CMS Searches with Multilepton Final States

DIS 2013

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for the CMS Collaboration

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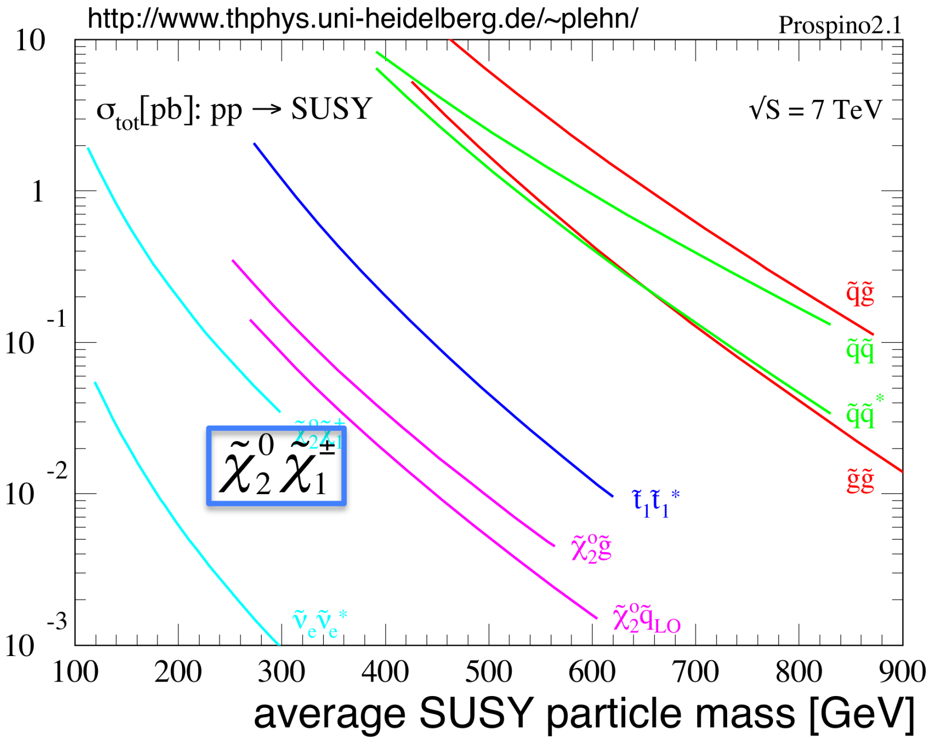
Outline

- **Introduction**
- Detector
- Signatures and Selection
- Background Predictions
- Results
- Interpretations
- Conclusions

Introduction

- Definition of “multileptons” in CMS: 3 or more leptons
  → Involves many flavor and charge combinations
- There's a lot of interesting physics in multileptons:
  - SUSY
  - Exotic quarks
- Recent results focus on
  - Natural SUSY
  - R-parity violation
  - Electroweak SUSY



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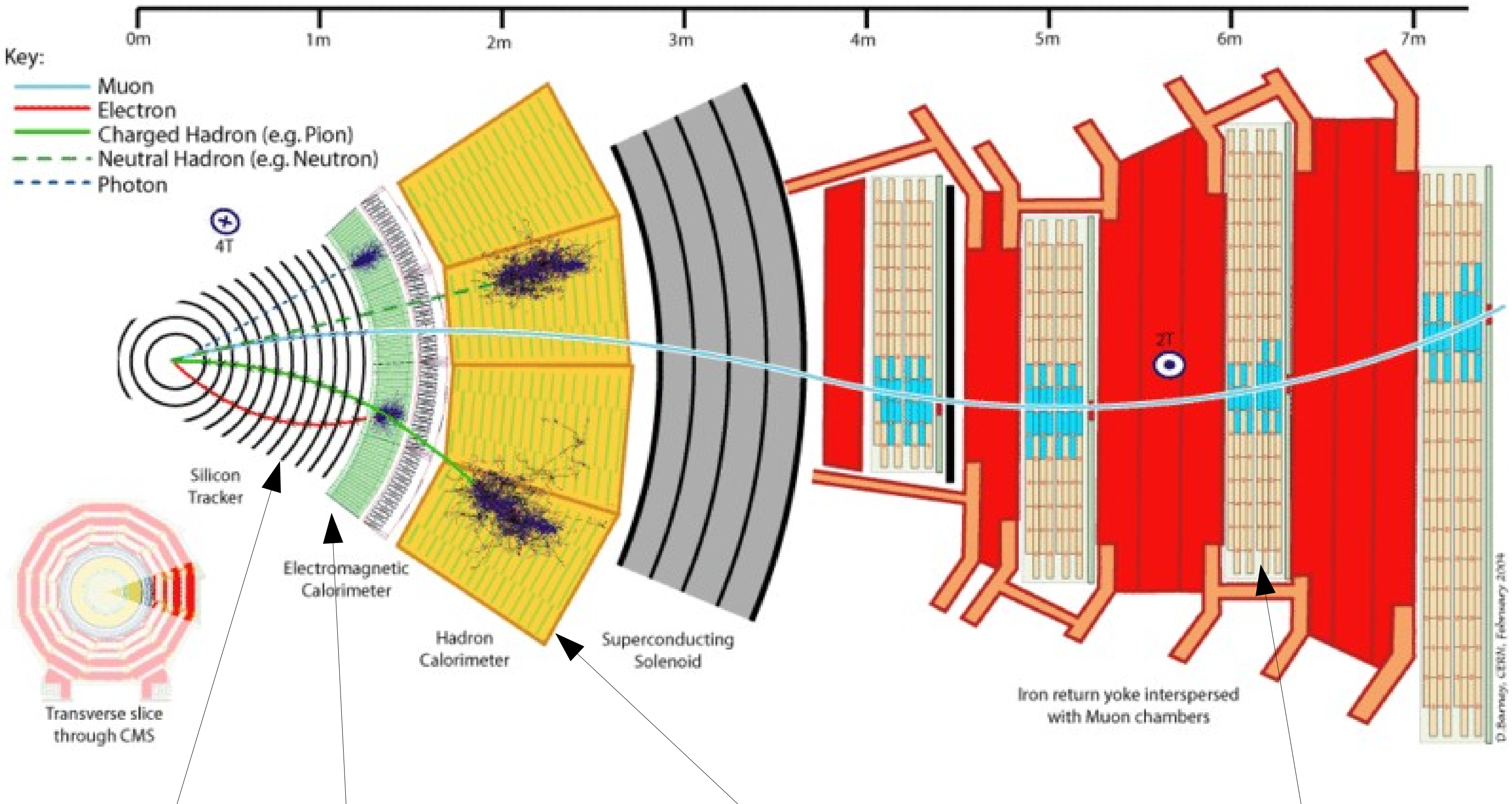
CMS Detector



Tracker:
Electrons, Muons, Charged Hadrons

Electromagnetic Calorimeter:
Electrons, Photons

Hadronic Calorimeter:
Hadrons
(neutral & charged)

Muon Chambers:
Muons

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Signatures and Selection

- Vast diversity in possible signal signatures → look in a large number of exclusive channels
  - Are there OSSF pairs (e^+e^-, $\mu^+\mu^-$)?
  - Is there a Z candidate (OSSF mass on Z peak)?
  - Are there hadronic taus?
  - Are there b-jets?
  - What is the total MET, H_T and S_T of the event?
- Using 8 TeV events from dilepton triggers
- Require leading lepton $p_T \geq 20$ GeV, 10 GeV otherwise
- Also require dilepton mass ≥ 12 GeV (to cut J/Ψ, …)

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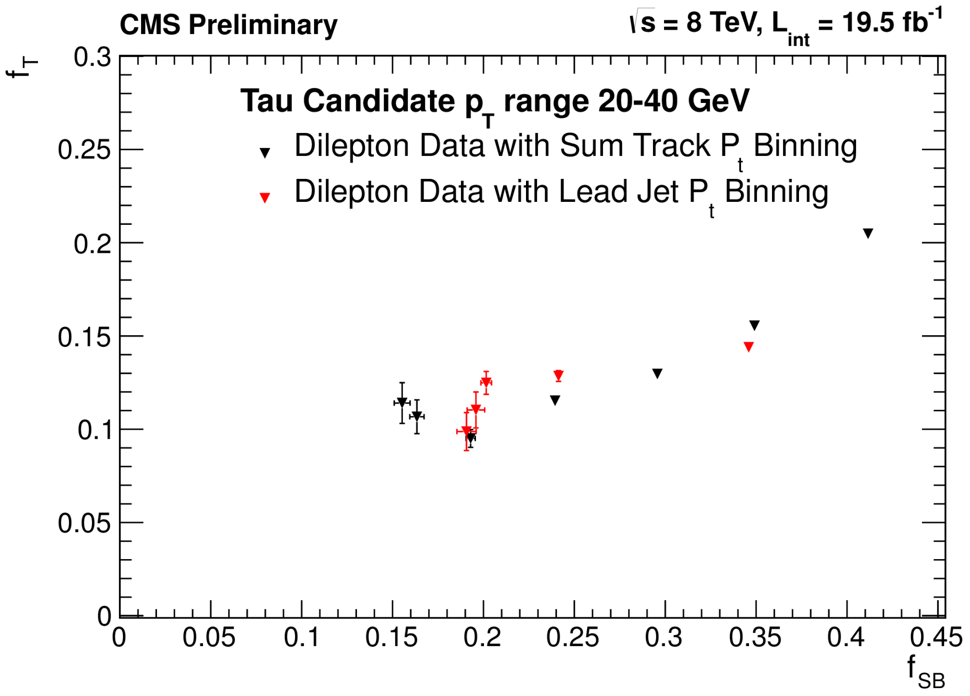
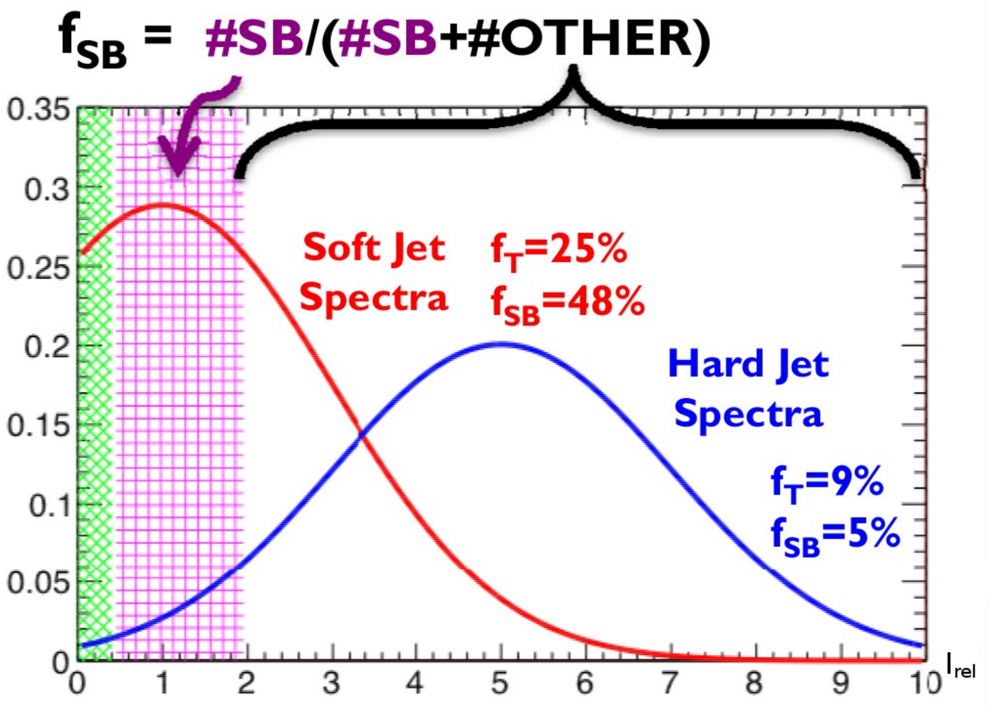
Background Predictions

- Uniform background determination across all search bins
- Use data-driven estimates as much as possible
  - Leptons from Standard Model backgrounds are estimated by calculating a fake rate in a control region which is applied to the search region
- MC simulation for $t\bar{t}$, WZ, ZZ and rare processes; validation in control regions
- Apply data-driven corrections to simulation to improve MET resolution
- Next slides: more details on data-driven methods

Background Predictions: Tau Fake Rates

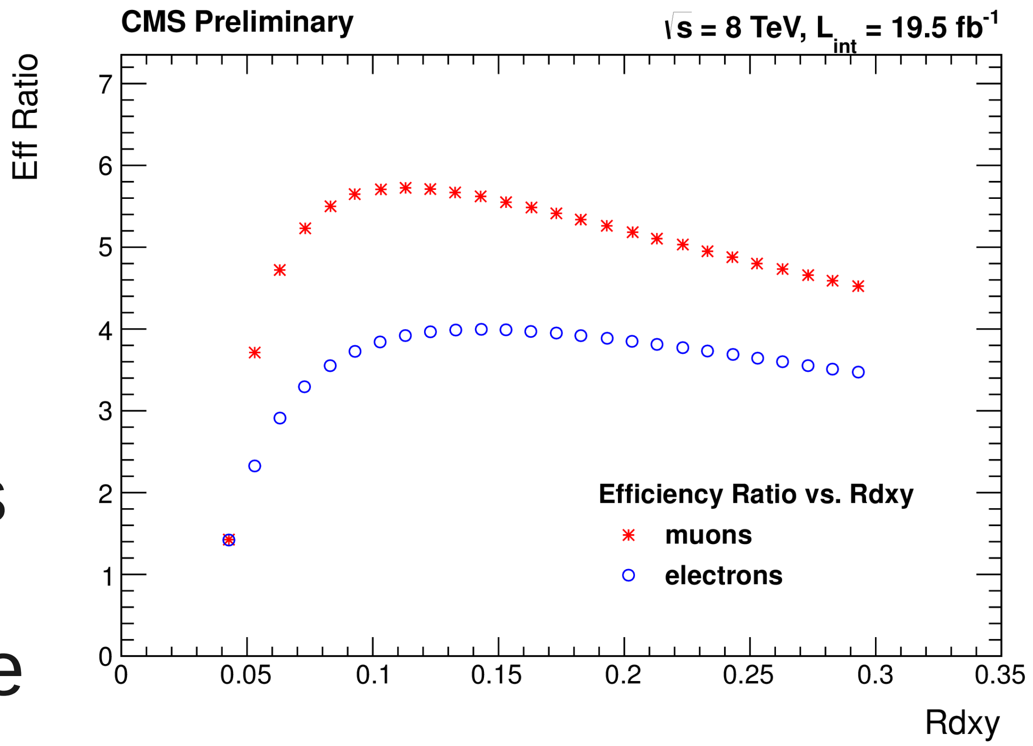
- Parametrize tau fake rate f_T by amount of jet activity in the event, using jet-dependent parameter f_{SB}





Background Predictions: Light Lepton Fake Rates

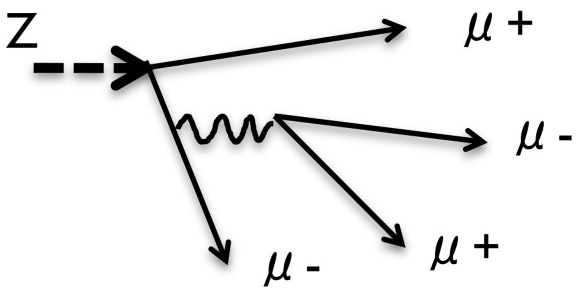
- Using CFO method, relating isolated tracks to the number of fake leptons
- Fake rate is a function of Rdxy (ratio of tracks with large impact parameter dxy to those with small dxy)



- Method first used in 2010, has withstood the data

Background Predictions: Asymmetric Photon Conv.

- For internal conversions, di-lepton invariant mass is not in the Z window, but tri-lepton mass might

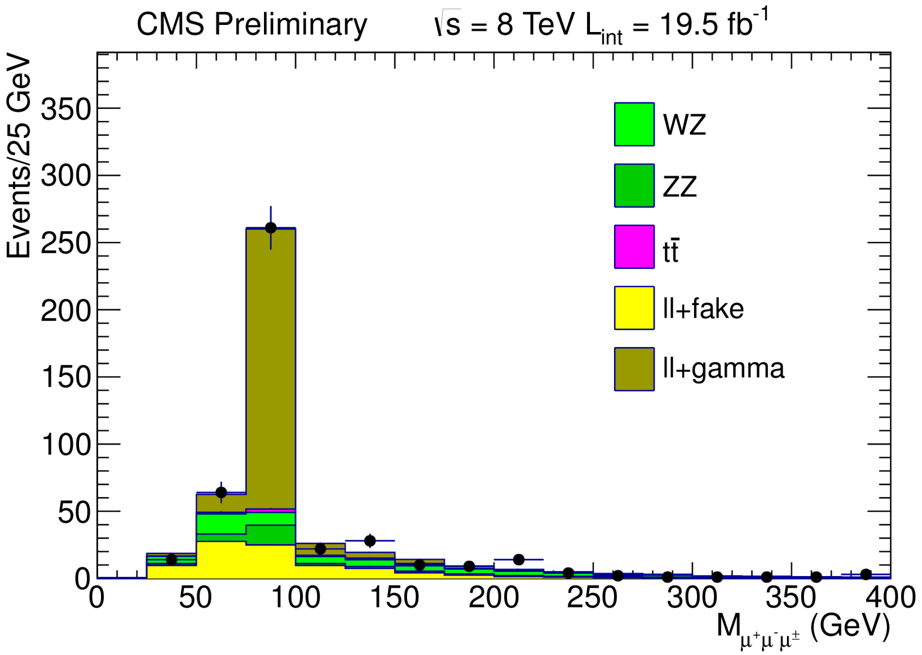


- Conversion factor

$$C = \frac{N(\ell^+\ell^-\ell^\pm)}{N(\ell^+\ell^-\gamma)}$$

- Prediction matches data

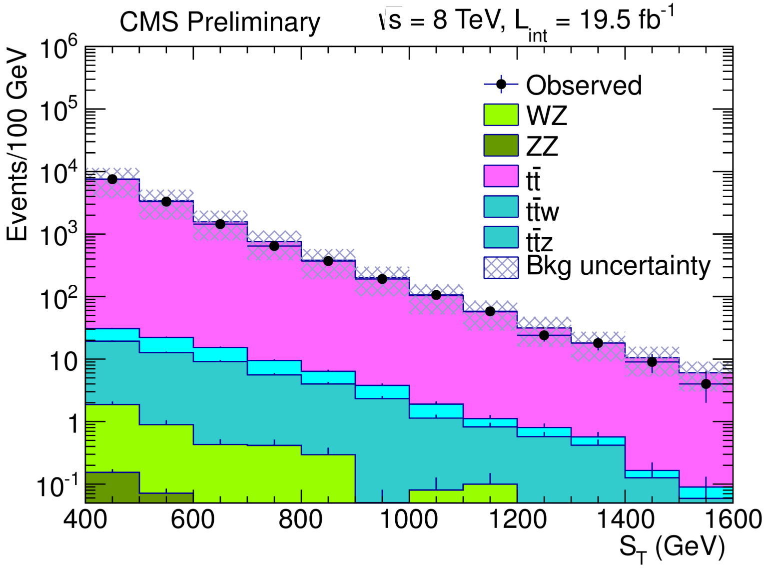
  Control region: 3 leptons including one OSSF off Z, (here: 3 muons), low MET/H_T



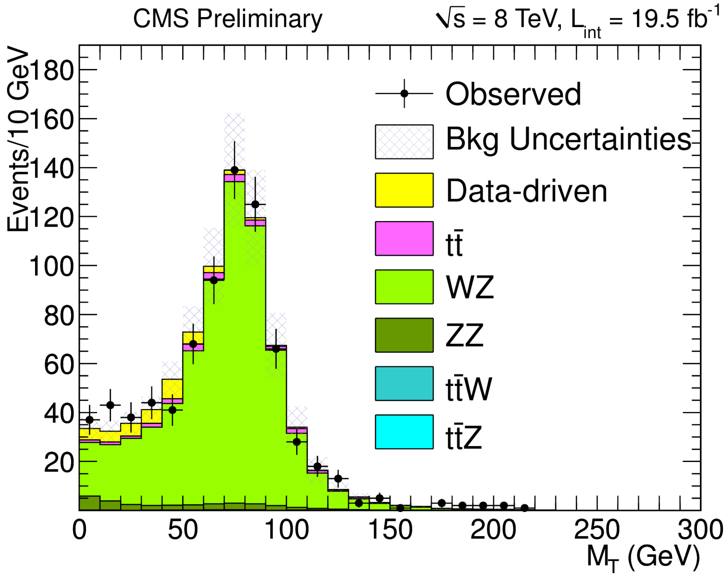
- Found by previous incarnation of Rutgers multilepton search
  hep-ph:arXiv:1110.1368 R.C. Gray et al.

Background Predictions: Simulation Validation

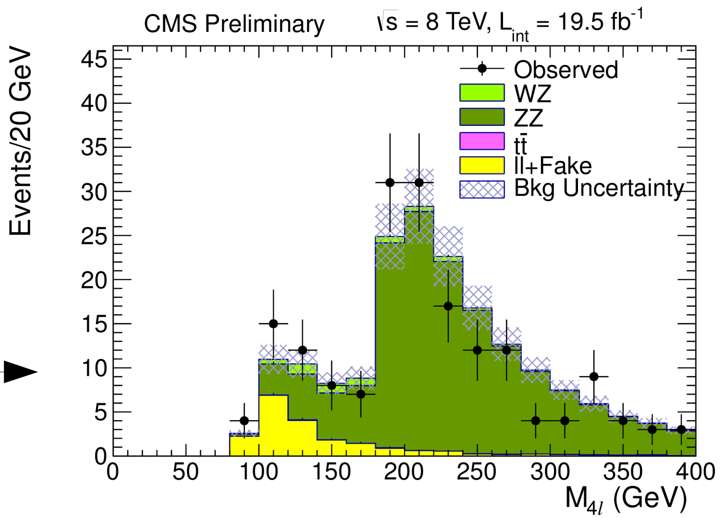
$t\bar{t}$ simulation validated in S_T distribution for events with an opposite-sign electron-muon pair



WZ simulation validated in M_T distribution for 3 leptons including one on-Z OSSF pair, 50 < MET < 100 GeV



ZZ simulation validated in invariant mass distribution for 4 leptons including at least one on-Z OSSF pair



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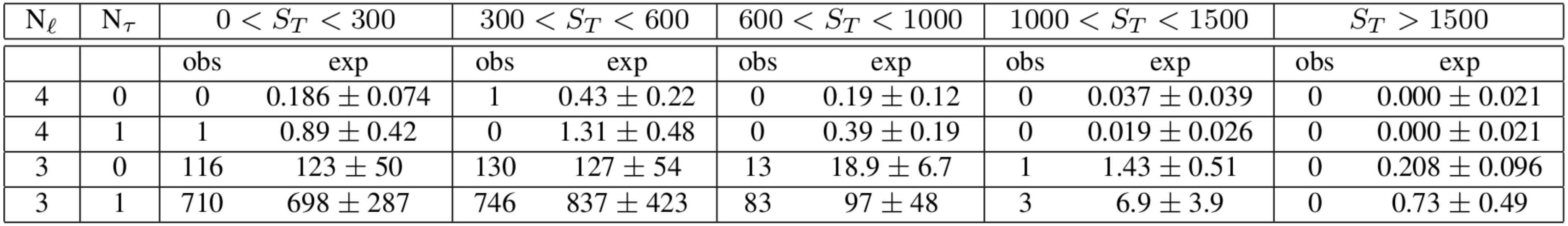
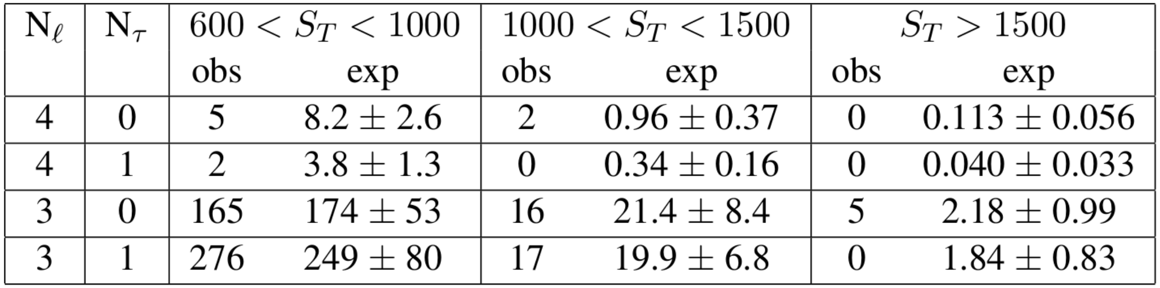
Results – S_T Tables

- Large amount of numbers due to large number of bins
- Below: Results binned in S_T



N_ℓ	N_τ	$0 < S_T < 300$		$300 < S_T < 600$		$600 < S_T < 1000$		$1000 < S_T < 1500$		$S_T > 1500$	
		obs	exp	obs	exp	obs	exp	obs	exp	obs	exp
4	0	0	0.186 ± 0.074	1	0.43 ± 0.22	0	0.19 ± 0.12	0	0.037 ± 0.039	0	0.000 ± 0.021
4	1	1	0.89 ± 0.42	0	1.31 ± 0.48	0	0.39 ± 0.19	0	0.019 ± 0.026	0	0.000 ± 0.021
3	0	116	123 ± 50	130	127 ± 54	13	18.9 ± 6.7	1	1.43 ± 0.51	0	0.208 ± 0.096
3	1	710	698 ± 287	746	837 ± 423	83	97 ± 48	3	6.9 ± 3.9	0	0.73 ± 0.49



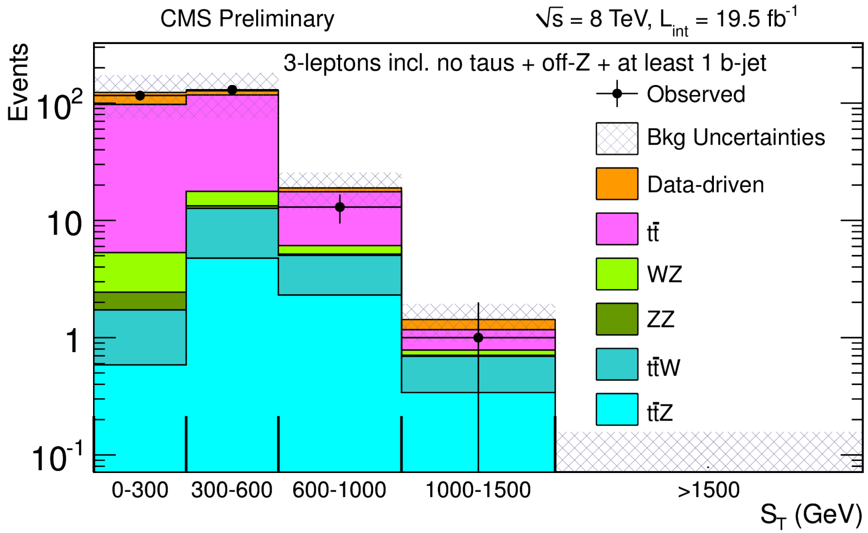
N_ℓ	N_τ	$600 < S_T < 1000$		$1000 < S_T < 1500$		$S_T > 1500$	
		obs	exp	obs	exp	obs	exp
4	0	5	8.2 ± 2.6	2	0.96 ± 0.37	0	0.113 ± 0.056
4	1	2	3.8 ± 1.3	0	0.34 ± 0.16	0	0.040 ± 0.033
3	0	165	174 ± 53	16	21.4 ± 8.4	5	2.18 ± 0.99
3	1	276	249 ± 80	17	19.9 ± 6.8	0	1.84 ± 0.83

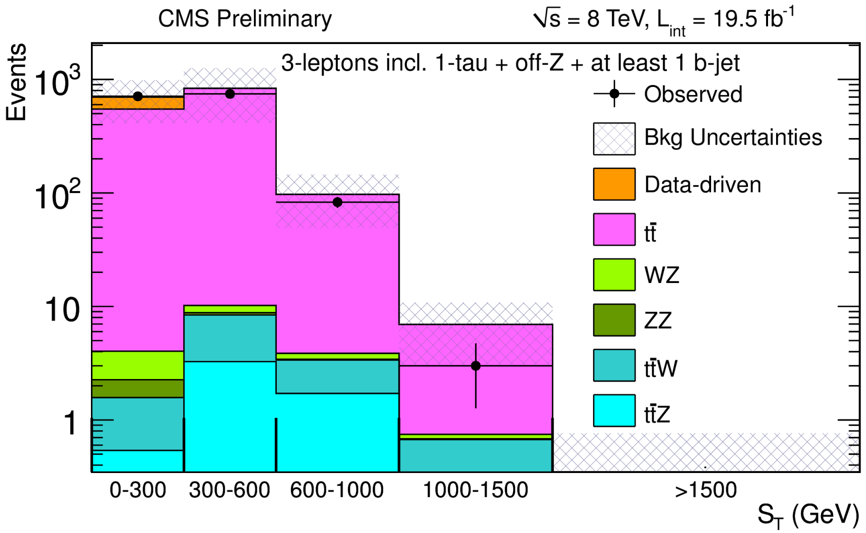
with b-tag and
off-Z OSSF pair
requirement

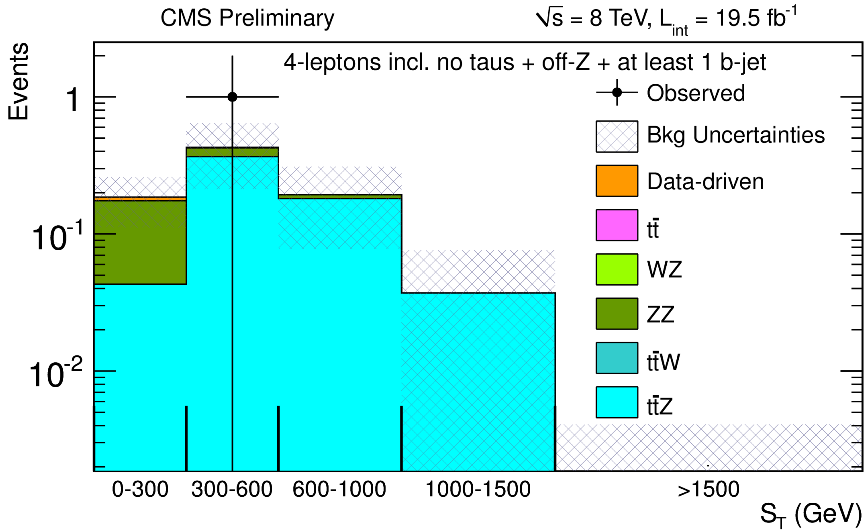
without this requirement

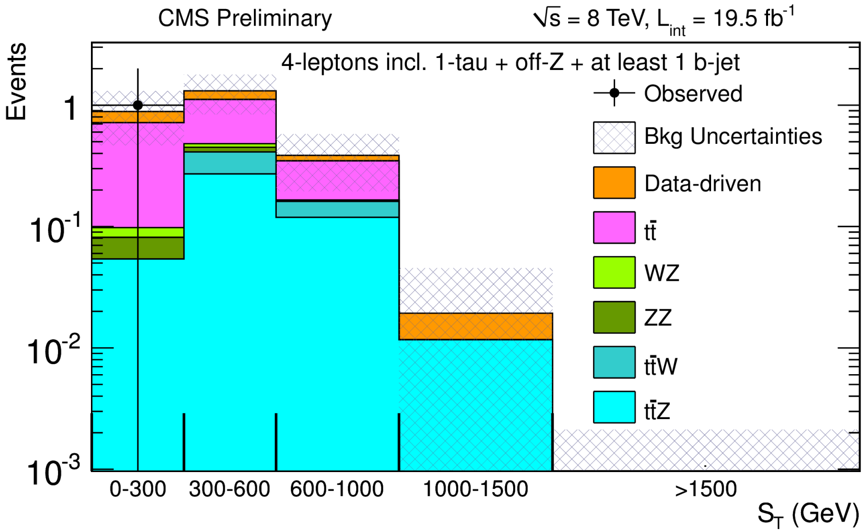
- MET/H_T-binned results with full 2012 dataset are in the pipeline

Results – S_T Plots









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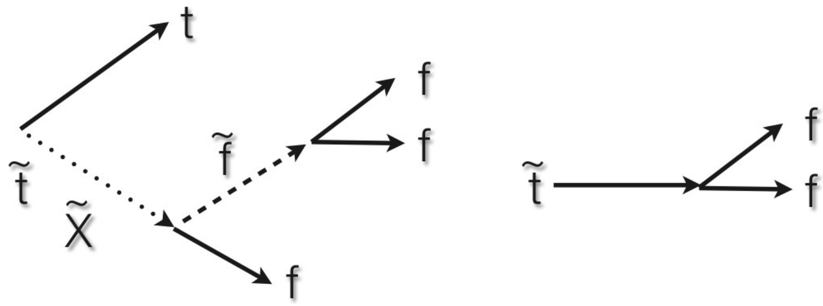
SUS-13-003:
Stop RPV – RPV Review

$$W_{RPV} = \underbrace{\lambda_{ijk} L^i L^j \bar{E}^k}_{\text{leptonic}} + \underbrace{\lambda'_{ijk} L^i Q^j \bar{D}^k}_{\text{mixed}} + \underbrace{\lambda''_{ijk} \bar{U}^i \bar{D}^j \bar{D}^k}_{\text{hadronic}} + \epsilon_i L_i H_2$$

- Three trilinear Yukawa couplings
- RPV couplings also violate lepton or baryon number conservation
- Focus on light stop pair production where the stop decays through off-shell bino



4-body decay

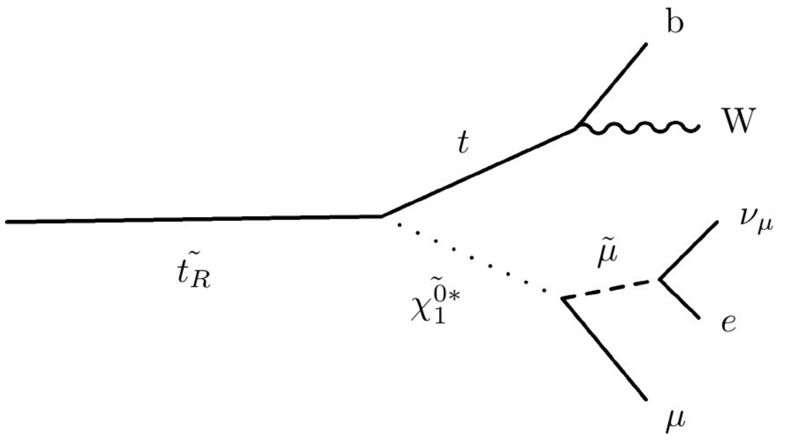
2-body decay

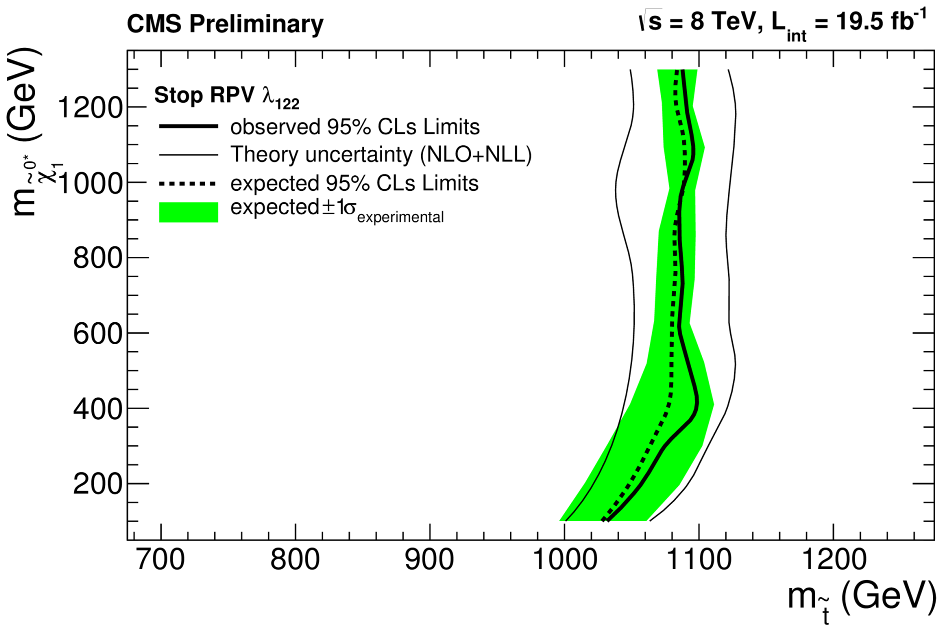
- Couplings chosen to have prompt decay, and to satisfy existing constraints (model by J. A. Evans, Y. Kats, arXiv:1209.0764 [hep-ph])

SUS-13-003: Stop RPV – LLE 122

$$W_{RPV} = \lambda_{ijk} L^i L^j \bar{E}^k + \lambda'_{ijk} L^i Q^j \bar{D}^k + \lambda''_{ijk} \bar{U}^i \bar{D}^j \bar{D}^k + \epsilon_i L_i H_2$$

leptonic



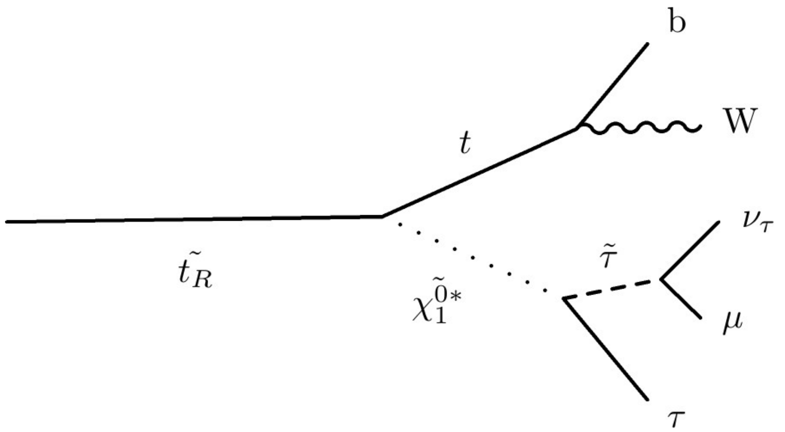


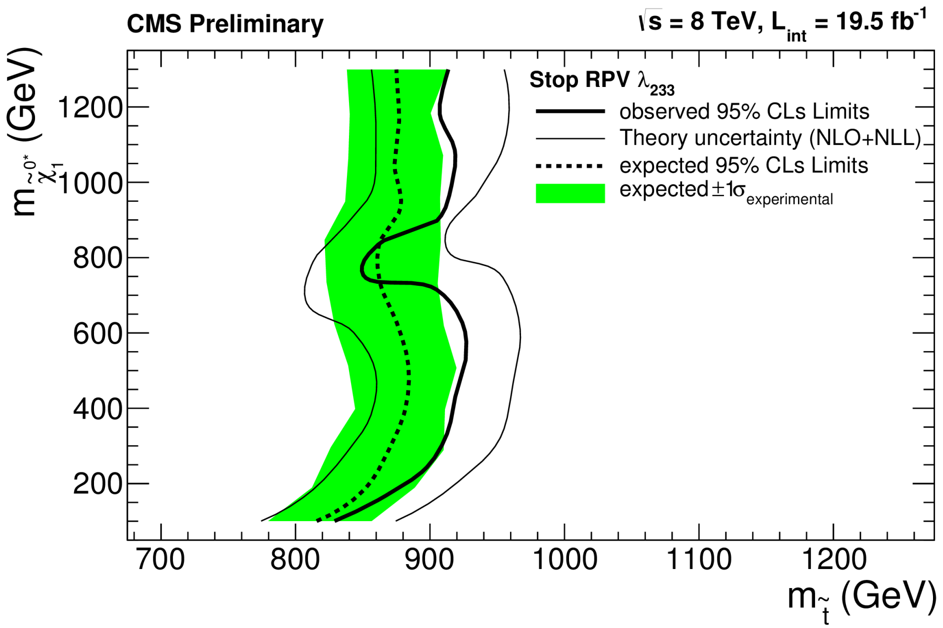
- Stop RPV model with LLE 122 coupling non-zero
- Excluding stop masses below 1050–1100 GeV; approximately independent of bino mass which decouples → little structure

SUS-13-003:
Stop RPV – LLE 233

$$W_{RPV} = \lambda_{ijk} L^i L^j \bar{E}^k + \lambda'_{ijk} L^i Q^j \bar{D}^k + \lambda''_{ijk} \bar{U}^i \bar{D}^j \bar{D}^k + \epsilon_i L_i H_2$$

leptonic

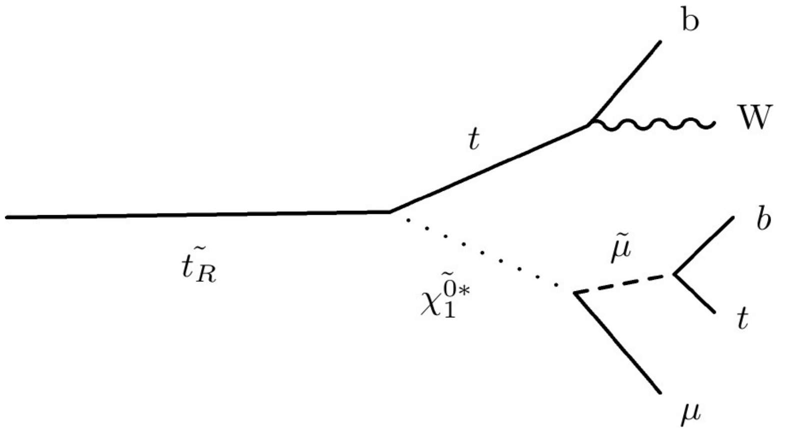


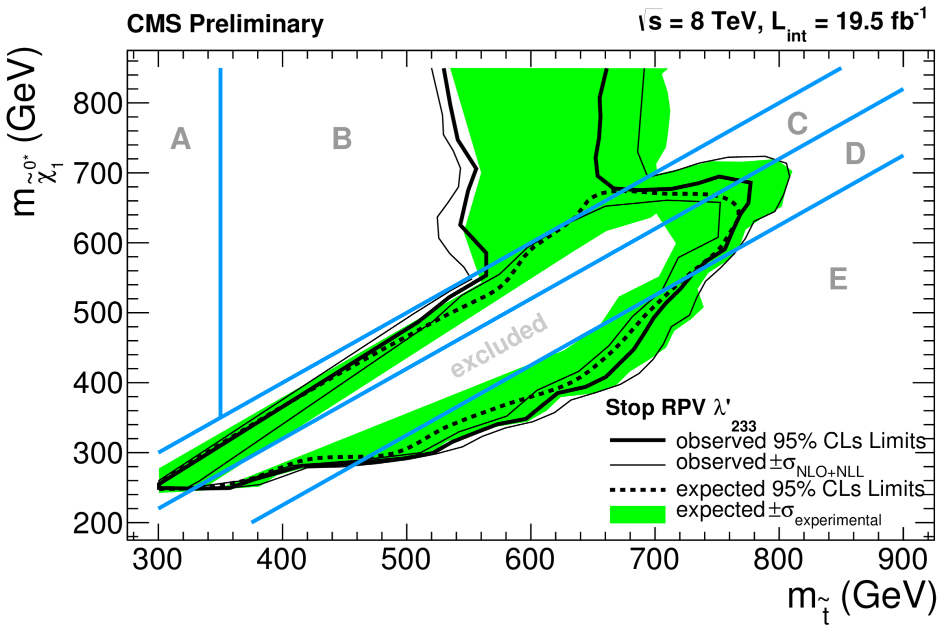


- Stop RPV model with LLE 233 coupling non-zero
- Excluding stop masses below 850–900 GeV;
  feature around diagonal due to kinematic transition

SUS-13-003:
Stop RPV – LQD 233

$$W_{RPV} = \lambda_{ijk}L^iL^j\bar{E}^k + \lambda'_{ijk}L^iQ^j\bar{D}^k + \lambda''_{ijk}\bar{U}^i\bar{D}^j\bar{D}^k + \epsilon_i L_i H_2$$

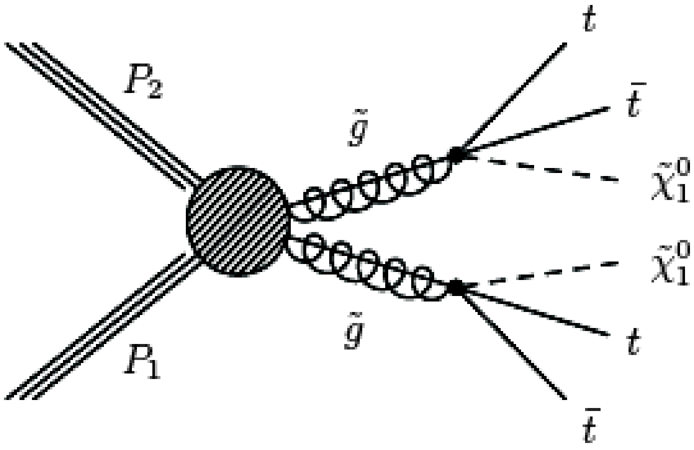


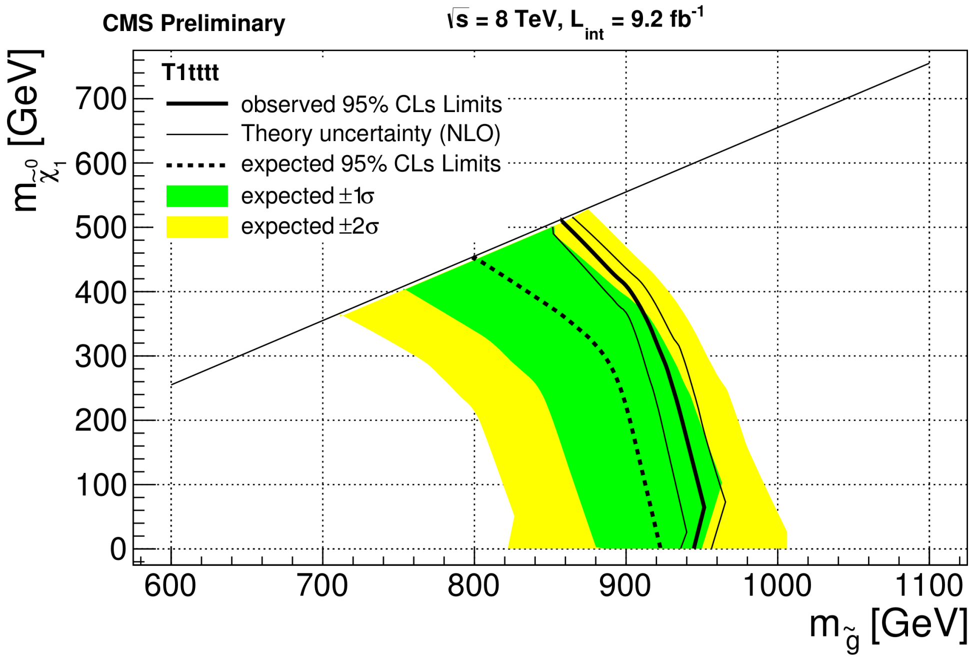


- Stop RPV model with LQD 233 coupling non-zero
- Several kinematic regions with different acceptance

region label	kinematic region	stop decay mode(s)
A	$m_t < m_{\tilde{t}} < 2m_t, m_{\tilde{\chi}_1^0}$	$\tilde{t} \to t\nu b\bar{b}$
B	$2m_t < m_{\tilde{t}} < m_{\tilde{\chi}_1^0}$	$\tilde{t} \to t\mu t\bar{b} + t\nu b\bar{b}$
C	$m_{\tilde{\chi}_1^0} < m_{\tilde{t}} < m_W + m_{\tilde{\chi}_1^0}$	$\tilde{t} \to \ell\nu b\tilde{\chi}_1^0 + jjb\tilde{\chi}_1^0$
D	$m_W + m_{\tilde{\chi}_1^0} < m_{\tilde{t}} < m_t + m_{\tilde{\chi}_1^0}$	$\tilde{t} \to Wb\tilde{\chi}_1^0$
E	$m_t + m_{\tilde{\chi}_1^0} < m_{\tilde{t}}$	$\tilde{t} \to t\tilde{\chi}_1^0$

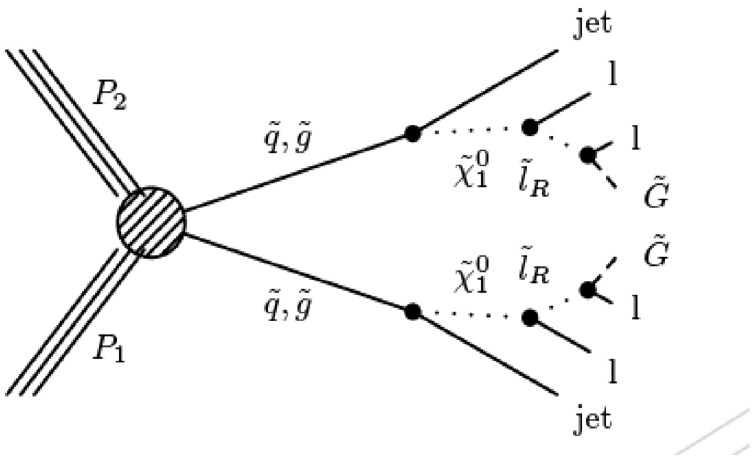
SUS-12-026: T1tttt

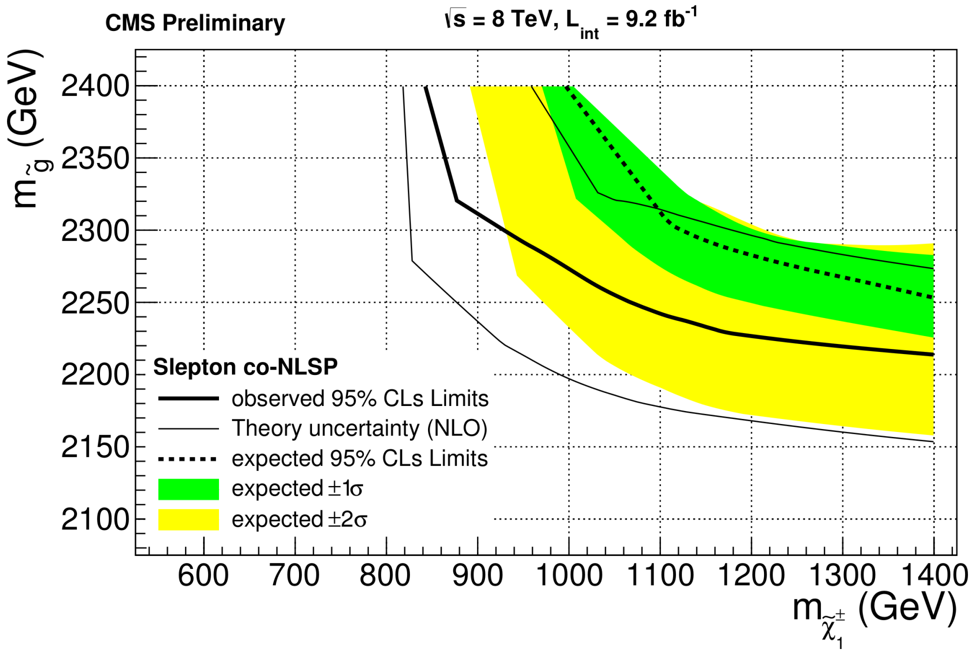




- Third generation stop production
- One of the CMS standard Simplified Models (SMS)

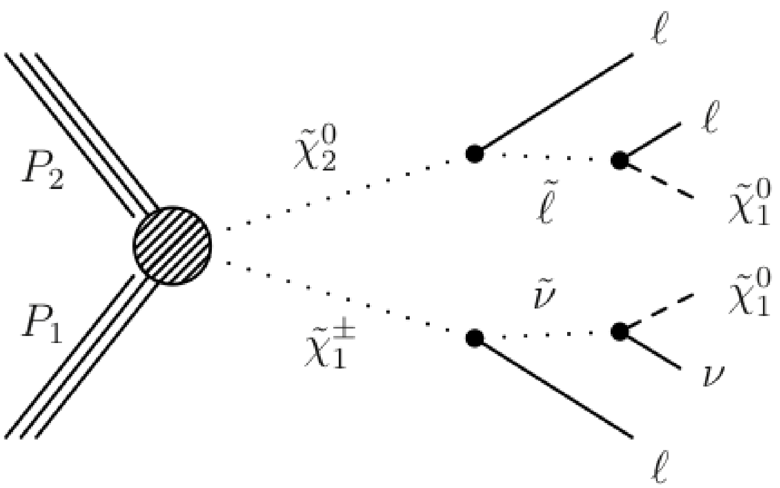
SUS-12-026: Slepton co-NLSP

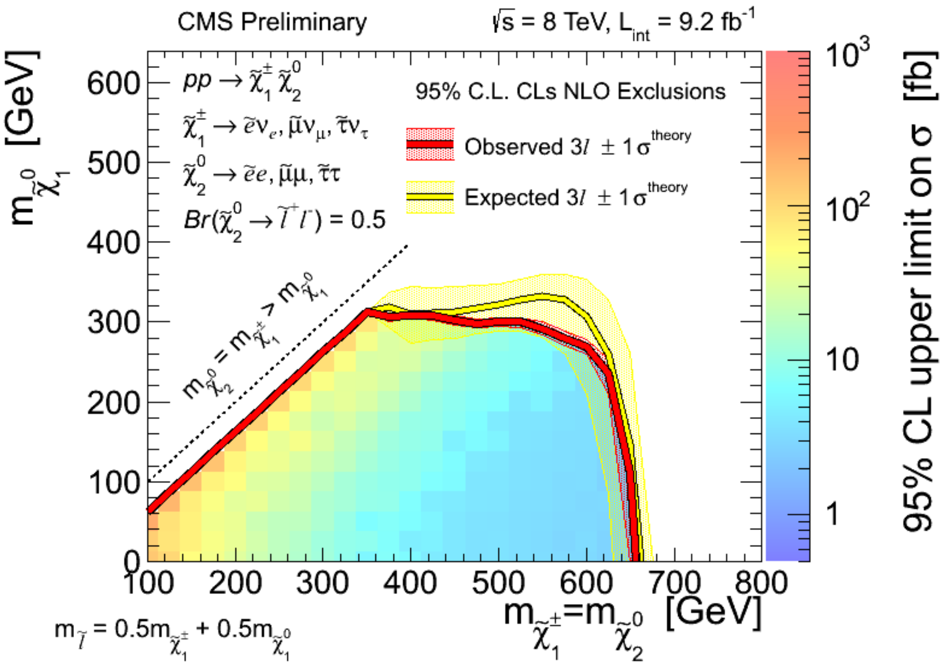




- LSP: Gravitino; NLSPs: sleptons; Higgsinos decoupled
$m_{\tilde{\ell}_R} = 0.3\, m_{\chi_1^\pm}, m_{\chi_1^0} = 0.5\, m_{\chi_1^\pm}, m_{\tilde{\ell}_L} = 0.8\, m_{\chi_1^\pm}, m_{\tilde{q}} = 0.8\, m_{\tilde{g}}$
- squarks/gluinos from strong production decay to sleptons (through bino)

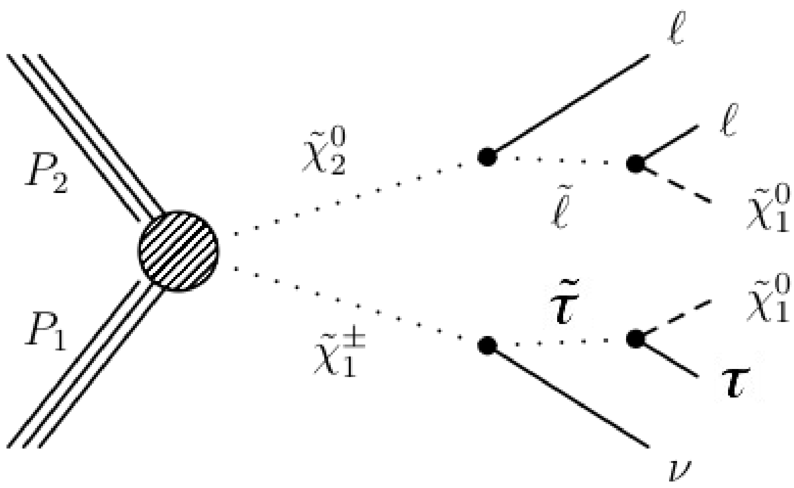
SUS-12-022: Weak Prod. TChiSlepSnu Democratic

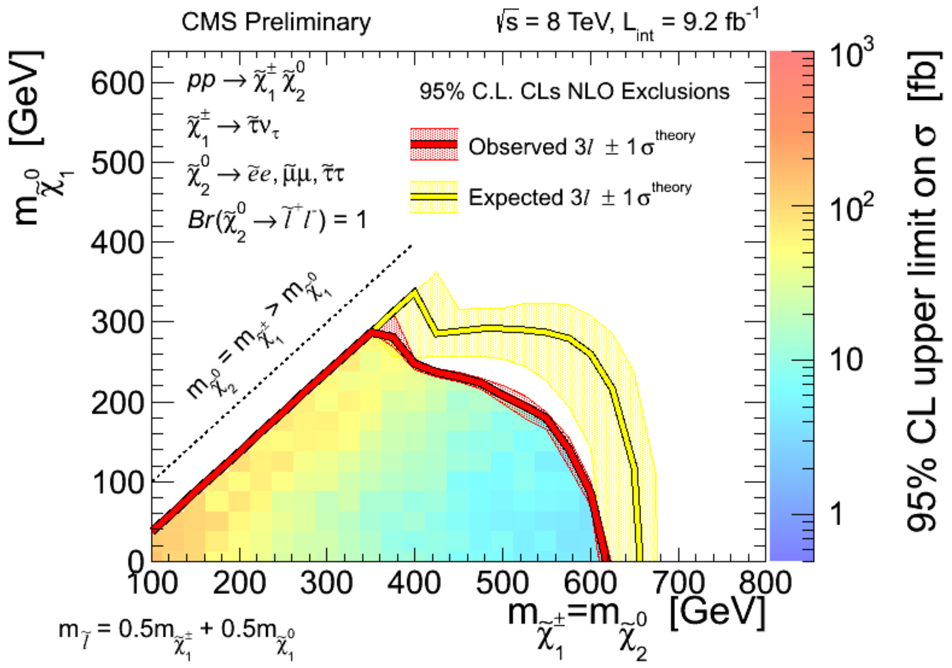




- Democratic with respect to sleptons; neutralino BR: 50%
- Exclusion in the LSP mass vs. chargino mass plane
- Sleptons midway between LSP and chargino

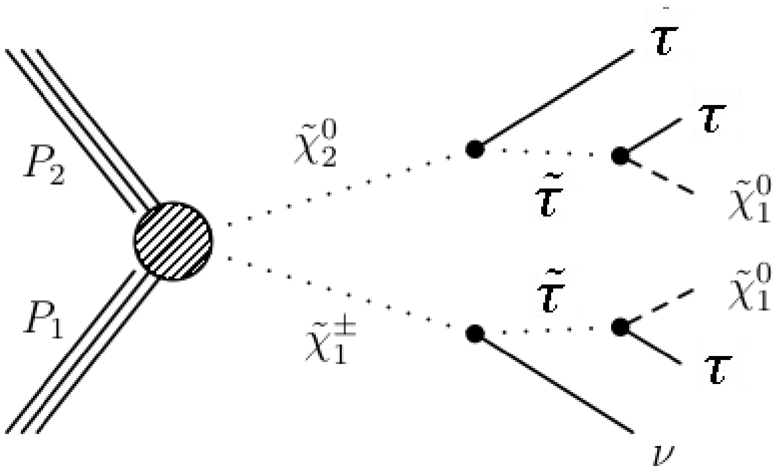
SUS-12-022: Weak Prod. TChiSlepSnu Tau-enriched

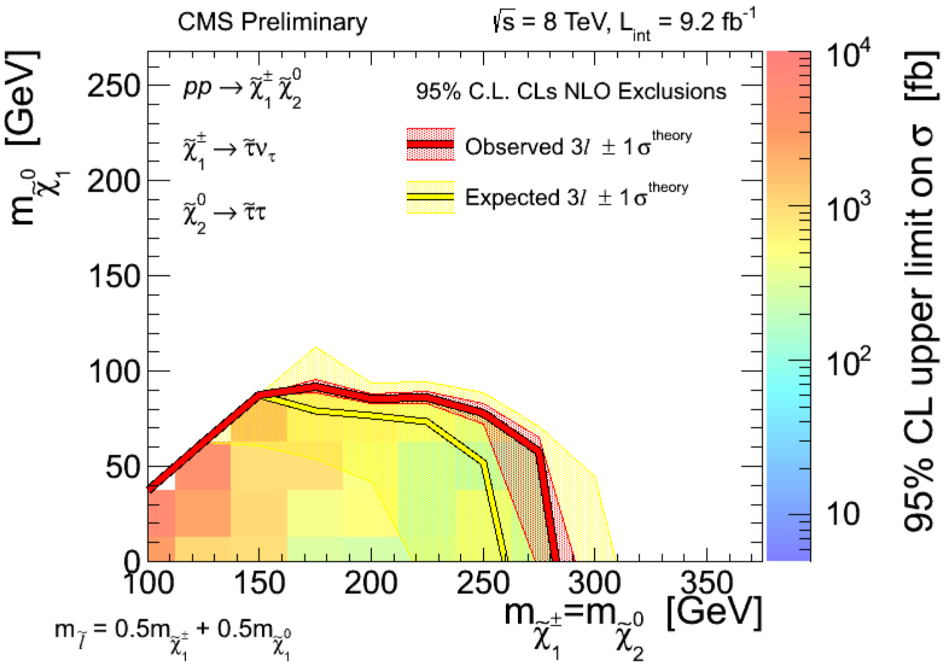




- Charginos decaying to staus (neutralino democratic)
- Exclusion in the LSP mass vs. chargino mass plane
- Sleptons midway between LSP and chargino

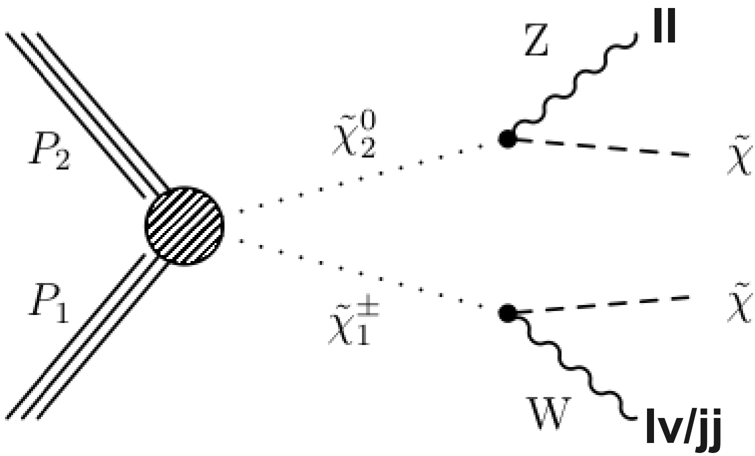
SUS-12-022: Weak Prod. TChiSlepSnu Tau-dominated

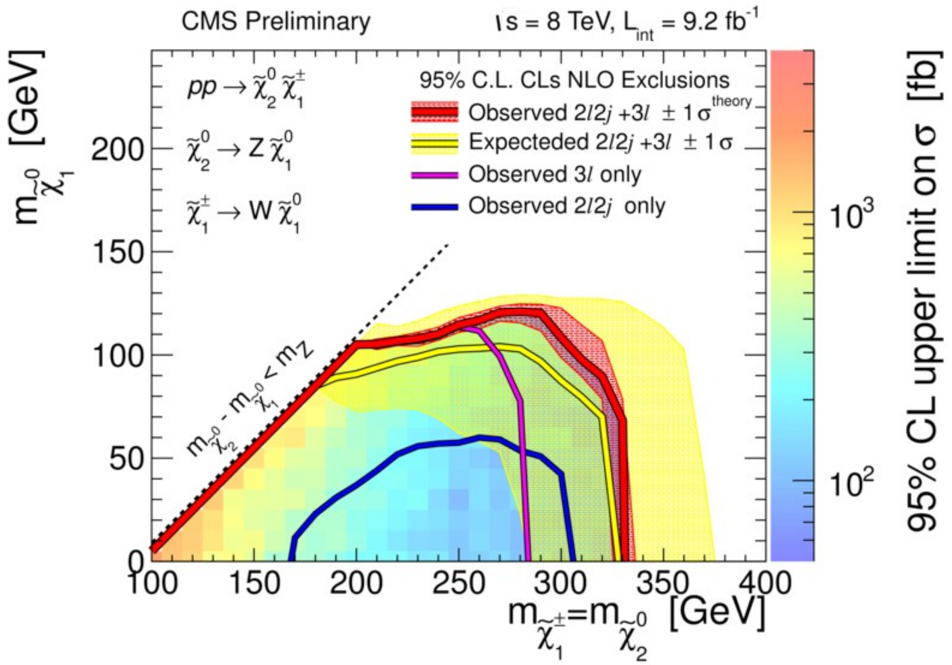




- Charginos and neutralinos decaying to staus
- Exclusion in the LSP mass vs. chargino mass plane
- Sleptons midway between LSP and chargino

SUS-12-022: Weak Prod. TChiWZ Resonant Search

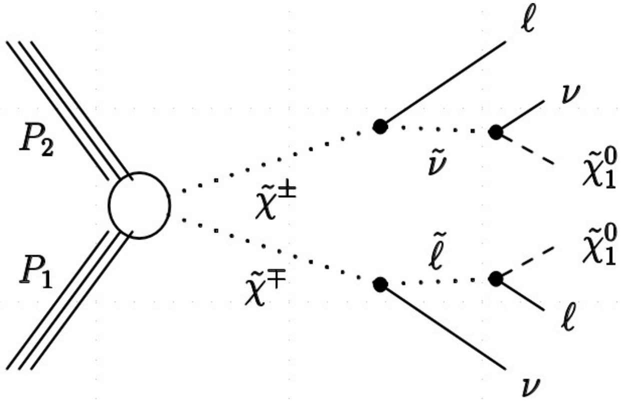


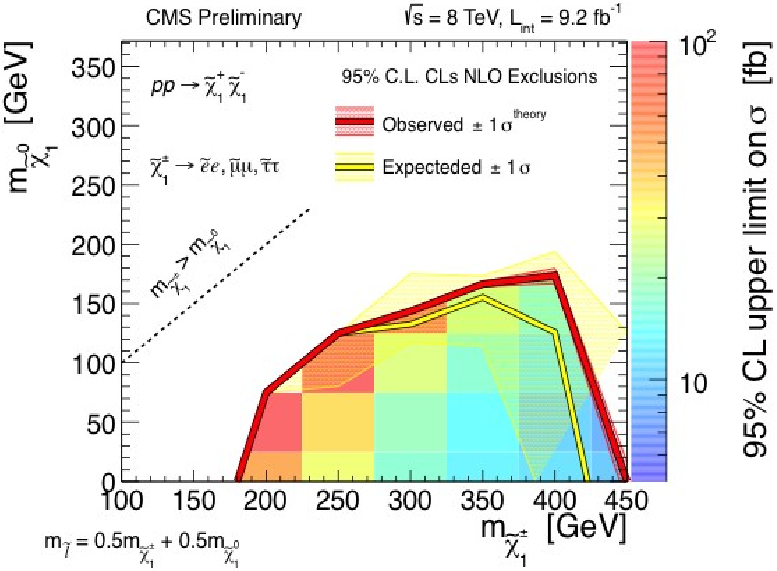


- Resonant production of trileptons, or dilepton + jets
- Exclusion in the LSP mass vs. chargino mass plane

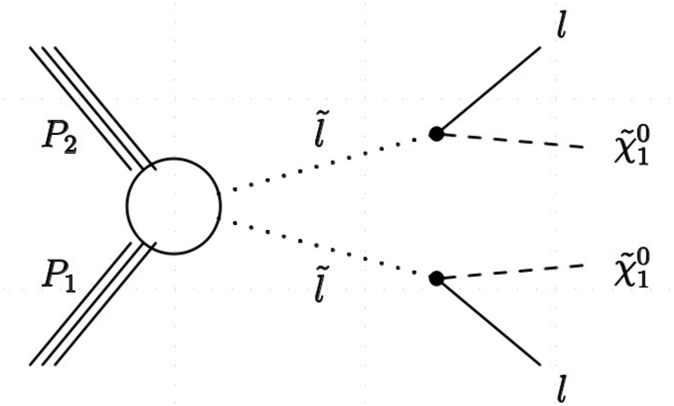
SUS-12-022: Weak Prod. Non-Resonant Dilepton

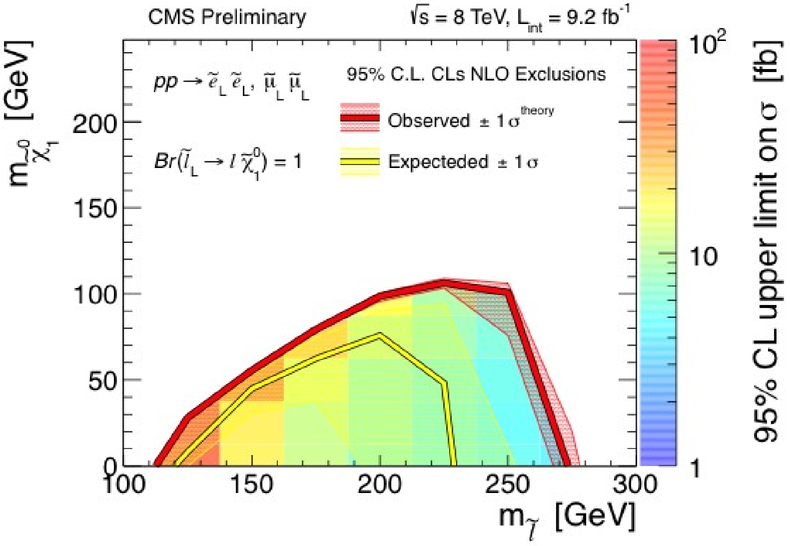
Chargino-Chargino Production



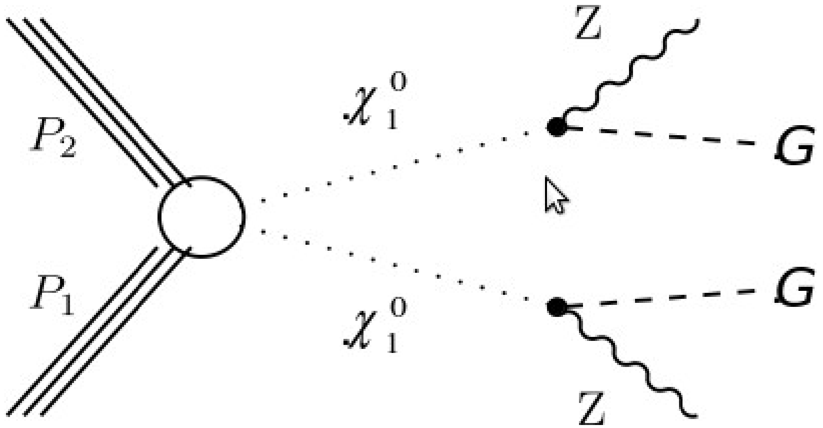


Slepton-Slepton Production





SUS-12-022: Weak Prod. Higgsino GMSB

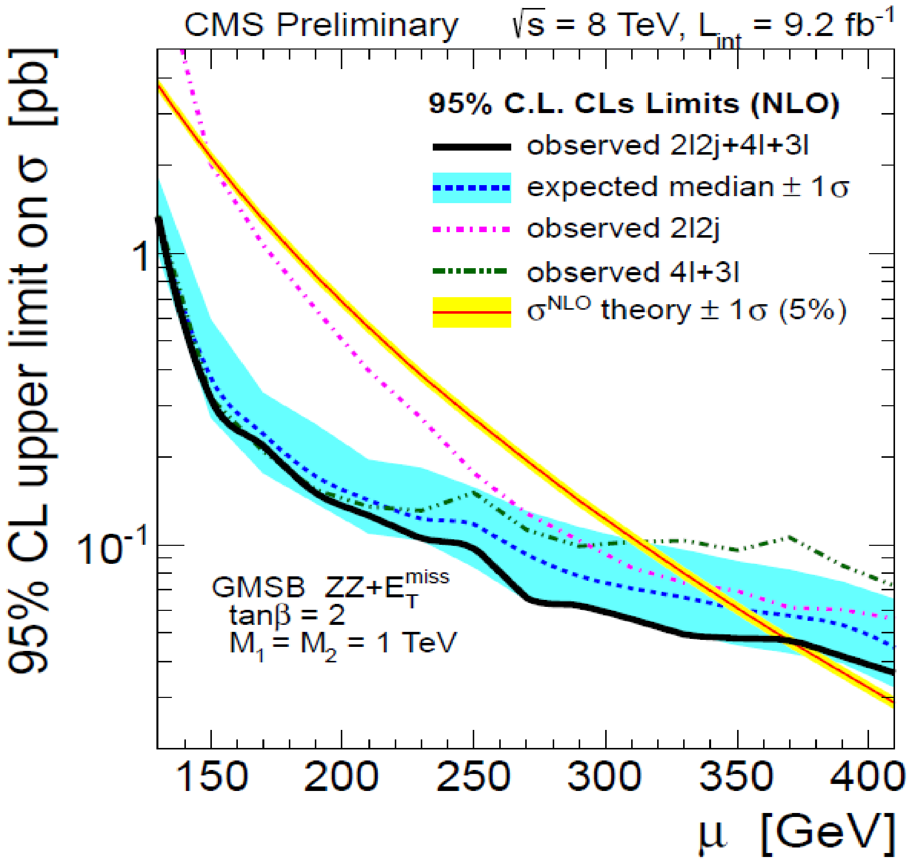


Setting limits on neutralino-neutralino production in the GMSB scenario

Exclusion in terms of parameter μ that controls the chargino and LSP masses:

$$m_{\tilde{\chi}_1^\pm} \approx m_{\tilde{\chi}_1^0} \approx m_\mu$$

Phys. Rev. D 62 (2000) 077702
JHEP 05 (2012) 105



Z+2j where Z → 4l

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Conclusions

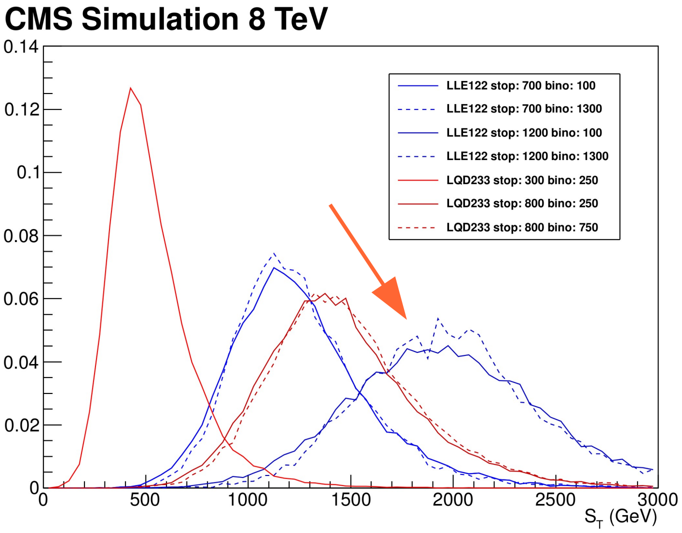
- Search for multilepton events in 2012 CMS data at 8 TeV
- Highlights:
  - Multiple exclusive channels
  - Uniform background predictions (both data-driven and MC)
  - Three types of binning (S_T, MET/H_T, MET/M_T) for different types of signal
- Good agreement between data and background

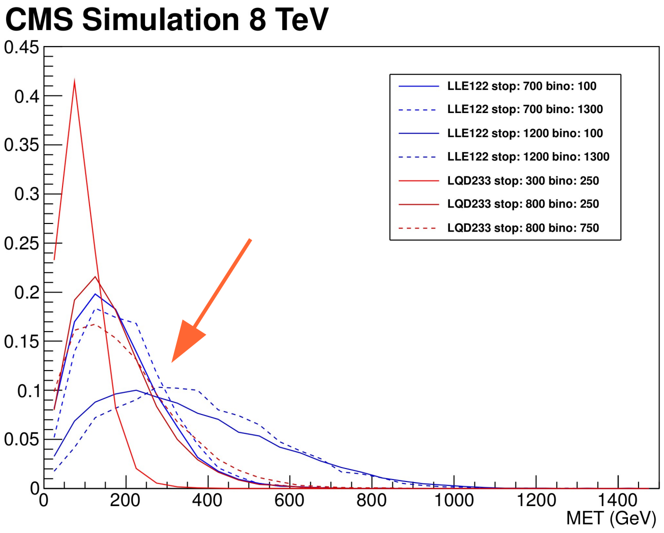
  → Excluded regions of parameter space

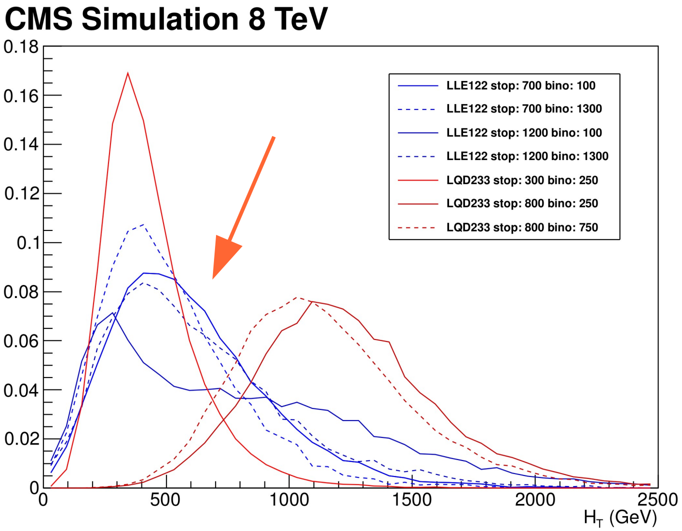
Extra slides

Why S_T?

- S_T provides discrimination from background and is sensitive to the stop mass







Lepton Selection

- Muons: official POG recommendation
  - Muon is Global
  - Muon is PF
  - normalizedChi2 < 10
  - At least one muon chamber hit in global fit
  - At least two muon stations
  - Dxy < 2 mm
  - dZ < 0.5
  - Number of pixel hits > 0
  - Number of tracker layers > 5
  - PFiso < 0.15 in 0.3 cone

- Electrons: official POG recommendation (loose)
  - cuts for barrel (endcap)
  - dEtaIn < 0.007 (0.009)
  - dPhiIn < 0.15 (0.10)
  - sigmaIEtaIeta < 0.01 (0.03)
  - H/E < 0.12 (0.10)
  - d0 < 0.02 (0.02)
  - dZ < 0.2 (0.2)
  - fabs(1/E - 1/p) < 0.05 (0.05)
  - PFiso < 0.15 (0.15) in 0.3 cone
  - conversion rejection

- Taus: official HPS tau selection
  - ByDecayModeFinding
  - AgainstElectronMVA
  - AgainstMuonTight
  - ByLooseCombinedIsolationDBSumPtCorr
  - pT > 20
  - eta < 2.3

- Light lepton p_T must pass 20/10/10(/10) GeV threshold (for the first, second, … lepton)

Other Selections

- Jets: official POG recommendation (loose)
  - Neutral Hadron Fraction < 0.99
  - Neutral EM Fraction < 0.99
  - Number Constituents > 1
  - Charged Hadron Fraction > 0
  - Charged Multiplicity > 0
  - Charged EM Fraction < 0.99
  - pT > 30
  - eta < 2.5
- MET filters applied
- Using PFMET
- b-tag
  - Combined Secondary Vertex Medium working point
- Cleaning of Objects:
  - Remove electrons within dR < 0.1 of muon
  - Remove taus within dR < 0.1 of muons or electrons
  - Remove jets within dR < 0.4 of muons, electrons, taus

Data Samples

Primary Dataset	Reco details	Luminosity (fb^{-1})
MuEG	Run2012A-recover-06Aug2012-v1	0.082
MuEG	Run2012A-13Jul2012-v1	0.809
MuEG	Run2012B-13Jul2012-v1	4.403
MuEG	Run2012C-24Aug2012-v1	0.495
MuEG	Run2012C-PromptReco-v2	6.584
MuEG	Run2012D-PromptReco-v1	7.718
DoubleMu	Run2012A-recover-06Aug2012-v1	0.082
DoubleMu	Run2012A-13Jul2012-v1	0.809
DoubleMu	Run2012B-13Jul2012-v4	4.403
DoubleMu	Run2012C-24Aug2012-v1	0.495
DoubleMu	Run2012C-PromptReco-v2	6.557
DoubleMu	Run2012D-PromptReco-v1	7.719
DoubleElectron	Run2012A-recover-06Aug2012-v1	0.082
DoubleElectron	Run2012A-13Jul2012-v1	0.809
DoubleElectron	Run2012B-13Jul2012-v1	4.403
DoubleElectron	Run2012C-24Aug2012-v1	0.495
DoubleElectron	Run2012C-PromptReco-v2	6.575
DoubleElectron	Run2012D-PromptReco-v1	7.727

Simulation Samples

Simulation sample	N events	cross section (pb)
/DYJetsToLL_M-10To50filter_8TeV-madgraph/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM	7,131,530	11050.0
/DYJetsToLL_M-50_TuneZ2Star_8TeV-madgraph-tarball/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM	30,459,503	3532.8
/TTJets_FullLeptMGDecays_8TeV-madgraph/Summer12_DR53X-PU_S10_START53_V7A-v2/AODSIM	12,119,013	23.08
/TTJets_SemiLeptMGDecays_8TeV-madgraph/Summer12_DR53X-PU_S10_START53_V7A_ext-v1/AODSIM	25,423,514	97.97
/TTGJets_8TeV-madgraph/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM	71,598	2.166
/TTWJets_8TeV-madgraph/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM	196,046	0.232
/TTZJets_8TeV-madgraph_v2/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM	209,677	0.208
/TTWWJets_8TeV-madgraph/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM	217,213	0.002
/TBZToLL_4F_TuneZ2star_8TeV-madgraph-tauola/Summer12_DR53X-PU_S10_START53_V7C-v1/AODSIM	148504	0.0217
/ZZZNoGstarJets_8TeV-madgraph/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM	224,902	0.0192
/WWWJets_8TeV-madgraph/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM	220,170	0.08217
/ZZJetsTo4L_TuneZ2star_8TeV-madgraph-tauola/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM	4,804,781	0.1769
/WZJetsTo3LNu_TuneZ2_8TeV-madgraph-tauola/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM	2,016,678	1.0575
/WWJetsTo2L2Nu_TuneZ2star_8TeV-madgraph-tauola/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM	1,932,249	5.8123
/WJetsToLNu_TuneZ2Star_8TeV-madgraph-tarball/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM	18,393,090	37509
/WWGJets_8TeV-madgraph/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM	215,121	1.44
/WWZNoGstarJets_8TeV-madgraph/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM	222,234	0.0633
/GluGluToHToTauTau_M-125_8TeV-powheg-pythia6/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM	967566	1.2466
/GluGluToHToWWTo2LAndTau2Nu_M-125_8TeV-powheg-pythia6/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM	299975	0.4437
/GluGluToHToZZTo4L_M-125_8TeV-powheg-pythia6/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM	995117	0.0053
/VBF_HToTauTau_M-125_8TeV-powheg-pythia6/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM	1000000	0.0992
/VBF_HToWWTo2LAndTau2Nu_M-125_8TeV-powheg-pythia6/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM	299687	0.0282
/VBF_HToZZTo4L_M-125_8TeV-powheg-pythia6/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM	49876	0.000423
/WH_ZH_TTH_HToTauTau_M-125_8TeV-pythia6-tauola/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM	200000	0.0778
/WH_ZH_TTH_HToWW_M-125_8TeV-pythia6/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM	200408	0.254

Light Lepton Fake Rates

- Estimate number of “fake” leptons
- Use CFO method:
  - Define fake rate with respect to a proxy object
  - Parametrize by other object to describe how conversion factors change between data sets
- Here: Use isolated tracks (pions, kaons) as proxies for electrons/muons from jets
- Parametrize by Rdxy, sensitive to jet composition

Light Lepton Fake Rates

- CFO: Use isolated tracks (pions, kaons) as proxies for electrons/muons from jets
- Parametrize by Rdxy, sensitive to jet composition
- Measure the efficiency ratio in a Z+jets sample (low Rdxy) and a $t\bar{t}$ sample (high Rdxy)
- Interpolate between the two samples using a linear combination to get Rdxy dependence

$$f_\mu = \frac{N_\mu^{Iso}}{N_T^{Iso}} = \boxed{\frac{N_\mu}{N_T}} \times \boxed{\frac{\epsilon_{Iso}^{\mu}}{\epsilon_{Iso}^{T}}}$$

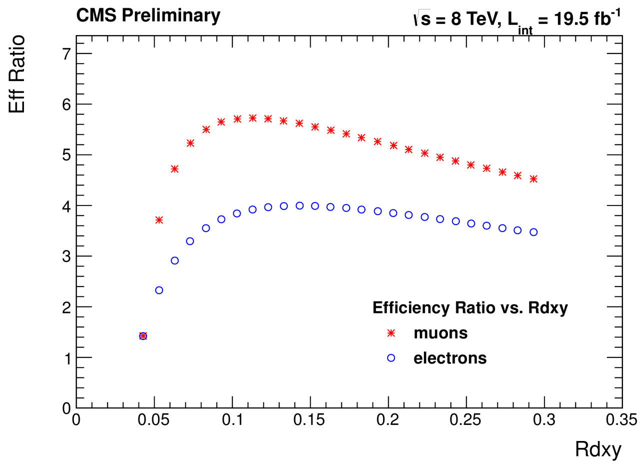
Ratio of lepton to track isolation efficiencies. Parameterize in di-jet data as a function of R_{dxy}

Non isolated leptons and tracks measured in seed to reduce dependence on control data.

Heavy Flavor produces displaced vertices and non-isolated tracks with large dxy

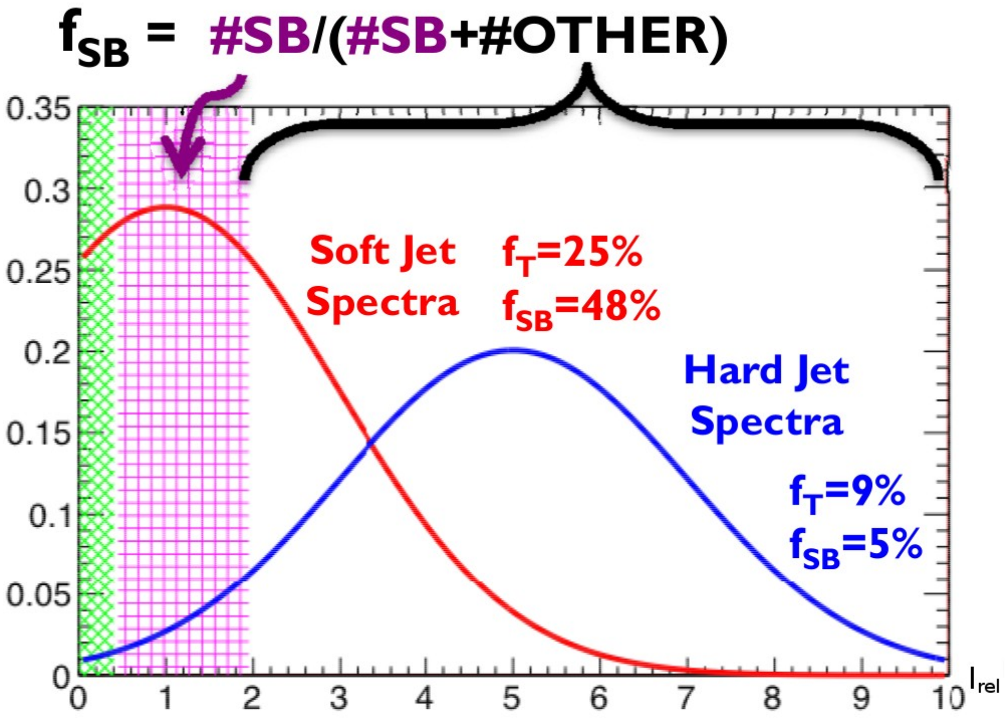
R_{dxy}=N(|dxy|>0.02cm)/N(|dxy|<0.02cm)

A sample of pure b-jets has Rdxy~30%
A sample of pure uds jets has Rdxy~3%



Tau Fake Rates

- Parametrize tau fake rate by amount of jet activity in the event (naturally accounts for pileup effects)
- Use f_{SB} to characterize jet spectra through isolation shape: $f_{SB} \rightarrow 0$ as jets become harder
- Use f_{SB} as a parameter for tau fake rate f_T



Asymmetric Photon Conversions

- External conversions taken care of by electron selection
- Internal conversions: Final state lepton from Z decay radiates a photon, which produces another OSSF lepton pair
- Often asymmetric in p_T
  → one lepton escapes detection
  → Invariant tri-lepton mass consistent with a Z
- Not properly simulated

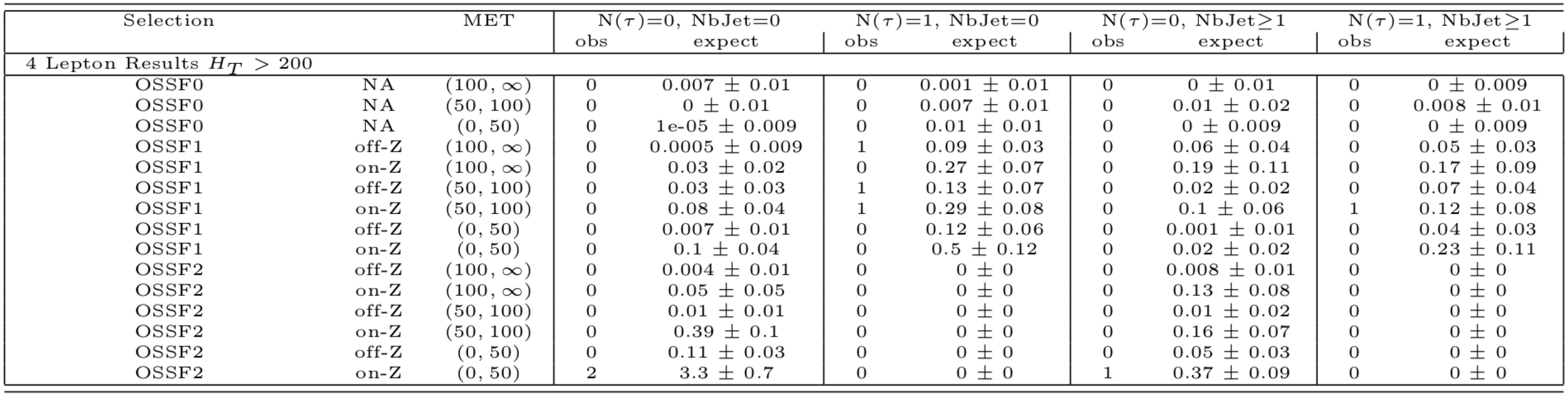
MET Resolution

- Apply smearing to simulation depending on pileup and jet activity
- Goal:
  - Match MET resolution in MC and data
  - Get systematic due to smearing
- Model the MET shape with Rayleigh distributions for different bins of N_{vert} and H_T
- The width of the Rayleigh distribution changes as a function of N_{vert} and H_T → fit in each of those bins and determine width

$$f_{MET}(x) = \frac{1}{\sigma^2} x \exp(-\frac{x^2}{2\sigma^2}); \; x \geq 0$$

$$\sigma^2 = \sigma_0^2 + \sigma_{vert}^2 N_{vert} + \sigma_{HT}^2 \lfloor \frac{H_T}{30} \rfloor$$

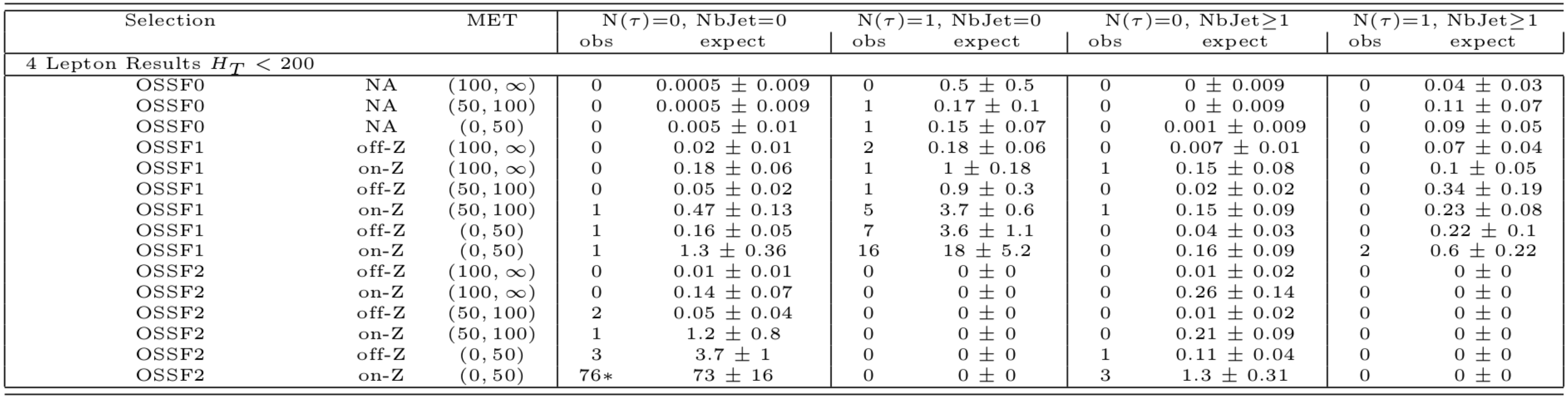
Results – MET/H_T Tables



Selection		MET	N(τ)=0, NbJet=0		N(τ)=1, NbJet=0		N(τ)=0, NbJet≥1		N(τ)=1, NbJet≥1	
			obs	expect	obs	expect	obs	expect	obs	expect
4 Lepton Results $H_T > 200$										
OSSF0	NA	(100, ∞)	0	0.007 ± 0.01	0	0.001 ± 0.01	0	0 ± 0.01	0	0 ± 0.009
OSSF0	NA	(50, 100)	0	0 ± 0.01	0	0.007 ± 0.01	0	0.01 ± 0.02	0	0.008 ± 0.01
OSSF0	NA	(0, 50)	0	1e-05 ± 0.009	0	0.01 ± 0.01	0	0 ± 0.009	0	0 ± 0.009
OSSF1	off-Z	(100, ∞)	0	0.0005 ± 0.009	1	0.09 ± 0.03	0	0.06 ± 0.04	0	0.05 ± 0.03
OSSF1	on-Z	(100, ∞)	0	0.03 ± 0.02	0	0.27 ± 0.07	0	0.19 ± 0.11	0	0.17 ± 0.09
OSSF1	off-Z	(50, 100)	0	0.03 ± 0.03	1	0.13 ± 0.07	0	0.02 ± 0.02	0	0.07 ± 0.04
OSSF1	on-Z	(50, 100)	0	0.08 ± 0.04	1	0.29 ± 0.08	0	0.1 ± 0.06	1	0.12 ± 0.08
OSSF1	off-Z	(0, 50)	0	0.007 ± 0.01	0	0.12 ± 0.06	0	0.001 ± 0.01	0	0.04 ± 0.03
OSSF1	on-Z	(0, 50)	0	0.1 ± 0.04	0	0.5 ± 0.12	0	0.02 ± 0.02	0	0.23 ± 0.11
OSSF2	off-Z	(100, ∞)	0	0.004 ± 0.01	0	0 ± 0	0	0.008 ± 0.01	0	0 ± 0
OSSF2	on-Z	(100, ∞)	0	0.05 ± 0.05	0	0 ± 0	0	0.13 ± 0.08	0	0 ± 0
OSSF2	off-Z	(50, 100)	0	0.01 ± 0.01	0	0 ± 0	0	0.01 ± 0.02	0	0 ± 0
OSSF2	on-Z	(50, 100)	0	0.39 ± 0.1	0	0 ± 0	0	0.16 ± 0.07	0	0 ± 0
OSSF2	off-Z	(0, 50)	0	0.11 ± 0.03	0	0 ± 0	0	0.05 ± 0.03	0	0 ± 0
OSSF2	on-Z	(0, 50)	2	3.3 ± 0.7	0	0 ± 0	1	0.37 ± 0.09	0	0 ± 0

Table 1: Results for 4 leptons wiht $H_T > 200$ GeV. $*$ denotes channels used as controls.

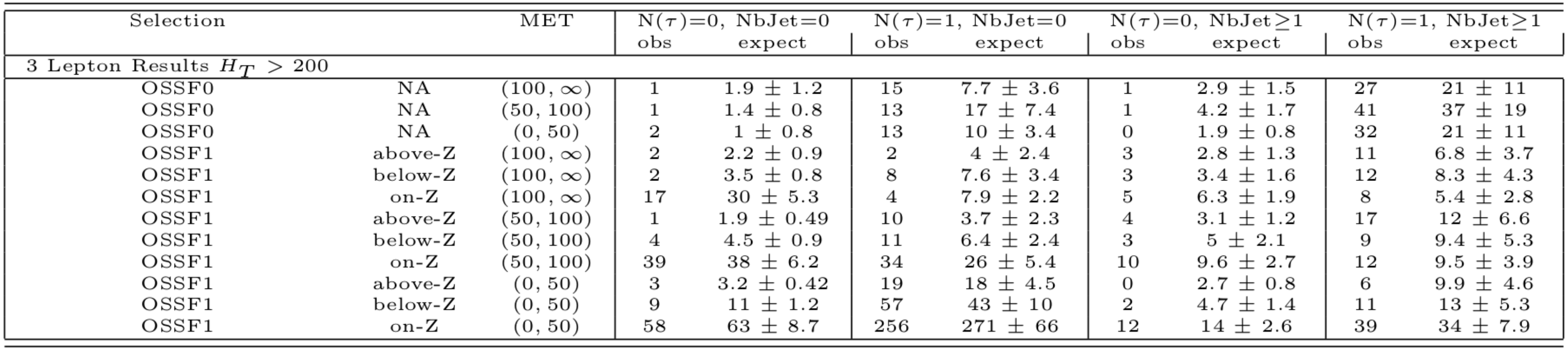
Results – MET/H_T Tables



Selection		MET	N(τ)=0, NbJet=0		N(τ)=1, NbJet=0		N(τ)=0, NbJet$\geq$1		N(τ)=1, NbJet$\geq$1	
			obs	expect	obs	expect	obs	expect	obs	expect
4 Lepton Results H_T < 200										
OSSF0	NA	(100, ∞)	0	0.0005 ± 0.009	0	0.5 ± 0.5	0	0 ± 0.009	0	0.04 ± 0.03
OSSF0	NA	(50, 100)	0	0.0005 ± 0.009	1	0.17 ± 0.1	0	0 ± 0.009	0	0.11 ± 0.07
OSSF0	NA	(0, 50)	0	0.005 ± 0.01	1	0.15 ± 0.07	0	0.001 ± 0.009	0	0.09 ± 0.05
OSSF1	off-Z	(100, ∞)	0	0.02 ± 0.01	2	0.18 ± 0.06	0	0.007 ± 0.01	0	0.07 ± 0.04
OSSF1	on-Z	(100, ∞)	0	0.18 ± 0.06	1	1 ± 0.18	1	0.15 ± 0.08	0	0.1 ± 0.05
OSSF1	off-Z	(50, 100)	0	0.05 ± 0.02	1	0.9 ± 0.3	0	0.02 ± 0.02	0	0.34 ± 0.19
OSSF1	on-Z	(50, 100)	1	0.47 ± 0.13	5	3.7 ± 0.6	1	0.15 ± 0.09	0	0.23 ± 0.08
OSSF1	off-Z	(0, 50)	1	0.16 ± 0.05	7	3.6 ± 1.1	0	0.04 ± 0.03	0	0.22 ± 0.1
OSSF1	on-Z	(0, 50)	1	1.3 ± 0.36	16	18 ± 5.2	0	0.16 ± 0.09	2	0.6 ± 0.22
OSSF2	off-Z	(100, ∞)	0	0.01 ± 0.01	0	0 ± 0	0	0.01 ± 0.02	0	0 ± 0
OSSF2	on-Z	(100, ∞)	0	0.14 ± 0.07	0	0 ± 0	0	0.26 ± 0.14	0	0 ± 0
OSSF2	off-Z	(50, 100)	2	0.05 ± 0.04	0	0 ± 0	0	0.01 ± 0.02	0	0 ± 0
OSSF2	on-Z	(50, 100)	1	1.2 ± 0.8	0	0 ± 0	0	0.21 ± 0.09	0	0 ± 0
OSSF2	off-Z	(0, 50)	3	3.7 ± 1	0	0 ± 0	1	0.11 ± 0.04	0	0 ± 0
OSSF2	on-Z	(0, 50)	76*	73 ± 16	0	0 ± 0	3	1.3 ± 0.31	0	0 ± 0

Table 2: Results for 4 leptons wiht $H_T < 200$ GeV. $*$ denotes channels used as controls.

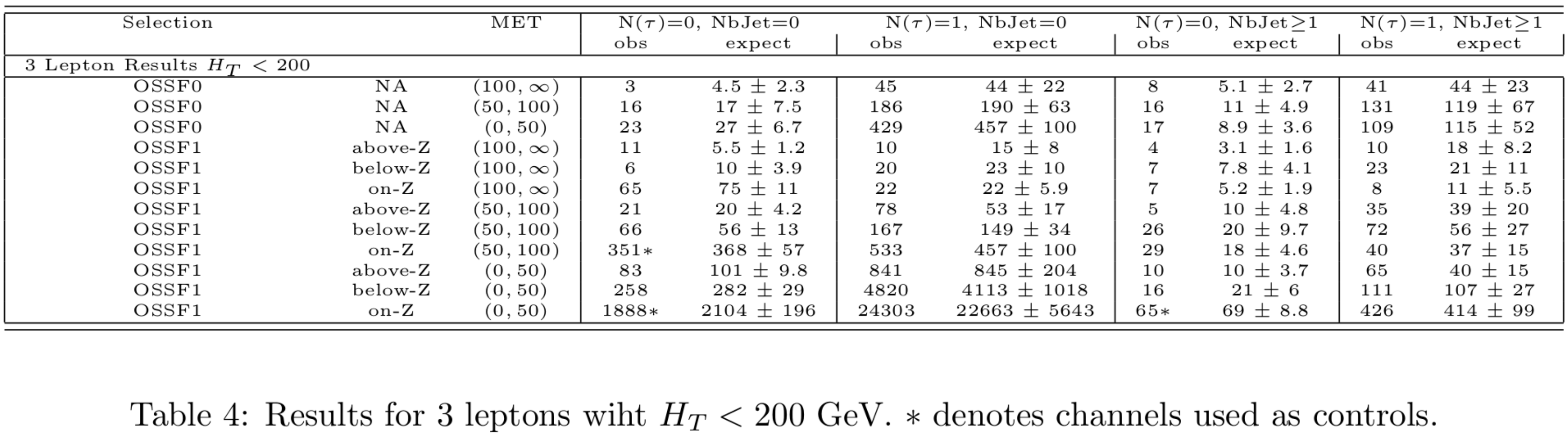
Results – MET/H_T Tables



Selection		MET	N(τ)=0, NbJet=0		N(τ)=1, NbJet=0		N(τ)=0, NbJet≥1		N(τ)=1, NbJet≥1	
			obs	expect	obs	expect	obs	expect	obs	expect
3 Lepton Results $H_T > 200$										
OSSF0	NA	$(100, \infty)$	1	1.9 ± 1.2	15	7.7 ± 3.6	1	2.9 ± 1.5	27	21 ± 11
OSSF0	NA	$(50, 100)$	1	1.4 ± 0.8	13	17 ± 7.4	1	4.2 ± 1.7	41	37 ± 19
OSSF0	NA	$(0, 50)$	2	1 ± 0.8	13	10 ± 3.4	0	1.9 ± 0.8	32	21 ± 11
OSSF1	above-Z	$(100, \infty)$	2	2.2 ± 0.9	2	4 ± 2.4	3	2.8 ± 1.3	11	6.8 ± 3.7
OSSF1	below-Z	$(100, \infty)$	2	3.5 ± 0.8	8	7.6 ± 3.4	3	3.4 ± 1.6	12	8.3 ± 4.3
OSSF1	on-Z	$(100, \infty)$	17	30 ± 5.3	4	7.9 ± 2.2	5	6.3 ± 1.9	8	5.4 ± 2.8
OSSF1	above-Z	$(50, 100)$	1	1.9 ± 0.49	10	3.7 ± 2.3	4	3.1 ± 1.2	17	12 ± 6.6
OSSF1	below-Z	$(50, 100)$	4	4.5 ± 0.9	11	6.4 ± 2.4	3	5 ± 2.1	9	9.4 ± 5.3
OSSF1	on-Z	$(50, 100)$	39	38 ± 6.2	34	26 ± 5.4	10	9.6 ± 2.7	12	9.5 ± 3.9
OSSF1	above-Z	$(0, 50)$	3	3.2 ± 0.42	19	18 ± 4.5	0	2.7 ± 0.8	6	9.9 ± 4.6
OSSF1	below-Z	$(0, 50)$	9	11 ± 1.2	57	43 ± 10	2	4.7 ± 1.4	11	13 ± 5.3
OSSF1	on-Z	$(0, 50)$	58	63 ± 8.7	256	271 ± 66	12	14 ± 2.6	39	34 ± 7.9

Table 3: Results for 3 leptons wiht $H_T > 200$ GeV. $*$ denotes channels used as controls.

Results – MET/H_T Tables



Selection		MET	N(τ)=0, NbJet=0		N(τ)=1, NbJet=0		N(τ)=0, NbJet$\geq$1		N(τ)=1, NbJet$\geq$1	
			obs	expect	obs	expect	obs	expect	obs	expect
3 Lepton Results $H_T < 200$										
OSSF0	NA	$(100, \infty)$	3	4.5 ± 2.3	45	44 ± 22	8	5.1 ± 2.7	41	44 ± 23
OSSF0	NA	$(50, 100)$	16	17 ± 7.5	186	190 ± 63	16	11 ± 4.9	131	119 ± 67
OSSF0	NA	$(0, 50)$	23	27 ± 6.7	429	457 ± 100	17	8.9 ± 3.6	109	115 ± 52
OSSF1	above-Z	$(100, \infty)$	11	5.5 ± 1.2	10	15 ± 8	4	3.1 ± 1.6	10	18 ± 8.2
OSSF1	below-Z	$(100, \infty)$	6	10 ± 3.9	20	23 ± 10	7	7.8 ± 4.1	23	21 ± 11
OSSF1	on-Z	$(100, \infty)$	65	75 ± 11	22	22 ± 5.9	7	5.2 ± 1.9	8	11 ± 5.5
OSSF1	above-Z	$(50, 100)$	21	20 ± 4.2	78	53 ± 17	5	10 ± 4.8	35	39 ± 20
OSSF1	below-Z	$(50, 100)$	66	56 ± 13	167	149 ± 34	26	20 ± 9.7	72	56 ± 27
OSSF1	on-Z	$(50, 100)$	351*	368 ± 57	533	457 ± 100	29	18 ± 4.6	40	37 ± 15
OSSF1	above-Z	$(0, 50)$	83	101 ± 9.8	841	845 ± 204	10	10 ± 3.7	65	40 ± 15
OSSF1	below-Z	$(0, 50)$	258	282 ± 29	4820	4113 ± 1018	16	21 ± 6	111	107 ± 27
OSSF1	on-Z	$(0, 50)$	1888*	2104 ± 196	24303	22663 ± 5643	65*	69 ± 8.8	426	414 ± 99

Table 4: Results for 3 leptons wiht $H_T < 200$ GeV. $*$ denotes channels used as controls.

Limit Setting Procedure

- We compute LHC-style CL_s limits using LandS, as recommended for CMS analyses
- To do so, we determine the most sensitive channels for each grid points (based on the expected limit of each single channel)
- We use as many channels as are required to cover 90% of the signal, up to 42 channels

SUS-13-003:
Stop RPV

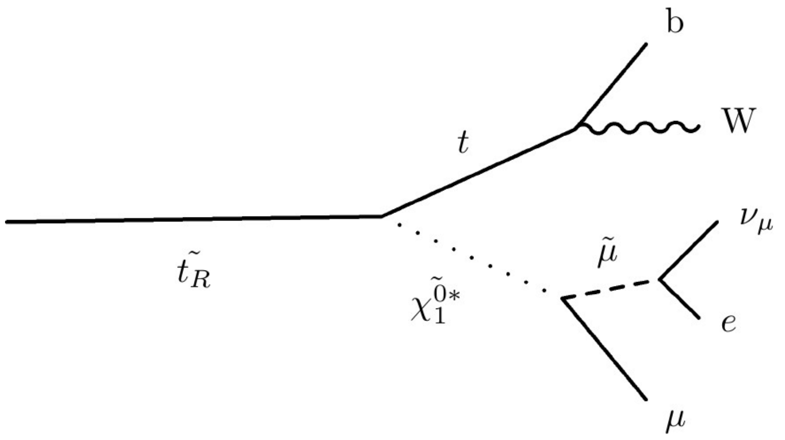
- Naturally, in a multilepton analysis, we look at RPV couplings that produce leptons
- $W_{RPV} = \underbrace{\lambda_{ijk} L^i L^j \bar{E}^k}_{\text{leptonic}} + \underbrace{\lambda'_{ijk} L^i Q^j \bar{D}^k}_{\text{mixed}} + \lambda''_{ijk} \bar{U}^i \bar{D}^j \bar{D}^k + \epsilon_i L_i H_2$

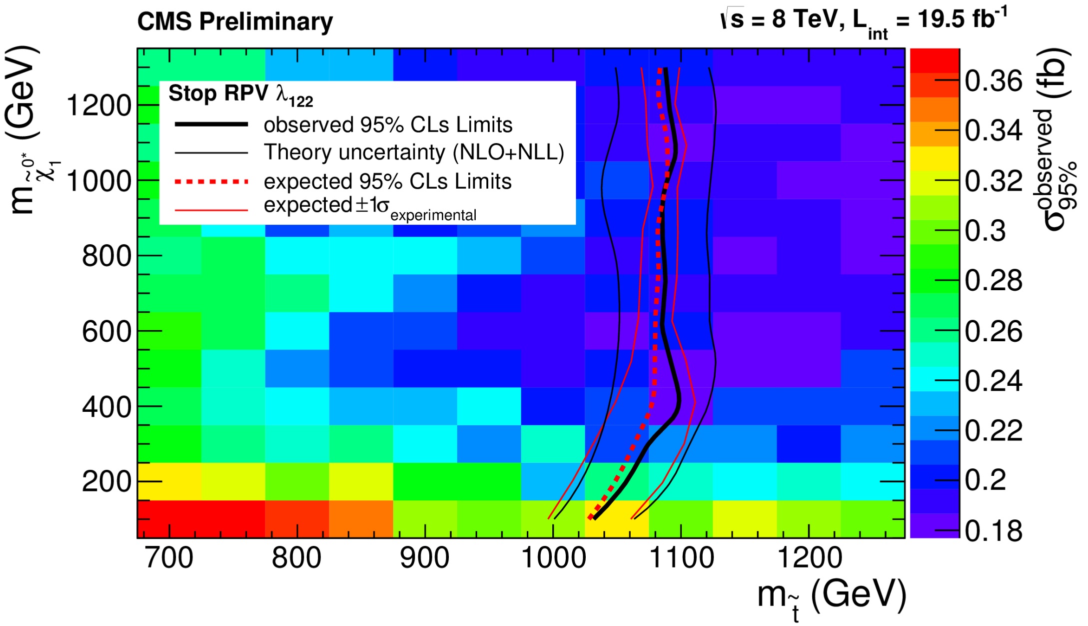
Coupling	LLE 122	LLE 233	LQD 233
decay products per stop	ℓ ℓ ν t	ℓ τ ν t τ τ ν t	ν b b t ℓ b t t
stop mass	700–1250 GeV stepsize: 50 GeV	700–1250 GeV stepsize: 50 GeV	300–1000 GeV stepsize: 50 GeV
bino mass	100–1300 GeV stepsize: 100 GeV	100–1300 GeV stepsize: 100 GeV	200–850 GeV stepsize: 50 GeV
Number of events	10k	20k	40k

SUS-13-003:
Stop RPV – LLE 122

$$W_{RPV} = \lambda_{ijk} L^i L^j \bar{E}^k + \lambda'_{ijk} L^i Q^j \bar{D}^k + \lambda''_{ijk} \bar{U}^i \bar{D}^j \bar{D}^k + \epsilon_i L_i H_2$$

leptonic



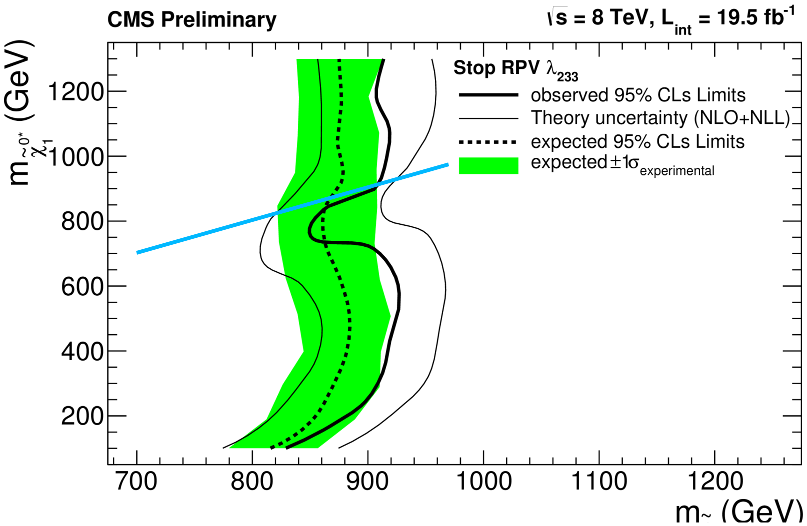


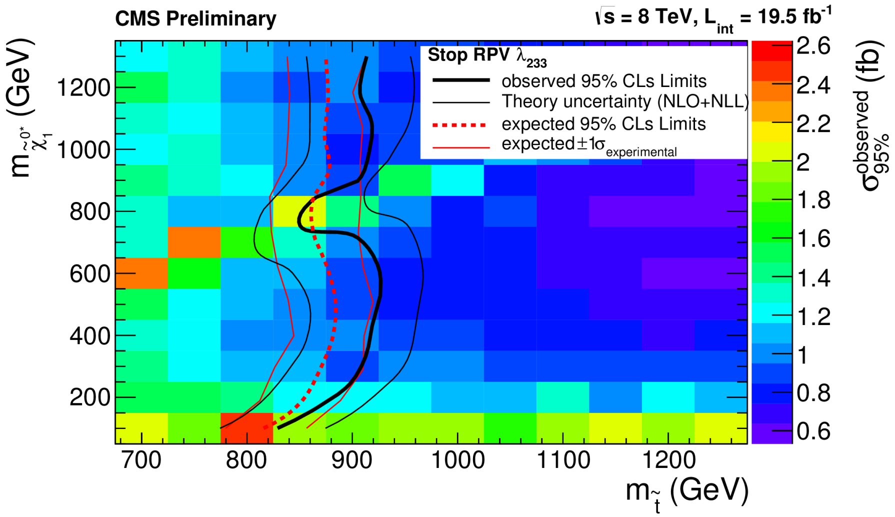
- Stop RPV model with LLE 122 coupling non-zero
- Excluding stop masses below 1050–1100 GeV; approximately independent of bino mass which decouples → little structure

SUS-13-003: Stop RPV – LLE 233

- Four-body decay above diagonal, two-body below
- In transition region, top is off-shell → low p_T leptons reduce sensitivity
- Additionally, a fluctuation in observation becomes relevant:

  3 leptons (no tau), OSSF pair above Z, $1000 < S_T < 1500$ GeV



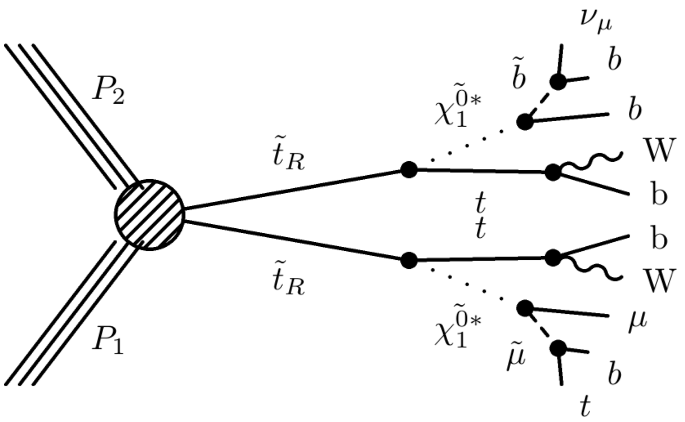


SUS-13-003:
Stop RPV – LQD 233

$$W_{RPV} = \lambda_{ijk}L^iL^j\bar{E}^k + \lambda'_{ijk}L^iQ^j\bar{D}^k + \lambda''_{ijk}\bar{U}^i\bar{D}^j\bar{D}^k + \epsilon_iL_iH_2$$

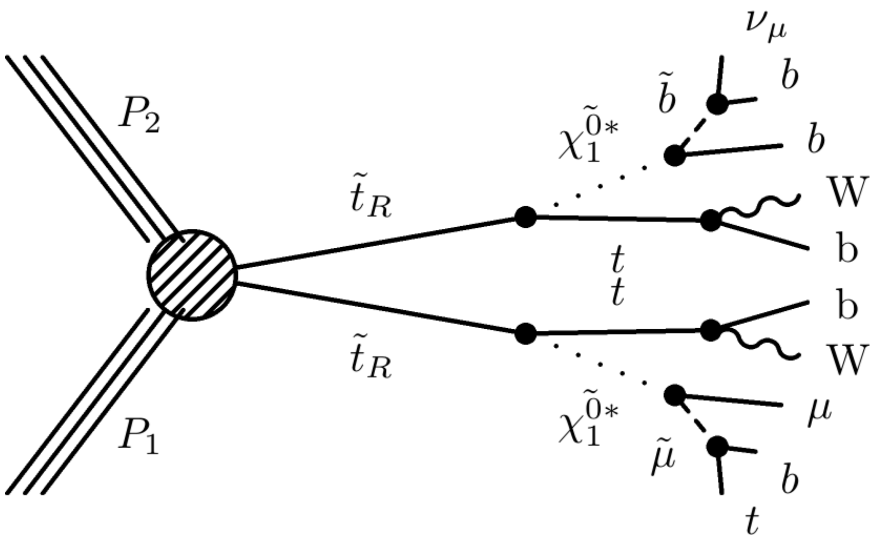
mixed

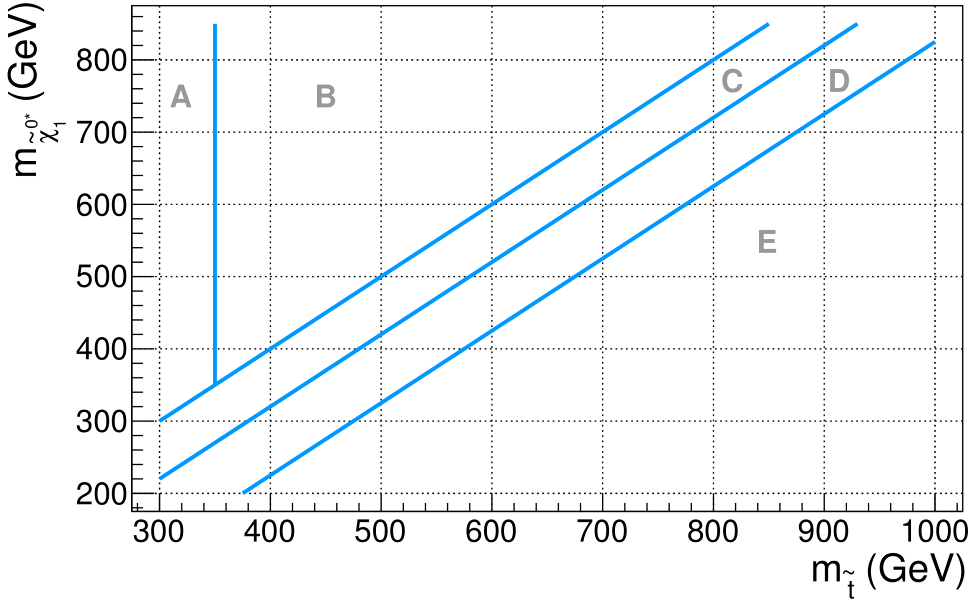
- The model produces one bino per stop
- Bino decays to νb$\bar{b}$ or μt$\bar{b}$
  → expect more structure due to presence of massive particles



SUS-13-003:
Stop RPV – LQD 233

$$W_{RPV} = \lambda_{ijk} L^i L^j \bar{E}^k + \lambda'_{ijk} L^i Q^j \bar{D}^k + \lambda''_{ijk} \bar{U}^i \bar{D}^j \bar{D}^k + \epsilon_i L_i H_2$$





- In each kinematic region, the BR to leptons and the cross-section change as the stop mass increases → acceptance varies

region label	kinematic region	stop decay mode(s)
A	$m_t < m_{\tilde{t}} < 2m_t, m_{\tilde{\chi}_1^0}$	$\tilde{t} \to t\nu b\bar{b}$
B	$2m_t < m_{\tilde{t}} < m_{\tilde{\chi}_1^0}$	$\tilde{t} \to t\mu t\bar{b} + t\nu b\bar{b}$
C	$m_{\tilde{\chi}_1^0} < m_{\tilde{t}} < m_W + m_{\tilde{\chi}_1^0}$	$\tilde{t} \to \ell\nu b\tilde{\chi}_1^0 + jjb\tilde{\chi}_1^0$
D	$m_W + m_{\tilde{\chi}_1^0} < m_{\tilde{t}} < m_t + m_{\tilde{\chi}_1^0}$	$\tilde{t} \to Wb\tilde{\chi}_1^0$
E	$m_t + m_{\tilde{\chi}_1^0} < m_{\tilde{t}}$	$\tilde{t} \to t\tilde{\chi}_1^0$

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Stop RPV – LQD 233

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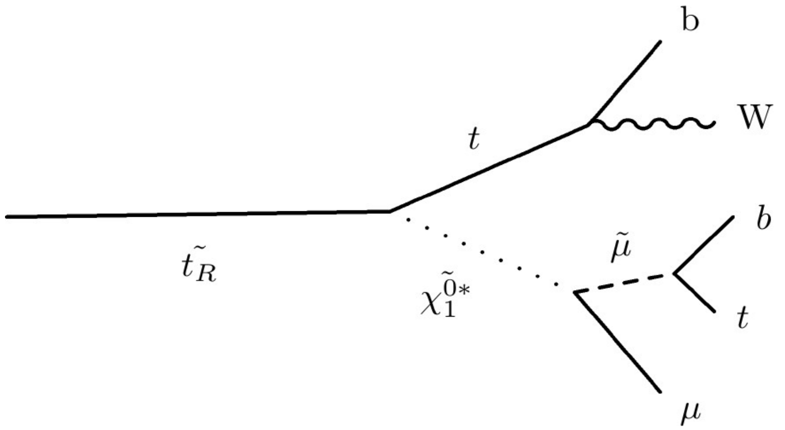

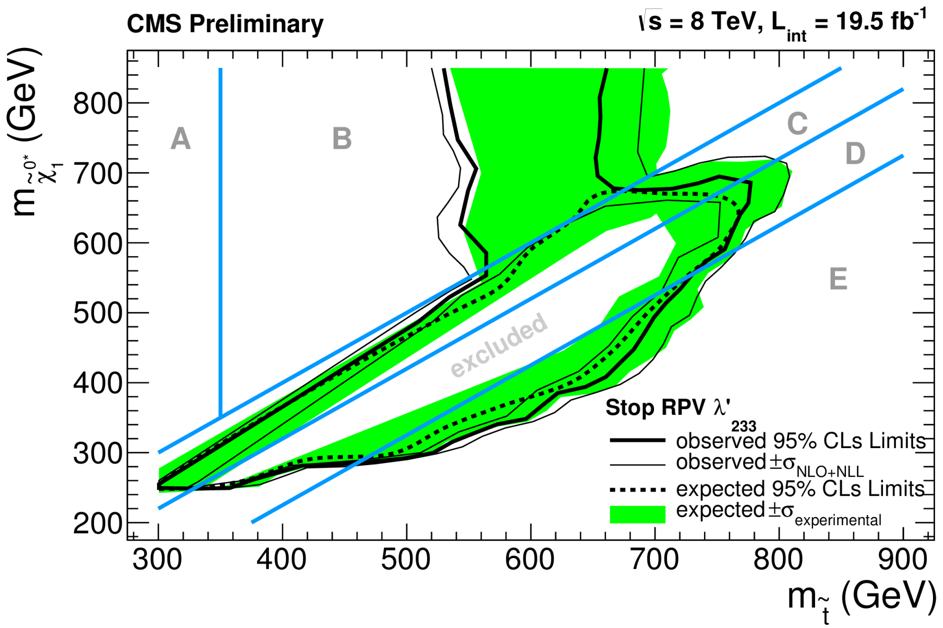

- Stop RPV model with LQD 233 coupling non-zero
- Several kinematic regions with different acceptance

region label	kinematic region	stop decay mode(s)
A	$m_t < m_{\tilde{t}} < 2m_t, m_{\tilde{\chi}_1^0}$	$\tilde{t} \to t\nu b\bar{b}$
B	$2m_t < m_{\tilde{t}} < m_{\tilde{\chi}_1^0}$	$\tilde{t} \to t\mu t\bar{b} + t\nu b\bar{b}$
C	$m_{\tilde{\chi}_1^0} < m_{\tilde{t}} < m_W + m_{\tilde{\chi}_1^0}$	$\tilde{t} \to \ell\nu b\tilde{\chi}_1^0 + jjb\tilde{\chi}_1^0$
D	$m_W + m_{\tilde{\chi}_1^0} < m_{\tilde{t}} < m_t + m_{\tilde{\chi}_1^0}$	$\tilde{t} \to Wb\tilde{\chi}_1^0$
E	$m_t + m_{\tilde{\chi}_1^0} < m_{\tilde{t}}$	$\tilde{t} \to t\tilde{\chi}_1^0$

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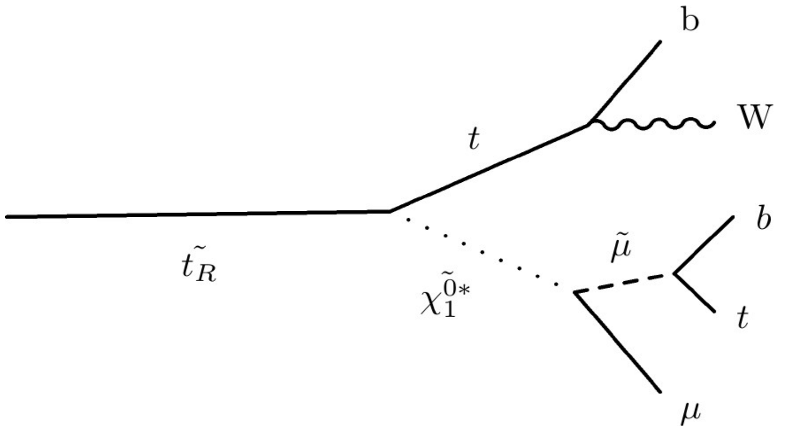
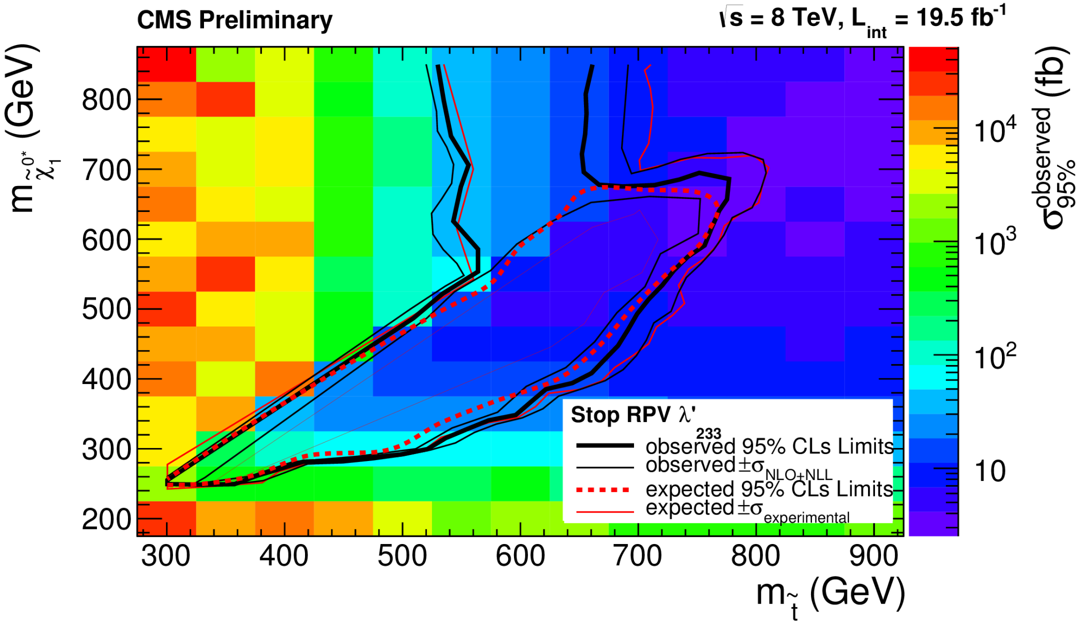
Stop RPV – LQD 233

$$W_{RPV} = \lambda_{ijk}L^iL^j\bar{E}^k + \lambda'_{ijk}L^iQ^j\bar{D}^k + \lambda''_{ijk}\bar{U}^i\bar{D}^j\bar{D}^k + \epsilon_i L_i H_2$$





region label	kinematic region	stop decay mode(s)
A	$m_t < m_{\tilde{t}} < 2m_t, m_{\tilde{\chi}_1^0}$	$\tilde{t} \to t\nu b\bar{b}$
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D	$m_W + m_{\tilde{\chi}_1^0} < m_{\tilde{t}} < m_t + m_{\tilde{\chi}_1^0}$	$\tilde{t} \to Wb\tilde{\chi}_1^0$
E	$m_t + m_{\tilde{\chi}_1^0} < m_{\tilde{t}}$	$\tilde{t} \to t\tilde{\chi}_1^0$

- Stop RPV model with LQD 233 coupling non-zero
- Several kinematic regions with different acceptance