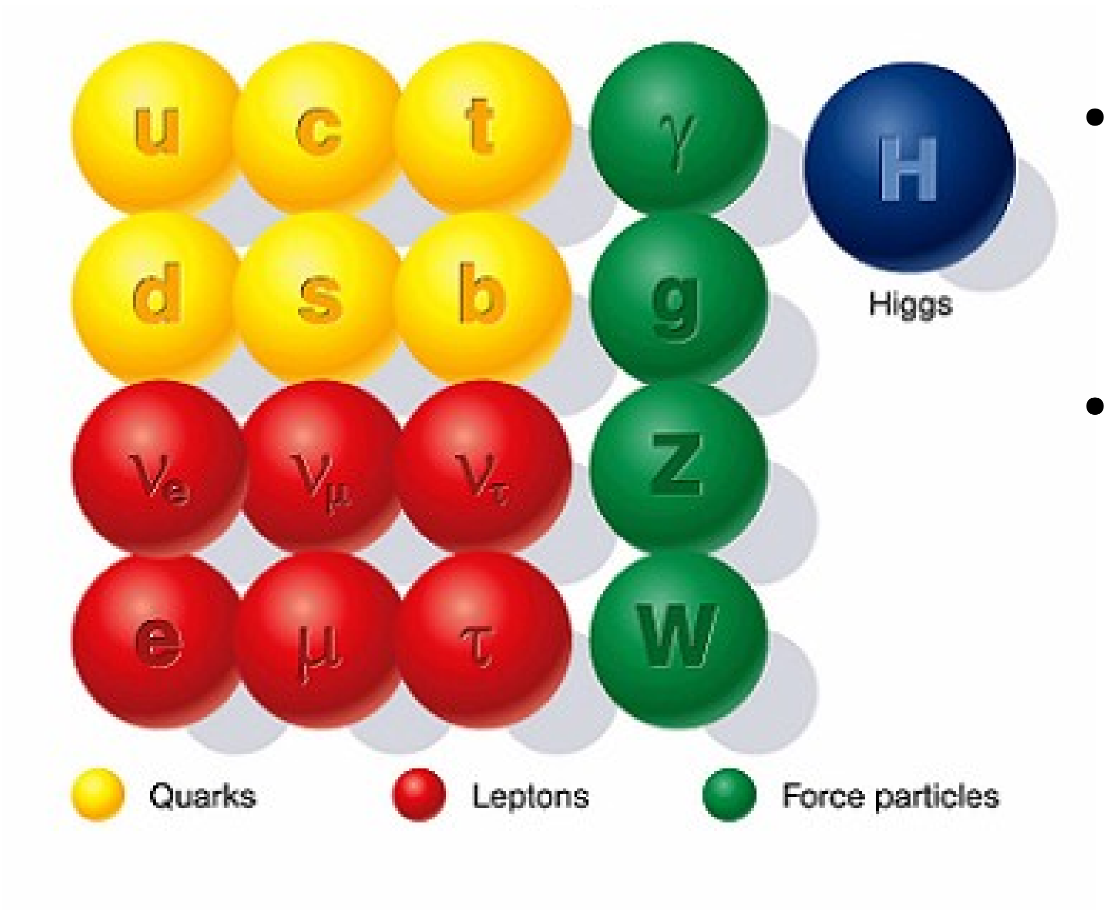
Searches for Dark Matter and Supersymmetry at 13 TeV with CMS

Dominick Olivito
University of California, San Diego

Overview

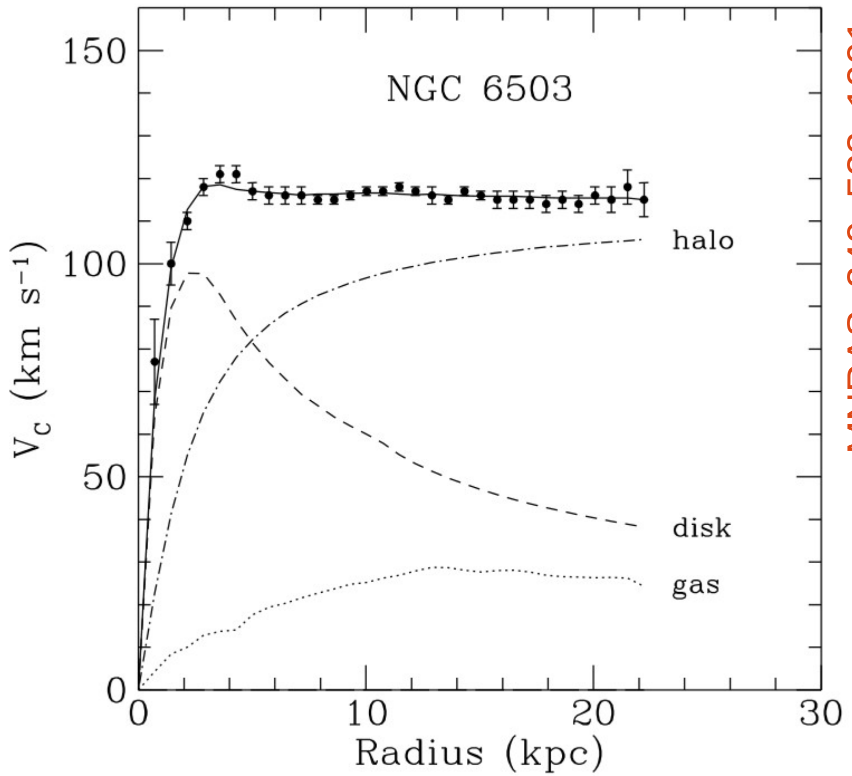
- The Standard Model, Dark Matter, and Supersymmetry
- The Large Hadron Collider, the CMS detector and trigger
- Searching for E_T^{miss} + jets: the M_{T2} analysis
- Searching for E_T^{miss} + $\ell^+\ell^-$ + jets: on and off the Z resonance
- Coming next: searches for electroweak Supersymmetry

The Standard Model of physics works wonderfully, and is incomplete



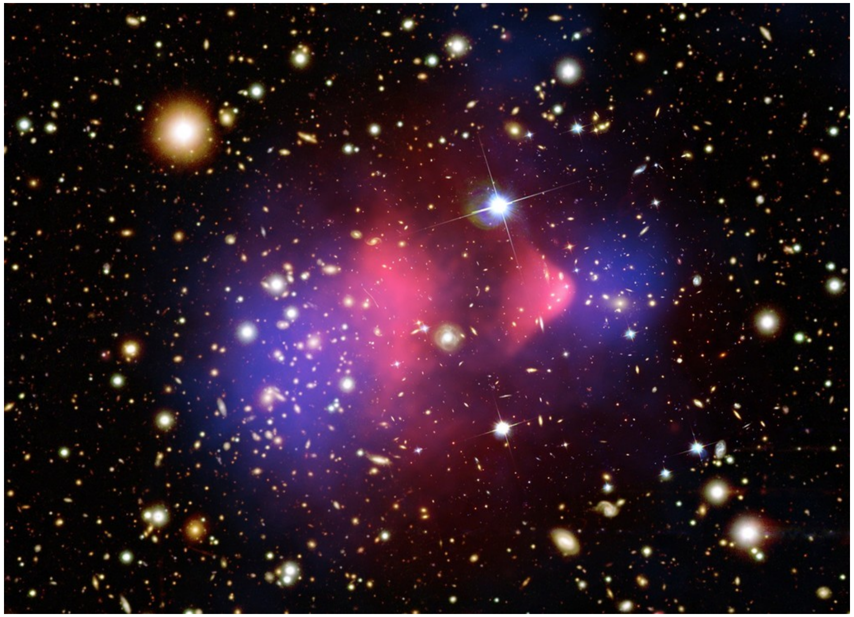
- Unexplained observations:
  - How does dark matter interact with known particles?
- Some theoretical issues:
  - Why is the Higgs boson mass stable at 125 GeV?
  - Do the strong, weak, and electromagnetic forces unite at some high scale?

Dark Matter is more abundant than known matter, but remains mysterious

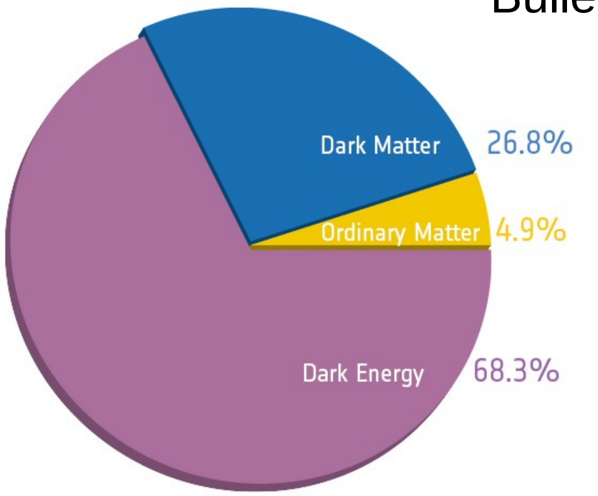


MNRAS, 249, 523, 1991

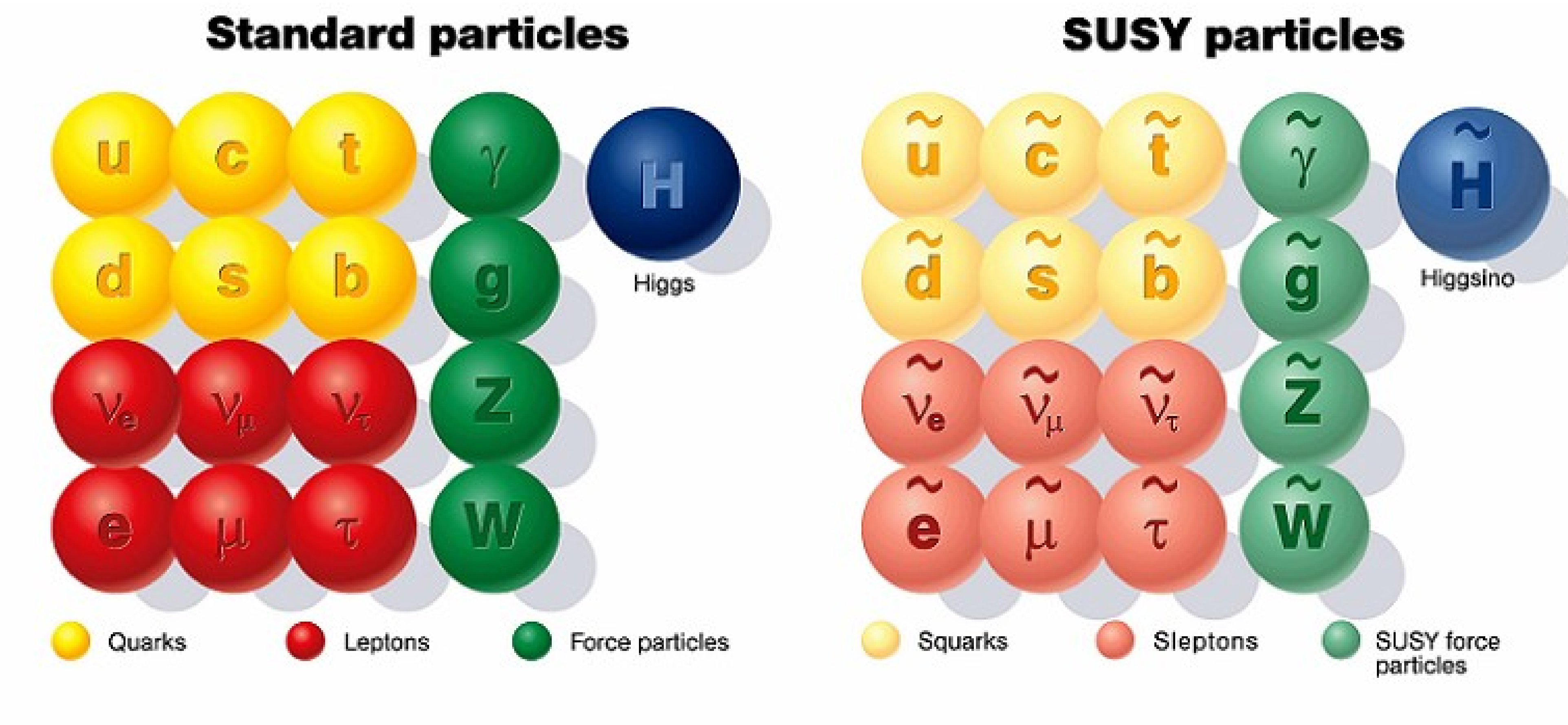
Galactic Rotation Curves



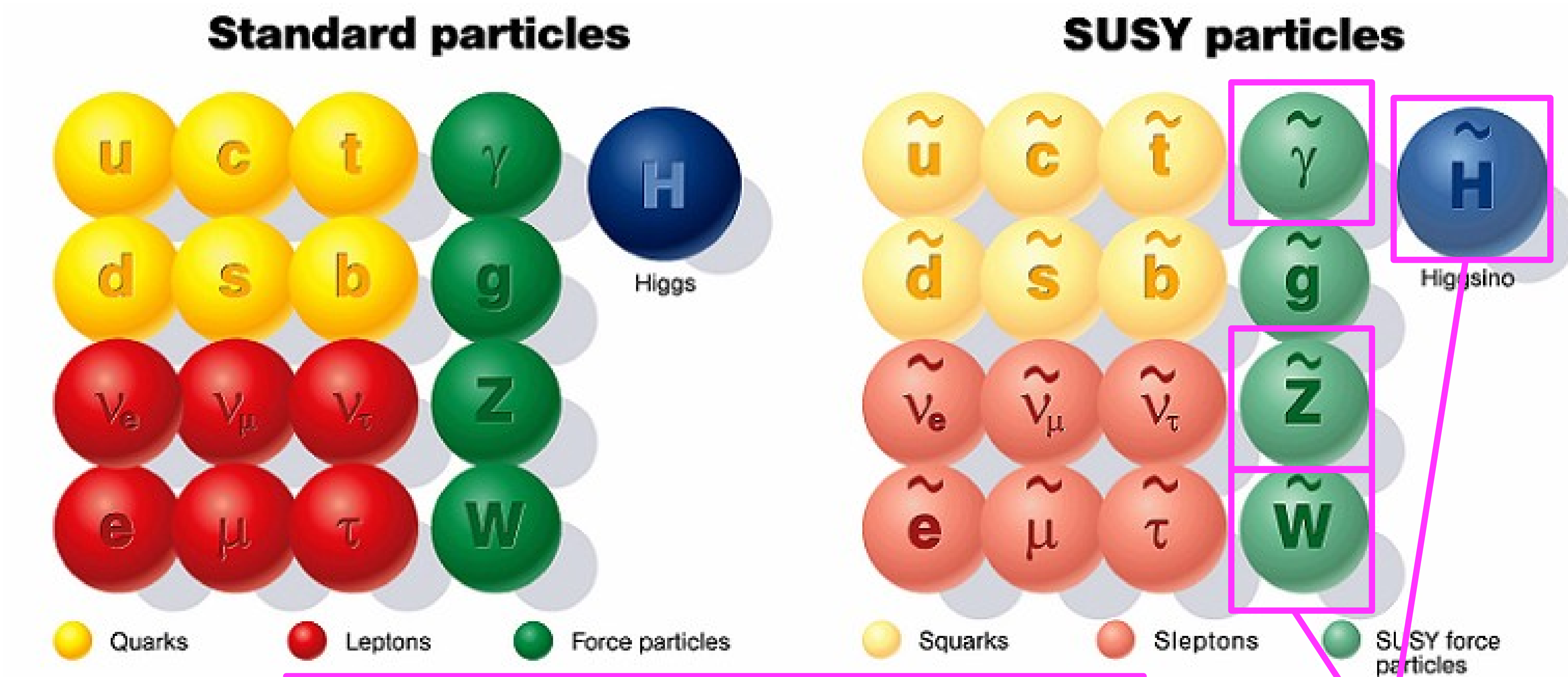
Bullet Cluster



Supersymmetry (SUSY) can explain Dark Matter and solve other problems



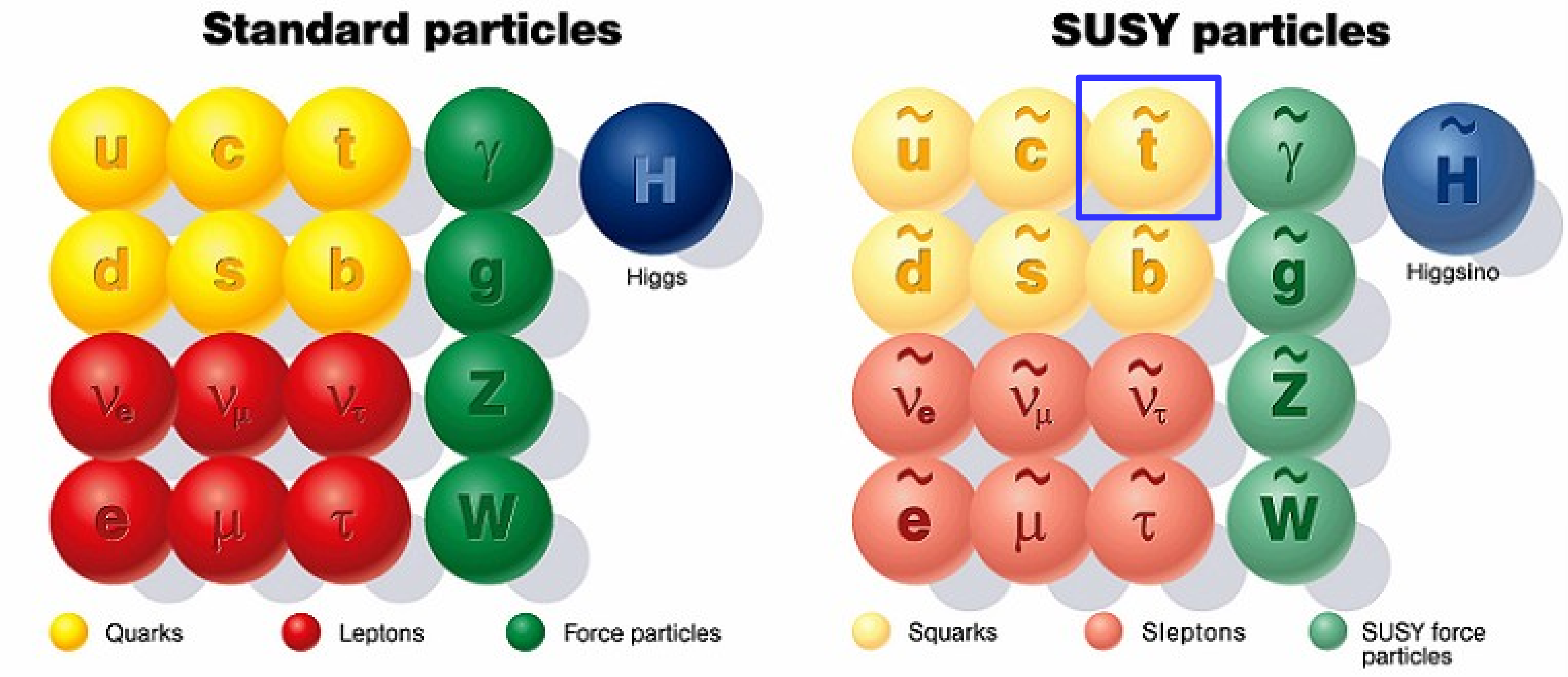
Supersymmetry (SUSY) can explain Dark Matter and solve other problems



$$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0 \qquad \tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$$

- The **lightest SUSY particle (LSP)** is a dark matter candidate if stable due to R-parity

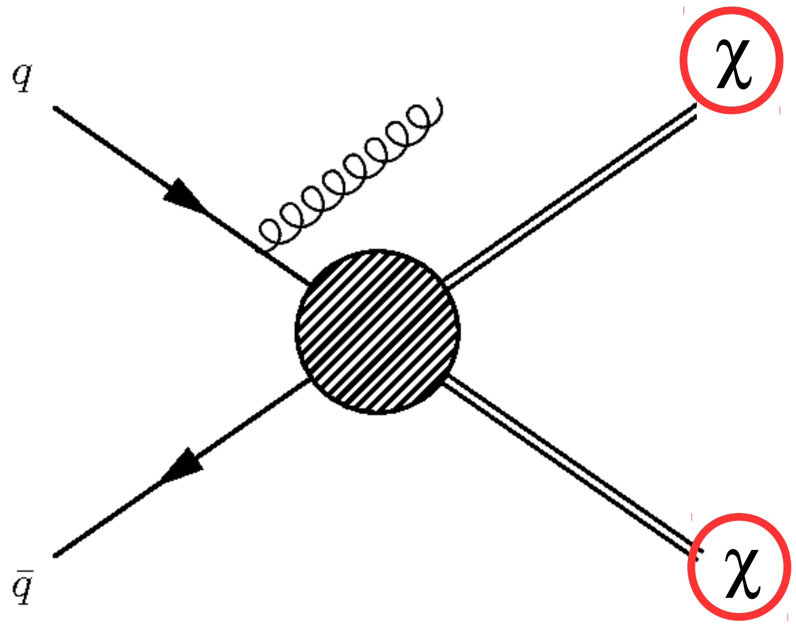
Supersymmetry (SUSY) can explain Dark Matter and solve other problems



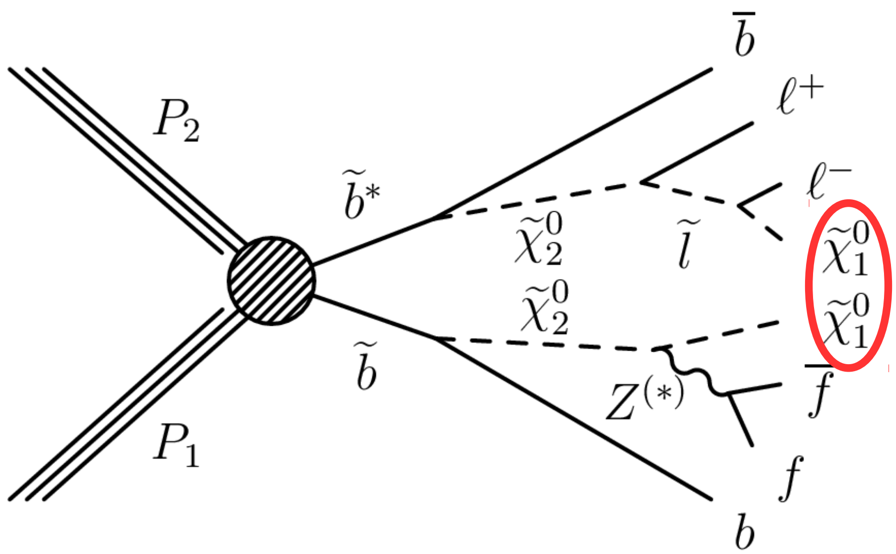
- The **top squark** can stabilize Higgs mass by canceling loop effects from the Standard Model top quark

Dark Matter particles could be produced in proton-proton collisions

- The SUSY LSP is part of a broader class of Weakly Interacting Massive Particles (WIMPs) that could appear

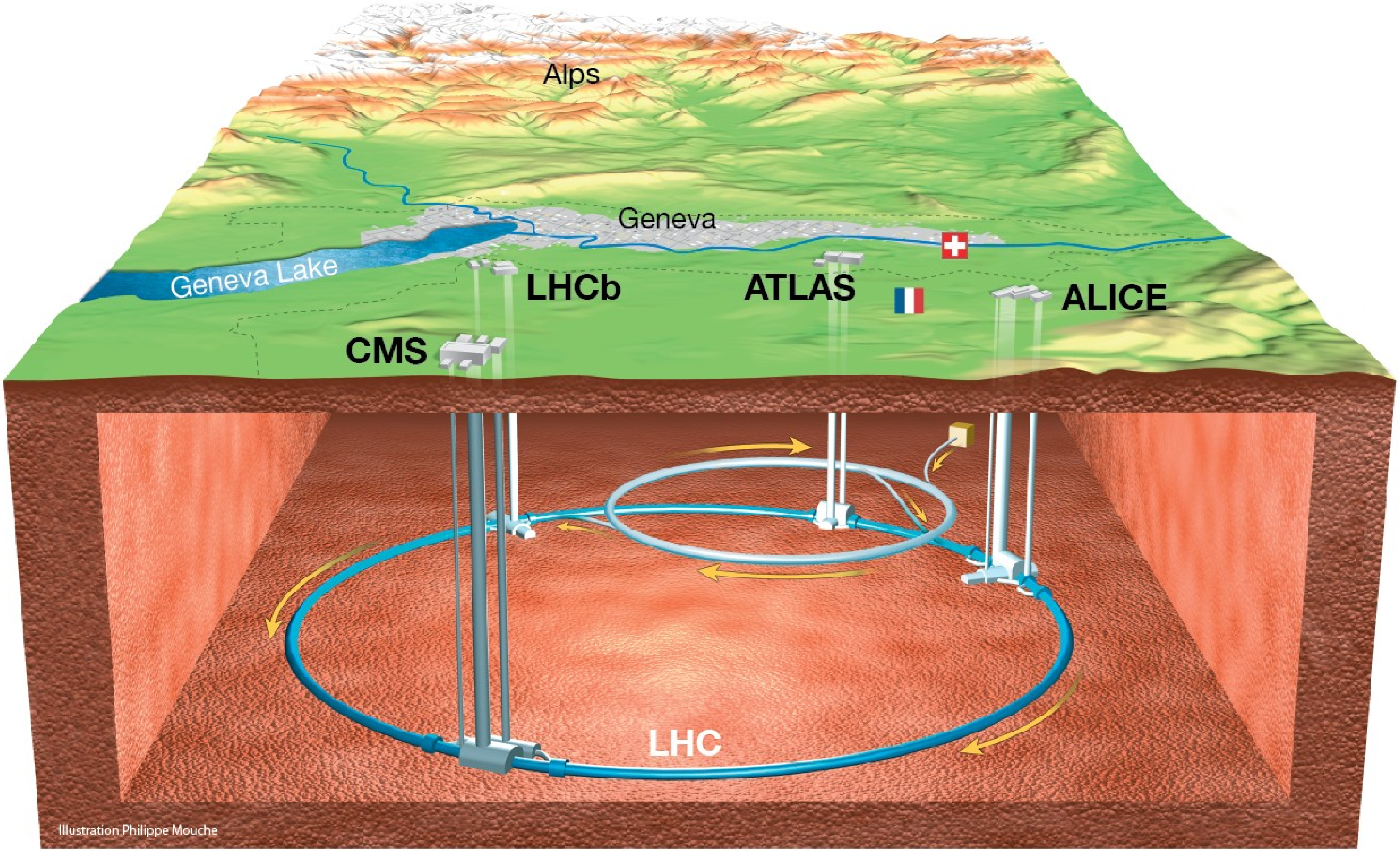


Anti-social
With minimal additional particles



Or social
With many additional particles

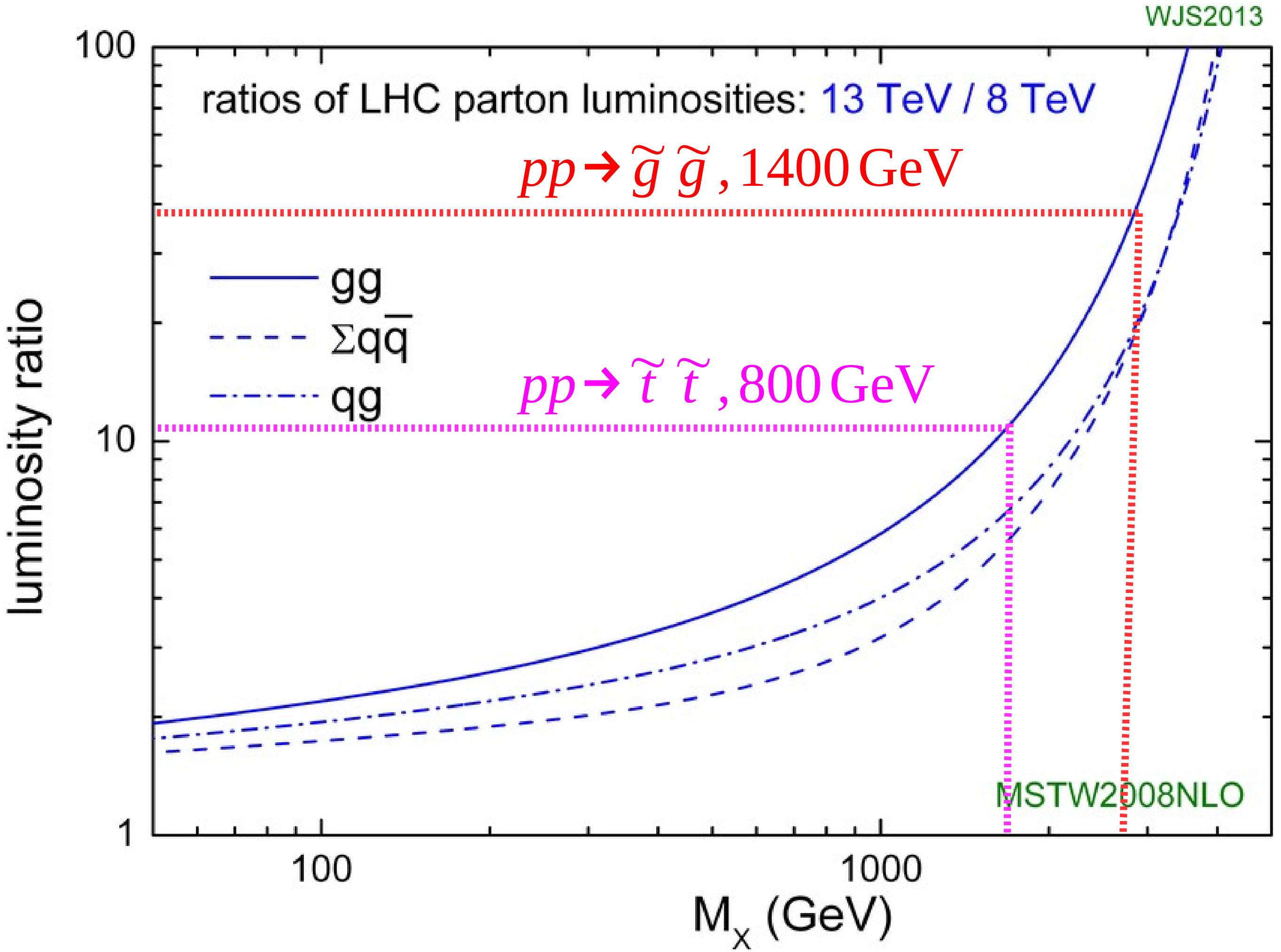
The Large Hadron Collider (LHC) is our instrument at the energy frontier



2015: pp center of mass energy increased from 8 to 13 TeV

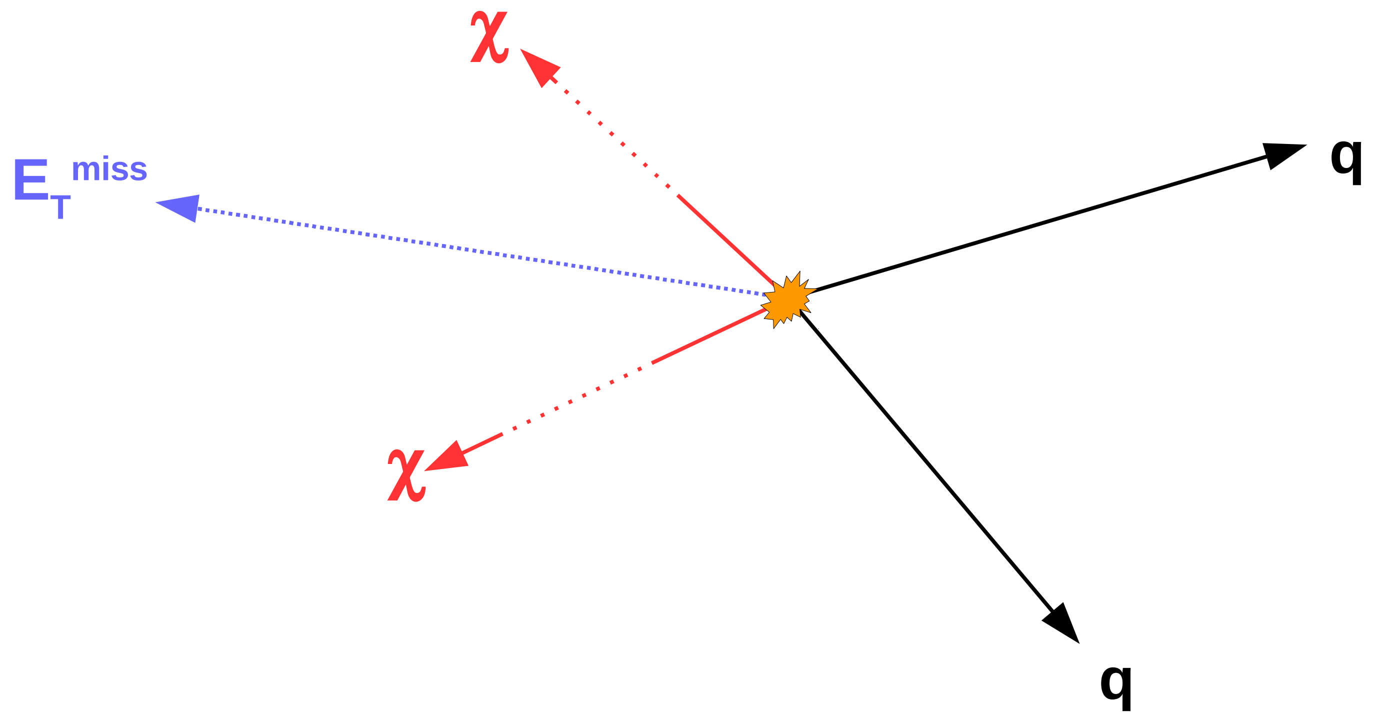
Strong production has the highest SUSY cross section

- Highest mass limits from LHC Run 1
- Benefits the most from 8→13 TeV energy increase



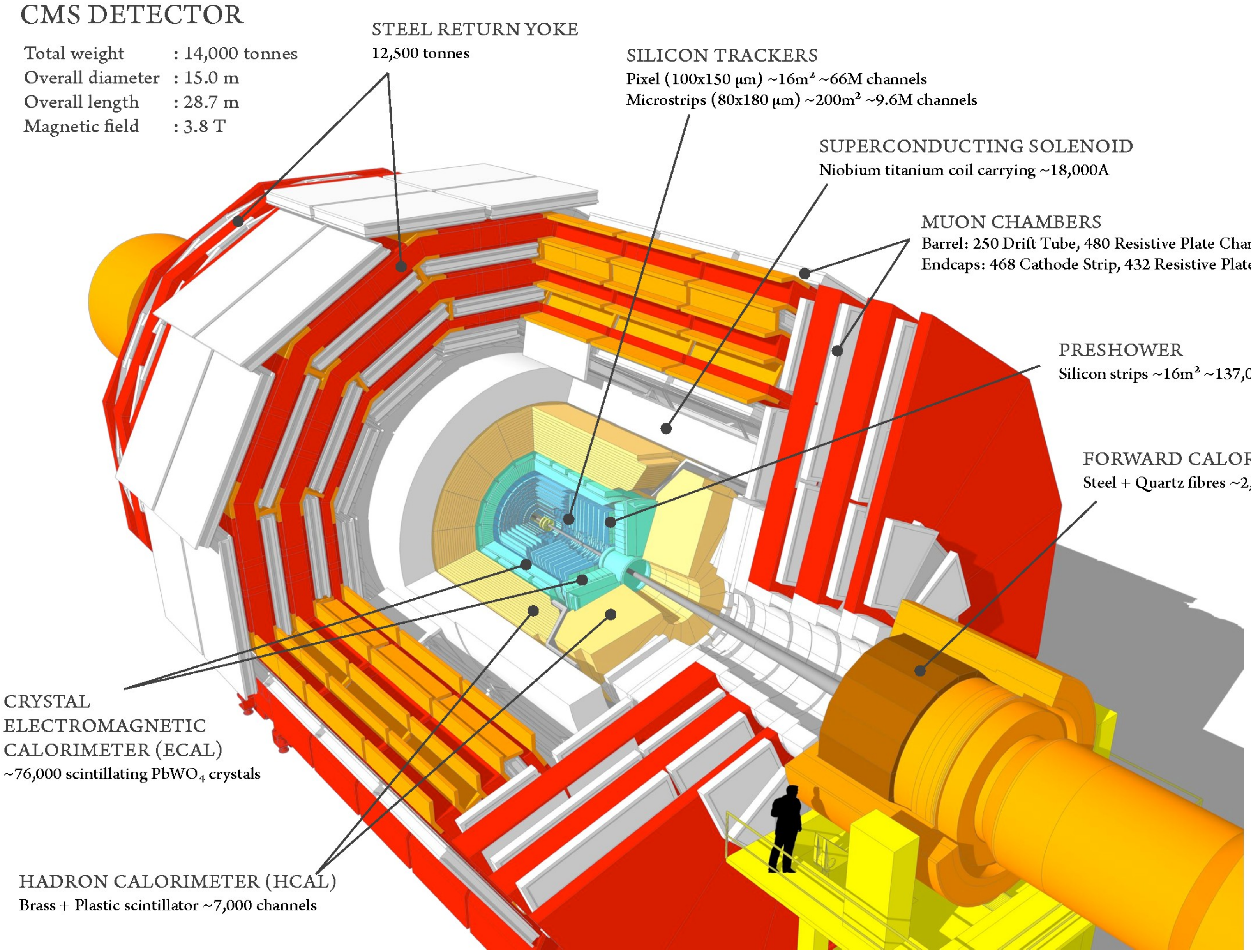
Missing Transverse Momentum (E_T^{miss}) is the signature of Dark Matter

- **WIMPs** do not interact and escape the detector
- We infer their presence through an **imbalance in the event**
- Strong production or initial state radiation → **hadronic jets**

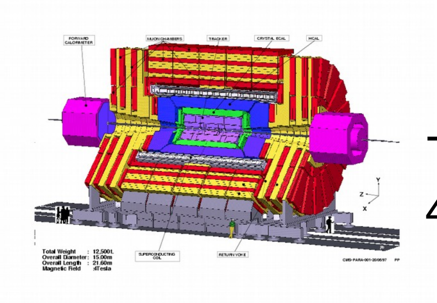


Plane transverse to beam

The CMS detector measures collision decay products precisely to infer E_T^{miss}



The CMS trigger quickly rejects the uninteresting 99.998% of events

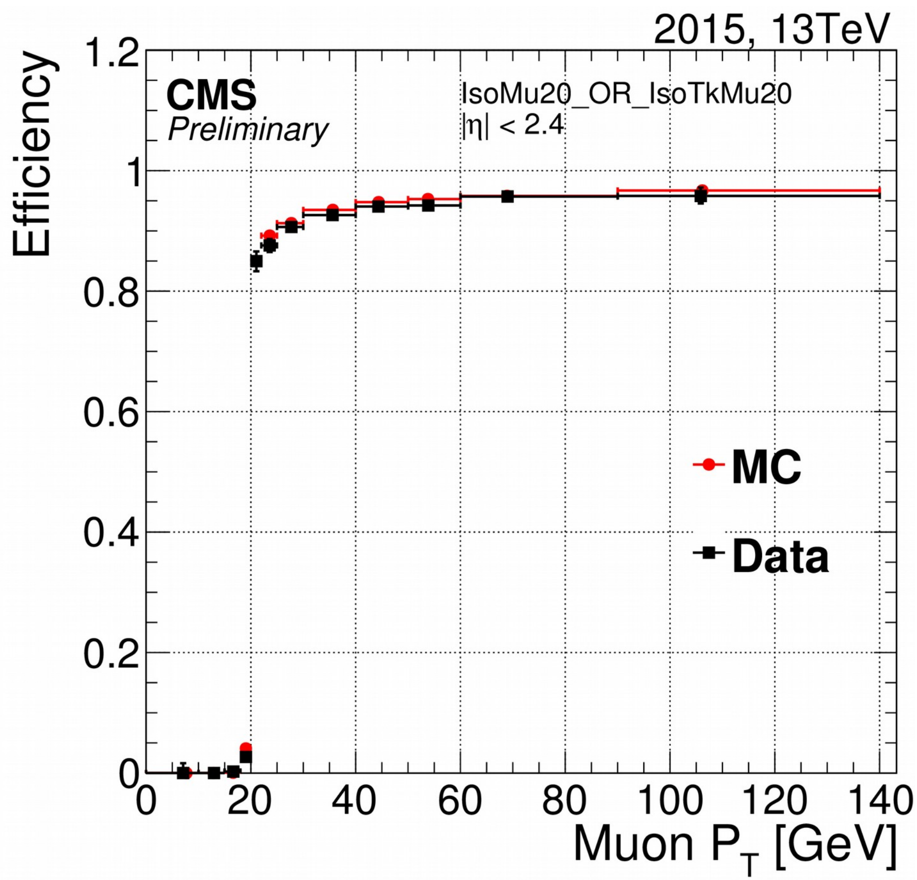


40 MHz → Level 1 (L1) Trigger → 100 kHz → High Level Trigger (HLT) → 1 kHz →

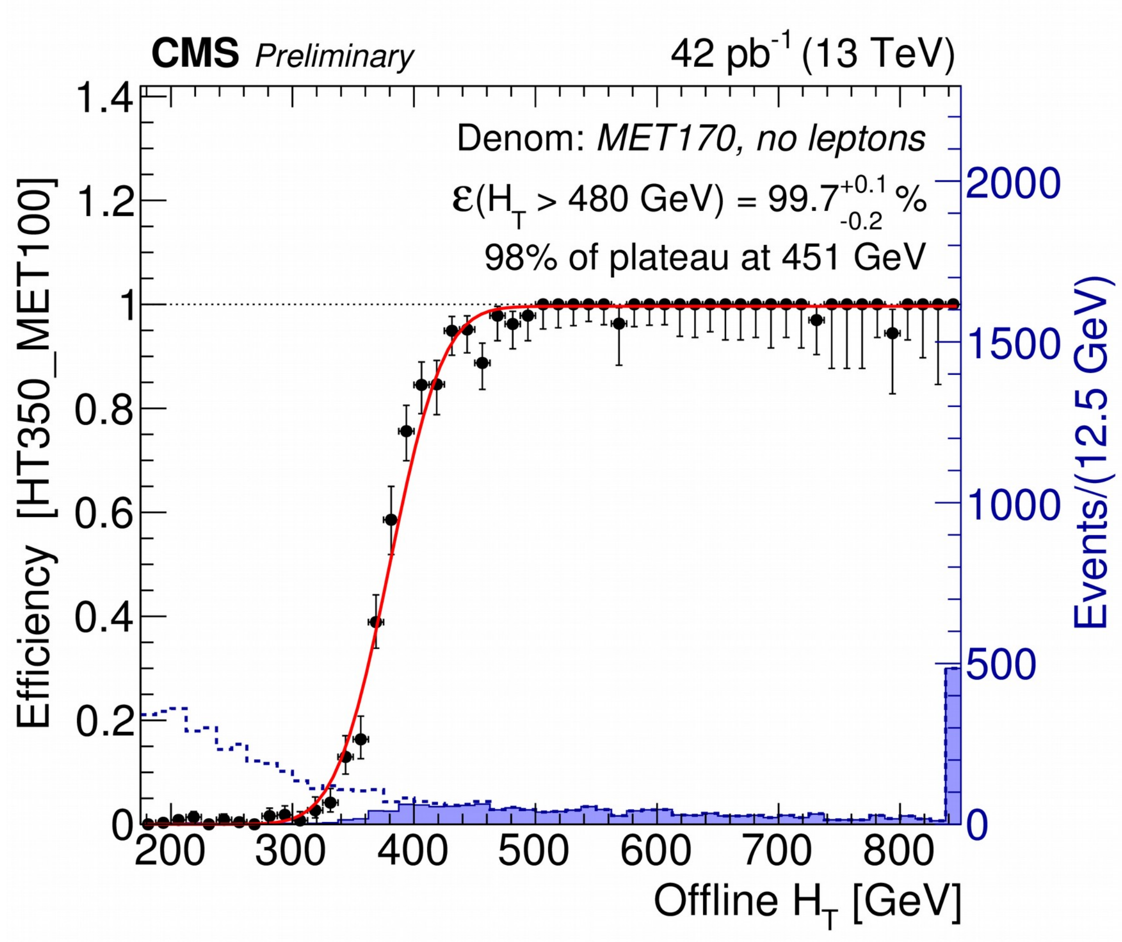
Level 1 (L1) Trigger	High Level Trigger (HLT)	
Hardware / Firmware	Software	Reconstruction, Storage

- Collision events not selected are lost forever
- Developed several of the trigger paths used in these analyses:
  - Tracker-based reconstruction for single muons
    - Complementary to existing outside-in reconstruction
    - Improved efficiency especially at lower p_T
  - Tracker-based isolation for muons
    - Improved speed and efficiency
  - Single photons, H_T (scalar sum of jet p_T), H_T+E_T^{miss}

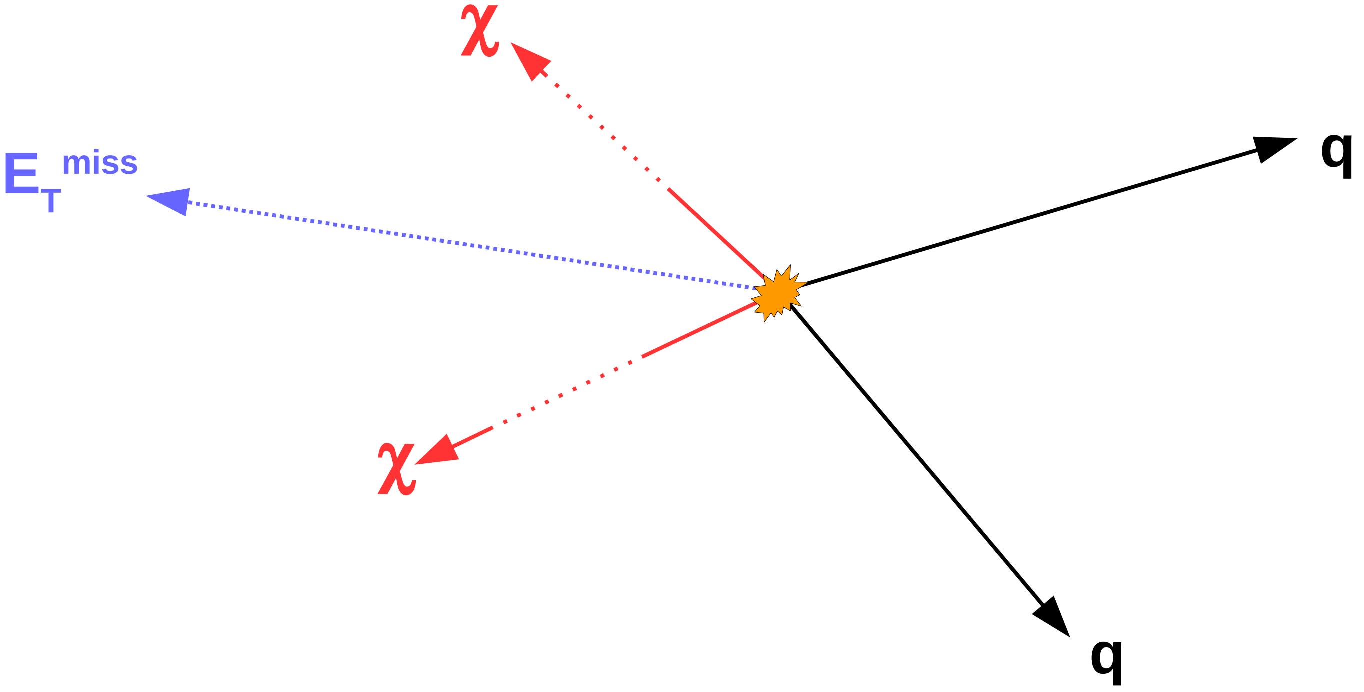
The triggers we use are highly efficient



Tracker muon reconstruction (IsoTkMu20) complements standard outside-in reco



H_T+E_T^{miss} path used for M_{T2} analysis



Searching for E_T^{miss} + jets: the M_{T2} analysis

CMS-PAS-SUS-15-003

The M_{T2} analysis searches for E_T^{miss} + jets as inclusively as possible

- Our baseline selection is as loose as possible given our triggers and targeted reduction of instrumental backgrounds
- We categorize events using four variables: H_T, N_J, N_B, M_{T2}

- <u>Main backgrounds:</u>
  - **$Z\rightarrow\nu\nu$+jets:** E_T^{miss} from $\nu\nu$
    - most SUSY-like background, estimated primarily using γ+jets
  - **"Lost lepton": $W\rightarrow\ell^{\pm}\nu$ in W+jets and ttbar:** E_T^{miss} from ν
    - reduce by vetoing on charged lepton, estimate with found lepton sample
  - **QCD multijets:** E_T^{miss} from jet mismeasurement
    - reduce with M_{T2} and other cuts, estimate from mismeasured jet sample

- We perform a simultaneous likelihood fit over all signal bins to place constraints on new physics models

We categorize events for sensitivity to a broad range of signatures

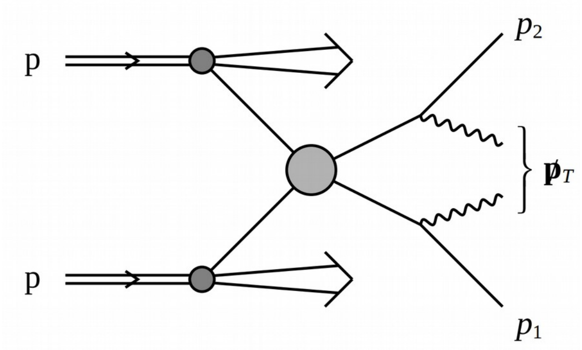
- Unknown mass scale and mass splittings
  - **H_T**: scalar sum of jet p_T → visible energy scale
    - Bins from 200 to > 1500 GeV
  - **M_{T2}**: missing energy scale
    - Bins from 200 to > 1000 GeV

- Unknown parton multiplicity
  - **N_J**: number of jets with p_T > 30 GeV, $|\eta| < 2.5$
    - Bins from 1 to ≥7

- Unknown flavor content
  - **N_B**: number of b-tagged jets, p_T > 20 GeV, $|\eta| < 2.5$
    - Bins from 0 to ≥3

The "stransverse mass" M_{T2} strongly suppresses jet mismeasurement

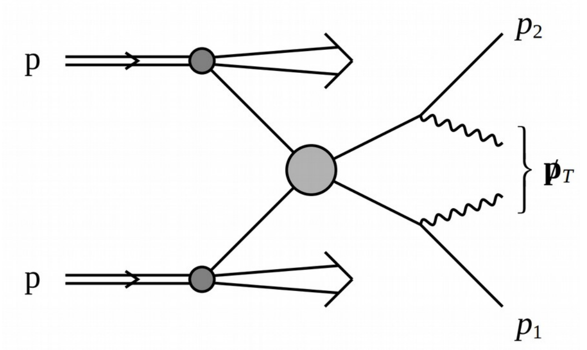
- M_{T2} is a generalization of M_T for decay chains with two unobserved particles
  - Typical in SUSY events
- As visible objects, use jets clustered into 2 hemispheres



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

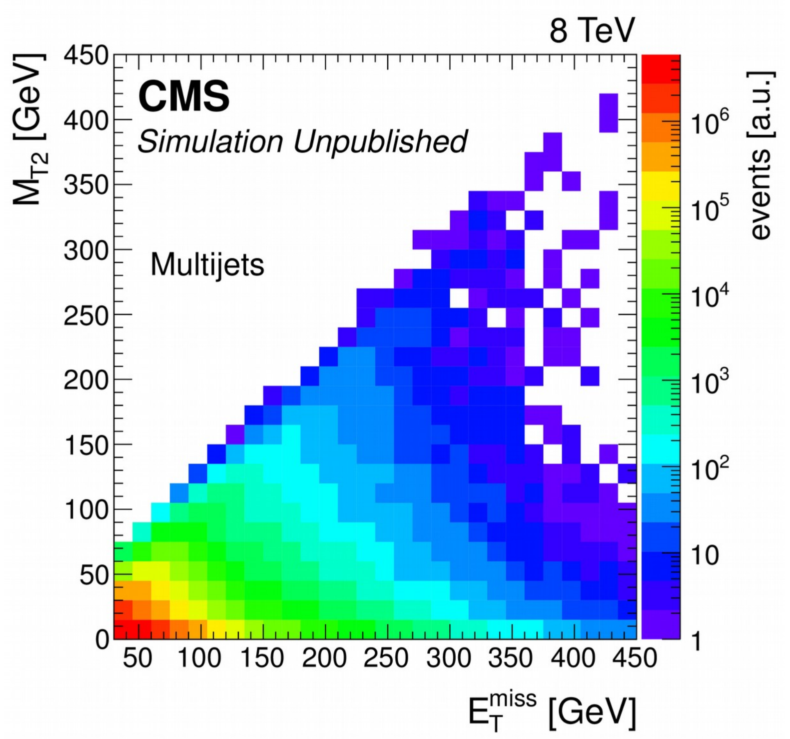
The "stransverse mass" M_{T2} strongly suppresses jet mismeasurement

- M_{T2} is a generalization of M_T for decay chains with two unobserved particles
  - Typical in SUSY events
- As visible objects, use jets clustered into 2 hemispheres



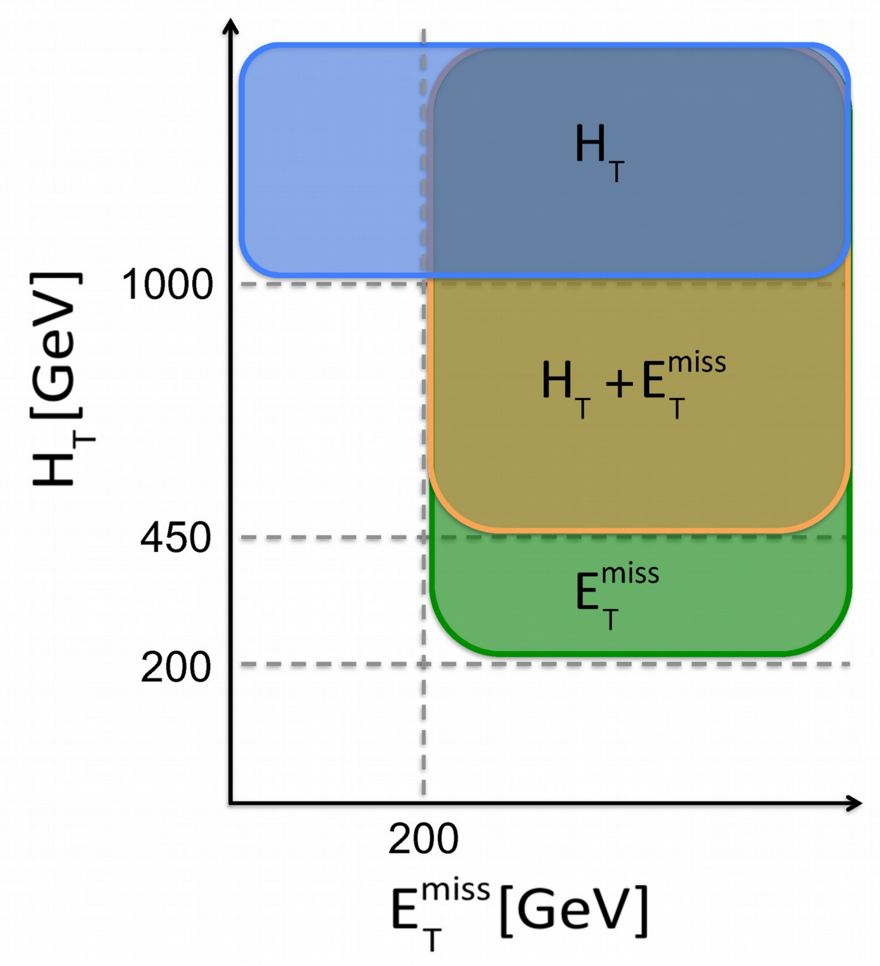
$$M_{T2} \simeq 2\, p_T^{vis(1)}\, p_T^{vis(2)} \left(1 + \cos\left(\Delta\phi_{1,2}\right)\right)$$

- **SUSY signals:**
  - Symmetric hemispheres
  - Small-ish angle
  - $M_{T2} \sim E_T^{miss}$
- **QCD multijet events:**
  - Hemispheres back-to-back
  - Or asymmetric
  - $M_{T2} << E_T^{miss}$

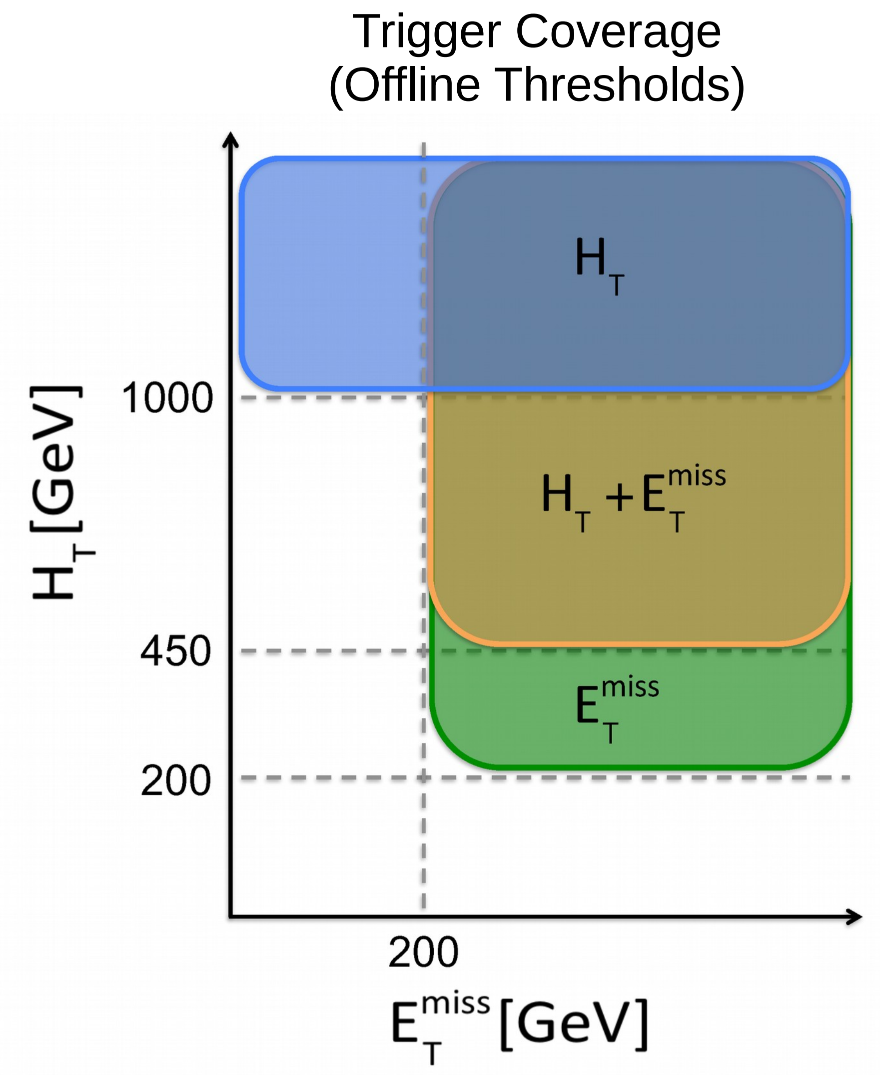


Our baseline selection is dictated by triggers plus multijet suppression

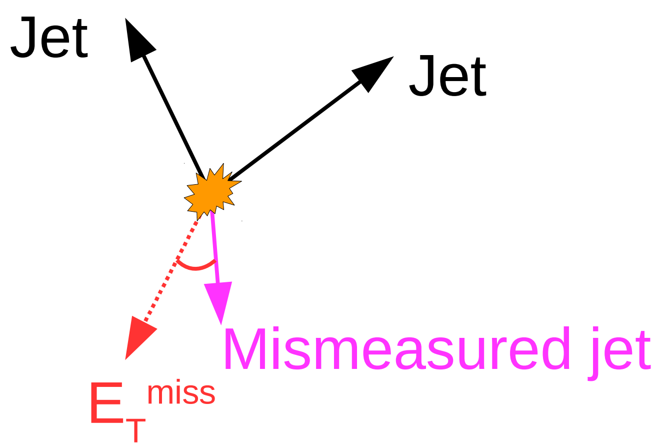
Trigger Coverage
(Offline Thresholds)



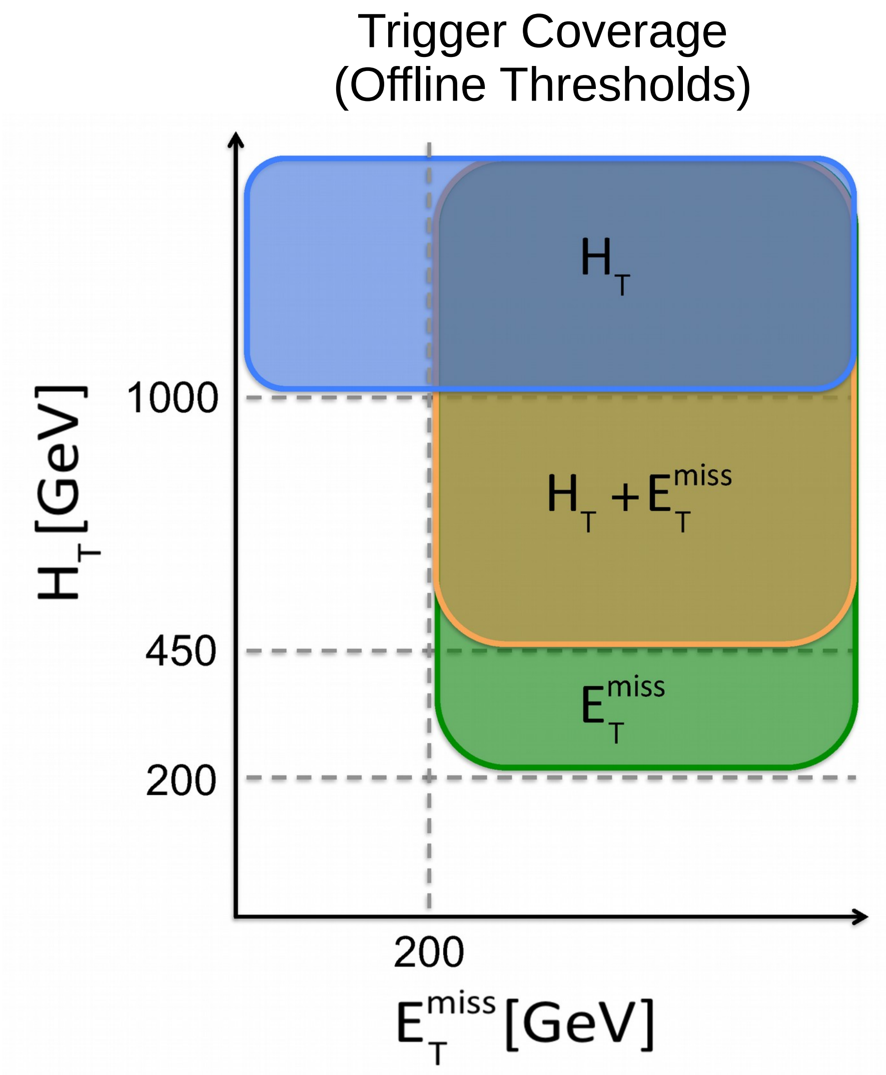
Our baseline selection is dictated by triggers plus multijet suppression



- **Reject multijets:**
  - $\Delta\phi_{min} > 0.3$
    - $\Delta\phi_{min} = \min(\Delta\phi(E_T^{miss}, j_{1,2,3,4}))$

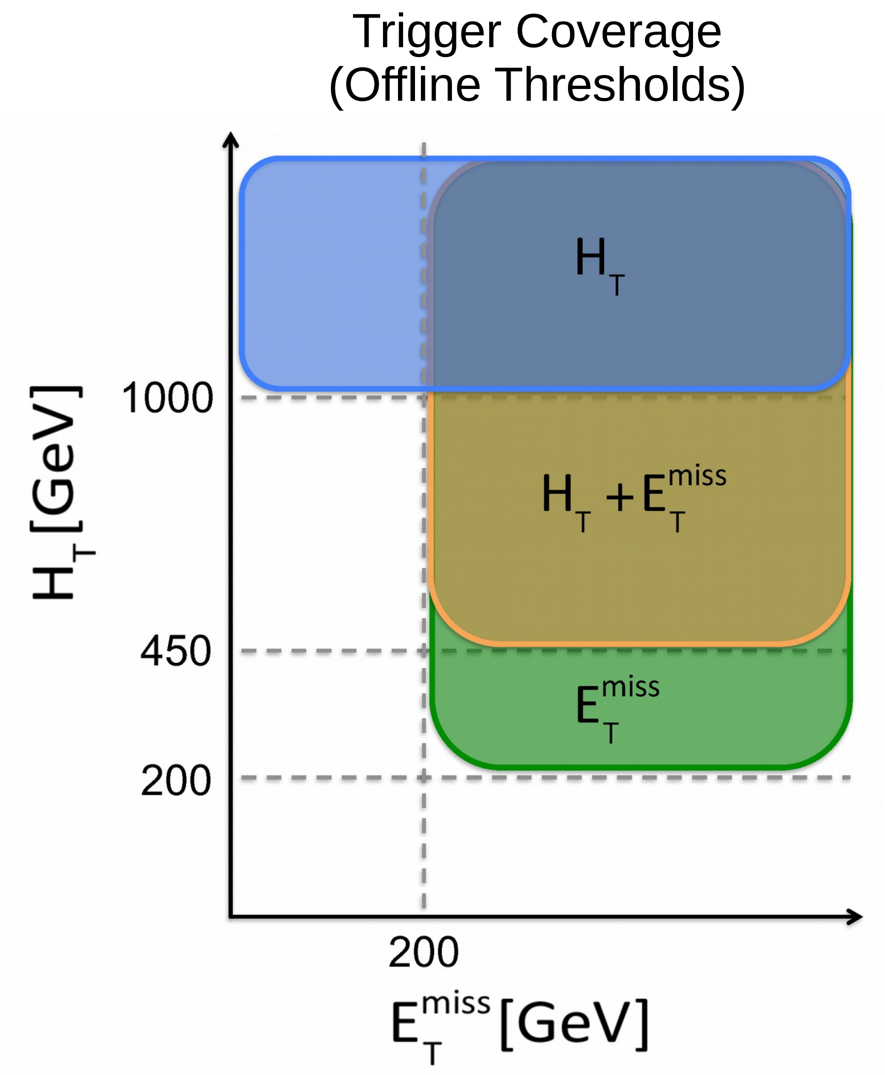


Our baseline selection is dictated by triggers plus multijet suppression



- **Reject multijets:**
  - $\Delta\phi_{min} > 0.3$
    - $\Delta\phi_{min} = \min(\Delta\phi(E_T^{miss}, j_{1,2,3,4}))$
  - $\frac{|\vec{H}_T^{miss} - \vec{E}_T^{miss}|}{E_T^{miss}} < 0.5$

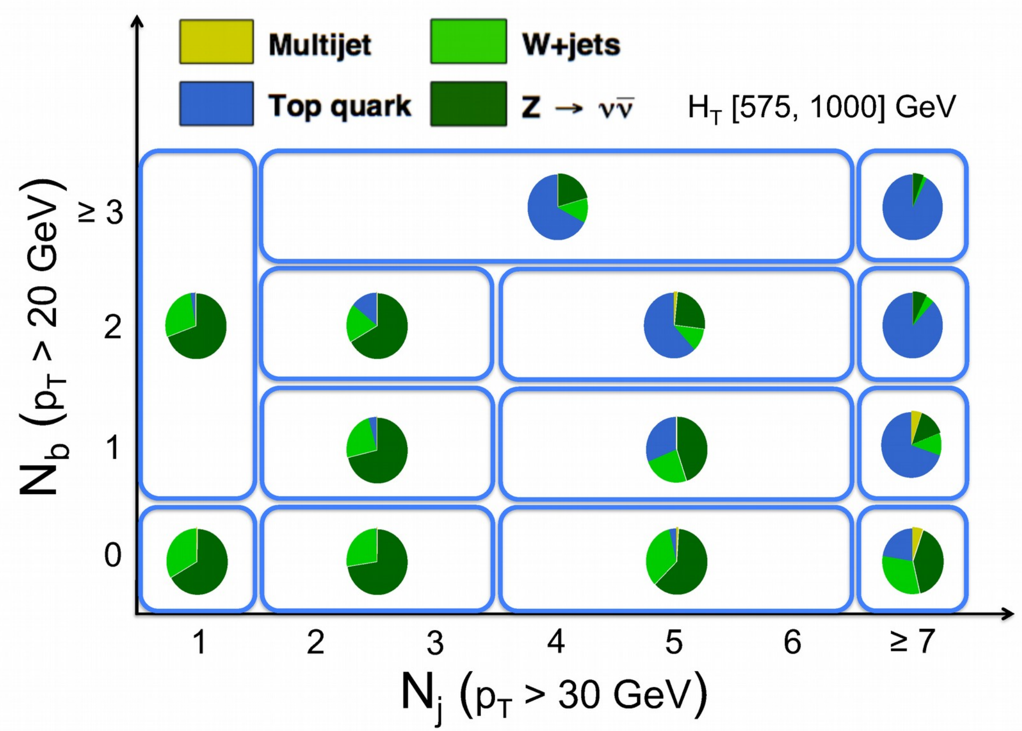
Our baseline selection is dictated by triggers plus multijet suppression



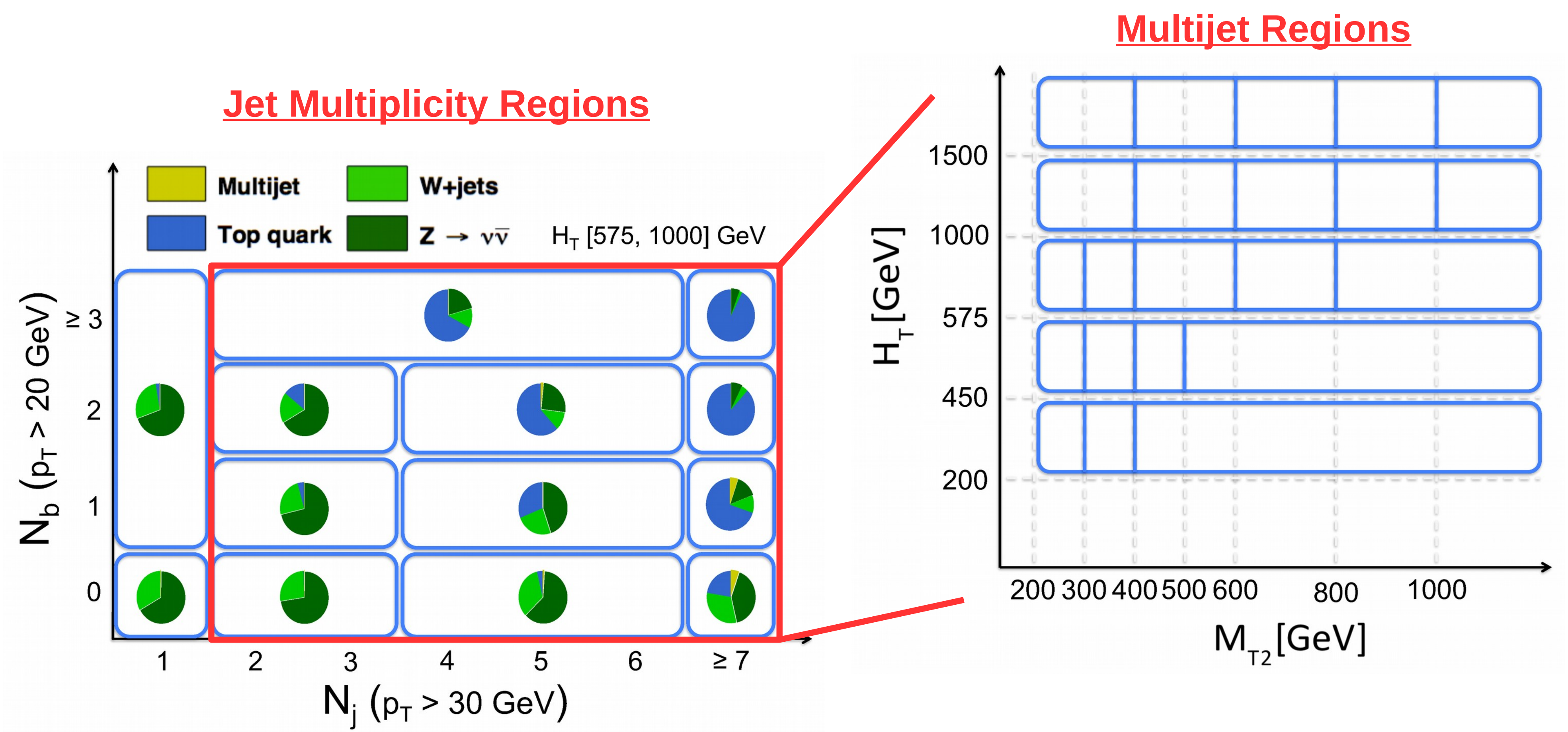
- **Reject multijets:**
  - $\Delta\phi_{min} > 0.3$
    - $\Delta\phi_{min} = \min(\Delta\phi(E_T^{miss}, j_{1,2,3,4}))$
  - $\frac{|\vec{H}_T^{miss} - \vec{E}_T^{miss}|}{E_T^{miss}} < 0.5$
- **Reject $W \rightarrow \ell^{\pm}\nu$:**
  - Charged lepton/track veto

We categorize events based on N_J, N_B

Jet Multiplicity Regions

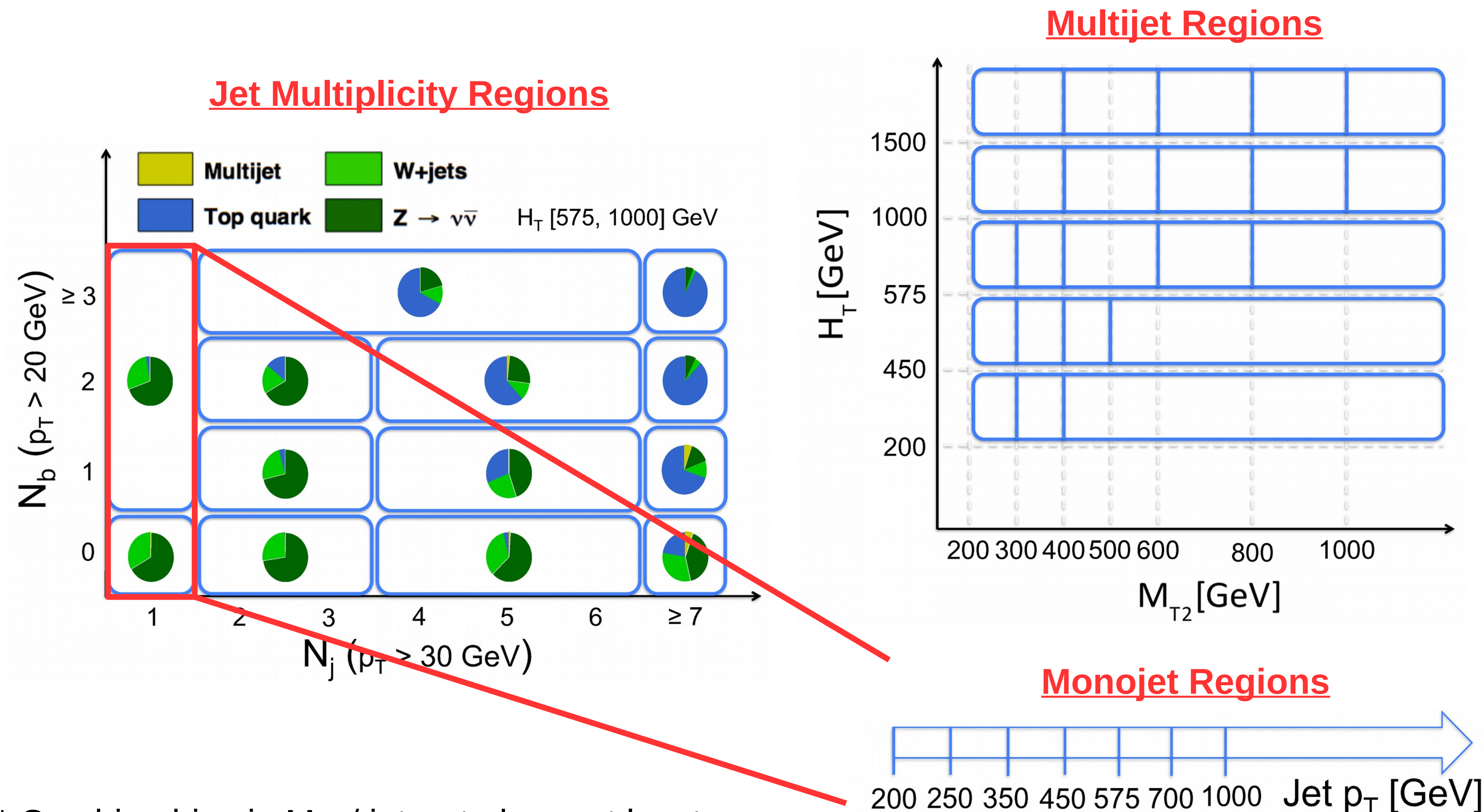


Then using H_T and M_{T2} for multijet



* Combine bins in M_{T2} / jet p_T to have at least
1 expected background event for each (H_T,N_J,N_B) region

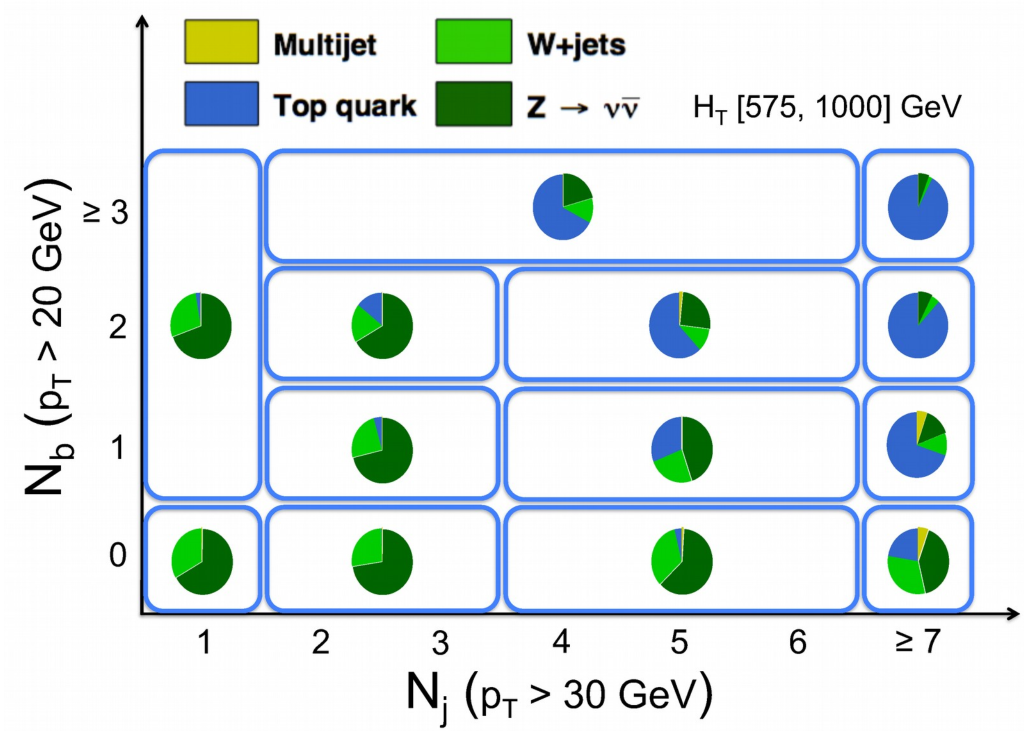
Or the jet p_T for monojet events



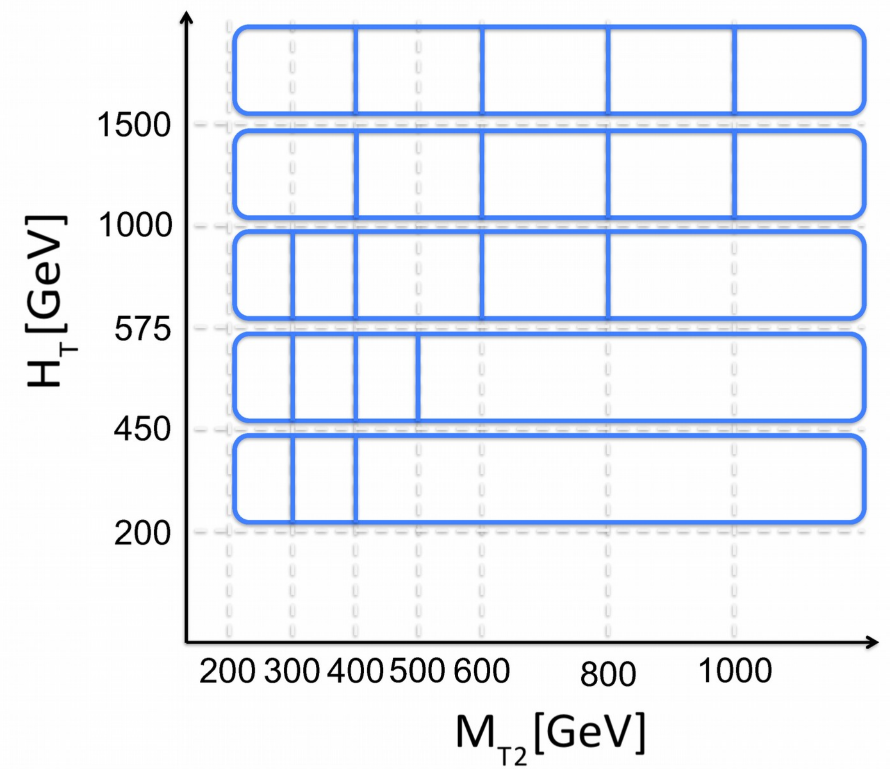
* Combine bins in M_{T2} / jet p_T to have at least 1 expected background event for each (H_T,N_J,N_B) region

We have in total 172 exclusive bins

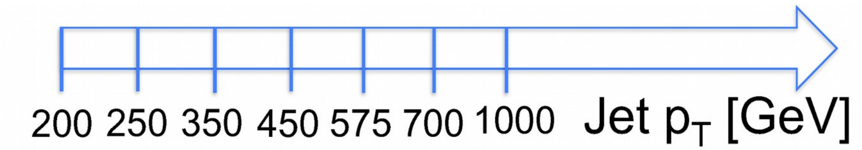
Jet Multiplicity Regions



Multijet Regions



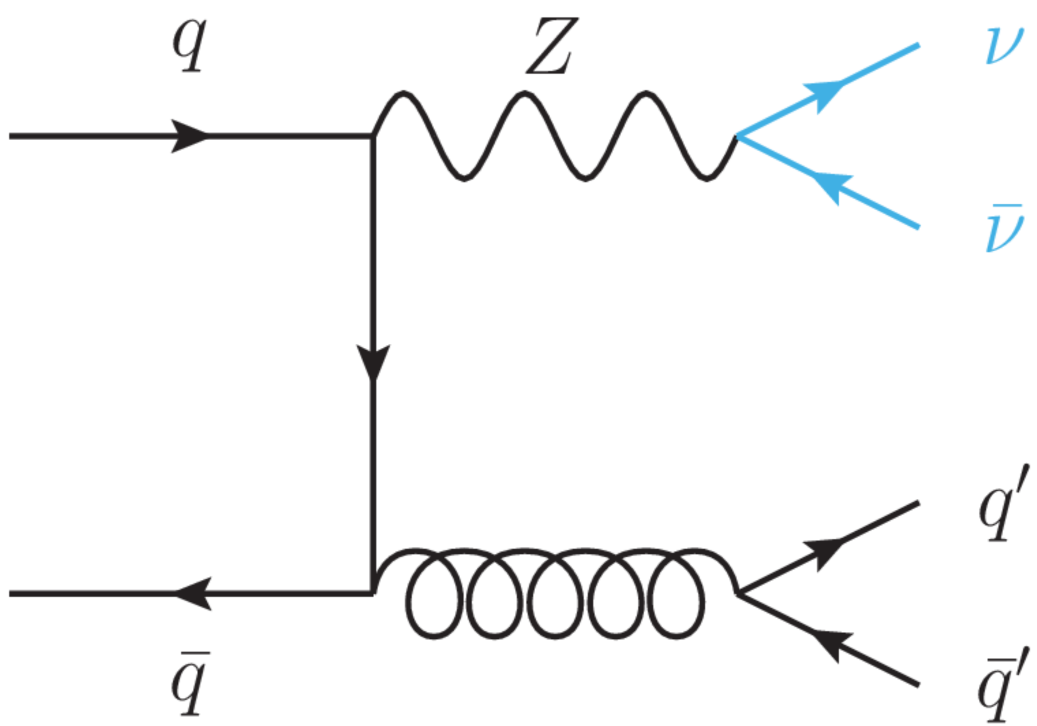
Monojet Regions



* Combine bins in M_{T2} / jet p_T to have at least
1 expected background event for each (H_T,N_J,N_B) region

$Z \rightarrow \nu\nu$: the closest impostor to Dark Matter in the Standard Model

- Can be suppressed only with kinematic/multiplicity variables:
  - H_T, N_J, N_B, M_{T2}

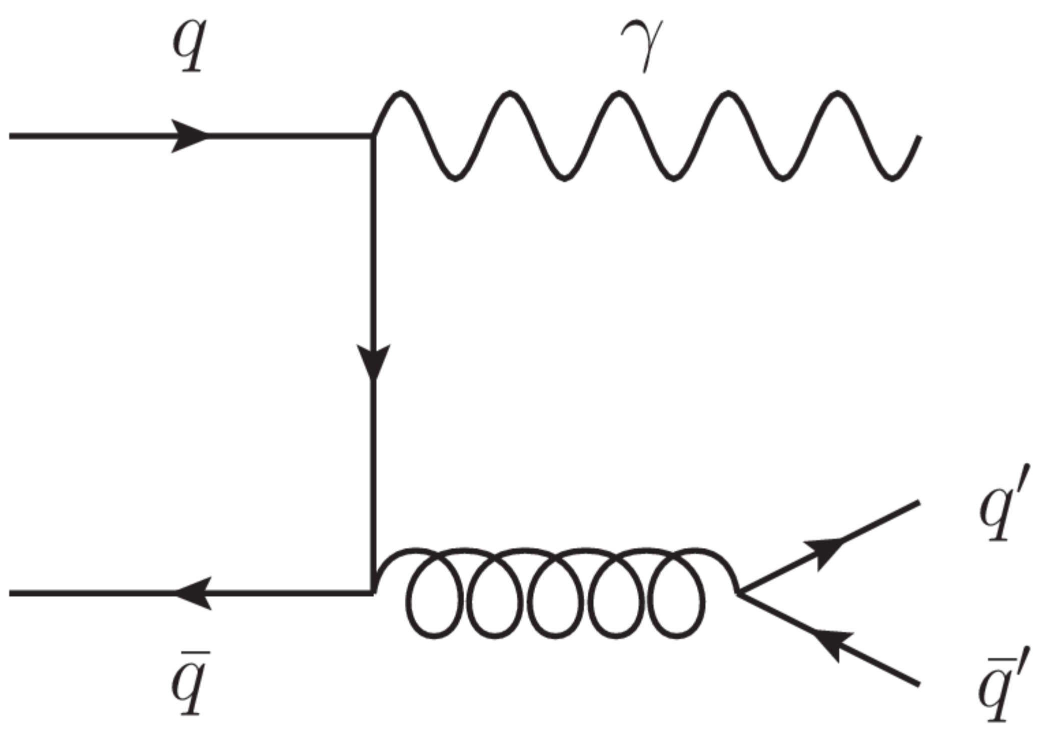


E_T^{miss} from neutrinos

Jets from QCD radiation

We use γ+jets to estimate $Z \rightarrow \nu\nu$

- Differences at theory level: couplings, boson mass
- Have around 2x more γ+jets events than $Z \rightarrow \nu\nu$ after reco cuts



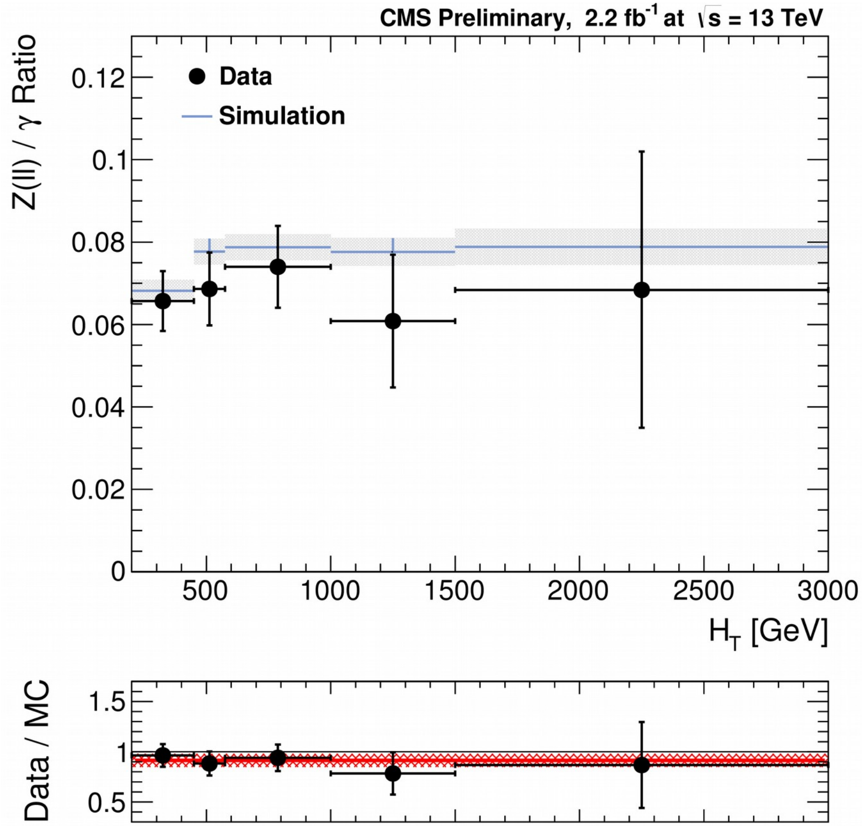
We transform the observed γ+jets yield into a prediction for $Z \rightarrow \nu\nu$

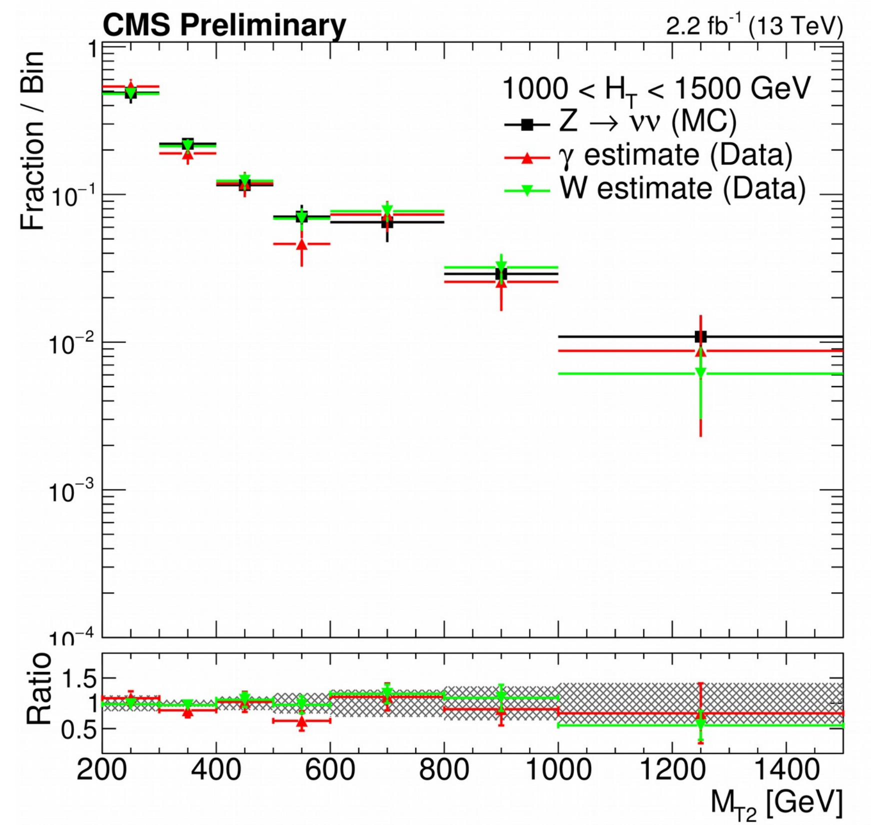
- Bin γ+jets in 3D: (H_T, N_J, N_B)
- Take from data:
  - γ+jets region yield and purity (isolation template fit)
- Use MC to predict:
  - Fraction of fragmentation photons
  - Ratio of $Z \rightarrow \nu\nu$ to γ+jets events, **R(Z/γ)**
  - Shape of $Z \rightarrow \nu\nu$ in M_{T2}
- R(Z/γ) and the M_{T2} shape are validated using data (next slide)

- Dominant uncertainties come from:
  - γ+jets control region statistics (1-100%)
  - Validation of R(Z/γ) using $Z \rightarrow \ell\ell$ events (15-100%)
  - M_{T2} shape (up to 40%)

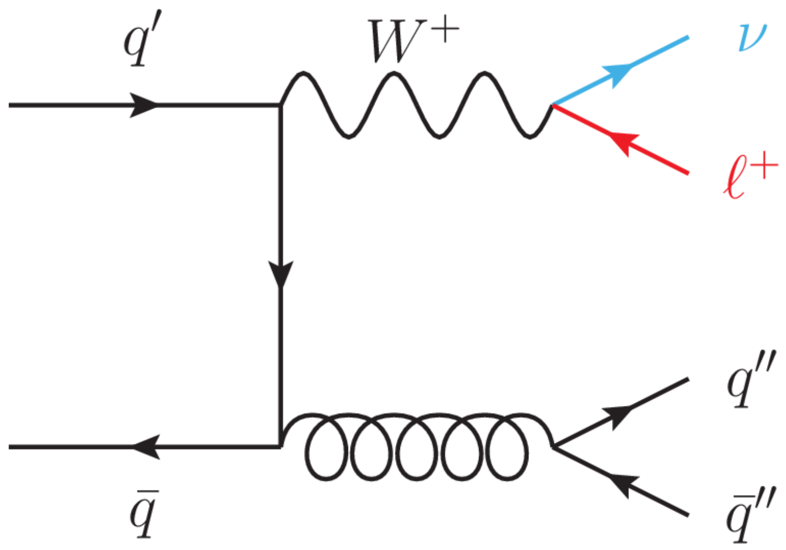
We validate the MC modeling of $R(Z/\gamma)$ and the M_{T2} shape using data

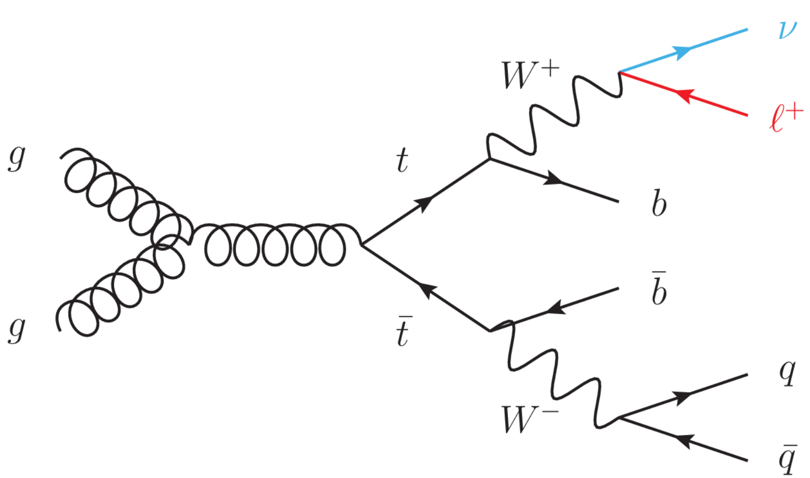
- **$R(Z/\gamma)$**: compare $R(Z_{\ell\ell}/\gamma)$ from MC with $R(Z_{\ell\ell}/\gamma)$ in data
  - Overall offset corrected for, no significant shape trends
  - Use statistical uncertainty on $R(Z_{\ell\ell}/\gamma)$ from data, 1D in H_T, N_J, N_B
- **M_{T2} shape**: compare $Z \rightarrow \nu\nu$ MC with γ+jets and $W \rightarrow \ell\nu$ estimates
  - Uncertainty from MC variations covers the observed data
  - Also perform estimate binning CR in (H_T, N_J, N_B, M_{T2}), statistically consistent with nominal





$W \to \ell\nu$: Events with a found lepton are used to estimate those with a lost one





- Reduce with aggressive veto on isolated leptons and tracks:
  - Veto e, μ with p_T > 10 GeV, or with p_T > 5 GeV & $M_T(\ell, E_T^{miss})$ < 100 GeV
  - Veto tracks with p_T > 10 GeV, $M_T(\ell, E_T^{miss})$ < 100 GeV
    - Targeting hadronic τ decays
    - 85% are 1-prong
- We invert the veto on e and μ to obtain data control regions
  - Require $M_T(\ell, E_T^{miss})$ < 100 GeV to reduce signal contamination in models with leptons
- Have 1-2x as many events in control as signal region

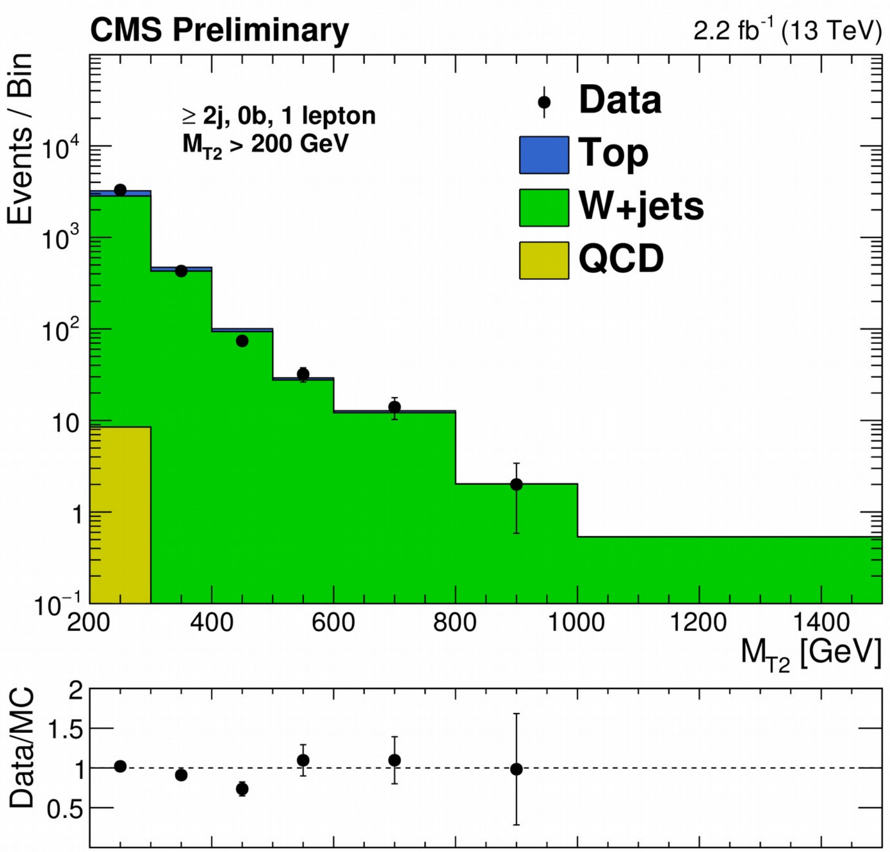
We transform the observed 1ℓ events into a prediction for lost leptons

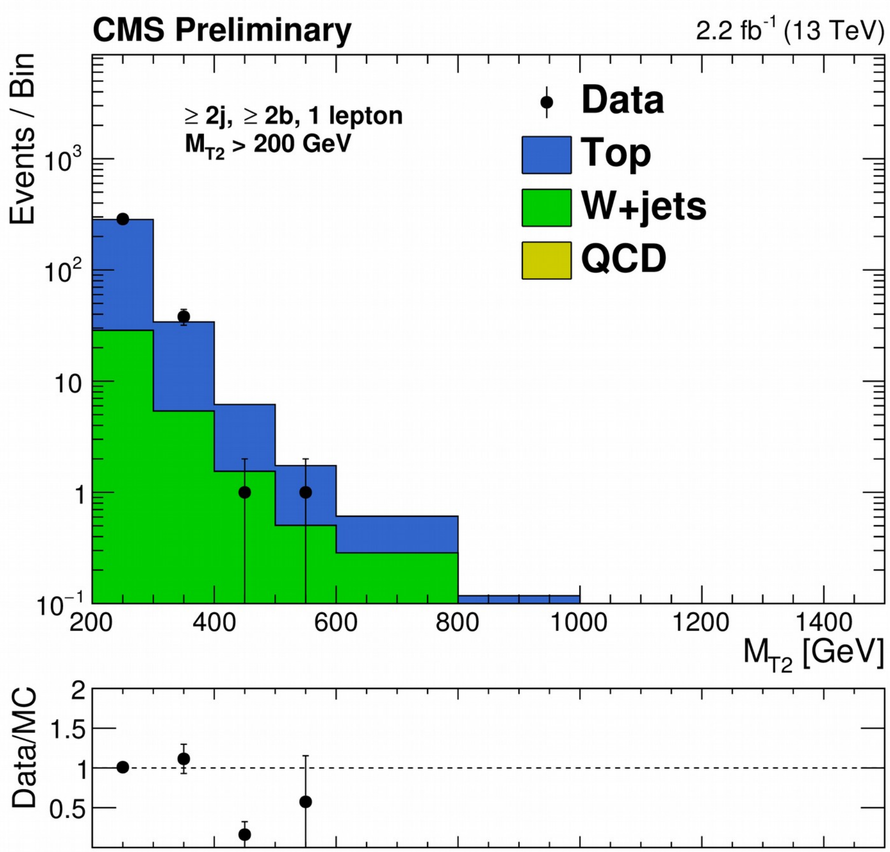
- Bin 1ℓ events in 3D: (H_T, N_J, N_B)
- Take from data:
  - 1ℓ region yield
  - Lepton efficiency (applied as correction to MC)
- Use MC to predict:
  - Lepton acceptance, $W \rightarrow \tau\nu \rightarrow$ hadron+X events
  - Shape of W+jets and ttbar in M_{T2}
- The M_{T2} shape is validated using data (next slide)

- Dominant uncertainties come from:
  - 1ℓ control region statistics (1-100%)
  - M_{T2} shape (up to 40%)

We validate the MC modeling of the M_{T2} shape using 1ℓ data

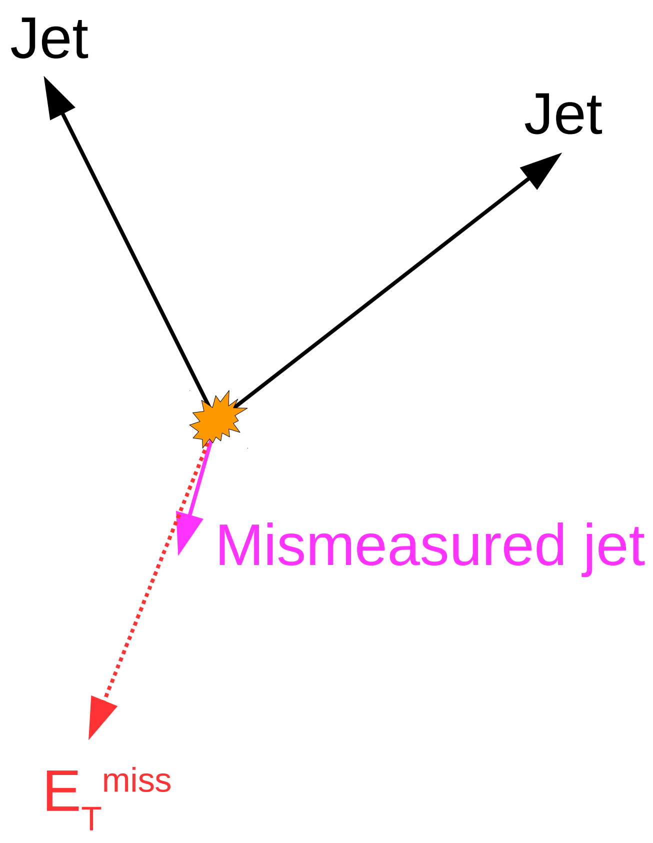
- Compare W+jets and ttbar MC with 1ℓ data
  - Observe good agreement, integrating over H_T, N_J
  - Also perform estimate binning 1ℓ CR in (H_T, N_J, N_B, M_{T2}), consistent with nominal within statistical error





QCD multijets: predict using events with an obviously mismeasured jet

- Use low $\Delta\phi_{min}$ = min($\Delta\phi(E_T^{miss}, j_{1,2,3,4})$) as a control region

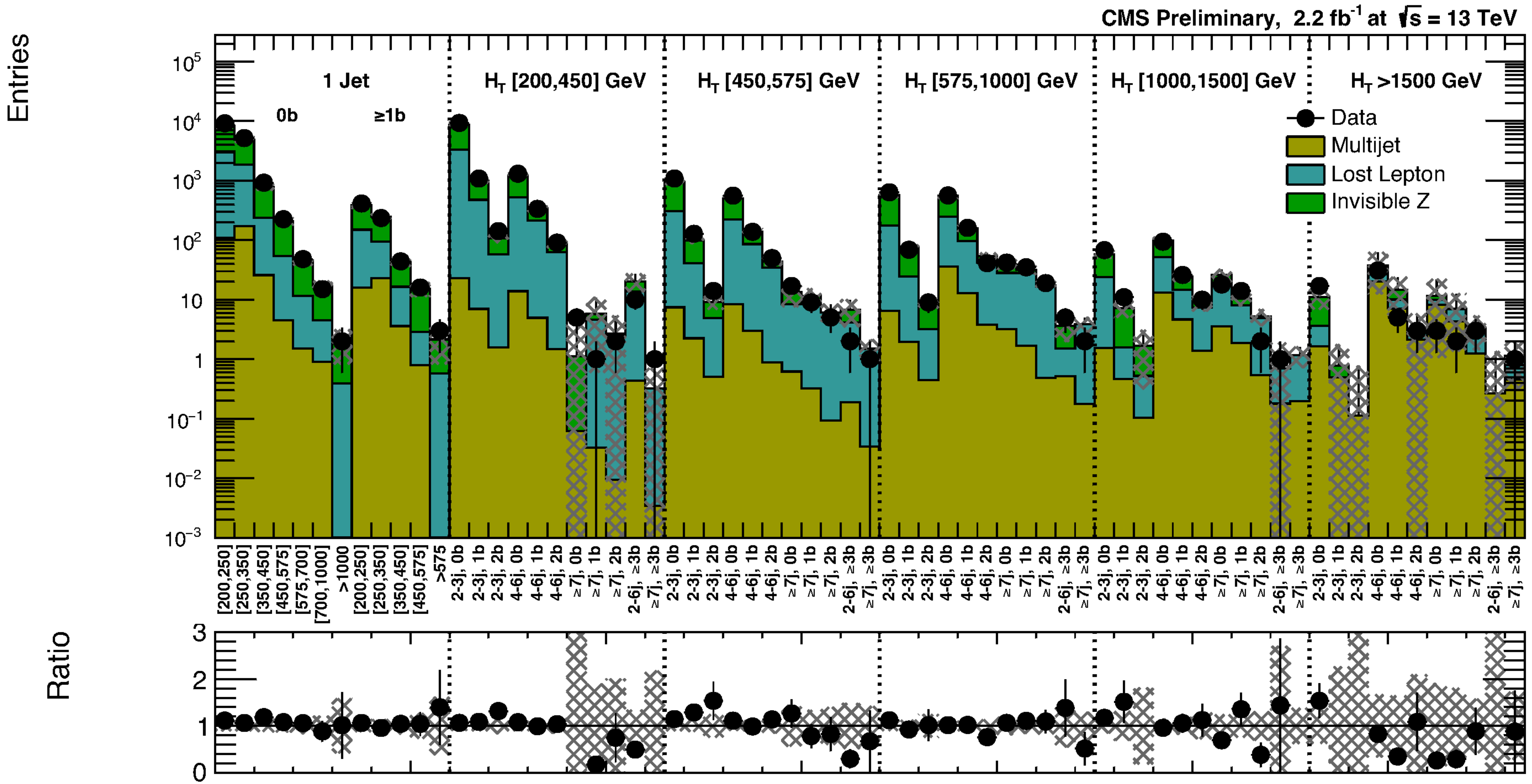


We transform the observed low $\Delta\phi_{min}$ events into a prediction for multijets

- Bin low $\Delta\phi_{min}$ events in 2D: (H_T, M_{T2})
- All main ingredients come from data:
  - **$r_\phi(H_T, M_{T2})$:** ratio of events with ($\Delta\phi_{min}$ > 0.3) / ($\Delta\phi_{min}$ < 0.3)
    - from fit to data in multijet-enriched sideband, M_{T2} < 100 GeV
  - **$f_j(H_T)$:** fraction of events in a given N_J bin
    - computed in data: $\Delta\phi_{min}$ < 0.3 and M_{T2} 100-200
  - **$r_b(N_J)$:** fraction of events in a given N_B bin
    - computed in data: $\Delta\phi_{min}$ < 0.3 and M_{T2} 100-200, integrated over H_T
- Full method validated in MC

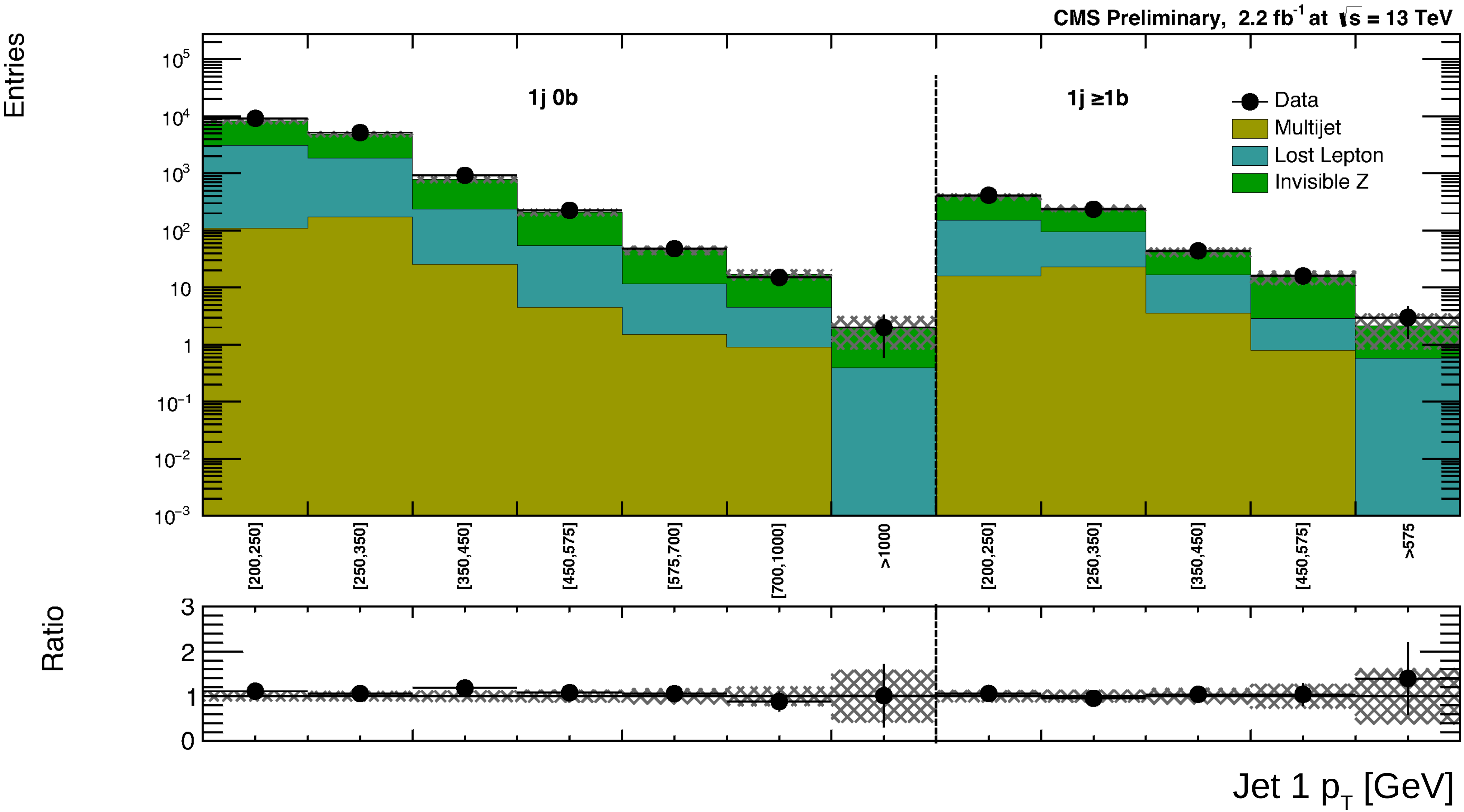
- Dominant uncertainties come from:
  - Low $\Delta\phi_{min}$ region statistics (5-100%)
  - Statistical error for r_ϕ fit in M_{T2} tail (50-100%)
  - Systematic error for r_ϕ fit, from variations in MC (16-200%)

Results: collapsing the M_{T2} dimension



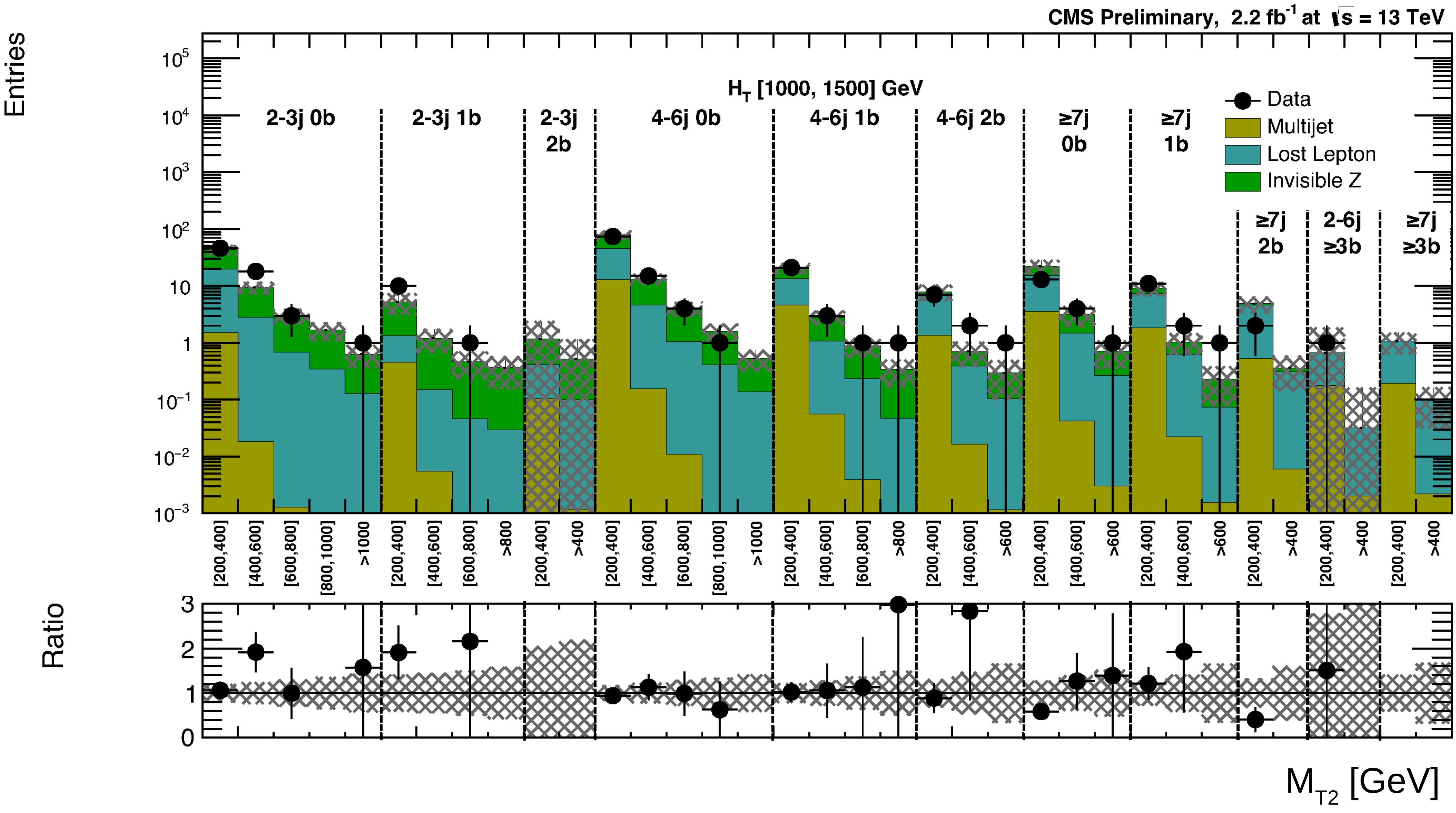
No significant deviations observed

Results: monojet events



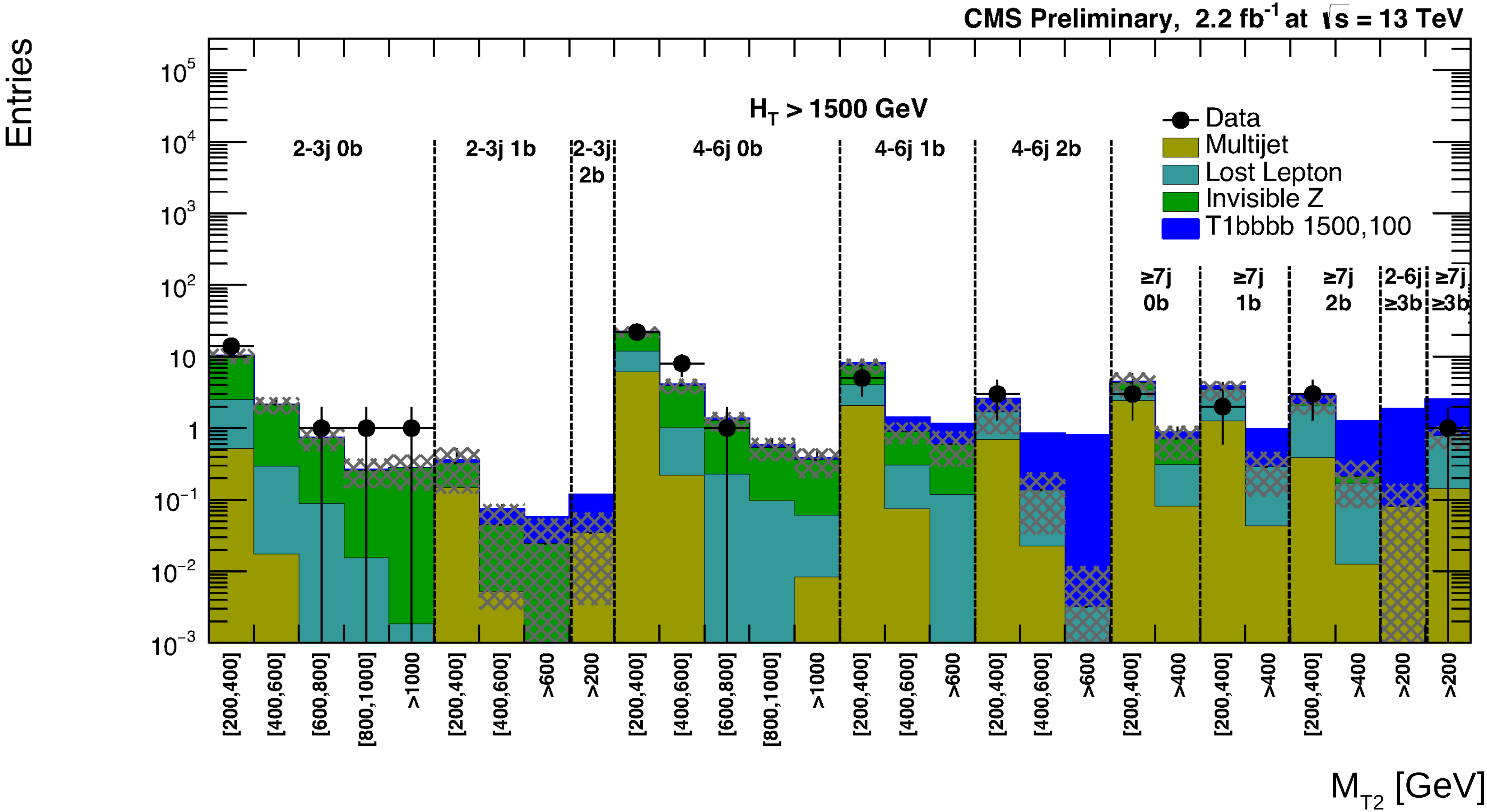
No significant deviations observed

Results: M_{T2} dimension for an H_T bin



No significant deviations observed

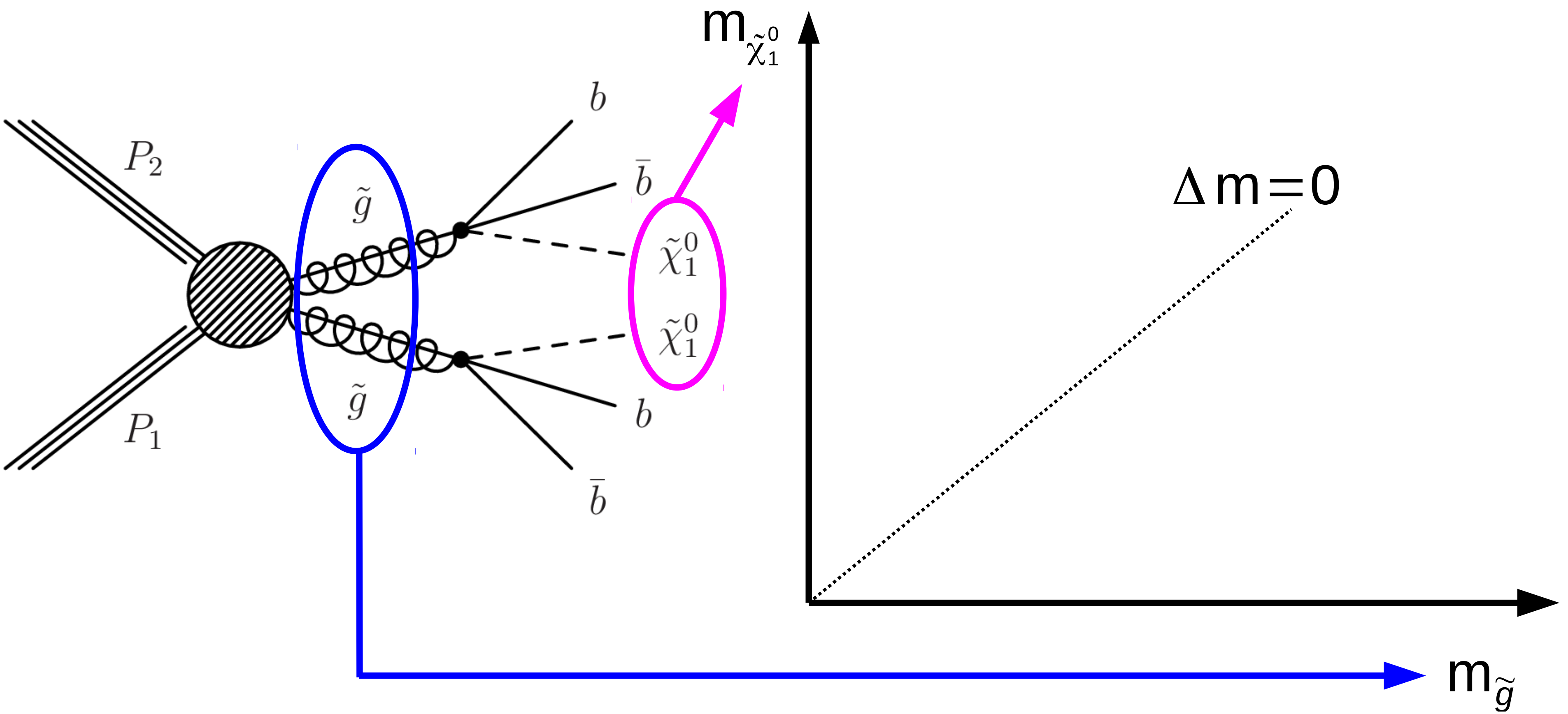
A signal would appear as a correlated excess across similar bins



No evidence for such a signal

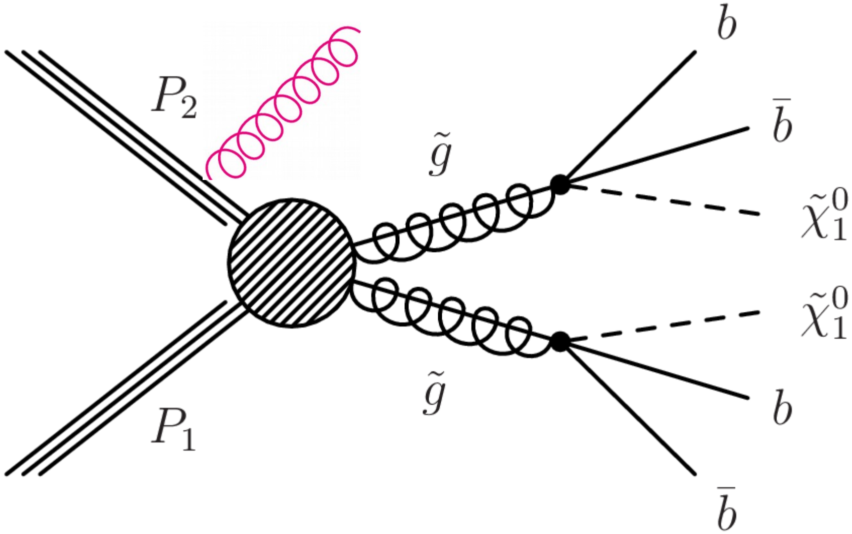
We use Simplified Models to interpret our results

$\Delta m \equiv m_{\tilde{g}} - m_{\tilde{\chi}_1^0}$

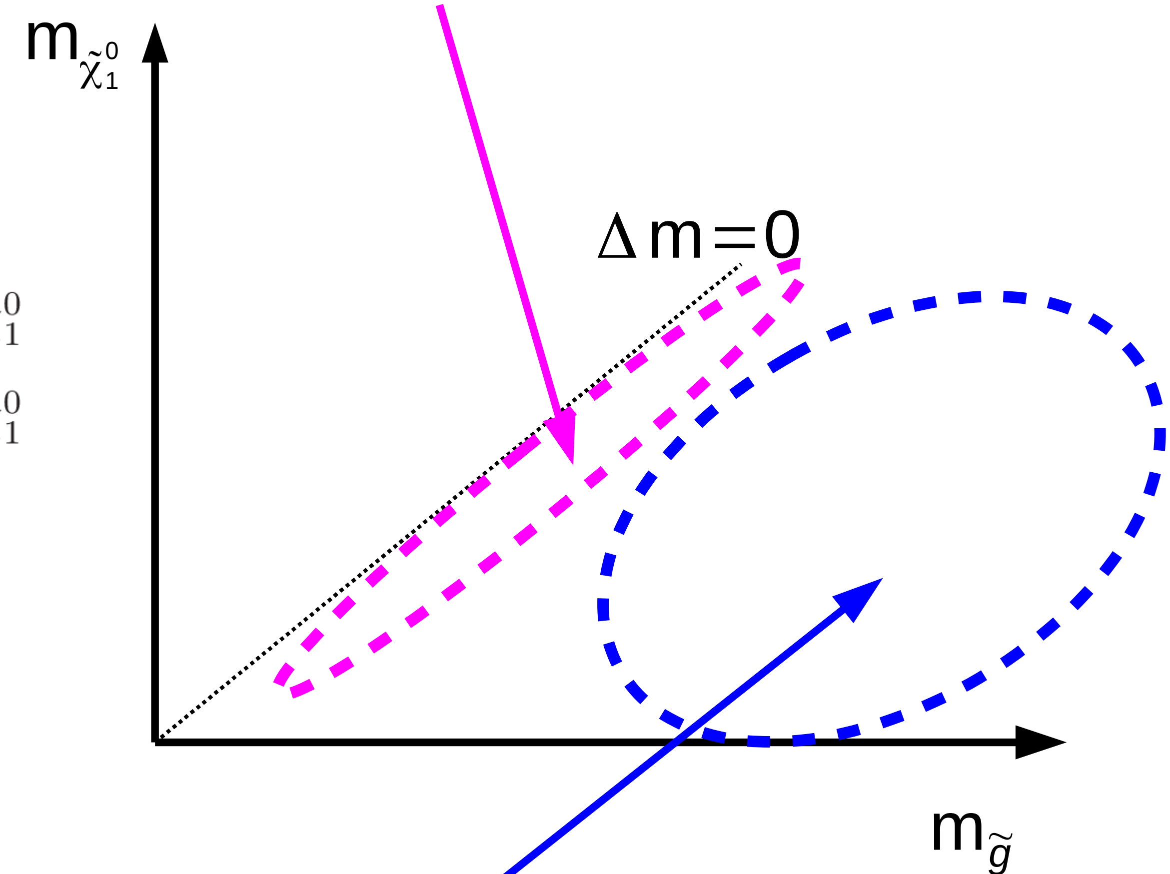


Signal kinematics vary with the splitting between sparticle masses

$$\Delta m \equiv m_{\tilde{g}} - m_{\tilde{\chi}_1^0}$$

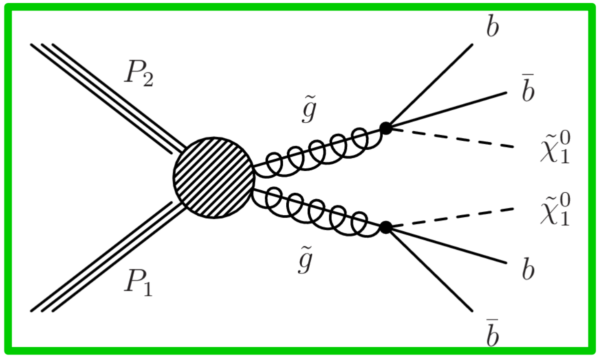


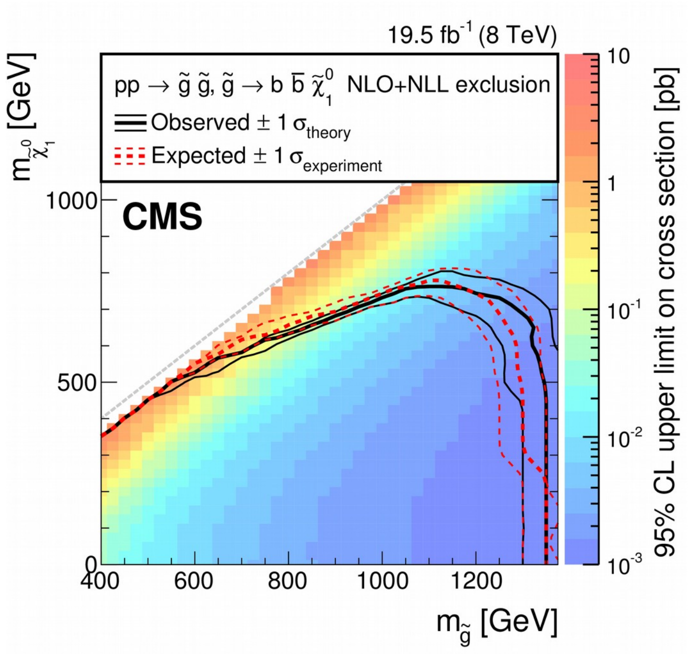
Small Δm region: low p_T or off-shell decay products, rely more on ISR boost



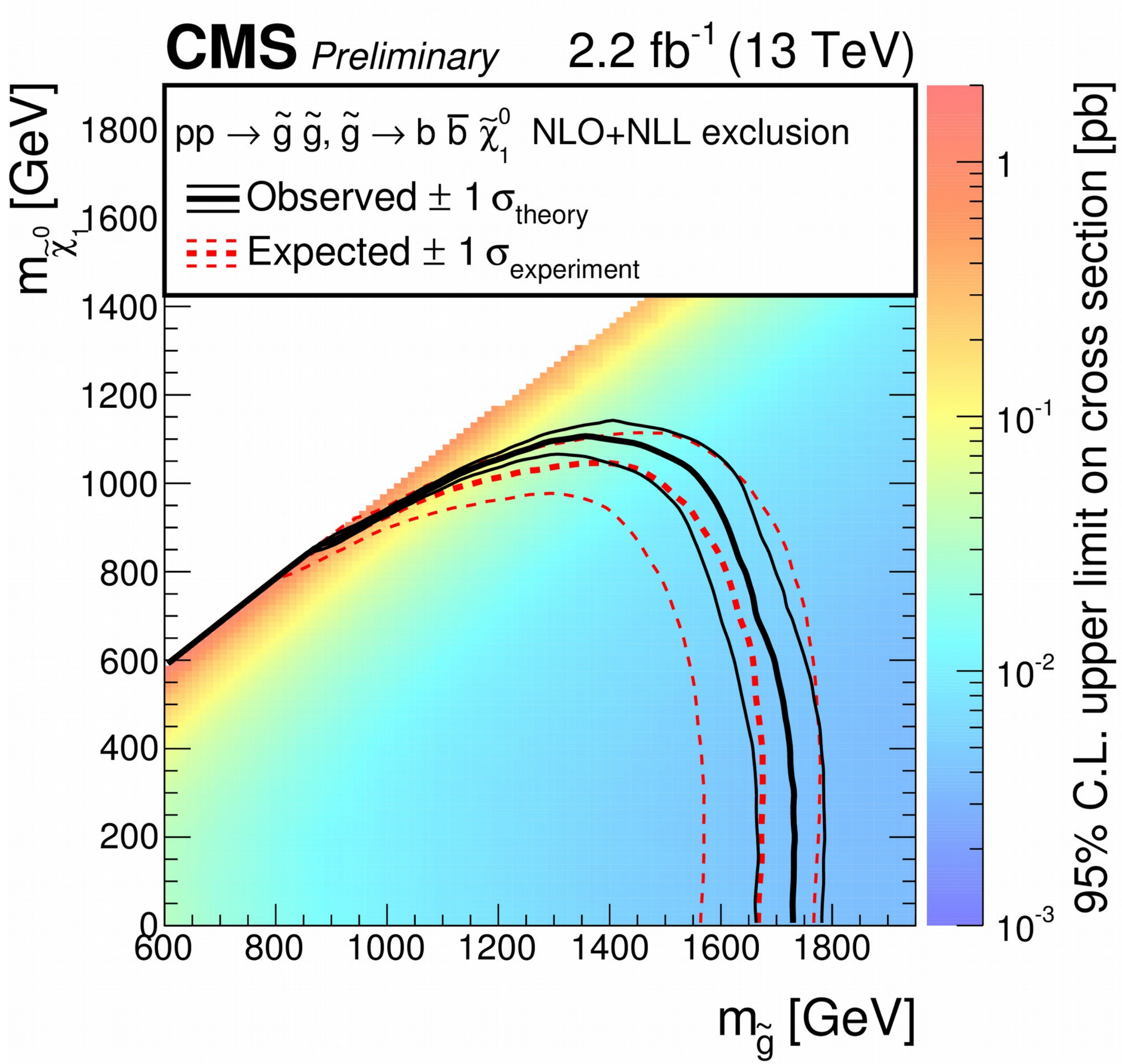
Large Δm region: bulk of phase space, high p_T decay products

Our 13 TeV results extend the 8 TeV gluino limits by up to 300 GeV

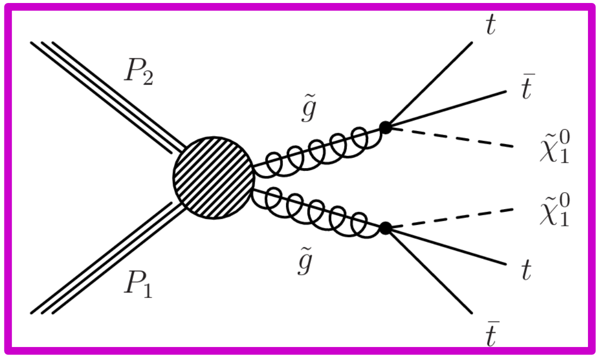


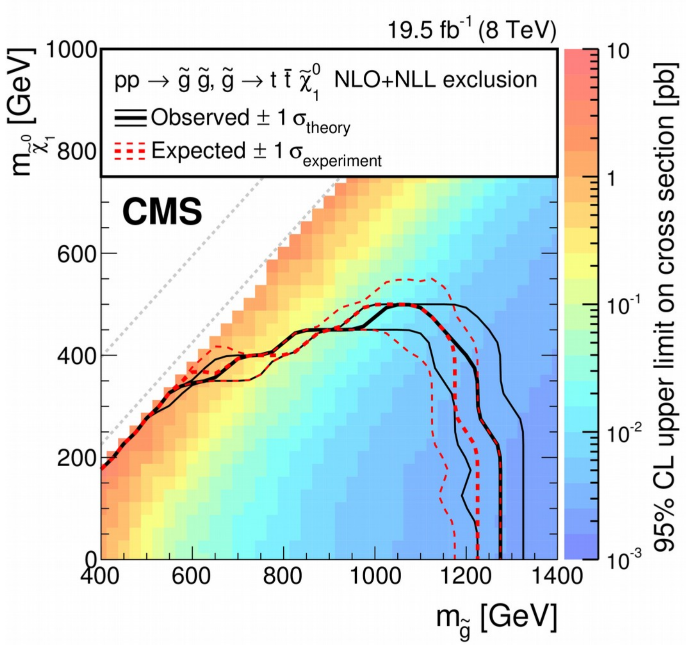


JHEP 05 (2015) 078

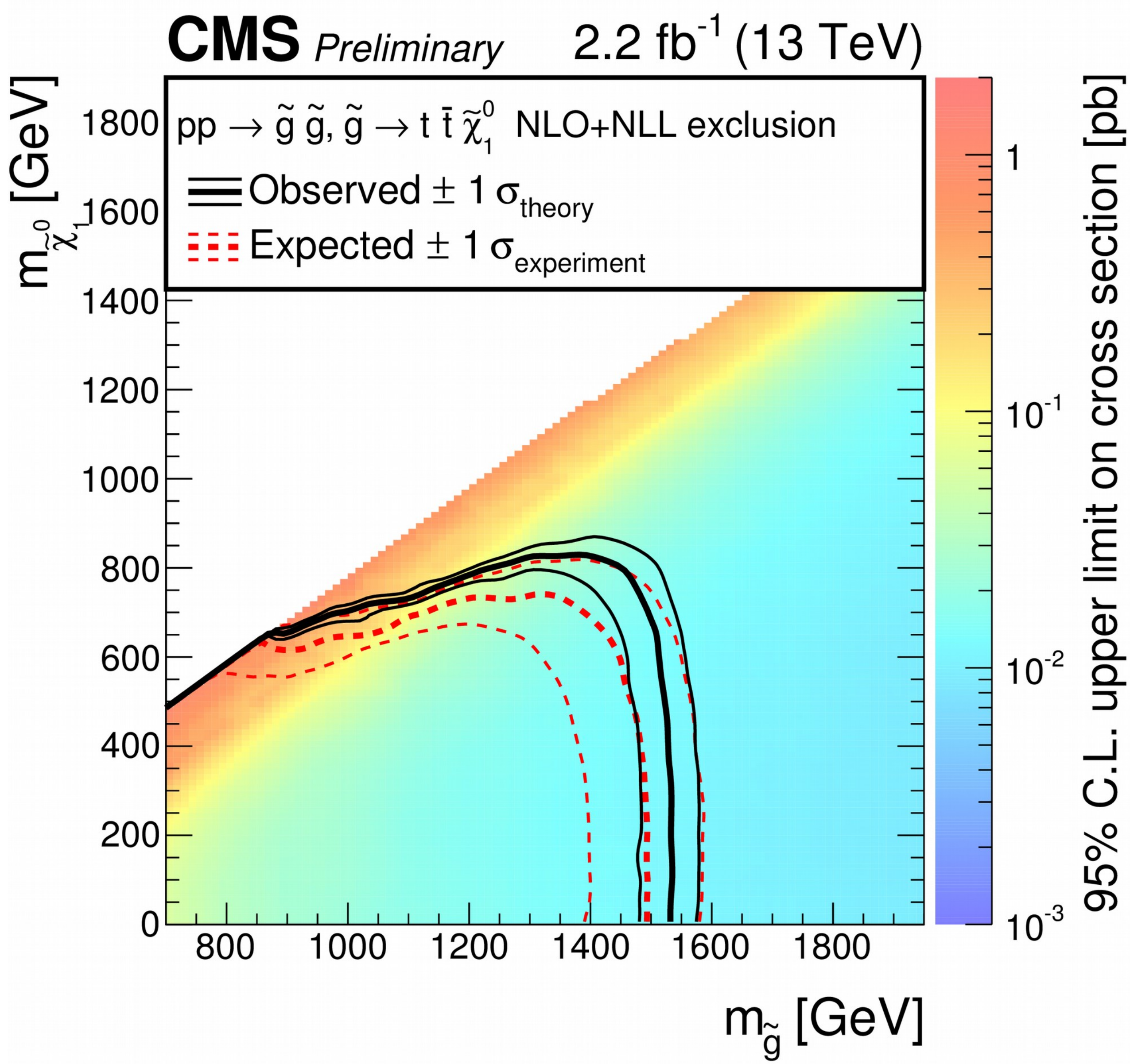


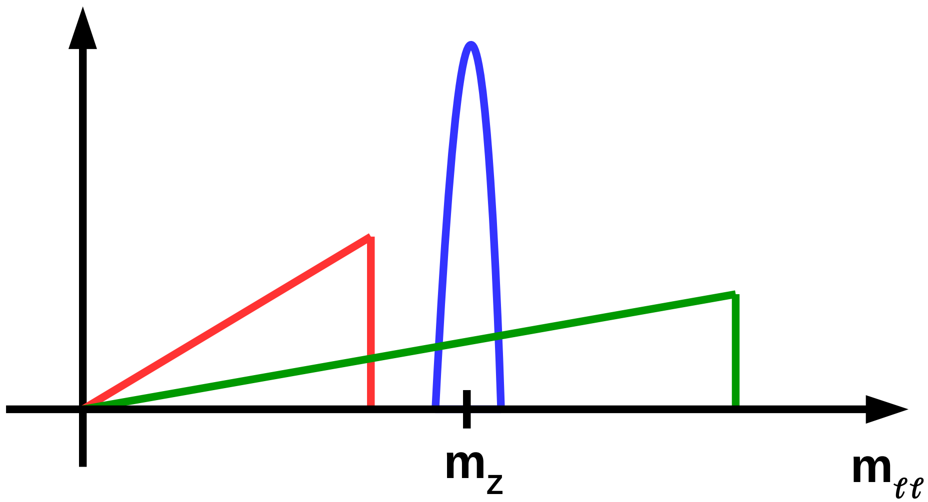
Our 13 TeV results extend the 8 TeV gluino limits by up to 200 GeV





JHEP 05 (2015) 078

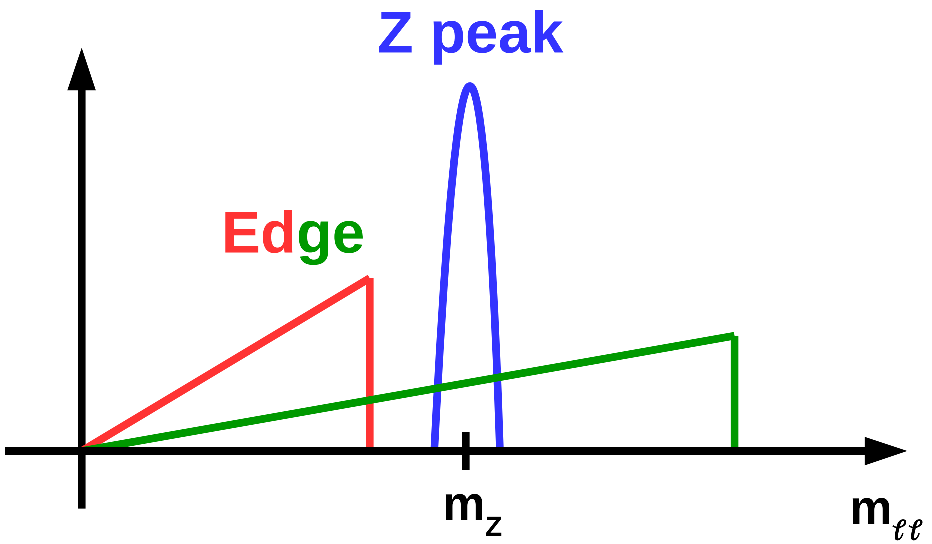


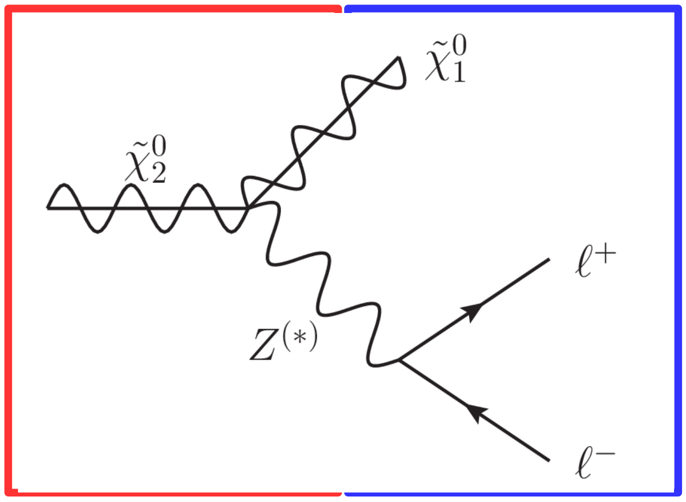


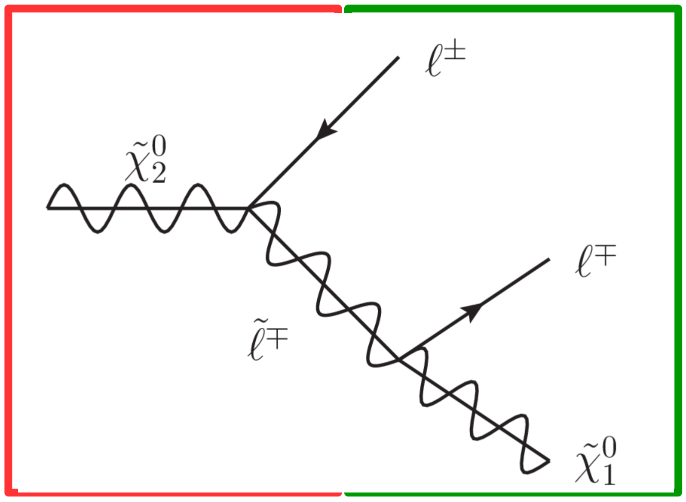
Searching for E_T^{miss} + $\ell^+\ell^-$ + jets: on and off the Z resonance

CMS-PAS-SUS-15-011

SUSY can produce characteristic features in the $m_{\ell\ell}$ spectrum





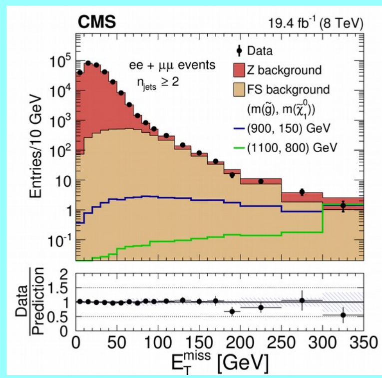


CMS and ATLAS have seen excesses in different channels

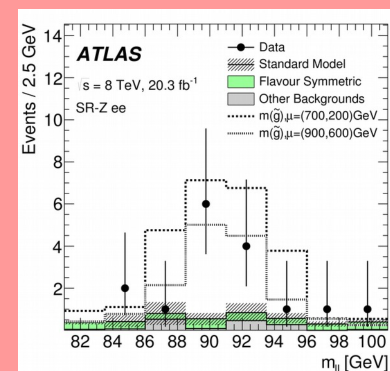
CMS

ATLAS

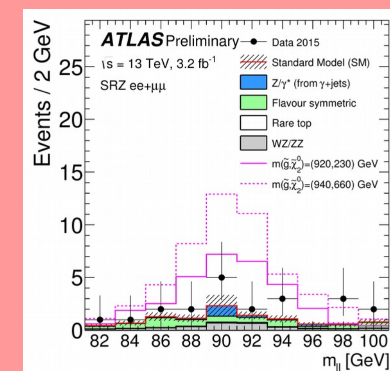
on-Z



2012: no excess, looser cuts

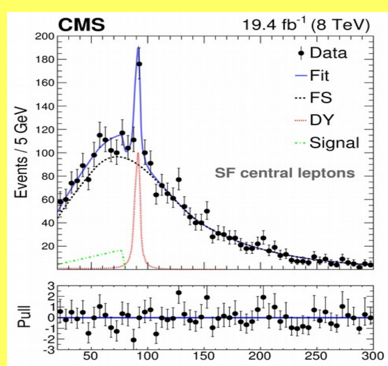


2012: 3σ

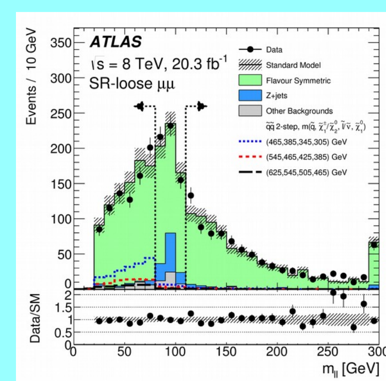


2015: 2.2σ

off-Z



2012: 2.6σ, low $m_{\ell\ell}$



2012: no excess

JHEP 04 (2015) 124

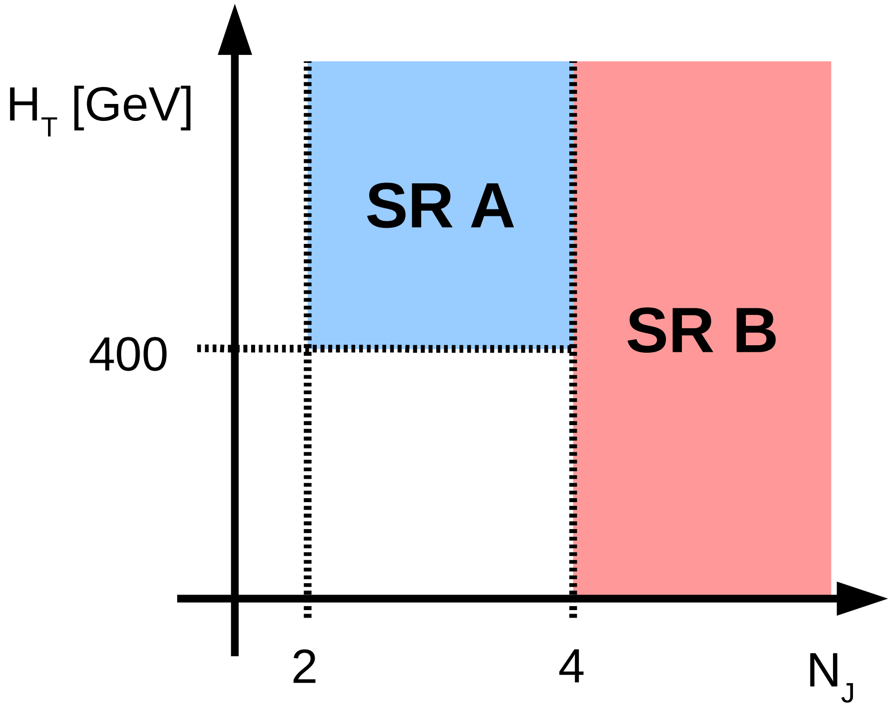
Eur. Phys. J. C75 (2015) 318
ATLAS-CONF-2015-082

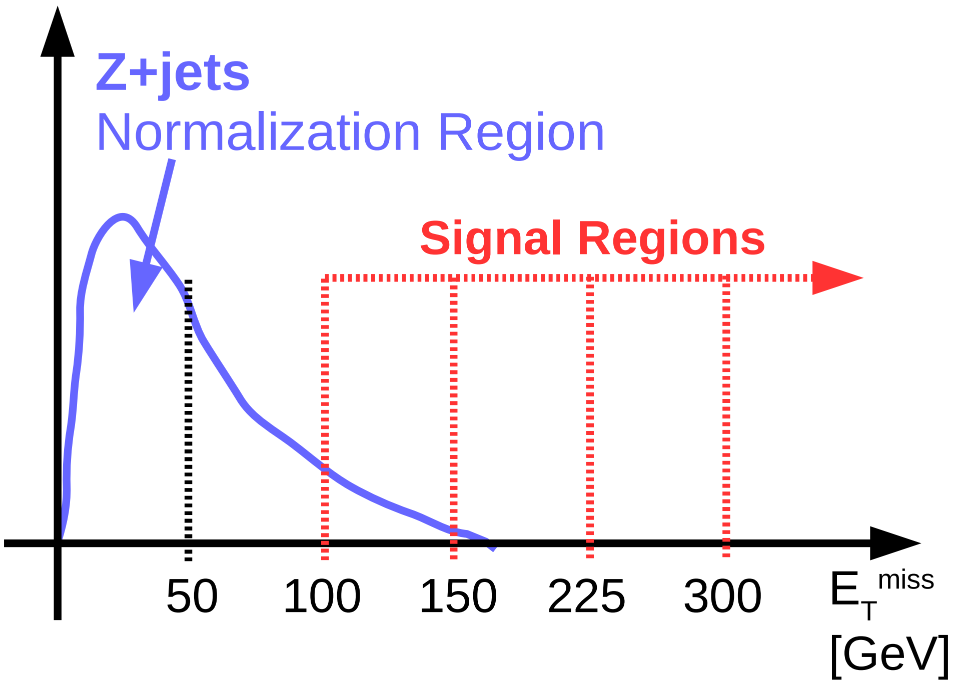
We search for either a Z boson or an Edge-like feature

- Select events with 2 opposite-sign same flavor (OSSF) leptons
  - $p_T > 20$ GeV, collected using dilepton triggers
  - $|\eta| < 2.4$, exclude ECAL transition region $1.4 < |\eta| < 1.6$
- Require at least 2 jets and $E_T^{miss} > 100$ GeV

- Main backgrounds:
  - **"Flavor symmetric"**: events with 2 W bosons, like ttbar
    - Use flavor symmetry to predict from $e\mu$ events
    - Important for full mass range
  - **Z+jets**: E_T^{miss} from jet mismeasurement
    - Use γ+jets events to predict instrumental E_T^{miss}
    - Important for search on the Z resonance, small otherwise
  - **Other SM**: events with a Z boson and genuine E_T^{miss}
    - WZ, ZZ, ttZ etc. Small contribution, estimated from simulation
    - Validate WZ and ZZ modeling in 3ℓ and 4ℓ regions

Z boson search: we classify events based on H_T, N_J, N_B, and E_T^{miss}





Binning in $\mathbf{N_B}$: 0, ≥1

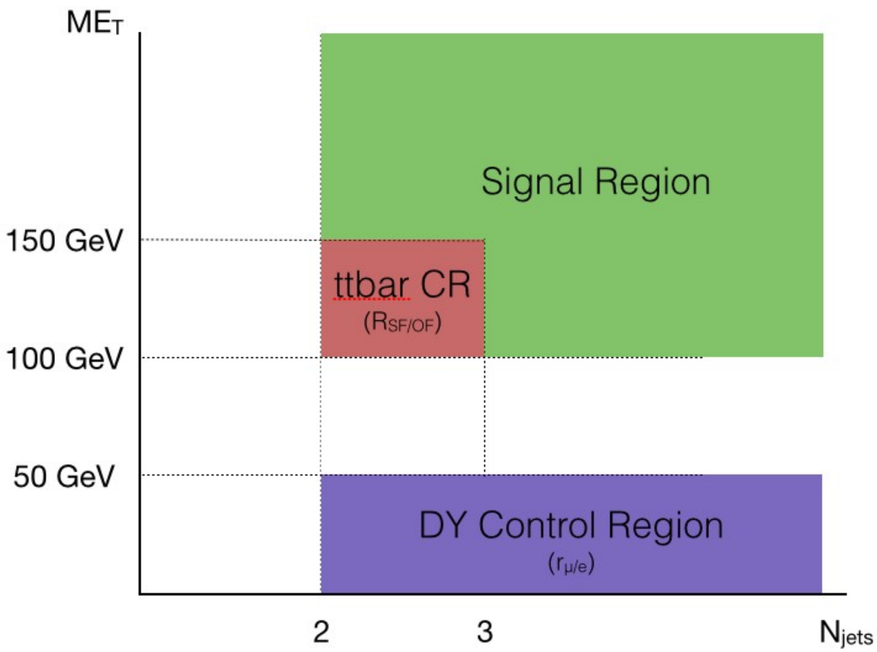
Additional "ATLAS-like" signal region to check the ATLAS 8 TeV excess:

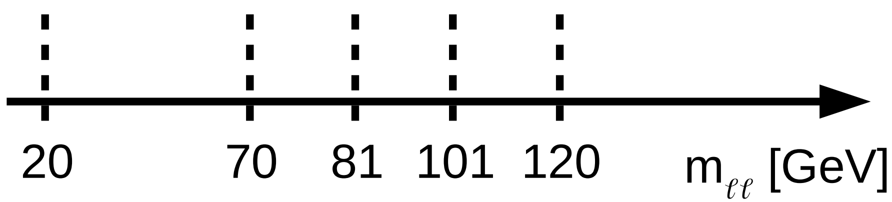
$H_T + p_T(\ell_1) + p_T(\ell_2) > 600$ GeV

$E_T^{miss} > 225$ GeV, $\Delta\phi(E_T^{miss}, j_{1,2}) > 0.4$

Total of 17 regions (16 exclusive)

Edge search: classify events based on E_T^{miss}, N_J, N_B, $m_{\ell\ell}$, and lepton $|\eta|$





Binning in $\mathbf{N_B}$: 0, ≥1

We also report N_B ≥0 for comparison to 8 TeV results

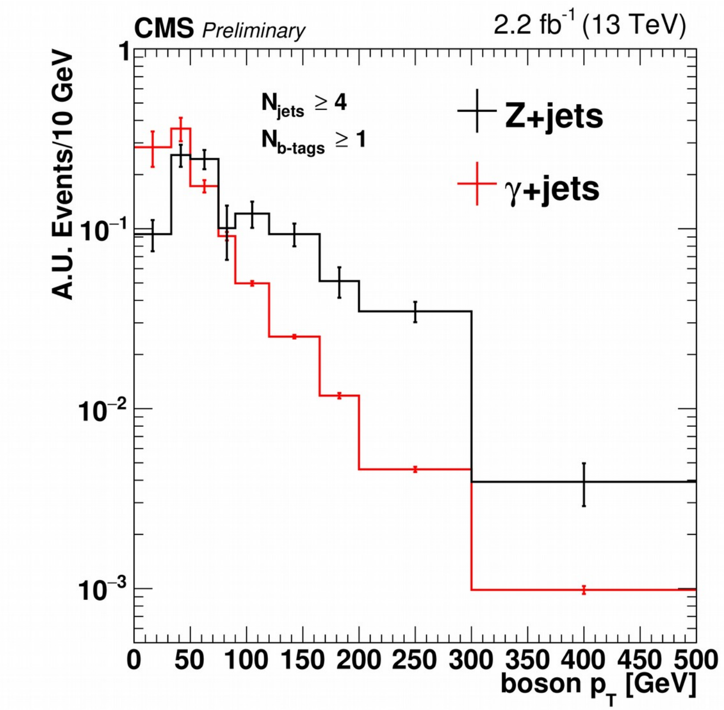
Finally, separate events by **lepton centrality**:

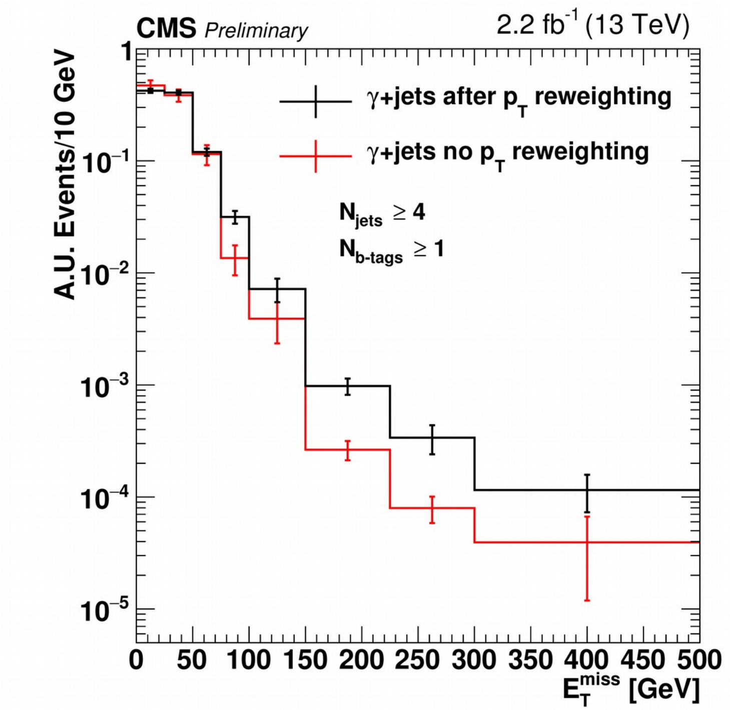
Central: both leptons $|\eta| < 1.4$, Forward: at least one lepton $|\eta| > 1.6$

Total of 30 regions (20 exclusive)

E_T^{miss} from jet mismeasurement in Z+jets is modeled using γ+jets

- γ+jets events are collected with prescaled triggers
  - p_T thresholds as low as 22 GeV
- We reweigh **$p_T(\gamma)$** to **$p_T(Z)$** to match kinematics
- Prediction is normalized to data in the Z+jets dominated region
  - E_T^{miss} < 50 GeV
- Done separately for SR A and B, N_B = 0 and ≥ 1, ATLAS SR

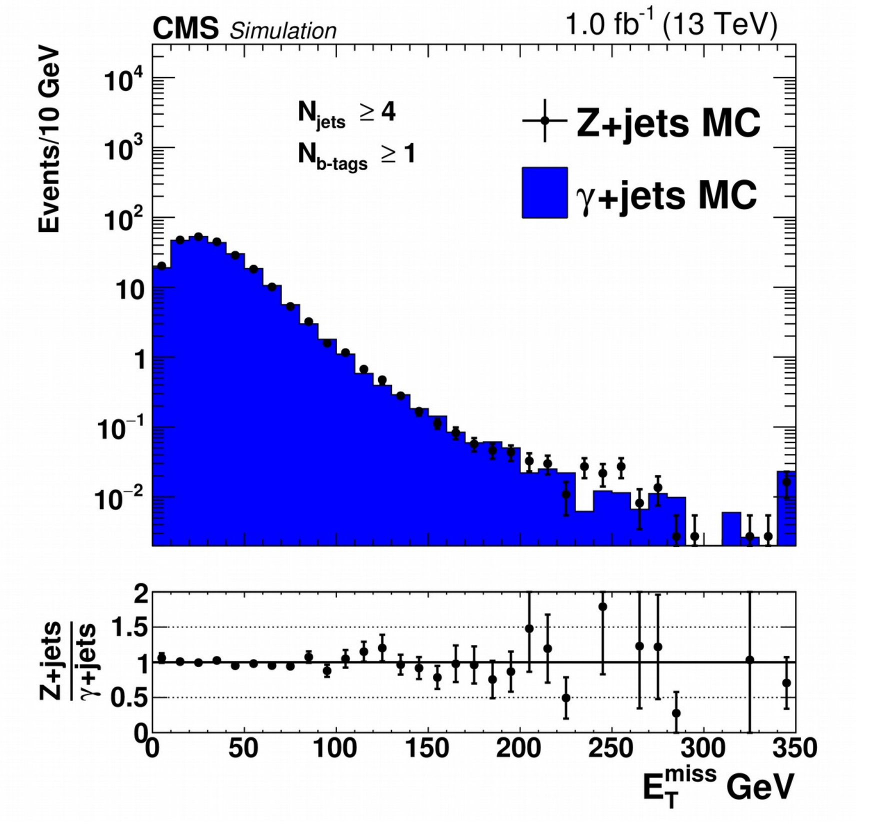




The Z+jets uncertainties are dominated by statistics at high E_T^{miss}

- Uncertainties from:
  - γ+jets data statistics at high E_T^{miss}: 10-50%
  - closure test of the method in MC: 4-50%, mostly statistics
  - normalization in low E_T^{miss} data, statistical: 3-10%

- Prediction for other $m_{\ell\ell}$ ranges:
  - Take $m_{\ell\ell}$ shape from MC
    - Validated in data
  - Uncertainty from variation with N_J and E_T^{miss}, up to 25%



Flavor symmetry is quantified with two statistically independent methods

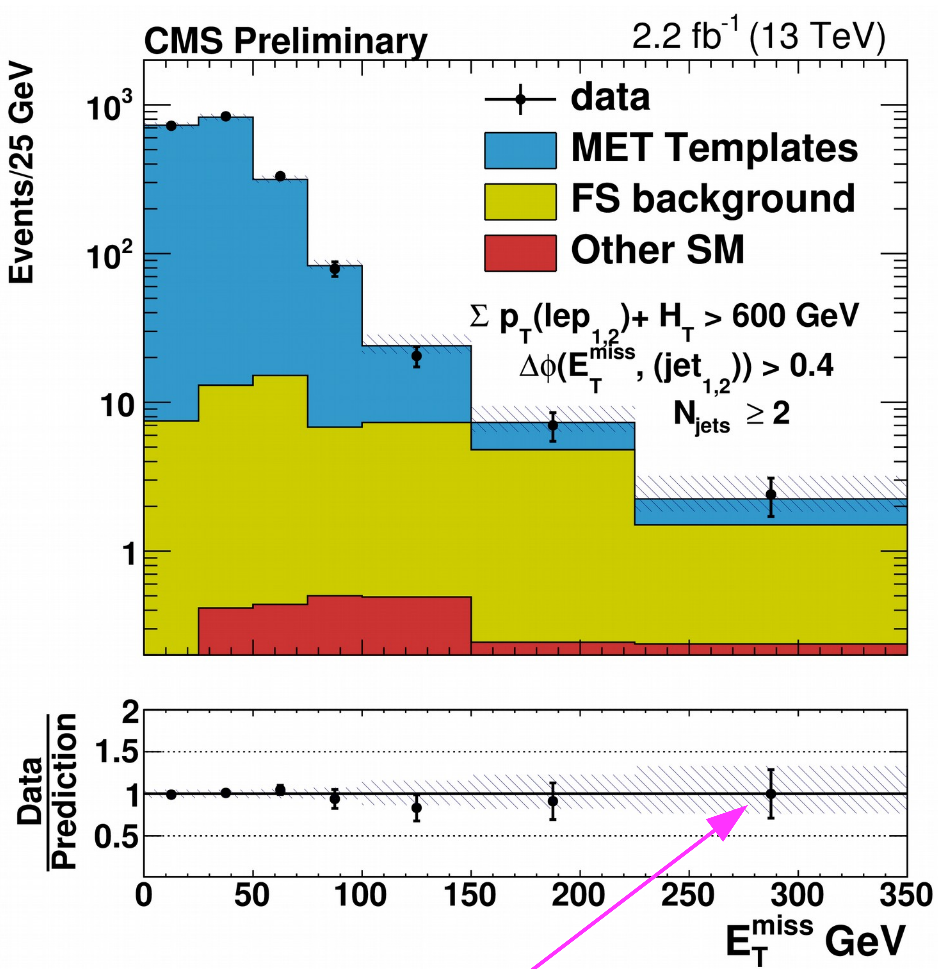
- **R_{SFOF}**: transfer factor between OF (eμ) and SF (ee+μμ)

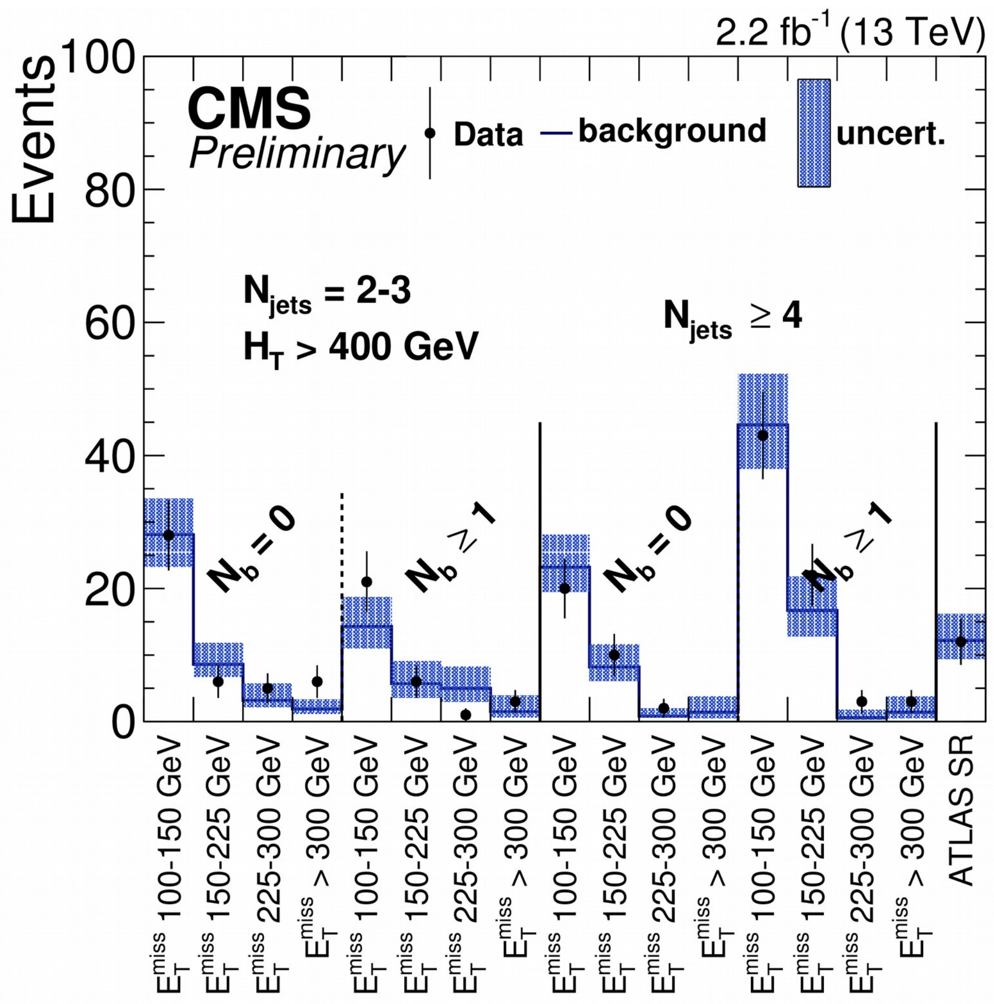
- 1) Measure R_{SFOF} directly in ttbar-dominated control region
  - E_T^{miss} 100-150, N_J = 2, $m_{\ell\ell}$ outside 81-101 GeV
  - Use statistical uncertainty from data

- 2) Compute R_{SFOF} from reconstruction and trigger efficiencies in data
  - **$r_{\mu e}$**: ratio of μ/e selection efficiencies.
    - Measured in Drell-Yan dominated region, E_T^{miss} < 50 GeV
  - **R_T**: ratio of dilepton trigger efficiencies
    - Measured using orthogonal H_T triggers
  - Uncertainty from statistics, dependence on kinematic variables

- Measurements consistent, combine using weighted average:
  - R_{SFOF} = 1.04 ± 0.05 for central category
  - R_{SFOF} = 1.10 ± 0.07 for forward category

Results on the Z resonance: no evidence for new physics

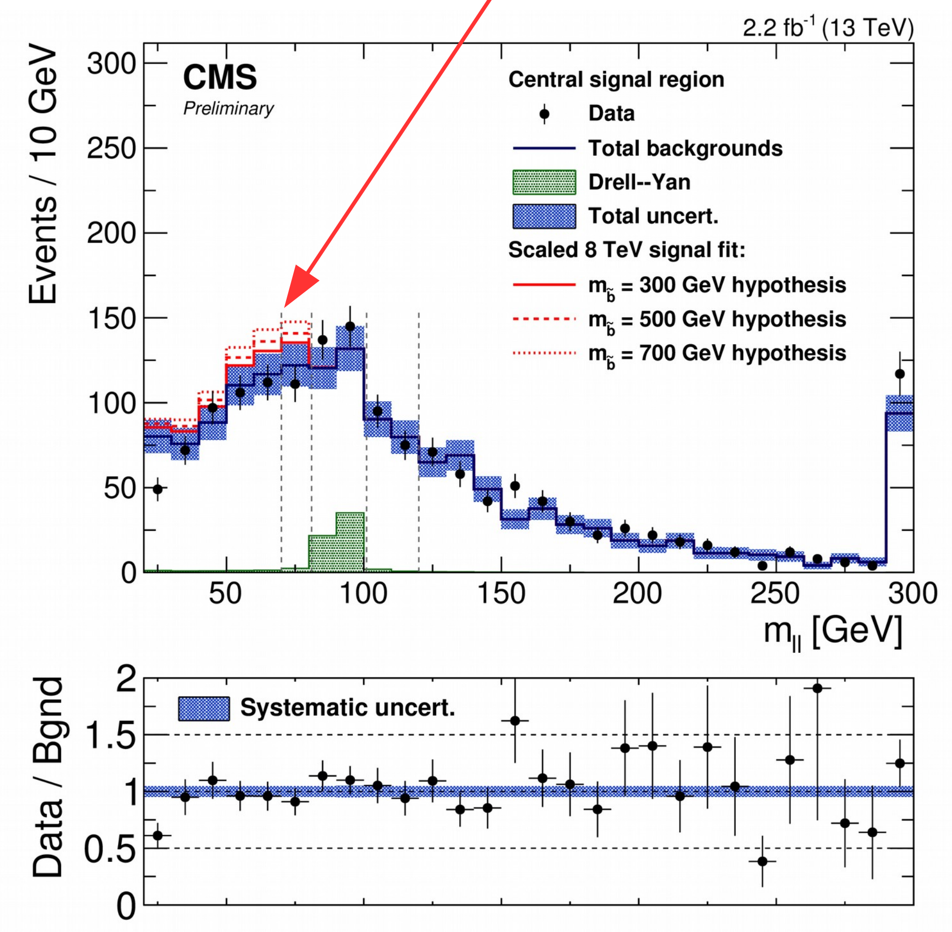




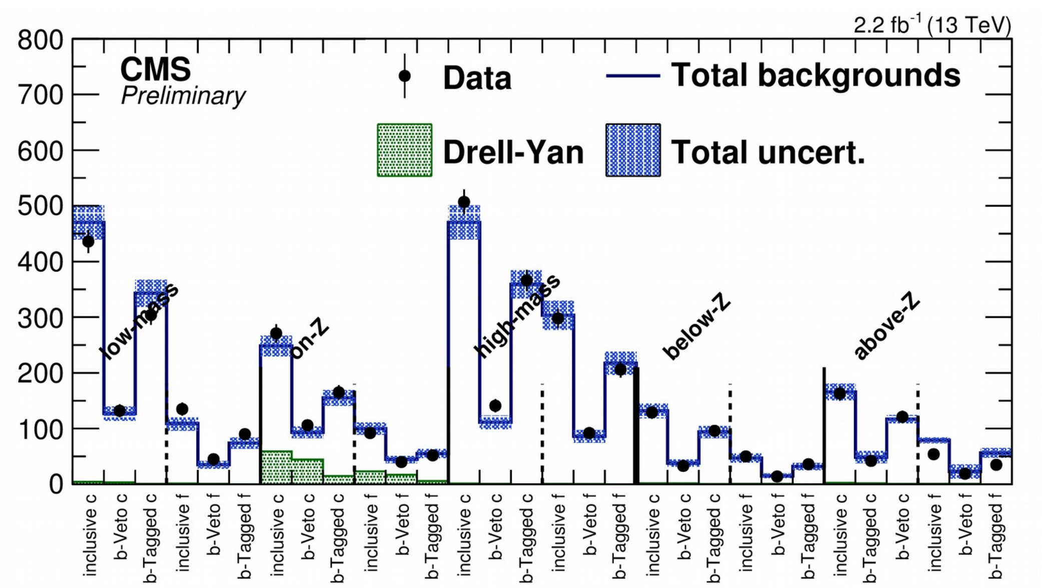
ATLAS-like SR consistent with background

Results for the Edge search: also no significant deviations

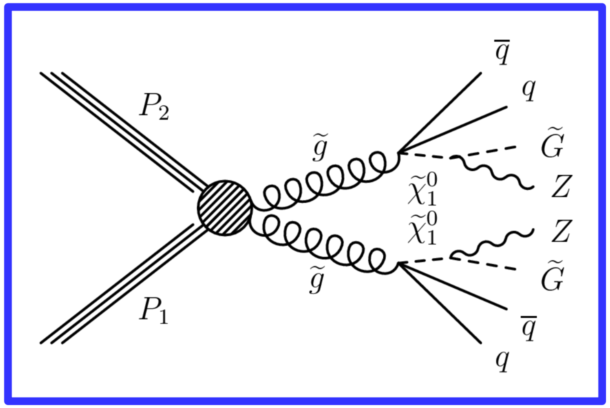
- Excess from 8 TeV CMS search does not appear again

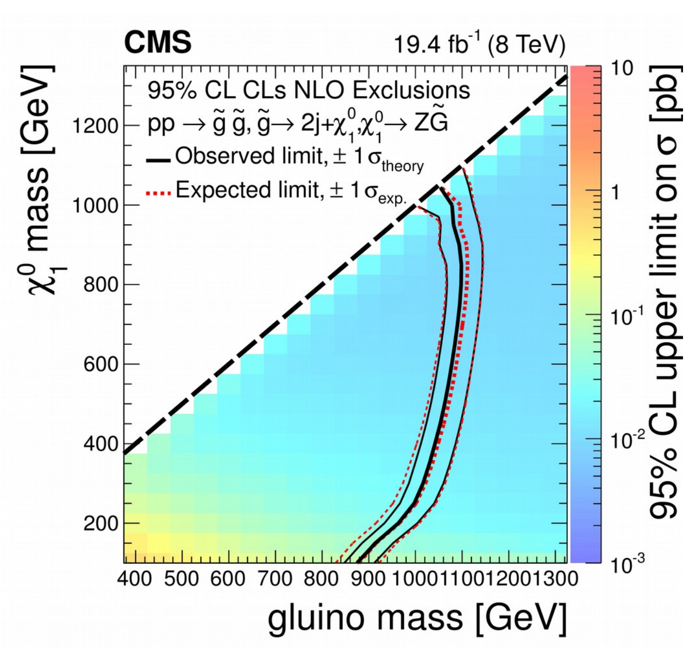


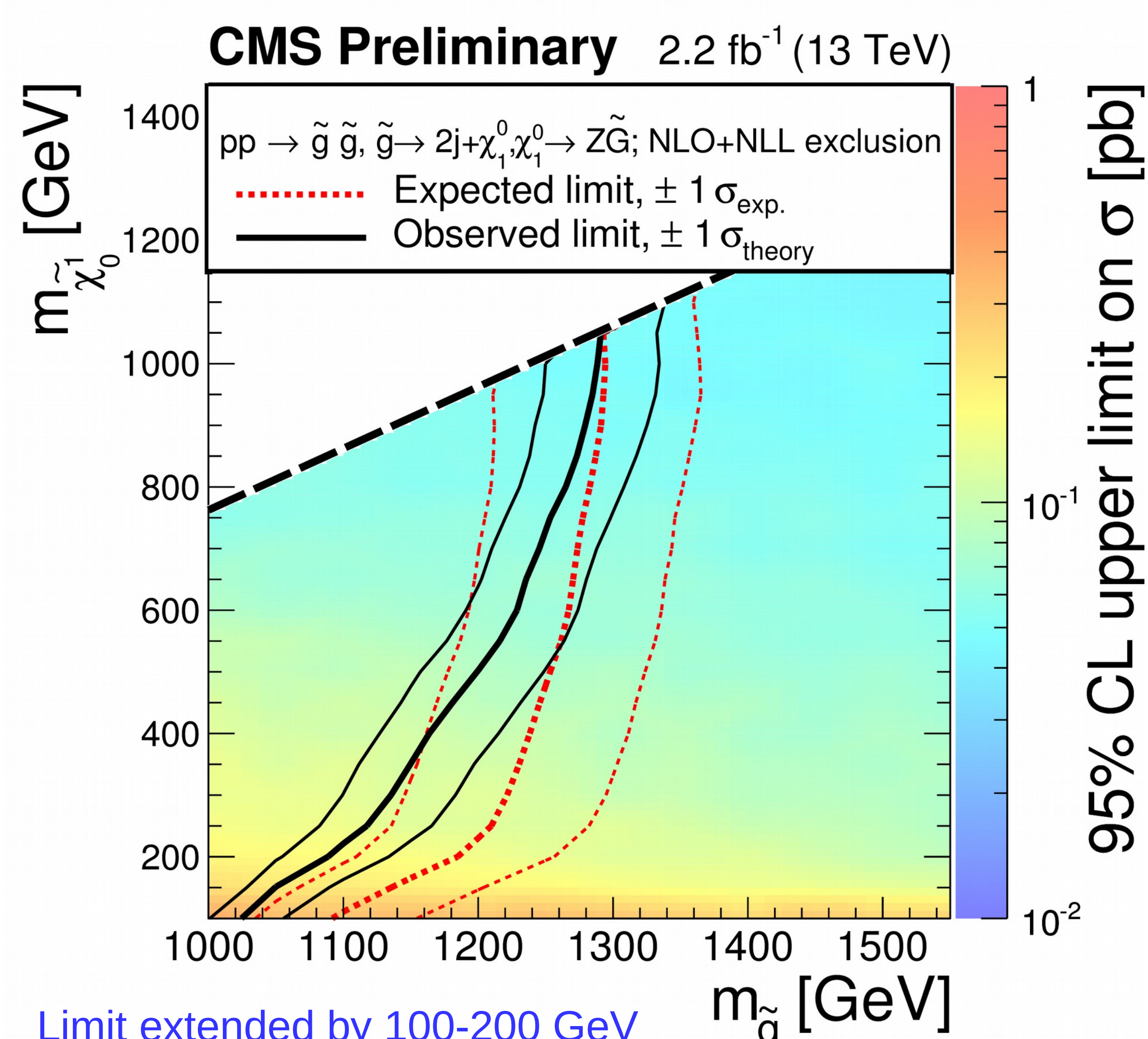
Central leptons
Inclusive in N_B



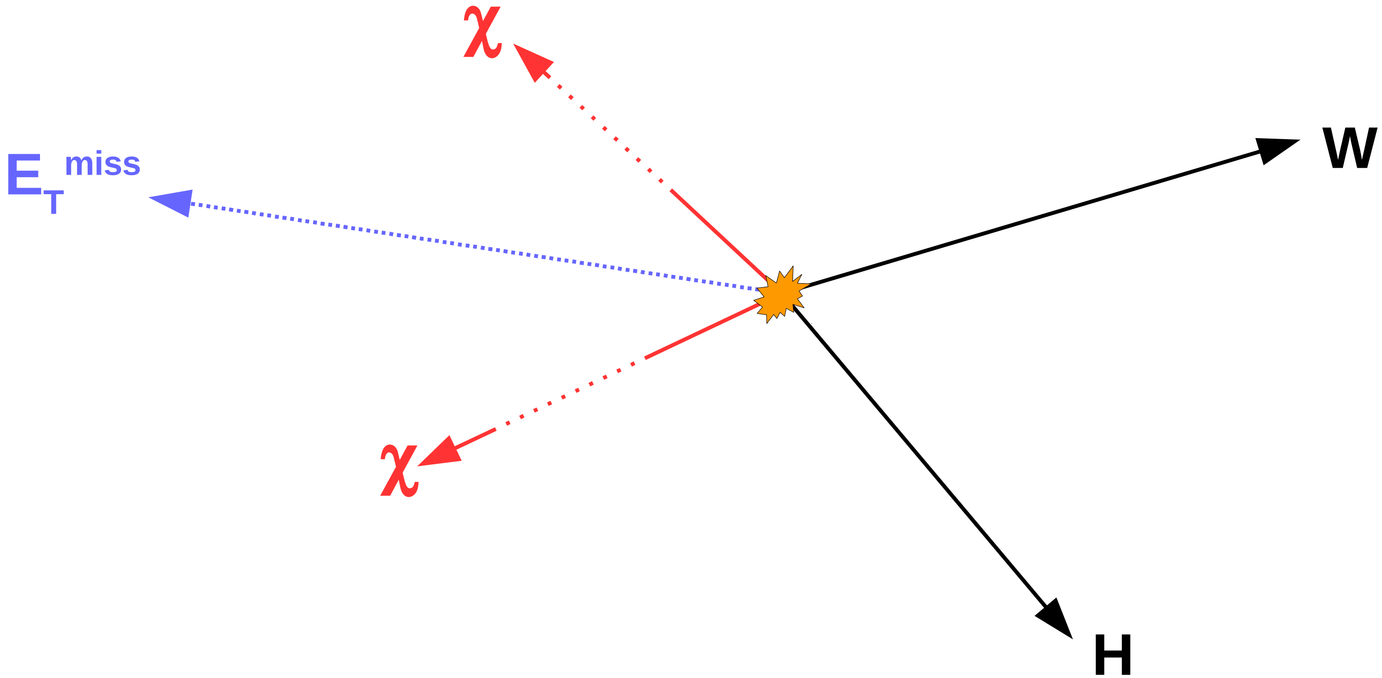
The Z region results are interpreted to constrain gluino production







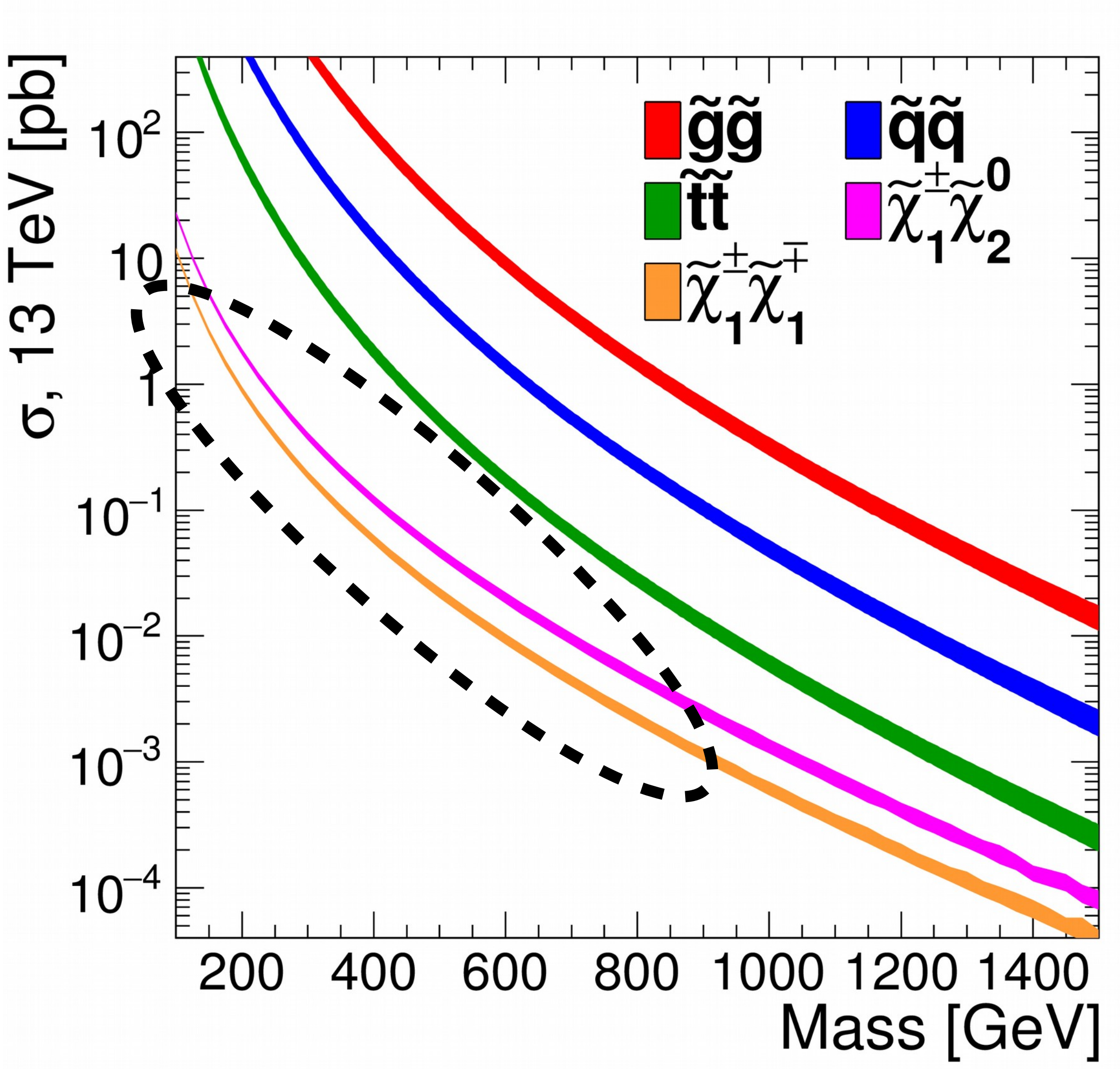
Limit extended by 100-200 GeV



Looking ahead:
Targeting electroweak sparticles

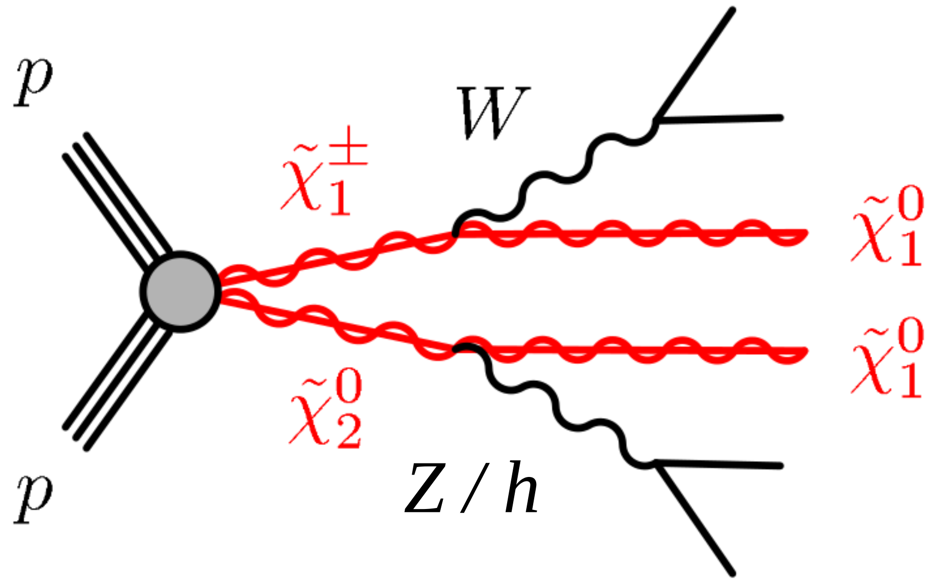
Electroweak production has a lower cross section, needs more luminosity

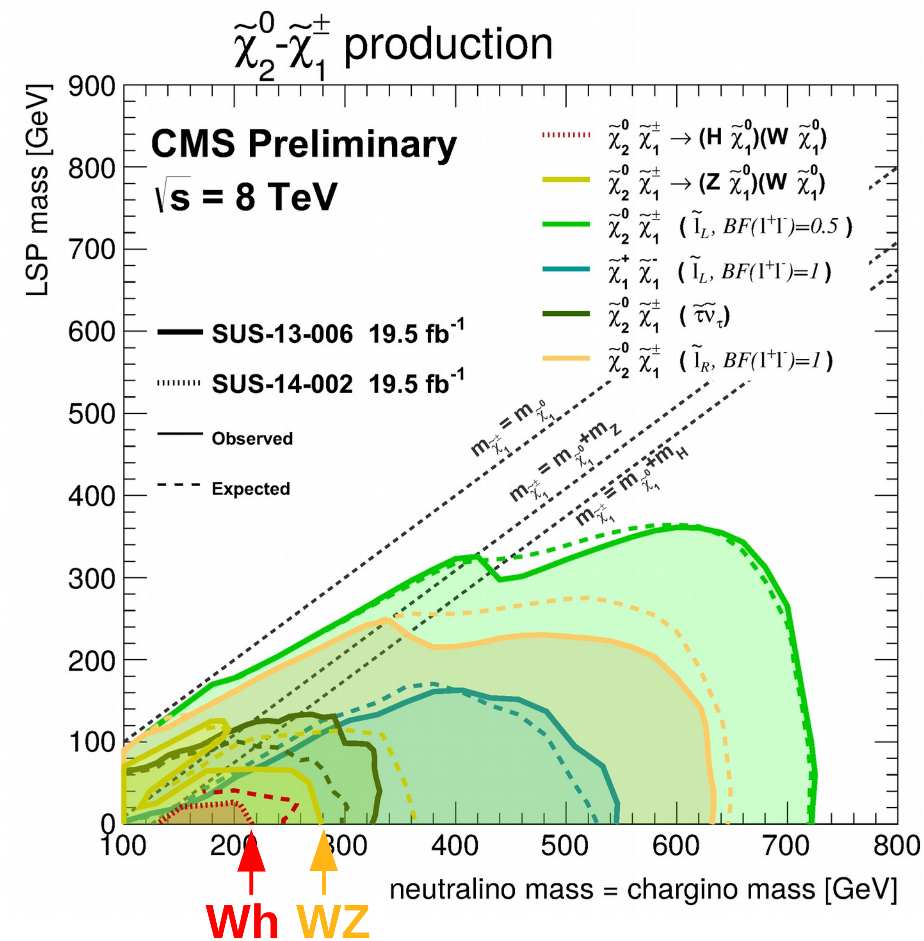
- With O(10) fb^{-1} at 13 TeV, will surpass 8 TeV results



Dibosons and E_T^{miss} are a typical signature; cover many final states

- Helped coordinate effort for 8 TeV, working on this for 13 TeV





Working on searches for:

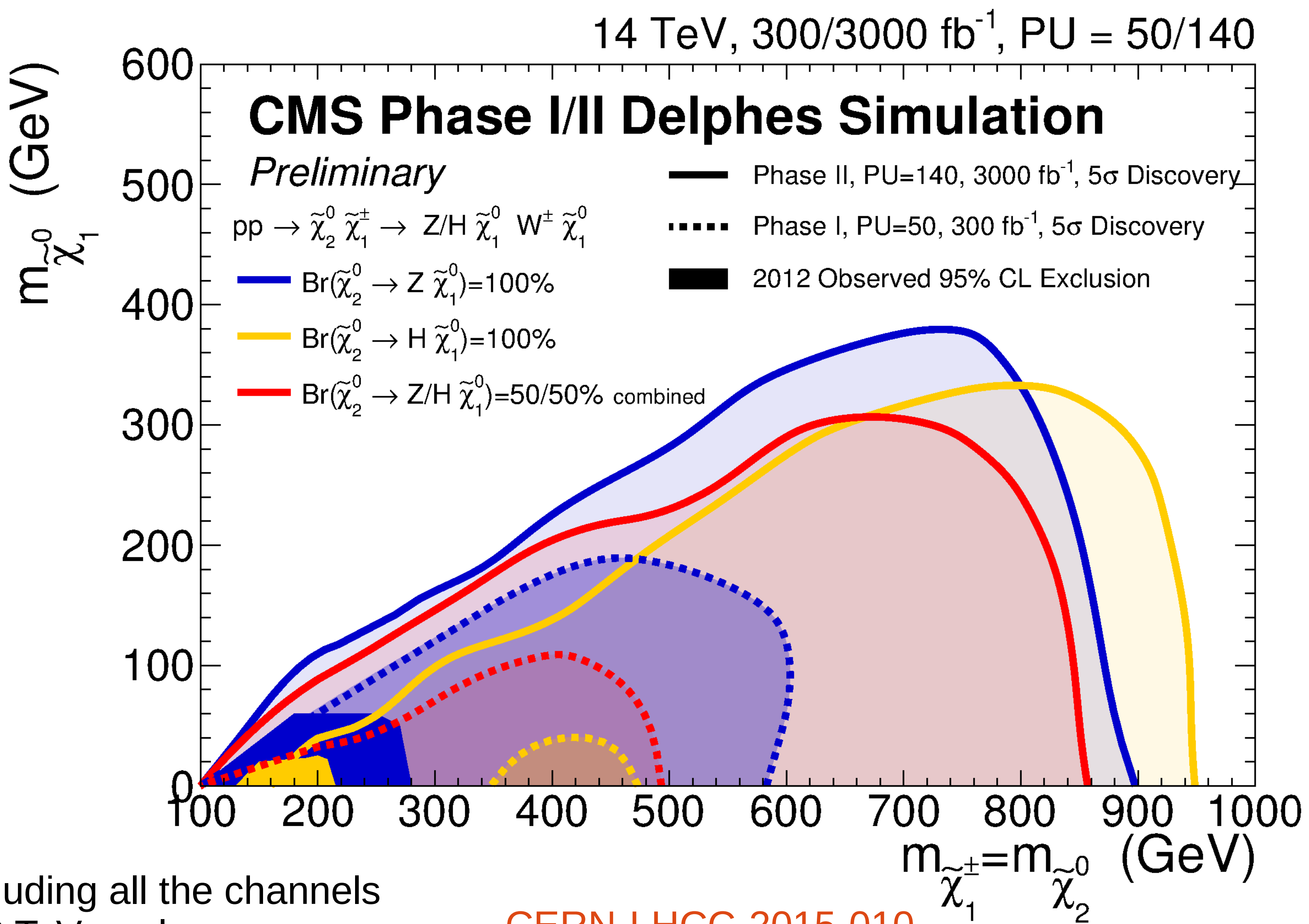
- $1\ell 2b$: $W(\ell\nu)h(bb)$
- OS $2\ell 2j$: $W(jj)Z(\ell\ell)$

Also:

- OS $2\ell 2b$: $h(bb)Z(\ell\ell)$

EPJC 74 (2014) 3036
PRD 90, 092007 (2014)

The HL-LHC will greatly extend sensitivity to electoweak production



* Not including all the channels used in 8 TeV analyses

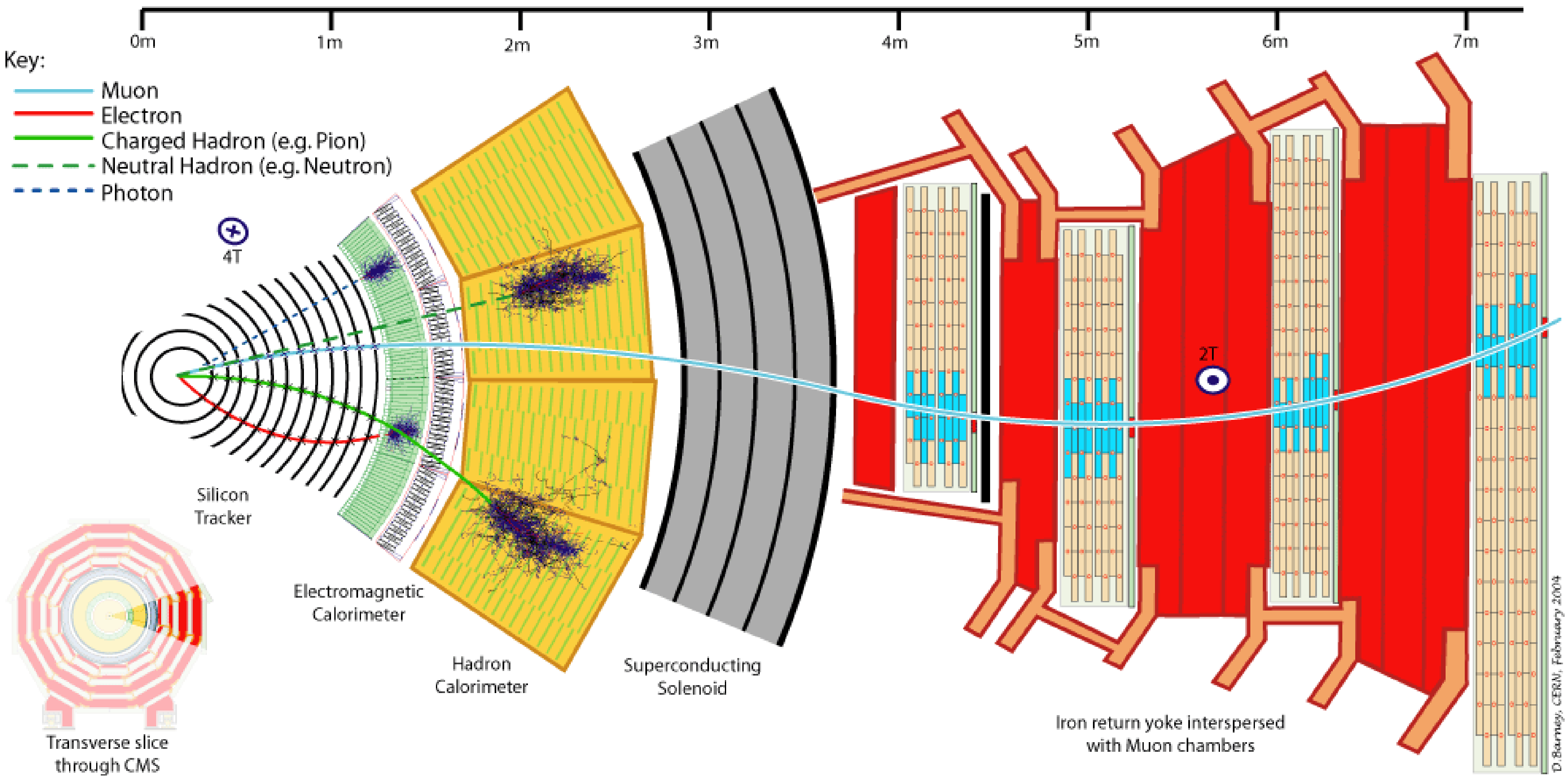
CERN-LHCC-2015-010

These are exciting times for searches

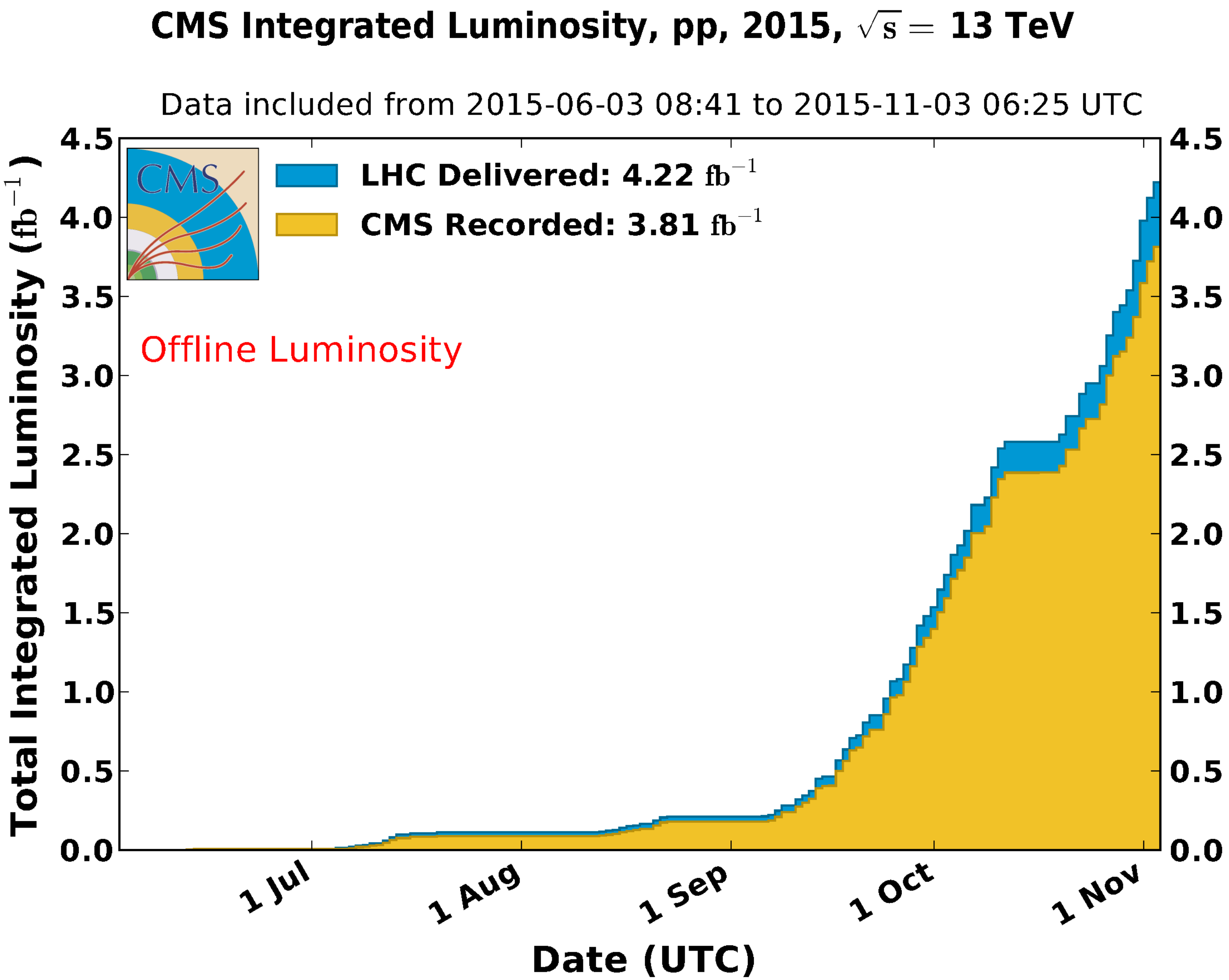
- Already exceeded Run 1 sensitivity with 1/10th of the luminosity
  - No evidence yet for new physics, but 40x more data coming in Run 2
- The M_{T2} inclusive analysis constrains a large range of SUSY (and dark matter) models
- Tension remains between ATLAS and CMS in Z+jets+E_T^{miss}
  - 2016 should be very interesting
- The CMS Edge search doesn't confirm the 8 TeV excess
- Electroweak SUSY searches will break new ground again in 2016
  - CMS event @ LPC April 27-29: Electroweak and Compressed SUSY

Bonus Slides: Intro

The CMS detector measures collision decay products precisely to infer E_T^{miss}



We use 2.3 fb^{-1} of data from 2015



Bonus Slides: M_{T2} Analysis

M_{T2} Object Selections

Jets:

- Anti-k_t 0.4 PF jets
- p_T > 30 GeV, $|\eta|<4.7$
- $|\eta|<2.5$ for N_J, N_B, H_T, M_{T2}
- Jet Cleaning for noise
- For 1-jet region: tighter noise cleaning

b-tagged jets:

- p_T > 20 GeV, $|\eta|<2.5$
- Medium WP of CSVv2IVF algo

MET:

- Particle flow, JECs applied
- Cleaning requirements for detector effects and non-collision backgrounds

Leptons: p_T > 10 GeV, $|\eta|<2.4$

- Electrons:
  - "Veto" ID, miniIso/p_T < 0.1
- Muons:
  - "Loose" ID, miniIso/p_T < 0.2
  - $|d_0|$ < 0.2 cm, $|dz|$ < 0.5 cm

Additional leptons for veto:

- PF Leptons (e, μ): m_T <100 GeV
  - p_T>5 GeV, $|dz|$<0.1 cm, RelTrkIso<0.2
- PF Charged Hadrons: m_T <100 GeV
  - p_T>10 GeV, $|dz|$<0.1 cm, RelTrkIso<0.1

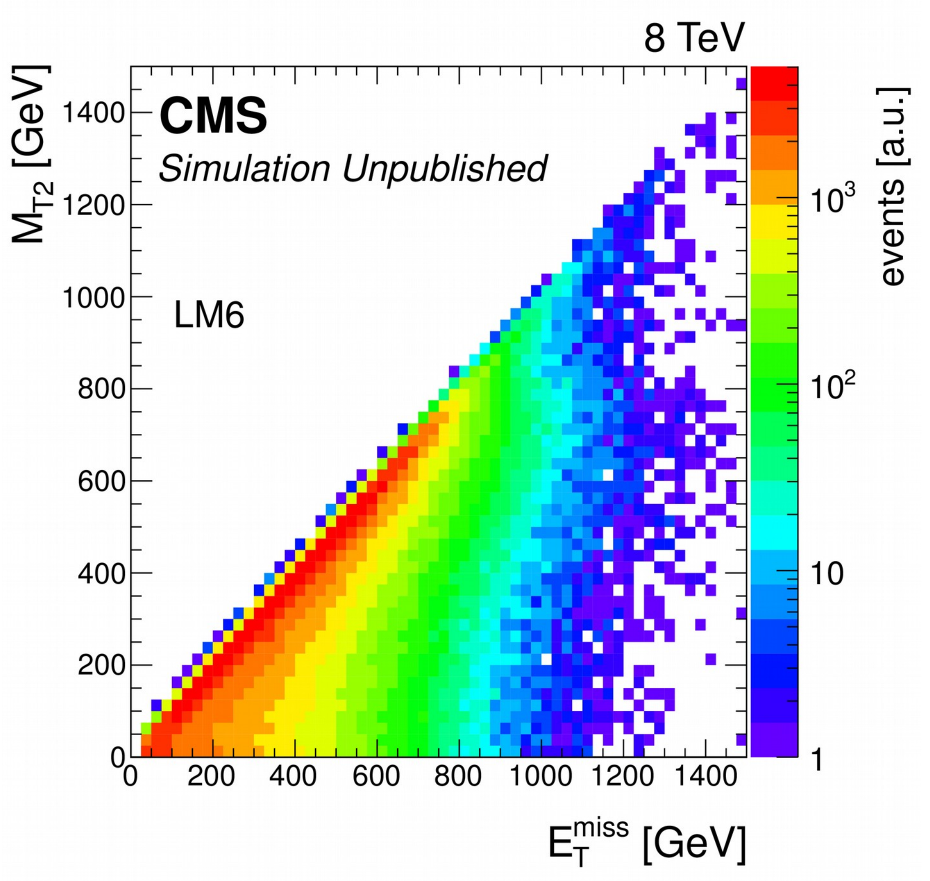
Photons: p_T > 180 GeV, $|\eta|<2.5$

- "Loose" ID
- PF Charged Iso < 2.5 GeV

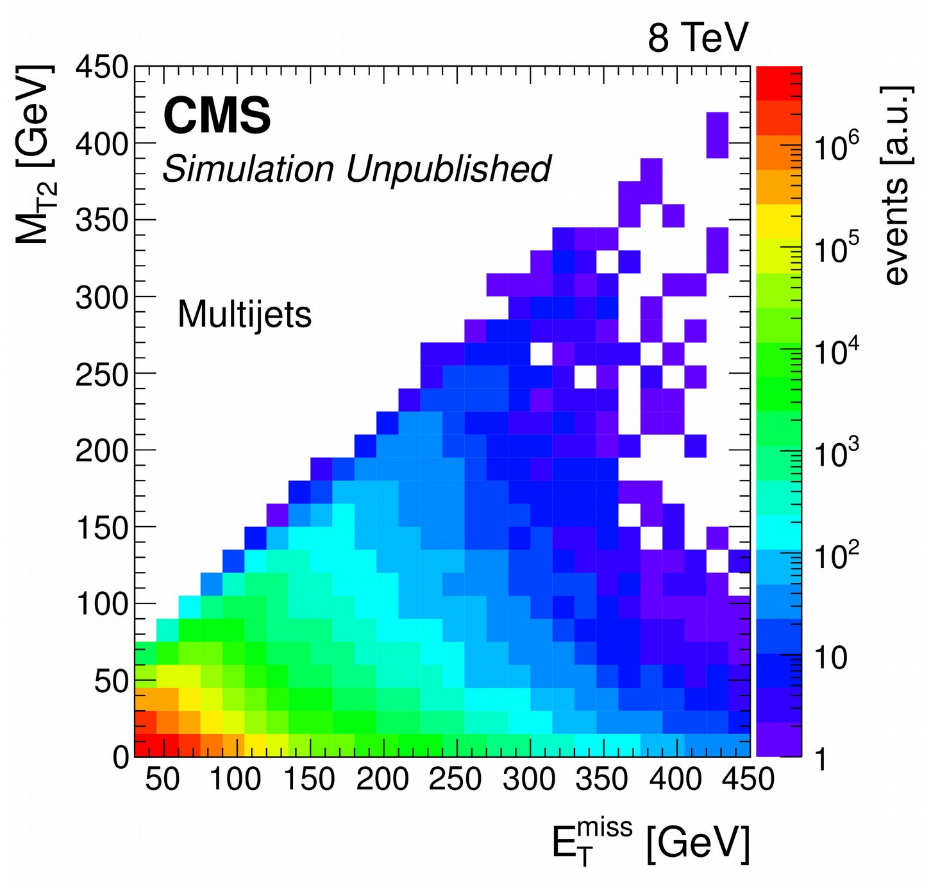
M_{T2} vs E_T^{miss} for signal, QCD multijets

$$M_{T2} = 2\, p_T^{vis(1)}\, p_T^{vis(2)} \left(1 + \cos\left(\Delta\phi_{1,2}\right)\right)$$

(assuming massless invisible particles, massless hemispheres)



Signal: $M_{T2} \sim E_T^{miss}$



Multijets: $M_{T2} \ll E_T^{miss}$

$Z \rightarrow \nu\nu$ prediction: details

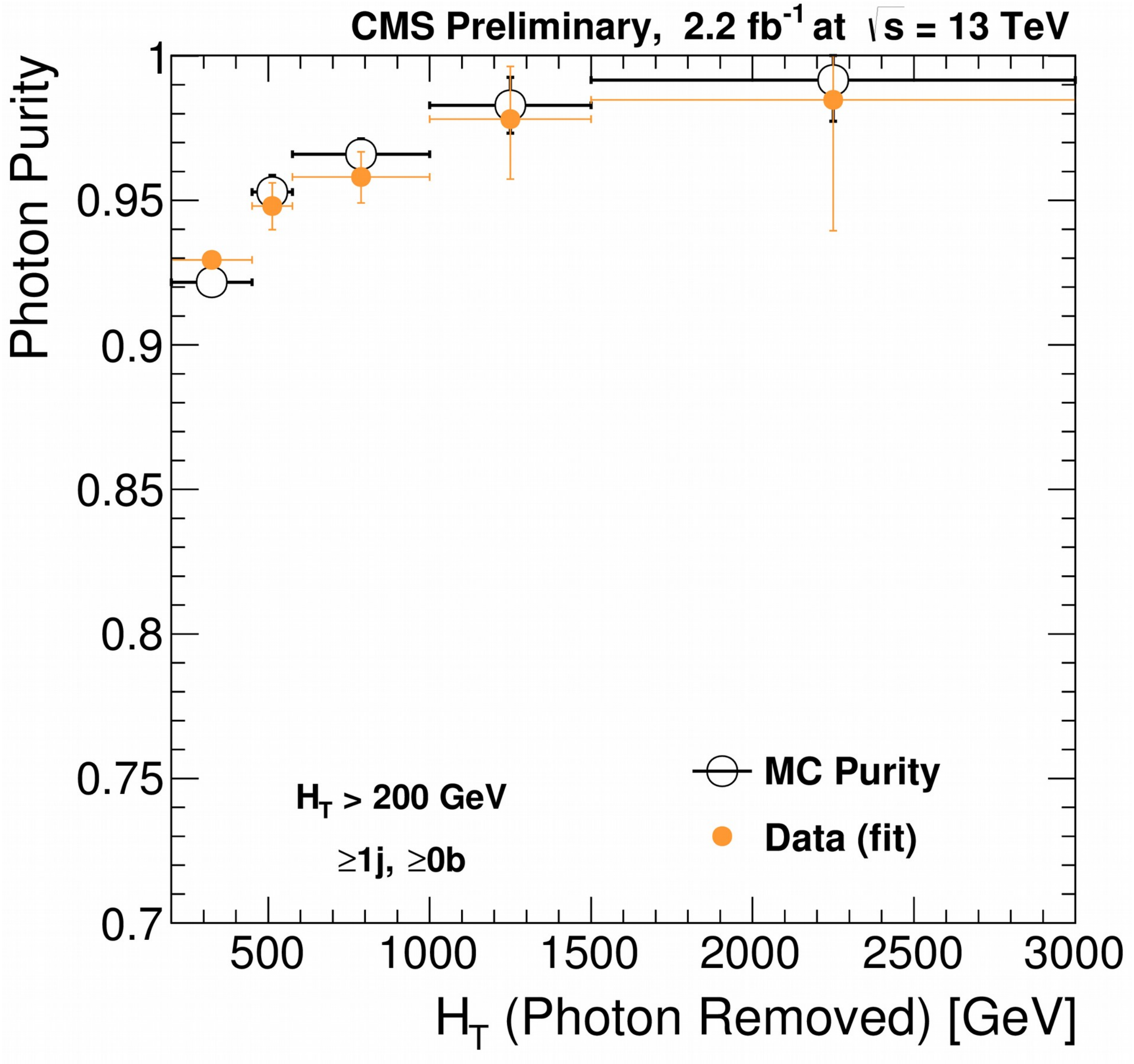
- Bin γ+jets in 3D (H_T, N_J, N_B) and use MC to predict M_{T2} shape

$$N^{\rm SR}_{Z\rightarrow\nu\bar{\nu}}\left(M_{T2}\right) = N^{\rm CR}_{\gamma}\left(H_T, {\rm N_j}, {\rm N_b}\right) \times P_\gamma \times f \times R^{Z/\gamma}_{\rm MC}\left(H_T, {\rm N_j}, {\rm N_b}\right) \times k_{\rm MC}\left(M_{T2}\right)$$

- **N_γ^{CR}**: observed γ+jets yield in control region
  - Photon treated as invisible
- **P_γ**: photon purity (accounts for π^0 and fakes)
  - ~0.95, data driven: isolation template fit
  - also have fake rate method as cross check
- **f**: fraction of direct prompt photons
  - Account for fragmentation using QCD multijet MC
  - ~0.92, MC based
- **R(Z/γ)**: ~0.4-0.5, MC based
  - Validated using $Z\rightarrow ll$: $R(Z_{ll}/\gamma)^{data}$ vs $R(Z_{ll}/\gamma)^{MC}$

- **k_{MC}**: fraction of events in each M_{T2} bin
  - Taken from $Z\rightarrow\nu\nu$ MC in each (H_T, N_J, N_B) region
  - M_{T2} shape from invisible Z is validated in data (γ+jets and $W\rightarrow l\nu$)
  - M_{T2} shape uncertainty is based on full set of MC variations
  - For monojet, CR binning is same as SR, no MC shape used

Photon purity measurement



Full uncertainties for $Z \rightarrow \nu\nu$ prediction

- **Photon control region:**
  - Statistics in data: 1-100%
  - Photon purity (stat): 1-100%, typically 5-10%
  - Photon purity (syst): 5% (from template variations, MC non-closure)
  - Fragmentation (syst): 8% (to cover for differences in MC)

- **R(Z/γ):**
  - MC statistics
  - Double ratio offset: 11% (from 0.95 ± 0.11 offset, MC vs data)
  - $R(Z_{ll}/\gamma)$ uncertainty: 15-100%
    - Stat uncertainty on $R(Z_{ll}/\gamma)$ in data, 1D projections along H_T, N_J, N_B

- **M_{T2} shape** (multijet regions with > 1 M_{T2} bin):
  - Full set of MC variations (theory + reco)
    - 40% in last bin
    - Linear morphing along M_{T2}

Lost lepton prediction: details

- Bin 1ℓ events in 3D (H_T, N_J, N_B) and use MC to predict M_{T2} shape

$$N_{1\ell}^{\mathrm{SR}}\left(M_{T2}\right) = N_{1\ell}^{\mathrm{CR}}\left(H_T, \mathrm{N_j}, \mathrm{N_b}\right) \times R_{\mathrm{MC}}^{0\ell/1\ell}\left(H_T, \mathrm{N_j}, \mathrm{N_b}\right) \times k_{\mathrm{MC}}\left(M_{T2}\right)$$

- **N_{1l}^{CR}**: observed 1ℓ yield in control region
  - Use signal triggers, require exactly 1 lepton
  - To avoid signal contamination (in signals with leptons):
    - MT(ℓ, E_T^{miss}) < 100 GeV
    - For ≥7j, extrapolate from 1-2b to ≥2b
- **$R(0l/1l)_{MC}$**: ~O(1), MC based
  - Accounts for lepton acceptance & efficiency, corrected for data T&P results
  - Accounts for hadronic tau decays
  - Uncertainty from T&P, MC variations

- **k_{MC}**: fraction of events in each M_{T2} bin
  - Taken from MC in each (H_T, N_J, N_B) region
  - M_{T2} shape from ttbar+W MC (including rares) is validated in 1 lepton data
  - M_{T2} shape uncertainty based on full set of MC variations
  - For monojet, CR binning is same as SR, no MC shape used

Full uncertainties for lost lepton prediction

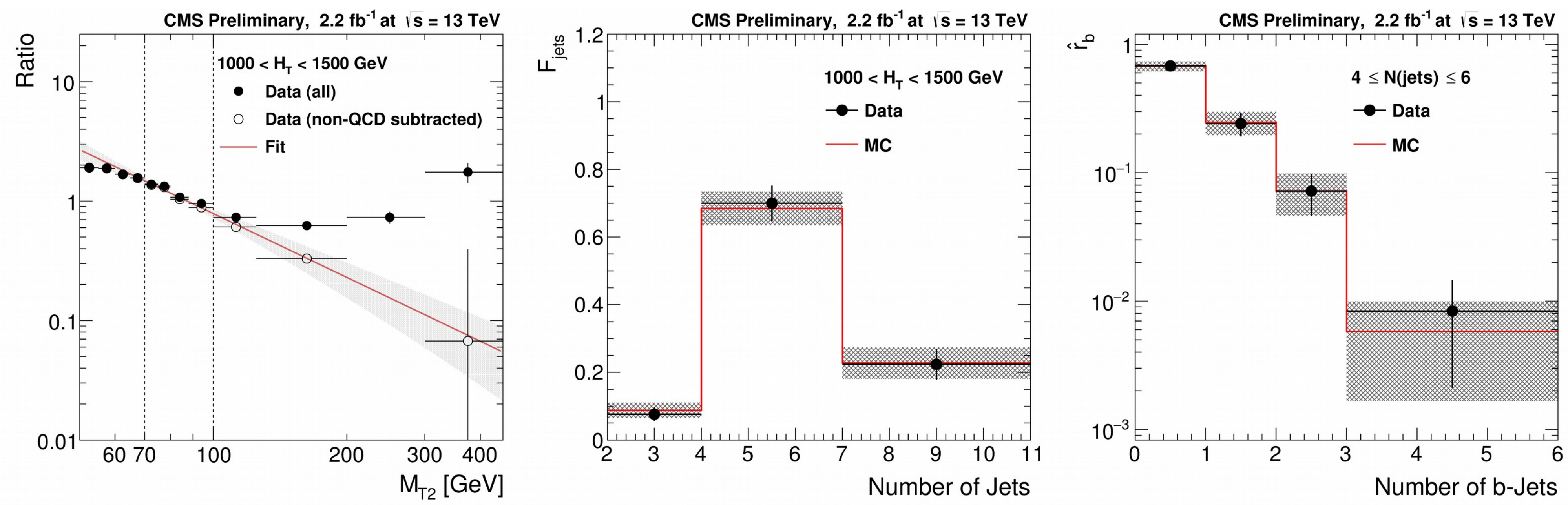
- **1l control region:**
  - Statistics in data: 1-100%

- **R(0l/1l):**
  - MC statistics
  - Lepton efficiency: 7%
  - MC variations (theory + reco): 10-40%
    - Theory (renormalization/factorization scales, PDF): < 5%
    - JES variation: up to 40% at very low HT and ≥7j
    - B-tag SF: 15% for ≥3b, < 5% elsewhere

- **M_{T2} shape** (multijet regions with > 1 M_{T2} bin)
  - Full set of MC variations (theory + reco)
    - 40% in last bin
    - Linear morphing along M_{T2}

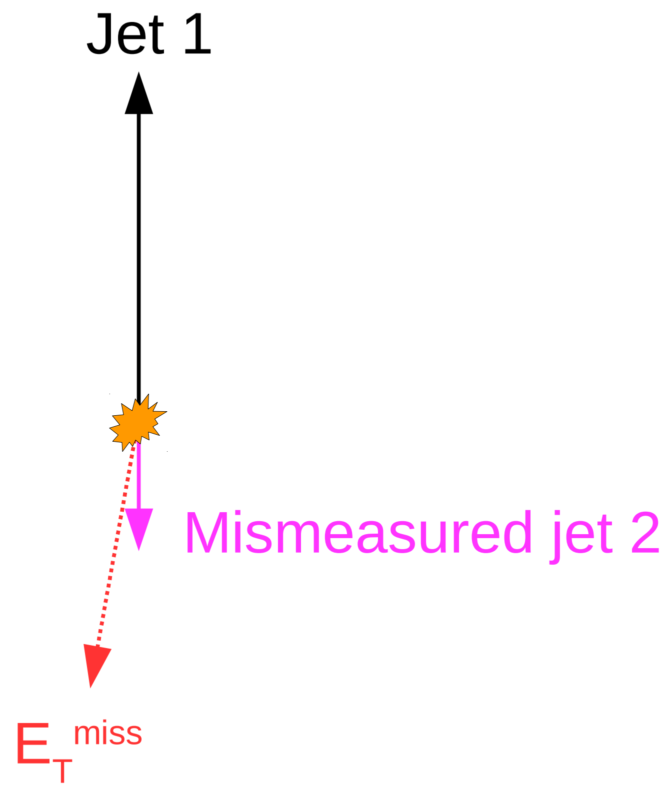
The transfer factors for the multijet estimate are extracted from data

- **$r_\phi(H_T, M_{T2})$:** fit to power law as function of M_{T2} in H_T bins
  - Stat uncertainty from fit, syst uncertainty from varying fit range
- **$f_j(H_T)$:** computed for each H_T bin
  - Uncertainty covers variation in MC with $\Delta\phi_{min}$, M_{T2}
- **$r_b(N_J)$:** computed for each N_J bin, integrated over H_T
  - Uncertainty covers variation in MC with $\Delta\phi_{min}$, M_{T2}, H_T



The multijet estimate for the monojet bins uses unbalanced dijet events

- Contribution to monojet regions small, 8% at most
- Use events with 2nd jet p_T 30-60 GeV to predict 0-30
  - Subtract other backgrounds taking 50% uncertainty



Full uncertainties for multijet prediction

- **Multijet regions: using $\Delta\phi_{min}$ sideband**
  - Control region stats: 5-100%
  - r_ϕ fit (stat): 50-100%, depending on H_T and M_{T2}
  - r_ϕ fit (syst): 16-200%, depending on H_T and M_{T2}
  - f_j (syst): 7-25%, covering invariance assumptions in MC
  - r_b (syst): 8-70%, covering invariance assumptions in MC

- **Monojet regions: using back-to-back dijet sideband**
  - Control region statistics: 5-100%
  - Electroweak subtraction: 50%

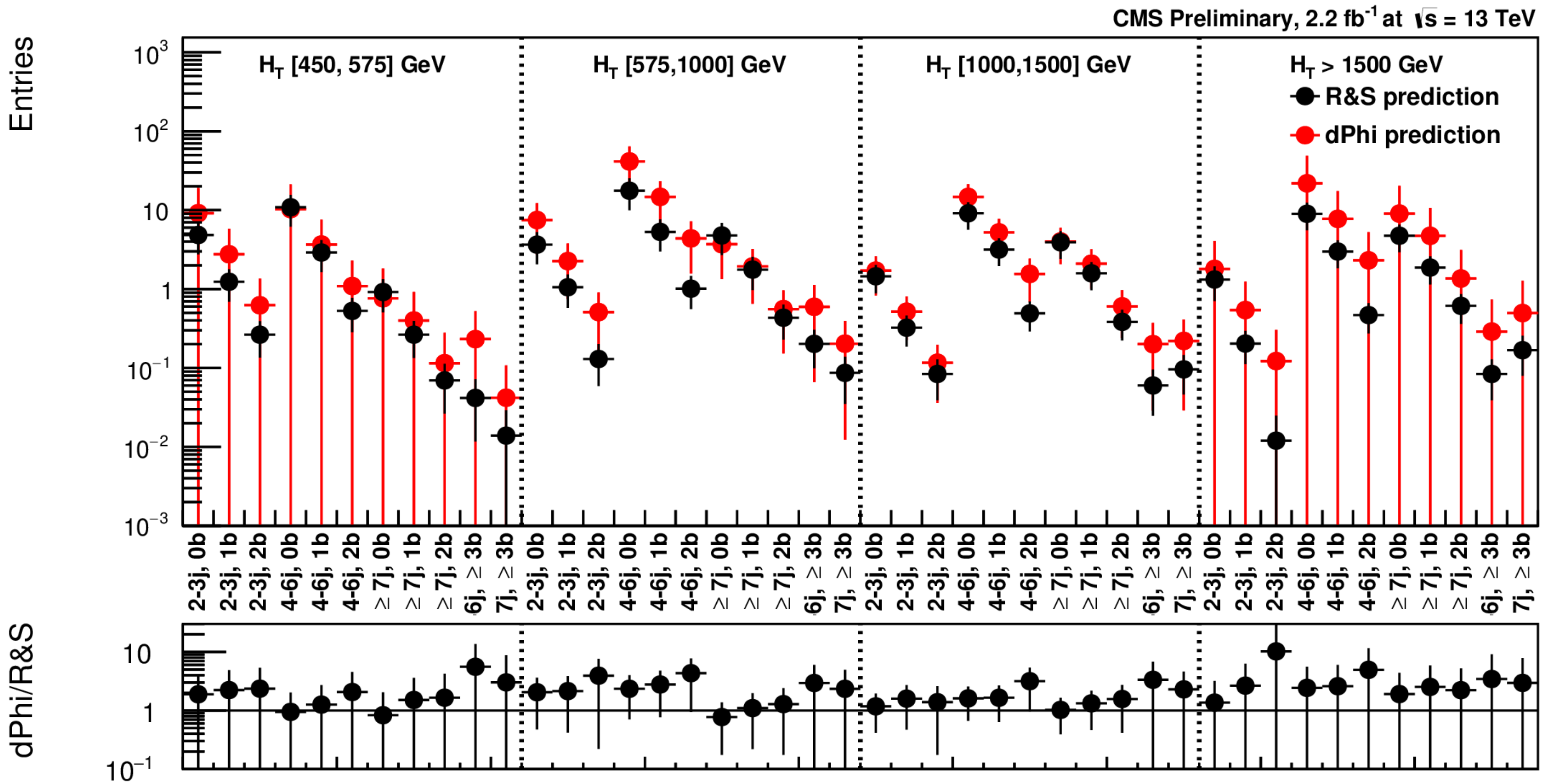
QCD multijet cross check: Rebalance and Smear method

- Select data multijet events
- **Rebalance** the jet momenta to give E_T^{miss} ~0 taking JER into account
- **Smear** jet momenta in each rebalanced event many times according to JER
  - JER from MC, separately for b and light flavor
  - Additional JER broadening for data from measurements
- Use smeared events to estimate QCD multijet background
  - Not done for H_T 200-450, no prescaled trigger

- Checked closure in QCD multijet MC
  - Found under-prediction of 20-25%
    - Correct prediction up, use full size of correction as uncertainty
  - Checked closure in data sidebands (low $\Delta\phi_{min}$ and/or low M_{T2})
    - Found over-prediction of ~35% → Take as additional systematic

Rebalance and Smear gives results consistent with nominal prediction

- Validation of standard multijet estimate with R&S prediction in signal regions, integrated over M_{T2}
- Two independent methods agree within uncertainties
  - Although there may be a systematic shift, less than 1σ

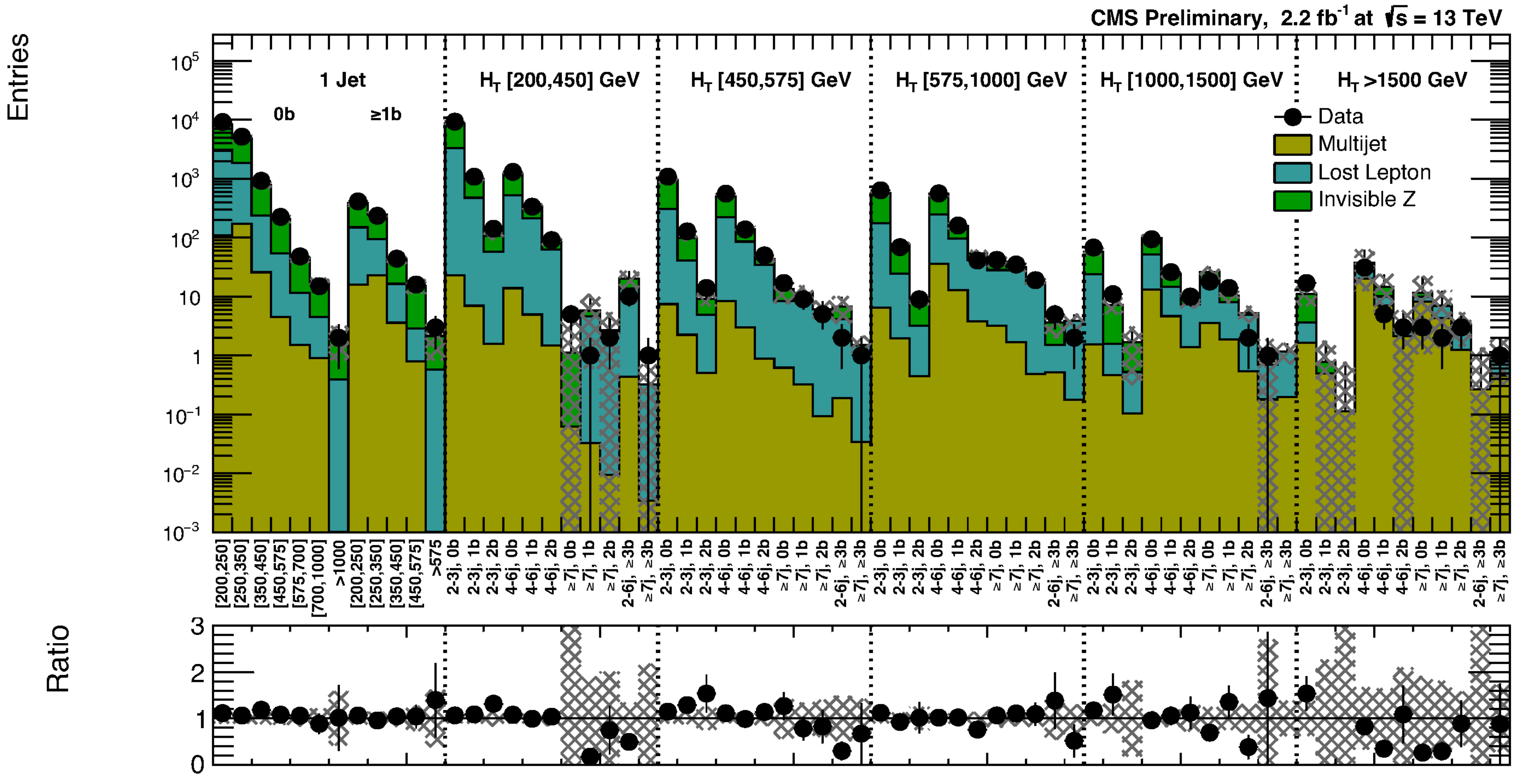


Systematic uncertainties for signals

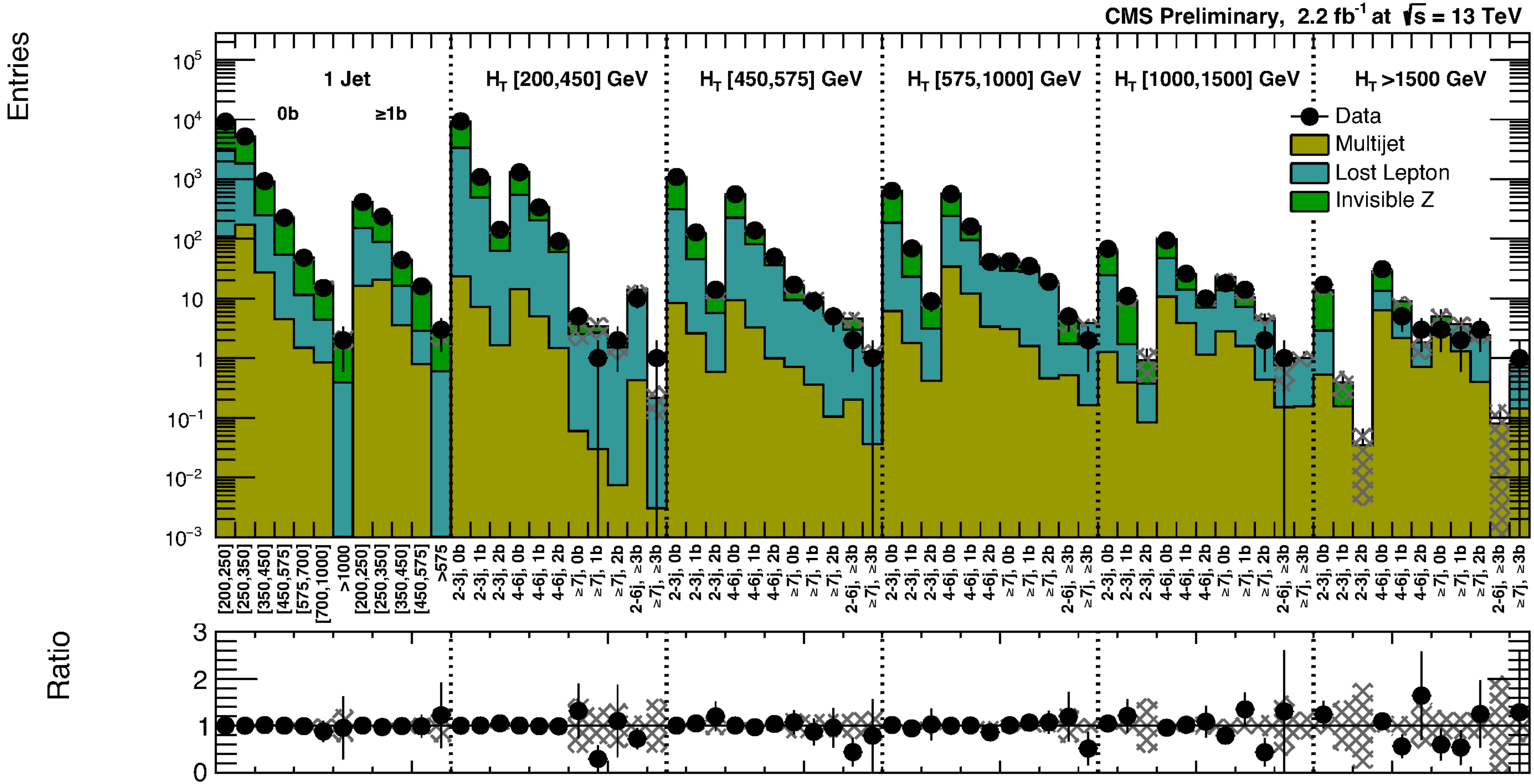
Source	Typical Values
Luminosity	4.6%
MC statistics	1–100%
Renormalization and factorization scales	5%
Parton distribution functions	10%
"ISR" recoil	0–30%
B-tagging efficiency, heavy flavor	0–40%
B-tagging efficiency, light flavor	0–20%
Lepton efficiency	0–20%
Jet energy scale	5%

Bonus Slides: M_{T2} Results

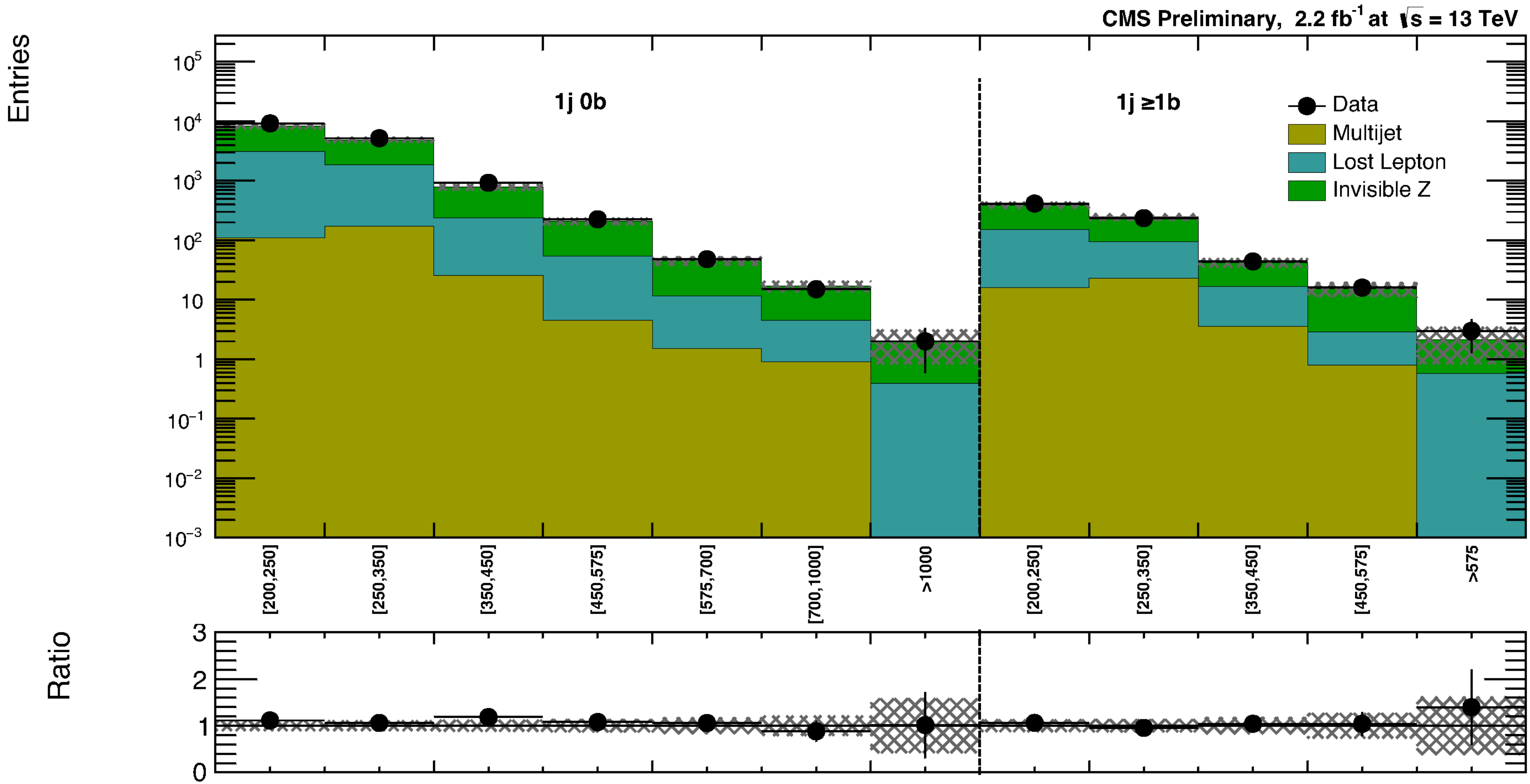
M_{T2} results: M_{T2} collapsed, pre-fit



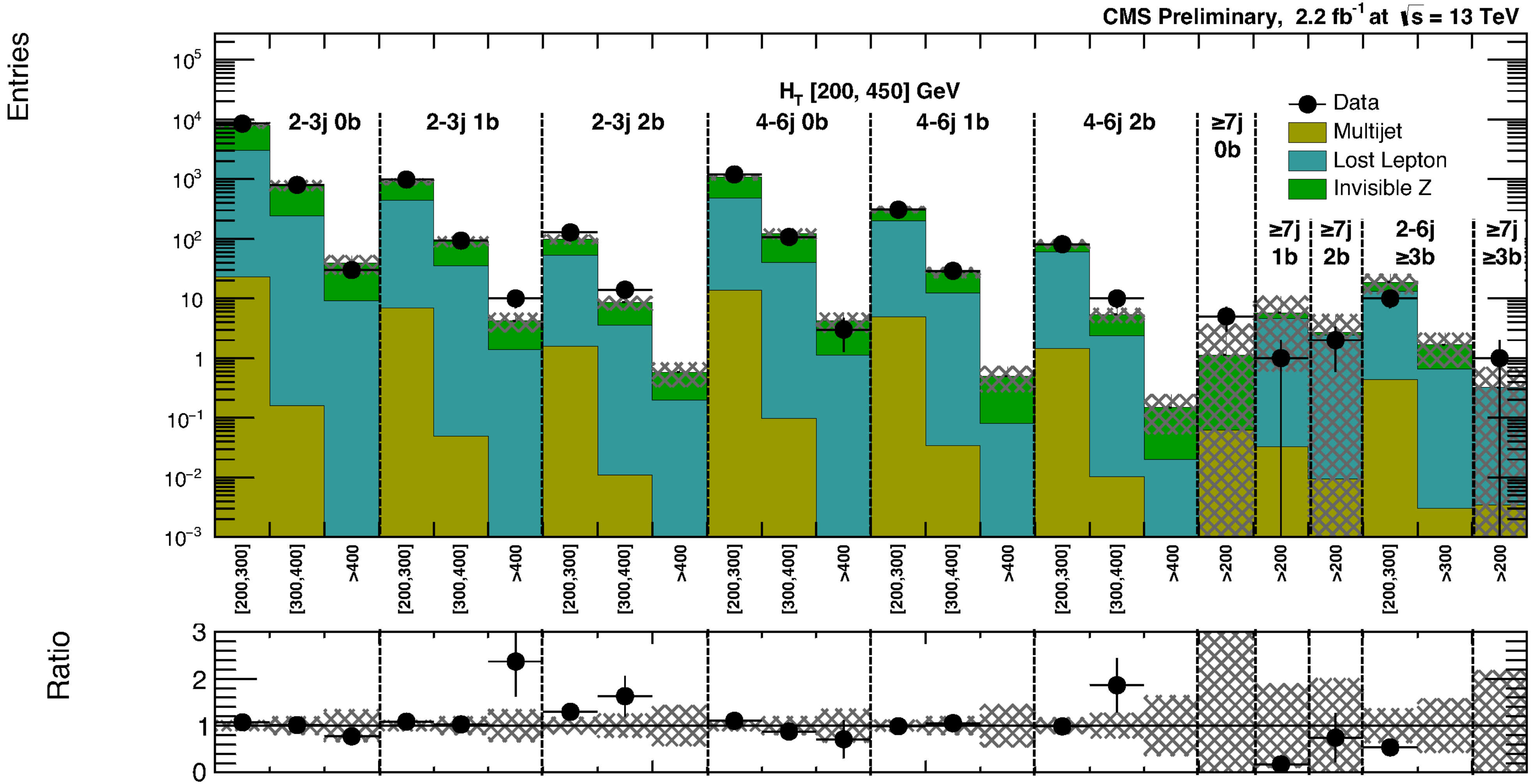
M_{T2} results: M_{T2} collapsed, post-fit



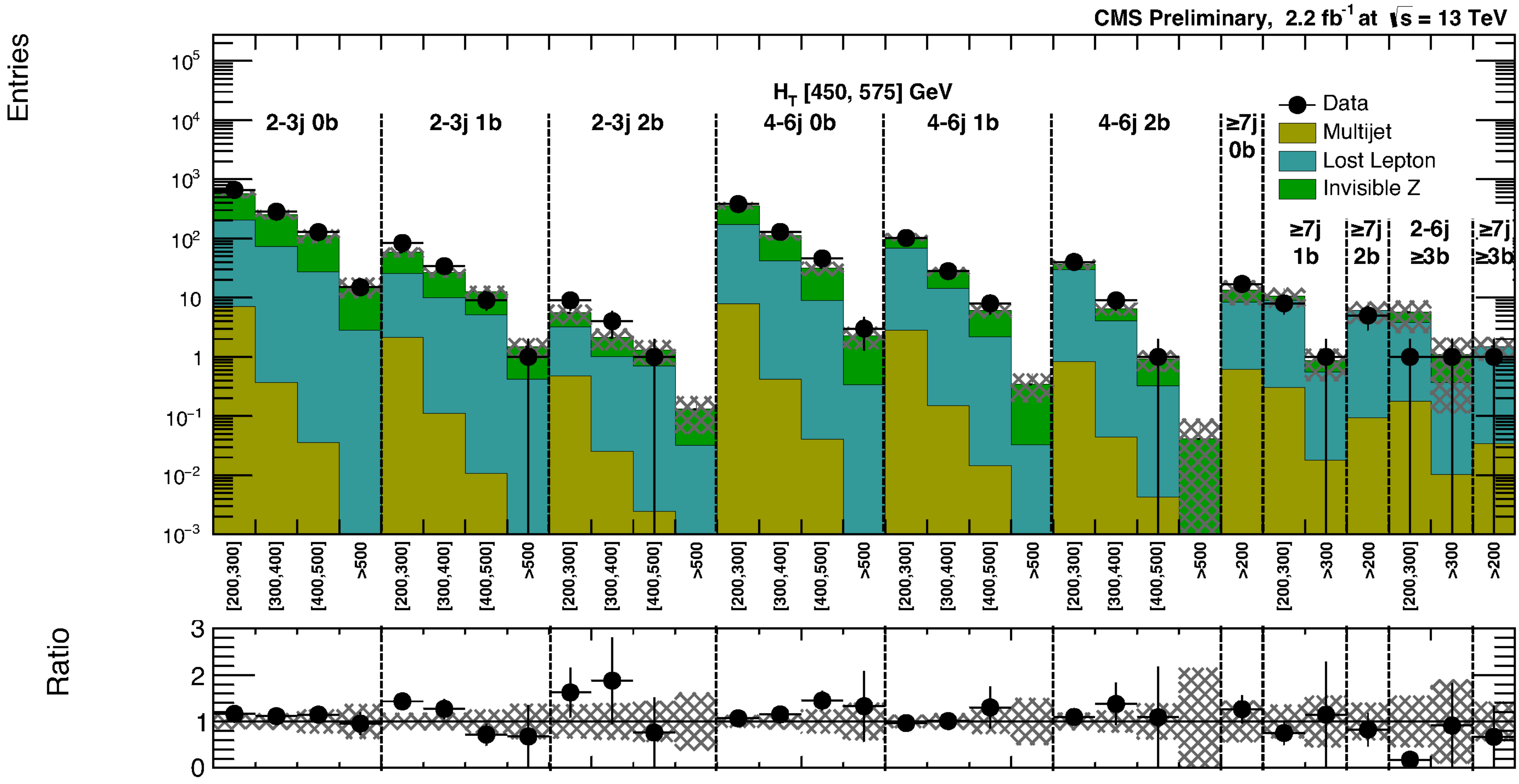
M_{T2} results: monojet, pre-fit



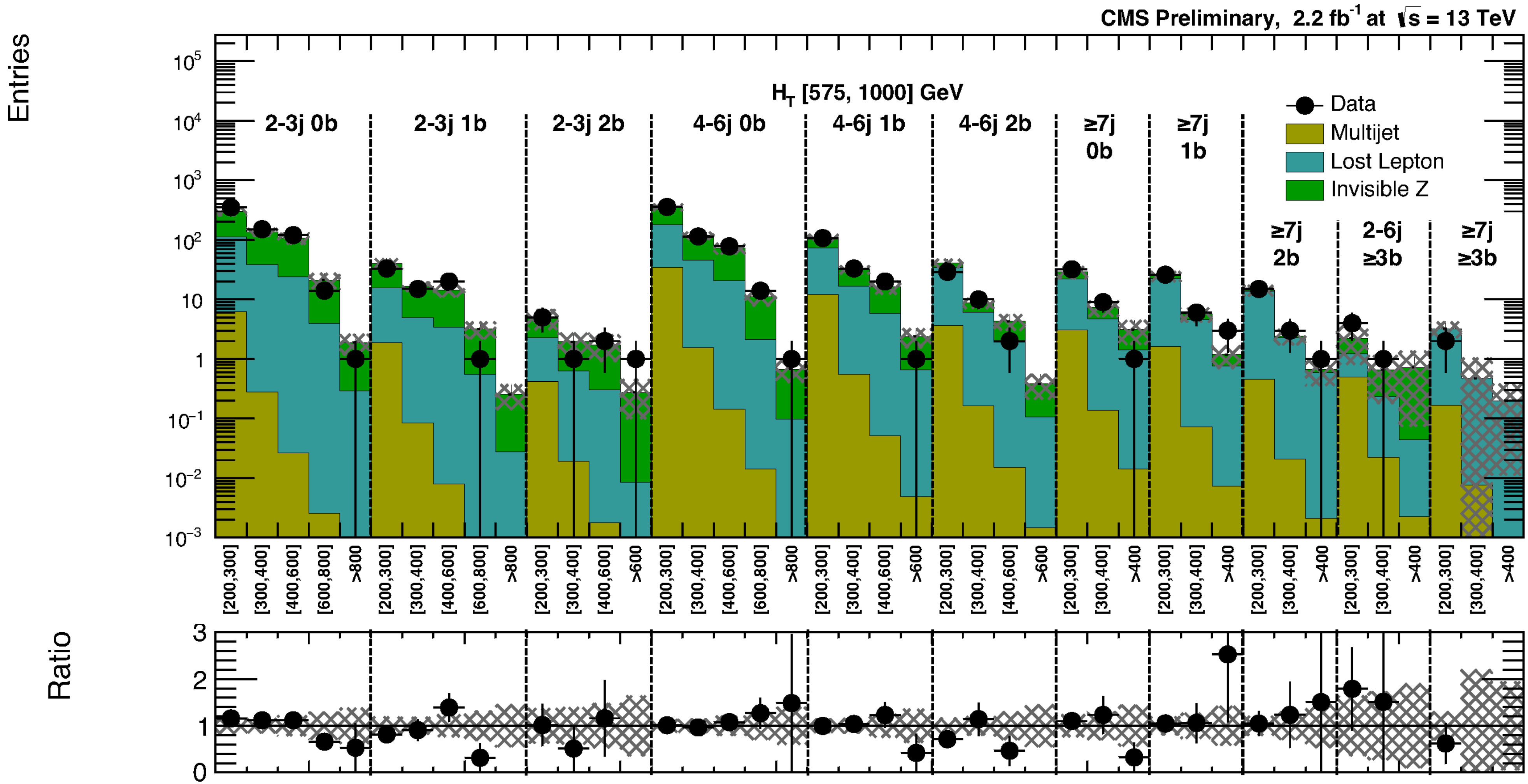
M_{T2} results: H_T 200-450, pre-fit



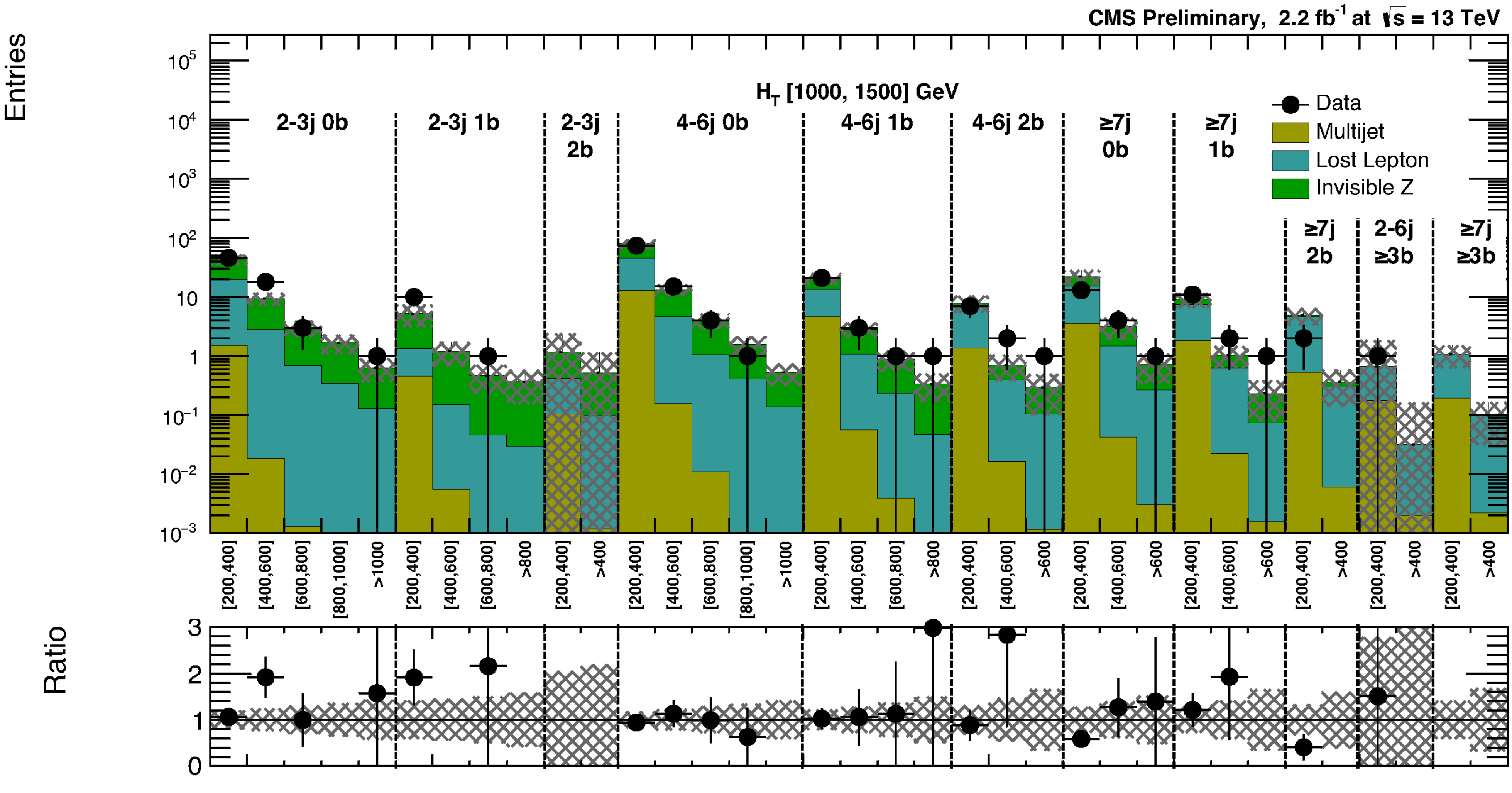
M_{T2} results: H_T 450-575, pre-fit



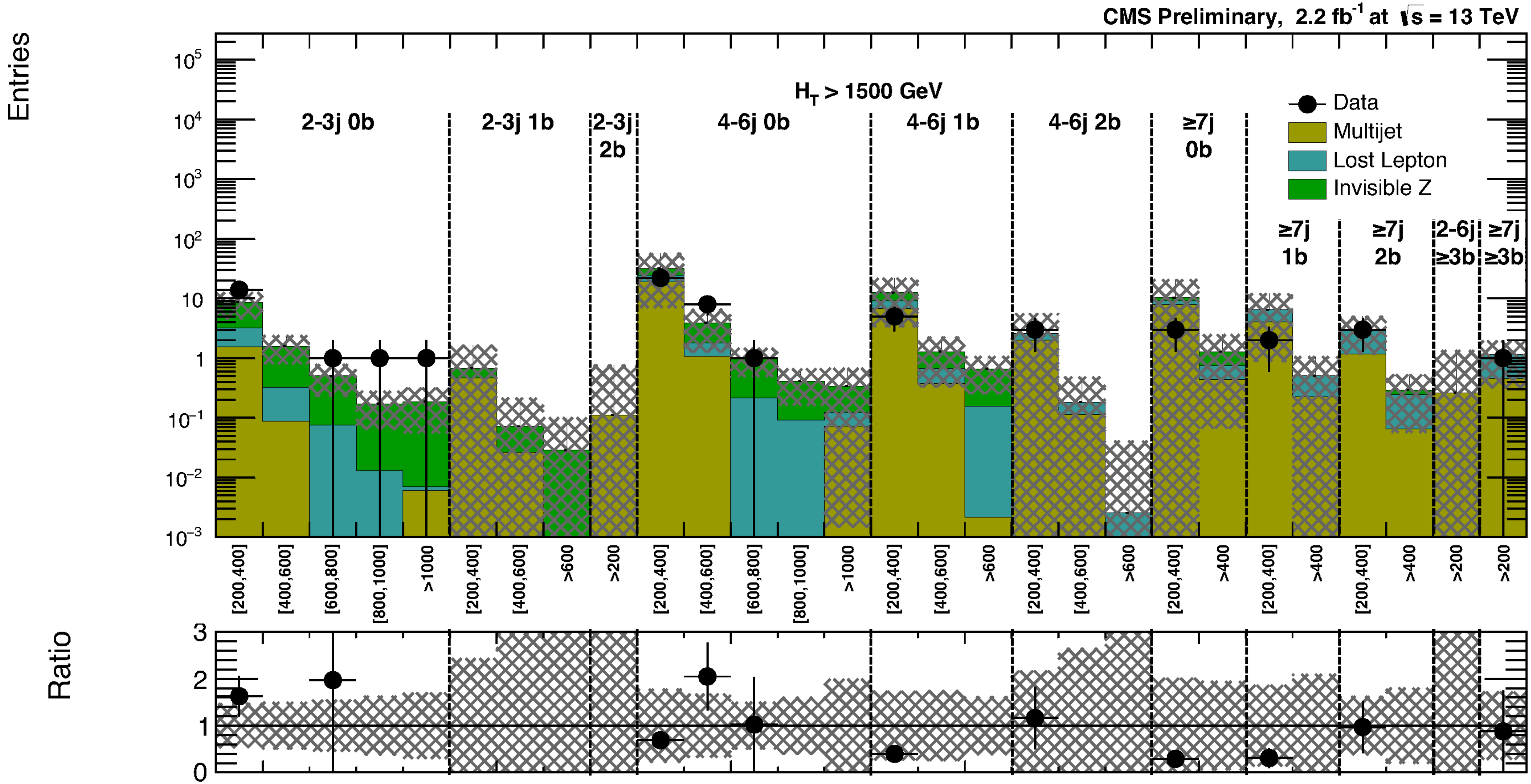
M_{T2} results: H_T 575-1000, pre-fit



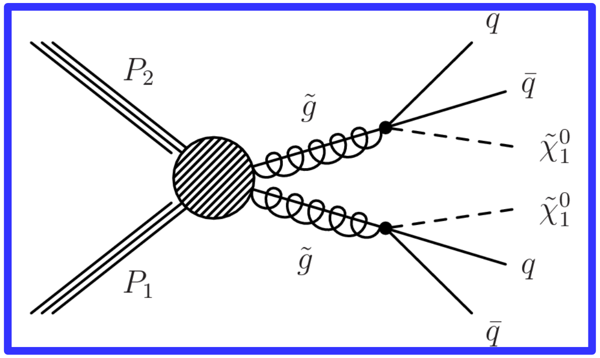
M_{T2} results: H_T 1000-1500, pre-fit

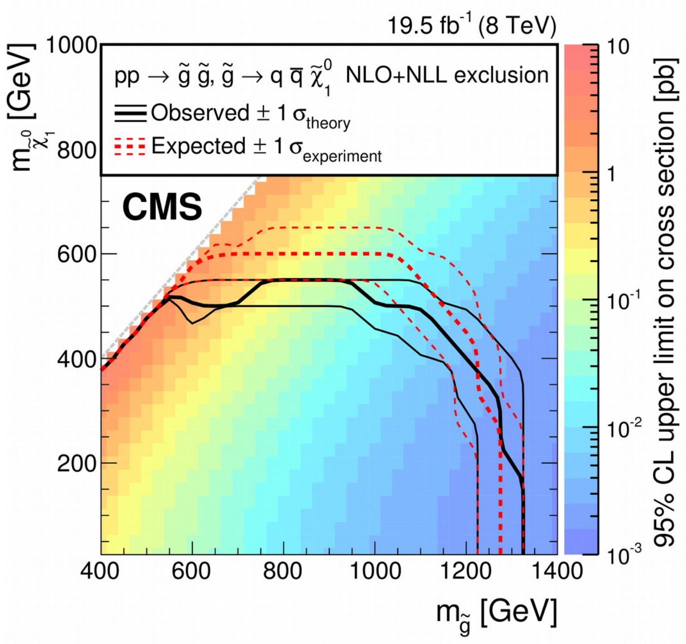


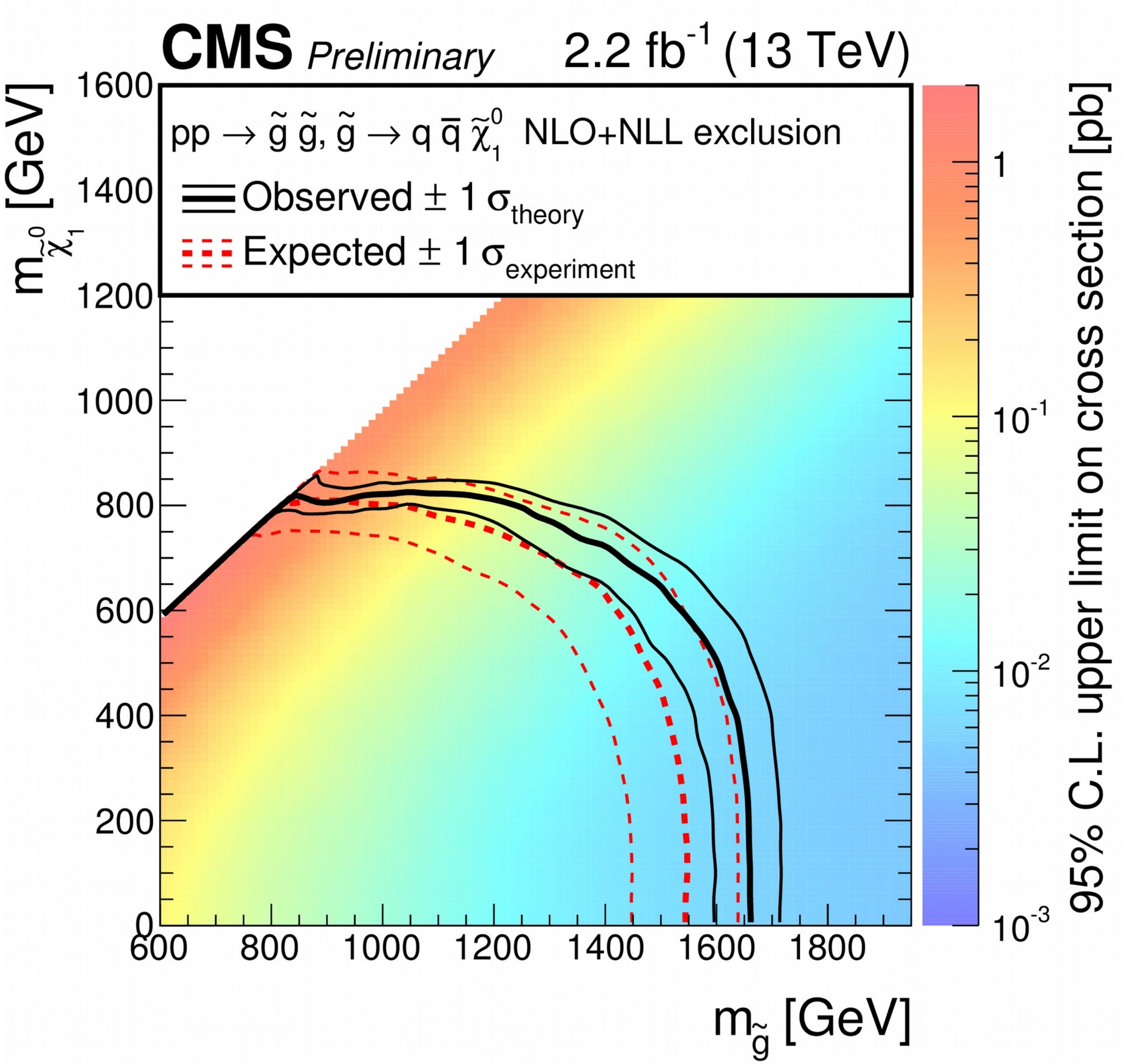
M_{T2} results: H_T > 1500, pre-fit



Our 13 TeV results extend the 8 TeV limits by up to 300 GeV







Bonus Slides: OS analysis

On-Z selection, comparison to ATLAS

- Highlight only cuts that are different
- ATLAS overlap removal cuts use 10 GeV leptons, 20 GeV jets

Cut	**CMS**	**ATLAS**
Triggers	Dilepton, iso OR noniso	Single or dilepton
Lepton p_T	20, 20	50, 25
Lepton η	$\lvert\eta\rvert < 2.4$, remove 1.4-1.6	$\lvert\eta\rvert < 2.47$ for e, $\lvert\eta\rvert < 2.4$ for μ
Lepton dR	> 0.1	> 0.01 for e wrt μ, no cut for SF
Jet p_T	35 GeV	30 GeV
Jet η	$\lvert\eta\rvert < 2.4$	$\lvert\eta\rvert < 2.5$
dR(jet, lep)	> 0.4	> 0.2 for non-btagged jets wrt leptons
dR(lep, jet)	-	> 0.2 for muons wrt b-tagged jets > 0.04 + 10 GeV/p_T for muons wrt jets > 0.4 for electrons wrt jets

Flavor Symmetry Method Details

$$r_{\mu e} = \sqrt{N_{\mu\mu}/N_{ee}}$$

Measured in DY-dominated region with ETmiss < 50 GeV
Uncertainty of 10-20% from variations with lepton kinematics and event kinematics
Contributes 1-4% uncertainty to R_{SFOF}

$$R_T = \frac{\sqrt{\epsilon_{\mu\mu}\epsilon_{ee}}}{\epsilon_{\mu e}}$$

Measured with orthogonal H_T triggers
Uncertainty of 7-9% from statistics, covers variation with kinematic variables

$$R_{SFOF} = \frac{1}{2}\left(r_{\mu e} + r_{\mu e}^{-1}\right) R_T$$

	Central		**Forward**	
	Data	MC	Data	MC
$\frac{1}{2}\left(r_{\mu/e} + r_{\mu/e}^{-1}\right)$	1.008 ± 0.013	1.008± 0.012	1.022± 0.042	1.026± 0.046
R_T	1.003 ± 0.072	1.027± 0.067	1.061± 0.090	1.029± 0.071
		$R_{SF/OF}$		
from factorization	1.011 ± 0.074	1.035 ± 0.068	1.084 ± 0.103	1.057 ± 0.087
direct measurement	1.055 ± 0.061	1.050 ± 0.013	1.107 ± 0.134	1.079 ± 0.021
weighted average	**1.037 ± 0.047**	**1.049 ± 0.013**	**1.097 ± 0.068**	**1.079 ± 0.020**

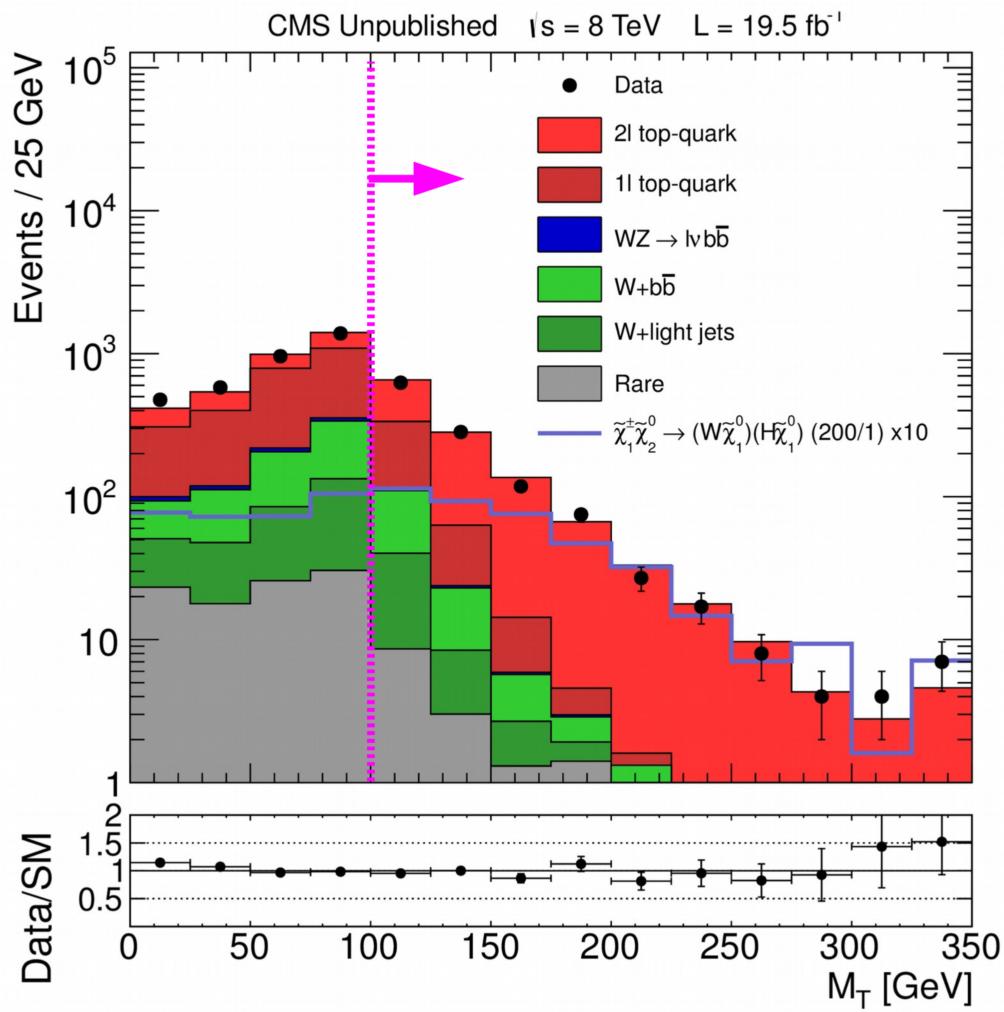
On-Z results comparison with ATLAS

Process	CMS, 2.2/fb	CMS, scaled to 3.2/fb	ATLAS, 3.2/fb
Z+jets	3.7 ± 0.7	5.4 ± 1.0	1.9 ± 0.8
Flavor symmetric	6.3 +3.8 -2.5	9.2 +5.5 -3.6	5.1 ± 2.0
WZ/ZZ + Rare	2.0 ± 0.9	2.9 ± 1.3	3.3 ± 0.8
Total prediction	12.0 +4.0 -2.8	17.5 +5.8 -4.0	10.3 ± 2.3
Data	12	-	21

Bonus Slides: Electroweak

1ℓ+bb search gives the best sensitivity for the Wh+MET topology at large Δm

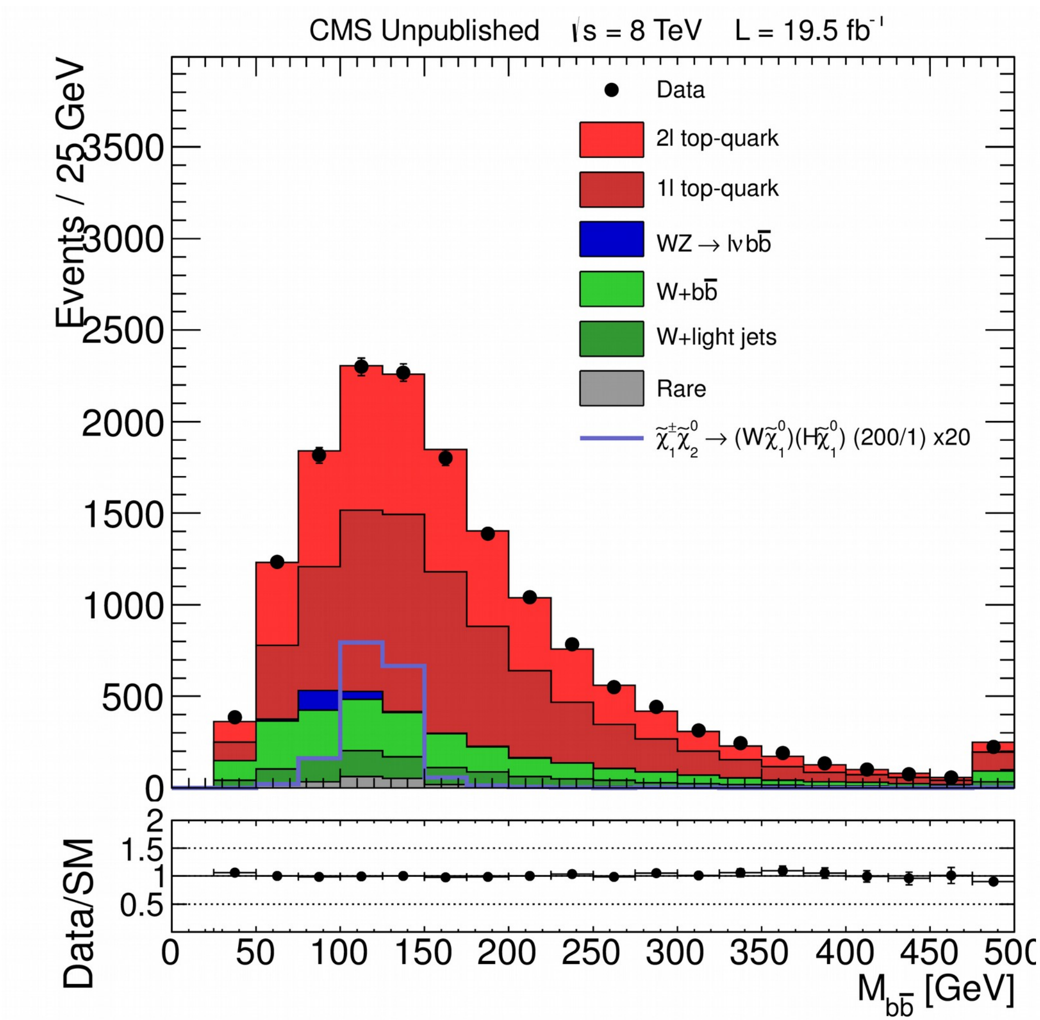
- Exactly 1ℓ (e,μ) and 2 b-jets
  - p_T(e/μ) > 30/25 GeV
  - p_T(jet) > 50/30 GeV
  - Look for resonance in M(bb)
- Main backgrounds: ttbar, W+jets, WZ
  - Suppress using kinematic variables to exploit extra MET in signal
  - M_T, M_{T2}^{bl}, also MET
  - Model mainly using MC with corrections from data control regions



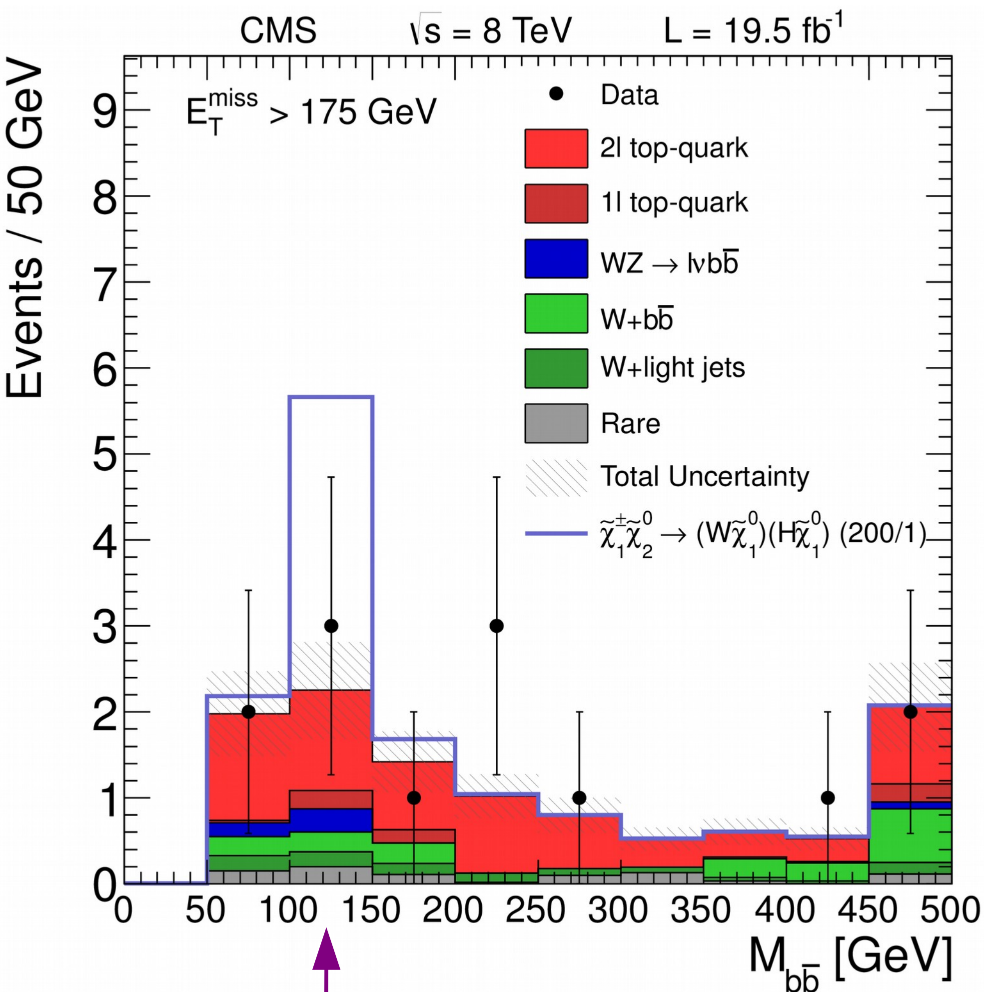
After preselection

EPJC 74 (2014) 3036

Observe good modeling of M(bb), no excess in signal regions



After preselection



Tightest signal region

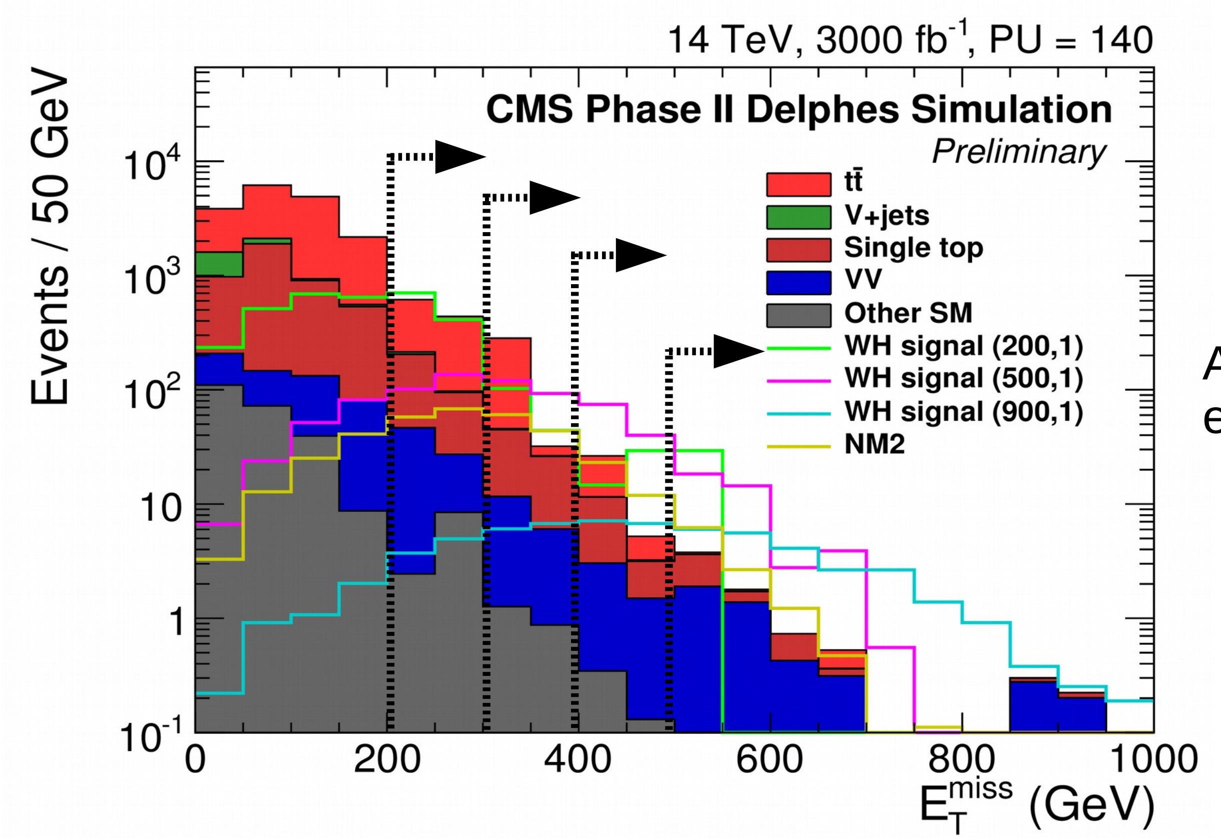
EPJC 74 (2014) 3036

Selection for HL-LHC projection

- Lepton: p_T > 40 GeV, $|\eta| < 2.4$
  - Veto additional leptons with p_T > 10 GeV
- Jets: p_T > 30, $|\eta| < 2.4$
  - Require exactly 2 jets to suppress ttbar → 1ℓ
- Cut on kinematic variable $M_{CT}(b_1,b_2)$: has endpoint for ttbar but not for signal
- Require M(bb) consistent with Higgs mass

Cut	Signal Requirement
N(leptons)	$= 1$
N(jets)	$= 2$
N(b-tags)	$= 2$
$M_{b\bar{b}}$	$\in$[90,150] GeV
M_T	$>$ 100 GeV
M_{CT}	$>$ 160 GeV
E_T^{miss}	$>$ 200,300,400(,500) GeV

Sensitivity comes in the tail of MET



After full selection except MET cut

Sample	$E_T^{miss} > 200$ GeV	$E_T^{miss} > 300$ GeV	$E_T^{miss} > 400$ GeV	$E_T^{miss} > 500$ GeV
$t\bar{t}$	1000 ± 260	261 ± 130	17 ± 13	0.5 ± 0.2
V + jets	14 ± 4	1.2 ± 0.3	0.1 ± 0.1	0.0 ± 0.0
single top	291 ± 38	66 ± 11	13 ± 4	2.5 ± 0.8
diboson	87 ± 16	24 ± 5	8.4 ± 2.0	4.4 ± 1.4
Other SM	14 ± 5	2.7 ± 0.6	0.6 ± 0.1	0.1 ± 0.0
Total SM	1410 ± 260	354 ± 130	39 ± 14	7.5 ± 1.6
WH signal (200,1)	1340 ± 140	220 ± 57	73 ± 33	29 ± 21
WH signal (500,1)	605 ± 18	367 ± 14	154 ± 9	40 ± 5
WH signal (900,1)	60 ± 1	51 ± 1	38 ± 1	24 ± 1
Natural Model 2	276 ± 4	150 ± 3	46 ± 2	11 ± 1