32.2 ± 6.5	9.7 ± 2.2	4.2 ± 1.1	
	Total background	3648 ± 80	439 ± 47	58 ± 19	11.9 ± 3.2	6.3 ± 2.2	
	Observed	3648	461	69	7	2	
HZ	$p_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	50–100	100–150	150–250	>250		
	DY+jets	163 ± 15	10.8 ± 4.1	1.3 ± 2.5	0.1 ± 0.3		
	Flavor-symmetric	3.9 ± 1.4	3.6 ± 1.3	3.3 ± 1.2	0.7 ± 0.3		
	Z+ν	1.3 ± 0.3	1.1 ± 0.2	1.0 ± 0.2	0.3 ± 0.1		
	Total background	168 ± 15	15.6 ± 4.3	5.6 ± 2.8	1.2 ± 0.4		
	Observed	168	14	5	0		

$Z + \nu$ Background Estimation

Source of uncertainty	Uncertainty (%)
Integrated luminosity	1.8
Limited size of simulated samples	1–15
Simulation modeling in data CRs	30–50
Trigger efficiency	3
NNLO/NLO κ-factor (for ZZ)	10–30
Lepton efficiency	5
b tagging efficiency	0–5
JES	0–5
Pileup modeling	1–2
μ_{R} and μ_{F} dependence	1–3

Systematic Uncertainties

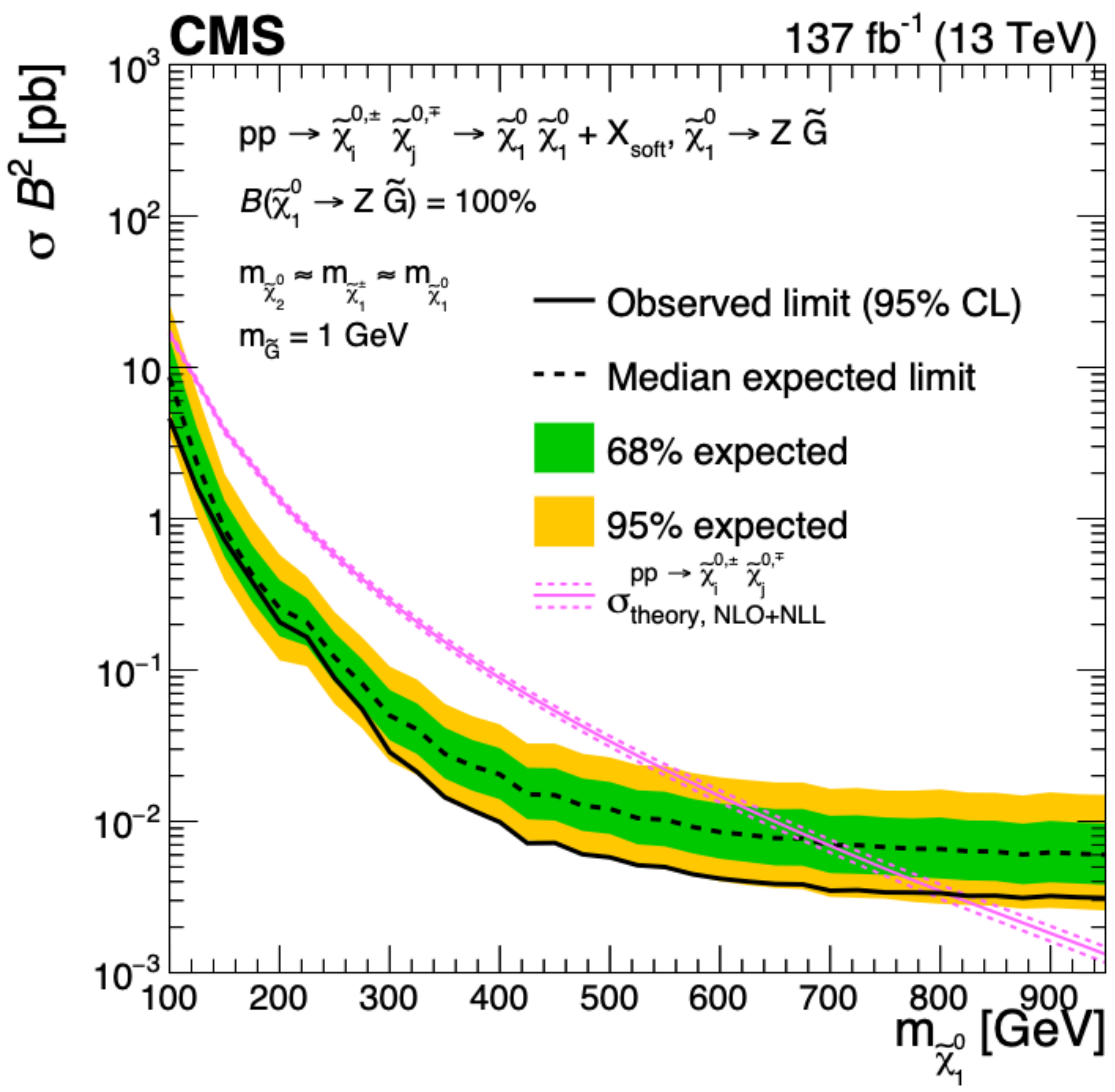
- Combined background of $Z/\gamma*$, WZ, ZZ and $t\bar{t}Z$.
- Estimated directly from simulation.
- Overall normalization determined from dedicated data CRs of trileptons and two pairs of OSSF leptons.

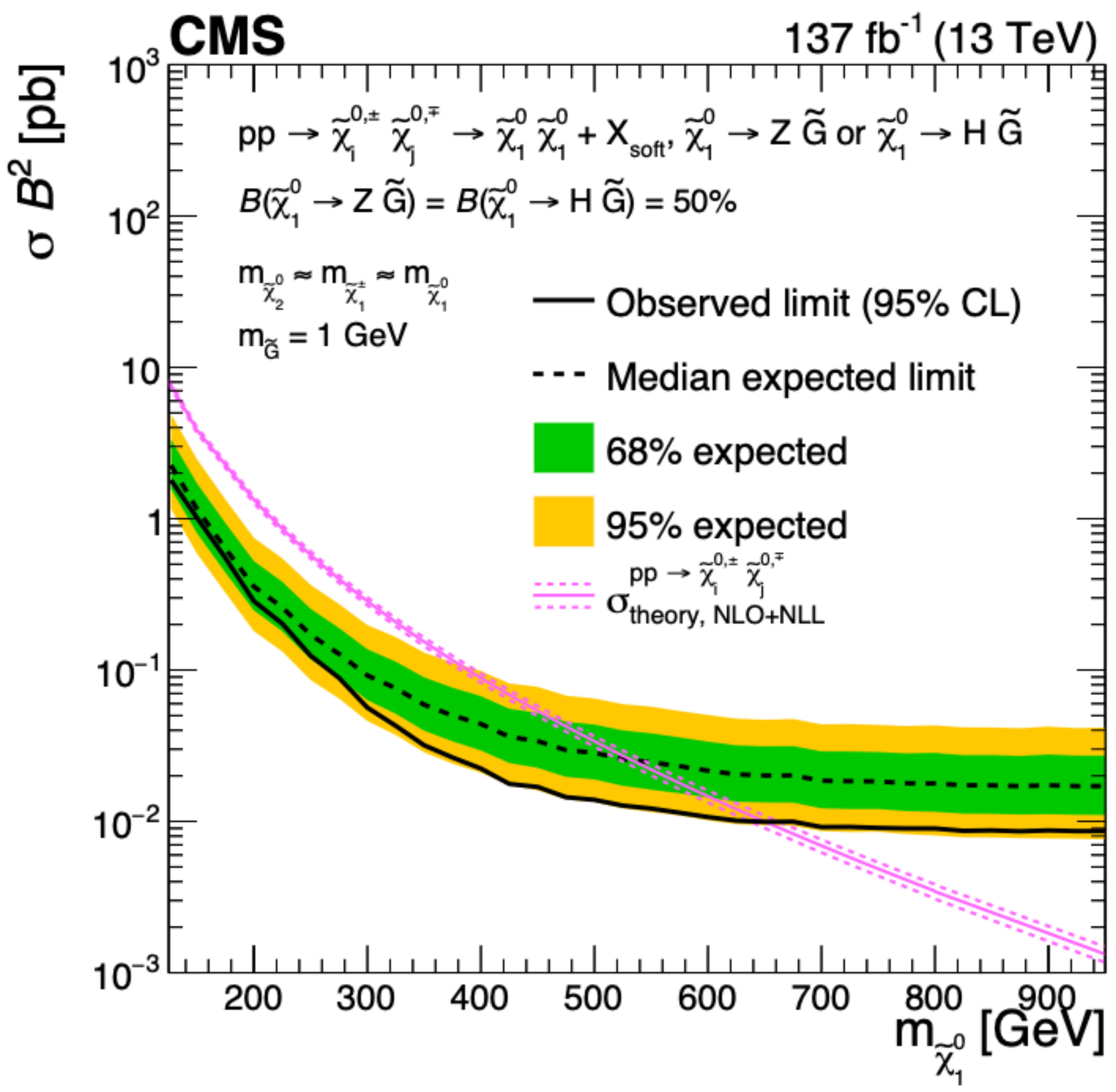
Background Estimation Uncertainties

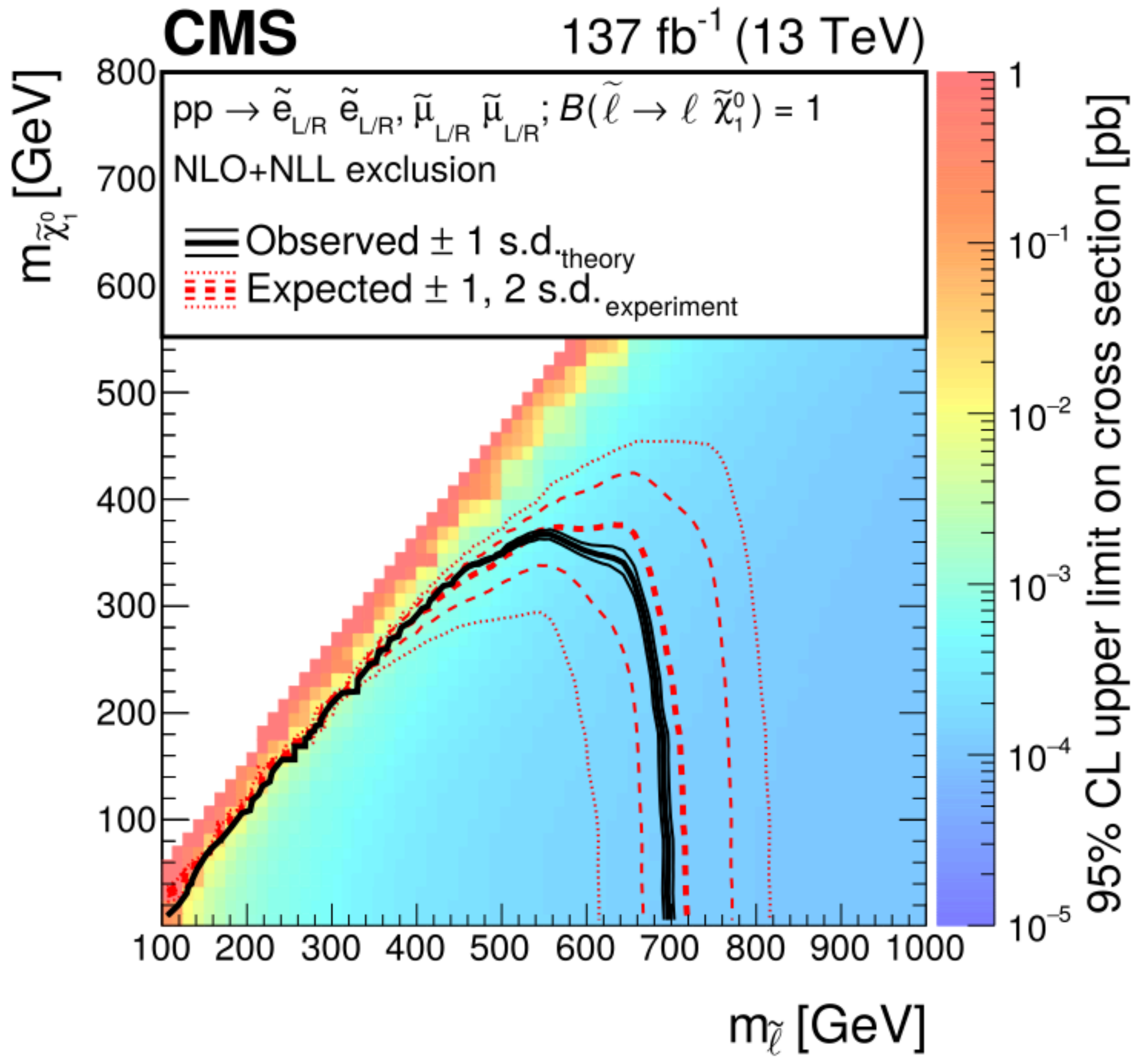
Source	Size
Flavor-symmetric backgrounds	
$r_{\mu/e}$ residual dependencies	5% flat
	5% p_T-dependent
	5% η-dependent
R_T uncertainty	4–5%
Statistical uncertainty in DF sideband	✓
κ uncertainty (on-Z SRs only)	20%
p_T^{miss} templates	
Closure in simulations	20–100%
Statistical uncertainty in γ+jets sample	✓
Statistical uncertainty in normalization bin	✓
EW subtraction	30% of EW yield
	in γ+jets sample
$r_{in/out}$ (edge SRs only)	50–100%
DY+jets in slepton SRs	
$r_{in/out}$ (slepton SRs only)	50%

SUS-20-001
arXiv:2012.08600

Additional Limits

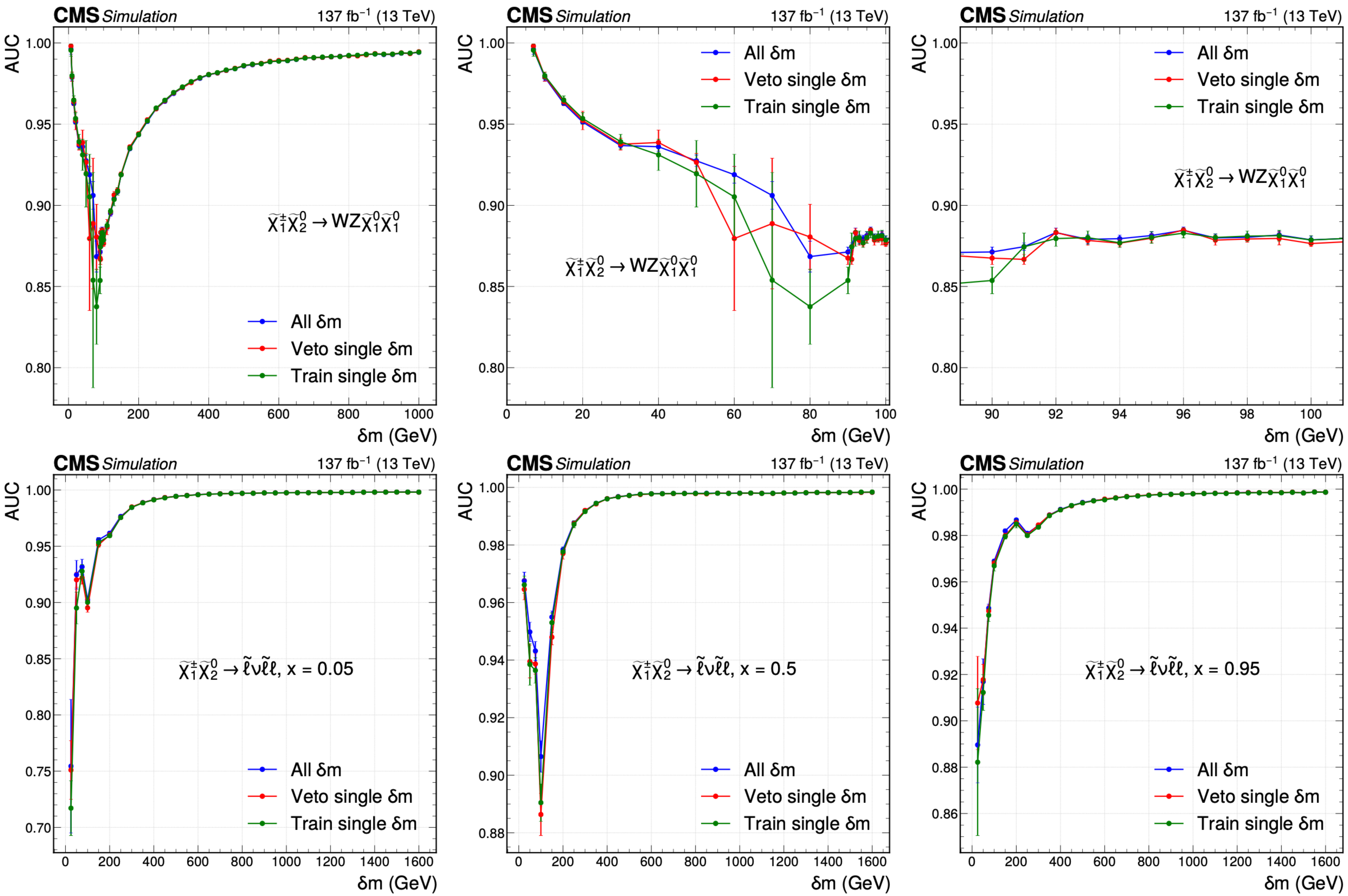




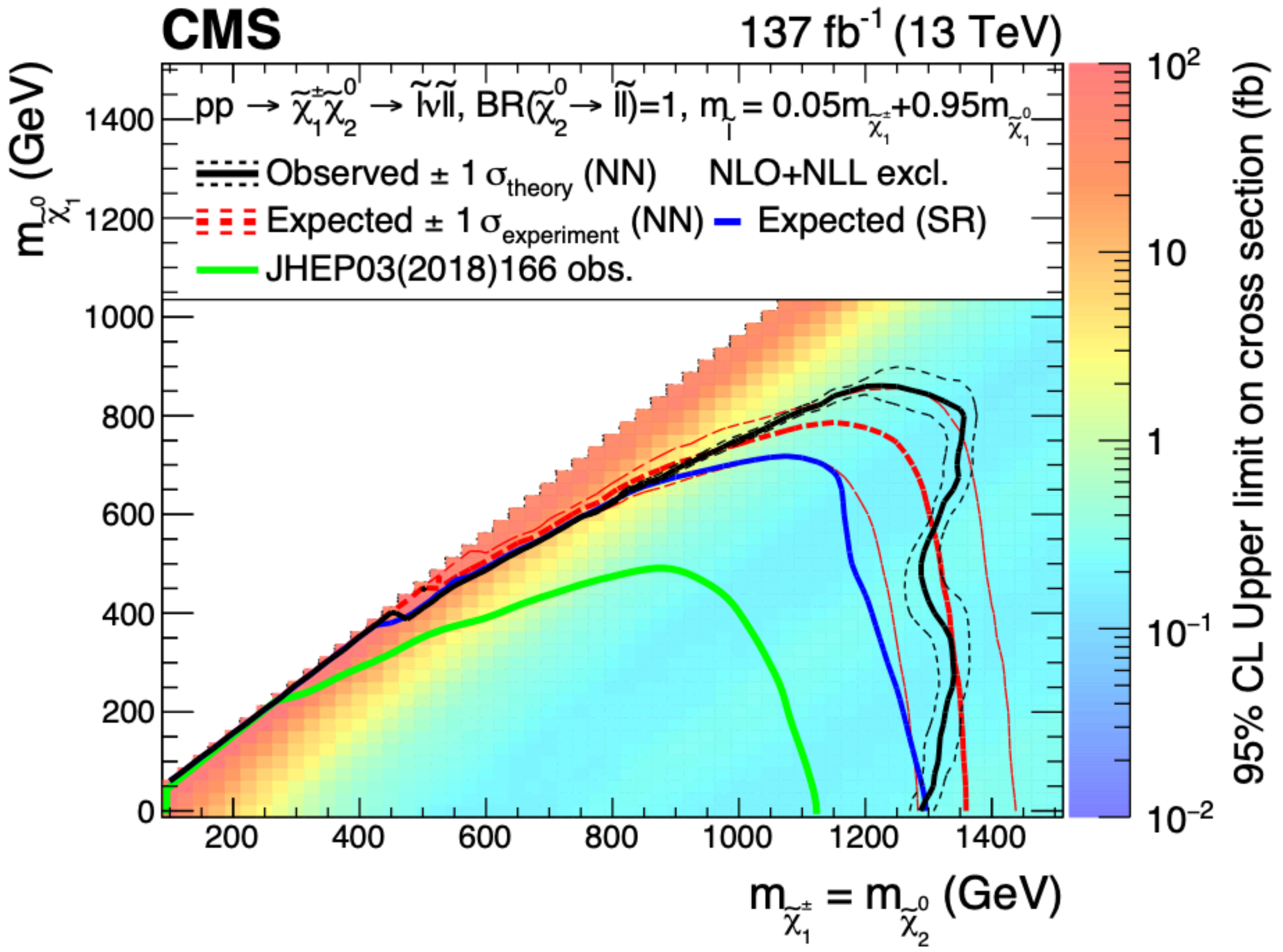


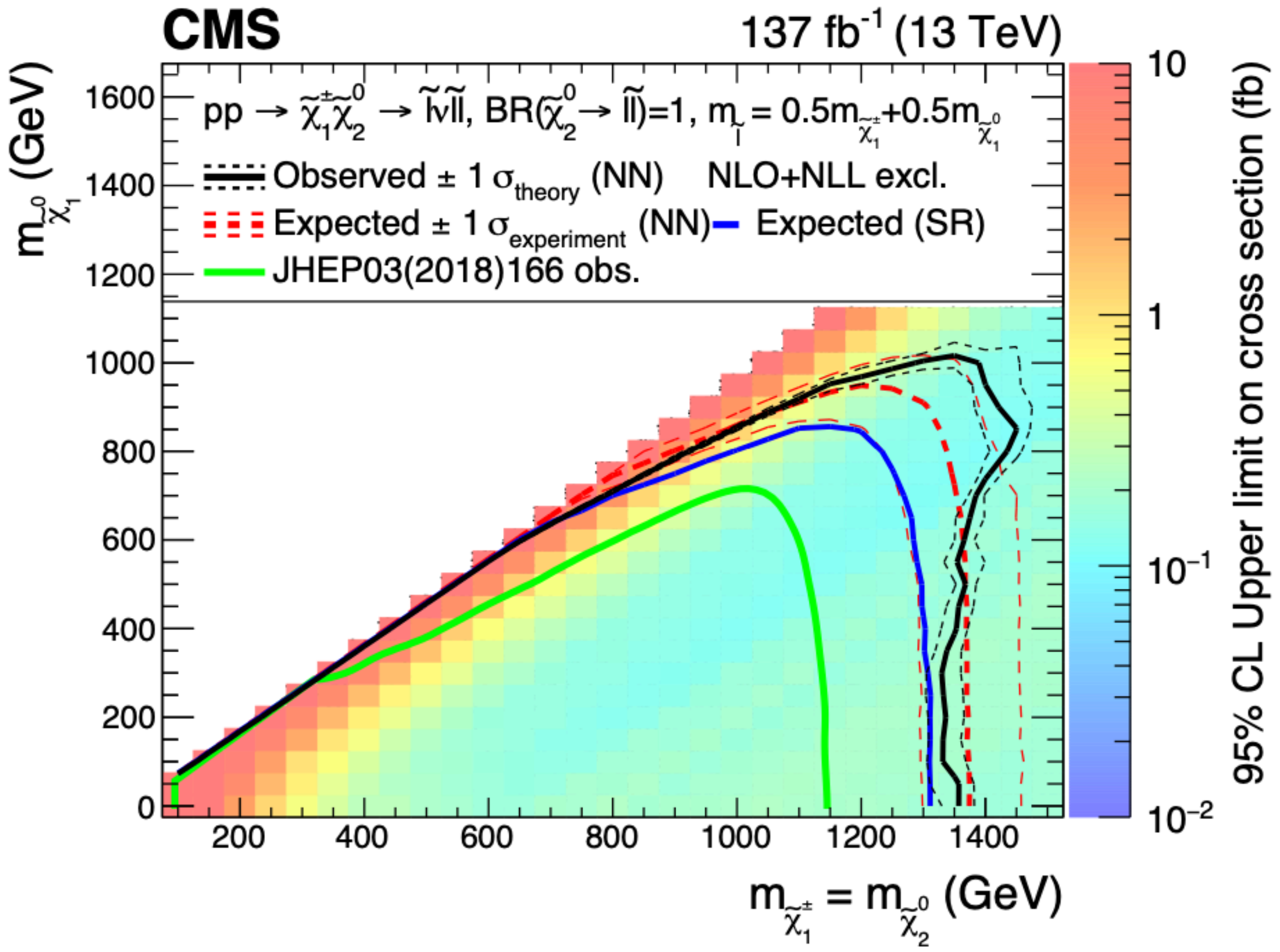
SUS-19-012

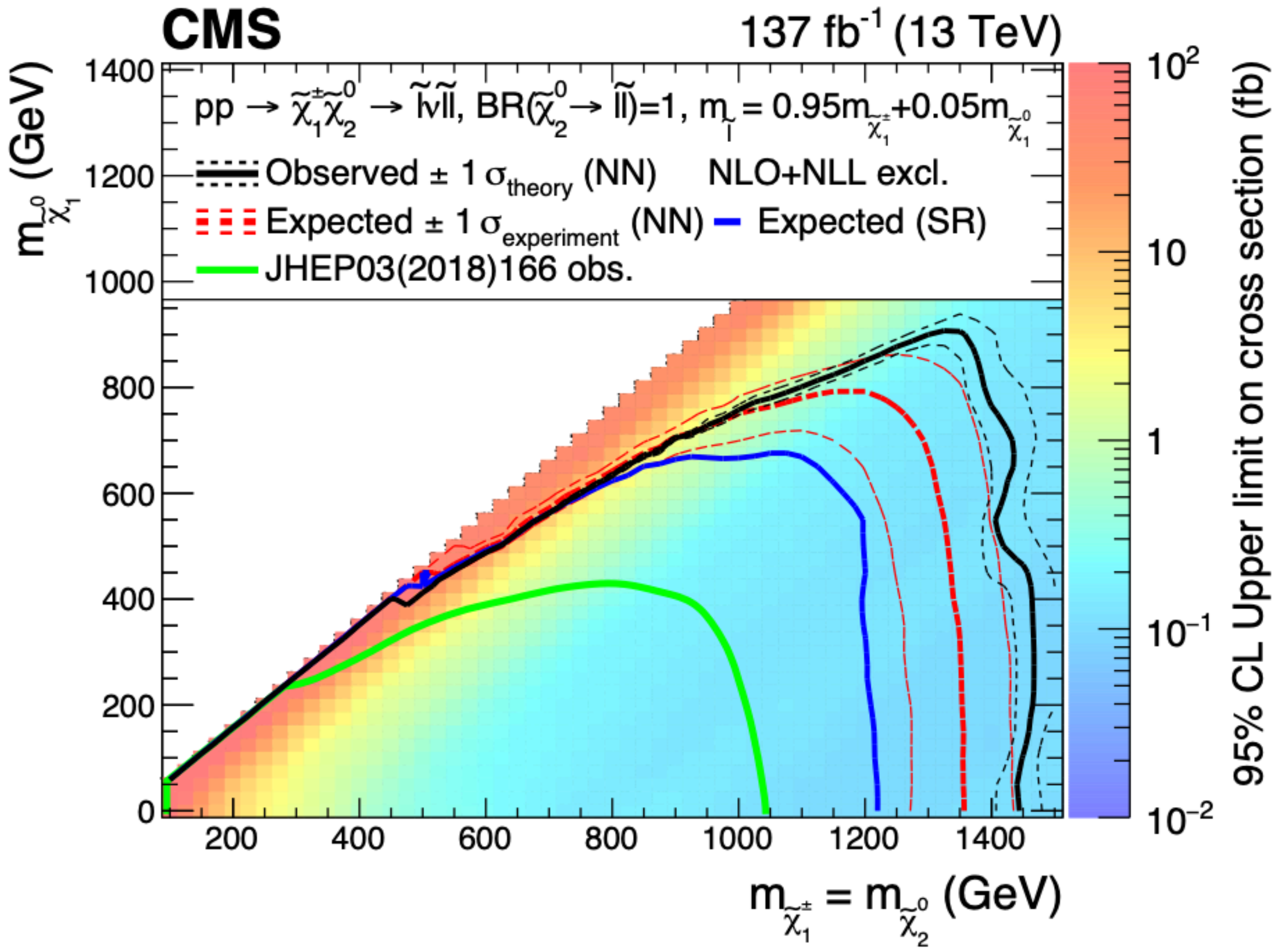
Parametric NN Area Under ROC



Slepton Limits

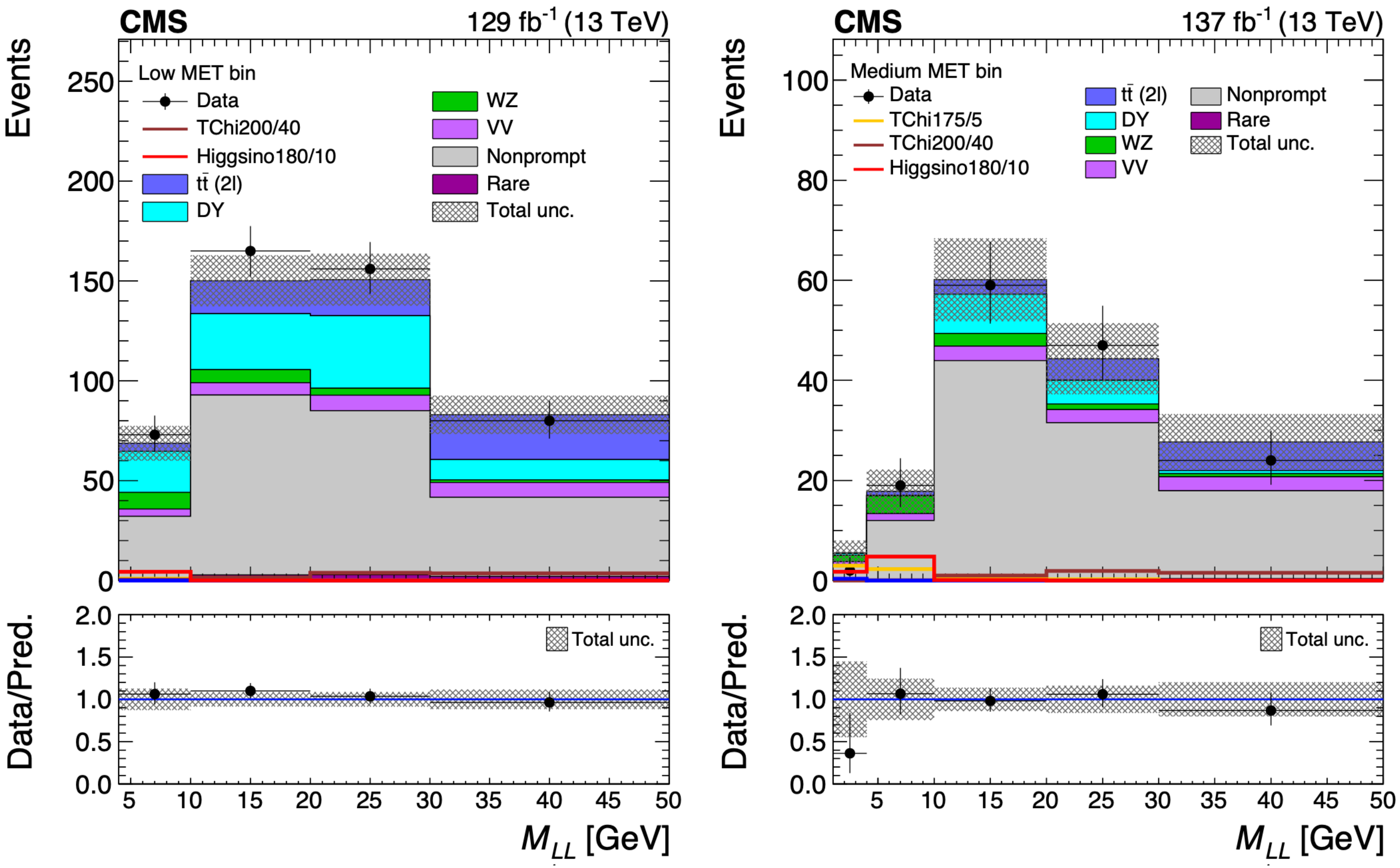




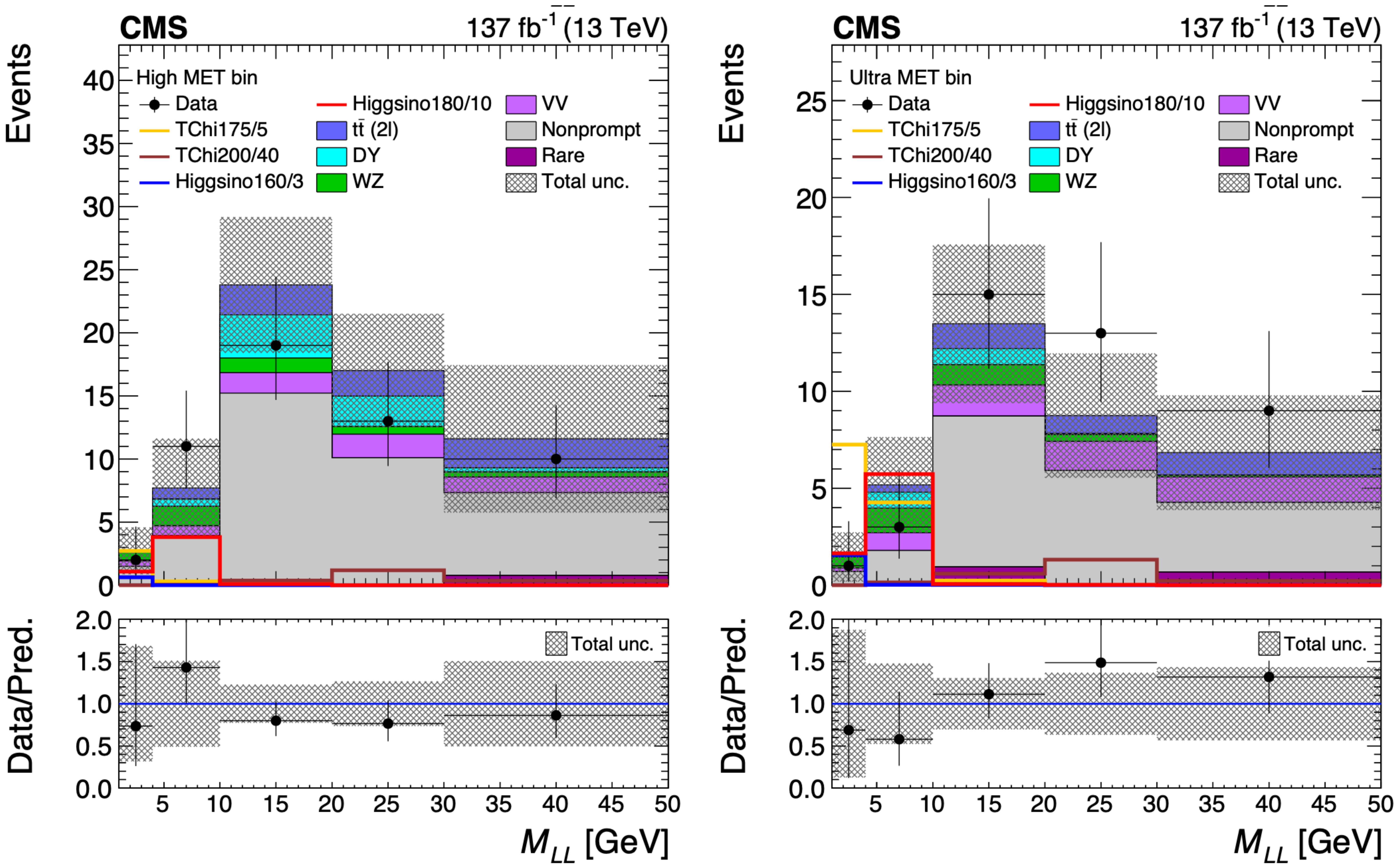


SUS-18-004

2ℓ Low-MET and Med-MET



2ℓ High-MET and Ultra-MET



Yields 2ℓ EWK

p_{T}^{miss} [GeV]	$M(\ell\ell)$ [GeV]	$t\bar{t}$	DY	VV	WZ	Rare	Nonprompt	Total bkg	Data
125–200	4–10	4.0 ± 2.0	20.6 ± 5.2	3.7 ± 2.4	8.3 ± 2.6	$0.28^{+0.72}_{-0.27}$	31.9 ± 5.6	68.7 ± 8.7	73
	10–20	16.5 ± 4.2	28.0 ± 6.2	6.2 ± 3.2	6.5 ± 2.3	2.8 ± 2.1	90.1 ± 9.3	151 ± 13	165
	20–30	18.0 ± 4.4	36.3 ± 7.1	7.8 ± 3.5	3.5 ± 1.7	2.9 ± 2.1	82.1 ± 8.9	151 ± 13	156
	30–50	22.4 ± 4.9	10.2 ± 3.7	7.4 ± 3.5	1.3 ± 1.0	2.1 ± 1.8	39.6 ± 6.2	82.9 ± 9.6	80
200–240	1–4	$0.11^{+0.33}_{-0.10}$	$0.37^{+0.72}_{-0.36}$	$0.7^{+1.1}_{-0.7}$	1.3 ± 1.0	$0.04^{+0.23}_{-0.03}$	3.0 ± 2.0	5.5 ± 2.5	2
	4–10	$0.75^{+0.90}_{-0.74}$	$0.15^{+0.50}_{-0.14}$	$1.4^{+1.5}_{-1.4}$	3.5 ± 1.7	$0.14^{+0.39}_{-0.13}$	11.9 ± 3.6	17.8 ± 4.4	19
	10–20	2.9 ± 1.7	7.9 ± 3.4	2.9 ± 2.2	2.5 ± 1.4	1.2 ± 1.2	42.8 ± 6.8	60.1 ± 8.3	59
	20–30	4.3 ± 2.1	4.7 ± 2.6	2.6 ± 2.0	1.1 ± 1.0	$0.27^{+0.54}_{-0.26}$	31.3 ± 5.8	44.3 ± 7.1	47
	30–50	5.7 ± 2.4	$0.6^{+1.0}_{-0.6}$	2.8 ± 2.1	$0.63^{+0.70}_{-0.62}$	$0.35^{+0.65}_{-0.34}$	17.6 ± 4.4	27.7 ± 5.6	24
240–290	1–4	< 0.02	< 0.1	$0.43^{+0.88}_{-0.42}$	0.8 ± 0.8	< 0.07	1.5 ± 1.3	2.7 ± 1.9	2
	4–10	$0.9^{+1.2}_{-0.9}$	$0.57^{+0.97}_{-0.56}$	$0.8^{+1.1}_{-0.8}$	1.5 ± 1.1	$0.3^{+2.6}_{-0.3}$	3.7 ± 2.0	7.7 ± 3.9	11
	10–20	2.4 ± 1.6	3.4 ± 2.3	1.6 ± 1.6	1.2 ± 0.9	$0.3^{+1.3}_{-0.3}$	14.9 ± 4.0	23.8 ± 5.4	19
	20–30	2.0 ± 1.5	2.4 ± 1.9	1.9 ± 1.7	$0.61^{+0.67}_{-0.60}$	$0.03^{+0.45}_{-0.02}$	10.1 ± 3.3	17.0 ± 4.5	13
	30–50	2.3 ± 1.7	$0.32^{+0.73}_{-0.31}$	$1.2^{+1.4}_{-1.1}$	$0.40^{+0.53}_{-0.39}$	$0.8^{+4.6}_{-0.7}$	6.6 ± 2.7	11.6 ± 5.8	10
> 290	1–4	< 0.02	< 0.1	$0.18^{+0.65}_{-0.17}$	$0.57^{+0.65}_{-0.56}$	< 0.01	$0.70^{+0.88}_{-0.69}$	1.5 ± 1.3	1
	4–10	$0.38^{+0.64}_{-0.37}$	$0.8^{+1.1}_{-0.8}$	$0.9^{+1.2}_{-0.9}$	1.3 ± 1.0	$0.12^{+0.44}_{-0.11}$	1.7 ± 1.3	5.2 ± 2.5	3
	10–20	1.3 ± 1.2	$0.8^{+1.2}_{-0.8}$	1.6 ± 1.6	1.05 ± 0.89	$0.9^{+1.4}_{-0.9}$	7.8 ± 2.9	13.5 ± 4.1	15
	20–30	$0.9^{+1.0}_{-0.9}$	$0.06^{+0.28}_{-0.05}$	$1.5^{+1.6}_{-1.5}$	$0.3^{+0.50}_{-0.34}$	< 0.09	5.9 ± 2.5	8.8 ± 3.2	13
	30–50	1.2 ± 1.1	< 0.1	$1.3^{+1.5}_{-1.3}$	$0.09^{+0.24}_{-0.08}$	$0.7^{+1.2}_{-0.7}$	3.6 ± 2.0	6.8 ± 3.0	9

Yields WZ-Enriched Region

p_T^{miss} [GeV]	$M_{SFOS}^{min}(\ell\ell)$ [GeV]	VV	WZ	Rare	Nonprompt	Total bkg	Data
125–200	4–10	$0.13^{+0.47}_{-0.12}$	2.6 ± 1.4	$0.31^{+0.67}_{-0.30}$	$0.49^{+0.70}_{-0.48}$	3.5 ± 1.8	4
	10–20	$0.14^{+0.47}_{-0.13}$	4.3 ± 1.8	$0.47^{+0.83}_{-0.46}$	1.2 ± 1.1	6.1 ± 2.3	11
	20–30	$0.17^{+0.51}_{-0.16}$	5.0 ± 2.0	$0.50^{+0.85}_{-0.49}$	2.1 ± 1.5	7.8 ± 2.6	9
> 200	1–4	$0.16^{+0.56}_{-0.15}$	$0.11^{+0.29}_{-0.10}$	$0.06^{+0.33}_{-0.05}$	$0.44^{+0.66}_{-0.43}$	$0.78^{+0.97}_{-0.77}$	0
	4–10	$0.22^{+0.60}_{-0.21}$	2.6 ± 1.4	$0.10^{+0.38}_{-0.09}$	$0.24^{+0.59}_{-0.23}$	3.1 ± 1.6	3
	10–20	$0.7^{+1.1}_{-0.7}$	10.6 ± 2.8	$0.9^{+1.1}_{-0.9}$	1.9 ± 1.4	14.0 ± 3.4	19
	20–30	$0.7^{+1.0}_{-0.7}$	15.2 ± 3.3	$1.2^{+1.3}_{-1.2}$	4.0 ± 2.0	21.0 ± 4.2	23

Yields 3ℓ EWK

p_T^{miss} [GeV]	$M_{SFOS}^{min}(\ell\ell)$ [GeV]	VV	WZ	Rare	Nonprompt	Total bkg	Data
125–200	4–10	$0.18^{+0.54}_{-0.17}$	4.8 ± 1.9	$0.08^{+0.38}_{-0.07}$	$0.61^{+0.83}_{-0.60}$	5.7 ± 2.2	3
	10–20	$0.08^{+0.35}_{-0.07}$	2.3 ± 1.3	$0.5^{+1.0}_{-0.5}$	1.9 ± 1.4	4.9 ± 2.2	7
	20–30	$0.03^{+0.23}_{-0.02}$	1.0 ± 1.0	$0.07^{+0.35}_{-0.06}$	1.3 ± 1.2	2.4 ± 1.5	4
	30–50	$0.01^{+0.13}_{-0.01}$	$0.39^{+0.55}_{-0.38}$	$0.08^{+0.37}_{-0.07}$	1.4 ± 1.2	1.8 ± 1.4	1
> 200	1–4	$0.01^{+0.18}_{-0.01}$	1.5 ± 1.0	$0.03^{+0.20}_{-0.02}$	$0.18^{+0.44}_{-0.17}$	1.7 ± 1.2	3
	4–10	$0.05^{+0.34}_{-0.04}$	2.9 ± 1.4	$0.16^{+0.47}_{-0.15}$	$0.85^{+0.99}_{-0.84}$	4.0 ± 1.8	1
	10–20	$0.06^{+0.32}_{-0.05}$	2.0 ± 1.2	$0.05^{+0.26}_{-0.04}$	2.1 ± 1.5	4.2 ± 2.0	5
	20–30	< 0.002	$0.52^{+0.60}_{-0.51}$	$0.06^{+0.29}_{-0.05}$	1.1 ± 1.1	1.7 ± 1.3	2
	30–50	< 0.002	$0.31^{+0.46}_{-0.30}$	$0.03^{+0.23}_{-0.02}$	1.0 ± 1.0	1.3 ± 1.1	1

Local Significance 2.4σ for $m_{\tilde{\chi}_2^0} = 125$ GeV and $\delta m = 40$ GeV

Background And Validation Regions

Region	Modified selection criteria
DY(2ℓ) CR	$0 < M_{\tau\tau} < 160\,\text{GeV}$ No upper requirement on the lepton p_T
$t\bar{t}$ (2ℓ) CR	At least one b-tagged jet with $p_T > 25\,\text{GeV}$ No requirement on $m_T(\ell_i, p_T^{miss})$ (instead of $< 70\,\text{GeV}$) No upper requirement on the lepton p_T
VV(2ℓ) VR	$m_T(\ell_i, p_T^{miss}) > 90\,\text{GeV}$ (instead of $< 70\,\text{GeV}$) No upper requirement on the lepton p_T
WZ(3ℓ) enriched region	No $M_{SFOS}^{min}(\ell\ell)$ upper requirement at 50 GeV No $M_{SFAS}^{max}(\ell\ell)$ requirement $p_T(\ell_1) > 30\,\text{GeV}$ $p_T(\ell_2) > 10\,\text{GeV}$ ($> 15\,\text{GeV}$ if ℓ is electron in high-MET bin) $p_T(\ell_3) > 10\,\text{GeV}$ ($> 15\,\text{GeV}$ if ℓ is electron in high-MET bin) At least one μ with $p_T > 20\,\text{GeV}$
SS(2ℓ) CR	Same-sign requirement on lepton electric charge No requirement on $m_T(\ell_i, p_T^{miss})$

Systematic Uncertainties

Source	Typical uncertainty (%)	Correlation across data-taking years
e/μ efficiency	1–2 per lepton	Correlated
τ_h efficiency	1–3 per lepton	Correlated
Pileup	1–2	Correlated
Integrated luminosity	1.8	Partially correlated
Trigger efficiency	1.4–5	Partially correlated
Jet energy corrections	1	Partially correlated
Jet energy corrections (fast simulation)	1	Correlated
b tagging efficiency	1–3	Correlated
b tagging efficiency (fast simulation)	1–3	Correlated
PDF	1–10	Correlated
Renormalization and factorization scales	1–10	Correlated
Signal ISR	1–5	Correlated
Signal p_T^{miss}	1–2	Correlated
WZ shape	5–30	Uncorrelated
WZ normalization	10	Correlated
ZZ normalization	10	Correlated
Conversion normalization	10	Correlated
Nonprompt normalization (e/μ/τ_h)	30	Correlated
Charge misidentification normalization	20	Correlated
$t\bar{t}X$ normalization	15	Correlated
Multiboson normalization	50	Correlated

Additional Limits