ETH Institute for Particle Physics

Search for SUSY in hadronic final states with the M_{T2} variable

Mario Masciovecchio
(ETH Zürich)

On behalf of the CMS Collaboration

4th July 2016

SUSY 2016, Melbourne (Australia)

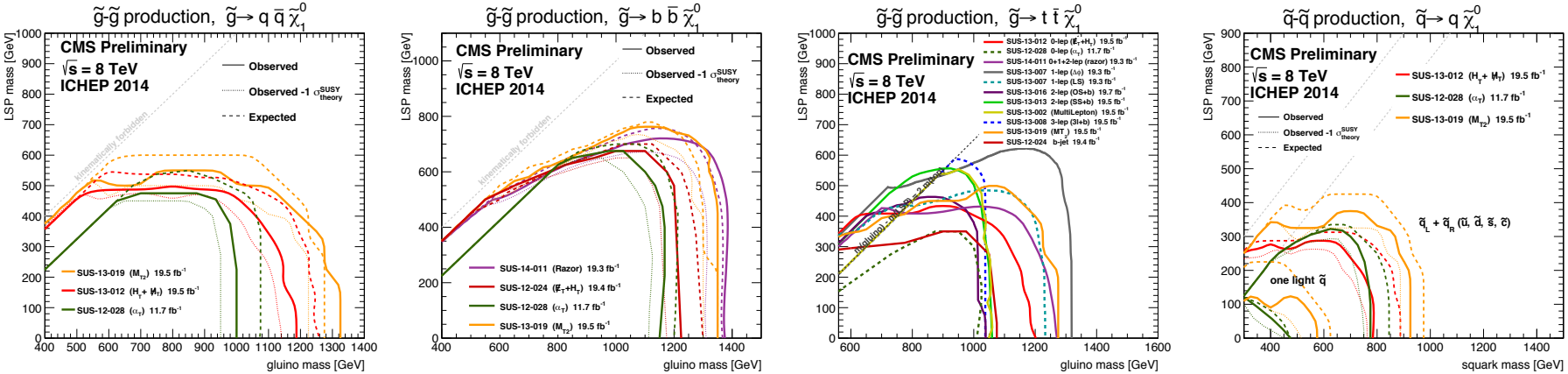
Outline

- Status and Publications
- Aim of the search
- The MT2 variable
- Search Strategy Overview
- Background Estimate Overview
- Results
- Interpretation of the Results

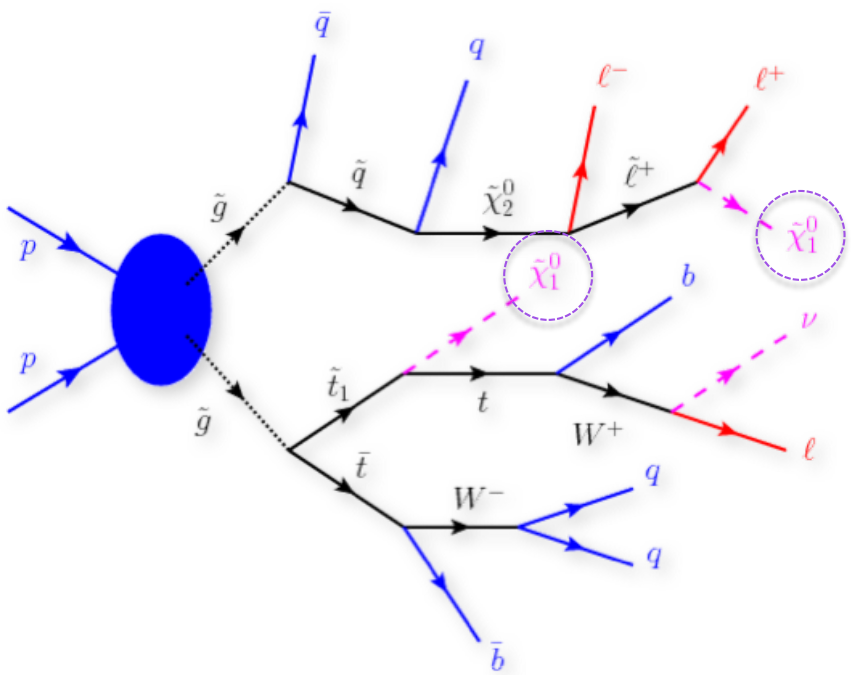
Status and Publications

- Search has been performed on 2.3/fb of 13 TeV pp collisions
  - ❖ First results public by end of 2015
  - ❖ Final results public by March 2016
    - CMS-SUS-15-003; CERN-EP-2016-067
    - Public Page
    - Paper submitted to JHEP (arXiv:1603.04053)

- Analogous searches successfully published @ 7 TeV and 8 TeV
  - 7 TeV (4.73/fb): JHEP 1210 (2012) 018
  - 8 TeV (19.5/fb): JHEP 1505 (2015) 078



Looking for SUSY



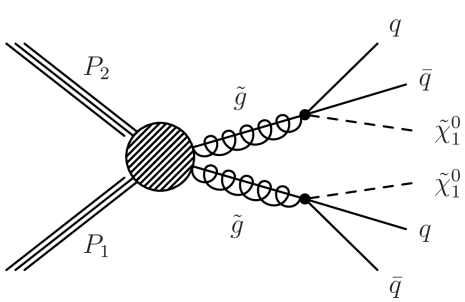
How to look for SUSY?

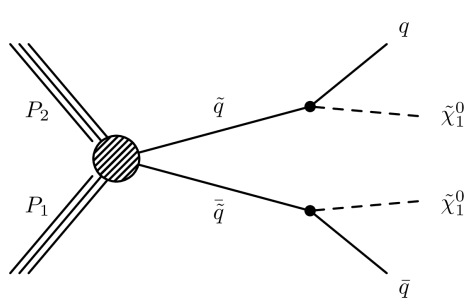
- If R-parity is conserved:
- ❖ s-particles come in pairs
- ❖ **LSP** is undetected → **ME_T**

➢ Search for events with:

- ❖ Large **ME_T**
- ❖ Large **hadronic activity**
- ❖ Low energy **leptons**

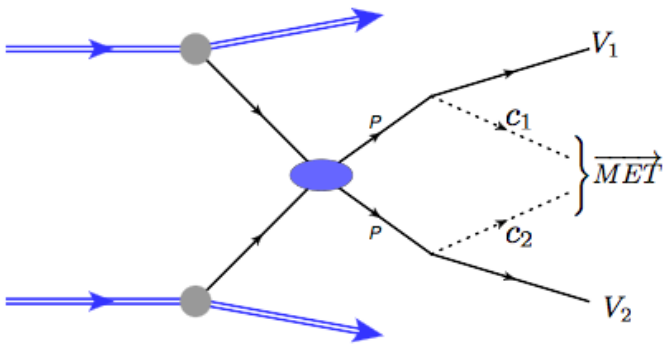
All-hadronic search
→ Lepton veto

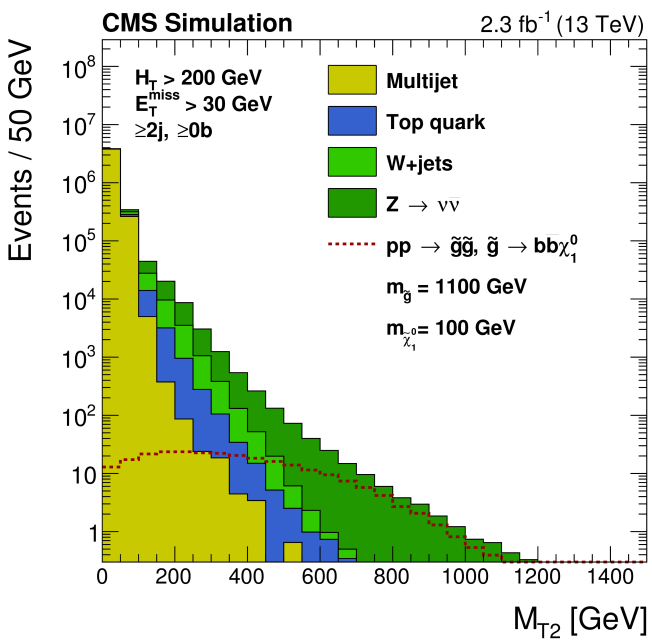




What is M_{T2}?

arXiv: hep-ph/9906349, hep-ph/0907.2713





- In case of two decay chains (visible system + ME_T), can **generalize** definition of transverse mass $\mathbf{M_T}$:

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

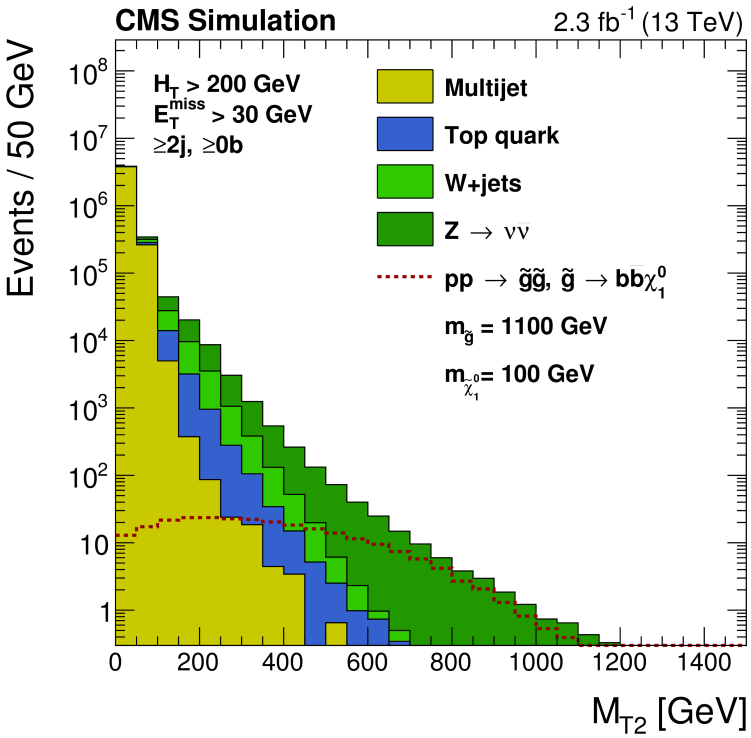
- In the hypothesis of $M_{LSP} = 0$

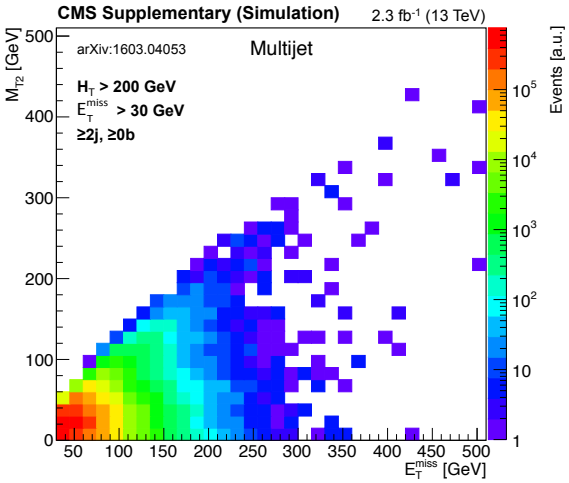
$$\boxed{M_{T2}^2 = 2p_T^{V_1}p_T^{V_2}(1+\cos\phi_{1,2})}$$

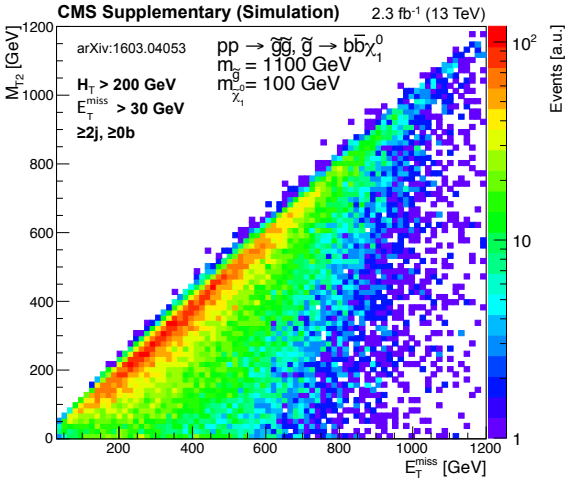
  - Depends on visible energy
  - Also on angular configuration

A bit more about M_{T2}

- M_{T2} is a powerful **discovery variable** for all-hadronic searches







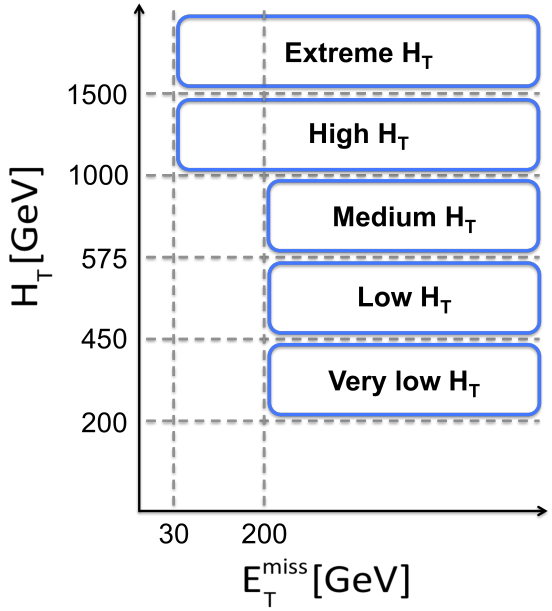
- ❖ If $\phi_{1,2} \sim \pi$, then $M_{T2} \sim 0$
  → Typical configuration of QCD multijet
- ❖ If **SUSY-like**, then $M_{T2} \lesssim ME_T$

Search Strategy Overview

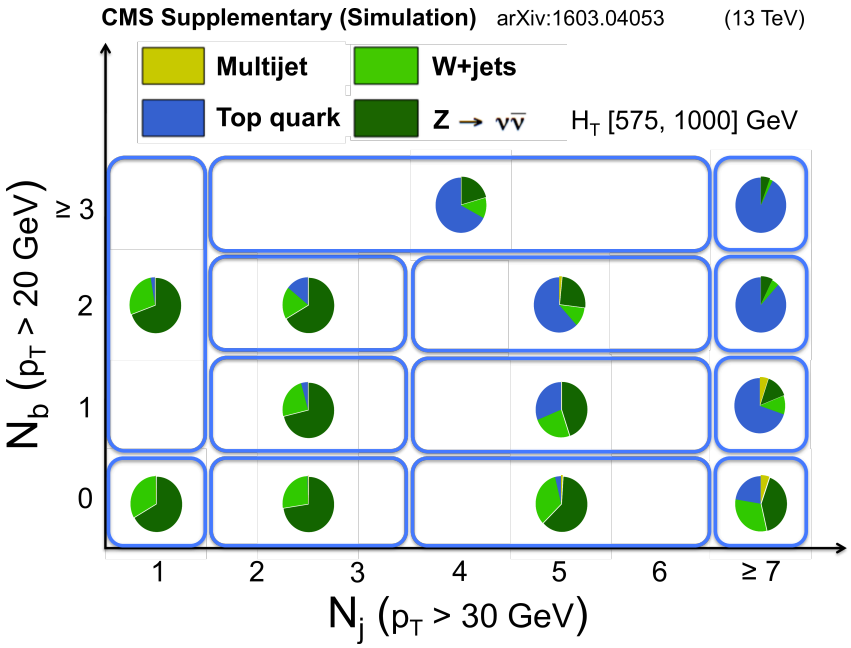
- Inclusive search for new physics in all-hadronic final states

→ Aim at covering as many signatures as possible

❖ Event categorization in **H_T + jet/b-tag multiplicity**



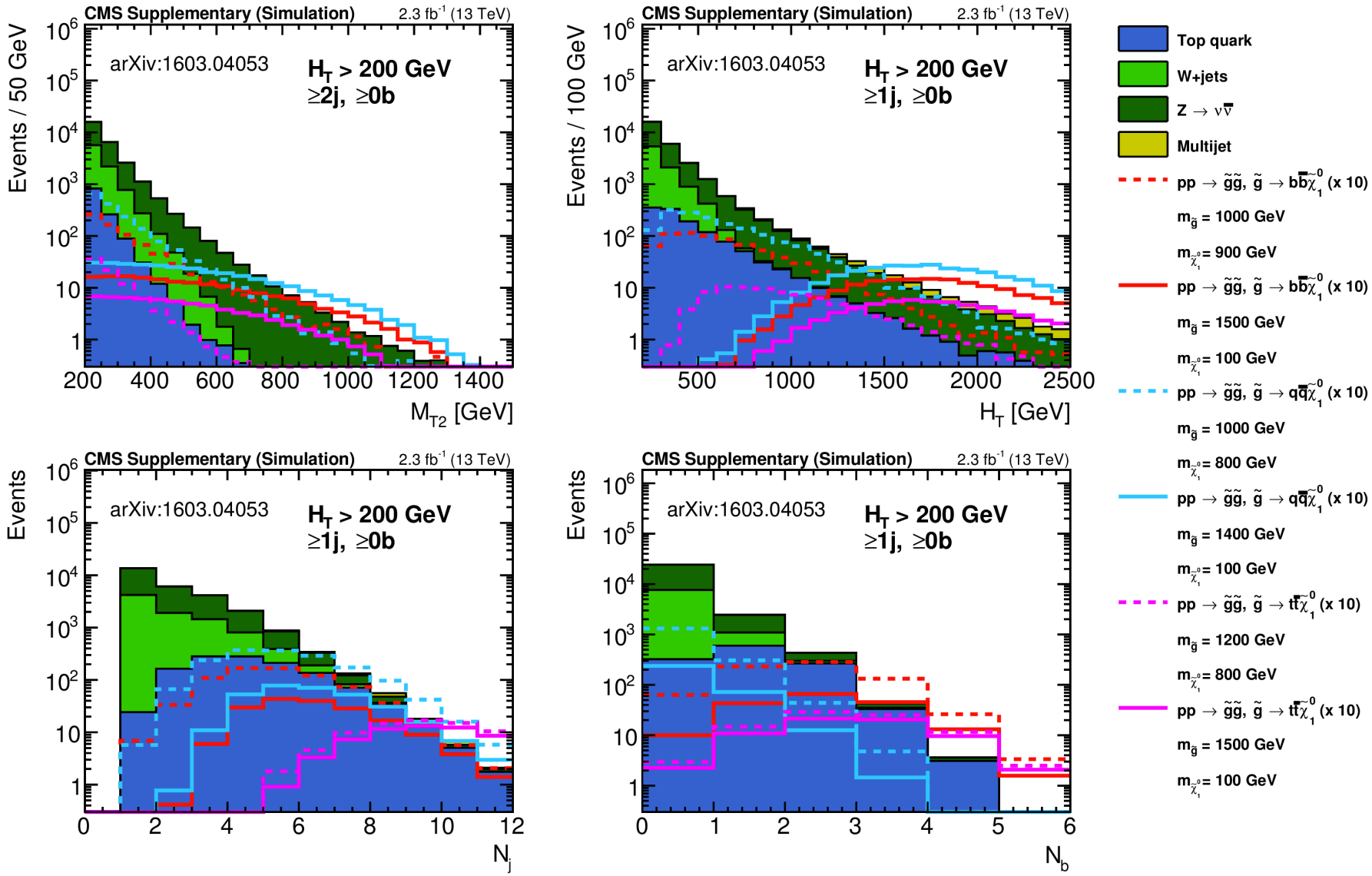
X



+ **M_{T2}** binning in each (H_T, N_j, N_b) region, from M_{T2} > 200 GeV
(for **monojet:** binning in **jet p_T**, from 200 GeV)

→ Total of **172 search bins**

A look at the kinematics



Background Overview

Background	Source	How to reject it?
Invisible Z	Real ME_T from **Z(νν)**, plus jets from radiation	Main, irreducible background, subdominant at high N_b
Lost lepton	Real ME_T from **W(lν)** – also top, with charged lepton that is lost (acceptance, isolation , or id)	Lepton veto requirement, dominant at high N_b
QCD multijet	Multijet events where **jet energy resolution** fluctuations create fake ME_T	$\Delta\phi_{min}$(4 jets, ME_T) > 0.3 $\lvert ME_T - MH_T \rvert / MET < 0.5$ M_{T2} > 200 GeV Jet ID on all jets Negligible at high M_{T2} Negligible at low H_T

The Invisible Z Estimate

- Estimate in **each (H_T, N_j, N_b) region** from identical region in **photon** dataset
  - All variables are re-computed after removing photon from event
    → Mimic Z(νν) kinematics
  - ❖ Inclusive in M_{T2}: then use Z(νν) MC to extrapolate in M_{T2} dimension

$$\boxed{N_{Z(\nu\nu)} = N_{\gamma}^{(CR)} \cdot \text{Purity} \cdot \text{fragmentation} \cdot R(Z/\gamma)}$$

Number of photons in the control region

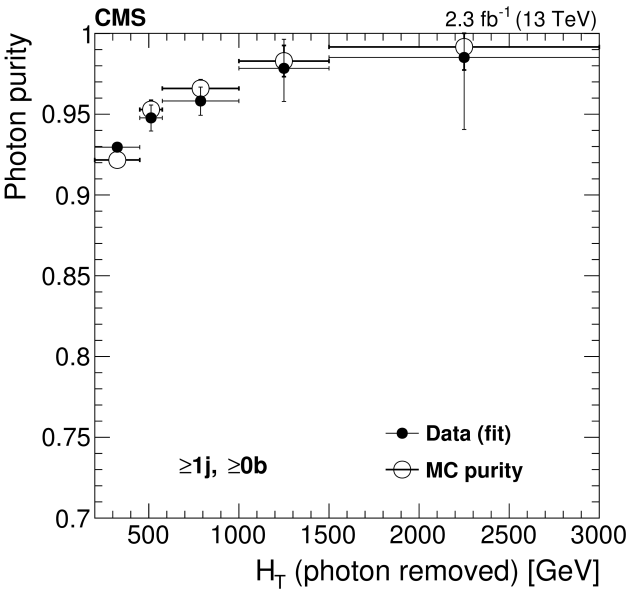
Account for fakes from meson decays (~0.95, from data)

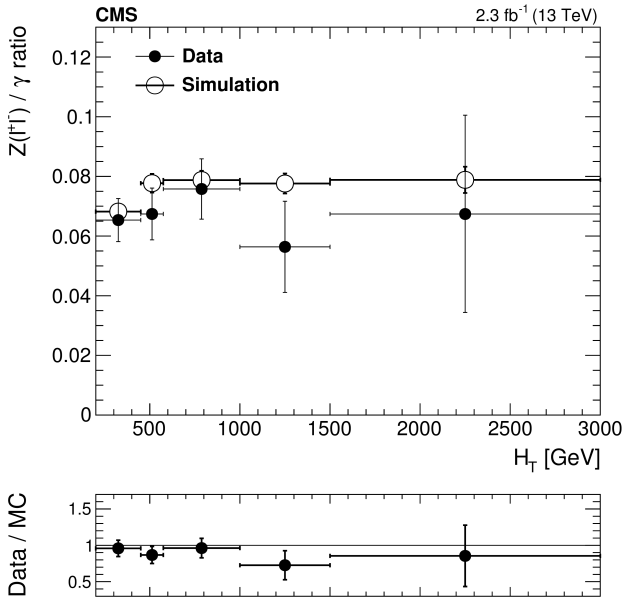
Hard photons from quark fragmentation (~0.92, from MC)

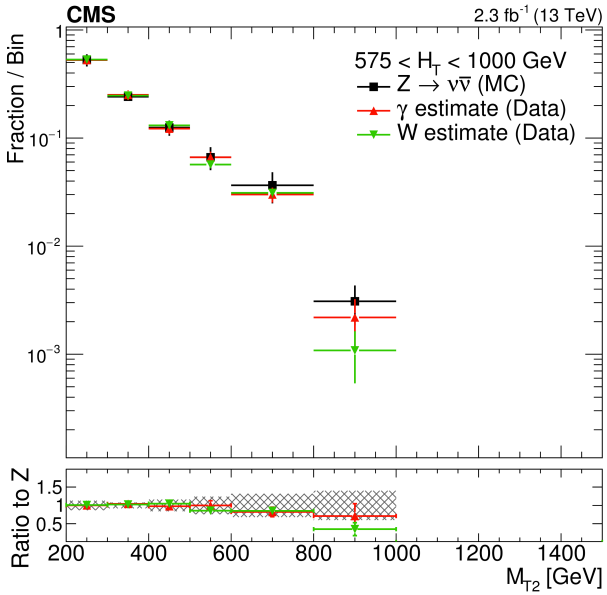
Account for different mass/couplings (from MC , validated in Z(ll) data)

The Invisible Z Ingredients

- **Photon Purity**
  - From fit to photon **data**
  - Isolation templates also from data
  - Typically ~0.95
- **Z/γ** ratio
  - Directly from **MC**
  - Validated in **Z(ll) data,** removing γ/leptons to mimic Z(νν) kinematics
- **M_{T2}** dimension
  - From Z(νν) **MC**
  - Validated in **data**
    1. **Photon** dataset
    2. **W(lν)** dataset







The Lost Lepton Estimate

- Estimate based on **single lepton (e/μ) control region**
  - ❖ Minimize **signal contamination**
  - → M_T (lepton, ME_T) < 100 GeV
  - → For regions with $N_j \geq 7$, extrapolate from $1 \leq N_b \leq 2$ to $N_b \geq 2$
  - ❖ Separately in **each (H_T, N_j, N_b) region**, inclusive in M_{T2}
  - → Use MC (top+W) to extrapolate in M_{T2} dimension

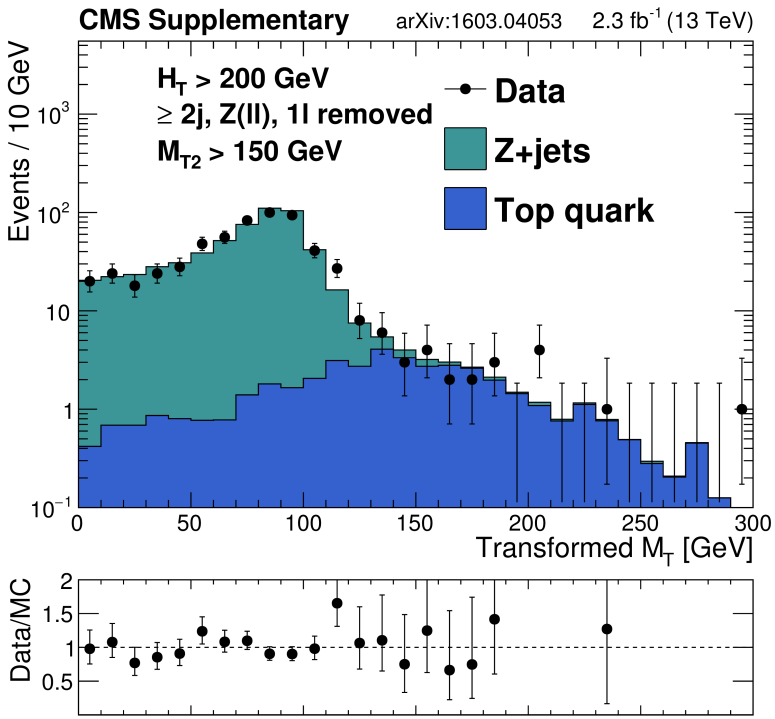
$$\boxed{N_{\text{lost lepton}} = N_{1l}^{(CR)} \cdot R_{MC}(SR/CR)}$$

Number of events in single lepton control region

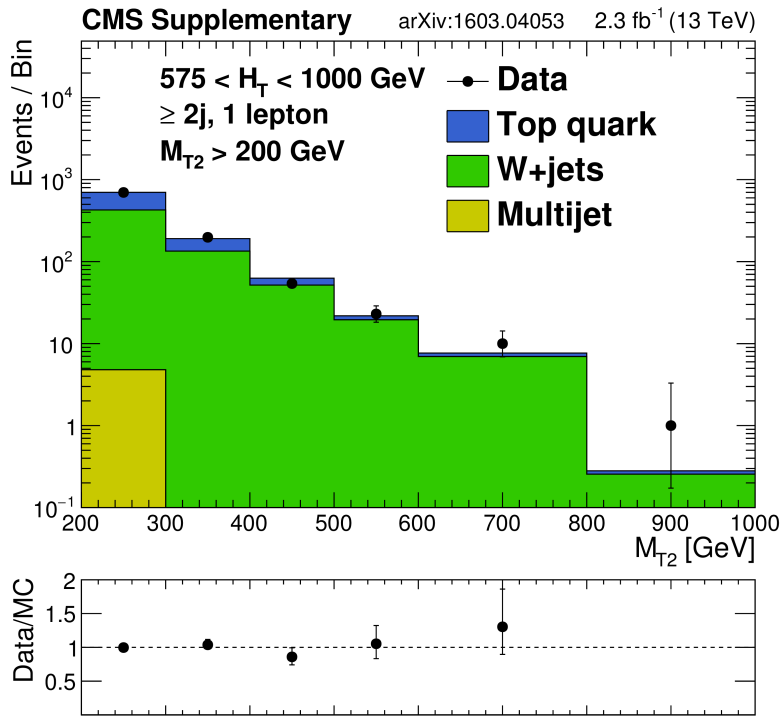
Transfer factor (from MC). Accounts for lepton acceptance, efficiency, τ's

Validation of MC Ingredients

- **M_T (lepton, ME_T)** modeling
  - ❖ Rely on MC
  - ❖ Validated in **Z(ll) data**
  - → Treat one lepton as "missing"

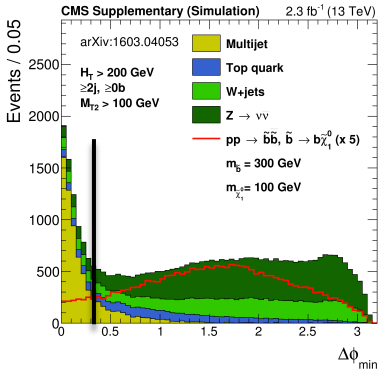


- **M_{T2}** dimension
  - ❖ From W(lν)+top **MC**
  - ❖ Validated in **data**



The QCD Estimate, for multijet

- Estimate based on **inverting $\Delta\phi_{min}$(4 jets, ME_T)** cut (>0.3)
- Transfer factor $\mathbf{r_\phi = N(\Delta\phi>0.3) / N(\Delta\phi<0.3)}$
  - **Fit** at low M_{T2}, then extrapolate to M_{T2}>200 GeV
- Inclusive in **each H_T** region
  - Then **split in N_j and N_b** with **data-driven** transfer factors



$$\mathbf{N_{QCD} = N_{\Delta\phi<0.3}(M_{T2}) \cdot r_\phi(M_{T2}) \cdot f_j(H_T) \cdot r_b(N_j)}$$

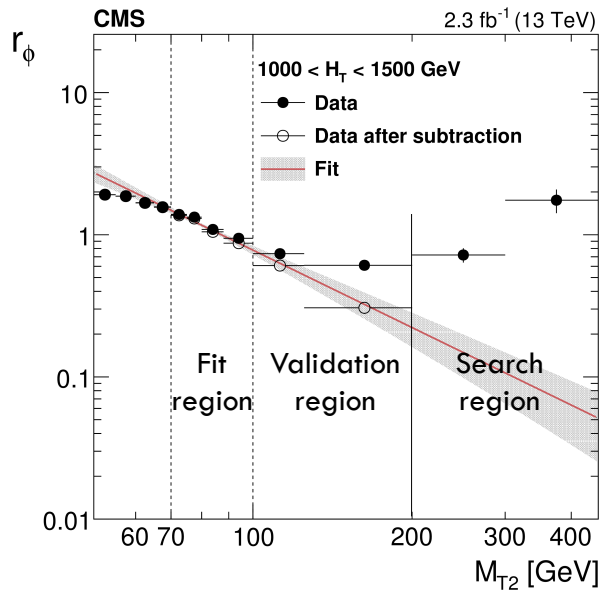
Number of events in **low-$\Delta\phi$** control region

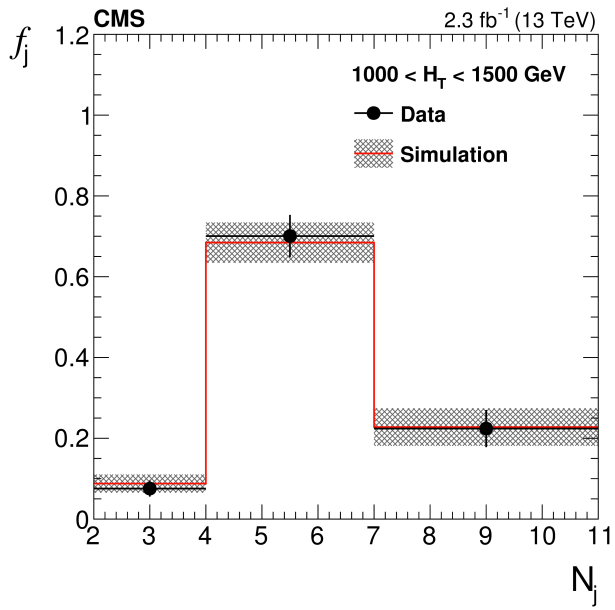
Low-$\Delta\phi$ → High-$\Delta\phi$ transfer factor (fit to low M_{T2} data)

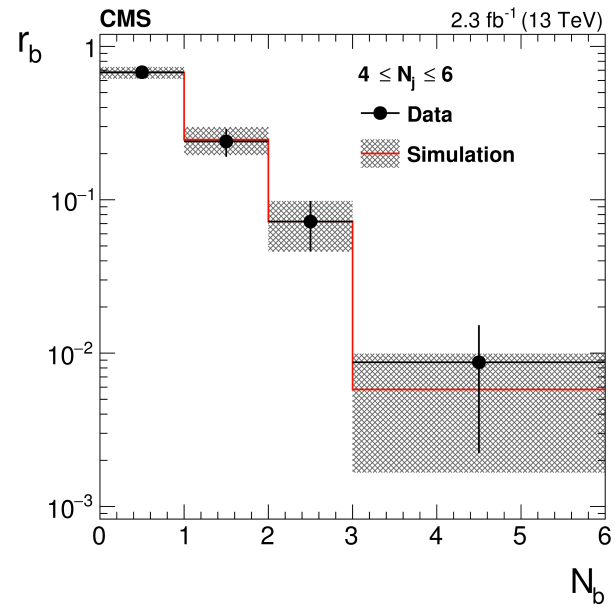
Split factor into N_j bins (measured in data, only depends on H_T)

Split factor into N_b bins (measured in data, only depends on N_j)

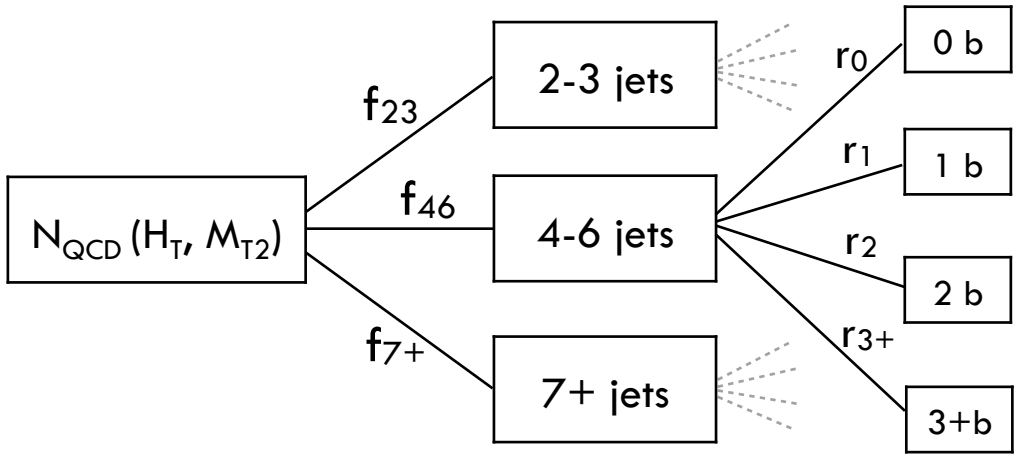
The QCD Estimate Ingredients





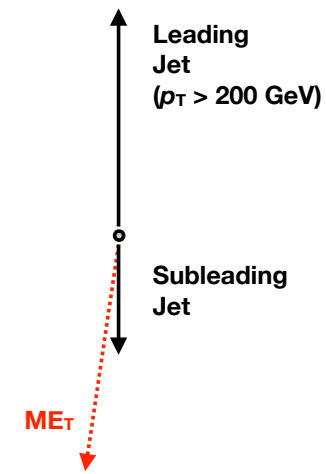


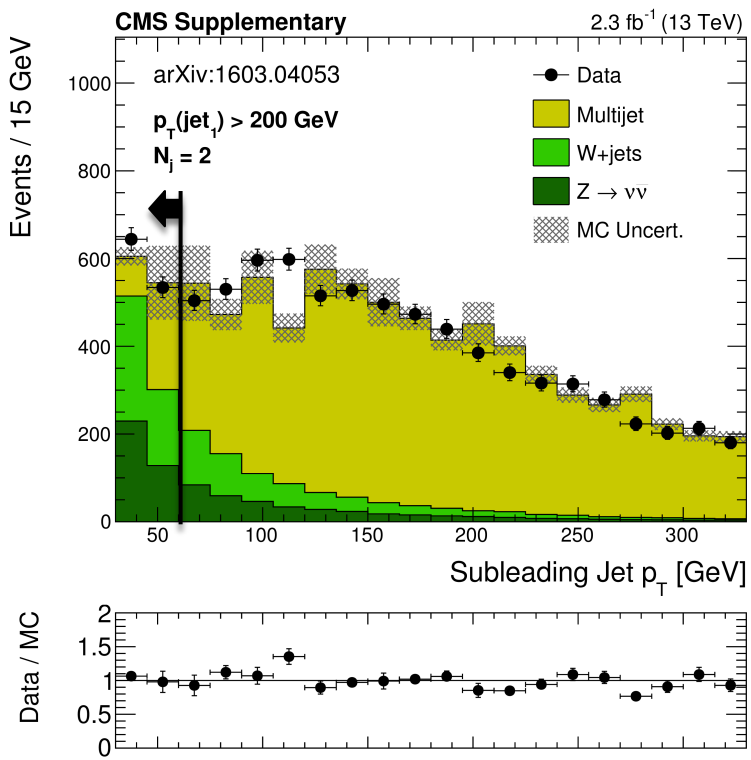
- **r_ϕ (M_{T2})**
  - ❖ Fit to **data** with power-law
  - ❖ Non-QCD MC subtraction
- **f_j (H_T) x r_b (N_j)**
  - ❖ Measured from **data**
  - ❖ At low-Δϕ (< 0.3)
  - ❖ At 100 < M_{T2} < 200 GeV



The QCD Estimate, for monojet

- Estimate based on imbalanced di-jet events
  - ❖ Leading jet with p_T > 200 GeV (as for signal region)
  - ❖ $\Delta\phi_{min}$(jets, ME_T) < 0.3
    - → ME_T pointing in sub-leading jet direction



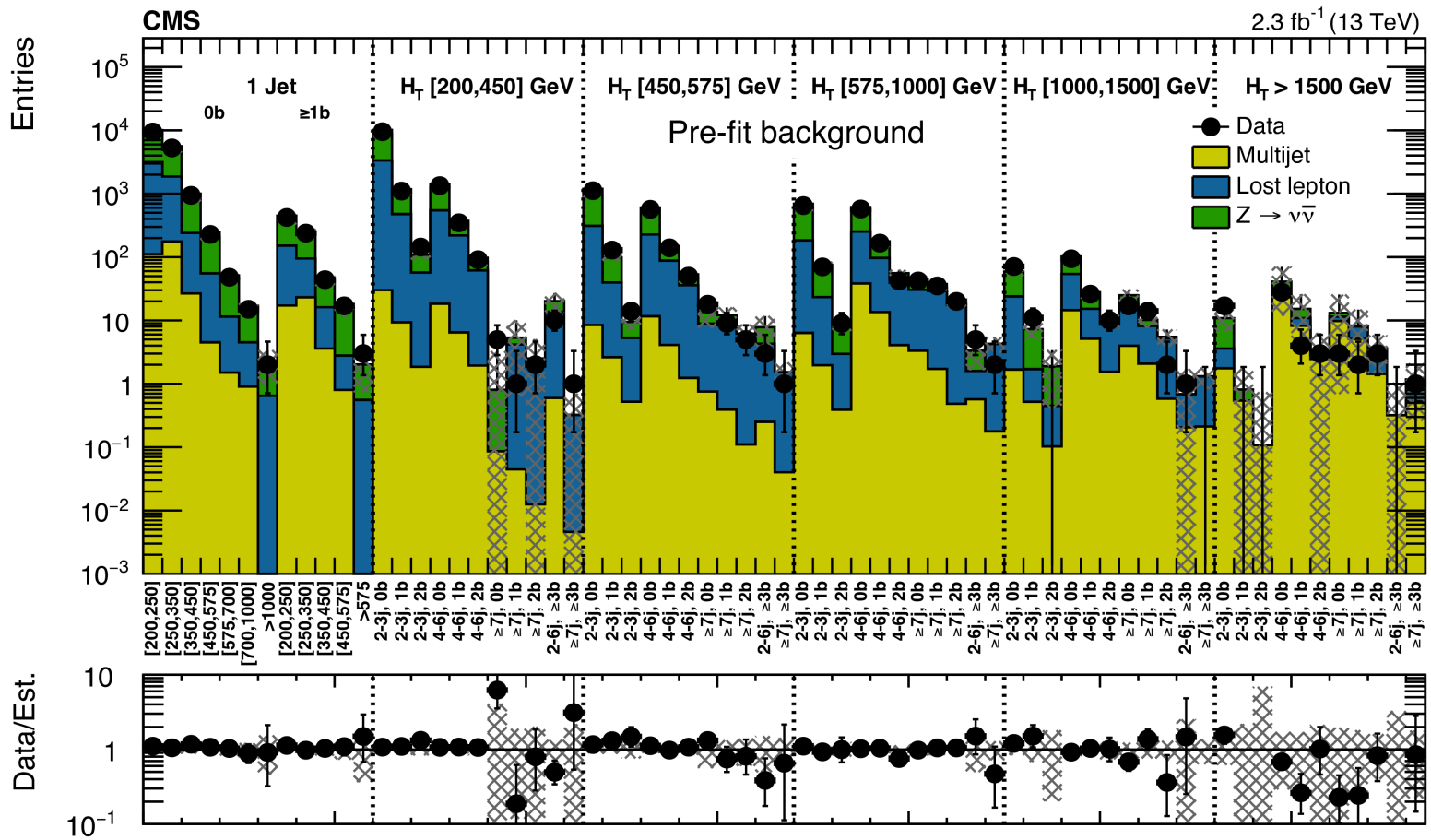


METHOD:

- ❖ Count events with sub-leading jet with 30 < p_T < 60 GeV
  - → Right above threshold
  - → If p_T < 30 GeV, it's a "monojet"
- ❖ Subtract non-QCD MC
- ❖ Result = QCD estimate
  - → Over-estimate, by construction
  - → Not a problem: QCD is negligible

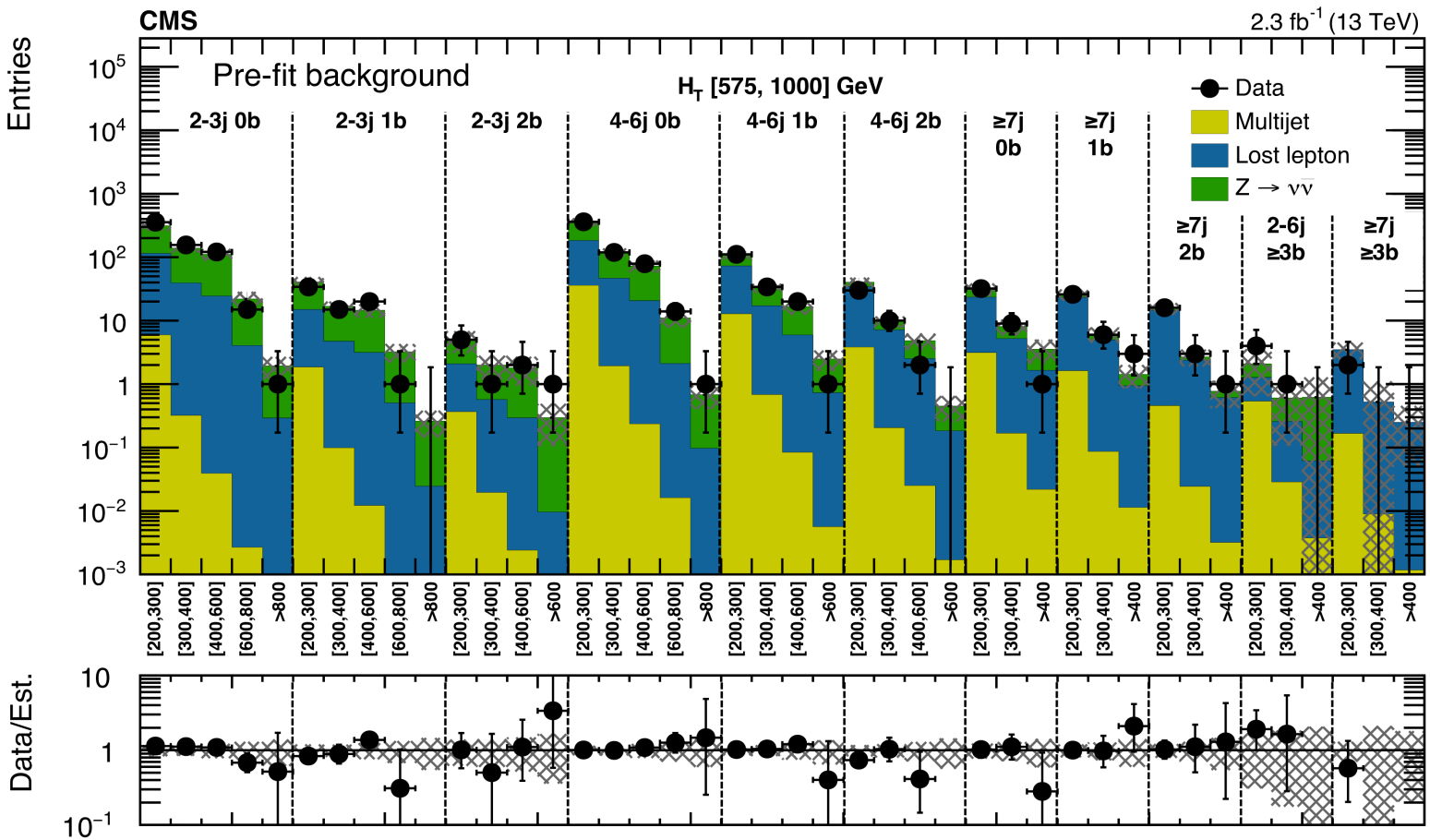
Results on 2015 data (2.3/fb)

- No excess has been observed
  - ❖ Results integrated over M_{T2}



Results Binned in M_{T2}

- No excess has been observed, also unrolling the M_{T2} dimension
  - ❖ Results for H_T [575, 1000] GeV (see backup for others)

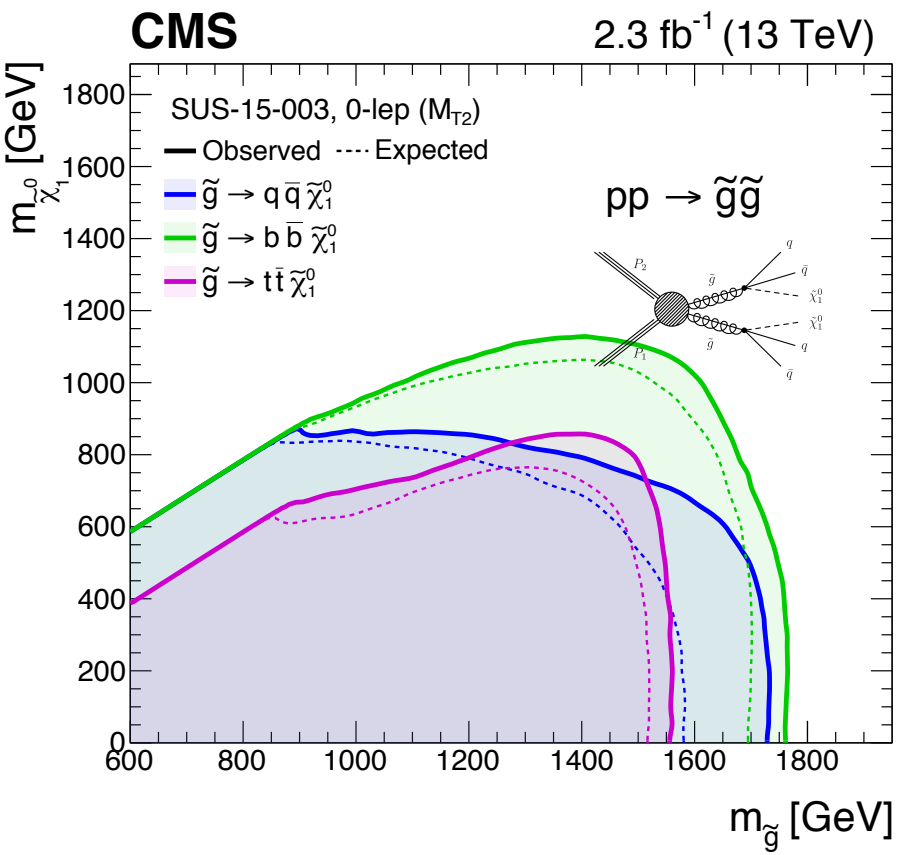


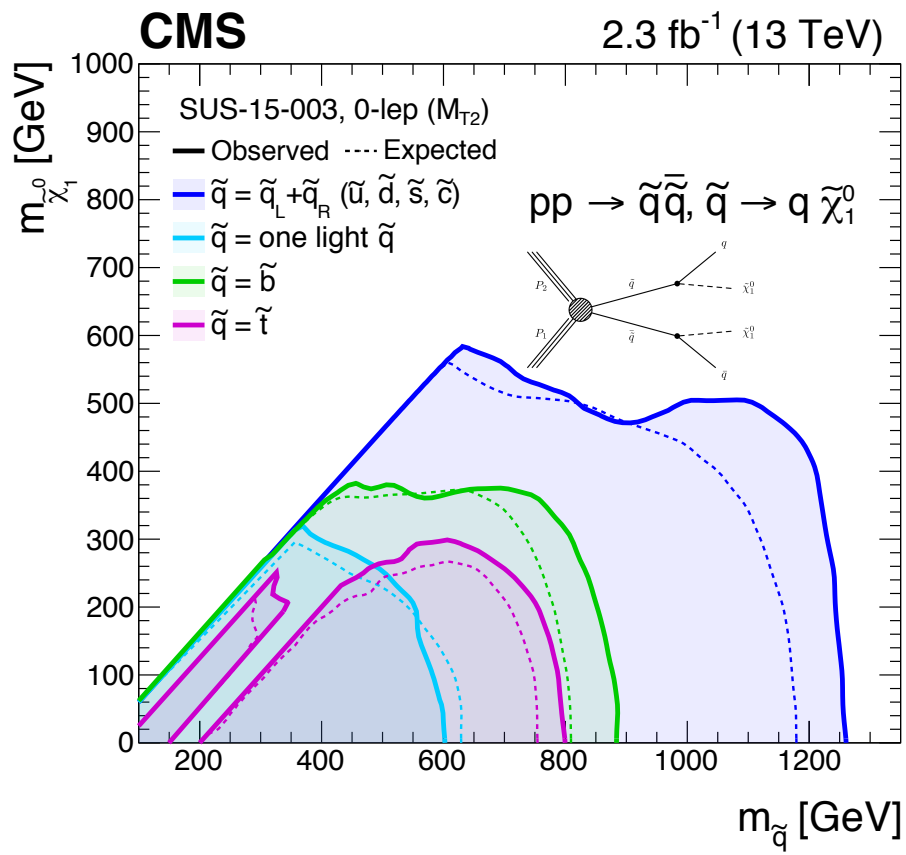
Interpretation of the Results

- No excess has been observed

→ Interpretation in terms of exclusion limits on SUSY simplified models

→ Extended exclusion reach from 8 TeV analysis by about 300 GeV





Summary

- The M_{T2} all-hadronic inclusive search has been presented
- Results based on full 2015 dataset (13 TeV) have been shown
- No excess has been observed

→ Results have been interpreted in terms of exclusion limits

- For gluino-gluino production, we have excluded (95% CL):
  - Gluino masses up to 1750 GeV
  - LSP masses up to 1125 GeV
- For direct squark production, we have excluded (95% CL):
  - Squark masses up to 1260 GeV
  - LSP masses up to 580 GeV

- **Outlook:** will repeat the search on 2016 data

  → **Let's hope to be luckier!** ☺

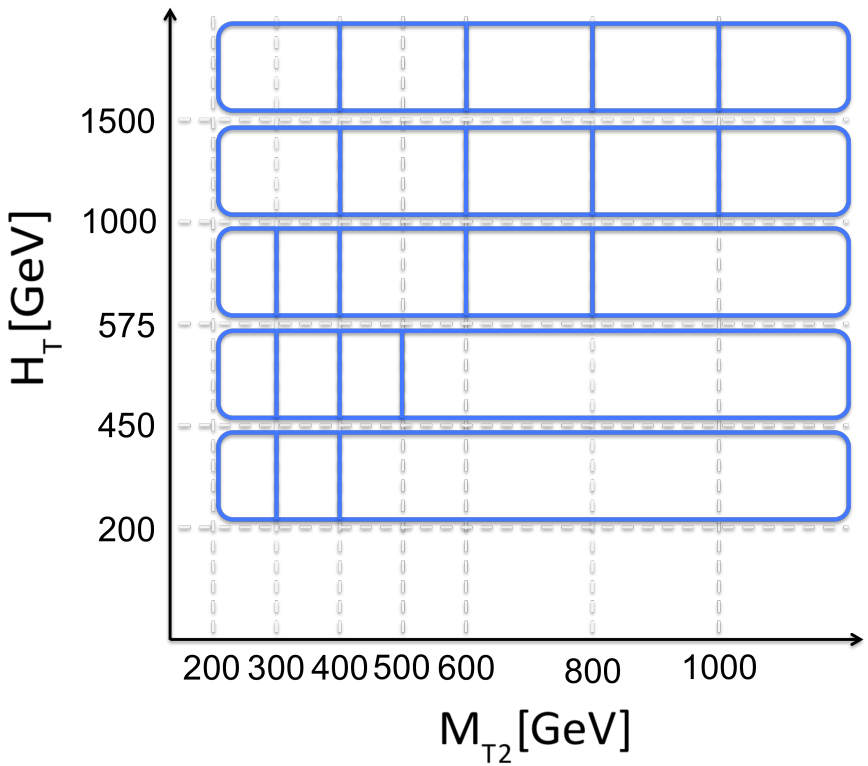
Backup

General

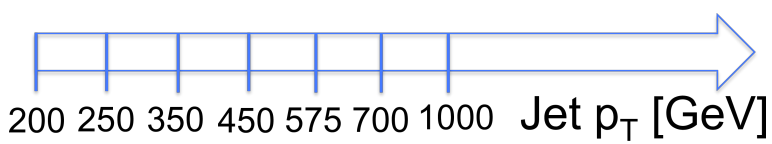
The M_{T2} Binning

- **M_{T2}** binning in each (H_T, N_j, N_b) region (from M_{T2} > 200 GeV)
  - For **monojet**: binning in **jet p_T**, from 200 GeV

$N_j \geq 2$:
- Up to 5 bins



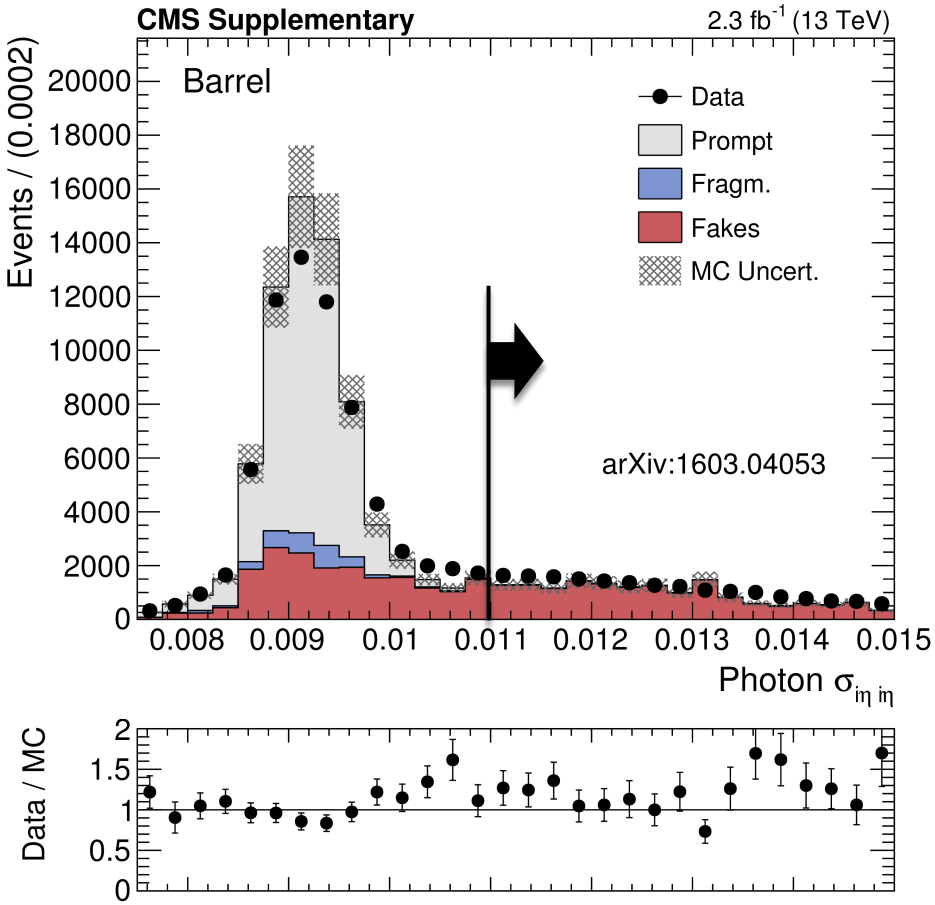
$N_j = 1$:
- Up to 7 bins

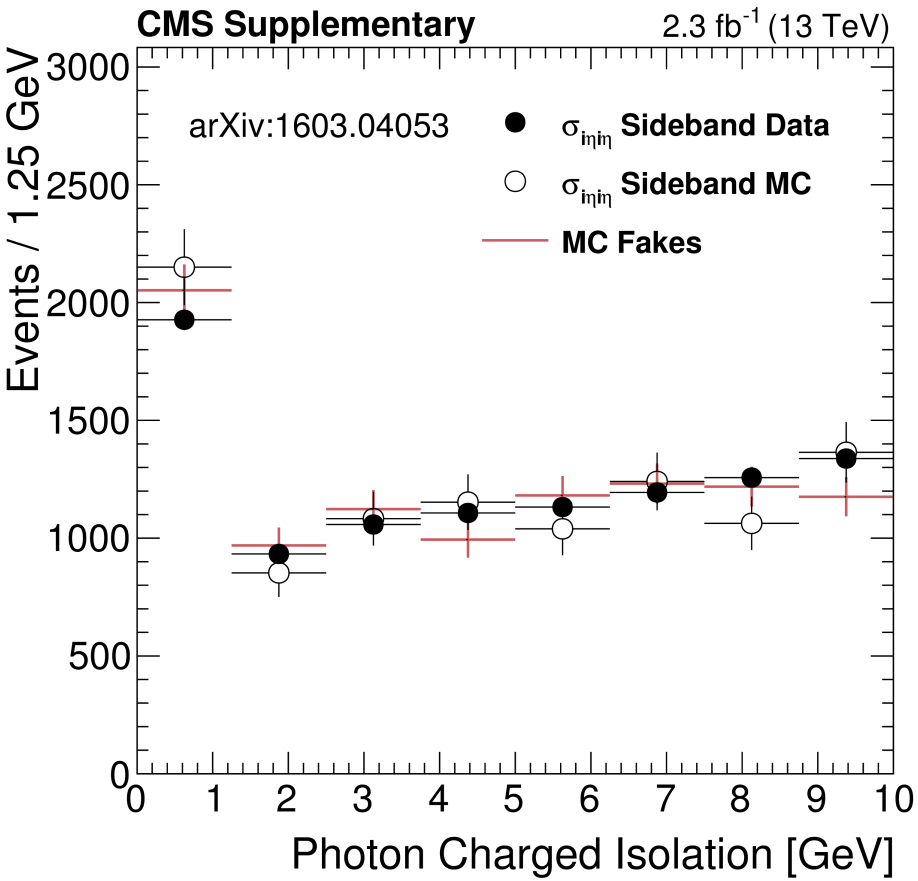


Invisible Z Background

Purity Fit Templates

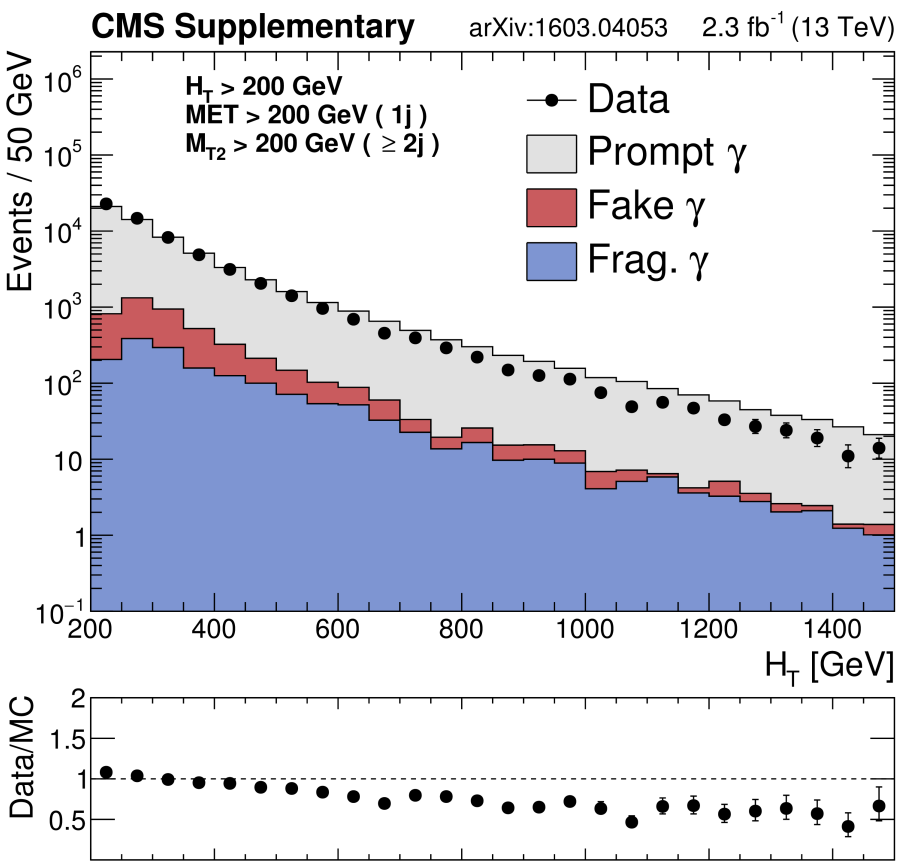
- Isolation templates for fake photons are taken from sidebands in cluster shape variable

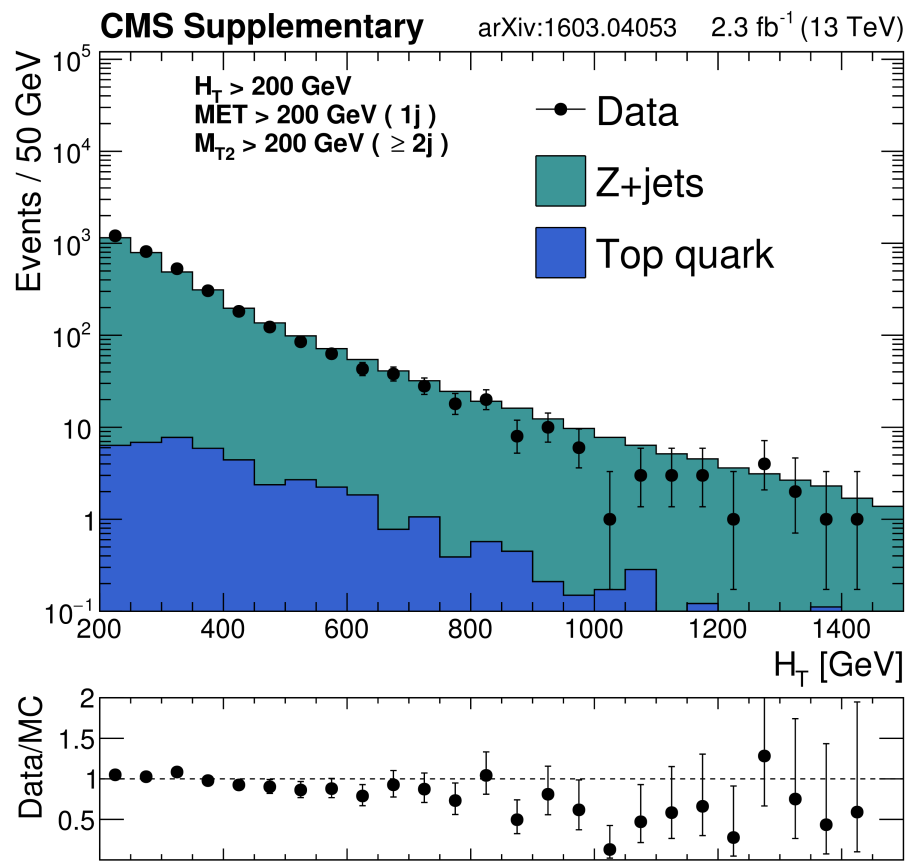




Z/γ Ratio Validation

- Z/γ ratio is taken directly from MC
- Validation is performed using Z(ll) data

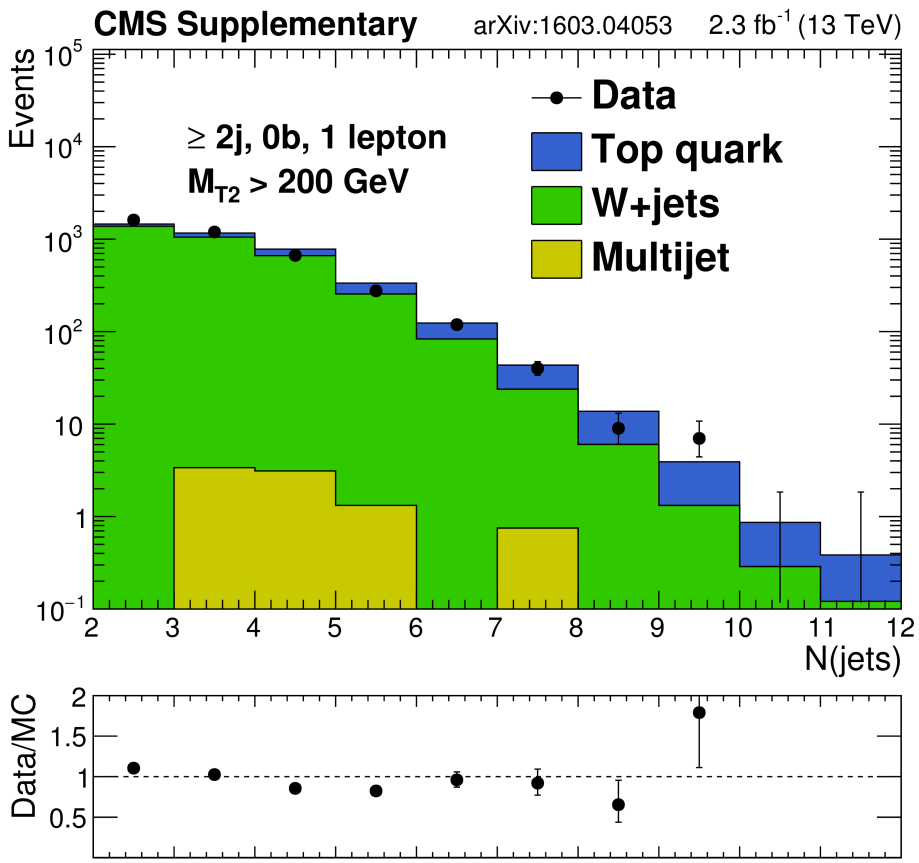


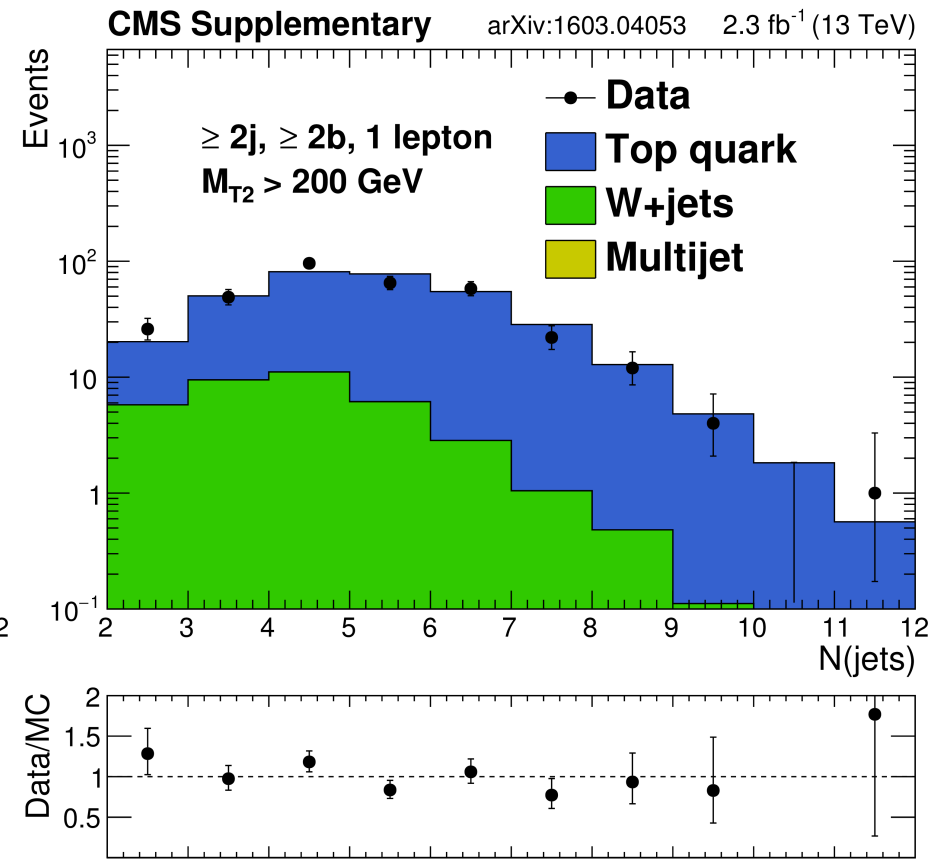


Lost Lepton Background

Transfer Factor Validation

- Transfer factor is taken directly from MC
- Shape agreement data/MC for the main kinematic variables is extensively validated in 1-lepton data, also for W and top enriched datasets separately

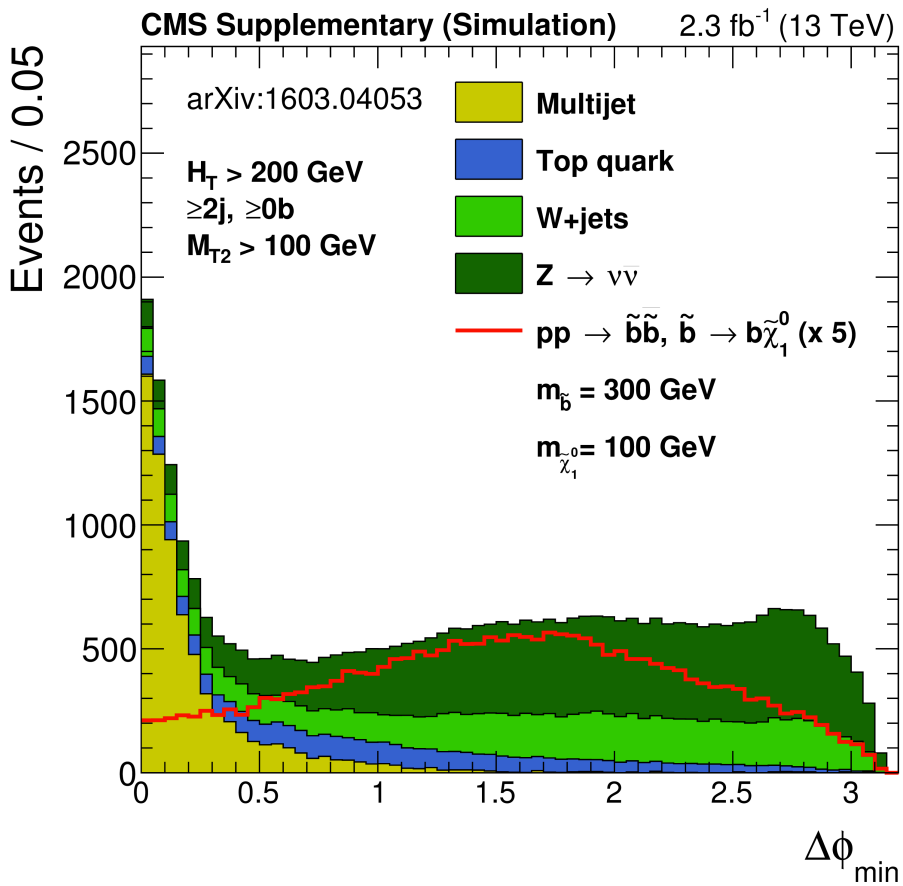




QCD Multijet Background

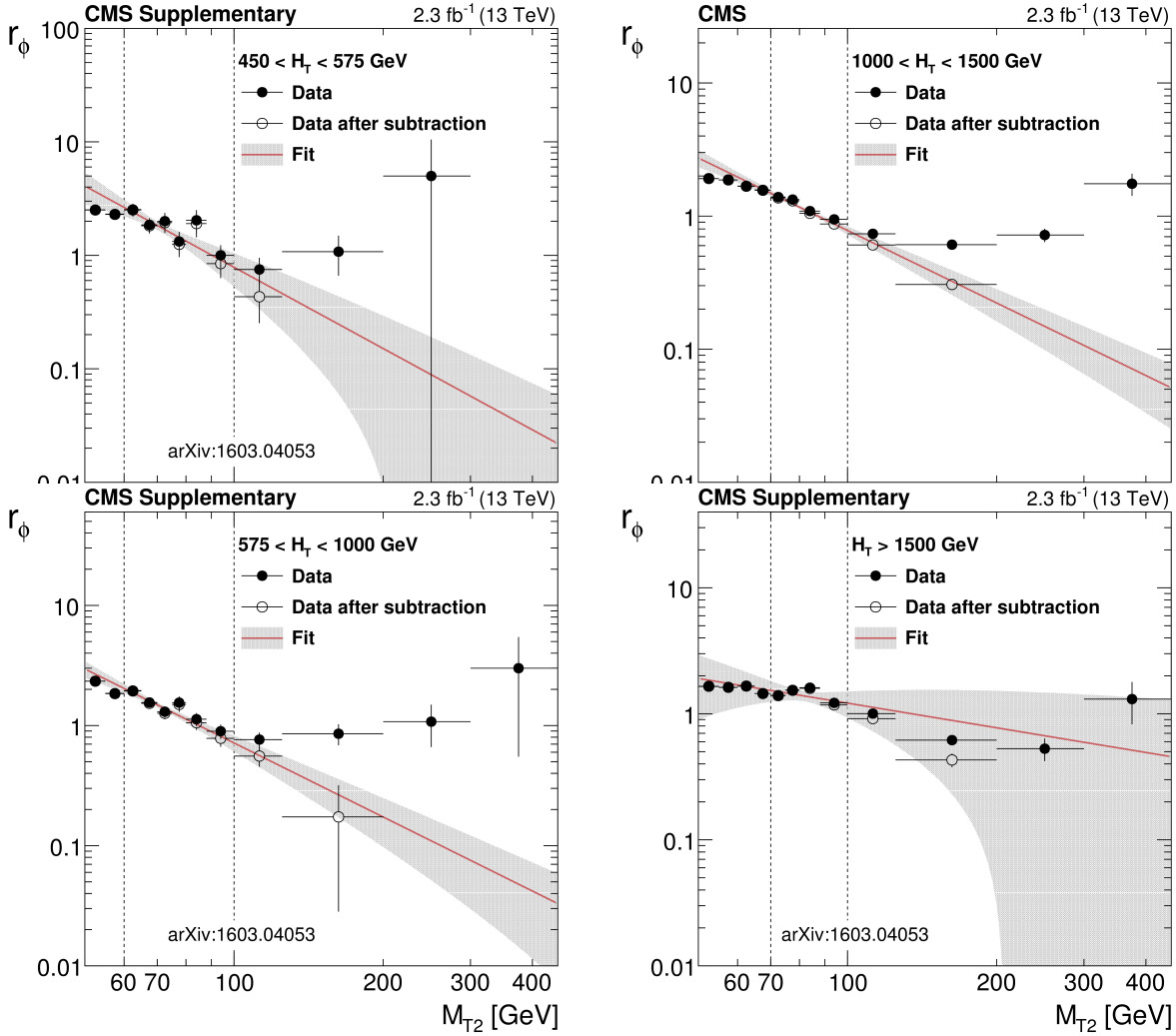
r_ϕ – From low $\Delta\phi$ to high $\Delta\phi$

- QCD multijet estimate is based on **inverting $\Delta\phi_{min}$(4 jets, ME_T)** cut (>0.3)
  - ❖ **Low $\Delta\phi$** region is QCD multijet enriched
  - → Transfer factor **r_ϕ = N($\Delta\phi$>0.3) / N($\Delta\phi$<0.3)**



r_ϕ Fit

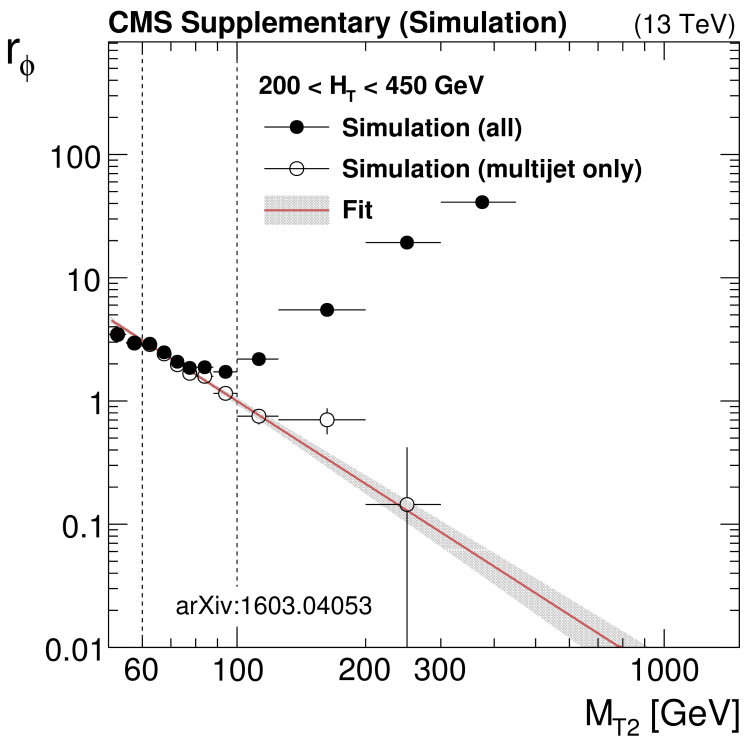
- $\mathbf{r_\phi}$ **(M_{T2})** is measured from a fit to data at low M_{T2} (60/70 → 100 GeV), then extrapolated in the search region, i.e., M_{T2} > 200 GeV

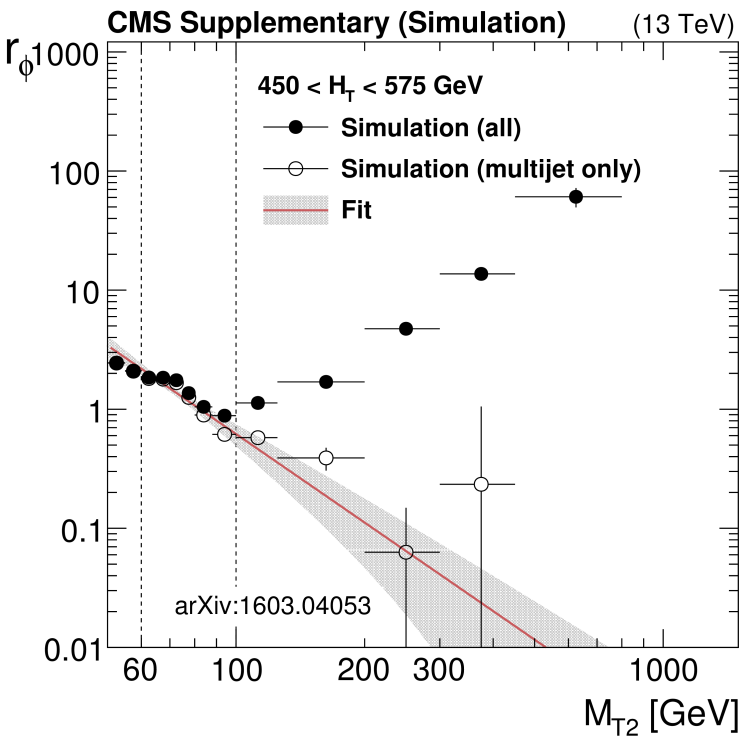


r_ϕ Fit at very low H_T

- Due to absence of suitable trigger, it is not possible to perform the $\mathbf{r_\phi}$ $\mathbf{(M_{T2})}$ fit at very low H_T (200 → 450 GeV)

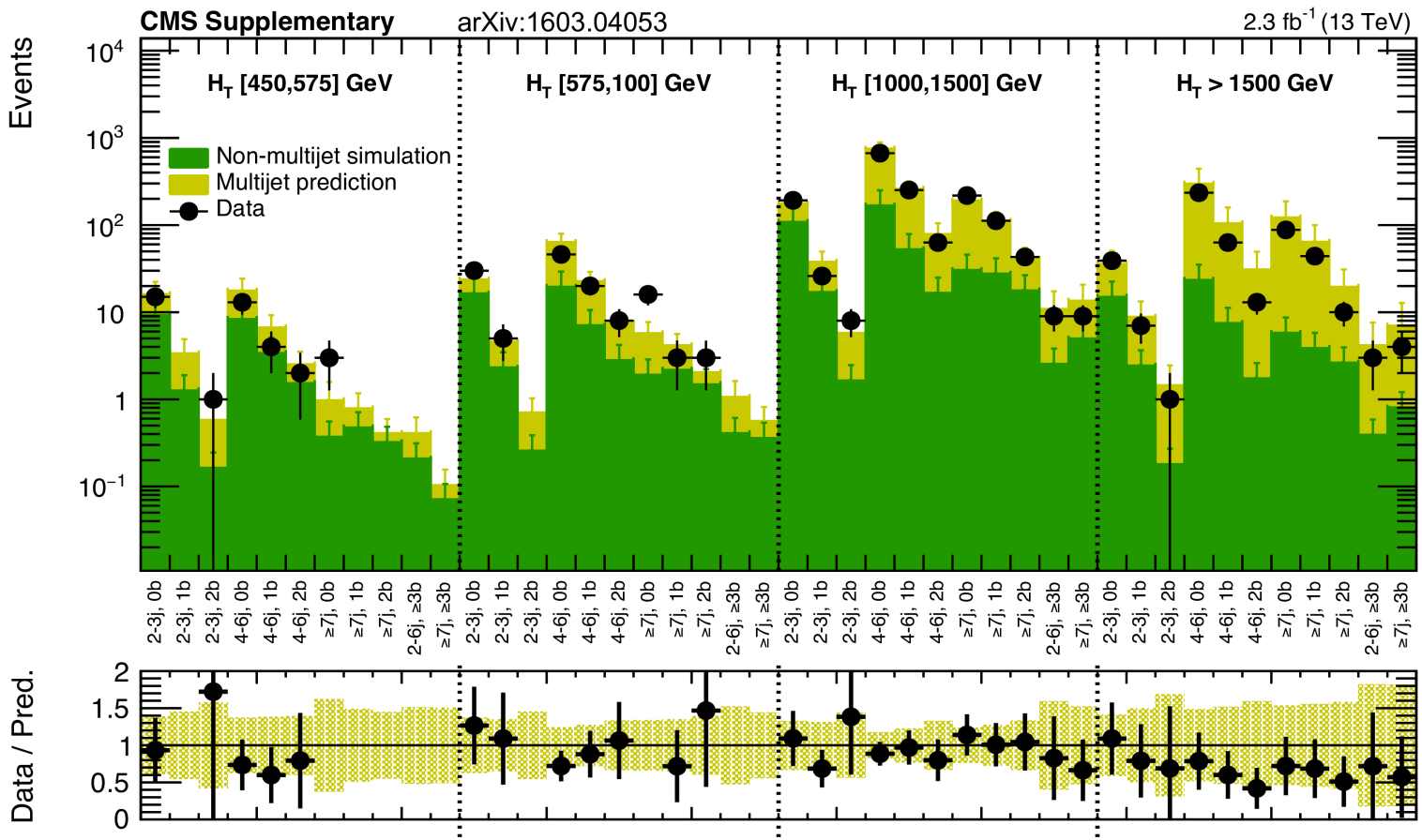
➢ The value obtained in the next lowest H_T region is used
  - ❖ Choice is validated using MC
  - ❖ However, QCD multijet is a negligible background at low H_T





QCD Estimate Validation

- $\mathbf{r_\phi}$ **(M_{T2})** is measured from a fit to data at low M_{T2} (60/70 → 100 GeV), then extrapolated in the search region, i.e., M_{T2} > 200 GeV
- The region 100 < M_{T2} < 200 GeV is used as a validation region



Results

Aggregated Regions

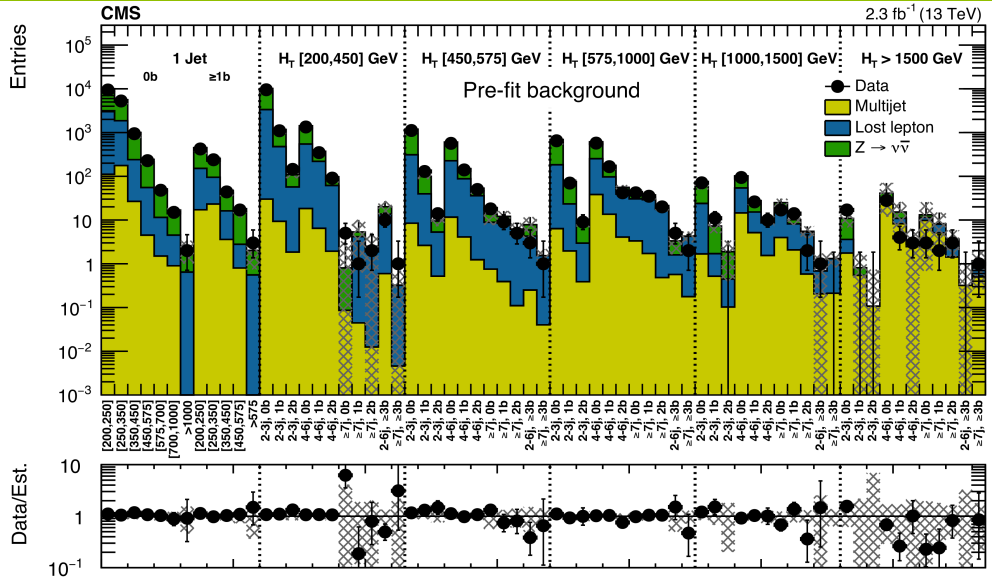
- **Aggregated regions** (14, NOT exclusive) are defined, to allow simpler reinterpretations
  - Background estimate as from sum of all search bins included in each aggregated region
  - Limits on cross-section are less stringent wrt. full binned (172 bins) analysis, by a factor ~2

Region	Prediction	Observation	N_{95}^{obs}, 15% unc.	N_{95}^{obs}, 30% unc.
1j loose	833 ± 95	902	246	273
1j medium	175 ± 22	185	60	66
1j tight	$15.9^{+3.2}_{-2.9}$	12	7.9	8.4
2j tight	$15.7^{+4.0}_{-3.9}$	12	8.9	9.5
4j medium	159 ± 25	165	60	66
4j tight	$16.2^{+5.0}_{-4.9}$	11	8.7	9.3
7j tight	$15.3^{+4.6}_{-4.5}$	14	11	12
7j very tight	$5.3^{+3.3}_{-3.2}$	3	5.7	6.1
2b medium	119 ± 14	98	21	23
2b tight	$13.5^{+3.3}_{-3.1}$	10	7.7	8.2
2b very tight	$4.5^{+2.3}_{-2.1}$	4	6.3	6.8
3b medium	$40.9^{+9.9}_{-8.8}$	24	11	11
3b tight	$11.0^{+3.2}_{-2.5}$	9	7.7	8.2
3b very tight	$3.5^{+1.9}_{-1.4}$	2	4.3	4.5

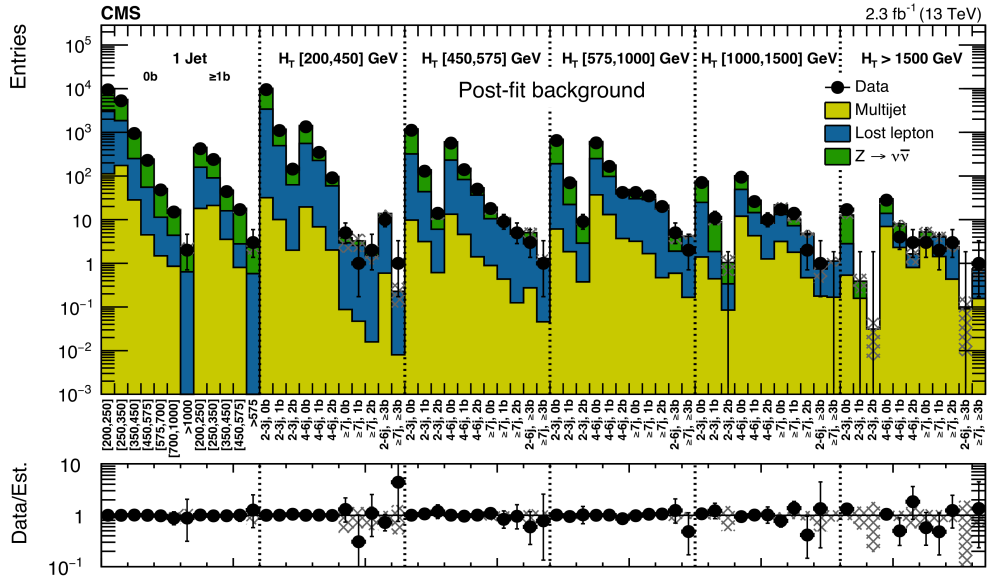
Region	N_j	N_b	H_T [GeV]	M_{T2} [GeV]
1j loose	=1	—	>450	—
	2–3	≤2	450–575	>400
	2–3	≤2	575–1000	>300
	2–3	≤2	>1000	>200
1j medium	=1	—	>575	—
	2–3	≤2	575–1000	>600
	2–3	≤2	>1000	>200
1j tight	=1	=0	>1000	—
	=1	≥1	>575	—
	2–3	=0	575–1000	>800
	2–3	1–2	575–1000	>600
	2–3	0–1	1000–1500	>800
	2–3	=2	1000–1500	>400
	2–3	0–1	>1500	>400
	2–3	=2	>1500	>200
2j tight	2–3	—	>1000	>600
	2–3	—	>1500	>400
	4–6	—	>1000	>800
	4–6	—	>1500	>600
4j medium	≥4	—	>575	>400
4j tight	≥4	—	>1000	>600
	≥7	—	>1500	>400
7j tight	≥7	—	>575	>400
7j very tight	≥7	0–1	>1000	>600
	≥7	≥2	>1000	>400
	≥7	—	>1500	>400
2b medium	≥2	≥2	>575	>200
2b tight	≥2	≥2	>575	>400
2b very tight	≥2	≥2	>1000	>400
3b medium	≥2	≥3	>200	>200
3b tight	≥2	≥3	>575	>200
3b very tight	≥2	≥3	>1000	>200

Results on 2015 data

1. From estimate:

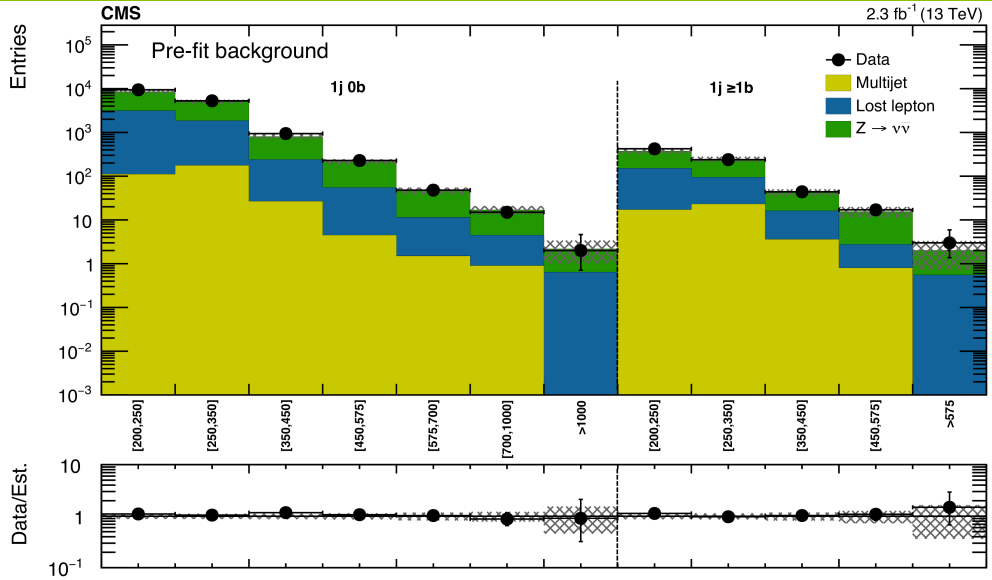


2. After ML fit of estimate to data:

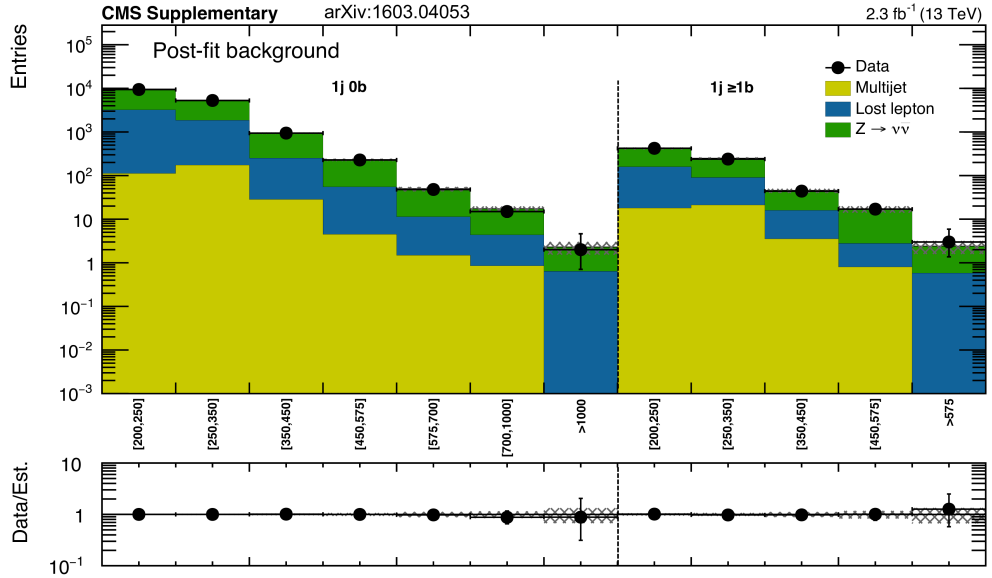


Results Binned in M_{T2} (i)

1. From estimate:

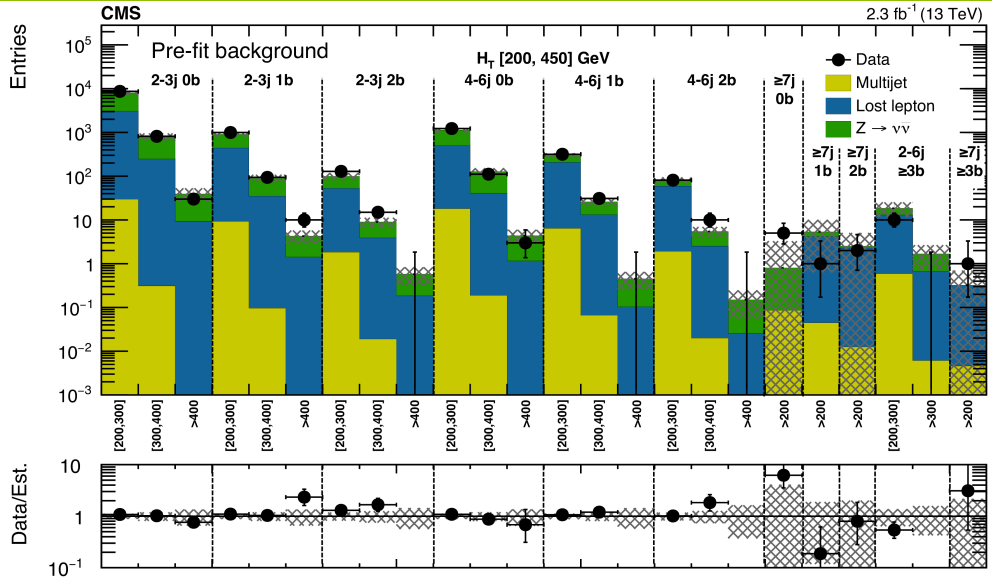


2. After ML fit of estimate to data:

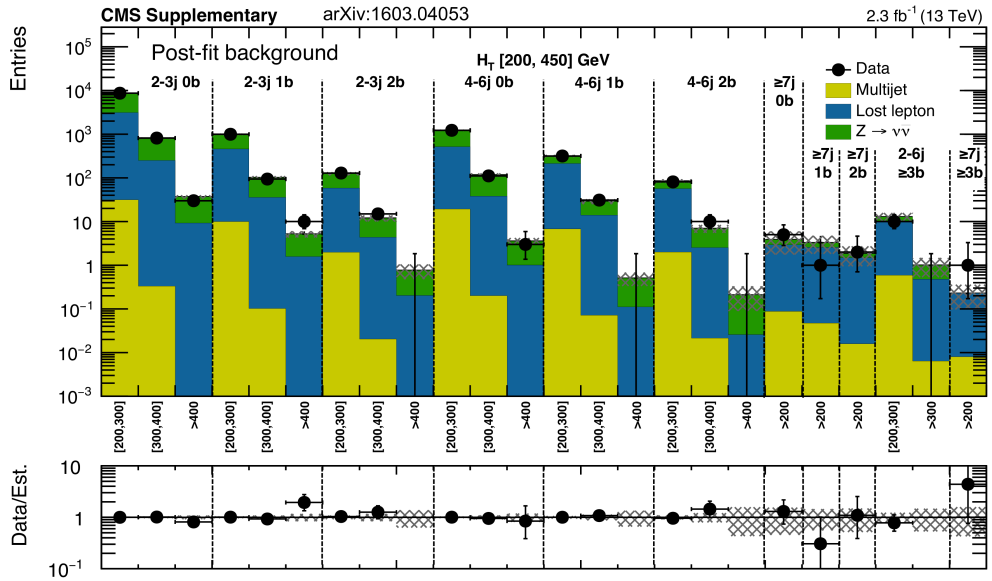


Results Binned in M_{T2} (ii)

1. From estimate:

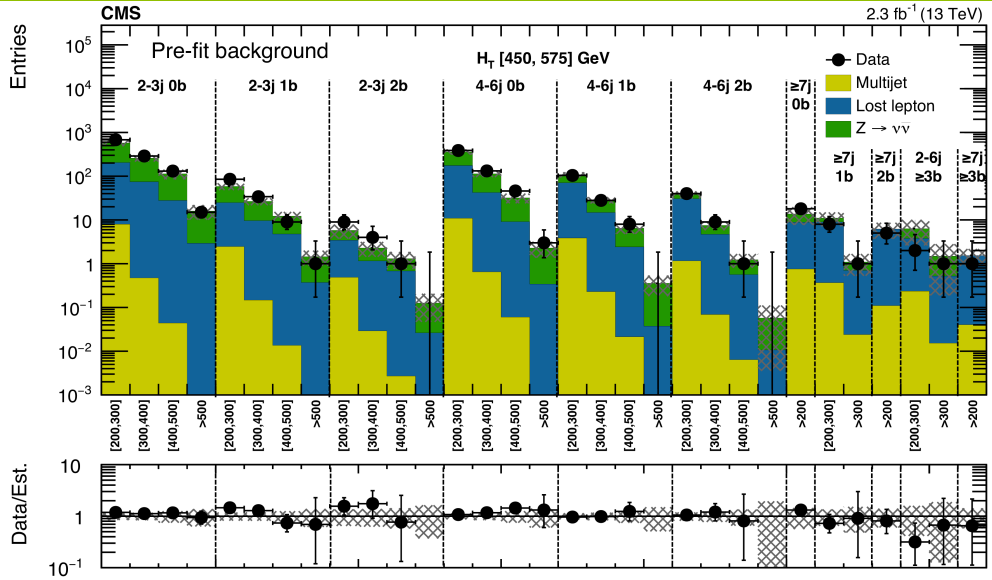


2. After ML fit of estimate to data:

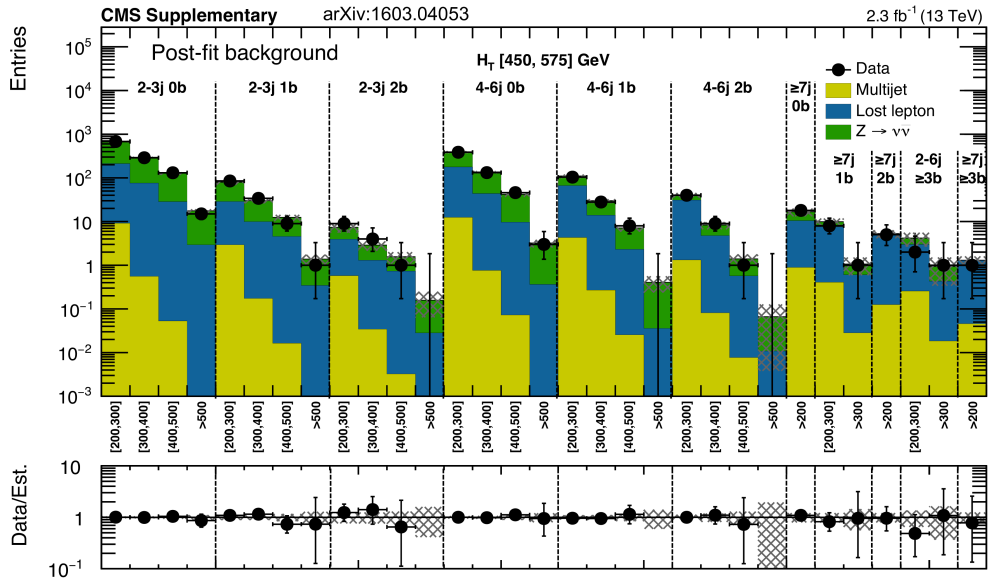


Results Binned in M_{T2} (iii)

1. From estimate:

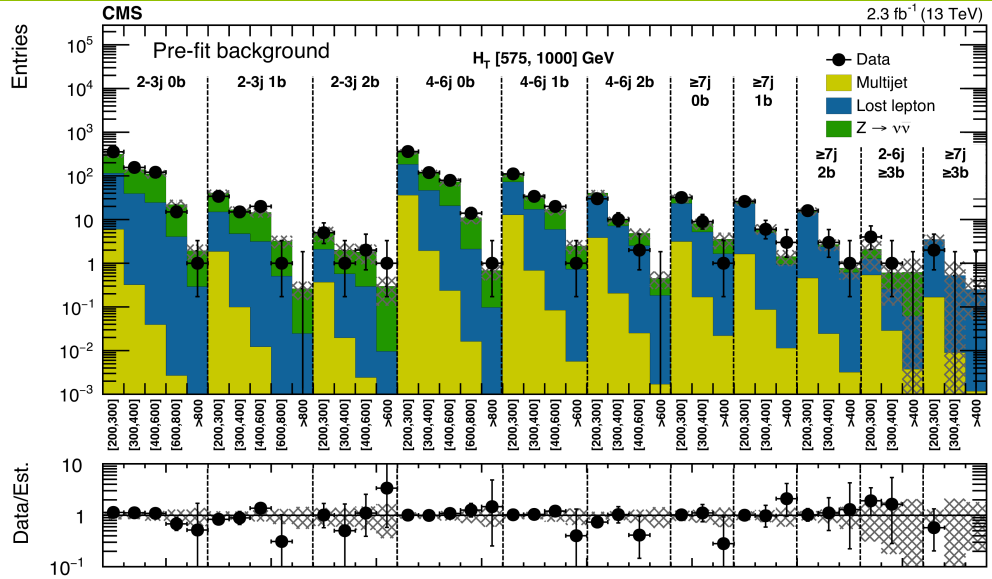


2. After ML fit of estimate to data:

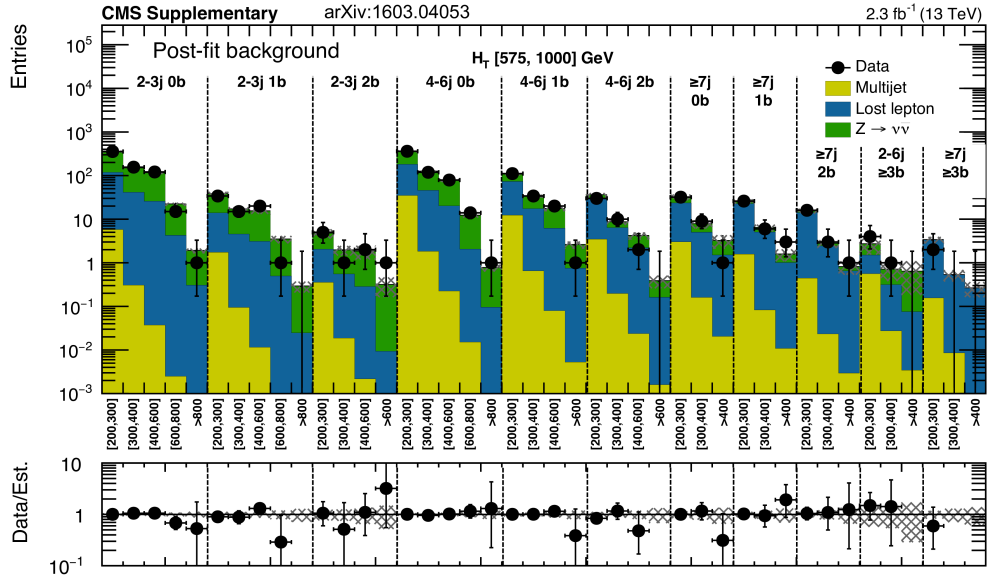


Results Binned in M_{T2} (iv)

1. From estimate:

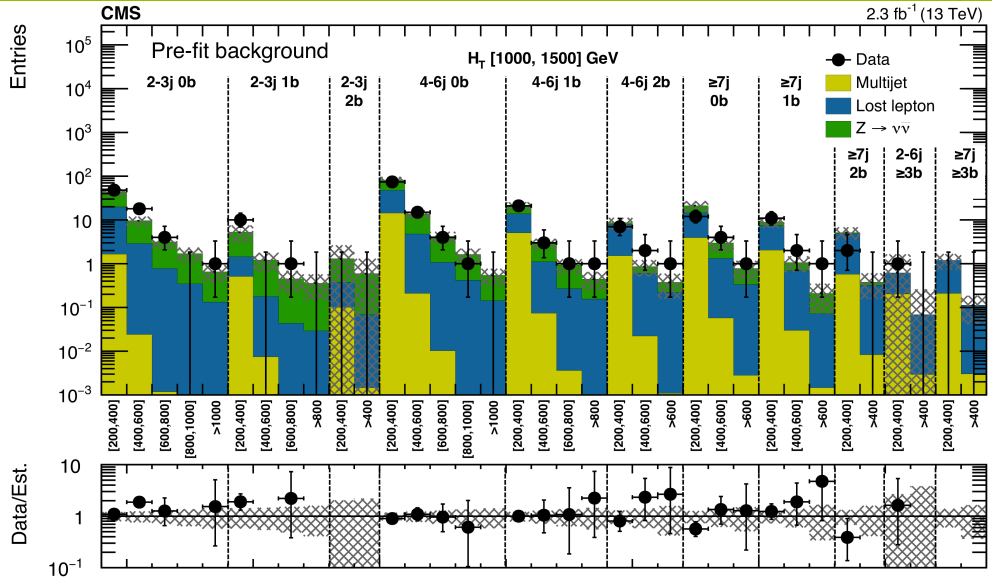


2. After ML fit of estimate to data:

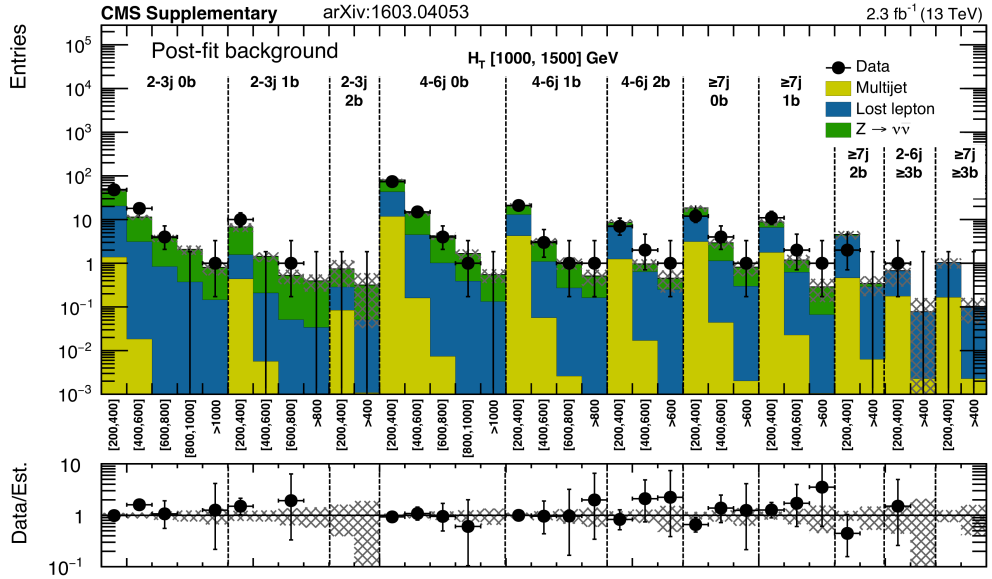


Results Binned in M_{T2} (v)

1. From estimate:

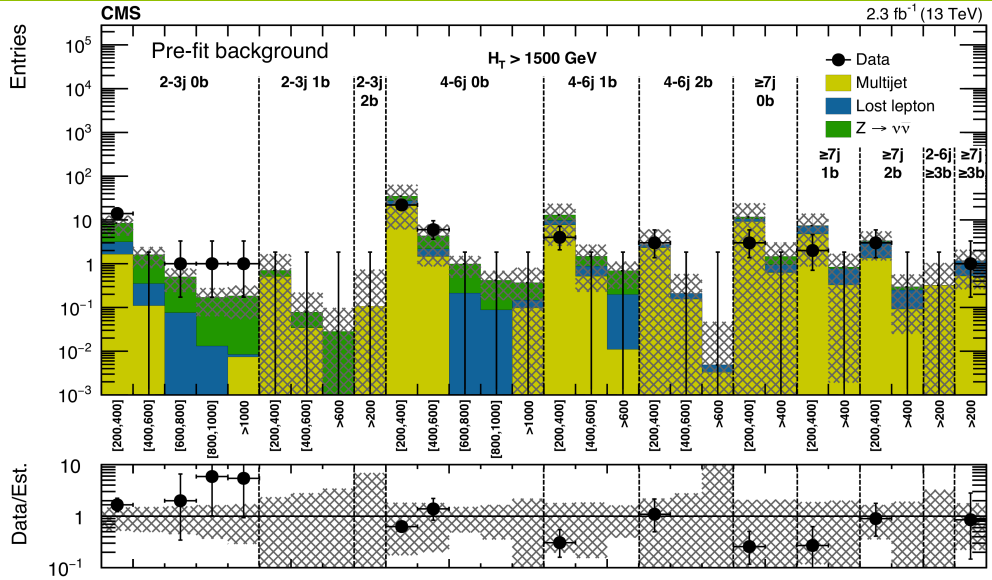


2. After ML fit of estimate to data:

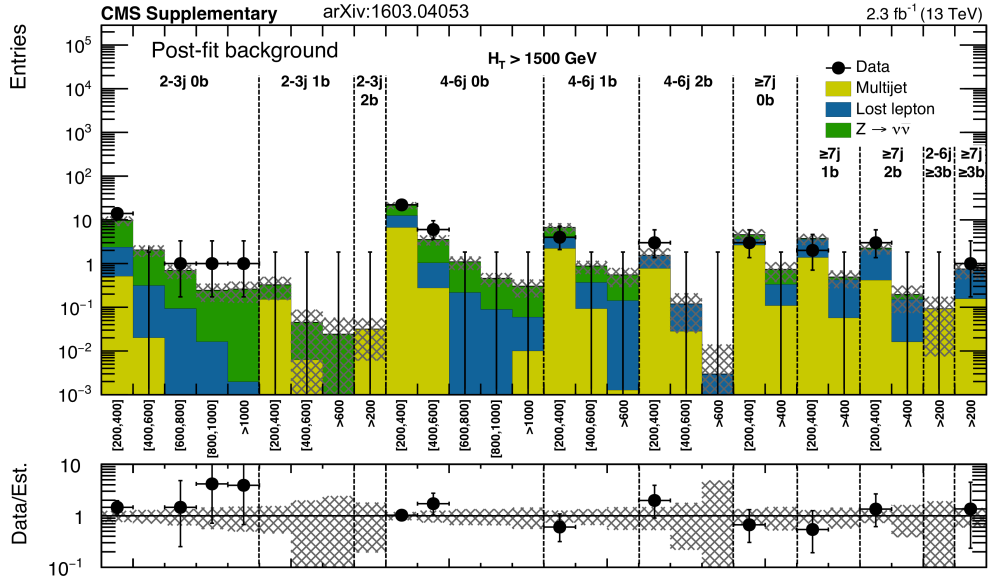


Results Binned in M_{T2} (vi)

1. From estimate:



2. After ML fit of estimate to data:



Interpretation of the Results

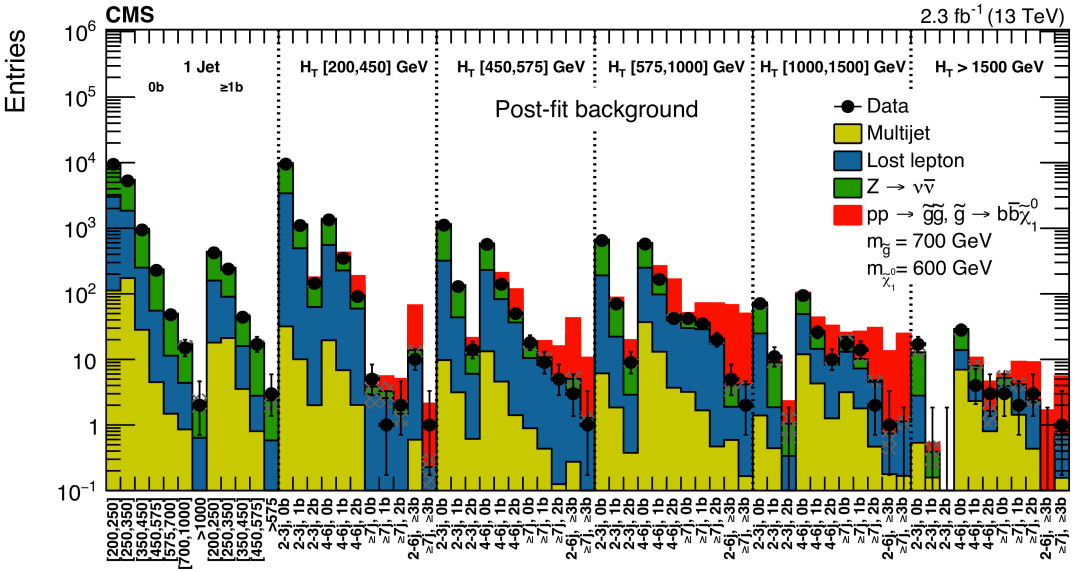
Signal Systematics

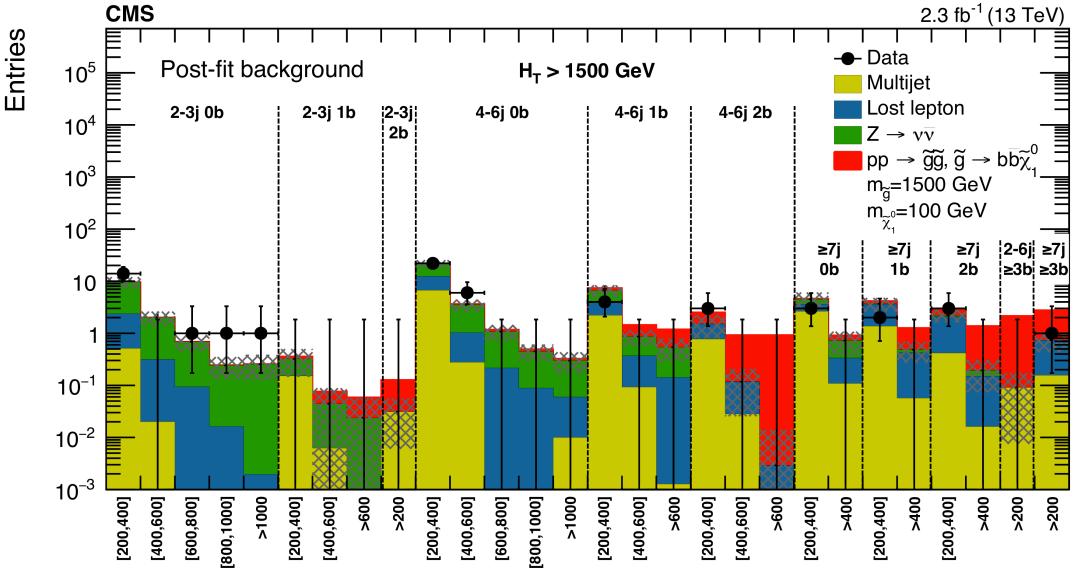
Source	Typical values [%]
Integrated luminosity	5
Limited size of MC samples	1–100
Renormalization and factorization scales	5
ISR	0–30
b tagging efficiency, heavy flavor	0–40
b tagging efficiency, light flavor	0–20
Lepton efficiency	0–20
Jet energy scale	5

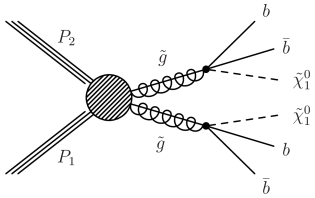
Summary of Exclusion limits (95% CL)

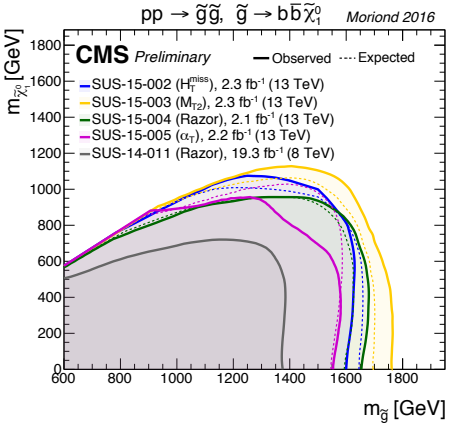
Simplified model	Limit on produced sparticle mass [GeV] for $m_{\tilde{\chi}_1^0} = 0\,\mathrm{GeV}$	Best limit on LSP mass [GeV]
Direct squark production		
Bottom squark	880	380
Top squark	800	300
Single light squark	600	300
8 degenerate light squarks	1260	580
Gluino mediated production		
$\tilde{g} \to b\bar{b}\tilde{\chi}_1^0$	1750	1125
$\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$	1550	825
$\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$	1725	850

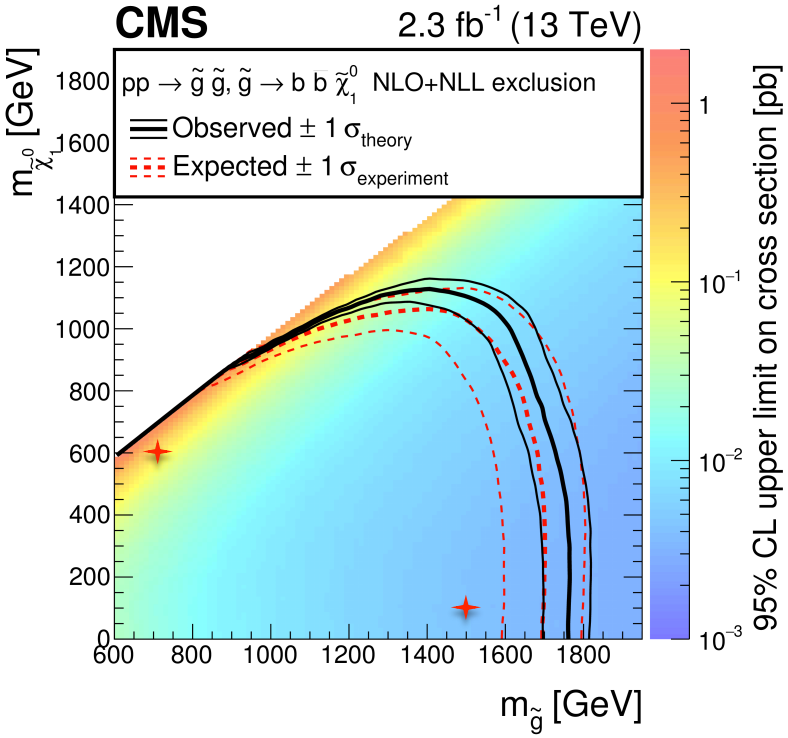
Interpretation of the Results (i)



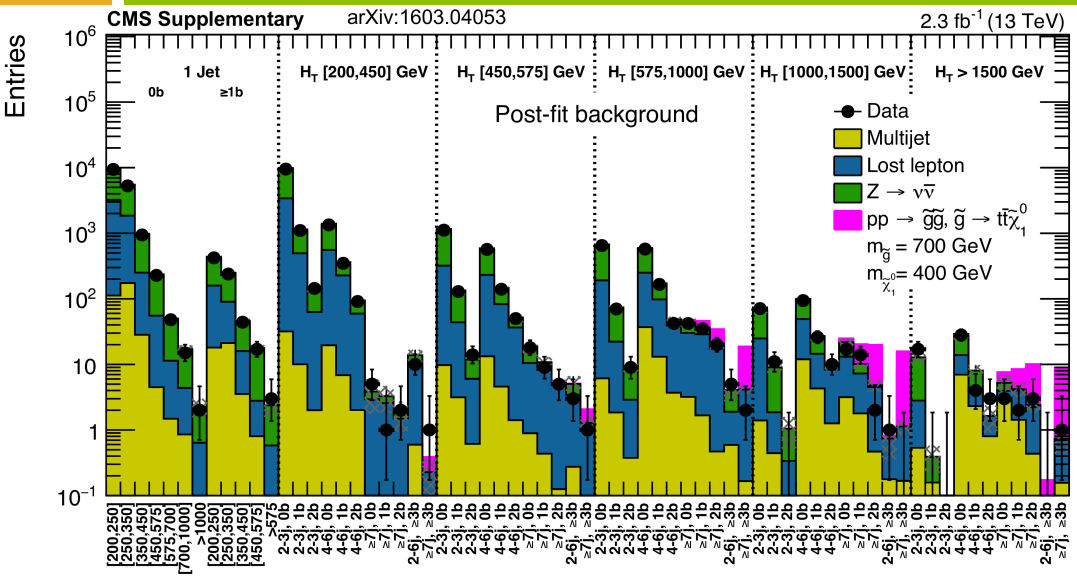


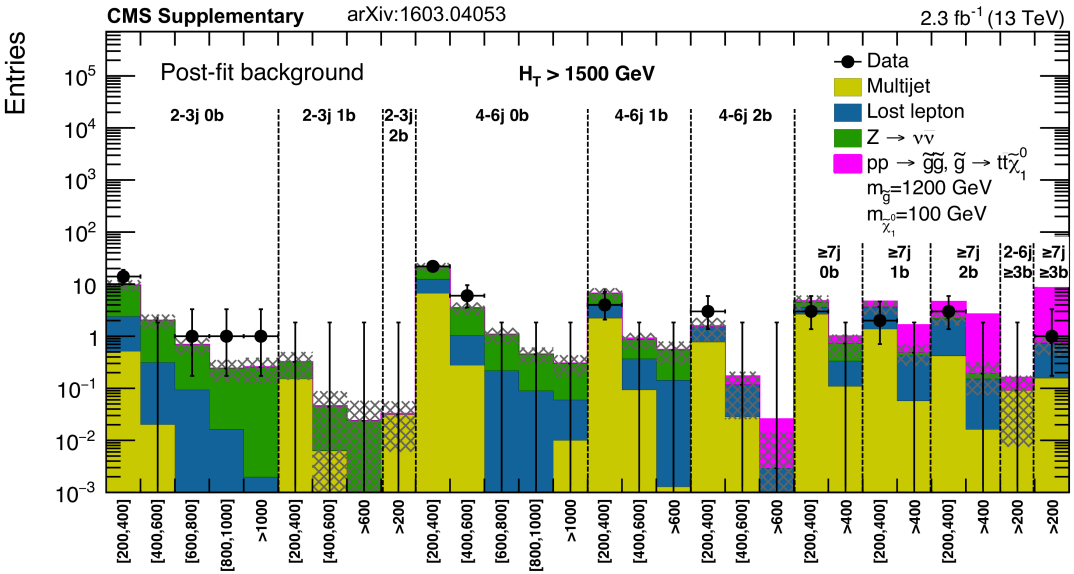


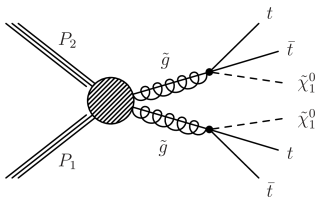


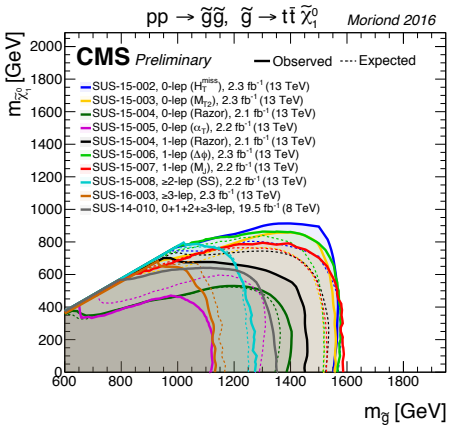


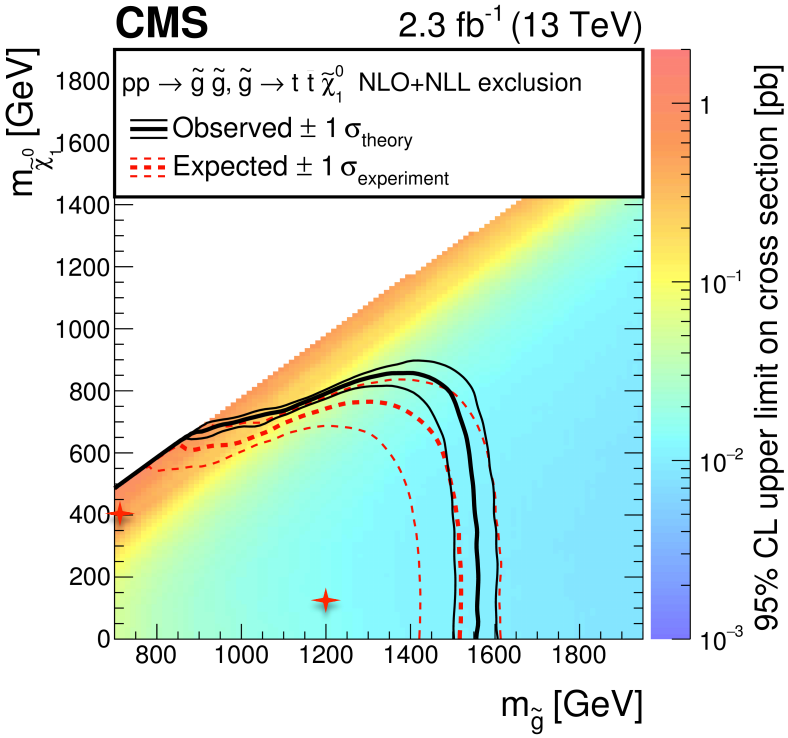
Interpretation of the Results (ii)



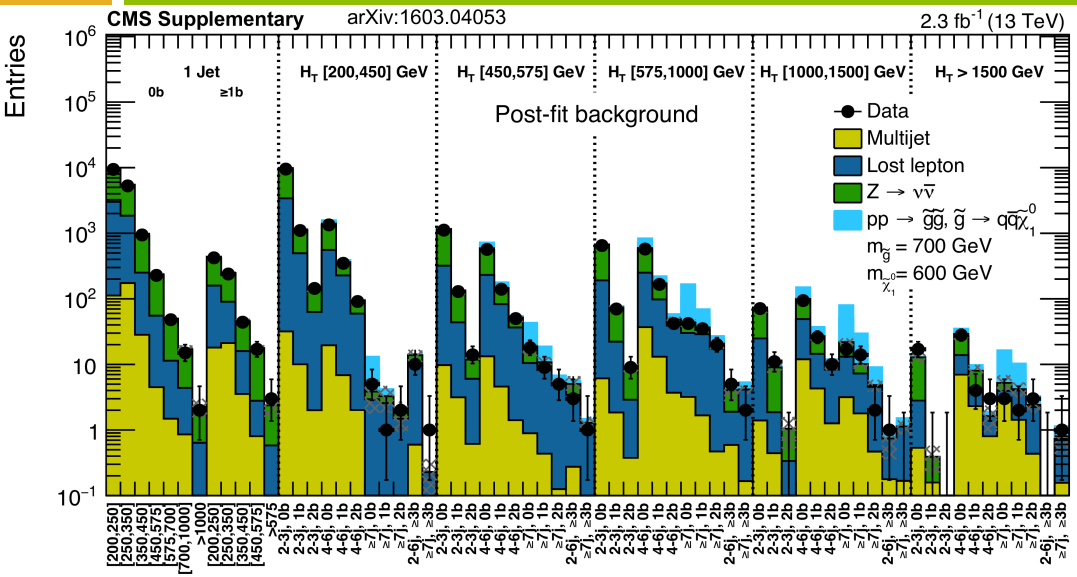


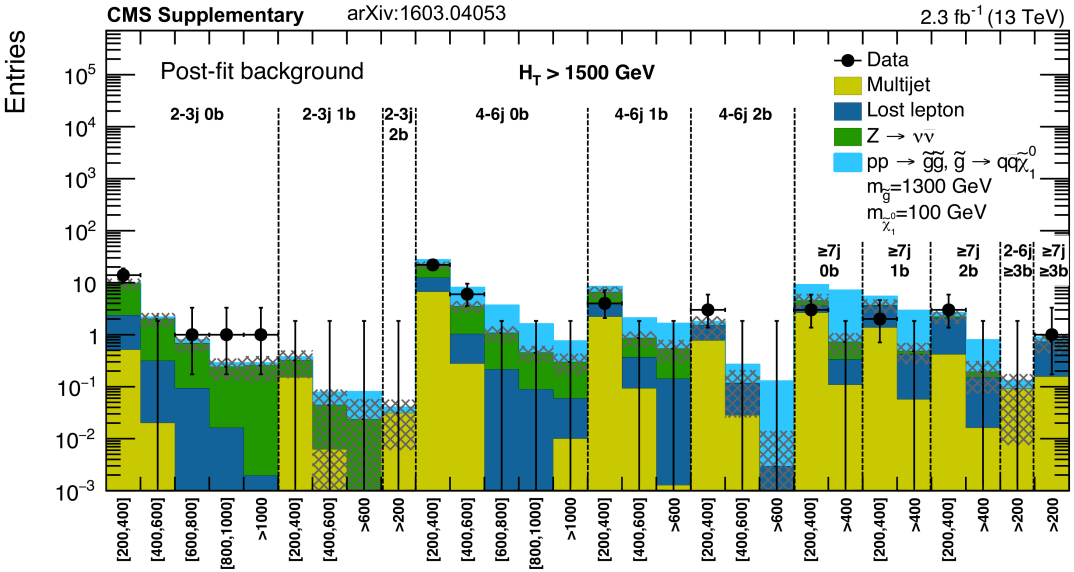


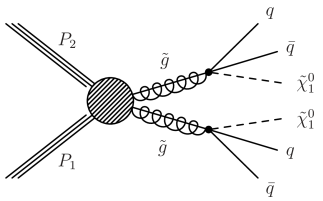


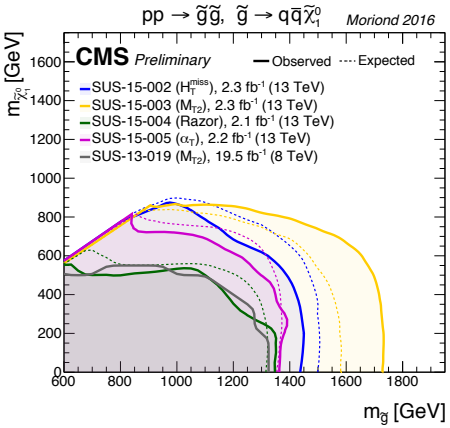


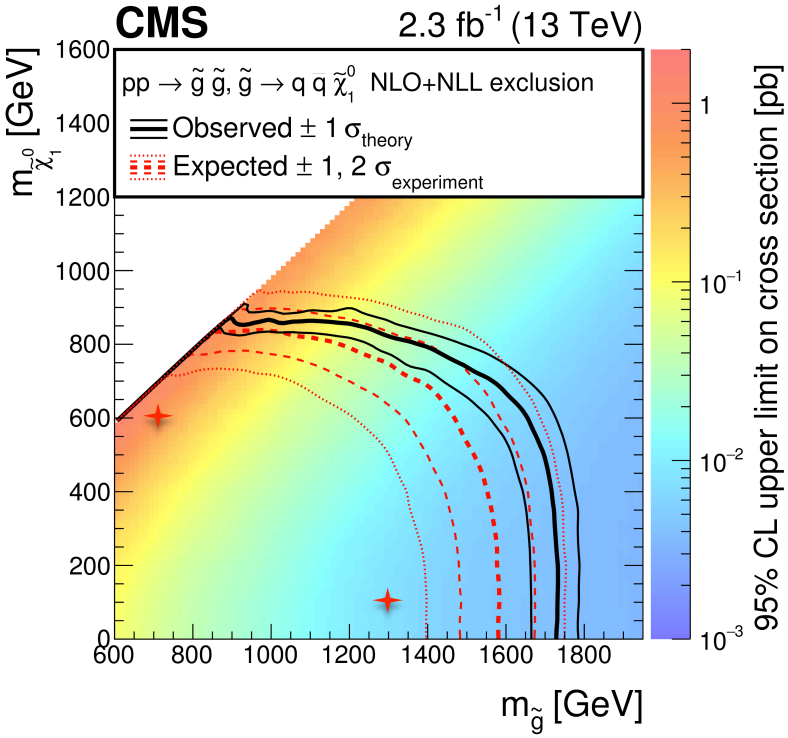
Interpretation of the Results (iii)



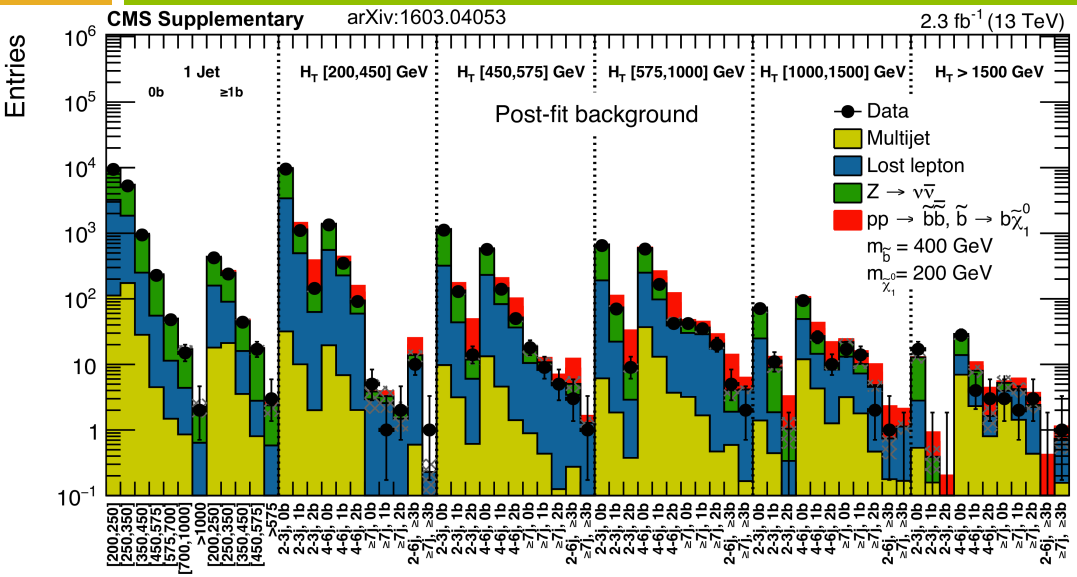


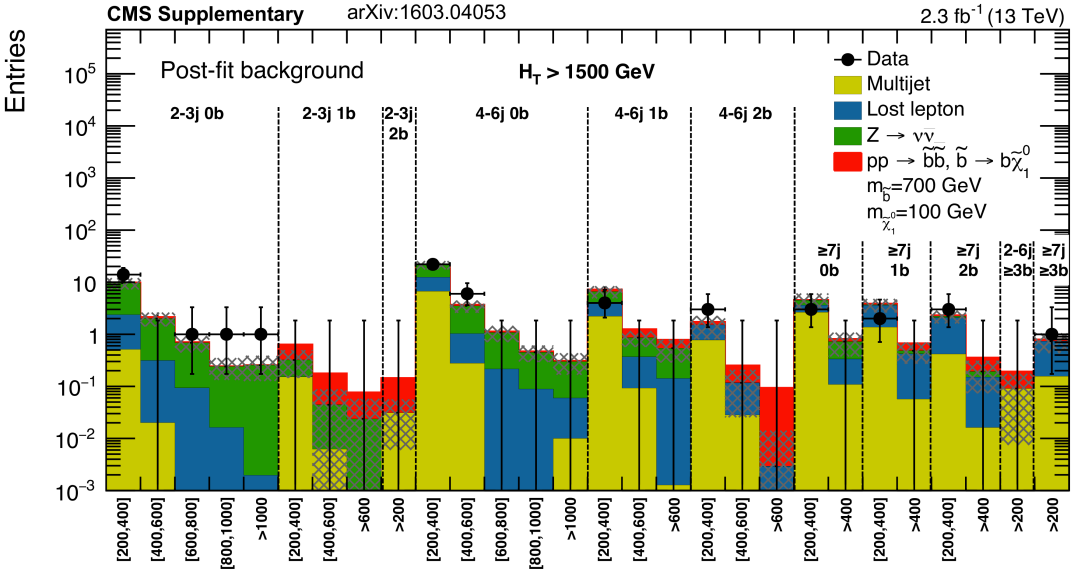


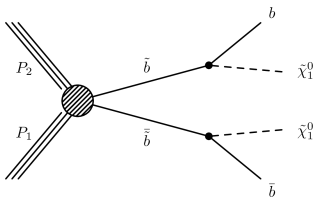


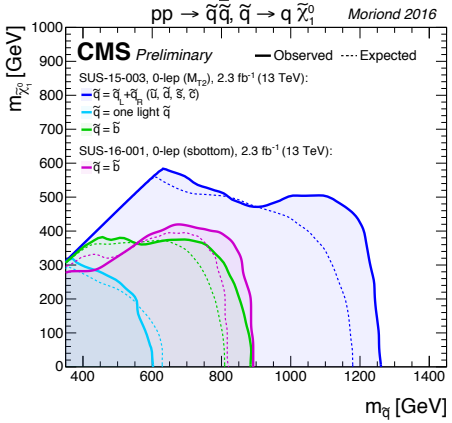


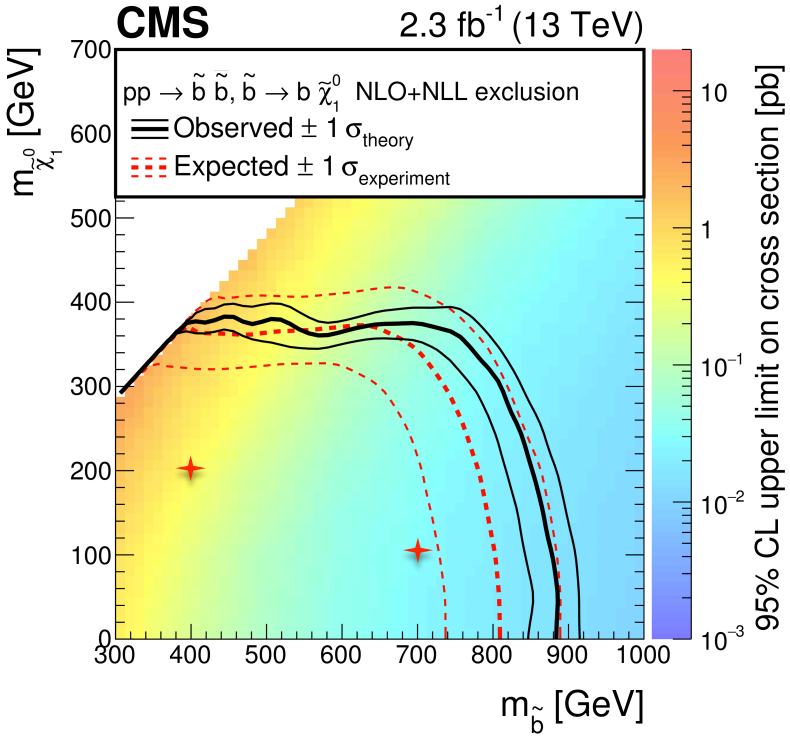
Interpretation of the Results (iv)



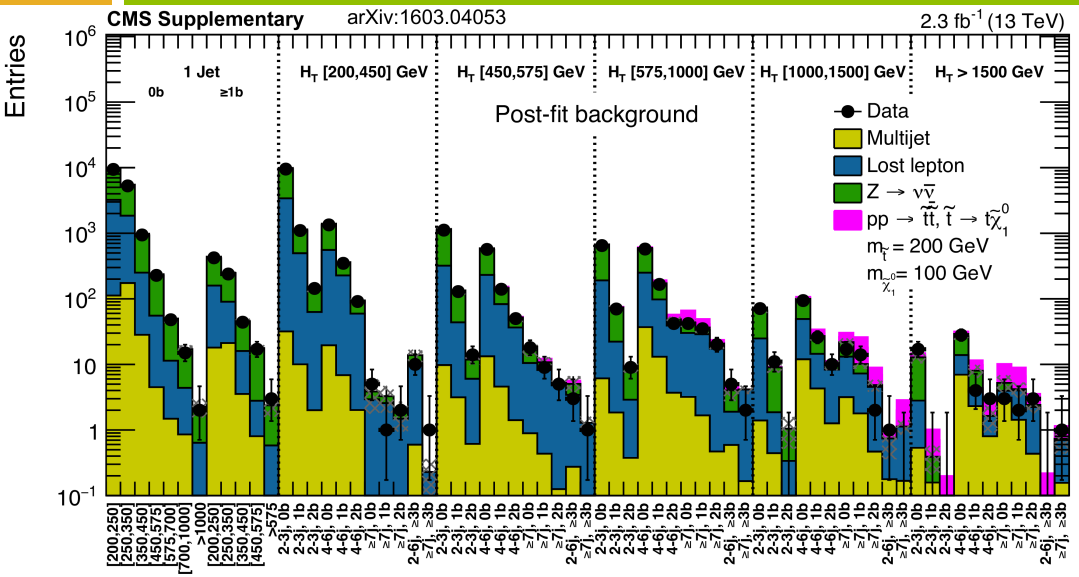


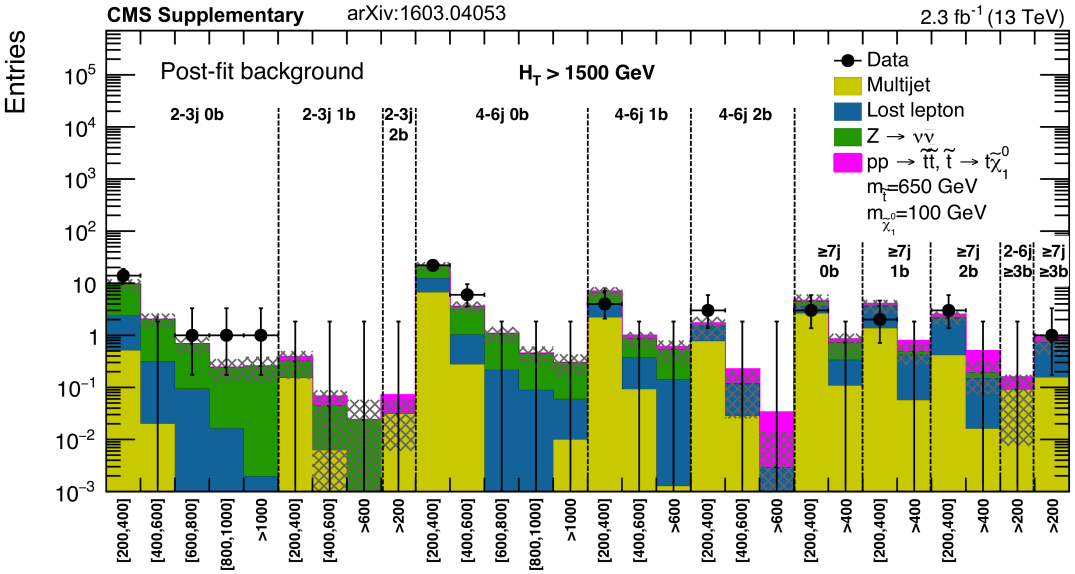


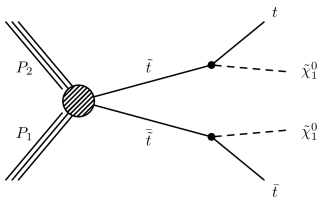


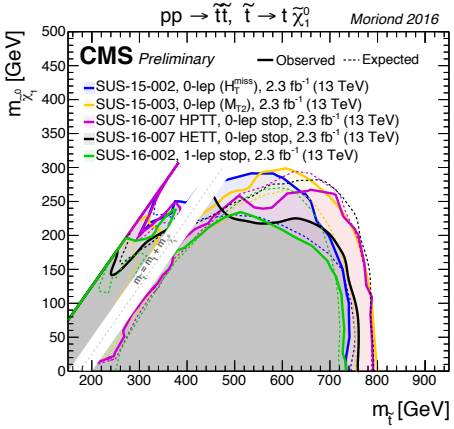


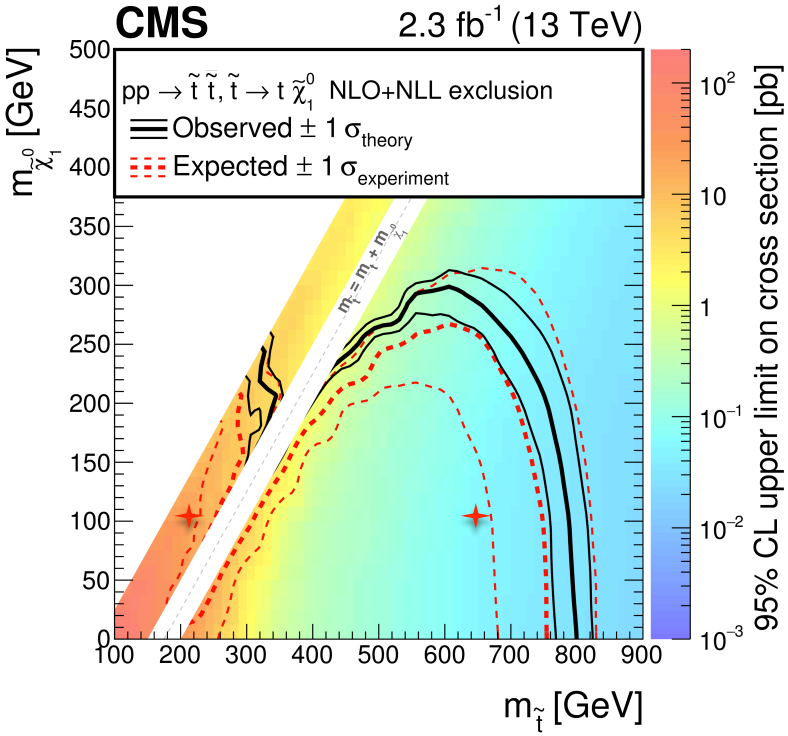
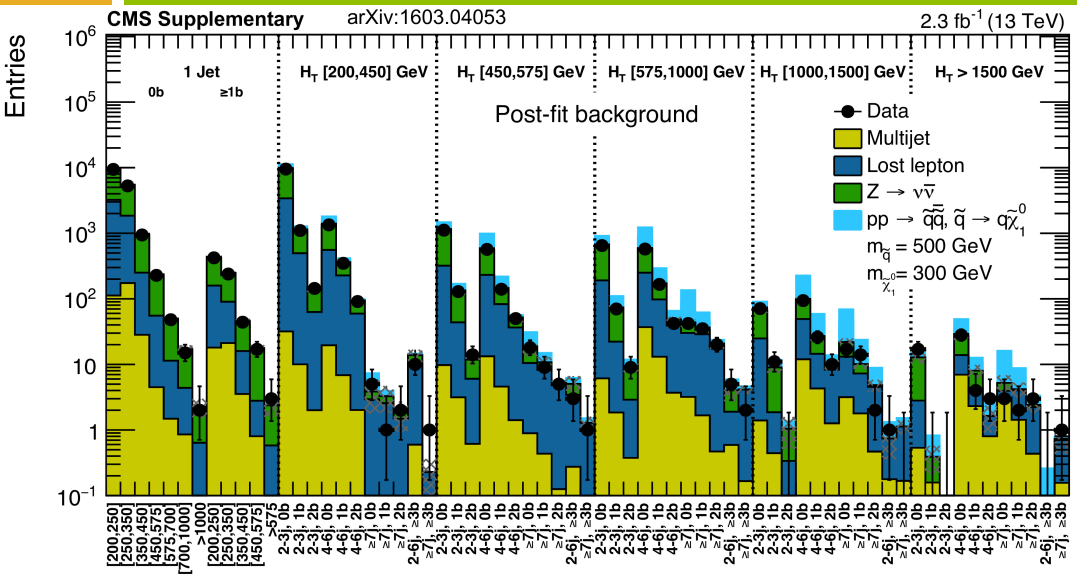
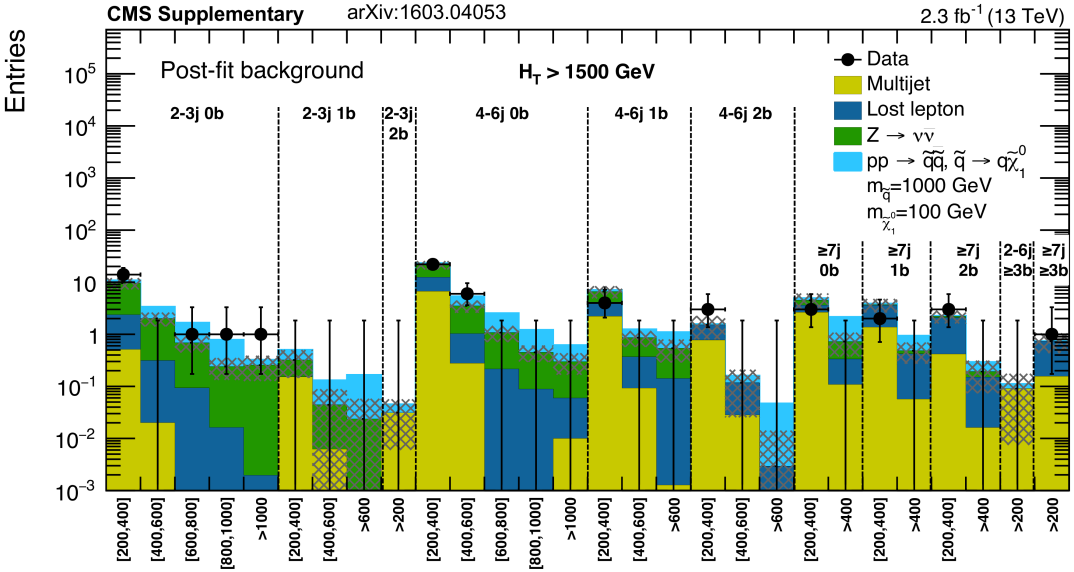
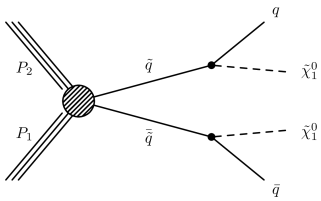
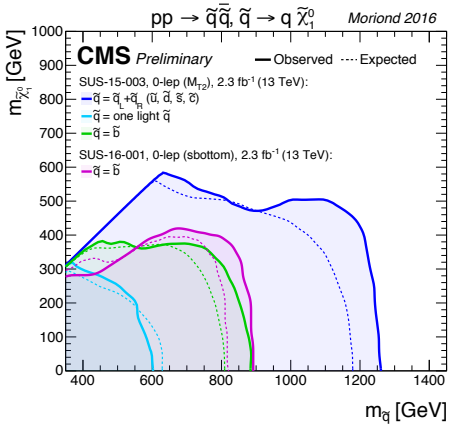
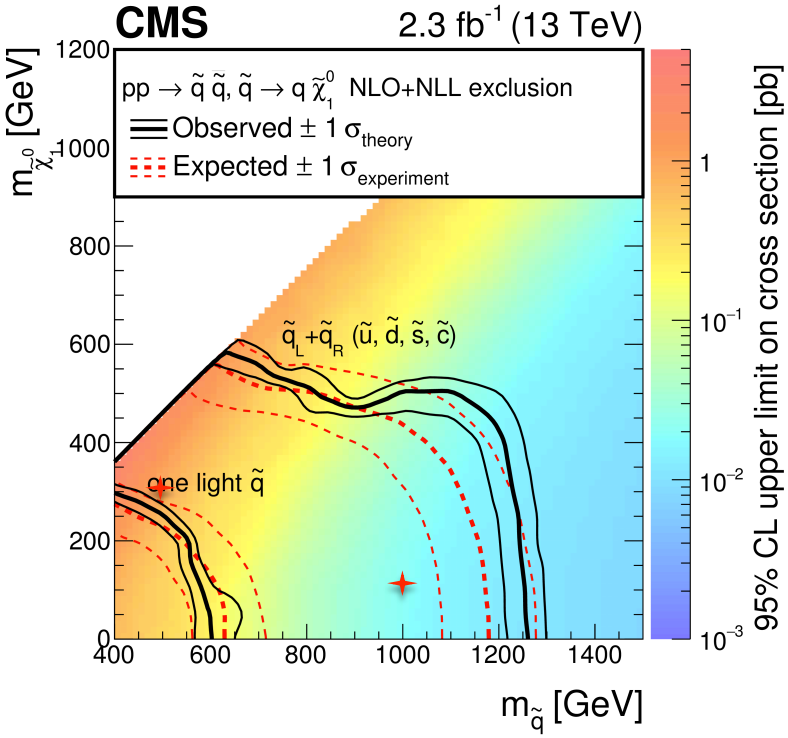
Interpretation of the Results (v)











Interpretation of the Results (vi)