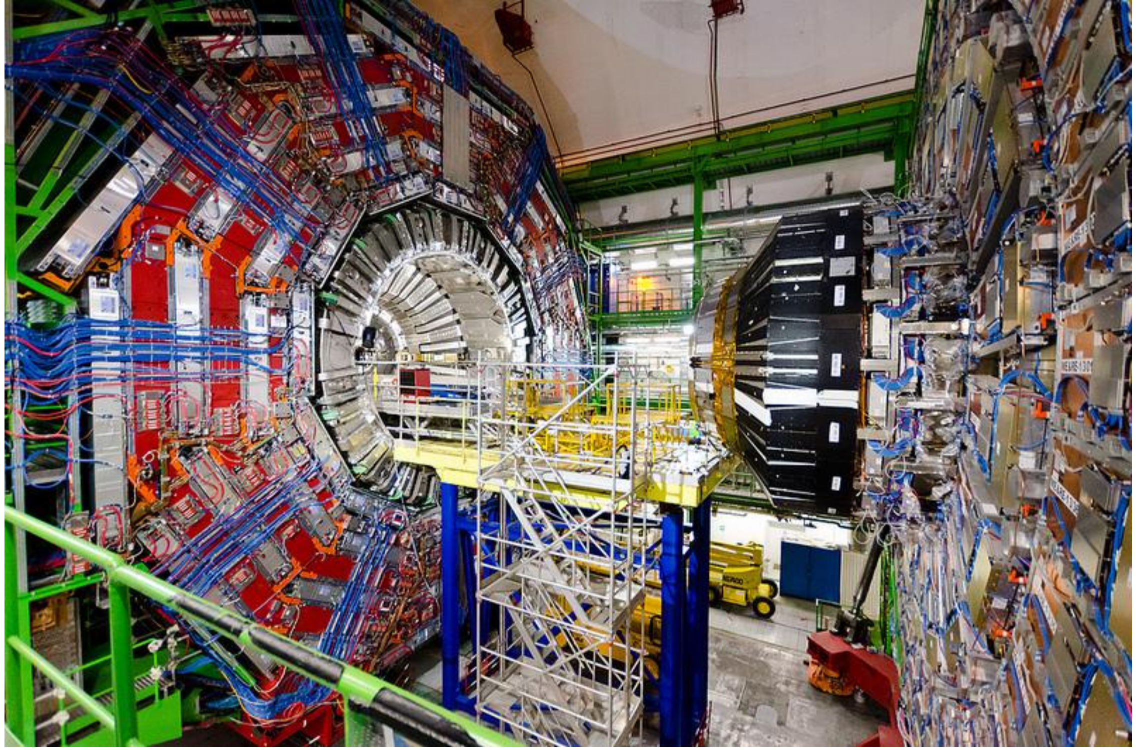
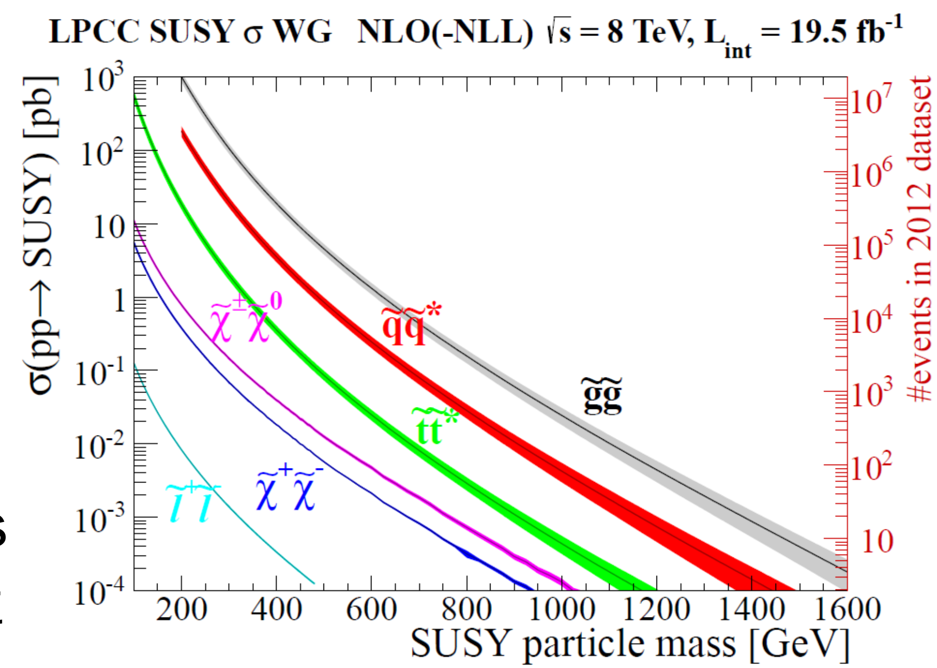


SUSY in Hadronic Final States at CMS

Joshua Thompson, Cornell University
26 Aug 2013
SUSY2013 Conference
Trieste, Italy

SUSY production at the LHC

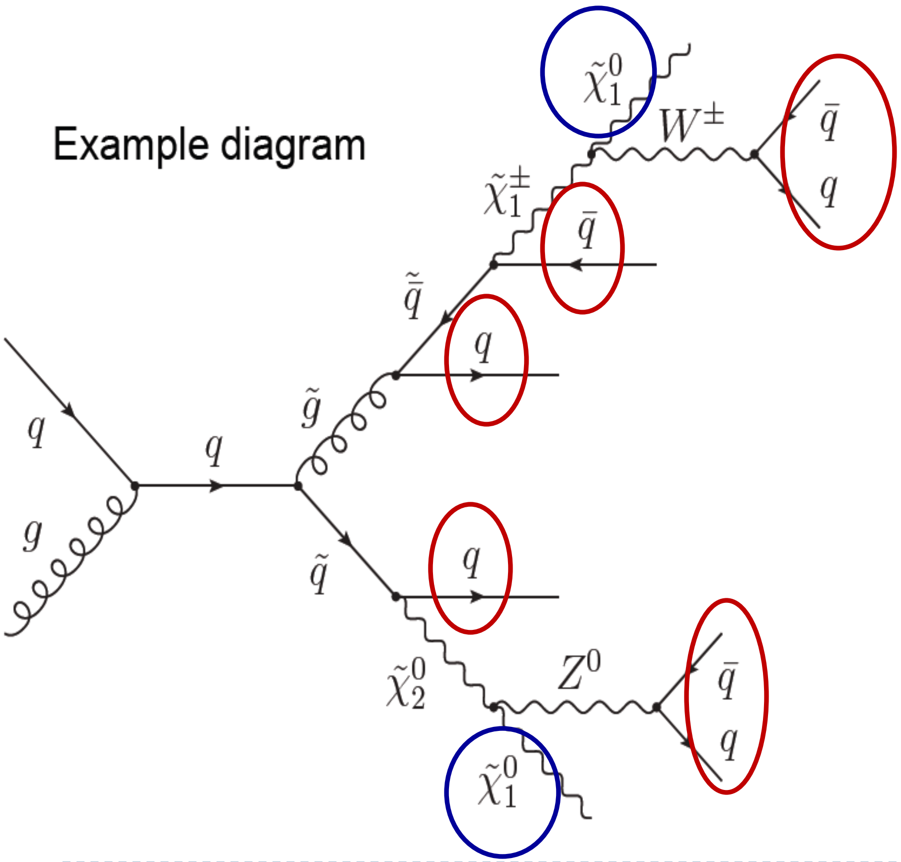
- Gluino and squark production processes have the highest cross-sections at the LHC
- Searches for these processes thus have the greatest mass reach
- Searches for the highest mass particles got the biggest boost from the 7→8 TeV increase
  - For 1400 GeV gluinos:
    - ~1 produced in 5 fb^{-1} @ 7 TeV
    - ~17 produced in 20 fb^{-1} @ 8 TeV



Hadronic SUSY signatures

- Heavy parent particles decay, often via a cascade, into energetic quarks and the lightest SUSY particle ($\tilde{\chi}_1^0$)

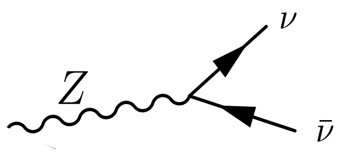
Example diagram



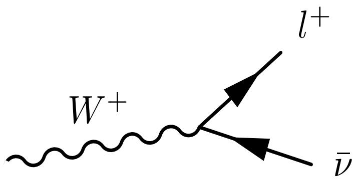
- Classic SUSY signature:
  - Large total jet energy
  - Large missing energy from pair of undetected $\tilde{\chi}_1^0$
- Inspired by natural SUSY, gluino pair-production with decays:
  - $\tilde{g} \to b\tilde{\bar{b}}_1 \to b\bar{b}\tilde{\chi}_1^0$
    - 4 b jets
  - $\tilde{g} \to t\tilde{\bar{t}}_1 \to t\bar{t}\tilde{\chi}_1^0$
    - 4 b jets
    - Large jet multiplicity from W→qq'

Major backgrounds

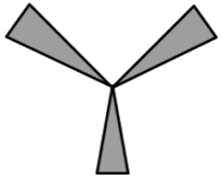
- Signature: jets+missing transverse energy
  - And optionally, b-tags



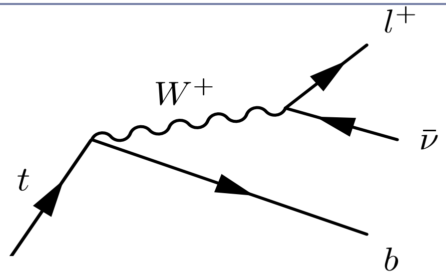
- Z+jets, where Z→νν
  - MET from undetected ν
  - "Irreducible" although production much smaller for Z+bb or Z+many jets



- W+jets, where W→lν
  - MET from ν
  - Reduced by rejecting events with l
  - W+bb, W+many jets production much smaller



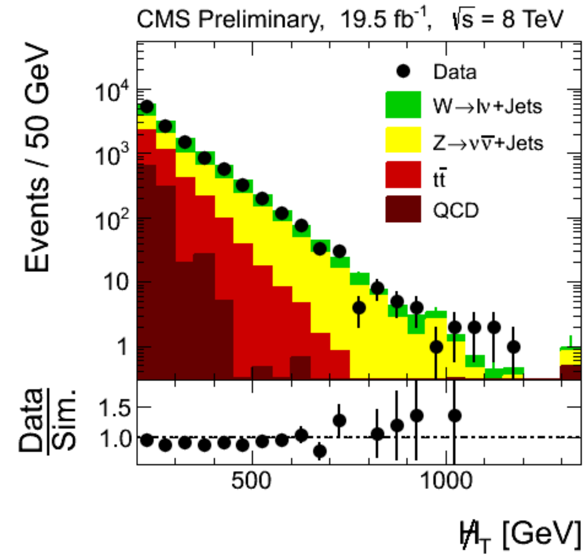
- QCD multijet
  - Huge production cross-section
  - MET arises from mismeasured jets or semileptonic b decays

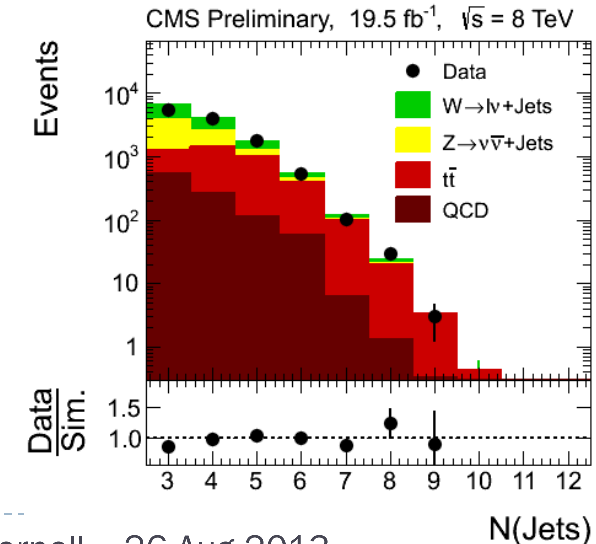


- ttbar, with one W→lν
  - MET from ν
  - 2b jets and ≥4 jets
  - Reduced by rejecting events with l

Search in Jets+MHT

- Generic search in the Jets+Missing energy signature
- Search performed in bins of 3 variables that discriminate between SM background and SUSY:
  - Missing transverse energy: MHT = - $|\Sigma_{jets}\ p_T|$
  - Scalar sum of jet energy: $H_T = \Sigma_{jets}\ |p_T|$
  - Jet multiplicity (for jets with p_T>50 GeV)
    - Search bins: n_{jets} = [3-5], [6-7], [>=8]
- Binned approach provides sensitivity to a variety of signal topologies and mass splittings
- Other selection details:
  - $\Delta\phi$(jet, MHT) > 0.5, 0.5, 0.3 for lead 3 jets
    - Rejects QCD events with fake MHT from mismeasured jets
  - Reject events with an isolated e or μ (p_T>10 GeV)
    - Reject W+jets and ttbar backgrounds



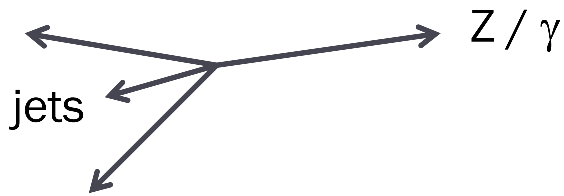


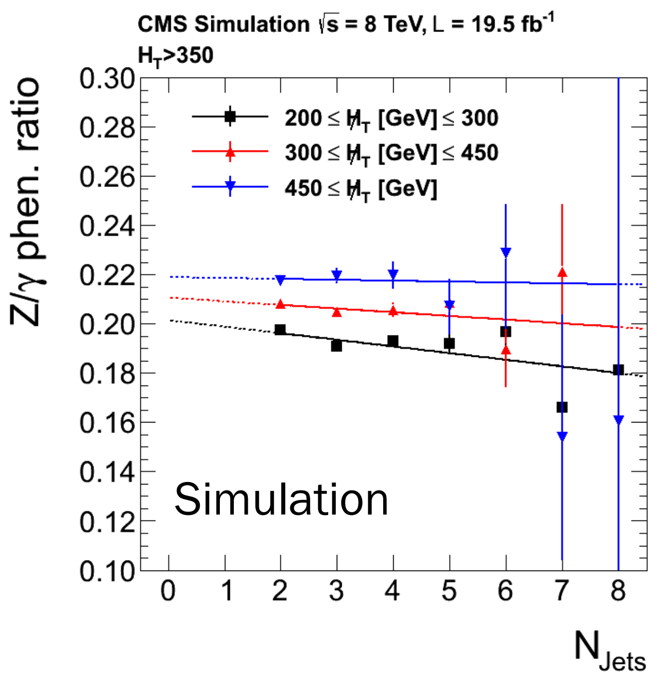
Background estimation overview

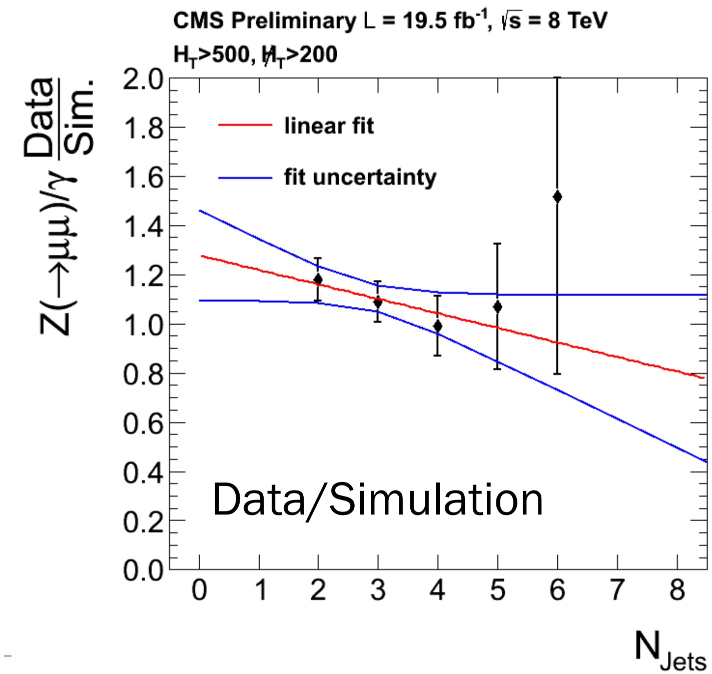
- General philosophy:
  - Avoid reliance on Monte Carlo simulation
  - Instead derive background estimates from data control samples
- Challenges:
  - Limited control sample data at high H_T, MHT, and jet multiplicity
- Backgrounds and control samples:
  - $Z \to \nu\nu$: γ+jets control sample
  - W+jets/ttbar: μ+jets control sample
  - QCD multijets: low MHT events

Z→νν background estimation

- Use similarity between high p_T γ+jets events and Z+jets events to predict Z→νν background
- Treat photon as if it was undetected, recalculate MHT
  - Correct for:
    - Photon acceptance and efficiency
    - Cross-section ratio: σ(Z+jets) / σ(γ+jets)
      - Ratio measured as a function of H_T, MHT, n jets in MC
      - N jets dependence corrected using a Z→μμ data control sample

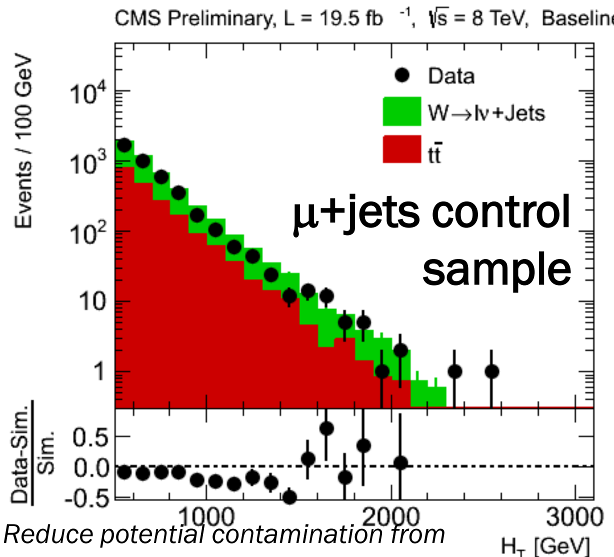






W/ttbar background estimation

- Use μ data control samples to model event kinematics and hadronic activity



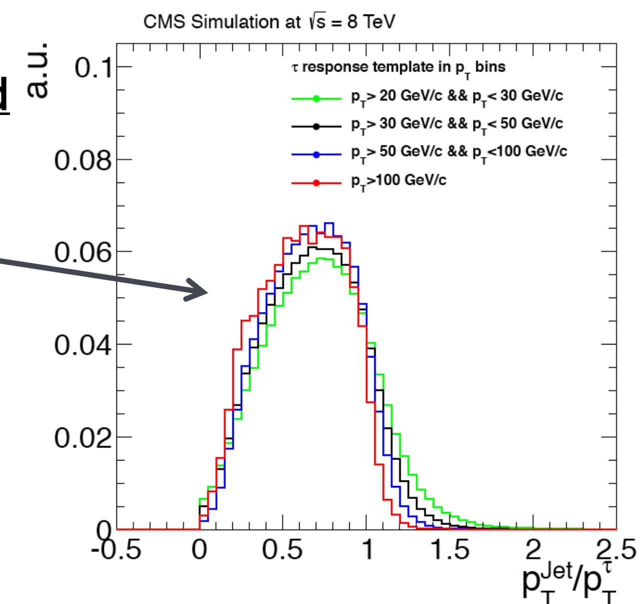
Reduce potential contamination from signal by requiring M_T(μ,MET)<100 GeV

Prediction of lost e/μ background

- Use MC to derive factors for lepton acceptance, reconstruction, and isolation efficiencies
  - Efficiencies checked in Z→μμ data sample
- Using these factors and control sample, get prediction of W→lν, where l=e,μ,τ→e,μ

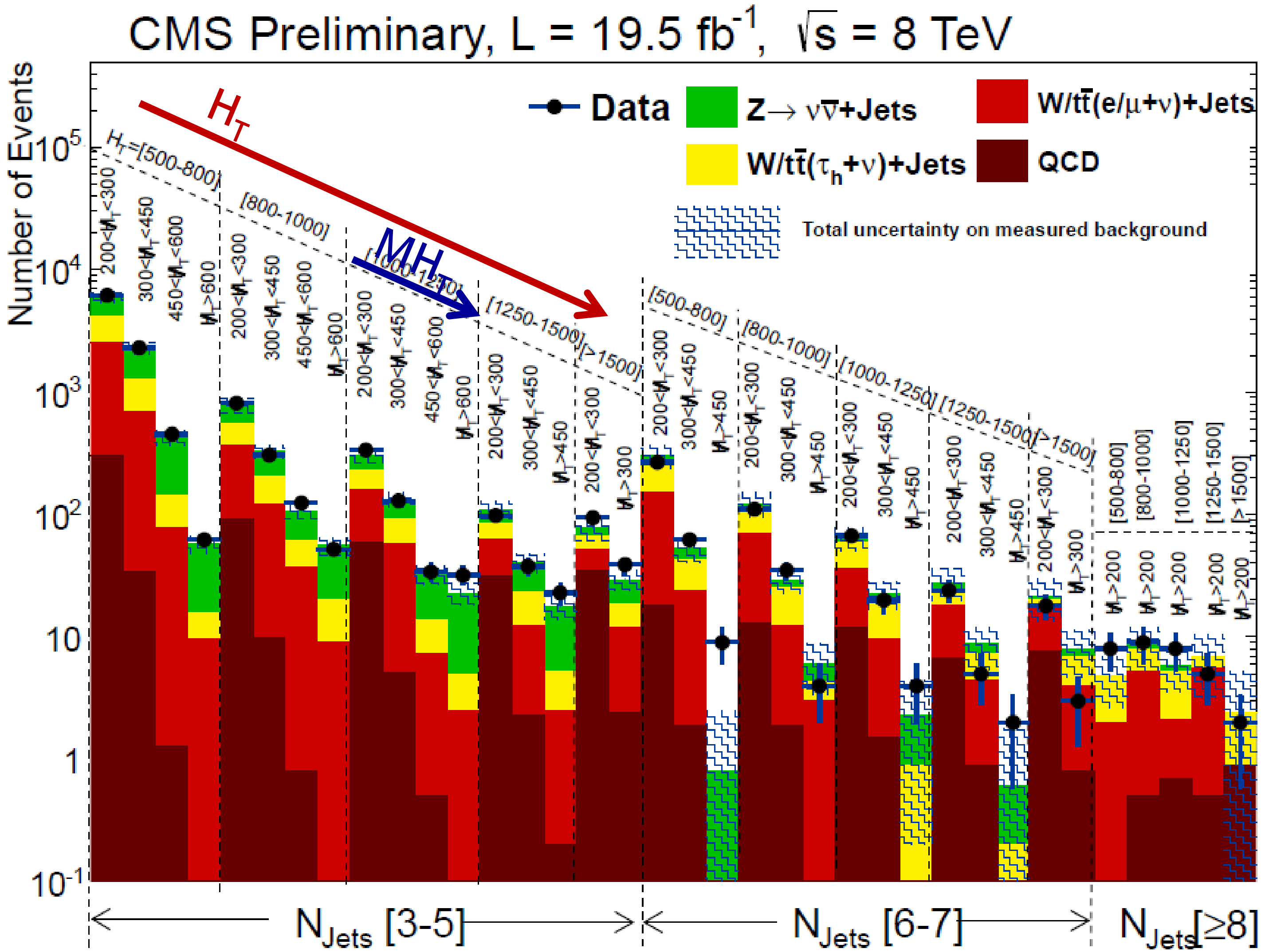
Prediction of τ→h background

- Use MC to derive visible energy templates for taus reconstructed as jets
- Use these templates and μ+jets control sample to predict background



Results: jets+MHT search

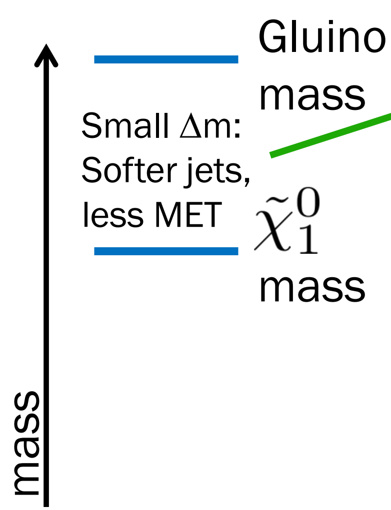
- Observed data compatible with background predictions

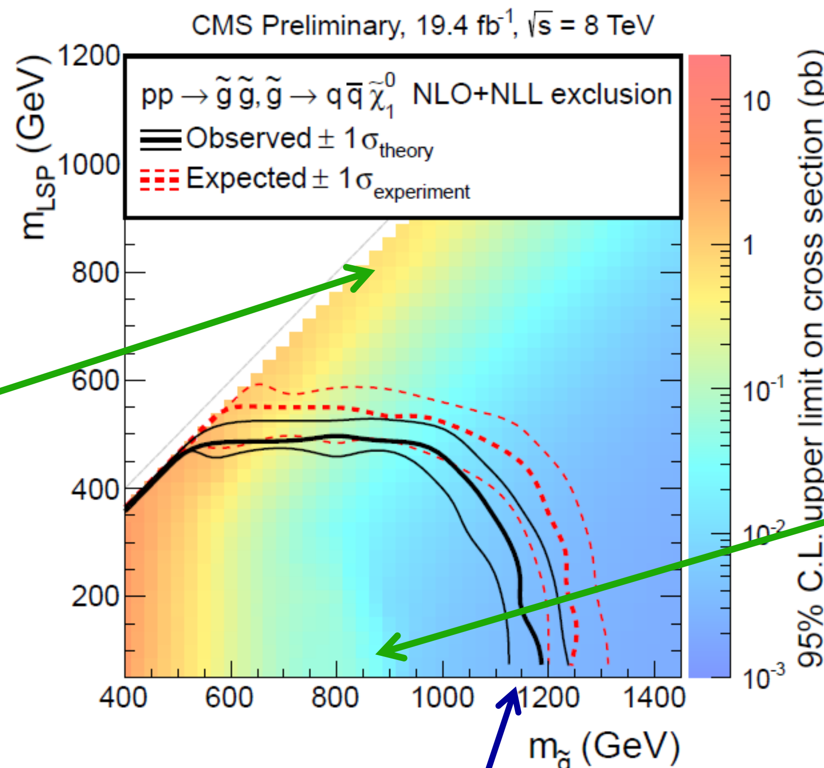


Interpretation of Jets+MHT search

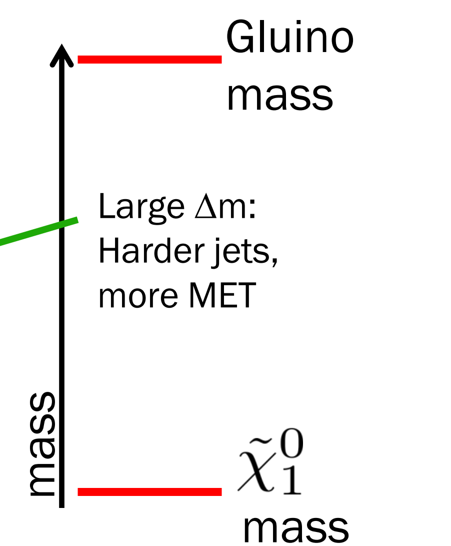
- Interpret results in terms of Simplified Models, which include only one decay possibility
- To simplify things further, for gluino decays via a squark, we (often) model the decay as a direct $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$ decay, placing the squark off-shell
  - Reduces the number of model parameters to 2!

"Compressed case"
Worse cross-section limit





"Large Δm case"
Better cross-section limit

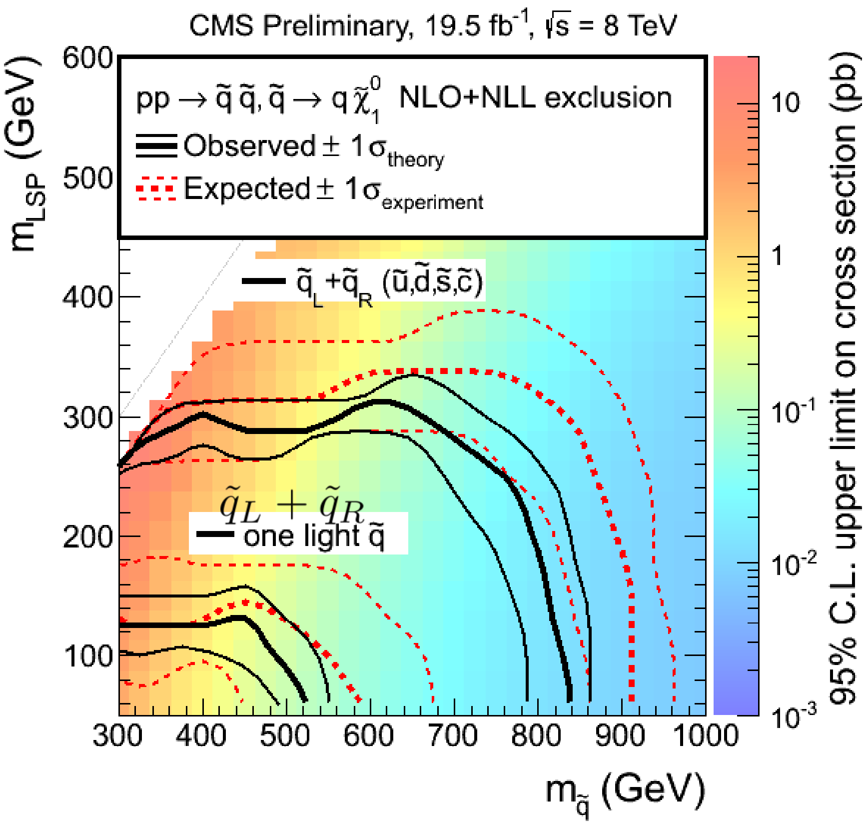


For light LSP, gluinos excluded to >1100 GeV

Squark-production interpretation

- Simplified model with squark pair production

- Limit of ~800 GeV for light LSP in the case of production of degenerate $\tilde{q}_L + \tilde{q}_R \ (\tilde{u}, \tilde{d}, \tilde{s}, \tilde{c})$
- Limit of ~500 GeV for the one flavor case with $\tilde{q}_L + \tilde{q}_R$



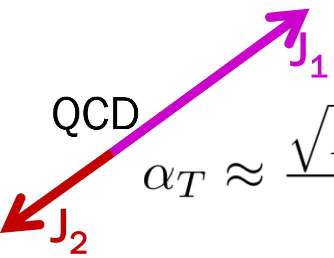
See F. Golf's talk for pMSSM interpretation

Search using Jets+α_T

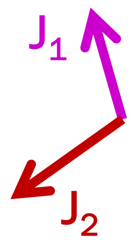
- α_T variable very effective at QCD rejection $\alpha_T = \frac{\sqrt{E_T^{J_2}/E_T^{J_1}}}{\sqrt{2(1-\cos\Delta\phi_{J_1 J_2})}}$

Randall, Tucker-Smith
PRL ***101*** *221803, 2008*

QCD



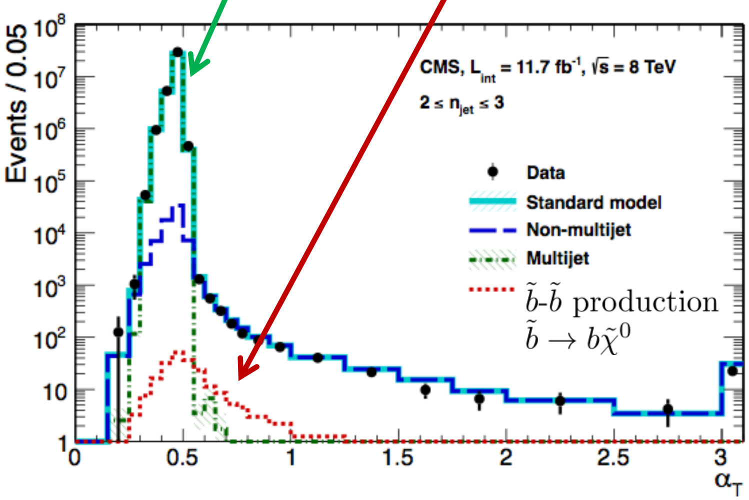
$$\alpha_T \approx \frac{\sqrt{E_T^{J_2}/E_T^{J_1}}}{2} \leq \frac{1}{2}$$



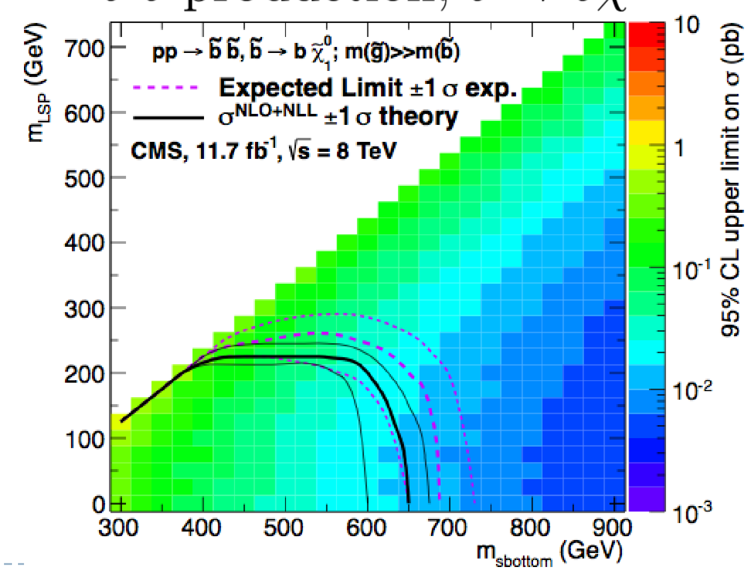
SUSY

$$\alpha_T \approx \frac{\sqrt{E_T^{J_2}/E_T^{J_1}}}{\Delta\phi_{J_1 J_2}}$$

For multijet events, form 2 pseudo-jets



$\tilde{b}$-$\tilde{b}$ production, $\tilde{b} \to b\tilde{\chi}^0$

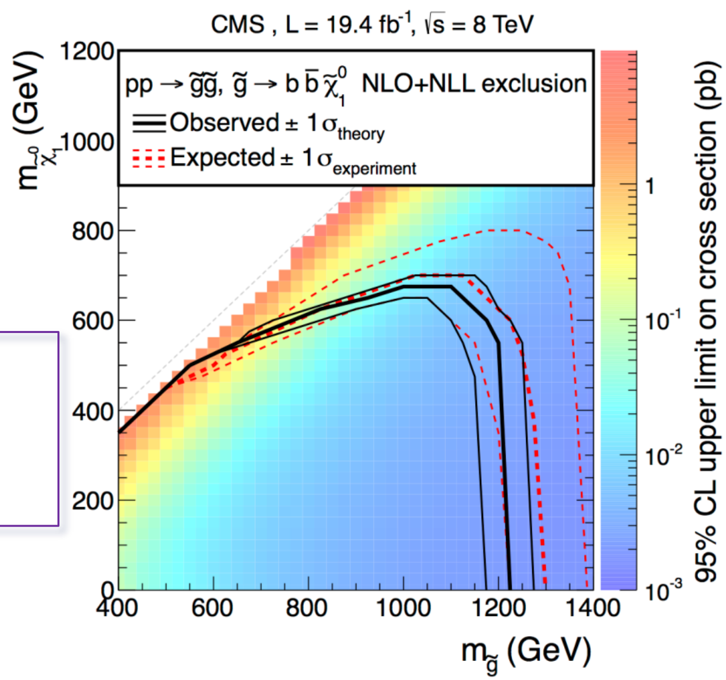


- Inclusive search, binned in:
  - H_T, jet multiplicity (2-3, ≥4), n b-tags
- Many interpretations in squark and gluino production models
- 11.7 fb^{-1}: Submitted to EPJC, arXiv:1303.2985

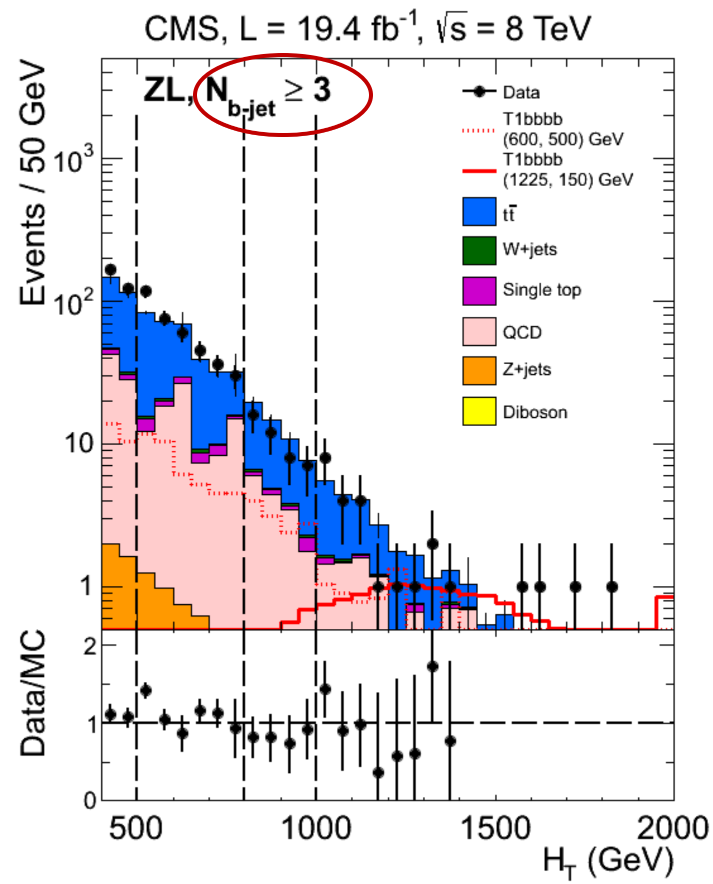
Search in Jets+MET+b-tag

- Gluino search in jets+MET+b-tag signature
  - Analysis binned in H_T, MET, number of b-tags
  - Includes ≥3b bin, which cuts down on ttbar background
- Backgrounds determined in a 3-d binned fit to control samples and search sample
  - Background shapes derived from data control samples
  - Data consistent with background predictions

19.4 fb^{-1}: Published as PLB 725, 243 (2013)



See F. Golf's talk for pMSSM interpretation



Search using the Razor variables

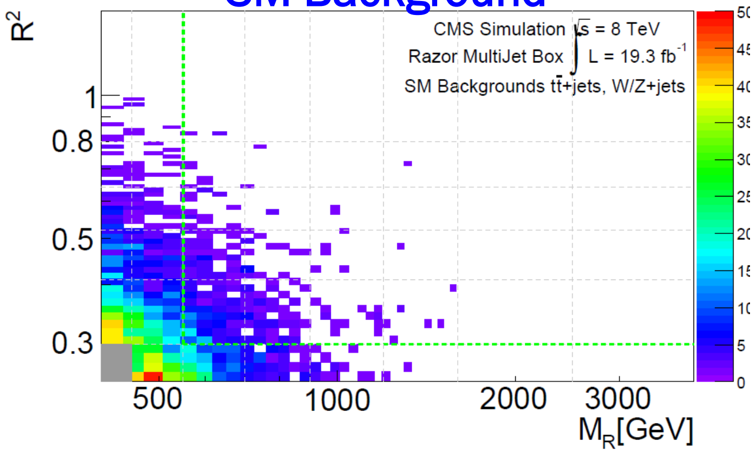
- "Razor" kinematic variables: *C. Rogan, arXiv:1006.2727*

$$M_R \equiv \sqrt{(p_{j_1} + p_{j_2})^2 - (p_z^{j_1} + p_z^{j_2})^2} \quad \text{and} \quad R \equiv \frac{M_T^R}{M_R}$$

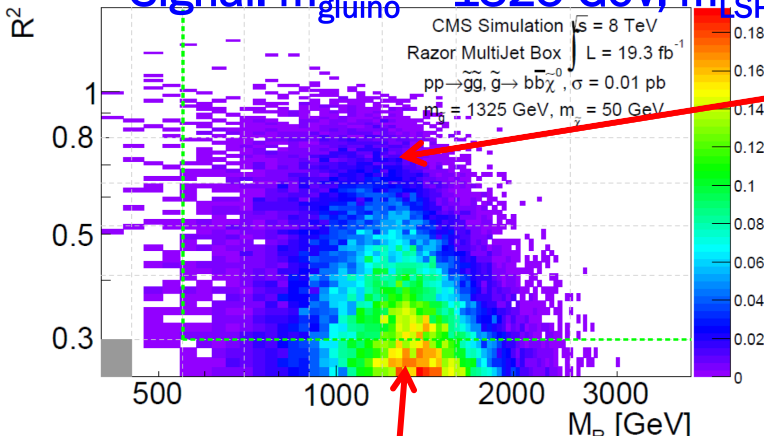
where
$$M_T^R \equiv \sqrt{\frac{E_T^{miss}(p_T^{j1} + p_T^{j2}) - \vec{E}_T^{miss}\cdot(\vec{p}_T^{\,j1} + \vec{p}_T^{\,j2})}{2}}$$

- Variables are defined in terms of a dijet topology
  - For higher jet multiplicity, cluster jets into two "megajets"

SM Background



Signal: m_{gluino} = 1325 GeV, m_{LSP}=50 GeV

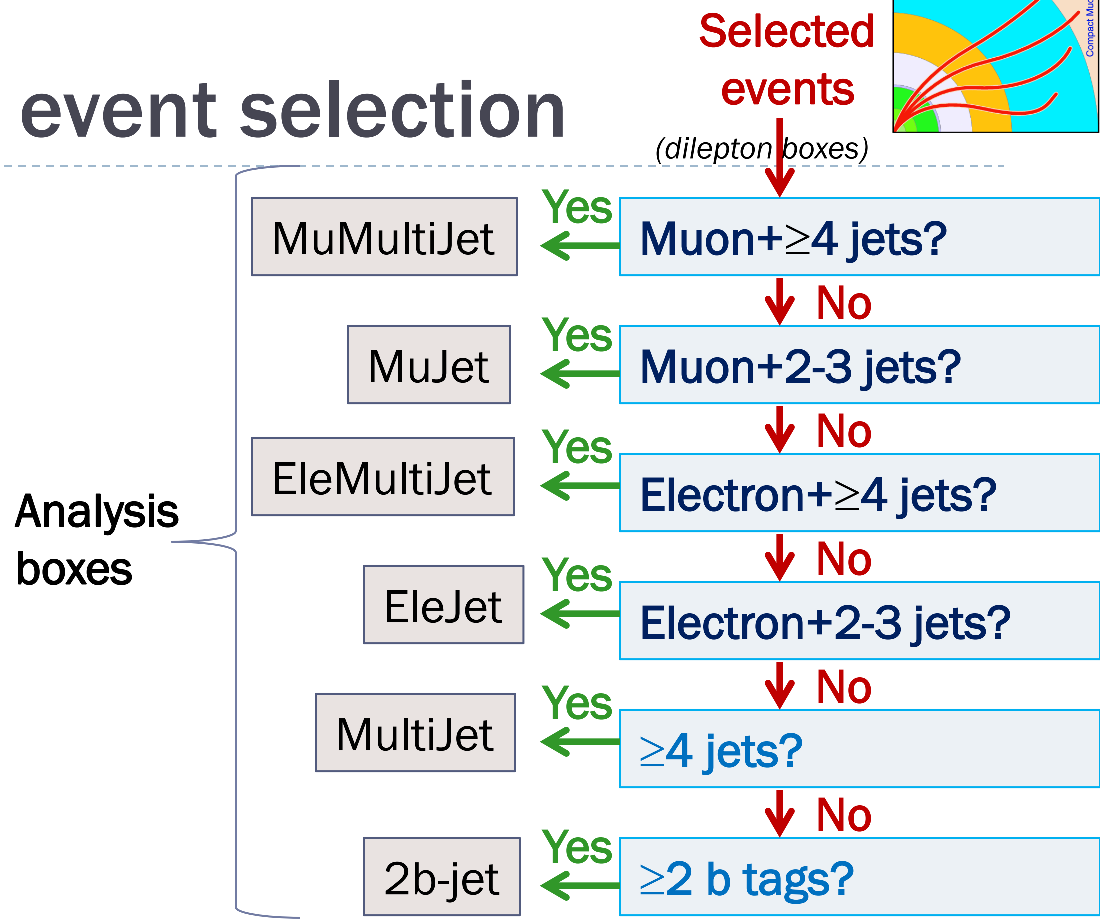


Signal has tail at high R^2

M_R peaks at ~ $M_\Delta = \frac{M_{\tilde{g}}^2 - M_{\tilde{\chi}}^2}{M_{\tilde{g}}}$

Razor analysis event selection

- Events selected online with custom triggers, calculating the Razor variables online
- ≥2 Jets with p_T>40 GeV
  - p_T>80 GeV for lead two jets
- ≥ 1 b-tagged jet
- Classify events based on the number of jets, leptons, and b-tags
  - Keep events with all different lepton multiplicities



- Each of the boxes is further subdivided in bins of b-jet multiplicity
  - =1b, =2b, ≥3b

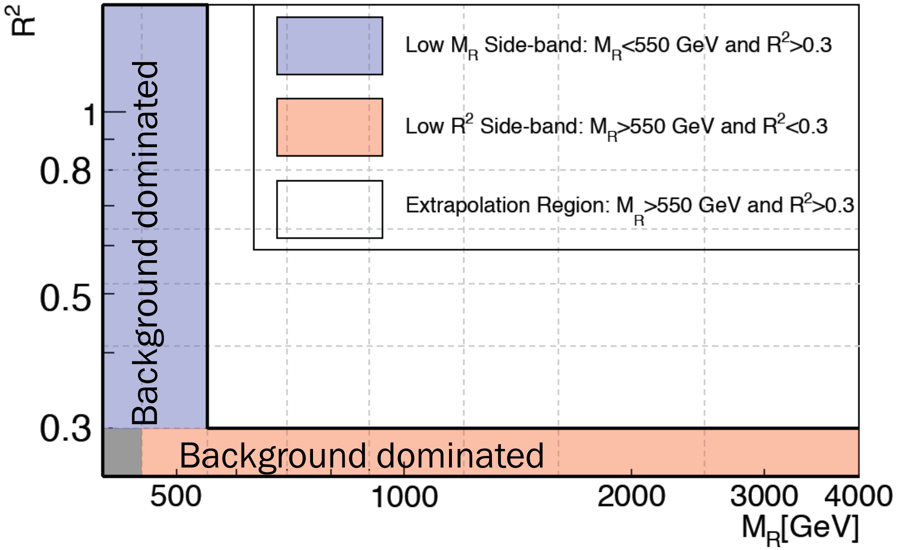
Razor analysis background estimate

- Backgrounds are parameterized using 2-d exponential:

$$f_{SM}(M_R, R^2) = [b(M_R - M_R^0)^{1/n}(R^2 - R_0^2)^{1/n} - 1]e^{-bn(M_R - M_R^0)^{1/n}(R^2 - R_0^2)^{1/n}}$$

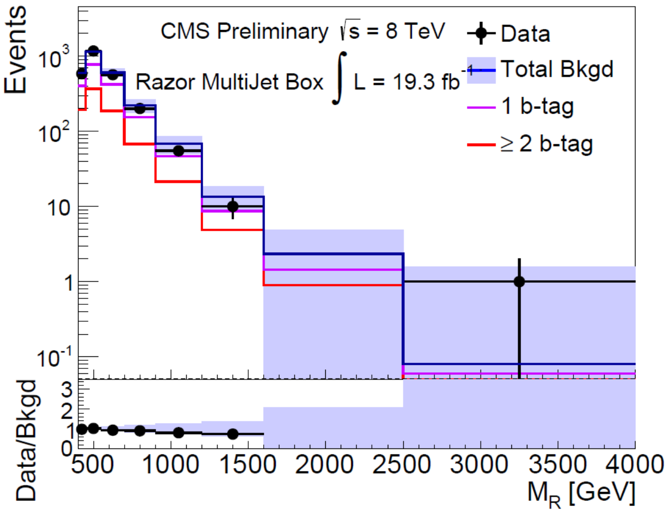
- Each "box" is analyzed independently
  - Simultaneous fit across b-tag multiplicity within a "box"
  - =2b and ≥3b bins constrained to share the same background shape

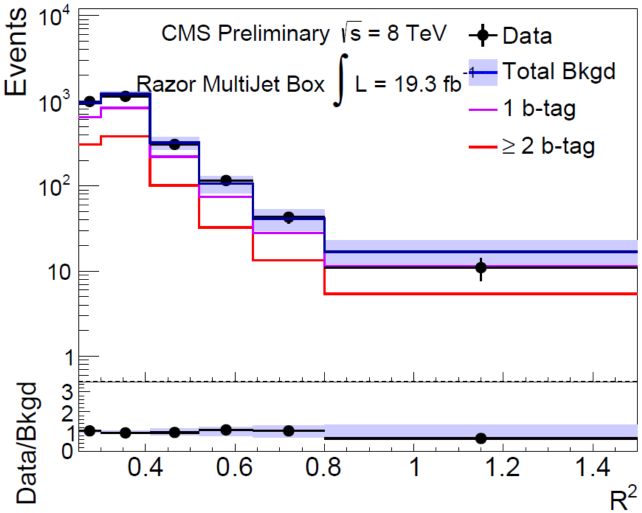
- Two types of fits:
  - Sideband fit to red/blue regions, with extrapolation to white region
    - Better for theorist reinterpretation
  - Full fit to whole plane
    - used in setting CL_s limits



Example fit results

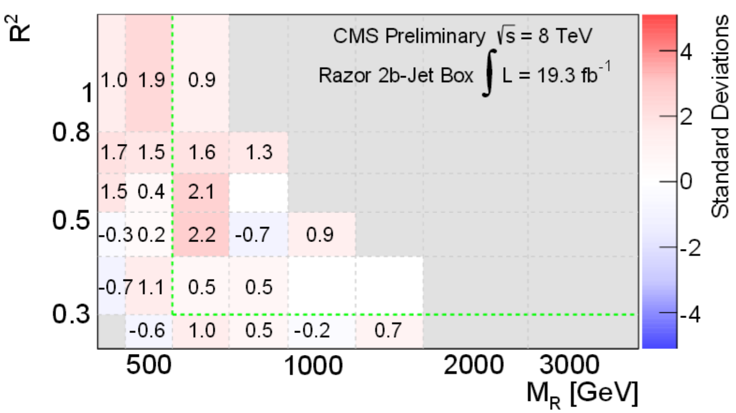
- Projections of the sideband fit, extrapolated to the full analysis region, for the multijet box

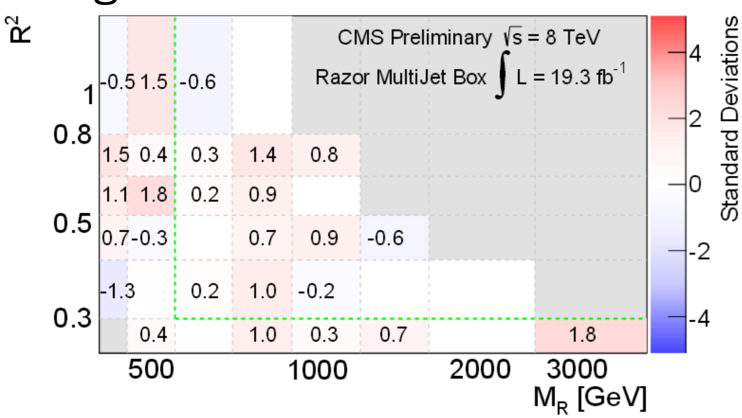




Data in agreement with predicted background

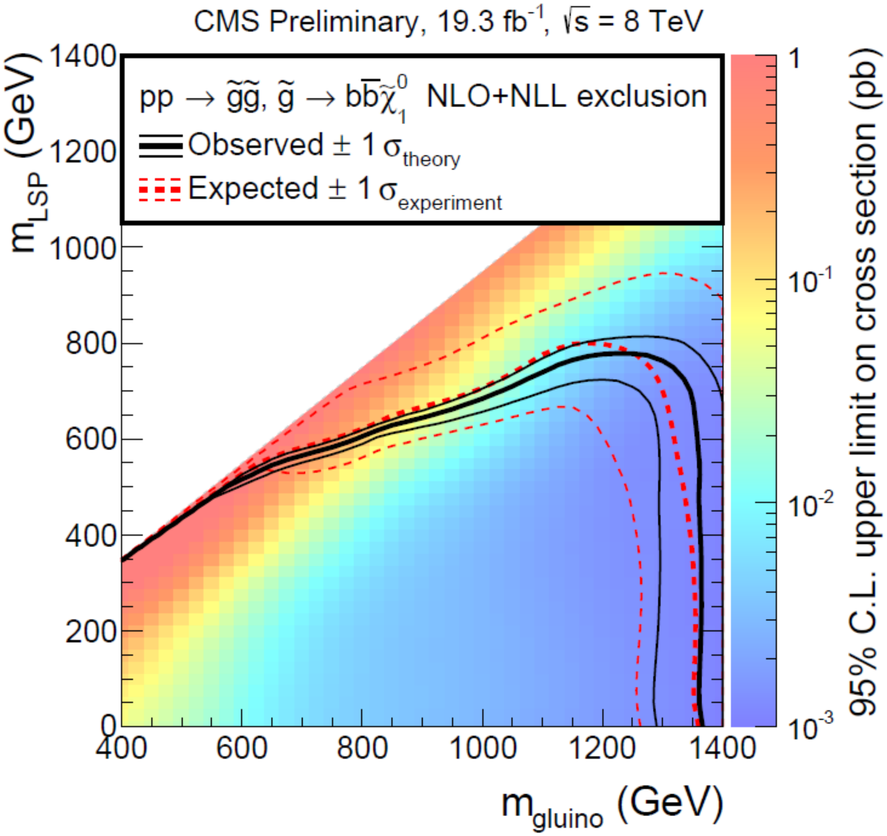
- P-values quantifying agreement of background model and data, translated into number of sigma

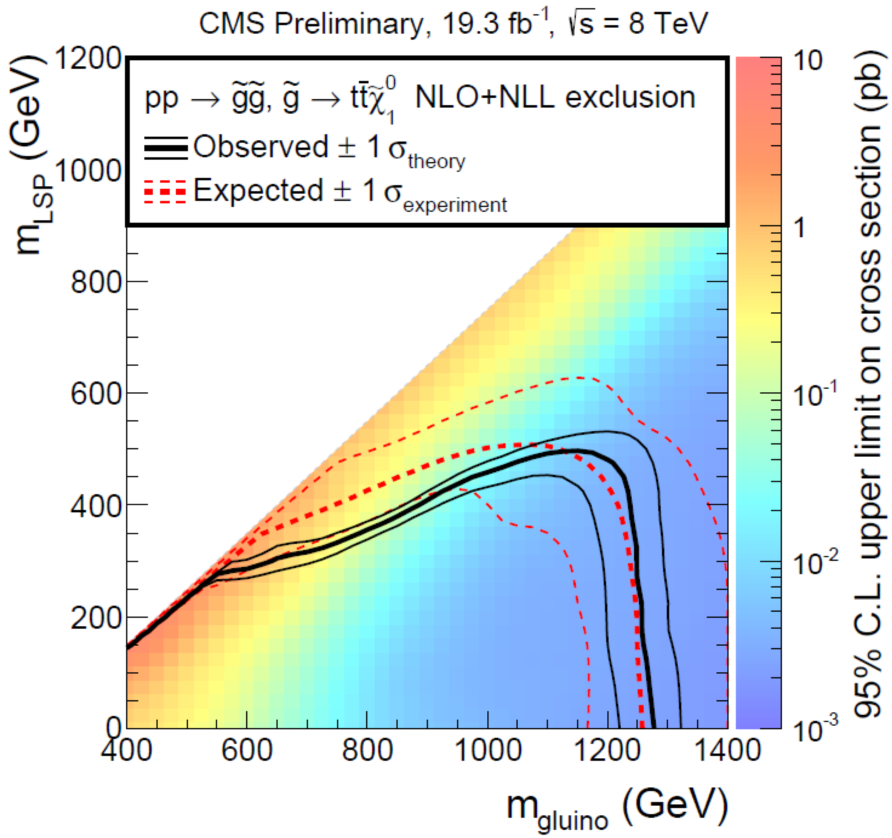




Interpretation of the Razor analysis

- Analysis requires a b-tag: interpret in models inspired by natural SUSY





- Interpretation uses:
  - Hadronic MultiJet box (≥4 jets)
  - ≥2 b-jet box

- Interpretation uses:
  - MultiJet boxes (≥4 jets)
    - Hadronic, e, and μ

See M. D'Alfonso's talk for stop interpretation

Summary

- Broad family of hadronic SUSY searches, most with the full LHC dataset
  - Multiple kinematic variables (MET/MHT, Razor, α_T)
  - Multiple background techniques with different systematics
  - Targeted at natural SUSY as well as more generic Jets+MET scenarios
- Observations are consistent with Standard Model background predictions
  - Limits on simplified topologies past 1.3 TeV for gluinos
- Other CMS parallel talks:
  - This session: Marco Andrea Buchmann (1-2 leptons), Andrea Gozzelino (≥3 leptons)
  - Tomorrow: David Morse (photons), Frank Golf (further details on interpretation)
  - Thursday: Mariarosaria D'Alfonso (3rd generation squarks), Ben Hooberman (EWKino)
  - Friday: Matthew Walker (RPV)

All results available from
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

Backup slides

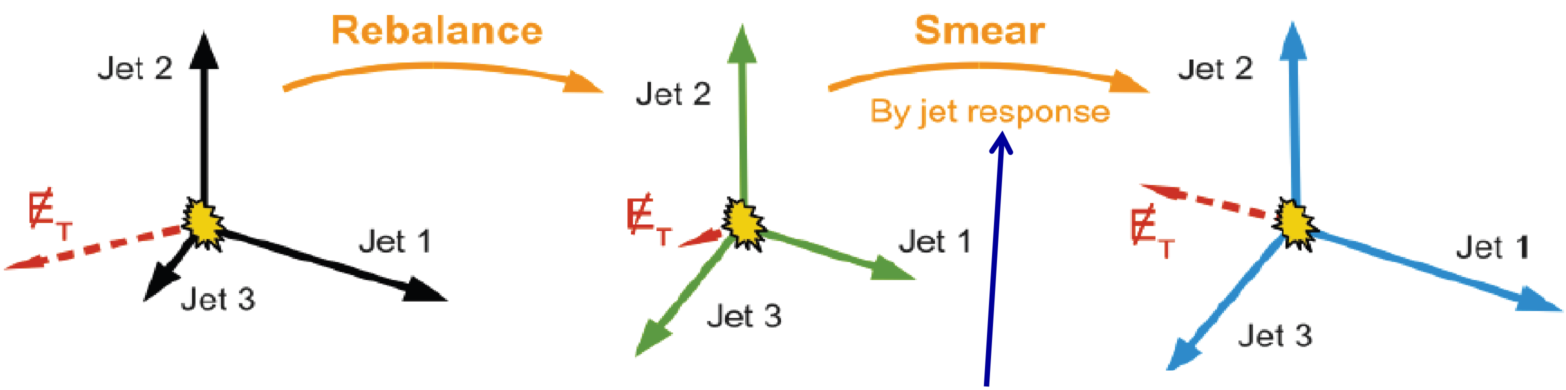
Full results table for jets+MHT search

- Predicted event yields compared to observation

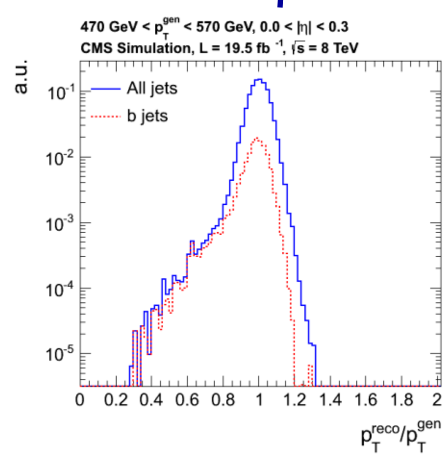
Selection N_{jets}	H_T	$\not{H}_T$	$Z \rightarrow \nu\bar{\nu}$ from γ+jets	$t\bar{t}/W \rightarrow e, \mu$+X	$t\bar{t}/W \rightarrow \tau_h$+X	QCD	Total background	Obs. data
3-5	500-800	200-300	1821.3±326.5	2210.7±447.8	1683.7±171.4	307.4±219.4	6023.1±620.2	6159
3-5	500-800	300-450	993.6±177.9	660.1±133.3	591.9± 62.5	34.5± 23.8	2280.0±232.1	2305
3-5	500-800	450-600	273.2± 51.1	77.3± 17.9	67.6± 9.5	1.3± 1.5	419.5± 55.0	454
3-5	500-800	> 600	42.0± 8.7	9.5± 4.0	6.0± 1.9	0.1± 0.3	57.6± 9.7	62
3-5	800-1000	200-300	215.8± 40.0	277.5± 62.4	191.6± 23.2	91.7± 65.5	776.7±101.6	808
3-5	800-1000	300-450	124.1± 23.7	112.8± 26.9	83.3± 11.2	9.9± 7.4	330.1± 38.3	305
3-5	800-1000	450-600	46.9± 9.8	36.1± 9.9	23.6± 3.9	0.8± 1.3	107.5± 14.5	124
3-5	800-1000	> 600	35.3± 7.5	9.0± 3.7	11.4± 3.2	0.1± 0.4	55.8± 9.0	52
3-5	1000-1250	200-300	76.3± 14.8	103.5± 25.9	66.8± 10.0	59.0± 24.7	305.6± 40.1	335
3-5	1000-1250	300-450	39.3± 8.2	52.4± 13.6	35.7± 6.2	5.1± 2.7	132.6± 17.3	129
3-5	1000-1250	450-600	18.1± 4.4	6.9± 3.2	6.6± 2.1	0.5± 0.7	32.1± 5.9	34
3-5	1000-1250	> 600	17.8± 4.3	2.4± 1.8	2.5± 1.0	0.1± 0.3	22.8± 4.7	32
3-5	1250-1500	200-300	25.3± 5.5	31.0± 9.5	22.2± 3.9	31.2± 13.1	109.7± 17.5	98
3-5	1250-1500	300-450	16.7± 4.0	10.1± 4.4	11.1± 3.6	2.3± 1.6	40.2± 7.1	38
3-5	1250-1500	> 450	12.3± 3.2	2.3± 1.7	2.8± 1.5	0.2± 0.5	17.6± 4.0	23
3-5	>1500	200-300	10.5± 2.8	16.7± 6.2	15.2± 3.4	35.1± 14.1	77.6± 16.1	94
3-5	>1500	> 300	10.9± 2.9	9.7± 4.3	6.5± 2.0	2.4± 2.0	29.6± 5.8	39
6-7	500-800	200-300	22.7± 6.1	132.5± 58.6	127.1± 21.5	18.2± 9.2	300.5± 63.4	266
6-7	500-800	300-450	9.9± 3.1	22.0± 10.8	18.6± 4.3	1.9± 1.7	52.3± 12.1	62
6-7	500-800	> 450	0.7± 0.6	0.0± 1.6	0.1± 0.3	0.0± 0.1	0.8± 1.7	9
6-7	800-1000	200-300	9.1± 2.8	55.8± 25.4	44.6± 8.2	13.1± 6.6	122.6± 27.7	111
6-7	800-1000	300-450	4.2± 1.6	10.4± 5.5	12.8± 3.1	1.9± 1.4	29.3± 6.6	35
6-7	800-1000	> 450	1.8± 1.0	2.9± 2.5	1.3± 0.5	0.1± 0.4	6.1± 2.7	4
6-7	1000-1250	200-300	4.4± 1.6	24.1± 12.0	24.0± 5.5	11.9± 6.0	64.4± 14.6	67
6-7	1000-1250	300-450	3.5± 1.4	8.0± 4.7	9.6± 2.5	1.5± 1.5	22.6± 5.7	20
6-7	1000-1250	> 450	1.4± 0.8	0.0± 1.8	0.8± 0.5	0.1± 0.3	2.3± 2.1	4
6-7	1250-1500	200-300	3.3± 1.3	11.5± 6.5	6.1± 2.5	6.8± 3.9	27.7± 8.1	24
6-7	1250-1500	300-450	1.4± 0.8	3.5± 2.6	2.9± 1.5	0.9± 1.3	8.8± 3.4	5
6-7	1250-1500	> 450	0.4± 0.4	0.0± 1.2	0.1± 0.2	0.1± 0.3	0.5± 1.3	2
6-7	>1500	200-300	1.3± 0.8	10.0± 6.9	2.3± 1.3	7.8± 4.0	21.5± 8.1	18
6-7	>1500	> 300	1.1± 0.7	3.2± 2.8	2.9± 1.2	0.8± 1.1	8.0± 3.3	3
≥8	500-800	> 200	0.0± 0.6	1.9± 1.5	2.8± 1.3	0.1± 0.4	4.8± 2.1	8
≥8	800-1000	> 200	0.6± 0.5	4.8± 2.9	2.7± 1.1	0.5± 0.9	8.7± 3.3	9
≥8	1000-1250	> 200	0.6± 0.5	1.4± 1.5	3.1± 1.2	0.7± 0.9	5.8± 2.2	8
≥8	1250-1500	> 200	0.0± 0.7	5.1± 3.5	1.3± 0.8	0.5± 0.9	6.9± 3.7	5
≥8	1500-	> 200	0.0± 0.6	0.0± 2.1	1.5± 1.0	0.9± 1.3	2.4± 2.8	2

QCD background estimation

- Established "Rebalance and Smear" technique in which low MHT data events are smeared, using measured jet resolutions, to emulate the high MHT tail from mismeasured jets

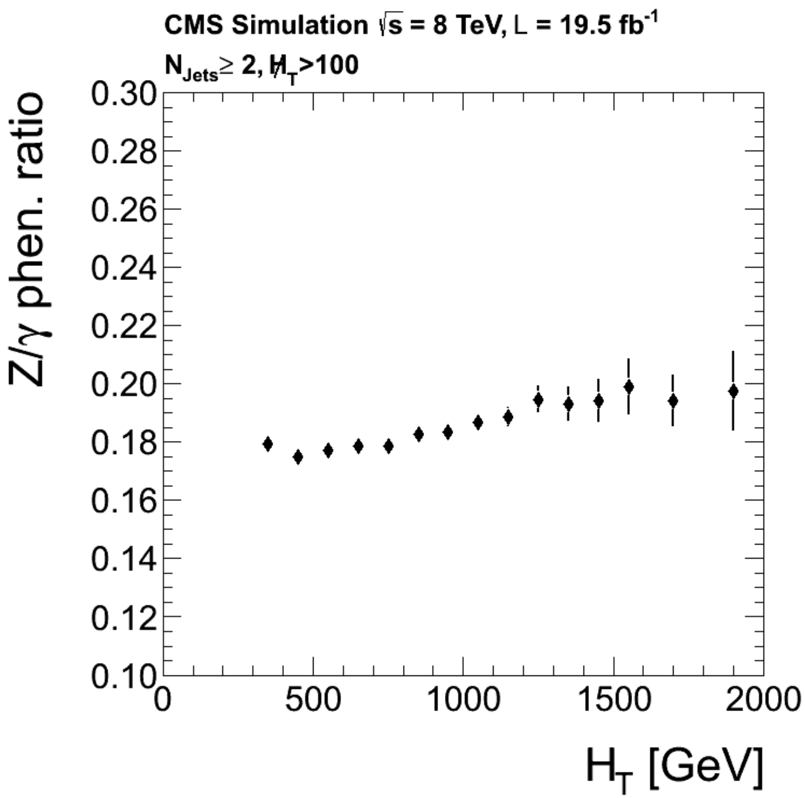


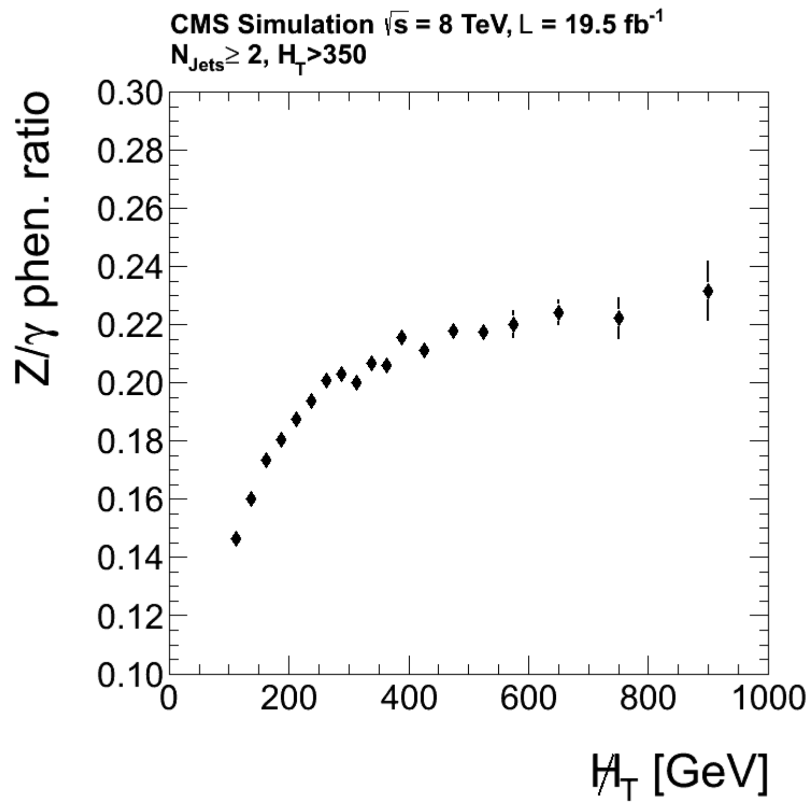
Jet response function includes non-Gaussian tails



Additional Z→νν plots

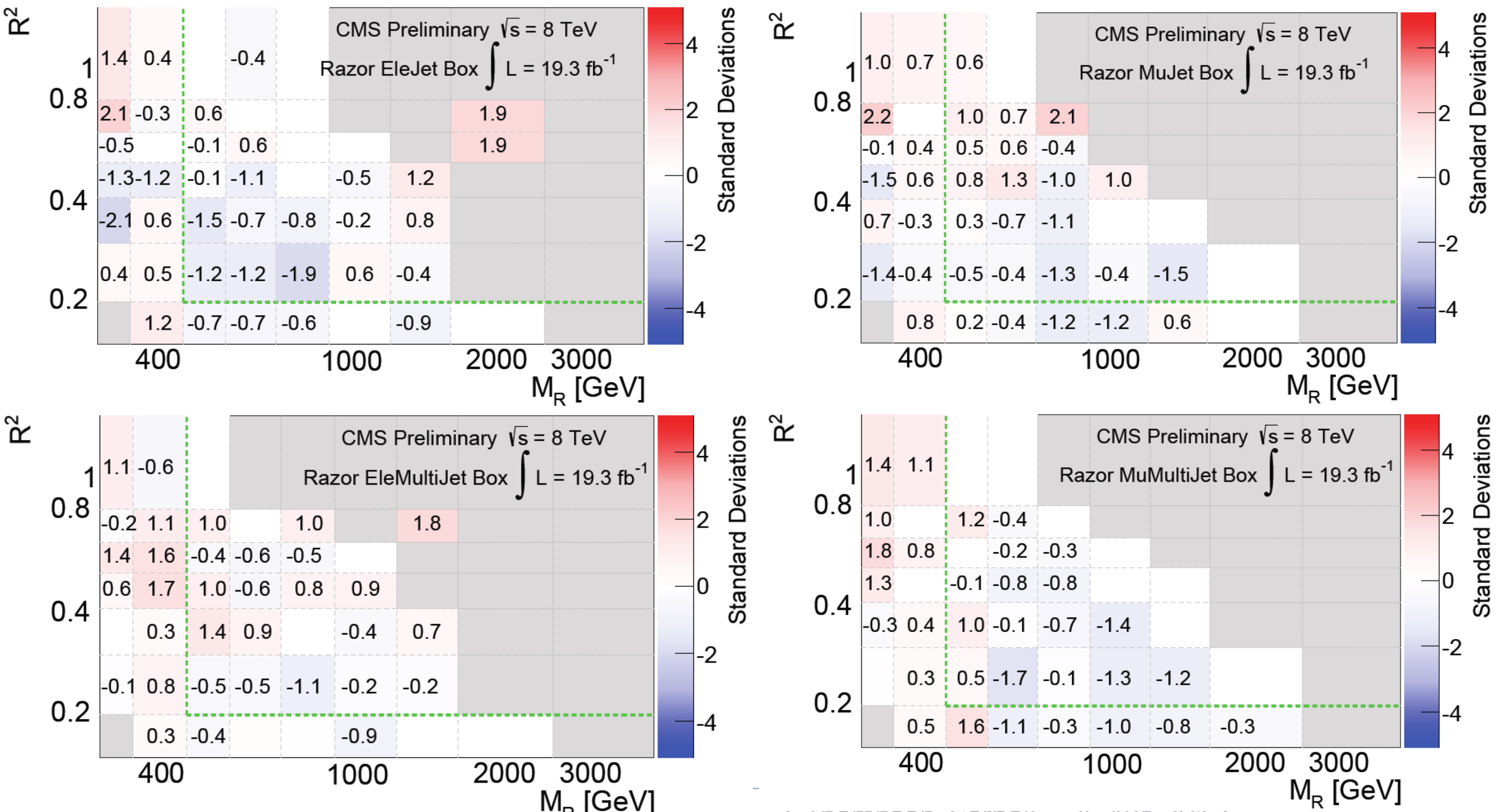
- HT and MHT dependence of Z/γ





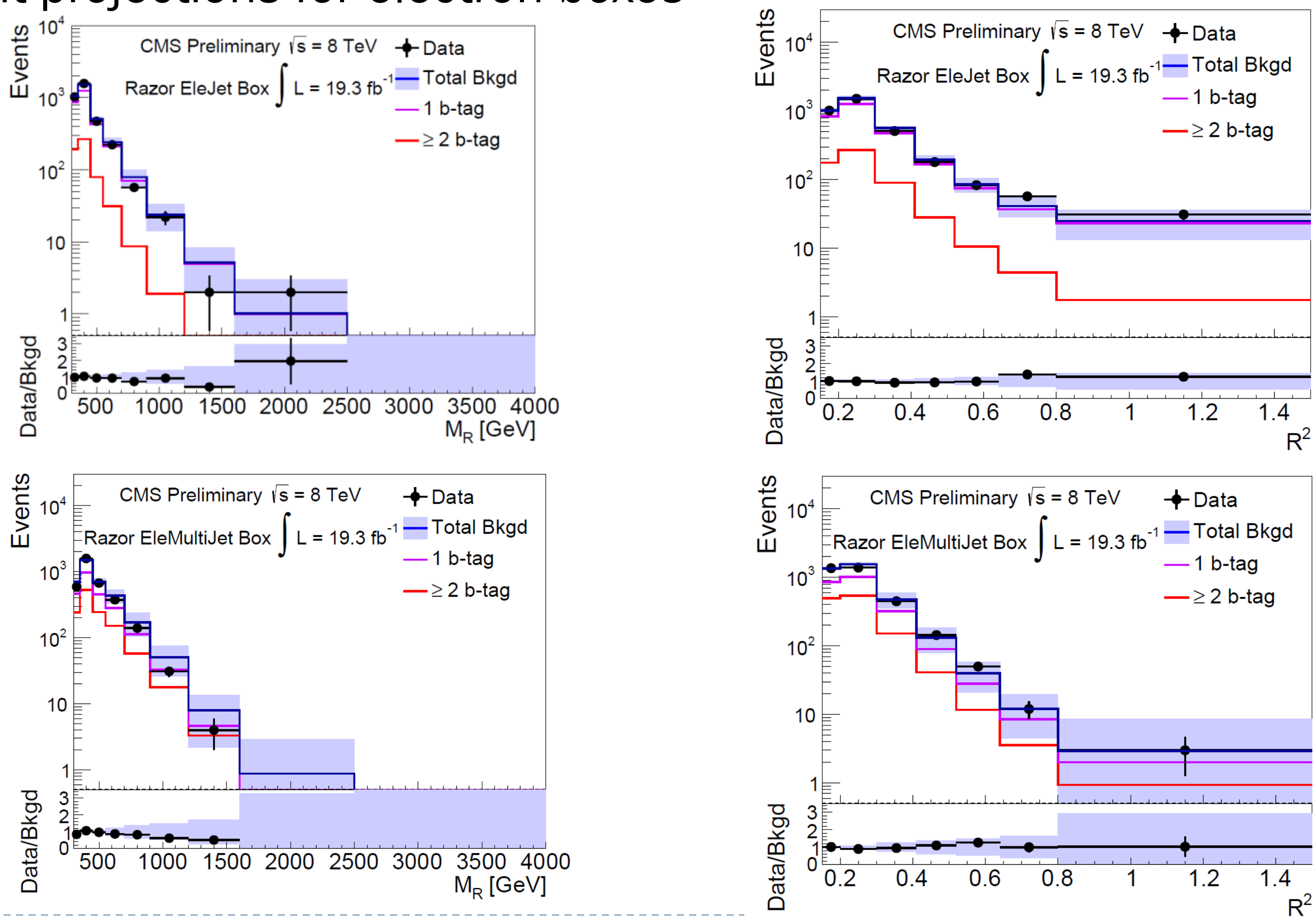
Razor: data/background agreement

- Quantification of compatibility between data and background model



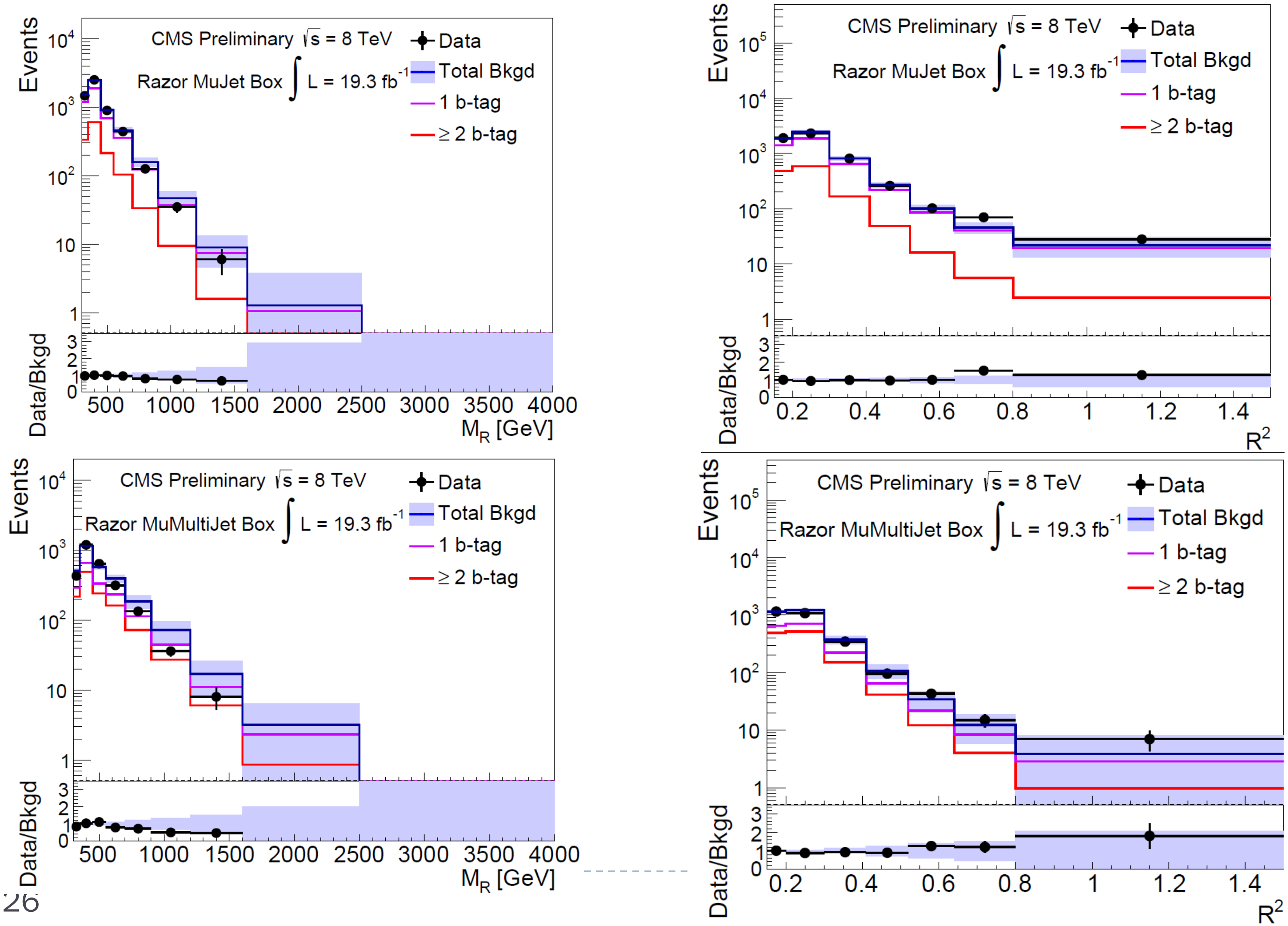
Razor: more fit projections

- Fit projections for electron boxes



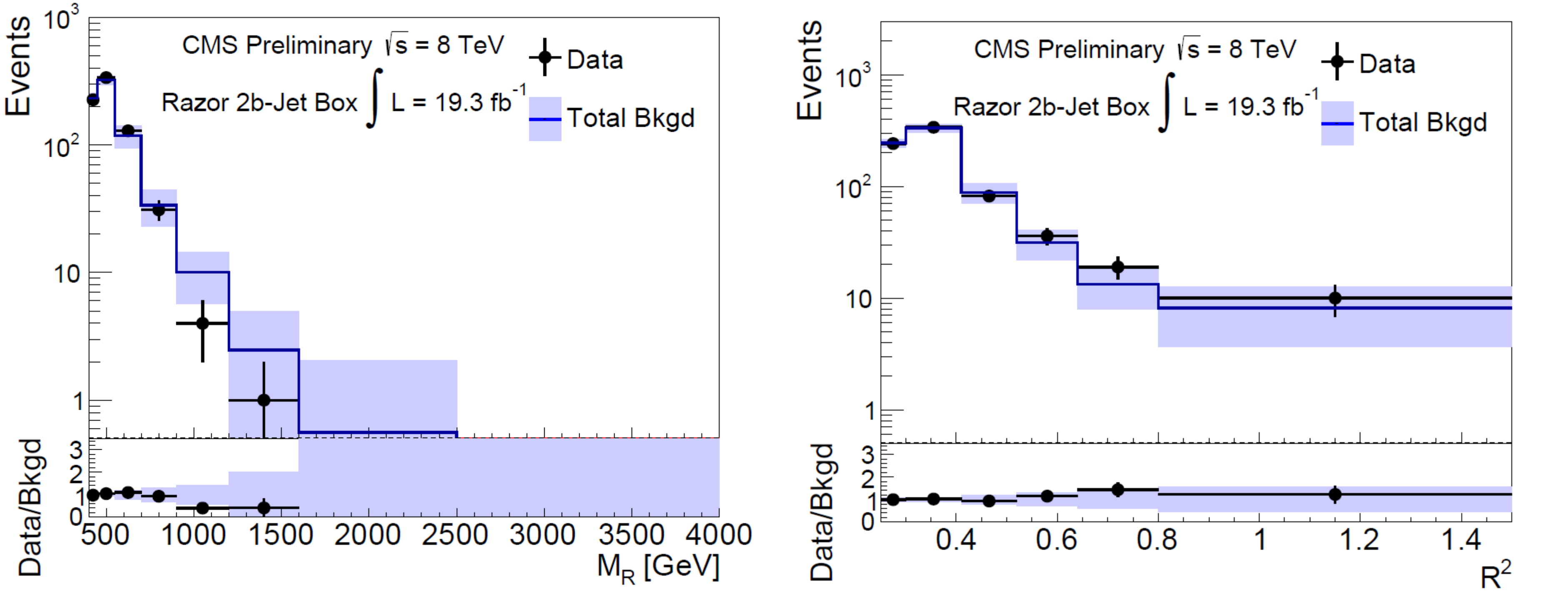
Razor: more fit projections

- Fit projections for muon boxes



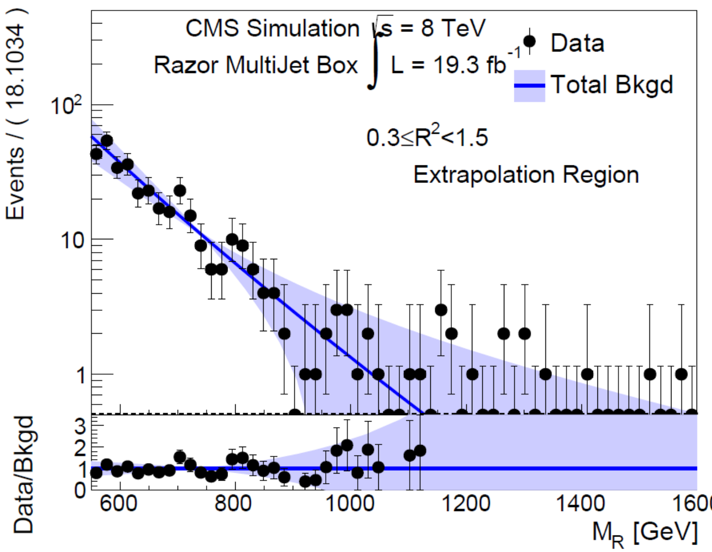
Razor: more fit projections

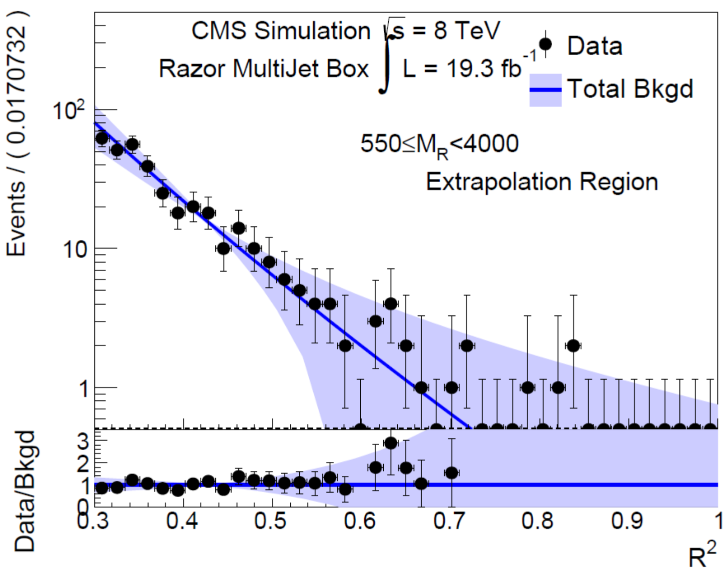
- 2b-jet box



Razor: fit validation

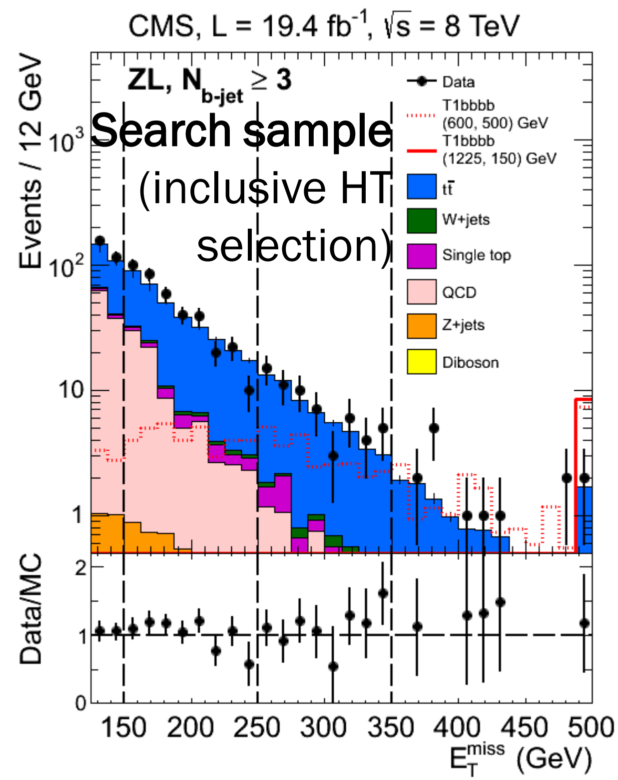
- Test of fit model using standard model simulation
  - Projections of a sideband fit using the Razor PDF to simulated SM events in the Multijet box, extrapolated to search region
  - The effect of varying the *n* parameter by +/- 1 sigma is shown by the shaded blue region

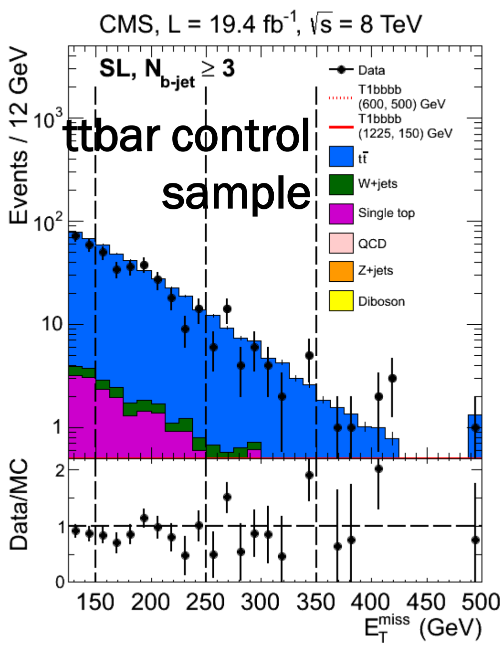


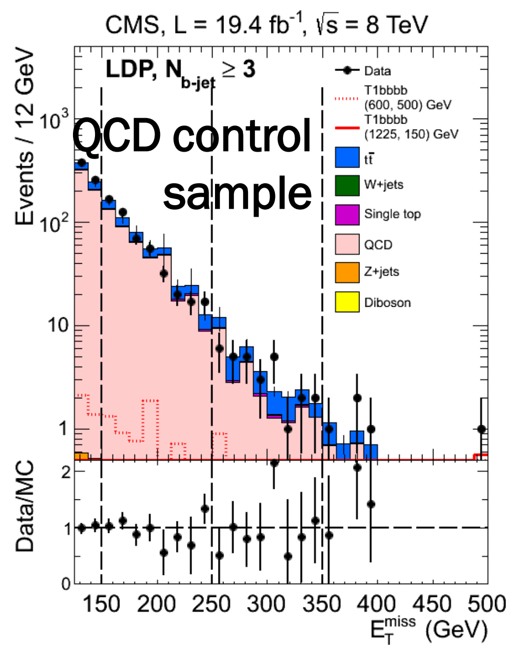


Jets+MET+b-tags: background methods

- Data-driven approach with no extrapolations in kinematics
- Backgrounds and control samples:
  - ttbar/W/single-top
    - 1 e/μ control sample
  - Z→νν
    - Z→ll control sample with loosened b-tagging
      - Extrapolation in b-tagging estimated with a data control sample
  - QCD
    - Inverted cut on jet-MET angle





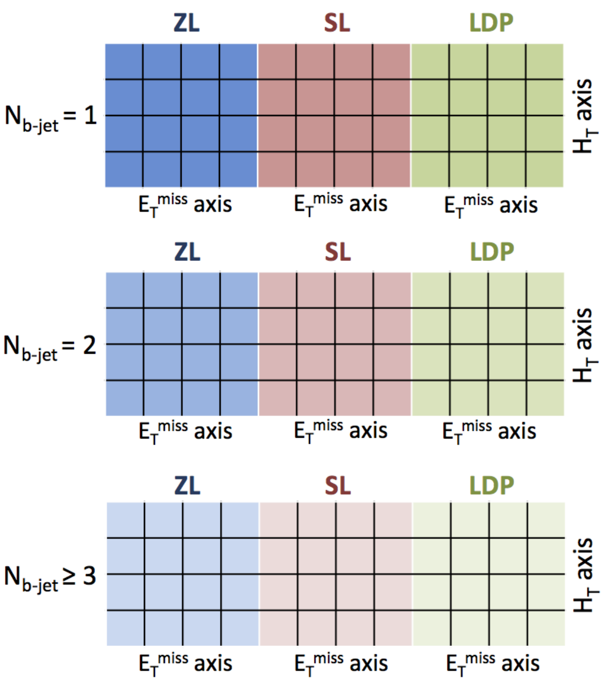


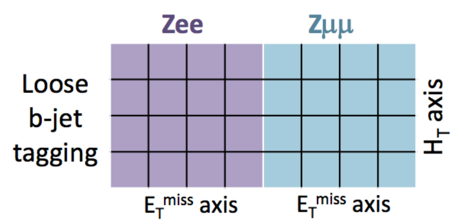
Jets+MET+b-tags: Fit setup

- Analysis is done in bins of:
  - H_T, MET, number of b-tags

Event sample legend

ZL = Zero Lepton; signal sample	SL = Single Lepton; top & W+jets control sample	LDP = low $\Delta\hat{\phi}_{min}$; QCD control sample	Zee = $Z \rightarrow e^+e^-$; Z to $\nu\bar{\nu}$ control sample	Zμμ = $Z \rightarrow \mu^+\mu^-$; Z to $\nu\bar{\nu}$ control sample





Bin	H_T (GeV)	E_T^{miss} (GeV)
1	400 – 500 (HT1)	125 – 150 (MET1)
2	500 – 800 (HT2)	150 – 250 (MET2)
3	800 – 1000 (HT3)	250 – 350 (MET3)
4	> 1000 (HT4)	> 350 (MET4)

- Simultaneous fit to the control samples and search samples
- For QCD and ttbar, each search bin has a corresponding control bin
  - For $Z \rightarrow \nu\nu$, there is an extrapolation in b-tagging
- In the fit:
  - Shapes of search sample are constrained by the data control samples
    - With corrections from MC, in the case of ttbar
  - Normalization of backgrounds in search sample is allowed to float

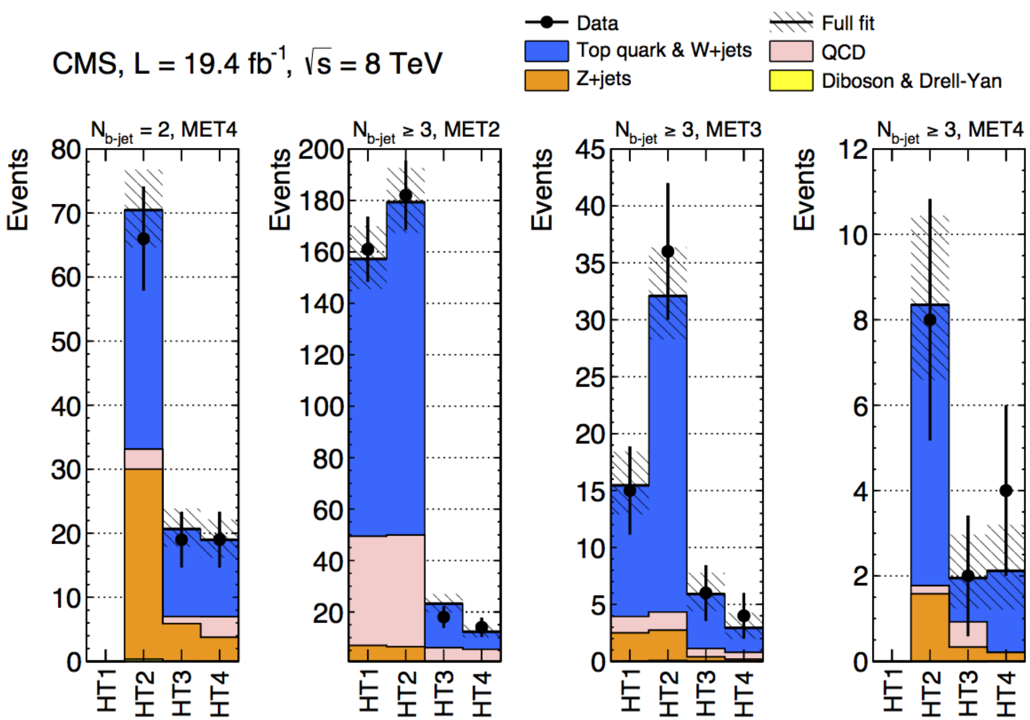
Fit results

- Observations consistent with background predictions

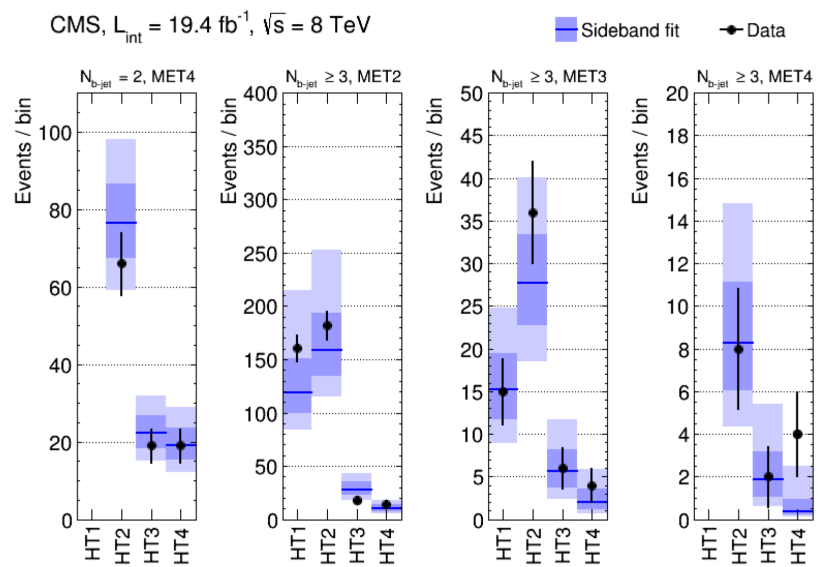
Fit performed in all search bins

This plot shows the most sensitive bins

CL_s Limits set using this method

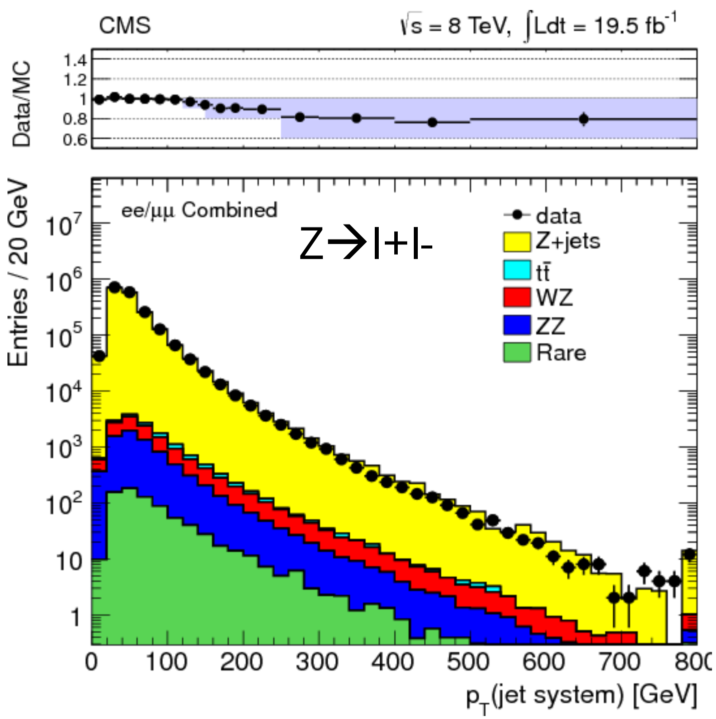


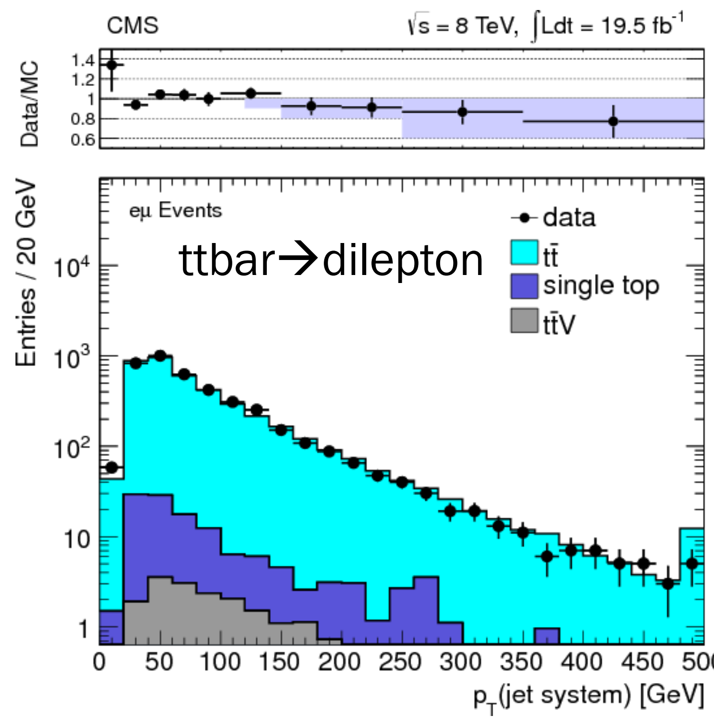
Alternate strategy: do a fit to only the less sensitive bins and extrapolate to the more sensitive bins



Signal Simulation

- Signal Monte Carlo samples generated with Madgraph with up to 2 additional partons
  - Studies done using Z+jets and ttbar+jets control samples to quantify agreement of ISR radiation in data and MC
- Correction to/uncertainty on p_T spectrum of gen-level SUSY system derived from these comparisons
  - Correction from 0-20%
  - Uncertainty from 0-20%
- This (conservative) procedure allows us to interpret our results even in regimes where the boost of the SUSY system from ISR is important





A note on the Jets+MHT results

Statistical interlude

- Consider the bin with
  - N(observed) = 9 events
  - N(background) = 0.8 ± 1.7 events

See CMS PAS SUS-13-012, Table 1, p. 10
Njets: 6-7
HT: 500-800 GeV
MHT>450 GeV

- First, let's ignore the uncertainty on the background. What is the probability for a Poisson with μ=0.8 to fluctuate to at least 9 events?
  - $\text{Prob}(\, n \geq 9 \mid \mu = 0.8\,) = 1.8 \times 10^{-7}$

  Have we discovered new physics?
- NO! The uncertainty is crucial!
  - $\text{Prob}(\, n \geq 9 \mid \mu = 0.8 \pm 1.7) \approx 0.15$
- This example highlights the importance of <u>quantifying the uncertainties on the SM backgrounds.</u>