A Search For 3-lepton Resonances In A Minimal SUSY B-L R-parity Violating Model

Jeff Dandoy, Ian Dyckes, Lucas Flores,
Leigh Schaefer, Evelyn Thomson

University Of Pennsylvania

August 01, 2019

Outline

- The B-L MSSM
  - → What is it and why is it so cool?
- Search Motivation
  - → What particles want to be found first?
- Search Strategy
  - → How do we look for these particles?
- Background Estimation and Fit
  - → Figuring out what are not these particles but look a lot like these particles
- Discovery Fit and Limit Setting Strategy
- Summary and Conclusion

Minimal SUSY B-L Model

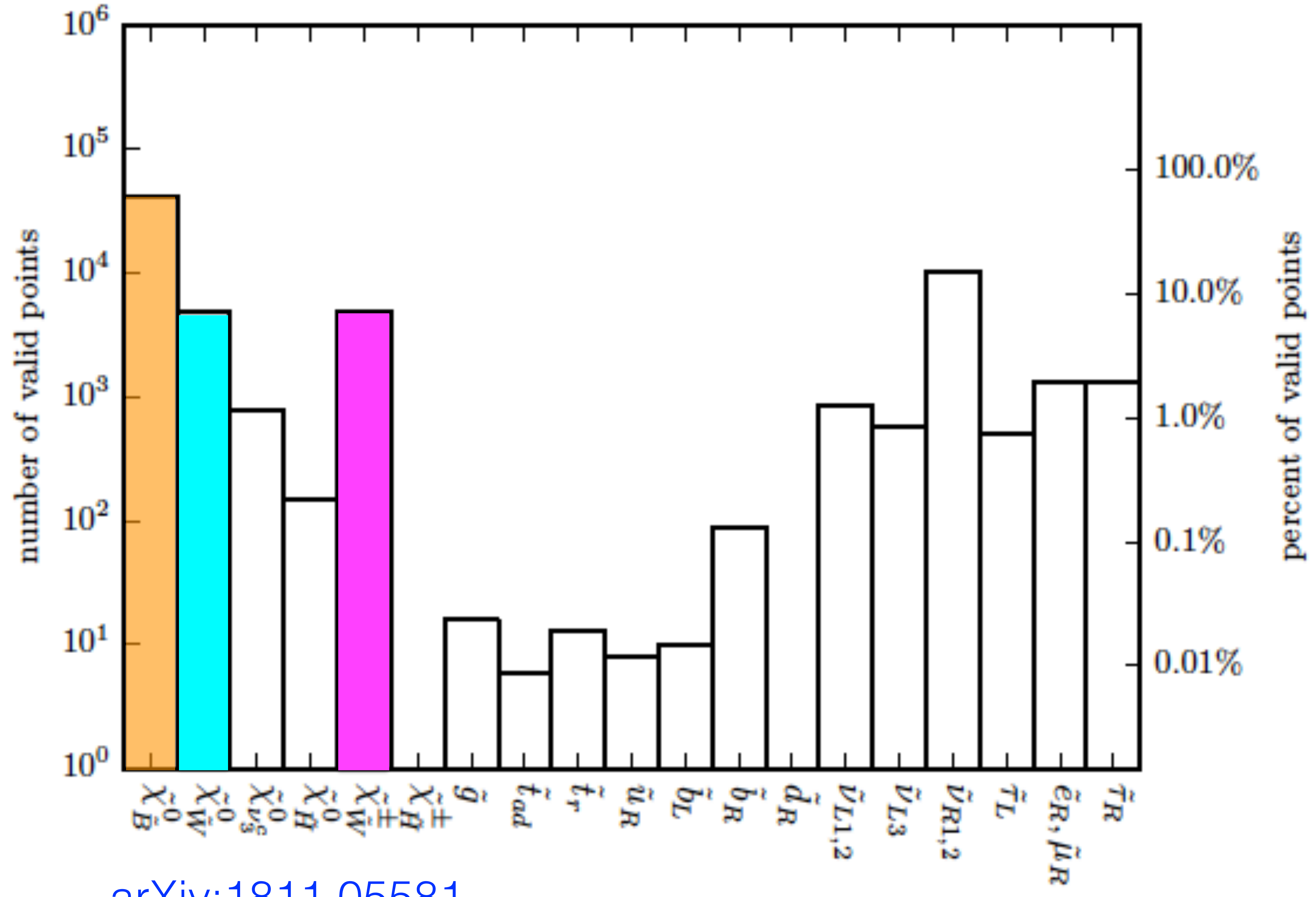
- SUSY introduces Baryon (**B**) and Lepton number (**L**) violating interactions
- Popular solution: "**R-parity**" (**$R=(-1)^{3(B-L)+2s}$**) conservation (RPC) which forbids B and L violation entirely
- RPC requires a stable, lightest SUSY particle → convenient dark matter candidate

  → However this solution is ad hoc
- Instead, we can add a gauged **$U(1)_{B-L}$** symmetry (with right handed neutrinos) and get away with only violating lepton number a bit

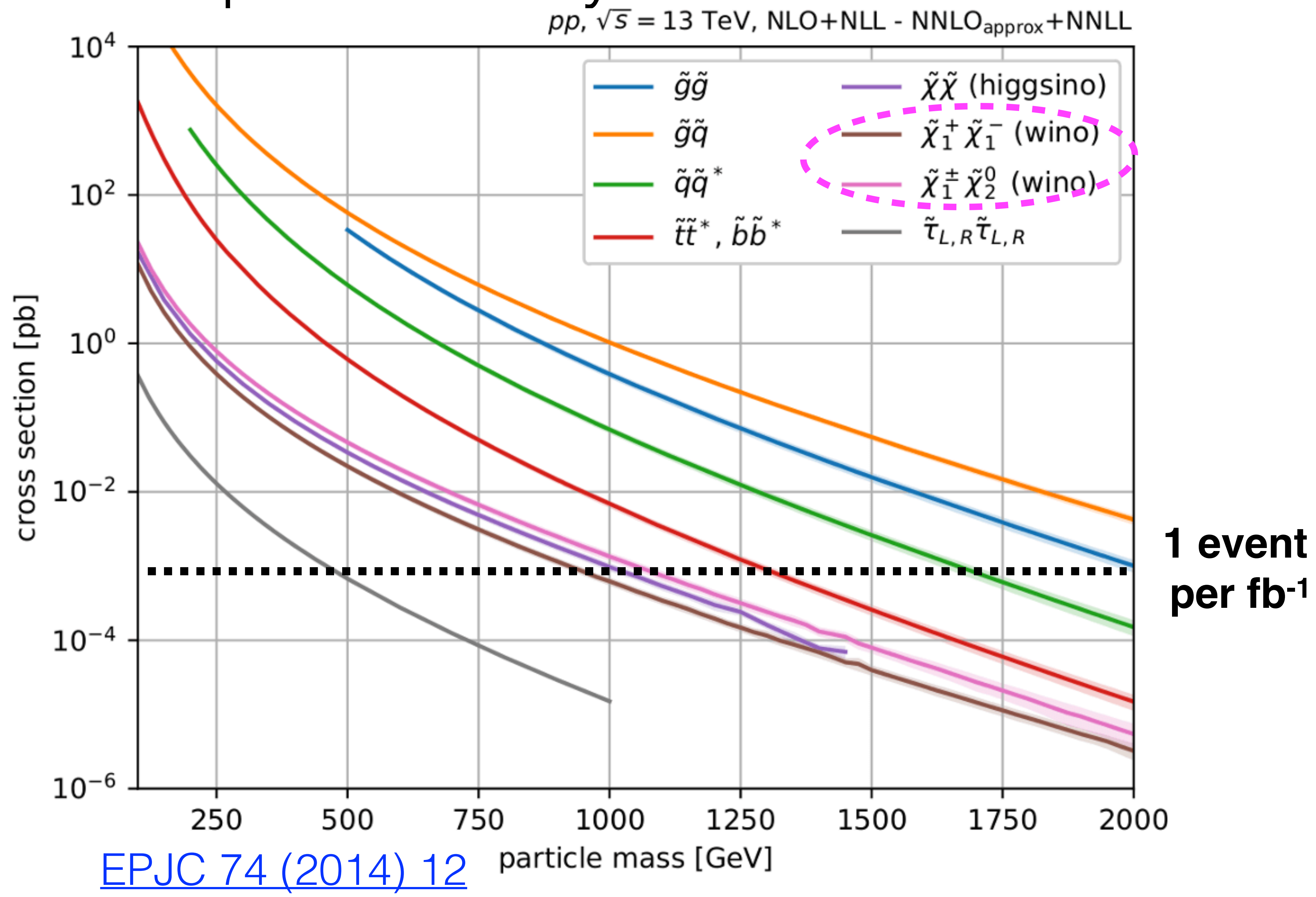
  → consistent with proton stability and bounds on L violation
- **dark matter candidate** in this theory via the **RH neutrino**
- Call this the *Minimal SUSY B-L Model* 1604.08588, 1501.01886, 1503.01473, 1811.05581

Search Motivation: Signals of Interest

- Theorists performed large statistical scan of SUSY initial parameters (10 million points)
  - LSP calculated for each point
- Wino **neutralino** (χ^0_W) and wino **chargino** ($\chi^\pm_W$) are have high LSP probability
- **Bino** (χ^0_B) production cross-section too low to be experimentally viable



[arXiv:1811.05581](https://arxiv.org/abs/1811.05581)



EPJC 74 (2014) 12

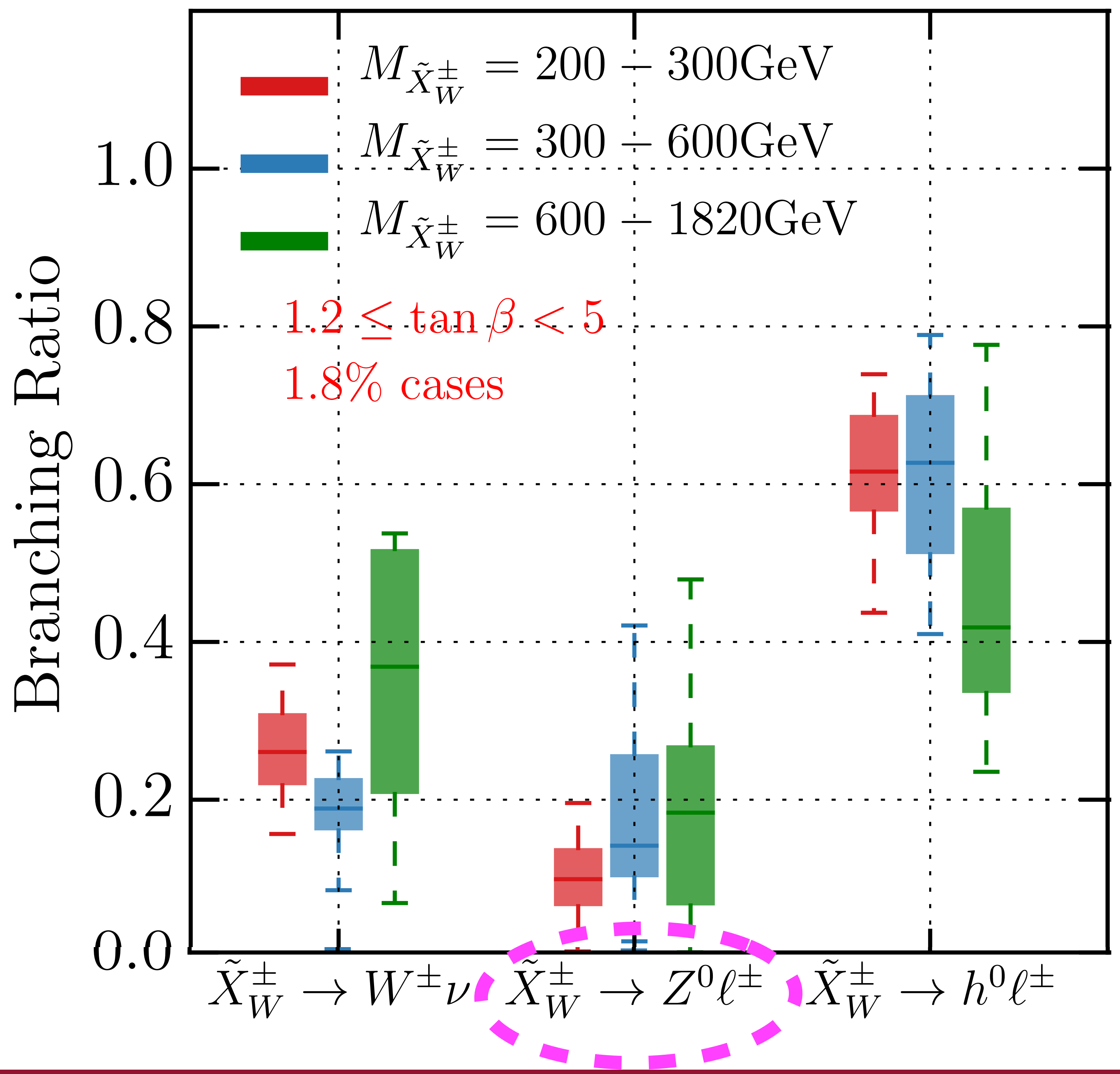
Search Motivation: Signals of Interest

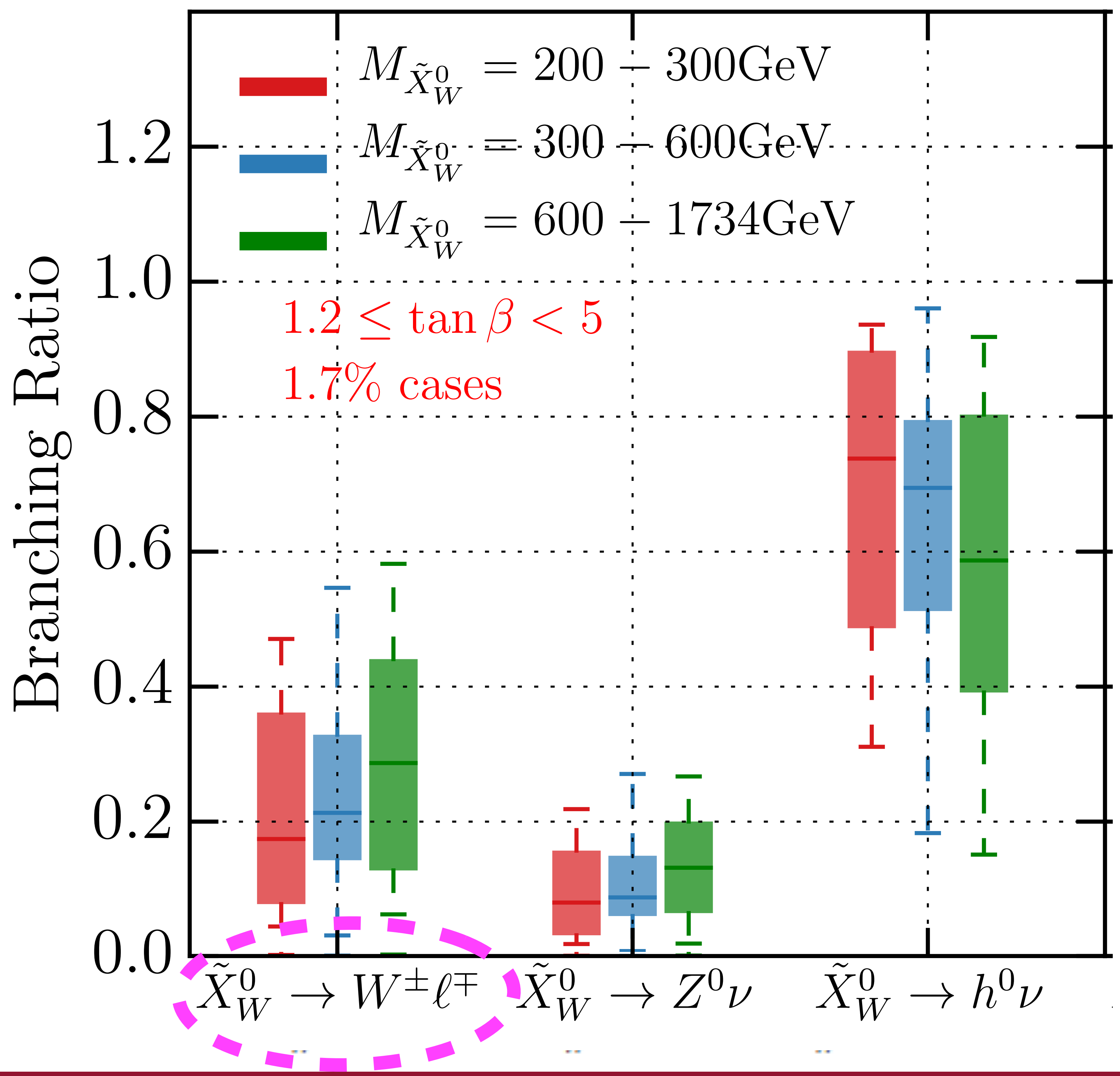
- Mass splitting between $\chi^{\pm}_{w}$ and χ^{0}_{w} is small regardless of which is LSP (≤200 MeV for most cases)
- Can assume **both particles RPV decay**

arXiv:1811.05581

Search Motivation: Signals of Interest

- Targeting the very visible 3-lepton resonance $\chi^{\pm}_{W} \rightarrow Z\ell^{\pm} \rightarrow \ell^{\pm}\ell^{\mp}\ell^{\pm}$
- The reconstruction of $\chi^{0}_{W} \rightarrow W\ell^{\pm} \rightarrow qq\ell^{\pm}$ when possible* also adds sensitivity
- We are setting limits for a large scan of $\chi^{\pm}_{W}$ and χ^{0}_{W} BRs which will cover the other possible decays



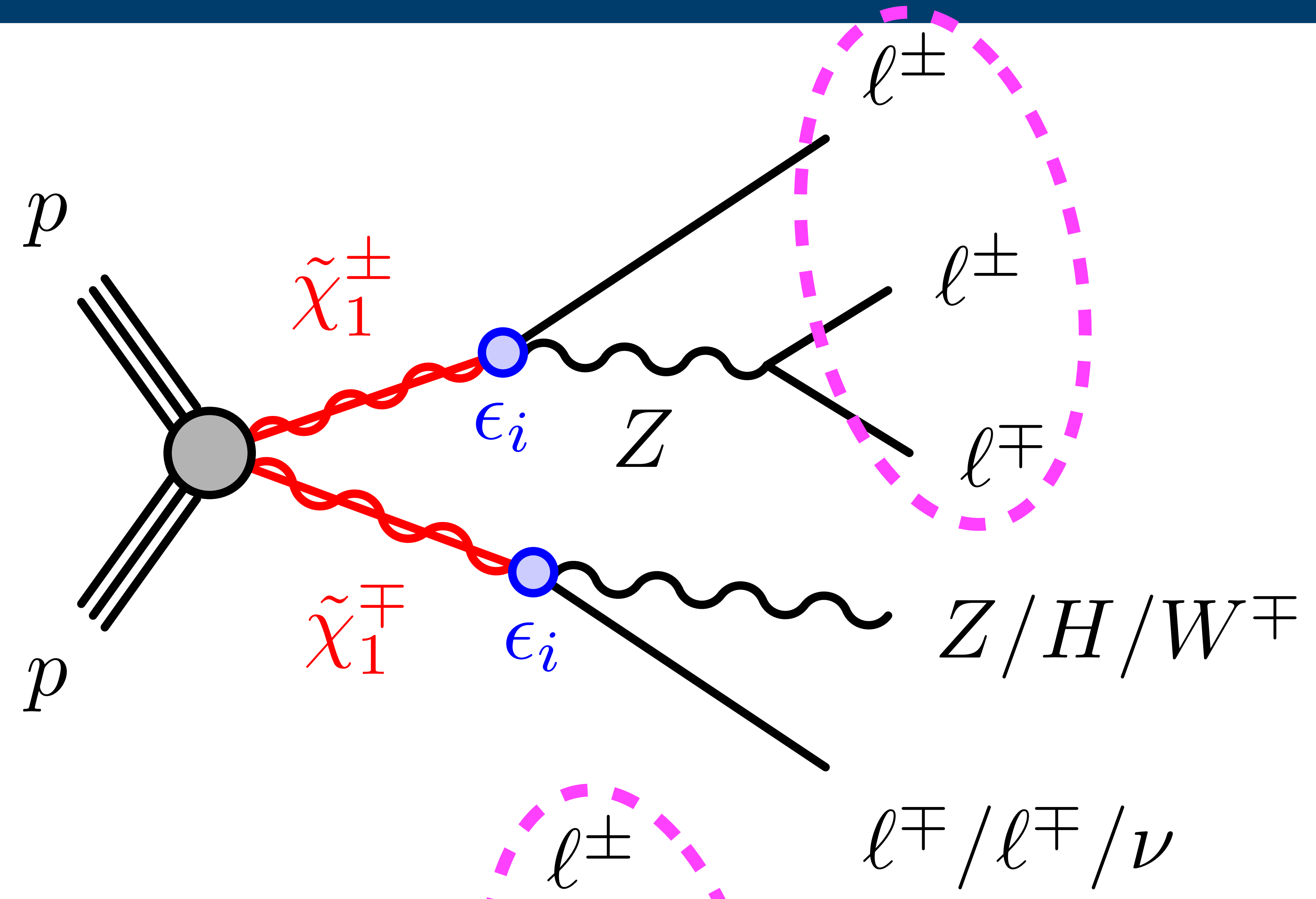


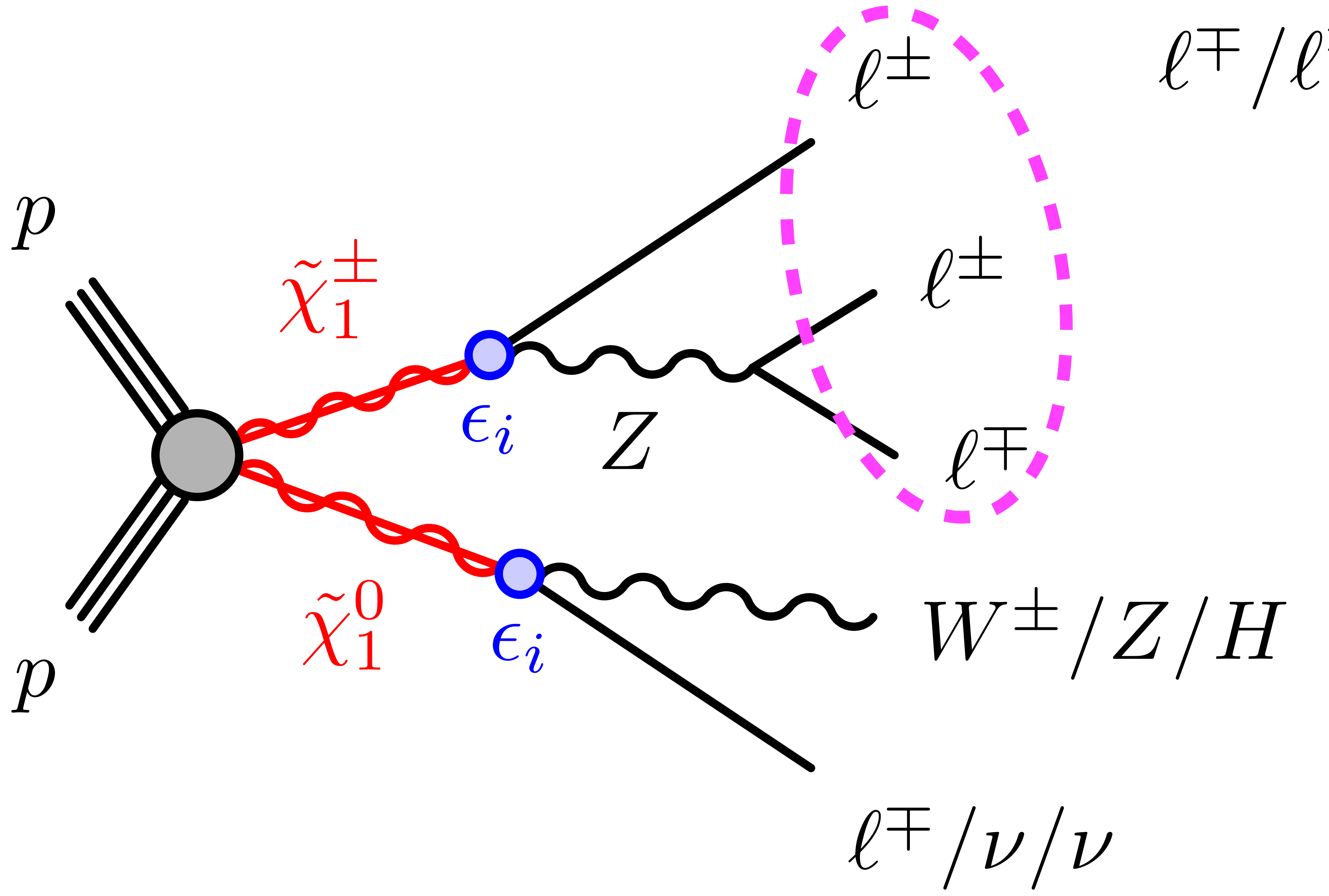
*discussed in "Two Leg" alg in slide 11

arXiv:1811.05581

Signals of Interest

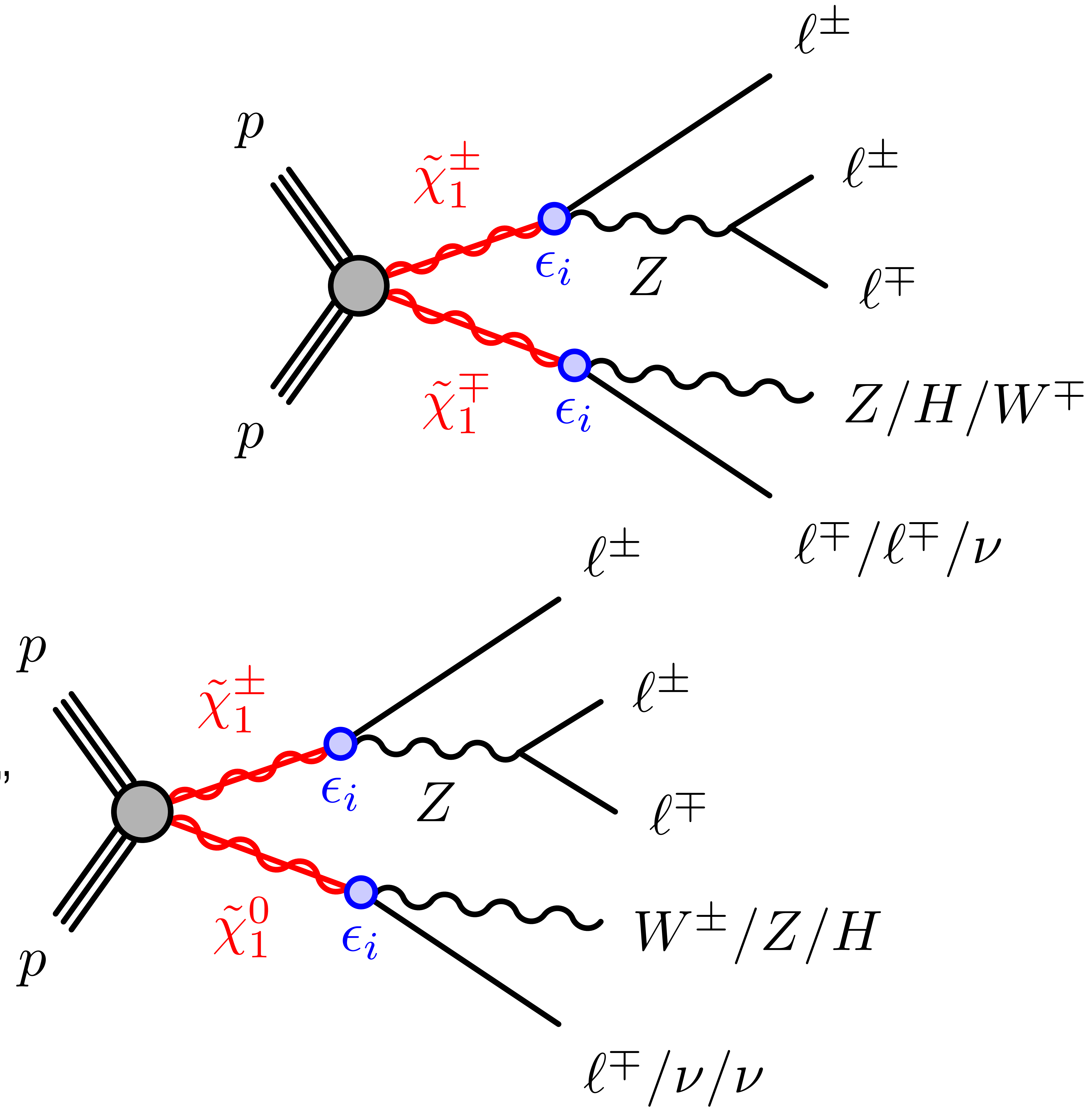
- With that we are considering both $\chi^{\pm}_{\mathrm{w}}\chi^{\mp}_{\mathrm{w}}$ and $\chi^{\pm}_{\mathrm{w}}\chi^{0}_{\mathrm{w}}$ production
- Will focus on $\chi^{\pm}_{\mathrm{w}}\rightarrow Z\ell\rightarrow\ell\ell\ell$, giving us a **resonance in the trilepton invariant mass**
- χ^{0}_{w} decaying via RPV offers further discrimination power in $\chi^{\pm}_{\mathrm{w}}\chi^{0}_{\mathrm{w}}$ production
- A 3 Lepton resonance search has **not been done in by either CMS or ATLAS since Run 1** (1506.01291)
- CMS has a similar **non**-resonant Run 2 analysis using 35.9 fb^{-1} (1708.07962)





Signal Regions: Motivation

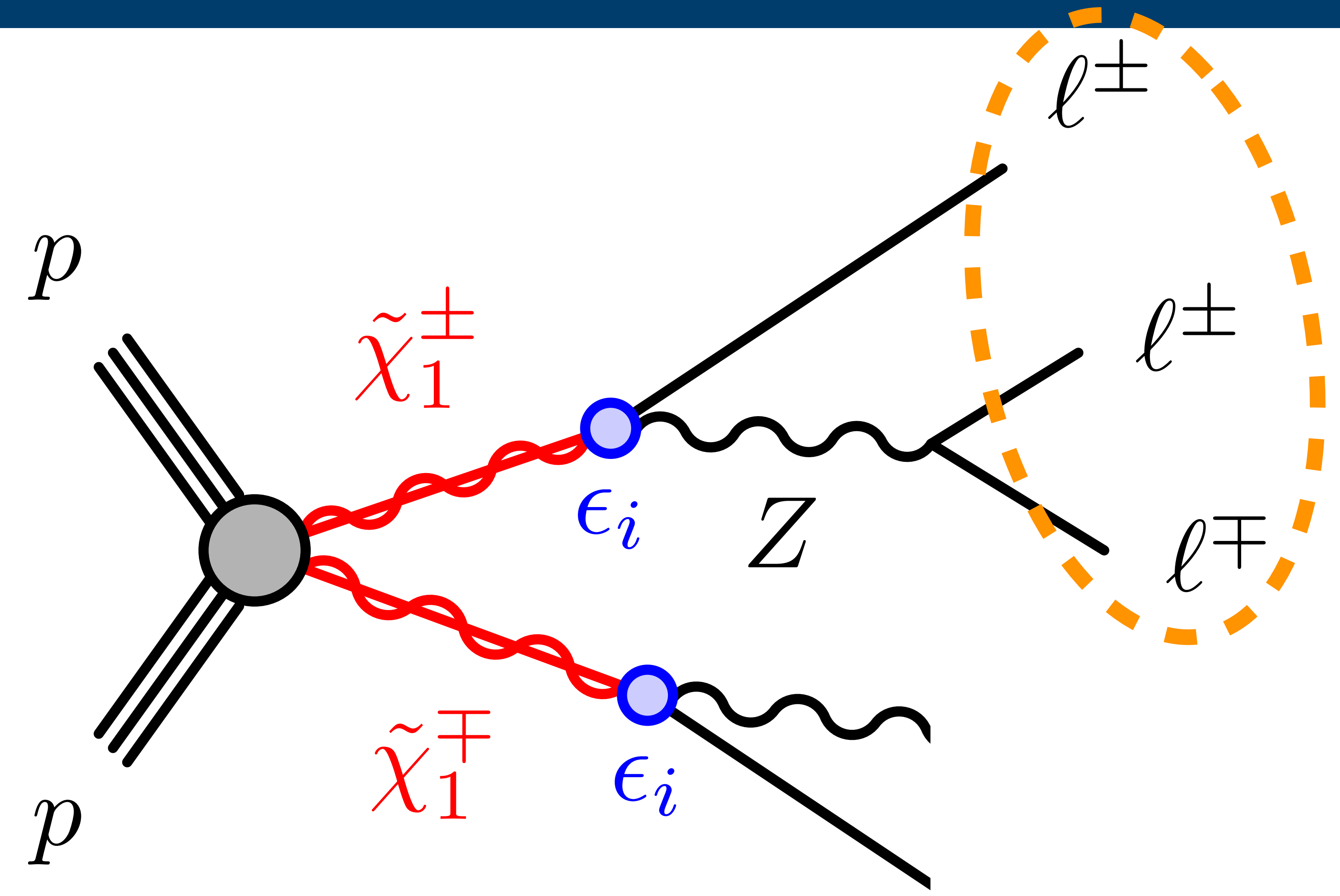
- Many final states possible
- Some fully visible and many with >3 leptons
- Design 3 search regions to target these different final states
- When other wino's decay is fully visible, fully reconstruct both winos
- When other wino decays semi-visibly, use extra leptons for discrimination with SM
- Divide up SRs based on number of "Legs" (winos) reconstructed



Signal Regions: Definitions

- SRO3ℓ: One Leg 3 ℓeptons

  $m_{Z\ell}$ is the invariant mass of the only 3 leptons



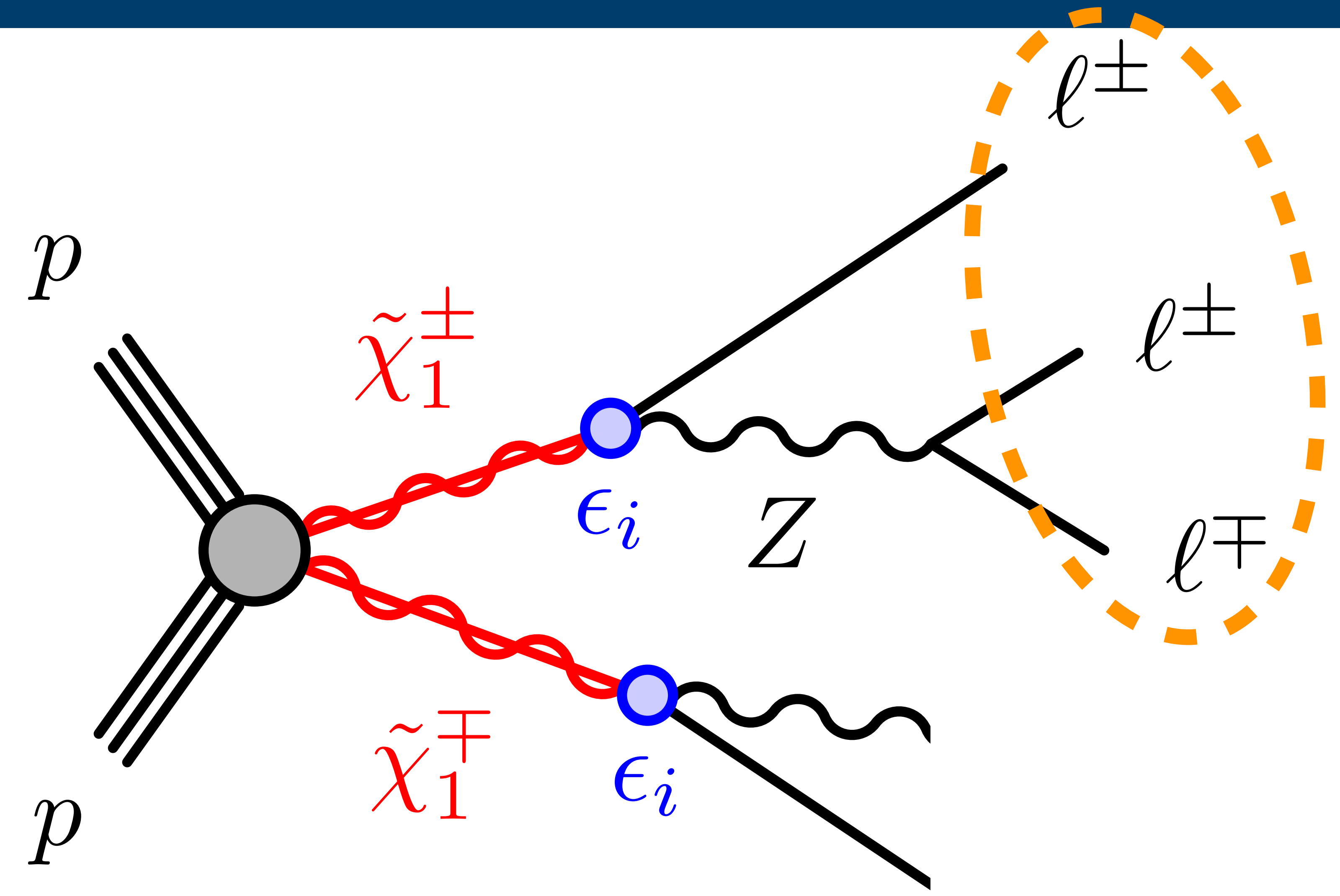
Signal Regions: Definitions

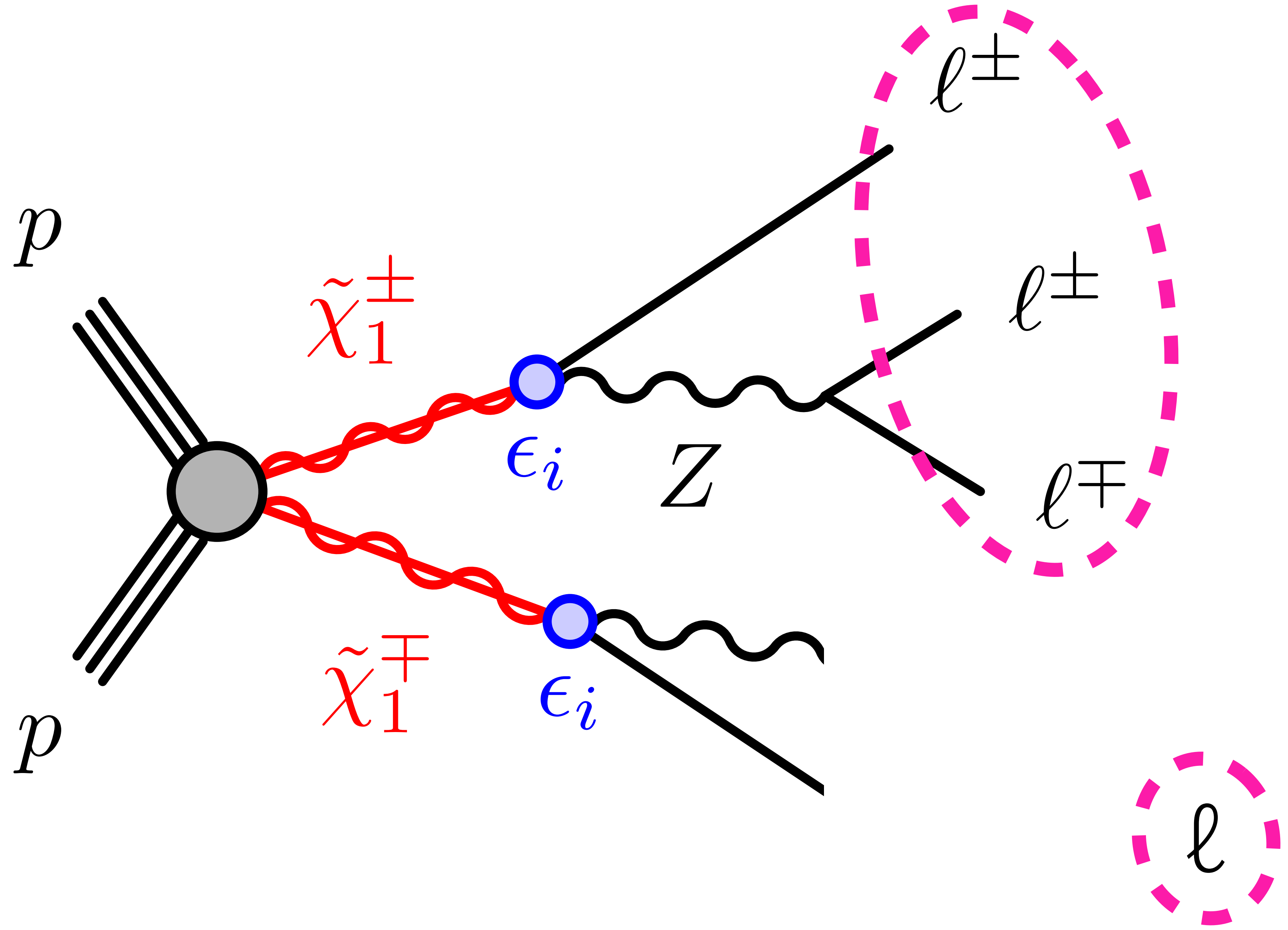
- SRO3ℓ: One Leg 3 ℓeptons

  $m_{Z\ell}$ is the invariant mass of the only 3 leptons

- SRO4ℓ: One Leg 4 ℓeptons

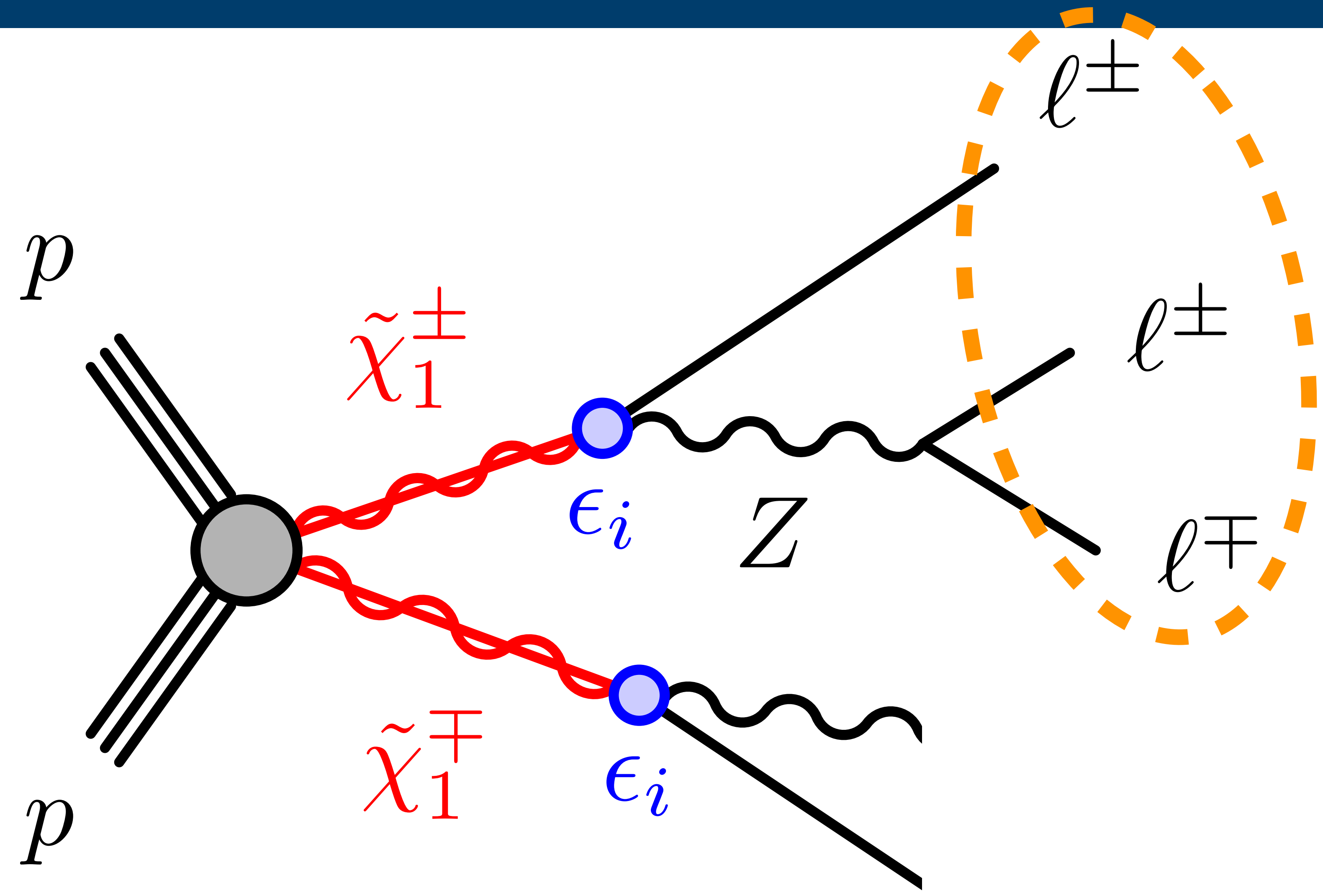
  4th lepton introduces ambiguity→ match using ΔR or max $m_{Z\ell}$ depending on energy

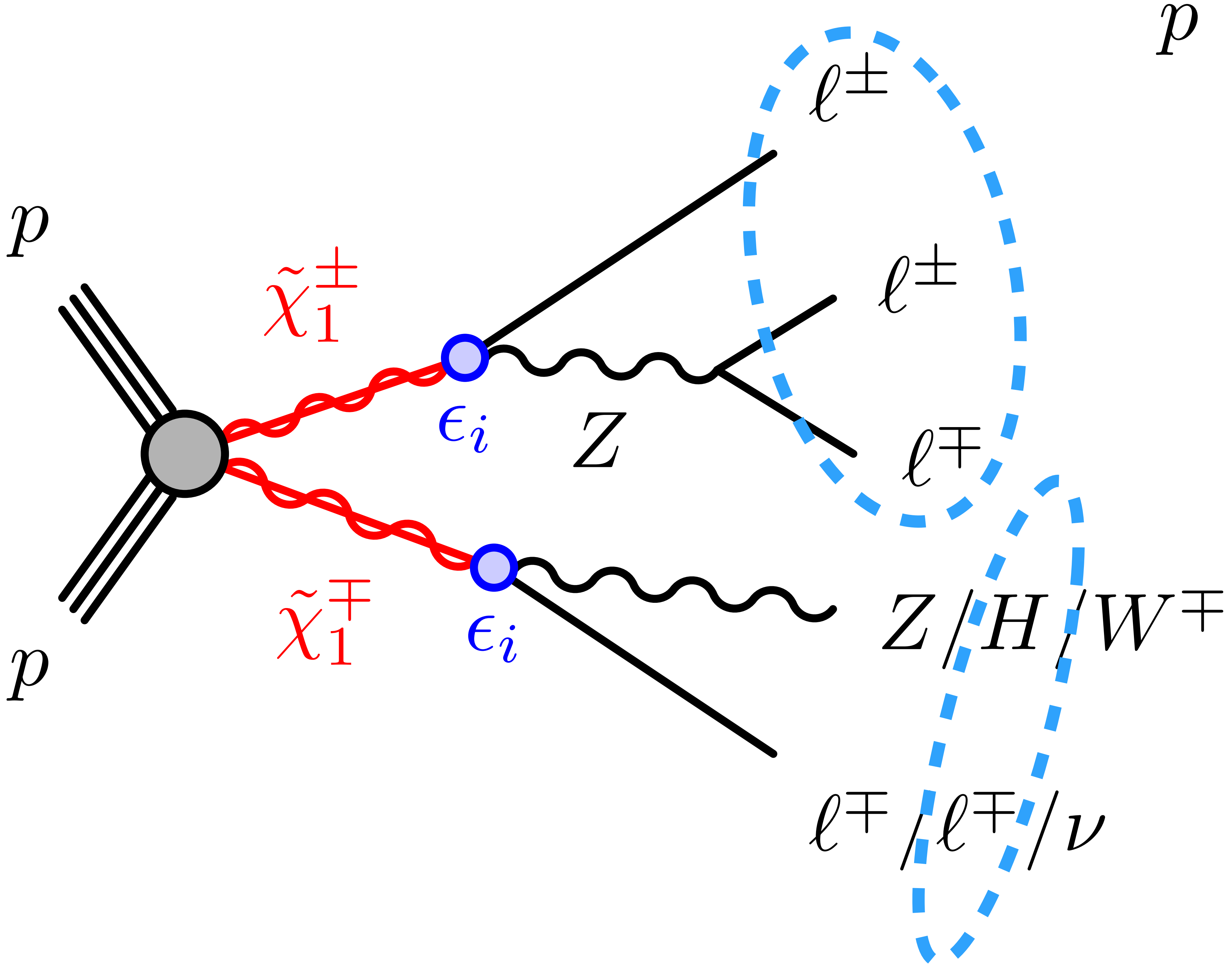


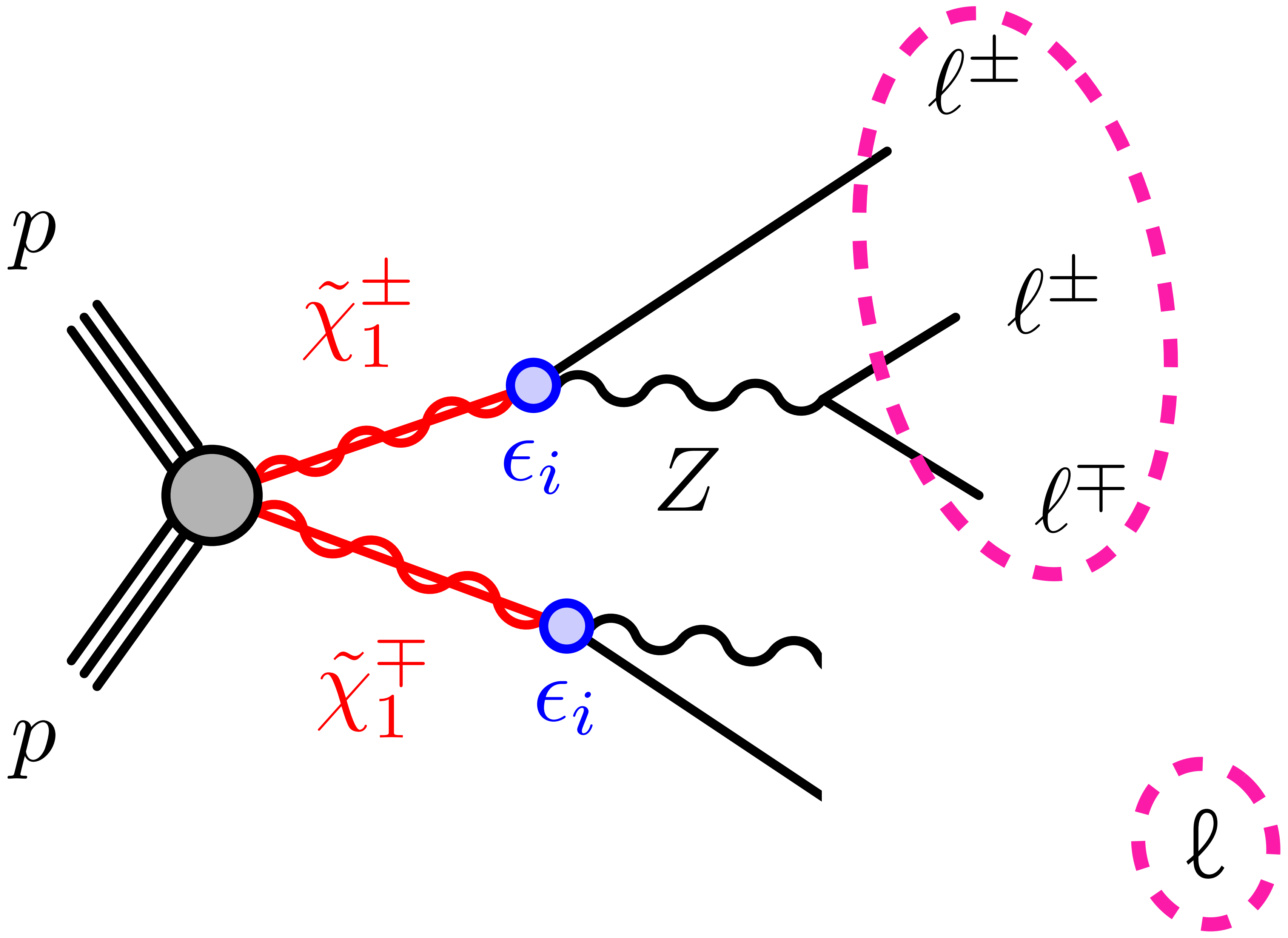


Signal Regions: Definitions

- SRO3ℓ: One Leg 3 ℓeptons
  $m_{Z\ell}$ is the invariant mass of the only 3 leptons
- SRO4ℓ: One Leg 4 ℓeptons
  4th lepton introduces ambiguity→ match using ΔR or max $m_{Z\ell}$ depending on energy
- SRTL: Two Leg
  Determine $m_{Z\ell}$ for each leg via minimizing
  ↓
  $$m_{Z\ell}^{asym} = \frac{|m_{Z\ell_i} - m_{B\ell_j}|}{(m_{Z\ell_i} + m_{B\ell_j})}$$
  B=Boson







Control and Validation Regions

N leptons	3	4
Prompt	WZ, ttZ	ZZ, ttZ, Higgs
Fake	Zjets, top	WZ, top

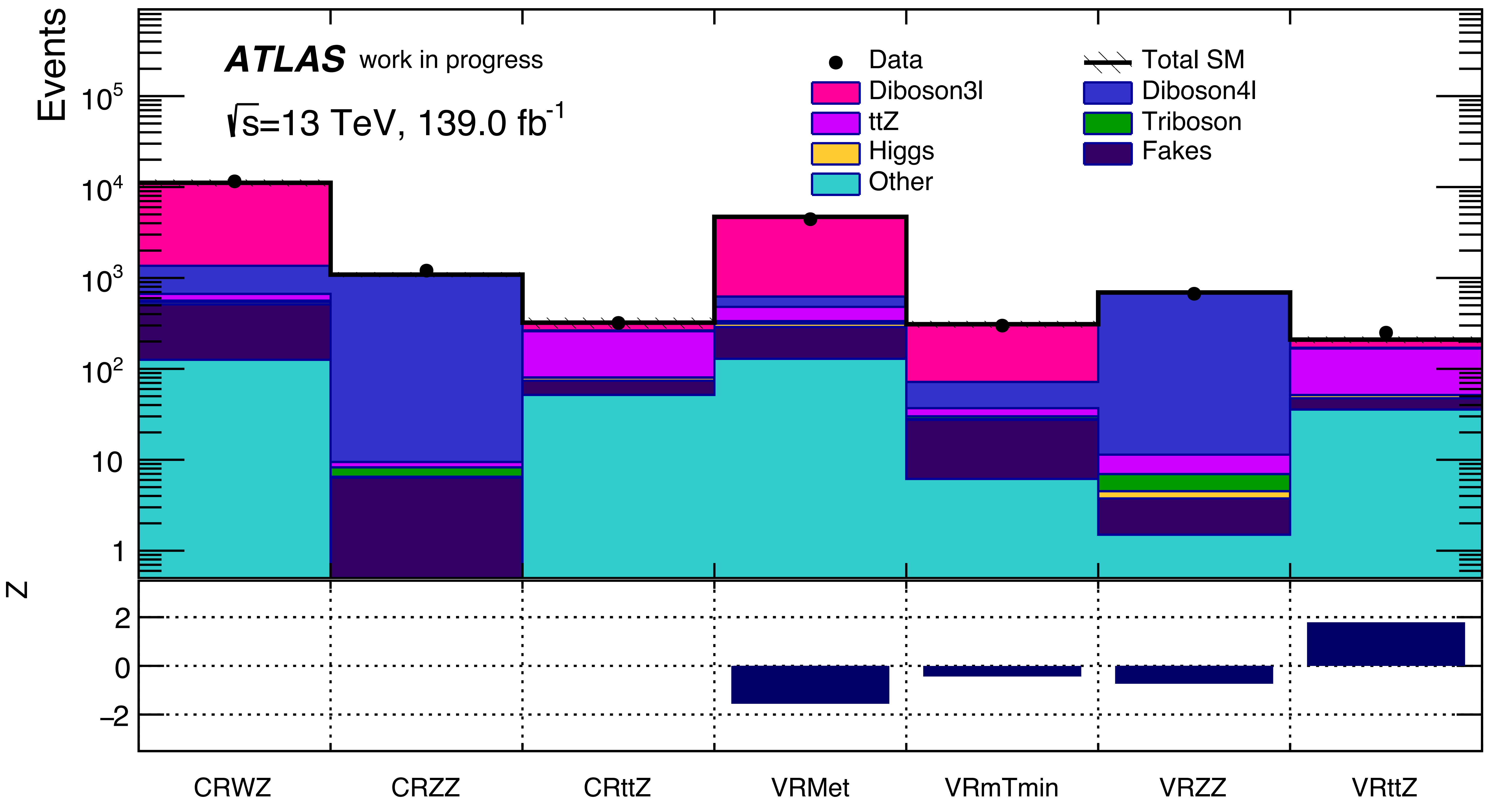
- Dominant SM and fake backgrounds change depending on lepton multiplicity
- SM backgrounds are normalized to data in dedicated Control Regions (CR) and checked in Validation Regions (VR)
- Targeting WZ, ZZ, and ttZ backgrounds
  - WZ: Require 3 leptons. Cuts on E_T^{miss} and m_T^{min}
  - ttZ: Cuts on E_T^{miss}, n-bjets≥2 (back-to-back $\Delta R(b_0,b_1)$)
  - ZZ: Require two Zs (four leptons)
- Fake backgrounds are estimated using data-driven fake factor method

  → Systematic accounts for several sources and compositions

  → Z+jets CR and VR also used for fake factor measurement

Background Estimation and Fit

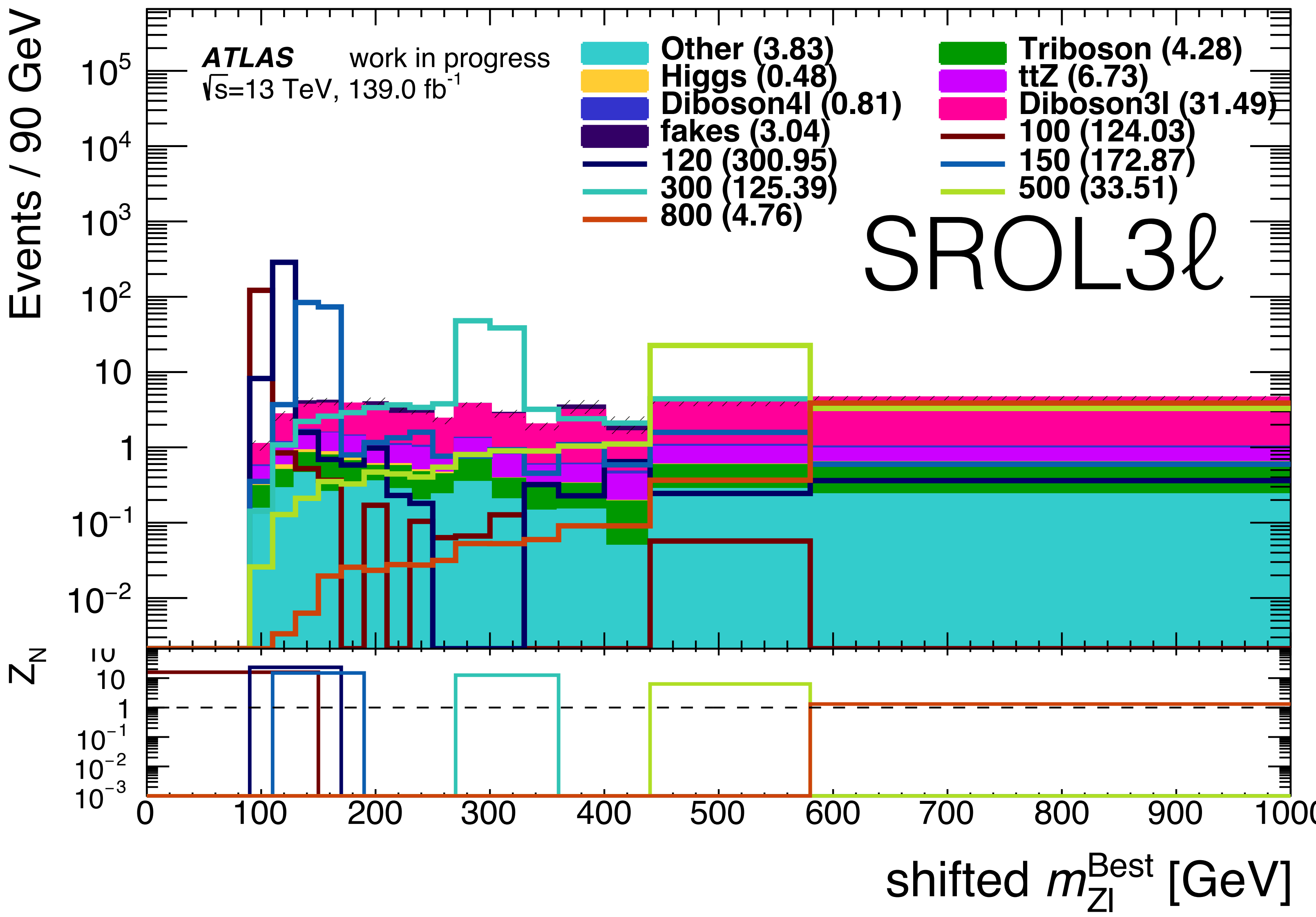
- Normalization factors are close to 1
- Good data/MC agreement in VRs post fit
- Do not yet include fake systematics

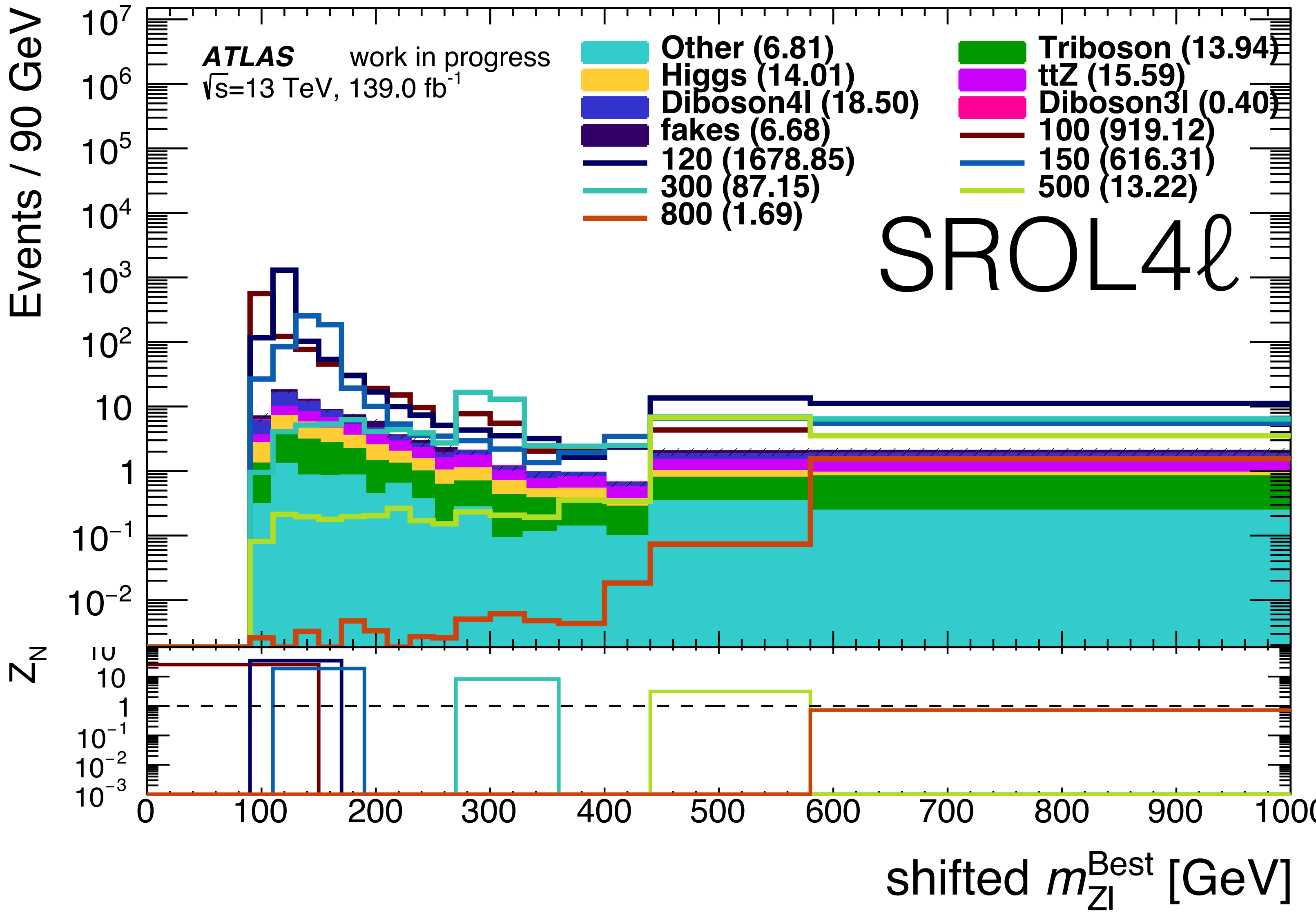


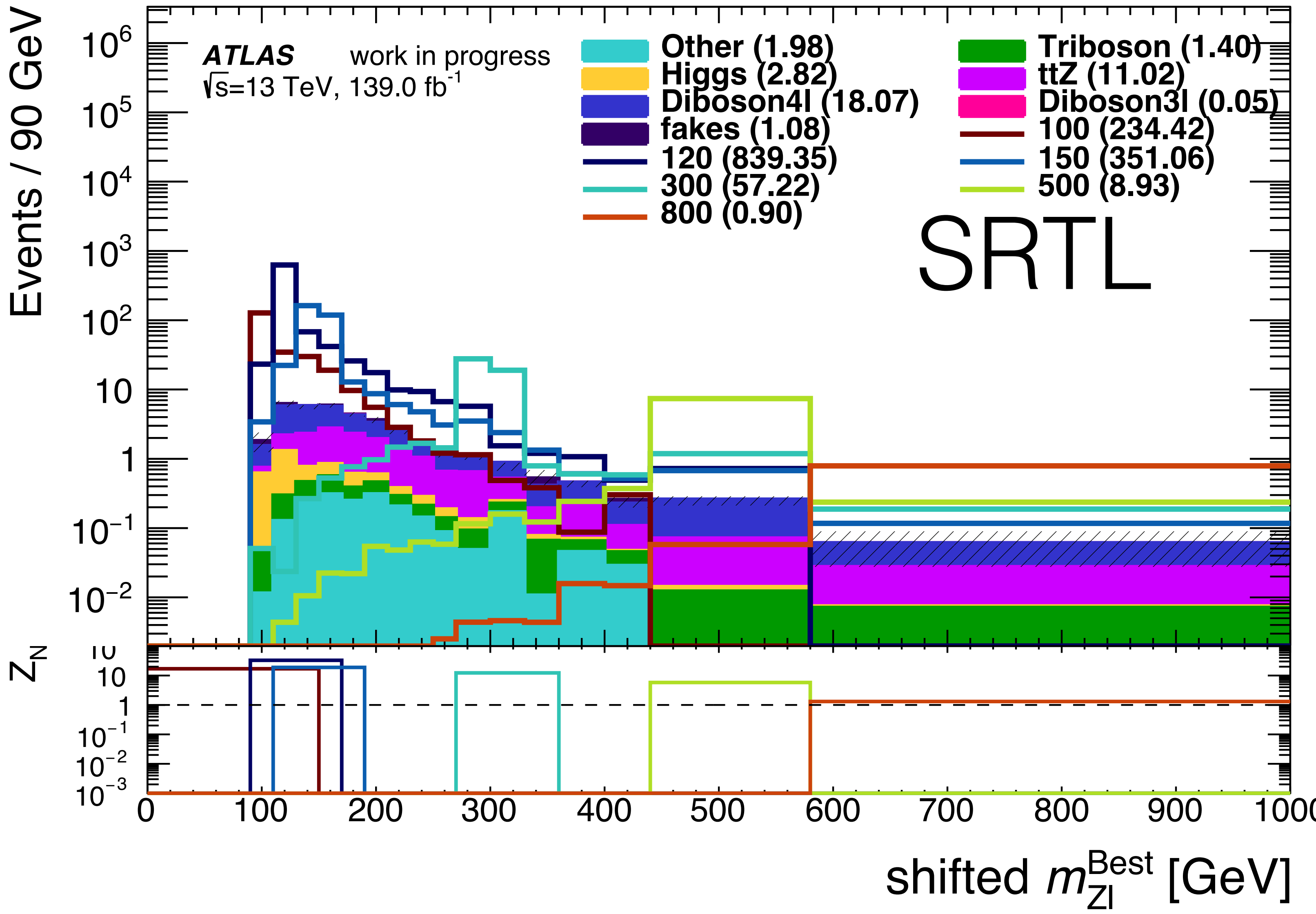
μ_{WZ}	1.0334 ±0.0880
μ_{ZZ}	1.1066 ±0.0732
μ_{ttZ}	0.9699 ±0.238

Search Strategy

- These 3 SRs have high $\chi^{\pm}_{W}$ and χ^{0}_{W} signal acceptance
- Multibin fit performed in “shifted $m_{Z\ell}$” distribution of each SR,
  - → $m_{Z\ell}$ = invariant mass of leptonic Z and associated lepton from $\chi^{\pm}_{W}$
  - → shifted $m_{Z\ell}=m_{Z\ell}-m_{Z}+91.2$
- Bins defined to optimize model sensitivity for full mass range considered (100-800 GeV).16 bins in each $m_{Z\ell}$ distribution →48 SR bins total
- Plots show sensitivities for combined $\chi^{\pm}_{W}\chi^{\mp}_{W}$ and $\chi^{\pm}_{W}\chi^{0}_{W}$ production







Discovery Fit and Limit Setting Strategy

- We will set limits across the full BR plane of possible wino decays, both boson type (Z, W, H) and lepton flavor (e,μ,τ)
- BRs can inform neutrino hierarchy
- We will also calculate a model-independent significance for each $m_{Z\ell}$ bin

arXiv:1811.05581

Summary and Conclusion

- Well-motivated signal in the context of the RPV B-L MSSM thanks to the great work and strong collaboration with the theorists who developed the model
- Background fits show good modeling of SM backgrounds
- Analysis fully defined and implemented
  - Limit setting and discovery fit strategies well defined
- Stay tuned for unblinded results!

back up

Object Selection

Baseline objects

Baseline muons:
- $|\eta|<2.7$, $p_T>10$ GeV,
- $z_0 \sin\theta<0.5$,
- ID: Medium

Baseline electrons:
- $|\eta|<2.47$, $p_T>10$ GeV,
- $z_0 \sin\theta<0.5$,
- Crack veto, Quality cuts,
- ID: LooseAndBLayerLLH

Baseline jets:
- $p_T>20$ GeV
- AntiKt4EMTopo, R=0.4

Overlap removal: HF-aware for b-jet $p_T<$ 100 GeV (MV2c10, Fixed 85%)

MET: Tight WP, using electrons, muons, jets, and photons

Signal objects

Signal muons:
- $p_T>12$ GeV,
- Iso: FCTight_FixedRad,
- $d_0/\sigma(d_0)<3$,
- cosmic veto,
- bad muon event veto

Signal electrons:
- $p_T>12$ GeV,
- ID: MediumLLH,
- Iso: FCTight,
- $d_0/\sigma(d_0)<5$

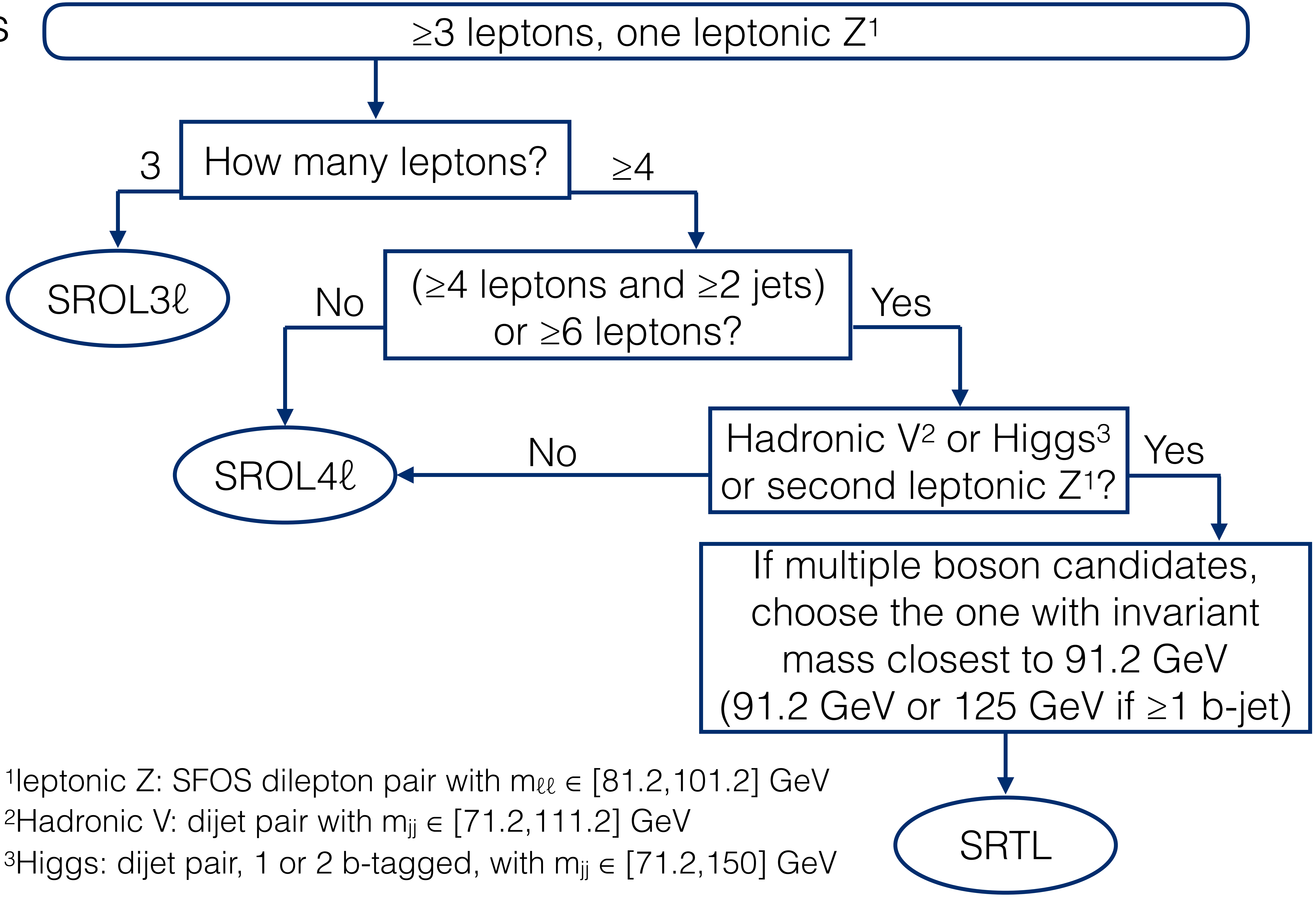
Signal jets:
$|\eta|<2.8$,
- Medium JVT for $p_T<120$ GeV and $|\eta|<2.5$,
- bad jet event veto

b jets:
- $|\eta|<2.5$, MV2c10, Fixed 85%

- **Preselection:** Require at least 3 signal leptons, 2 of which are SFOS within [81,101] GeV. Using **SUSY2** derivations and requiring that a **single lepton trigger** is fired by a signal lepton.

Object Selection

- 3 types of Signal regions (SRs) defined by way of the object selection
- **SRO3ℓ**: One Leg 3 Leptons
- **SRO4ℓ**: One Leg 4 Leptons
- **SRTL**: Two Leg



[1]leptonic Z: SFOS dilepton pair with $m_{\ell\ell} \in [81.2, 101.2]$ GeV

[2]Hadronic V: dijet pair with $m_{jj} \in [71.2, 111.2]$ GeV

[3]Higgs: dijet pair, 1 or 2 b-tagged, with $m_{jj} \in [71.2, 150]$ GeV

Object Selection: Algorithms in Brief

- SRO3ℓ: Very straight forward → just compute the invariant mass of the 3 leptons
- SRO4ℓ: Very much not straight forward → If a 2nd boson **is not** reconstructed there is ambiguity as to which lepton should be used for the trilepton leg. Because of the varying kinematics depending on chargino mass, **there is no lepton matching choice that performs best for all mass points**. Many options were studied and the chosen scheme uses L_T, the scalar sum of the p_T of all leptons in an event, as a proxy for the chargino mass.
  - L_T <550 GeV: lepton closest in ΔR to the Z is assigned. At low mass the Z and the lepton from the same chargino leg are generally collimated
  - L_T >550 GeV: lepton which maximizes $m_{Z\ell}$ is assigned. At high mass it is unlikely that a random combination of Zℓ pairs would have a large invariant mass, in both signal and background
- SRTL: Pretty straight forward → A 2nd boson (besides the Z) is successfully reconstructed and the leptons are matched in a way that the $m_{Z\ell}$ asymmetry = $|m_{Z\ell} - m_{B\ell}| / (m_{Z\ell}+m_{B\ell})$ is minimized

Regions Defined

- All regions require SFOS lepton pair with $m_{\ell\ell} \in [81.2, 101.2]$ GeV and $m_{Z\ell} > 90$ GeV

	SROL3ℓ	CRWZ	VRMet	VRmTmin	CRZj	VRZj	CRttZ	VRttZ	SROL4ℓ	SRTL	CRZZ	VRZZ
n leps	==3	==3	==3	==3	==3	==3	≥3	≥3	≥4	≥4	==4	==4
n bjets	-	-	-	-	-	-	≥2	≥2	-	-	-	-
dRbb	<1.5	<1.5	<1.5	<1.5	<1.5	<1.5	>2.5	[1.5,2.5]	<1.5	<1.5	<1.5	<1.5
4l2Z; mll2 window [GeV]	-	-	-	-	-	-	veto; <20	veto; <20	veto; <20	veto; <20	require; <5	require; [5,20]
MET [GeV]	>150	<80	>80	<80	<30	[30,80]	>40	>40	>80* (SF)	-	-	-
m_T^{min} [GeV]	>125	[50,100]	<100	>125	<30	<30	-	-	-	-	-	-
Second boson	-	-	-	-	-	-	-	-	no	yes	-	-
$m_{Z\ell}$ asymmetry	-	-	-	-	-	-	-	-	-	<0.1	-	-

- CRWZ, CRZZ, CRttZ: control regions used to normalize WZ, ZZ, ttZ expectations to data yields. VRMet, VRmTmin, VRZZ, VRttZ: validation regions to test performance of CR normalizations.
- CRZj and VRZj: fake factor measurement and validation regions

Limit Setting Strategy

- We will set limits across the full plane of possible wino decays by reweighting signal events according to truth decay
- Do a coarse scan in lepton flavor:
  - (BR($\chi^{\pm}_{W}\to$Be), BR($\chi^{\pm}_{W}\to$Bμ), BR($\chi^{\pm}_{W}\to$Bτ))=(1,0,0), (0,1,0), (0,0,1), (0.33,0.33,0.34)
  - For BR($\chi^{\pm}_{W}\to$Be/Bμ)=1, require that non-Z lepton is e or μ
    - SROL3ℓ, SROL4ℓ: requirement only on non-Z lepton
    - SRTL: requirement on both non-boson leptons
    - Effectively tripling our SR count. Expected yield tables will be included in appendix.
- For each of these lepton BR points, do a fine scan of boson BR (increments of 0.25 or smaller)
  - Each lepton BR point will have a corresponding triangle limit plot (Higgs BR vs Z BR)
- $\chi^{\pm}_{W}\,\chi^{0}_{W}$: Set BR($\chi^{\pm}_{W}\to$Zℓ)=1. Ignoring possible correlations between $\chi^{\pm}_{W}$ and χ^{0}_{W} BRs. No large correlation seen by theorists.

Uncertainties

- Detector uncertainties: CP/PMG/SUSY recommendations are used. Fully implemented.
  - Jet energy scale and resolution (8 JES and 8 JER), flavor tagging, pileup tagging
  - Lepton scale and resolution and efficiencies (including trigger)
  - MET uncertainties
  - Luminosity: 1.7%
- Theory systematics: In progress.
  - Diboson, Triboson, and ttZ samples:
    - Using internal weights (scale, αS, PDF). Diboson and Triboson are ready, currently implemented in HF as a flat systematic. Results binned in $mZ\ell$ are available but not yet implemented in HF.
    - We will run available alternative samples through SimpleAnalysis for hard scatter, PS, ISR. Not all samples are available (ttZ ISR)
  - Other background samples, including Higgs: flat uncertainty is taken
  - Signal samples: Private alternative samples will be generated to assess relevant variations.
- Fake systematics: In progress.
  - Propagation of statistical uncertainty from measurement region
  - Prompt subtraction, to account for MC cross section uncertainty
  - Closure, to account for differences in source and composition between regions
  - Parameterization, to account for FF dependence on kinematic variables other than pTcone

Signals of Interest: $\chi^{\pm}_{W}$ and χ^{0}_{W} BRs

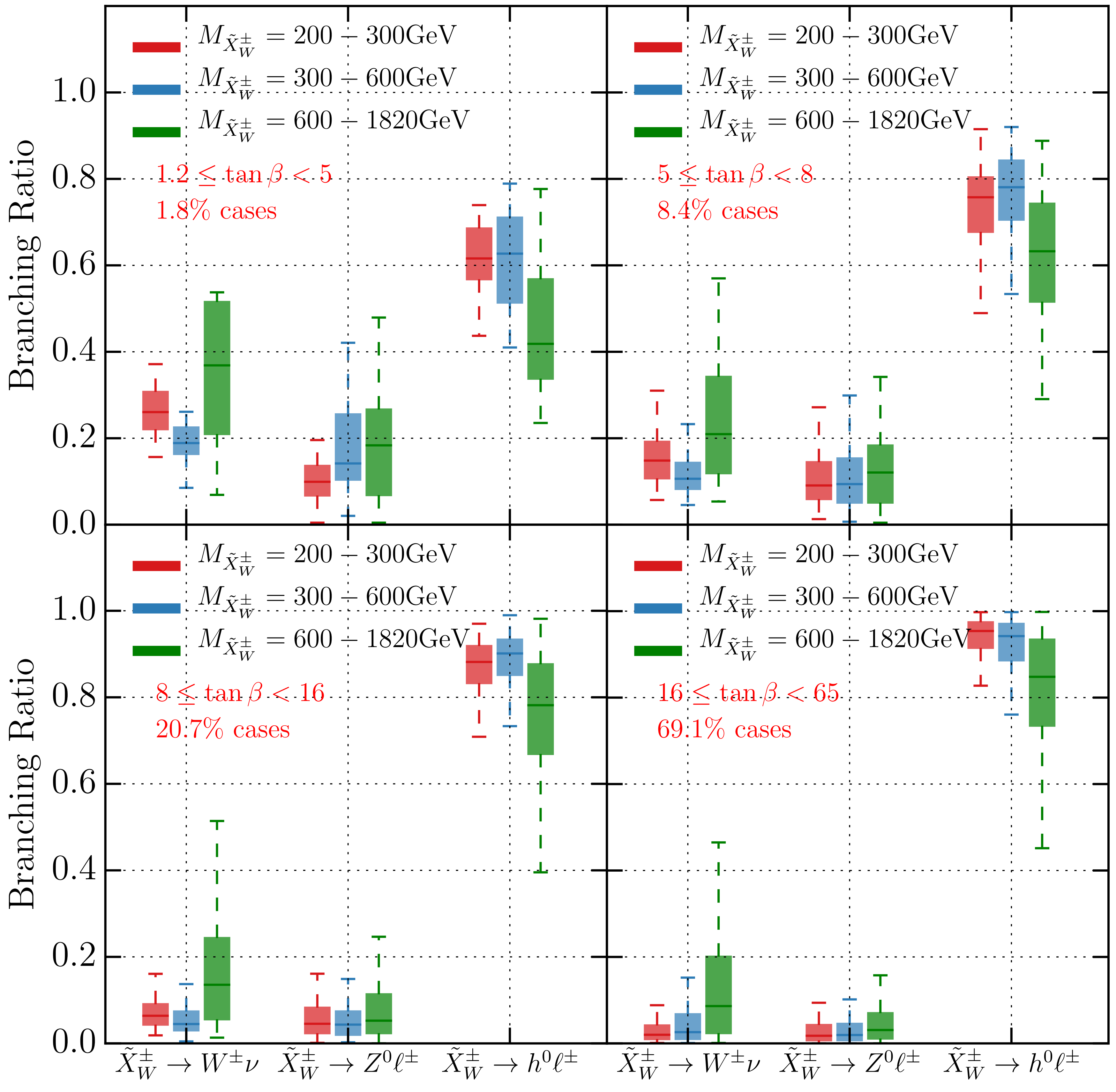


Figure 6: Branching ratios for the four possible decay channels of the Wino chargino LSP, presented for the three $M_{\tilde{X}^{\pm}_{W}}$ mass bins and four $\tan\beta$ regions. The colored horizontal line inside each box indicate the median value of the branching fraction in that bin, the colored box indicates the interquartile range in that bin, while the dashed error bars show the range between the maximum and the minimum values of the branching ratio for that bin. The case percentage indicate what percentage of the valid initial points have $\tan\beta$ values within the range indicated. For each channel, we sum over all three families of possible leptons. Note that $\tilde{X}^{\pm}_{W} \to h^0\ell^{\pm}$ is strongly favored– except perhaps in the $1.2 < \tan\beta < 5$ bin. The calculations were performed assuming a normal neutrino hierarchy, with $\theta_{23} = 0.597$.

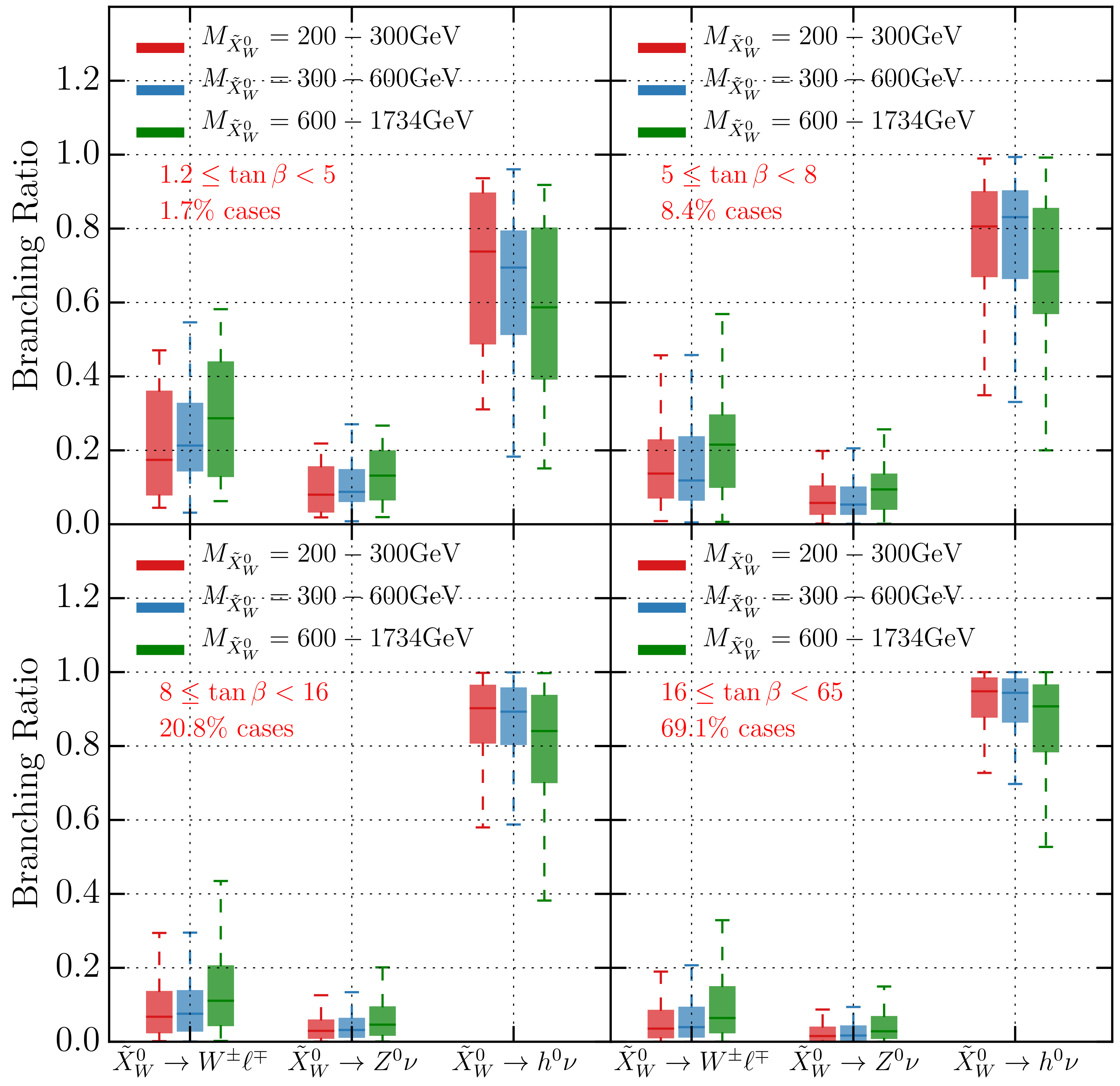


Figure 12: Branching ratios for the three possible decay channels of a Wino neutralino LSP divided over three mass bins and four $\tan\beta$ regions. The colored horizontal lines inside the boxes indicate the median values of the branching fraction in each bin, the boxes indicate the interquartile range, while the dashed error bars show the range between the maximum and the minimum values of the branching fractions. The case percentage indicate what percentage of the physical mass spectra have $\tan\beta$ values within the range indicated. We assumed a normal neutrino hierarchy, with $\theta_{23} = 0.597$.

each of these, we compute the decay rates via RPV processes, using the expressions (E.2)-(E.8) with $n = 2$ given in Appendix E. The branching ratios of the main channels take different values for different valid points in our simulation. These values are scattered around the median values of these

arXiv:1811.05581

Neutrino Hierarchy

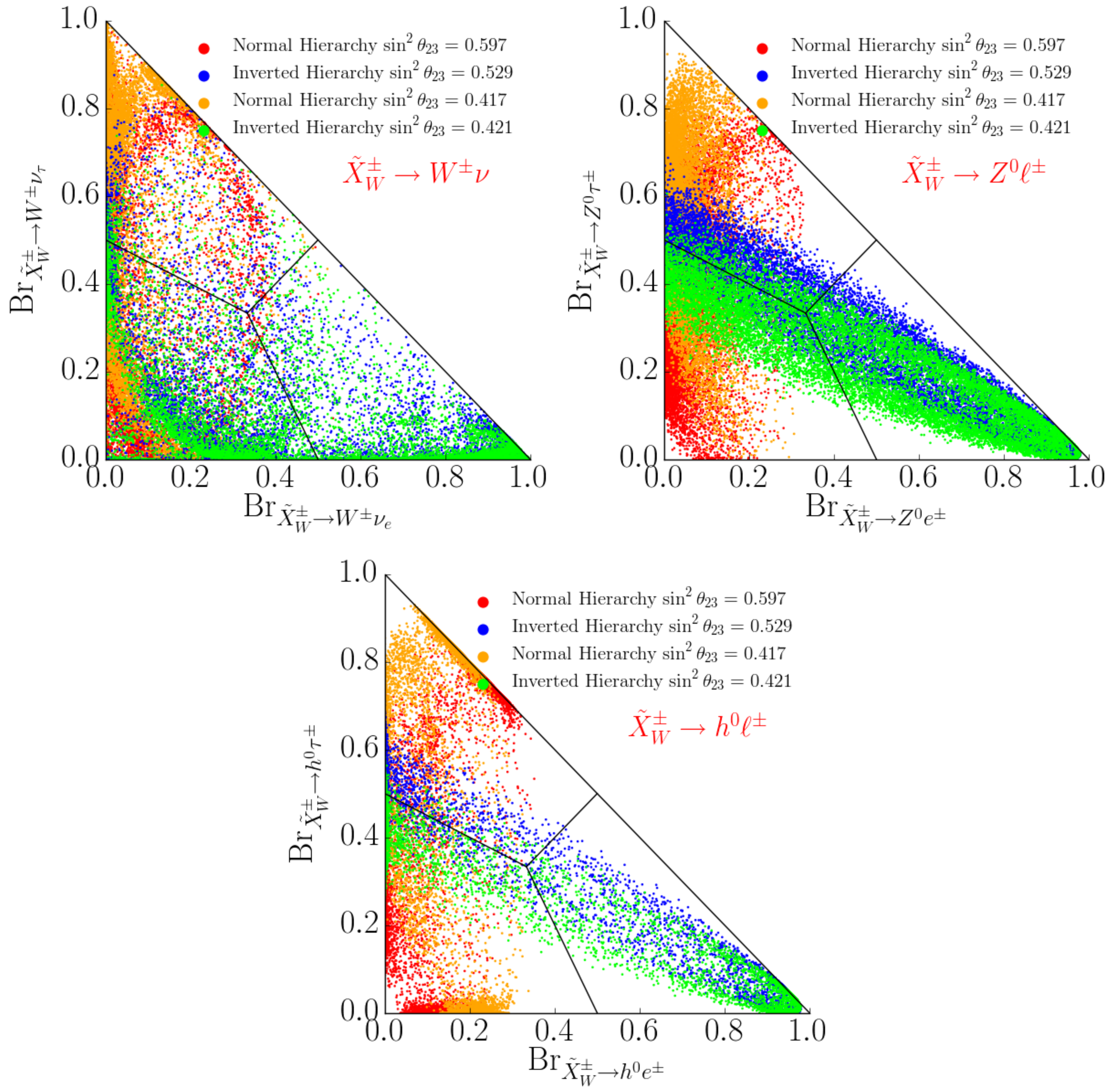


Figure 10: Branching ratios into the three lepton families, for each of the three main decay channels of a Wino chargino LSP. The associated neutrino hierarchy and the value of θ_{23} is specified by the color of the associated data point.

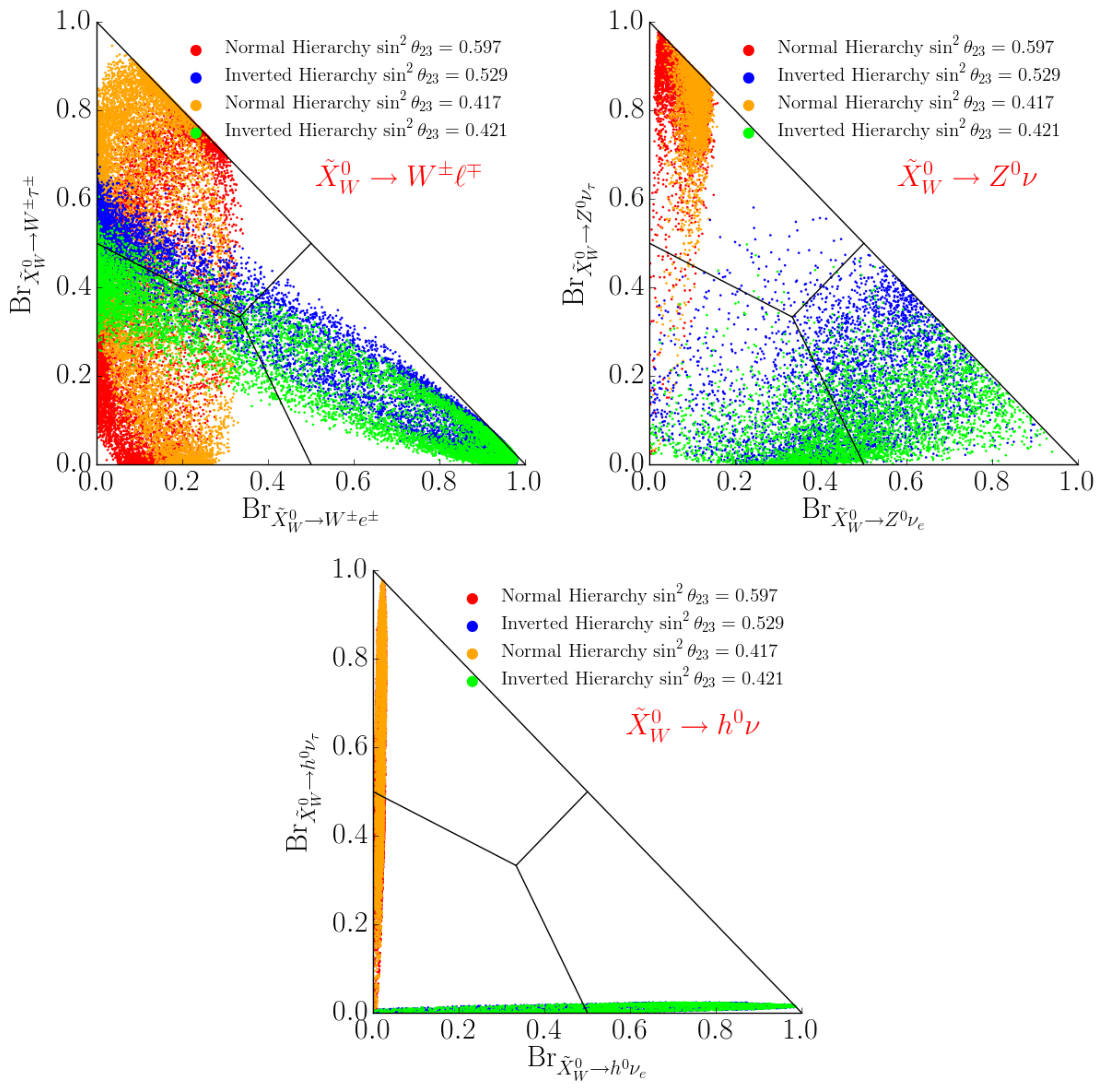


Figure 15: Branching ratios into the three lepton families, for each of the three main decay channels of a Wino neutralino LSP. The associated neutrino hierarchy and the value of θ_{23} is specified by the color of the associated data point.

arXiv:1811.05581

Statistical Scan of MSSM B-L RPV Model

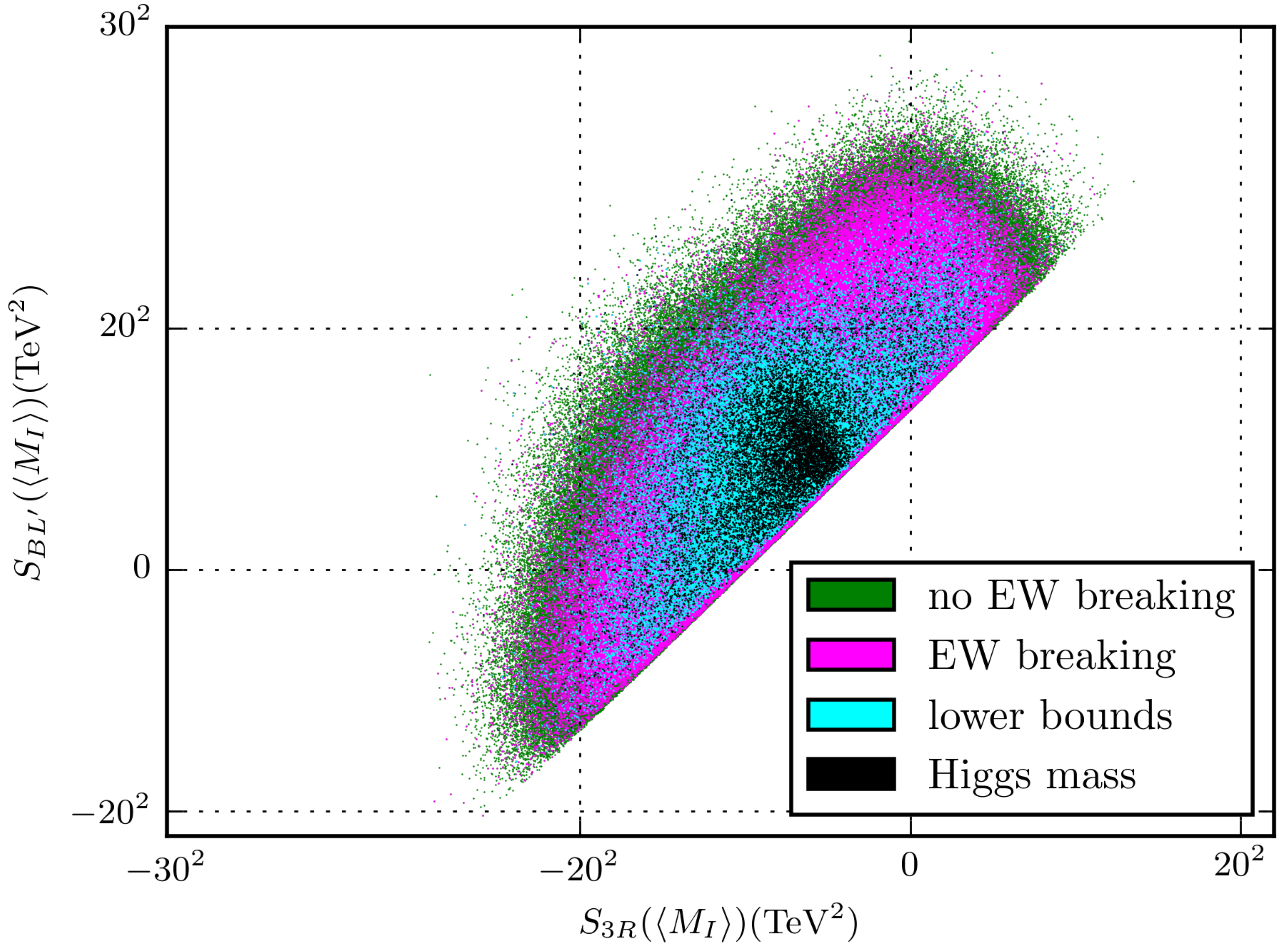


Figure 2: Plot of the 100 million initial data points for the RG analysis evaluated at M_I . The 4,351,809 green points lead to appropriate breaking of the $B-L$ symmetry. Of these, the 3,142,657 purple points also break the EW symmetry with the correct vector boson masses. The cyan points correspond to 342,236 initial points that, in addition to appropriate $B-L$ and EW breaking, also satisfy all lower bounds on the sparticle masses. Finally, as a subset of these 342,236 initial points, there are 67,576 valid black points which lead to the experimentally measured value of the Higgs boson mass.

arXiv:1810.11035

Long Lived?

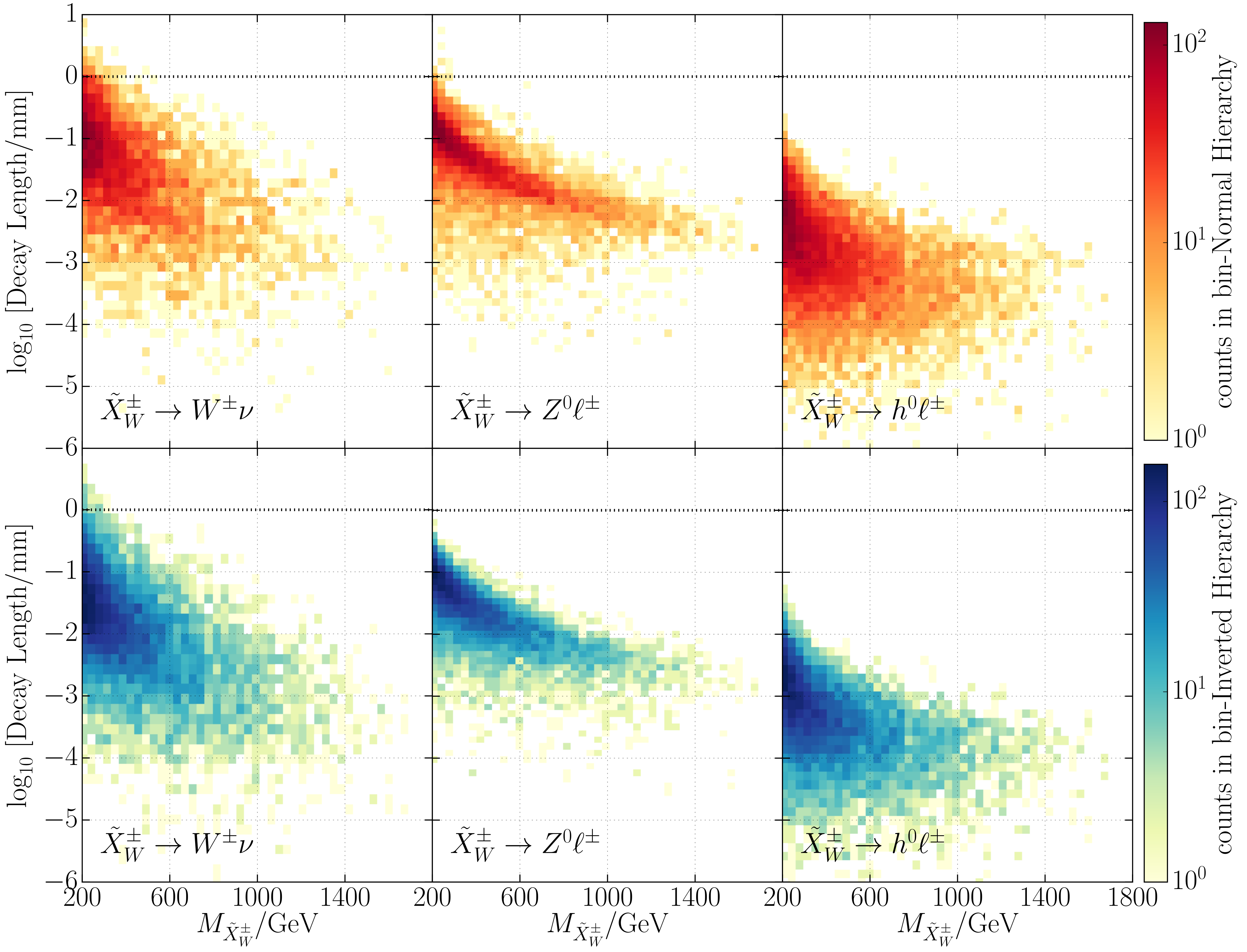


Figure 9: Wino Chargino LSP decay length in milimeters, for individual decay channels, for both normal and inverted hierarchies. We have chosen $\theta_{23} = 0.597$ for the normal neutrino hierarchy and $\theta_{23} = 0.529$ for the inverted hierarchy. The choice of θ_{23} has no impact on the decay lengths. All individual channels have decay lengths < 1mm

arXiv:1811.05581