Searches for Heavy Neutral Leptons

J. Almond[1] U. Yang[1] H.Lee[1] J.Kim[1]
Y.Kim[1] S. Jeon[1] J.Bhyun[1]

Seoul National University

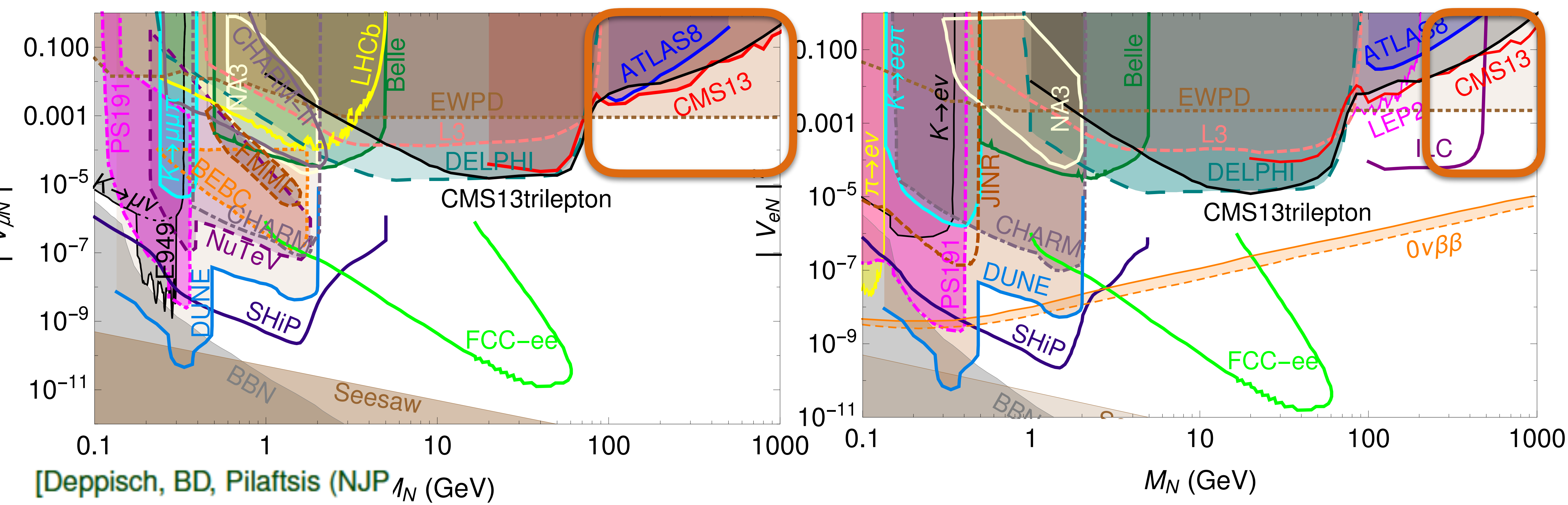
NAPP Workshop

Thursday 30 March 2023

Motivation For Type-1 HNL's

- Neutrino oscillations -> SM neutrinos have mass
  - Smallness of neutrino masses -> heavy neutrino (N_R) by “SeeSaw”
- Candidate for dark matter
- Many models of interest predict new heavy neutral leptons (HNL) .

- If HNLs exist at or below TeV scale we should be able to see them at the LHC.
- SNU group have a strong interest in searches for HNL at CMS, EXO-17-028 (SNU) current world leading direct limits for mN> 200 GeV.
- Still much more improvements can done with Full Run 2.



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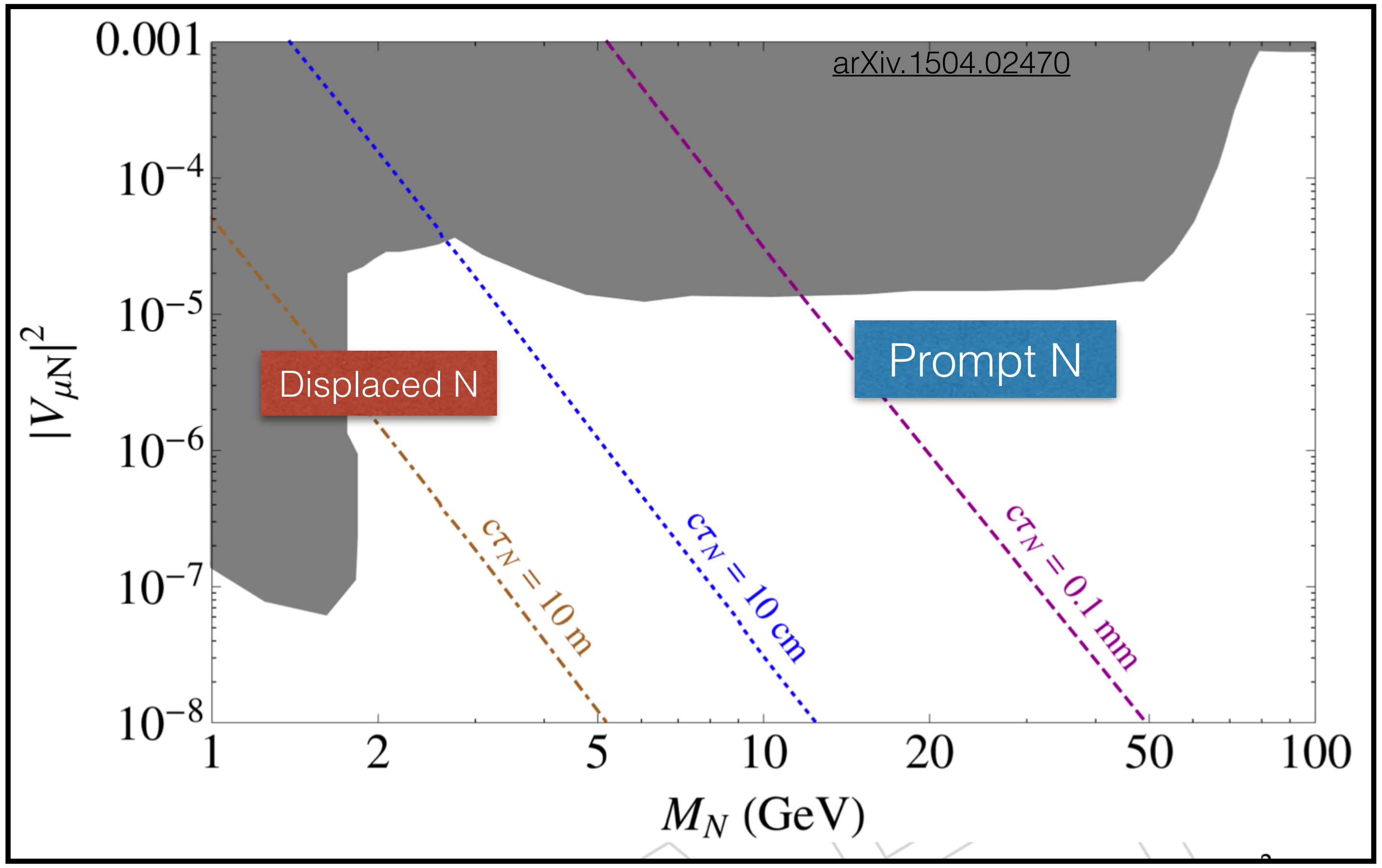
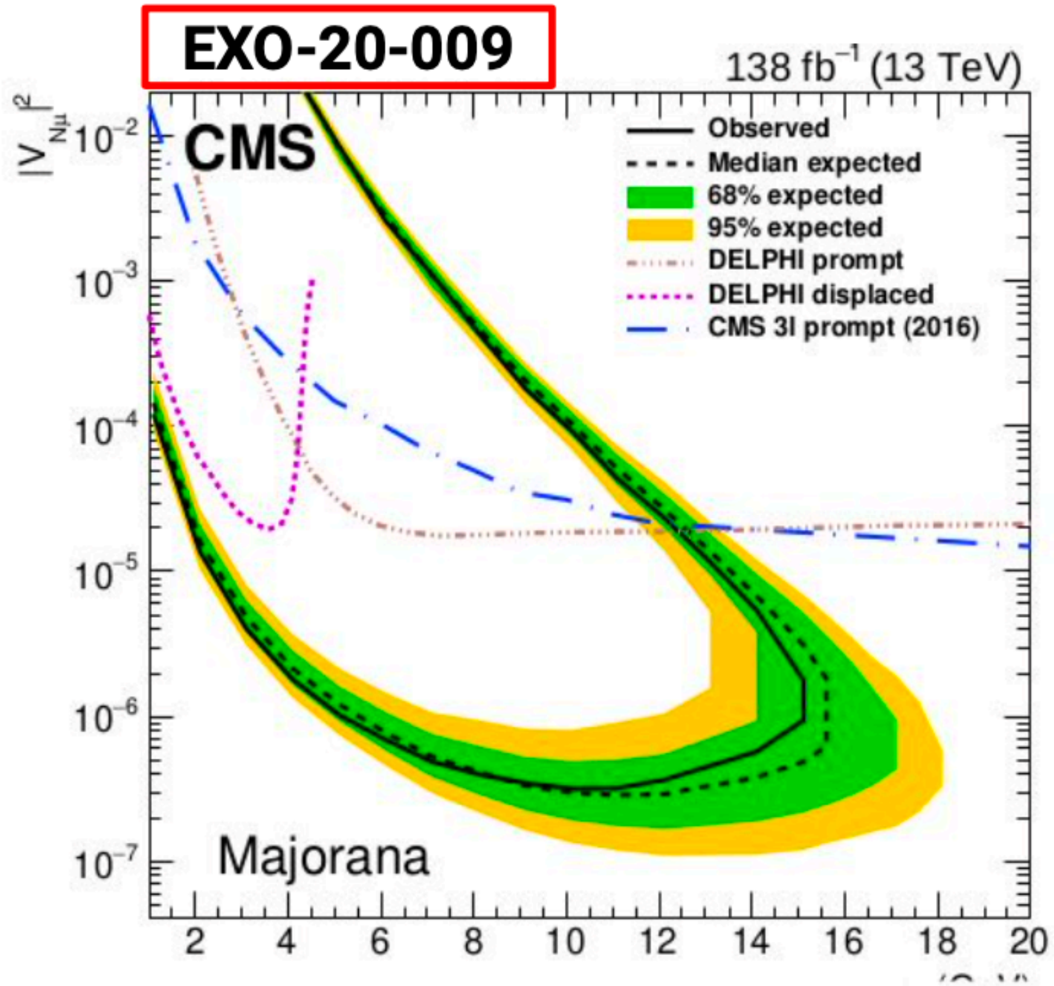
Direct Searches For Type-1 HNL's



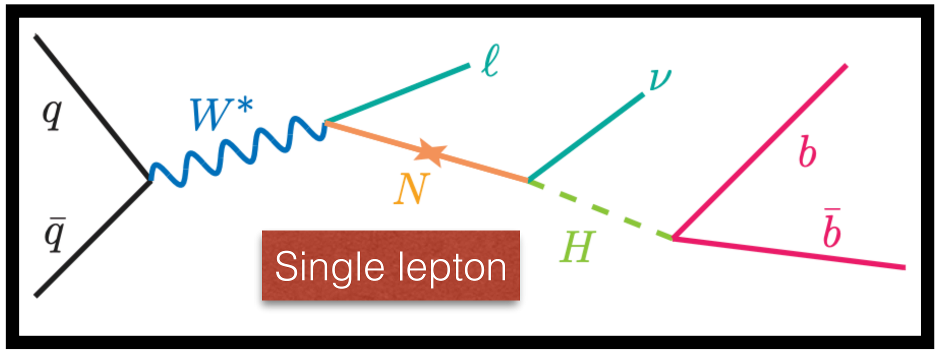


- Below 20 GeV strong limit from Long Lived channels.
- Above 20 GeV N is prompt and can can be produced in many channels.

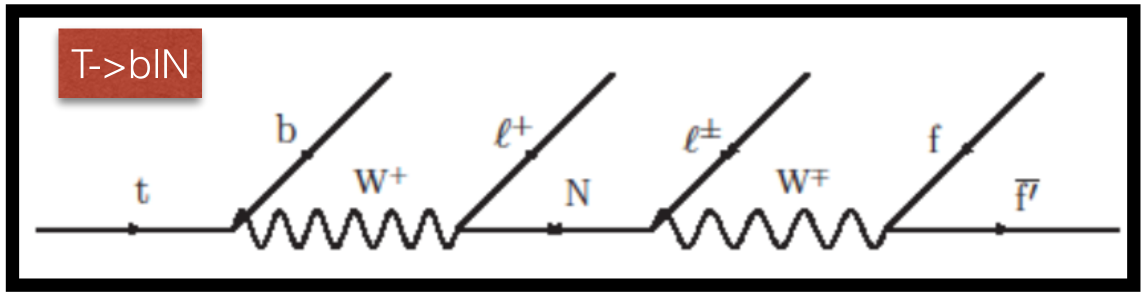
Full Run 2 Searches For Type-1 HNL

This talk will discuss 3 Full Run 2 analyses searching for HNL using 138 fb^{-1}:

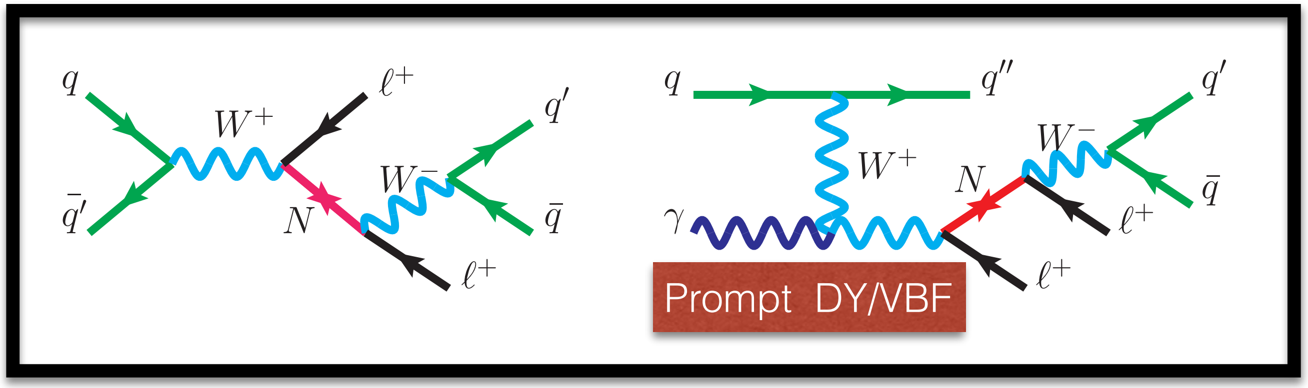
- Search for HNL in Single lepton events (*CADI https://cms.cern.ch/iCMS/analysisadmin/cadilines?line=EXO-22-023*)
  - Sensitive to [$1 < m_N < 950$ GeV]
  - Unblinded & Thesis endorsed
  - Novel analysis



- t->bIN (prompt 2l same sign (SS))
  - [$20 < m_N < 100$ GeV]
  - Novel analysis
  - Blinded



- W*->IN (prompt 2 lepton+Jets) + WW VBF
  - Sensitive to [$85 < m_N < 30$ TeV].
  - Blinded
  - Updated on EXO-17-028



CMS

Compact Muon Solenoid

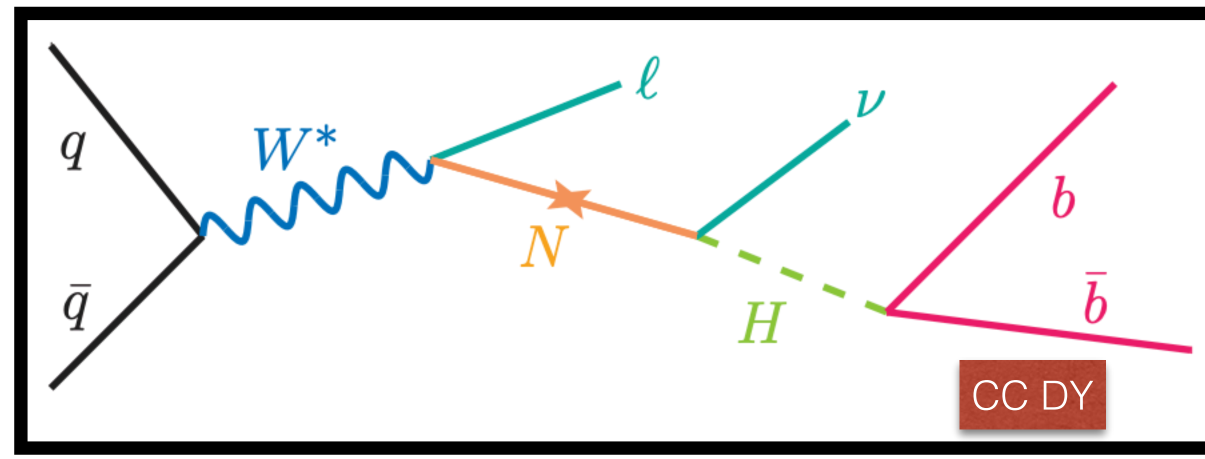
Search for heavy neutrino in single lepton channel

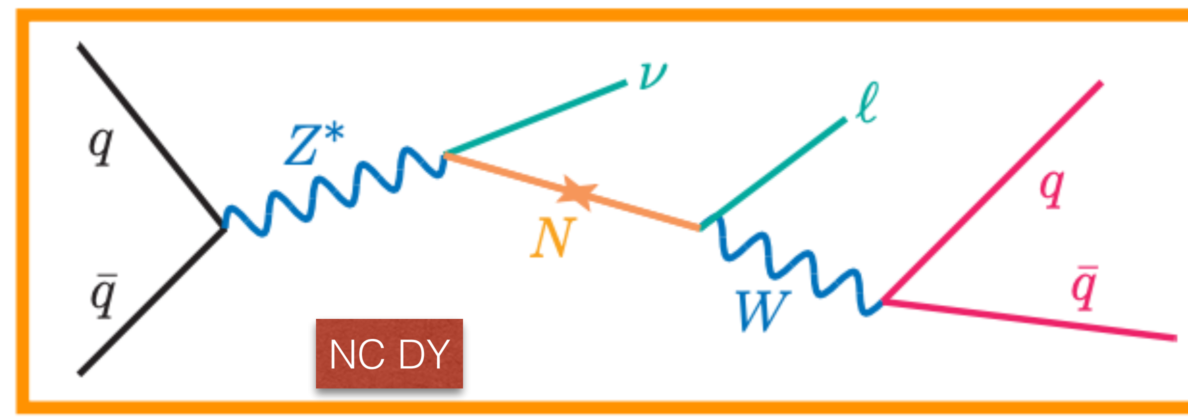
EXO-22-023

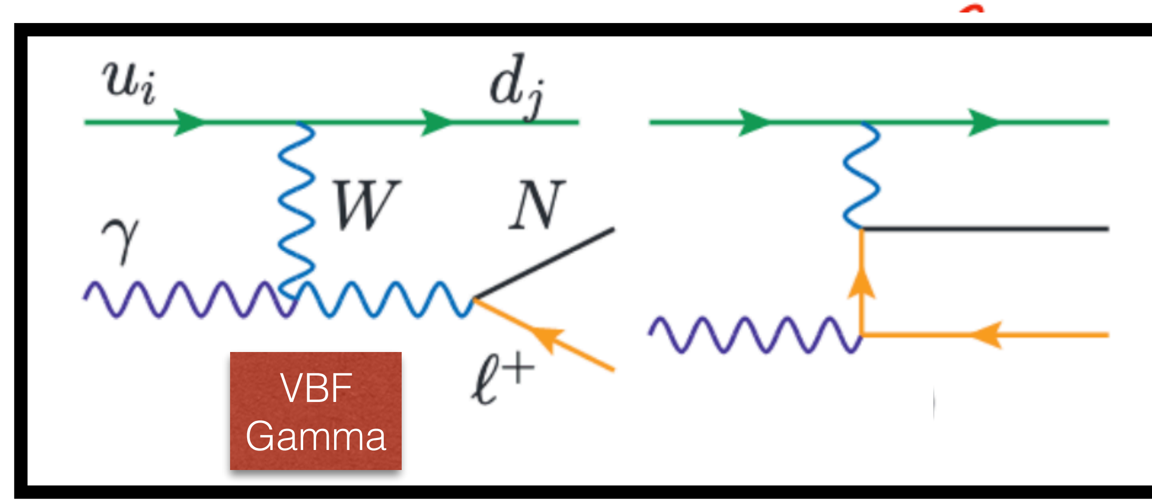
Single Lepton Channels (SLC)

Signal Processes

- Consider three dominant N production modes:
  - CC DY $p\,p \rightarrow W^{*} \rightarrow \ell\ N$
  - NC DY $p\,p \rightarrow Z^{*} \rightarrow \nu\ N$
  - VBF production $p\,\gamma \rightarrow \ell\ N\ q$
- Signals generated with MadGraph_aMCatNLO in mass range 500-1500 GeV
- Consider four decay modes of N:
  - $N \rightarrow \nu\ H \rightarrow \nu\ b\ \bar{b}$
  - $N \rightarrow \nu\ Z \rightarrow \nu\ b\ \bar{b}$
  - $N \rightarrow \nu\ Z \rightarrow \nu\ q\ \bar{q}$
  - $N \rightarrow \ell\ W \rightarrow \ell\ q\ \bar{q}$
- Final state 1 Lep, 2 Jets + MET



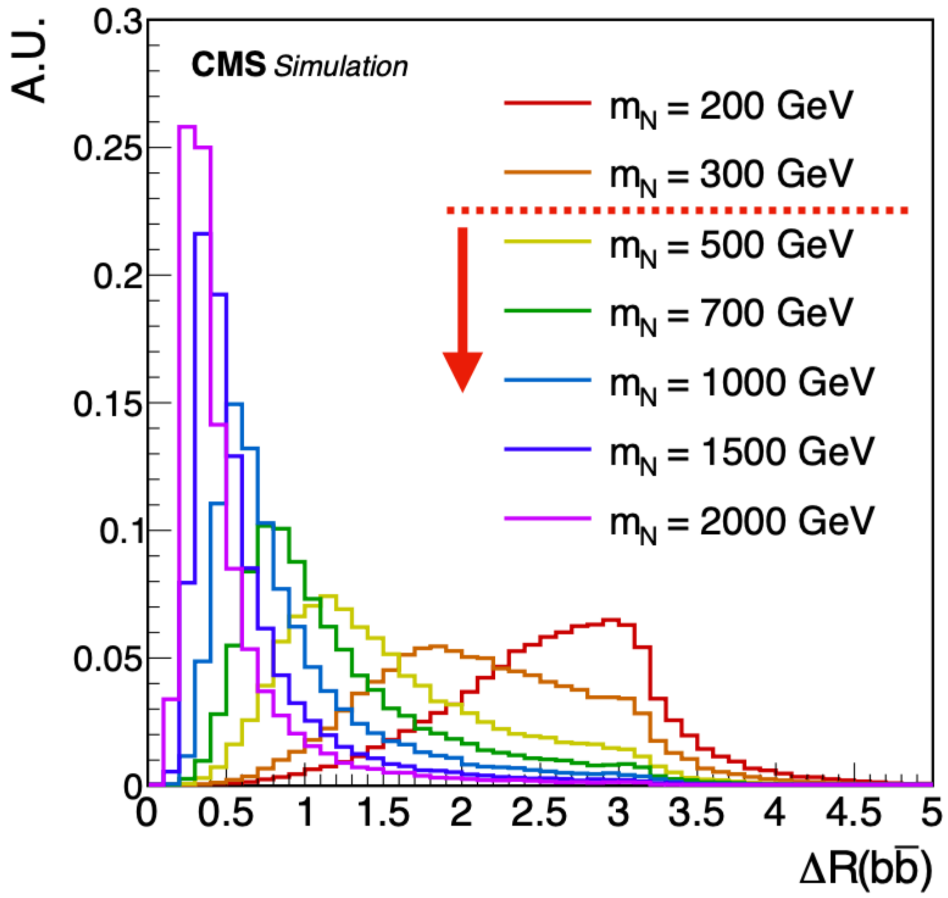


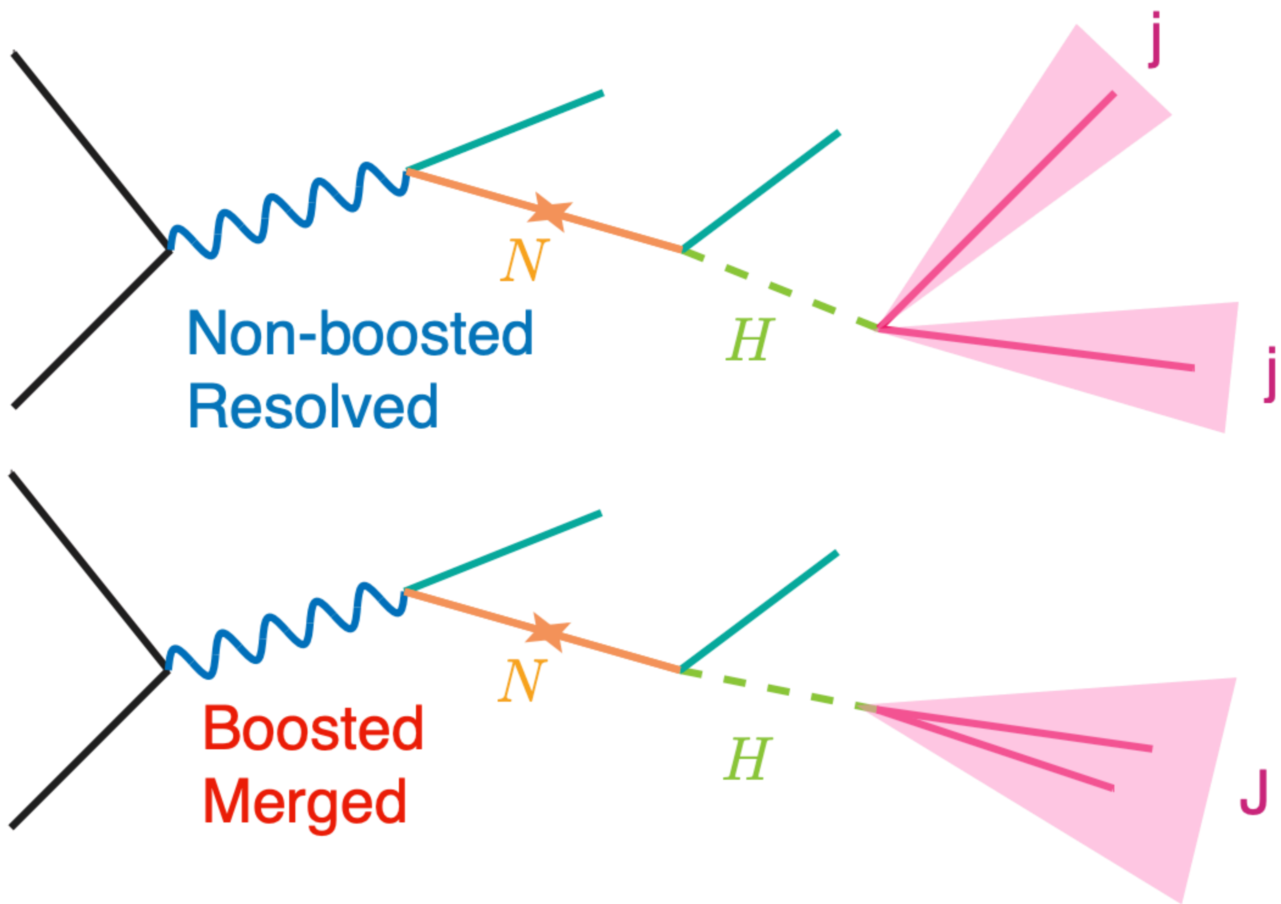


SLC Signal region criteria

Signal Processes

- Signals split into boosted and resolved categories

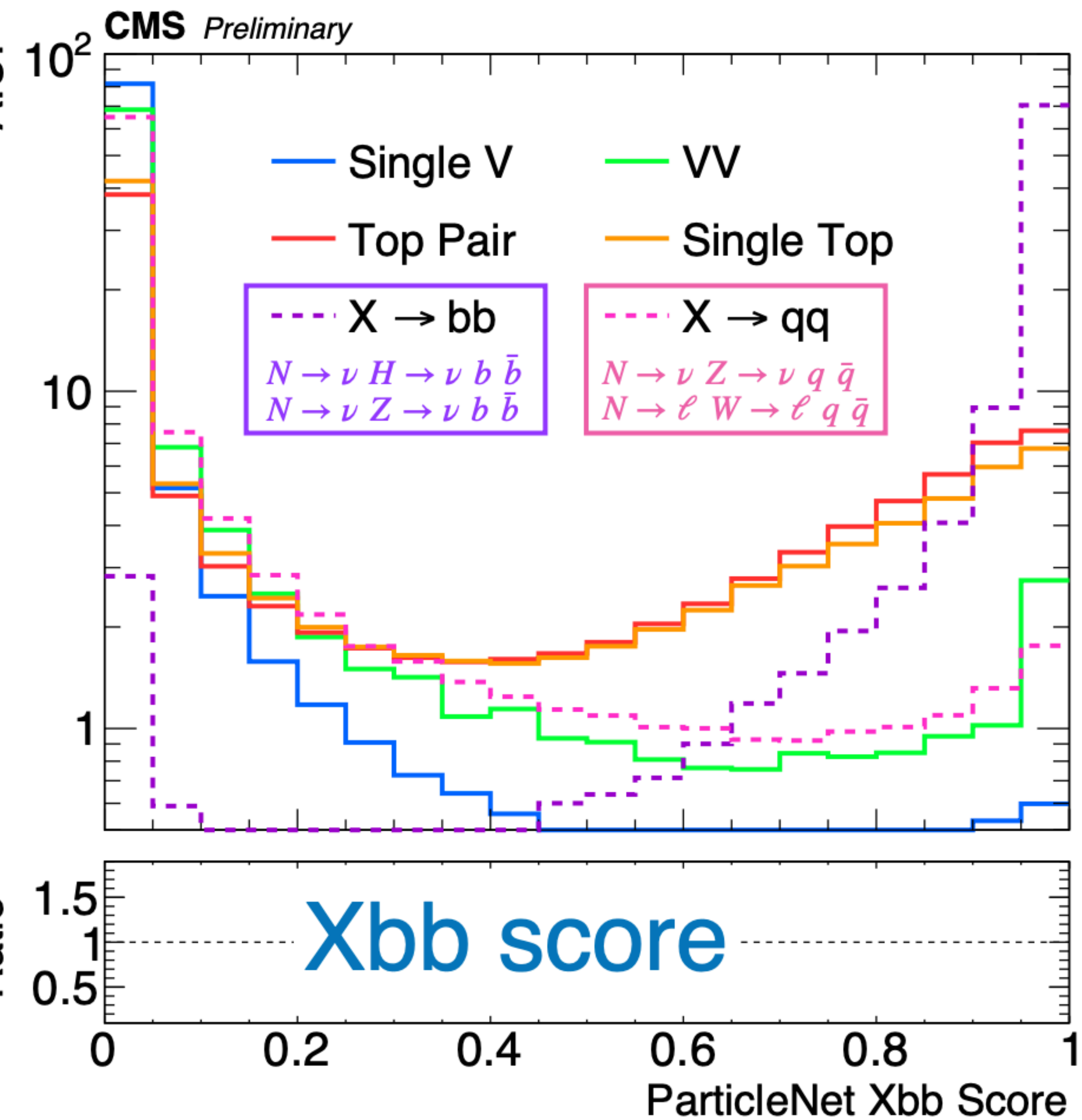


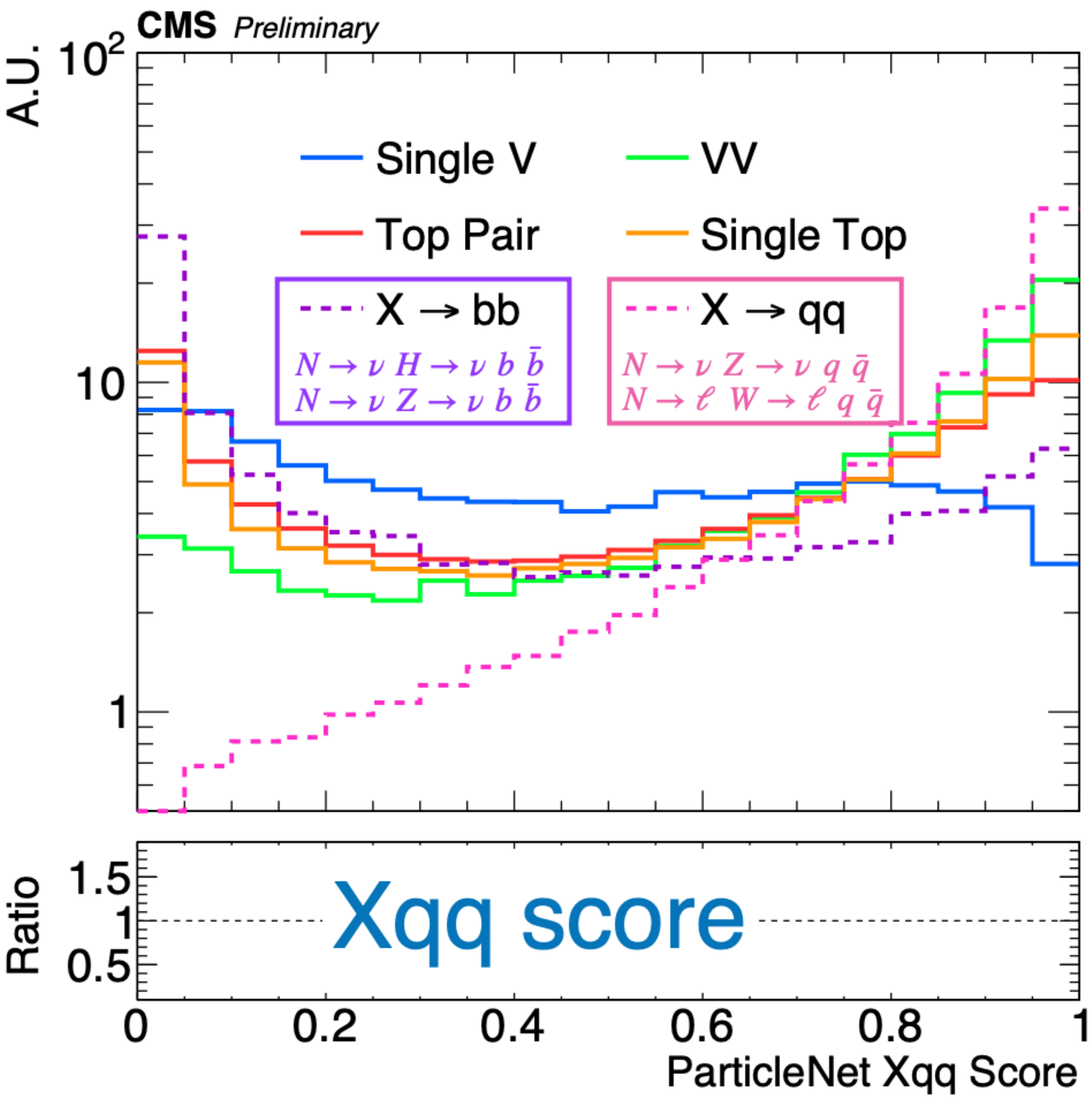


Merged Selection: Signals contain 1 AK8 Jet + Large MET + Lepton
Resolved Selection: Signals contain 2 separated AK4 jets + Large MET + Lepton

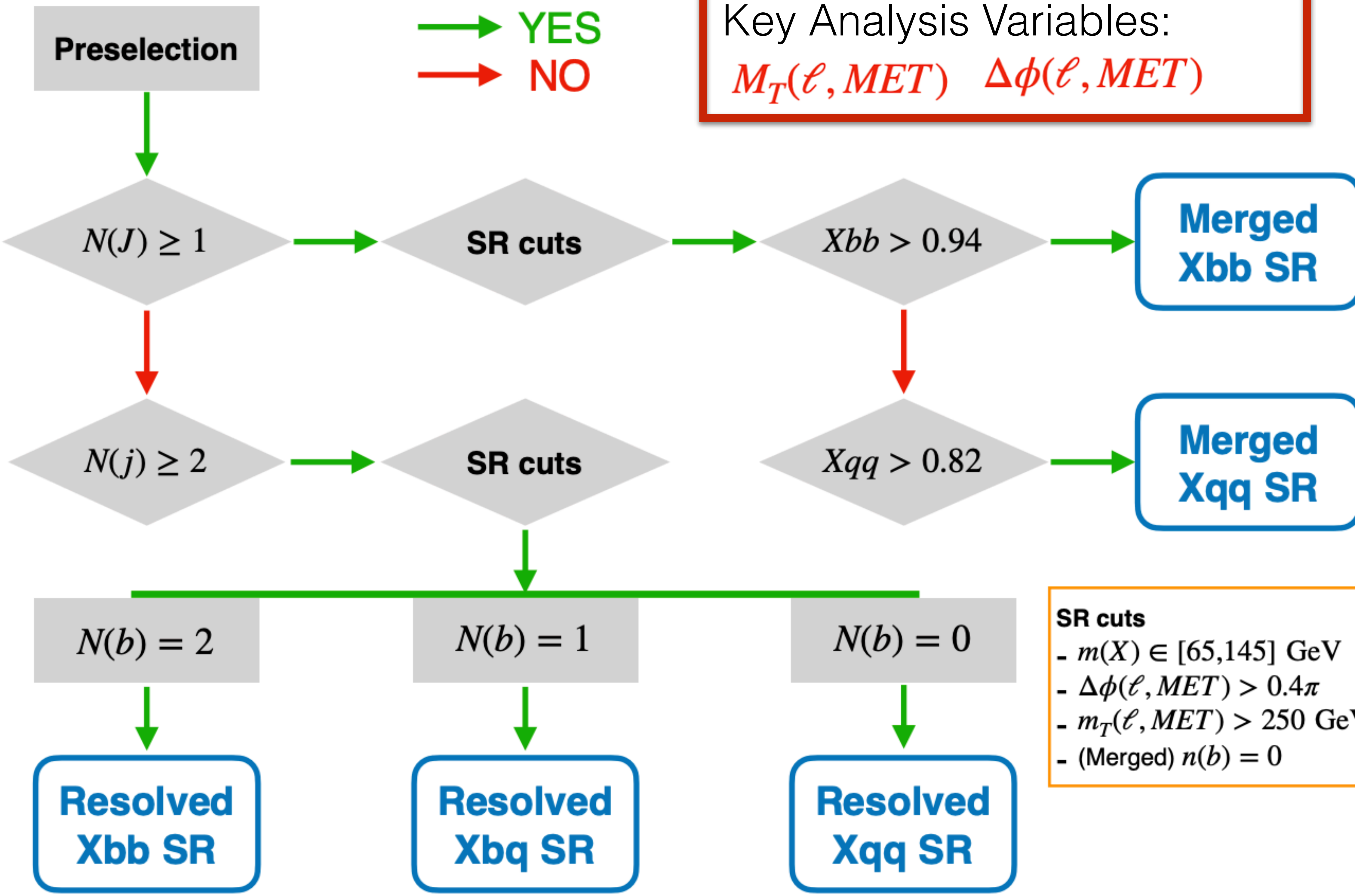
SLC ParticleNet Jet Tagger

ParticleNet tagger provides great discrimination power for signals (dashed) against backgrounds





SLC Analysis Strategy



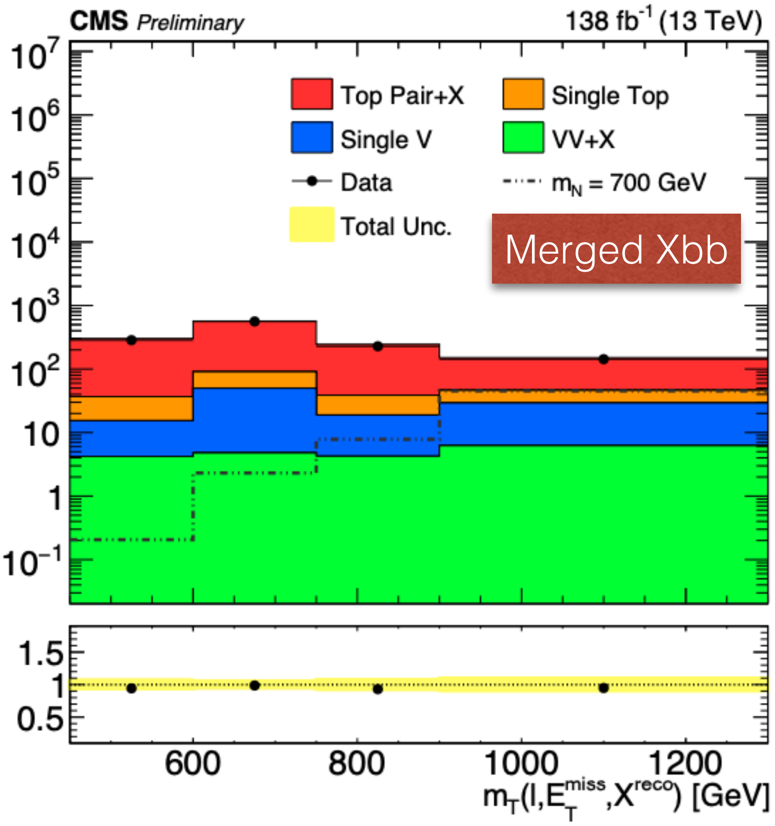
Key Analysis Variables:
$M_T(\ell, MET)$ $\Delta\phi(\ell, MET)$

SR cuts
- $m(X) \in [65,145]$ GeV
- $\Delta\phi(\ell, MET) > 0.4\pi$
- $m_T(\ell, MET) > 250$ GeV
- (Merged) $n(b) = 0$

SLC Limit Extraction

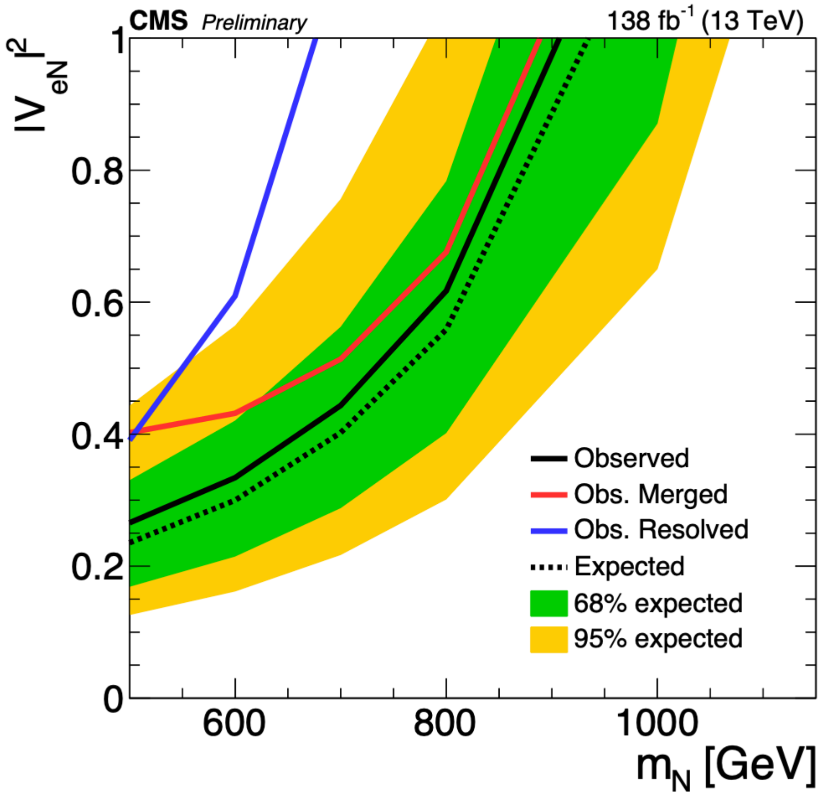
Distributions of $M_T(\ell, MET, X)$ from all SR/CR used to extract the upper limits with Asymptotic method

Shape considered for some of the sources



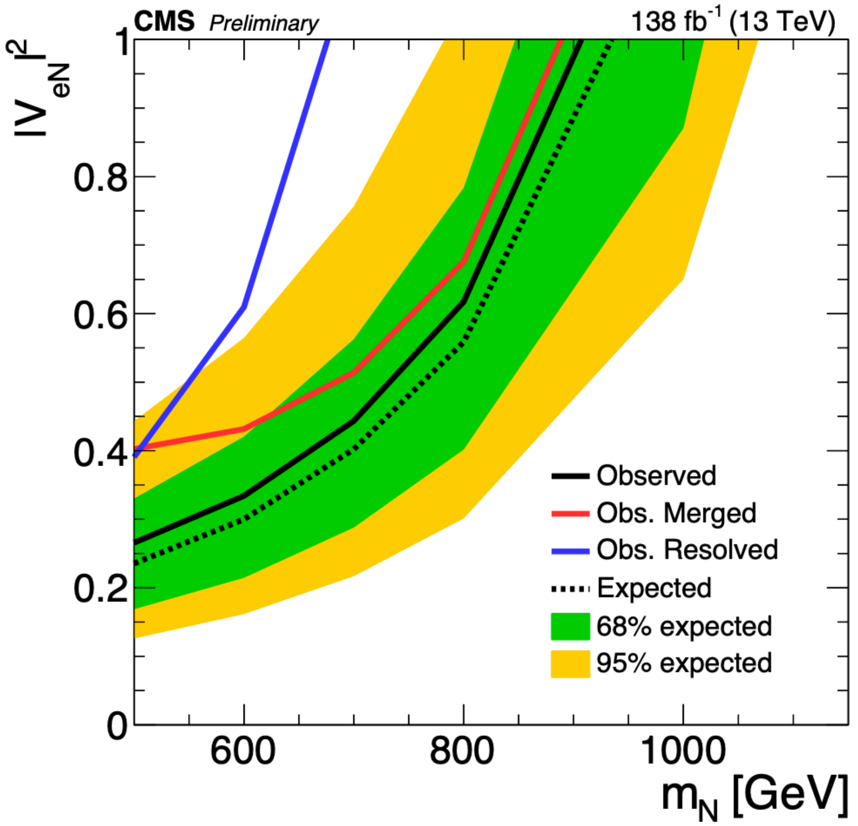
Higgs Combined

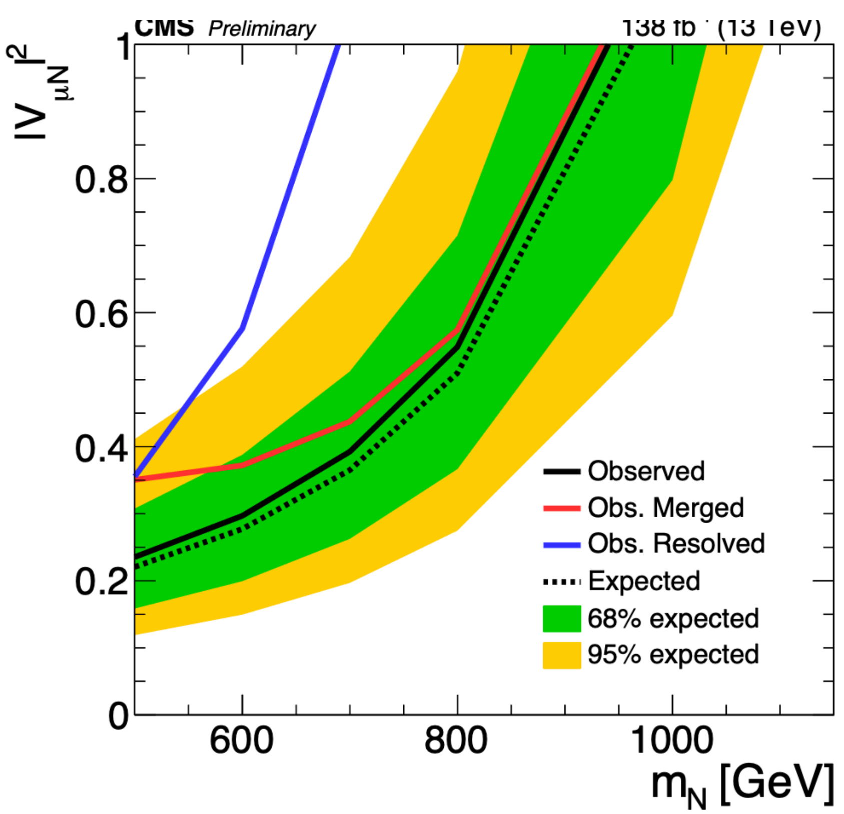
Electron



Dominant systematics from JES, 5-10% for background

SLC Limit Extraction





Summary

- Excludes N up to [obs.] 910 (940) GeV for scenarios ([exp.] 930 (960) GeV)
- First limit in this channel ay LHC
- First search looking for Higgs decay to N

OutLook

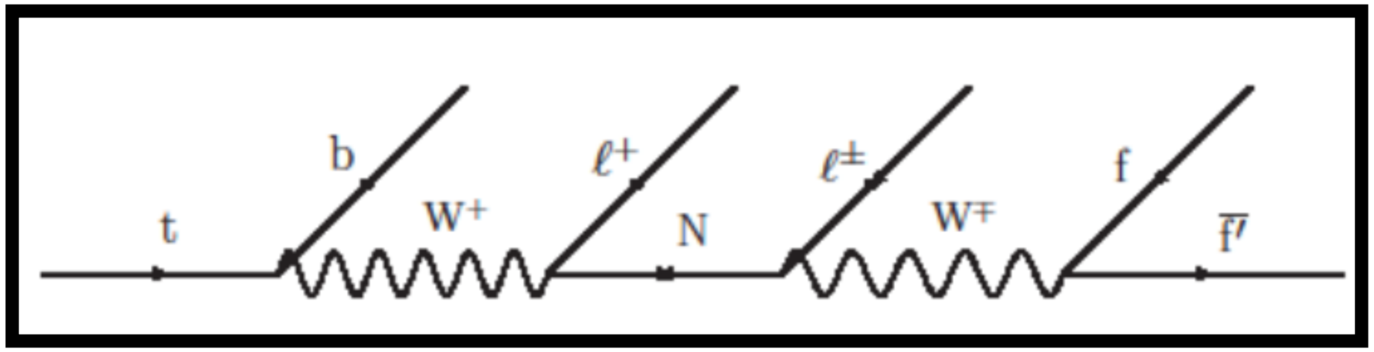
- Dirac type N interpretation possible
- Possible extension to split charge

Search for heavy neutrino in Top decays

Motivation and Selection overview

Motivation

- LNV top decay mode can open if m(N)<m(t)
- most stringent type-1 seesaw limit permits O(100)-O(1000) LNV top events in CMS-Run-2
- Top channel is particularly interesting in CPV HN scenario [1] - N(++)/N(--)≠ 1,
  - in contrast, DY channel (pp→lN) is affected by PDF even in the absence of CPV
  - this has to be 1 in tt channel, CPV effect can be more clear
- Consider 20≤m(N) ≤100GeV



Baseline event selection

- two leptons with same-flavour and same-charge (ee or $\mu\mu$, no additional lepton),
- p_T (μ)>20,10 GeV ($\mu\mu$ channel), p_T (e)>25,15 GeV (ee channel),
- M($\mu\mu$)>4 GeV (only for $\mu\mu$ events)
- |M(ee) − 91.2| >10 GeV (only for ee events),
- $N_{\text{b tags}} \geq 1$,
- $N_{\text{jets}} \geq 3$.
- $N_{\text{untagged jets}} \geq 1$ (2) for $m_N < 80$ GeV ($m_N > 80$ GeV).

Lepton Identification

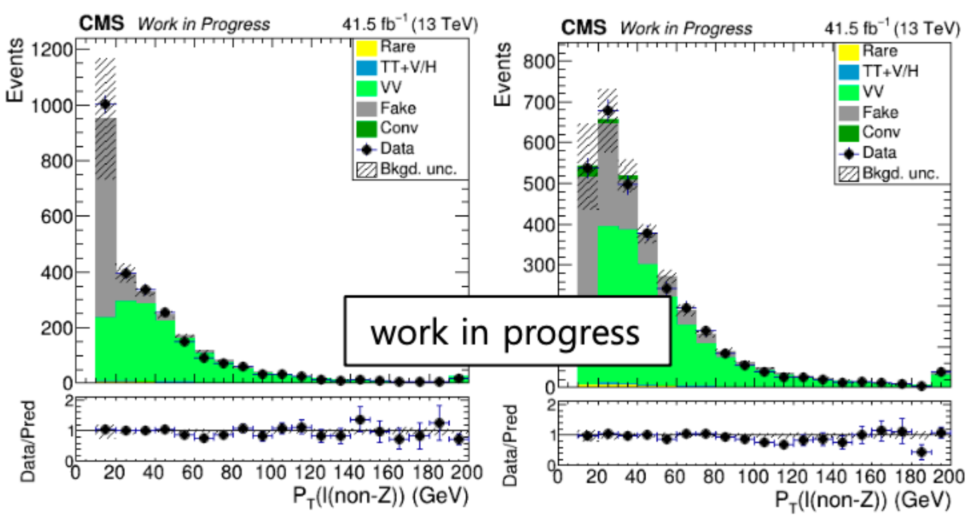
ID Variable	Cut Value	
	Tight WP	Loose WP
POG Medium ID	✓	✓
rel. mini-isolation	< 0.1	<0.6
|SIP3D|	< 3	< 5
Trigger Emulation Cuts		
rel. tracker isolation (R03)	<0.4	<0.4
$\|d_z\|$(cm)	<0.1	<0.1

ID Variable	Cut Value	
	Tight WP	Loose WP
MVA	POG ID (wp90)	>(0.96,0.93,0.85) (16) >(0.94,0.79,0.50) (17–18)
rel. mini-isolation	< 0.1	< 0.4
|SIP3D|	< 4	-
expected missing inner hits	≤ 1	≤ 1
conversion veto	✓	✓
tight charge	✓	✓ (sideband) / - (veto)

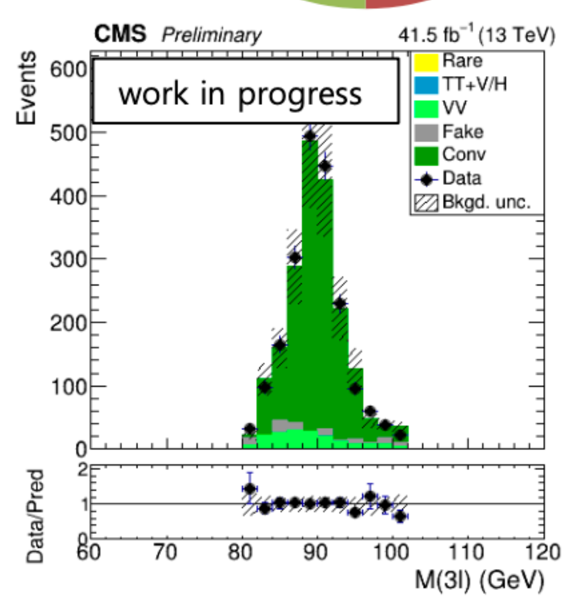
Background Estimation in SS2l

jet-induced nonprompt lepton bkgd. (tt)

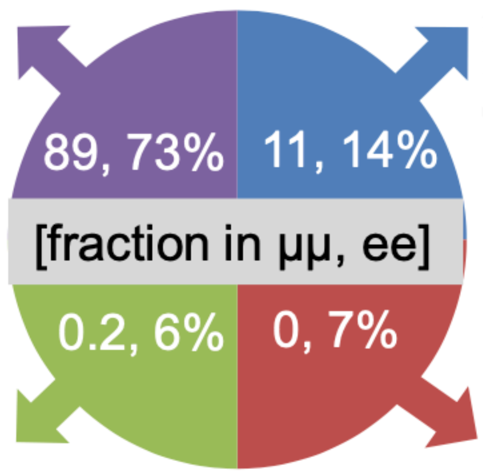
- <u>apply fake rate (N(T)/N(L)) to sideband (fail tight ID)</u>
- FR measured using l+j events in di-jet topology
- validity tested with Z+fake CR



- <u>estimate with MC</u>
- unc. based on CR agreement
- CR enriched with Z→llγ, γ→e(e)

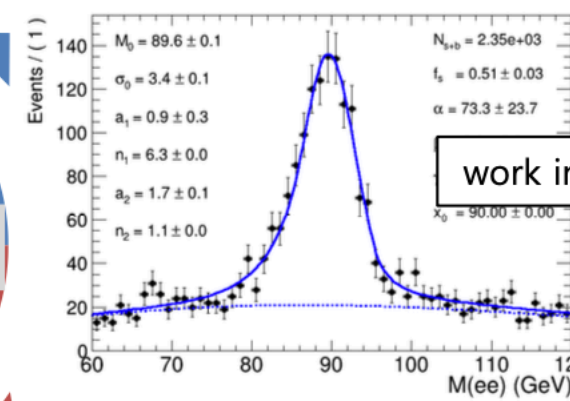


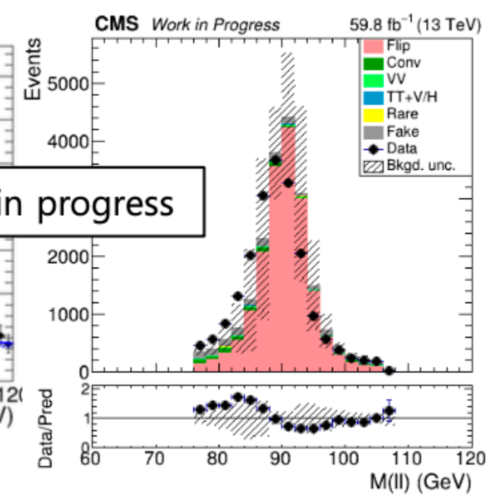
conversion bkgd. (tt)



prompt SS dilepton (tt+W/Z/H)

- <u>estimate with MC</u>
- main:tt+V/H, rare: VV, VVV, H, VH



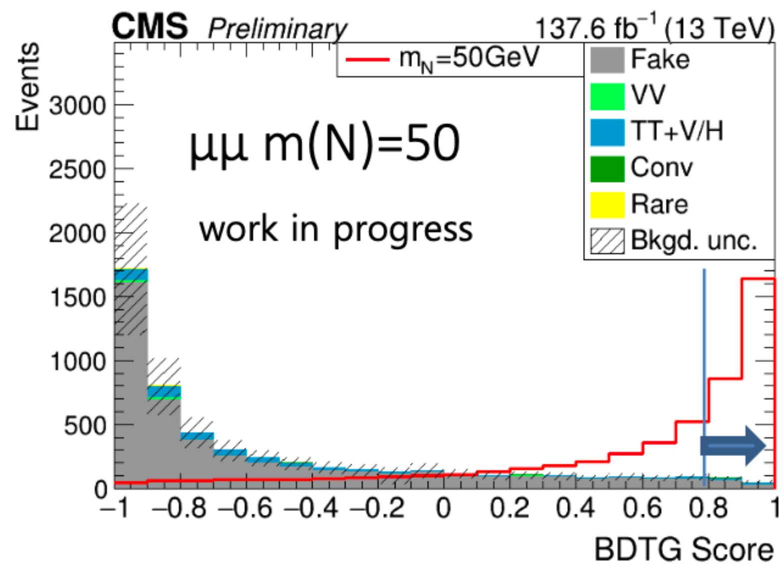


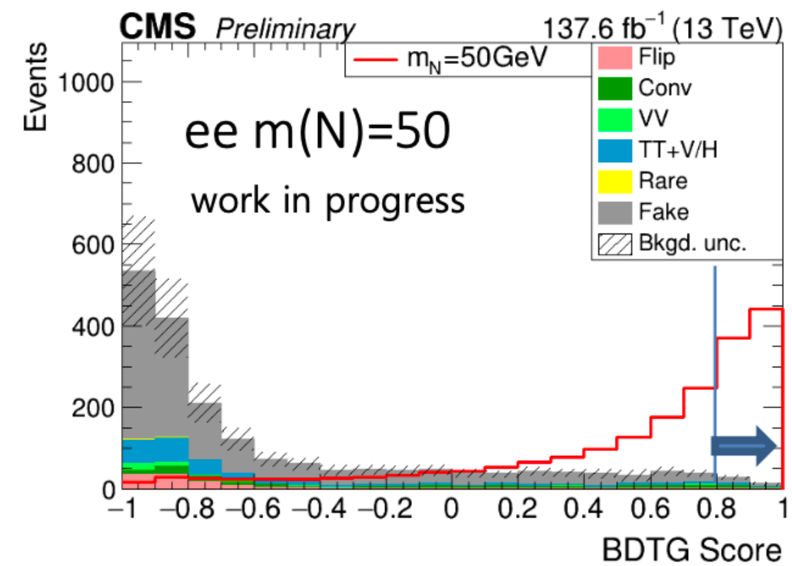
- <u>apply charge mis-ID rate (CFR) to OS MC corrected with SF(RD/MC)</u>
- measure CFR-SF using Z→ee in SS, OS
- validity checked with Z →ee CR

charge mis-ID bkgd. (tt)

Analysis strategy Overview & Systematic

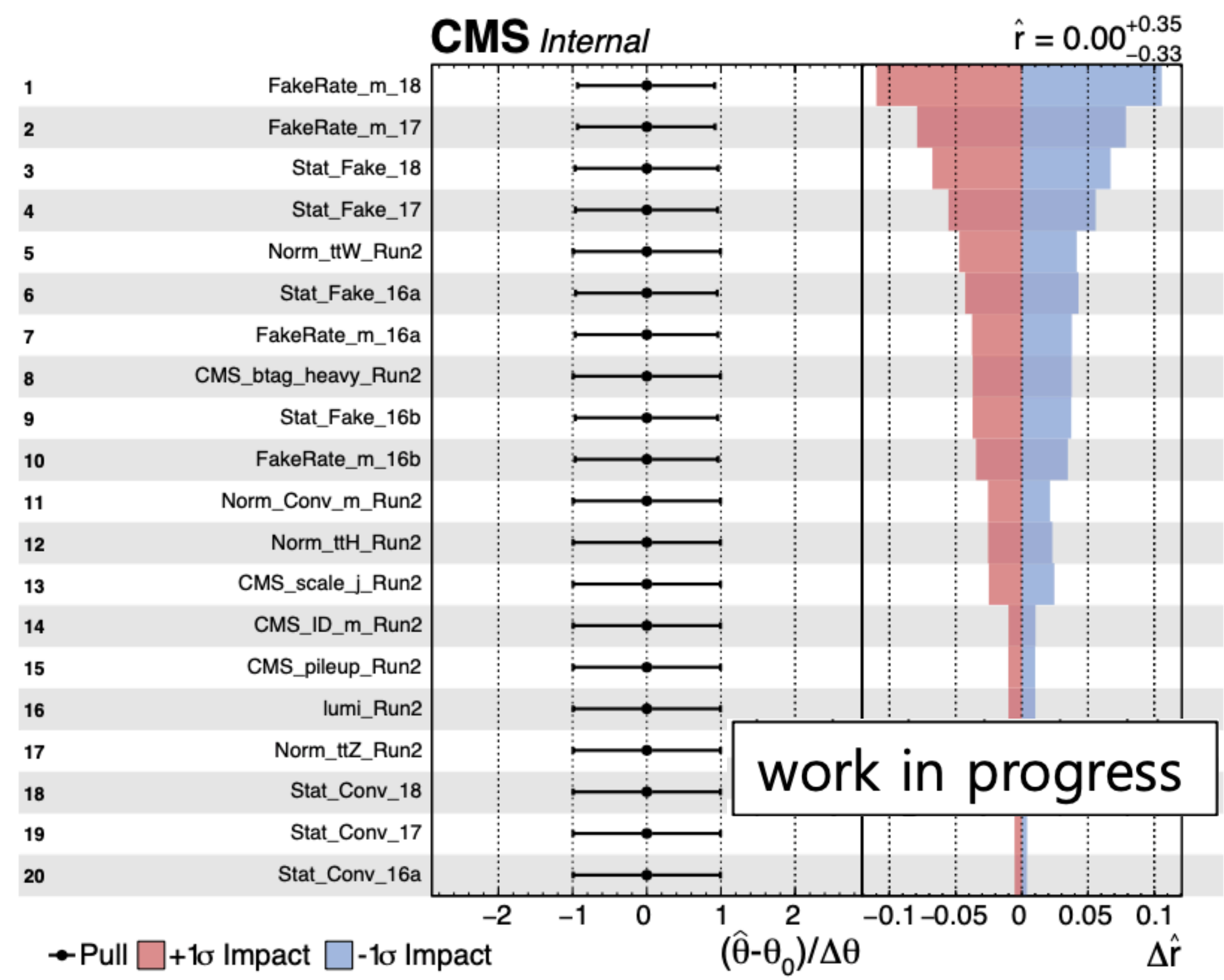
- BDT trained per mass hypothesis





- extract signal by <u>cut-and-count</u> approach

- cut optimized at each mixing-mass WP
- optimized to maximize exp. significance
- checked similar results with shape approach



- systematic uncertainty studied

- checked 70/83 nuisances for μμ/ee
- most important one : <u>FR unc</u>.
- subleading : stat (nonpr. est.), σ(ttW), b-tag,

JES, conv. rate

- syst unc./ tot. unc. (signal strength): 0.24-0.48

→ stat. unc. is the leading component

<u>syst. unc. impact is relatively small</u>

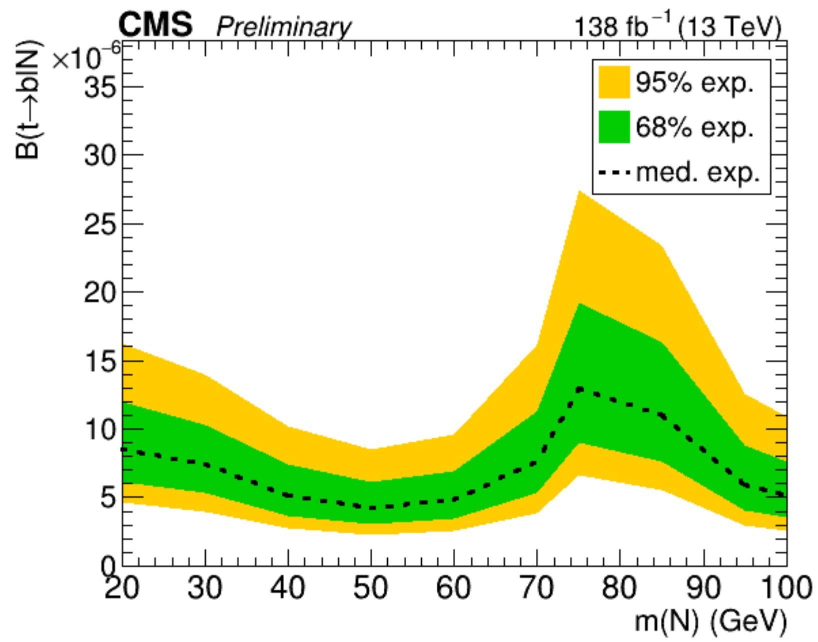
Limit extraction and outlook

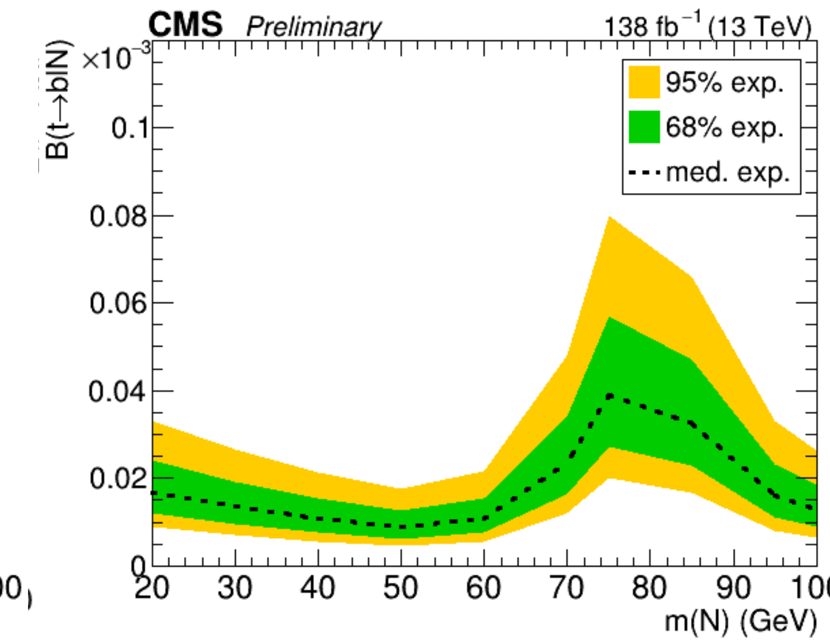
- search sensitivity shown as expected 95% CL limit
- B(t→blN) < 4.31-13.5 ($\times10^{-6}$) (μμ)

  B(t→blN) < 8.74-40.4 ($\times10^{-6}$) (ee)

- m(N)~m(W): inferior lepton acc.

  & classifier performance

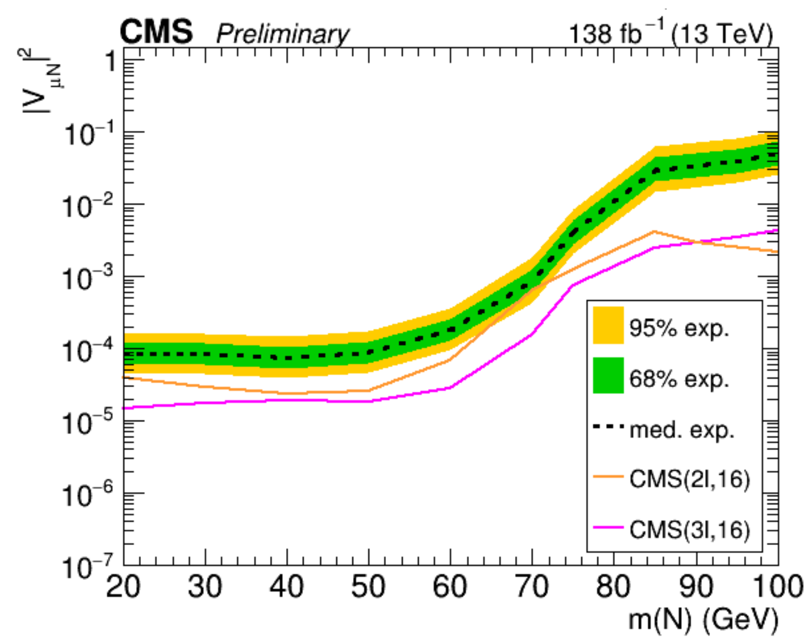


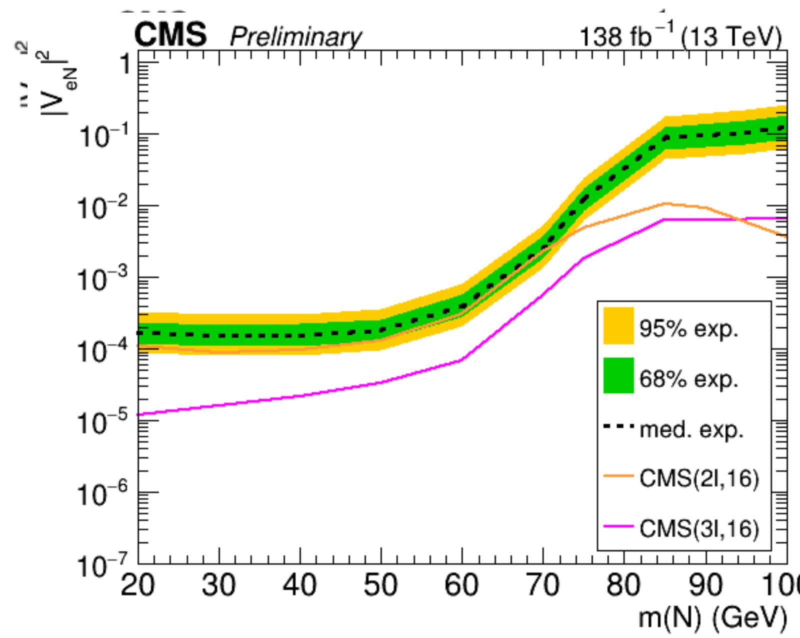


- this can be translated to $|V_{lN}|^2$, for comparison with existing type-1 seesaw results (other channels)

- varies in 8.2×10^{-5} - 0.12
- larger than DY3l limit by 1 order
- within factor 2 from DY2e limit

→ at some m(N) values, similar result to DY2l possible by stat. fluc.





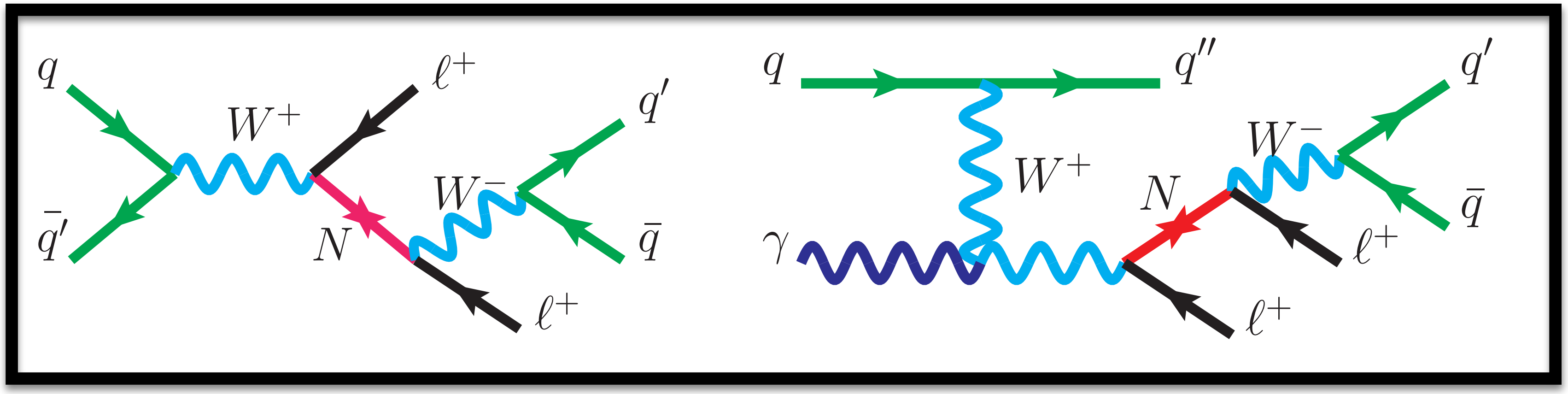
8

Search for heavy neutrino in SS Dilepton W^*/W^+W^+

Update of EXO-17-028

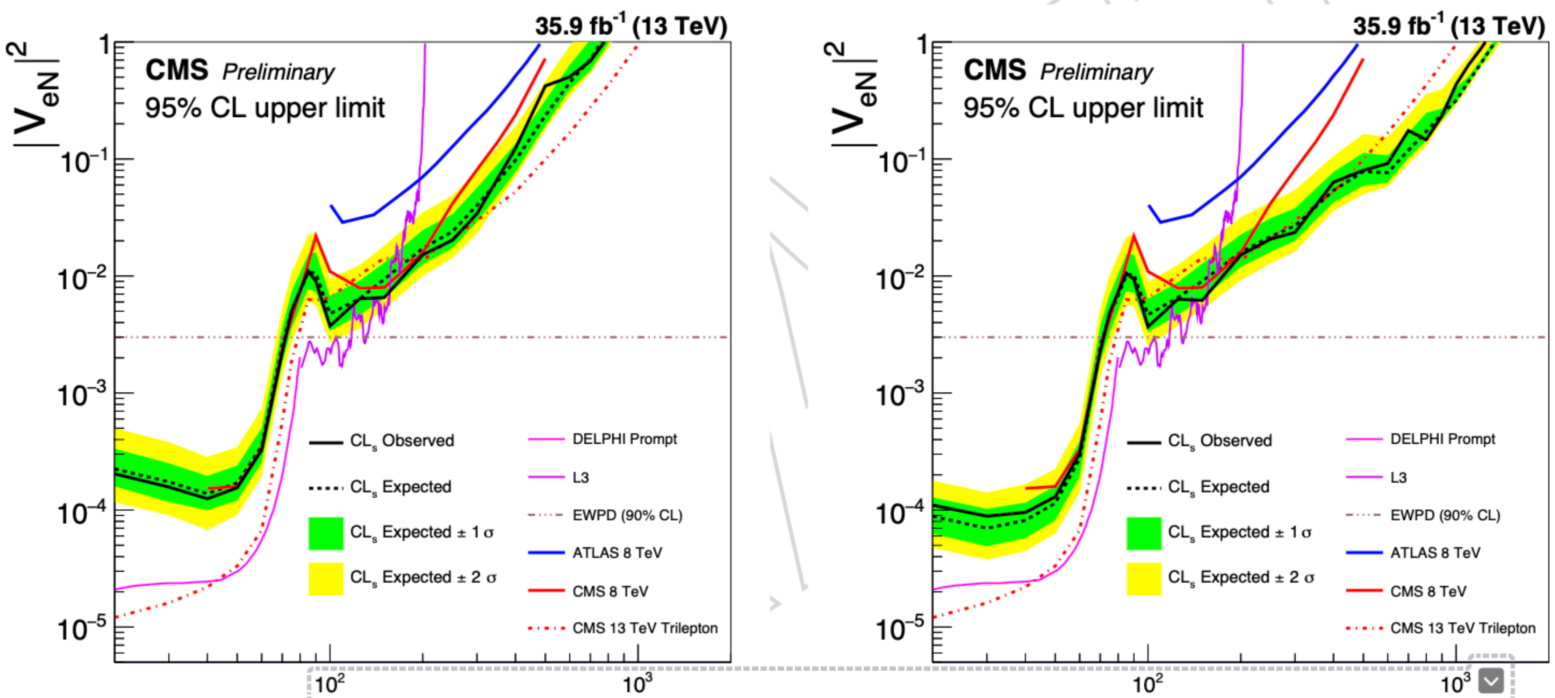
Run 2 Type 1 SSDilepton W* analysis

- SNU performed 2016 analysis in DY+VBF channel (EXO-17-028)



Analysis strategy

- Look for 2 SS leptons + Jets
- Split into Boosted (SR1) and resolved (SR2) signal regions
- Apply cut and count analysis, optimised per mass point

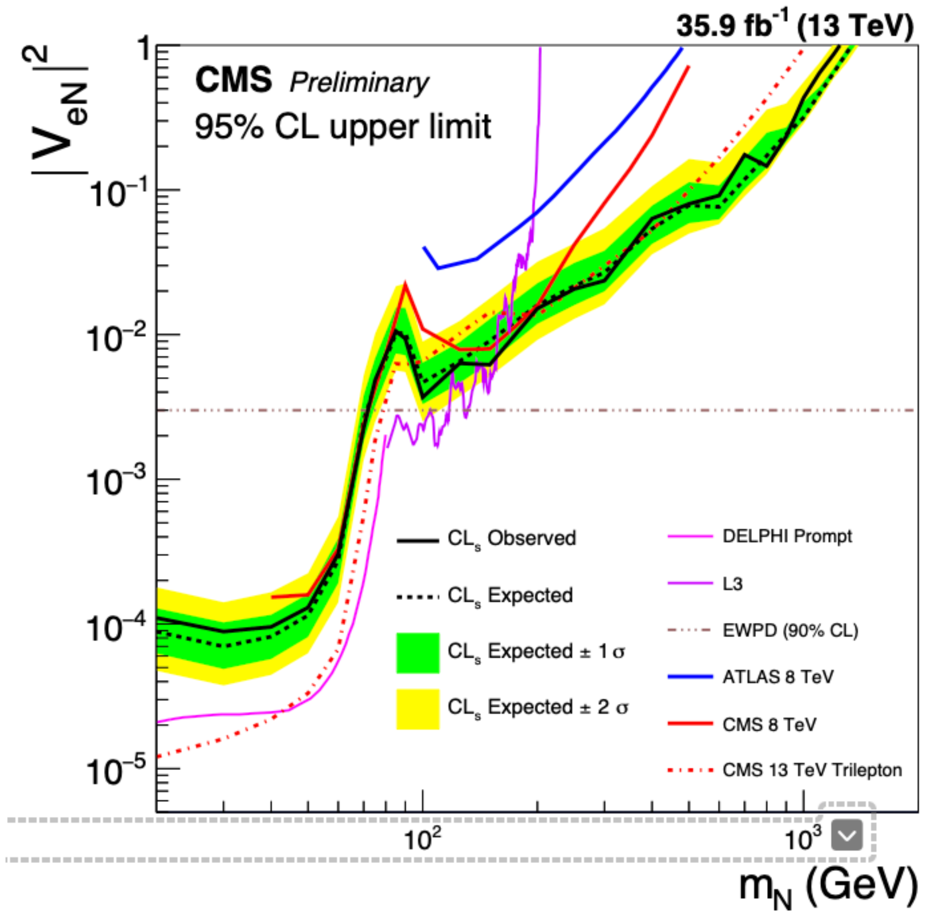


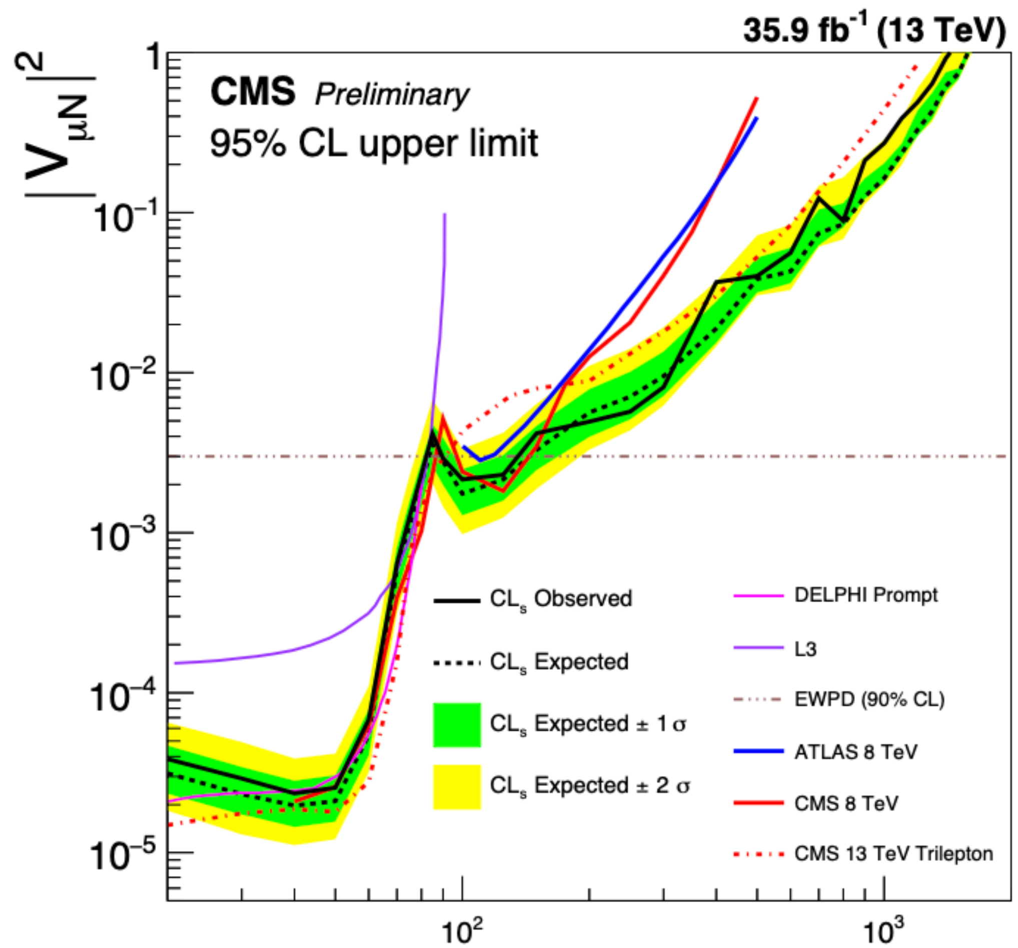
Still has world best sensitivity for masses > 200 GeV

Type 1 SSDilepton W* analysis

Observations/Improvements considered for Full Run 2 Analysis:

1. Lower Mass (< 300 GeV) SS2l has very large Fake backgrounds
2. For High mass standard Electron ID perform poorly
3. Cut and count technique looses many signals events
4. Higher mass (> 1 TeV) has poor sensitivity.
5. mN < mW region is most sensitive in 3 lepton final state channel





Type 1 SSDilepton W* analysis

Observations/Improvements to consider for Full Run 2 Analysis:

1. Lower Mass (< 300 GeV) SS2l has very large Fake backgrounds

- Update ID to use dedicated BDT trained to discriminate signal like leptons from non-prompt leptons (Muon use TOP_UL MVA, electron train our own BDT)

Training Variables

Kinematics	
p_{T}	Transverse momentum of a lepton
$\lvert\eta\rvert$	Pseudorapidity of a lepton
Isolation	
I_{rel}	Relative isolation using the cone size of 0.4
$I^{\mathrm{ch}}_{\mathrm{mini}}$ $I^{\mathrm{neu}}_{\mathrm{mini}}$	Relative mini-isolation with p_{T}-dependent cone size including charged (neutral) PF objects
Properties of the closest jet	
N_{trk}	Number of charged particles associated with the jet
$p^{\mathrm{rel}}_{\mathrm{T}}$	Fraction of the lepton momentum in transverse direction to the jet axis
$p^{\mathrm{ratio}}_{\mathrm{T}}$	Ratio between the lepton and jet transverse momenta
B_{tag}	The DeepJet b tagging discriminator

Impact parameter	
SIP_{3D}	3D impact parameter significance
$log(\lvert d_{xy}\rvert)$	Transverse impact parameter with respect to the primary vertex
$log(\lvert d_{z}\rvert)$	Longitudinal impact parameter with respect to the primary vertex
Other	
ID^{e}_{MVA}	POG electron MVA ID discriminant (Fall17v2noIso)
P^{μ}_{seg}	Compatibility of track segments in the muon system with the expected pattern of a minimum ionizing particle

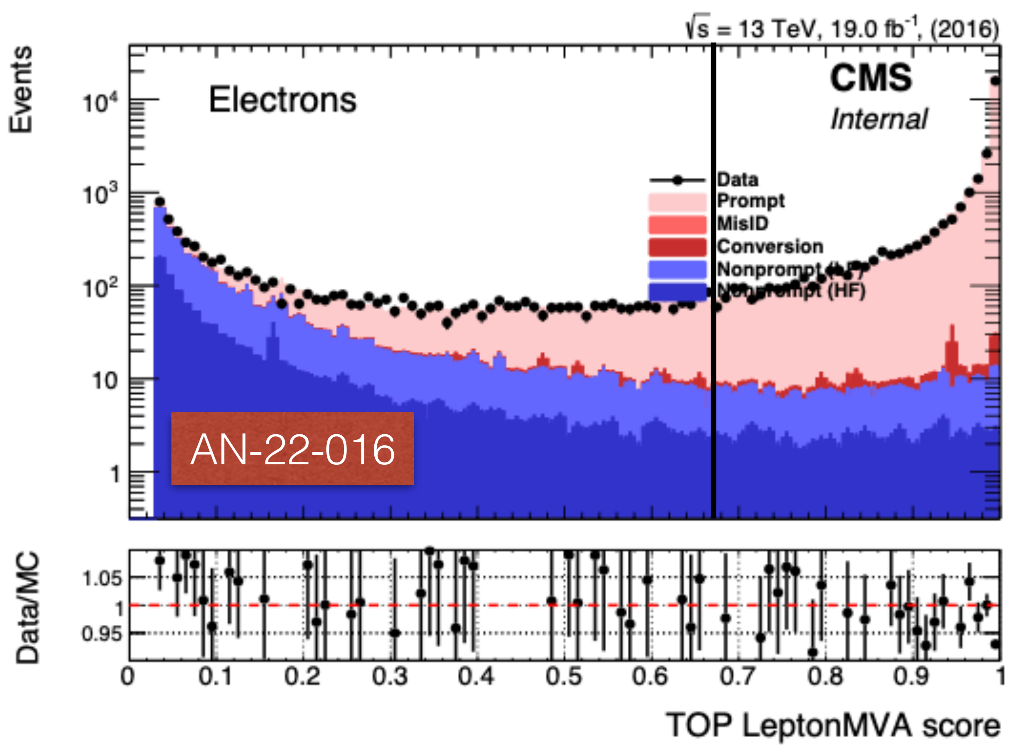
AN-22-016

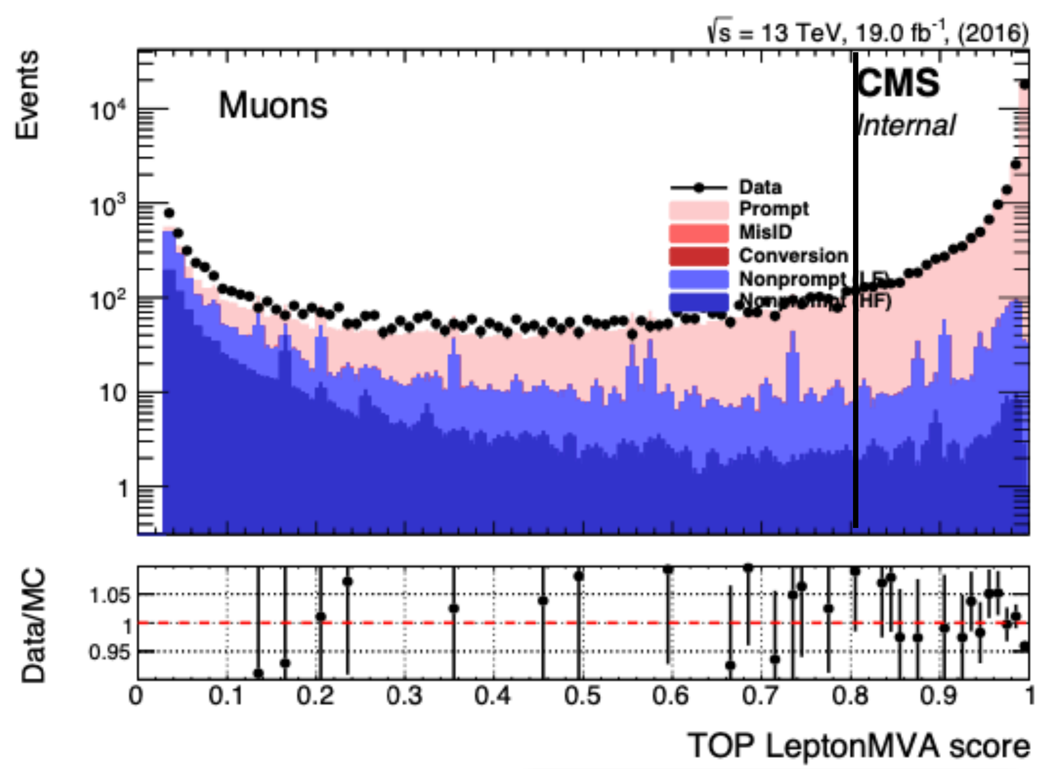
Type 1 SSDilepton W* analysis

Observations/Improvements to consider for Full Run 2 Analysis:

1. Lower Mass (< 300 GeV) SS2l has very large Fake backgrounds

- Update ID to use dedicated BDT trained to discriminate signal like leptons from non-prompt leptons (Muon use TOP_UL MVA, electron train our own BDT)
- **Improvement in lowest mass sensitivity by 50% verses previous ID**





Discrimant

Electron Efficiecny

Tagger	Working point	Nonprompt	Prompt
TOP-UL(v2)	Medium	0.009	0.946

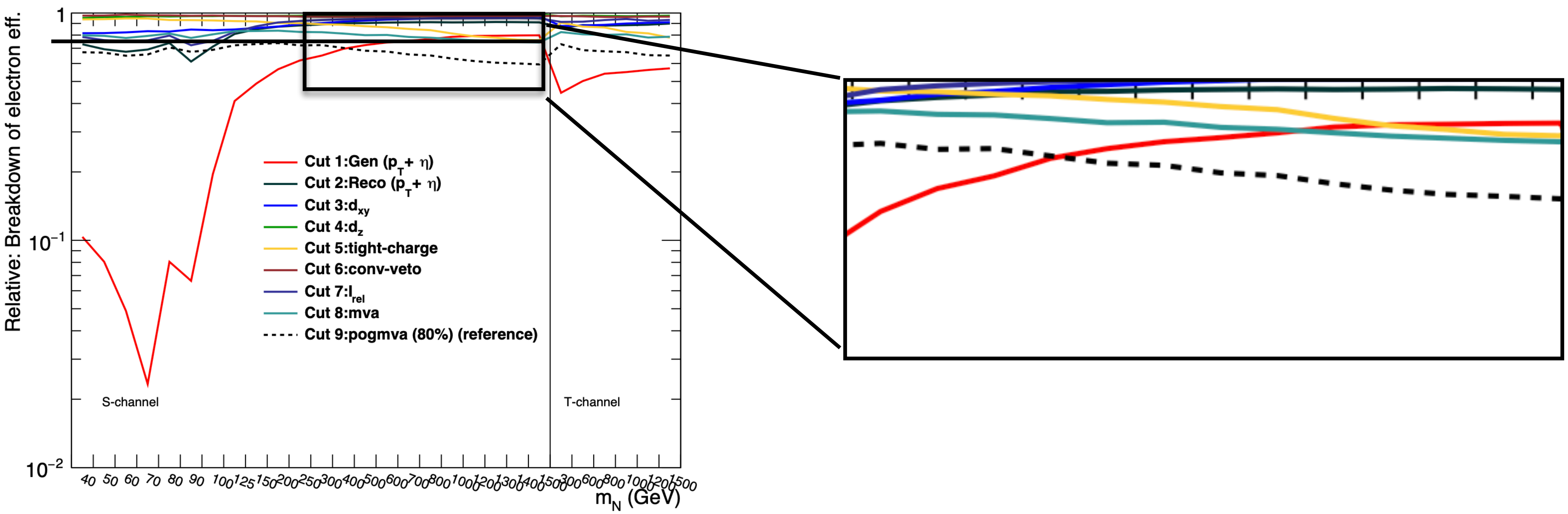
Muon Efficiecny

Tagger	Working point	Nonprompt	Prompt
TOP-UL(v2)	Medium	0.008	0.955

Type 1 SSDilepton W* analysis

Observations/Improvements to consider for Full Run 2 Analysis:

2. For High mass standard Electron ID perform poorly, mainly Tight charge and POG MVA (both loose ~25% signal for mN > 1 TeV)



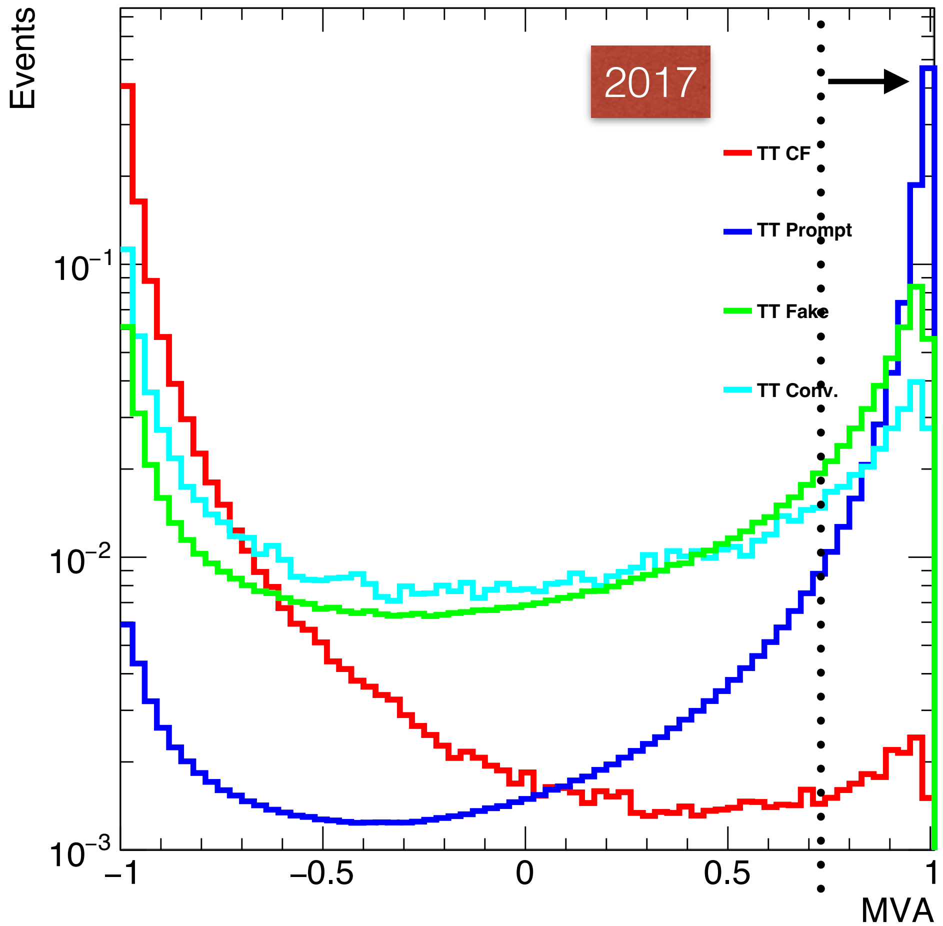
Type 1 SSDilepton W* analysis

Observations/Improvements to consider for Full Run 2 Analysis:

Run 2 Strategy

- Remove standard MVA, Tight IP and Tight charge cuts and instead use a BDT trained to separate signal like leptons from Charge MisID leptons
- Improvement in sensitivity for mN > 2000 by 48% using new ID.

Mass of HNL	Improvement in Exp Limit
250 GeV	6.5%
500 GeV	10.4%
1000 GeV	31%
2000 GeV	48%



- Table shows ratio of limit using POG Tight with Tight charge vs POG Tight + BDT ID cut

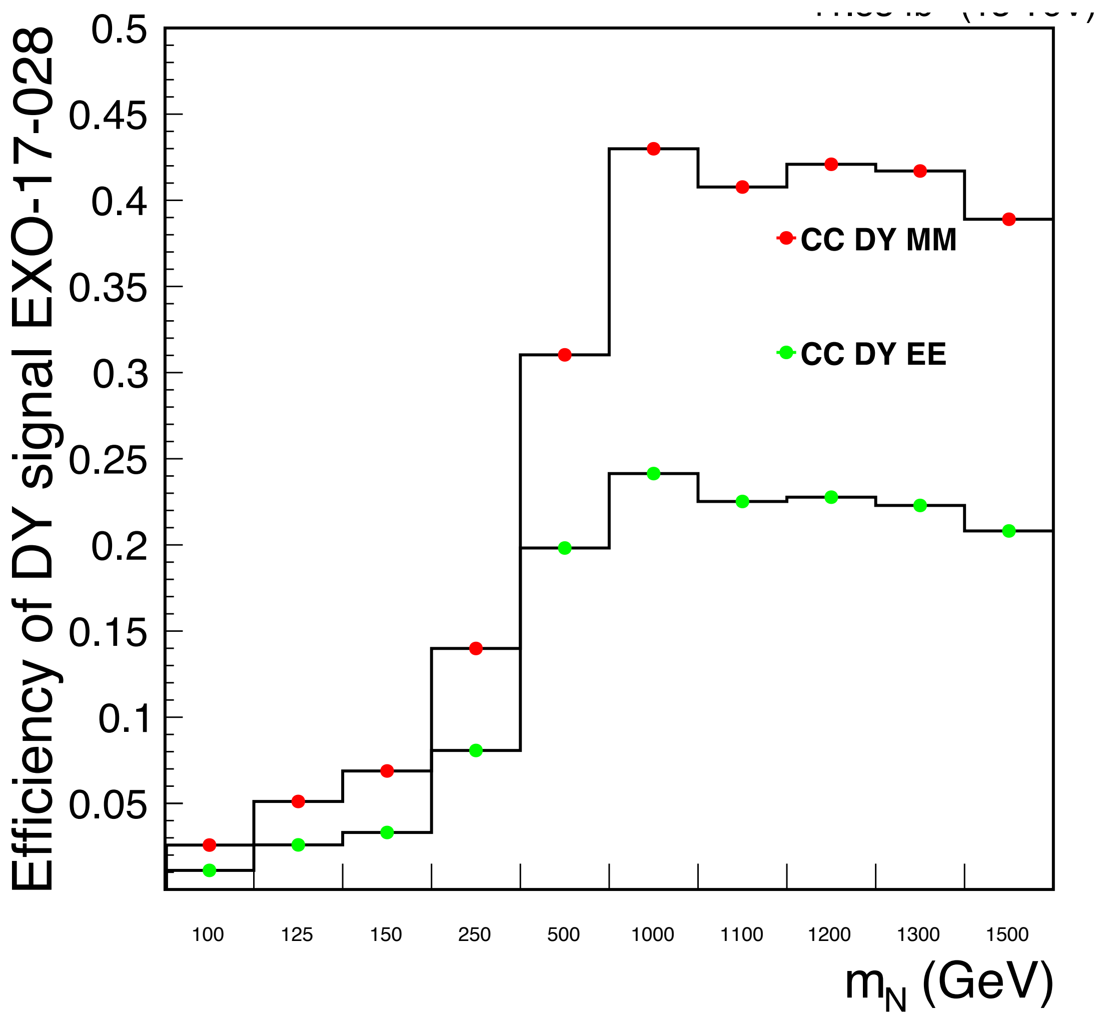
Type 1 SSDilepton W* analysis

Observations/Improvements to consider for Full Run 2 Analysis:

3. Cut and count technique looses many signals events, cut on several variables to optimise sensitivity.

Variable	High-Mass SR1	High-Mass SR2
Number of AK4 jets	✓	-
p_T of leading jet of W_{jet}	✓	-
ΔR(sub-leading lepton, W-jets)	✓	-
ΔR(leptons)	✓	-
p_T of leading lepton	✓	✓
p_T of sub-leading lepton	✓	✓
$m(W_{jet})$	✓	✓
$m(\ell\ell W_{jet})$	✓	✓
$m(\text{leading lepton} + W_{jet})$ $m(\text{sub-leading lepton} + W_{jet})$	✓	✓
$m(\ell\ell)$	-	-
E_T^{miss}	-	-
E_T^{miss2}/S_T	✓	✓

CC Table EXO-17-028

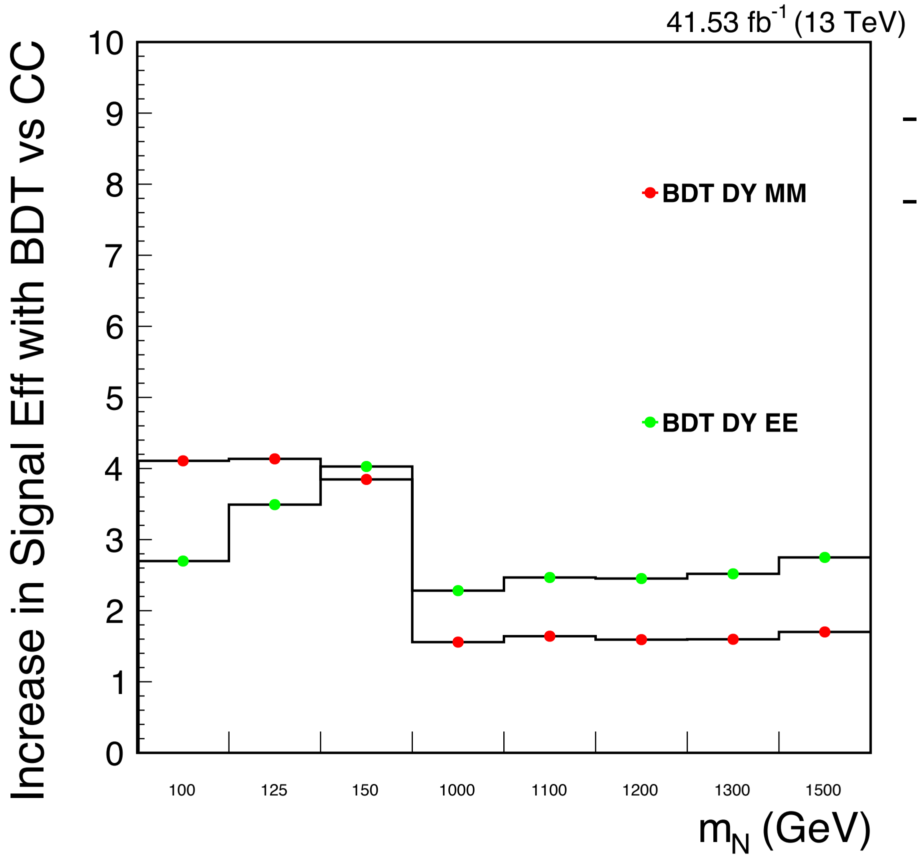


- Masses < 250, larger bkg, so have low efficiency, as low as 0.5% .

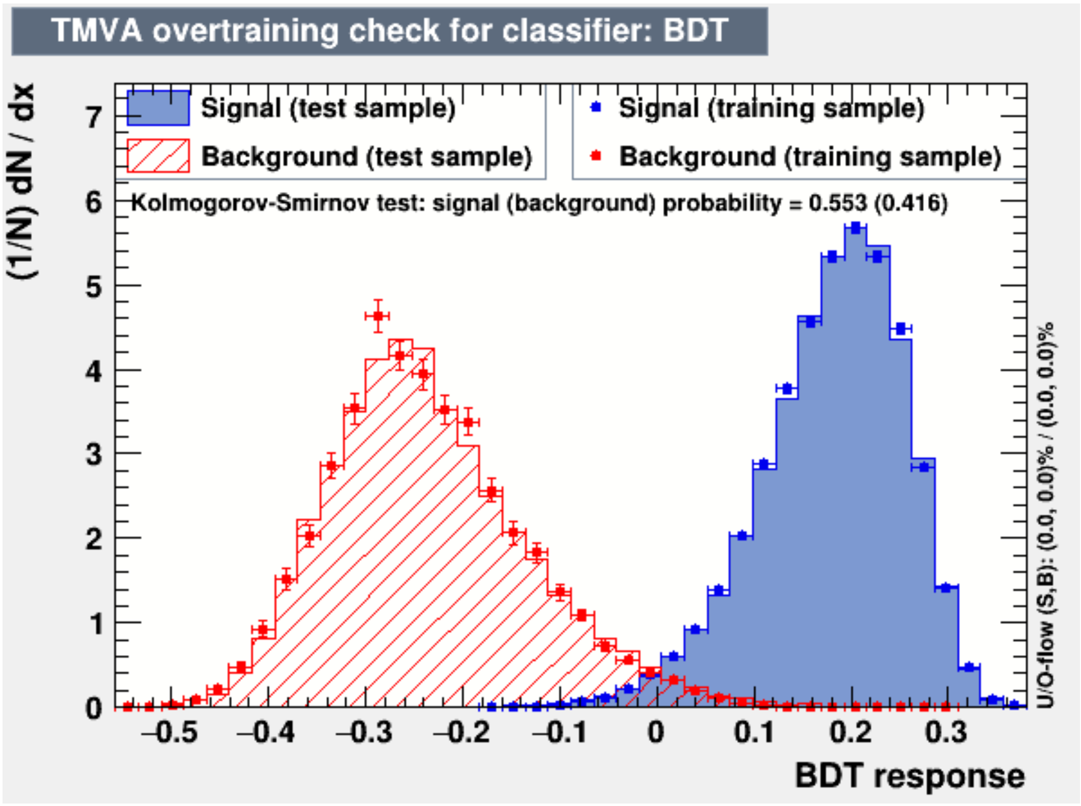
Type 1 SSDilepton W* analysis

Full Run 2 Strategy

For masses of N <=. 500 GeV we change CC to use a shape BDT as input to limit.

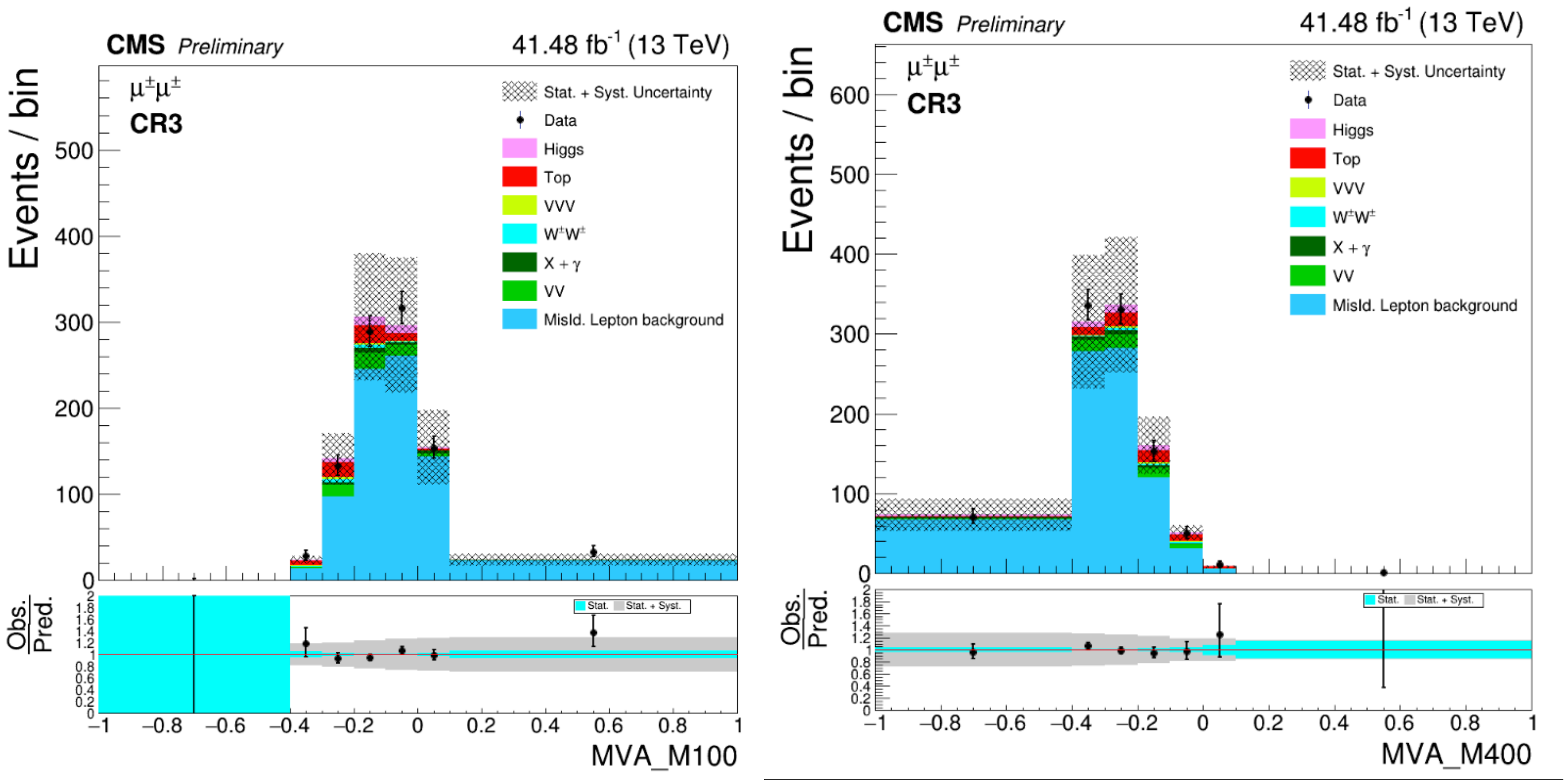


- Up to 4 times more signal efficiency.
- Separation between bkg and signal enhanced and also giving much better sensitivity (up to 5 times better limit for mass 100 GeV)



- Training variables
  - Number of jets, p_T^l, p_T^j, MET^2/S_T, H_T/p_T^l
    - H_T : scalar p_T sum of jets
    - S_T : scalar p_T sum of all reconstructed particles
  - $\Delta R(l,l)$, $\Delta R(l,j)$, $m(ll)$, $m(lj)$
  - $\Delta R(l,W_{jet})$, $m(W_{jet})$, $m(l+W_{jet})$, $m(ll+W_{jet})$, etc.
    - W_{jet} : 2 jets having mass close to W mass

Validation of Signal Region MVA Score

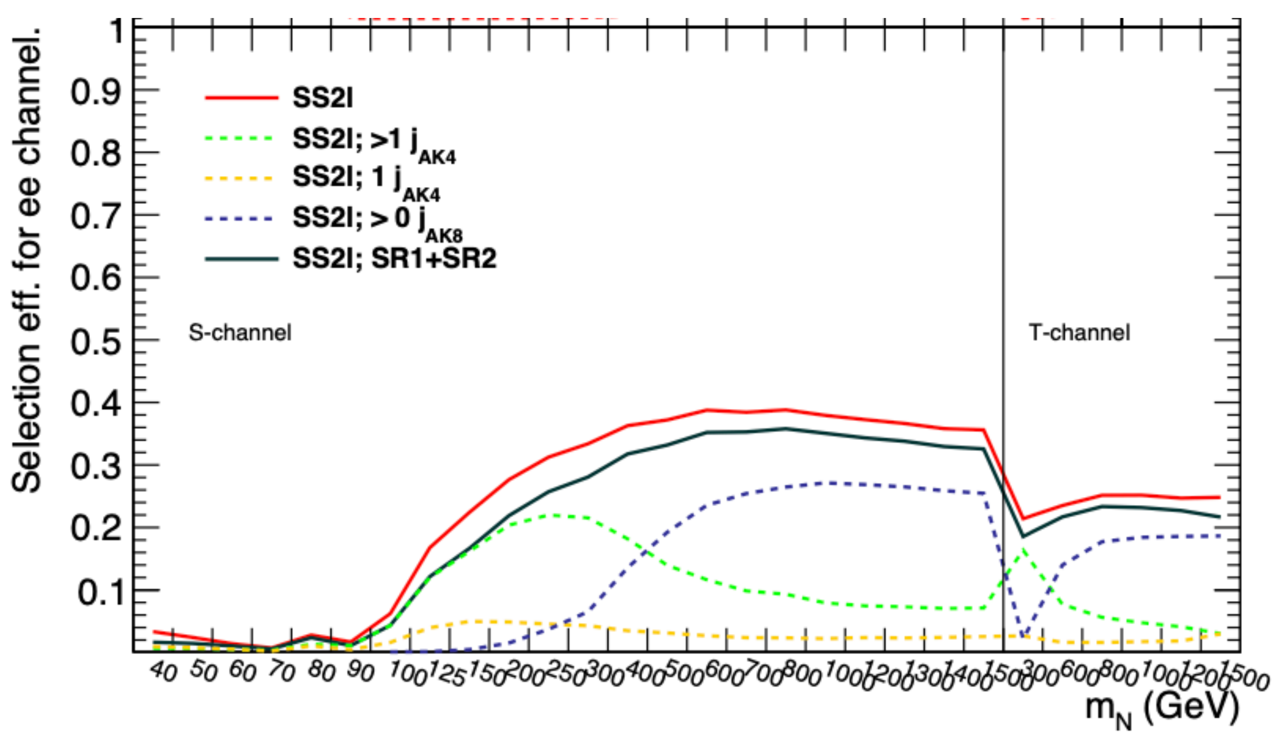


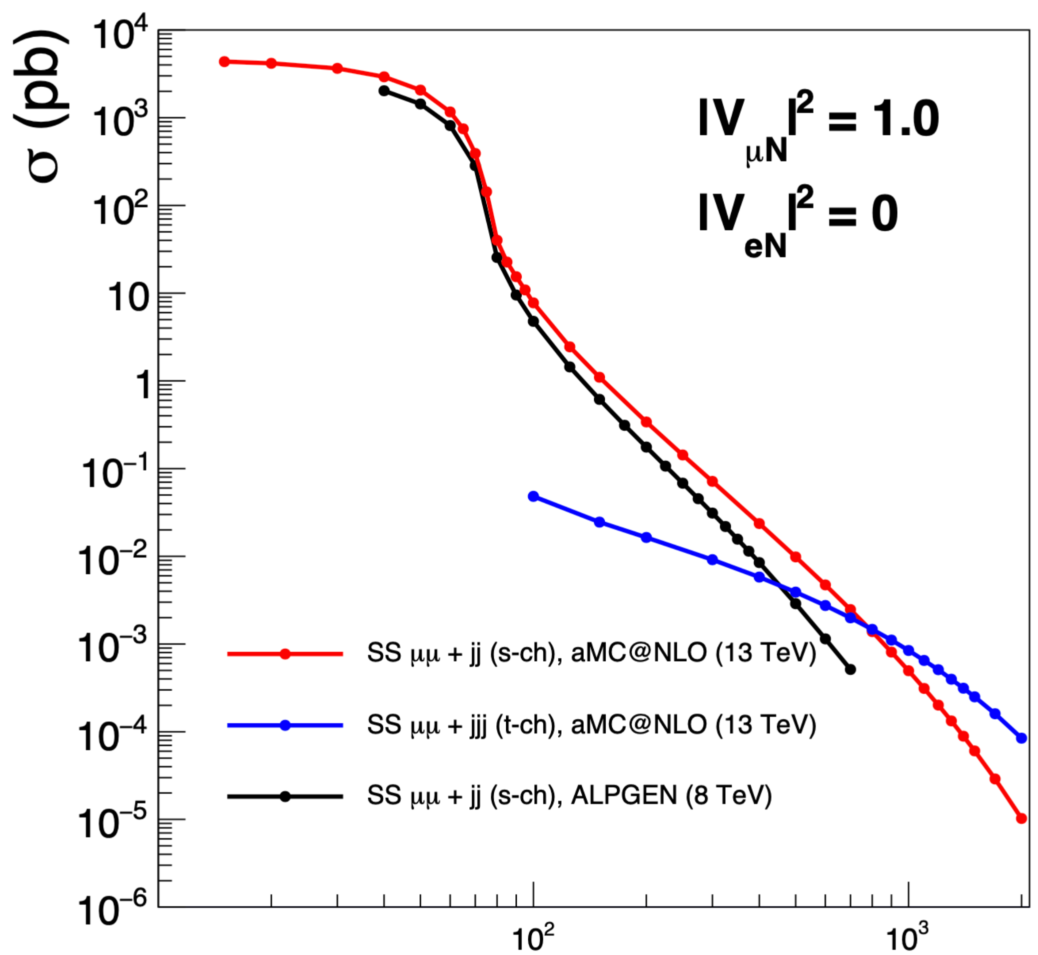
- MVA score validated in CR Identical to SR but with high MET OR Bjet
- Good agreement observed in MVA score for all flavors and data eras

Type 1 SSDilepton W* analysis

Observations/Improvements to consider for Full Run 2 Analysis:

4. Signal efficiency plateaus above 500 GeV and xsec drops so unlikely to increase mass range sensitivity in Full Run 2



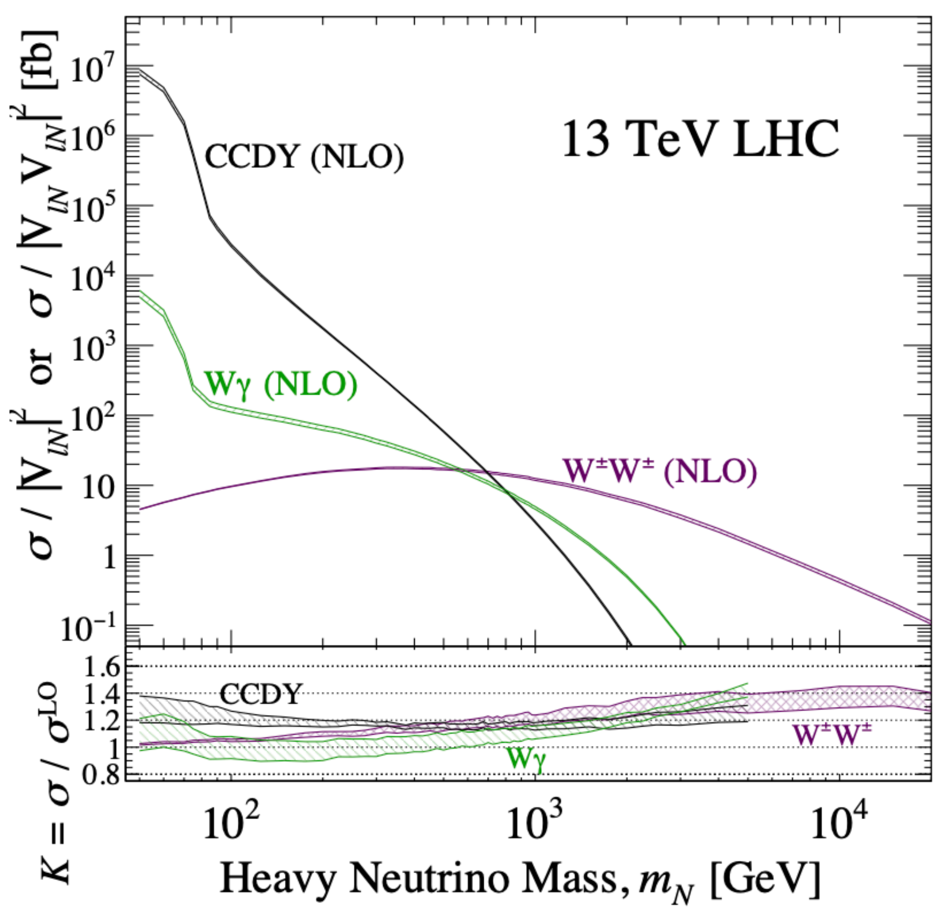


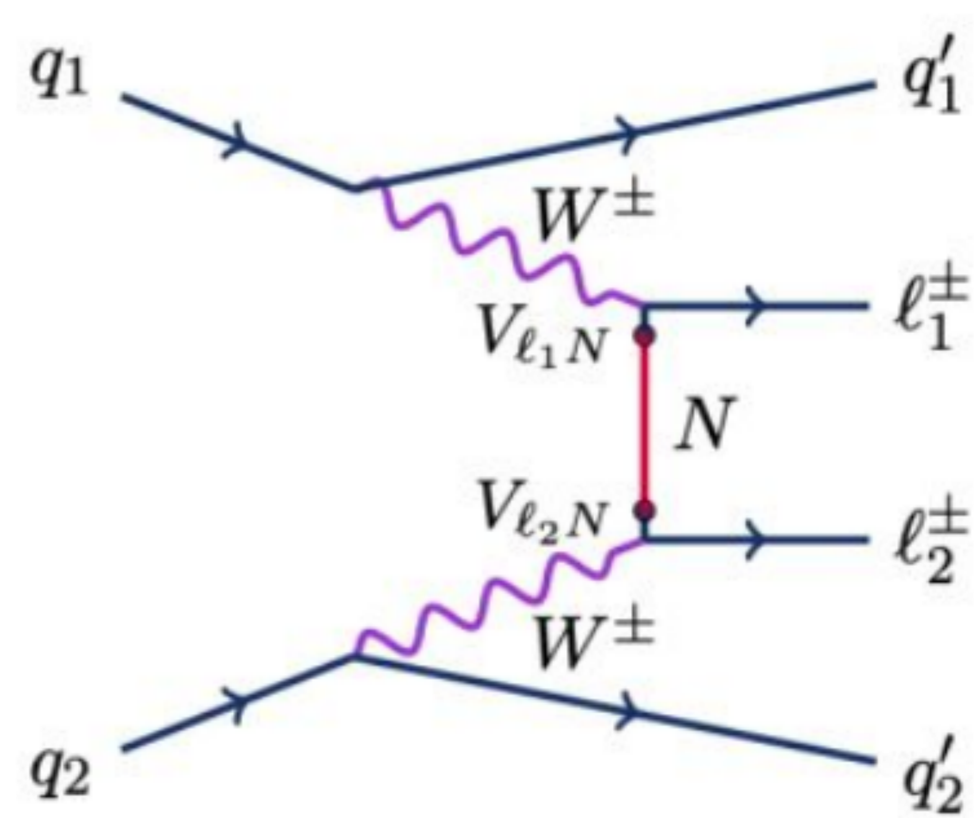
Type 1 SSDilepton W* analysis

<u>Observations/Improvements to consider for Full Run 2 Analysis:</u>

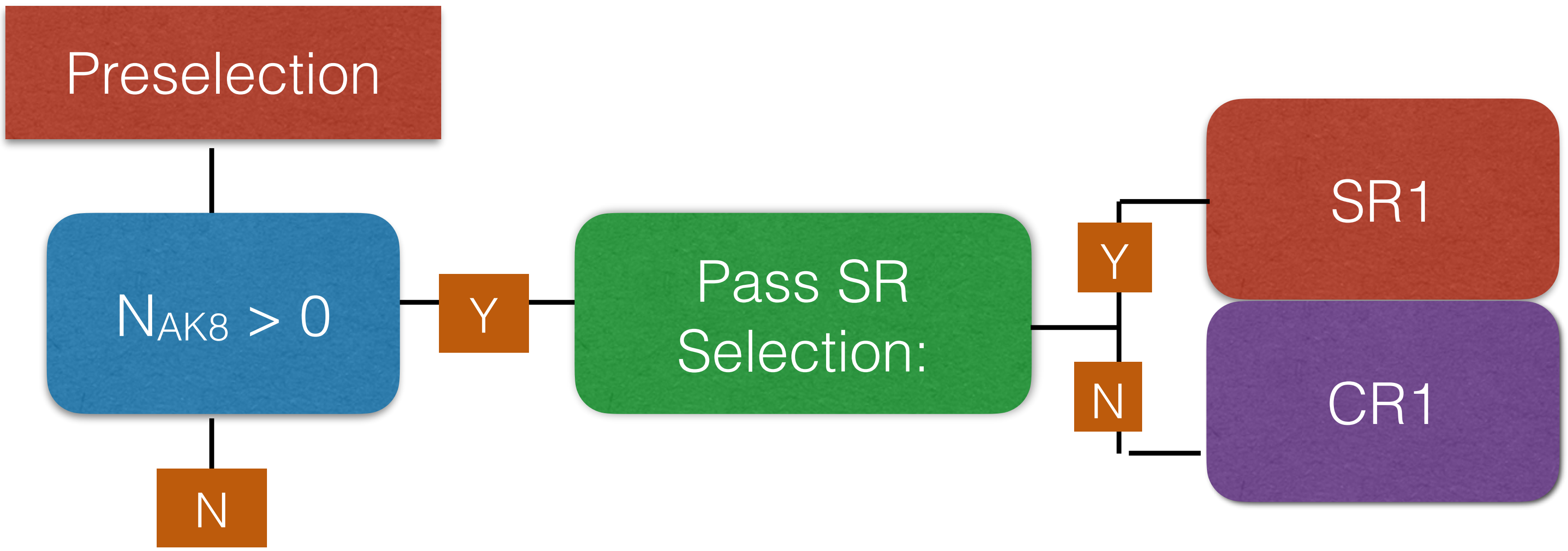
<u>Run 2 Strategy</u>

- Add an additional Signal process SSWW, which allows us to be sensitive to masses > 20 TeV
- Same final state SS2l + Jets
- Jets are forward





Analysis Strategy Type 1 SS2l W*



Preselection

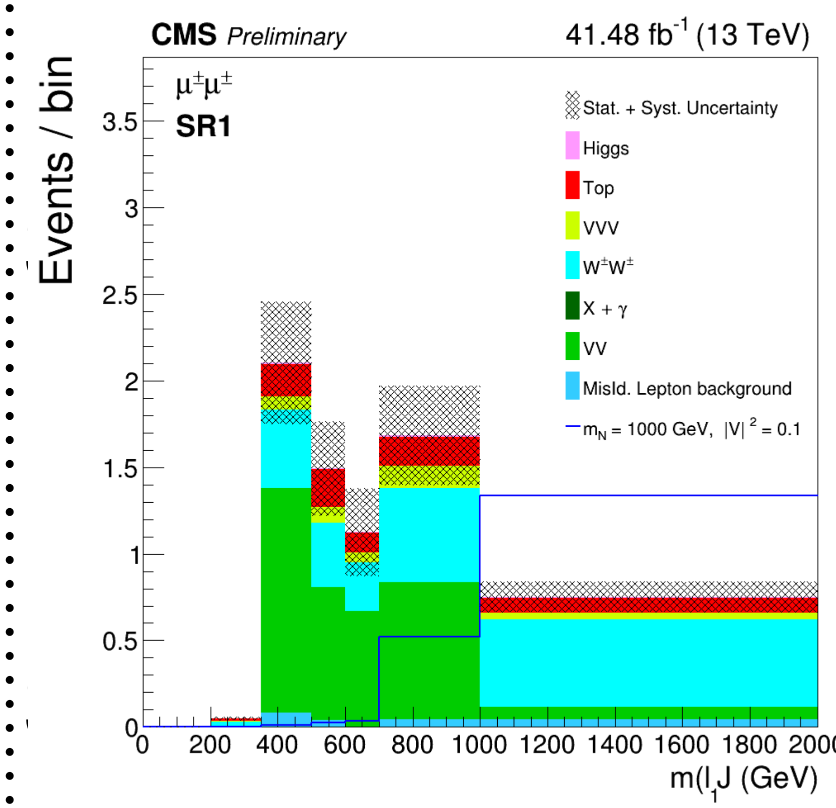
- two leptons with same-flavour and same-charge (ee or $\mu\mu$, no additional lepton),
- p_T (μ)>20,10 GeV ($\mu\mu$ channel), p_T (e)>25,15 GeV (ee channel),
- M($\mu\mu$)>4 GeV (only for $\mu\mu$ events)
- $|M(ee) - 91.2| > 10$ GeV (only for ee events),

SR Selection:

- N_b=0 (Medium DeepJet)
- $MET^2/S_T < 15$

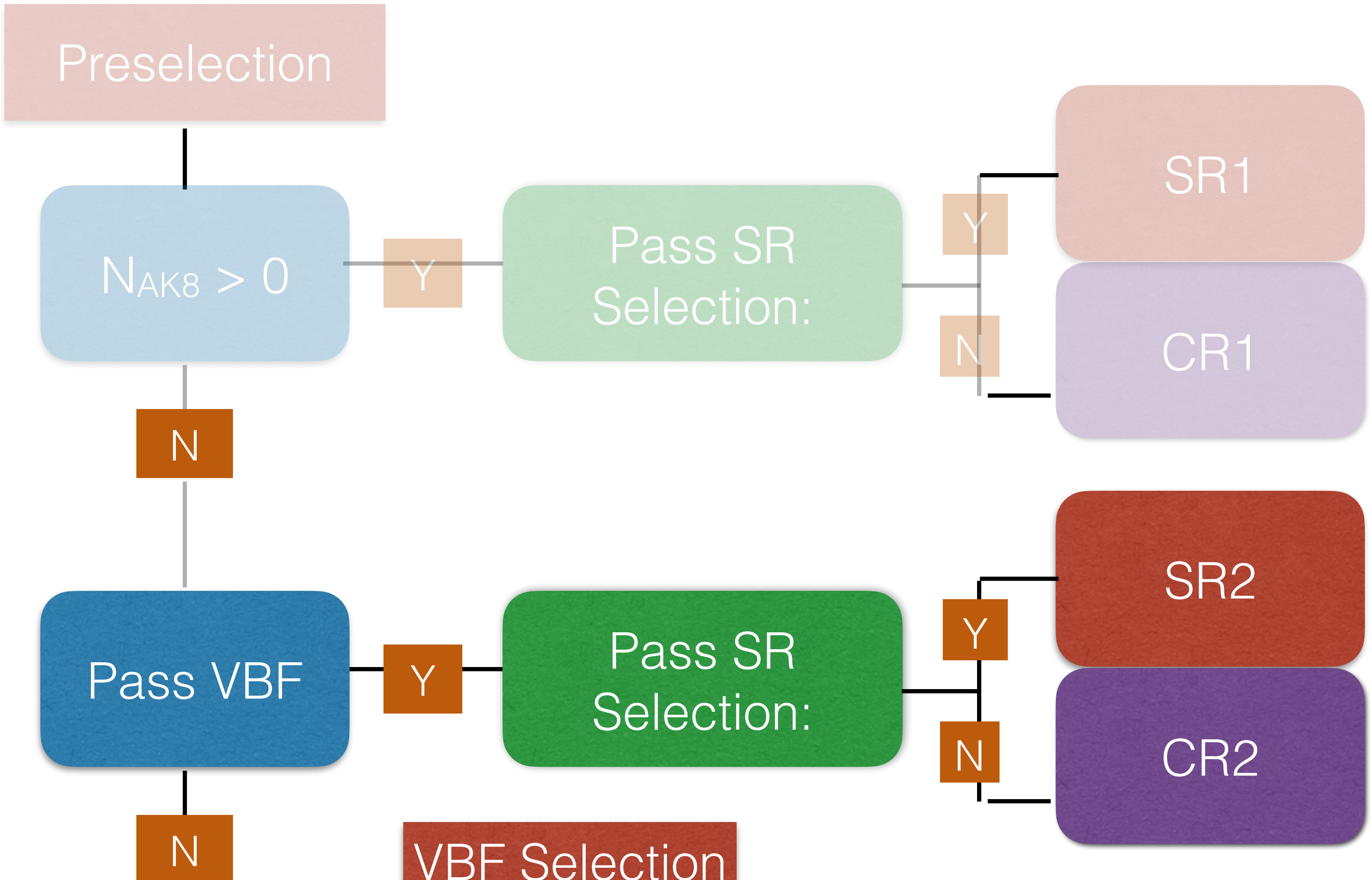
Limit Variable

SR1: Mass l_1J



Boosted Signals

Analysis Strategy Type 1 SS2l W*

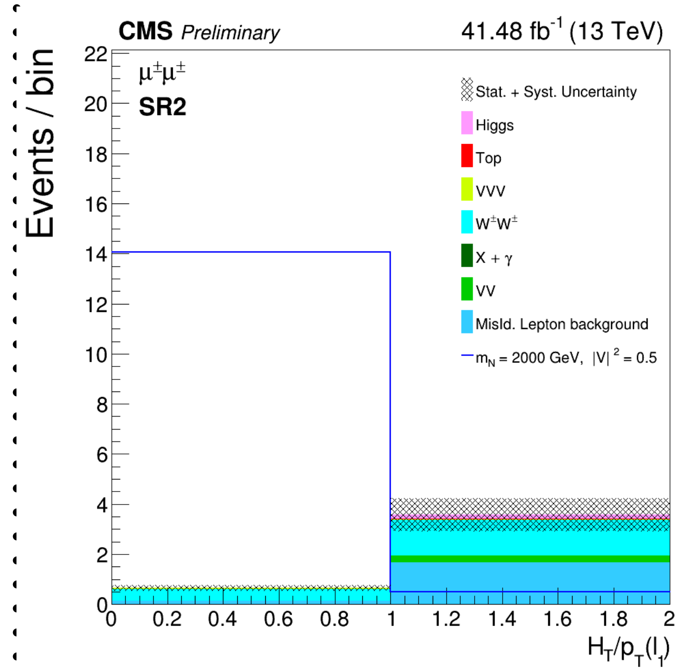


VBF Selection

Variable	$W^{\pm}W^{\pm}$ SR
# leptons	2 same sign muons
lepton p_T	$> 30/30$ GeV
di-lepton mass $m_{\ell\ell}$	> 20 GeV
$\lvert m_{\ell\ell} - m_Z \rvert$	-
tri-lepton mass $m_{\ell\ell\ell}$	-
max $zepp(\ell)$	< 0.75
jet p_T	> 30 GeV
$\lvert \Delta\eta_{jj} \rvert$	> 2.5
m_{jj}	> 750 GeV

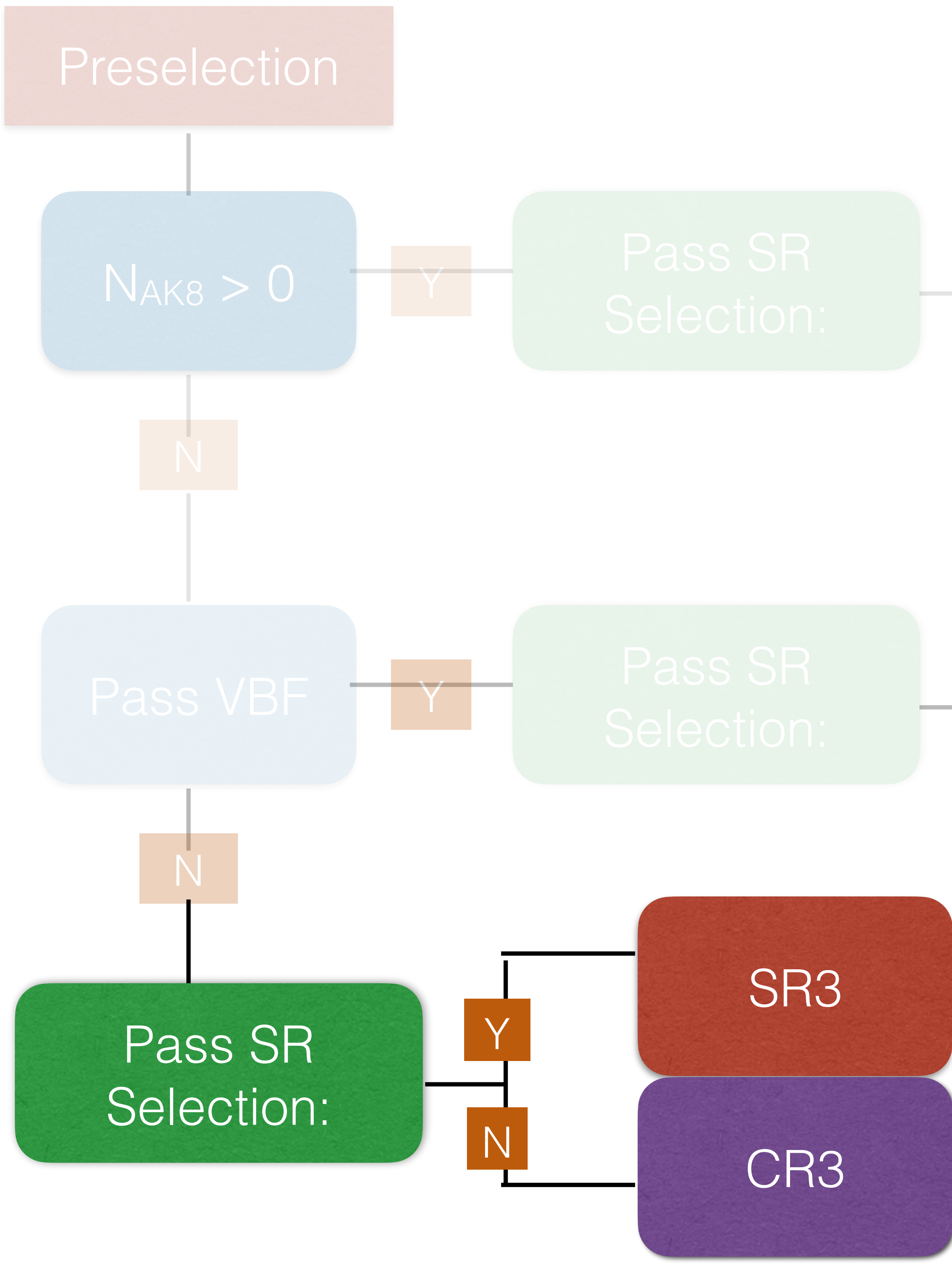
Limit Variable

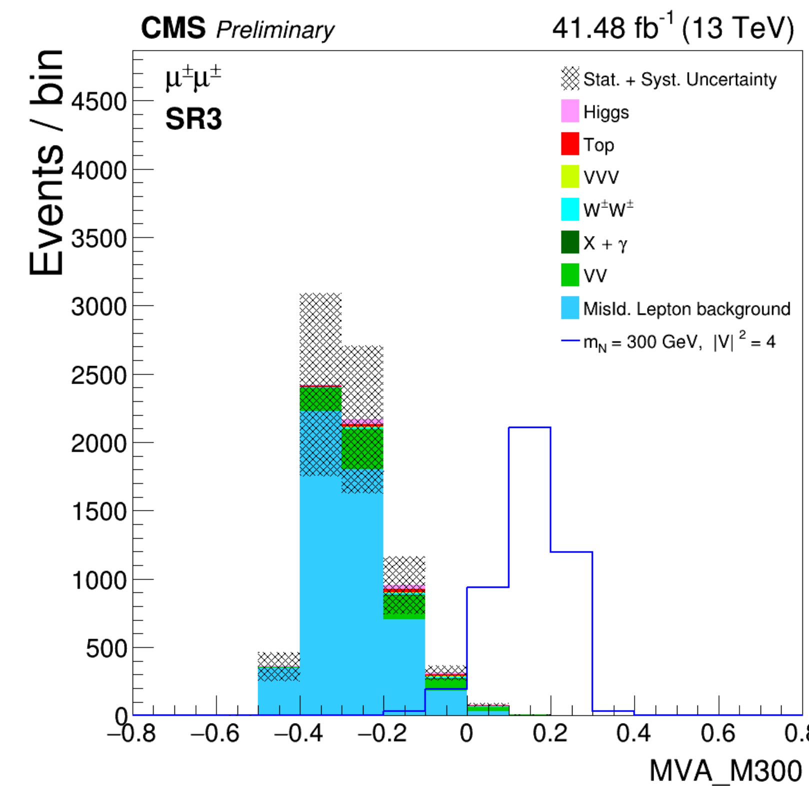
SR1: H_T/Pt



WW **VBF Signals**

Analysis Strategy Type 1 SS2l W*



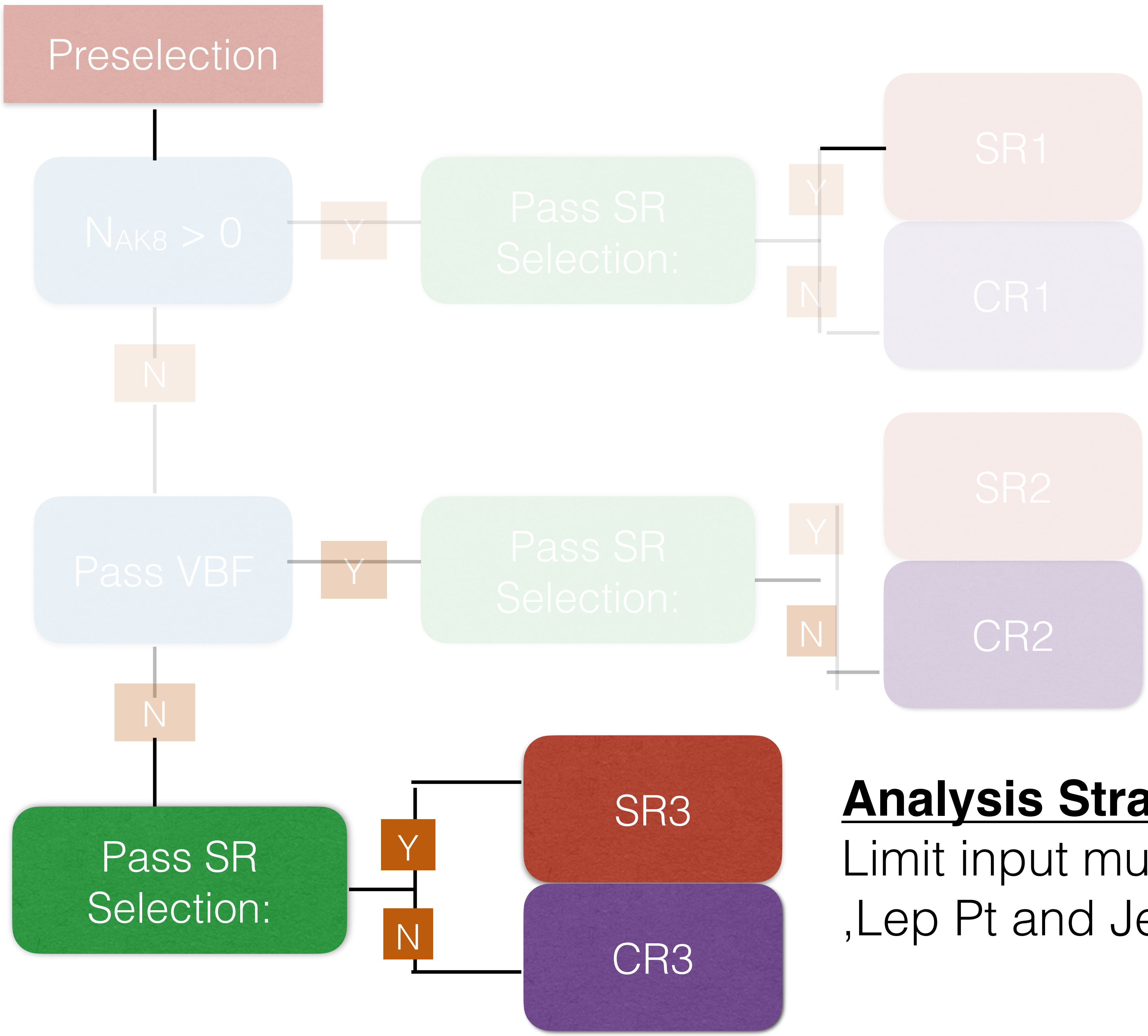


Analysis Strategy MN <= 500

Limit Input BDT, trained per mass

Resolved Signals

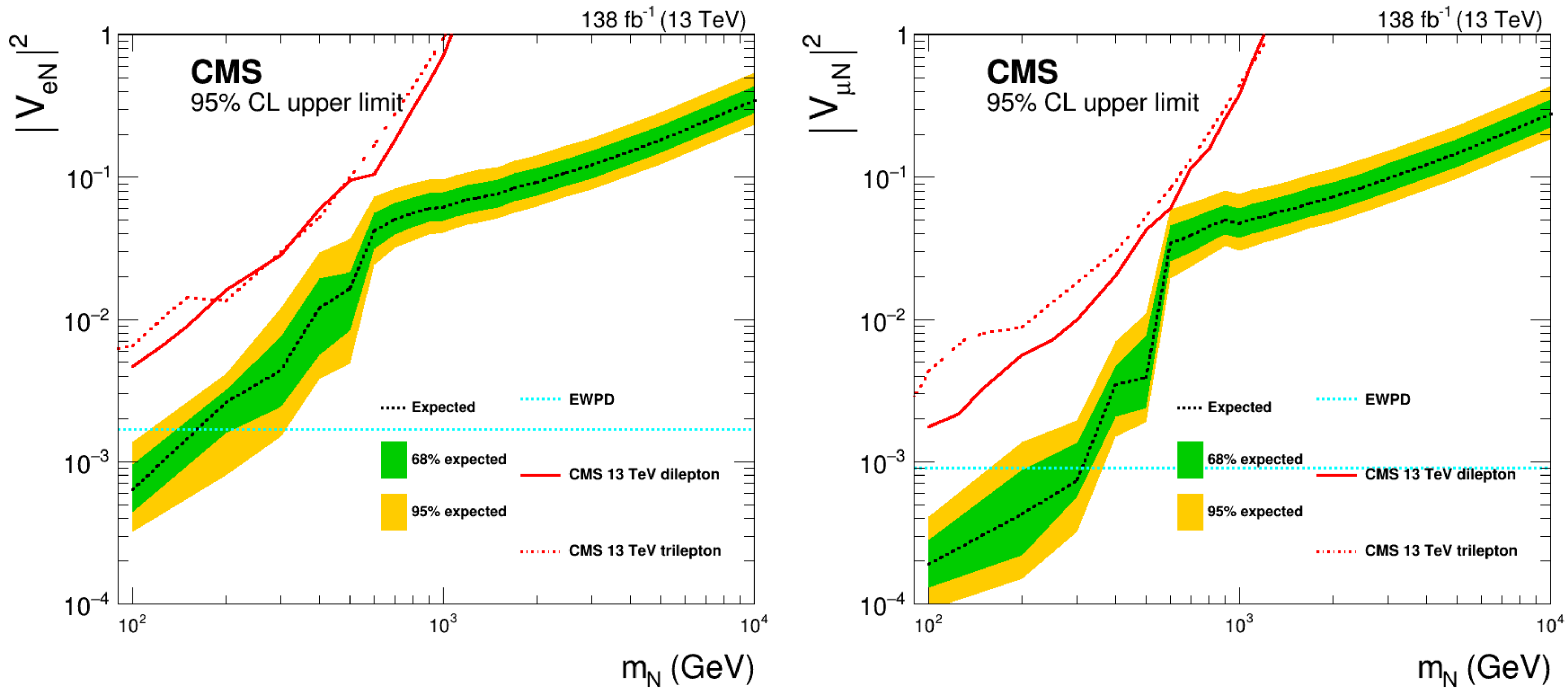
Analysis Strategy Type 1 SS2l W*



<u>Analysis Strategy M_N > 500</u>

Limit input multi binned based on M_N ,Lep Pt and Jet multiplicity

Expected Run 2 Limit && Summary



Summary

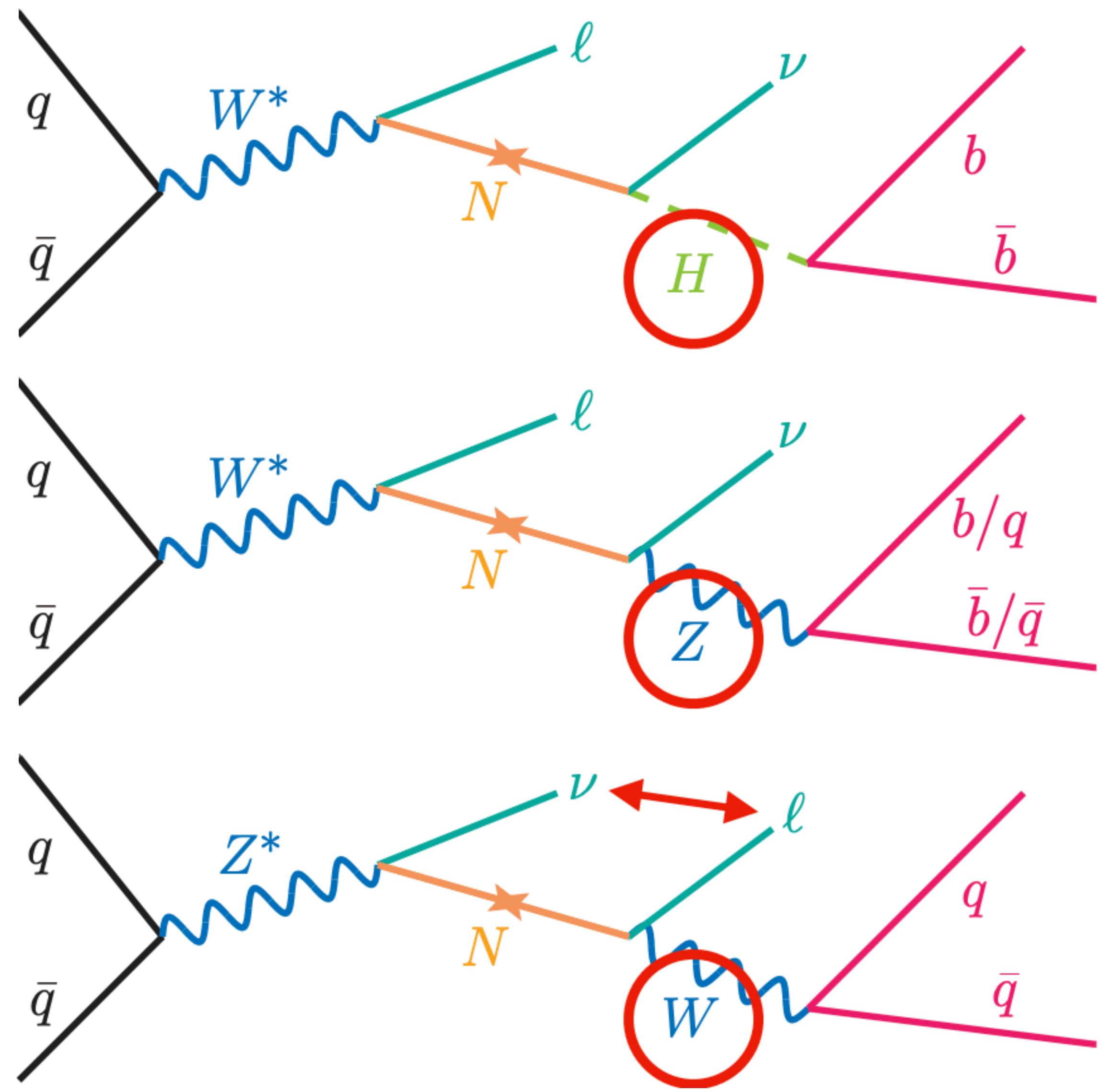
- We have/are performed searches for HNL using full Run 2
- Single lepton channel is unblinded but no observed excess,
- First expected limits are found from HNL produced in top decays
- SS2l W* analysis extended expected limits up to 25 TeV, and greatly improved sensitivity across full mass range mN > 85 GeV.

Back Up

SLC Analysis Variables

Signal processes are mutually very similar

- Mass of X : $m_W \simeq m_Z \simeq m_H$
- Positions of ℓ and ν are always in both ends of N while other object pairs don't have fixed correlated positions



Key Analysis Variables:
$M_T(\ell, MET)$ $\Delta\phi(\ell, MET)$

Type 1 SSDilepton W* analysis

Observations/Improvements to consider for Full Run 2 Analysis:

2. mN < mW region is most sensitive in 3 lepton final state channel

Full Run 2 Solution

- We do no longer search for N below mW in Full Run 2 SS2l channel.