CMS Supersymmetry and Exotic Higgs Results

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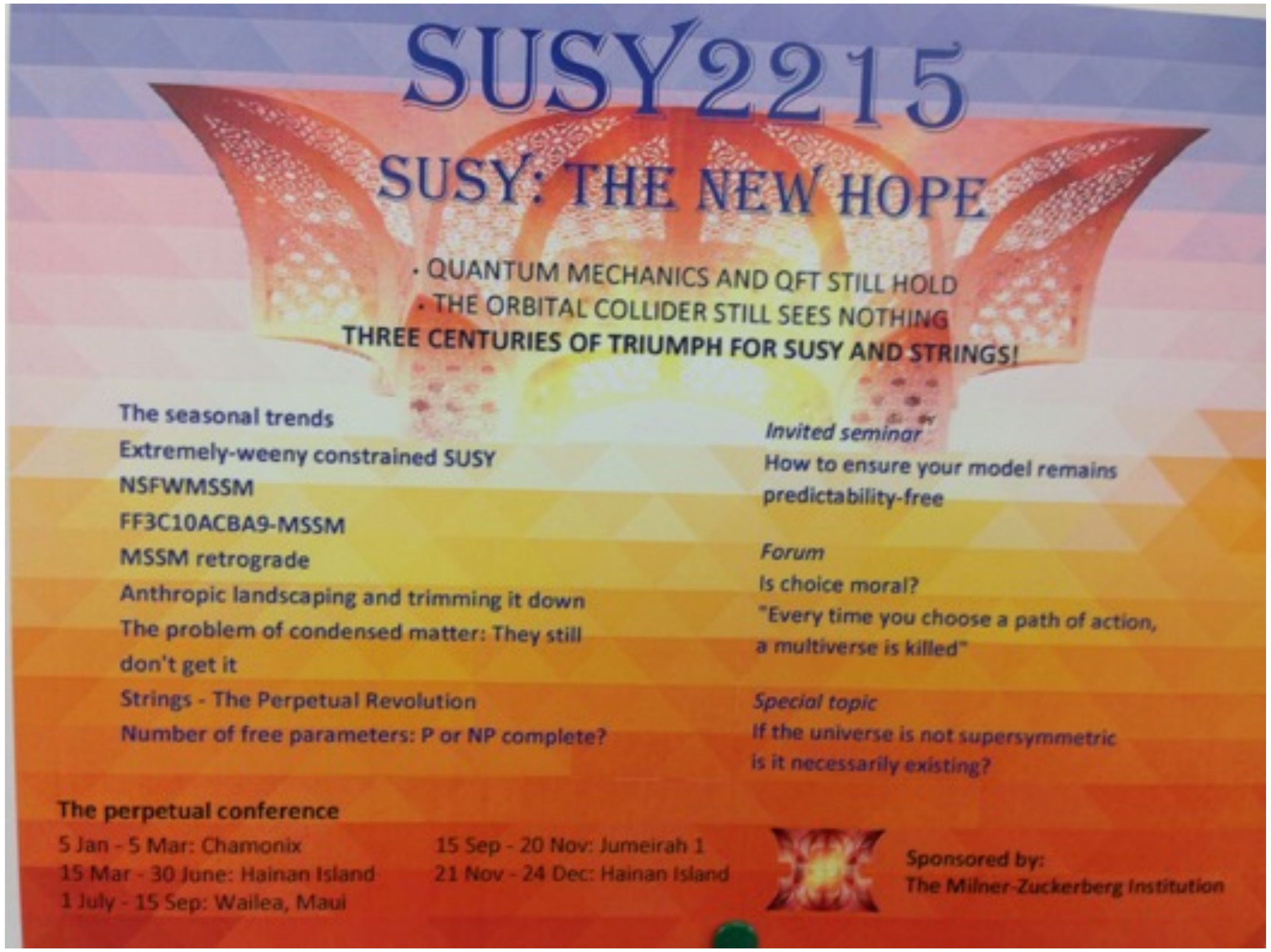
Supersymmetry today

- Supersymmetry (SUSY) offers a clear and elegant solution to the hierarchy problem
- Many null results, but…
  - …searches targeting third generation sfermions yield important insights into naturalness
  - …many viable extensions of the minimal model (MSSM) exist
  - …the 125-GeV Higgs boson gives new impetus to searches targeting the SUSY Higgs sector



CMS SUSY and non-SM Higgs searches

SUSY

- **M_{T2} all-hadronic**
  - Inclusive search with enormous reach in squark and gluino mass
  - Use of robust data-driven background estimations
- **Dilepton edge fit**
  - Mostly independent of jet energy scale and resolution uncertainties
  - Broad applicability within SUSY
- **4-W final state combination**
  - Demonstrates the power of combining channels to extend exclusion limits
- **b-tagged razor**
  - Novel discriminating variables allow the SM background to be parametrized by a simple function
  - Excellent rejection of QCD multijet backgounds

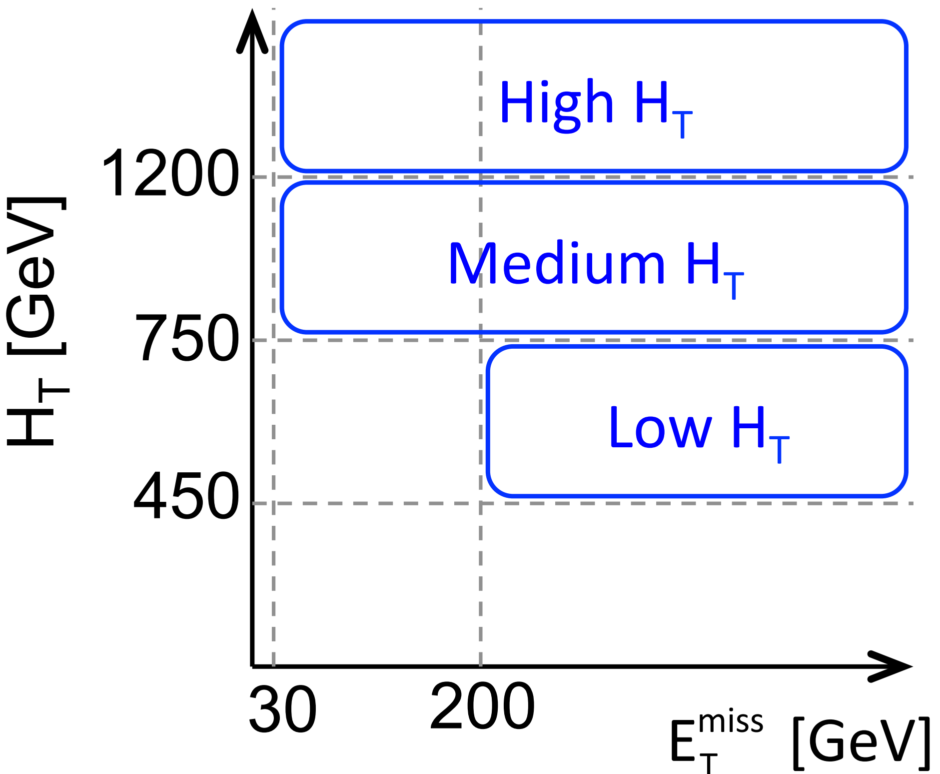
Exotic Higgs

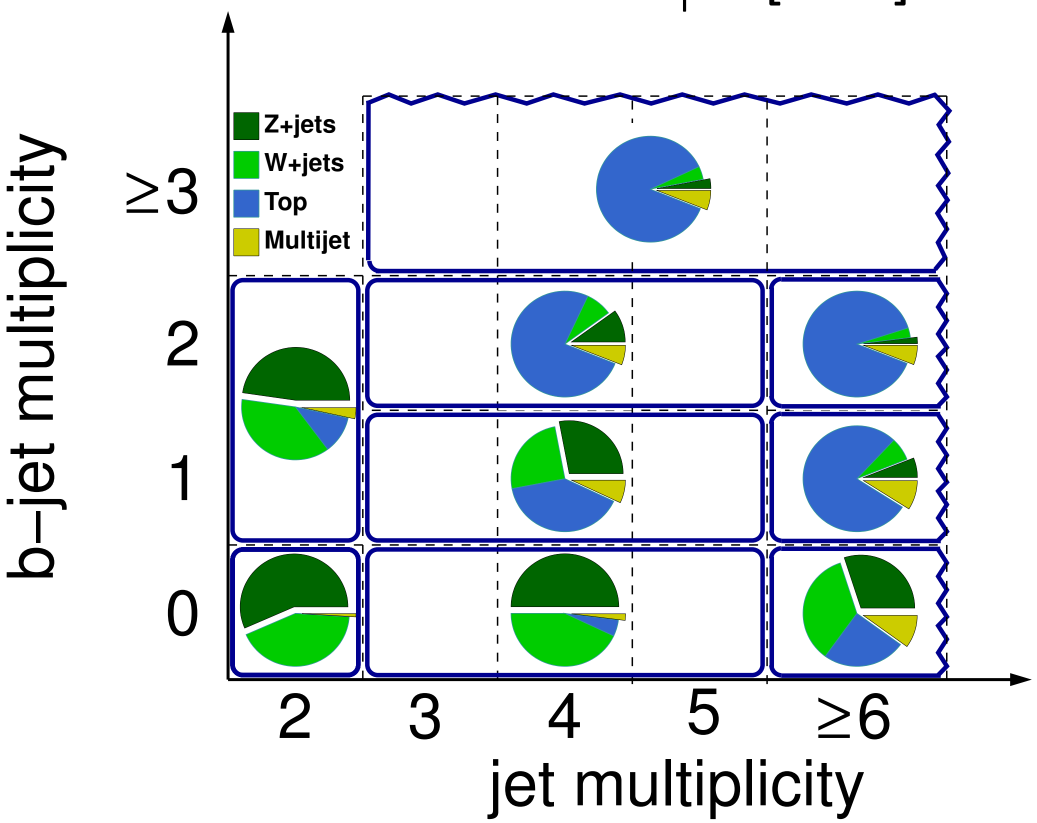
- **Lepton flavor violating Higgs**
  - Direct search with order of magnitude better reach than previous indirect limit
  - Standard control region techniques and data-driven backgrounds
- **Low-E_T mono-photon**
  - Difficult kinematic region to trigger ⇒ dedicated parked data trigger
- **Higgs + single top**
  - Very small cross section ⇒ multivariate discriminators necessary
- **High mass pseudoscalar $A \rightarrow Z\gamma$**
  - Clean signal well suited to CMS's strengths

For the latest CMS results on SUSY and related topics, see https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

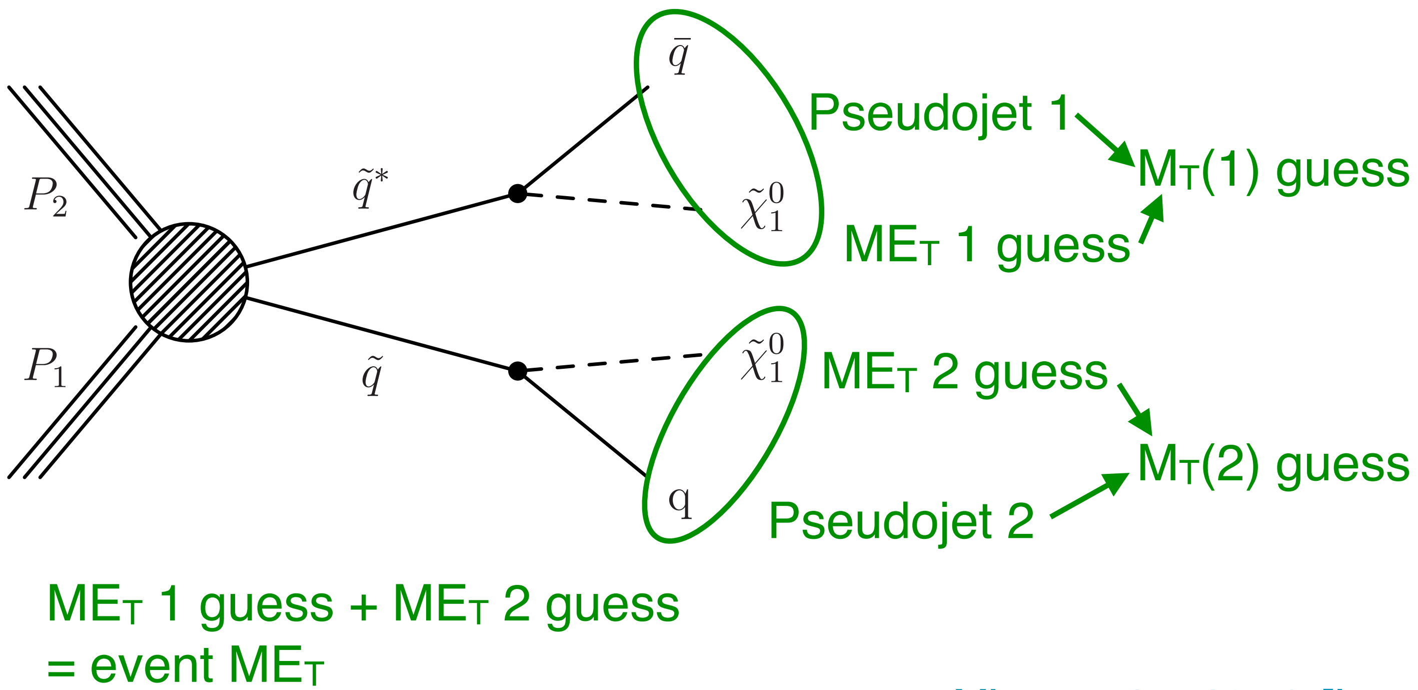
M_{T2} all-hadronic

New





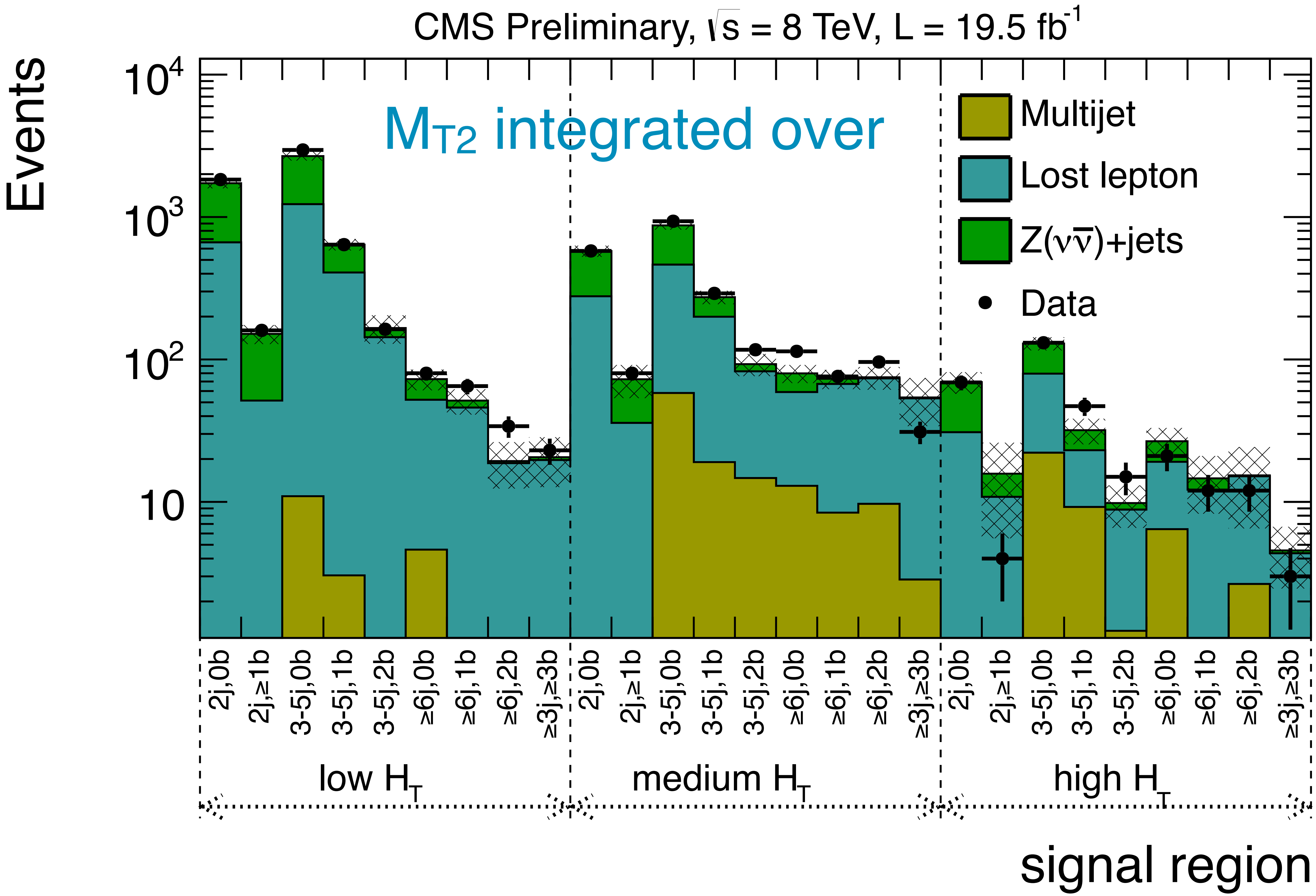
- **Combination of 123 signal regions defined by light jet multiplicity, b jet multiplicity, ME_T, H_T, and M_{T2}**
  - M_{T2} accesses the mass of pair-produced particles that both decay via an undetected massive particle
- **H_T and ME_T triggers**
- Anti-k_T R = 0.5 (“AK5”) particle flow jets corrected for charged and neutral energy from overlapping pp interactions (“pileup”)
- **Isolated charged lepton veto**
  - Critical background from W/Z/top→leptons where the lepton is lost



arXiv:1502.04358 [hep-ex]

M_{T2} all-hadronic: results

New



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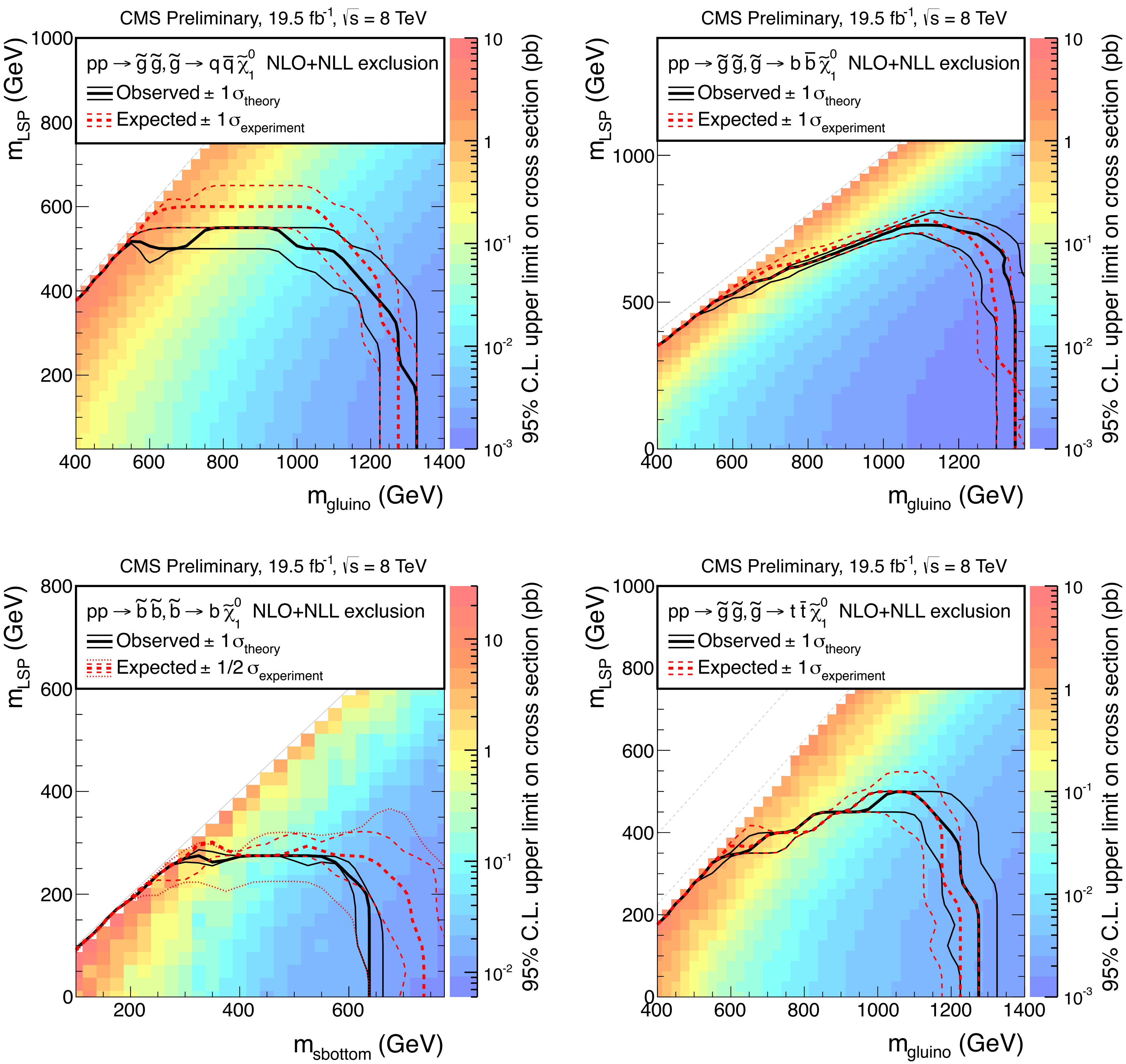
M_{T2} all-hadronic: interpretation

New

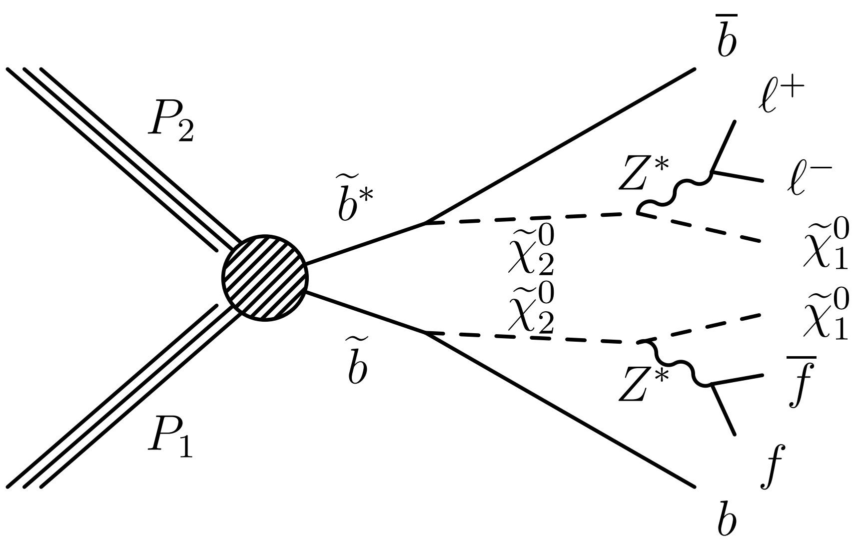


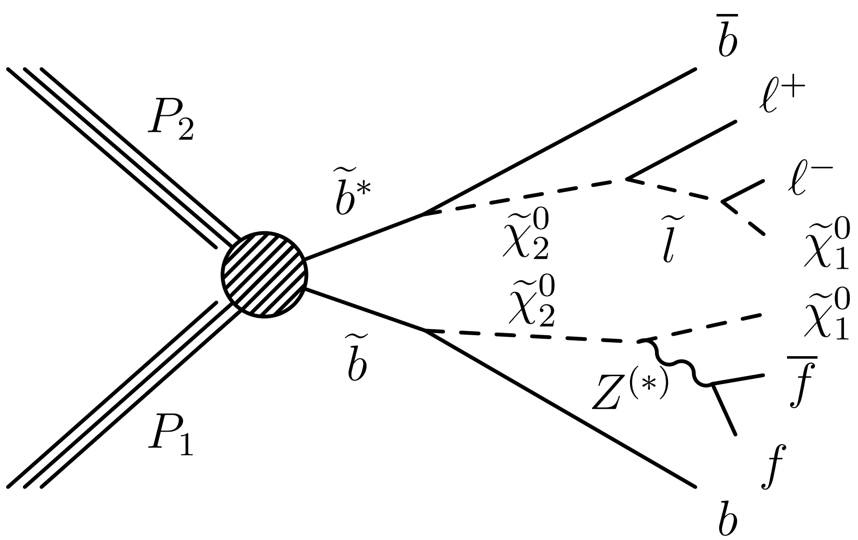
- Limits from a combination of relevant signal regions
- Furthest reach in gluino mass
- Observed limit worse than expected limit for sbottom mass likely due to downward fluctuation in lost lepton control sample

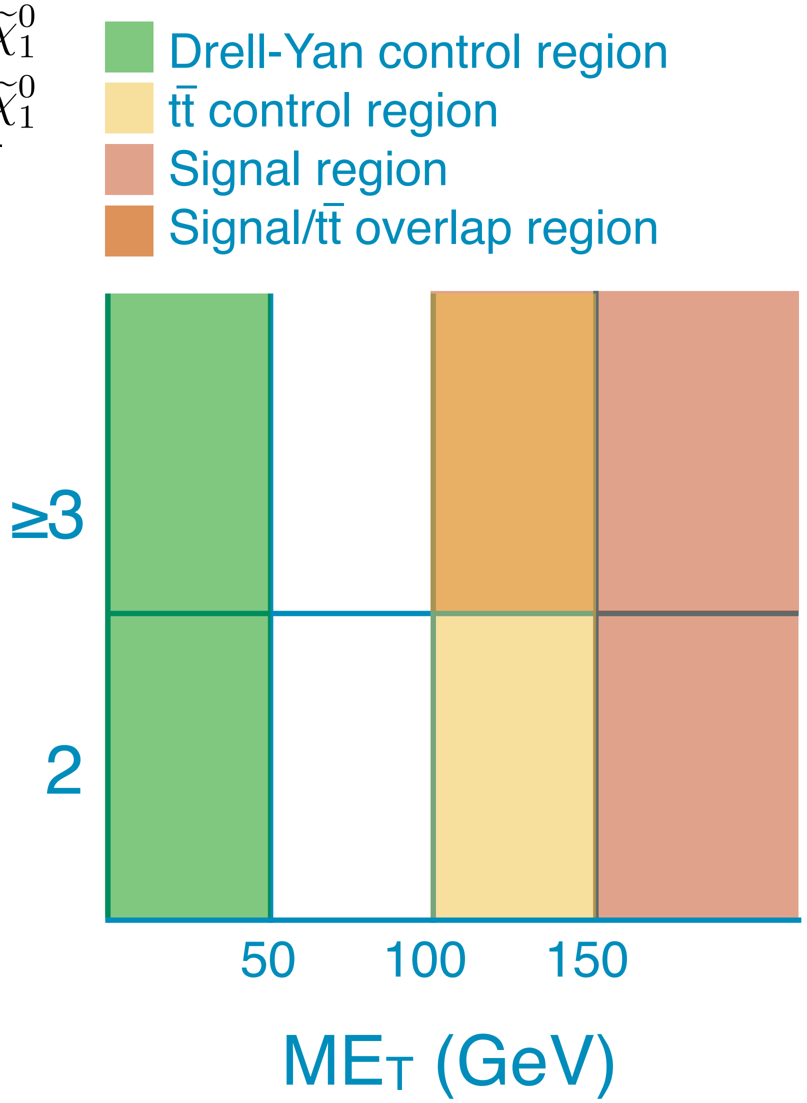
arXiv:1502.04358 [hep-ex]

Dilepton edge fit

New





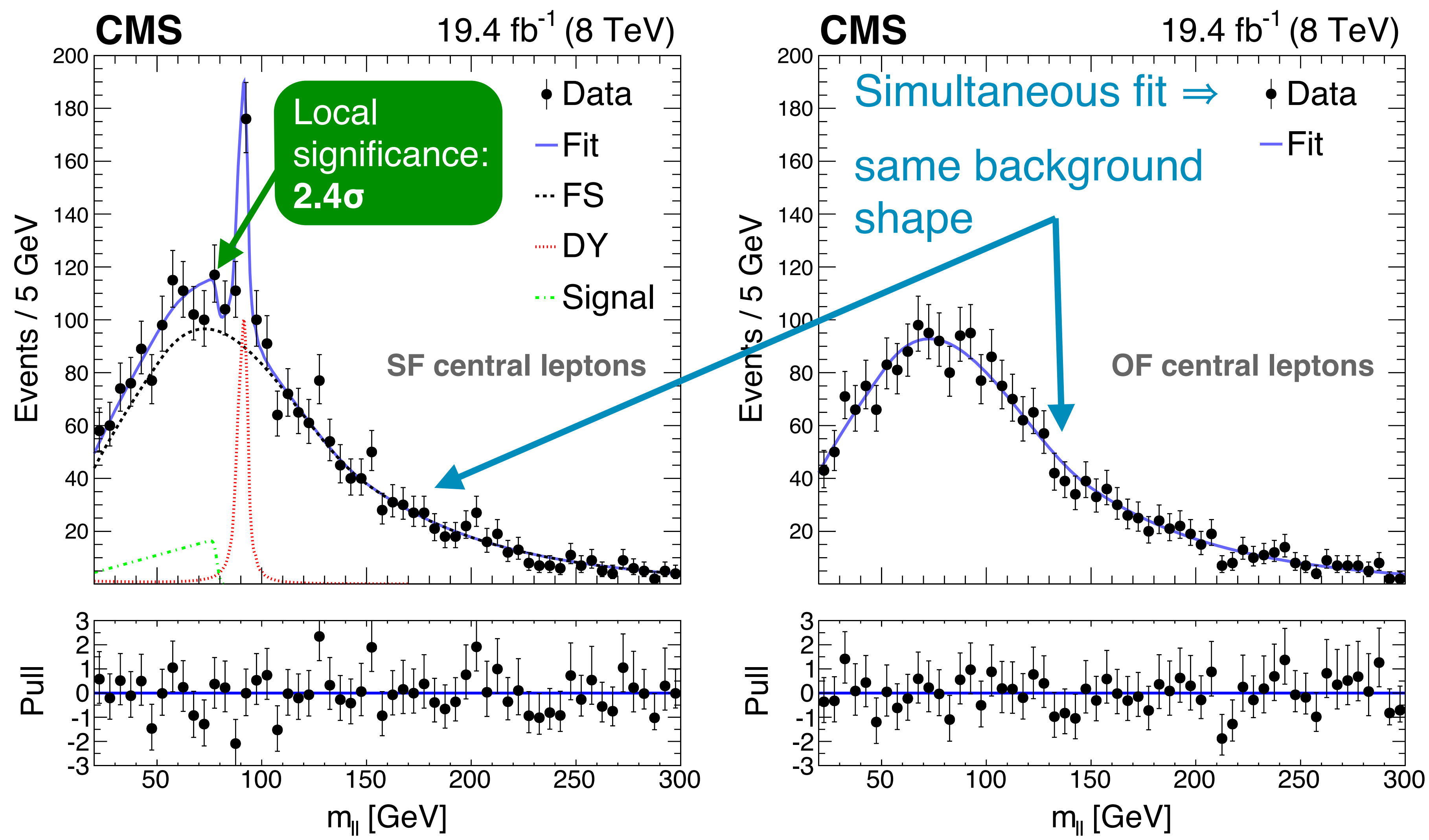


- $e^+e^-/\mu^+\mu^-$ (Z* decay or decay via slepton) + jets (sbottom decay) + ME_T (lightest neutralino)
- Isolated, non-overlapping leptons with $p_T > 20$ GeV
- AK5 particle flow jets with corrected $p_T > 40$ GeV and $|\eta_j| < 3.0$
- Focus here on the central region ($|\eta_l| < 1.4$)
- Backgrounds
  - Drell-Yan di-electron and di-muon pairs
  - tt̄, WW, Drell-Yan di-tau, tW, b/c decays to leptons, and jet fakes: all result in ee/μμ as often as eμ

arXiv:1502.06031 [hepex]

Dilepton edge fit: results

New



Drell-Yan component

- Exponential (low-mass side) + Breit-Wigner ⊗ crystal ball
- **Shape parameters fixed to values determined in fit to control region**
- Normalization left floating

$t\bar{t}$ (i.e. eμ) component

- Power law for the low-mass side
- Exponential for the high-mass side
- Low→high mass transition
- **ee, μμ, and eμ regions fit simultaneously**

Signal component

- Triangle convolved with Gaussian
- Edge position and normalization left floating

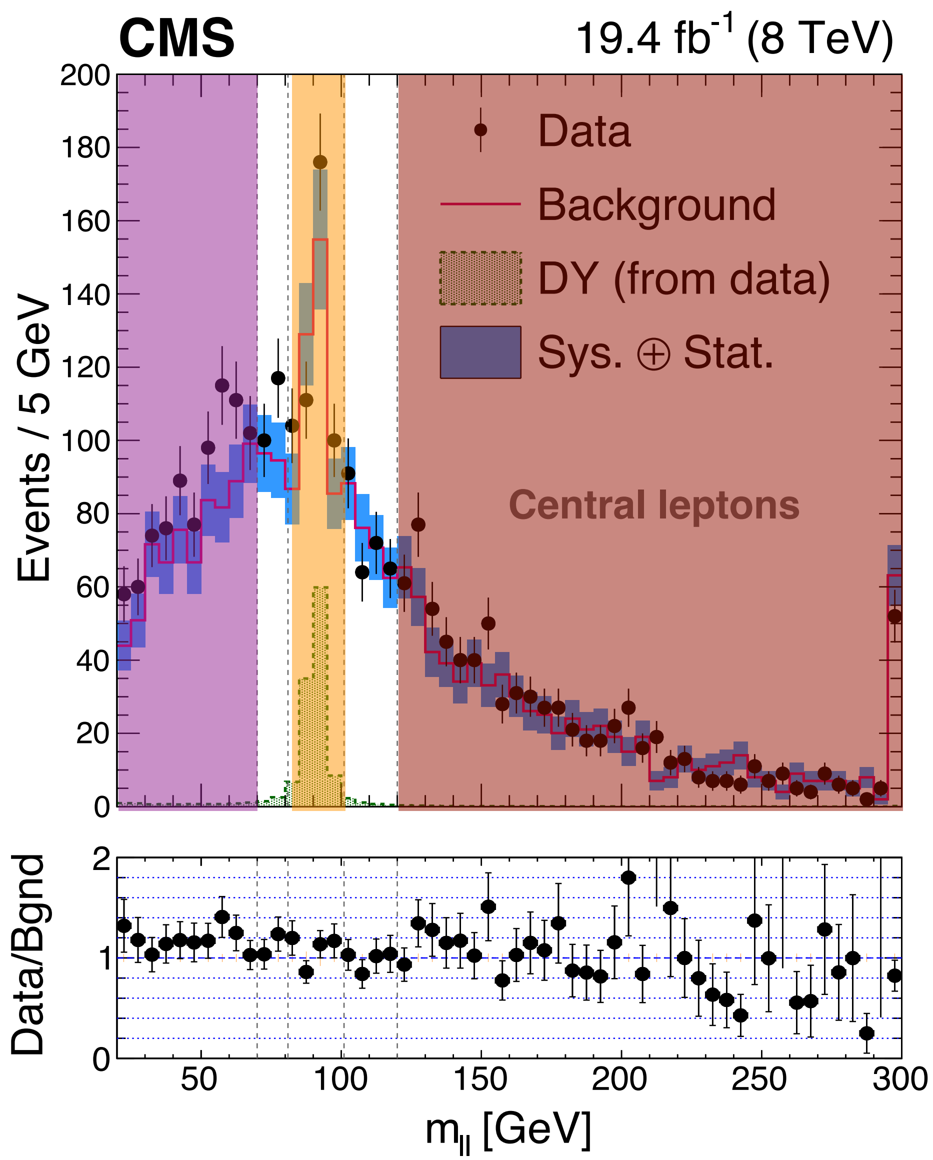
Simultaneous extended un-binned maximum likelihood fit to di-lepton invariant mass

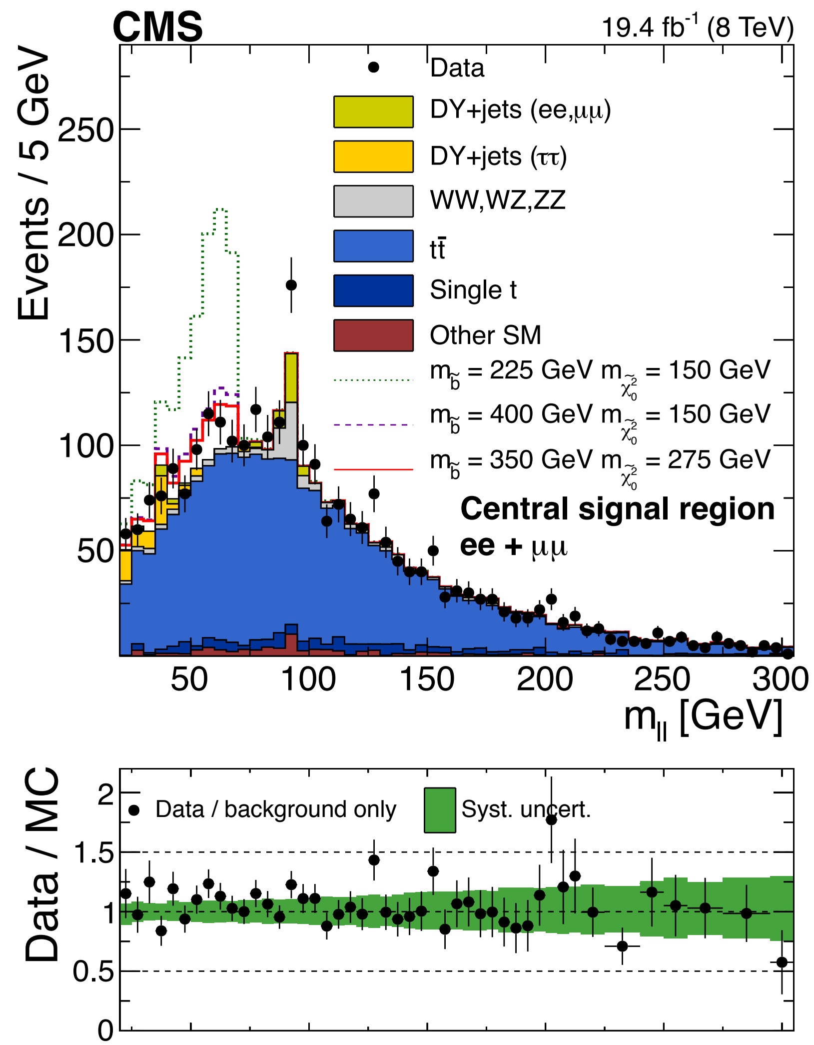
Best-fit edge position (~ $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$): **78.7 ± 1.4 GeV**

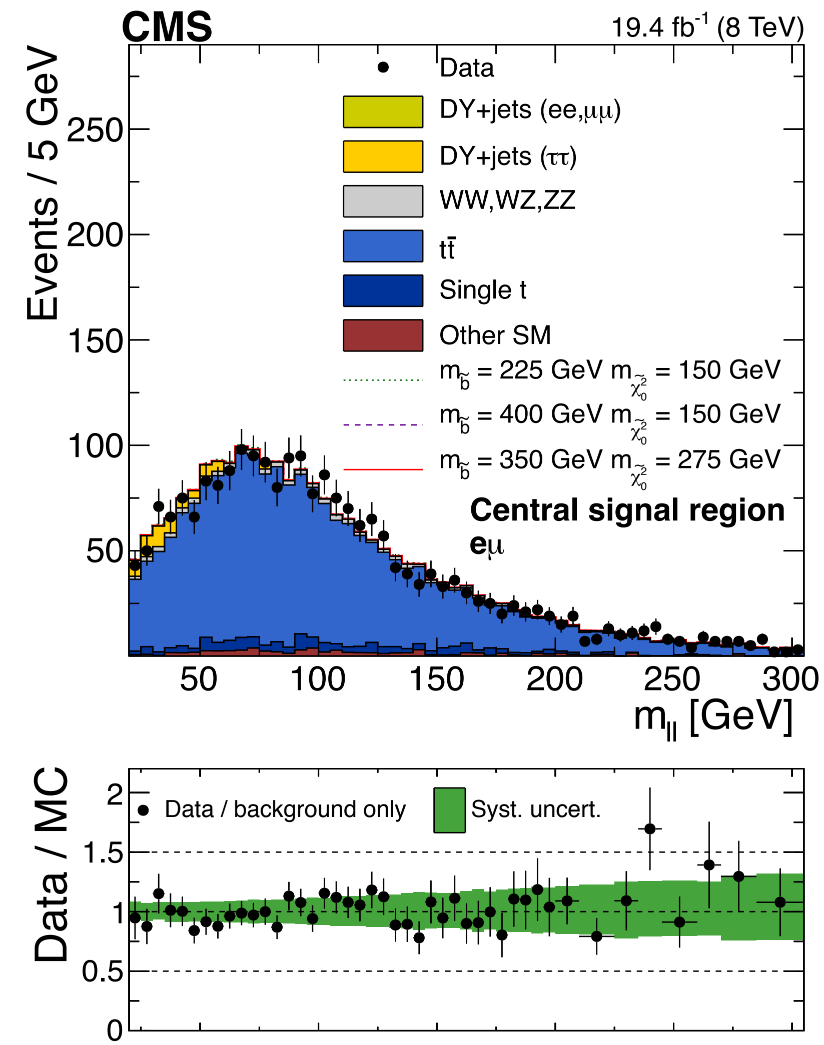
arXiv:1502.06031 [hepex]

Dilepton edge fit: cross checks

New







Backgrounds from simulation

Counting experiment (backgrounds from control samples)

Counting experiment local significance

20-70 GeV: 2.6σ

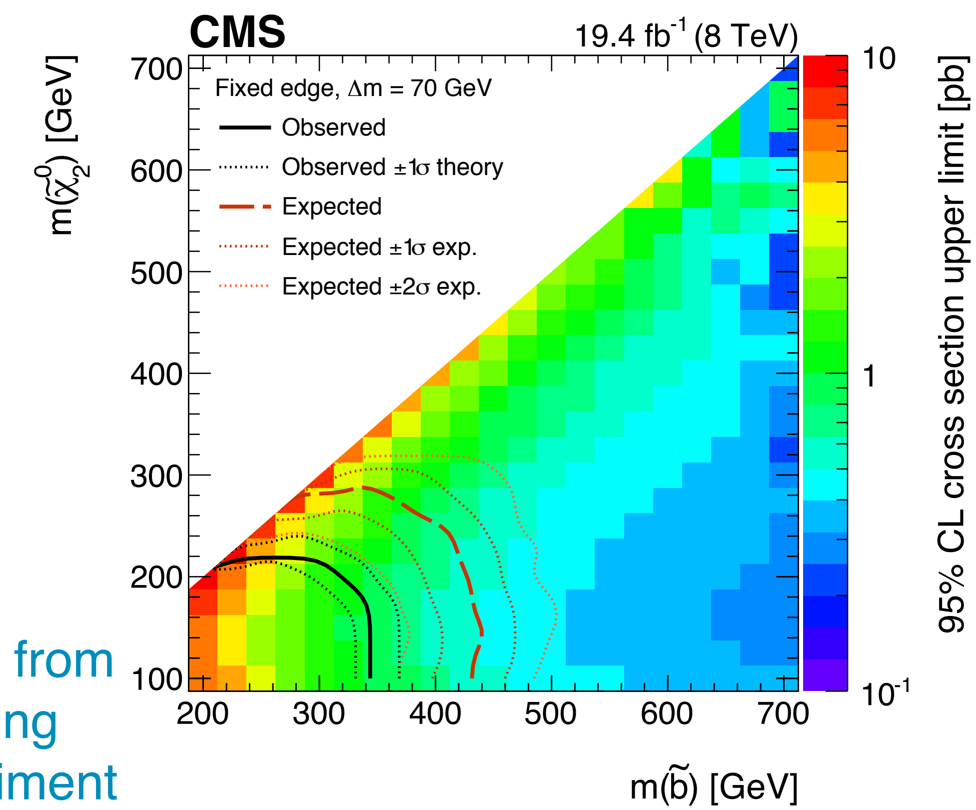
81-101 GeV: 0.4σ

>120 GeV: 0.9σ

arXiv:1502.06031 [hepex]

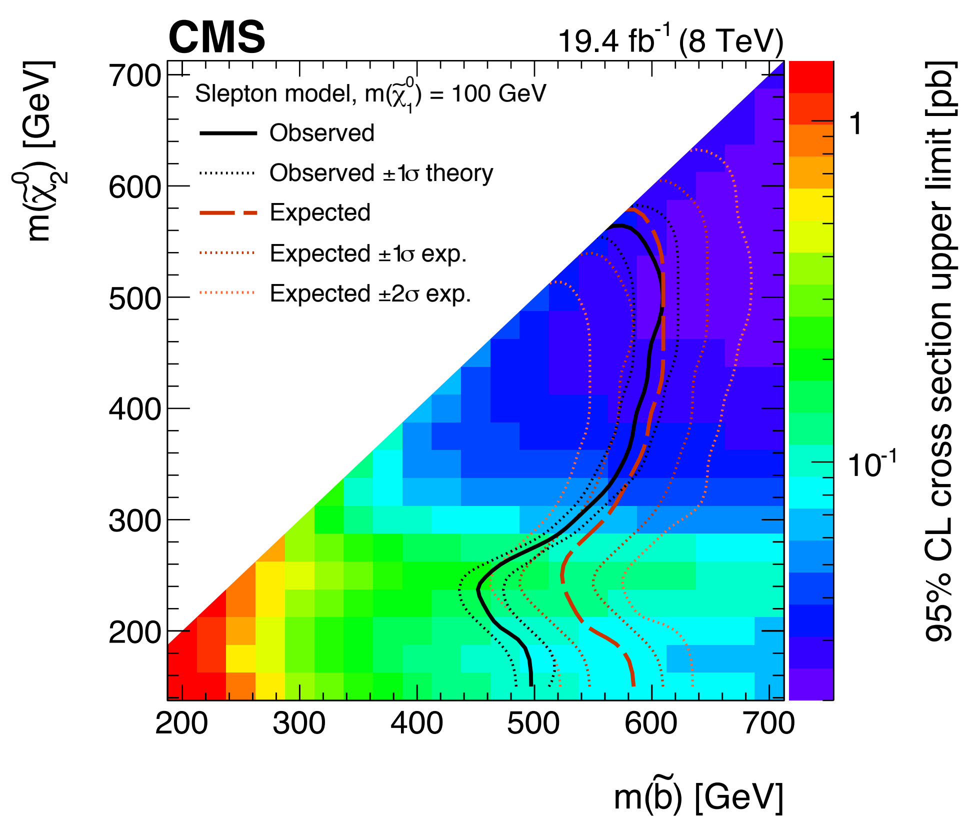
Dilepton edge fit: interpretation

New



- $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} = 70$ GeV (motivated by fit result)
- Kinematic phase space limitation in BR($\tilde{b} \to \tilde{\chi}_2^0 b$) as $\tilde{\chi}_2^0$ gets heavier

Limits from counting experiment

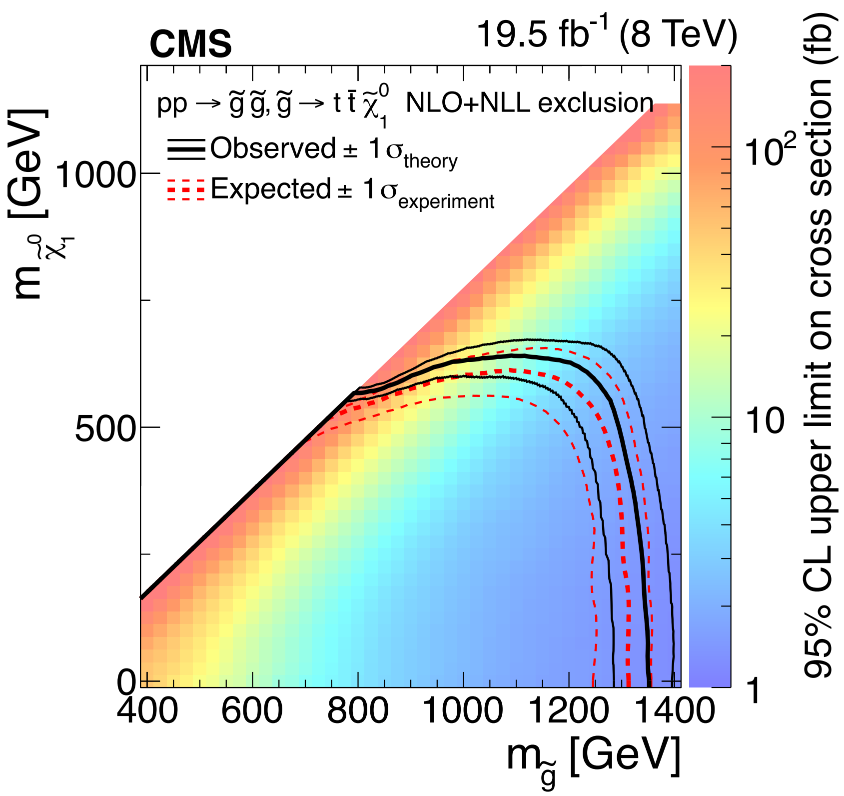


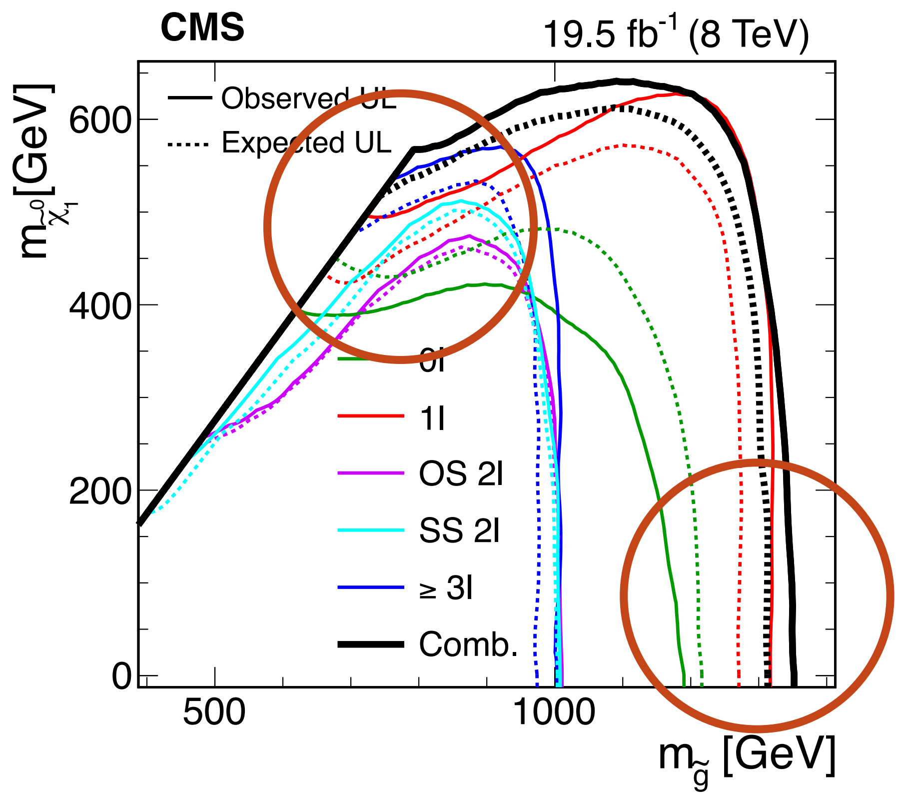
- $m_{\tilde{\chi}_1^0} = 100$ GeV
- $m_{\tilde{b}}$ limited by $\tilde{b}\tilde{b}^*$ cross section
- $m_{\tilde{\chi}_2^0}$ limited by kinematic requirement $m_{\tilde{\chi}_2^0} < m_{\tilde{b}}$

arXiv:1502.06031 [hepex]

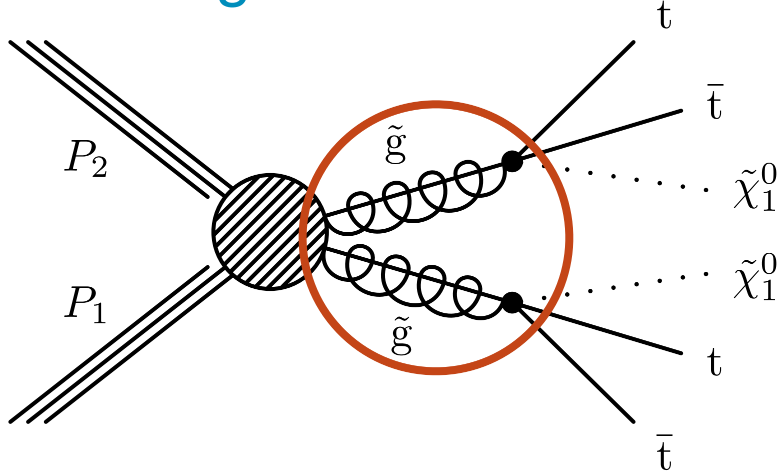
MSSM 4-W final states: gluino production

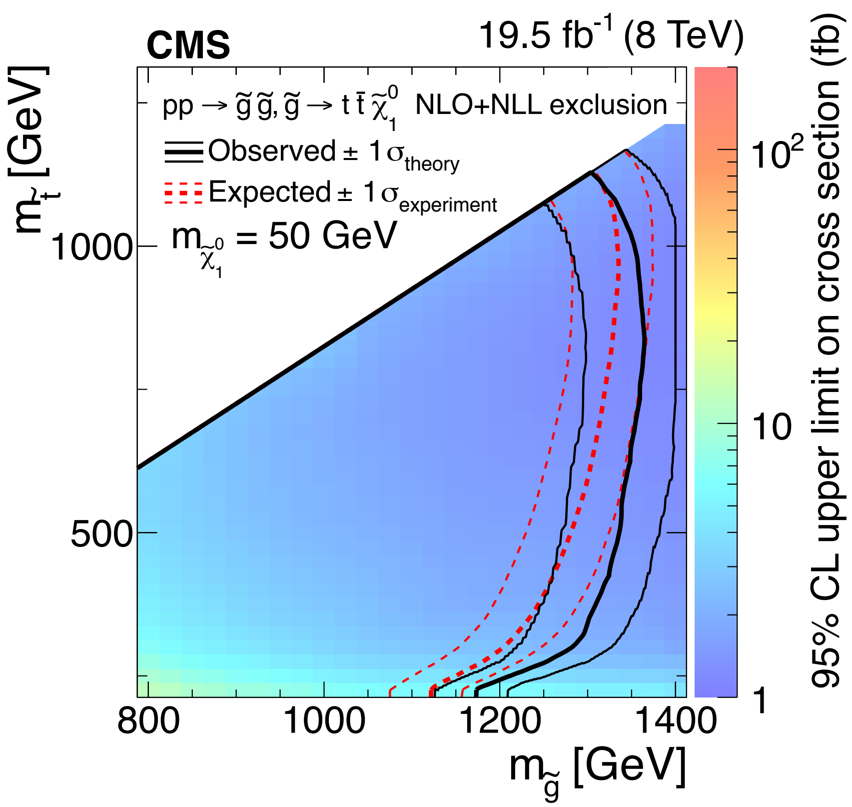
New

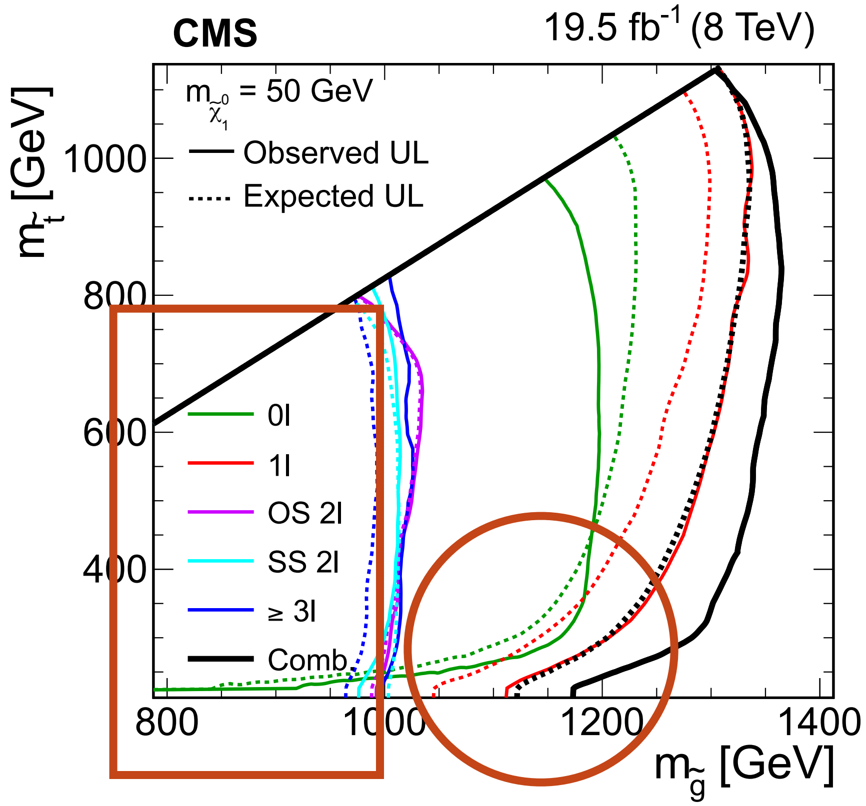




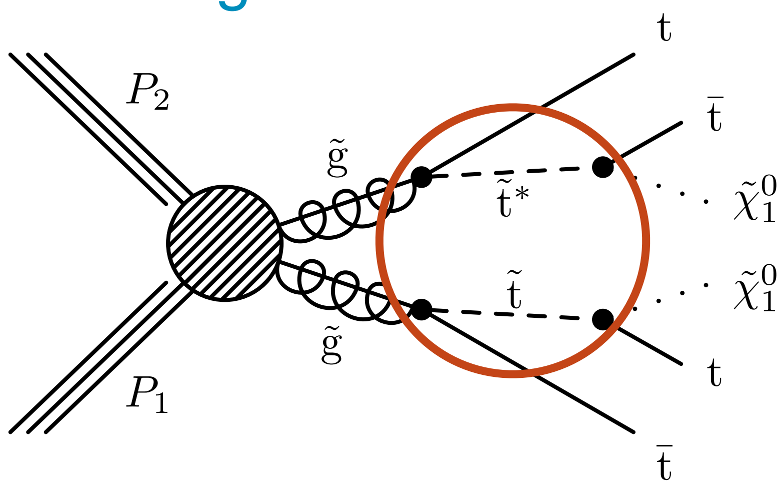
$m_{\tilde{g}} < m_{\tilde{t}}$







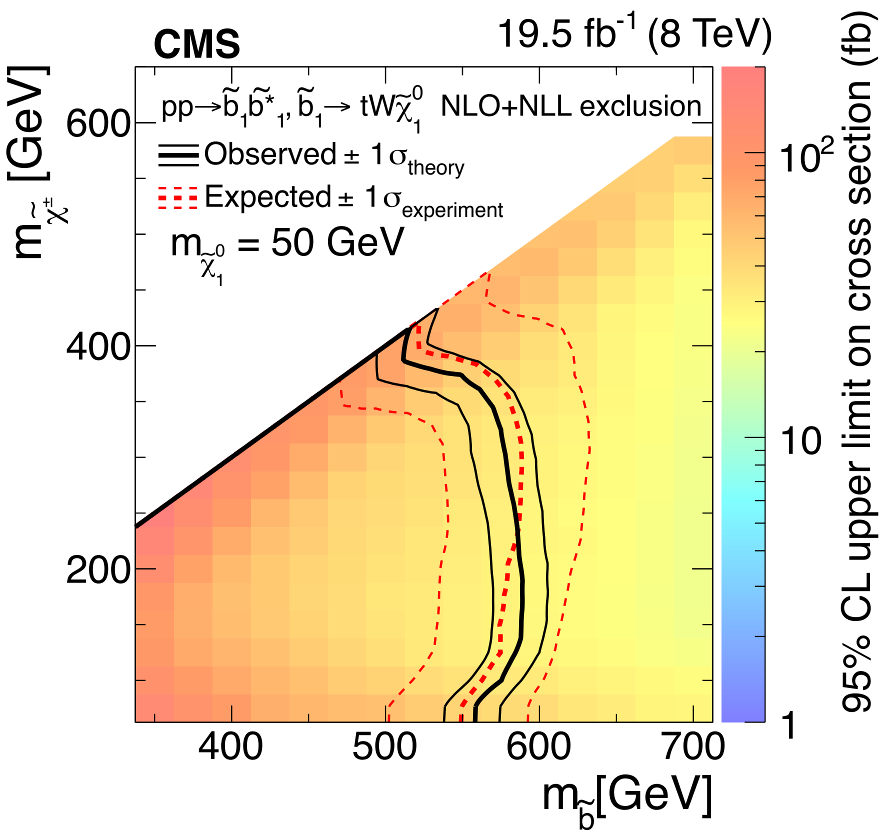
$m_{\tilde{g}} > m_{\tilde{t}}$

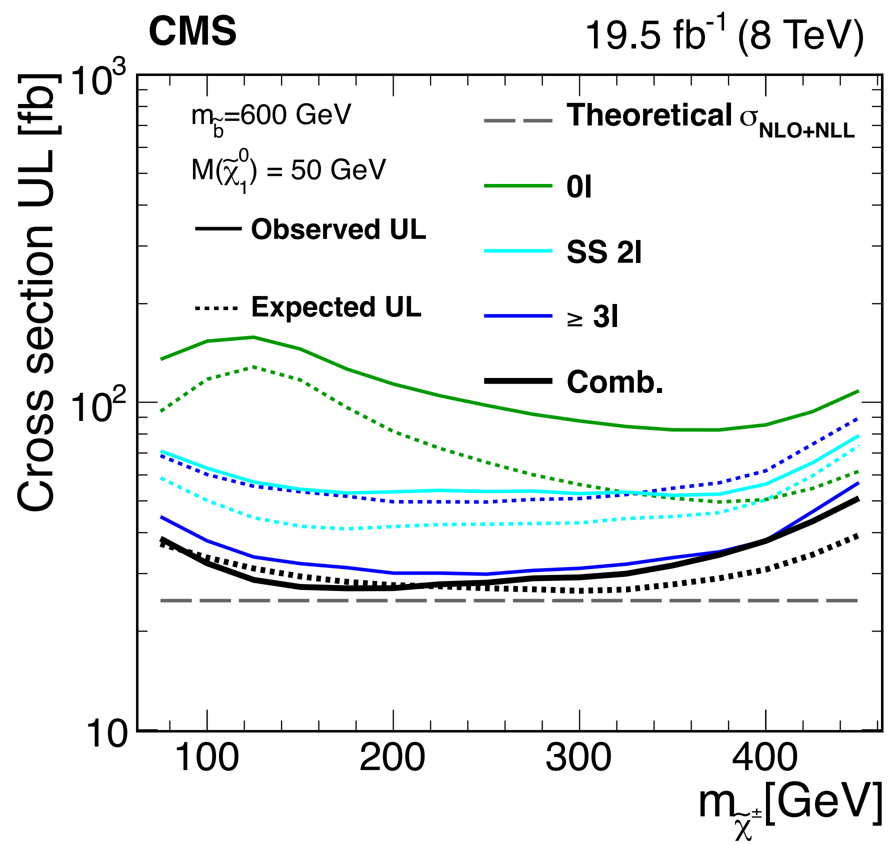


arXiv:1412.4109 [hepex]

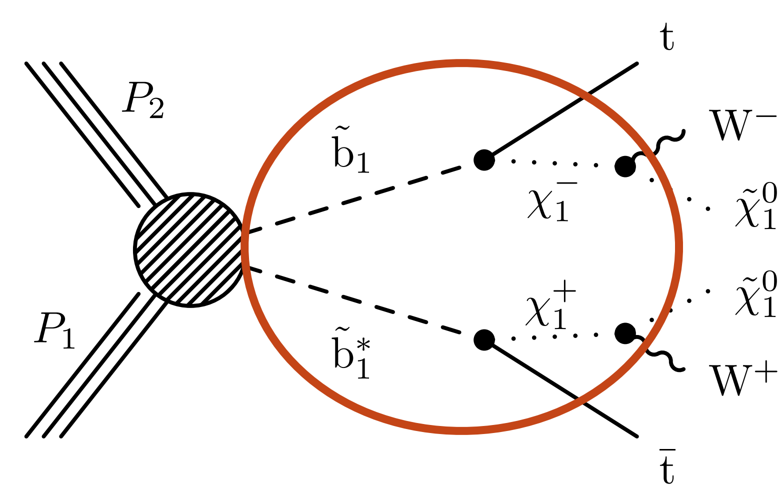
MSSM 4-W final states: sbottom production

New





$m_{\tilde{b}} > m_{\tilde{\chi}_1^{\pm}}$

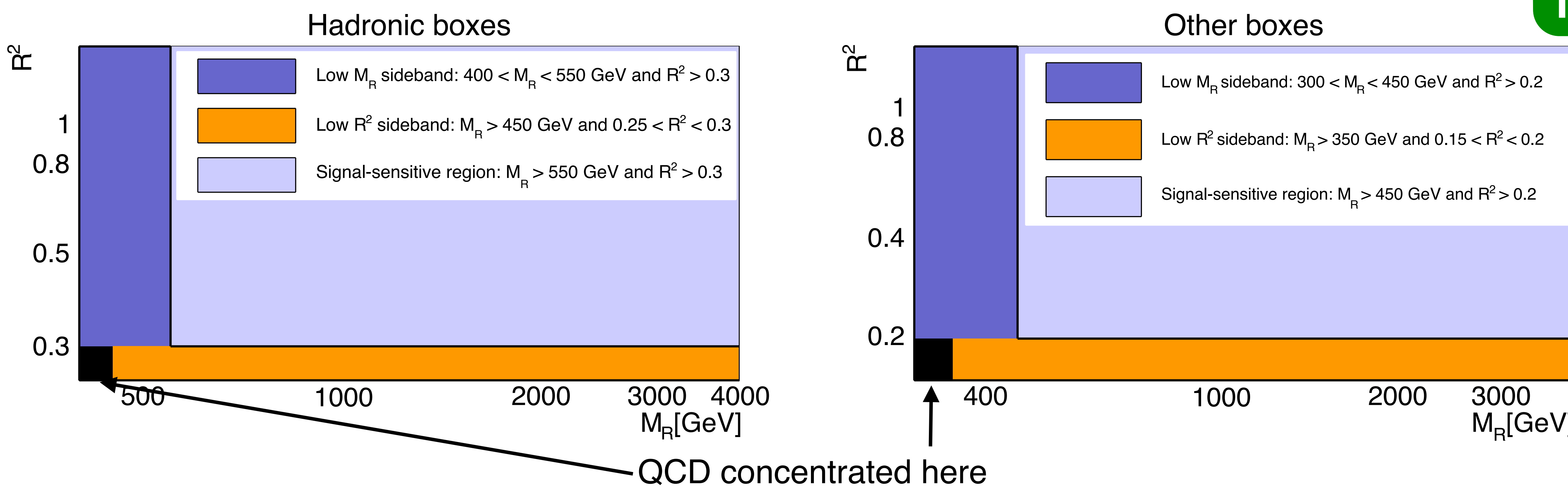


Loose b tag requirement optimal for only 2 tops

arXiv:1412.4109 [hepex]

b-tagged razor

New



- Razor variables efficiently reject QCD multijet backgrounds and estimate the mass scale of new particles

$$M_R \equiv \sqrt{(|\vec{p}^{j_1}| + |\vec{p}^{j_2}|)^2 - (p_z^{j_1} + p_z^{j_2})^2},$$

$$M_T^R \equiv \sqrt{\frac{E_T^{miss}(p_T^{j_1} + p_T^{j_2}) - \vec{p}_T^{miss} \cdot (\vec{p}_T^{j_1} + \vec{p}_T^{j_2})}{2}},$$

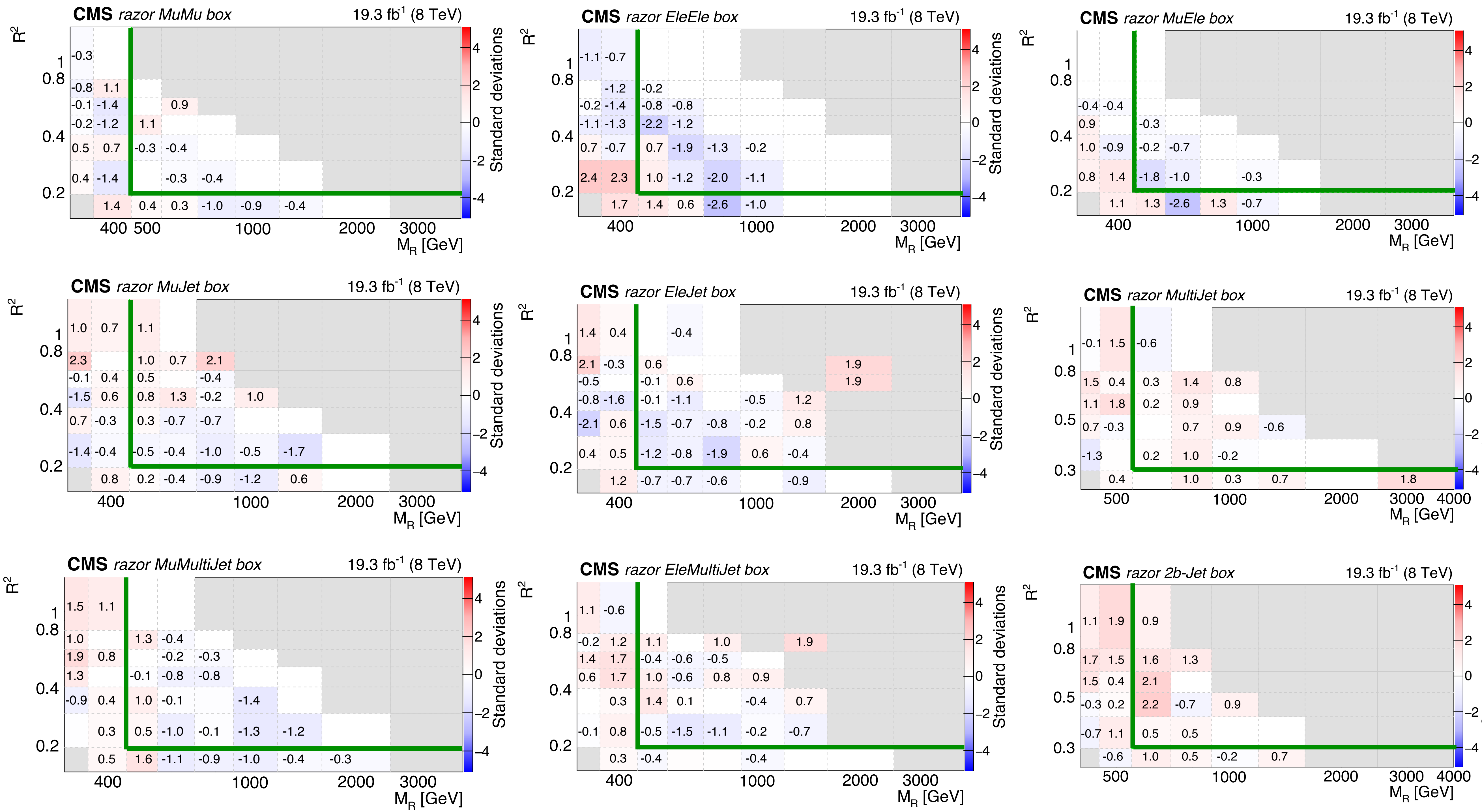
$$R \equiv \frac{M_T^R}{M_R}.$$

- R^2-M_R triggers allow lower jet and lepton p_T compared to single- or di-object triggers
- Events divided into 0-lepton, 1-lepton, and 2-lepton boxes; each box further subdivided into exclusive N_b bins
- Backgrounds: V + jets (maximum 25%) and $t\bar{t}$
- Maximum likelihood fit to background model $f(M_R, R^2)$ in sideband regions extrapolated to signal region

arXiv:1502.00300 [hep-ex]

b-tagged razor: results

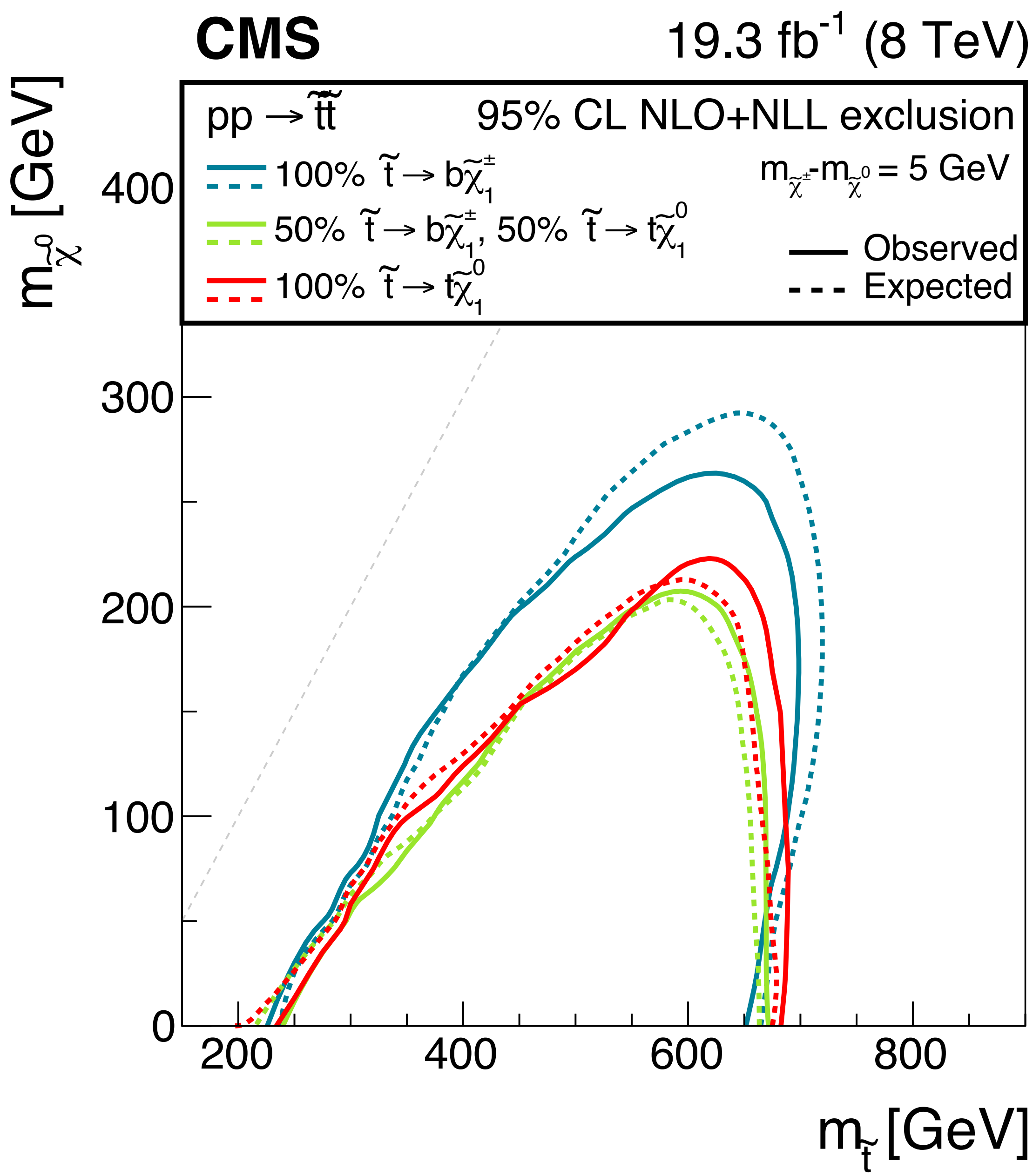
New

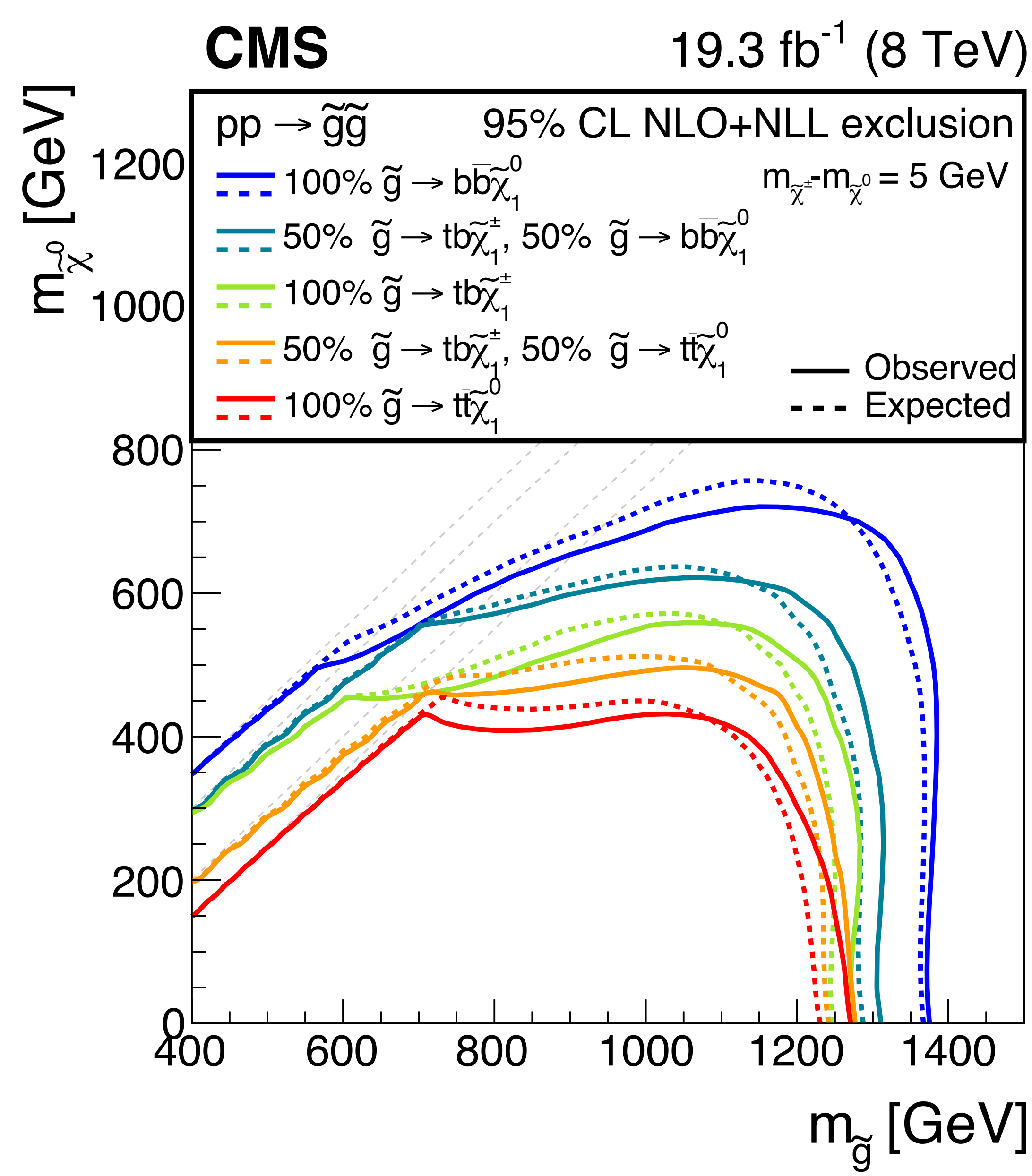


arXiv:1502.00300 [hep-ex]

b-tagged razor: interpretation

New





arXiv:1502.00300 [hep-ex]

Lepton flavor violating Higgs

- $H \to ll'$ a generic prediction of SUSY and other 2HDM
  - μe couplings strongly constrained by $\mu \to e\gamma$ searches
  - BR($H \to \mu\tau$) ≲ 10%
- 2 decay modes ($\mu\tau_e$, $\mu\tau_h$) × 3 jet bins (0, 1, 2 jets)
  - Opposite sign, isolated lepton selection in each bin
  - Further optimization of p_T, M_T, and $\Delta\Phi$ done separately in each bin

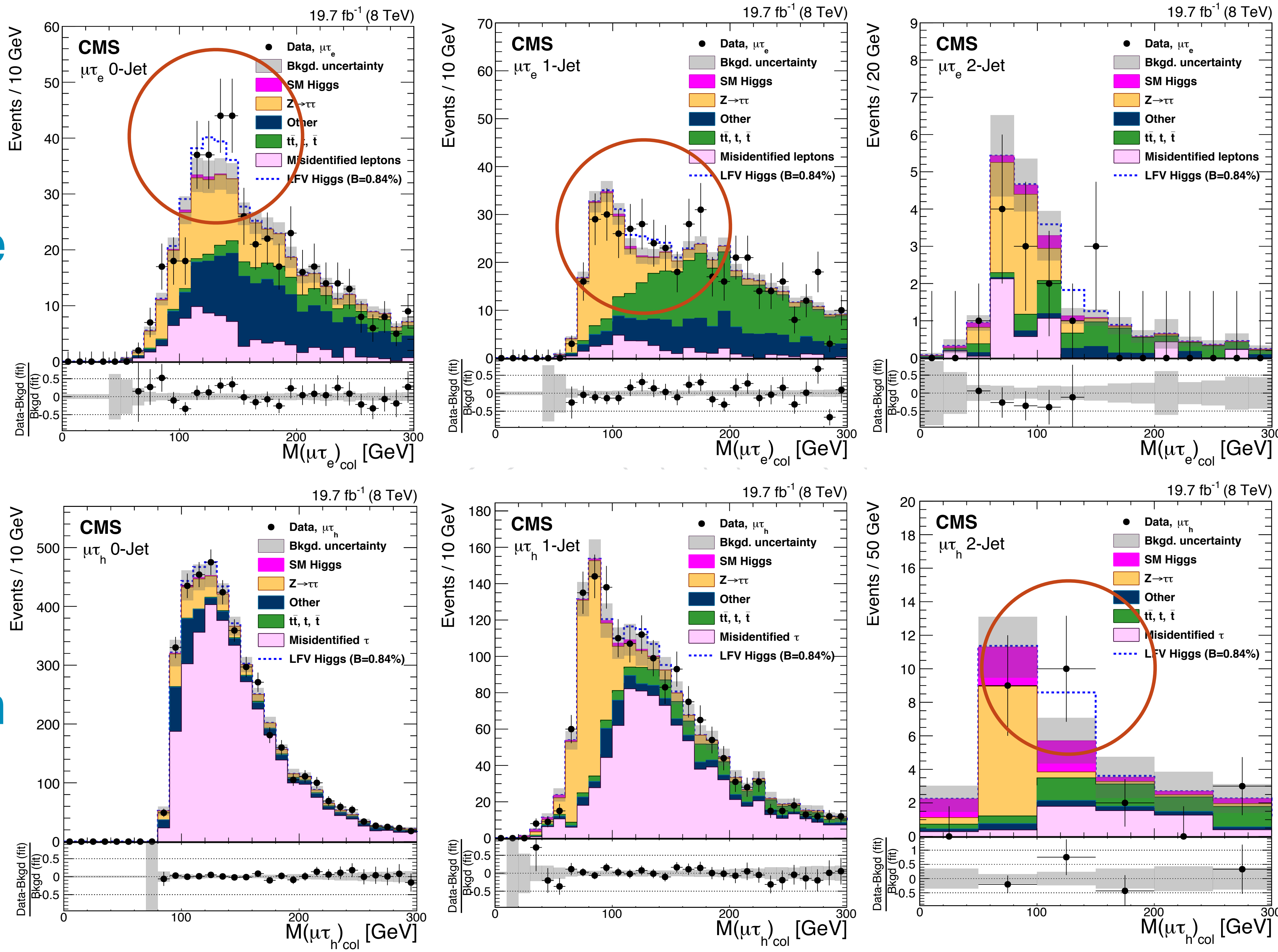
	$\mu\tau_e$	$\mu\tau_h$
0 jets	Main bkg.: $Z \to \tau\tau$, $t\bar{t}$ Main sig.: ggH Trigger: iso. μ + iso. e	Main bkg.: jet fakes Main sig.: ggH Trigger: iso. μ
1 jet	Main bkg.: $Z \to \tau\tau$, $t\bar{t}$ Main sig.: ggH, VH Trigger: iso. μ + iso. e	Main bkg.: jet fakes Main sig.: ggH, VH Trigger: iso. μ
2 jets b veto	Main bkg.: $Z \to \tau\tau$, $t\bar{t}$ Main sig.: VBF Trigger: iso. μ + iso. e	Main bkg.: jet fakes Main sig.: VBF Trigger: iso. μ

arXiv:1502.07400 [hep-ex]

LFV Higgs: results

μτe

μτh



0 jets 1 jet 2 jets

Z→ττ (MC tau embedding in data)

Top (shape from MC, scale from data)

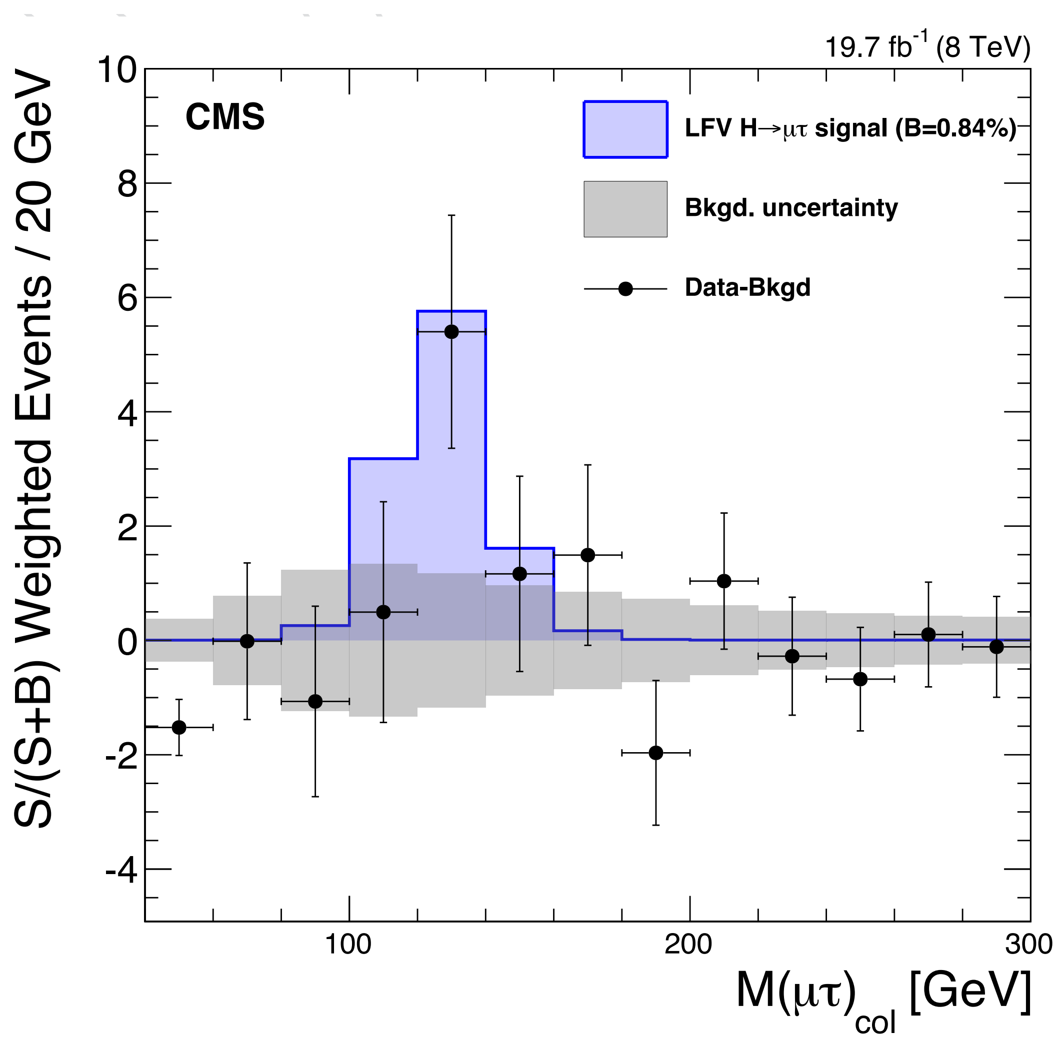
Jet fakes (fake rates from data)

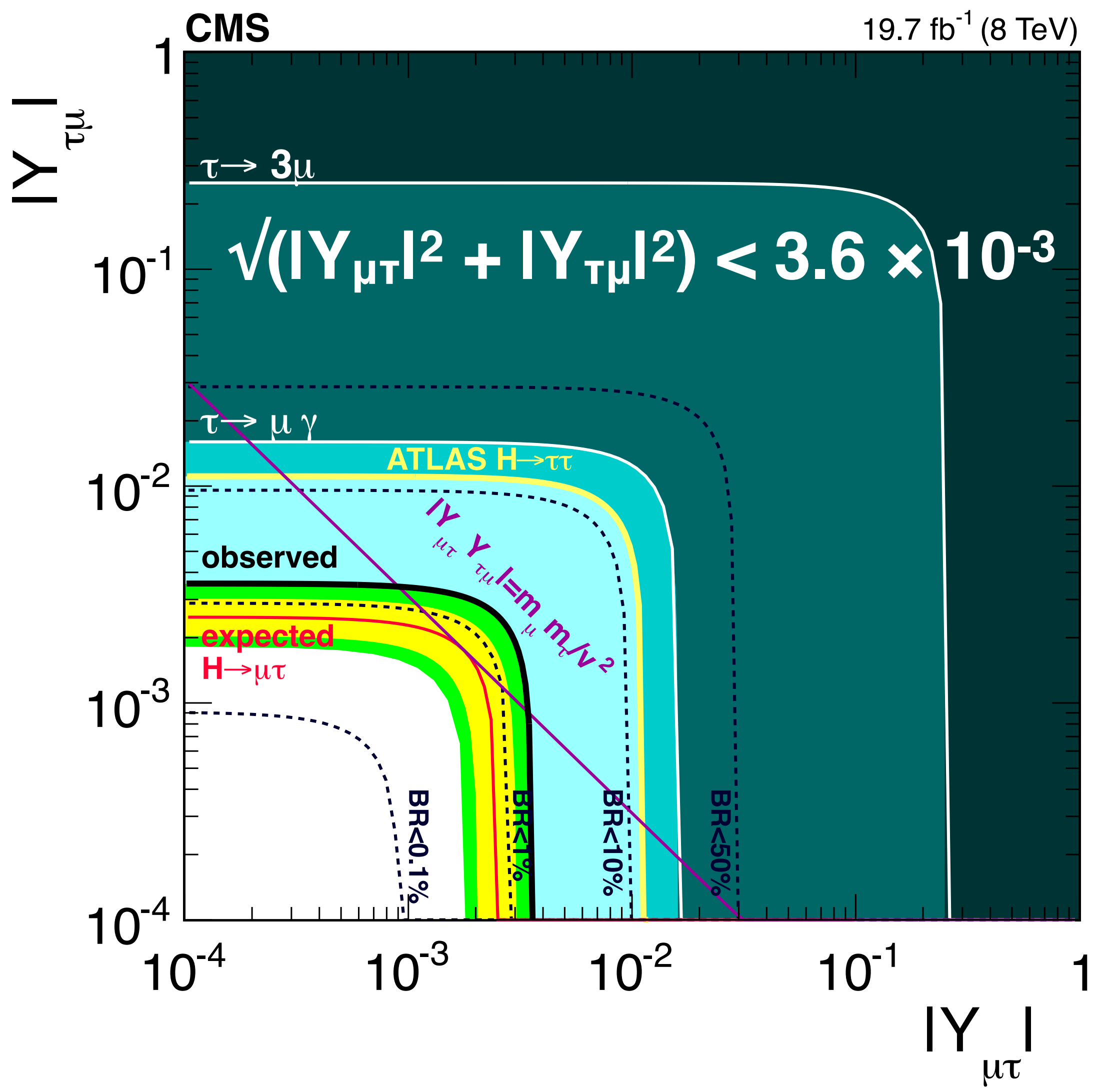
Limit BR(H→μτ): < 1.51% (95% CL)

Best-fit BR(H→μτ): $(0.84^{+0.39}_{-0.37})\%$

arXiv:1502.07400 [hep-ex]

LFV Higgs: interpretation



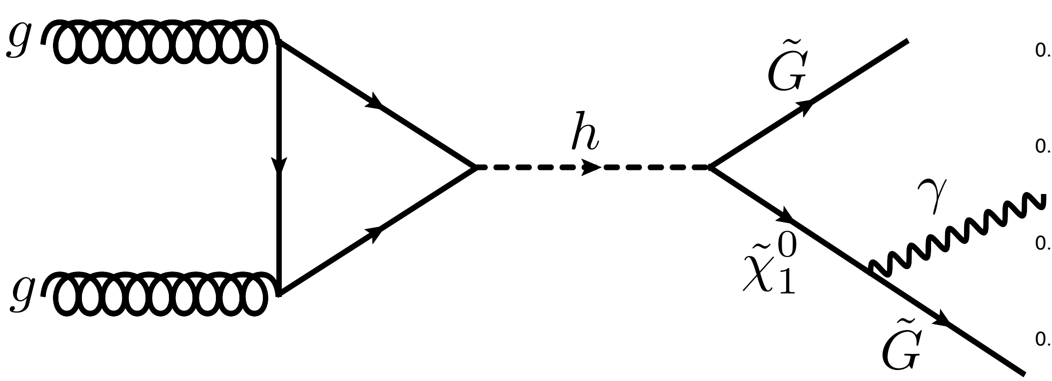


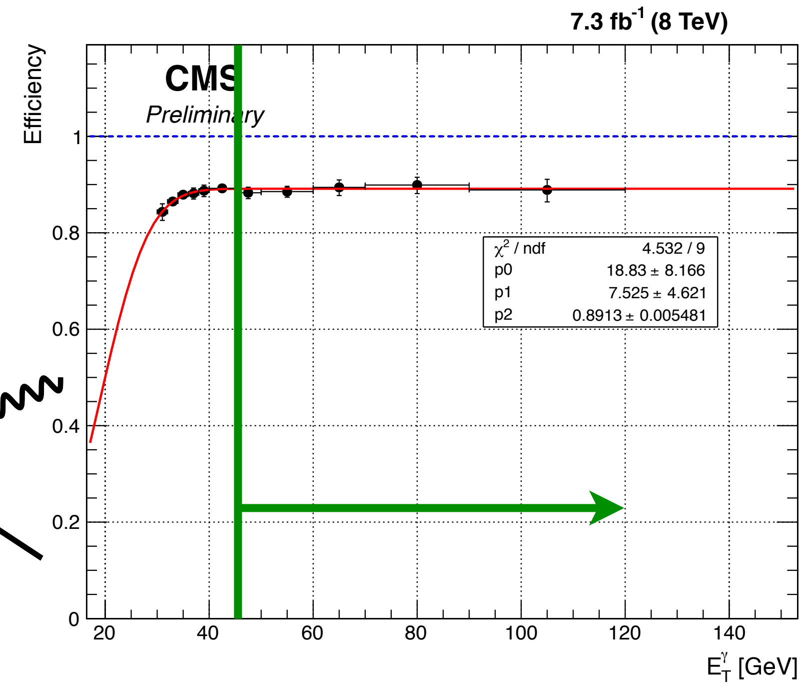
- Limit on BR(H→μτ) translated into upper limit on LFV Yukawa coupling
- Direct search limit ~10× more stringent than previous limit derived from H→ττ measurement

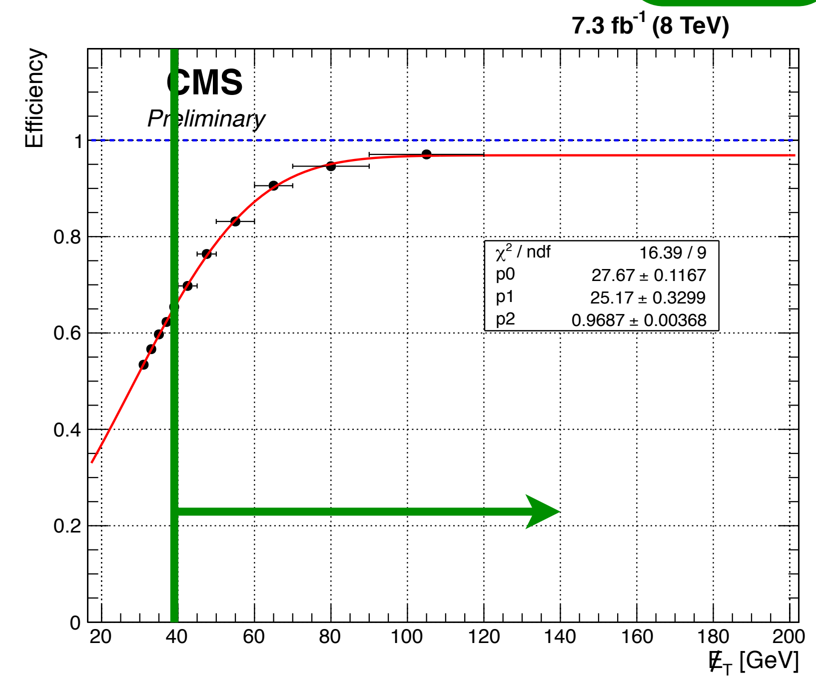
arXiv:1502.07400 [hep-ex]

Low-E_T mono-photon

New







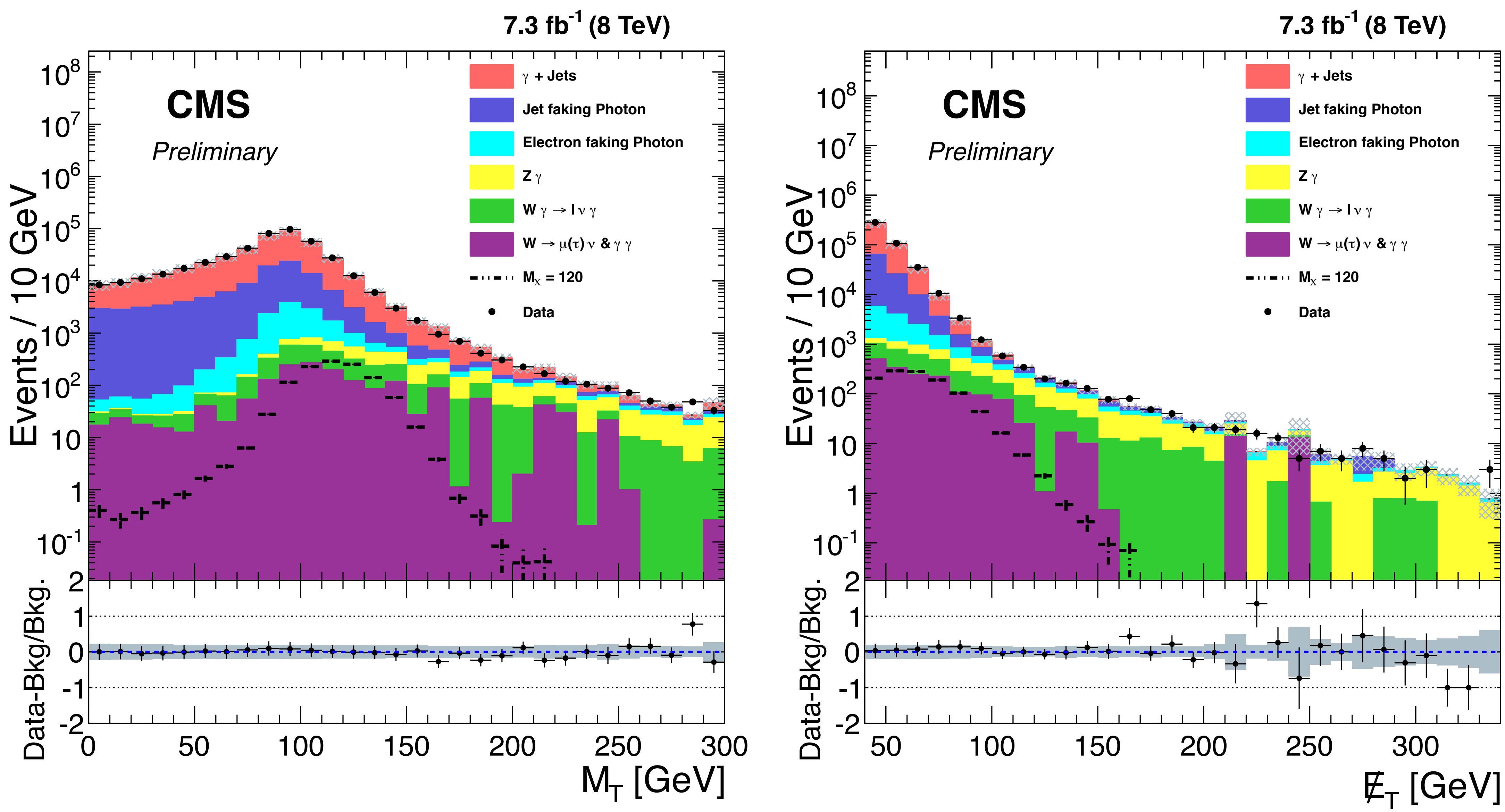
- GMSB $H \rightarrow \tilde{\chi}_1^0 G \rightarrow \gamma + ME_T$, 125 GeV Higgs ⇒ relatively **low-E_T photon and low-E_T neutralinos**
- Kinematic region of interest: $m_H/2 < m_{\tilde{\chi}_1^0} < m_H$
- **30 GeV isolated central photon + 25 GeV ME_T trigger from 8 TeV 7.3 fb^{-1} parked data (only reconstructed in 2013)**
- Isolated electron and muon veto
- Two novel methods for rejecting multijet and γ + jet events with mis-measured ME_T
  - ME_T significance: Event-by-event likelihood that ME_T is real based on known energy resolutions
  - MH_T minimization: cut on recalculated ME_T from particle 4-vectors that minimize the X^2 and require X^2 probability < 10^{-3}
- **Model-independent analysis: 0 or 1 jet, photon and jet not back to back**
- **Targeted analysis: no jet requirement, but cuts on ME_T significance and application of MH_T minimization**

$$\chi^2 = \sum_{i=objects} \left(\frac{(p_T^{reco})_i - (\tilde{p}_T)_i}{(\sigma_{p_T})_i} \right)^2 + \left(\frac{\tilde{\not{E}}_x}{\sigma_{\not{E}_x}} \right)^2 + \left(\frac{\tilde{\not{E}}_y}{\sigma_{\not{E}_y}} \right)^2$$

CMS-PAS-HIG-14-024

Low-E_T mono-photon: results

New



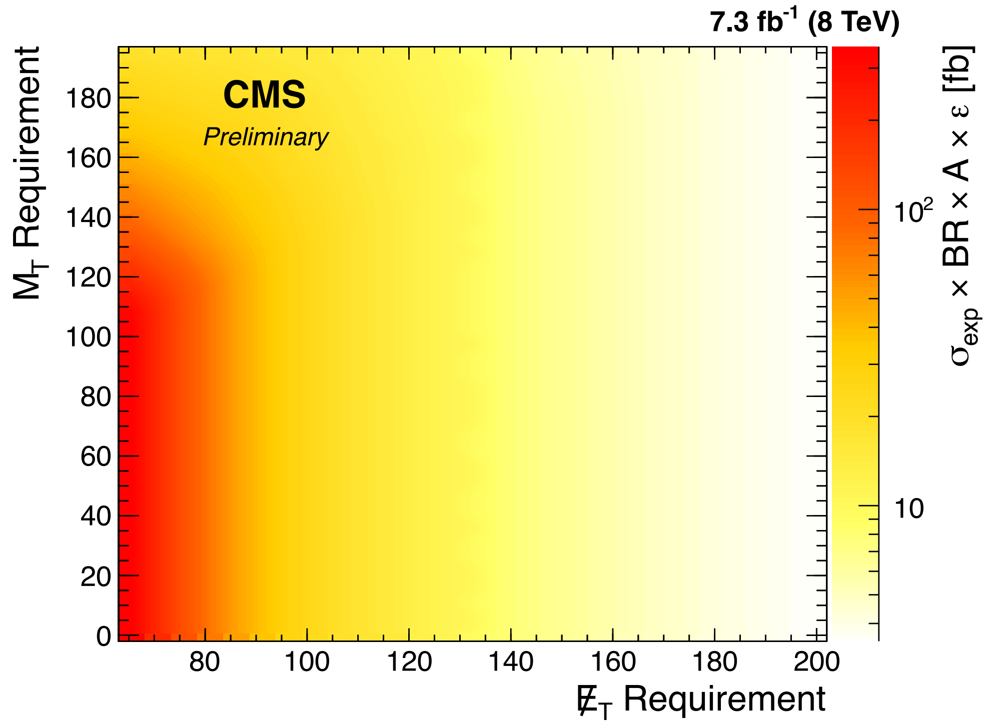
Model-independent selection

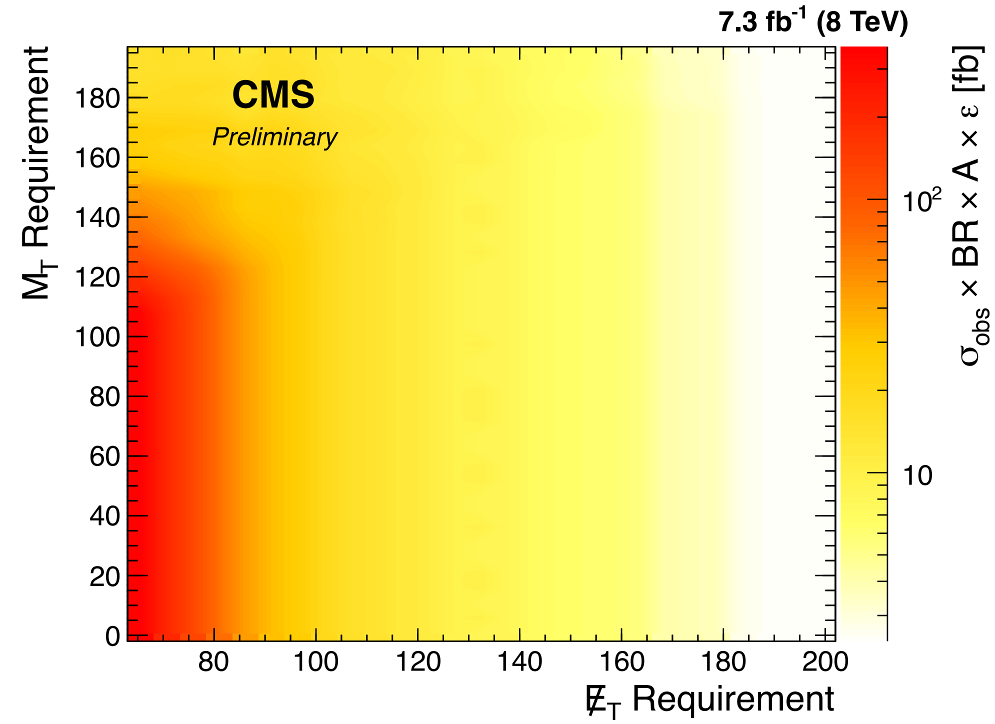
Shape from MC, normalization from data — Fully data-driven — NLO MC

CMS-PAS-HIG-14-024

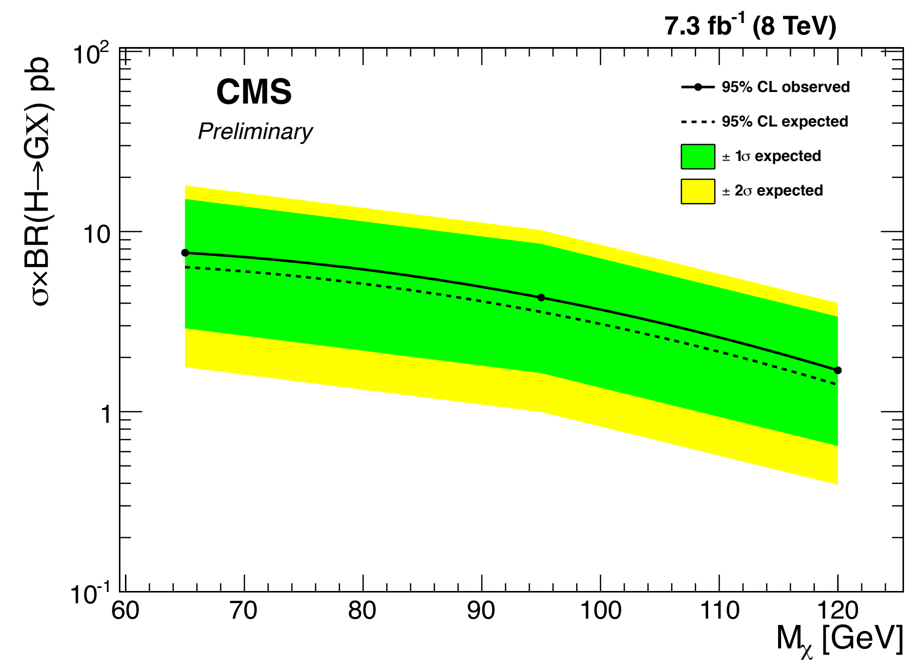
Low-E_T mono-photon: interpretation

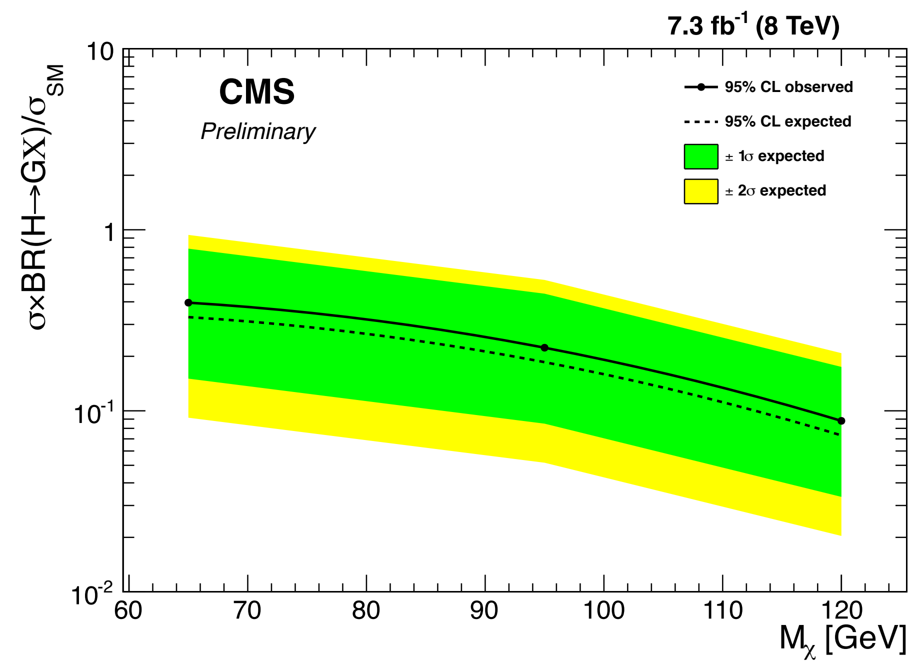
New





Model-independent selection



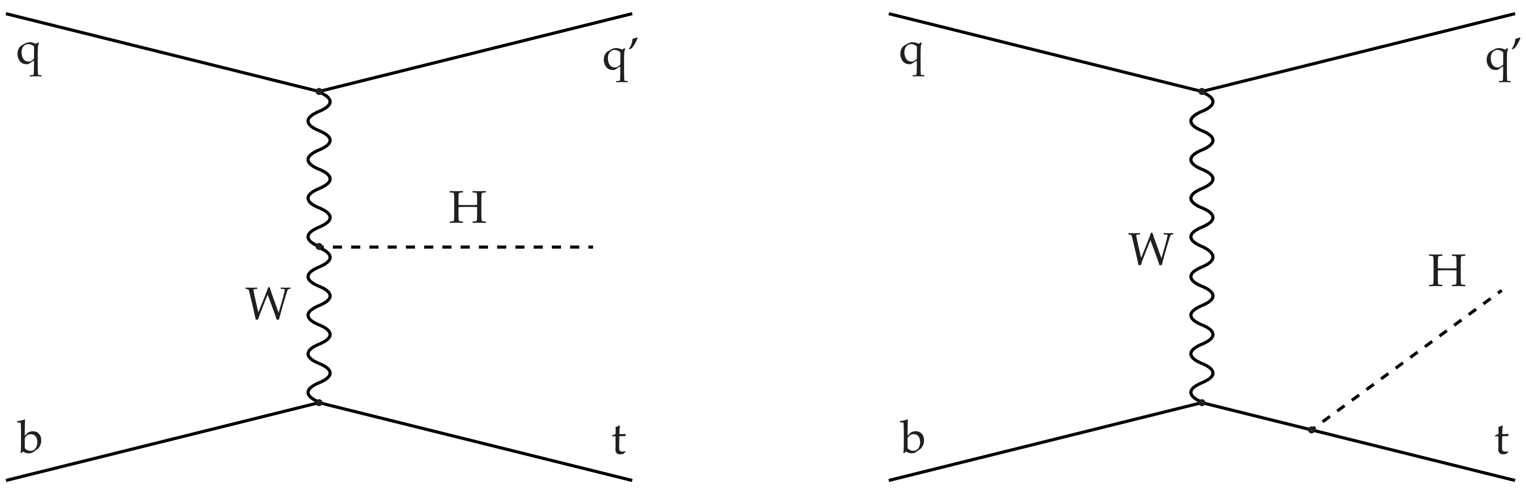


Model-specific selection using MH_T minimization

CMS-PAS-HIG-14-024

Higgs + single top

New



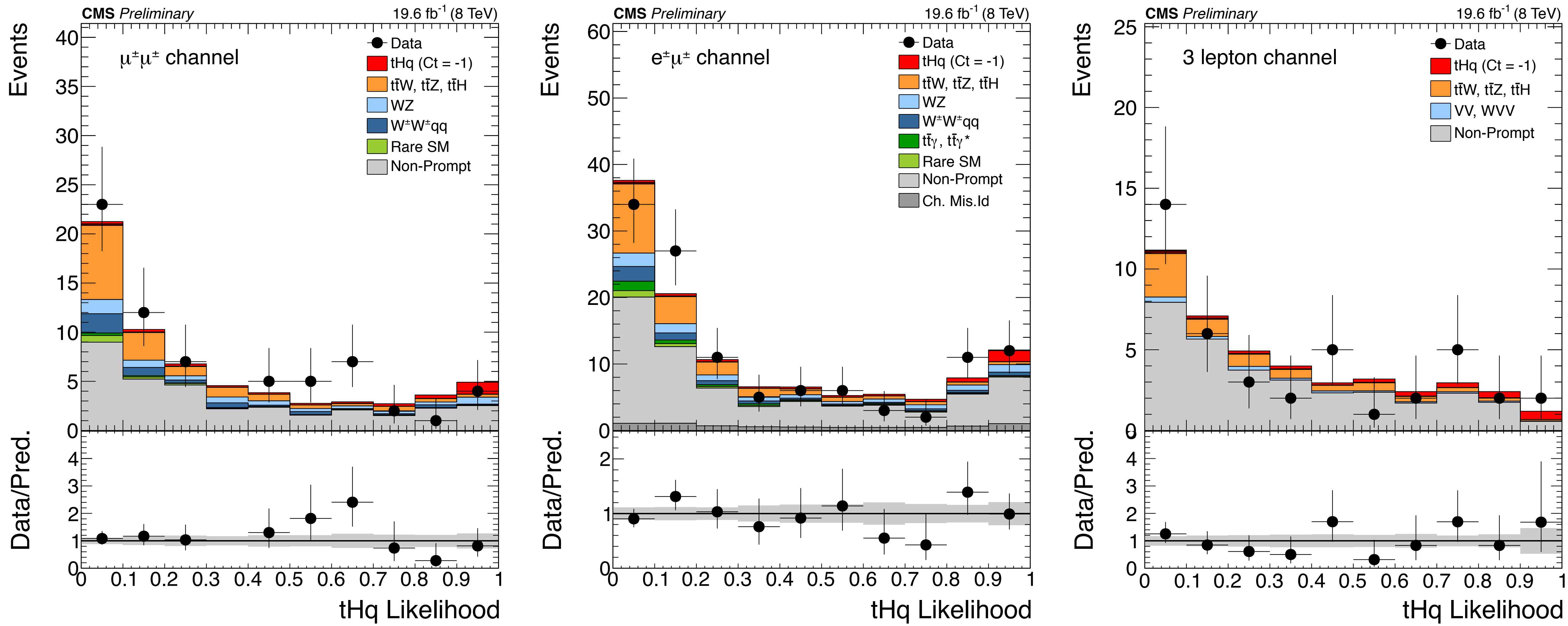
$C_t = -1 \Rightarrow$ **15× rate increase**

- qb→tHq', t→Wb, W→(e/μ)ν, H→WW
    - **Both W's decay leptonically ⇒ tri-lepton final state**
    - **W with same charge as top decays leptonically ⇒ same-charge di-lepton final state**
    - Hadronic tau veto
- **Same- and opposite-flavor di-lepton triggers**
- **Multivariate lepton ID discriminator in same-charge di-lepton analysis to reject jet fakes, hadron decays, and photon conversions**
- Agreement on electron charge assignment between 3 independent sources
- Multivariate muon isolation for tri-lepton analysis, standard electron isolation
- Counting experiment with signal region defined by output of multivariate likelihood discriminator

CMS-PAS-HIG-14-026

Higgs + single top: results

New



- Fitted background yields from simultaneous fit to data in 3 channels (some correlated uncertainties)
- $e^\pm e^\pm$ channel provides no additional sensitivity and is excluded from the combination

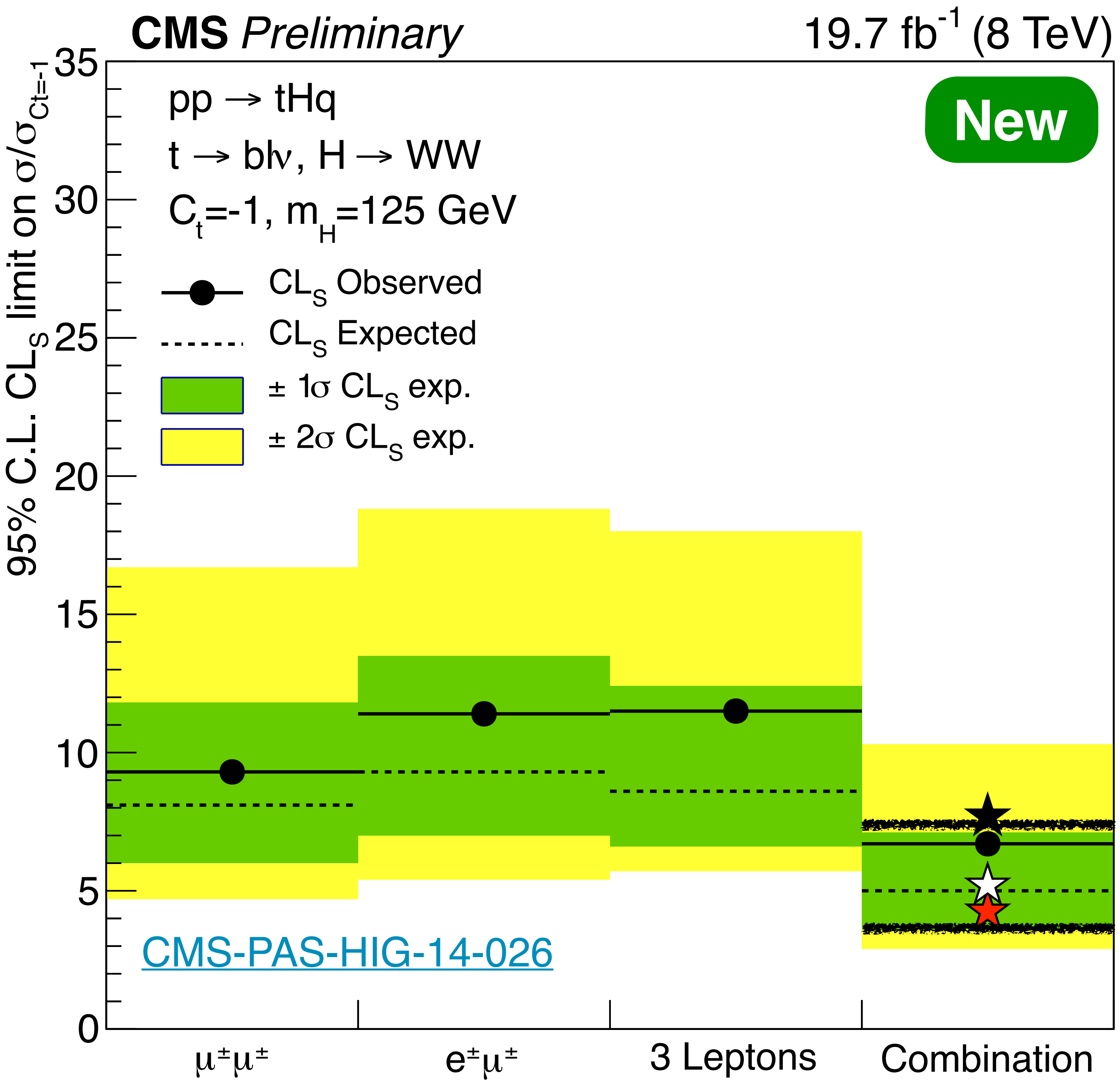
Jet fakes and hadron→lepton decays from isolation and impact parameter sidebands

Charge mis-ID rate from Z→ll tag and probe

NLO MC

CMS-PAS-HIG-14-026

Higgs + single top: interpretation



☆ tHq, H→$b\bar{b}$ expected (CMS-PAS-HIG-14-015)

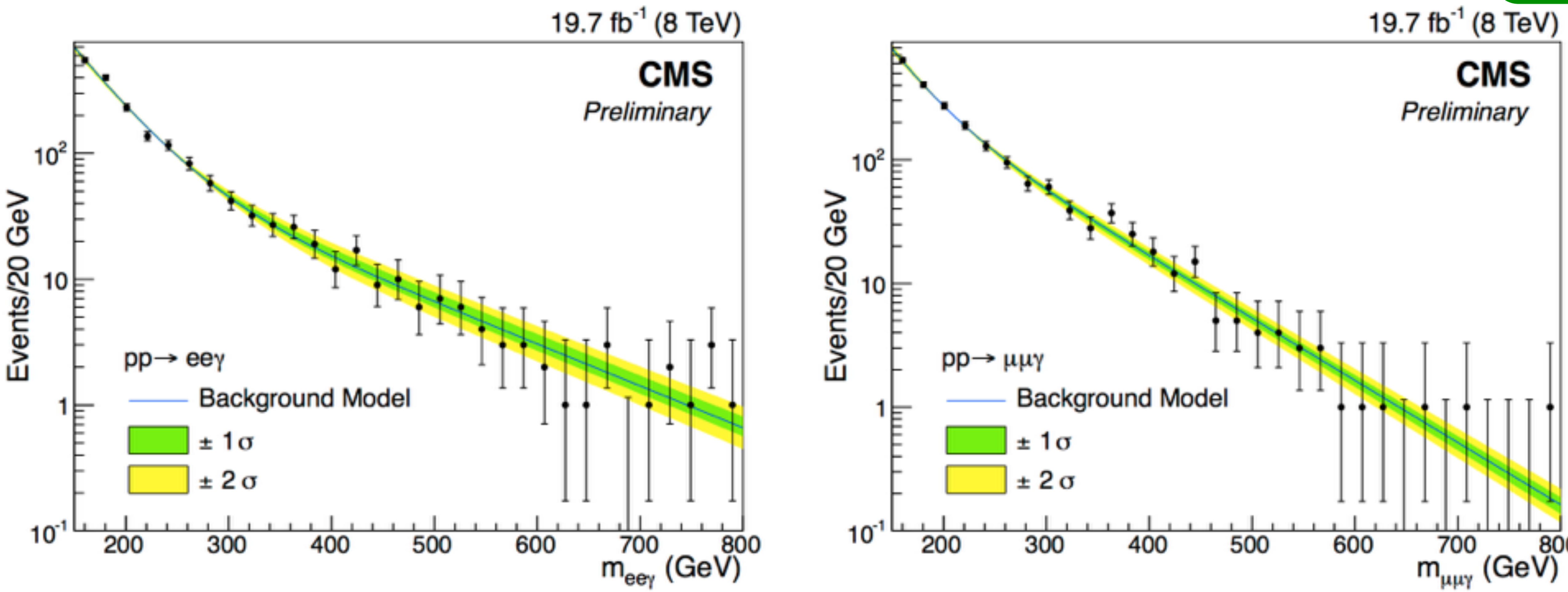
tHq, H→$b\bar{b}$ expected ± 1σ

★ tHq, H→$b\bar{b}$ observed

★ tHq, H→γγ observed (CMS-PAS-HIG-14-001)

Heavy A→Zγ

New

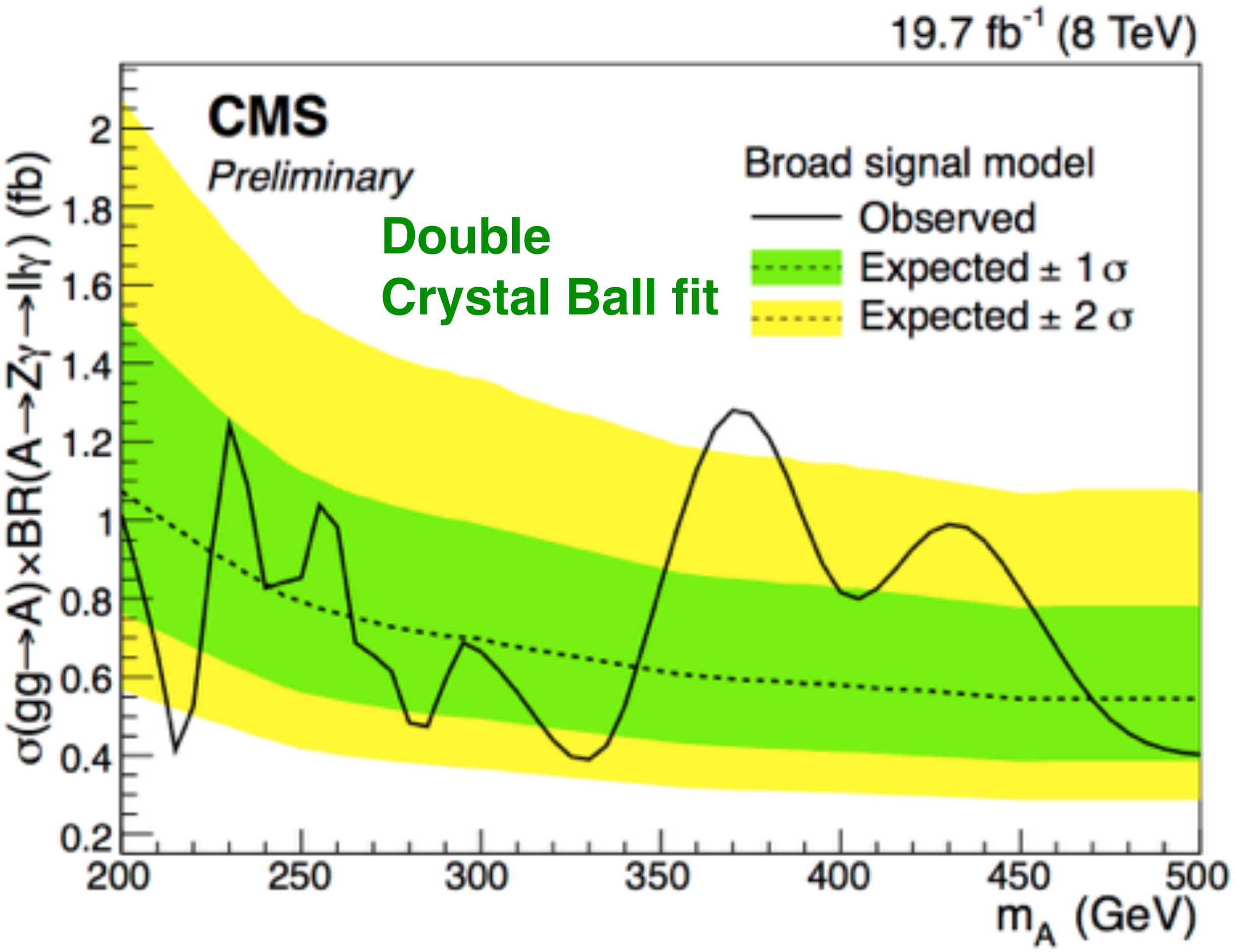


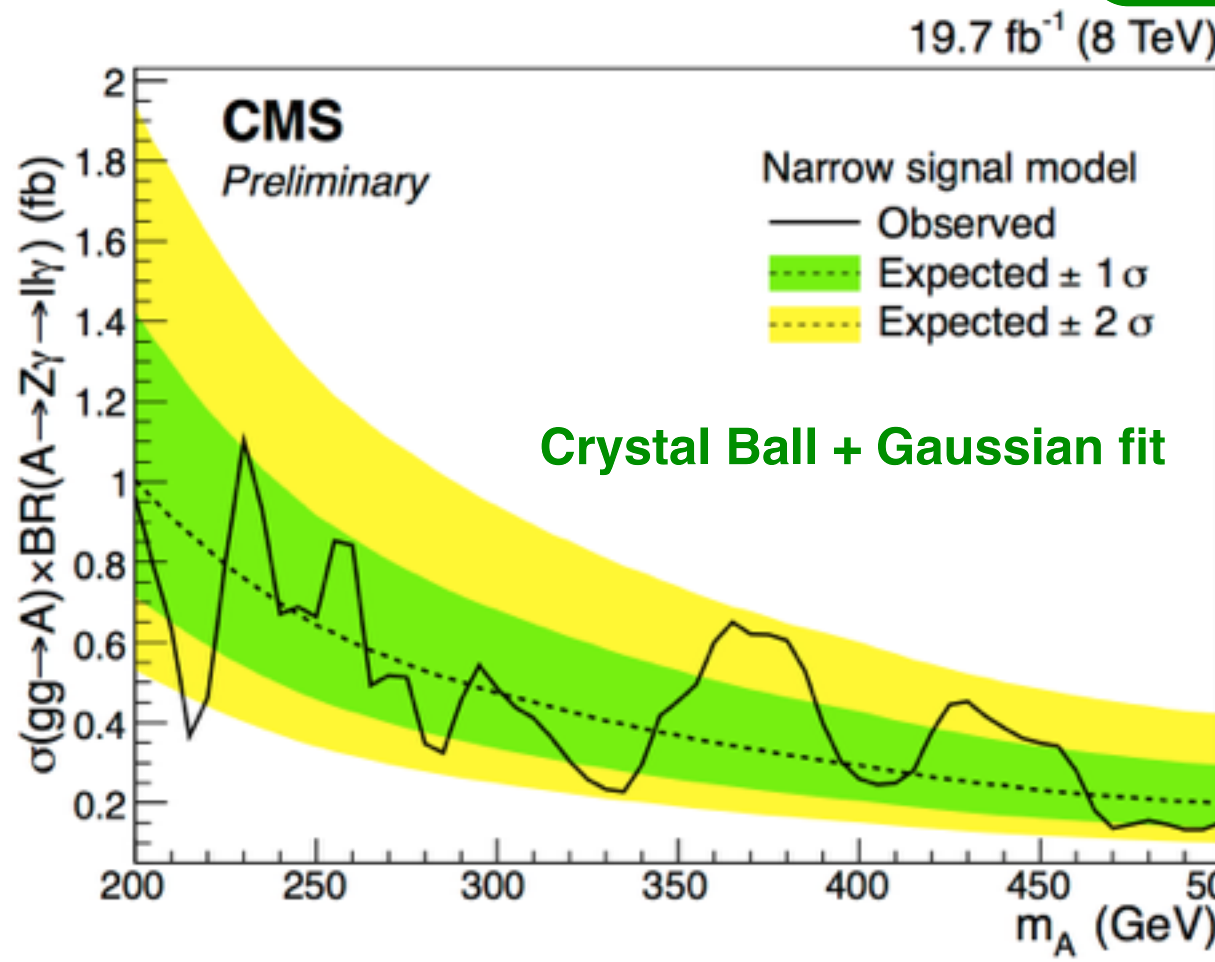
- Motivated by 2HDM
- Backgrounds are SM Zγ (80%) and Z + jets where the jet fakes a photon (20%)
- Unbinned fit to $m_{ll\gamma}$ using triple exponential to reduce signal bias to 20% background statistical uncertainty

CMS-PAS-HIG-14-031

Heavy A→Zγ: interpretation

New

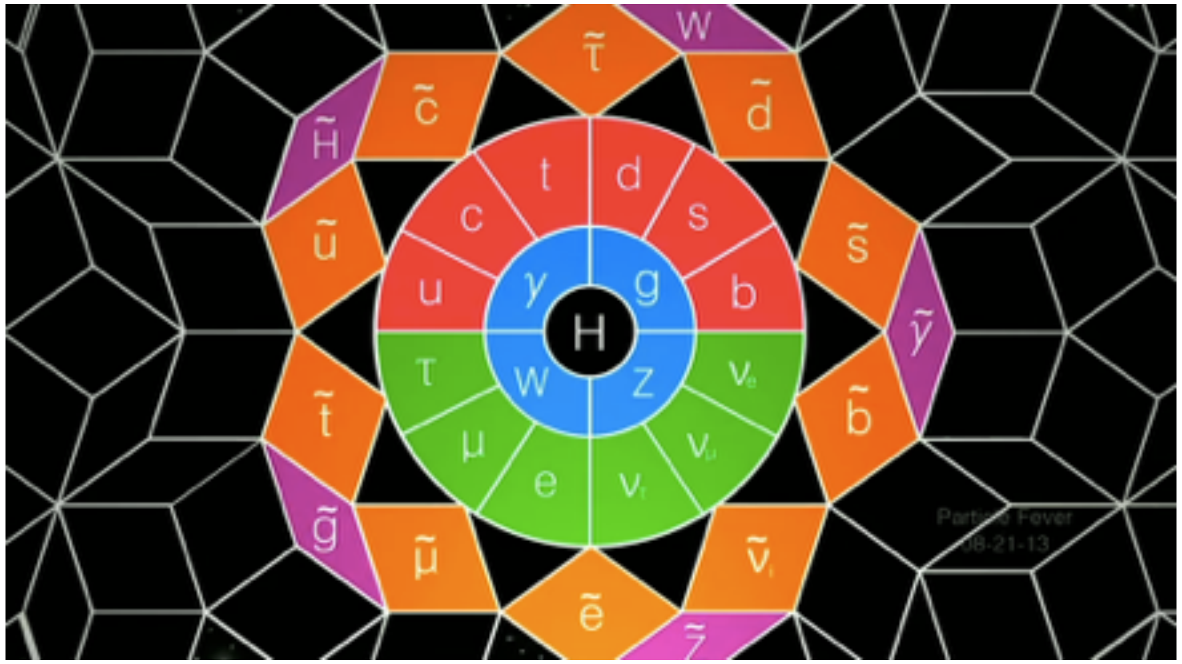




- Broad resonance model: SM Higgs width
- Narrow resonance model: width = 1% mass
- Models generated in 50 GeV steps in mass and interpolated in between

CMS-PAS-HIG-14-031

Conclusion

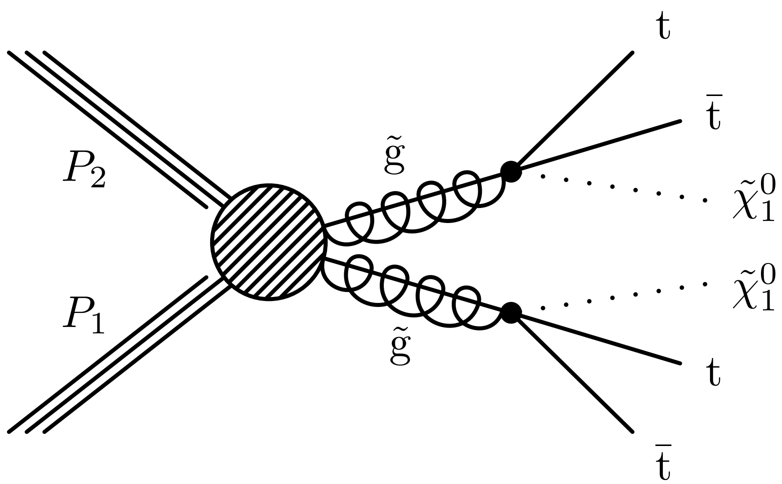


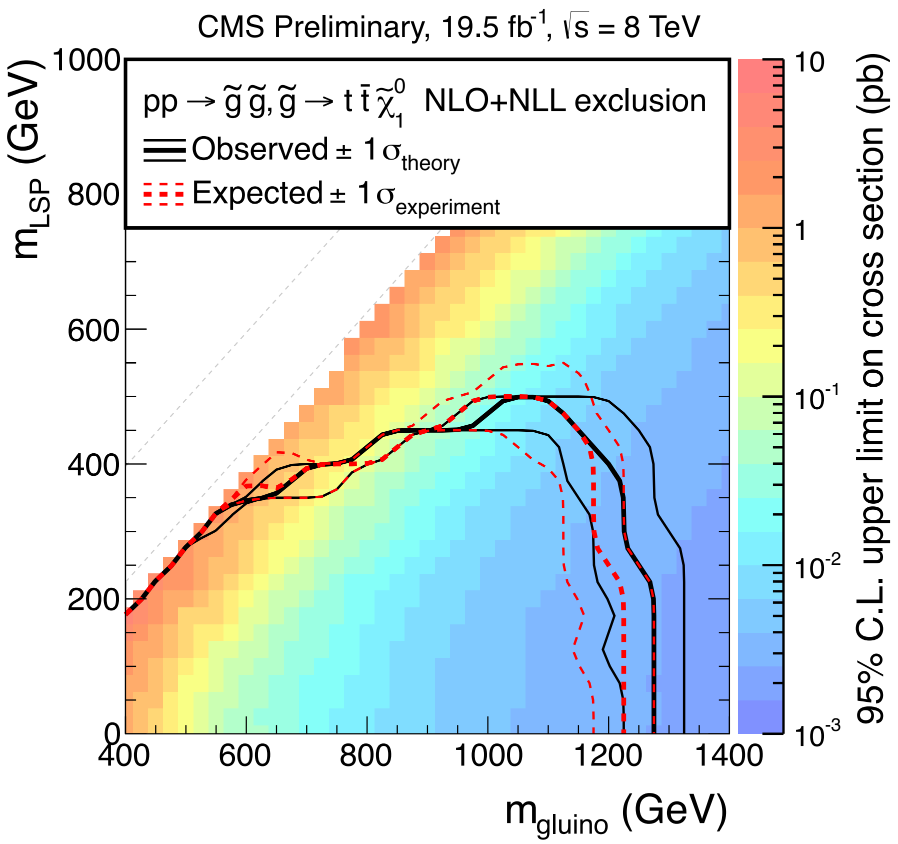
[Particle Fever]

- **Research into supersymmetric models remained active and fruitful during the LHC long shutdown**
- **Searches require finesse and creativity, as well as luminosity**
- **We eagerly await Run II, ready to catch whatever nature throws our way!**

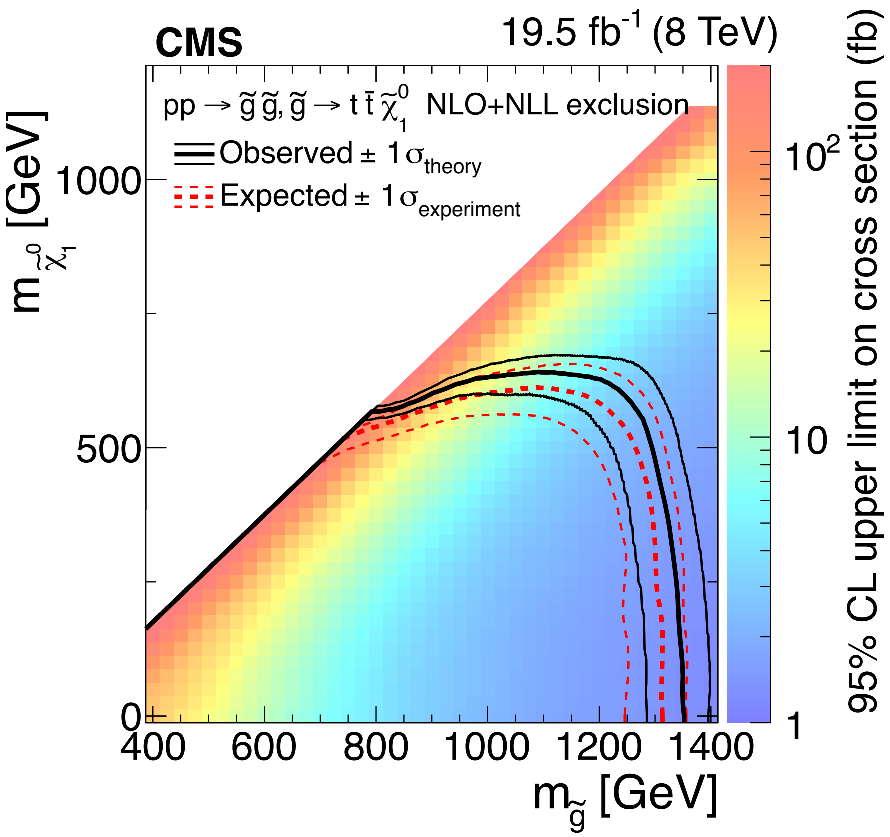
Backup

MSSM reach: gluino vs. LSP mass

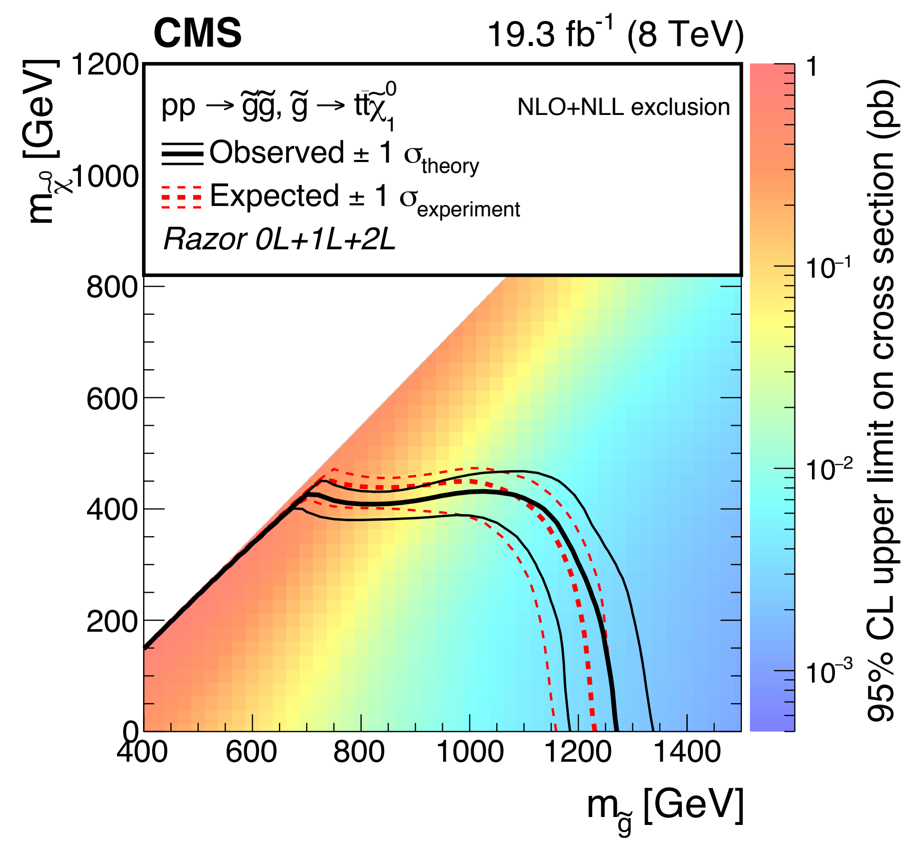




MT2



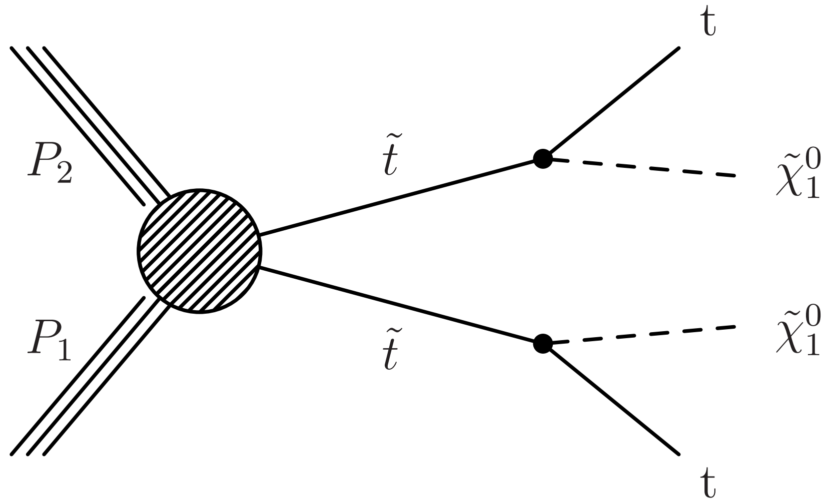
4W



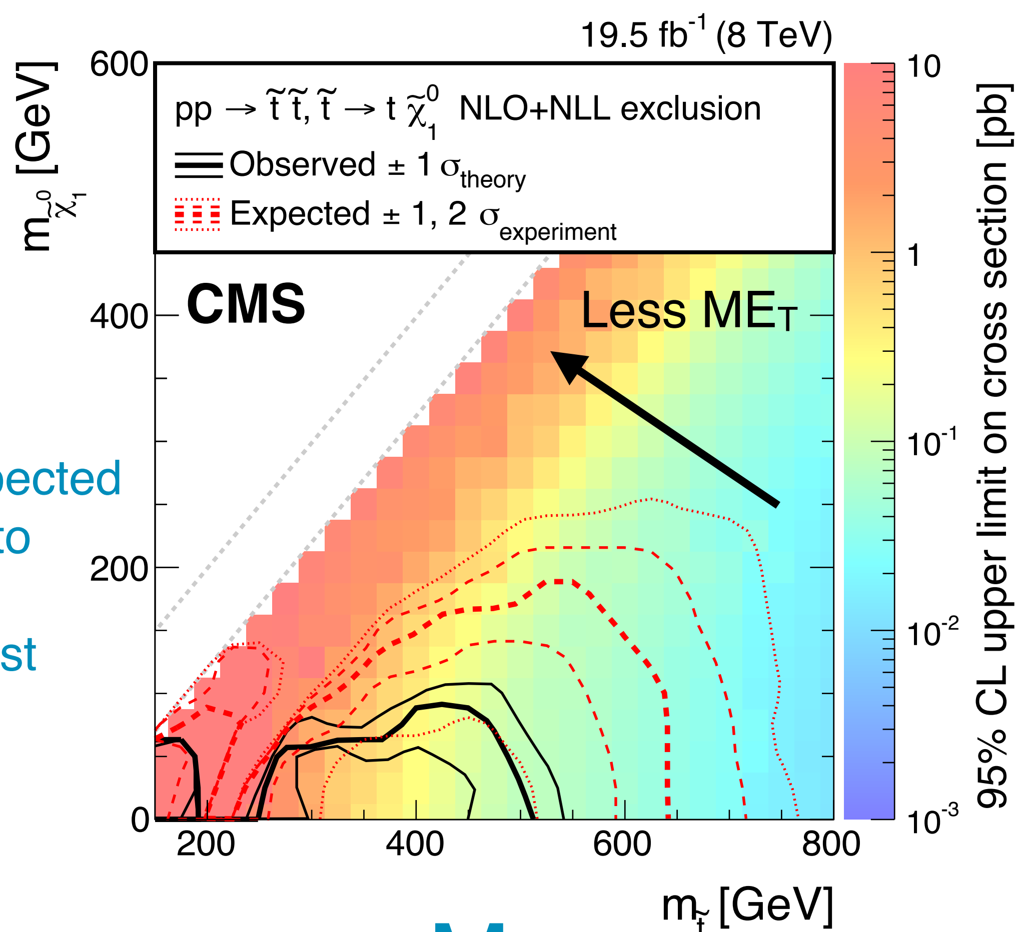
Razor

MSSM reach: stop vs. LSP mass

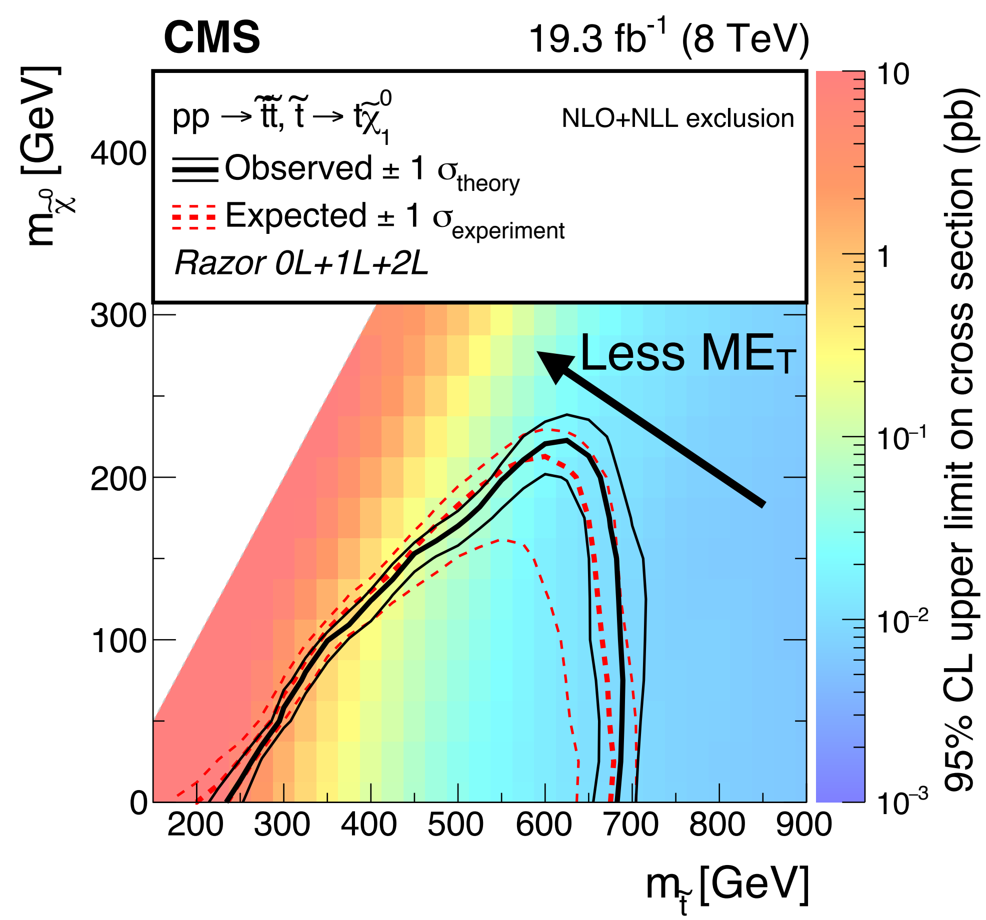
New



Observed limit worse than expected limit likely due to downward fluctuation in lost lepton control sample



M_{T2}



Razor

LHC-style CLs

Likelihoods constructed from Poisson probabilities

μ = signal strength = $\frac{\text{cross section}}{\text{reference cross section}}$

θ = nuisance parameter

Minimizes the likelihood for this μ

$$q_\mu = -2\ln\frac{\mathcal{L}(\text{data}|\mu,\hat{\theta}_\mu)}{\mathcal{L}(\text{data}|\hat{\mu},\hat{\theta})}, \qquad \text{with } 0 \leq \hat{\mu} \leq \mu,$$

Profile likelihood test statistic

Minimizes the likelihood for all μ,θ

H_1 = signal + background hypothesis
H_0 = background-only hypothesis

$$\text{CL}_{\text{s+b}}(\mu) = P(q_\mu \geq q_\mu^{\text{obs}}|H_1),$$

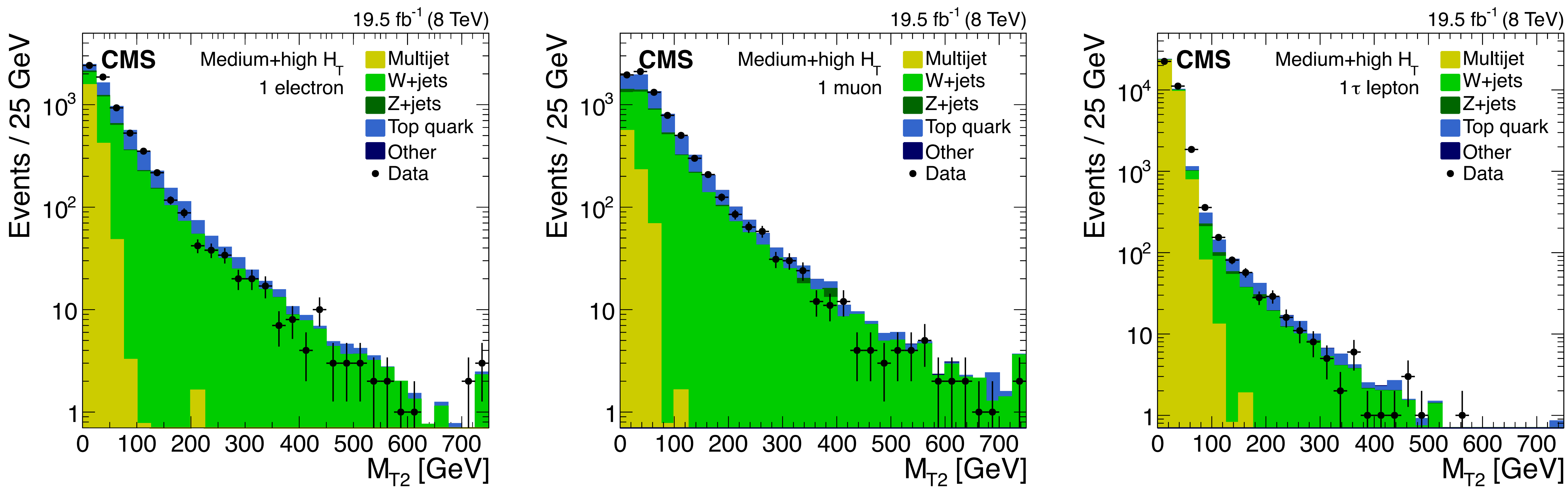
$$\text{CL}_{\text{b}}(\mu) = P(q_\mu \geq q_\mu^{\text{obs}}|H_0).$$

$\text{CL}_S(\mu) \leq 0.05 \Rightarrow 95\%$ CL

$$\text{CL}_{\text{s}}(\mu) = \frac{\text{CL}_{\text{s+b}}(\mu)}{\text{CL}_{\text{b}}(\mu)}.$$

J. Phys. G **28** (2002) 2693

M_{T2} all-hadronic: backgrounds



- **Multijet background**
  - Data control region from sideband in $\Delta\Phi_{min}$ (minimum $\Delta\Phi$(jet, ME_T) over the 4 highest p_T jets in the event); signal region $\Delta\Phi_{min} > 0.3$ rad
  - M_{T2}-dependent scaling factor derived in low-M_{T2} dataset (50-80 GeV) and extrapolated to high M_{T2} via exponential + constant parametrization
- **Lost lepton background**
  - 1-lepton data control region with M_T(lepton, ME_T) < 100 GeV
  - Contributions from jet fakes and leptonic decays of hadrons subtracted
  - Scaled by “lost lepton factor” depending on lepton ID and M_T efficiency
  - No binning in M_{T2} for better statistical precision → M_{T2} distribution from MC
- **Z→νν background**
  - γ + jet data scaled by predicted Z/γ ratio
  - Validated with Z→ll + jet data

arXiv:1502.04358 [hep-ex]

M_{T2} all-hadronic: signal bins

	Low-H_T region M_{T2} bin [GeV]			Medium-H_T region M_{T2} bin [GeV]			High-H_T region M_{T2} bin [GeV]	
$N_j = 2$, $N_b = 0$	200–240	350–420	570–650	125–150	220–270	425–580	120–150	260–350
	240–290	420–490	>650	150–180	270–325	580–780	150–200	350–550
	290–350	490–570		180–220	325–425	>780	200–260	>550
$N_j = 2$, $N_b \geq 1$	200–250	310–380	450–550	100–135	170–260	>450	100–180	
	250–310	380–450	>550	135–170	260–450		>180	
$N_j = 3$–5, $N_b = 0$	200–240	420–490		160–185	300–370	>800	160–185	350–450
	240–290	490–570		185–215	370–480		185–220	450–650
	290–350	570–650		215–250	480–640		220–270	>650
	350–420	>650		250–300	640–800		270–350	
$N_j = 3$–5, $N_b = 1$	200–250	310–380	460–550	150–175	210–270	380–600	150–180	230–350
	250–310	380–460	>550	175–210	270–380	>600	180–230	>350
$N_j = 3$–5, $N_b = 2$	200–250	325–425		130–160	200–270	>370	130–200	
	250–325	>425		160–200	270–370		>200	
$N_j \geq 6$, $N_b = 0$	200–280	>380		160–200	250–325	>425	160–200	>300
	280–380			200–250	325–425		200–300	
$N_j \geq 6$, $N_b = 1$	200–250	>325		150–190	250–350		150–200	>300
	250–325			190–250	>350		200–300	
$N_j \geq 6$, $N_b = 2$	200–250	>300		130–170	220–300		130–200	
	250–300			170–220	>300		>200	
$N_j \geq 3$, $N_b \geq 3$	200–280	>280		125–175	175–275	>275	>125	

arXiv:1502.04358 [hep-ex]

M_{T2} all-hadronic: systematics

Process	Source/Region	Effect	Shape
Multijet	$M_{\mathrm{T2}} < 200\,\mathrm{GeV}$	10-50%	–
	$M_{\mathrm{T2}} \geq 200\,\mathrm{GeV}$	50-100%	–
$W(l\nu)$+jets and Top	Lost-lepton method	10-65%	–
	b-tagging scale factor	–	x
	Jet energy scale	–	x
	Matching scale	–	x
	Renormalization and factorization scale	–	x
	p_{T} MC NLO uncertainty	–	x
$Z(\nu\bar{\nu})$+jets	Systematics on $Z(\nu\bar{\nu})/\gamma$ ratio (0-1 b jets)	20-30%	–
	Systematics on $1b/0b$ ratio from Z_{ll} (1 b jet)	10-75%	–
	Statistics from γ+jets data (0-1 b jet)	5-100%	–
	simulation ($\geq$ 2 b jets)	100%	–
Signal	Luminosity uncertainty	2.6%	–
	Trigger efficiency	1%	–
	Parton distribution functions	5-15%	–
	b-tagging scale factor	5-40%	x
	Jet energy scale	5-40%	x
	p_{T} MC NLO uncertainty	10-20%	x

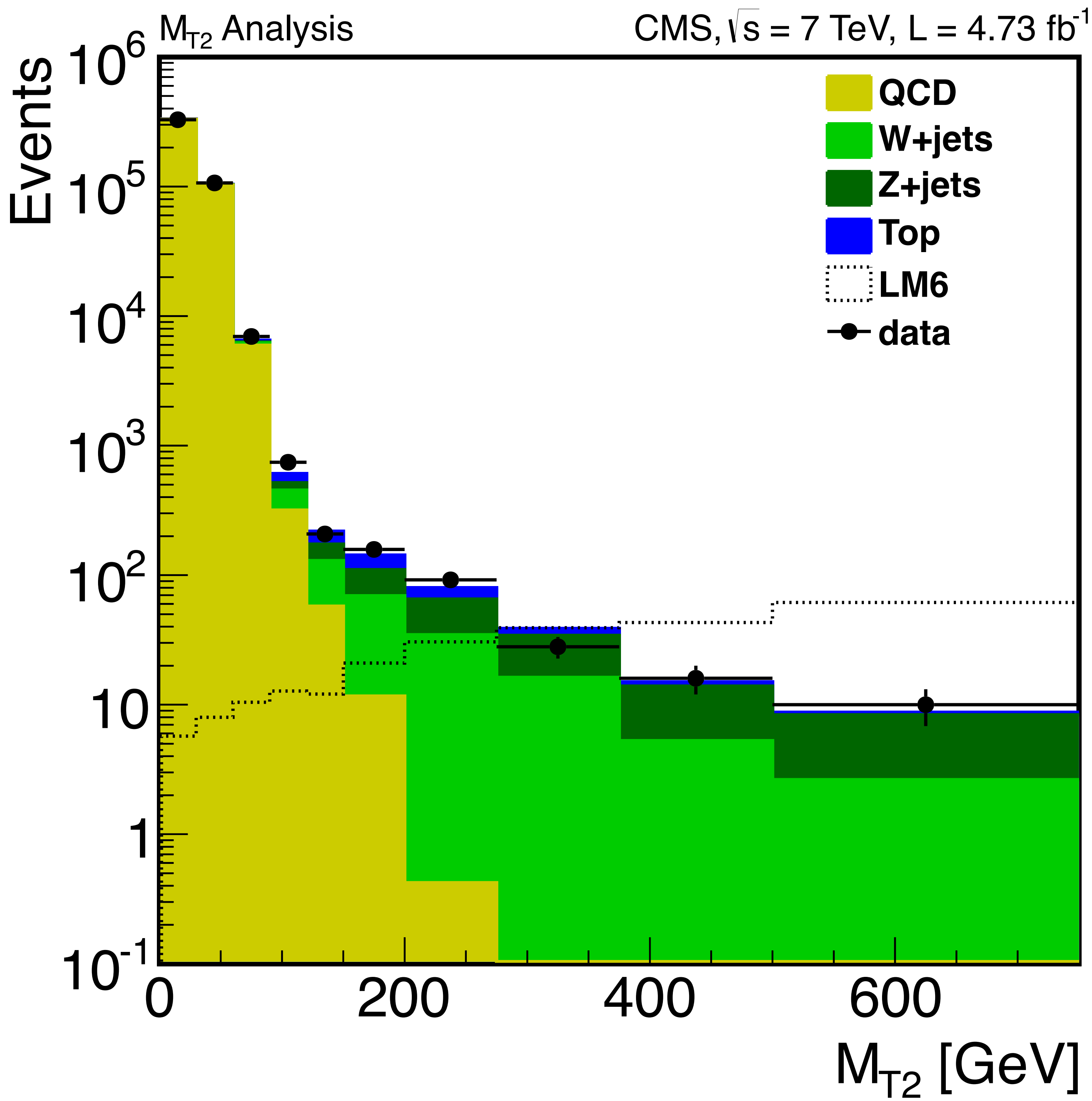
arXiv:1502.04358 [hep-ex]

M_{T2} all-hadronic: limits

Simplified model	Limit on parent particle mass at $m_{\tilde{\chi}_1^0} = 0$	Best limit on LSP mass	Limit on mass splitting
Direct squark production			
Single light squark	$m_{\tilde{q}} > 520\,\mathrm{GeV}$	$m_{\tilde{\chi}_1^0} > 120\,\mathrm{GeV}$	$\Delta m(\tilde{q}, \tilde{\chi}_1^0) < 200\,\mathrm{GeV}$
8 degenerate light squarks	$m_{\tilde{q}} > 875\,\mathrm{GeV}$	$m_{\tilde{\chi}_1^0} > 325\,\mathrm{GeV}$	$\Delta m(\tilde{q}, \tilde{\chi}_1^0) < 50\,\mathrm{GeV}$
Bottom squark	$m_{\tilde{b}} > 640\,\mathrm{GeV}$	$m_{\tilde{\chi}_1^0} > 275\,\mathrm{GeV}$	$\Delta m(\tilde{b}, \tilde{\chi}_1^0) < 10\,\mathrm{GeV}$
Top squark			
$m_{\tilde{t}} > m_t + m_{\tilde{\chi}_1^0}$	$m_{\tilde{t}} > 450\,\mathrm{GeV}$	$m_{\tilde{\chi}_1^0} > 60\,\mathrm{GeV}$	$\Delta m(\tilde{t}, \tilde{\chi}_1^0) < 230\,\mathrm{GeV}$
$m_{\tilde{t}} < m_t + m_{\tilde{\chi}_1^0}$	$m_{\tilde{t}} > 175\,\mathrm{GeV}$	$m_{\tilde{\chi}_1^0} > 60\,\mathrm{GeV}$	$\Delta m(\tilde{t}, \tilde{\chi}_1^0) < 90\,\mathrm{GeV}$
Direct gluino production			
$\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$	$m_{\tilde{g}} > 1225\,\mathrm{GeV}$	$m_{\tilde{\chi}_1^0} > 510\,\mathrm{GeV}$	$\Delta m(\tilde{g}, \tilde{\chi}_1^0) < 25\,\mathrm{GeV}$
$\tilde{g} \to b\bar{b}\tilde{\chi}_1^0$	$m_{\tilde{g}} > 1300\,\mathrm{GeV}$	$m_{\tilde{\chi}_1^0} > 740\,\mathrm{GeV}$	$\Delta m(\tilde{g}, \tilde{\chi}_1^0) < 50\,\mathrm{GeV}$
$\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$	$m_{\tilde{g}} > 1225\,\mathrm{GeV}$	$m_{\tilde{\chi}_1^0} > 450\,\mathrm{GeV}$	$\Delta m(\tilde{g}, \tilde{\chi}_1^0) < 225\,\mathrm{GeV}$
$\tilde{g}_1 \to q\bar{q}\tilde{\chi}_2^0$, $\tilde{\chi}_2^0 \to h\tilde{\chi}_1^0$, $\tilde{g}_2 \to qq'\tilde{\chi}_1^{\pm}$, $\chi_1^{\pm} \to W^{\pm}\tilde{\chi}_1^0$	$m_{\tilde{g}} > 825\,\mathrm{GeV}$	$m_{\tilde{\chi}_1^0} > 410\,\mathrm{GeV}$	$\Delta m(\tilde{g}, \tilde{\chi}_1^0) < 225\,\mathrm{GeV}$
cMSSM/mSUGRA model	Mass limit for $m_{\tilde{q}} = m_{\tilde{g}}$	Gluino mass limit	Squark mass limit
	$m_{\tilde{g},\tilde{q}} > 1550\,\mathrm{GeV}$	$m_{\tilde{g}} > 1150\,\mathrm{GeV}$	$m_{\tilde{q}} > 1450\,\mathrm{GeV}$

arXiv:1502.04358 [hep-ex]

M_{T2} all-hadronic: discrimination



arXiv:1207.1798 [hep-ex]

Dilepton edge fit: $R_{SF/OF}$

	Central	Forward
Factorization method		
$R_{SF/OF}$	$1.03 \pm 0.01 \pm 0.06$	$1.11 \pm 0.04 \pm 0.08$
$R_{ee/OF}$	$0.47 \pm 0.01 \pm 0.06$	$0.46 \pm 0.02 \pm 0.10$
$R_{\mu\mu/OF}$	$0.56 \pm 0.01 \pm 0.07$	$0.65 \pm 0.03 \pm 0.14$
$r_{\mu e}$	$1.09 \pm 0.00 \pm 0.11$	$1.18 \pm 0.00 \pm 0.24$
R_T	$1.03 \pm 0.01 \pm 0.06$	$1.10 \pm 0.04 \pm 0.07$
Control-region method		
$R_{SF/OF}$	$0.99 \pm 0.05 \pm 0.02$	$1.11 \pm 0.11 \pm 0.03$
$R_{ee/OF}$	$0.44 \pm 0.03 \pm 0.01$	$0.49 \pm 0.06 \pm 0.02$
$R_{\mu\mu/OF}$	$0.55 \pm 0.03 \pm 0.01$	$0.62 \pm 0.07 \pm 0.02$
$r_{\mu e}$	1.12 ± 0.04 (stat)	1.12 ± 0.08 (stat)
R_T	0.98 ± 0.05 (stat)	1.11 ± 0.11 (stat)
Combined		
$R_{SF/OF}$	1.00 ± 0.04	1.11 ± 0.07
$R_{ee/OF}$	0.45 ± 0.03	0.48 ± 0.05
$R_{\mu\mu/OF}$	0.55 ± 0.03	0.63 ± 0.07

arXiv:1502.06031 [hepex]

Dilepton edge fit: systematics

Uncertainty source	Impact on signal yield [%]
Luminosity	2.6
PDFs on acceptance	0–6
Lepton identification/isolation	2
Fast simulation lepton identification/isolation	2
Dilepton trigger	5
Lepton energy scale	0–5
$E_{\mathrm{T}}^{\mathrm{miss}}$	0–8
Jet energy scale/resolution	0–8
ISR modeling	0–14
Additional interactions	1

arXiv:1502.06031 [hepex]

b-tagged razor: boxes

Box	Lepton	b-tag	Kinematic	Jet
Two-lepton boxes				
MuEle	$\geq$1 tight electron and $\geq$1 loose muon	$\geq$1 b-tag	$(M_R > 300\,\text{GeV}$ and $R^2 > 0.15)$ and $(M_R > 350\,\text{GeV}$ or $R^2 > 0.2)$	$\geq$2 jets
MuMu	$\geq$1 tight muon and $\geq$1 loose muon	$\geq$1 b-tag	$(M_R > 300\,\text{GeV}$ and $R^2 > 0.15)$ and $(M_R > 350\,\text{GeV}$ or $R^2 > 0.2)$	$\geq$2 jets
EleEle	$\geq$1 tight electron and $\geq$1 loose electron	$\geq$1 b-tag	$(M_R > 300\,\text{GeV}$ and $R^2 > 0.15)$ and $(M_R > 350\,\text{GeV}$ or $R^2 > 0.2)$	$\geq$2 jets
Single-lepton boxes				
MuMultiJet	1 tight muon	$\geq$1 b-tag	$(M_R > 300\,\text{GeV}$ and $R^2 > 0.15)$ and $(M_R > 350\,\text{GeV}$ or $R^2 > 0.2)$	$\geq$4 jets
EleMultiJet	1 tight electron	$\geq$1 b-tag	$(M_R > 300\,\text{GeV}$ and $R^2 > 0.15)$ and $(M_R > 350\,\text{GeV}$ or $R^2 > 0.2)$	$\geq$4 jets
MuJet	1 tight muon	$\geq$1 b-tag	$(M_R > 300\,\text{GeV}$ and $R^2 > 0.15)$ and $(M_R > 350\,\text{GeV}$ or $R^2 > 0.2)$	2 or 3 jets
EleJet	1 tight electron	$\geq$1 b-tag	$(M_R > 300\,\text{GeV}$ and $R^2 > 0.15)$ and $(M_R > 350\,\text{GeV}$ or $R^2 > 0.2)$	2 or 3 jets
Hadronic boxes				
MultiJet	none	$\geq$1 b-tag	$(M_R > 400\,\text{GeV}$ and $R^2 > 0.25)$ and $(M_R > 450\,\text{GeV}$ or $R^2 > 0.3)$	$\geq$4 jets
$\geq$2 b-tagged jet	none	$\geq$2 b-tag	$(M_R > 400\,\text{GeV}$ and $R^2 > 0.25)$ and $(M_R > 450\,\text{GeV}$ or $R^2 > 0.3)$	2 or 3 jets

- Fit in each box independently
- Fit b tag categories within a box simultaneously
- Common background shape parameters for 2b and ≥3b bins

MSSM 4-W final states

- Fully hadronic
  - H_T-ME_T triggers
  - 3-5, 6-7, and ≥8 jet categories, no b tags
  - Backgrounds: invisible Z, lost lepton, $W \rightarrow \tau_{had}$ (prompt W or $t \rightarrow W$), multijet
- 1 lepton: lepton-H_T-ME_T and lepton-H_T triggers
  - ≥6 jets, of which ≥2 b tags
  - High S_T^{lep} = lepton p_T + ME_T, $\Delta\Phi$(lepton p_T + ME_T, lepton p_T) > 1
  - Backgrounds: lost lepton, semi-leptonic $t\bar{t}$, single top
- 2-3 leptons, ≥2 same sign: ee, eμ, and μμ triggers
  - Same-sign dilepton and tri-lepton: b tags, non-prompt lepton background evaluated from data, diboson/ttW/ttZ from MC, electron charge mis-ID from Z tag and probe
- Combination of 5 channels: most background systematics uncorrelated, any correlated uncertainties (luminosity, lepton ID, etc.) assumed 100% correlated

arXiv:1412.4109 [hepex]

LFV Higgs: signal bins

Variable [GeV]	$H \to \mu\tau_e$ 0-jet	$H \to \mu\tau_e$ 1-jet	$H \to \mu\tau_e$ 2-jet	$H \to \mu\tau_h$ 0-jet	$H \to \mu\tau_h$ 1-jet	$H \to \mu\tau_h$ 2-jet
$p_T^\mu >$	50	45	25	45	35	30
$p_T^e >$	10	10	10	—	—	—
$p_T^\tau >$	—	—	—	35	40	40
$M_T^e <$	65	65	25	—	—	—
$M_T^\mu >$	50	40	15	—	—	—
$M_T^\tau <$	—	—	—	50	35	35
[radians]						
$\Delta\phi_{\vec{p}_T^\mu - \vec{p}_T^{\tau_h}} >$	—	—	—	2.7	—	—
$\Delta\phi_{\vec{p}_T^e - \vec{E}_T^{miss}} <$	0.5	0.5	0.3	—	—	—
$\Delta\phi_{\vec{p}_T^e - \vec{p}_T^\mu} >$	2.7	1.0	—	—	—	—

arXiv:1502.07400 [hep-ex]

LFV Higgs: systematics

Systematic uncertainty	$H \to \mu\tau_e$	$H \to \mu\tau_h$
hadronic tau energy scale	—	3
jet energy scale	3–7	3–7
unclustered energy scale	10	10
$Z \to \tau\tau$ bias	100	—

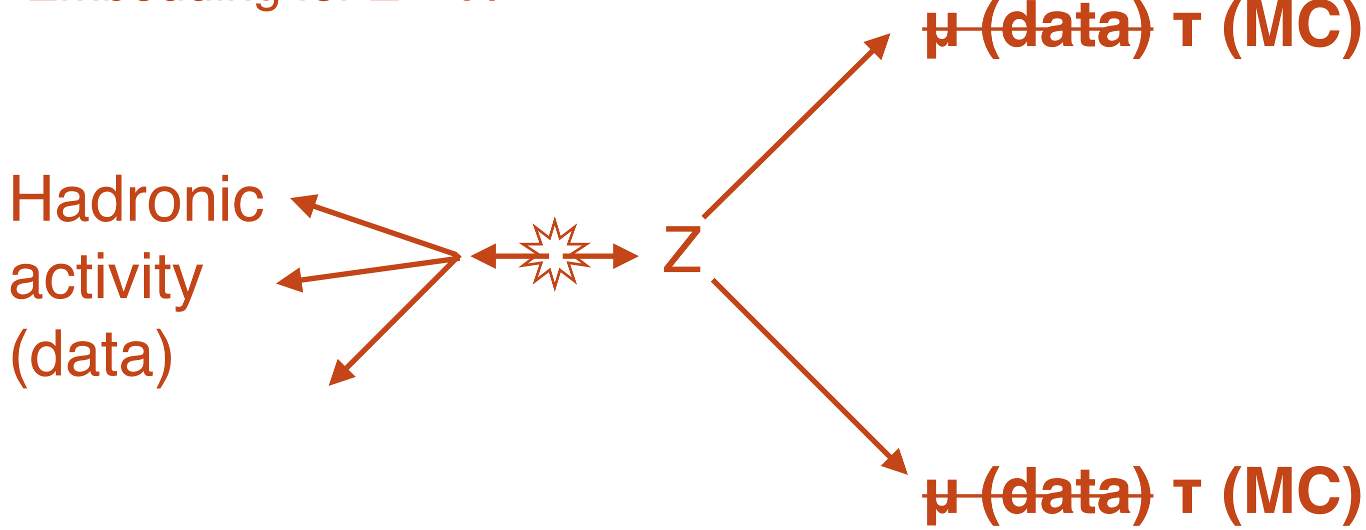
Systematic Uncertainty	Gluon-Gluon Fusion			Vector Boson Fusion		
	0-Jets	1-Jets	2-Jets	0-Jet	1-Jet	2-Jets
parton density function	+9.7	+9.7	+9.7	+3.6	+3.6	+3.6
renormalization/factorization scale	+8	+10	−30	+4	+1.5	+2
underlying event/parton shower	+4	−5	−10	+10	<1	−1

Systematic uncertainty	$H \to \mu\tau_e$			$H \to \mu\tau_h$		
	0-Jet	1-Jet	2-Jets	0-Jet	1-Jet	2-Jets
electron trigger/ID/isolation	3	3	3	—	—	—
muon trigger/ID/isolation	2	2	2	2	2	2
hadronic tau efficiency	—	—	—	9	9	9
luminosity	2.6	2.6	2.6	2.6	2.6	2.6
$Z \to \tau\tau$ background	3+3*	3+5*	3+10*	3+5*	3+5*	3+10*
$Z \to \mu\mu$, ee background	30	30	30	30	30	30
misidentified μ, e background	40	40	40	—	—	—
misidentified τ_h background	—	—	—	30+10*	30	30
WW, ZZ+jets background	15	15	15	15	15	65
$t\bar{t}$ background	10	10	10+10*	10	10	10+33*
$W + \gamma$ background	100	100	100	—	—	—
b-tagging veto	3	3	3	—	—	—
single top production background	10	10	10	10	10	10

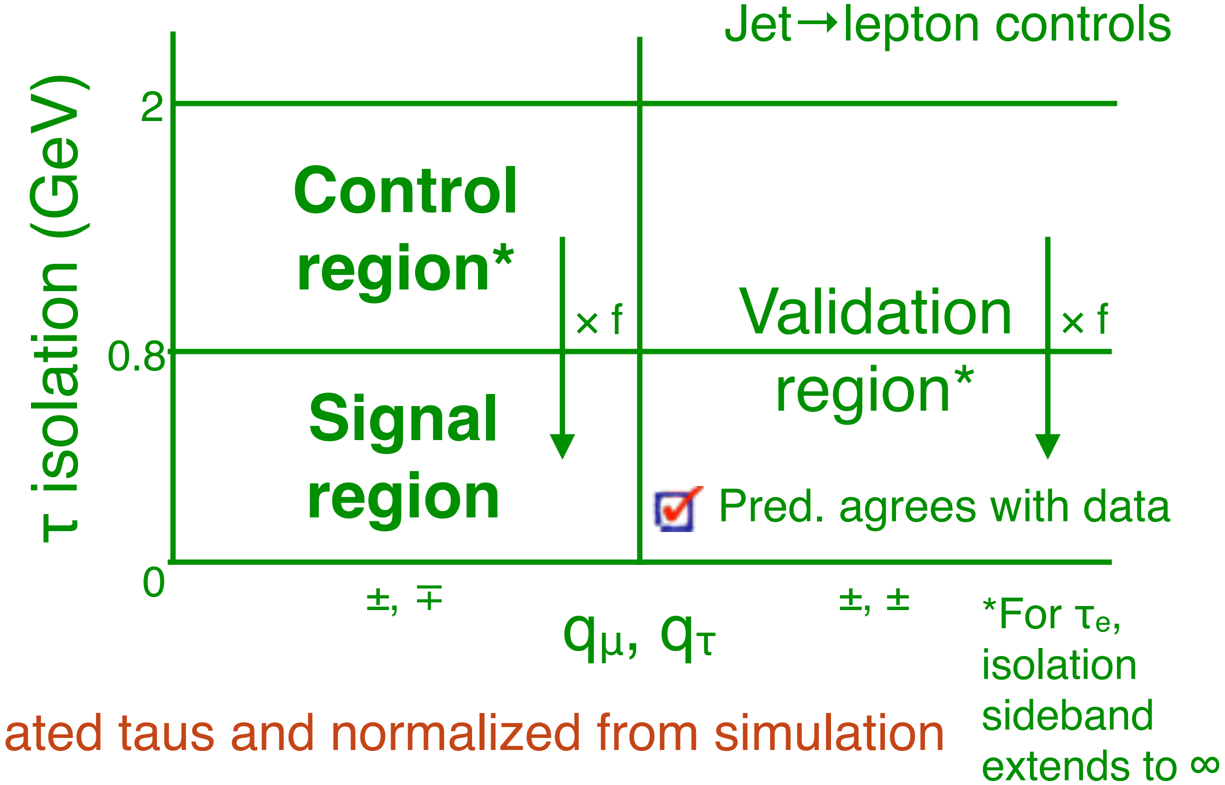
arXiv:1502.07400 [hep-ex]

LFV Higgs: backgrounds

Embedding for $Z \to \tau\tau$



Jet→lepton controls



- $Z \to \tau\tau$
  - Muons from $Z \to \mu\mu$ data replaced with simulated taus and normalized from simulation
  - Difficult-to-model hadronic activity and multiple pp interactions taken from data
- Jet faking lepton
  - Fake rate $f_X = N_{X,iso}/N_{X,non\text{-}iso}$ measured in $Z \to \mu\mu$ + X data sample (X = e,μ) and multiplied by yield in e(μ) + non-isolated τ_X/τ_h data sample (along with small trigger efficiency correction)
  - Test case for the fake rate method: predict yield in same-sign isolated μτ samples
  - Fake rate cross checked in multijet data sample
- $t\bar{t}$ from simulation with data normalization (2 jets, of which ≥1 is b tagged)
- SM Higgs, diboson, Wγ, and single top from simulation

arXiv:1502.07400 [hep-ex]

Low-E_T mono-photon: signal bins

Selection requirements	Model ndependent		SUSY benchmark model		
Advanced selection	$Z\gamma \to \nu\bar{\nu}\gamma$	γ+jet	$Z\gamma \to \nu\bar{\nu}\gamma$	γ+jet	$M_{\tilde{\chi}_1^0} = 120\,\mathrm{GeV}$
Number of jets < 2	0.909	0.769	-	-	-
$\Delta\phi(\gamma,\mathrm{jet}) < 2.5$	0.834	0.262	-	-	-
Transverse mass > 100 GeV	-	-	0.867	0.292	0.829
$H_\mathrm{T} < 100$ GeV	-	-	0.785	0.188	0.804
MH_T minimization: $\widetilde{\not{E}}_T > 45$ GeV	-	-	0.761	0.071	0.743
MH_T minimization: Prob(χ^2)$< 10^{-3}$	-	-	0.626	0.033	0.467
$\not{E}_T$ significance > 20	-	-	0.440	0.001	0.195
$\alpha > 1.2$	-	-	0.390	0.001	0.165
$\mathrm{E}_\mathrm{T}^\gamma < 60$ GeV	-	-	0.074	0.0002	0.106

CMS-PAS-HIG-14-024

Low-E_T mono-photon: systematics

Source	Signal	Jet$\rightarrow\gamma$	Electron$\rightarrow\gamma$	γ + jet	$Z\nu\nu\gamma$	$W\gamma$
PDF	10(0)	-	-	-	4(4)	4(4)
Luminosity	2.6(2.6)	-	-	2.6(2.6)	2.6(2.6)	2.6(2.6)
Photon energy scale $\pm$ 1 %	4(0.5)	-	-	4(0.5)	4(0.5)	4(0.5)
$\not\!\!E_T$ energy scale	4(2)	-	-	4(2)	4(2)	4(2)
Jet energy scale	3(2)	-	-	5(5)	3(2)	3(2)
Pileup	1(1)	-	-	1(1)	1(1)	1(1)
$Z\nu\nu\gamma$ MCFM NLO calculation	-	-	-	-	3(3)	-
γ+ jet normalization	-	-	-	16(16)	-	-
$W\gamma$ MCFM NLO calculation	-	-	-	-	-	3(3)
Jet$\rightarrow\gamma$ unc.	-	35(35)	-	-	-	-
Electron$\rightarrow\gamma$ unc.	-	-	6(6)	-	-	-

CMS-PAS-HIG-14-024

Low-E_T monophoton: backgrounds

- Jet faking photon
  - Fake rate measured in low-ME_T sideband ($ME_T < 40$ GeV) and applied to high-ME_T data control sample of photons passing looser identification criteria than nominal
  - Real photon component estimated by fitting shower shape templates, then subtracted out
    - Isolated photon template from simulation
    - $\pi^0 \to \gamma\gamma$ template from photon isolation sideband in data sample
  - 35% error due to choice of isolation sideband for fake rate denominator
- Electron faking photon
  - Due to missing seed pixel hit for the track reconstruction of a real electron
  - Pixel seed veto efficiency (97.7%) measured in $Z \to ee$ events, then applied to a data sample with the pixel seed requirement inverted
- $Z\gamma$, $W\gamma$, and $W \to (\mu/\tau)\nu$ backgrounds from NLO simulation
- γ + jet shape from simulation; normalization from data with inverted ME_T requirement
  - Scale factor of 1.7(1.1) for 0(>0) jets

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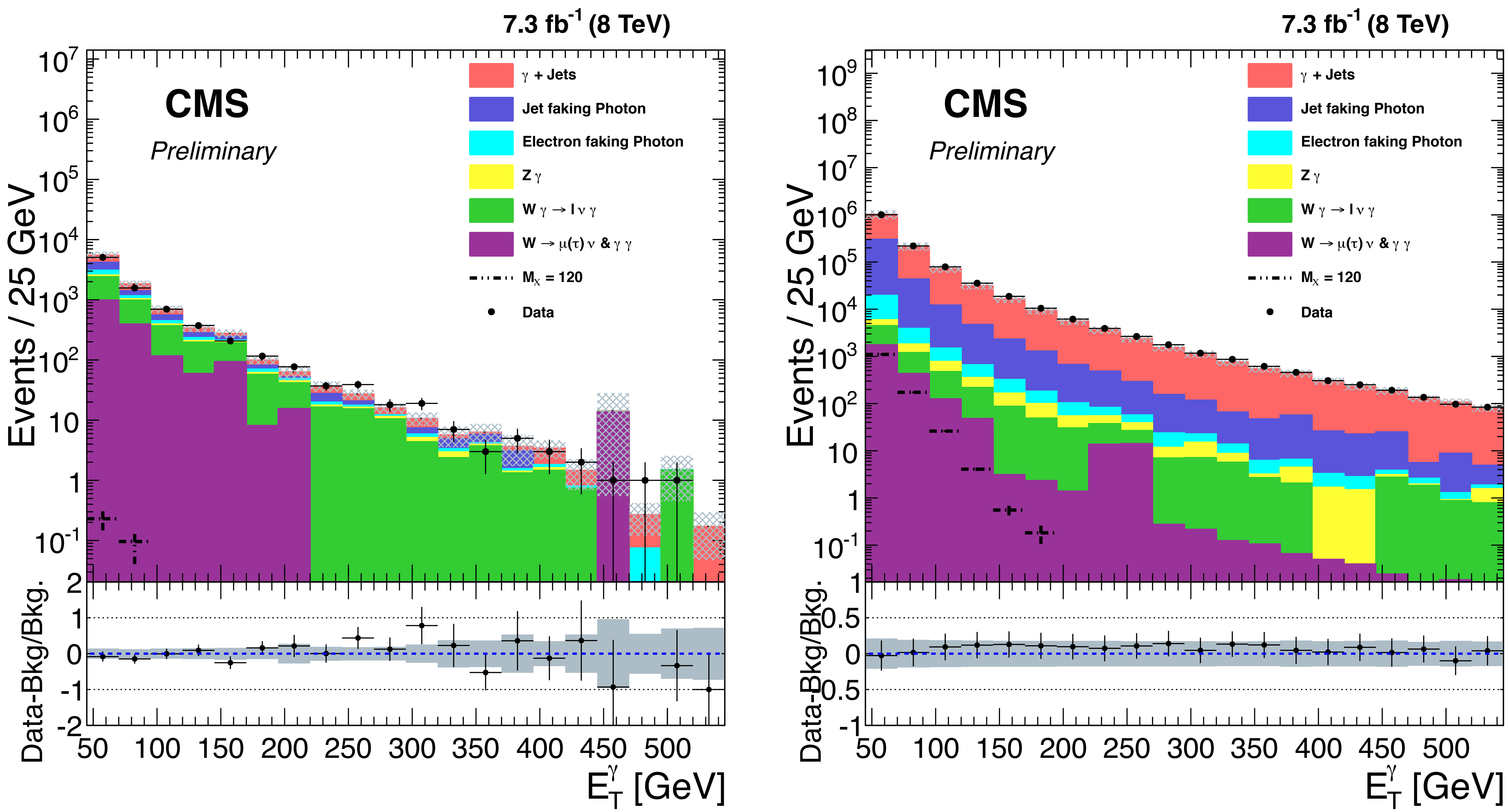
Low-E_T mono-photon: control samples

Wγ-enriched control sample

γ+jet-enriched control sample



Shape from MC, normalization from data

Fully data-driven

NLO MC

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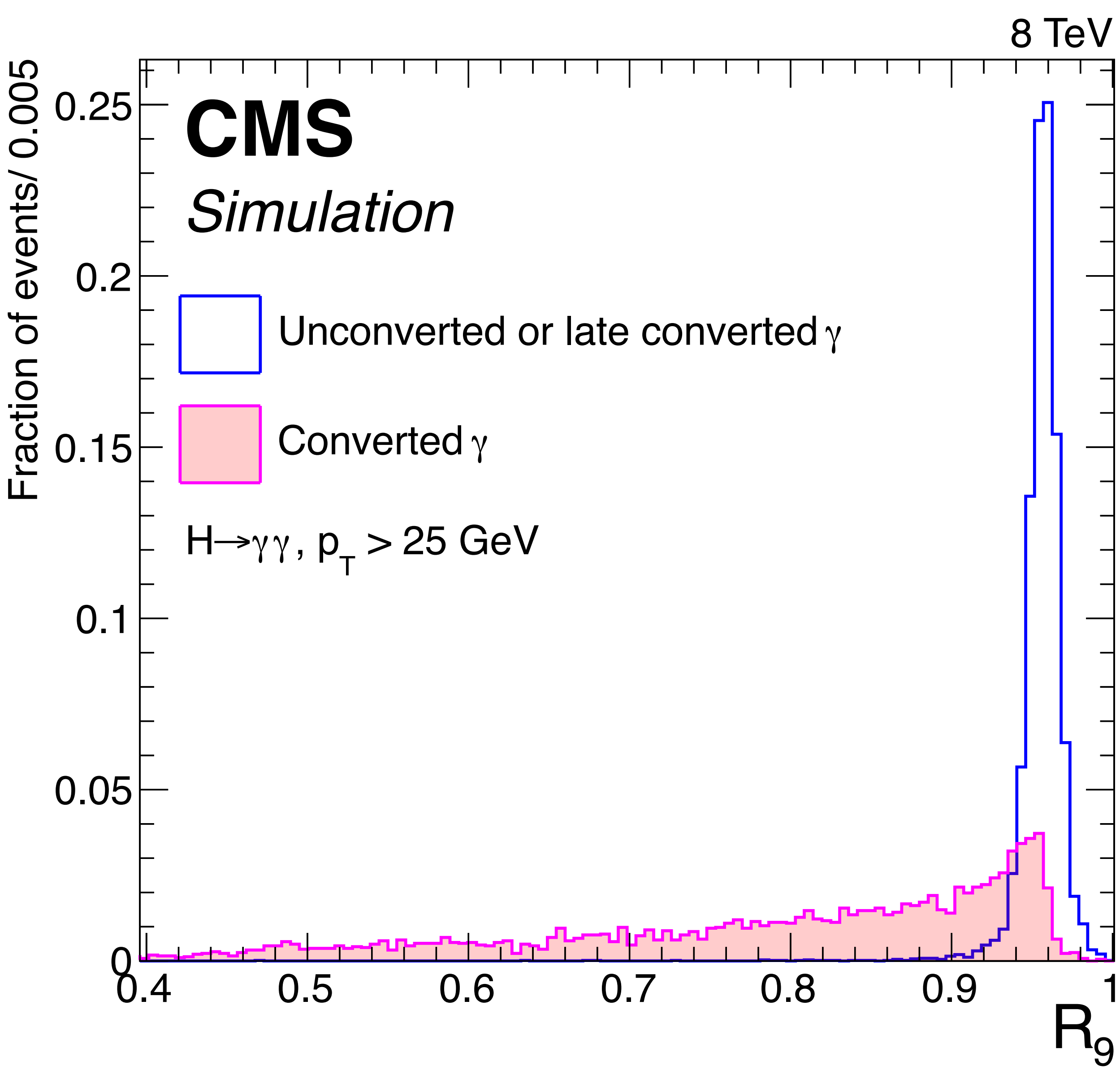
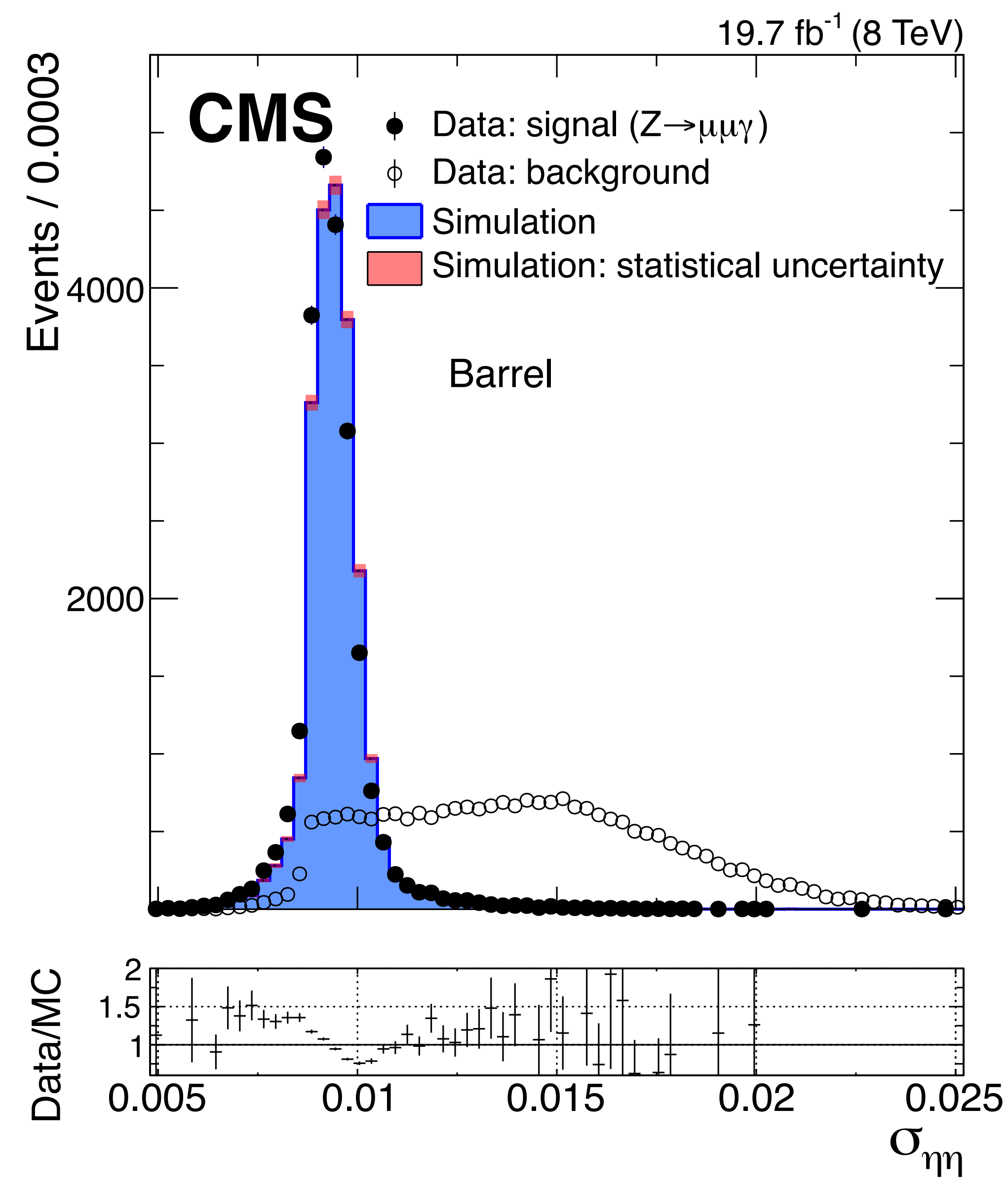
Low-E_T mono-photon: photon ID





arXiv:1502.02702 [physics.ins-det]

Higgs + single top: signal bins

Same-sign $\ell\ell$ channel	**$\ell\ell\ell$ channel**
Two leptons of equal charge, $p_T > 20\,\text{GeV}$	Three leptons with $p_T > 20/10/10$ GeV
No additional leptons with lepton MVA $>$ 0.35	No additional tight leptons
$m_{ll} > 20\,\text{GeV}$	$m_{ll} > 20\,\text{GeV}$
No identified hadronically-decaying τ leptons	Z-veto: $\lvert m_{ll} - m_Z \rvert > 15\,\text{GeV}$
At least one central jet ($\lvert\eta\rvert < 1.0$)	$E_T^{\text{miss}} > 30$ GeV
At least one central jet tagged as CSV-L	Exactly one jet with tagged as CSV-M
At least one forward jet ($\lvert\eta\rvert < 1.0$)	At least one forward jet ($\lvert\eta\rvert > 1.5$)

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