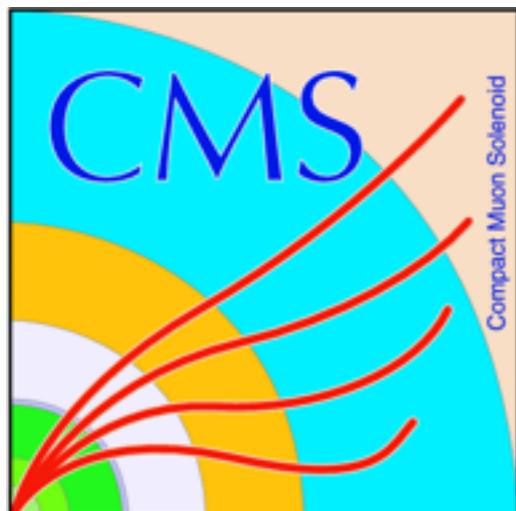# Searches for supersymmetry in fully hadronic final states with CMS

Nadja Strobbe (Fermilab)

Pheno 2017

8-10 May 2017, University of Pittsburgh

Intro

- CMS has a long history of doing searches for supersymmetry in the fully-hadronic final state

- This talk will feature the most recent results using the full 2016 dataset (36 fb^{-1}) of 13 TeV data

- Covered analyses:

  - Inclusive searches: H_T + H_T^{miss} search, M_{T2} search

  - Highlights from search with top quark tagging
    (Full details in talk by Z. Wu on third generation SUSY searches later in this session, which also covers similar SUS-16-049)

  - Targeted hh + p_T^{miss} search

NEW
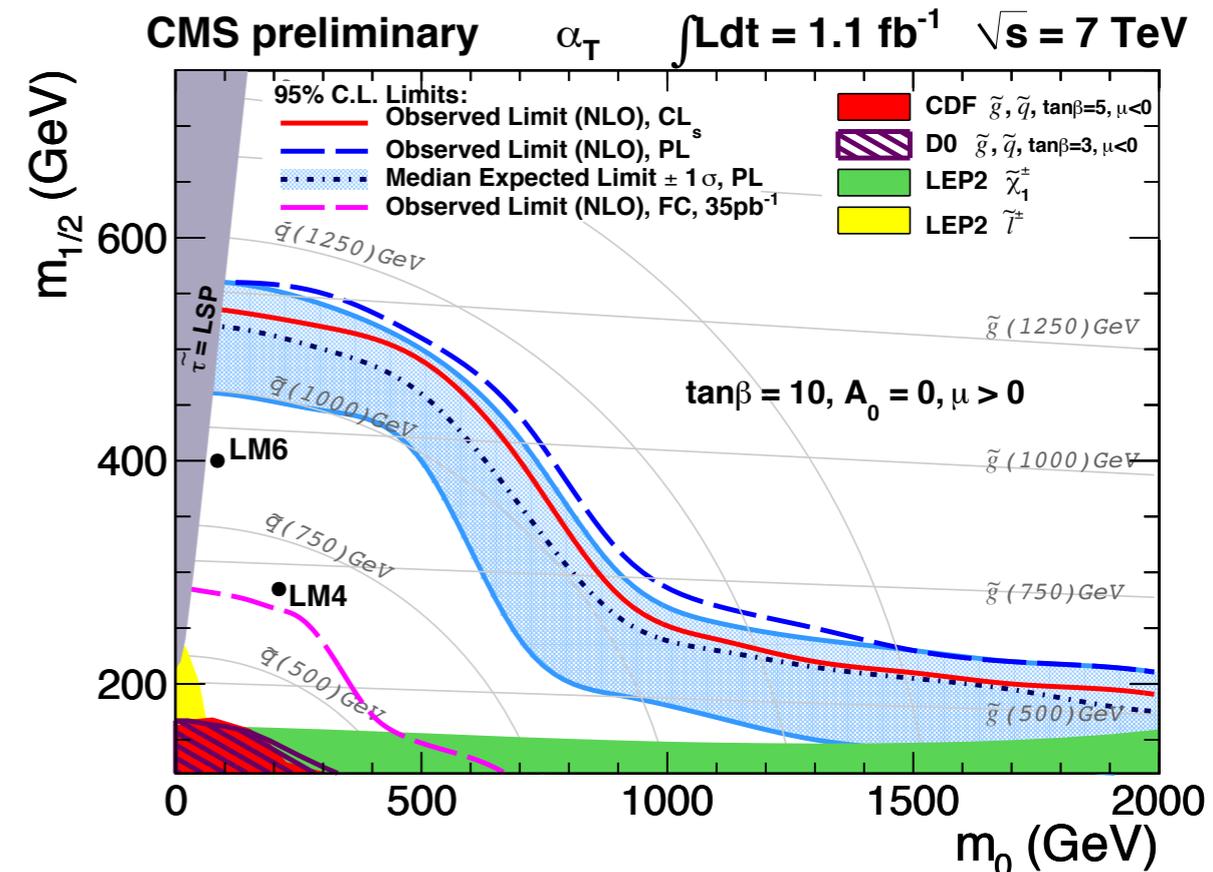
arXiv:1704.07781 [hep-ex]
CMS-SUS-16-036
CMS-SUS-16-050
CMS-SUS-16-044

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Inclusive SUSY searches

- Target gluino and squark pair production
- Define event selection such that the search is sensitive to **broad range of signal topologies**
- Binning rather than hard selection cuts, resulting in >100 exclusive signal regions

A few example simplified models

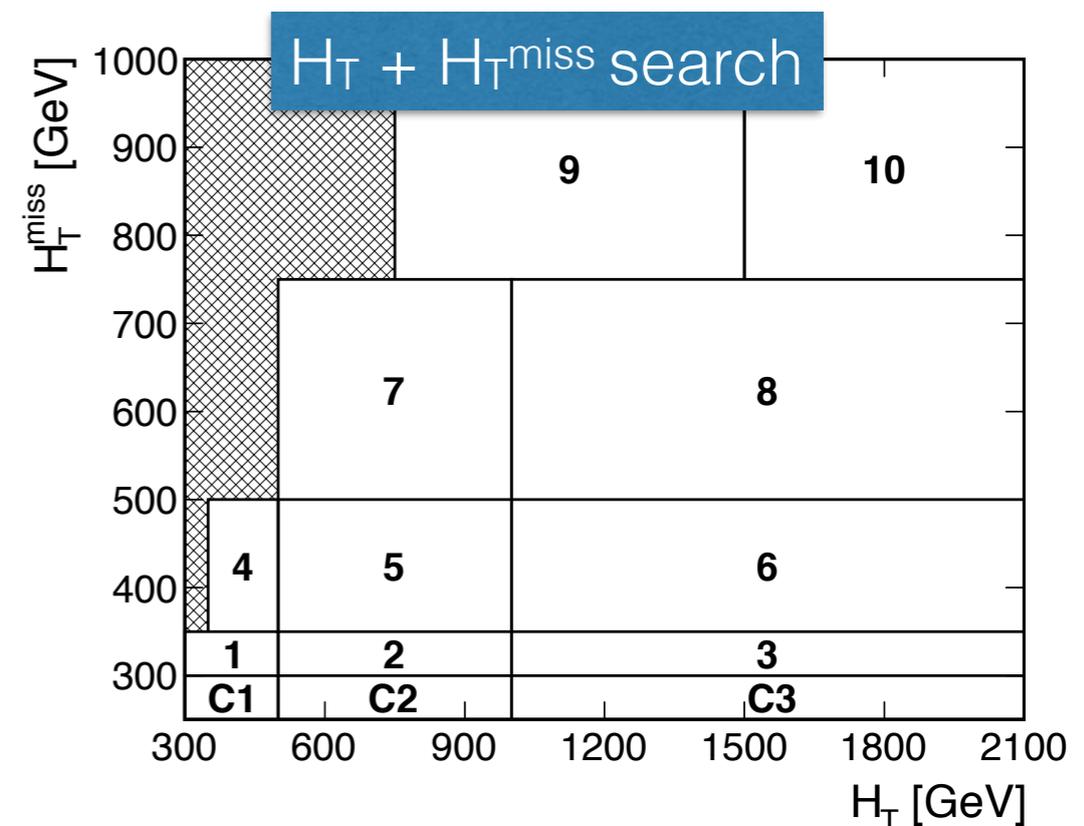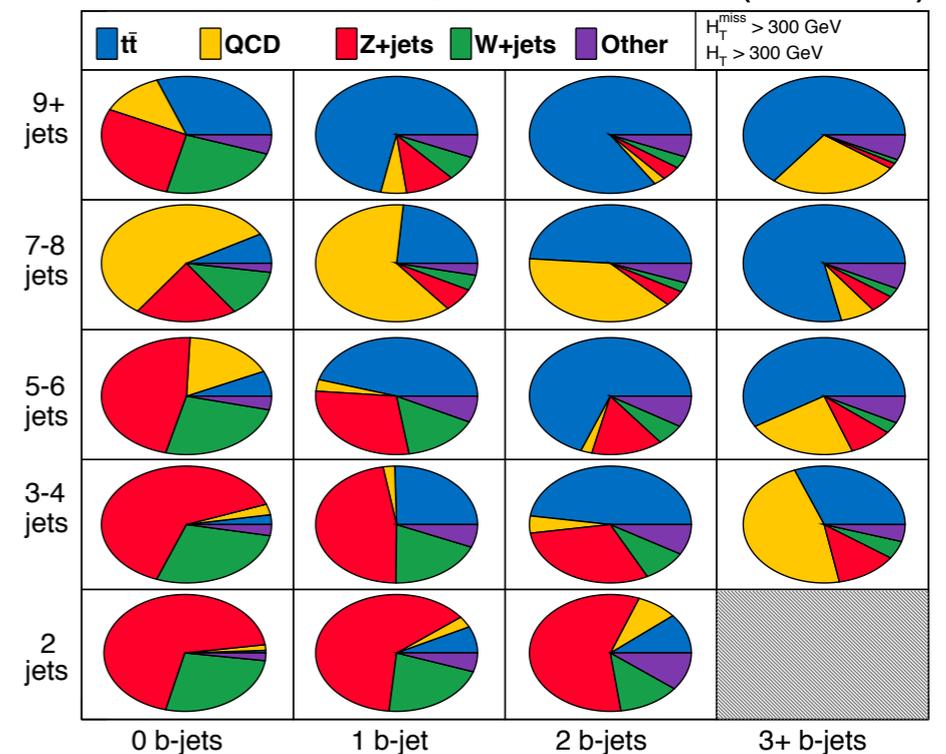Usually assume 100% BF for a given decay chain

3
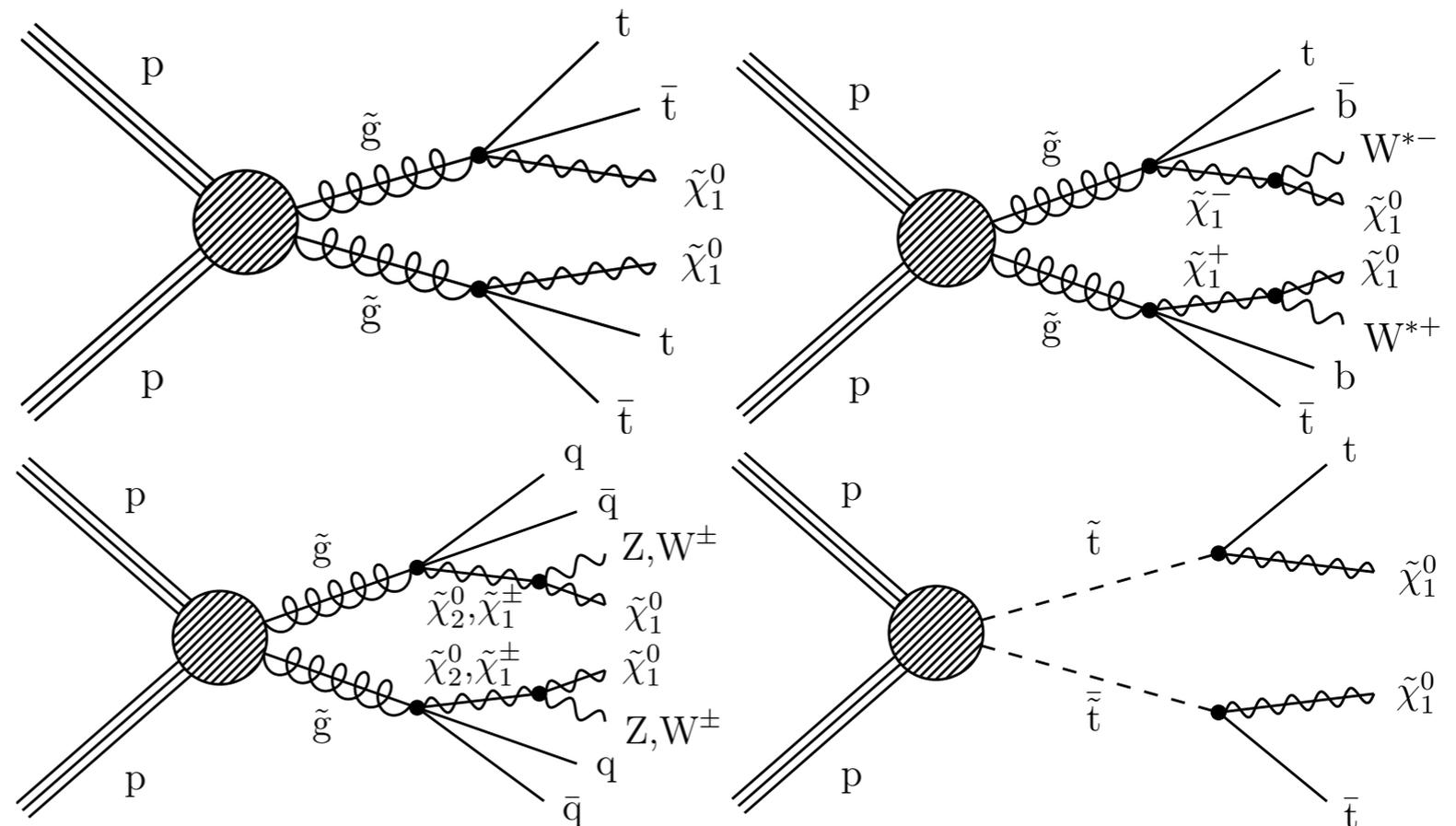
Search variables

Common variables used for event categorization:

- **N$_{jet}$** : as low as 1 (M$_{T2}$ search) or 2 jets, as high as ≥9 jets

- **N$_{bjet}$** : bins starting at 0 bjets, and up to ≥3 bjets

- **H$_T$**: scalar sum of jet p$_T$

- **H$_T^{miss}$**: |- vector sum of jet p$_T$|

- **M$_{T2}$**: "stransverse mass", a generalization of transverse mass M$_T$ for decay chains with two unobserved particles.

$$M_{T2} = \min_{\vec{p}_T^{\text{miss}X(1)} + \vec{p}_T^{\text{miss}X(2)} = \vec{p}_T^{\text{miss}}} \left[\max\left(M_T^{(1)}, M_T^{(2)} \right) \right]$$

CMS *Supplementary (Simulation)*   (13 TeV)

H$_T^{miss}$ > 300 GeV
H$_T$ > 300 GeV

Legend: tt̄, QCD, Z+jets, W+jets, Other

Rows: 9+ jets, 7-8 jets, 5-6 jets, 3-4 jets, 2 jets
Columns: 0 b-jets, 1 b-jet, 2 b-jets, 3+ b-jets
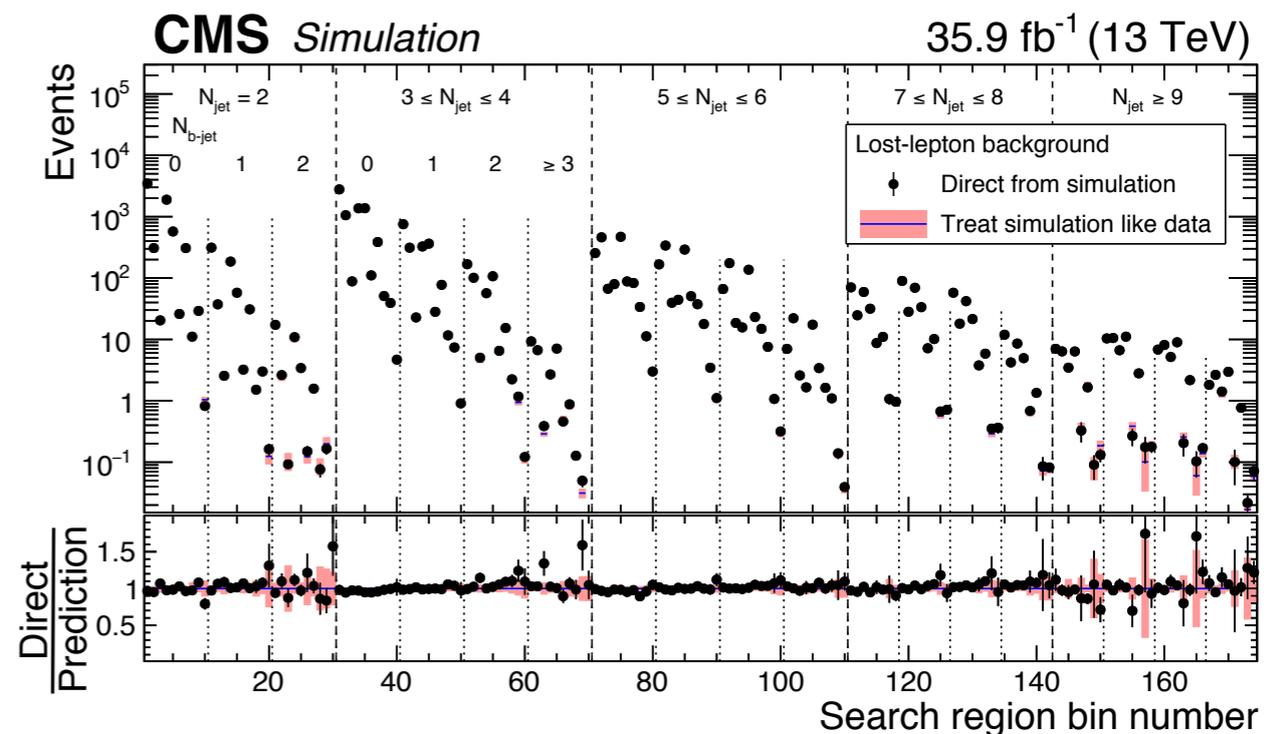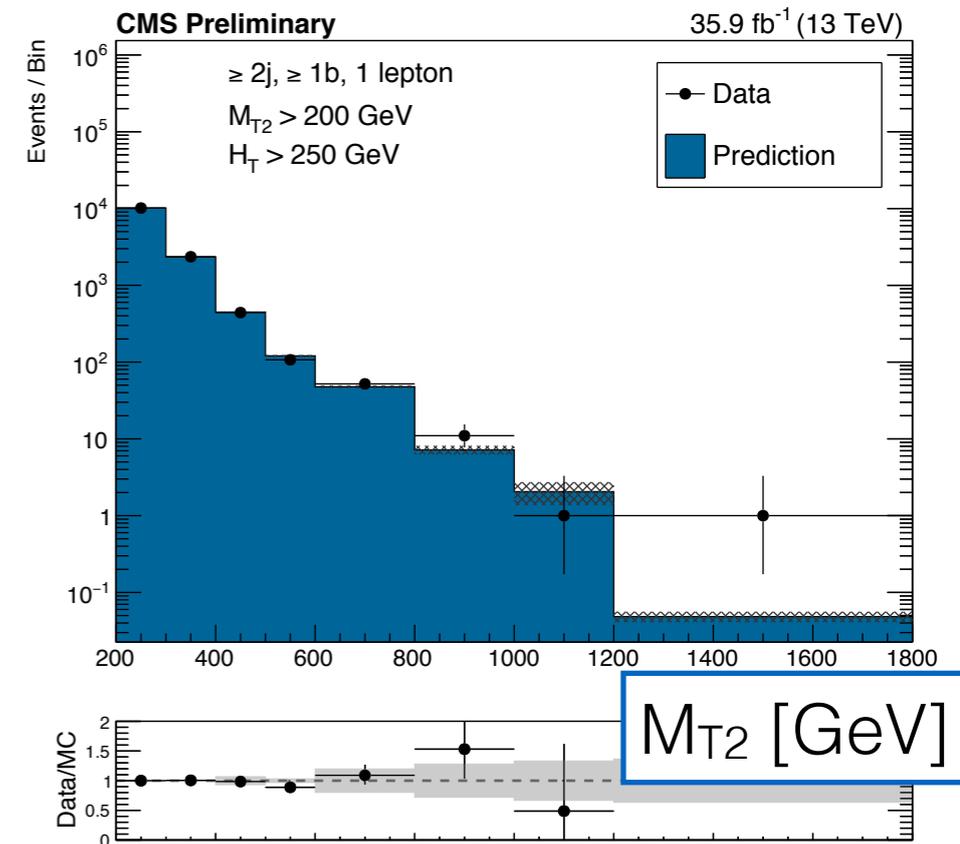

H$_T$ + H$_T^{miss}$ search

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Dominant backgrounds

Background events populate signal regions when they feature **signficant p_T^{miss} and hadronic activity**

1) **Leptonic W decays** in ttbar or W+jets

- "Lost" e or μ: out of acceptance, not reconstructed, not isolated
- Hadronically decaying τ leptons
- Sizeable p_T^{miss} because of neutrino
- ttbar mainly contributes at large N_{jet} and N_{bjet}
- Estimated using **single-lepton control regions** in data and simulated transfer factors that are validated in data

CMS Preliminary   35.9 fb^{-1} (13 TeV)

≥ 2j, ≥ 1b, 1 lepton
M_{T2} > 200 GeV
H_T > 250 GeV

- Data
- Prediction

Events / Bin

Data/MC

M_{T2} [GeV]

CMS *Simulation*   35.9 fb^{-1} (13 TeV)

N_{jet} = 2   3 ≤ N_{jet} ≤ 4   5 ≤ N_{jet} ≤ 6   7 ≤ N_{jet} ≤ 8 N_{jet} ≥ 9

N_{b-jet} 0   1   2   0   1   2   ≥ 3

Lost-lepton background
- Direct from simulation
- Treat simulation like data

Events

$\frac{Direct}{Prediction}$

Search region bin number

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Dominant backgrounds

2) **Z(νν)+jets**

- Sizeable p_T^{miss} because of neutrinos
- Mainly contributes at low N_{bjet}
- Estimated using **dilepton and photon+jets control regions**, based on similarity between Z(νν), Z(ll), photon+jets processes
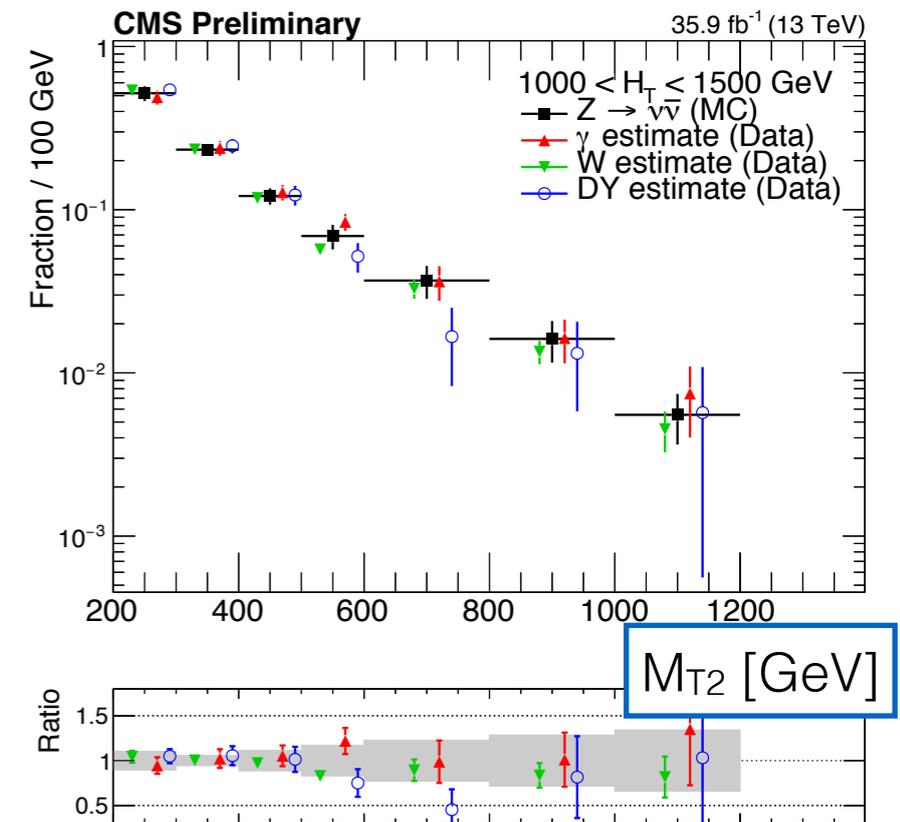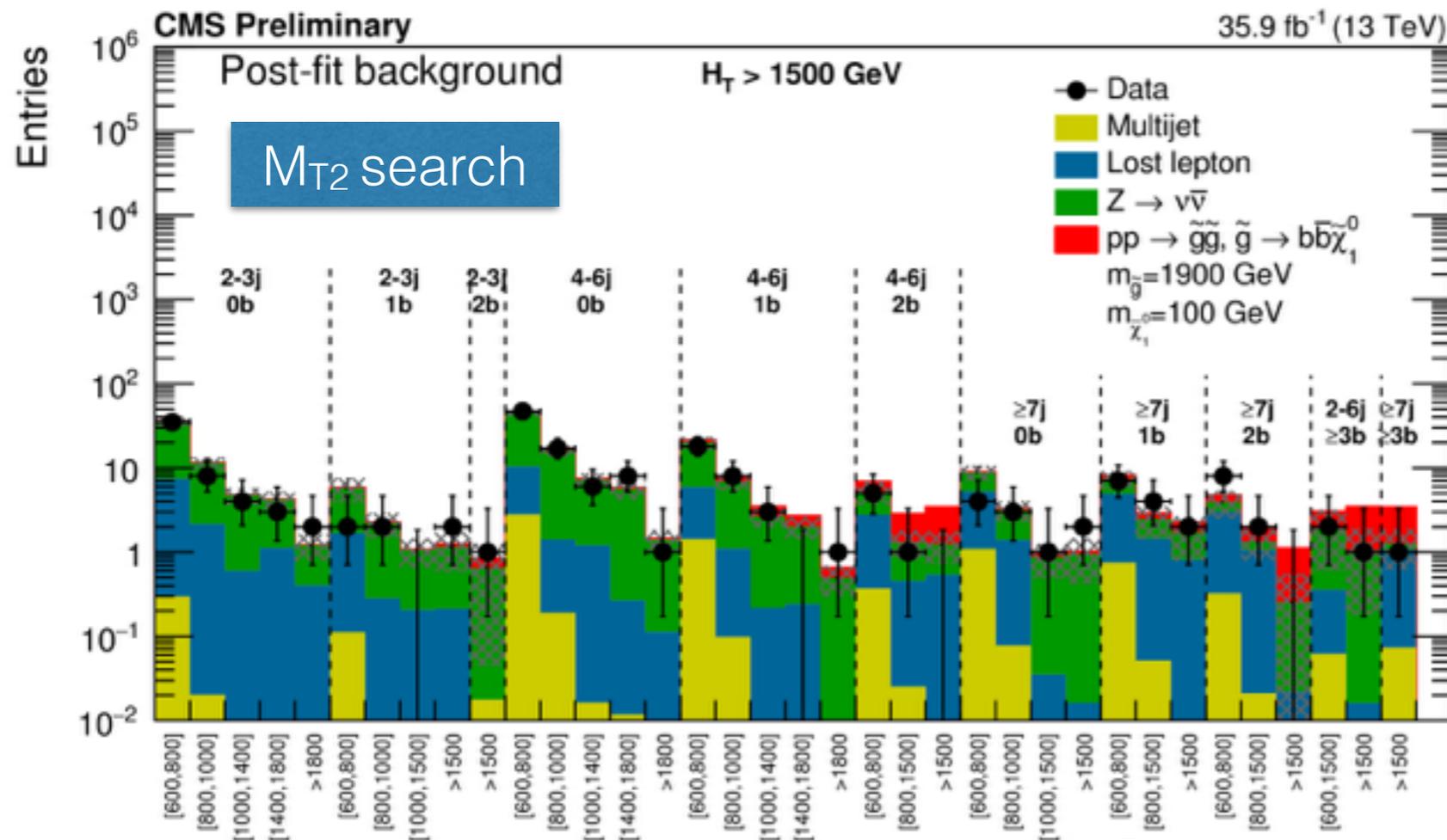
3) **QCD multijet** with mismeasured jet energies

- Traditionally estimated using **inverted-Δφ control samples** in data and translation factors between low and high Δφ
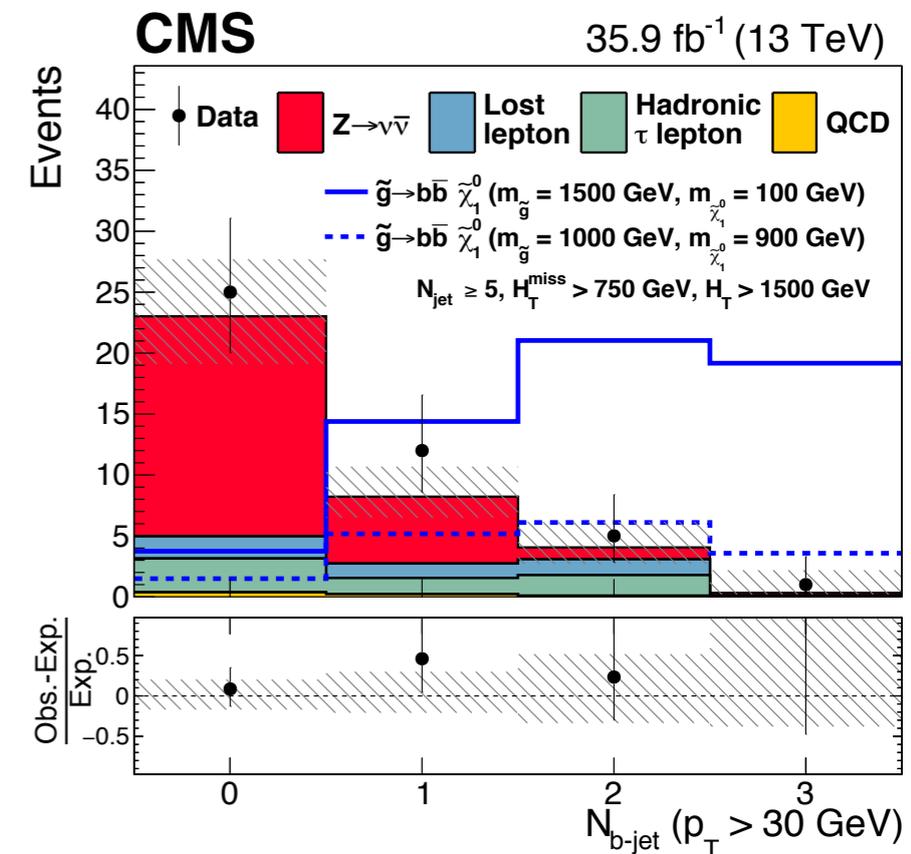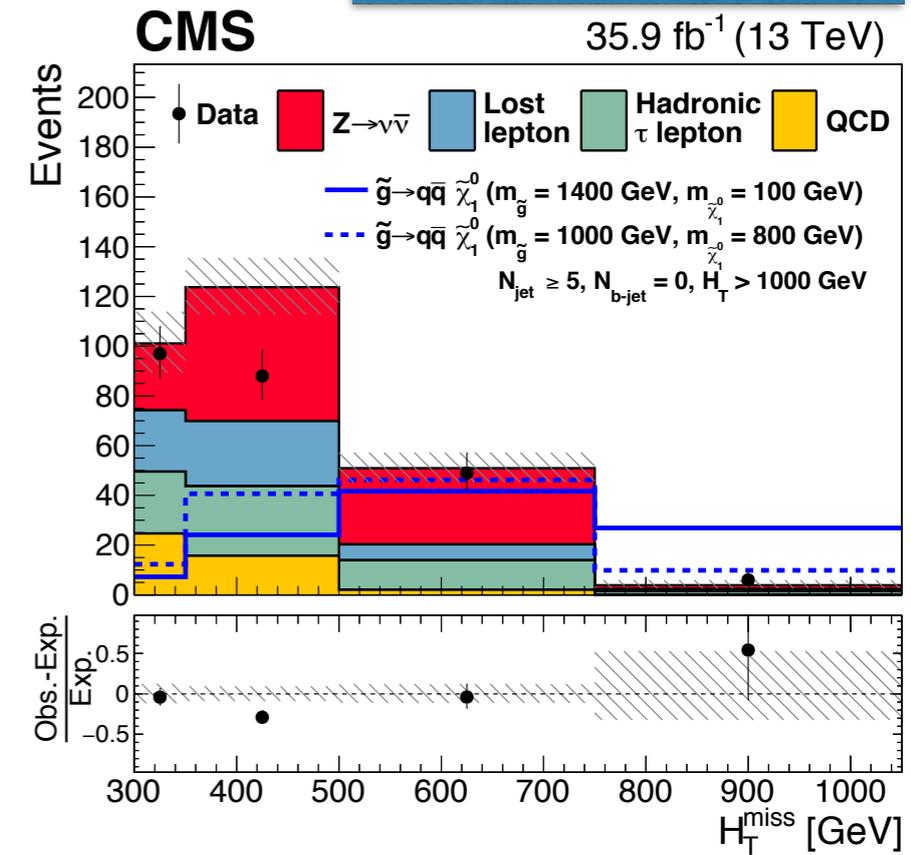- $H_T + H_T^{miss}$ search uses new approach: "**rebalance & smear**"
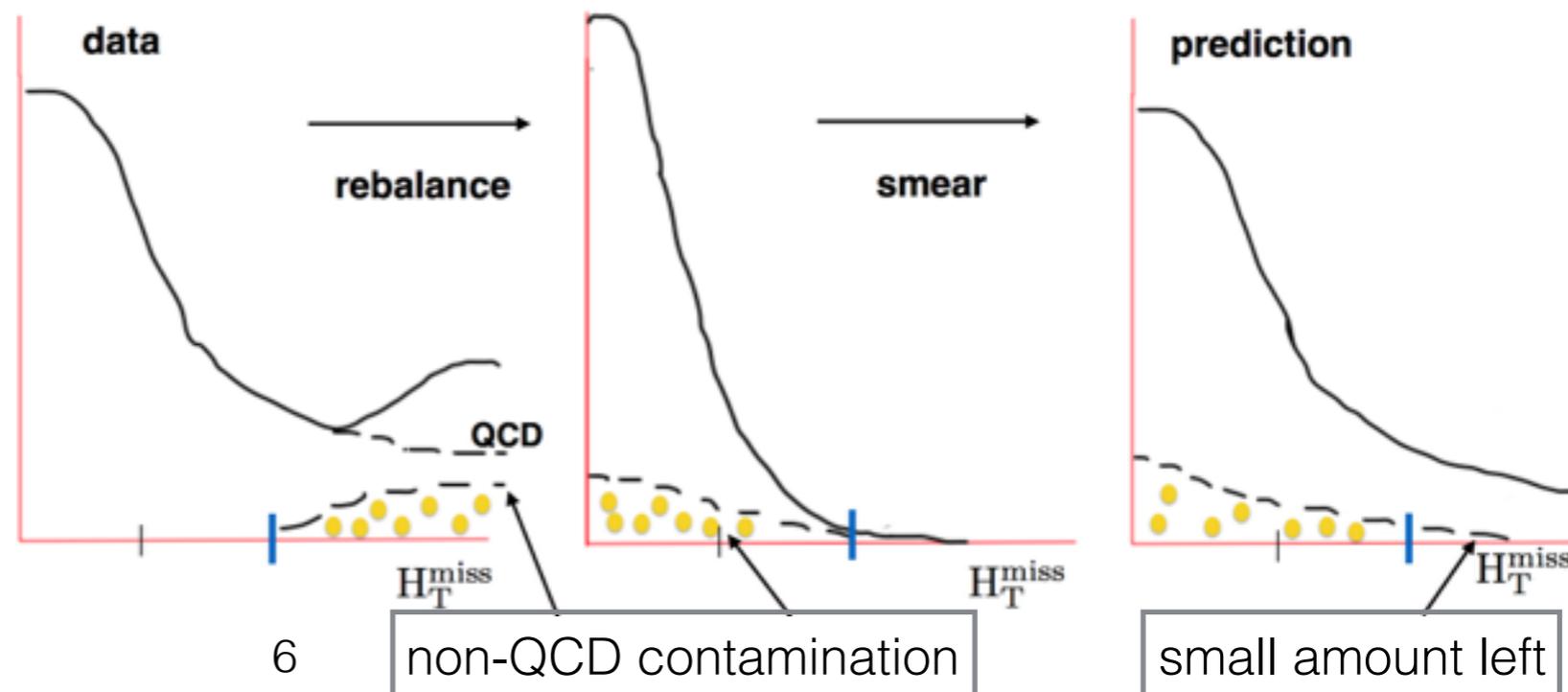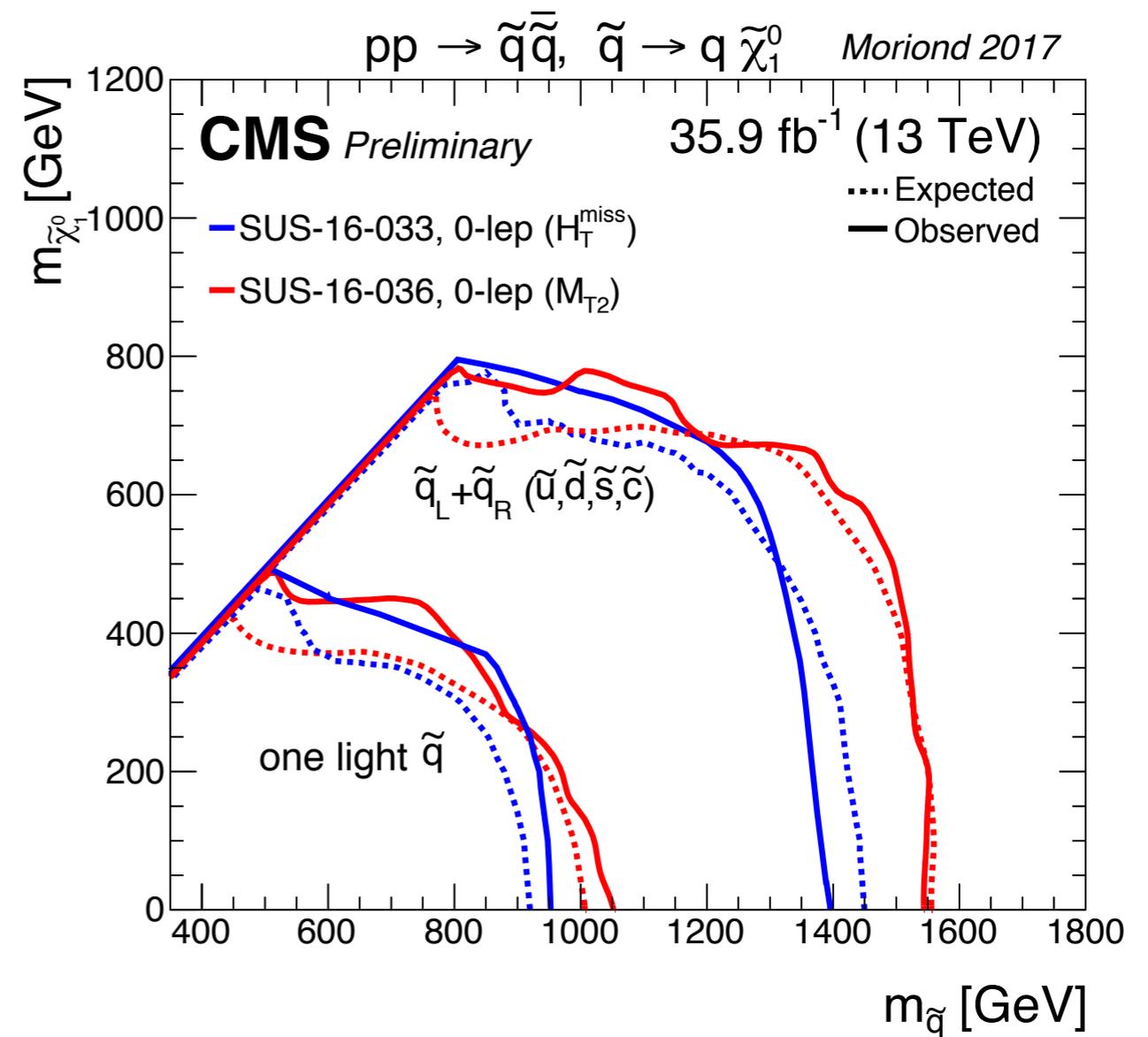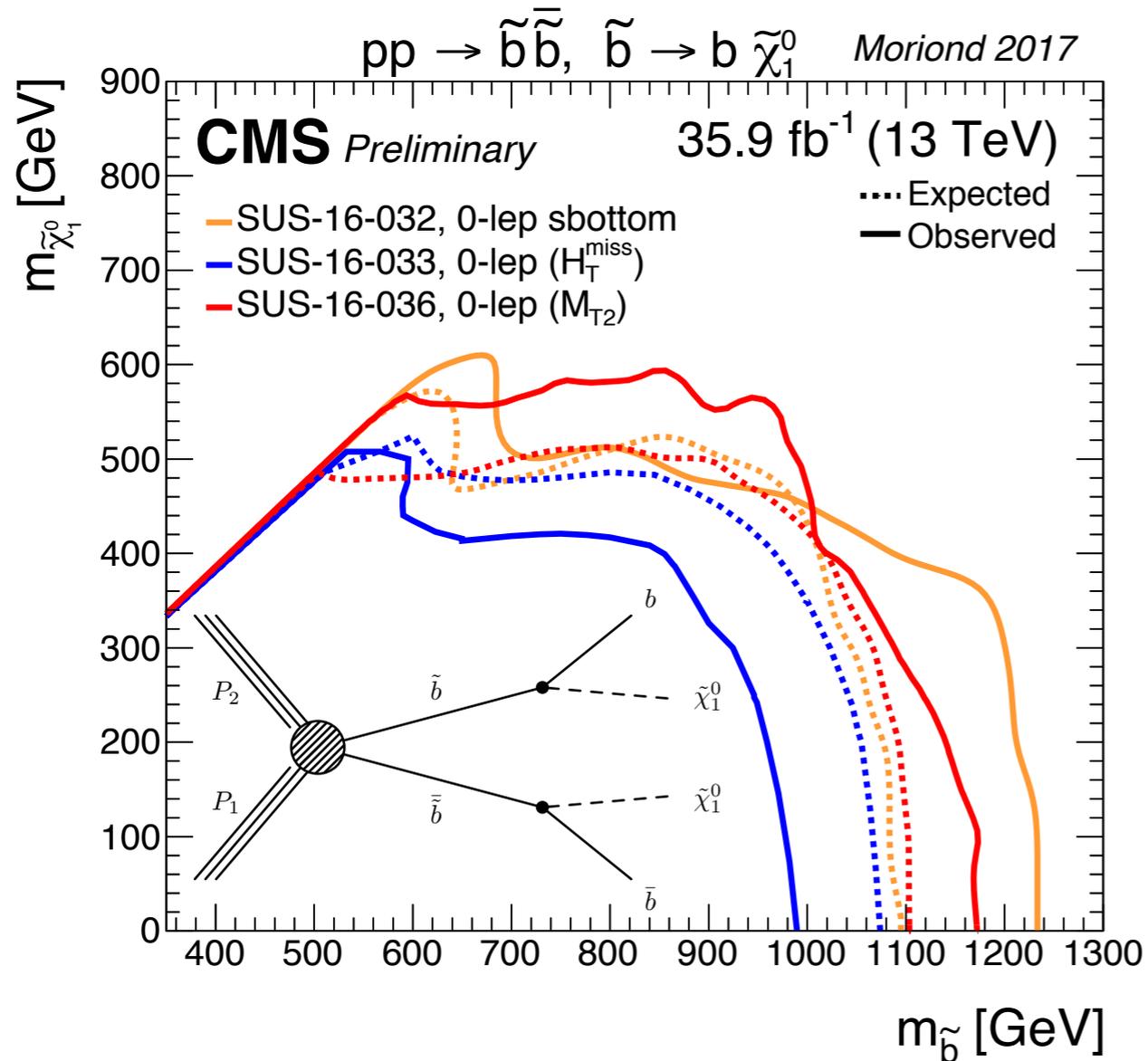
Results

- Unfortunately, **background predictions agree well with the observed data**

- Searches also provide small number of **aggregate search bins** to help our theory colleagues with the interpretation of our results

- All data including correlations will go on HEPdata

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Interpretation - Squarks

$pp \rightarrow \tilde{b}\bar{\tilde{b}}, \; \tilde{b} \rightarrow b \, \tilde{\chi}_1^0$ *Moriond 2017*

CMS *Preliminary*   35.9 fb^{-1} (13 TeV)

- SUS-16-032, 0-lep sbottom
- SUS-16-033, 0-lep (H_T^{miss})
- SUS-16-036, 0-lep (M_{T2})

···· Expected
— Observed

$pp \rightarrow \tilde{q}\bar{\tilde{q}}, \; \tilde{q} \rightarrow q \, \tilde{\chi}_1^0$ *Moriond 2017*

CMS *Preliminary*   35.9 fb^{-1} (13 TeV)

- SUS-16-033, 0-lep (H_T^{miss})
- SUS-16-036, 0-lep (M_{T2})

$\tilde{q}_L + \tilde{q}_R$ ($\tilde{u}, \tilde{d}, \tilde{s}, \tilde{c}$)

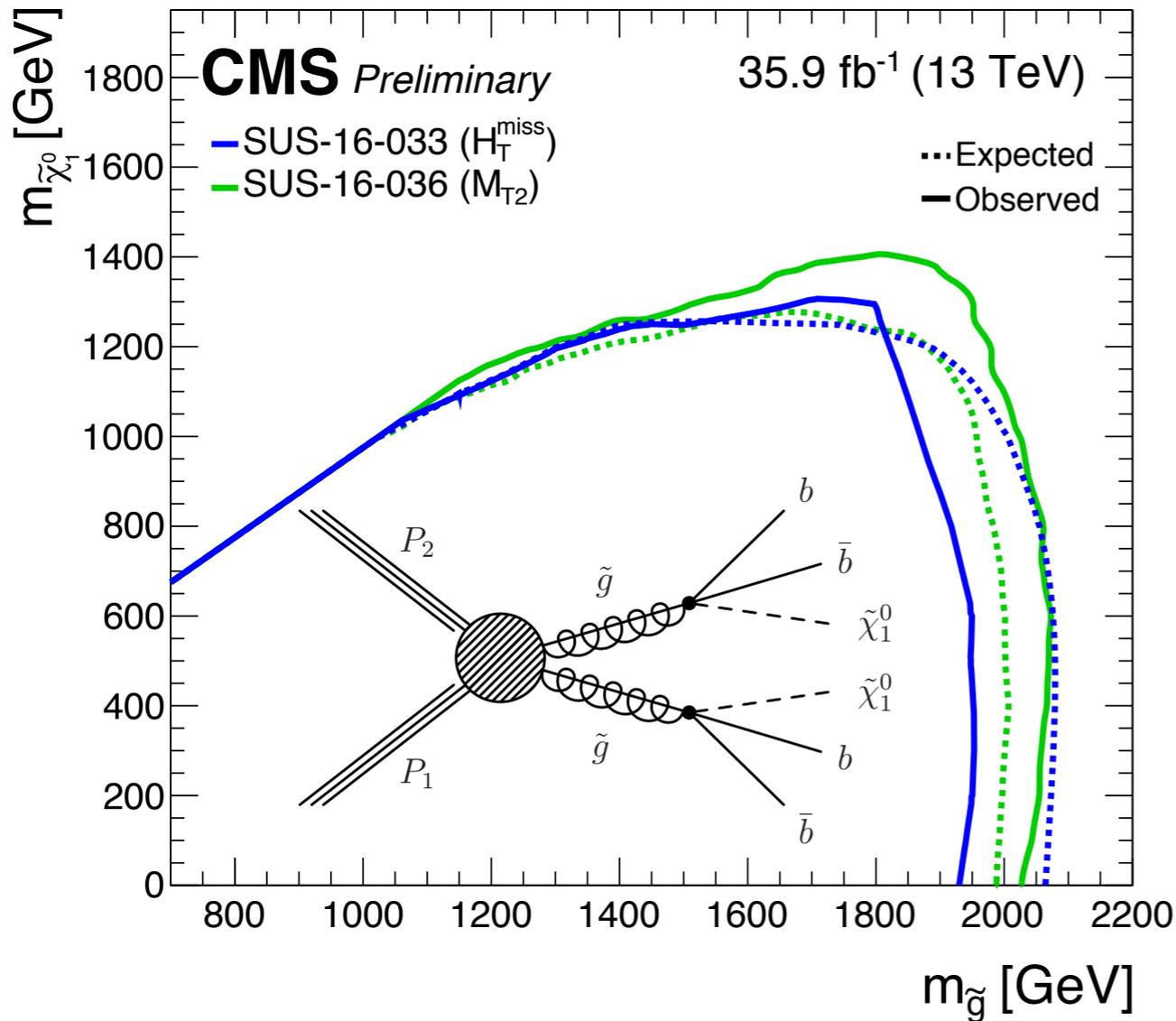one light $\tilde{q}$

SMS exclusion now extends beyond **1 TeV** for direct sbottom and squark production, with neutralino mass < 500 GeV.

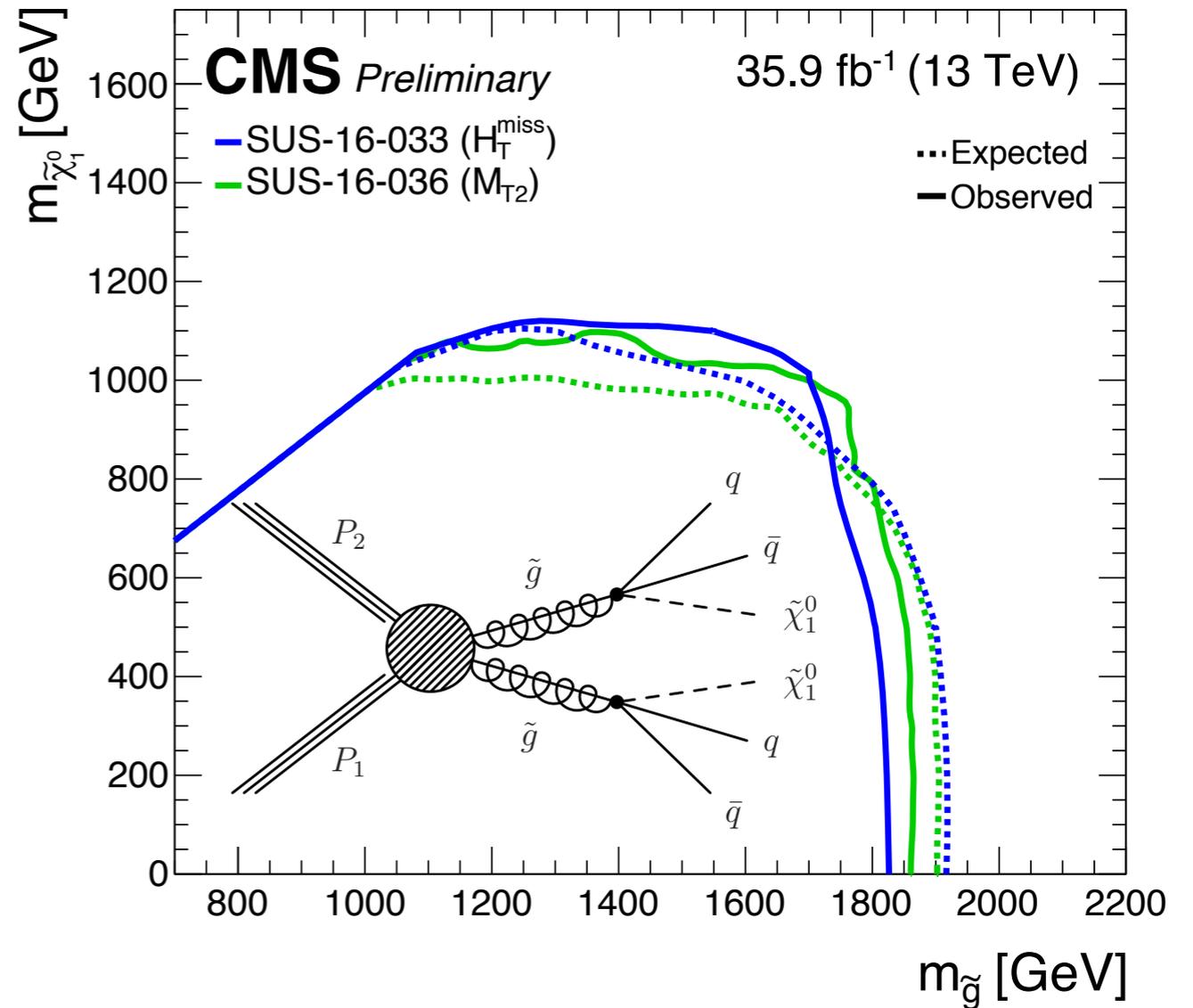H_T^{miss} is expected to have better sensitivity near the diagonal compared to M_{T2}.

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arXiv:1605.01416

Interpretation - Gluino

SMS exclusion around **2 TeV** for gluino production with decays to light or bottom quarks, for neutralino mass < 1.2 TeV.

NEW

SUSY with top tagging

- Newly released fully-hadronic analysis uses **top quark tagging to increase sensitivity to final states with top quarks**

- SUSY events can have multiple top quarks of varying p_T

- Top tagger has **high efficiency for wide range of top quark p_T** and can tag **any number of top quarks** per event

- Uses fat jets for merged top quark tagging

- Uses machine learning techniques to reduce fake rate for low-p_T "resolved" top quarks

See talk by Z. Wu for details

Resolved — 3 jets | Intermediate — 2 jets | Merged — 1 jet

Low p_T High p_T
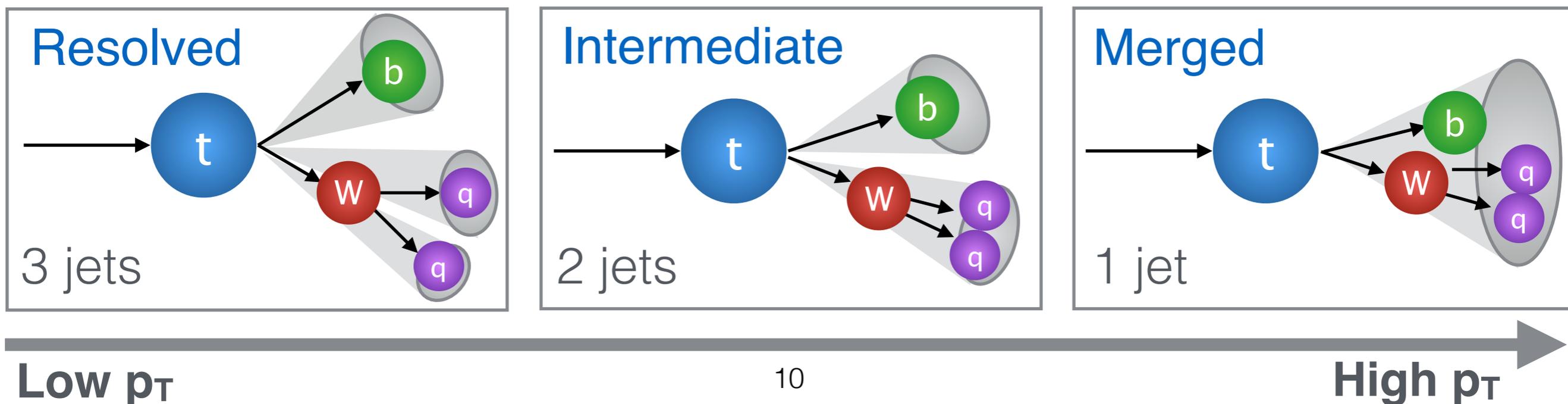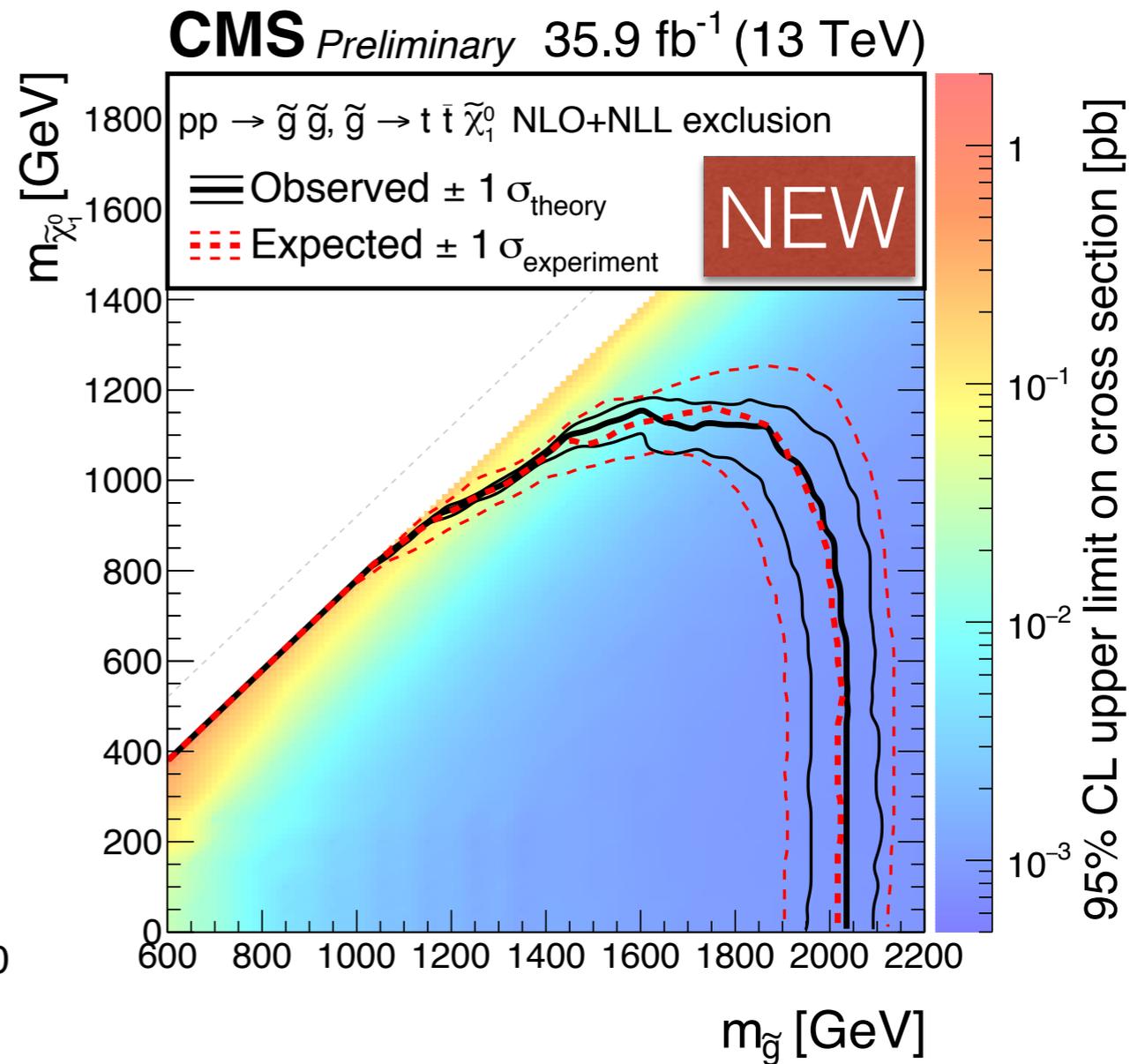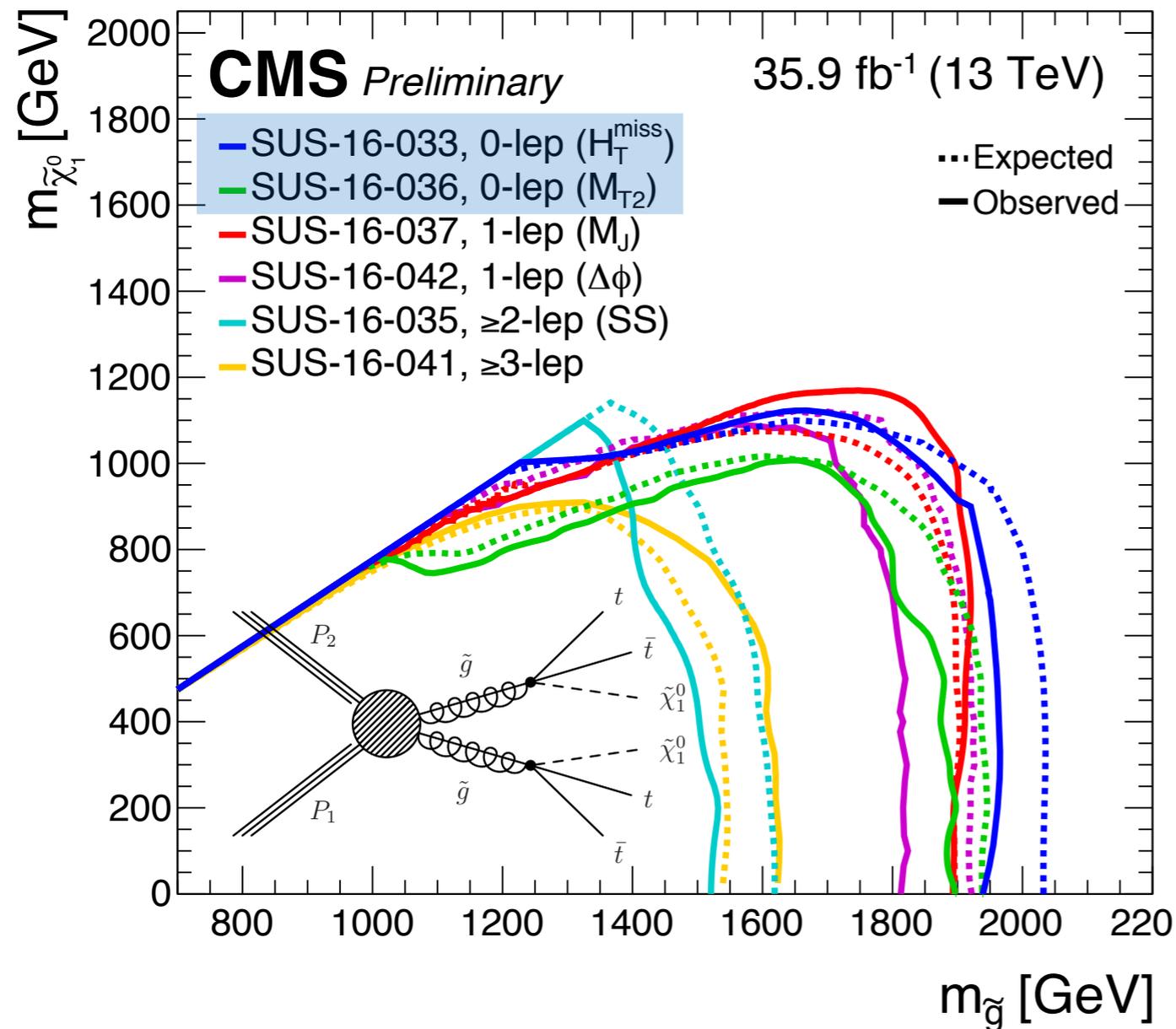
Top tagging

- Gluino mass reach up to **2 TeV** for gluino to ttbar + neutralino decays
- Top tagging increases the reach at high neutralino mass by suppressing background in low p_T^{miss} region, and helps characterize the signal, if observed

hh + p_T^{miss}

- **Reconstruct two h→bb candidates** in events with 4 or 5 jets, 0 leptons, $p_T^{miss} > 150$ GeV

  - Use 4 jets with highest b jet probability (using new DeepCSV b-tagging algorithm)

  - Minimize $\Delta m = |m_{h1} - m_{h2}|$

  - Calculate average Higgs mass $\langle m \rangle$

- Signal regions: **3b and 4b categories**

  - 4 signal **bins in p_T^{miss}** each

  - Higgs candidates with similar mass: $\Delta m < 40$ GeV

  - 100 < average mass < 140 GeV

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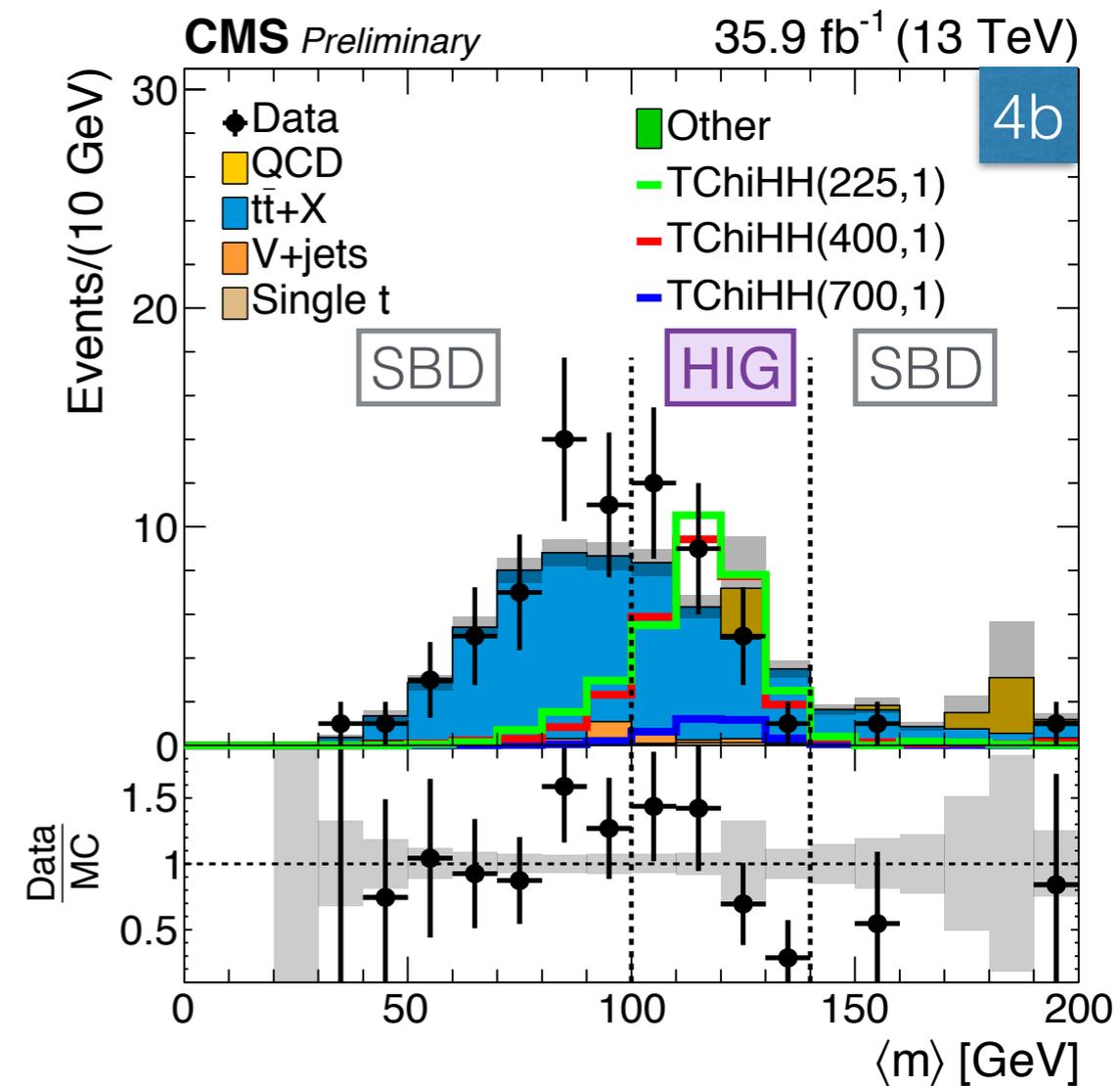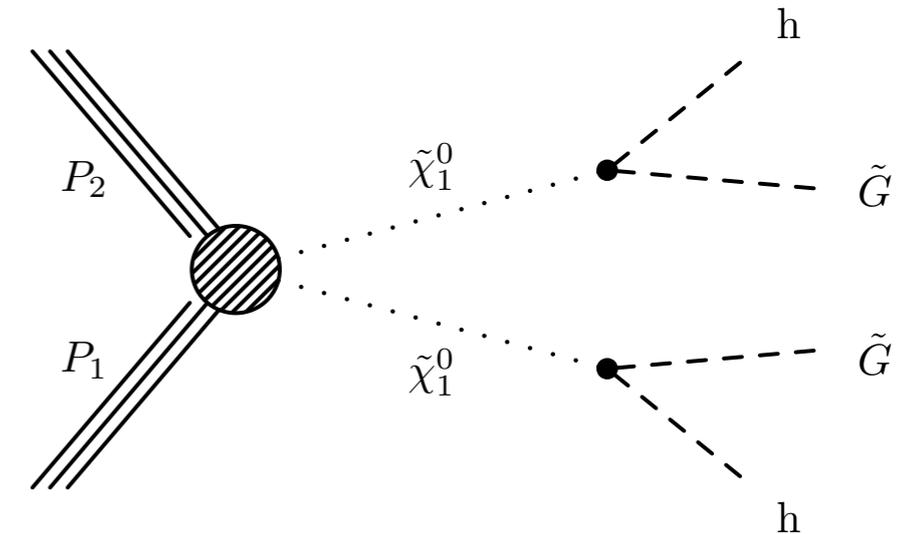
hh + p_T^{miss}

- Main backgrounds: ttbar and Z→vv+jets

- Most of the SM background has at most 2 b quarks, so additional b-tags are mostly fake → **<m> shape is independent of N_b**

- **Measure <m> shape in 2b sample and extrapolate shape to 3b and 4b categories**, separately for each p_T^{miss} bin

$$N_{3b}^{HIG} = N_{3b}^{SBD} \times \frac{N_{2b}^{HIG}}{N_{2b}^{SBD}}$$

- Validated with 1-lepton, 2-lepton, low-Δφ control regions

- **Exclude Higgsino masses between 225 and 770 GeV** for 4 degenerate Higgsinos decaying to h+goldstino

CMS *Preliminary*   35.9 fb⁻¹ (13 TeV)

$pp \rightarrow \widetilde{\chi}_i^{0,\pm} \widetilde{\chi}_j^{0,\mp} \rightarrow \widetilde{\chi}_1^0 \widetilde{\chi}_1^0 + X_{soft} \rightarrow hh\widetilde{G}\widetilde{G} + X_{soft}$

$m_{\widetilde{\chi}_2^0} \approx m_{\widetilde{\chi}_1^\pm} \approx m_{\widetilde{\chi}_1^0}, m_{\widetilde{G}} = 1$ GeV

NLO+NLL theory ± s.d.

95% CL upper limits
Observed
68% expected
95% expected

σ × BF(hh → bbbb) [fb]

Higgsino mass $m_{\widetilde{\chi}_1^0}$ [GeV]
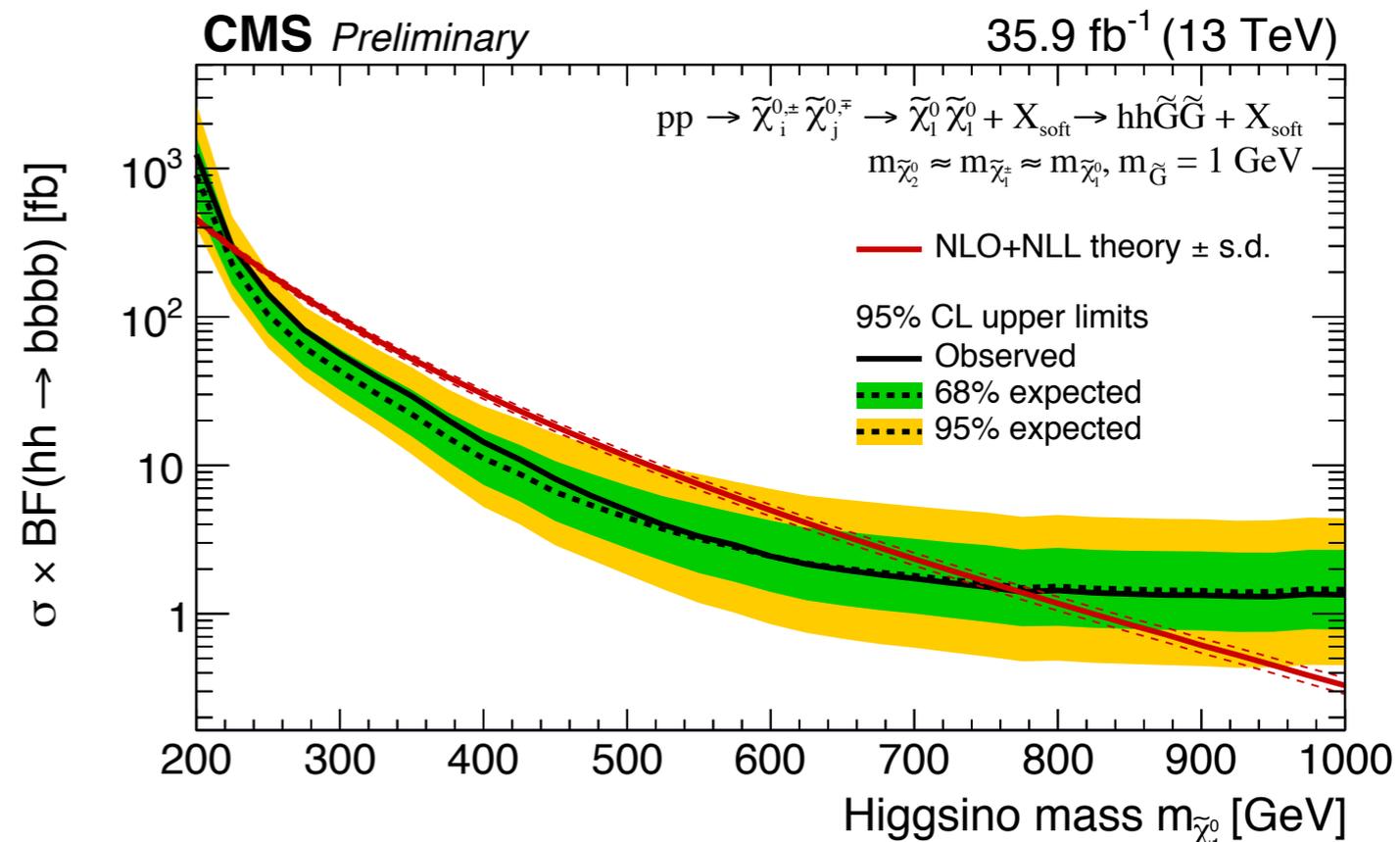
Summary

- Fully-hadronic SUSY analyses are sensitive to wide range of models and signal topologies

- Sensitivity can be further increased by tagging more complex objects such as top quarks or Higgs bosons

- No significant excess observed in the full 2016 dataset

- Gluinos excluded up to masses of about 2 TeV
  Squarks excluded up to masses of about 1 TeV
  (keeping usual caveats wrt simplified models in mind)

Questions?

H$_T$ + H$_T^{miss}$ search
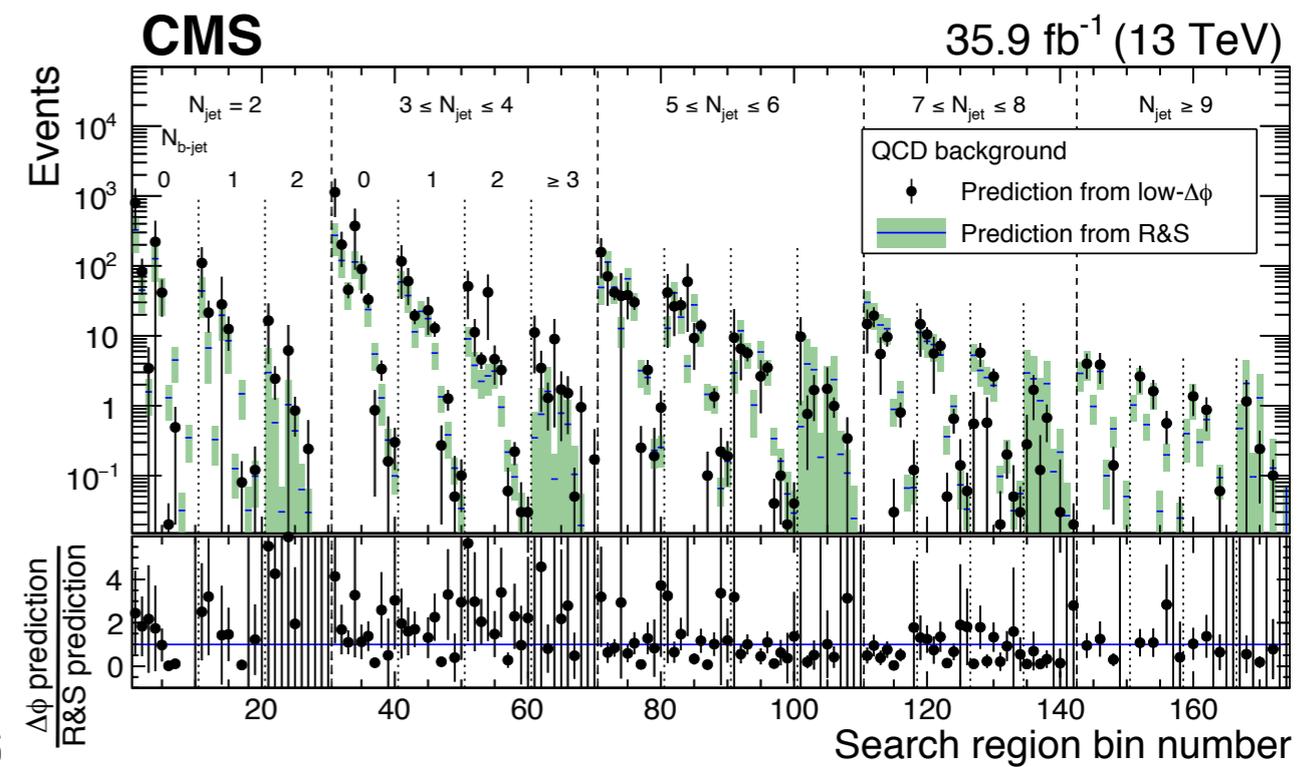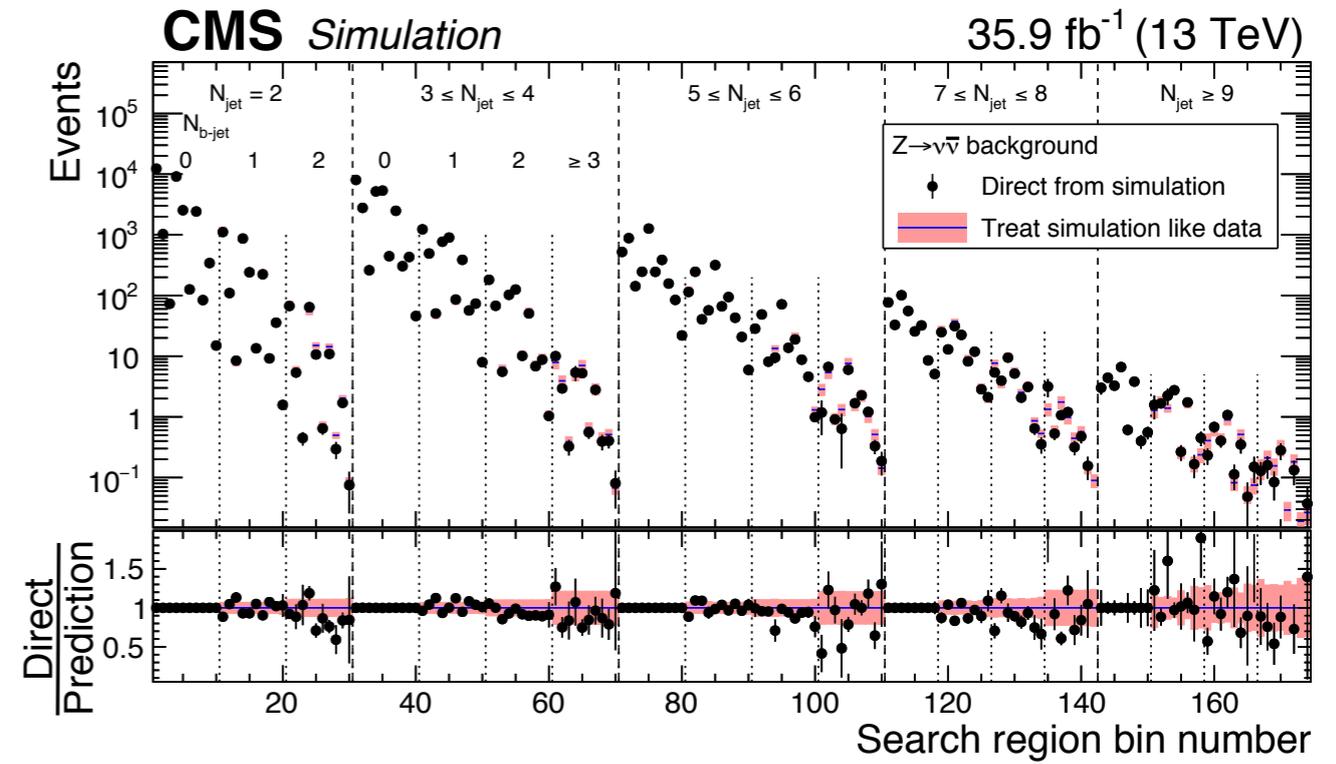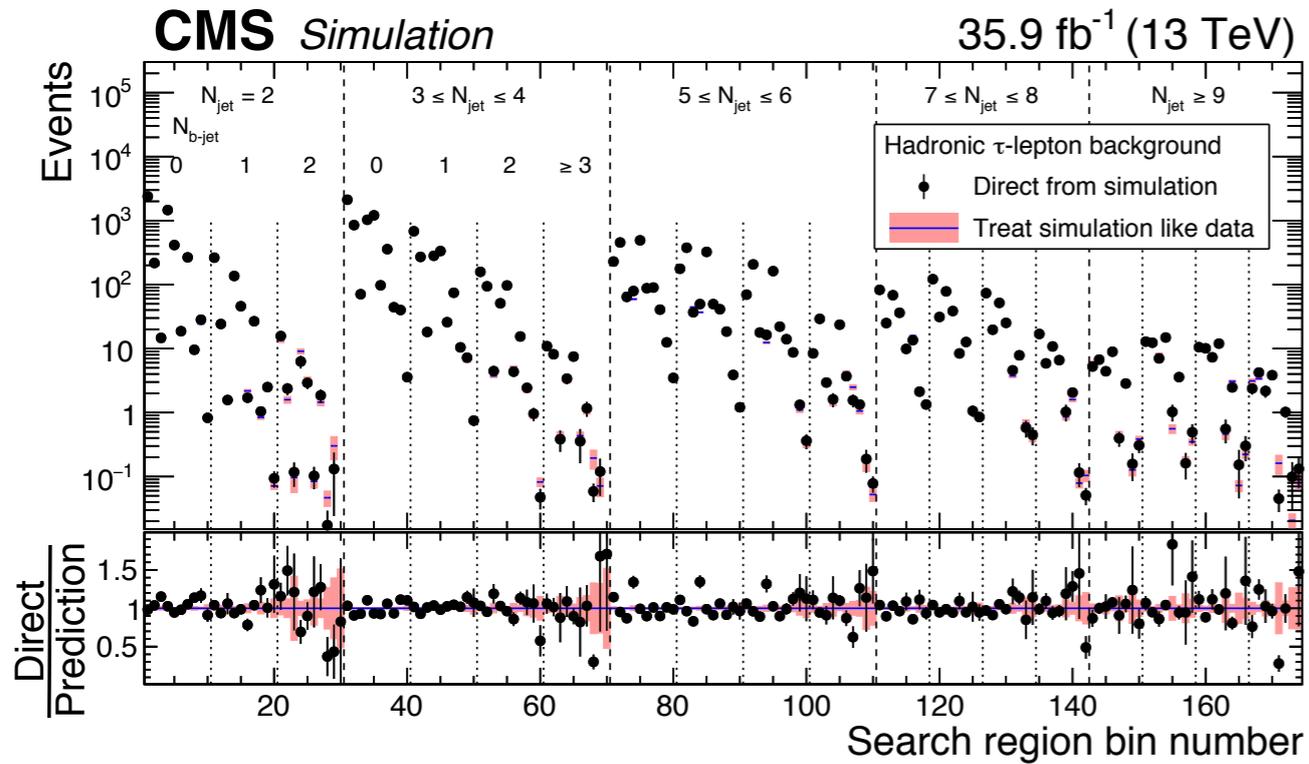
Closure tests for other
background estimations

$H_T + H_T^{miss}$ search

H$_T$ + H$_T^{miss}$ search

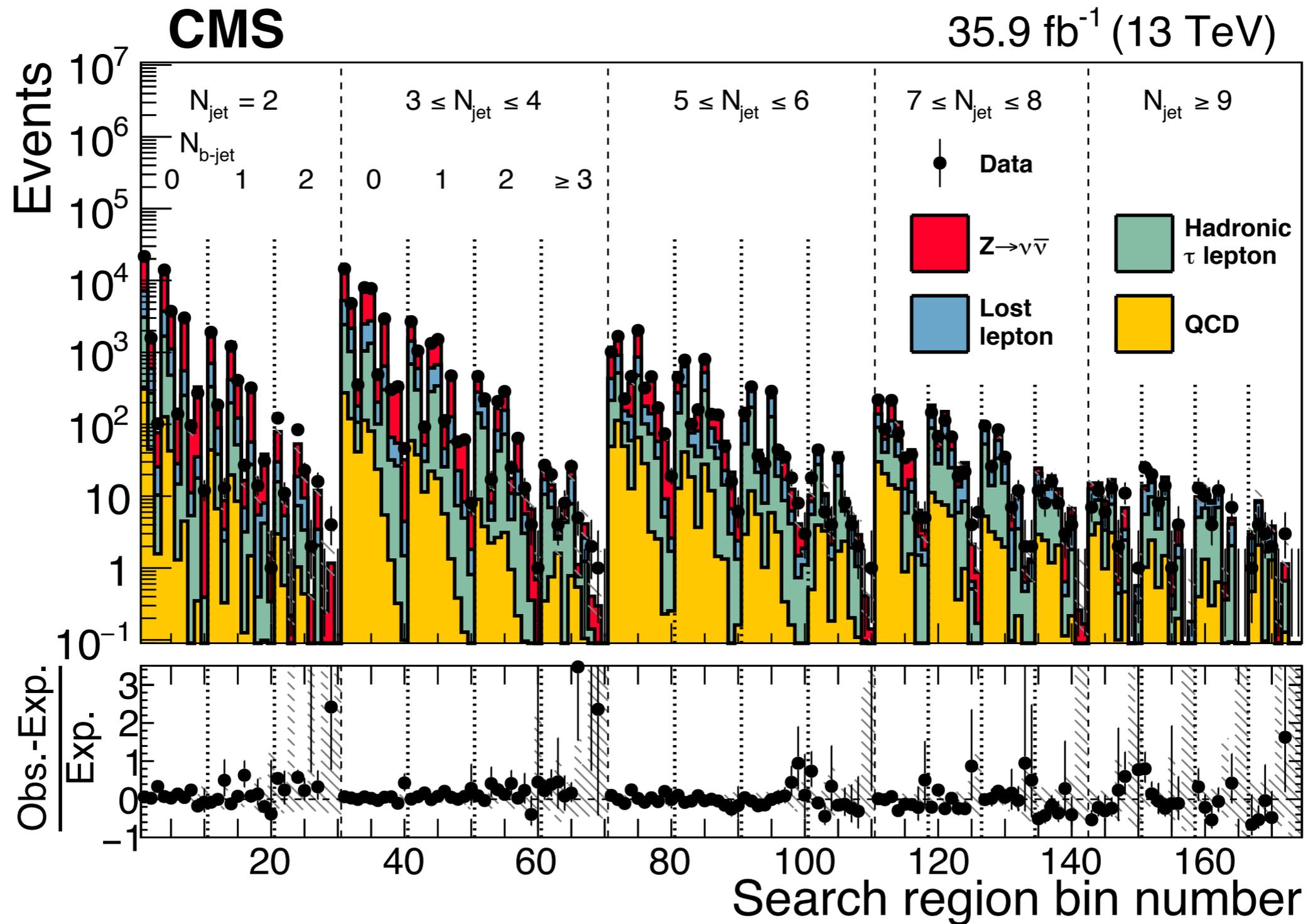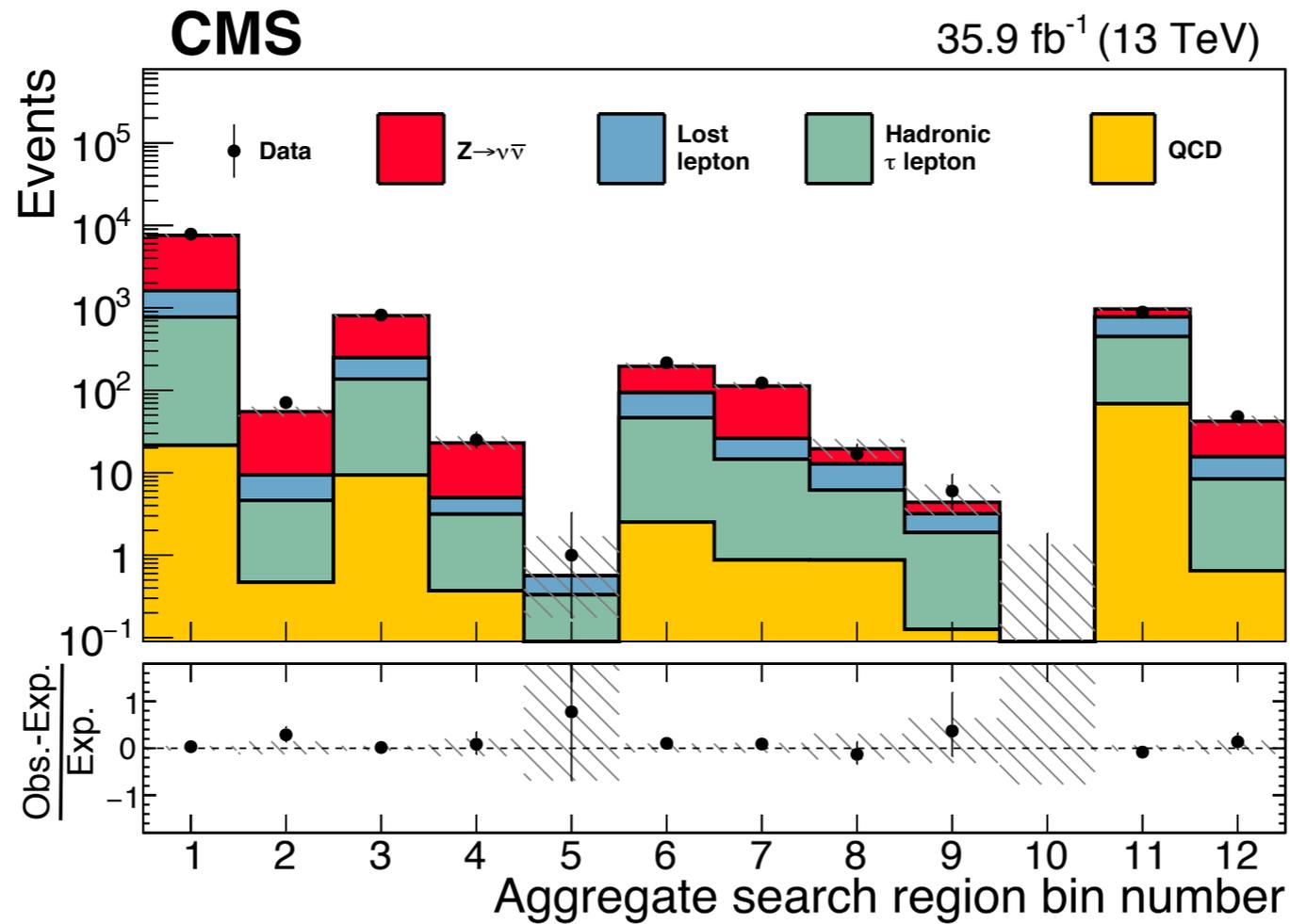| Region	N_{jet}	$N_{b\text{-}jet}$	H_T [GeV]	H_T^{miss} [GeV]	Parton multiplicity	Heavy flavor ?	Δm
1	≥ 2	0	≥ 500	≥ 500	Low	No	Small
2	≥ 3	0	≥ 1500	≥ 750	Low	No	Large
3	≥ 5	0	≥ 500	≥ 500	Medium	No	Small
4	≥ 5	0	≥ 1500	≥ 750	Medium	No	Large
5	≥ 9	0	≥ 1500	≥ 750	High	No	All
6	≥ 2	≥ 2	≥ 500	≥ 500	Low	Yes	Small
7	≥ 3	≥ 1	≥ 750	≥ 750	Low	Yes	Large
8	≥ 5	≥ 3	≥ 500	≥ 500	Medium	Yes	Small
9	≥ 5	≥ 2	≥ 1500	≥ 750	Medium	Yes	Large
10	≥ 9	≥ 3	≥ 750	≥ 750	High	Yes	All
11	≥ 7	≥ 1	≥ 300	≥ 300	Medium high	Yes	Small
12	≥ 5	≥ 1	≥ 750	≥ 750	Medium	Yes	Large

M$_{T2}$ search

Super signal regions (aka aggregate search bins)

Region	N_j	N_b	H_T [GeV]	M_{T2} [GeV]	Prediction	Data	N_{95}^{obs}
2j loose	≥ 2	–	> 1000	> 1200	38.9 ± 11.2	42	26.6–27.8
2j tight	≥ 2	–	> 1500	> 1400	2.9 ± 1.3	4	6.5–6.7
4j loose	≥ 4	–	> 1000	> 1000	19.4 ± 5.8	21	15.8–16.4
4j tight	≥ 4	–	> 1500	> 1400	2.1 ± 0.9	2	4.4–4.6
7j loose	≥ 7	–	> 1000	> 600	$23.5^{+5.9}_{-5.6}$	27	18.0–18.7
7j tight	≥ 7	–	> 1500	> 800	$3.1^{+1.7}_{-1.4}$	5	7.6–7.9
2b loose	≥ 2	≥ 2	> 1000	> 600	$12.9^{+2.9}_{-2.6}$	16	12.5–13.0
2b tight	≥ 2	≥ 2	> 1500	> 600	$5.1^{+2.7}_{-2.1}$	4	5.8–6.0
3b loose	≥ 2	≥ 3	> 1000	> 400	8.4 ± 1.8	10	9.3–9.7
3b tight	≥ 2	≥ 3	> 1500	> 400	2.0 ± 0.6	4	6.6–6.9
7j3b loose	≥ 7	≥ 3	> 1000	> 400	5.1 ± 1.5	5	6.4–6.6
7j3b tight	≥ 7	≥ 3	> 1500	> 400	0.9 ± 0.5	1	3.6–3.7

Deep CSV: btagging with deep neural networks

√s=13 TeV, 2016

CMS Simulation *Preliminary*

tt̄ events
AK4jets (p_T > 30 GeV)

CSVv2
DeepCSV
cMVAv2

udsg
c

misid. probability
b-jet efficiency