Search for heavy neutral leptons in the trilepton final state at CMS: Moriond electroweak 2018

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arXiv:1802.02965

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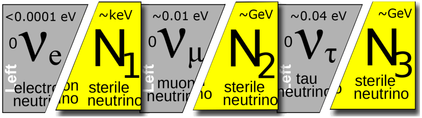
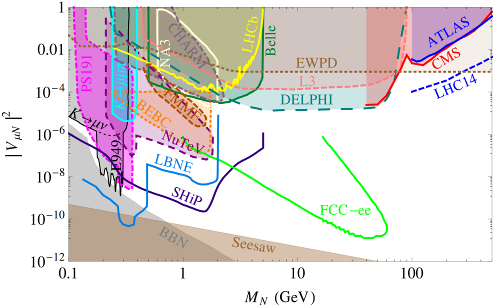
Heavy neutral leptons: overview



- no right-handed neutrinos in SM
- introduce **sterile neutrinos** N
- has **mixing angle** $V_{\ell N}$ to SM neutrino ν_ℓ

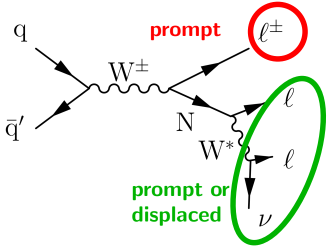


arXiv:1502.06541

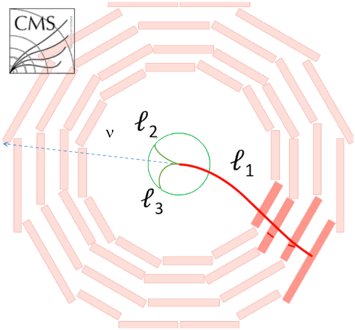
could **solve several open questions** in SM:

- smallness of **neutrino masses**: see-saw mechanism
- **baryon asymmetry**: degenerate $\mathbf{N}_2$ and $\mathbf{N}_3$ could dramatically increase CP-violation
- **dark matter**: $\mathbf{N}_1$ if $m_{\mathbf{N}_1} \sim \mathrm{keV}$

Trilepton final state



- focus on W$\to \ell$N $\to 3\ell\nu$ ($\ell = e/\mu$)
- **no N mass peak** because of escaping ν
- can detect decay products of **very light N** ($P_T^\ell > 5$ GeV)
- search for **prompt decays** of N



$$\Gamma\left(\mathrm{W} \to \ell\mathrm{N}\right) = \left|V_{\ell\mathrm{N}}\right|^2 \Gamma\left(\mathrm{W} \to \ell\nu_\ell\right)$$

$$\tau_N \propto \left|V_{\ell\mathrm{N}}\right|^{-2} m_N^{-5}$$

- when probing small $|V_{\ell\mathrm{N}}|$ and m_N ℓ_1 and ℓ_2 become displaced

Backgrounds

WZ $\rightarrow 3\ell\nu$, ZZ $\rightarrow 4\ell$

- **signal-like leptons**
- **OSSF pair** present through $Z \rightarrow \ell\ell$

Nonprompt e/μ

- dominated by Drell-Yan$\rightarrow 2\ell$ and $t\bar{t} \rightarrow 2\ell$
- third **lepton from jet-fragmentation**

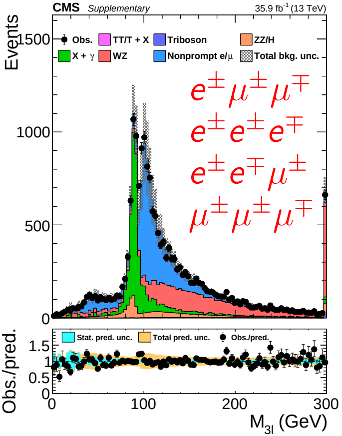
Conversions

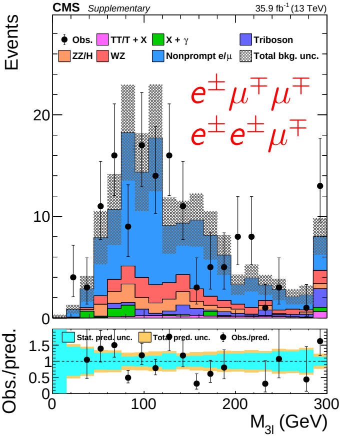
- dominated by $Z\gamma$ with $\gamma^{(*)} \rightarrow 2\ell$
- almost always **has OSSF** pair

rare processes

- $t\bar{t} + X$, triboson, Higgs
- **very small**

OSSF = opposite sign and same flavor





two orders of magnitude more background for events with an OSSF pair!

Search strategy

search variables:

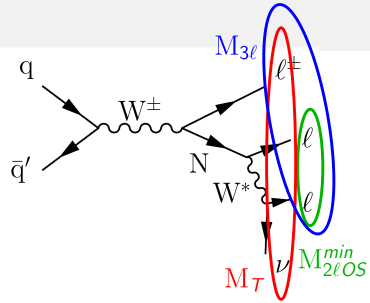
- $M^{min}_{2\ell OS}$, **proxy for** m_{N}
- M_T, very **high for high** m_{N}
- $M_{3\ell}$, for **background rejection**

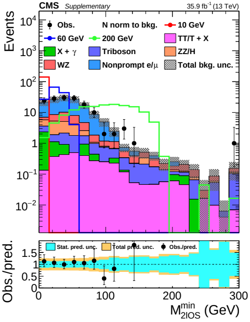
low mass $(m_{\mathrm{N}} < m_{\mathrm{W}})$

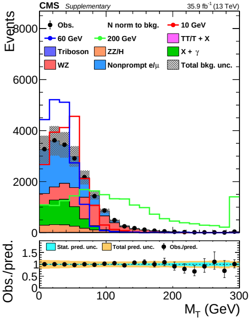
- only use **events without OSSF**
- low P_T thresholds
- categorize according to $P_T^{leading}$

high mass $(m_{\mathrm{N}} > m_{\mathrm{W}})$

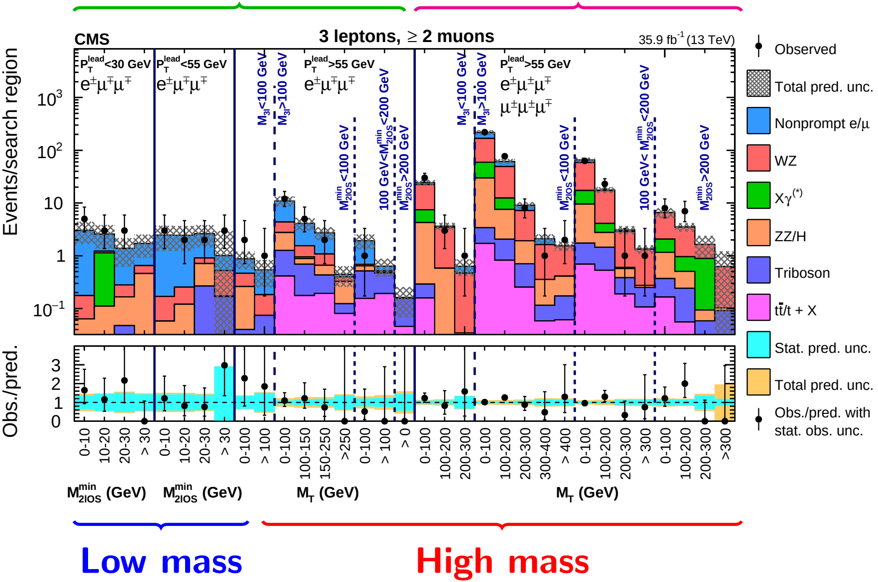
- use both events **with- and without OSSF**
- high P_T thresholds



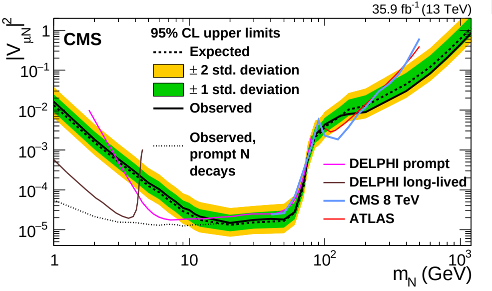


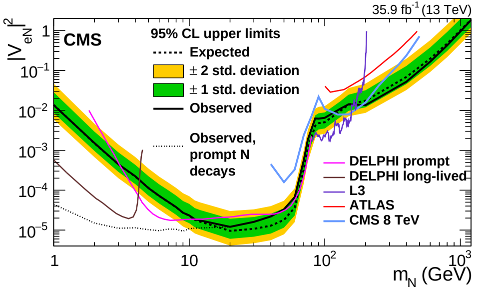


Signal regions



Exclusion limits



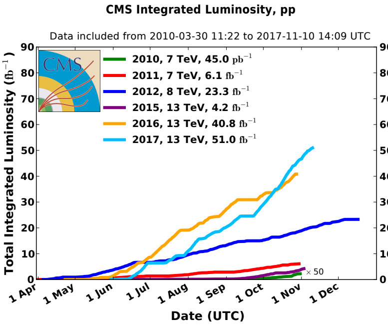


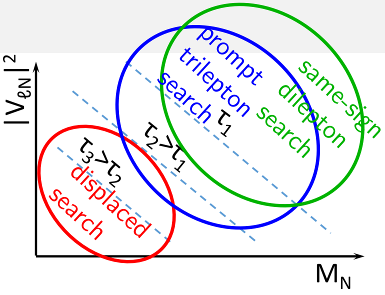
First direct results for $m_\mathrm{N} > 500$ GeV

First hadron collider results for $m_\mathrm{N} < 40$ GeV

- **improve upon DELPHI** limits for $m_N \gtrsim 15$ GeV
- **improve upon 8 TeV** ATLAS and CMS limits for high mass
- lose sensitivity due to **N lifetime at low m_N**

Outlook





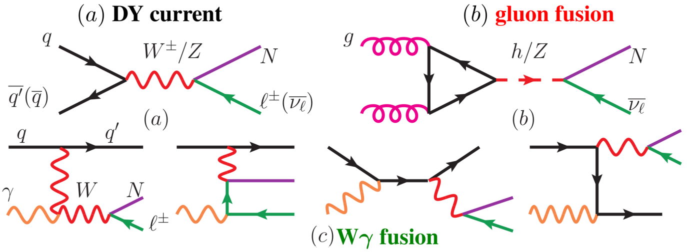
- presented new stringent limits on HNL based on **prompt trilepton** search
- uncertainties are **statistically dominated**
- reach to improve significantly as LHC collects more data

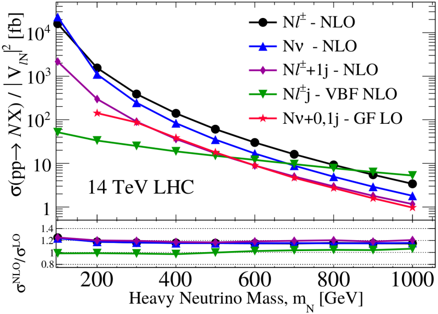
more channels to explore:

- **same-sign dilepton + jets** $\rightarrow$ higher sensitivity at high masses because of large branching fraction (**See Giullia's talk tomorrow!**)
- searches with **displaced leptons or jets** capable of probing the low $|V_\ell|/m_{\mathrm{N}}$ plane

bright future for HNL searches at the LHC with more data and new channels being explored!

Backup: HNL production

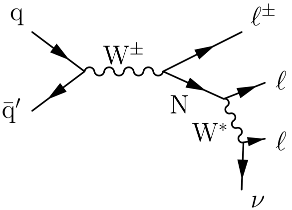




- Drell-Yan current dominant up to $m_{\mathrm{N}} = 800$ GeV
- for very high masses VBF becomes dominant
- gluon fusion very small for 13 TeV collisions

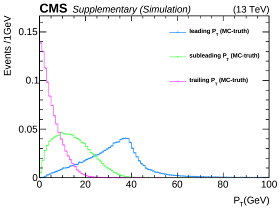
arXiv:1602.06957

Backup: HNL P_T spectra

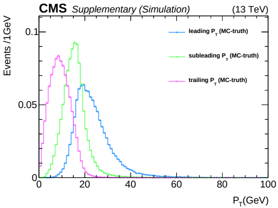


- $m_N << m_W$: leading lepton similar to prompt W decay, two very soft leptons
- $m_N \approx m_W$: very compressed trailing lepton (no leftover phase-space), all leptons rather soft
- $m_N > m_W$: hard leading lepton, relatively soft trailing lepton because of W off-shellness

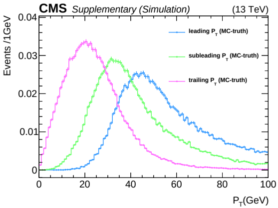
$m_N = 5$ GeV



$m_N = 60$ GeV



$m_N = 130$ GeV



Backup: Event selection

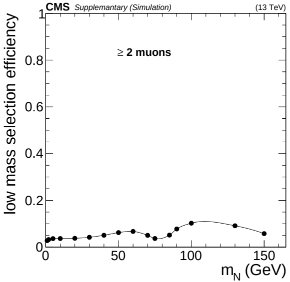
- exactly **3 well identified leptons** in event
- veto *loose* CSVv2 b-jets

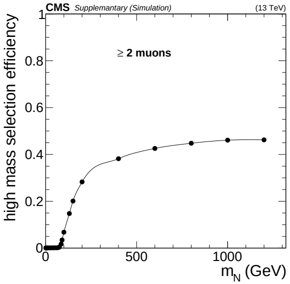
low mass ($m_{\mathrm{N}} < m_W$):

- **veto presence of OSSF pair**
- $P_T^{\ell} > 15, 10, 5(10)$ GeV in case of a trailing muon (electron) + some additional requirements for triggering
- $M_{3\ell} < 80$ GeV
- $E_T^{miss} < 75$ GeV

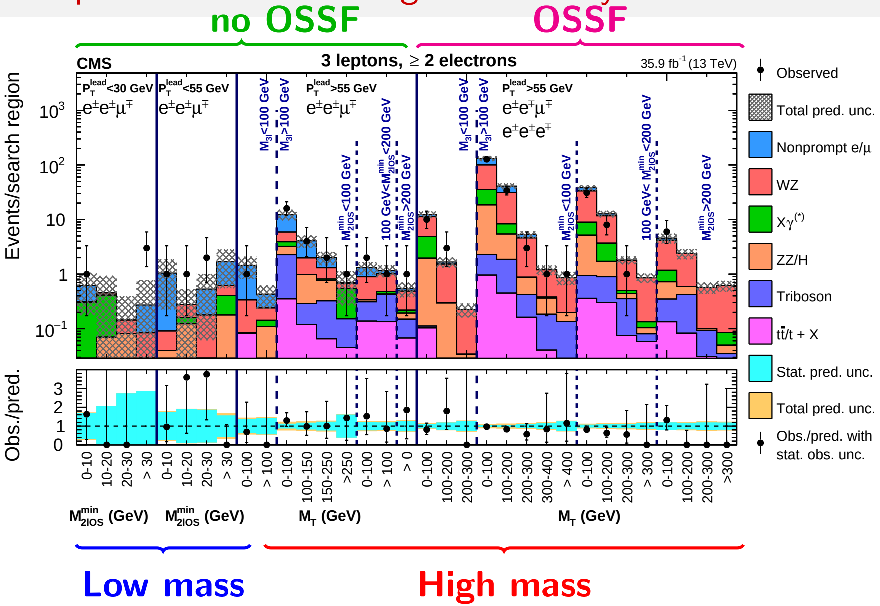
high mass ($m_{\mathrm{N}} > m_W$):

- $P_T^{\ell} > 55, 15, 10$ GeV
- OSSF: $|M_{\ell\ell} - M_Z| < 15$ GeV (veto WZ, Drell-Yan)
- OSSF: $|M_{3\ell} - M_Z| < 15$ GeV (veto conversions)



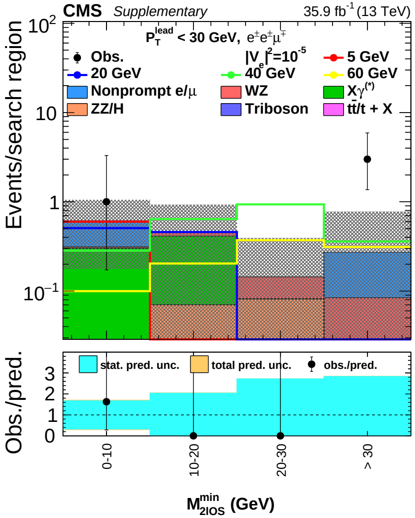


Backup: Electron search region summary

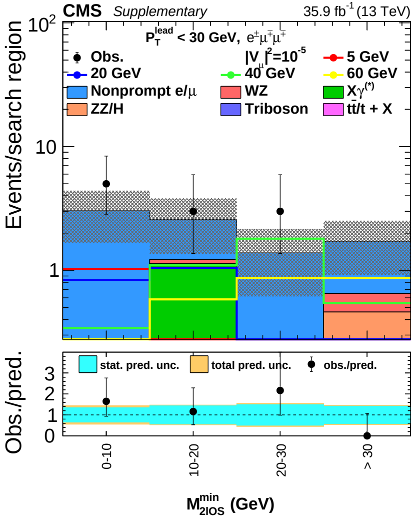


Backup: Low mass search regions, low P_T

≥ 2 **electrons**

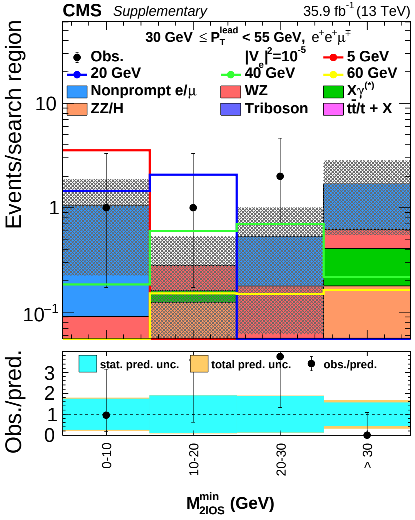


≥ 2 **muons**

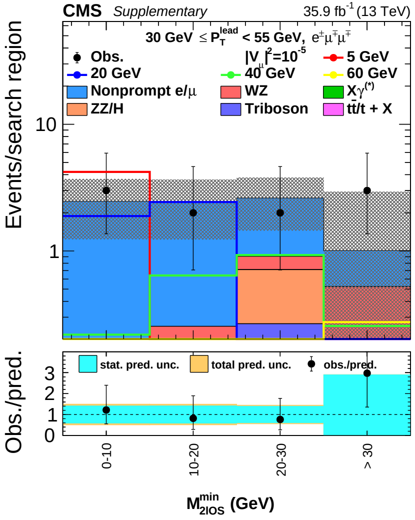


Backup: Low mass search regions, high P_T

$\geq$ 2 electrons

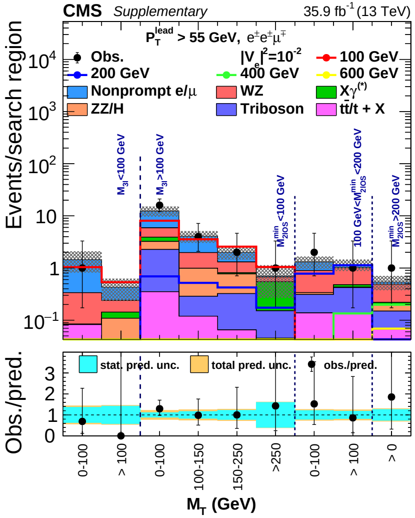


$\geq$ 2 muons

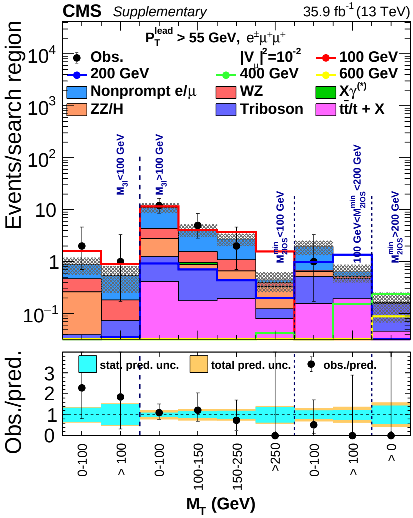


Backup: High mass search regions, no-OSSF

$\geq$ 2 **electrons**

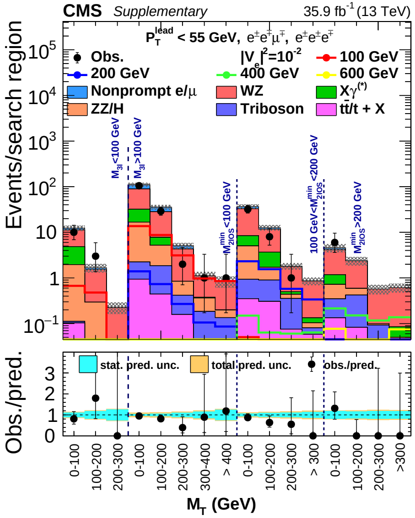


$\geq$ 2 **muons**

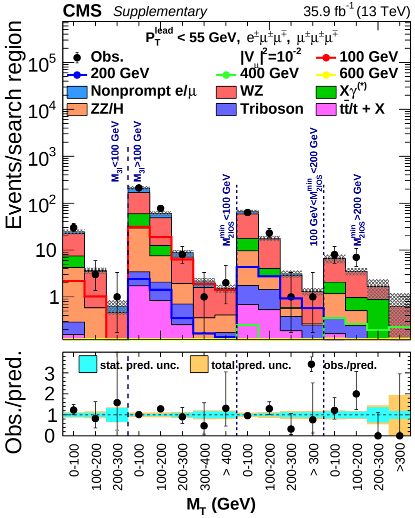


Backup: High mass search regions, OSSF

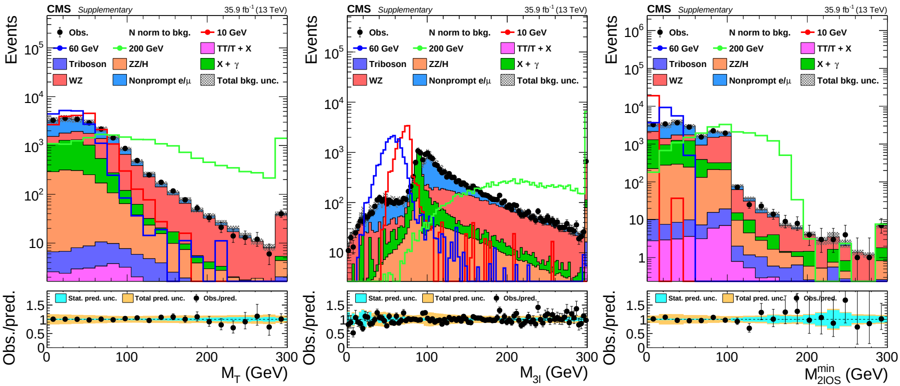
$\geq$ 2 **electrons**



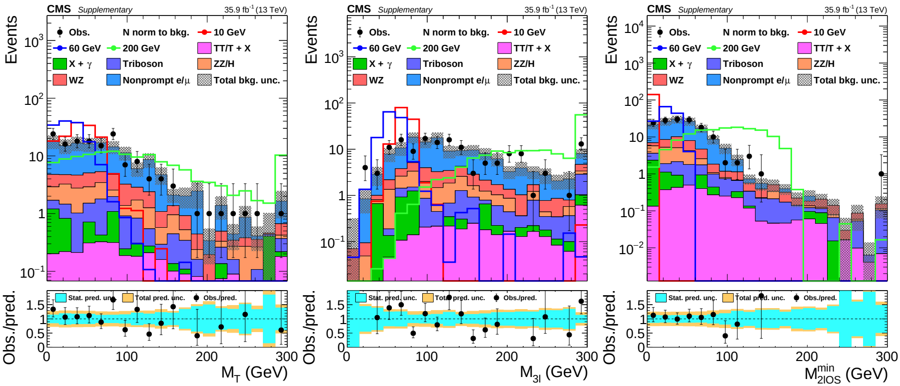
$\geq$ 2 **muons**



Backup: Search variables, OSSF



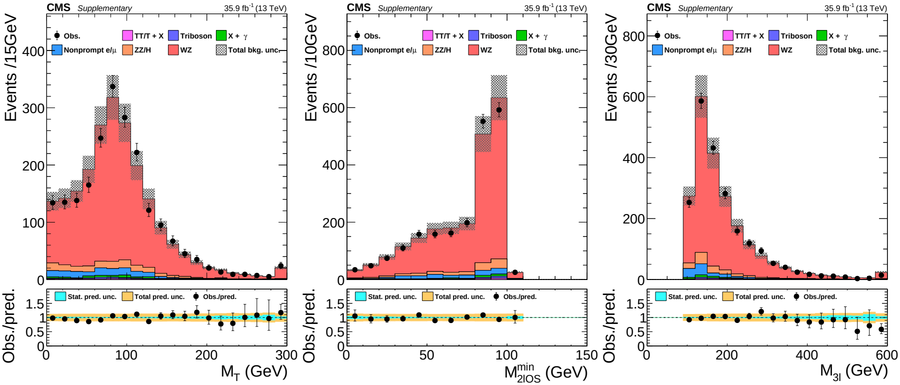
Backup: Search variables, no-OSSF



Backup: WZ control region

- OSSF pair present
- $|M_{\ell\ell} - m_Z| < 15$ GeV, $|M_{3\ell} - m_Z| > 15$ GeV
- $P_T(\ell) > 25, 15, 10$ GeV
- 0 b-jets
- $E_T^{miss} > 50$ GeV

$$\frac{data}{MC} = 1.08 \pm 0.09$$

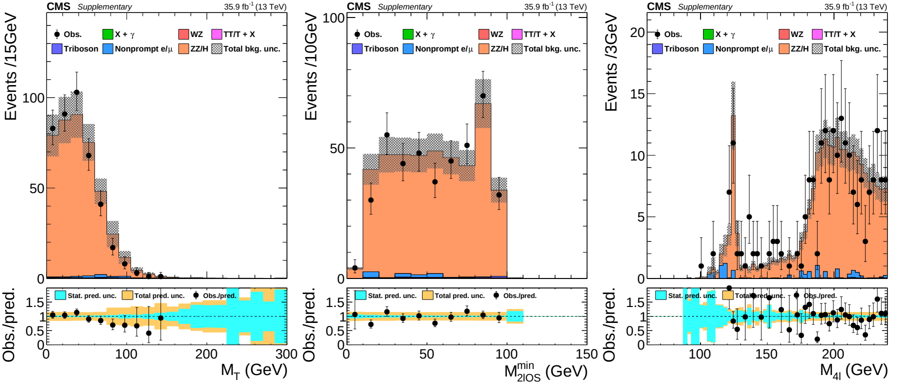


Backup: ZZ control region

- 2 OSSF pairs present
- $|M_{\ell\ell} - m_Z| < 15$ GeV (for both pairs when extracting normalization)
- $P_T(\ell) > 15, 10, 5(10)$ GeV
- 0 b-jets

$$\frac{data}{MC} = 1.029 \pm 0.11$$

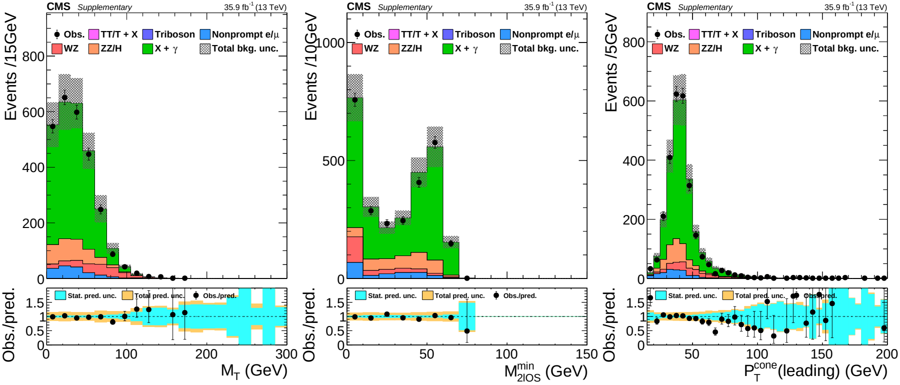
- add extra 25% nuisance to ZZ events with $M_T > 75$ GeV



Backup: Conversion control region

- OSSF pair present
- $|M_{\ell\ell} - m_Z| > 15$ GeV,
  $|M_{3\ell} - m_Z| < 15$ GeV
- $P_T(\ell) > 15, 10, 5(10)$ GeV
- 0 b-jets

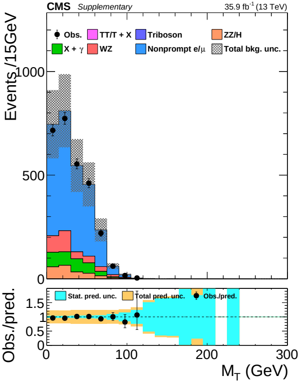
$$\frac{data}{MC} = 0.95 \pm 0.08$$

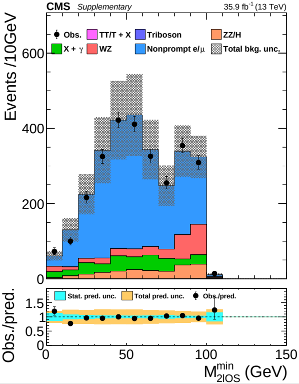


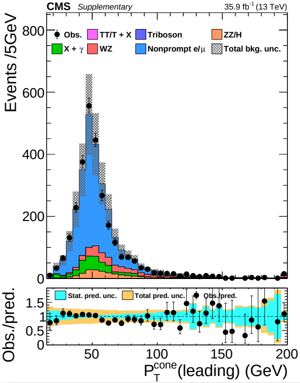
Backup: Drell-Yan control region

- OSSF pair present
- $|M_{\ell\ell} - m_Z| > 15$ GeV, $|M_{3\ell} - m_Z| < 15$ GeV
- $P_T(\ell) > 15, 10, 5(10)$ GeV
- 0 b-jets
- $E_T^{miss} < 30$ GeV, $M_T(\mathrm{W}) < 30$ GeV

- 2ℓ + "nonprompt" lepton
- predicted directly from data
- probability for lepton passing "loose" selection to pass "tight" measured in jet-enriched region
- apply to lepton passing "loose" but failing "tight"



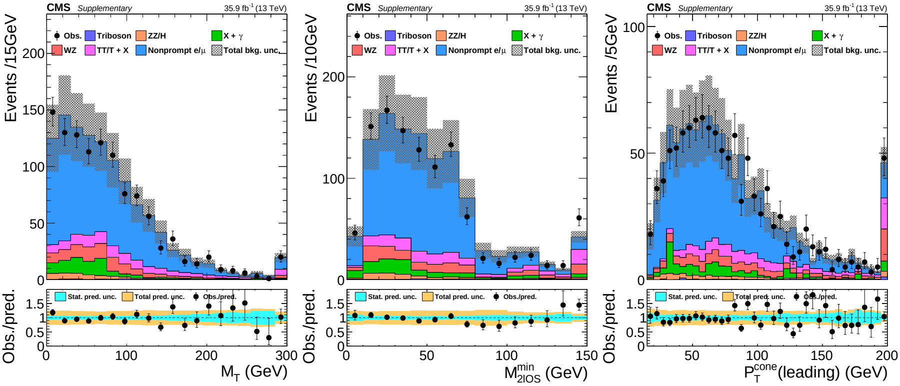




Backup: $t\bar{t}$ control region

- OSSF pair present
- $|M_{\ell\ell} - m_Z| < 15$ GeV,
  $|M_{3\ell} - m_Z| < 15$ GeV
- $|M_{\ell\ell}| > 12$ GeV
- $P_T(\ell) > 15, 10, 5(10)$ GeV
- ≥ 1 b-jet

- 2ℓ + "nonprompt" lepton
- predicted directly from data



Backup: Systematic uncertainties

Source	typical uncertainty value (%)	Treatment
e/μ selection	3 (per ℓ)	normalization
Trigger efficiency	2–5	normalization
Jet energy scale	0–3	shape
b-tag veto	1–5	shape
Pileup	1–5	shape
Integrated luminosity	2.5	normalization
Scale variations	1-15	shape & normalization
PDF variations	0.1-1	shape
Other backgrounds	50	normalization
MC samples statistical precision	1–30	normalization
Nonprompt leptons	30	normalization
Nonprompt leptons (W, Z bkg. subtraction)	5–20	shape
Xγ normalization	15	normalization
WZ normalization	9.4	normalization
ZZ normalization	10	normalization
ZZ ($M_T > 75$ GeV non-closure)	25	normalization