Search for Heavy Neutral Leptons in Same-Sign Dilepton and Jets Final States with CMS Run-II Data

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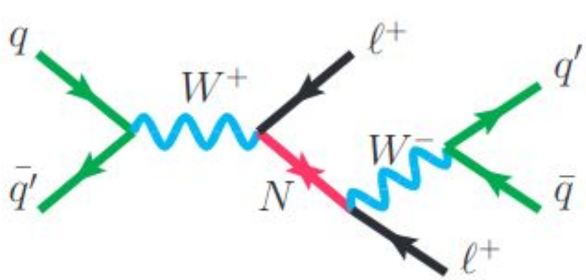
Motivation of the search

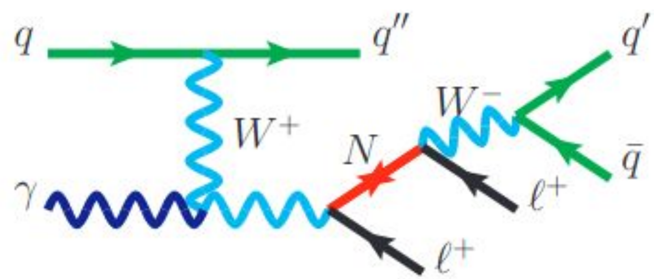
- Neutrino oscillation → ν have non-zero masses.
  - Observed limit of $m_\nu \lesssim 0.1$ eV scale.
  - Why is it extremely small?

- Type-I seesaw model
  - Postulates heavy Majorana neutrino N.
  - m_ν is determined by $m_\nu \sim y_\nu^2 v^2/m_N$. ($y_\nu$: Yukawa coupling, v : Higgs VEV)

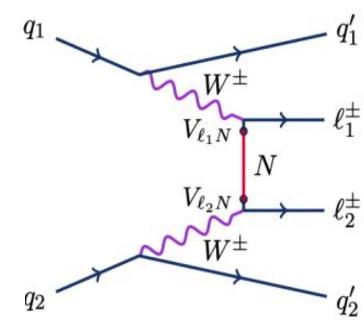
- N can be produced via mixing with SM neutrino → xsec ∝ $|V_{lN}|^2$ or $|V_{lN}|^4$
  - **Drell-Yan (DY)** process (left) / **Wγ fusion** process (center) / **SSWW** process (right)



DY



Wγ

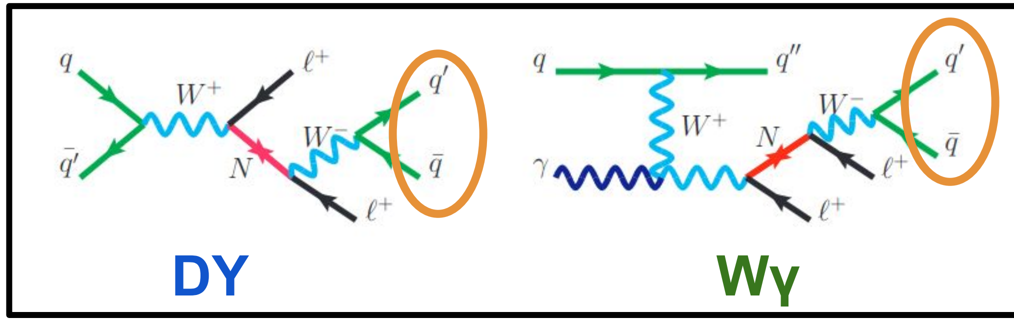


SSWW

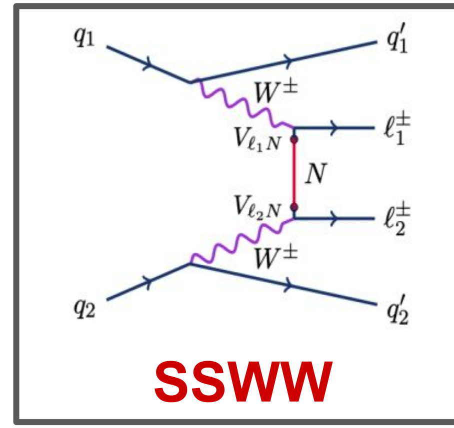
JHEP 01 (2019) 122
2016 Data : μμ, ee, eμ

PRL **131**, 011803
Run 2 Data : μμ

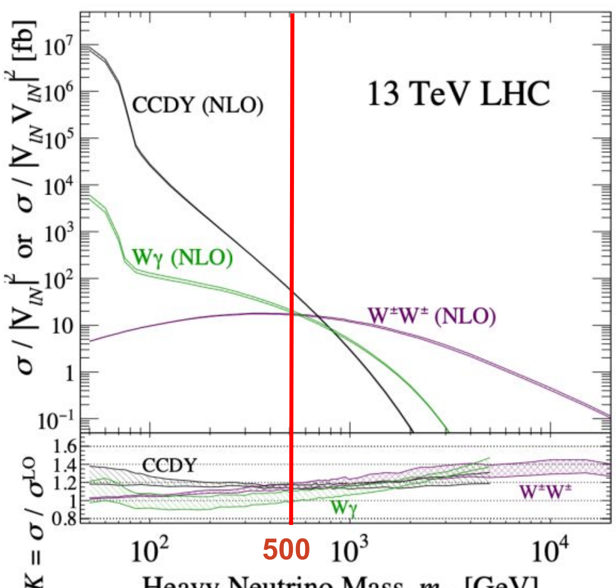
Features of signals



- Signal kinematics
  - <u>Resonant N</u>: **DY**, **Wγ**
    - **Low mass** (m_N < **500 GeV**) : Resolved
    - **High mass** (m_N > **500 GeV**) : Boosted
  - Non-resonant N: **SSWW**
    - Vector boson fusion (VBF) topology



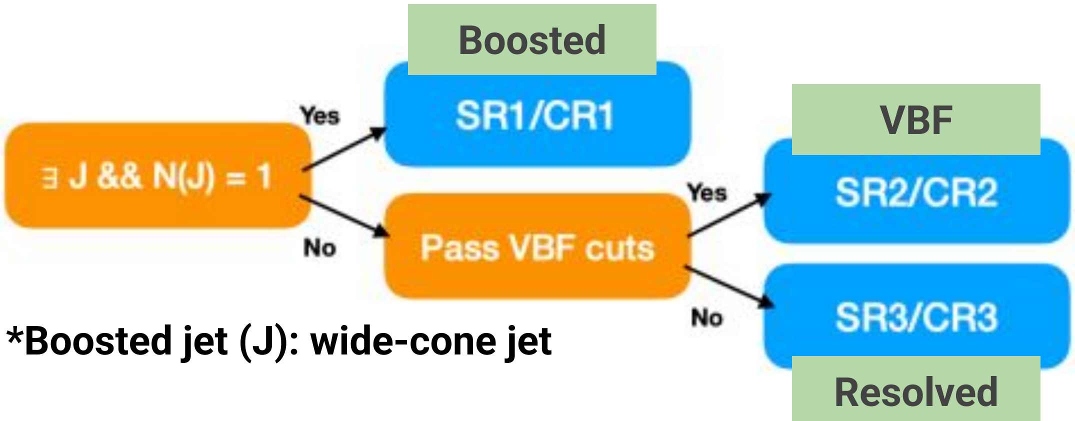
- Signal contribution
  - **Low mass** (m_N < **500 GeV**)
    - **DY** (dom.) + **Wγ**
  - **High mass** (m_N > **500 GeV**)
    - **SSWW** (dom.) + **Wγ**



Search strategy

* Details in back-up

- Signal and control regions (SR/CR) are carefully defined.



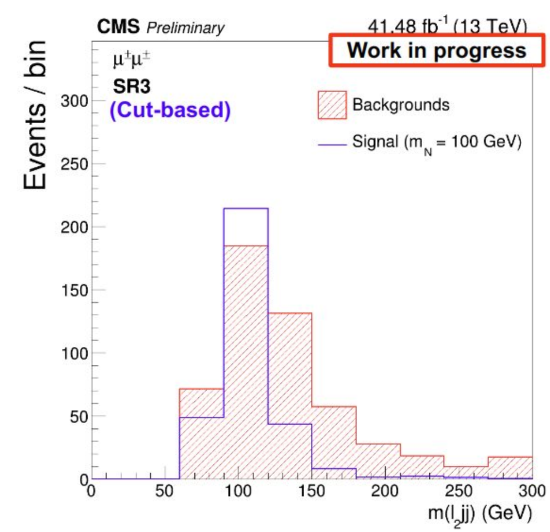
*Boosted jet (J): wide-cone jet

Variable	Cut
$m(\ell\ell)$	> 20 GeV
$\lvert\Delta\phi(\ell,\ell)\rvert$	> 2
$m(jj)$	> 750 GeV
$\lvert\Delta\eta(j,j)\rvert$	> 2.5
$\max(\mathcal{Z}_\ell)$	< 0.75

VBF cuts

  - SR: Small MET and no b-tagged jets
  - CR: Large MET or 1 b-tagged jets

- **N mass dependent SR3**
  - High mass: low backgrounds
    → **Cut-based** selection
  - Low mass: high backgrounds
    → Adopting **BDT** to discriminate signals from SM backgrounds.



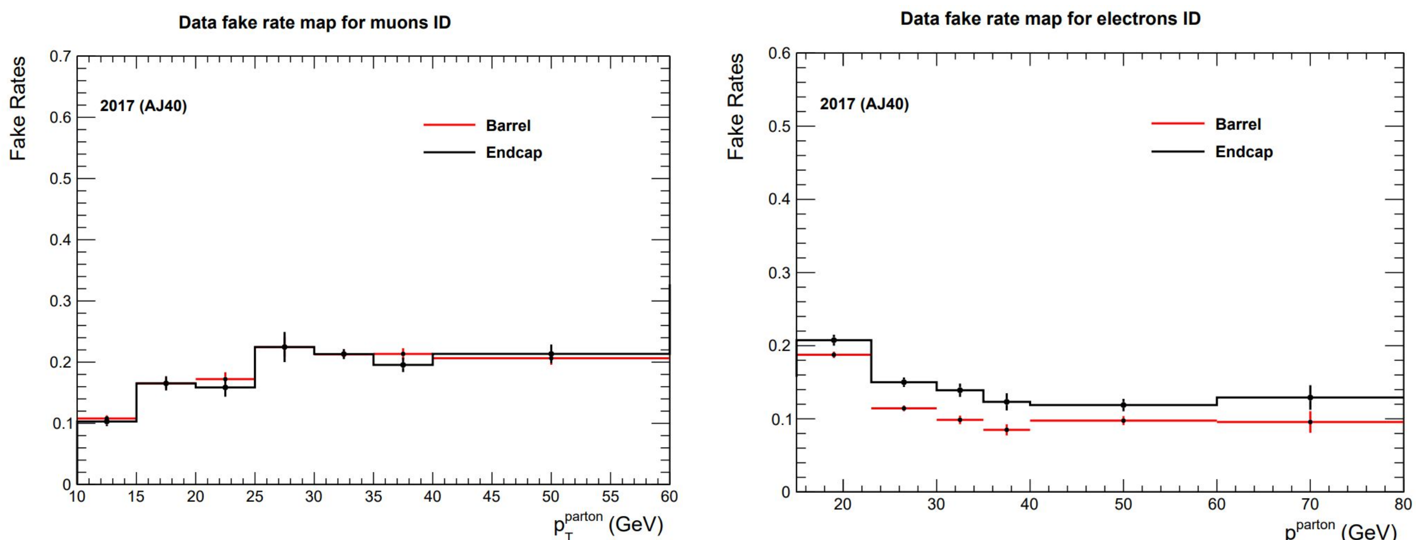
Background Estimation:

Fake, Charge-flip, Prompt

Background estimation: Fake leptons

- Fake leptons: misidentified hadrons, leptons from heavy-flavor jets, etc.

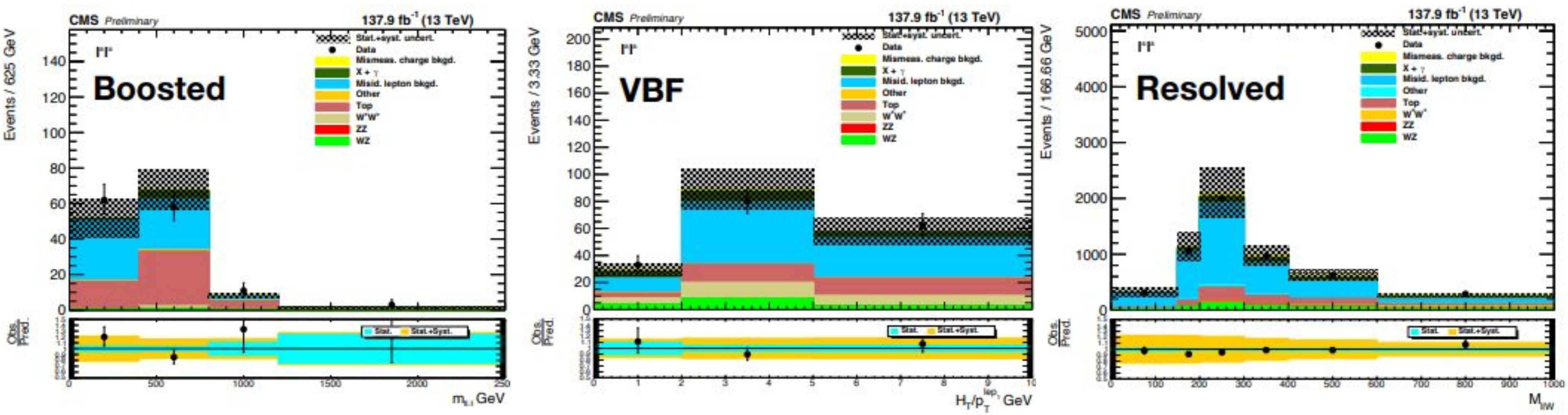
- Data-driven fake rate method is used
  - Fake rate: ratio of fake leptons to pass the lepton ID
    - Measured as a function of mother jet's p_T and $|\eta|$ using data



  - Systematics
    - MC closure (20%)
    - Variation on measurement region selection (10%)

Background estimation: Fake leptons – validation

- Validated in fake-dedicated control regions:
  - SR, but having large MET or 1 b-jet

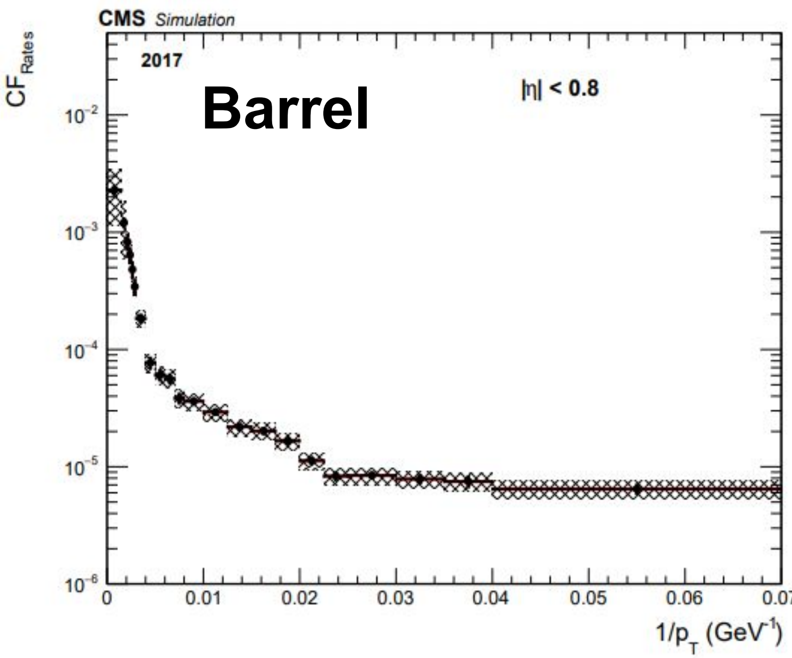


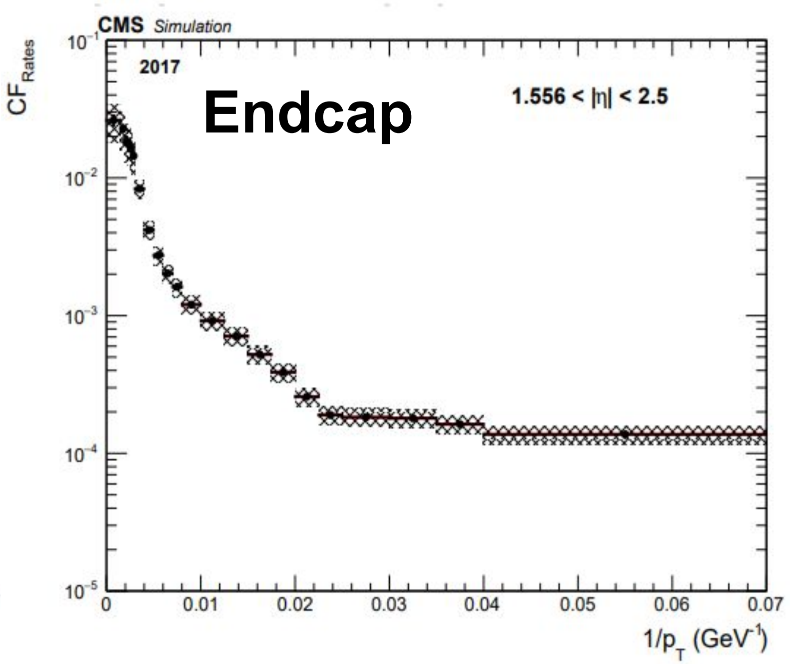
- Confirmed good agreement within systematic uncertainty.

Background estimation: Charge-flip leptons

- Charge-flip leptons: charge-mismeasured leptons
  - Dominant in electron channel
  - Muon is negligible

- Charge-flip rate is measured using DY MC in electron p_T and $|\eta|$ bin

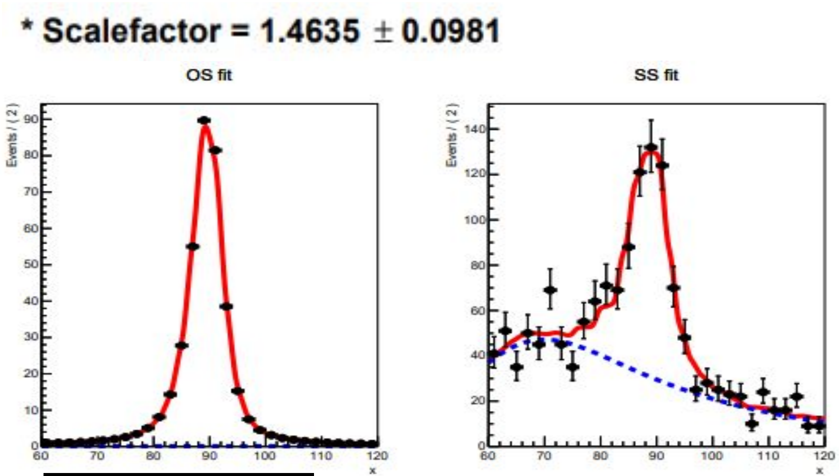


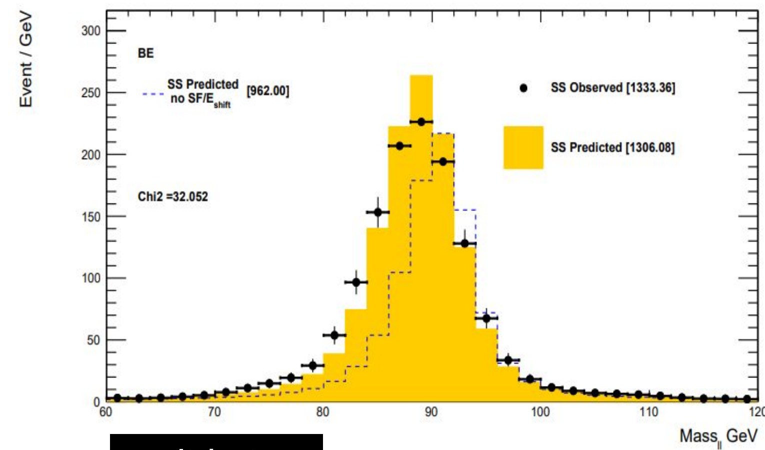


  - Rates of $O(10^{-5})$ to $O(10^{-2})$ depending on electron p_T and $|\eta|$.

Background estimation: Charge-flip leptons – validation

- Scale factors are estimated using **same-sign ee** data within Z mass





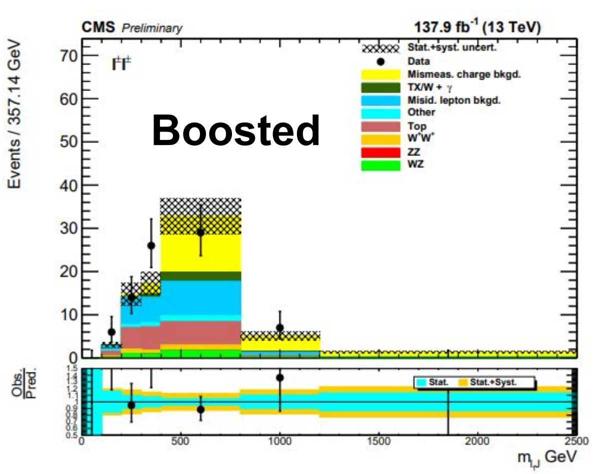
Measurement

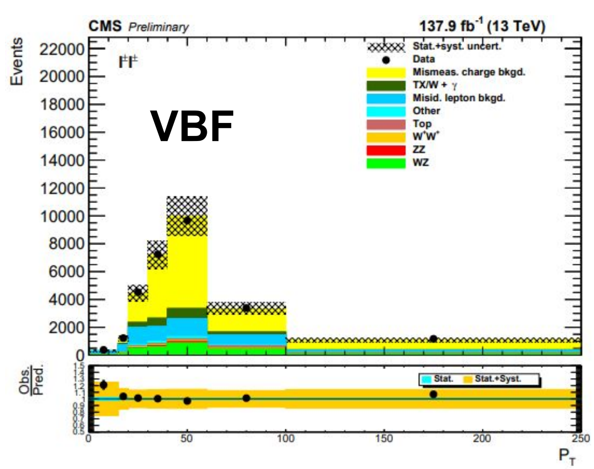
Barrel-Barrel / Endcap-Endcap events

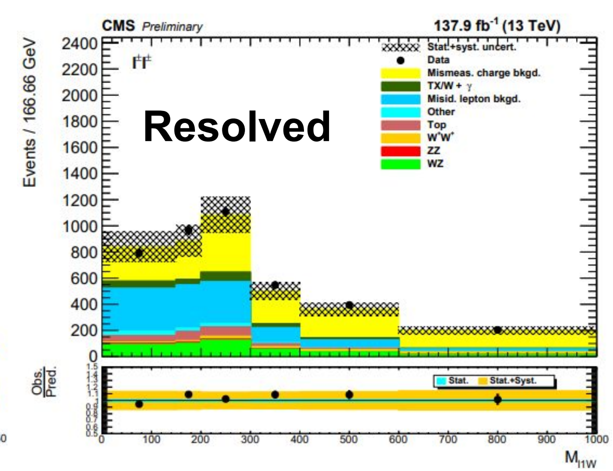
Validation

Barrel-Endcap events

- Validated in dedicated CRs

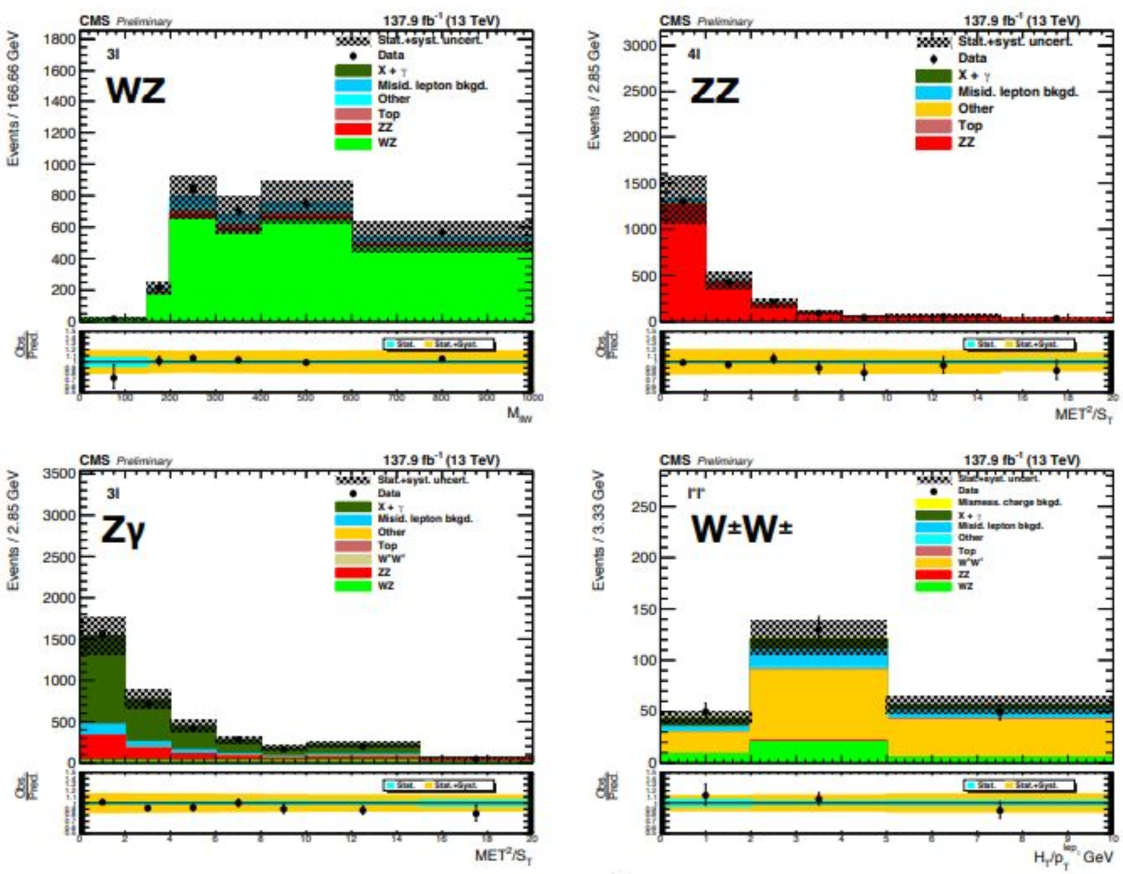






Background estimation: Prompt leptons

- Some SM processes can mimic SS dilepton + jets events
  - Major processes are WZ, ZZ, Zγ, $W^{\pm}W^{\pm}$, estimated by MC
  - The agreement in CRs are confirmed
    - Included in the likelihood fit to give further constraints

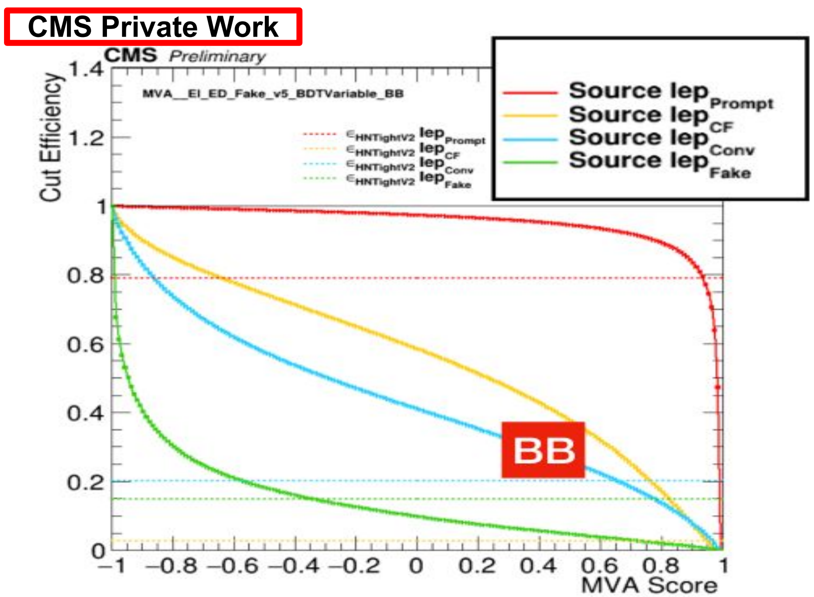


Optimizations:

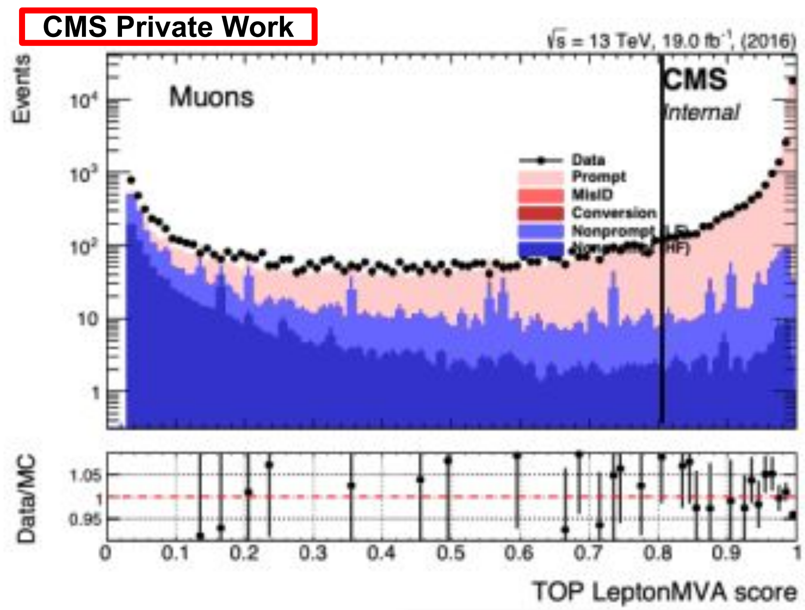
Object IDs, Signal Region Binning

Object ID optimization: Leptons

- Leptons
  - **BDT trainings** have been conducted for muon/electron IDs
    - Muon: against fake leptons
    - Electron: against fake, charge-flip, photon-conversion leptons
  - MVA distributions have been validated in dedicated control regions



Efficiencies on BDT trained electron ID



Control plots with muon ID

  - Final selections are then determined based on figures of merit

Object ID optimization: Jets

- Jets
  - Figures of merits are calculated while varying jet selections
    - Jet p_T, invariant mass, MVA scores to veto pileups, b-jets, etc.

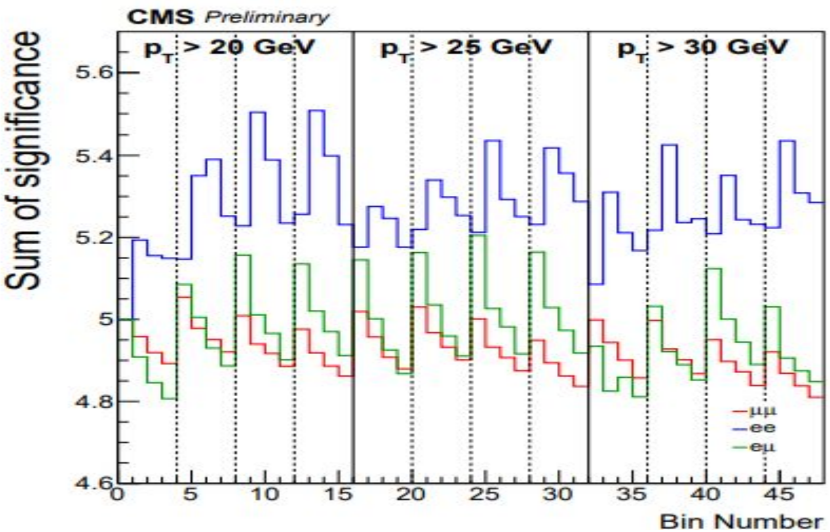
Figure of merit

$$Z_A = \sqrt{2\left((s+b)\ln\left(1+\frac{s}{b}\right) - s\right)}$$

Jet p_T scan

Jet	p_T cut > (GeV)
AK8	200, 225, 250
AK4 (central)	20, 25, 30
AK4 (b tagged)	20, 25, 30

Comparison

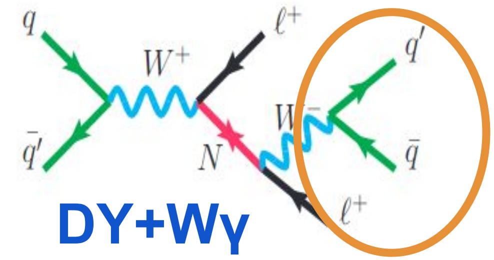


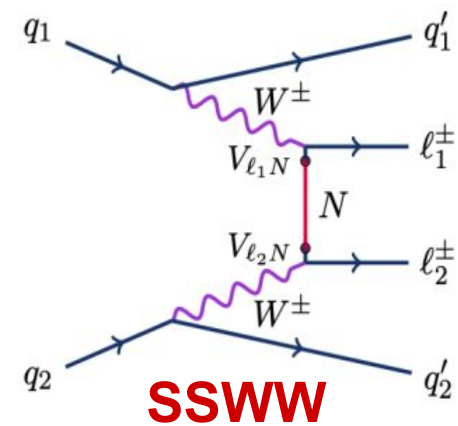
Other variable scan

Jet	Variables and cuts
AK8	No W tagging : without or with jet mass cut ($40 < m(J) < 130$ GeV) τ_{21} : low purity WP, high purity WP ParticleNet WvsQCD : mistag rate of 5%(without or with jet mass cut), 1%, 0.5%
AK4	Pileup MVA WP: none, loose, medium, tight For each pileup MVA WP, p_T cut of H_T jets : $> 15, 20, 25, 30$ GeV
AK4 (b tagged)	DeepJet WP: loose, medium, tight

Bin optimization with SRs

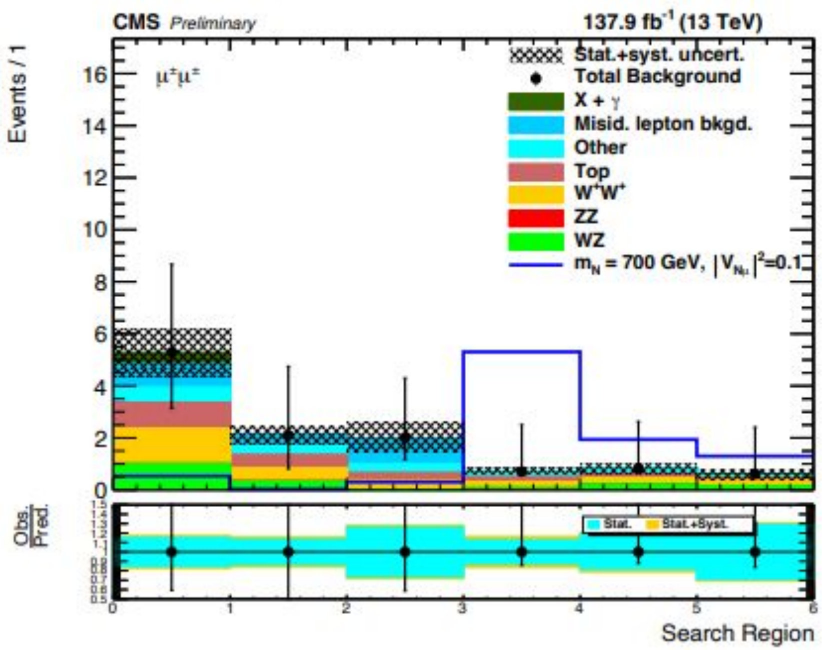
- Signal regions are binned to extract the maximal sensitivity.
  - Boosted SR divided into **6 bins**
    - Key variables: Reconstructed N mass – **m(l_1J)**, lepton p_T
      - **DY+Wγ**: high m(l_1J)
  - VBF SR divided into **3 bins**
    - Key variables: Scalar sum of jet energy (**H_T**), **lepton p_T**
      - **SSWW**: low $H_T/p_T(l)$
  - Resolved SR (high mass) divided into **14 bins**
    - Key variables: **Number of jets**, **m(llW)**, lepton p_T, MET
      - **DY+Wγ**: high m(llW)
      - **SSWW**: <u>**low number of jets**</u> (Bonus!)
  - Resolved SR (low mass) divided into **17 bins**
    - Binned by **BDT score** giving the maximal sensitivity

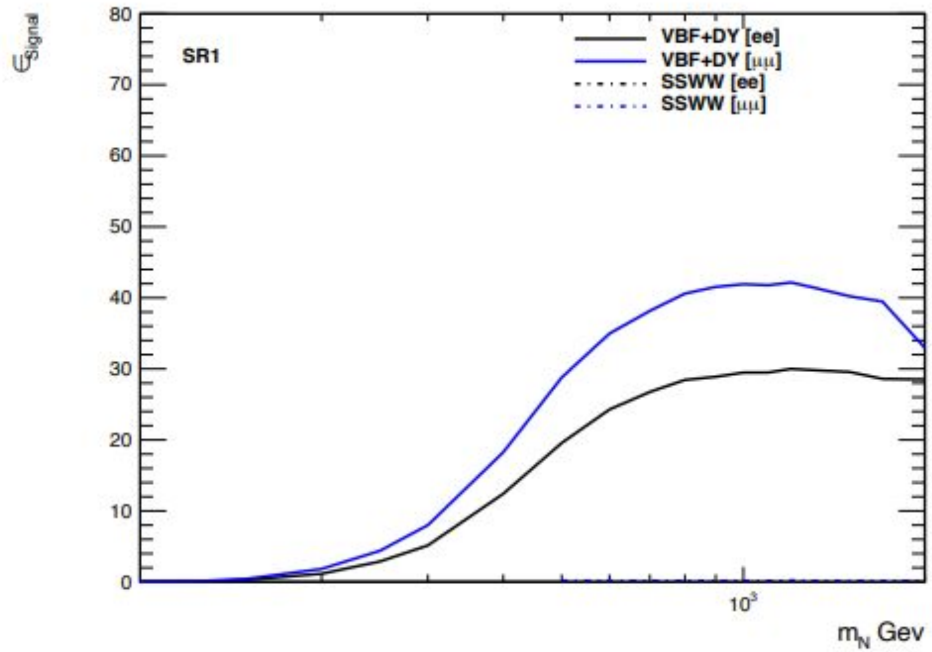




Results (Blinded)

- **Boosted** SR: distribution (left), signal efficiency (right)



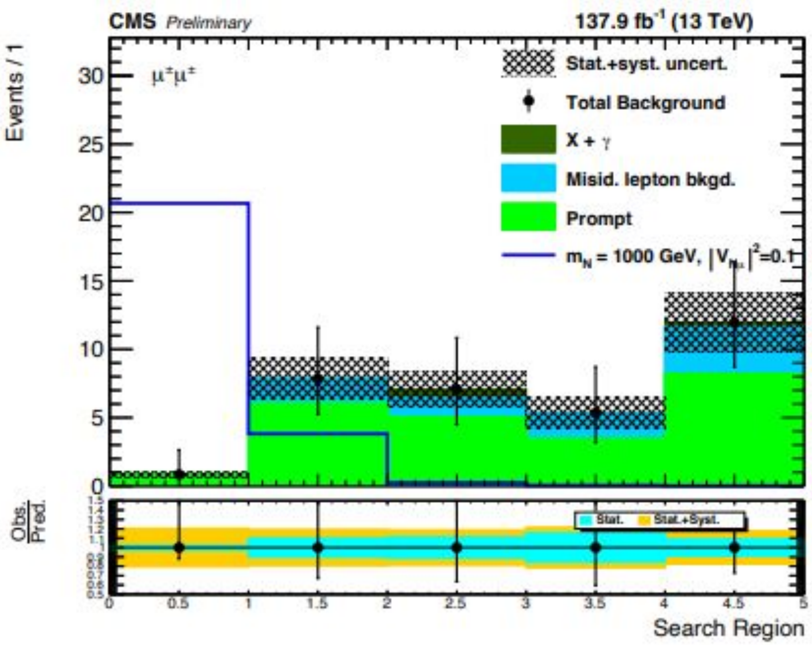


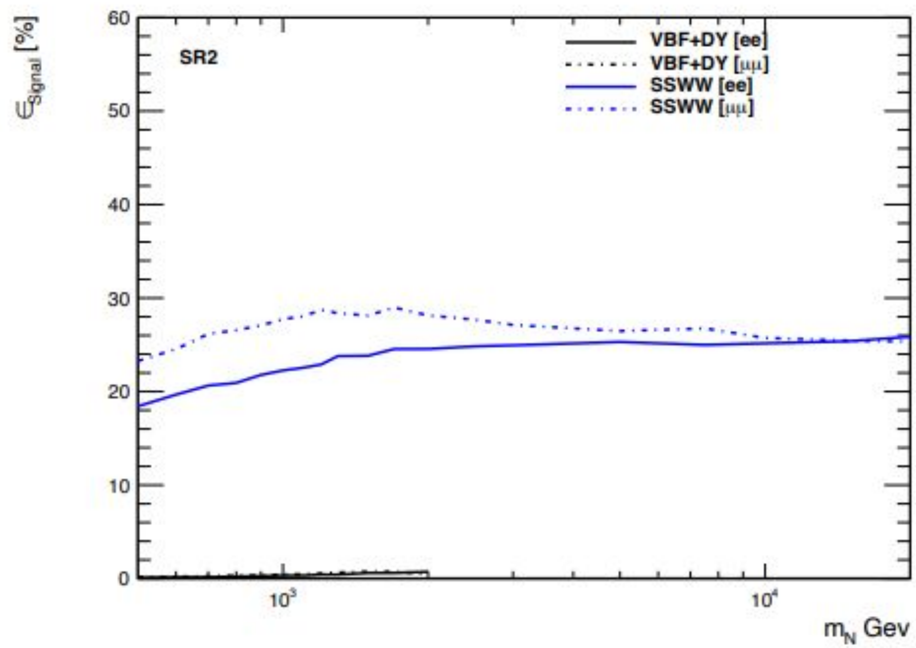
- **DY+Wγ** signals:
  - High $m(l_1J)$

- **DY+Wγ** signal efficiency increases with N mass.
  - Boosted topology

Results (Blinded)

- **VBF** SR: distribution (left), signal efficiency (right)



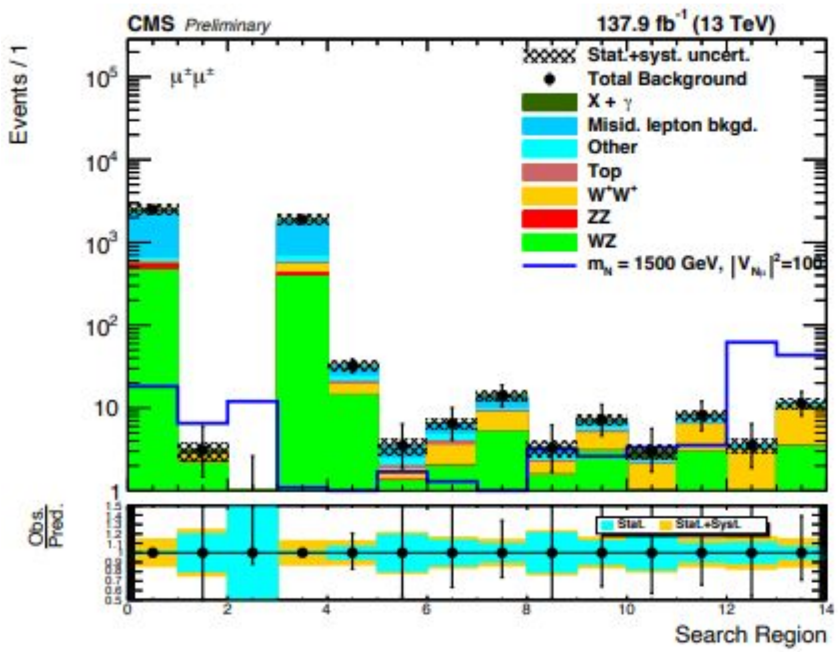


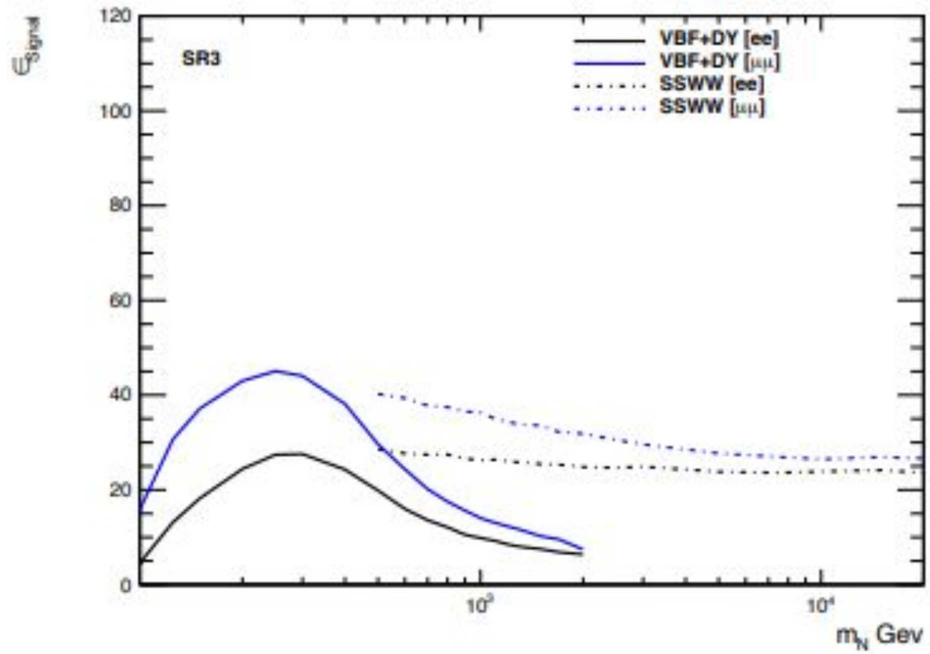
- **SSWW** signals:
  - Low H_T compared to lepton p_T

- **SSWW** signal efficiency is maximized
  - VBF topology

Results (Blinded)

- **<u>Resolved</u>** SR: distribution (left), signal efficiency (right)





- **DY+Wγ** signals:
  - High m(llW)
- **SSWW** signals:
  - Low number of jets

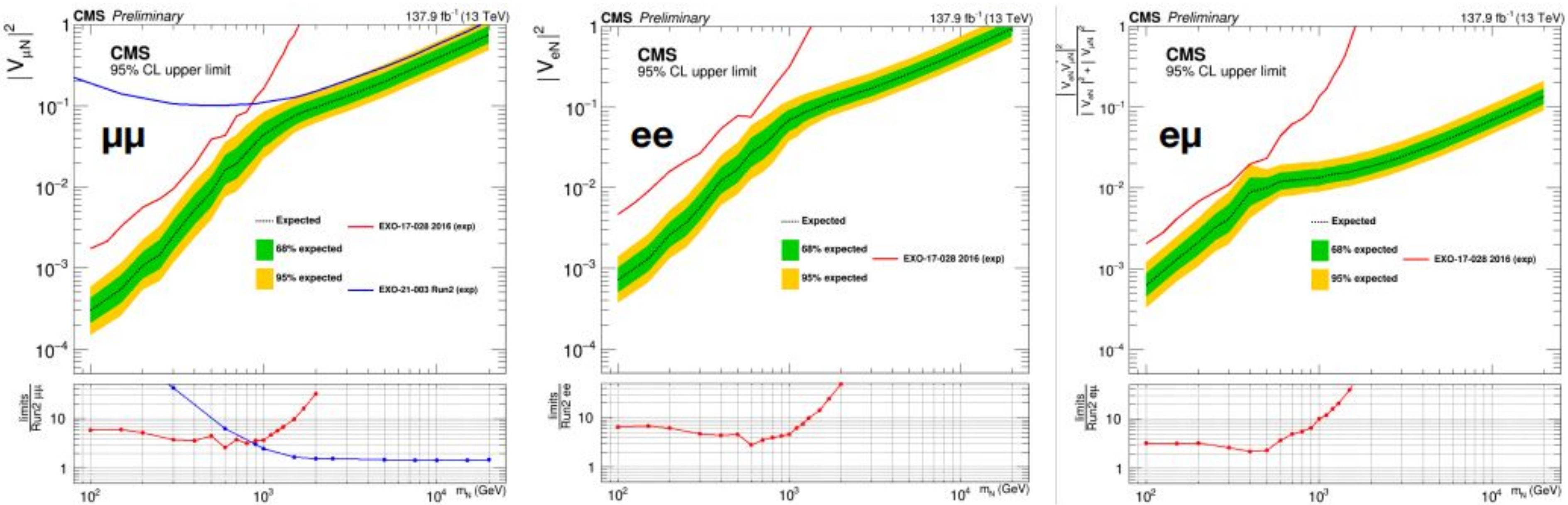
- **DY+Wγ**: maximal in low mass (BDT selection)
- **SSWW**: **<u>still captured</u>** by cut-based selection

Expected Limits:

Comparison with Existing Analyses

Expected limits & Comparison with prev. CMS searches

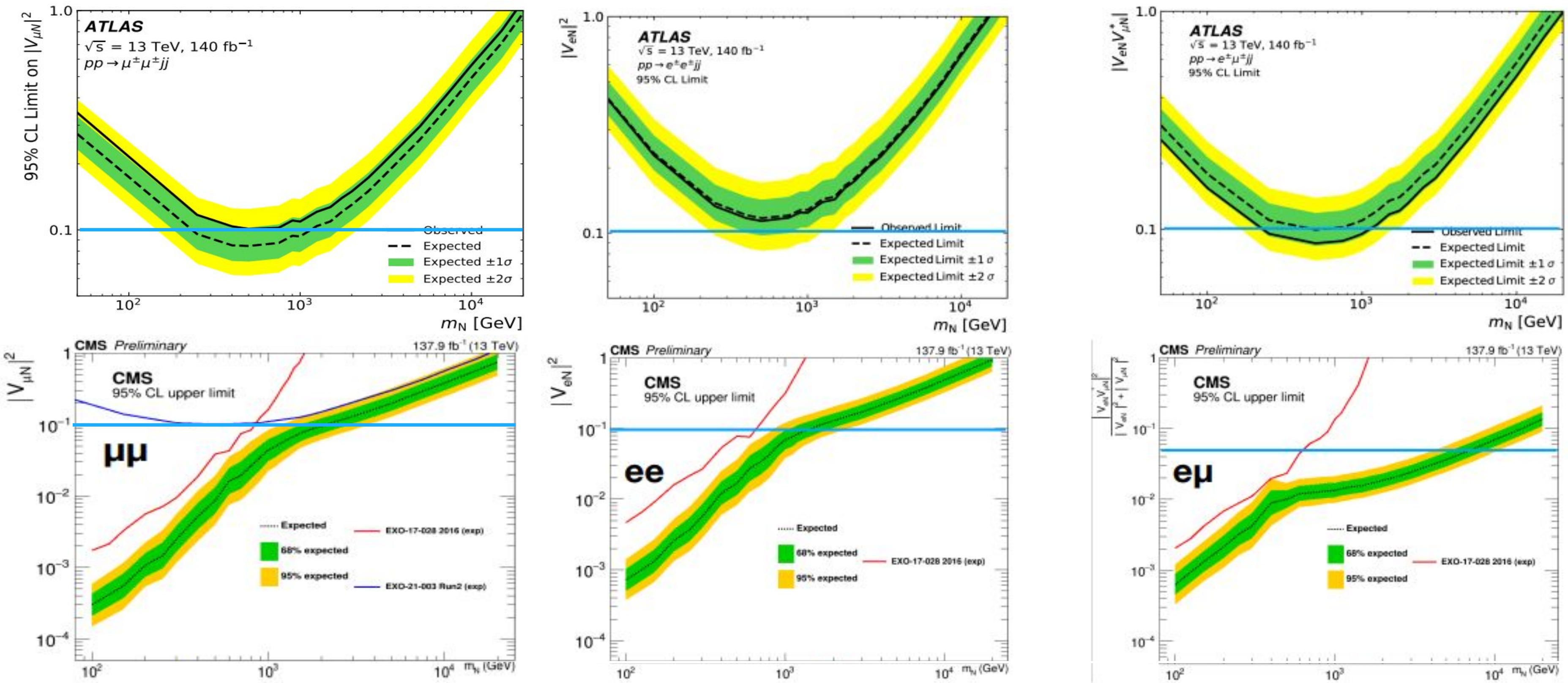
- Expected limits using full Run-II data
  - Results compared with previous CMS searches
    - **JHEP 01 (2019) 122** : DY+Wγ / 2016 / μμ, ee, eμ (**red**)
    - **PRL 131, 011803** : SSWW / Run-II / μμ (**blue**)
  - Improved sensitivity across all mass points up to factor of 7



- **μμ**: Enhanced even when compared with the previous Run-II analysis
  - SSWW signals are additionally captured in the resolved SR.
- **ee, eμ**: The first CMS search using these channels in SSWW

Comparison with ATLAS results

- <u>ATLAS</u> **Phys. Lett. B 856 (2024) 138865** (top) to **<u>this search</u>** (bottom)
  - Azure lines at $|V|^2 = 0.1$



- Achieved better sensitivity across all lepton channels.
  - The first LHC search integrating 3 signal processes.
  - SSWW signals are additionally captured in the resolved SR.

Summary

- Search for heavy neutral leptons with same-sign dilepton + jets final states using CMS Run-II data has been presented.
  - **The first CMS search** using **ee** and **eμ** final states in the SSWW signal
  - **The first LHC search** to include 3 heavy Majorana neutrino processes

- Key aspects of the search strategy and relevant studies were discussed:
  - Signal kinematics and the concept of event selection
  - Background estimation and validation
  - Object ID optimization
  - Signal region binning optimization

- Significant improvements achieved across a wide range of N mass:
  - Up to **7x better** results than previous CMS searches
  - Better sensitivity compared to the ATLAS searches
  - Reached 25 TeV, **breaking the CMS center of mass energy limit**

- Pre-approval preparation ongoing (CMS SUS-24-014).

Back-ups