Searches for Electro-Weak and 3rd Generation Superpartners

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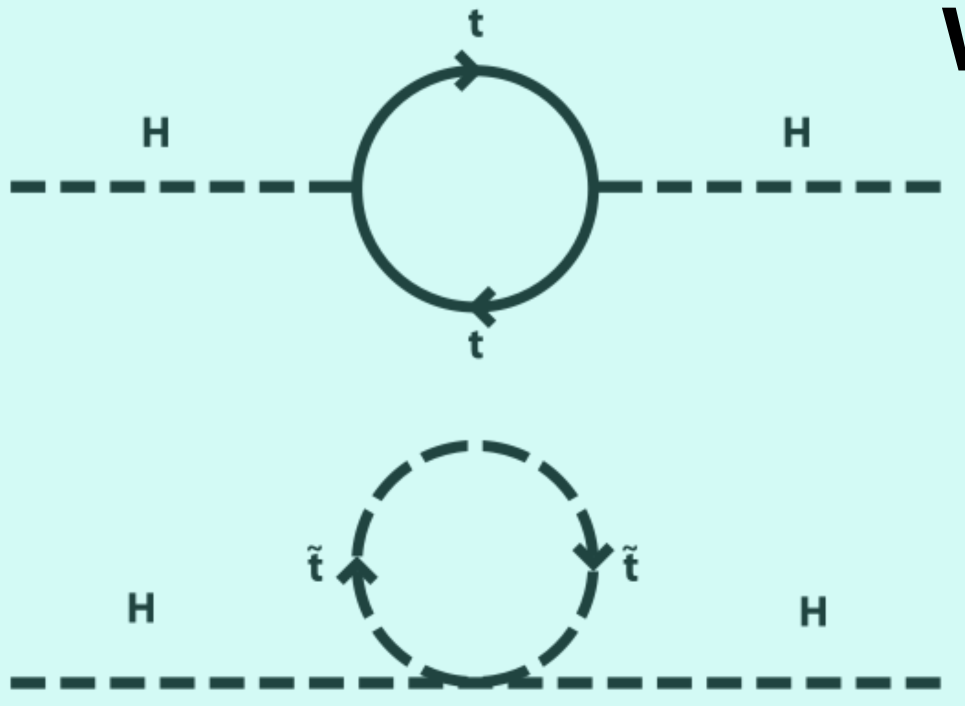
Liverpool HEP Christmas Meeting-2019

Why SUSY?

The Hierarchy Problem:



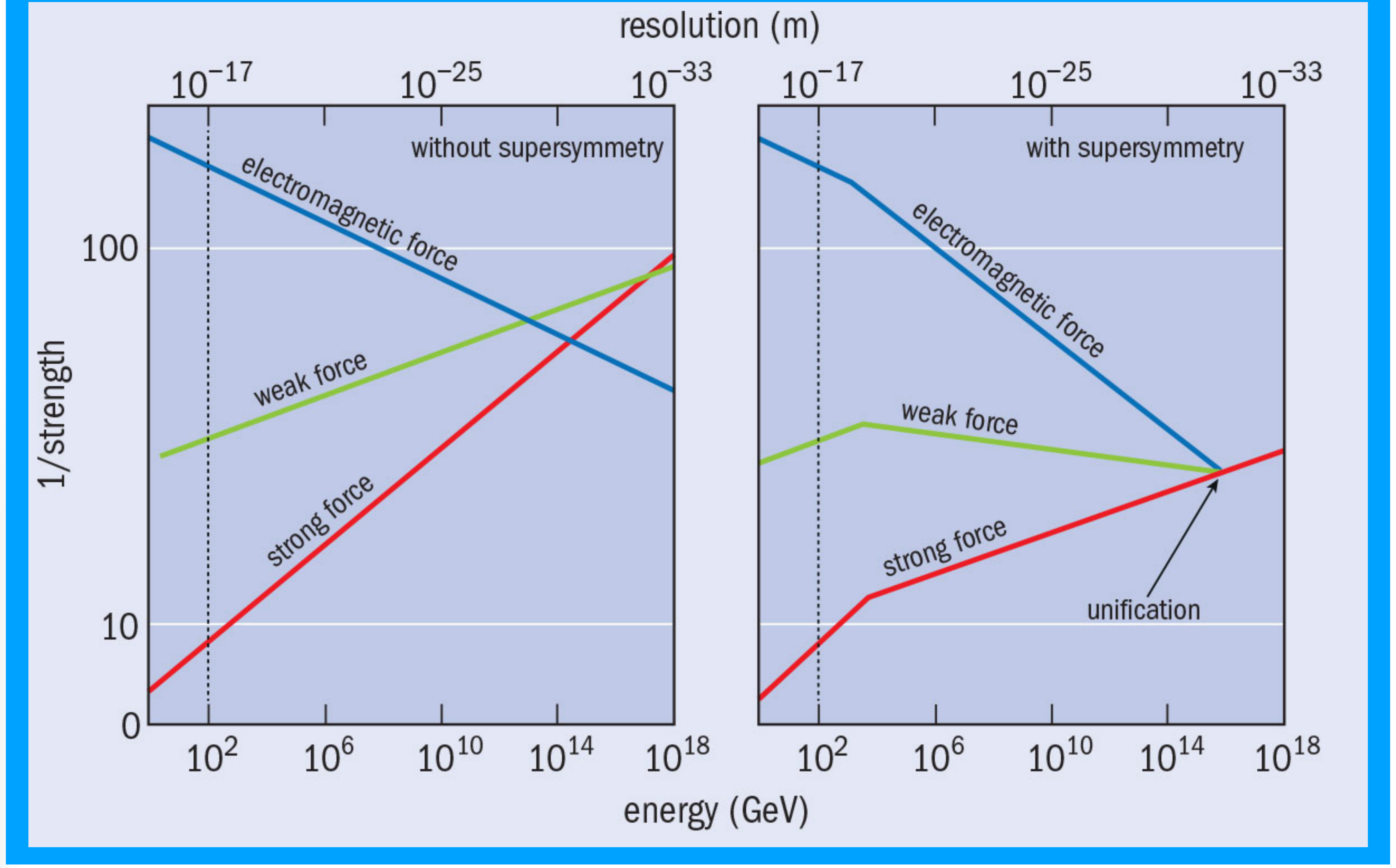
Why is the higgs mass so small?

Solved Elegantly in SUSY

Dark Matter

SUSY predicts a Massive, Weakly interacting and Stable particle: Dark Matter Candidate

Guage coupling unification: Extension to GUTs



Signal Phenomenology

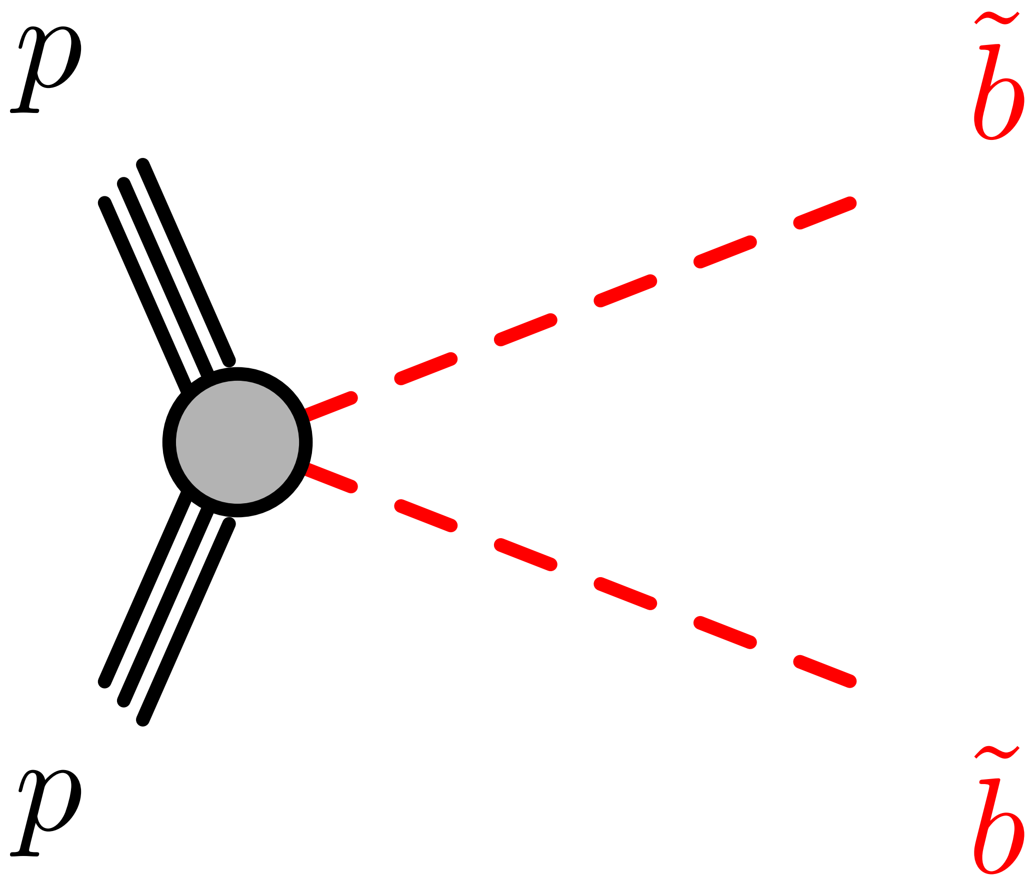
What are we looking for?

SUSY predicts boson-fermion symmetry:

$$Q\,|\,\text{fermion}> \;=\; |\,\text{boson}>\;,\; Q\,|\,\text{boson}> \;=\; |\,\text{fermion}>$$

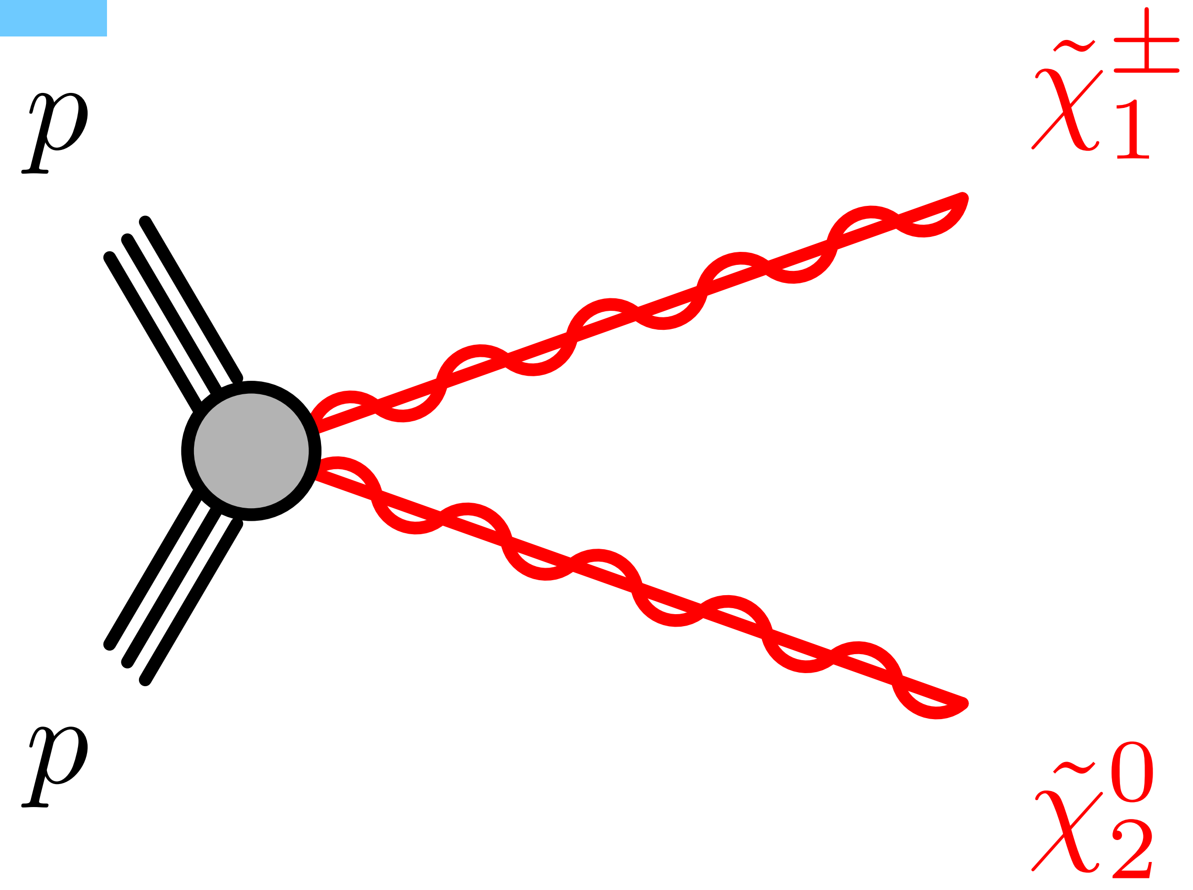
- **SM particles have super-partners differing by spin 1/2**

3rd Generation



We consider that SUSY particles are produced in pairs at the LHC

Electro-Weak



$\tilde{b}$:

- **Partner of the SM bottom quark**

$\tilde{\chi}_2^0$:

- **Second-lightest partner of neutral EWK guage bosons**

$\tilde{\chi}_1^{\pm}$:

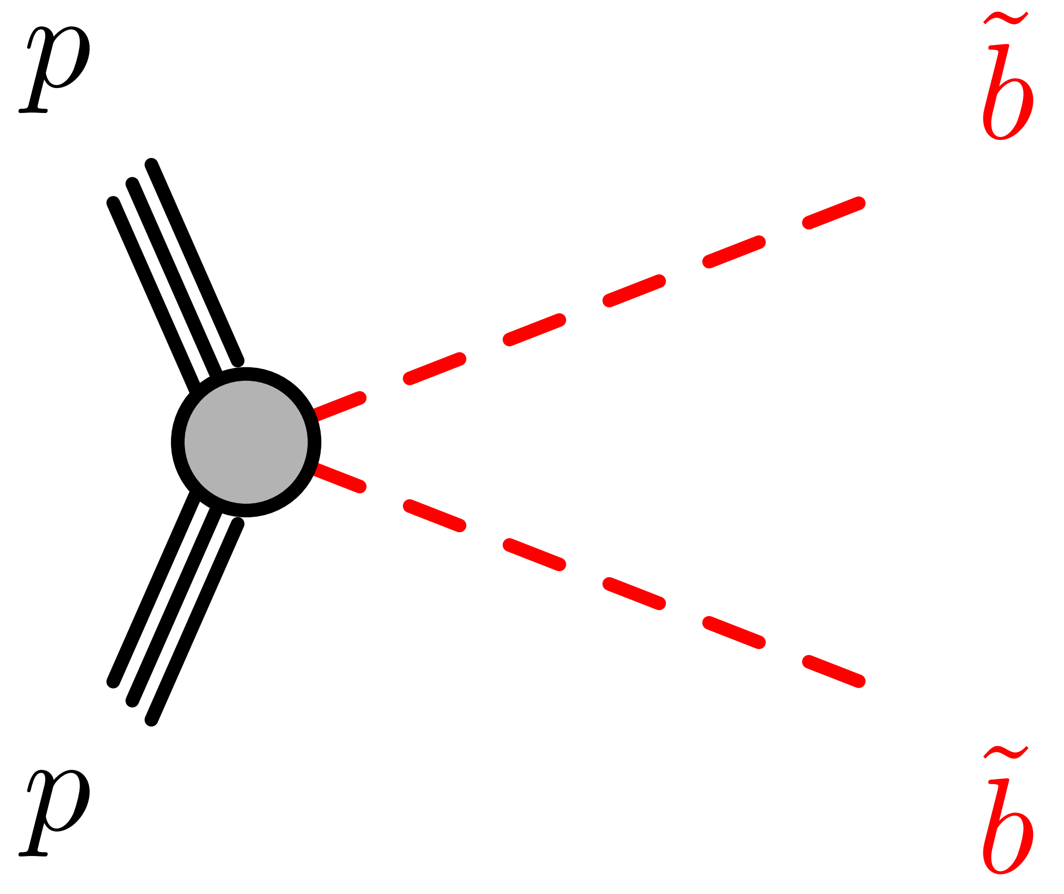
- **Lightest partner of charged EWK guage bosons**

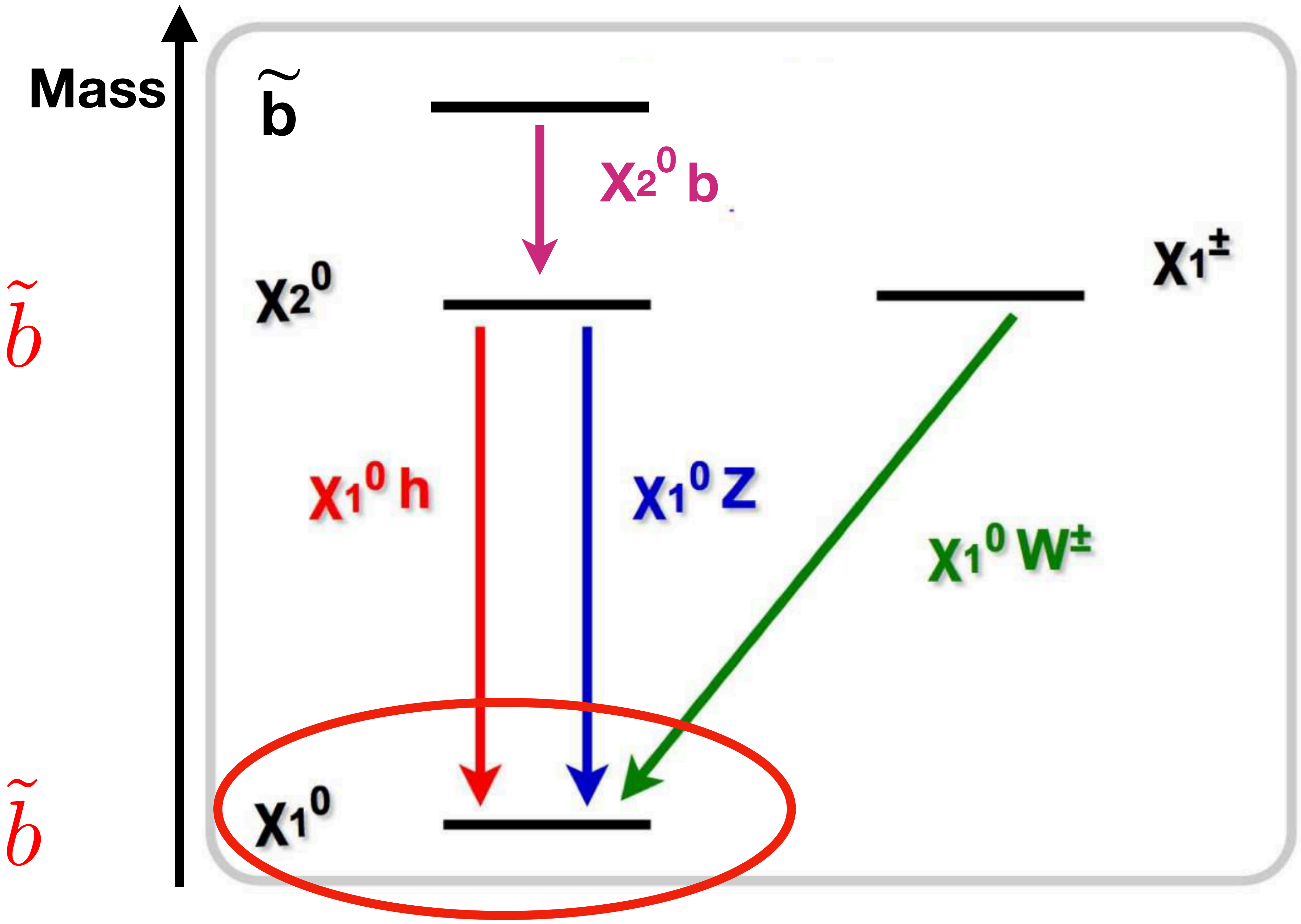
Signal Phenomenology

UNIVERSITY OF LIVERPOOL

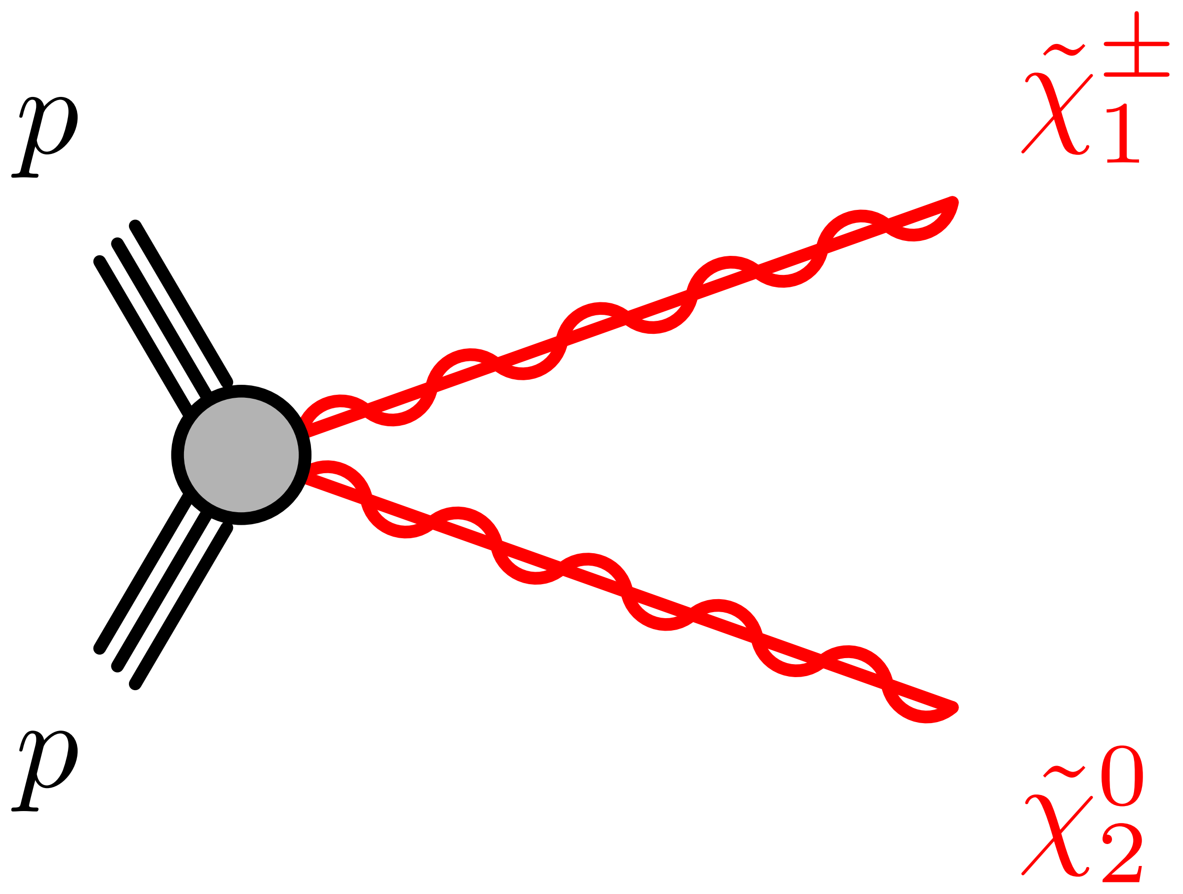
What are we looking for?

3rd Generation





Electro-Weak



Mass hierarchy such that particles decay to $\tilde{\chi}_1^0$:

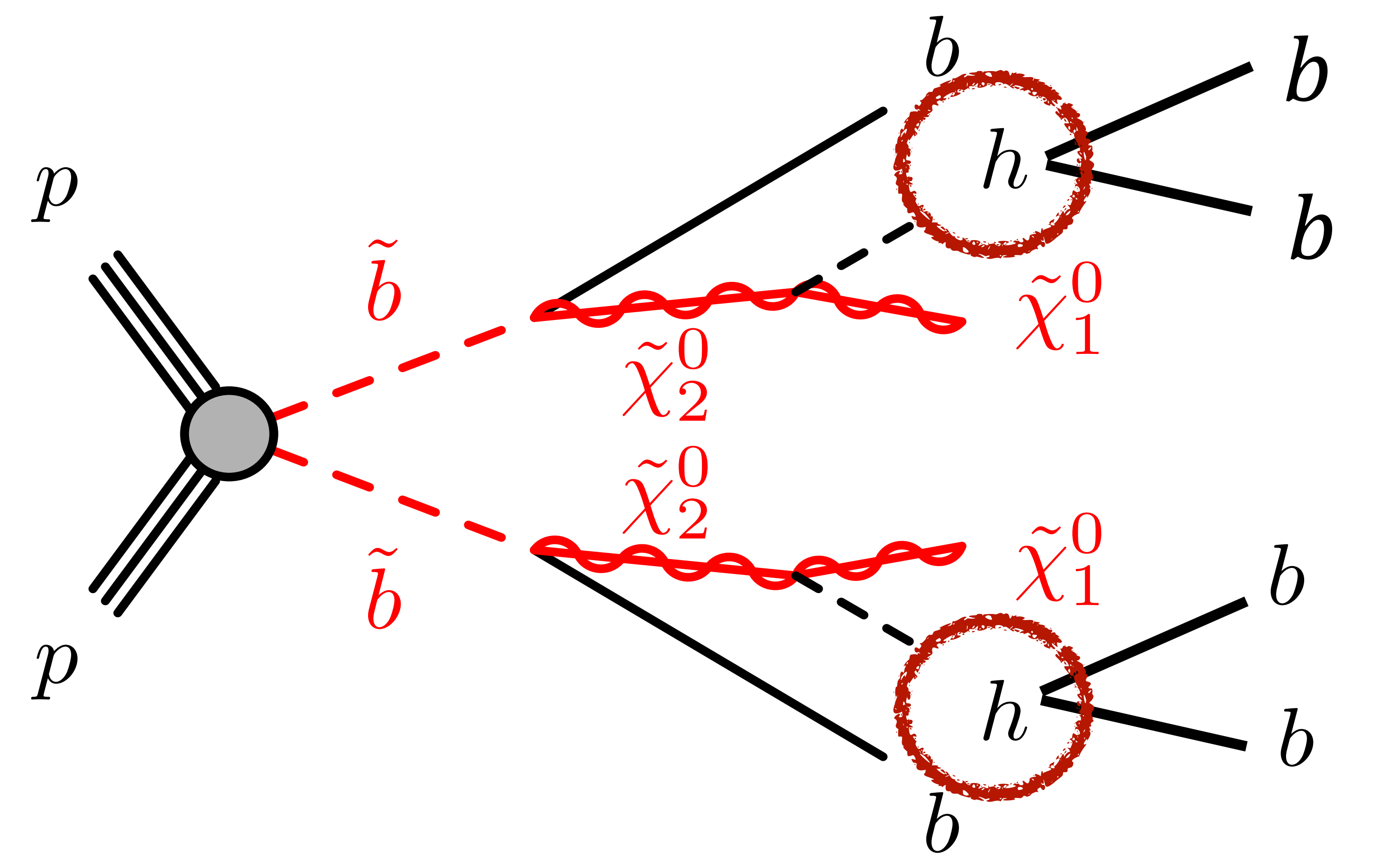
- Lightest Supersymmetric Particle
- Partner for the neutral electroweak guage bosons
- Weakly interacting, stable

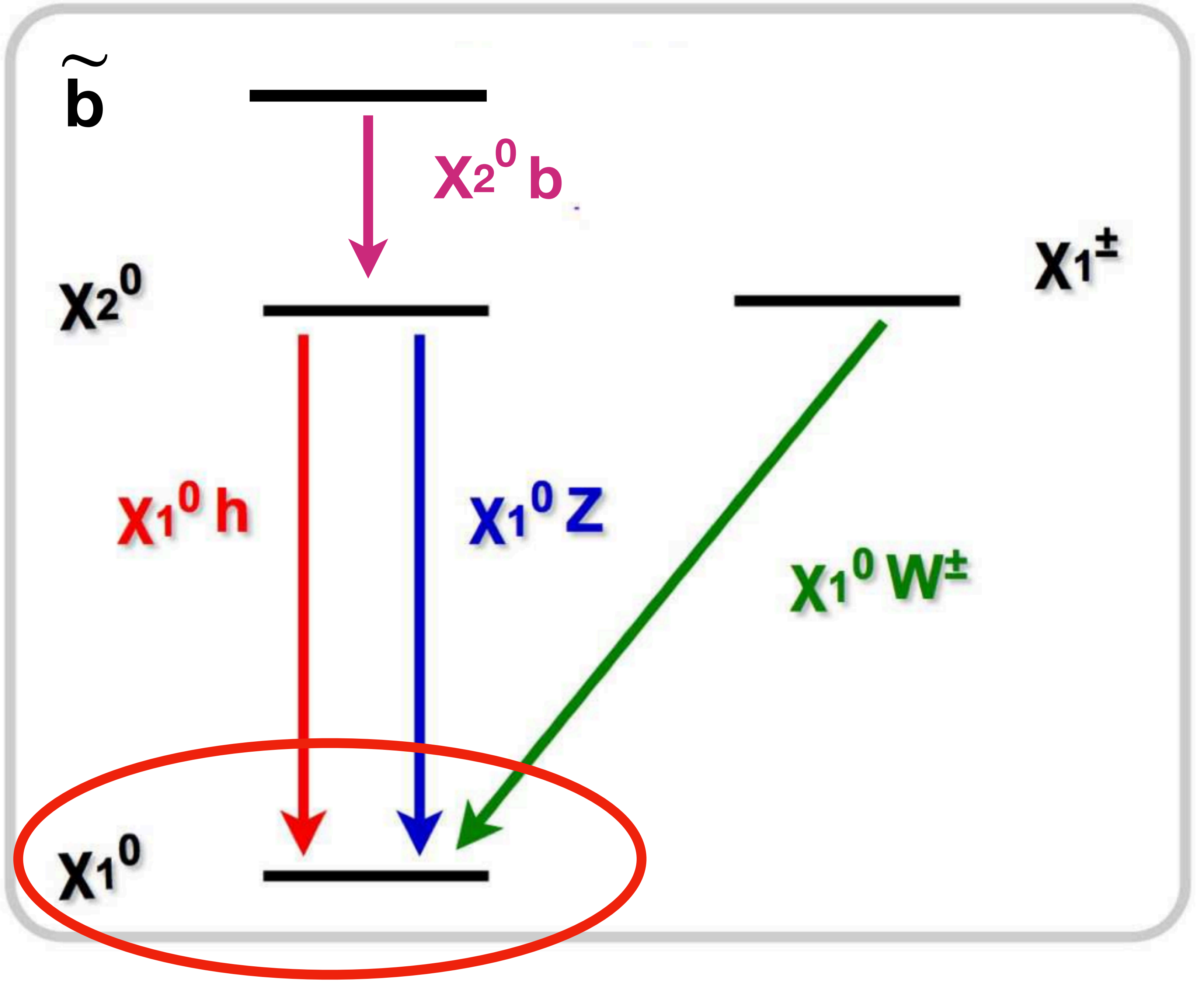
$\tilde{\chi}_1^0$: SUSY Dark Matter candidate

Signal Phenomenology

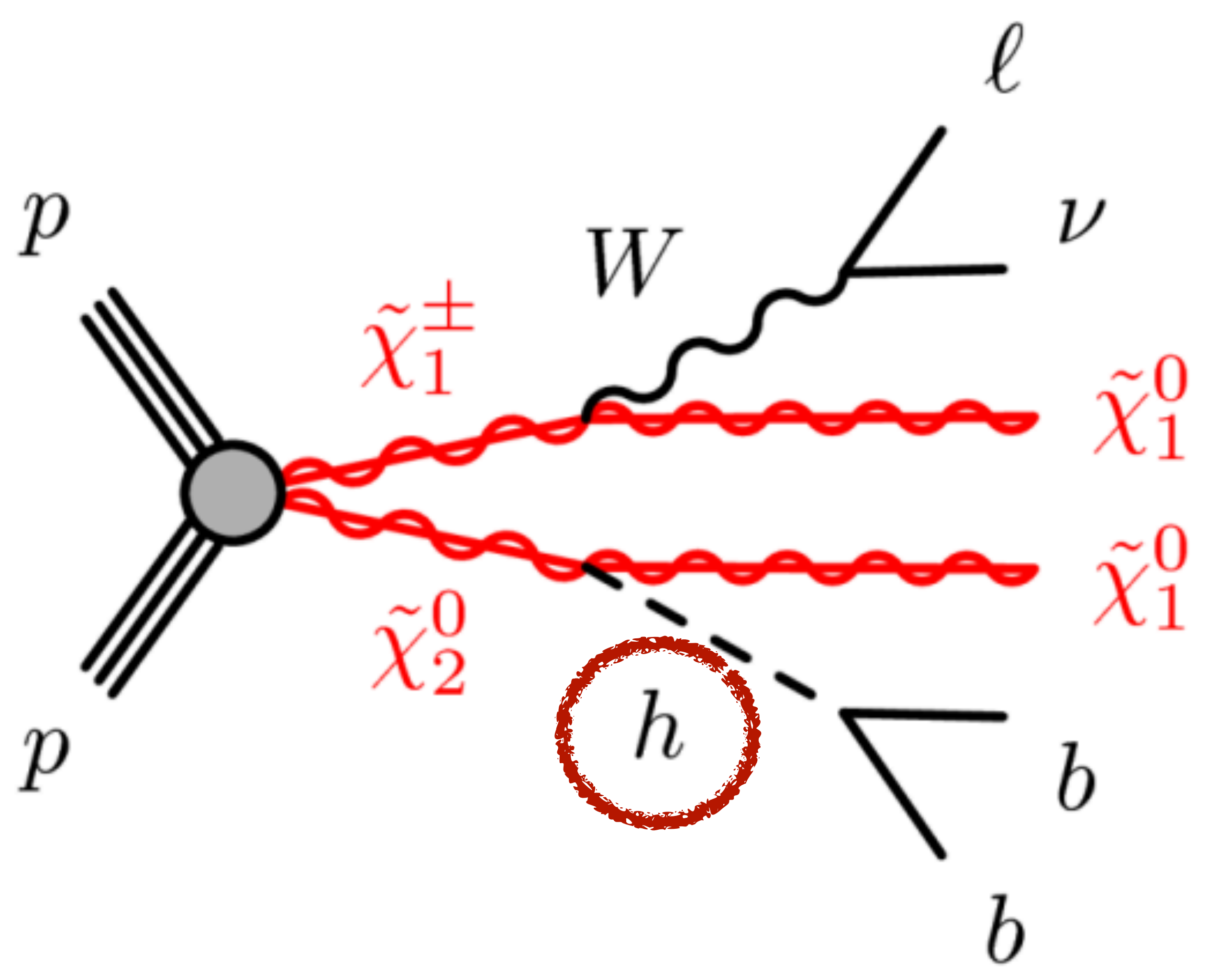
What are we looking for?

3rd Generation





Electro-Weak



Common features:

- Multiple b-quarks
- Missing Transverse Energy carried away by $\tilde{\chi}_1^0$
- Higgs decay to b-quarks as a handle in the signal

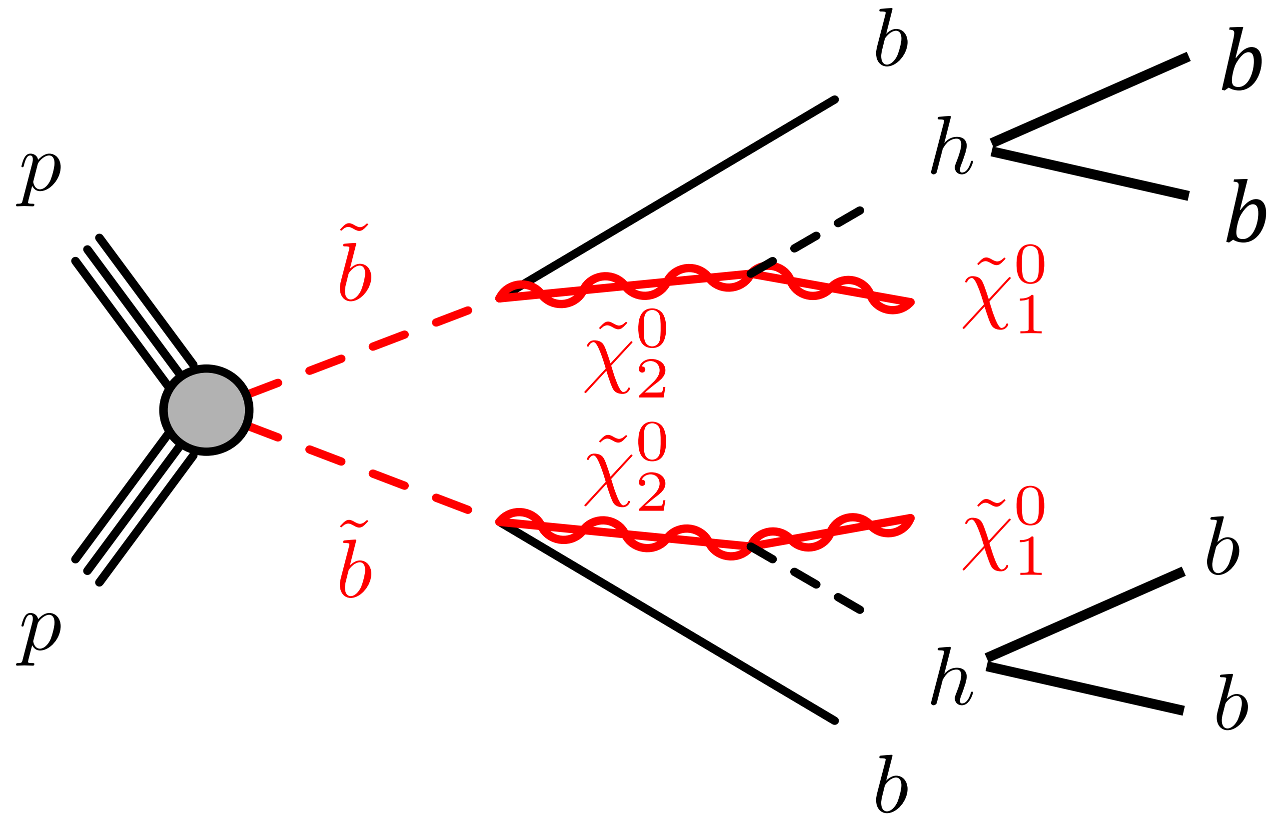
Sbottom-multi-B Analysis

My main contribution:

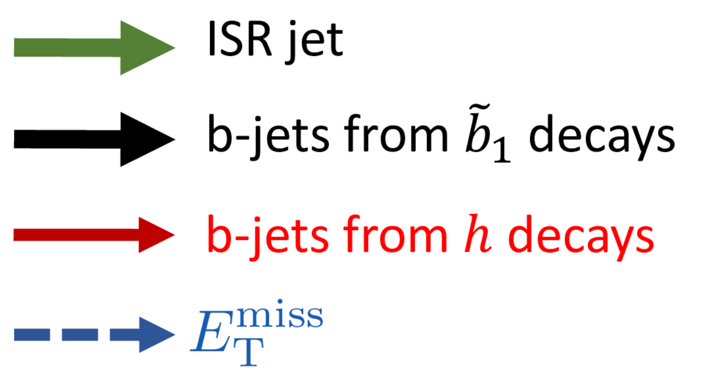
Developing signal region for compressed scenarios:

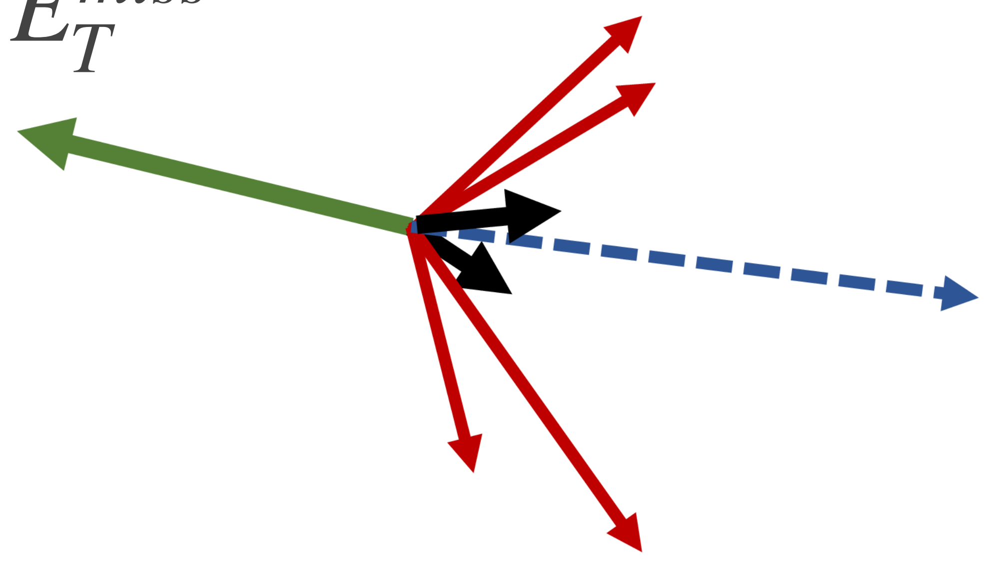
$\Delta M(\widetilde{b}, \widetilde{\chi}_2^0)\ 5 - 40 GeV$

$\Delta M(\widetilde{\chi}_2^0, \widetilde{\chi}_1^0) \sim 125 GeV$



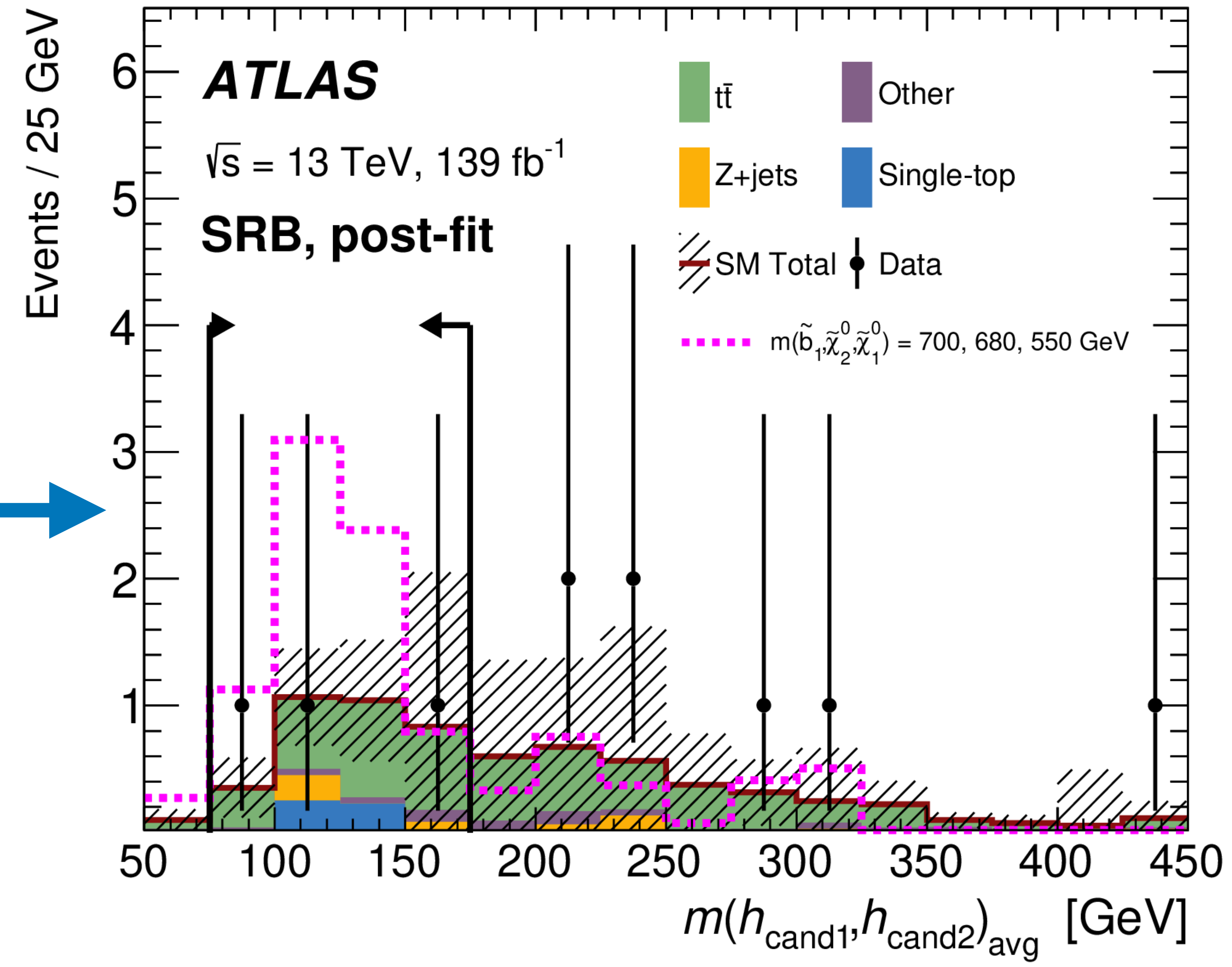
Target





Select events with initial state radiation (ISR) to recover E_T^{miss}

Use toplogy-specific algorithm to reconstruct higgs mass



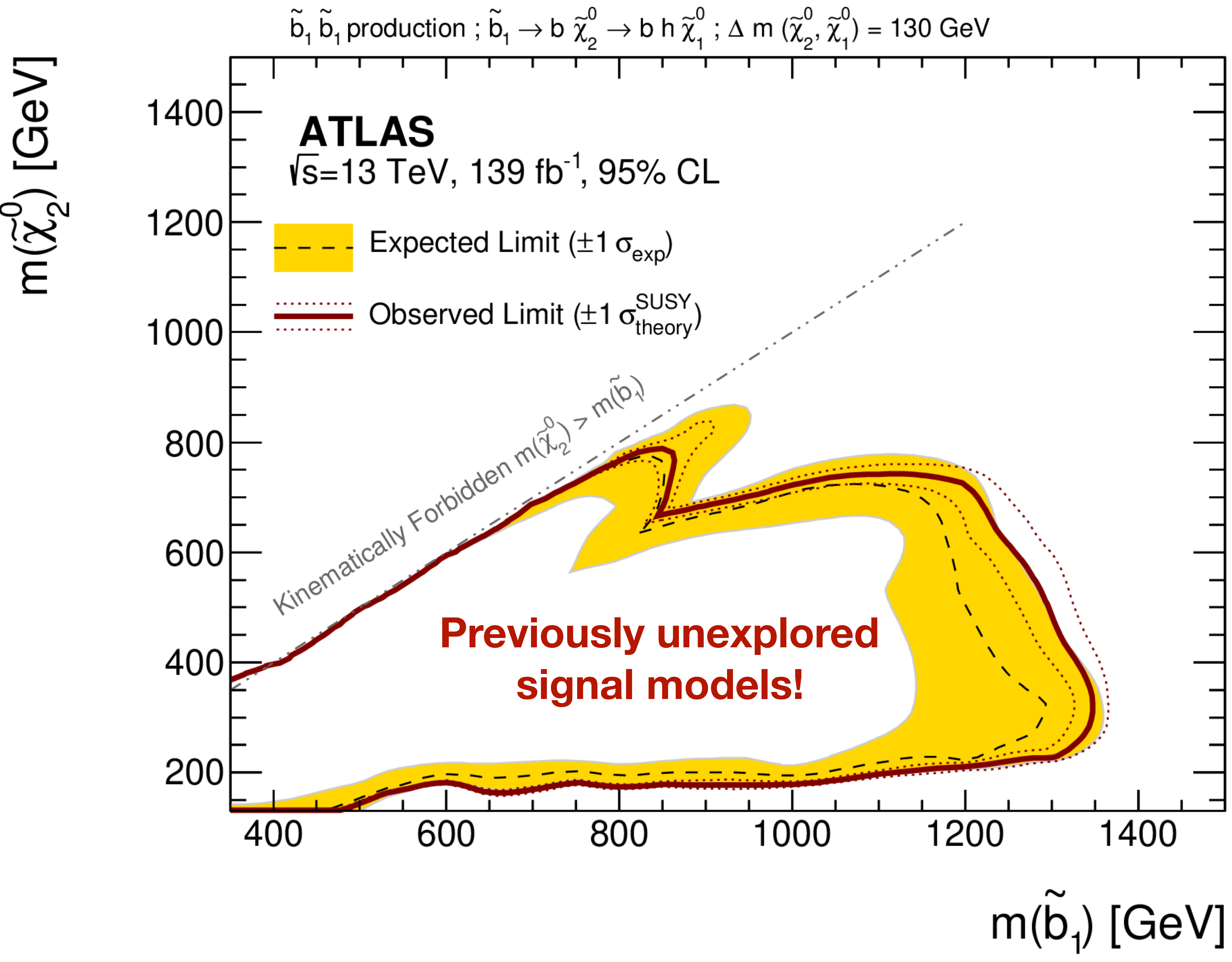
Compressed Features

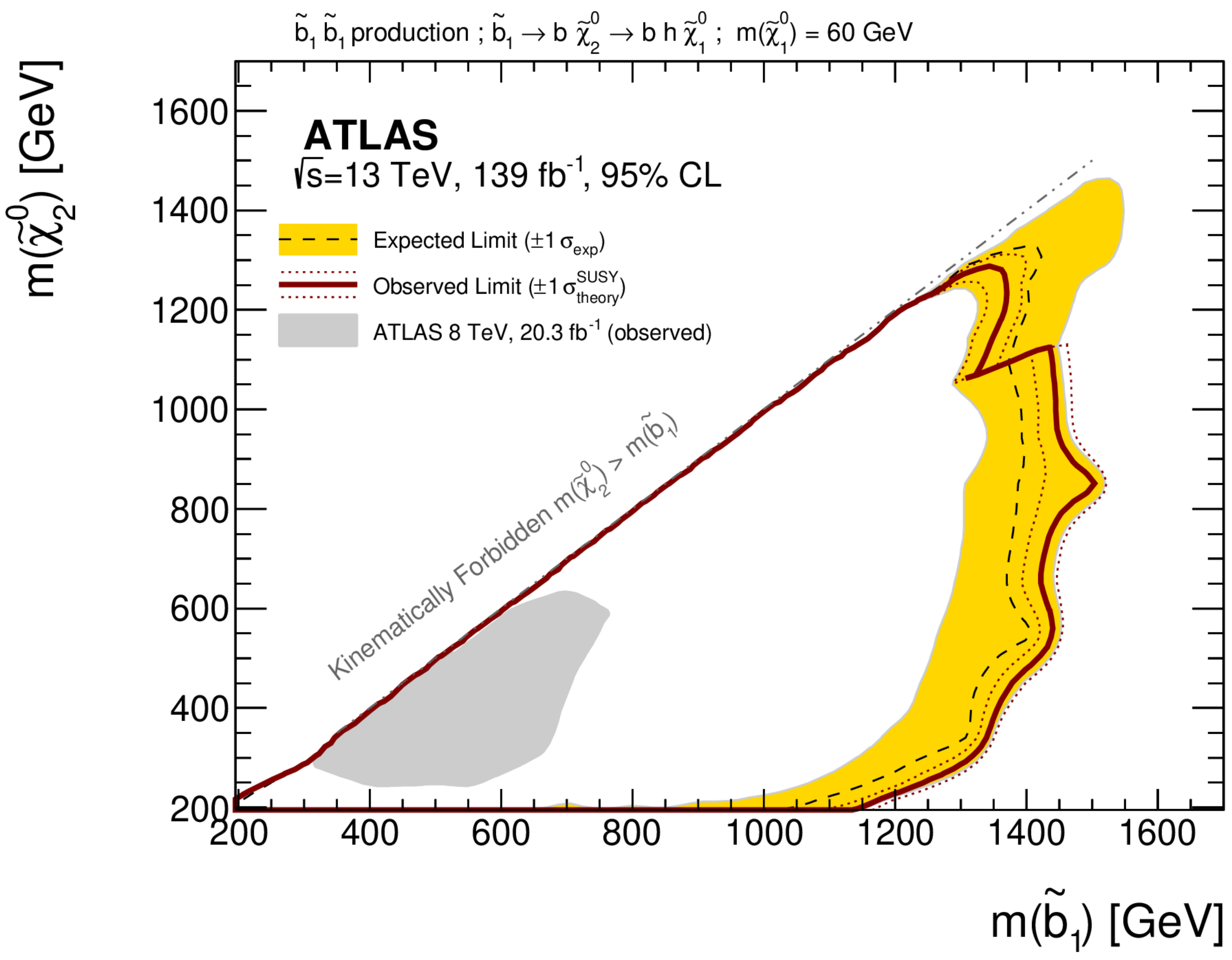
- **Low-momentum b-quarks (from $\widetilde{b}$) -> Hard to reconstruct**
- **Low momentum $\widetilde{\chi}_1^0$ -> Low Missing Transverse Energy E_T^{miss}**
- **2 Higgs are produced at rest -> Complex b-jet topology**

Public Results

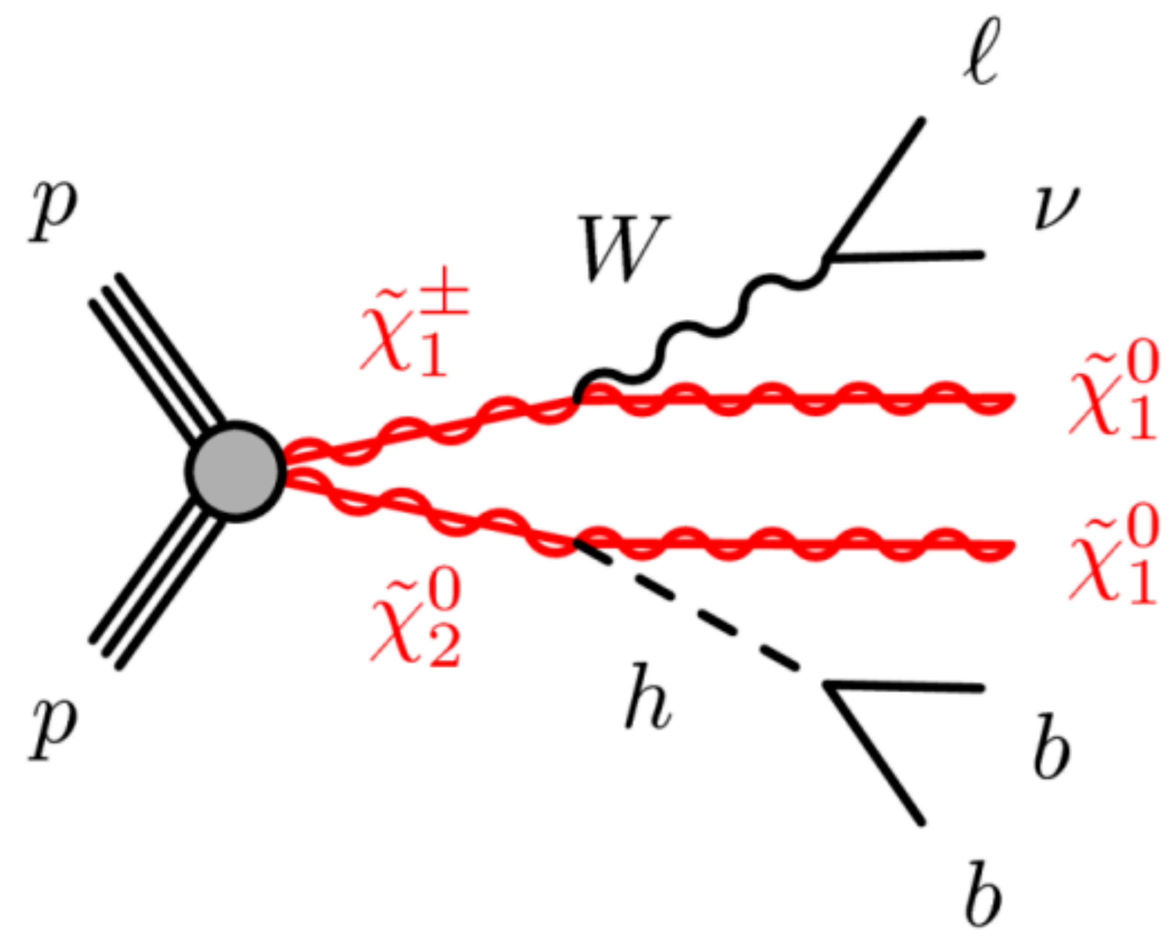
No siginificant excess was observed
We place limits on signals under two mass constraints

The first SUSY result on full run2 dataset!
The analysis has now been accepted by JHEP-arXiv link





Electro-weak SUSY



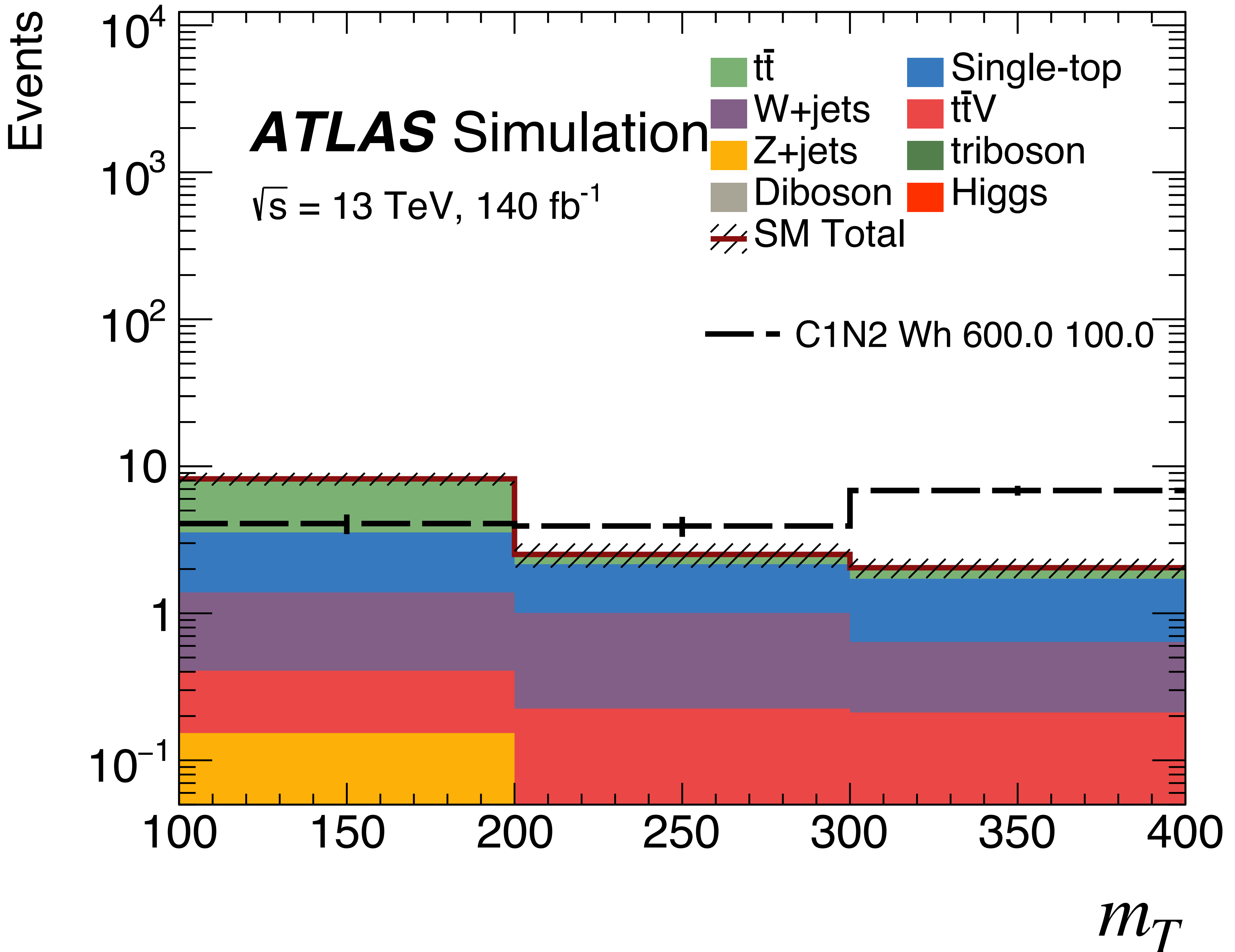
<u>Analysis is based on 2 key variables:</u>

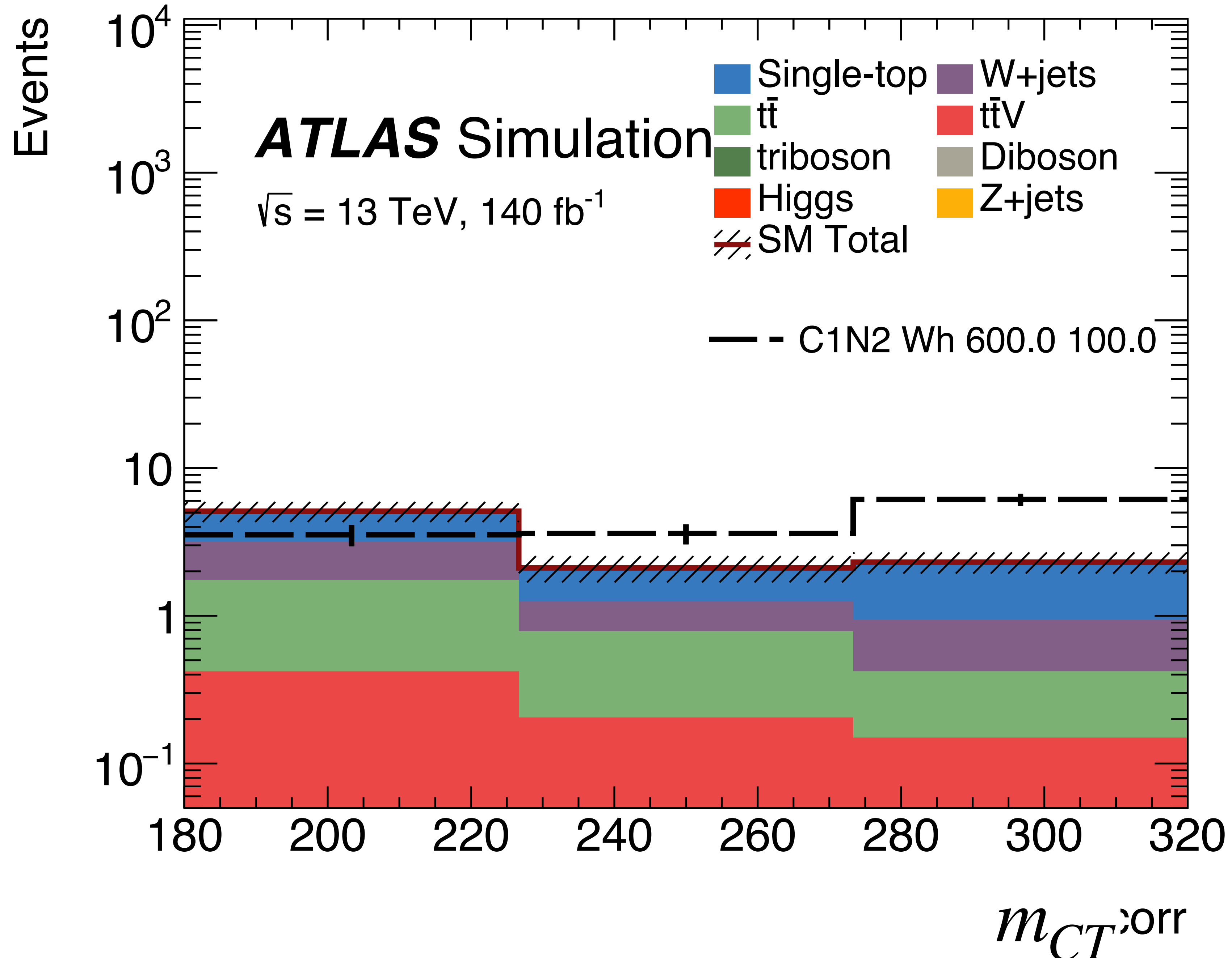
$$m_T = \sqrt{2p_T^l E_T^{miss}(1 - cos[\Delta\phi(\mathbf{p_T^l}, \mathbf{p_T^{miss}})])}$$

$$m_{CT} = \sqrt{2p_T^{b1}p_T^{b2}(1 + cos\Delta\phi_{bb})}$$

Low kinematic endpoints for SM backgrounds but high endpoints for SUSY

We exploit differences in signal and background shape using a statistical fit.



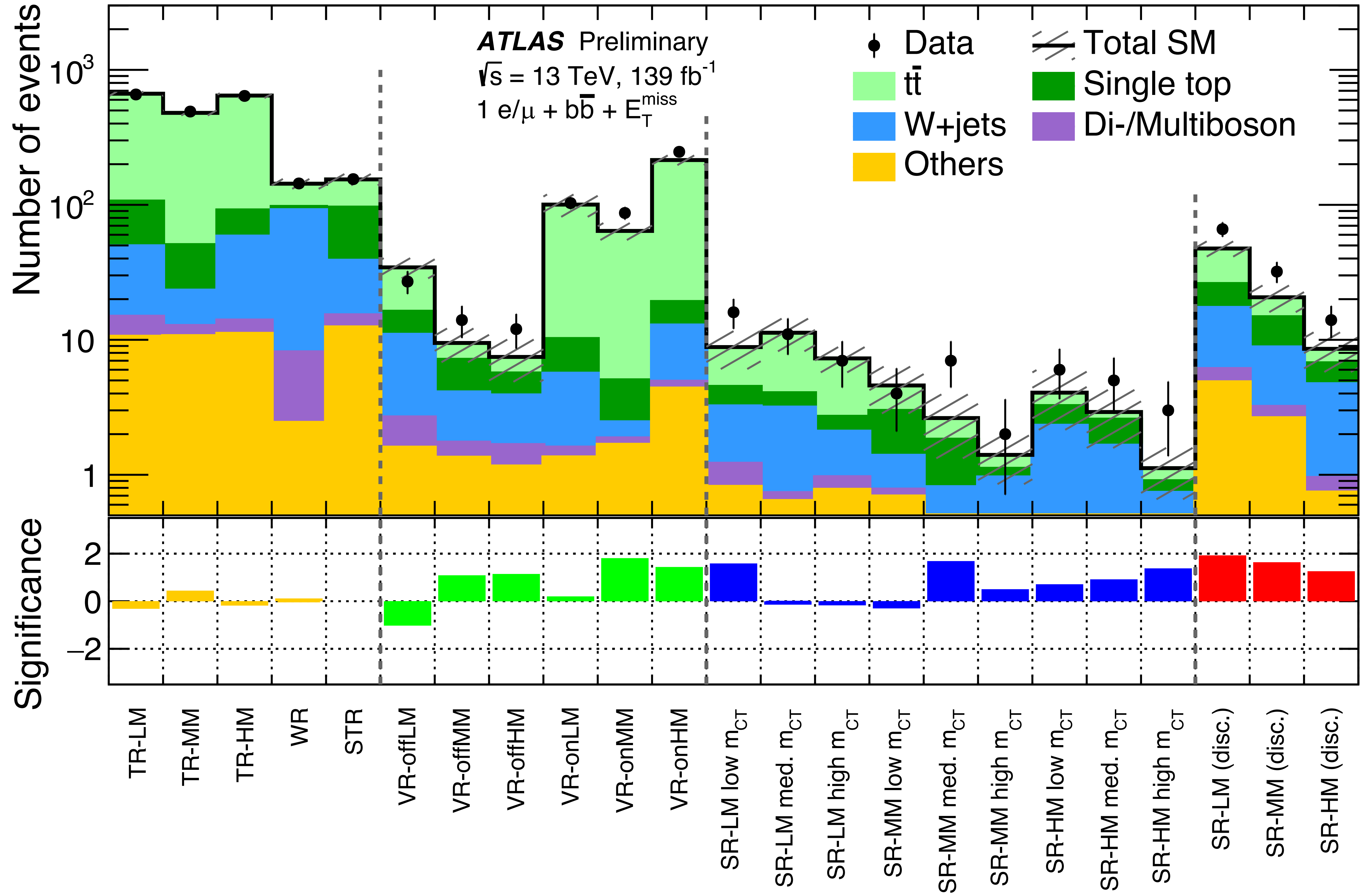


Analysis Result

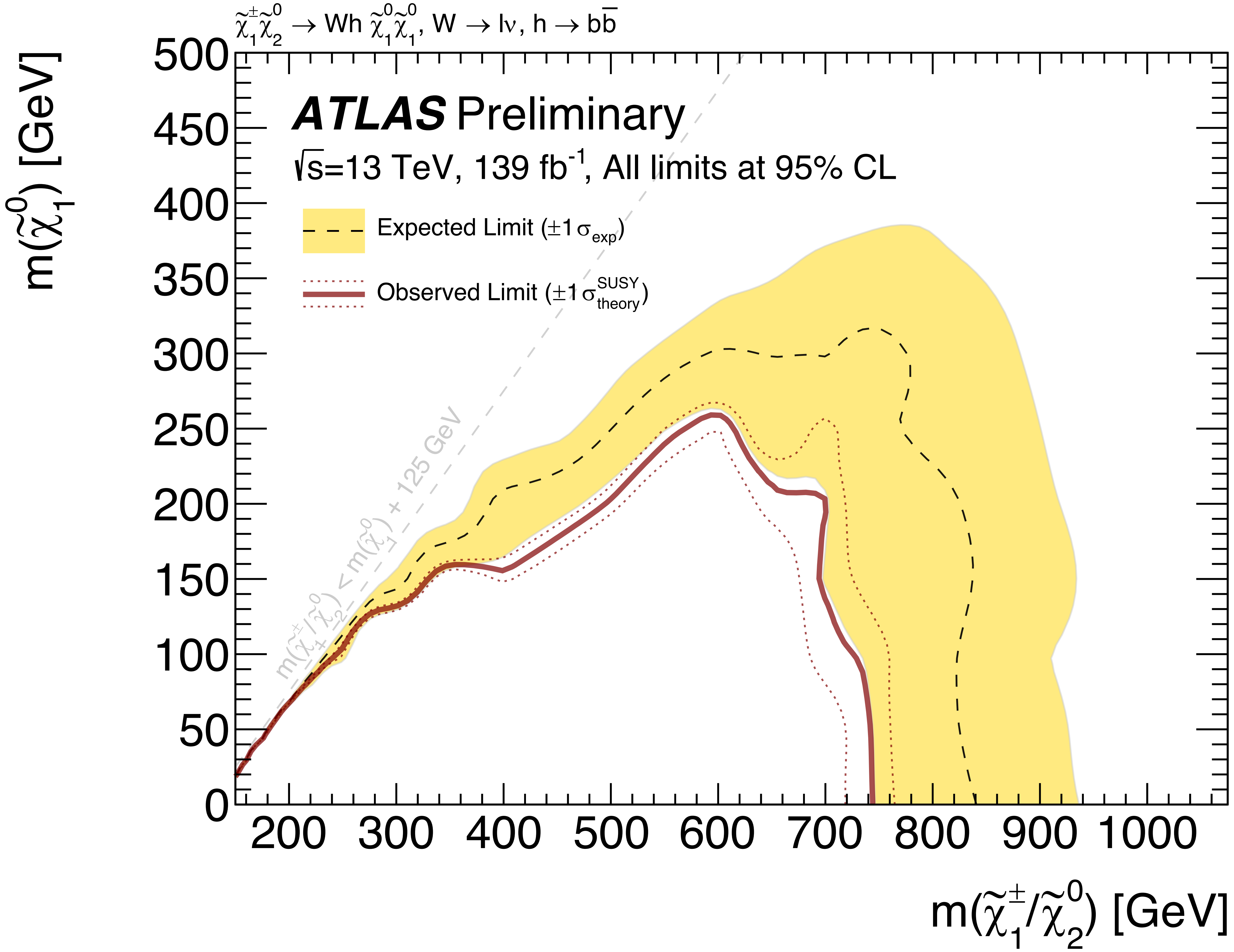
No significant excesses observed:

- **Limits are set for $\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ up to 750GeV**
- **The result is public on arXiv (link) and has been submitted to EPJC.**

Data vs MC for all regions defined



Exclusion limit for 95% CLs



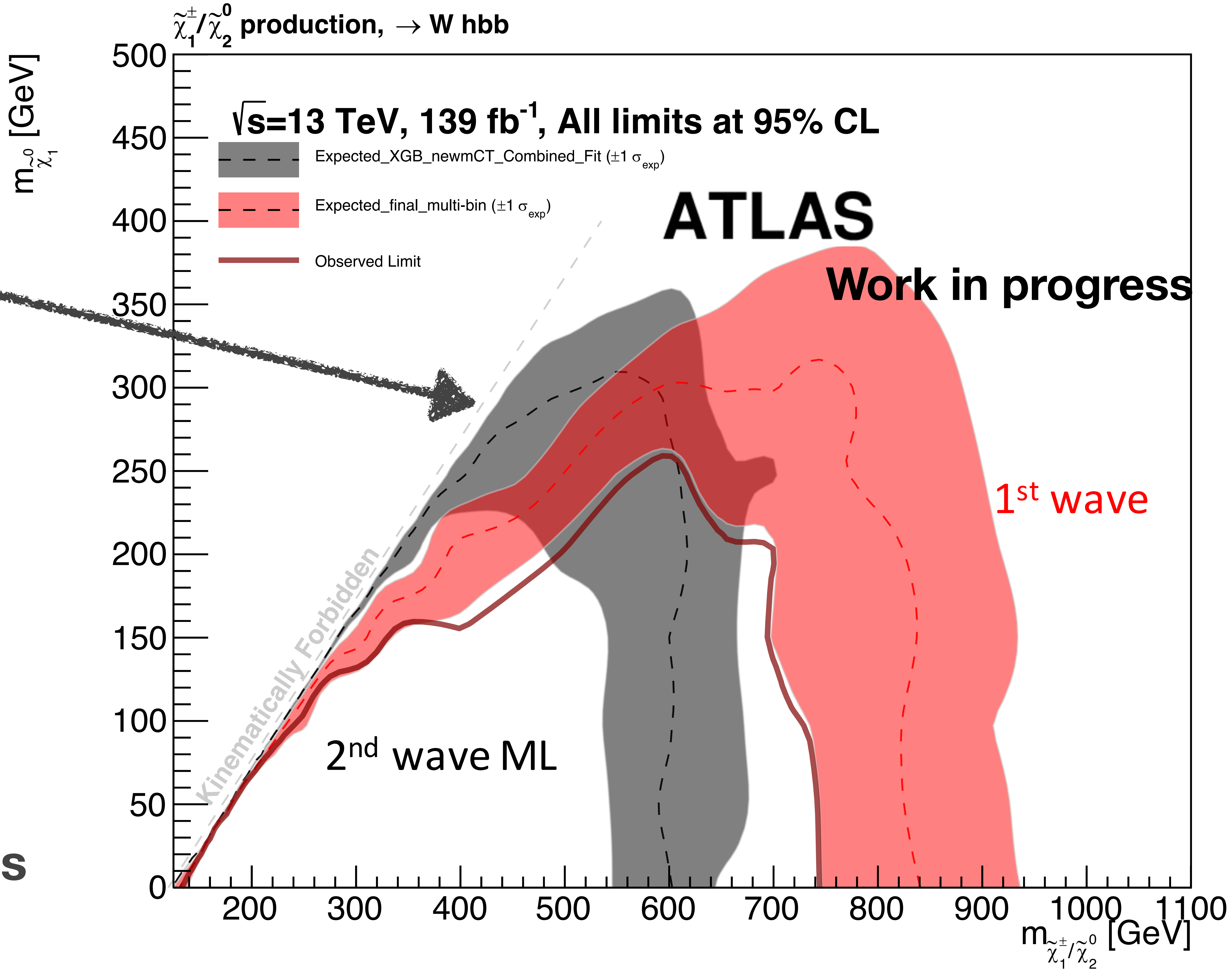
Small (~1σ) excess observed in all signal regions

EWK-Pushing Further

Make the most of the run2 datset:

- Investigate the excess seen.
- Complex/More Specific analysis of the full run2 dataset.
- Target unexplored compressed region.

$\Delta M(\widetilde{\chi}_2^0/\widetilde{\chi}_1^\pm, \widetilde{\chi}_1^0)$ ~125GeV

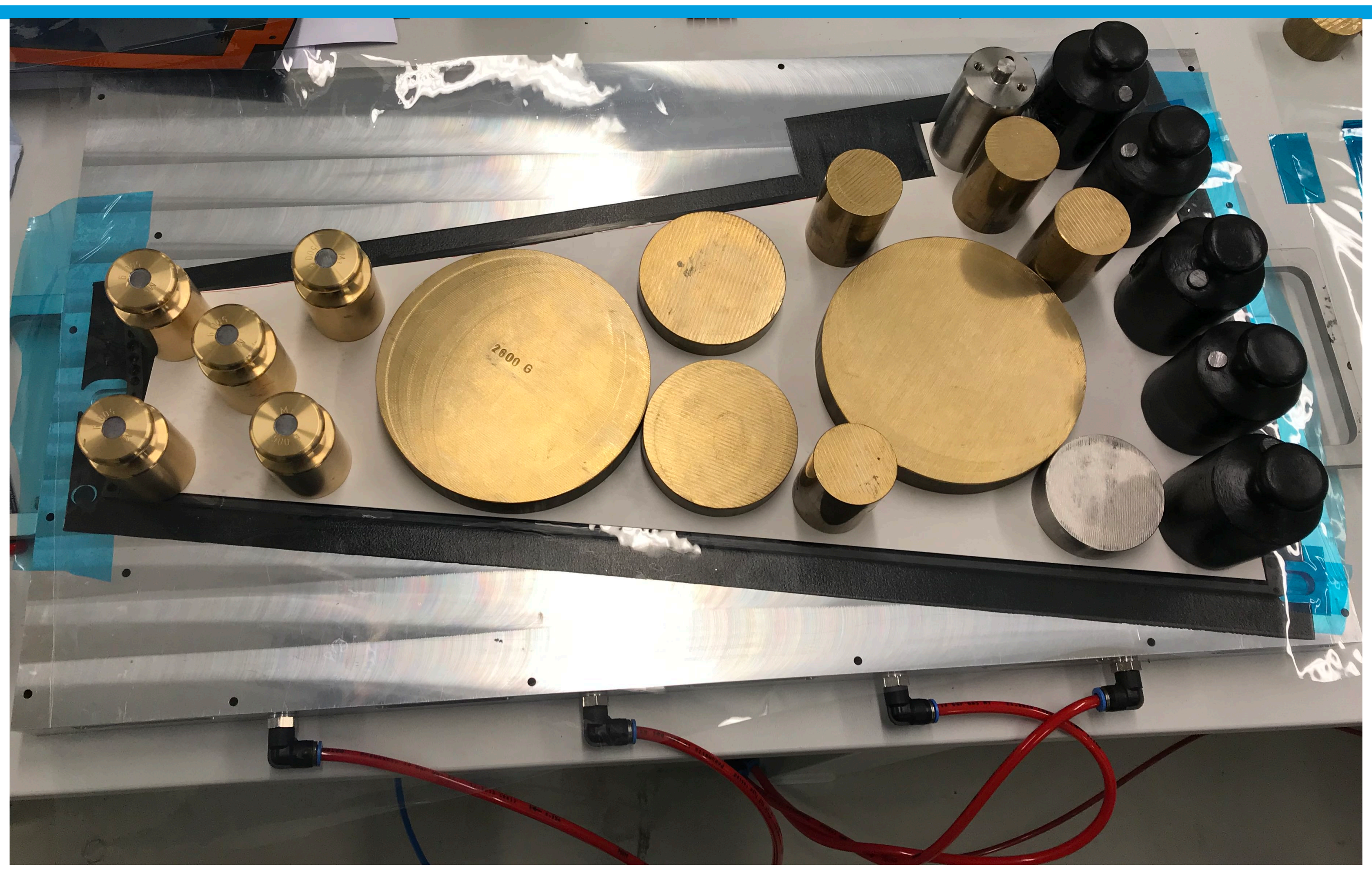


Analysis strategy:

- Use Gradient-Boosted Decision Trees to exploit kinematic correlations in events.
- BDT discriminates dominant backgrounds vs signal.

This work is under development, aiming to publish results in summer 2020.

Conclusions

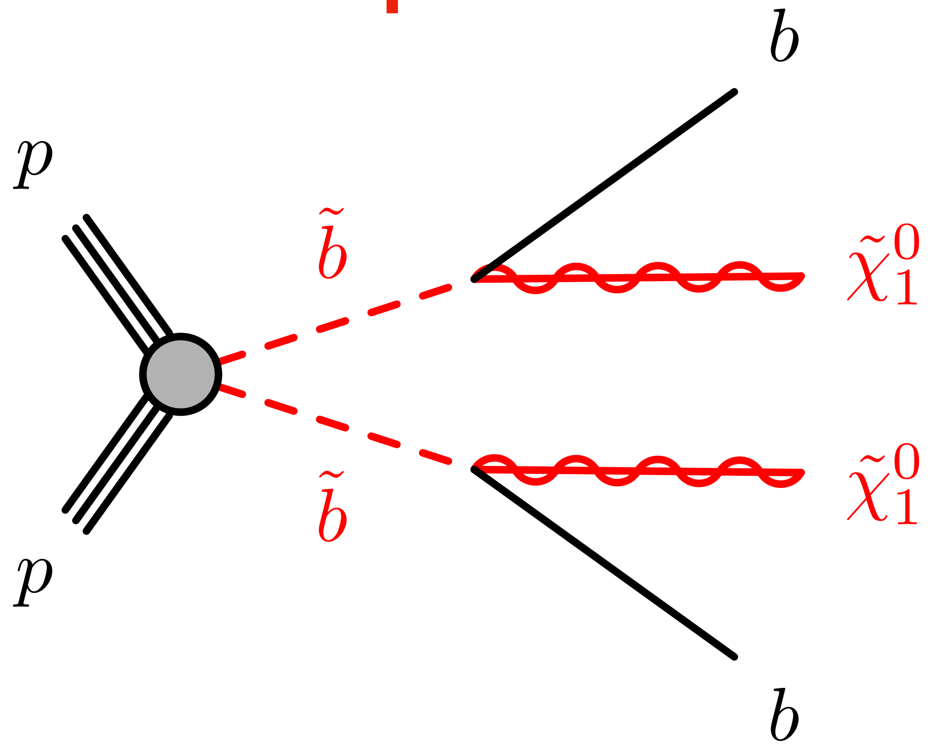


- I have qualified as an ATLAS author:
  - Measurements of ITK support structures for ATLAS HL upgrade
- Results are public for the Run2 dataset - EWK and sbottom analyses

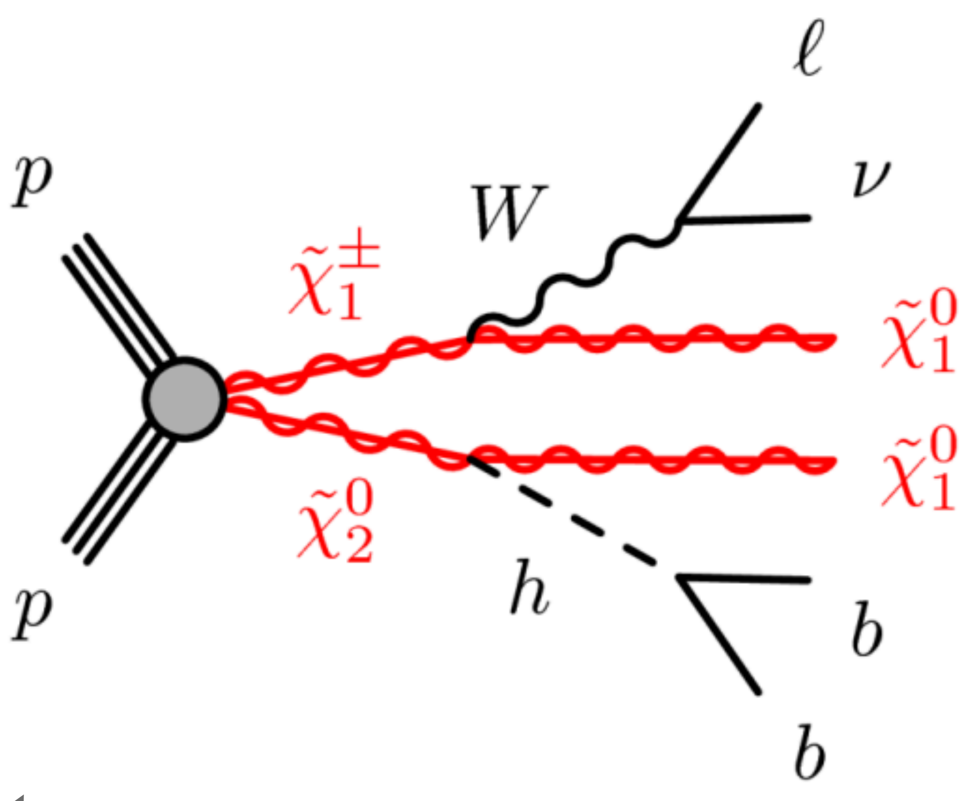
For the future

- Continue work on sbottom analysis, now for direct decay

Focus again on compressed scenarios

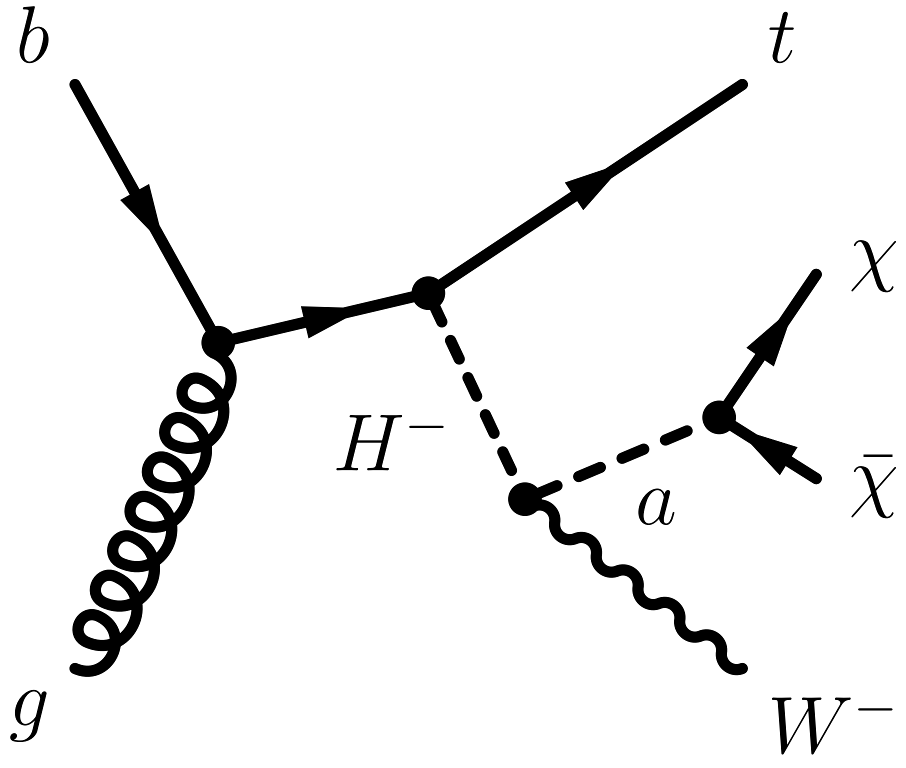


- Develop EWK analysis for 2nd-wave result



Aim to publish both in summer

- Contribute towards uncertainties and truth studies for Dark Matter-2HDMa-tW analysis



See Matt Sullivan's great poster for the full analysis!

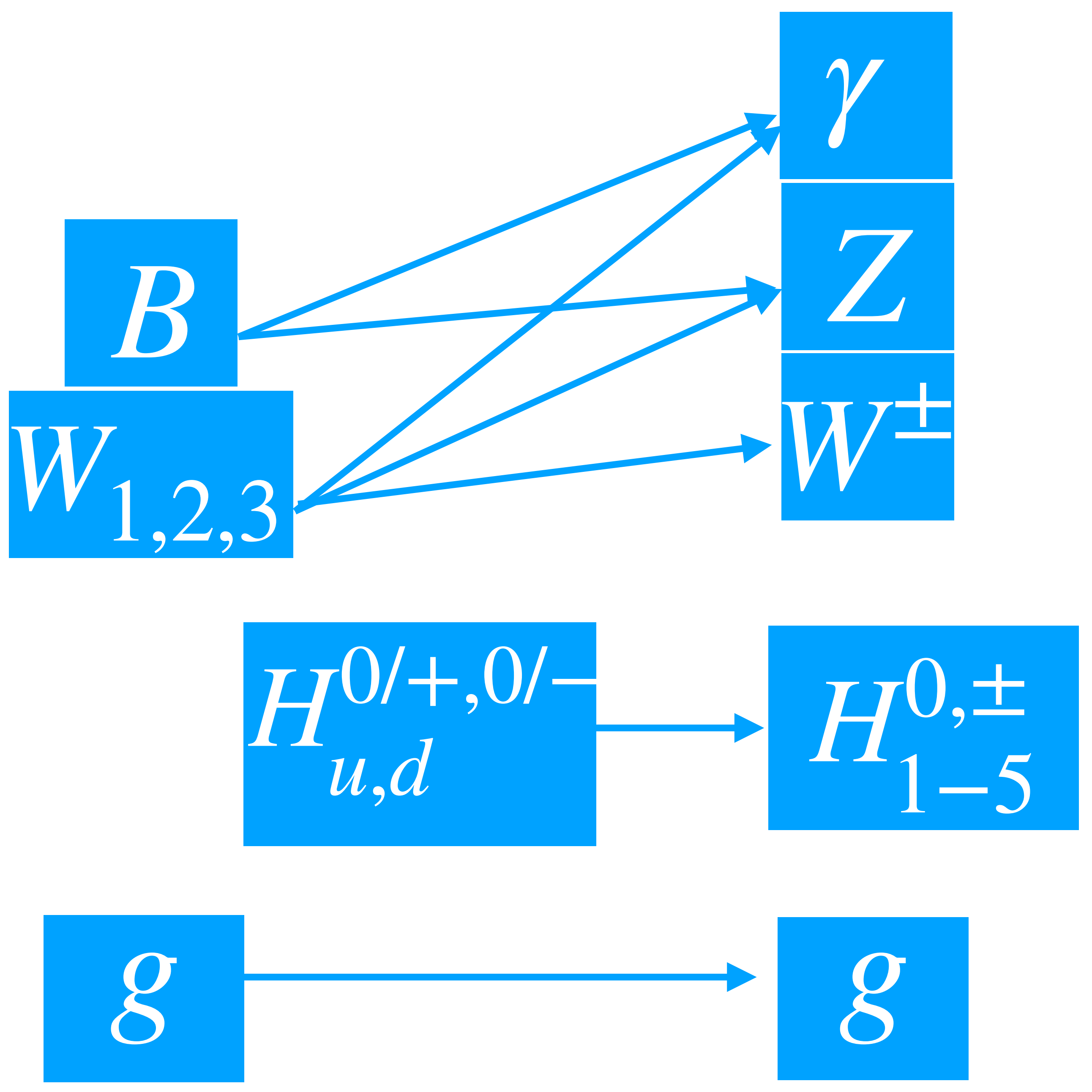
Thanks and Happy Holidays!

SUSY MSSM Guaginos

What are we looking for?

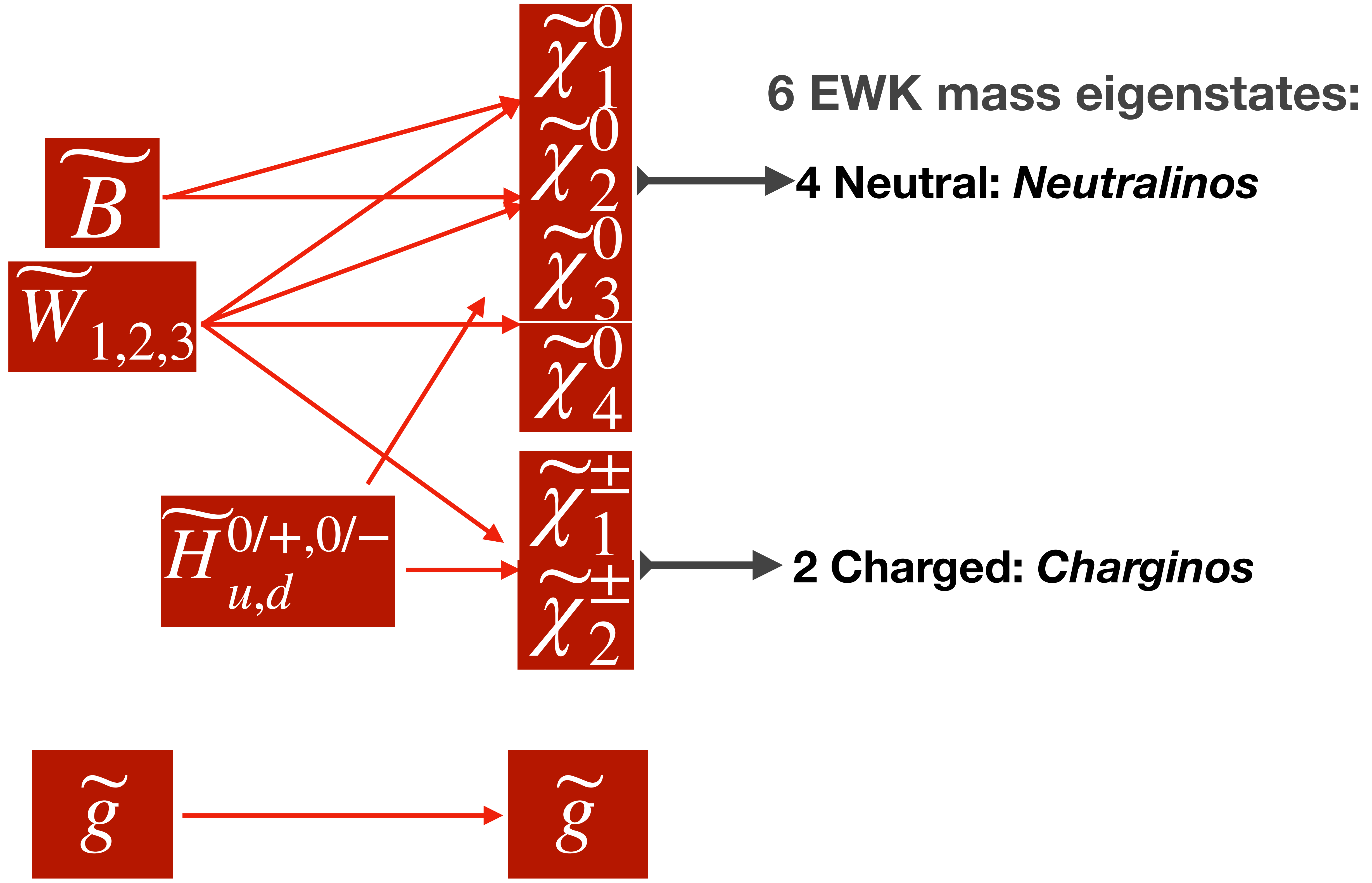
SM Bosons

Before EWK symmetry breaking | After EWK symmetry breaking



SUSY Partners

Before EWK symmetry breaking | After EWK symmetry breaking



Why are these interesting?

3rd Generation

The Hierarchy Problem

Quantum corrections to the higgs mass

$$\Delta m_h^2 = -\frac{|\lambda_f|^2}{8\pi^2}[\Lambda_{UV}^2 + ..]$$

SM contribution

$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}[\Lambda_{UV}^2 - 2m_S^2 ln(\Lambda_{UV}/m_S) + \ldots]$$

SUSY contribution

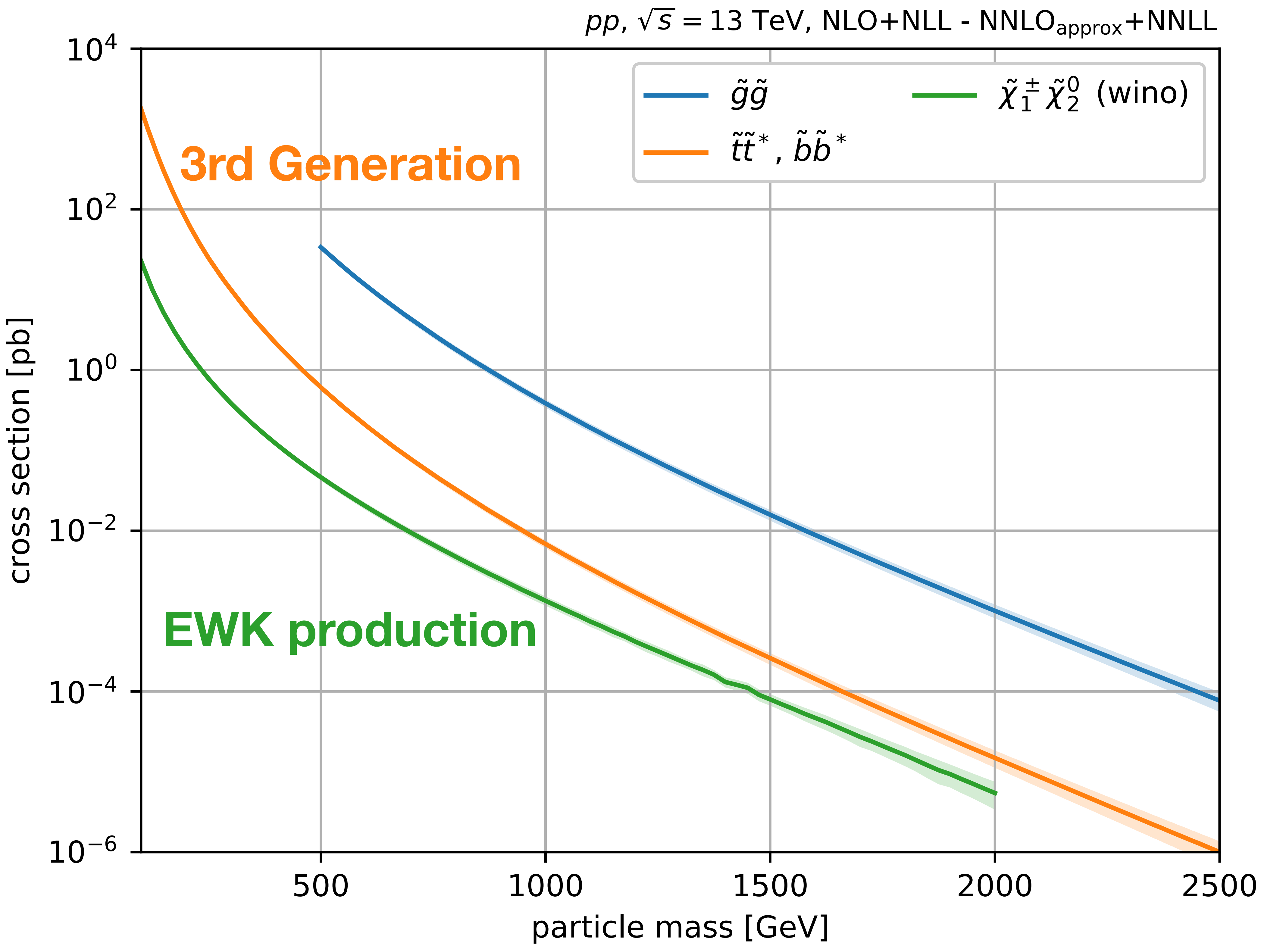
->Terms from 3rd Gen squarks essential in solving the hierarchy problem

->Expect that $\tilde{t}$ and $\tilde{b}$ are relatively light
->High production x-section

Electro-Weak

EWK production has low cross-section compared strong and 3rd Generation

- Relatively unexplored models only accessible with full run2 data
- If strong and 3rd Gen are ~TeV, EWK production can be dominant



SUSY Models

Why are we interested in these particles?

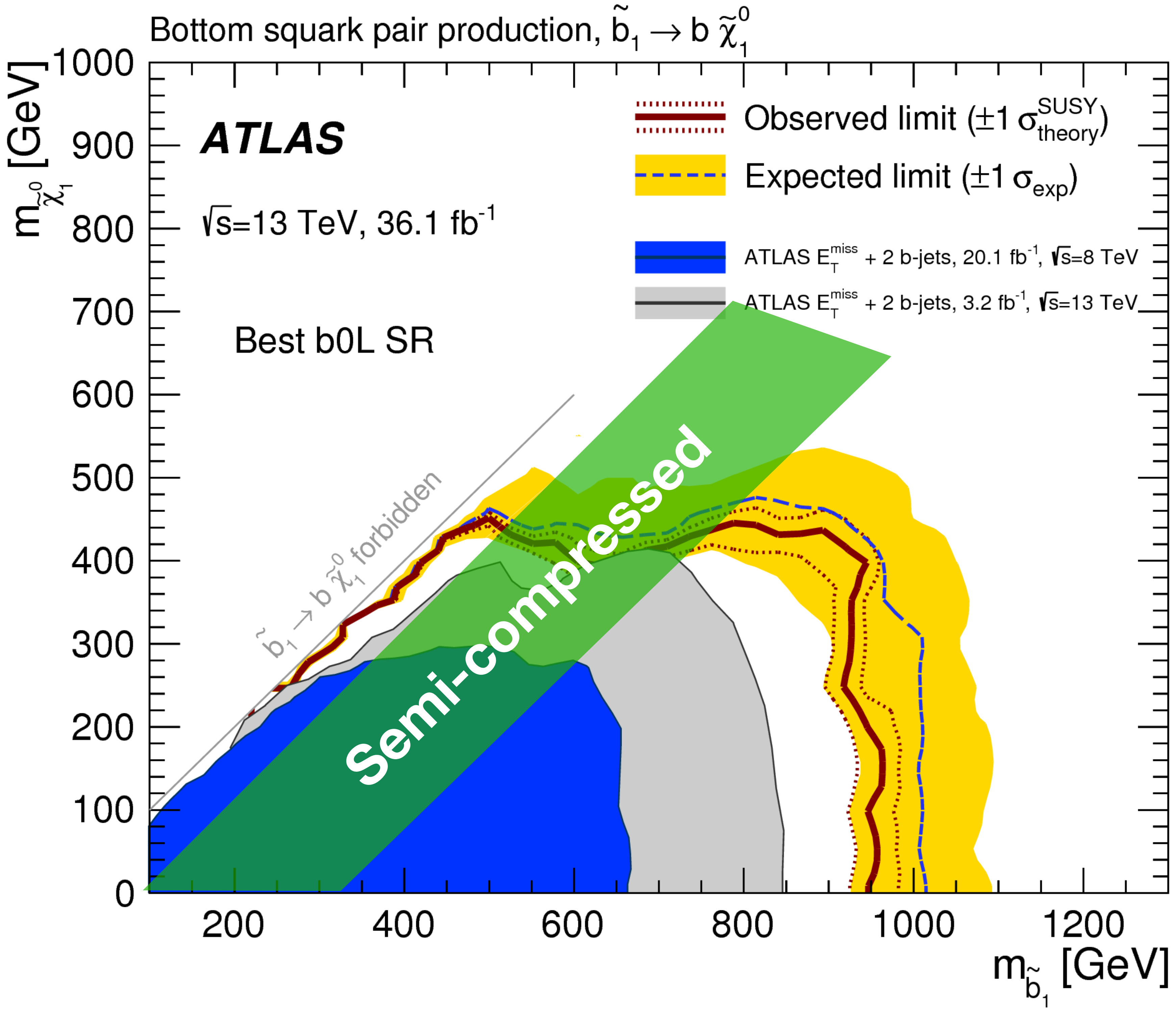
Searching for Electroweak SUSY: not because it is easy, but because it is hard

By ATLAS Collaboration, 20th May 2019

Strong SUSY limits of the order~TeV

SRB: $\tilde{b}$ Semi-Compressed

Semi-Compressed signal points: $\Delta M(\tilde{b}, \tilde{\chi}^0_1) \sim 20 - 200GeV$



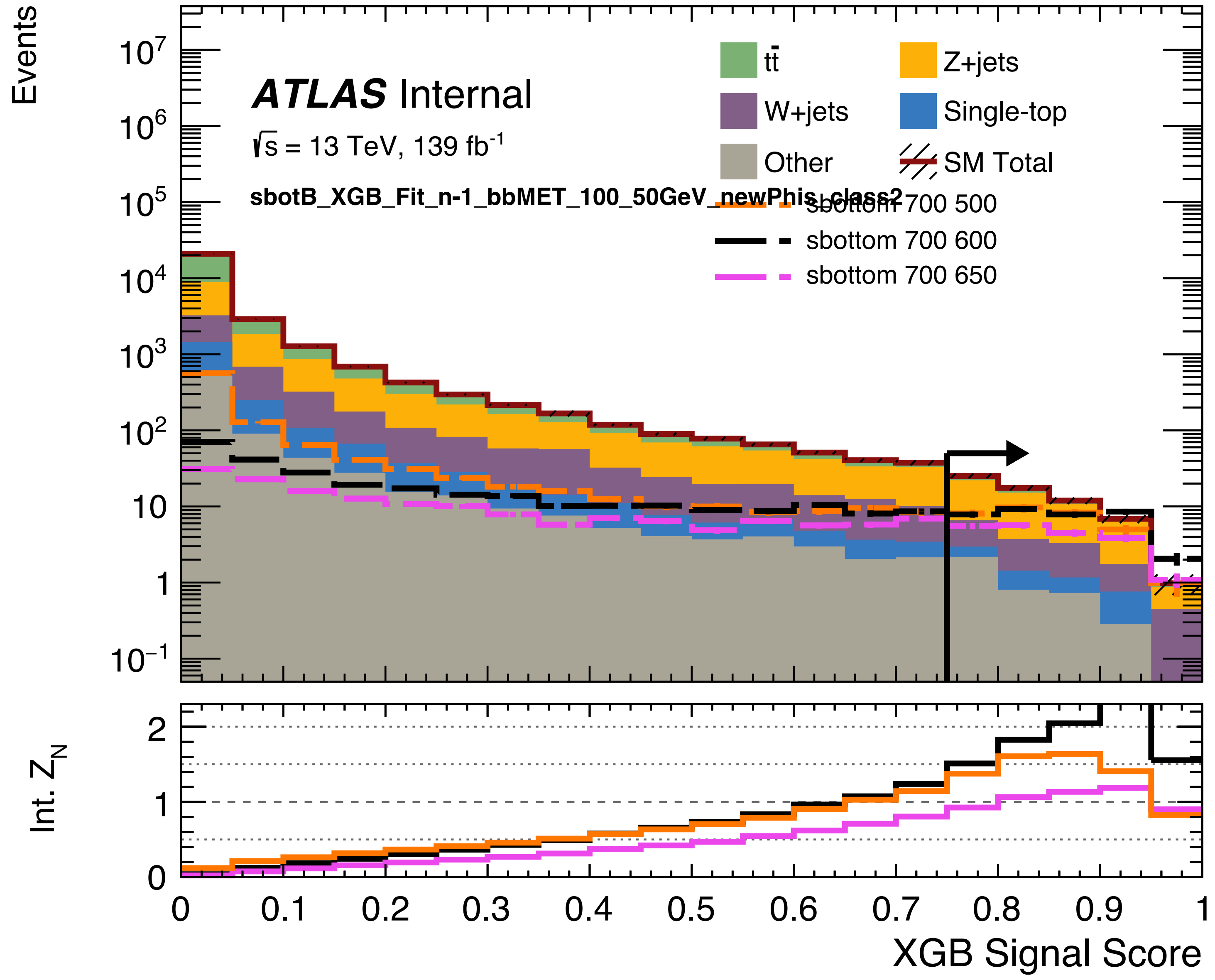
SemiCompressed Signal Features:

- Background-like in kinematic variables (m_{Eff}, m_{CT})
- Non-soft b-jets
- Low jet multiplicity

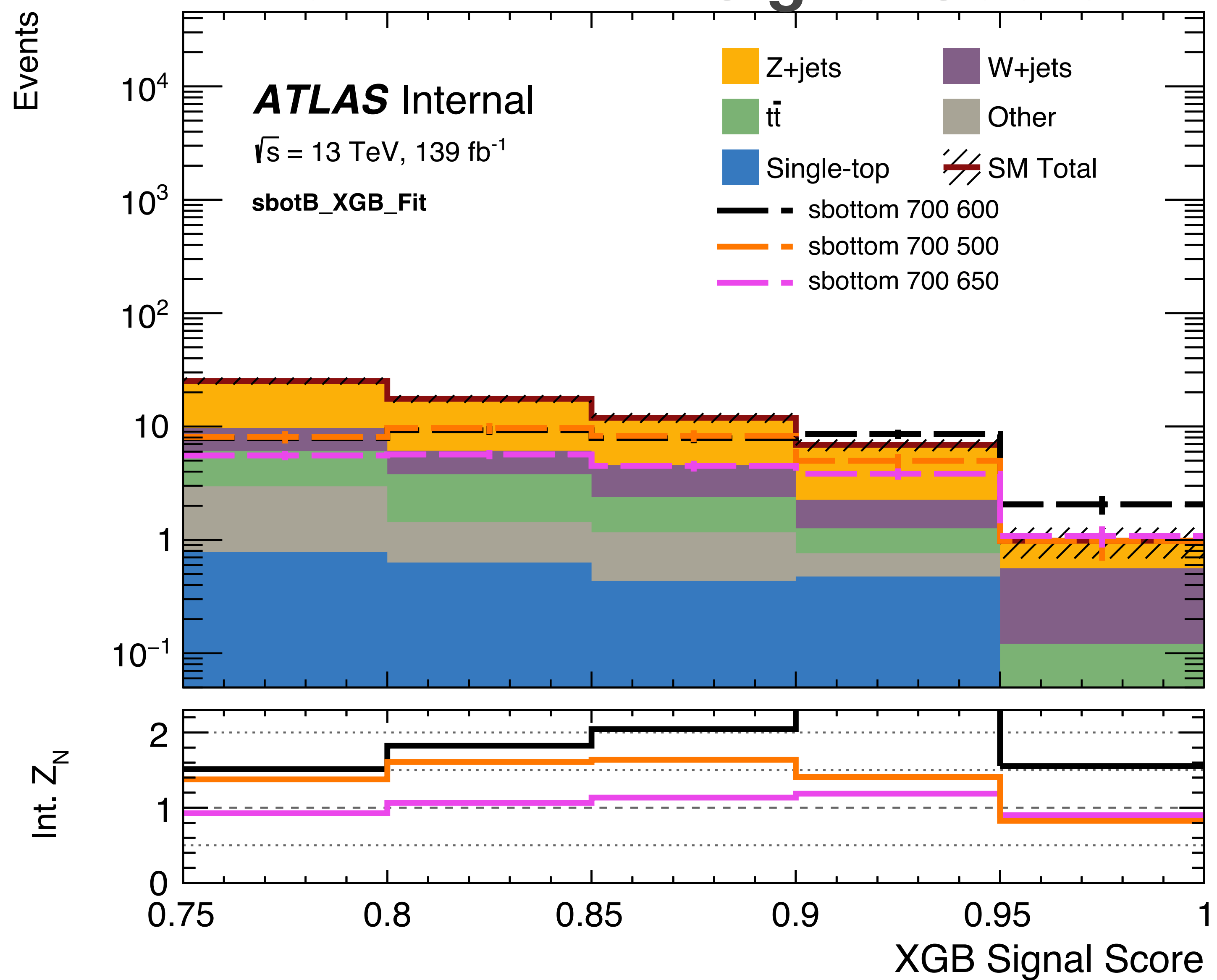
Signal Region outline:

- Gradient Boosted decision trees (XGBoost).
- Multi-classification with "1 vs all strategy," Classes: ttbar, zJets, wJets, signal.
- Target Low m_{CT} region, orthogonal to SRA.

Discovery Region:
1Bin cut on Signal score:



Exclusion Region:
Multi-Bin fit in Signal Score



SRB: $\tilde{b}$ Semi-Compressed

Semi-Compressed signal points: $\Delta M(\tilde{b}, \tilde{\chi}_1^0) \sim 20 - 200 GeV$

Inputs to th

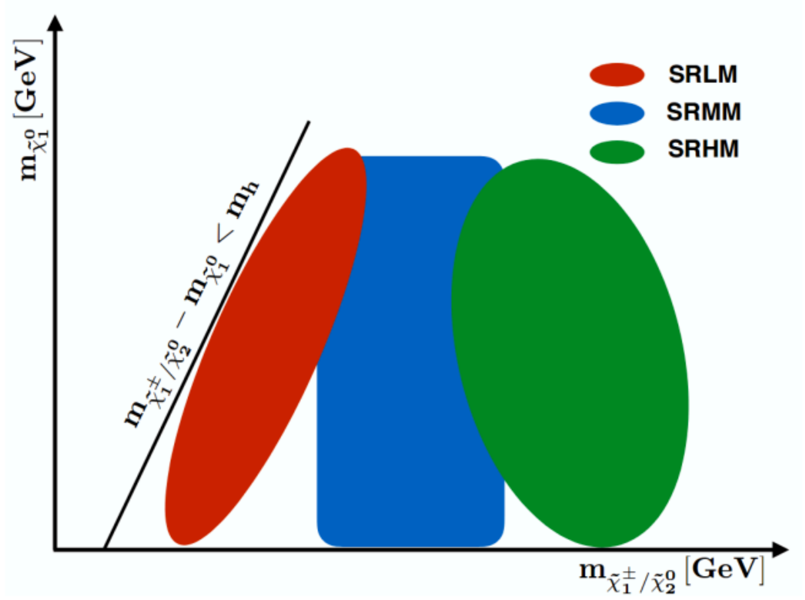
- **4-vectors**
- **b-tag bo**

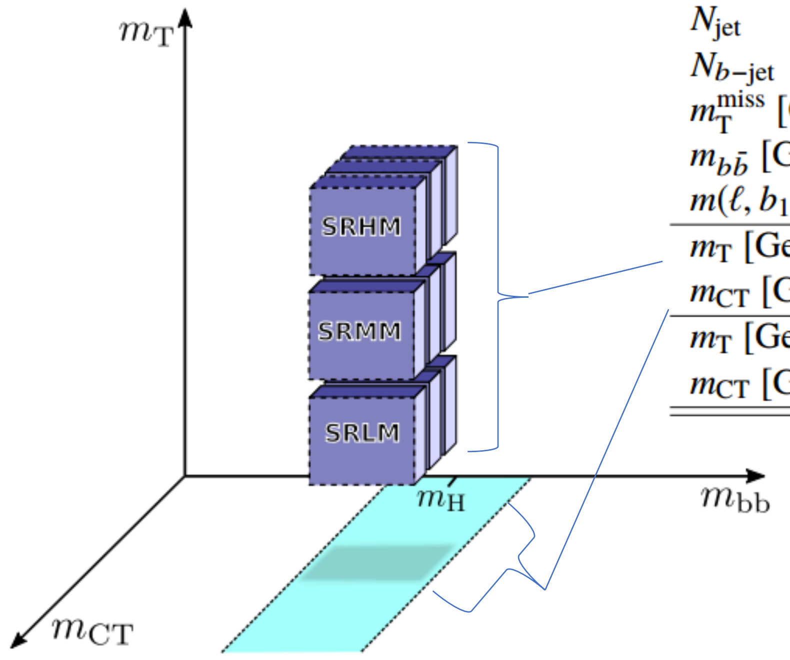
$p_T^j \quad \eta_j \quad \phi_j^{Ro}$

- E_T^{miss}
- $nJets$
- m_{CT}^{2b}

Signal Region Definitions

1. We first split the plane of $m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0), m(\tilde{\chi}_1^0)$ is split in regions of low, medium and high m_T.





Illustrations by Jeanette Lorenz

2. Then we bin each m_T region in 3 bins of m_{CT}. This gives a total of 9 orthogonal regions.

	SR-LM	SR-MM	SR-HM
N_{lepton}		= 1	
p_T^ℓ [GeV]		> 7(6) for $e(\mu)$	
N_{jet}		= 2 or 3	
N_{b-jet}		= 2	
m_T^{miss} [GeV]		> 240	
$m_{b\bar{b}}$ [GeV]		∈ [100, 140]	
$m(\ell, b_1)$ [GeV]	–	–	> 120
m_T [GeV](excl.)	∈ [100, 160]	∈ [160, 240]	> 240
m_{CT} [GeV](excl.)		{∈ [180, 230], ∈ [230, 280], > 280}	
m_T [GeV](disc.)	> 100	> 160	> 240
m_{CT} [GeV](disc.)		> 180	

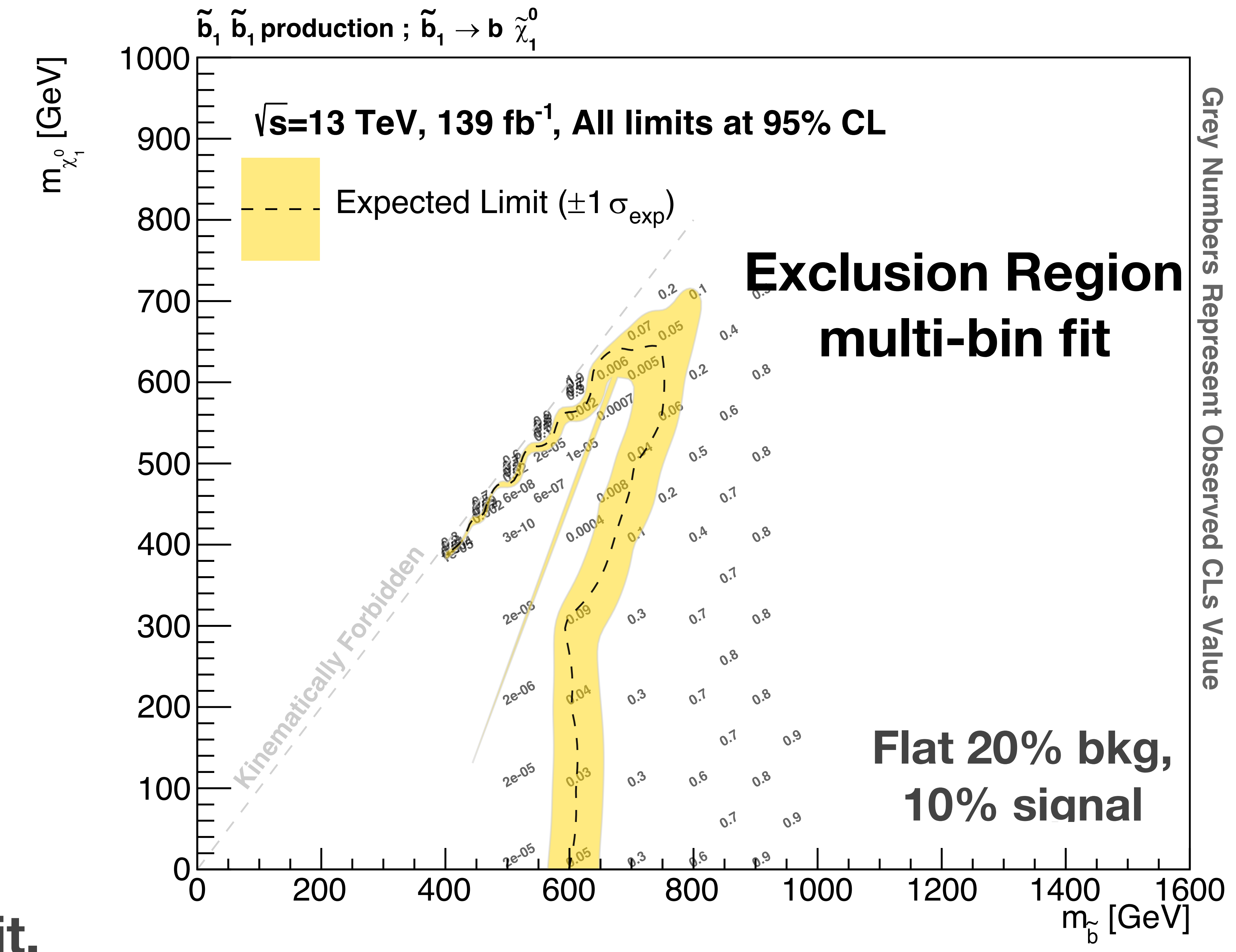
3

Poss

-
- **Pseudo**

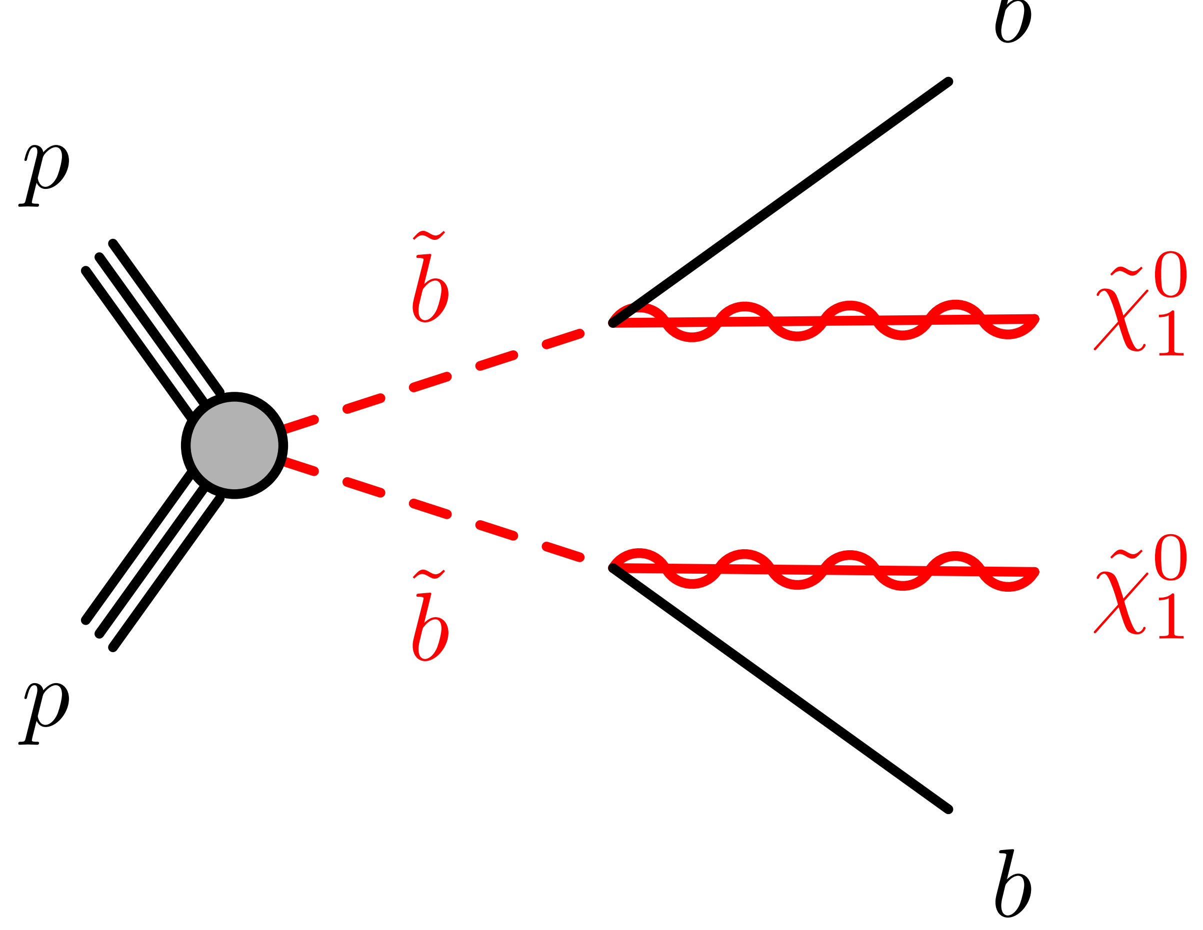
->Won't affect SR strategy but may improve BDT discrimination

d fit.



Exclusion Region multi-bin fit

Flat 20% bkg, 10% signal



Wh-1Lbb Compressed

How can we improve on the 1st wave compressed?

***Pre-selection* (Run 2)**

- E_T^{miss} triggered: Offline E_T^{miss} >240GeV
- Jet multiplicity requirement: 2 or 3 jets
- B-jet requirement: exactly 2
- Exactly 1 signal lepton (e/mu)

Key discriminating kinematic variables: ***(Run 2)***

$$m_T = \sqrt{2 p_T^{\ell} m_T^{miss}(1 - \cos[\Delta\phi(\boldsymbol{p}_T^{\ell}, \boldsymbol{p}_T^{miss})])}$$

- Kinematic endpoint at W mass for $W + jets$ and semi-leptonic $t\bar{t}$

$$m_{CT} = \sqrt{2 p_T^{b_1} p_T^{b_2} (1 + \cos\Delta\phi_{bb})},$$

- Kinematic endpoint for $t\bar{t}$ at $(m^2(t) - m^2(W))/m(t)$.

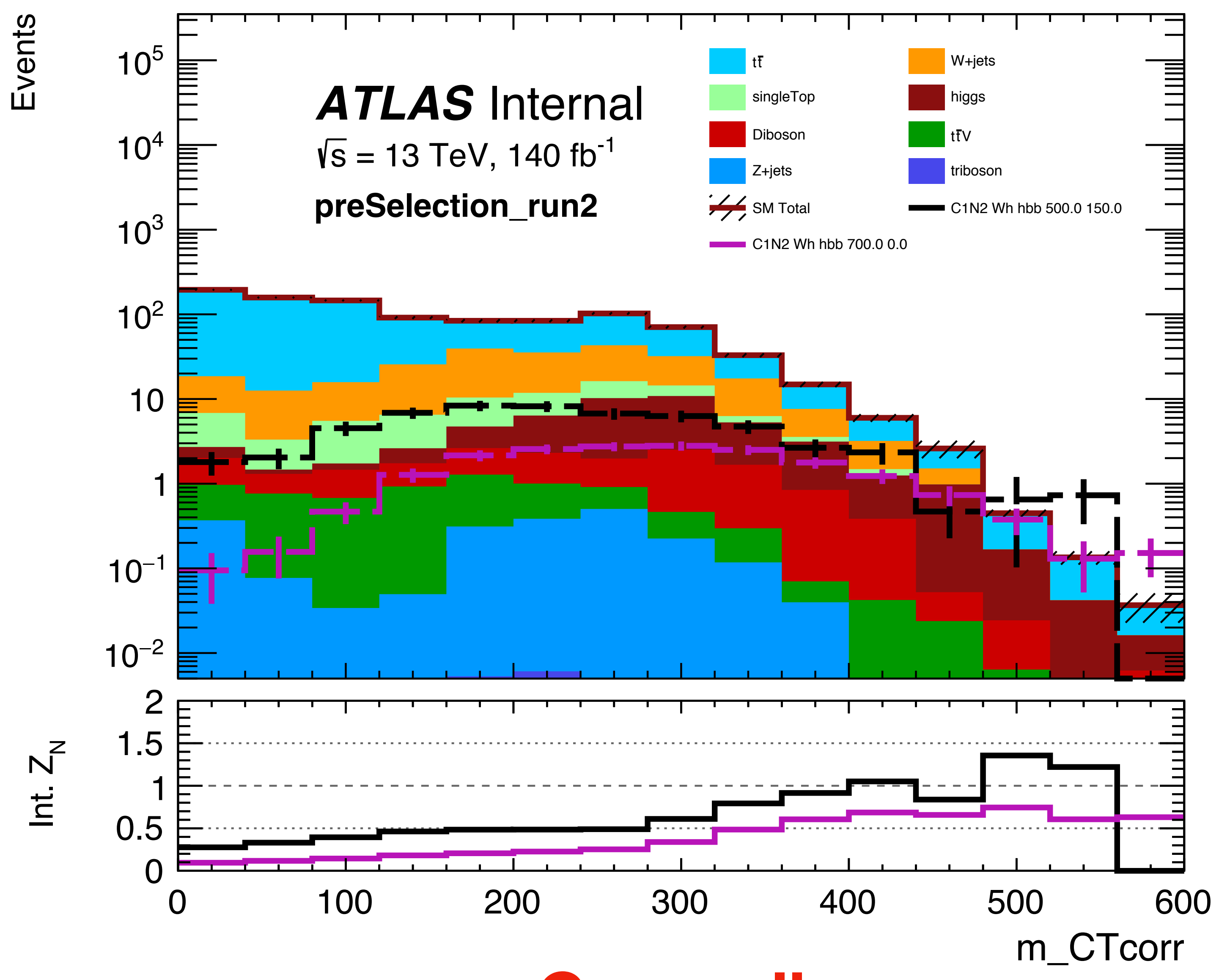
$$m_{b\bar{b}}$$

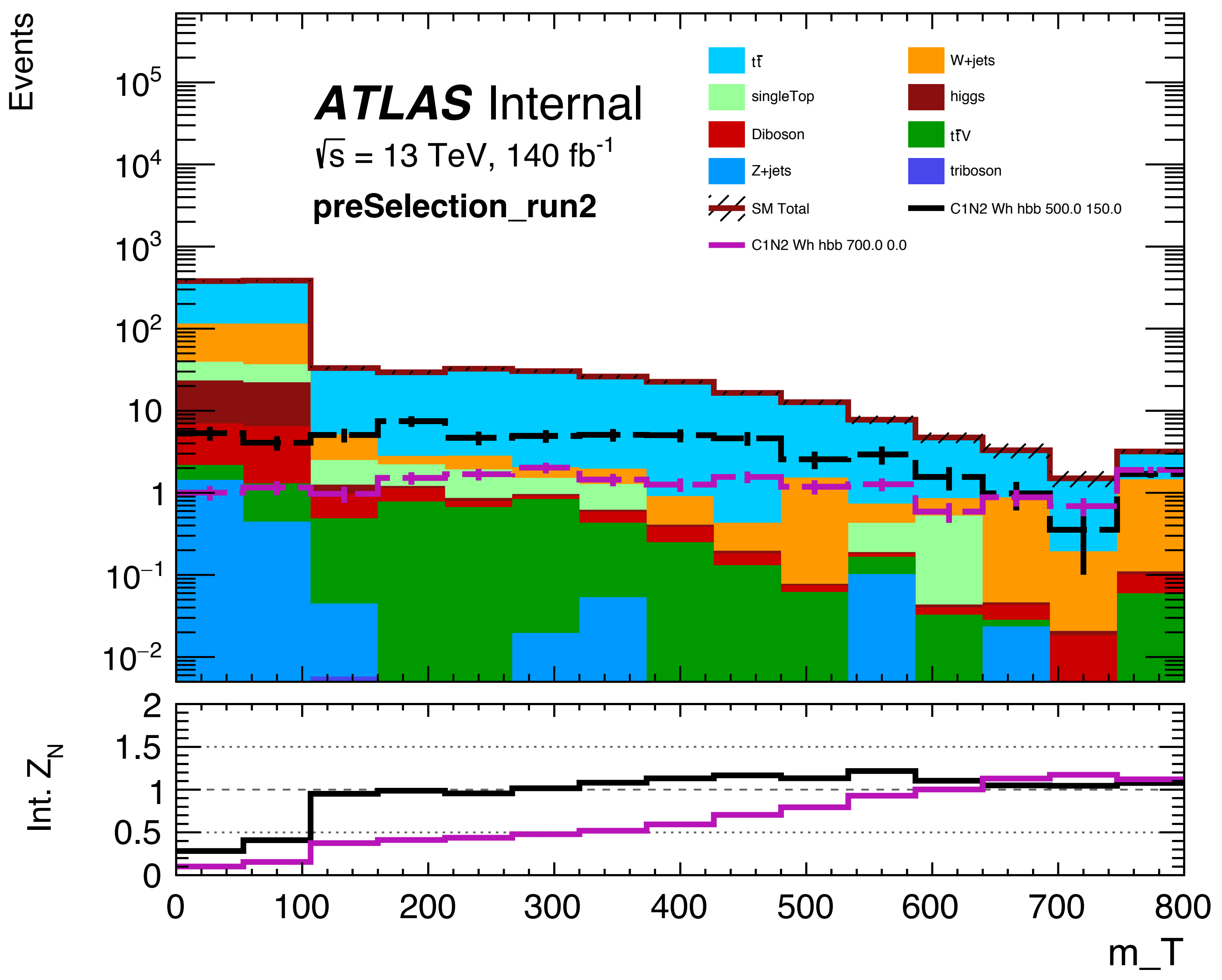
- Peak at higgs mass for signal.

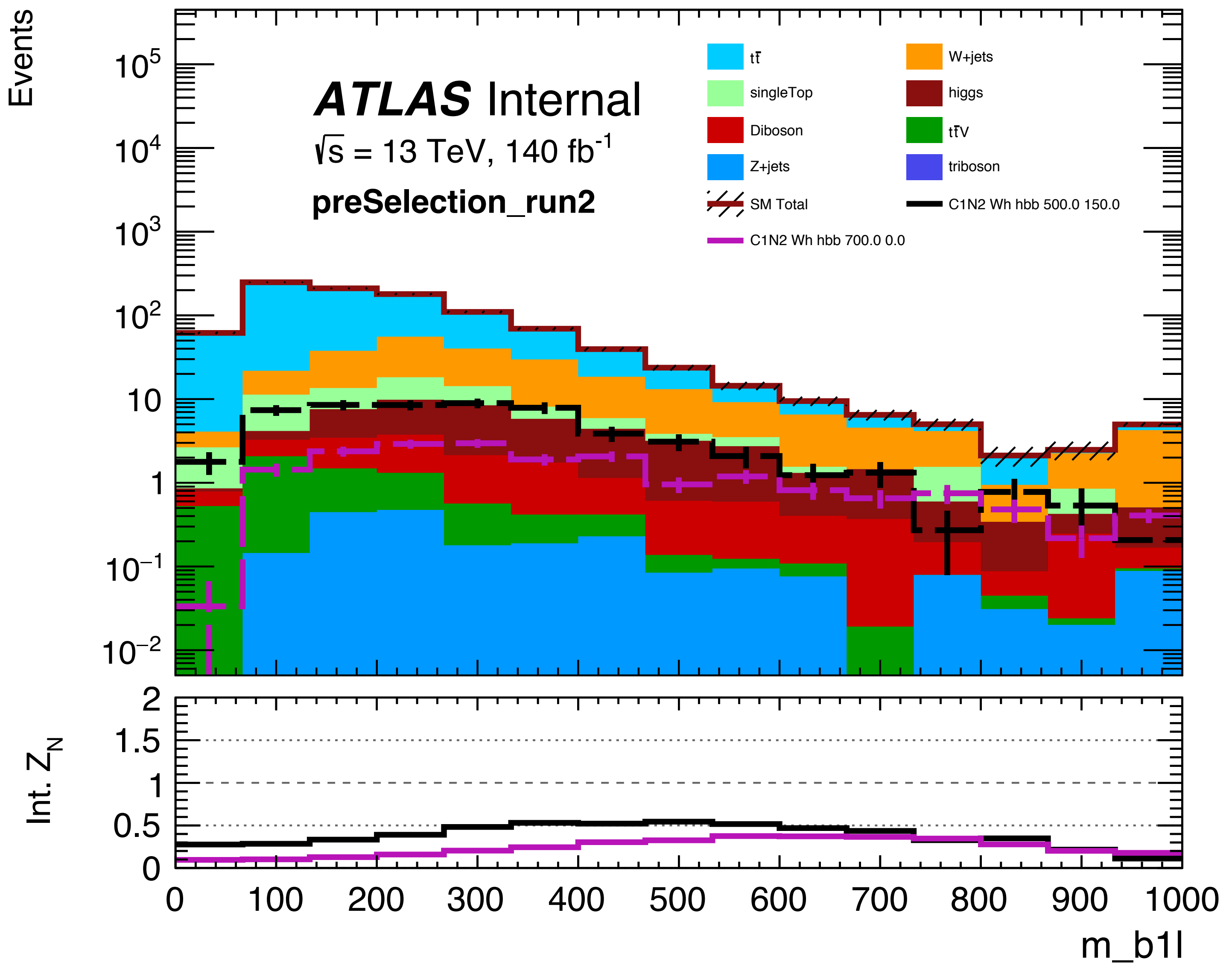
$$m(\ell, b_1)$$

- If l and b_1 come from the same top quark, endpoint at $\sqrt{m(t)^2 - m(W)^2}$

Key Discriminants for <u>compressed</u> signals:







Generally compressed signals look SM-like (reduced tails wrt higher-mass splitting)

Wh-1Lbb Compressed

How can we improve on the 1st wave compressed?

Preselection-2nd wave ML

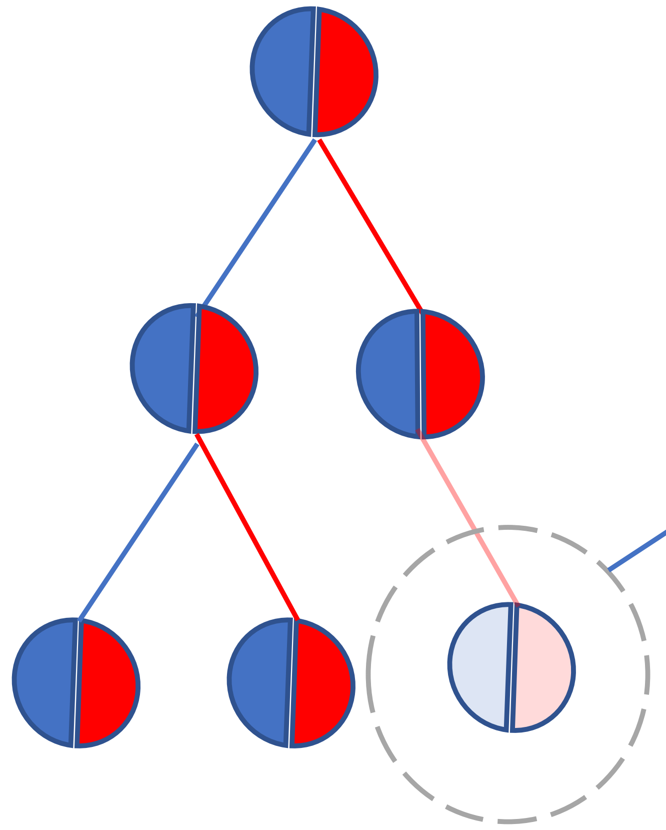
Variable	Pre-selection cut
Nlepton	1
$p_T^l[GeV]$	>27
Njets	2 or 3
Nb-jets	2
$E_T^{miss}[GeV]$	>50
Object-based S	>5
m_{bb}	ϵ[50,200]

→ **Switch to single-lepton triggers** (p_T^l > 27)

→ **Alows lower E_T^{miss} requirement** (E_T^{miss} > 50)

Machine Learning using XGBoost

XGBoost='Extreme gradient boosted (decision trees)'



A new split in the tree is calculated by optimising according to the gradient of given loss function (objective function).

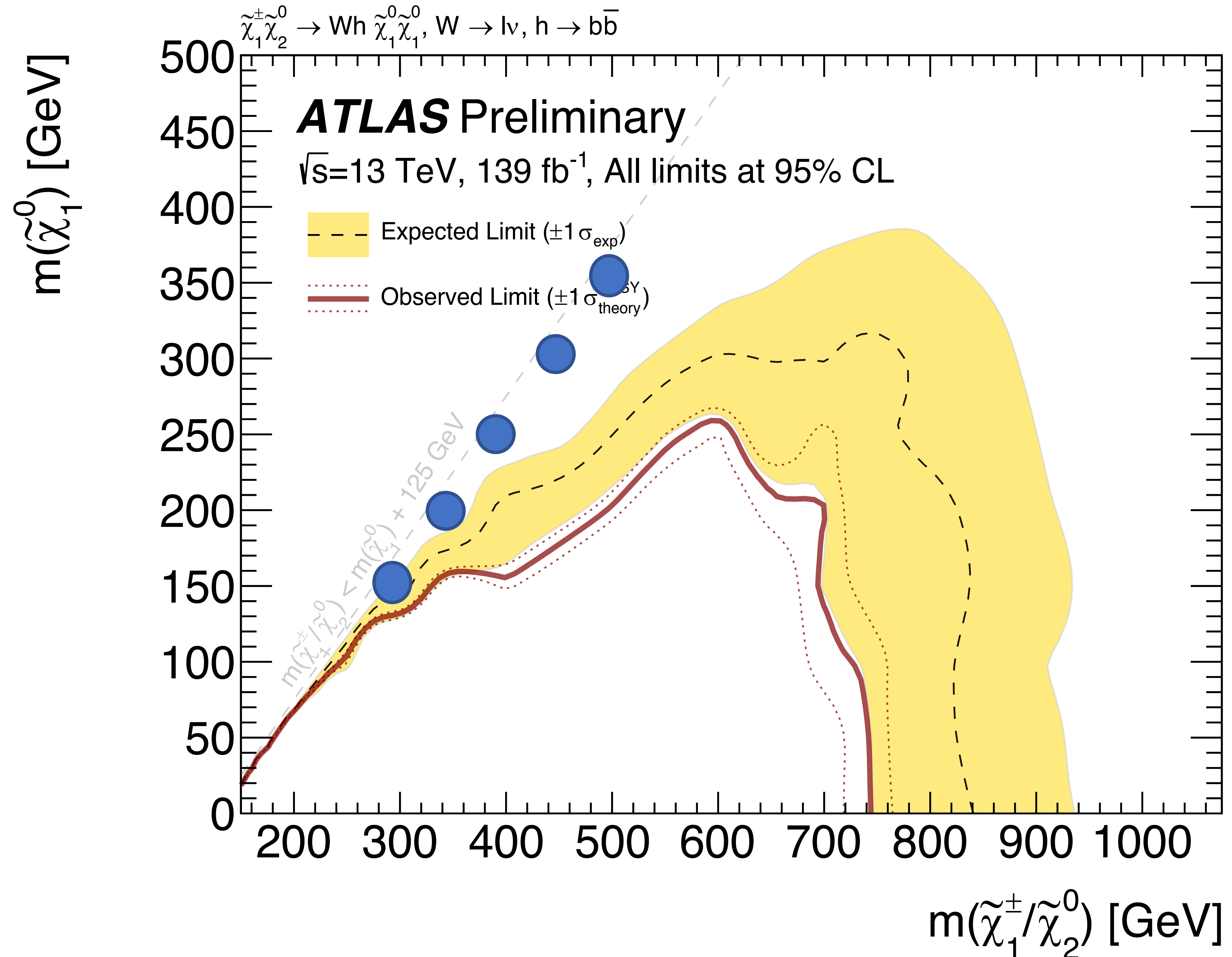
Training Samples

Backgrounds:

- **Reco-backgrounds**
- **70-30 train-test split**

Signal:

- **Locally produced high-statistics Truth Samples**
- **Smear Truth events to be reco-like with SimpleAnalysis**
- Combine a range of compressed mass signal samples



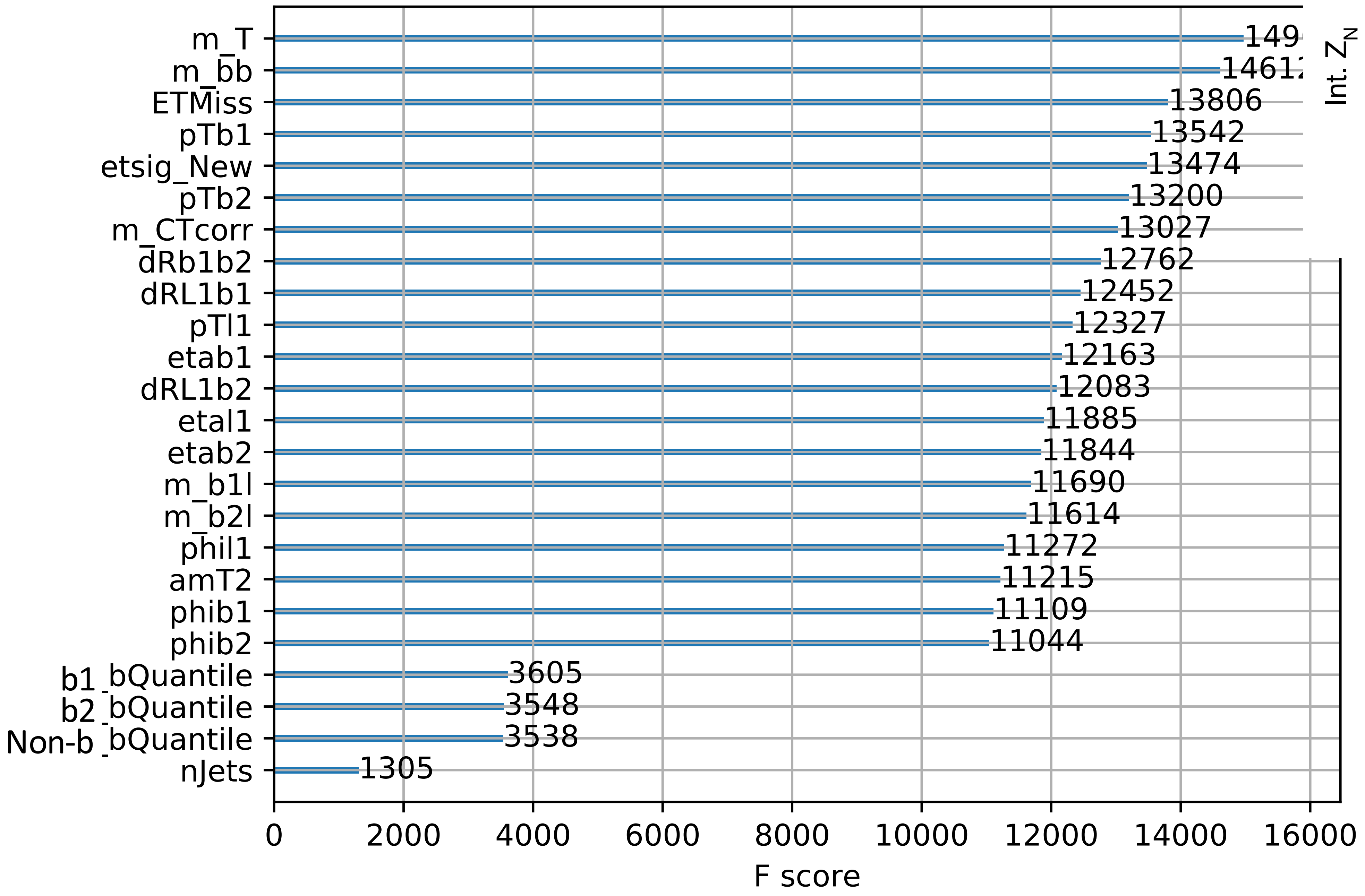
Wh-1Lbb Compressed

- Using the 'multi-class: softprobability' objective function.

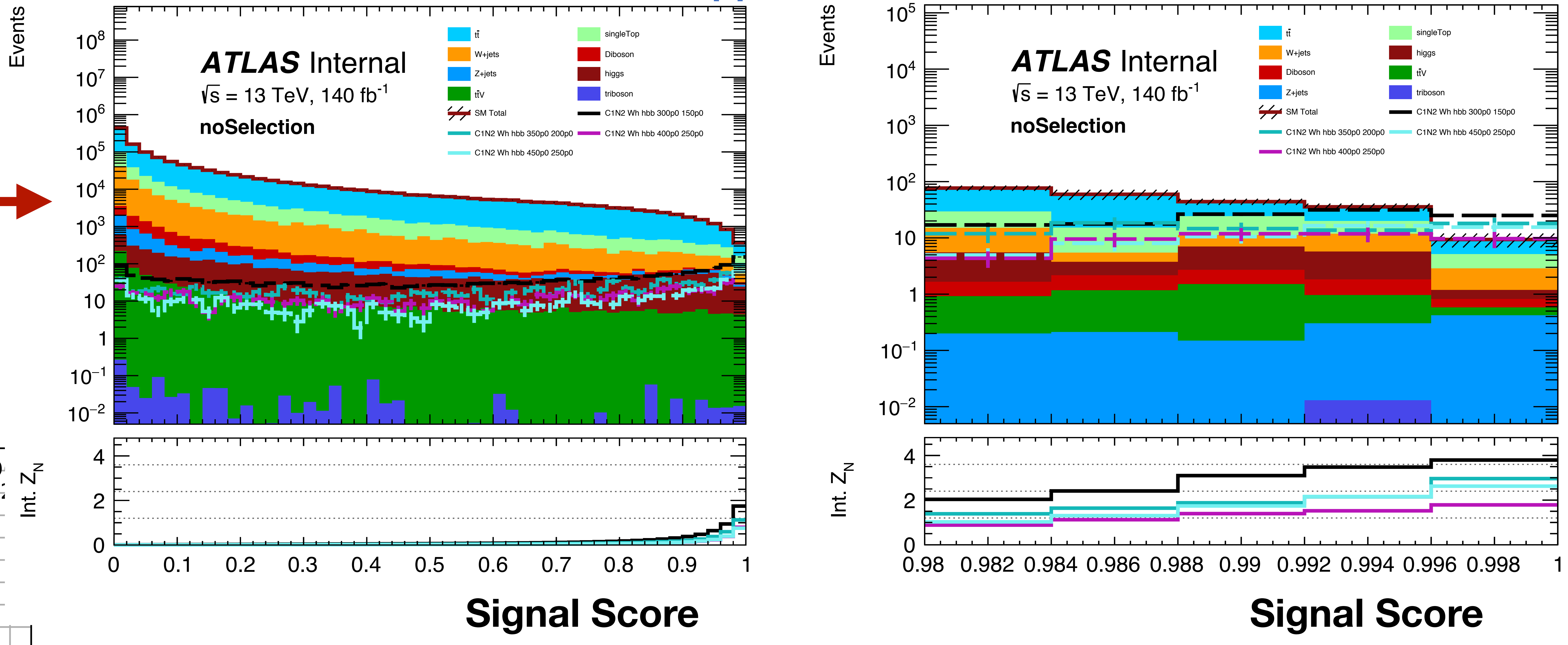
We train for: 4 categories:

- *wJets*
- *$t\bar{t}$*
- *singleTop*
- *signal*

Input Variables and usage score



Signal Output score



Sensitivity is pushed into very high signal scores

->Due to weighting to cross-section in training and loose preselection

Wh-1Lbb Compressed

Signal Region Definition

	XGB Low	XGB Med	XGB High
E_T^{miss}	>50	>50	>50
$p_T^l[GeV]$	>27	>27	>27
Njets	2 or 3	2 or 3	2 or 3
Nb-jets	2	2	2
m_{bb}	ϵ[95,140]	ϵ[95,140]	ϵ[95,140]
Object-based S	> 5	> 8	> 8
XGB Signal Score	5ϵ[0.97,1]	5ϵ[0.97,1]	5ϵ[0.97,1]
m_{CT}	ϵ[0,50]	ϵ[50,150]	>150

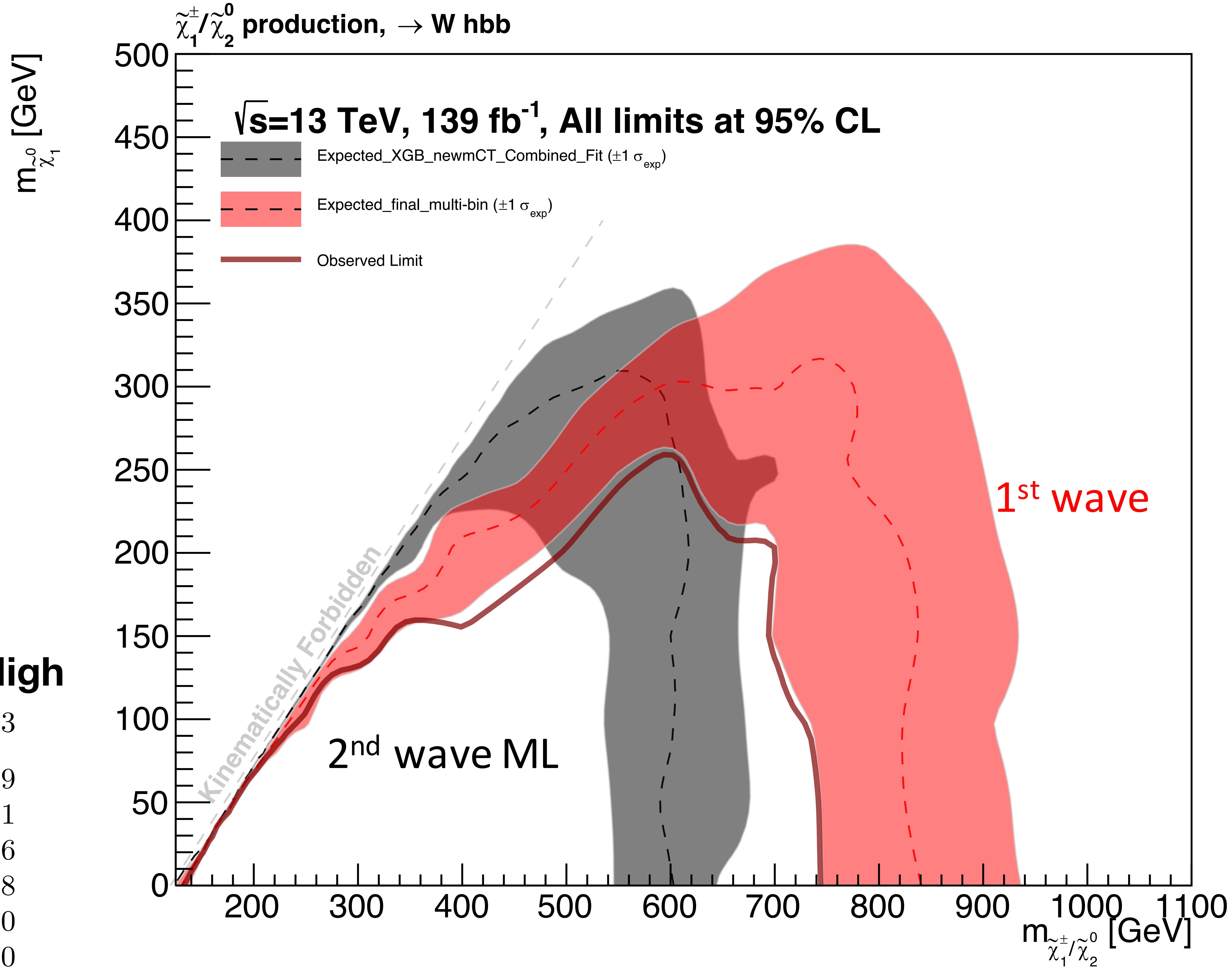
Use a combined fit in mCT and XGB signal score.

3 regions in m_{CT}

5 Bin fit in XGB signal score

	SR-Low	SR-Med	SR-High
MC exp. SM events	89.62	52.19	23.03
MC exp. ttbar events	65.62	41.09	11.89
MC exp. singleTop events	5.90	2.02	1.51
MC exp. Wjets events	12.42	6.10	3.46
MC exp. Zjets events	2.67	0.07	0.08
MC exp. higgs events	1.91	1.31	4.20
MC exp. diBoson events	0.00	0.00	0.00
MC exp. ttV events	0.41	0.81	0.75

***Expected Exclusion*- (ML: 20% flat background, 10% flat signal)**



Why SUSY?

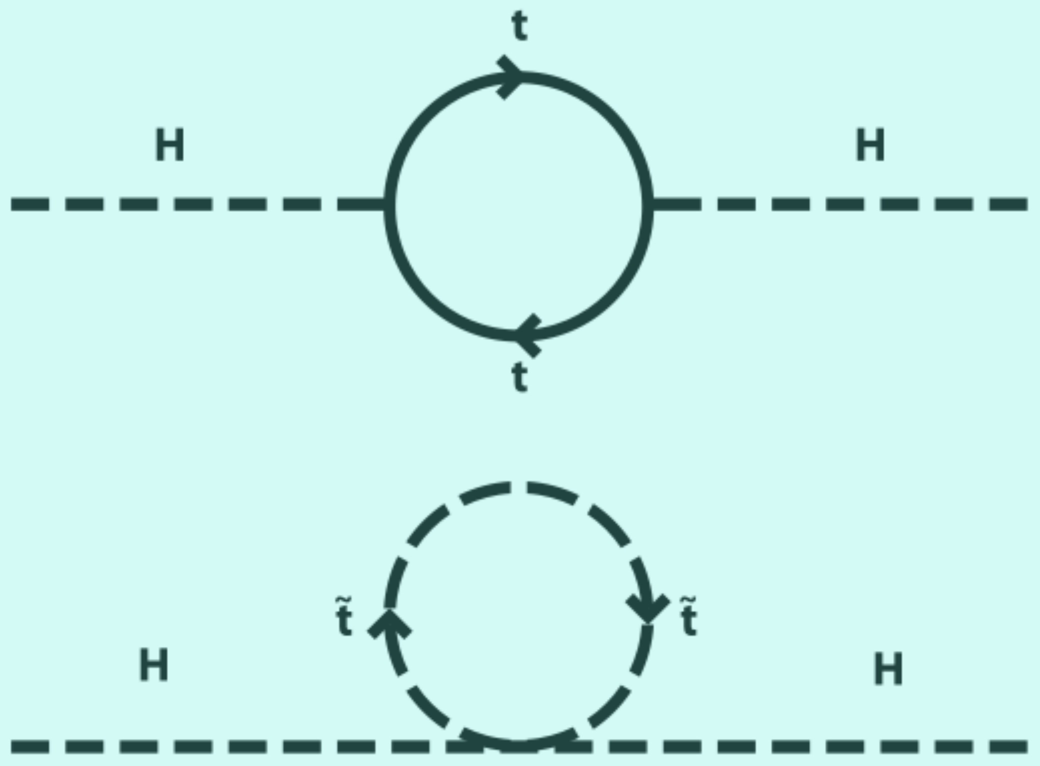
The Hierarchy Problem

Why is the higgs mass so small?

$$\Delta m_h^2 = -\frac{|\lambda_f|^2}{8\pi^2}[\Lambda_{UV}^2 + ..]$$

$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}[\Lambda_{UV}^2 - 2m_S^2 ln(\Lambda_{UV}/m_S) + ...]$$

->Divergent terms for fermionic quantum corrections protected from by SUSY



Refs:

g-2(1) g-2(2) DM