# Search for boosted Higgs bosons in SUSY Cascades at CMS

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# Outline of Talk

- Signal Model
- Analysis Overview
- Event Selection
- QCD Estimation Method
- Expected Limits
- Conclusion

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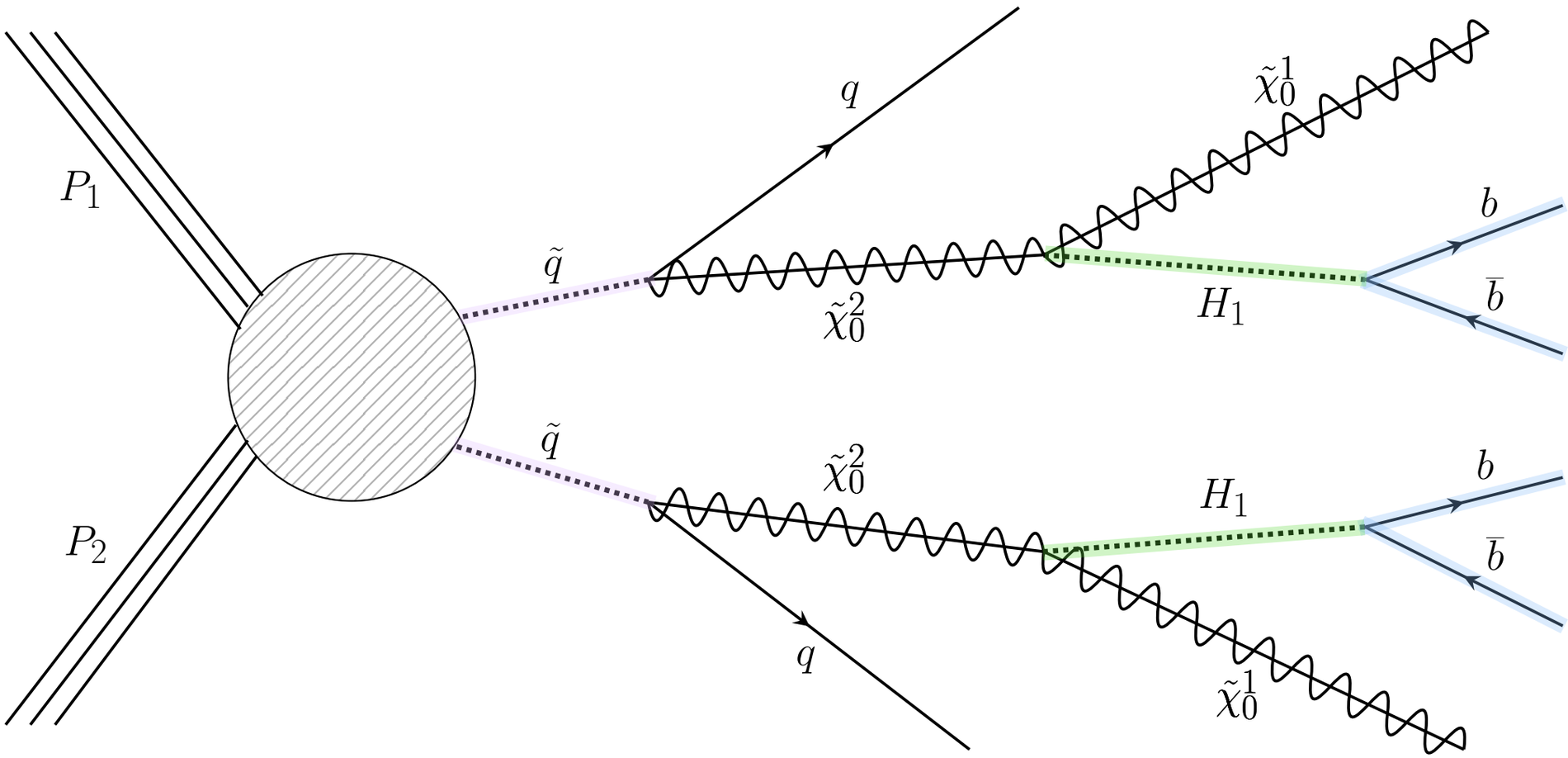
# Signal Model: Introduction

***for more info see Alex Titterton's talk**

Search for **light Higgs bosons** in **NMSSM decay cascades***, following the production of **squarks** and **gluinos** (*arXiv:1406.7221v2*).




Search in bb decay channel for both Higgs'.

The decay arm also arises from gluino→squark+quark

$H_1 \neq H_{SM}$, it is one of the other CP even Higgs' in NMSSM.

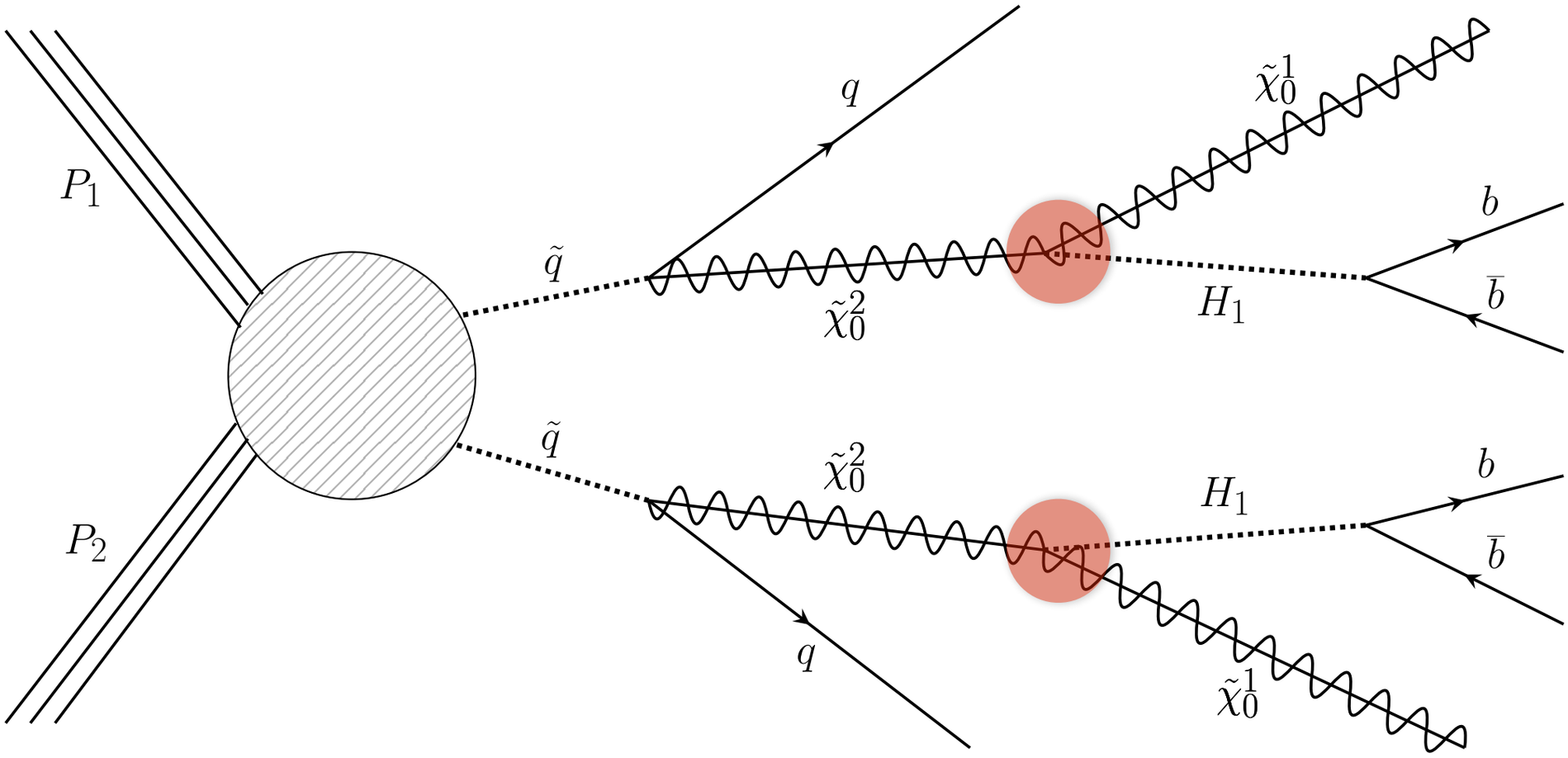
# Signal Model: Mass Parameterisation

**$M_{SUSY}$** *the mass scale of the squarks and gluino*

**$M_H$** *the mass of the Higgs, $M_H < 125$ GeV*

**$R_M = M_H / M_{NLSP}$** ***as $R_M \rightarrow 1$, LSP momentum $\rightarrow 0$***

**$\Delta_M = M_{NLSP} - M_H - M_{LSP}$** *constrained to be small as $R \rightarrow 1$*




→ **Hadronic final state with no ‘true’ MET.**

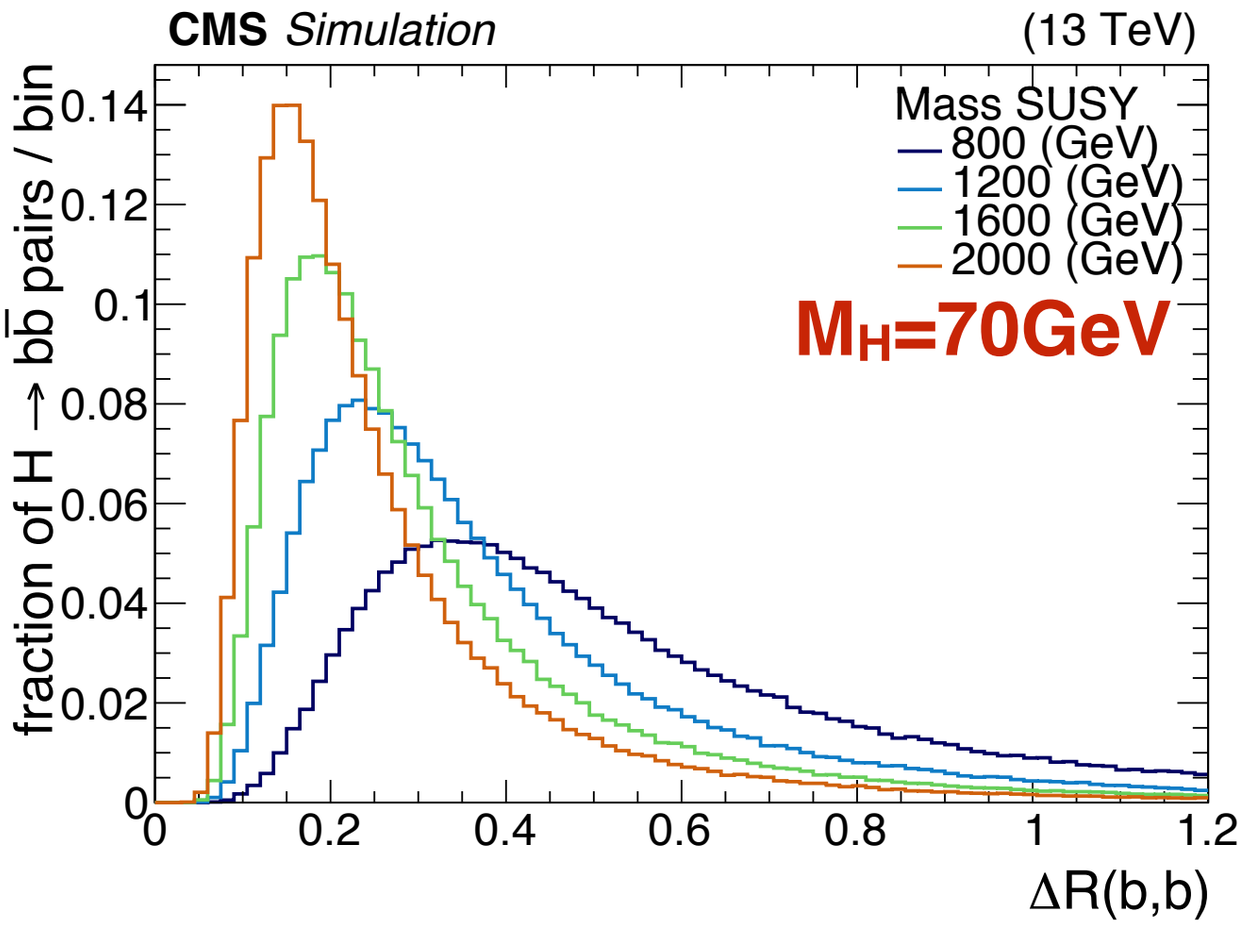
→ Key signature is the pair of light Higgs bosons.

# Signal Model: Key Properties (1)

Mass parameters → low LSP energy

&

boosted Higgs → small ΔR between b quarks.



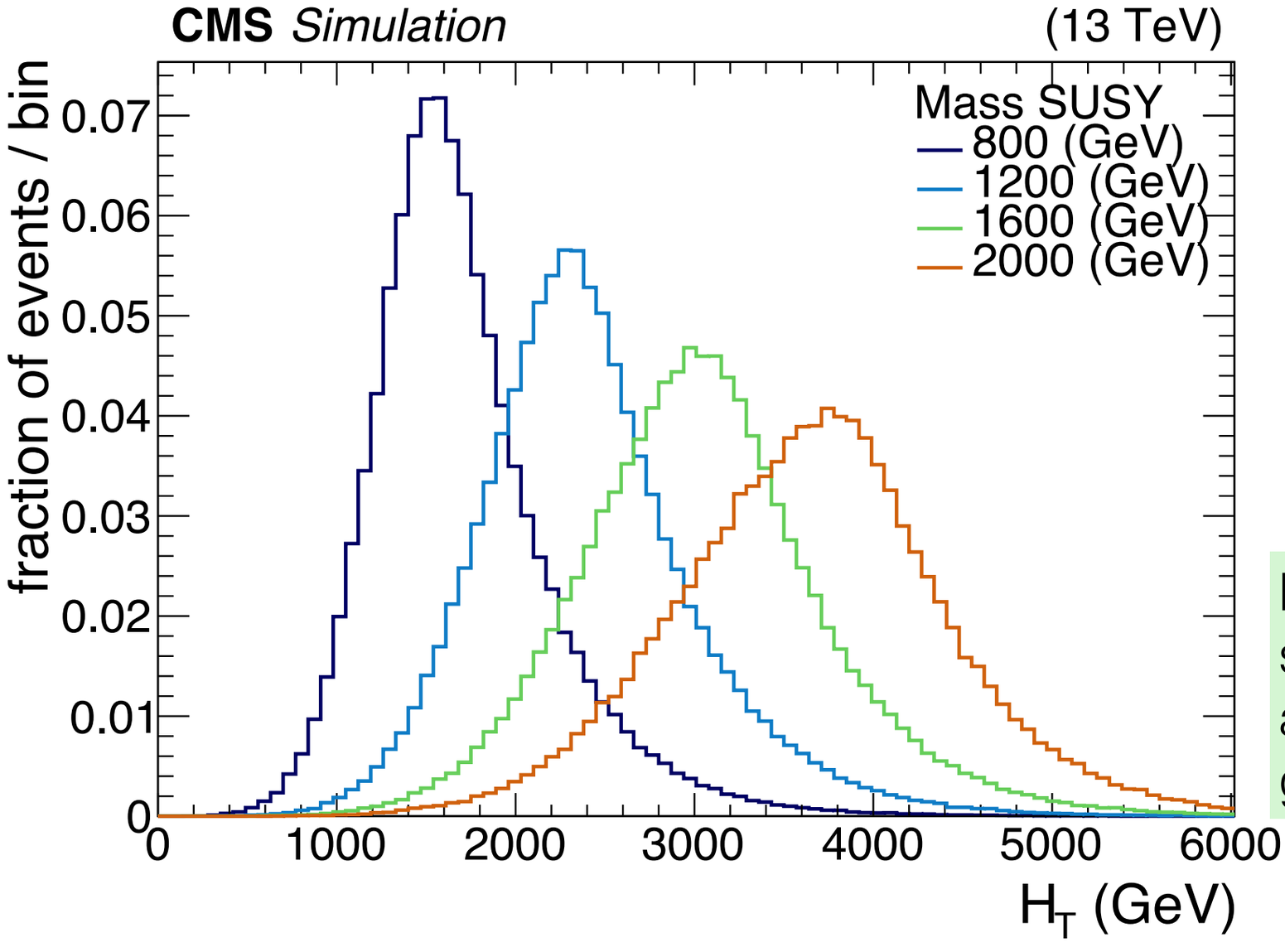

→ Reconstruct each Higgs boson in a single AK8Jet.

→ Use the CMS double-b-tag discriminator*: CMS-PAS-BTV-15-00*

# Signal Model: Key Properties (2)

The signal model has very high valued $H_T$ distribution.
→ Use $H_T$ to trigger.

The $H_T$ distribution changes significantly with $M_{SUSY.}$
→ Use different $H_T$ bins in the event selection.




$H_T$ = the scalar sum of the $p_T$ of all jets above a given threshold.

- Signal Model
- **Analysis Overview**
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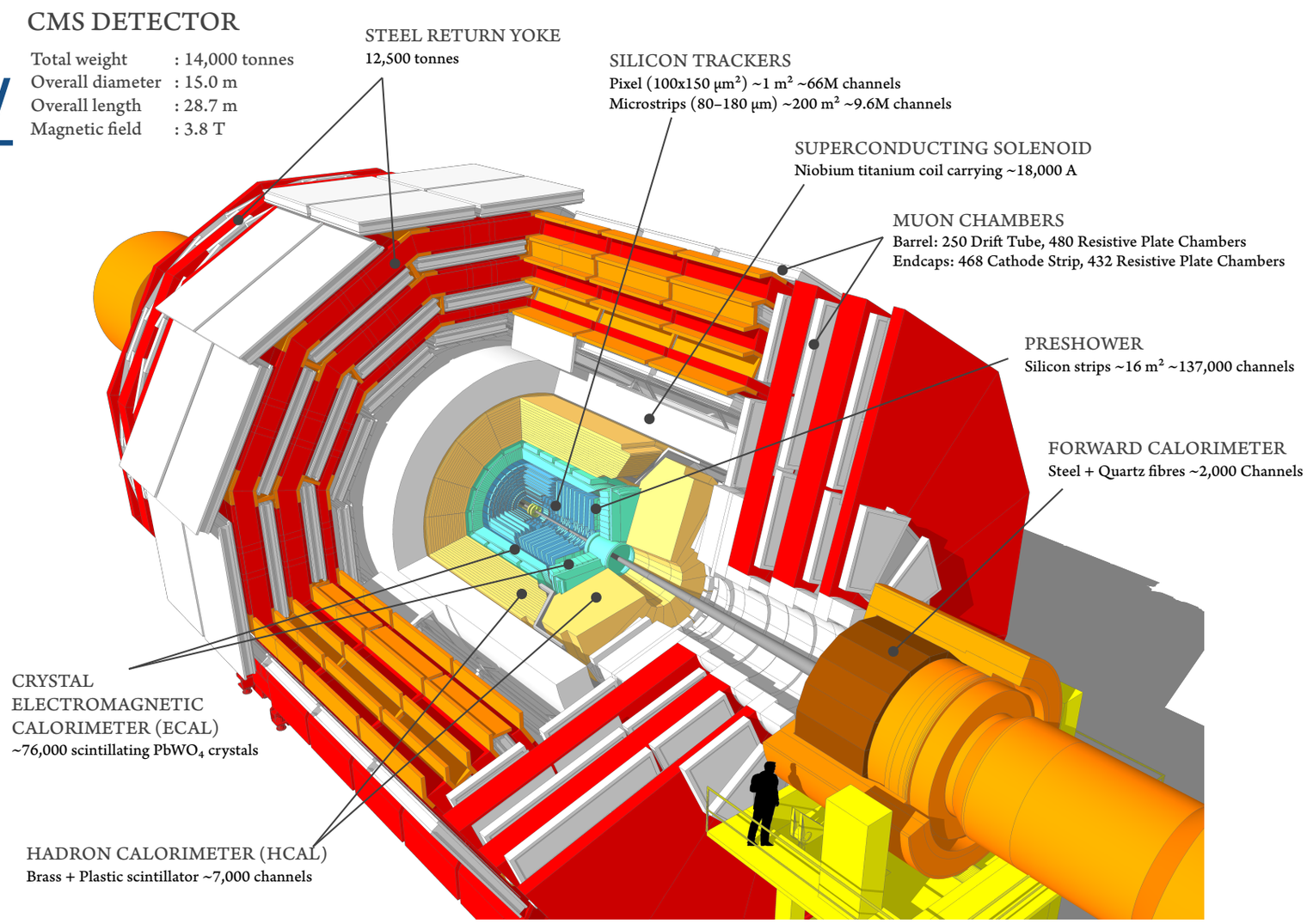
# Analysis Overview

Analysis conducted using CMS data and simulation.




- Uses the 2016 (35.9 $fb^{-1}$) + 2017 (41.5 $fb^{-1}$) datasets.
- Handles them in parallel, brought together for limits.

Signal samples:

- Use an array of $M_H$ and $M_{SUSY}$ masses *(see backup slides)*.
- Low MET parameters: $R_M = 0.99$ and $\Delta_M = 0.1$ GeV.

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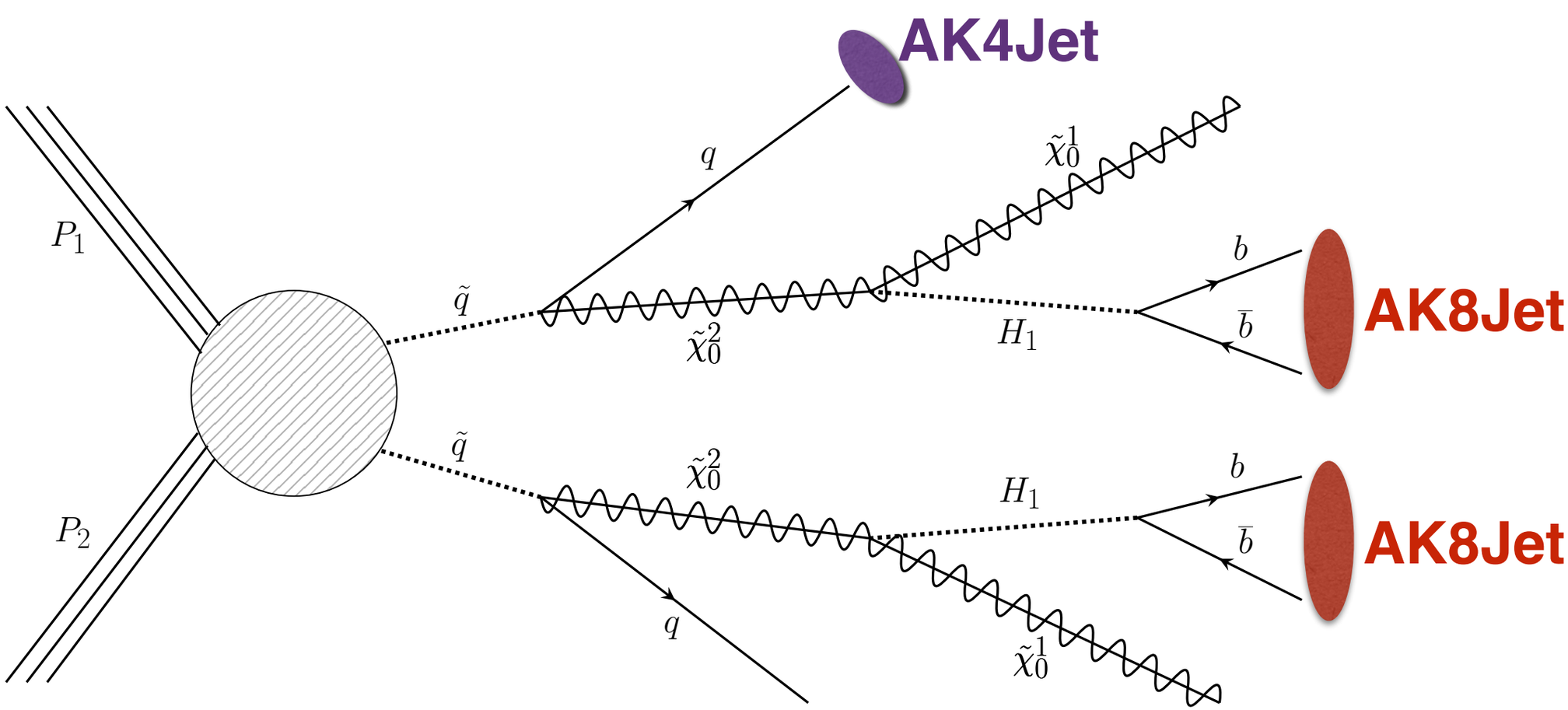
# Event Selection: Kinematic Cuts

**Pre-Selection**

- two AK8Jets: $p_T$ >170GeV, $|\eta|$<2.4, select two with highest double-b-tag discriminators.

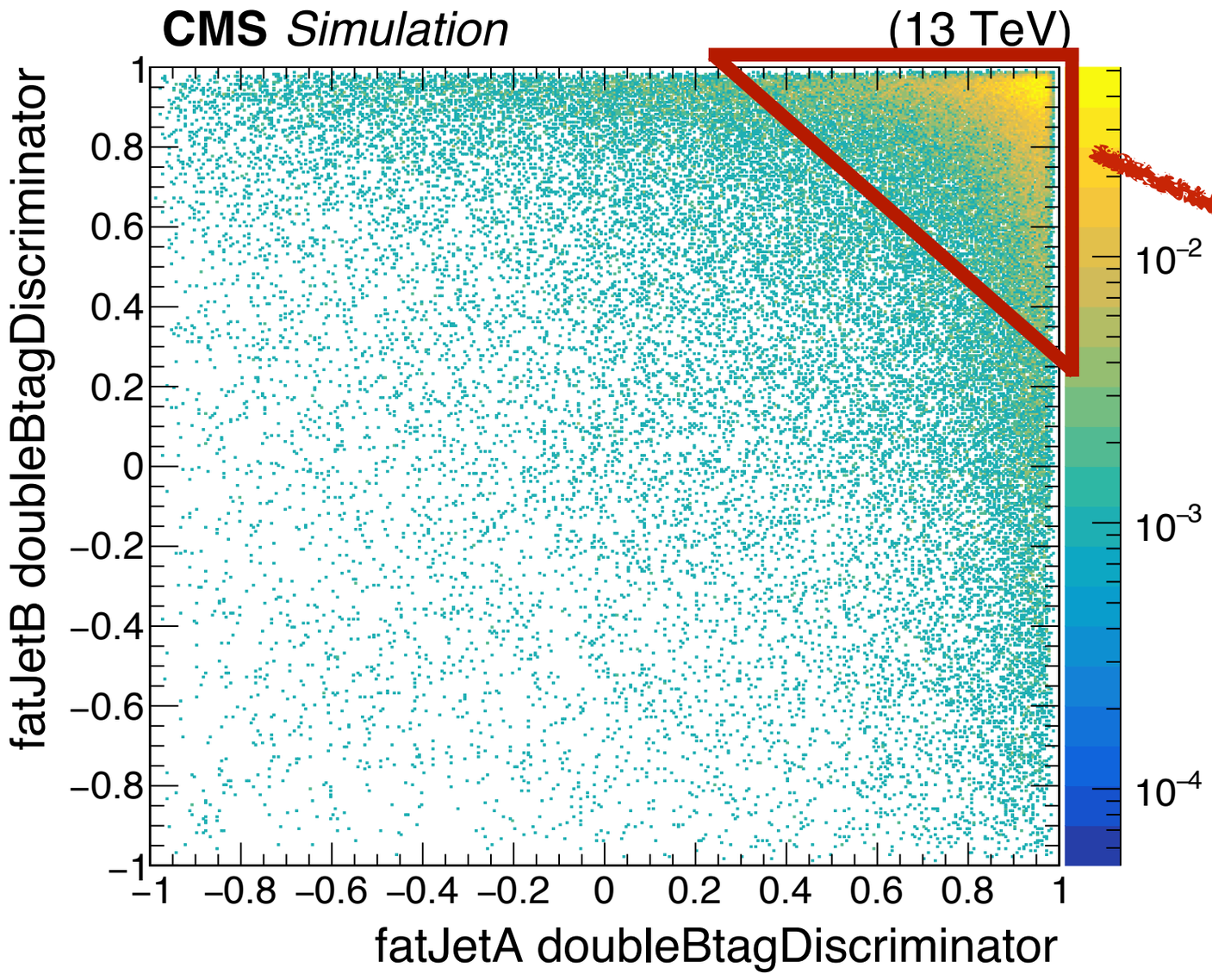
**Kinematic Cuts**

1. both selected AK8Jets $p_T$ > **300 GeV**
2. at least one additional AK4Jet ($\Delta R$>1.4 from selected AK8Jets), $|\eta|$<3.0, $p_T$ > **300 GeV**
3. $H_T \in$ **[1500-2500, 2500-3500, 3500+] GeV** (using AK4 Jets, $p_T$ >40GeV & $|\eta|$<3.0)



# Event Selection: Tag Double-b-tag Region

Two AK8Jets → 2D double-b-tag (DBT) plane → Define a ‘tag’ DBT region in this plane.

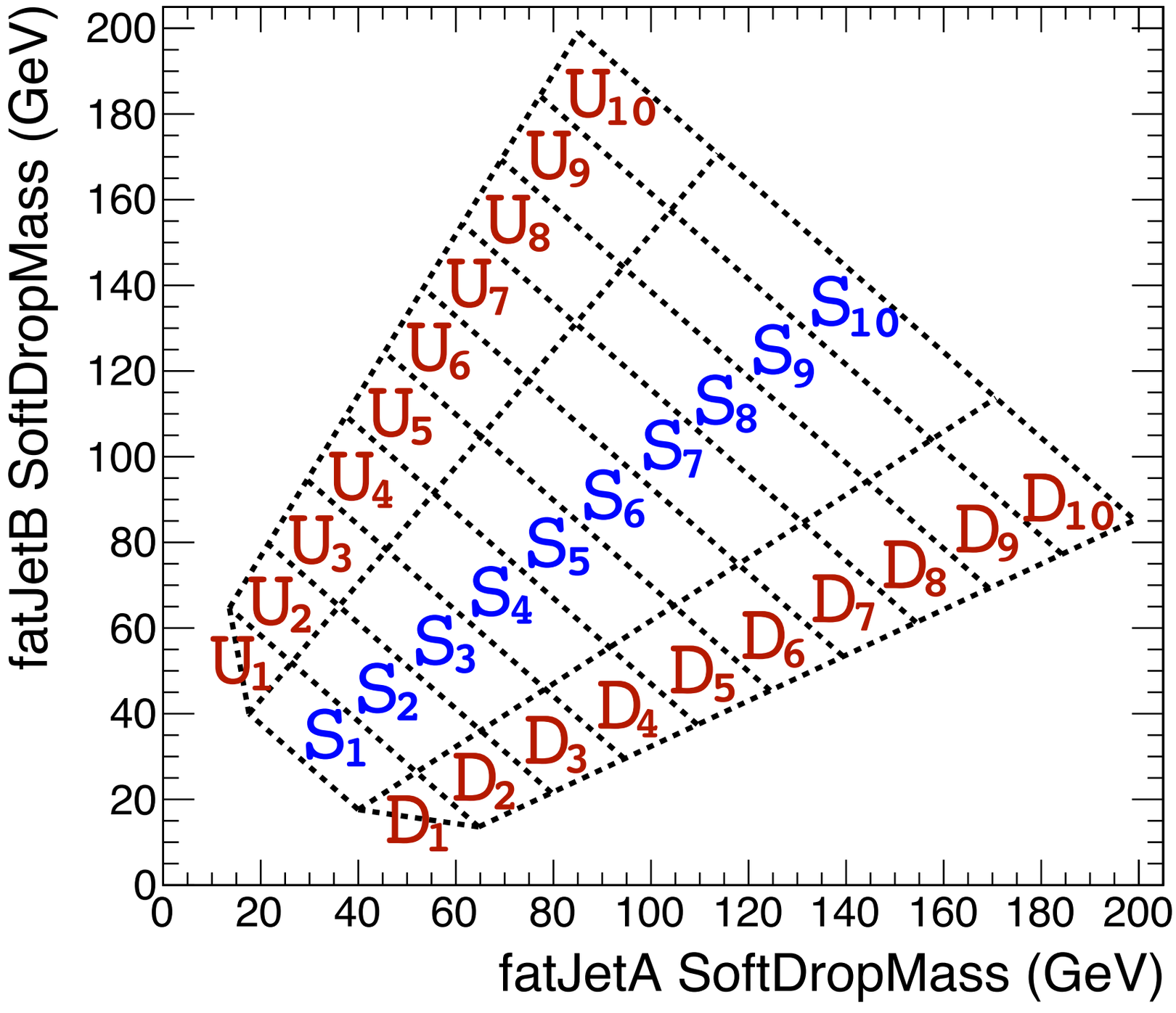



**tag DBT Region**

*Note: The two AK8Jets are randomly allocated as fatJetA and fatJetB so that the distribution is symmetric upon reflections in the y=x line of this plane.*

# Event Selection: 2D Mass Regions

Two AK8Jets → 2D soft-drop mass plane → Divide into Signal mass regions and Sideband mass regions.




**$U_n$**
Up-Sidebands

**$S_n$**
Signal Regions

**$D_n$**
Down-Sidebands

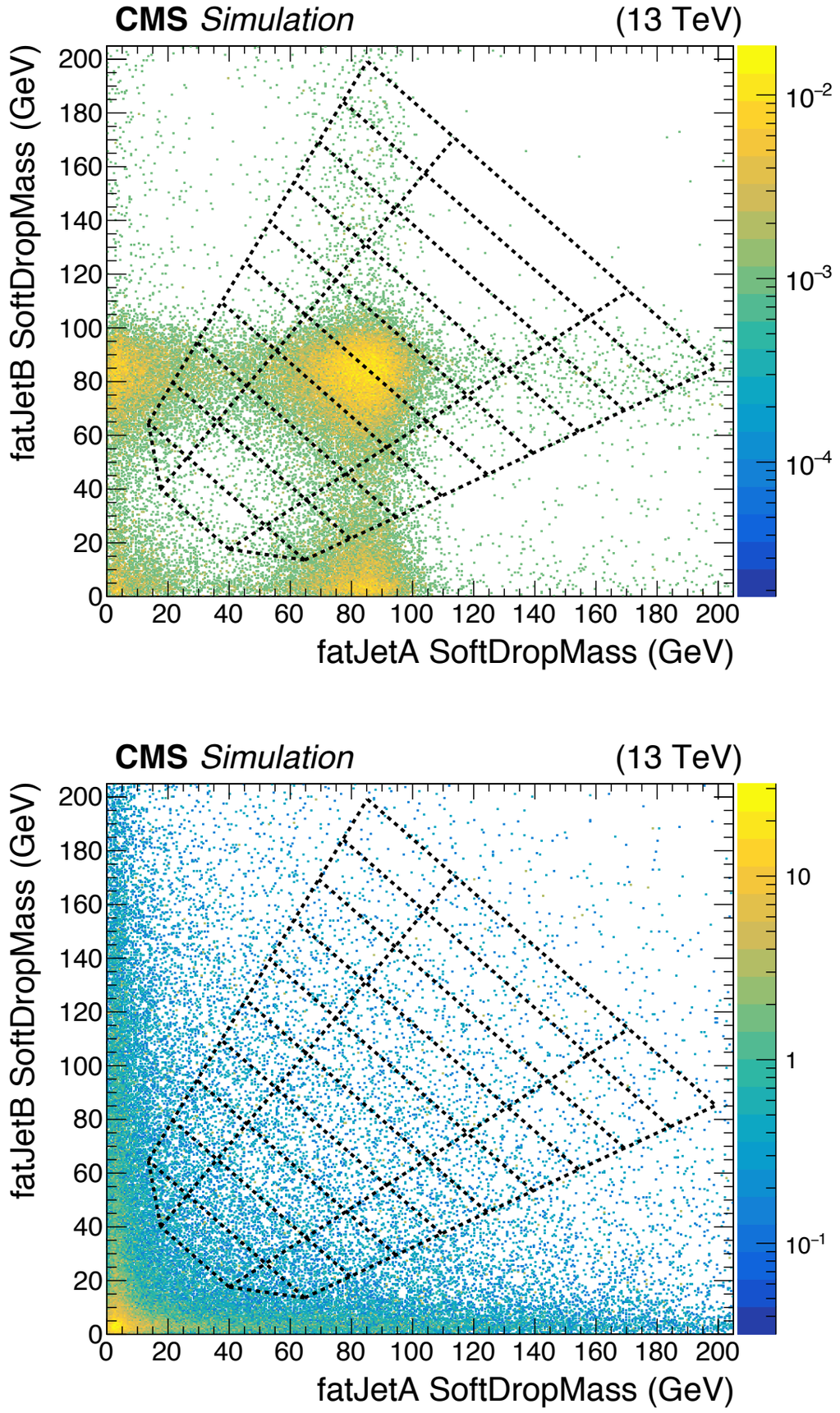
n > 1,

$Area(S_n) = Area(U_n+D_n)$

n = 1,

$Area(S_n) \sim= 2 * Area(U_n+D_n)$

# Event Selection: 2D Mass Regions (cont.)



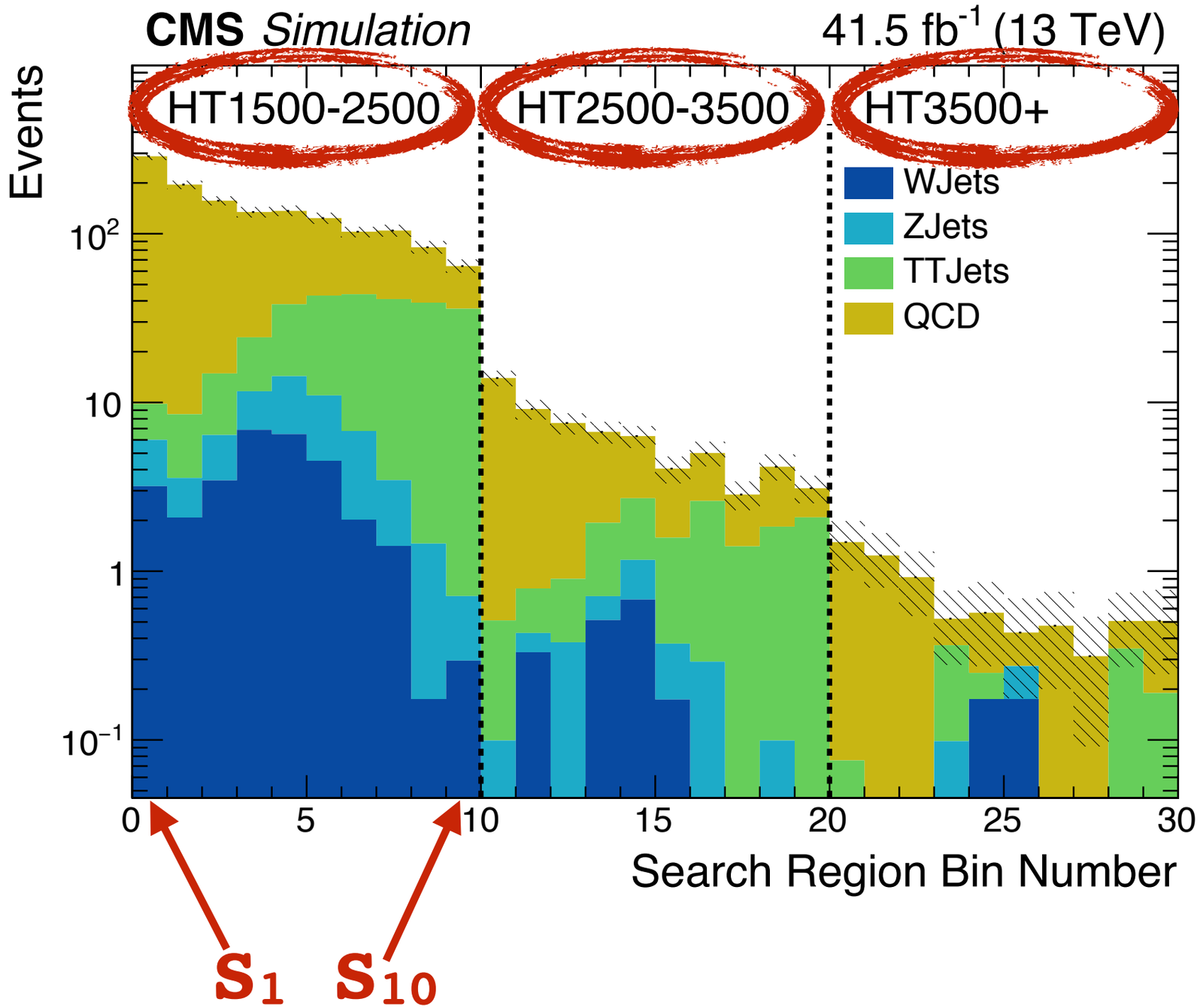

2016 Signal Monte Carlo
$M_H$ = 90 GeV, $M_{SUSY}$ = 2000 GeV
Full Cuts with $H_T \in$ 3500+ GeV




2016 QCD Monte Carlo
Full Cuts with $H_T \in$ 1500-2500 GeV

# Event Selection: 1D Mapping

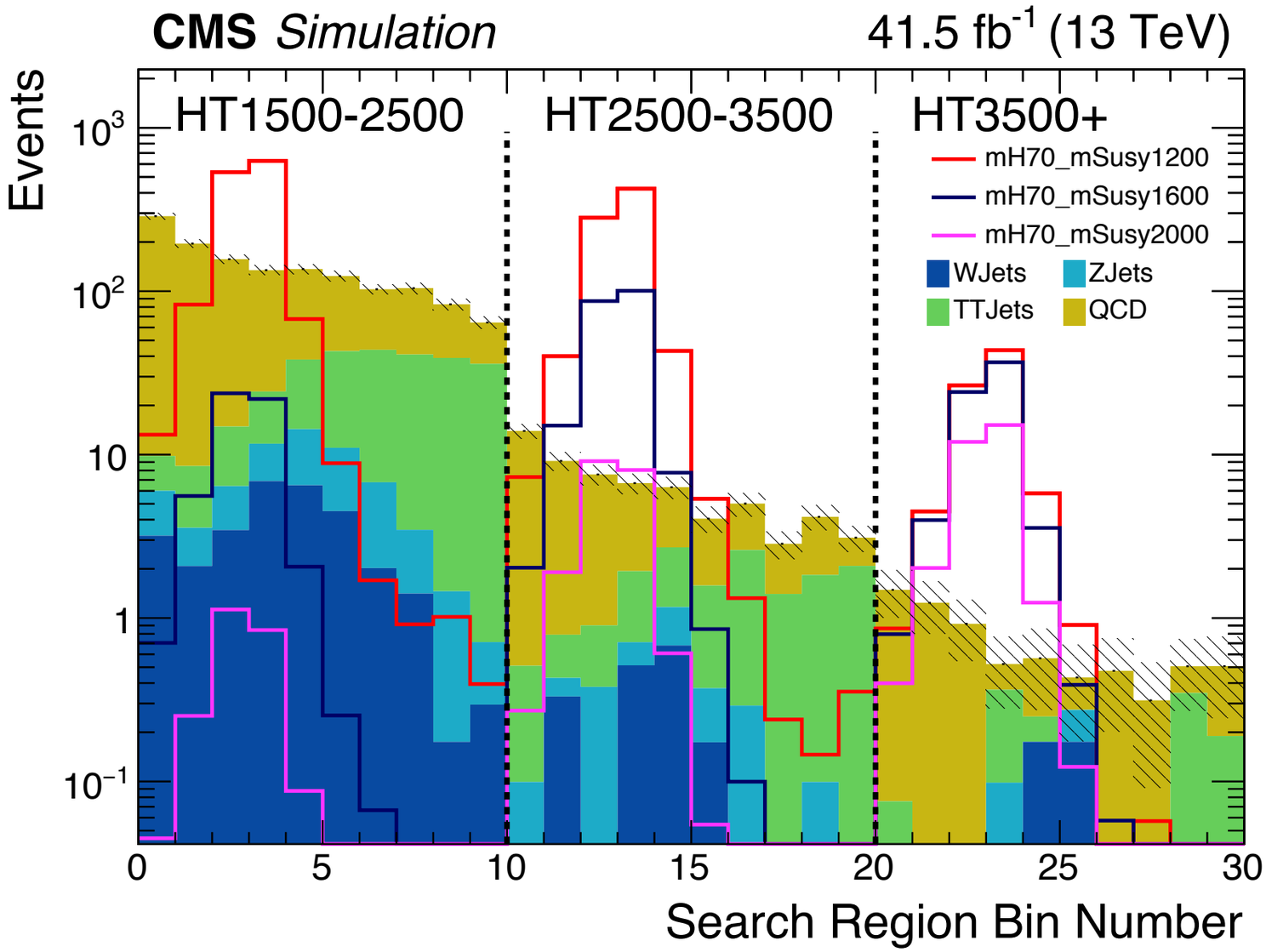
Three $H_T$ bins and ten mass regions → Map onto a 30 bin 1D histogram.




ten 2D mass regions within each $H_T$ division

# Event Selection: Simulated Results

2017 Signal vs background at 41.5 $fb^{-1}$ for different $M_{SUSY}$ with $M_H$ = 70 GeV.




→ QCD is largest background, ttbar also significant.
→ Signal peaks in bins corresponding $S_3$ and $S_4$.
→ $H_T$ binning helps extract signal for large $M_{SUSY}$.

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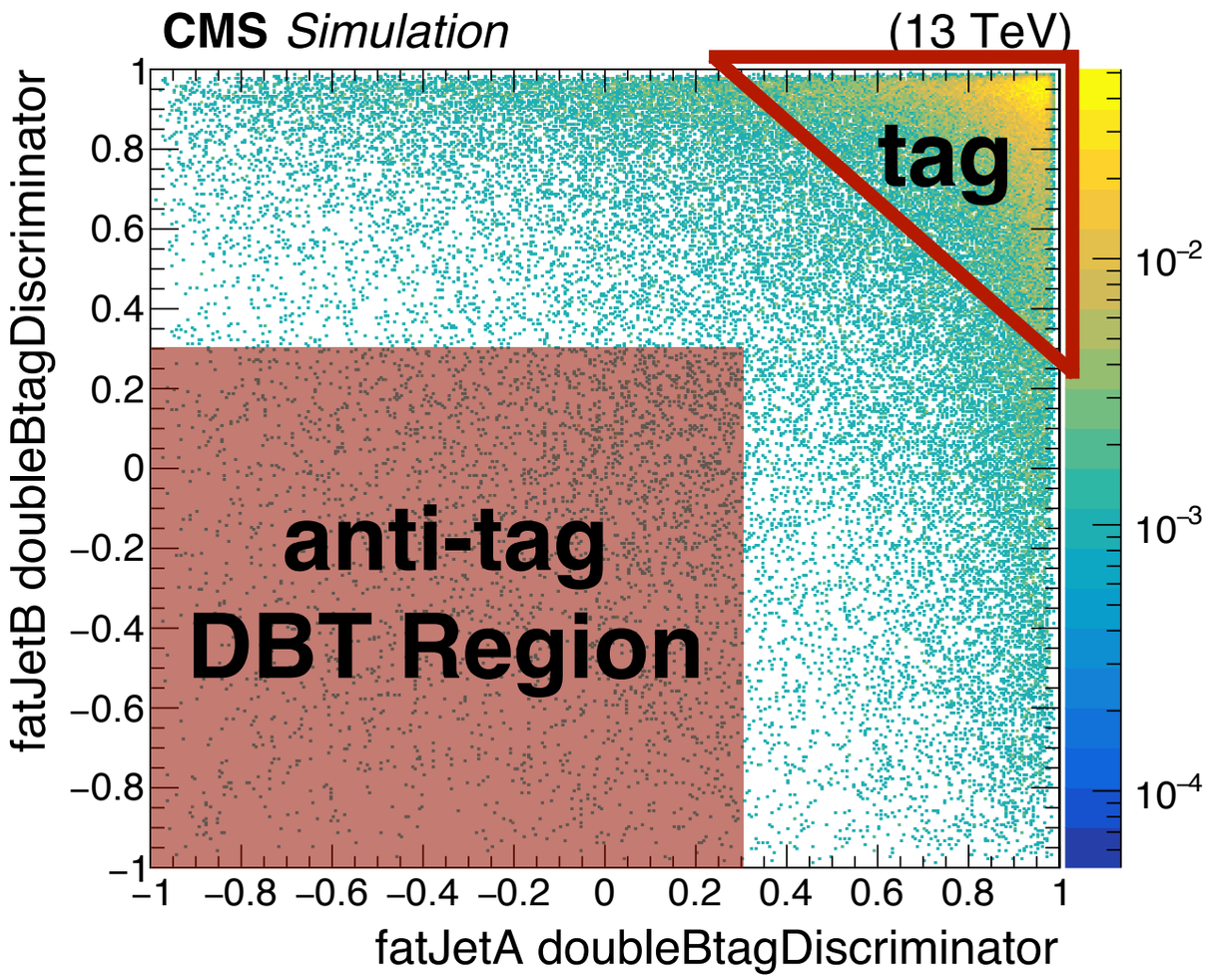
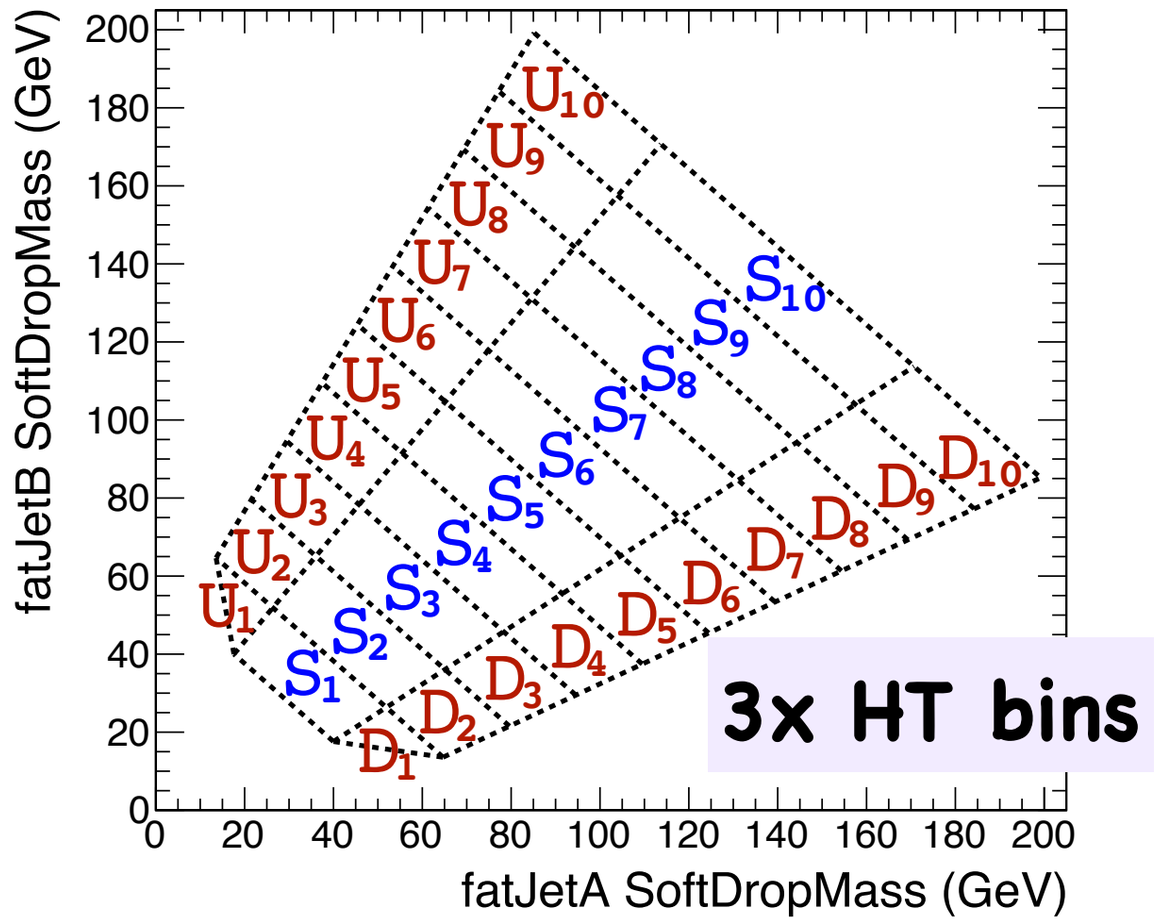
# QCD Background Estimation: The Method

$$S_i^{\text{tag PRED}} = \frac{S_i^{\text{anti-tag}}}{U_i^{\text{anti-tag}} + D_i^{\text{anti-tag}}} \cdot (U_i^{\text{tag}} + D_i^{\text{tag}})$$



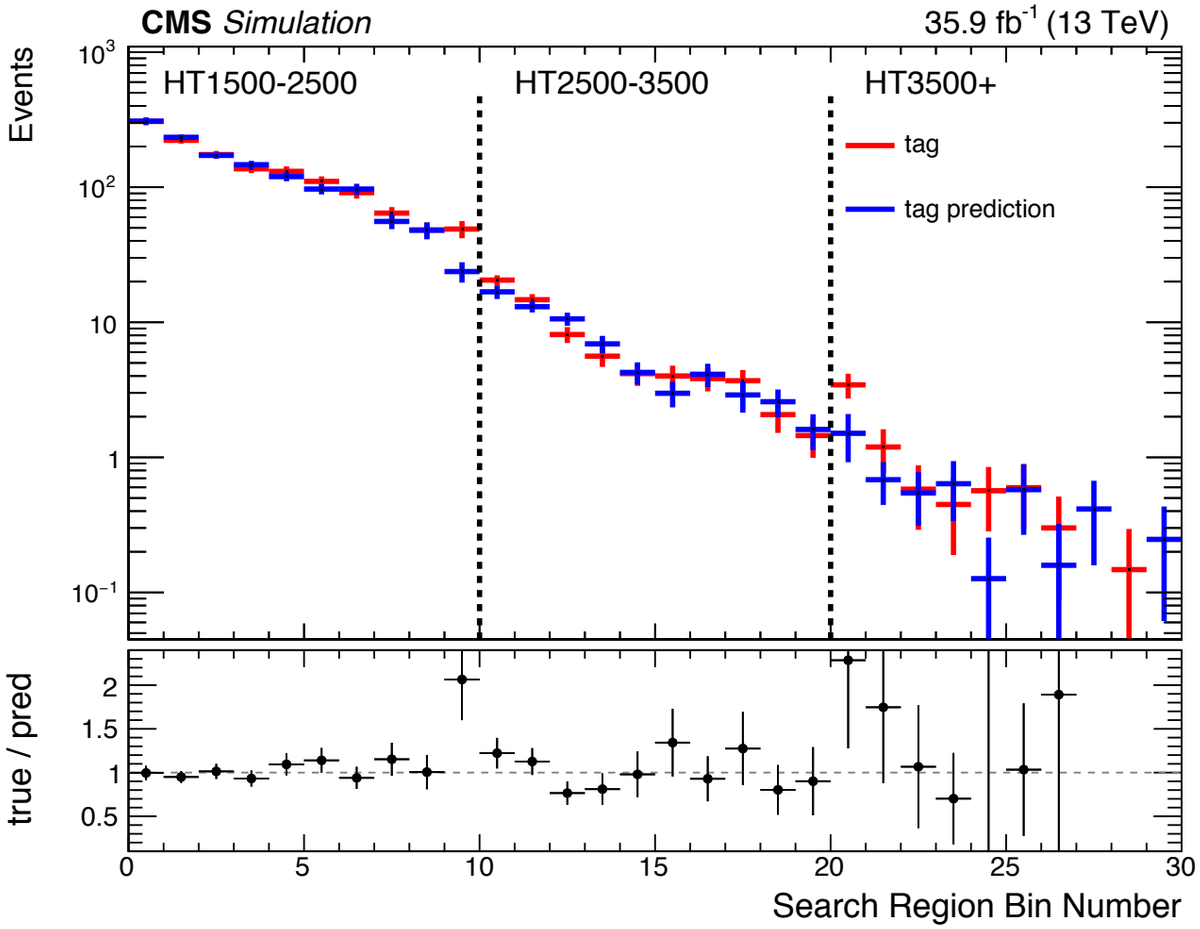



# QCD Estimation: Check in Monte Carlo

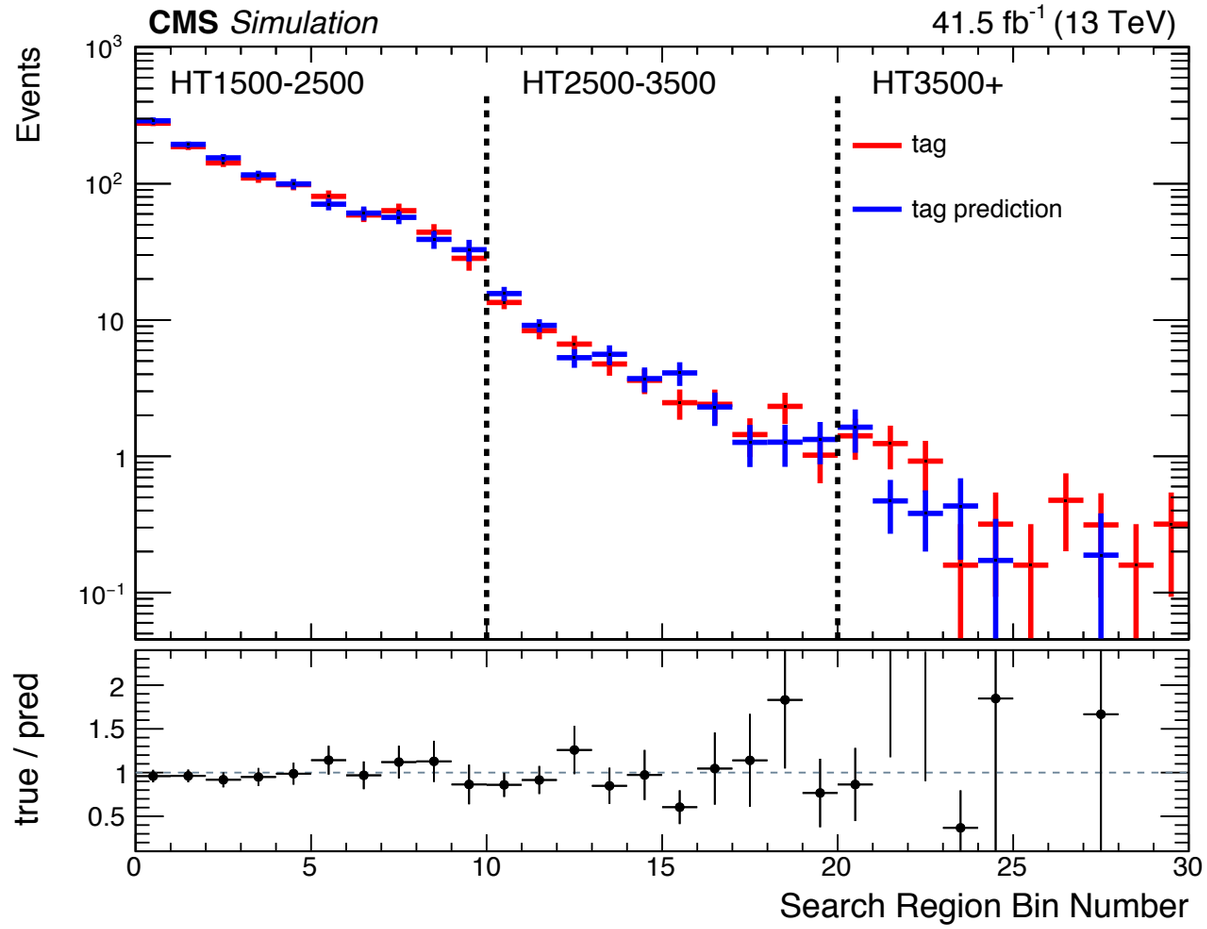
Test the QCD estimation method on the QCD Monte Carlo.

**RED = true QCD MC yield.**

**BLUE = predicted QCD yield using method on QCD MC.**




**2016**




**2017**

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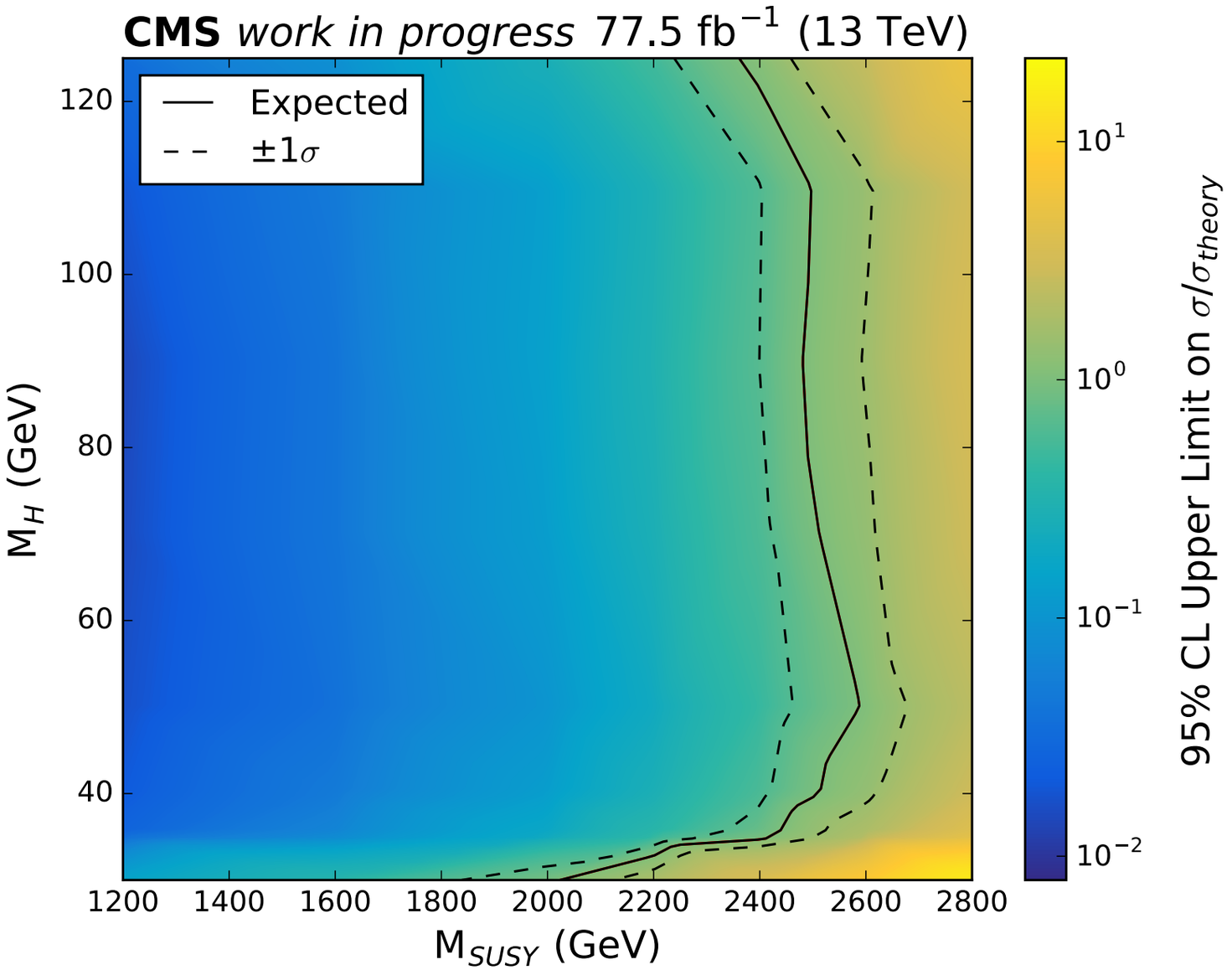
# Expected Limits

- Calculated expected limits using the asymptotic approximation of profile likelihood ratio: arXiv:1007.1727v3
- Linear Interpolation → Limit plot in $M_H$ vs $M_{SUSY}$ plane.
- Analysis currently blinded.



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# Conclusion

Signal Model = NMSSM cascades with boosted light Higgs bosons.

→ Low MET means other searches lack sensitivity.

Event Selection and QCD estimation method outlined:

→ Both depend on the double-b-tag and soft-drop mass 2D planes.

Expected limits demonstrate good signal sensitivity.

→ Hopefully unblind soon.

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**Thanks for listening**

# Backup

# Sample Details: Private Signal Samples

**$M_H$ = [30, 35, 40, 50, 70, 90, 110, 125] GeV**

*BR ($H_1 \rightarrow bb$) ≃ 85% for $M_H$ = 30-90 GeV and BR ($H_1 \rightarrow bb$) = 58% for $M_H$ = 125 GeV*

Most interested in the range $63 < M_H < 90$ GeV

Avoids the decay sequences; $H_{125} \rightarrow H_1 H_1$ and NLSP→LSP+Z; Z→$\nu\nu$(MET)

**$M_{SUSY}$ =**
**[800, 1200, 1600, 2000, 2200, 2400, 2600, 2800] GeV**

$M_{squark} = M_{SUSY}$ & $M_{gluino} = 1.01 * M_{SUSY}$

SUSY mass scales ranging from those
in the theory paper to around the limits
currently set in traditional SUSY searches.

$\sigma$ ($M_{SUSY}$ 800 GeV) = 6.4720 pb
$\sigma$ ($M_{SUSY}$ 1200 GeV) = 0.4951 pb
$\sigma$ ($M_{SUSY}$ 1600 GeV) = 0.0604 pb
$\sigma$ ($M_{SUSY}$ 2000 GeV) = 0.0091 pb
$\sigma$ ($M_{SUSY}$ 2400 GeV) = 0.0015 pb
$\sigma$ ($M_{SUSY}$ 2800 GeV) = 0.0003 pb

**R = 0.99**

Chosen to ~maximally suppress the MET due to the LSPs.

**Δ = 0.1GeV**

Constrained to be small due to the requirement on R.

Around 200k events produced for each signal sample in both CMSSW 80X and 94X.

# Event Selection: CMS Object Reconstruction

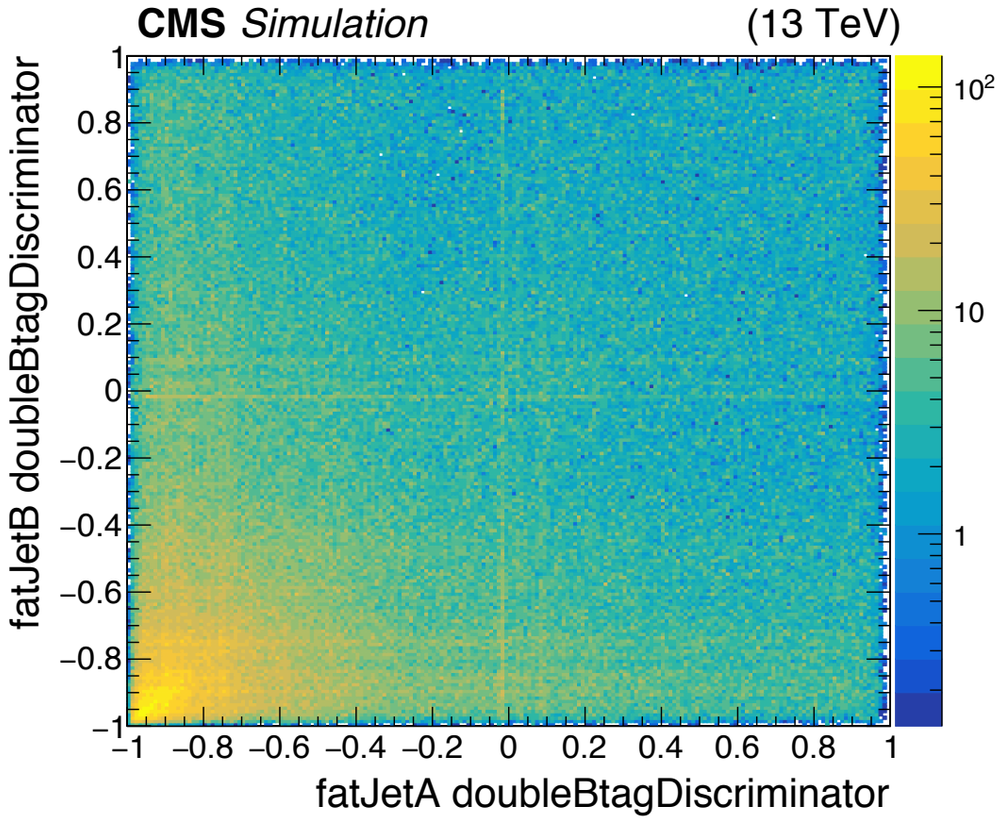
Jets
CMS uses a particle-flow reconstruction technique to describe events.
More info: arXiv:1706.04965v2
The jets are then clustered (with anti-kT) using the particle-flow candidates.

Double-b-tag discriminator
Gives a value between -1 and +1 (+1 is more double-b like).
Trained on displaced tracks and secondary vertices relative to sub-jet axes.
More info: CMS-PAS-BTV-15-00

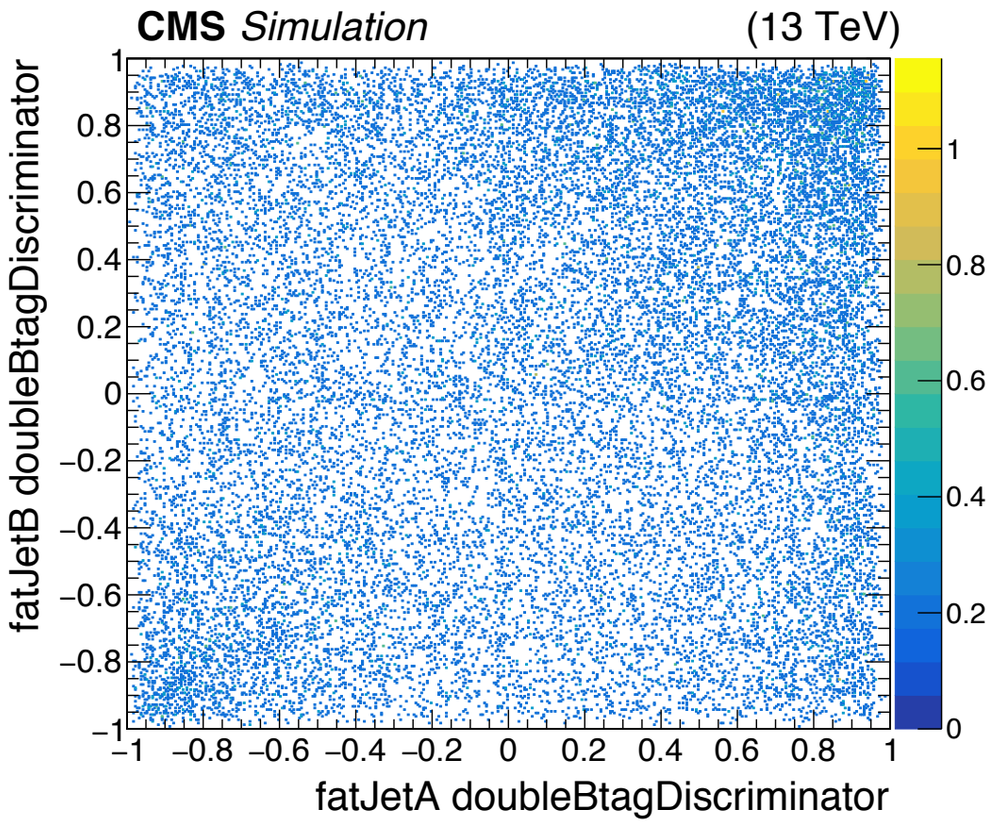
Soft-drop Mass
Applies soft-drop grooming algorithm before evaluating mass.
Params: beta = 0, zcut = 0.1
More info: arXiv:1402.2657v2

Uses PUPPI algorithm to mitigate pile-up before grooming.
More info: arXiv:1407.6013v2

# Event Selection: Additional DBT Plots



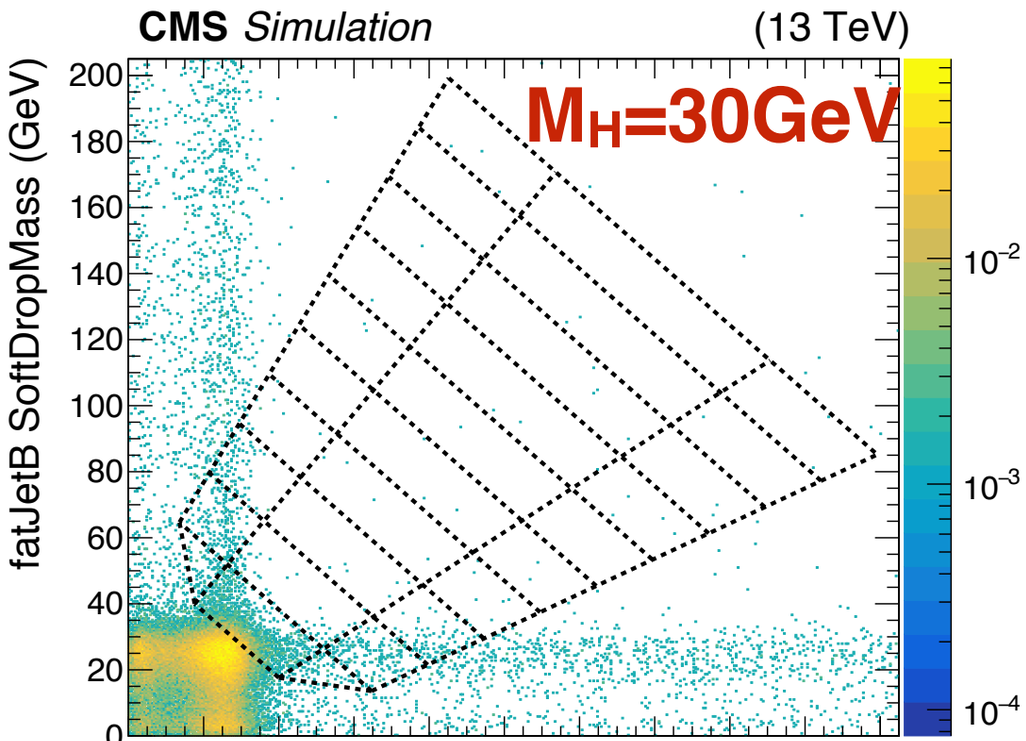

Top Plot:
QCD Monte Carlo
Kinematics cuts; $H_T \in$ 1500-2500 GeV
both fatJet softDropMasses > 15 GeV

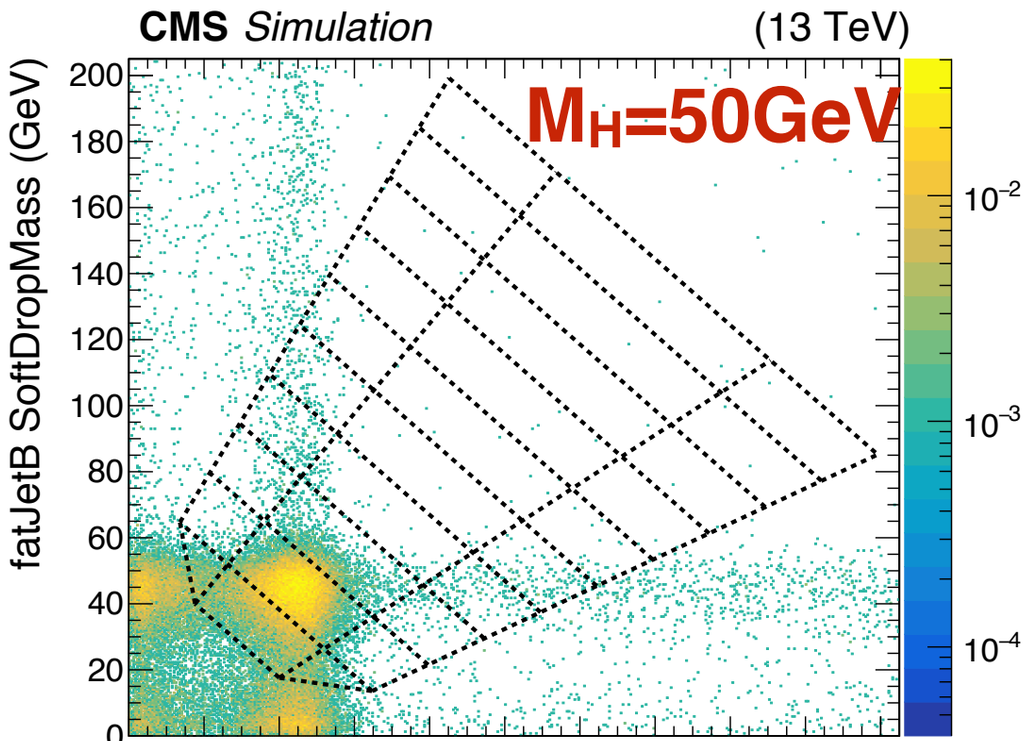


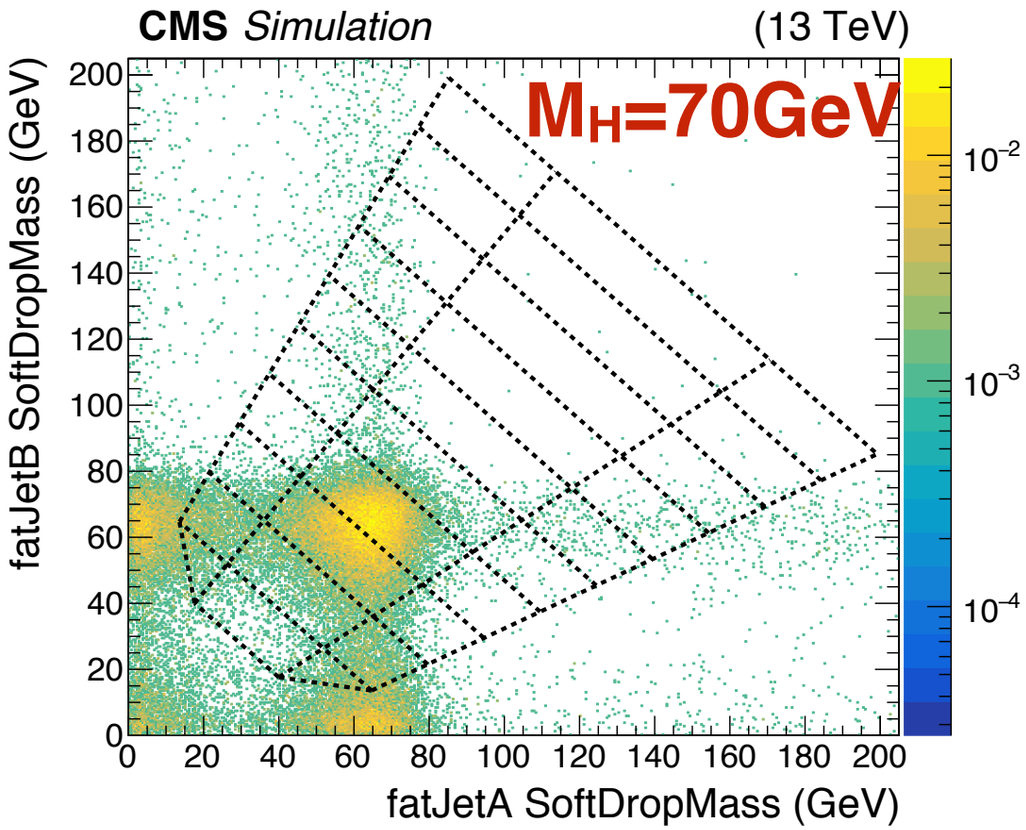

Bottom Plot:
ttbar Monte Carlo
Kinematics cuts; $H_T \in$ 1500-2500 GeV
both fatJet softDropMasses > 15 GeV

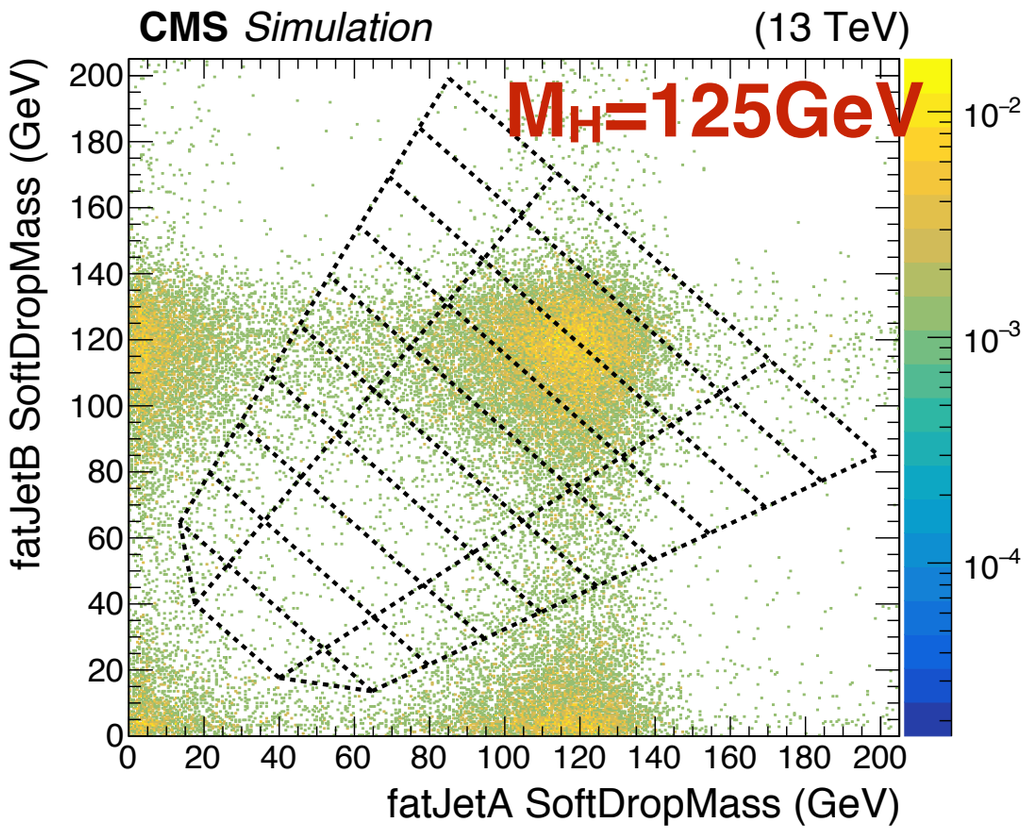
# Event Selection: Signal Mass Plots

*Signal with $M_{SUSY}$ =2000 GeV*
*Full cuts with $H_T \in$ 3500+ GeV*

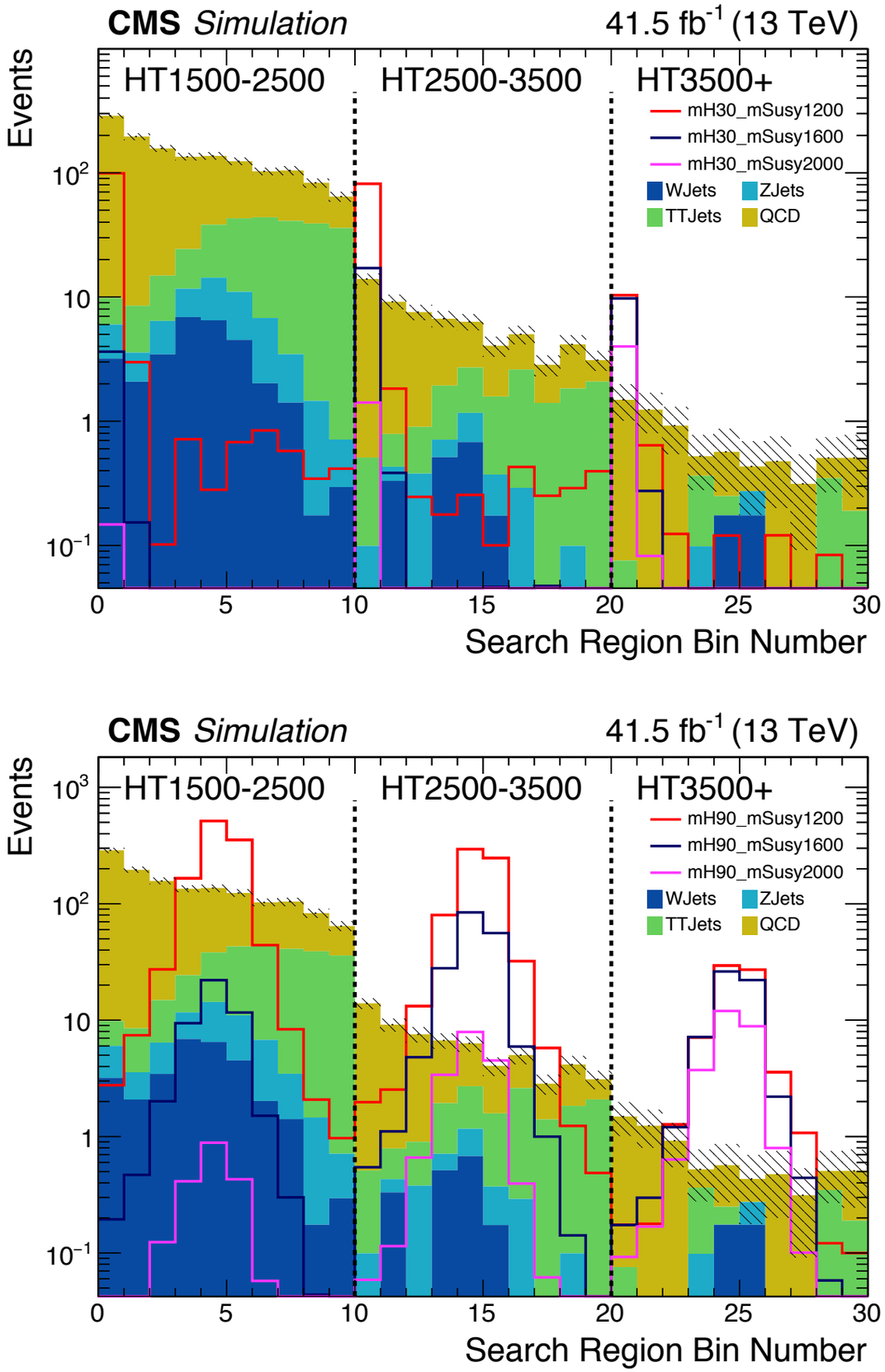


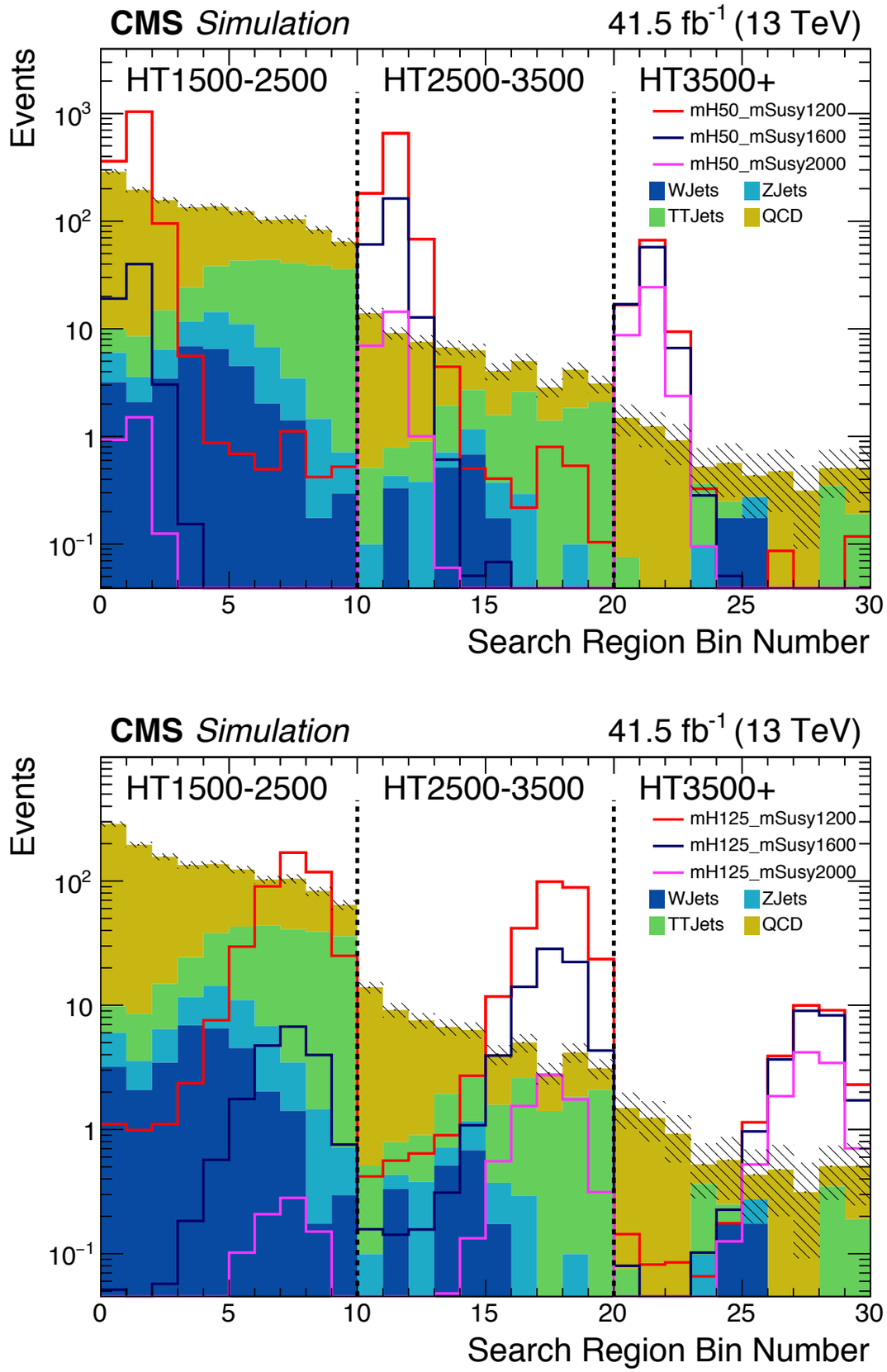



# Event Selection: Extra Simulated Results



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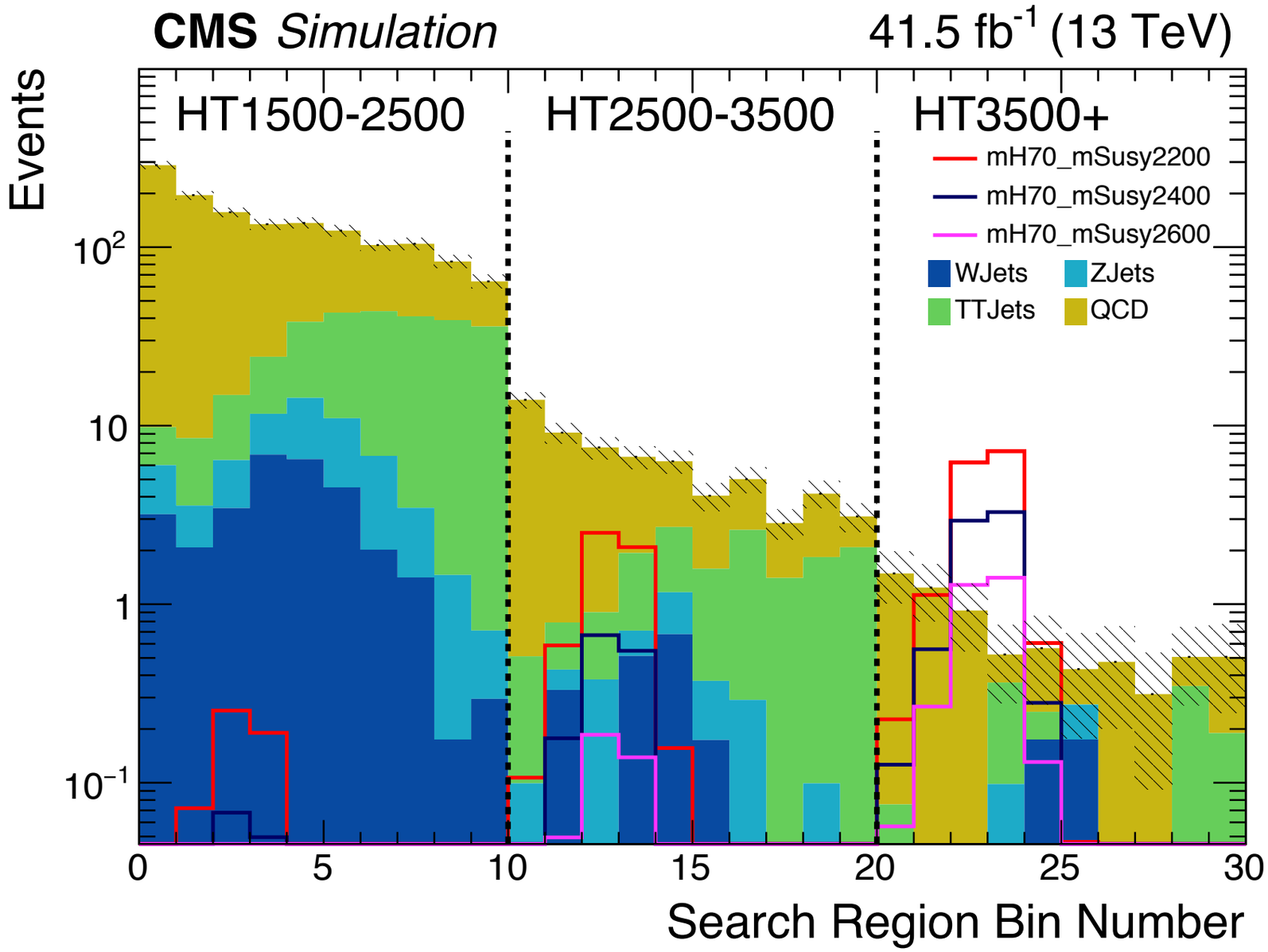
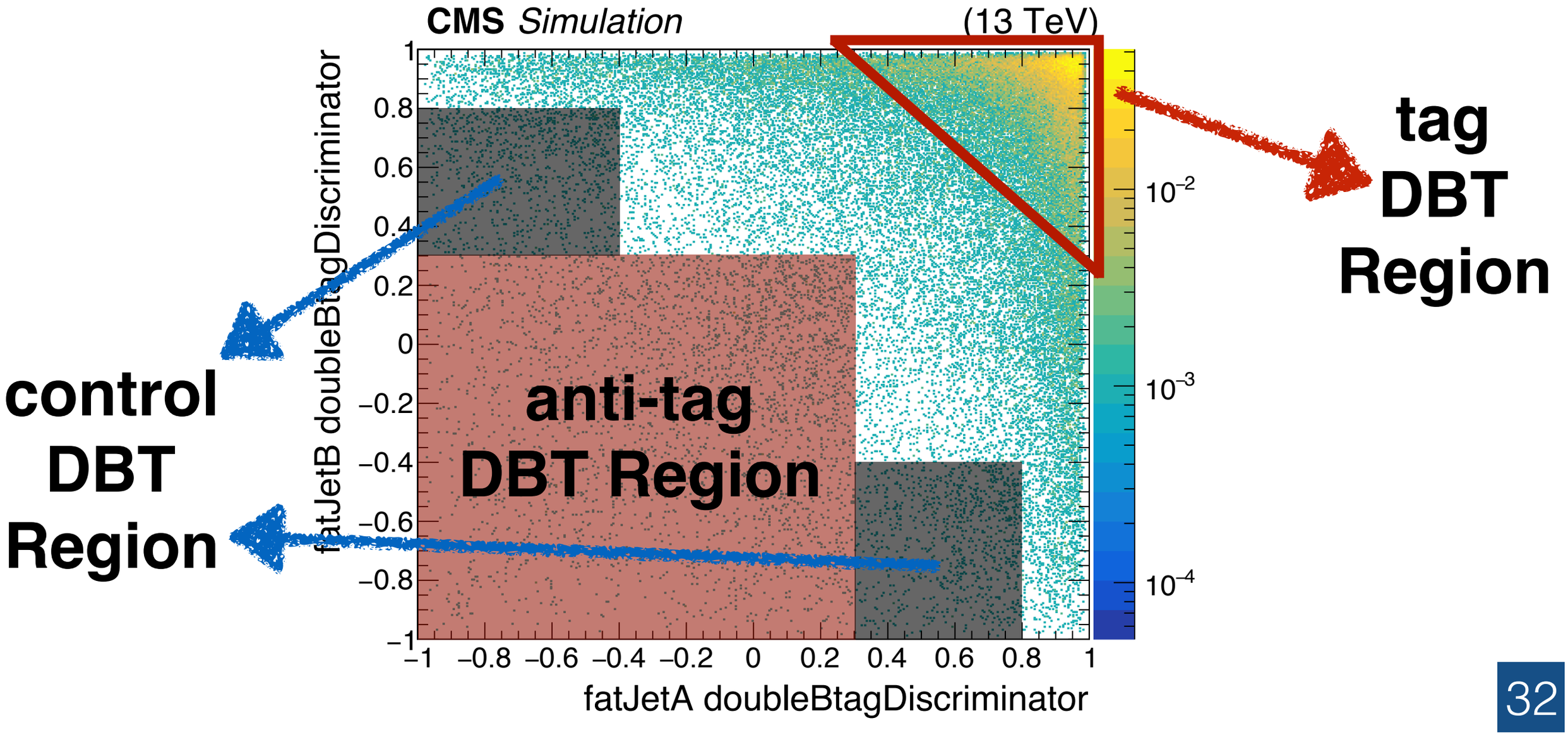


# QCD Estimation: Control Region

Define a DBT control region to test QCD estimation method on data.

→ Negligible signal contamination. Small TTJets, ZJets and WJets contributions.

$$S_i^{\text{control PRED}} = \frac{S_i^{\text{anti-tag}}}{U_i^{\text{anti-tag}} + D_i^{\text{anti-tag}}} \cdot (U_i^{\text{control}} + D_i^{\text{control}})$$

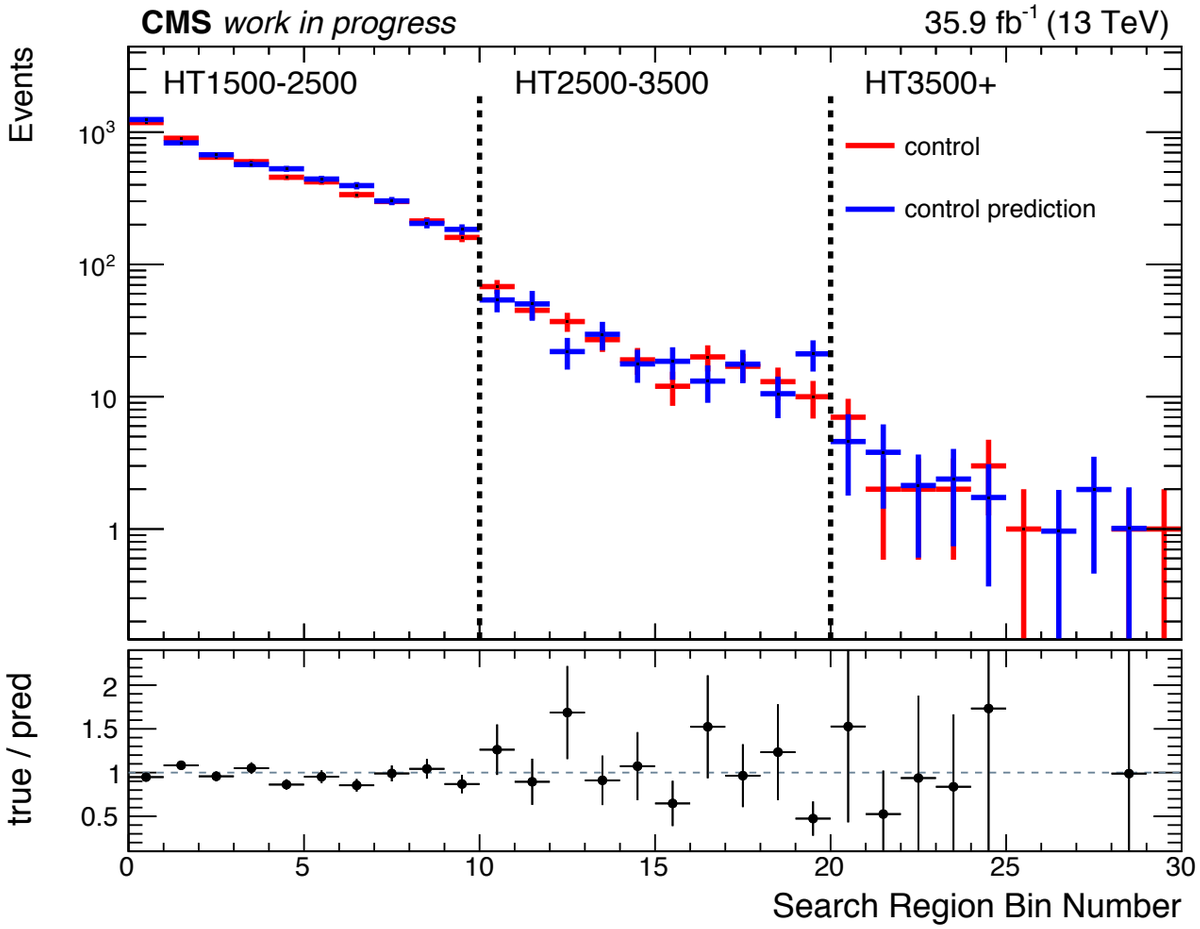


# QCD Estimation: Check in Control Region

Test the QCD estimation method with data, using control region.

**RED = true data yield in control region.**

**BLUE = predicted yield in control region using method on data.**

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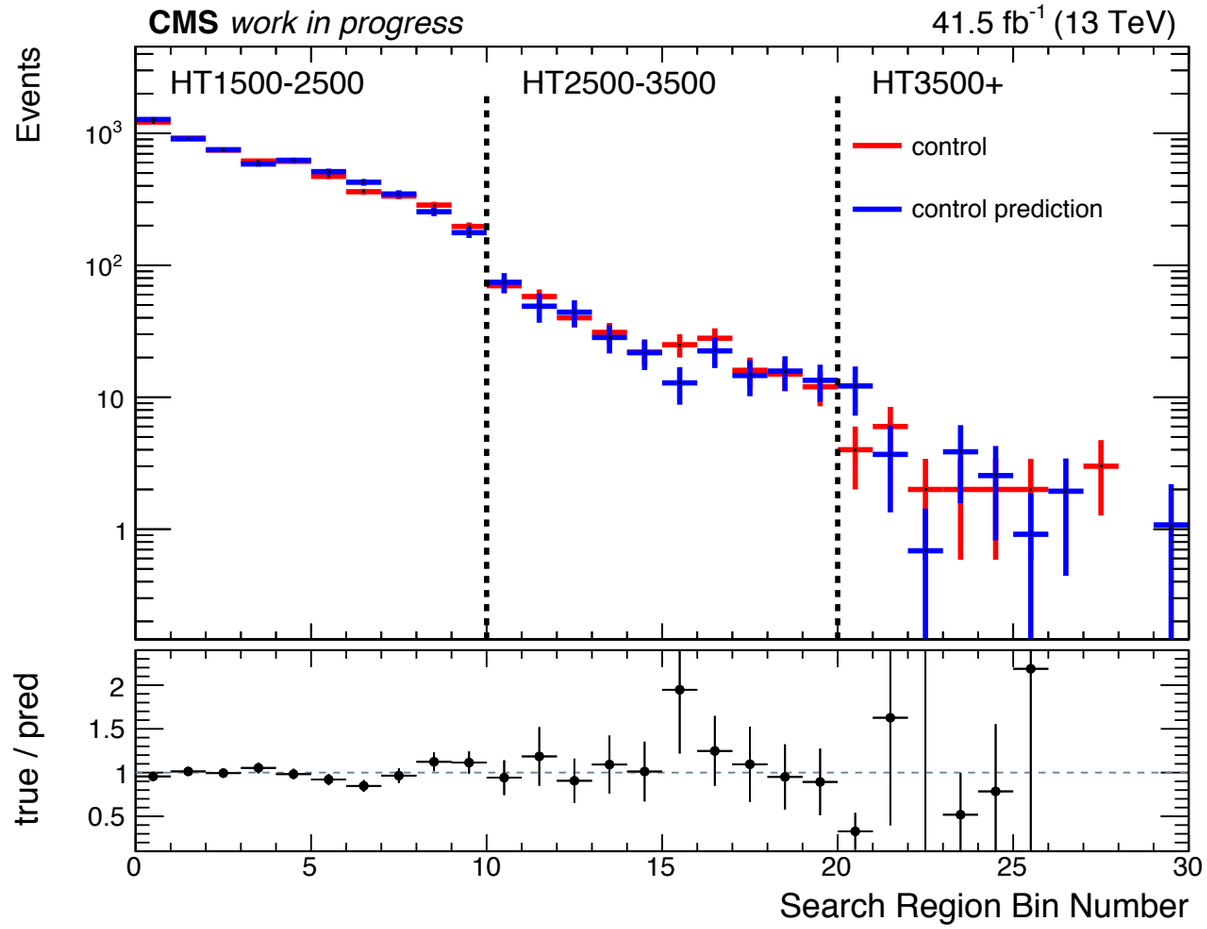


**2017**

# Expected Limits: Squark Production Only

Limit plot for the case where the gluino is decoupled.