Search for Type-III Seesaw Heavy Fermions With Multilepton Final States using 2.3 fb^{-1} of $\sqrt{s}$ = 13 TeV proton–proton Collision Data

Ph. D. Defense

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RUTGERS

Outline

- Introduction
- Theoretical Overview
- Experimental Apparatus
- Datasets and Event Selection
- Search Strategy
- Background Estimation
- Systematic Uncertainties
- Results

Bio

- Bachelor's and Master's program at Würzburg University (Germany)
- Participated in exchange year to Rutgers during 1st year of Master's
  - full switch to Rutgers after exchange year
  - Master's degree awarded in 2012 (SUSY search at $\sqrt{s} = 7$ TeV)
- Enrolled as a Ph. D. student at Rutgers
  - qualifiers along with Master's defense
- Received financial support from
  - sdw (Foundation of German Business)
  - DAAD (German Academic Exchange Service)
  - NSF
  - Rutgers

Contributions during LHC Run I

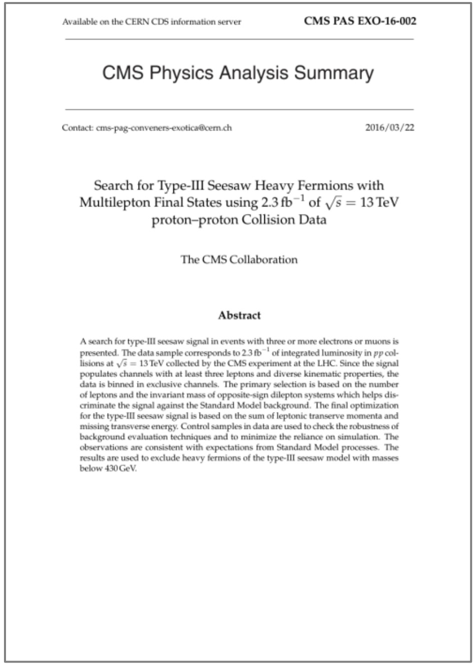
- Involved with the Rutgers Multilepton search
  - Very broad, generic search with interpretations mostly in SUSY
  - Contributed code for statistical interpretation
- Resulted in 6 papers
  - various SUSY and Heavy Higgs models
  - $t \rightarrow cH$ measurement
  - Results were combined with other research groups
  - Acted as a contact person for the combination
- Also participated in PLT detector development
  - Pixel Luminosity Telescope: a luminometer for CMS, installed by now

Preparation for LHC Run II

- Wrote new software framework (together with Matt Walker)
  - computes all quantities that are of interest for the analysis
  - categorizes event into search regions
  - estimates background in each region
  - produces output files used for statistical interpretation
- Used the new software framework to
  - reproduce Run I results
  - refine background estimation methods used during Run I, anticipating Run II needs
- Rest of the talk focused on work for Run II Seesaw result

Motivation

- While the Standard Model (SM) describes most particle phenomena with remarkable accuracy, some issues remain
  - Example: Neutrino mass is small, but not zero
- Extensions to the SM have been proposed to remedy these issues
  - The "seesaw mechanism" explains why neutrinos are so light by postulating massive partner particles (which decay to SM particles)
- This search looks for evidence of these heavy particles in final states with at least 3 leptons
  - It was announced by CMS on March 22, 2016



Available on the CERN CDS information server **CMS PAS EXO-16-002**

CMS Physics Analysis Summary

Contact: cms-pag-conveners-exotica@cern.ch 2016/03/22

Search for Type-III Seesaw Heavy Fermions with Multilepton Final States using 2.3 fb^{-1} of $\sqrt{s} = 13$ TeV proton–proton Collision Data

The CMS Collaboration

Abstract

A search for type-III seesaw signal in events with three or more electrons or muons is presented. The data sample corresponds to 2.3 fb^{-1} of integrated luminosity in pp collisions at $\sqrt{s} = 13$ TeV collected by the CMS experiment at the LHC. Since the signal populates channels with at least three leptons and diverse kinematic properties, the data is binned in exclusive channels. The primary selection is based on the number of leptons and the invariant mass of opposite-sign dilepton systems which helps discriminate the signal against the Standard Model background. The final optimization for the type-III seesaw signal is based on the sum of leptonic transerve momenta and missing transverse energy. Control samples in data are used to check the robustness of background evaluation techniques and to minimize the reliance on simulation. The observations are consistent with expectations from Standard Model processes. The results are used to exclude heavy fermions of the type-III seesaw model with masses below 430 GeV.

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Standard Model of Particle Physics

- Quantum Field Theory of elementary particles
  - leptons, quarks, bosons
- … and their interactions
  - electromagnetism
  - weak interaction
  - strong interaction

	particle	mass $[\mathrm{MeV}/c^2]$	spin	electrical charge $[e]$
		fermions		
leptons	e	0.511	$1/2$	-1
	ν_e	$0 < m_{\nu_e} < 2.2 \cdot 10^{-6}$	$1/2$	0
	μ	105.7	$1/2$	-1
$L = 1$,	ν_μ	$0 < m_{\nu_\mu} < 0.17$	$1/2$	0
$B = 0$	τ	$1.78 \cdot 10^3$	$1/2$	-1
	ν_τ	$0 < m_{\nu_\tau} < 15.5 \cdot 10^{-6}$	$1/2$	0
quarks	u	2.4	$1/2$	$2/3$
	d	4.8	$1/2$	$-1/3$
	c	$1.27 \cdot 10^3$	$1/2$	$2/3$
$L = 0$,	s	104	$1/2$	$-1/3$
$B = 1/3$	t	$173.34 \cdot 10^3$	$1/2$	$2/3$
	b	$4.2 \cdot 10^3$	$1/2$	$-1/3$
		bosons		
	γ	0	1	0
	g	0	1	0
$L = 0$,	Z	$91.2 \cdot 10^3$	1	0
$B = 0$	$\mathrm{W}^\pm$	$80.4 \cdot 10^3$	1	± 1
	H	$125.09 \cdot 10^3$	0	0

Table 2.1: Elementary particles in the Standard Model [7, 18, 19]. For electrically charged particles, anti-particles with opposite charge exist. Neutrinos presumably have anti-particles with opposite chirality. Anti-particles have been omitted in this summary.

Shortcomings of the Standard Model

- While remarkably successful, the following issues remain:
  - The SM does not describe *gravity* at all.
  - The SM does not explain *Dark Matter*.
  - The Higgs boson mass is expected around 10^{15} GeV within the SM, but it is in fact on the electroweak scale (125 GeV). This is called the *Hierarchy Problem*.
  - This *very small neutrino mass* is not motivated within the SM.
- The last issue may be resolved by extending the SM with additional heavy fermions that couple to leptons ("seesaw mechanism")
  - The purpose of this search is to look for such seesaw signal with ≥ 3 e/μ

Seesaw Mechanism

- Small Majorana mass is mediated by massive partners with Yukawa copulings to leptons through Higgs
- Type I: Invokes a right-handed singlet state
- Type II: Scalar triplet state
- <u>Type III</u>: Implements particle mass for fermionic SU(2) triplet
  - Heavy Dirac charged leptons: $\Sigma^{\pm}$
  - Heavy Majorana neutral lepton: Σ^{0}

C. Biggio and F. Bonnet, "Implementation of the type III seesaw model in FeynRules /MadGraph and prospects for discovery with early LHC data", Eur. Phys.J. C (2012) 72:1899, doi:10.1140/epjc/s10052-012-1899-z

Phenomenology

- Heavy fermions are produced in pairs
  - $\Sigma^+\Sigma^0, \Sigma^-\Sigma^0, \Sigma^+\Sigma^-$
- Decay modes (per fermion):
  - $\Sigma^\pm \rightarrow W^\pm \upsilon, \Sigma^\pm \rightarrow Z\, l^\pm, \ \Sigma^\pm \rightarrow H\, l^\pm$
  - $\Sigma^0 \rightarrow W^\pm l^\pm, \Sigma^0 \rightarrow Z\upsilon, \ \Sigma^0 \rightarrow H\upsilon$
- We consider all 27 channels, combining production + decays

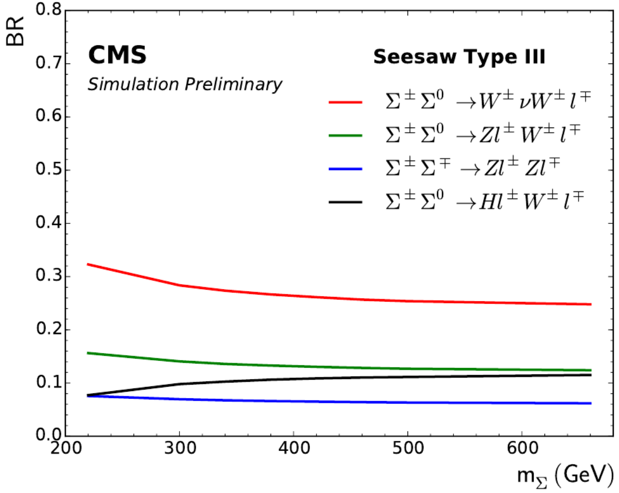


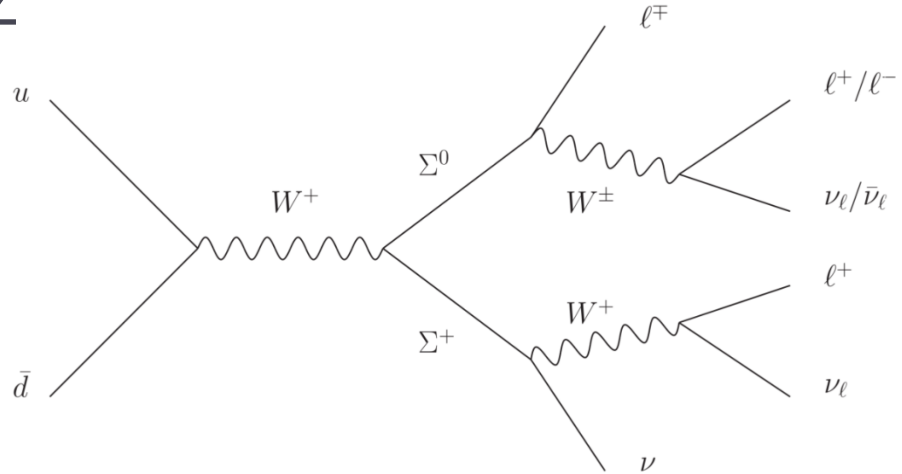
Figure 2.3: Branching ratios from the pair-produced fermions to the bosonic level of the most relevant decay modes.

Table 4: Seesaw production cross-sections

Process	σ at 220 GeV [pb]	σ at 340 GeV [pb]
$\Sigma^+\Sigma^0$	0.60	0.113
$\Sigma^-\Sigma^0$	0.31	0.053
$\Sigma^+\Sigma^-$	0.45	0.081

Phenomenology (II)

- How do multileptons (≥ 3) arise?
  - Most modes produce a lepton directly
  - W, Z, H yield ≥ 2 additional leptons
  - Leptons might be on or off Z
- If W's are present, some MET is expected
- We don't expect b-jets or very high hadronic activity



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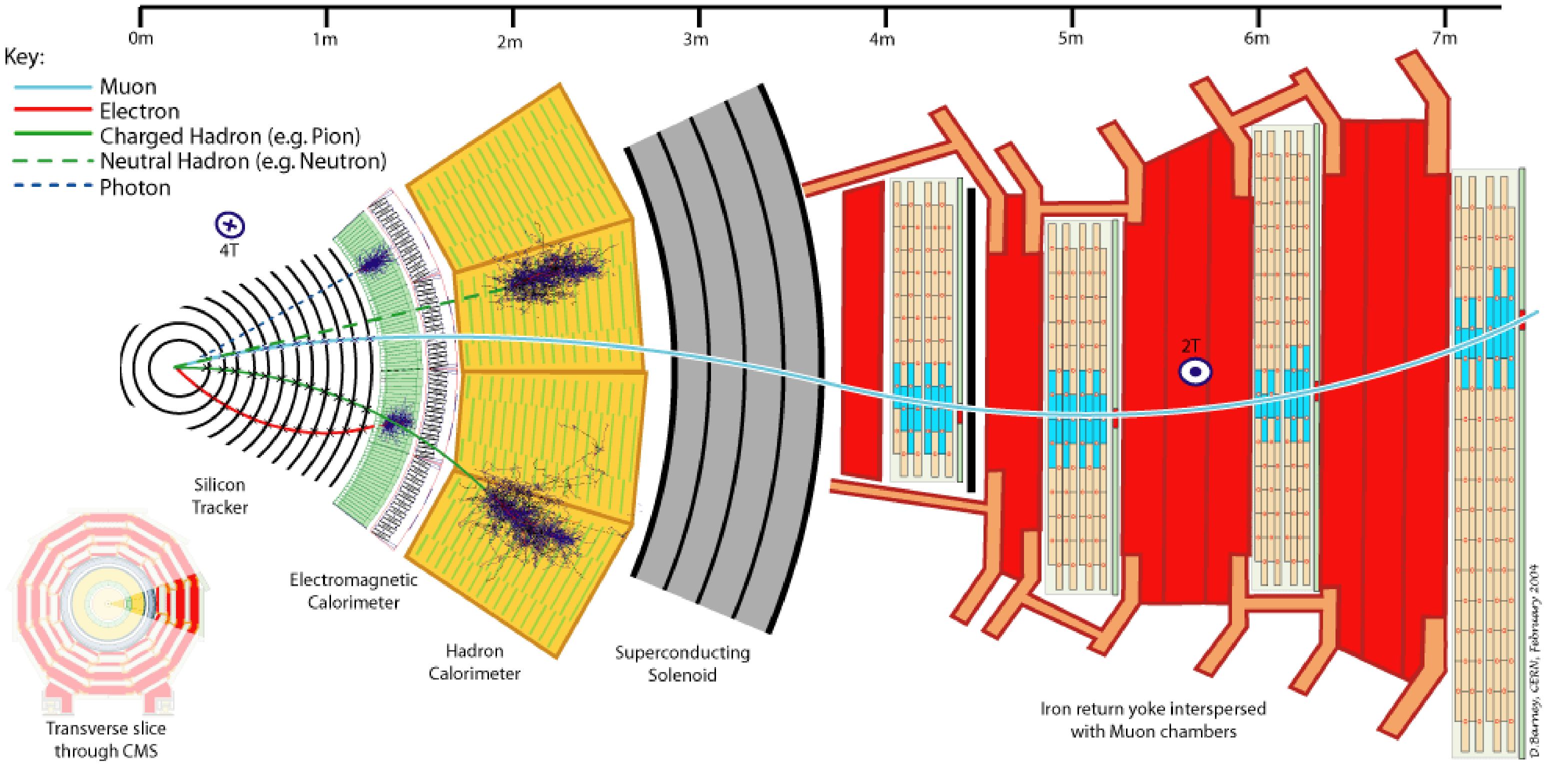
Large Hadron Collider

- Operated by CERN
- Located 100 m underground near Geneva (Switzerland)
- 26.7 km circumference
- ~ 1200 superconducting magnets $\rightarrow$ field of 8.33 T
  - used to accelerate protons which collide at designated interaction points surrounded by particle detectors
- Design center-of-mass energy $\sqrt{s}$ = 14 TeV
- 2015: $\sqrt{s}$ = 13 TeV with 25 ns bunch spacing

CMS Detector

- Large, general purpose detector system at the LHC
  - 15 m diameter, weight of 12,500 tons
  - Main feature: Superconducting solenoid, providing a 3.8 T magnetic field for precise measurement of charged particles
- Coordinate system:
  - *x* towards center, *y* upwards, *z* along beampipe (counterclockwise)
  - cylindrical coordinates ϕ and θ; pseudorapidity $\eta = -\log \tan(\theta/2)$
  - distance measurements: $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$
- 2015 integrated luminosity: 2.3 fb^{-1}
  - Trigger system to skim data before permanent storage

Slice through the CMS Detector



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Data samples

- Triggers, reconstruction periods, and integrated luminosity listed on the right

Table 4.1: Data samples.

Primary Dataset	Reconstruction labels	L [fb^{-1}]
DoubleEG	Run2015D-05Oct2015-v1	0.59
DoubleEG	Run2015D-PromptReco-v4	1.66
DoubleMuon	Run2015D-05Oct2015-v1	0.59
DoubleMuon	Run2015D-PromptReco-v4	1.66
MuonEG	Run2015D-05Oct2015-v1	0.59
MuonEG	Run2015D-PromptReco-v4	1.66

- p_T (transverse momentum) thresholds:
  - DoubleEG: 17 GeV, 12 GeV
  - DoubleMuon: 17 GeV, 8 GeV
  - MuonEG: a) 17 GeV μ, 12 GeV e; b) 17 GeV e, 8 GeV μ

Object ID and Preselection

- Selections:
  - Using standard object ID
  - electrons: $p_T > 10$ GeV, $|\eta| < 2.5$, non-triggering MVA (tight)
  - muons: $p_T > 10$ GeV, $|\eta| < 2.4$, medium ID
  - jets: $p_T > 30$ GeV, $|\eta| < 2.4$
- Leptons are required to pass
  - 20/15/10 GeV thresholds (to achieve trigger efficiency ~100%)
  - $d_z < 0.1$cm, $d_{xy} < 0.05$cm (rejecting leptons from heavy quark decays)
- We reject events with an opposite-sign same-flavor (OSSF) lepton pair with an invariant mass below 12 GeV (low-mass resonances like J/Ψ, …)

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Search Strategy: Event Classification

- Basics: require 3 or more light leptons
- Apart from that: Don't cut, but bin in certain event properties
  - Take advantage of the power of cuts (high signal-to-background ratio), but still make use of the rest of the data
- Bin in the number of leptons
- Bin in the number of opposite-sign same-flavor (OSSF) pairs
  - For events with an OSSF pair, categorize by its invariant mass (below/on/above Z window, which is 91 ± 10 GeV)
- Bin in L_T + MET (details later)

Signal Regions: Kinematic Binning

- The signal populates regions with 3 or $\geq$ 4 leptons, both with or without OSSF pairs which may (or may not) be on Z
- The transverse momentum sum (L_T) of the signal leptons is much higher than from standard model background, due to the higher parent particle masses (~400 GeV)
- However, the amount of MET and the signal lepton p_T's vary depending on the decay channel. Examples:
  - $\Sigma^{\pm} \rightarrow l^{\pm} Z \rightarrow l^{\pm} l'^{+} l'^{-}$ high lepton p_T's, no MET
  - $\Sigma^{0} \rightarrow H\upsilon \rightarrow WW\upsilon$ lower lepton p_T's, significant MET
- The quantity L_T + MET covers both cases

Signal Regions: Kinematic Binning

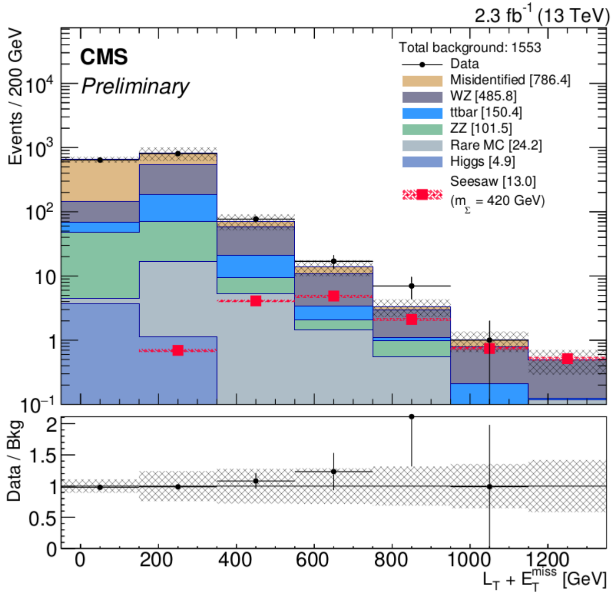

Figure 6.3: $L_{\mathrm{T}} + E_{\mathrm{T}}^{\mathrm{miss}}$ distribution after event selection cuts from Sec. 5.2, to illustrate the signal separation power of this variable (last bin includes overflow). Backgrounds are described in Chapter 7. The signal ($m_\Sigma = 420\,\mathrm{GeV}$, sum of all production and decay modes) is shown as white square dots with a pink hashed uncertainty band. The background uncertainty is specified by the gray band. Uncertainty bands include both statistical and systematic uncertainties. Numbers in square brackets denote the number of events contributed by each process.

Signal Regions

- This leads us to the following binning scheme (total: 20)

Table 6.1: Signal Regions. Overlap with control regions removed everywhere.

n_{leptons}	OSSF pair	$L_T + E_T^{\text{miss}}$ [GeV]
3		
	none	350..1150 in steps of 200, plus overflow
	on-Z	
	above-Z	
≥ 4	≥ 1	350..1150 in steps of 200, plus overflow

- Overlap with background control regions is removed (details later)

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Background Estimation

- Backgrounds in the top 10 most signal sensitive regions, by relative importance:
  - WZ $\rightarrow$ lll: about 51%
  - fully leptonic ttbar decays with a fake lepton from a b-jet: about 21%
  - Z $\rightarrow$ ll + fake lepton from a jet: about 17%
  - ZZ $\rightarrow$ 4l: about 3%
  - rare backgrounds (ttV, VVV, Higgs)
- Most background estimates are data-driven / data-normalized
  - foundations of these methods come from Run I research

Background Estimation

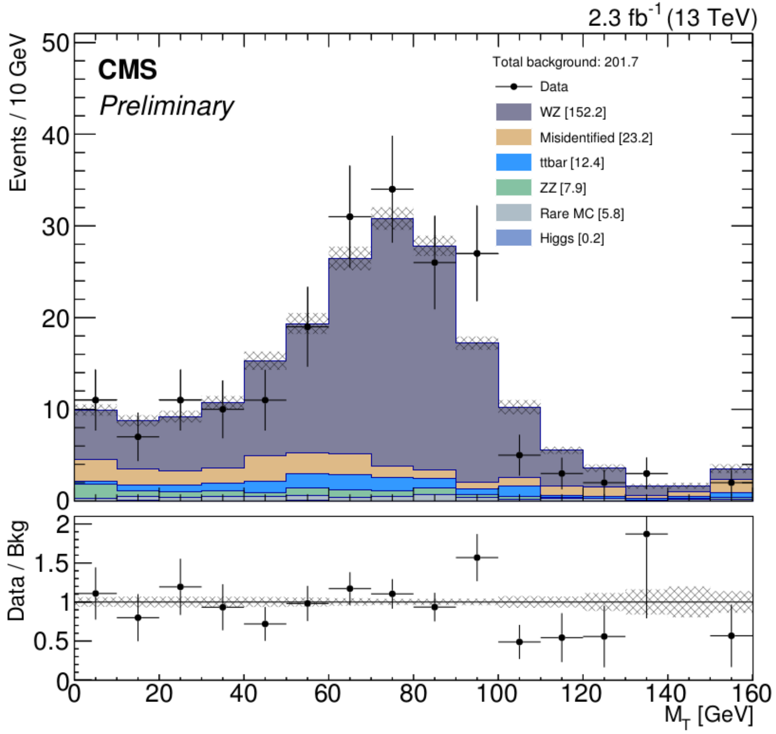
- General approach: WZ and ZZ are obtained from simulation, but normalized and weighted in data control regions where necessary
- For fake processes (Z + fake, ttbar + fake), fake rates are measured in control regions
  - Z + fake fully data-driven
  - In ttbar, we use a data-driven fake rate with kinematics from MC

	n_{leptons}	OS pair	$n_{\text{b-tags}}$	S_T [GeV]	E_T^{miss} [GeV]
$t\bar{t}$	2	1 opposite flavor	≥ 1	> 300	
Z + fake	3	1 same flavor, on-Z			< 50
WZ	3	1 same flavor, on-Z			50–150
ZZ	≥ 4	2 same flavor, at least one on-Z			< 50

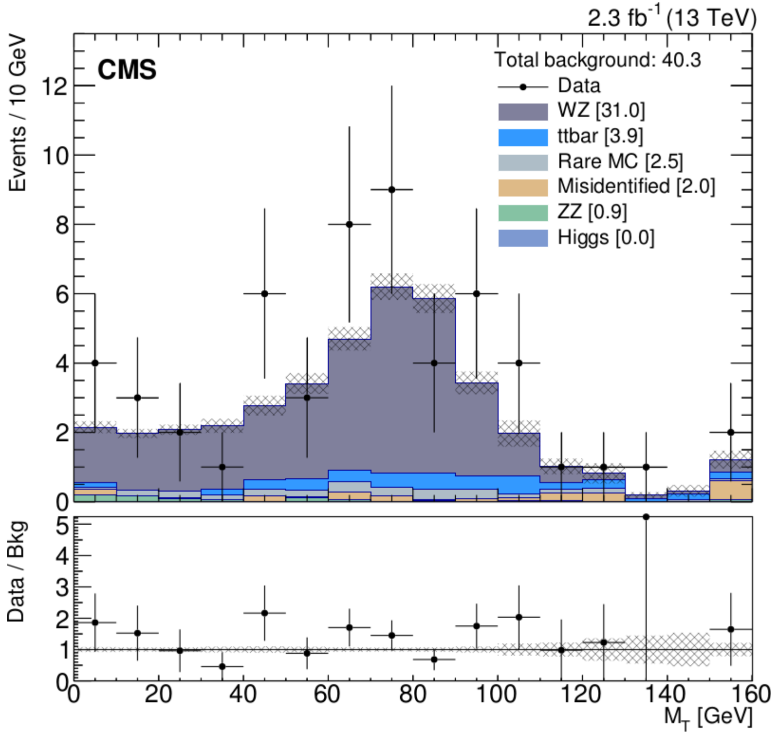
3L Background: WZ

- Primary background: around 51%
- WZ simulation is compared in M_T distribution for three leptons
  - Control region: 3L incl. OSSF pair on Z, 50 GeV < MET < 100 GeV
- Normalization factor: 0.95 ± 0.07(stat)
- No need for n_{jets} weights
- Based on comparison with 100 GeV < MET < 150 GeV, we apply a systematic uncertainty of 50%

3L Background: WZ



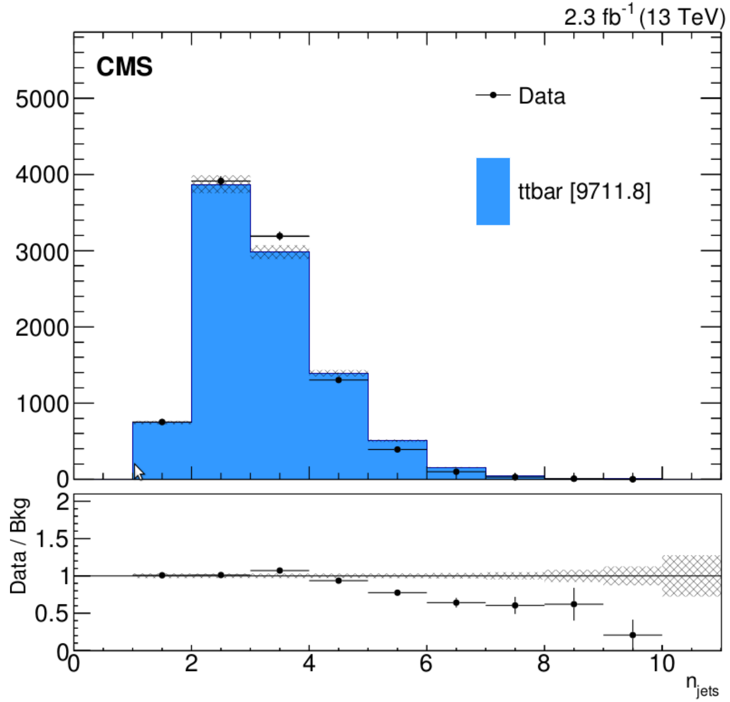
(a) $50\,\text{GeV} < E_T^{\text{miss}} < 100\,\text{GeV}$



(b) $100\,\text{GeV} < E_T^{\text{miss}} < 150\,\text{GeV}$

3L Background: ttbar (2L studies)

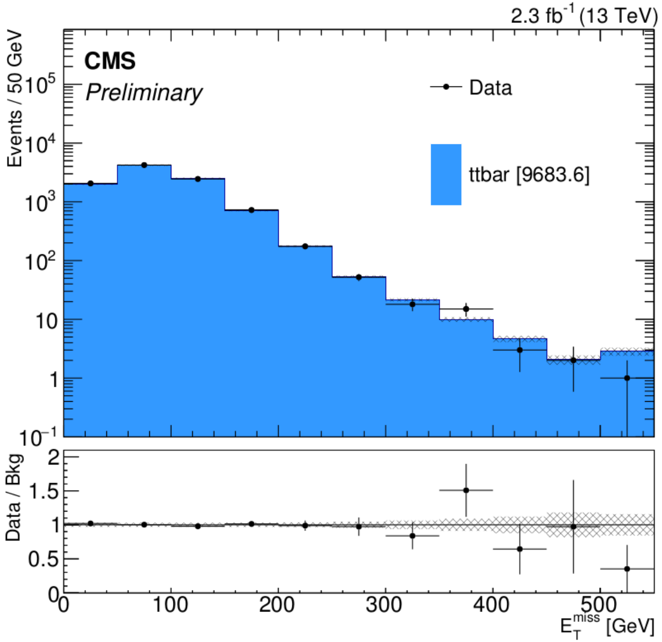
- ttbar makes up about 21%
- We rely on MC for process-specific kinematic properties
  - Therefore, we first make sure the simulation is reliable in dileptons
- Normalization: 0.80 ± 0.01(stat)
- We compare the n_{jets} distribution for dilepton events with an opposite-sign electron-muon pair and S_T > 300 GeV
  - apply n_{jets} weights



(a) $n_{\rm jets}$ distribution before weights

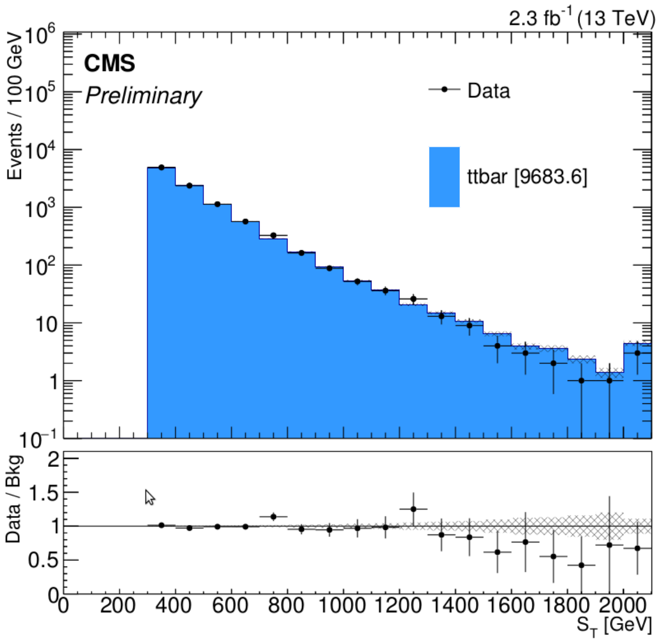
3L Background: ttbar (2L studies)

MET



(a) E_T^{miss} distribution

S_T



(b) S_T distribution

3L Background: ttbar (3L studies)

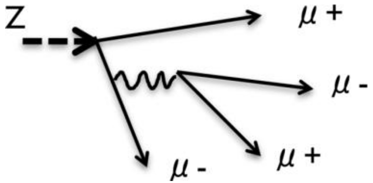
- Having verified the validity of the MC kinematics, we compare the number of ttbar fake events in data and MC
  - Since the dilepton behavior has been validated, this amounts to comparing the fake rates in data and MC
  - For this purpose, we use semi-leptonic ttbar decays with a very tight lepton and an additional non-prompt (fake) lepton
- We then scale the MC fake rate to match the one in data
  - This allows us to predict the correct number of fakes, with kinematics taken from MC
- The scale factor is 1.5 $\pm$ 50%
  - systematic uncertainty based on statistical uncertainty, plus safety margin
  - impact on signal regions is < ~0.3 events

3L Background: Fake e/μ

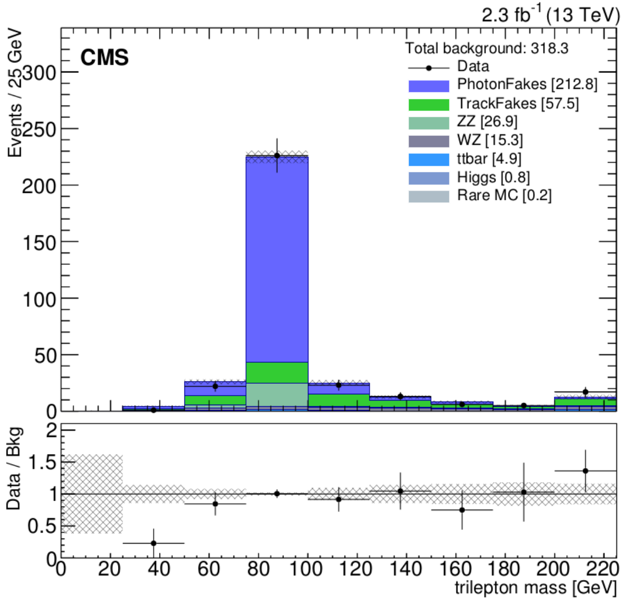
- Secondary background: about 17%
- General idea: Use correlated objects (“proxies”) to predict the number of fake leptons
  - isolated tracks act as proxies for fake leptons from jets
  - photons act as proxies for fake leptons from photon conversion
- Foundations of the method developed in 2010
  - scope of applicability has since then been improved
- <u>Control region</u>: 3L with an OSSF pair, MET < 50 GeV
- Fake rate is measured on Z and applied to dilepton events with presence of certain proxies
  - We subtract overlap from ttbar prediction

3L Background: AIC leptons

- In internal conversions, the photon may decay asymmetrically ("AIC")
  - One lepton is lost, the other is the fake lepton, carrying most of the momentum
  - In this case, the trilepton mass will be consistent with the Z mass (arXiv:1110.1368)



- <u>Control region</u>: 3 leptons, MET < 50 GeV, H_T < 200 GeV, m_{OSSF} < 81 GeV, m_{3l} on Z
- We use isolated photons as proxies for such fake leptons. Fake rates:
  - μ: 1.60% (ee environment), 1.05% (μμ environment)
  - e: 3.5% (ee environment), 4.5% (μμ environment)

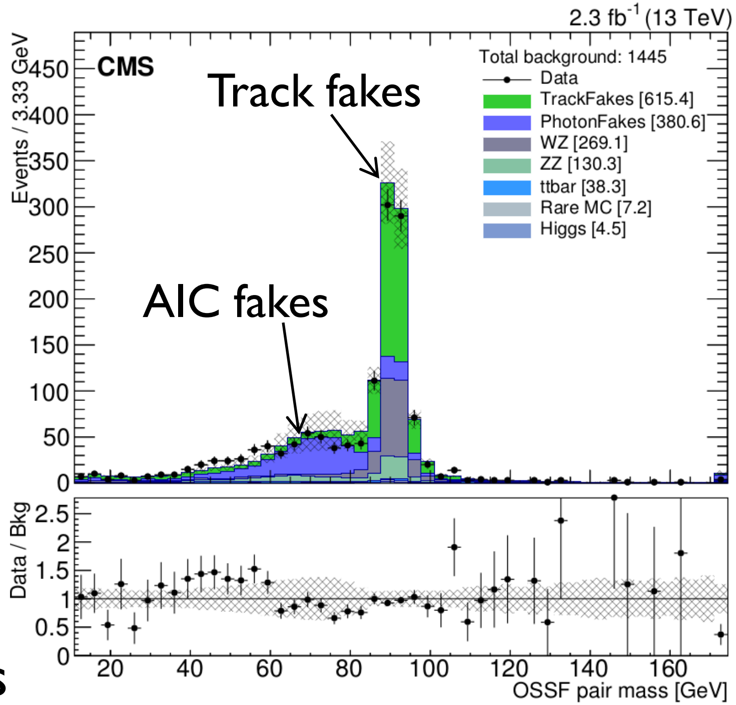


(b) fake electron

Figure 7.7: $m_{3\ell}$ distribution in AIC-dominated control region.

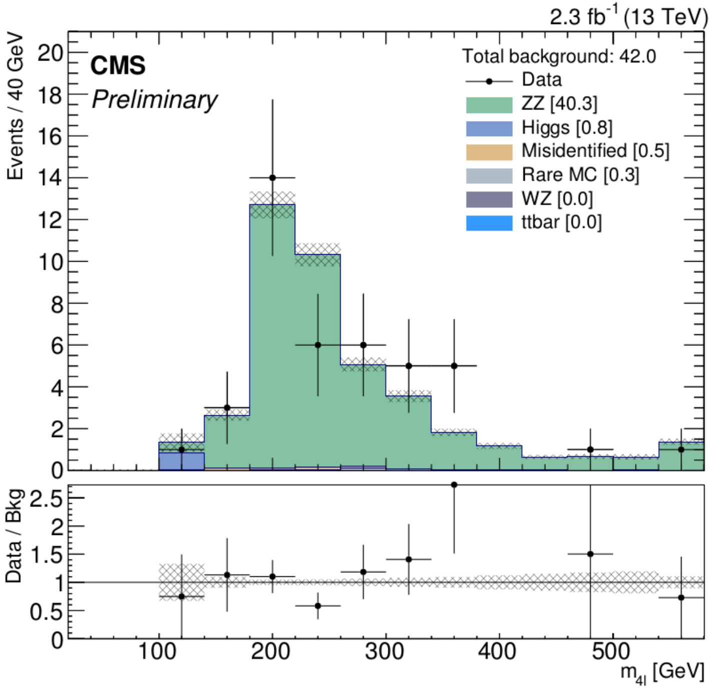
3L Background: Fake e/μ

- We use isolated tracks as proxies for prompt fake leptons from jets, normalized around Z
- <u>Control region</u>:
  3L with OSSF pair on Z, MET < 50 GeV
- Fake rates:
  - electrons: $(1.59 \pm 0.15(\text{stat}))$ %
  - muons: $(1.49 \pm 0.13(\text{stat}))$ %
- Systematic uncertainty of 14% based on variation as a function of the flavor of remaining prompt lepton pair
- Closure + validation plots in extra slides



4L Background: ZZ

- ZZ makes up about 3%
- We compare the MC simulation in the four-lepton invariant mass distribution
  - <u>Control region</u>: 4L incl. 2 OSSF pair (at least one on Z), MET < 50 GeV
- Normalization factor: 1.38 ± 0.23(stat)
  - 17% systematic uncertainty from control region size



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Systematic Uncertainties

- Almost all our signal regions are limited by statistics
  - Statistical uncertainties are usually large
- Systematic uncertainties play a minor role
- Exception: 3 leptons with an OSSF pair on Z
  - WZ-dominated
  - The WZ normalization uncertainty is relevant
- Other systematic uncertainties are still applied
  - Correlations and anti-correlations are taken into account
  - Detailed list on next slide

Systematic Uncertainties

Table 8.1: Systematic uncertainties. The channels listed here have three leptons and $550\,\mathrm{GeV} < L_\mathrm{T} + E_\mathrm{T}^\mathrm{miss} < 750\,\mathrm{GeV}$.

Source of uncertainty	Magnitude	Impact on background/signal estimate in channel with no OSSF pair	OSSF pair above-Z	OSSF pair on-Z
WZ normalization	50 %	13 %	2.8 %	41 %
ZZ normalization	16 %	0.1 %	0.5 %	0.4 %
Integrated luminosity	2.7 %	0.6 %	0.2 %	0.3 %
Lepton ID and isolation	3 %	3 %	3 %	3 %
$E_\mathrm{T}^\mathrm{miss}$ resolution/smearing	50 %	4.1 %	6.3 %	0.6 %
Pile-up reweighting	5 %	1.5 %	0.3 %	1.3 %
$\mathrm{t\bar{t}}$ fake rate	50 %	21 %	11 %	1.8 %
Z + fake rate	14 %	9.2 %	1.1 %	1.0 %
AIC fake rate	52 %	5.4 %	1.1 %	0.8 %
Rare MC cross section	50 %	11 %	2.7 %	5.2 %
Signal cross section	10 %	10 %	10 %	10 %
Total Background (for comparison)		0.3 events	3.0 events	3.5 events
Signal ($m_\Sigma = 420\,\mathrm{GeV}$, for comparison)		0.8 events	1.8 events	0.8 events

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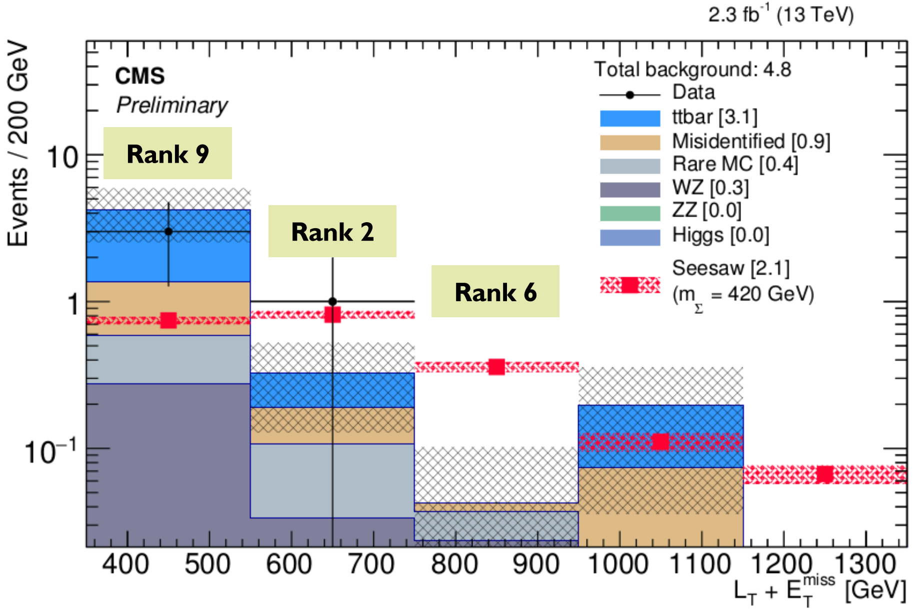
Results

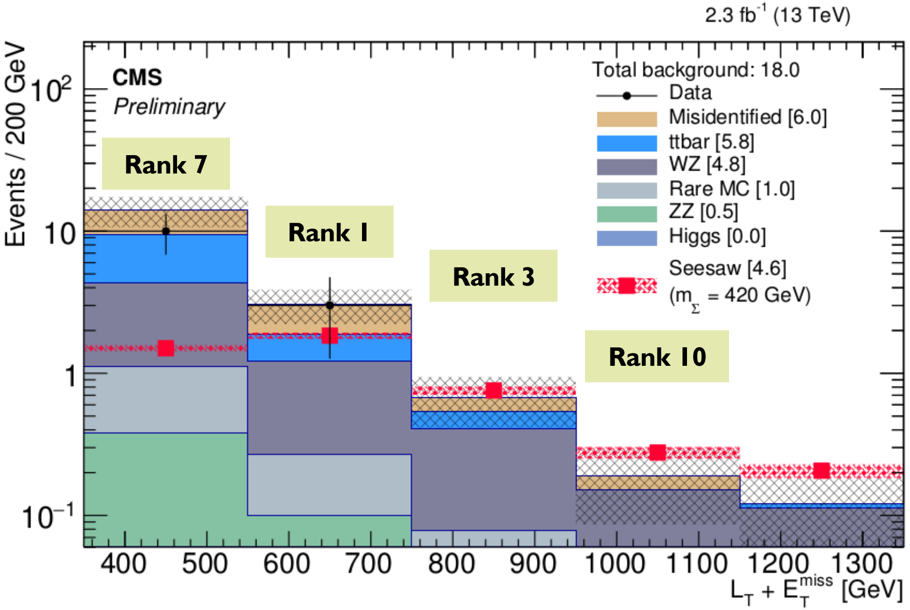
- 3 leptons, no OSSF pair
- Signal value and uncertainty at the m_Σ = 420 GeV point are shown on top of background breakdown
  - Signal uncertainties displayed as red hashed band
  - Includes both statistical and systematic uncertainties



(c) 3 leptons, no OSSF pair

Results

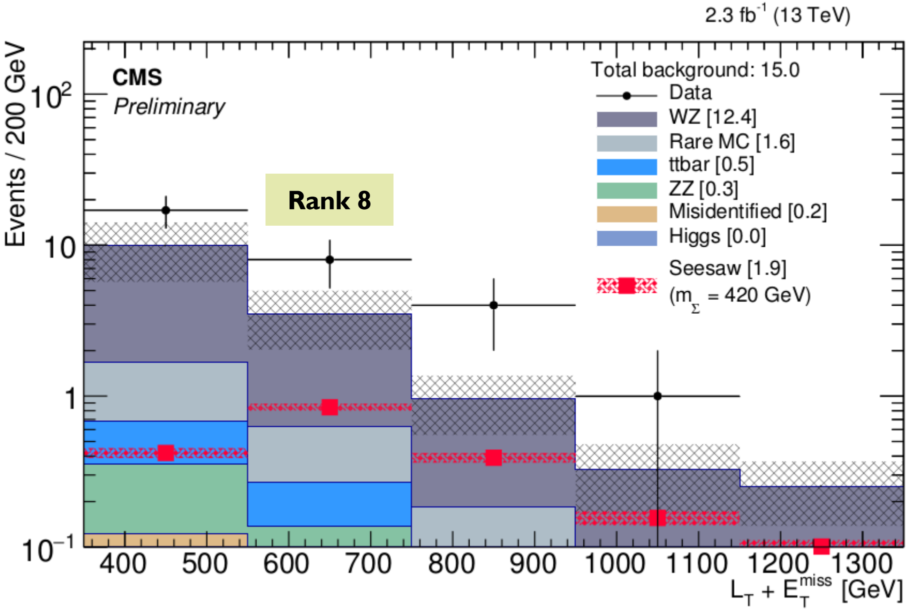
- 3 leptons, OSSF pair above Z



(b) 3 leptons with OSSF pair above-Z

Results

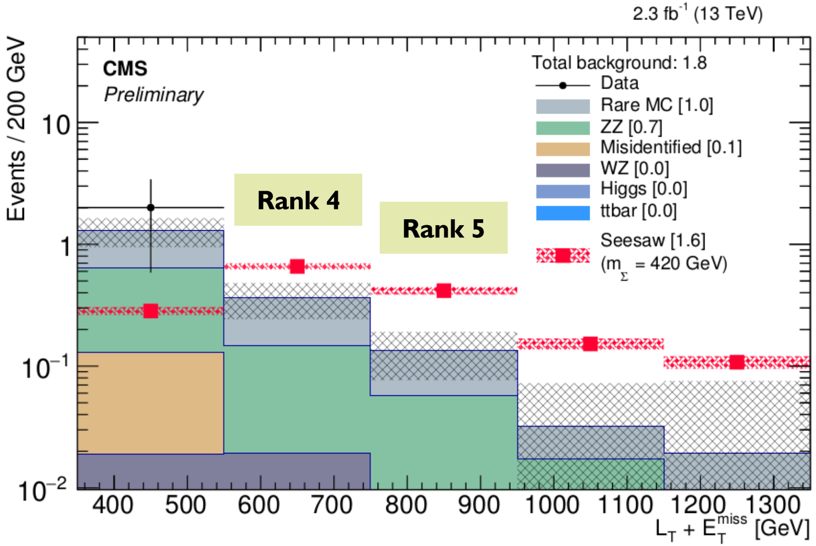
- 3 leptons, OSSF pair on Z
  - observation: 17, 8, 4, 1
  - these events have MET > 150 GeV
- At MET < 100 GeV, the WZ agreement is fine
  - this is the control region, free of signal
- Above 100 GeV, the WZ prediction does not agree as well with the data
- Does not impact limits significantly



(a) 3 leptons with OSSF pair on-Z

Results

- 4 leptons, ≥ 1 OSSF pair



(d) 4 leptons, at least 1 OSSF pair

Seesaw Results: CL_s limits

- We compute 95% CL_s exclusion limits on the signal cross-section

Table 9.1: Relative Sensitivity of Signal Regions.

n_{leptons}	OSSF pair	$L_T + E_T^{\text{miss}}$ [GeV]	r_{exp}
3	above-Z	550–750	2.6953
3	none	550–750	3.6094
3	above-Z	750–950	4.0781
≥ 4	n/a	550–750	4.1094
≥ 4	n/a	750–950	5.5938
3	none	750–950	5.8750
3	above-Z	350–550	6.2500
3	on-Z	550–750	6.7188
3	none	350–550	7.5938
3	above-Z	950–1150	8.7812

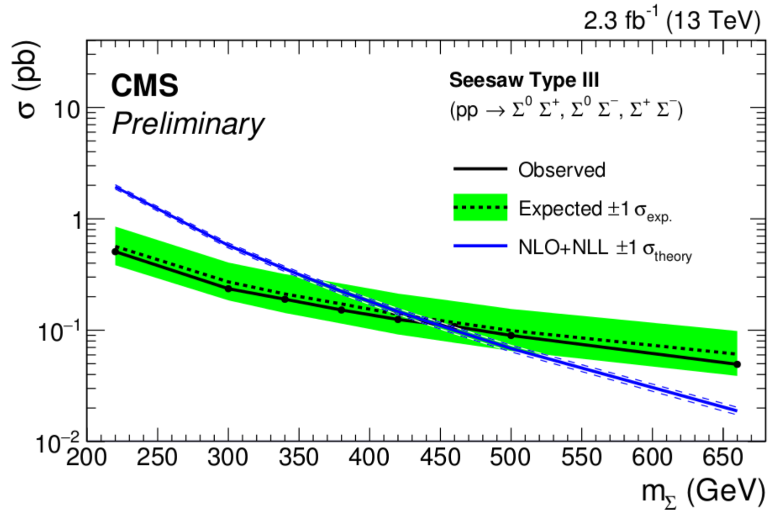


Figure 9.4: Exclusion for the flavor-democratic type-III seesaw model ($V_e = V_\mu = V_\tau = 10^{-6}$). We exclude heavy fermion pair production for masses below $m_\Sigma = 440$ GeV (expected: 430 GeV) and give upper limits on the pair production cross section.

Conclusion

- We conducted a search for Type-III seesaw signal in multilepton final states
  - Our sensitivity exceeds that of Run I
  - No evidence of seesaw signal has been observed
- Exclusion limits were derived from the results
  - We exclude the signal hypothesis for heavy fermion masses $m_{\Sigma} < 440$ GeV

Thanks!

- A big thanks to …
  - My Ph. D. committee
  - The Rutgers multilepton group
    - high energy theorist Scott Thomas
    - our postdocs R. C. Gray, M. Walker, H. Saka
    - my fellow grad students S. Arora, C. & E. Contreras-Campaña, M. Heindl, S. Panwalkar, P. Zywicki
    - as well as to K. Feigelis

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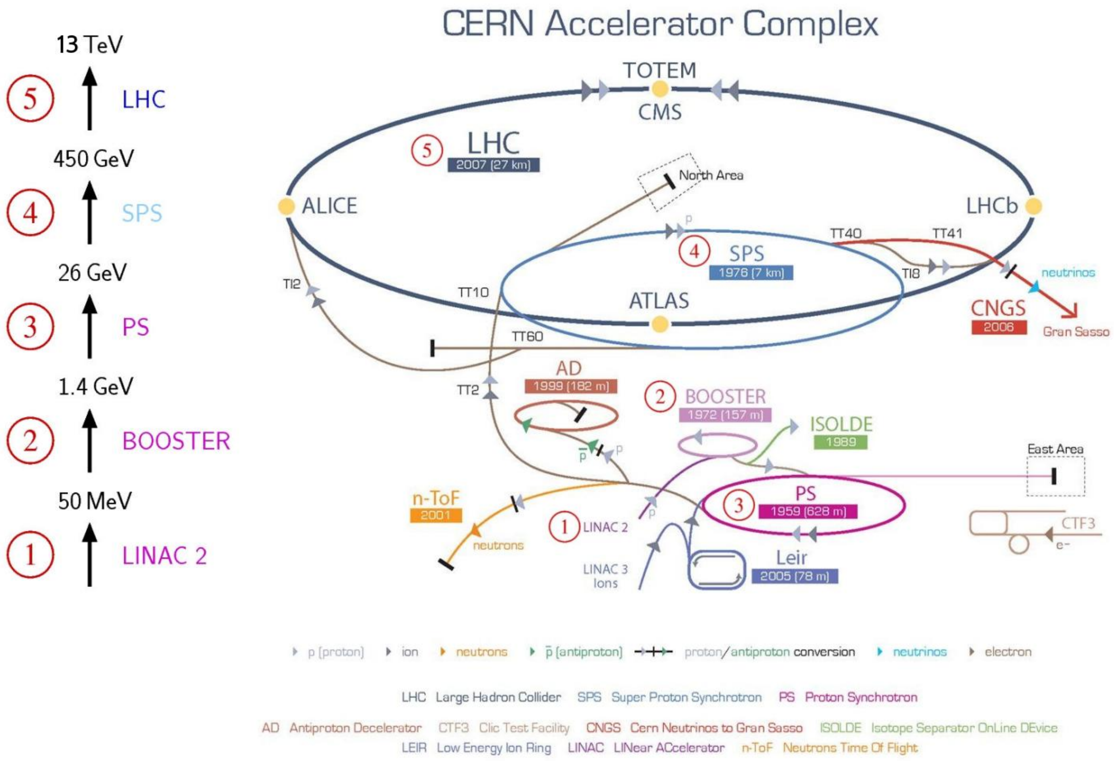
    - as well as to K. Feigelis
  - My supervisor Sunil Somalwar

Extra Slides

LHC in the Accelerator Complex



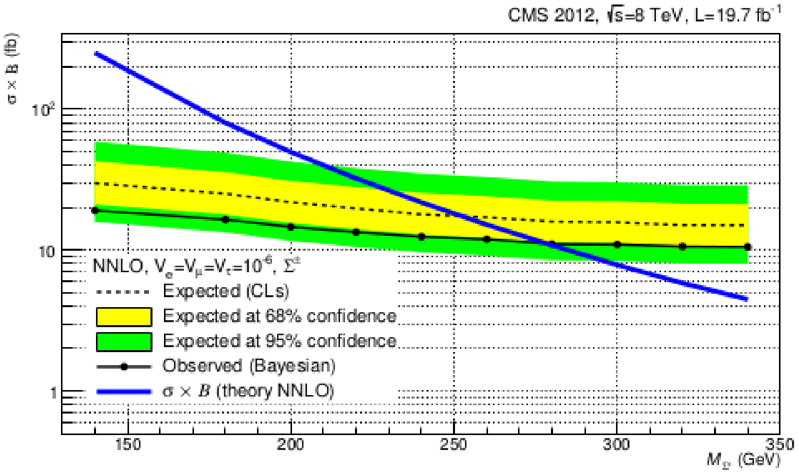
Background MC samples

Table 4.2: Background MC samples.

Sample	xsec [pb]	L [pb^{-1}]	No. events read
/WZTo3LNu_TuneCUETP8M1_13TeV-powheg-pythia8 /RunIISpring15DR74-Asympt25ns_MCRUN2_74_V9-v1/MINIAODSIM	4.42965	447169	1.9808e+06
/WZJets_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8/ RunIISpring15MiniAODv2-74X_mcRun2_asymptotic_v2-v1/MINIAODSIM	5.263	2.37929e+06	1.252220e+07
/ZZTo4L_13TeV-amcatnloFXFX-pythia8 /RunIISpring15DR74-Asympt25nsRaw_MCRUN2_74_V9-v1/MINIAODSIM	1.212	8.71378e+06	1.05611e+07
/TTTo2L2Nu_13TeV-powheg /RunIISpring15DR74-Asympt25ns_MCRUN2_74_V9-v1/MINIAODSIM	87.31	69711.1	4.997e+06
/TTWJetsToLNu_TuneCUETP8M1_13TeV-amcatnloFXFX-madspin-pythia8 /RunIISpring15DR74-Asympt25ns_MCRUN2_74_V9-v1/MINIAODSIM	0.2043	1.23792e+06	252908
/TTZToLLNuNu_M-10_TuneCUETP8M1_13TeV-amcatnlo-pythia8 /RunIISpring15DR74-Asympt25ns_MCRUN2_74_V9-v1/MINIAODSIM	0.2529	1.57374e+06	398000
/WWZ_TuneCUETP8M1_13TeV-amcatnlo-pythia8/ RunIISpring15MiniAODv2-74X_mcRun2_asymptotic_v2-v1/MINIAODSIM	0.1651	1.51423e+06	250000
/WZZ_TuneCUETP8M1_13TeV-amcatnlo-pythia8/ RunIISpring15MiniAODv2-74X_mcRun2_asymptotic_v2-v1/MINIAODSIM	0.05565	4.49236e+06	250000
/ZZZ_TuneCUETP8M1_13TeV-amcatnlo-pythia8/ RunIISpring15MiniAODv2-74X_mcRun2_asymptotic_v2-v1/MINIAODSIM	0.01398	1.78827e+07	250000
/GluGluHToZZTo4L_M125_13TeV_powheg_JHUgen_pythia8 /RunIISpring15MiniAODv2-74X_mcRun2_asymptotic_v2-v1/MINIAODSIM	0.01212	4.10891e+07	498000
/VBF_HToZZTo4L_M125_13TeV_powheg_JHUgen_pythia8 /RunIISpring15MiniAODv2-74X_mcRun2_asymptotic_v2-v1/MINIAODSIM	0.001034	4.73362e+08	489456
/DYJetsToLL_M-10to50_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8 /RunIISpring15MiniAODv2-74X_mcRun2_asymptotic_v2-v1/MINIAODSIM	18610	1613.2	3.002156+e07
/DYJetsToLL_M-50_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8 /RunIISpring15MiniAODv2-74X_mcRun2_asymptotic_v2-v1/MINIAODSIM	6025.2	4771.29	2.874797+e07

Comparison to Run I Result

- EXO-14-001 PAS (Padova)
- Generated 3L final states based on $\Sigma^{\pm} \rightarrow W^{\pm}\upsilon$, $\Sigma^{\pm} \rightarrow Z\, l^{\pm}$, $\Sigma^{0} \rightarrow W^{\pm} l^{\pm}$ processes
- <u>Selection</u>:
  - MET > 50 GeV, H_T < 150 GeV, b-tag veto, Z veto, AIC veto
  - lepton p_T's > 30, 20, 20 GeV and charge sum binning
- Limits placed on $\sigma \cdot BR$
  - now: limits on σ only (less analysis-specific approach)
- M_Σ limit placed at 278 GeV observed, ~250 GeV expected



Details of Improvements after Run I

- We take the Run I result r_{exp}(340 GeV) = 3.26 and transform it for comparability
  - remove the k-factor, apply xsec scaling and √(19.5/2.3)
  - thus, the Run I analysis would achieve r_{exp} = ~3.06 with the current amount of 13 TeV data
- We repeat the Run I analysis approximately and obtain r_{exp} = 4.11
  - Difference of 34% (comparable to uncertainty of the result) is in the conservative direction, and due to the approximations and binning differences in the mock-up analysis
- We then add improvements step by step

Table 9.4: Sensitivity improvements compared to the Run I analysis.

r_{exp}	Gain	Step
3.26		Run I result
3.06		Run I result translated to 2.3 fb^{-1} at 13 TeV
4.11	–	Run I result with Run I mock-up analysis setup
1.96	52 %	mock-up analysis with current p_{T} thresholds and kinematic cuts
1.19	39 %	adding signal with Higgs decay modes
0.78	34 %	switching to $L_{\mathrm{T}} + E_{\mathrm{T}}^{\mathrm{miss}}$ binning (= current search with only 3 leptons)
0.60	23 %	adding 4-lepton channels (= current result)

3L Background: Fake e/μ

- Verify that method works in data and MC

H_T in control region

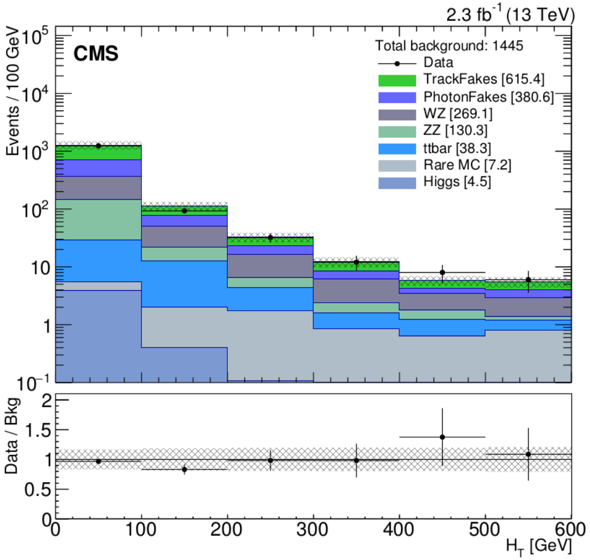


Figure 7.11: H_T distribution in the dilepton fake region (no OSSF pair mass cut).

MC closure test

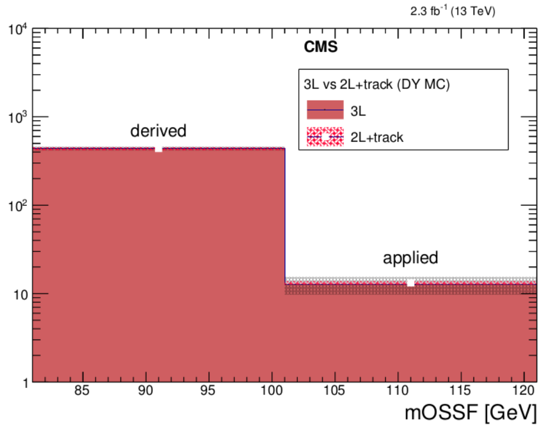
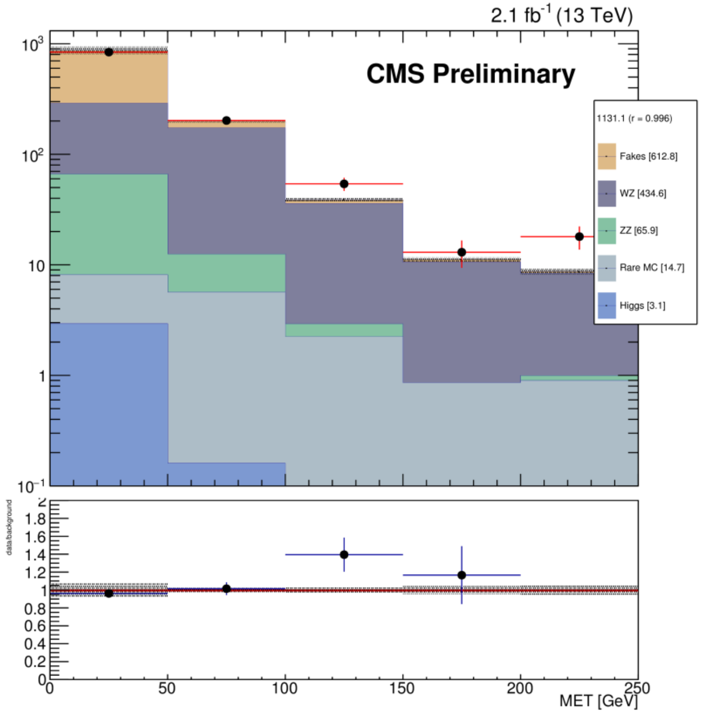


Figure 7.12: Closure test in Drell-Yan MC for the track-based fake rate method. The plot compares the 3-lepton yield with the prediction from 2 leptons + track proxy. The second bin in this plot ranges from 101 GeV to infinity.

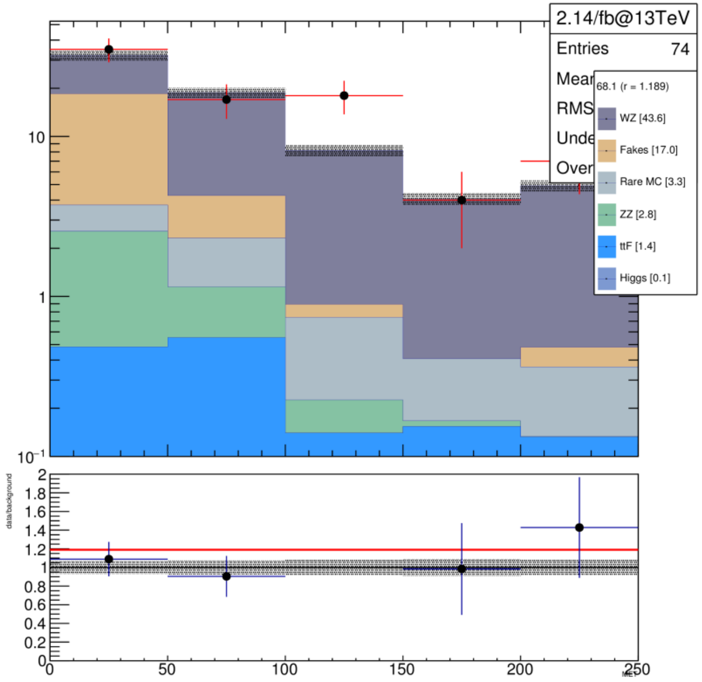
WZ Investigations

- There seems to be a discrepancy in the region with 3 e/μ and MET > 100 GeV
- We tried various MC samples, but the problem remains
  - WZTo3LNu (Powheg)
  - WZJets (amcatnlo)
- MET distribution for 3 light leptons, with OSSF pair on Z



WZ Investigations

- We see a discrepancy in the region with 3 e/μ and MET > 100 GeV
- At H_T > 200 GeV and with b-veto, the significance increases from roughly 2 sigma to roughly 3 sigma
- We want to put out a specific Seesaw result. Normally we put out big multilepton tables with all kinds of binning.
  - However, we don't think that the 2015 data is large enough / has been sufficiently digested (e.g. state of the MC's) for such a result. However the Seesaw result itself is quite robust.



Seesaw at 13 TeV

- In the previous CMS result, some decay processes (like 4L modes) were not considered
  - In total, there are 27 processes to be considered
- We produced all 27 processes
  - So far only private production for a few points
  - Generation scheme: Model file (Biggio and Bonnet) → FeynRules → UFO file → MadGraph → LHE (W/Z/H undecayed) → Pythia8 (all decays & hadronization) → trilepton filter → CMS simulation
- Next step: Official MC signal generation
  - 100k events per process
  - Triplet masses in range 140–660 GeV
  - Official samples are being requested
- Following results are from privately produced MC test points

FeynRules and Model

- Input is a model file which includes model-specific Lagrangians and particle parameters
- Runs as a Mathematica package that calculates decay widths, vertices, Feynman rules
- Outputs a "UFO" model directory which may be imported for usage with an MC generator
  - MadGraph is used in the following
- FeynRules model file with neutrino mass via Type III Seesaw was created by C. Biggio, and F. Bonnet

Event Generation with MadGraph

- Takes FeynRules UFO directory as input
- Generates events, and all relevant Feynman diagrams for each process
- Allows for some general kinematic parameter tuning
  - Beam energies, polarization, p_T cuts, jet cuts
- Outputs LHE formatted event files

Event Generation with MadGraph (II)

- Started with privately generated sample
  - 25k events per process, per mass point
- Currently we have 340, 220 GeV points
- All 27 total processes evaluated per mass
- Relevant σ*BR extracted from in LHE files
- Decay chains are specified in proc cards
- Decay product kinematic constraints are relaxed in run cards
- Processes all end at bosonic level – to be decayed in Pythia8

```
#************************************************************
#*                     MadGraph 5                           *
#*                                                          *
#*                *                       *                 *
#*                  *        * *        *                   *
#*                    * * * * 5 * * * *                     *
#*                  *        * *        *                   *
#*                *                       *                 *
#*                                                          *
#*                                                          *
#*    The MadGraph Development Team - Please visit us at    *
#*    https://server06.fynu.ucl.ac.be/projects/madgraph     *
#*                                                          *
#************************************************************
#*                                                          *
#*               Command File for MadGraph 5                *
#*                                                          *
#*     run as ./bin/mg5  filename                           *
#*                                                          *
#************************************************************
import model Seesaw_340GeV_UFO
# Define multiparticle labels
define p = g u c d s b u~ c~ d~ s~ b~
define j = g u c d s b u~ c~ d~ s~ b~
define l+ = e+ mu+ ta+
define l- = e- mu- ta-
define vl = v1 v2 v3
define w = w+ w-
define l = l+ l-
# Specify process(es) to run

generate p p > tr+ tr- , tr+ > w+ vl , tr- > z l-

# Output processes to MadEvent directory
output condor/output/Seesaw_340_tr+w+vltr-zl- -f
# This will create a directory PROC_$MODELNAME_$X
# If you want to specify the path/name of the directory use
# output PATH
```

Filtering and Hadronization

- Use Pythia8 for Hadronization and further decays
- MCMultiParticleFilter is used to remove all generated events which do not pass the following criteria:
  - Final state with three or more leptons possible
  - Each with a minimum p_T of 4 GeV
  - Light leptons must have status 1, taus must have status 2

Filtering and Hadronization (II)

- Pythia picks up the leftovers from the particle filter
- After Pythia runs, relevant cross sections for both before and after filter are available, as well as filter efficiencies
- These filter efficiencies are then used in the analysis step to reweight signals to real luminosities

Signal Regions: Kinematic Binning

- Comparing L_T (left) and L_T + MET (right)

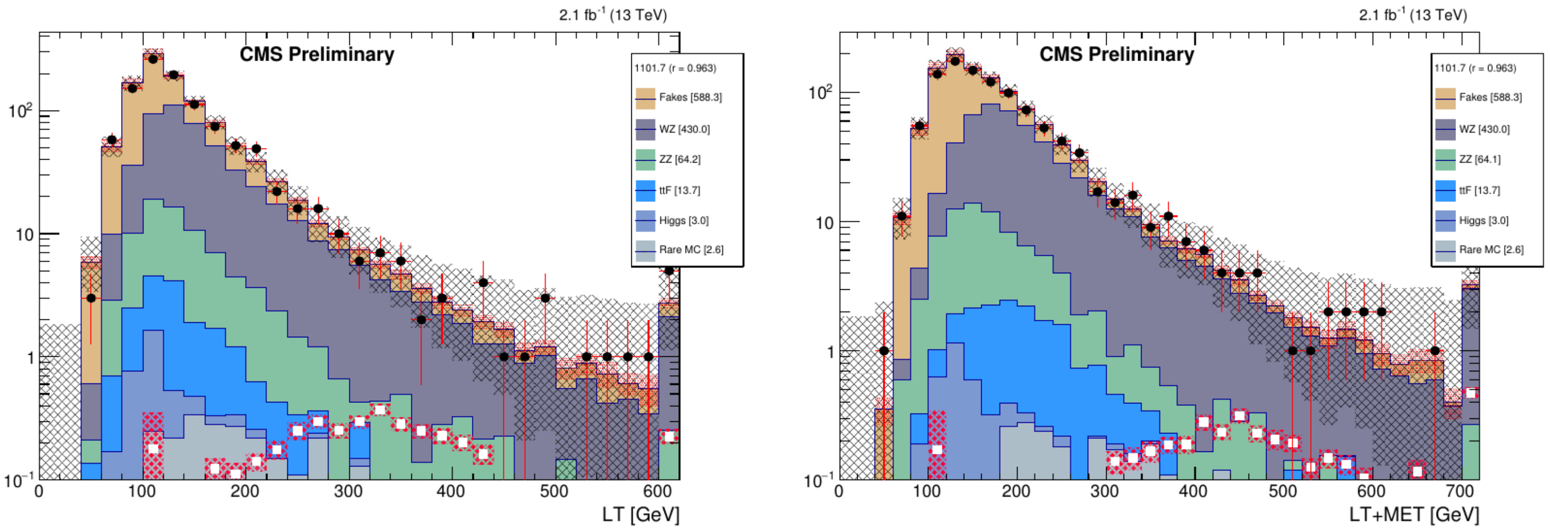


Figure 6: left) L_T distribution in a trilepton region with an OSSF pair on Z right) $L_T + E_T^{miss}$ distribution in the (last bin overflow). The signal (m_Σ = 340 GeV) is shown as white square dots with a pink hashed uncertainty band.