Institute of High Energy Physics
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Evidence for vector boson scattering in semileptonic $l\nu qq$ final states in proton-proton collisions at $\sqrt{s}$= 13 TeV with CMS

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On behalf of the CMS Collaboration

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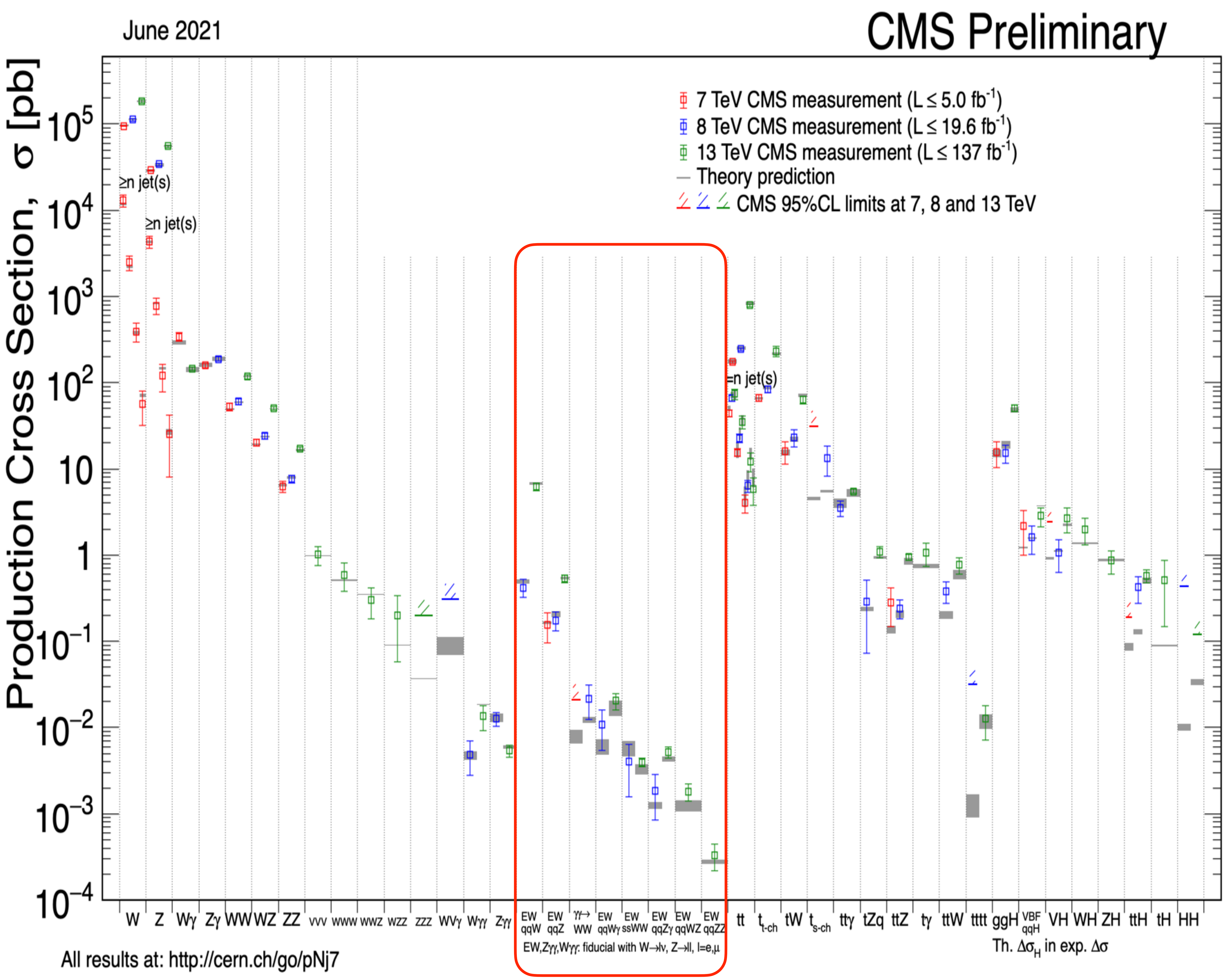
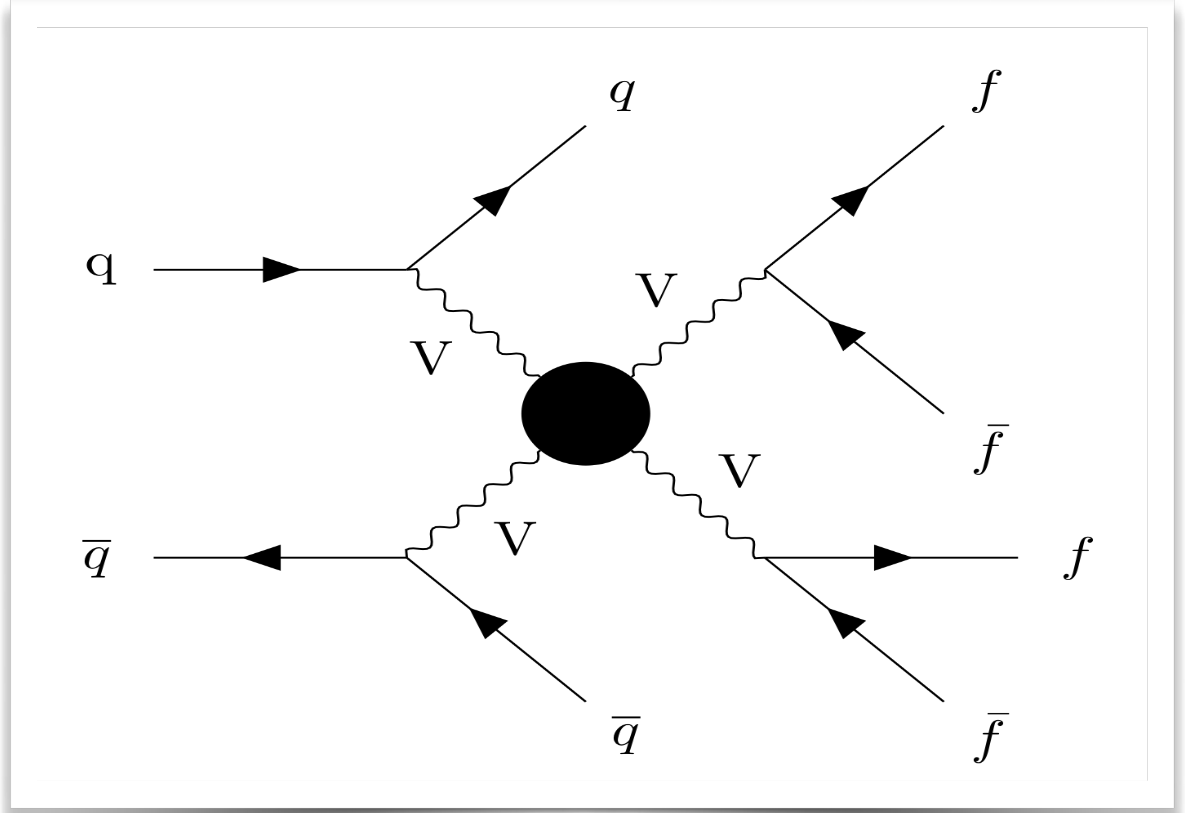
Vector Boson Scattering

- Tested and measured SM cross-sections over 10 orders of magnitude
- Discovered Higgs
- **Still need to understand the mechanism** behind the Electroweak Symmetry Breaking Mechanism (**EWSB**).

- Without Higgs, Vector Boson Scattering (VBS) cross-section violate unitarity at the TeV scale.
  - VBS: the radiated gauge bosons by quarks from the two protons and interact with each other and decay afterwards.
  - VBS measurement gives way to probe the EWSB.
  - Rare process in SM, requires good discrimination against enormous backgrounds.
    - With advancement in ML techniques, provide way to improve signal discrimination
  - First evidence of VBS in WV semi-leptonic channel at LHC. ★
  - First measurement of aQGC measurement with WV (& ZV) semi-leptonic channel at LHC. ★





VBS Diagram

aQGC in the EFT Framework

- BSM search using model independent way:
  - Modify triple and quartic gauge couplings by redefining SM Lagrangian

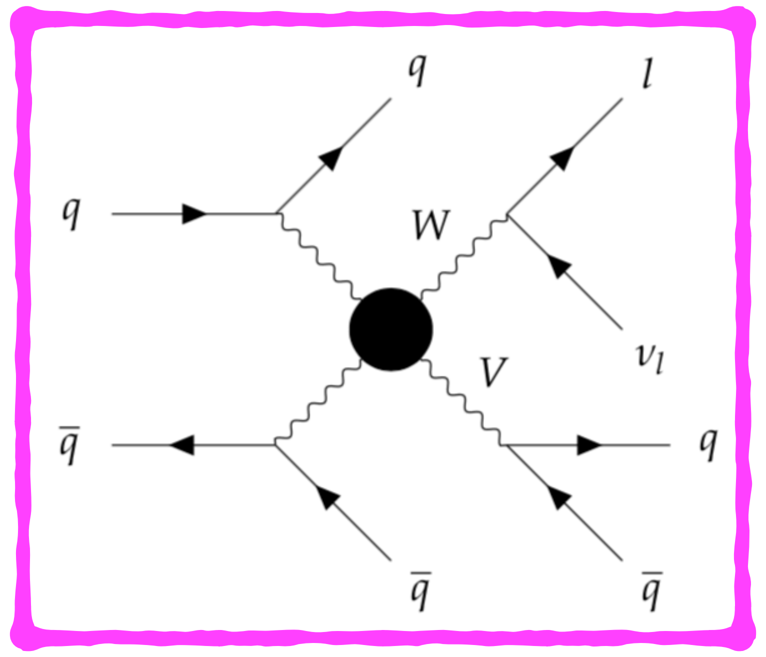
$$L_{SM} \longrightarrow L_{eff} = L_{SM} + \sum_{n=1}^{\infty} \sum_{i} \frac{c_i^{(n)}}{\Lambda^n} \mathcal{O}_I^{(n+4)}$$

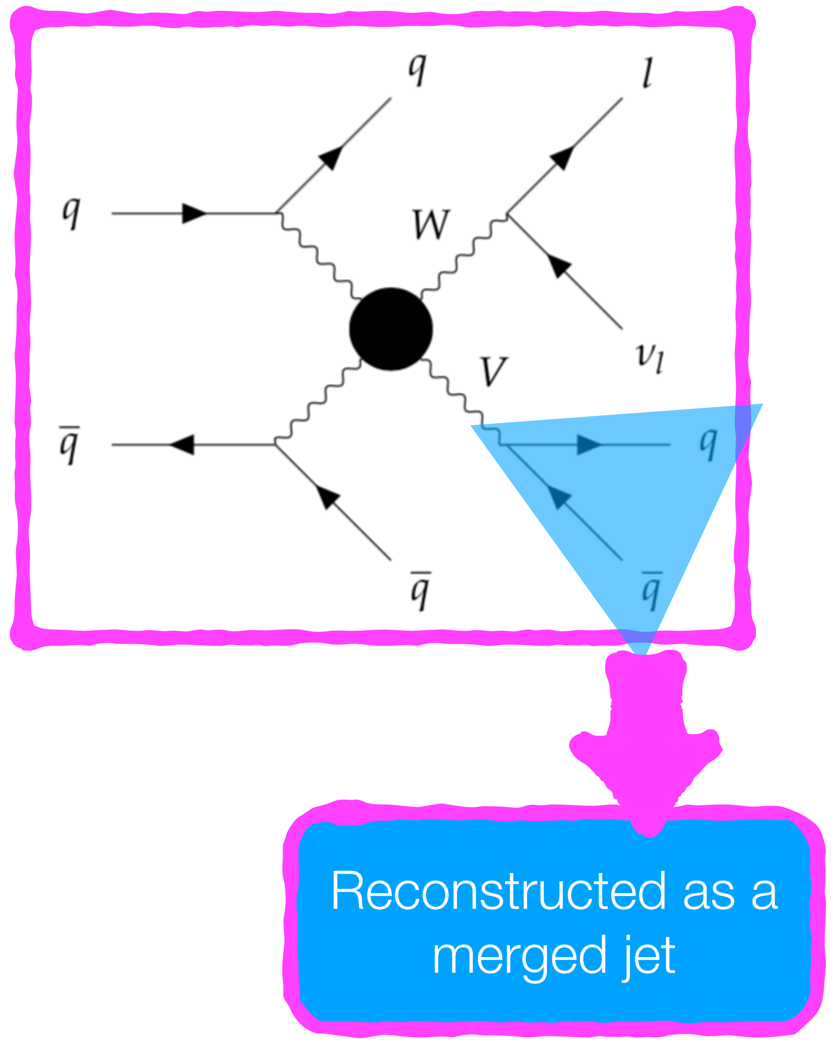
  - $\Lambda >> m$ & $L_{eff} \rightarrow L_{sm}$ as $\Lambda \rightarrow \infty$
  - An effective field theory is the low energy approximation to the new physics, where “low” means $< \Lambda$

	$WWWW$	$WWZZ$	$WW\gamma Z$	$WW\gamma\gamma$	$ZZZZ$	$ZZZ\gamma$	$ZZ\gamma\gamma$	$Z\gamma\gamma\gamma$	$\gamma\gamma\gamma\gamma$
$\mathcal{O}_{S,0}, \mathcal{O}_{S,1}$	✓	✓			✓				
$\mathcal{O}_{M,0}, \mathcal{O}_{M,1}, \mathcal{O}_{M,6}, \mathcal{O}_{M,7}$	✓	✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{M,2}, \mathcal{O}_{M,3}, \mathcal{O}_{M,4}, \mathcal{O}_{M,5}$		✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{T,0}, \mathcal{O}_{T,1}, \mathcal{O}_{T,2}$	✓	✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,5}, \mathcal{O}_{T,6}, \mathcal{O}_{T,7}$		✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,8}, \mathcal{O}_{T,9}$					✓	✓	✓	✓	✓

Motivation of WV Channel (V = W/Z)

- WV production in association with two jets
  - Semi-leptonic final state with a boosted & resolved hadronic W/Z
- Benefits:
  - **larger branching** ratio than same sign analysis WW final state.
  - **Full WW invariant mass reconstruction** (neutrino pz calculation by constraining W-boson mass)
  - **Contribution from all possible QGC and TGC vertex** (for WVjj/ZVjj process):
    - WWWW, ZZWW, WWγγ, γZWW and ZZZZ

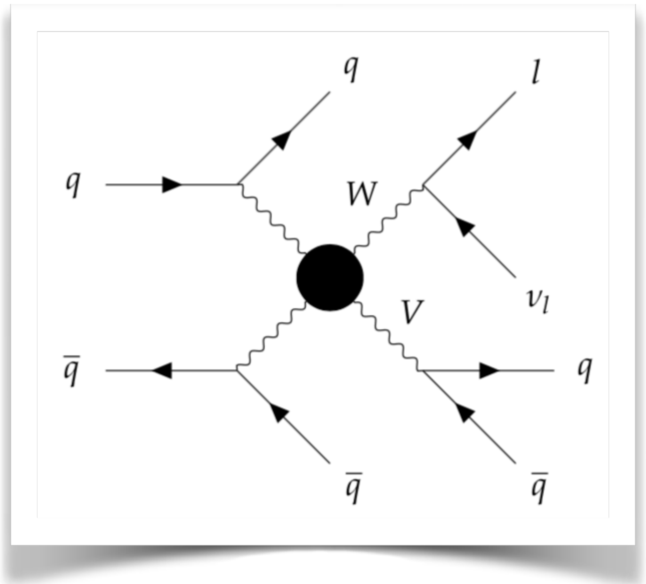




Event Selection

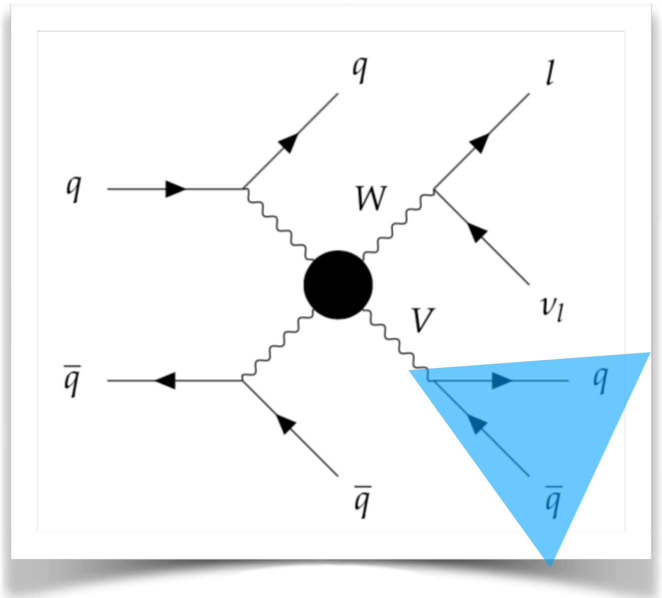
Event selection:

- Two VBS jets
- Two vector bosons WV:
  - Leptonic decays of W bosons into electron and muons with associated neutrinos
  - V (= W/Z) always decay hadronically. It has two categories:
    - Boosted category: Reconstructed as a fat jet having radius parameter of 0.8
    - Resolved category: Reconstructed as two resolved jets having radius parameter of 0.4



Resolved Category

Two jets, pT>30 GeV



Boosted Category

One fat jet pT > 200 GeV

- VBS Topology:
  - **High pseudo-rapidity gap** between VBF jets: $\Delta\eta_{jj} > 2.5$ ($\Delta\eta_{jj} > 4.0$ for aQGC)
  - **Larger di-jet invariant mass**: $M_{VBS\text{-}jj} > 500$ GeV (>800 GeV for aQGC)

- Additional requirement to enhance VBS:
  - Zeppenfeld Variable : $Z = \dfrac{\eta - \dfrac{\eta_{j1}+\eta_{j2}}{2}}{|\eta_{j1}-\eta_{j2}|}$
    Phys. Rev. D 54, 6680)
  - Centrality: Phys. Rev. D 95, 032001
    $\xi_V = min\{\Delta\eta_-, \Delta\eta_+\}$
    where,
    $\Delta\eta_- = min\{\eta(V_{had}), \eta(V_{lep})\} - min\{\eta_{j1}, \eta_{j2}\},$
    $\Delta\eta_+ = max\{\eta_{j1}, \eta_{j2}\} - max\{\eta(V_{had}), \eta(V_{lep})\}$

- Signal extraction using DNN

Analysis Phase Space

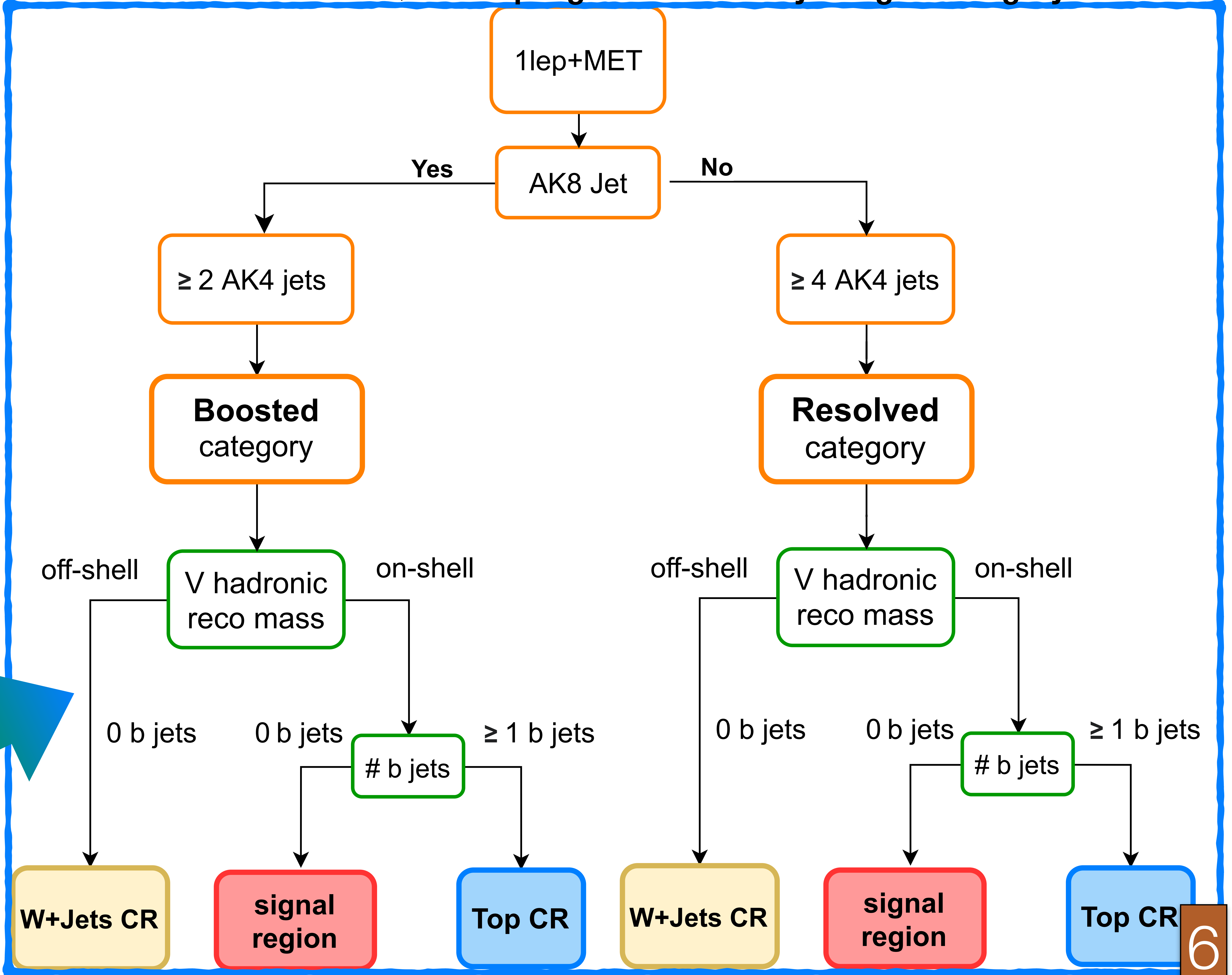
- Control region (CR): Region orthogonal to the signal region
  - W+jet CR: $m_W < 65\ GeV\ or\ m_W > 115\ GeV$
  - Top CR: requires $\geq$ 1 b-jets
- Split according to leptons flavour
- Final fit combining all regions

Object selection

Phase space selection

Simultaneous fit regions

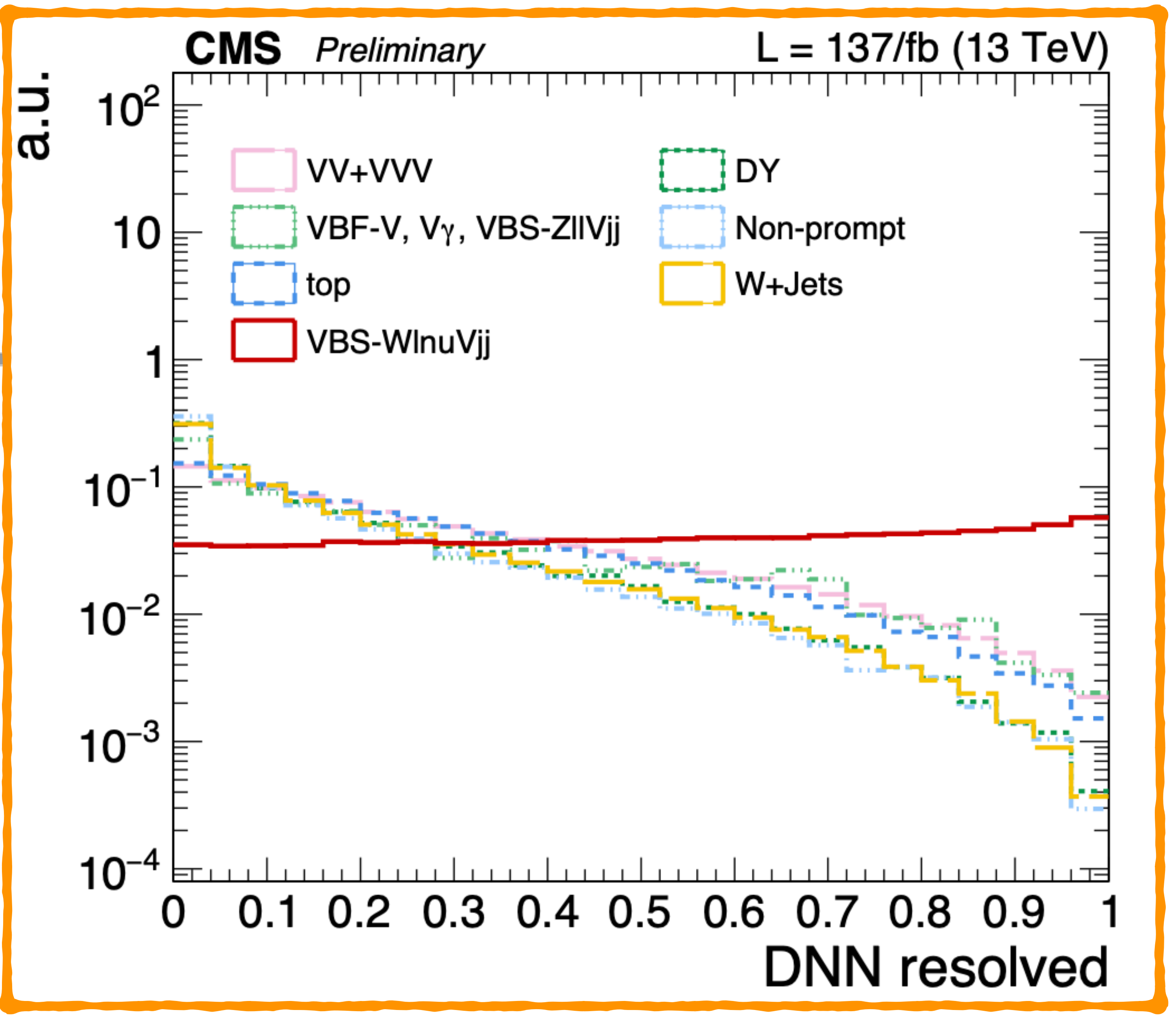
*For aQGC coupling constraint only merged category was used



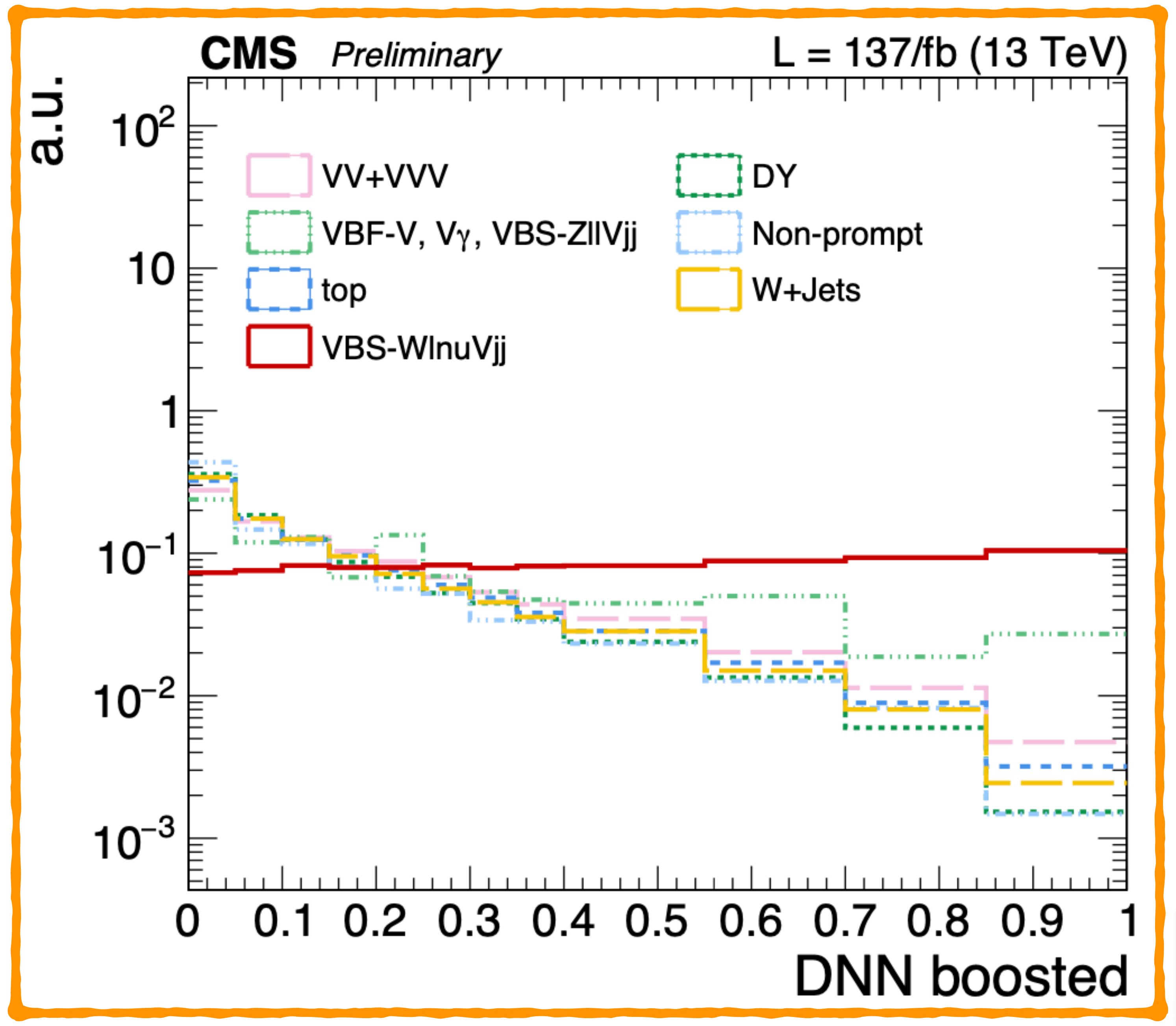
Deep Neural Network (DNN) Training

- **Binary DNN** trained with VBS as signal vs all backgrounds
- Separate model for resolved and boosted categories:
    - Resolved category: Fully connected DNN having 64-64-64-64 nodes with 16 input variables
    - Boosted category: Fully connected DNN having 64-32-32-32 nodes with 13 input variables
- To avoid overtraining dropout layers and L2 weight regularisation was used.

Variable	Resolved	Boosted
Lepton pseudorapidity	✓	✓
Lepton transverse momentum	✓	✓
Zeppenfeld variable for the lepton	✓	✓
Number of jets with $p_T > 30$ GeV	✓	✓
VBS leading tag-jet p_T	-	✓
VBS trailing tag-jet p_T	✓	✓
Pseudorapidity interval between VBS tag-jets	✓	✓
Quark Gluon discriminator of the highest p_T jet of the VBS tag-jets	✓	✓
Azimuthal angle distance between VBS tag-jets	✓	✓
Invariant mass of the VBS tag-jets pair	✓	✓
p_T of jets from V_{had}	✓	-
Pseudorapidity difference between V_{had} jets	✓	-
Quark Gluon discriminator of the V_{had} jets	✓	-
V_{had} p_T	-	✓
Invariant mass of the V_{had}	✓	✓
Zeppenfeld variable for the V_{had}	-	✓
V_{had} centrality	-	✓



DNN Score Distribution



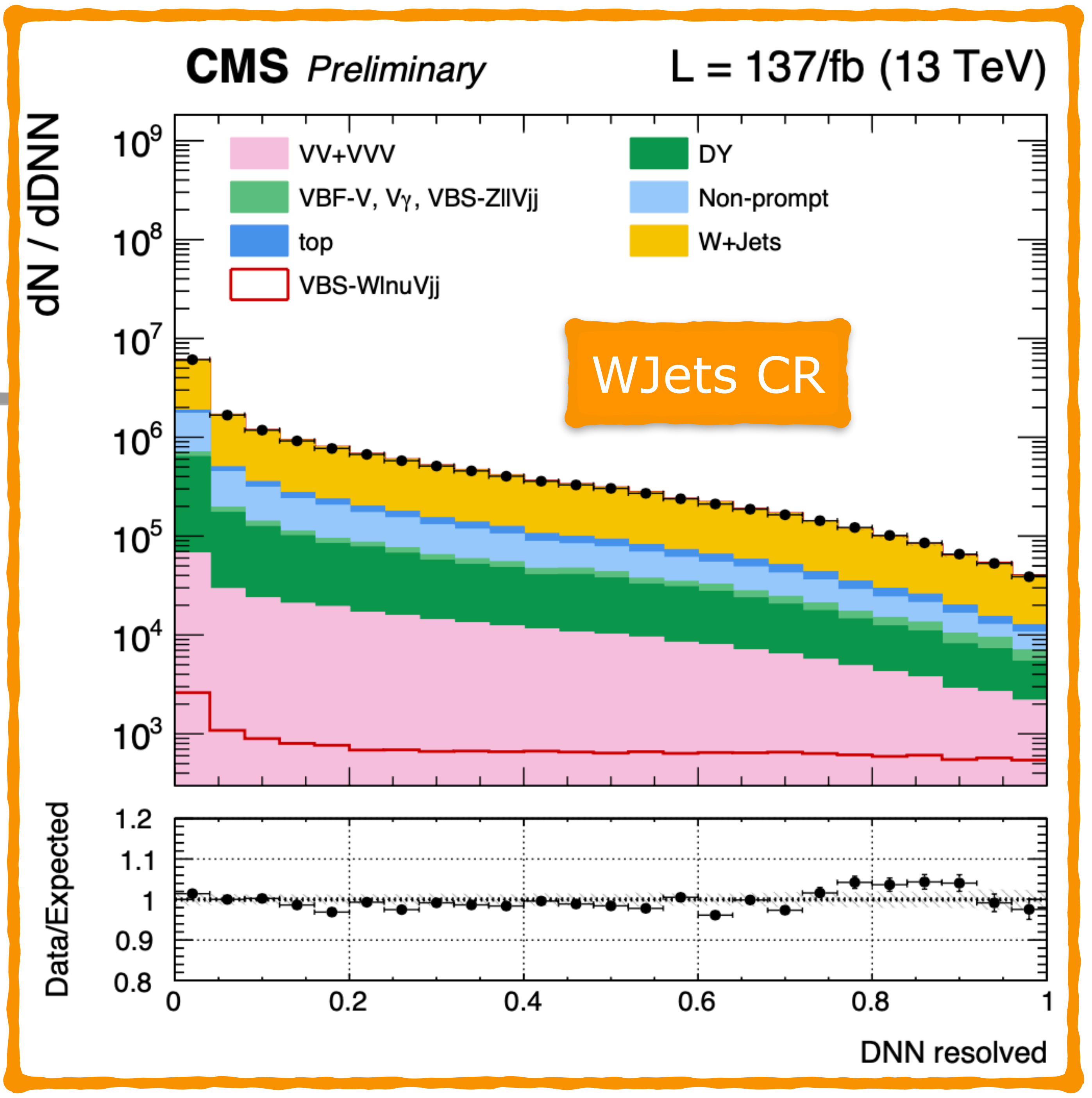
DNN Input variables

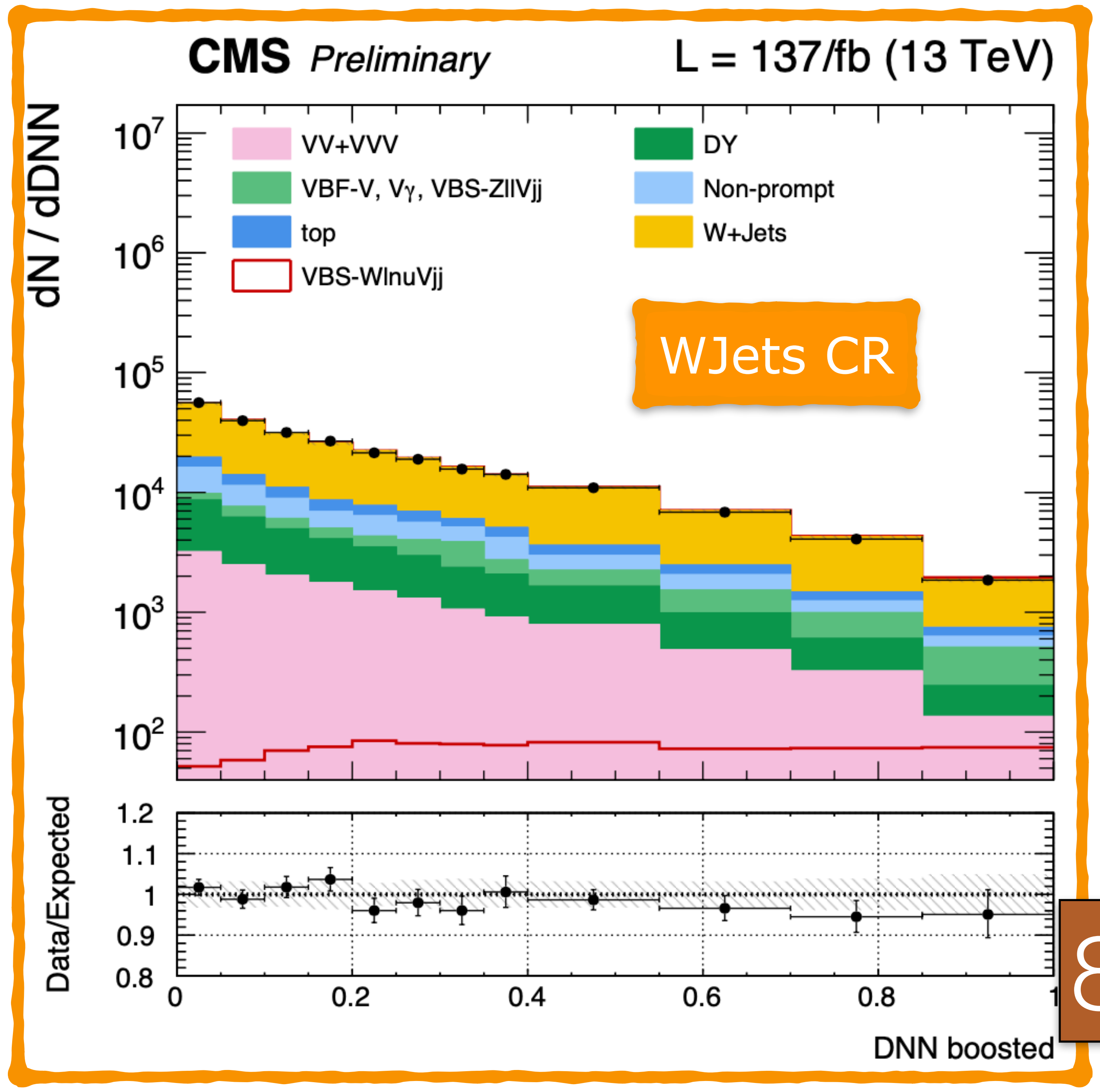
Background Estimation

- QCD multijet background: Estimated using data-driven method
  - Tight/Loose efficiency for fake (prompt) lepton measured in QCD (Drell-Yan) enriched data sample
  - Construct relation between # prompt/ fake leptons and # passing/failing tight ID
  - Weight events in Loose data control region by (probability to have at least one non-prompt lepton) x (probability to still pass tight selection)

- W+Jets:
  - Mismodelling of the jet pT spectrum for W+many-jets sample → data-driven differential corrections
  - W+Jets contribution taken from MC but corrected in a data driven way.
  - Fit their normalization in the global fit in the W+jets CR
  - After the data driven estimation → Predictions and data agree within uncertainties

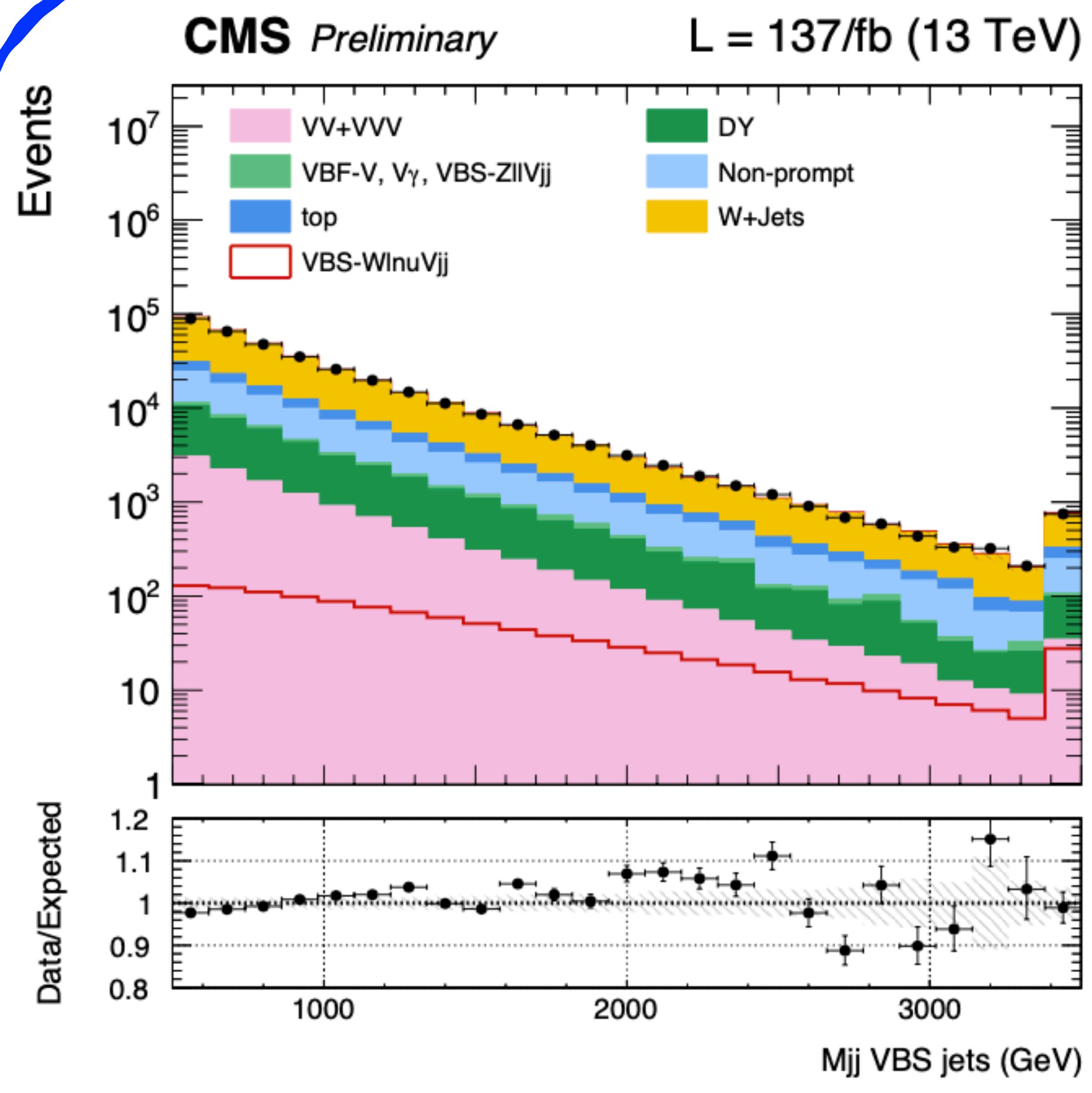
- Top background: Shape from MC, normalisation extracted from top CR in the final fit to the data



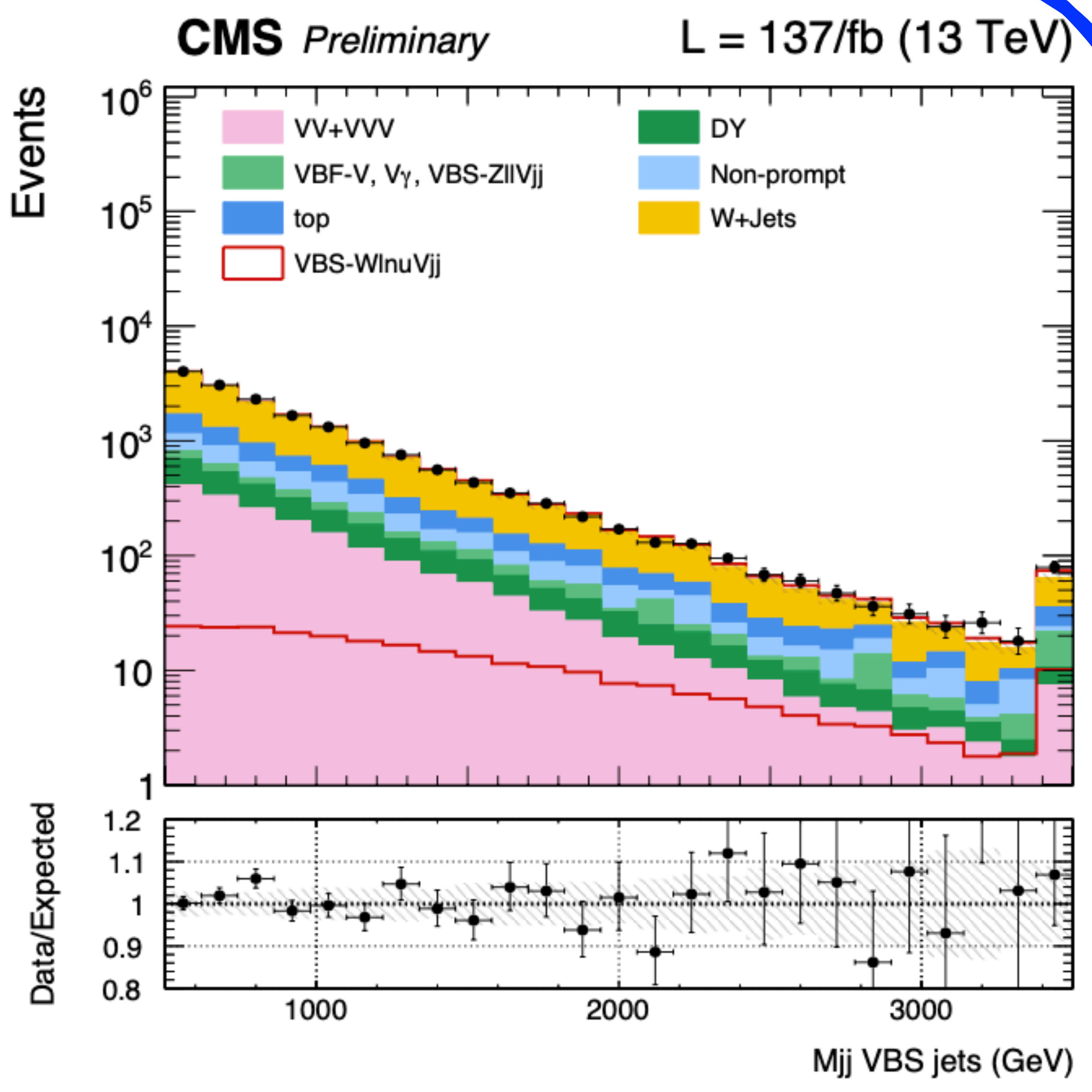


Signal Region

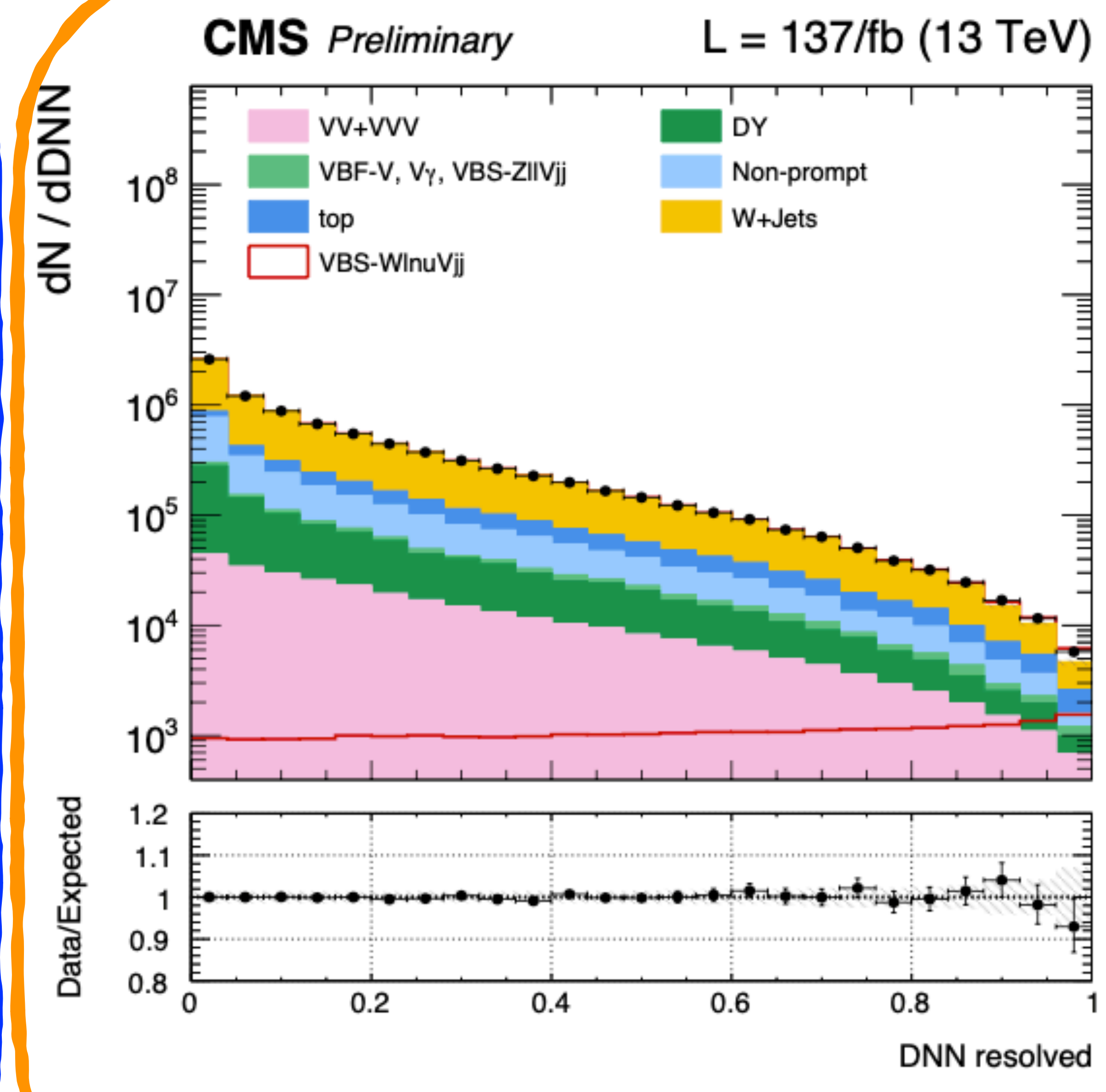
- Signal region distribution for one of highest ranked variable, di-jet invariant mass of VBF jets and DNN score, for both resolved and boosted case



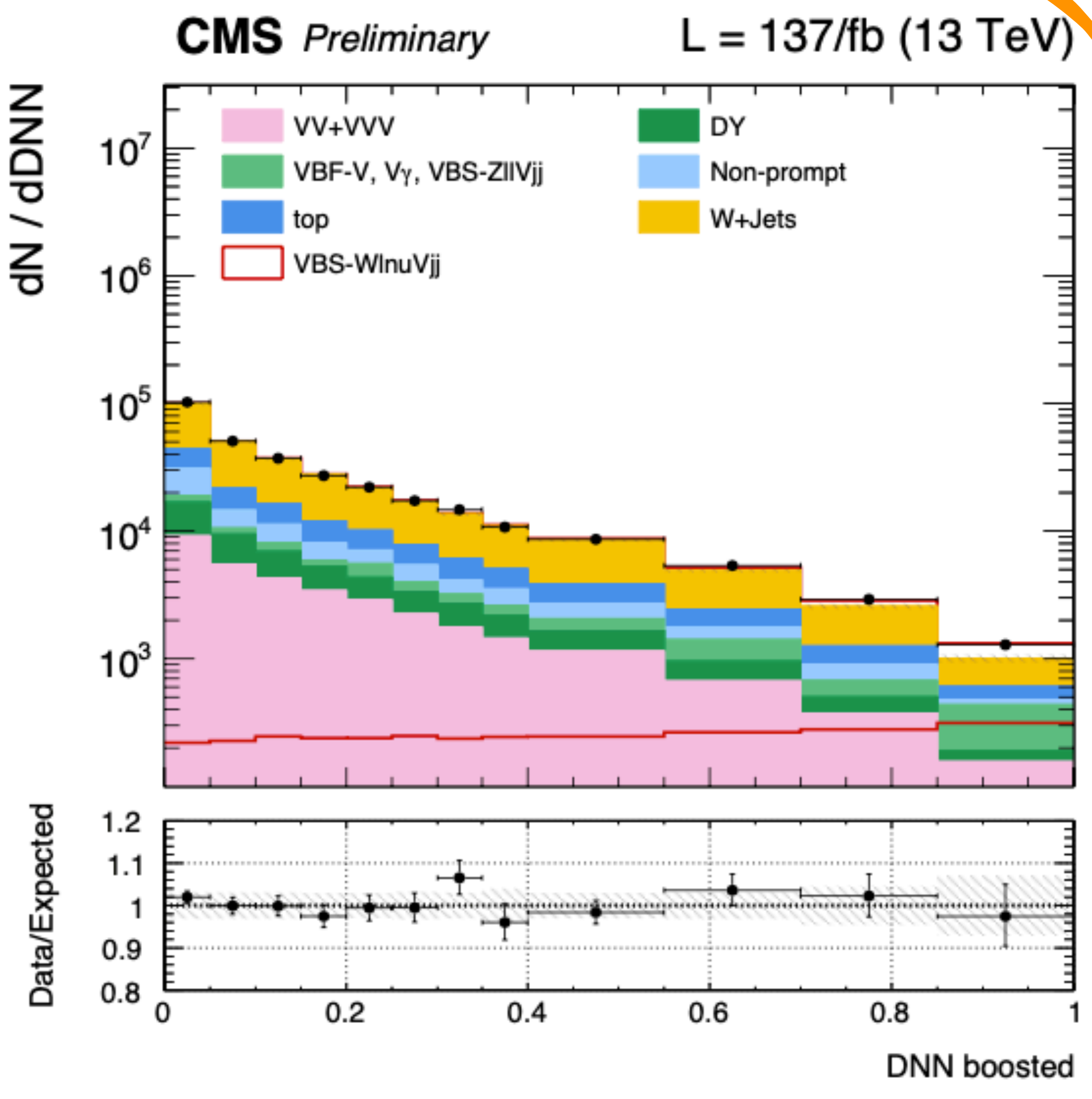
Resolved Category



Boosted Category



Resolved Category



Boosted Category

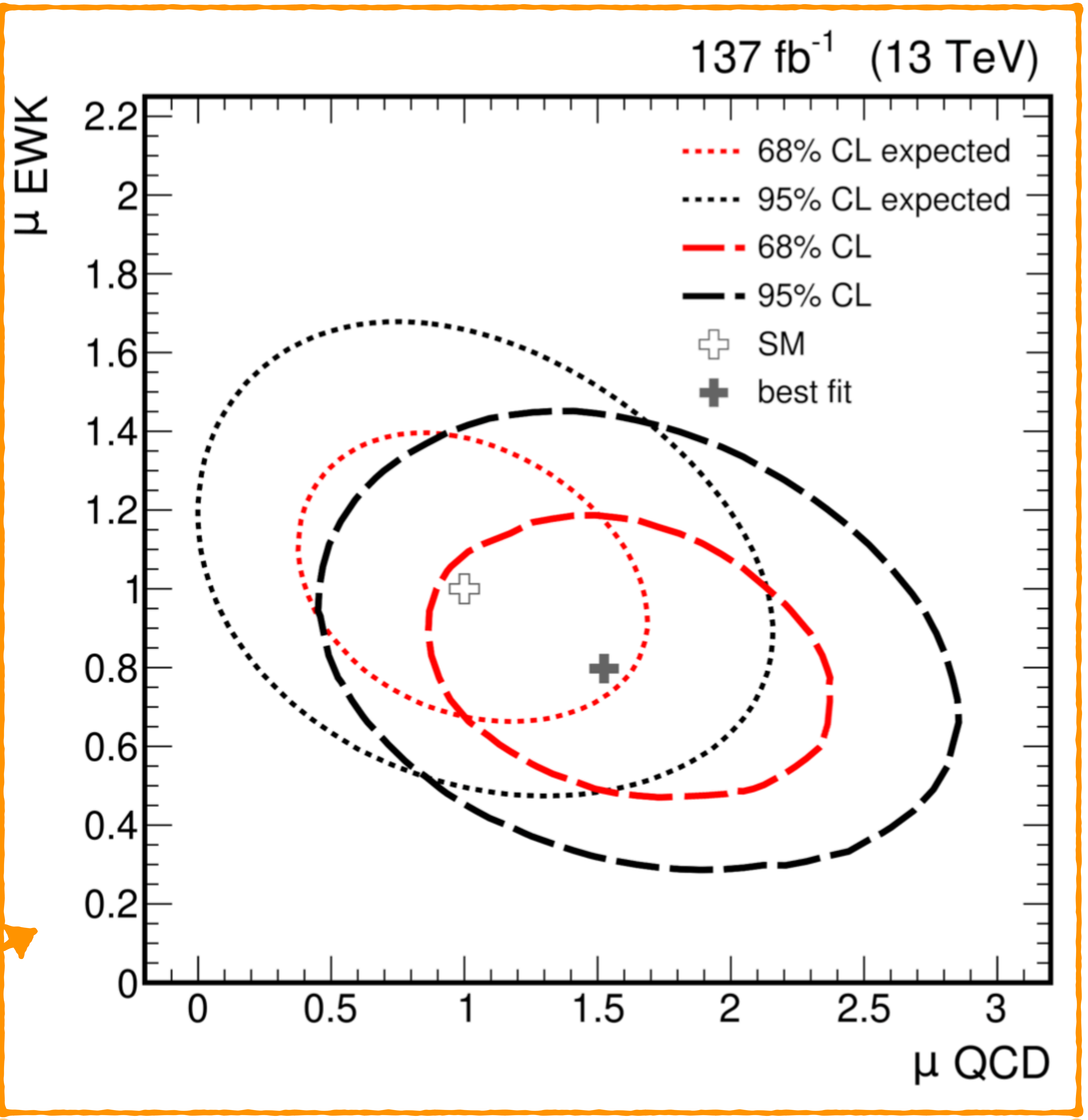
Systematic Uncertainty

- Systematic uncertainty can affect the shape and normalization of the DNN distribution.
    - Largest impact is from statistics.
        - Expected as VBS signal is a rare process.
    - Experimental uncertainty is mainly dominated by b-tagging and jet energy scale/resolution

Uncertainty source	$\Delta\mu_{EW}$
Statistical	0.12
Limited sample size	0.10
Normalization of backgrounds	0.08
Experimental	0.06
b-tagging	0.05
Jet energy scale and resolution	0.04
Luminosity	0.01
Leptons identification	0.01
Boosted V boson identification	0.01
Theory	0.12
Signal modeling	0.09
Background modeling	0.08
Total	0.22

Summary & Results - I

- Fit DNN shape in the signal regions
- Fit W+jets subcategories normalizations in W+jets control regions
- Fit only normalization in top-quark control regions
- Results:
  - **SM EW signal strength**:
    $\mu_{EW} = \sigma^{obs}/\sigma^{SM} = 0.85^{+0.24}_{-0.20} = 0.85^{0.21}_{-0.17}\ (syst)^{+0.12}_{-0.12}\ (stat)$
    Signal significance of $4.4\ \sigma$ ($5.1\ \sigma$ expected)
    - Observed fiducial cross-section ($m_{qq} > 100\ GeV$, $p_t^q > 10\ GeV$) of 1.9 ± 0.5 pb
  - Considering **EW and QCD WV production** as signal, the **signal strength**:
    $\mu_{EW} = \sigma^{obs}/\sigma^{SM} = 0.98^{+0.20}_{-0.17} = 0.98^{0.19}_{-0.16}\ (syst)^{+0.07}_{-0.07}\ (stat)$
    - Measured cross-section: $16.6^{+3.4}_{-2.9}$ pb
  - Simultaneous 2D fit of the EW and QCD WV signal strengths

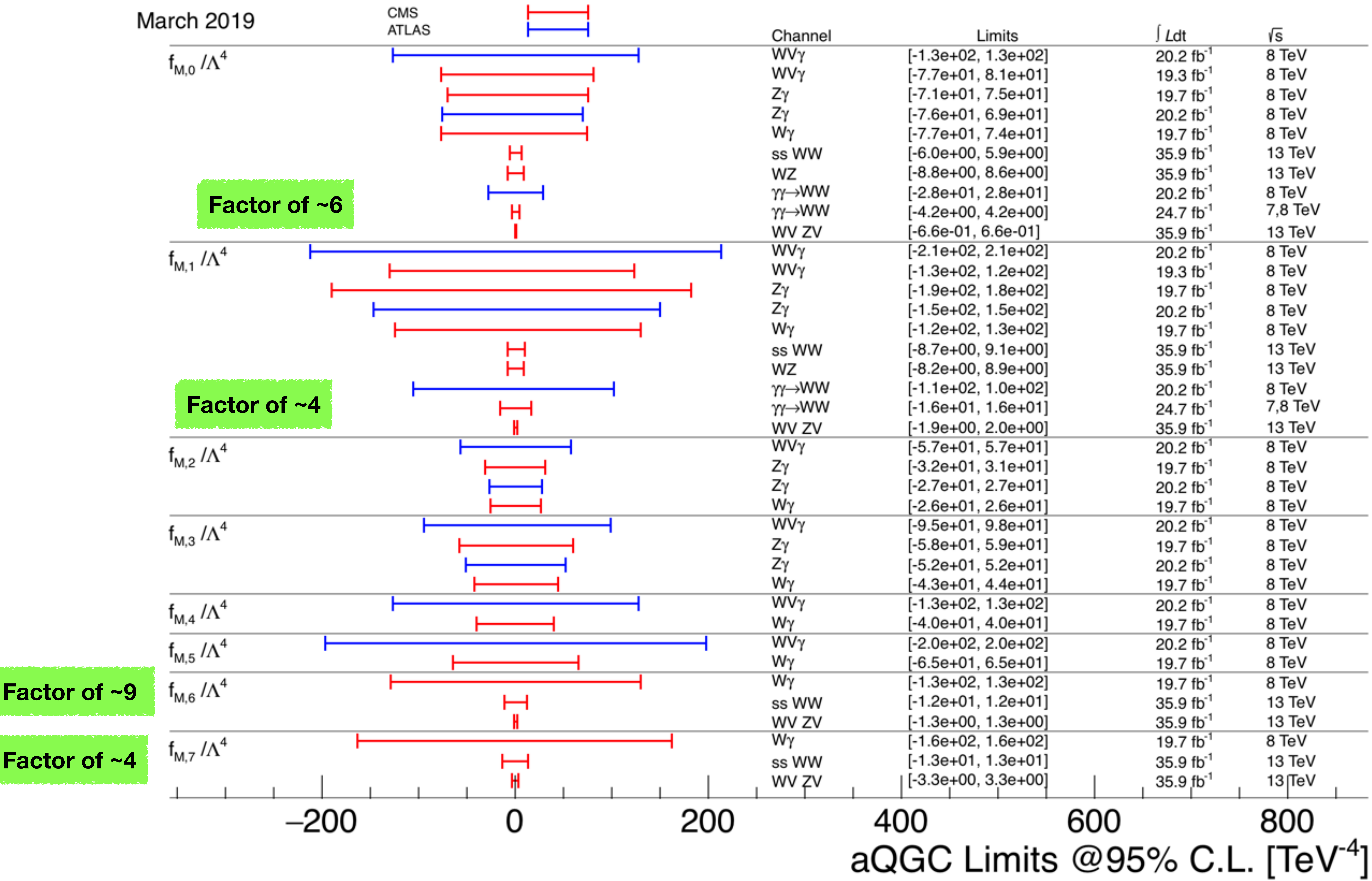


Summary & Results - II

- Limits for the WV and ZV final states and combination
  - As expected WV significantly more sensitive compared to ZV

	Observed (WV) (TeV^{-4})	Expected (WV) (TeV^{-4})	Observed (ZV) (TeV^{-4})	Expected (ZV) (TeV^{-4})	Observed (TeV^{-4})	Expected (TeV^{-4})
f_{S0}/Λ^4	$[-2.6, 2.7]$	$[-4.0, 4.0]$	$[-37, 37]$	$[-29, 29]$	$[-2.6, 2.7]$	$[-4.0, 4.0]$
f_{S1}/Λ^4	$[-3.2, 3.3]$	$[-4.9, 4.9]$	$[-30, 30]$	$[-23, 23]$	$[-3.3, 3.3]$	$[-4.9, 4.9]$
f_{M0}/Λ^4	$[-0.66, 0.66]$	$[-0.95, 0.95]$	$[-6.9, 6.9]$	$[-5.1, 5.1]$	$[-0.66, 0.66]$	$[-0.95, 0.95]$
f_{M1}/Λ^4	$[-1.9, 2.0]$	$[-2.8, 2.8]$	$[-21, 21]$	$[-15, 15]$	$[-1.9, 2.0]$	$[-2.8, 2.8]$
f_{M6}/Λ^4	$[-1.3, 1.3]$	$[-1.9, 1.9]$	$[-14, 14]$	$[-10, 10]$	$[-1.3, 1.3]$	$[-1.9, 1.9]$
f_{M7}/Λ^4	$[-3.3, 3.2]$	$[-4.8, 4.8]$	$[-33, 33]$	$[-24, 24]$	$[-3.3, 3.3]$	$[-4.8, 4.8]$
f_{T0}/Λ^4	$[-0.11, 0.10]$	$[-0.16, 0.15]$	$[-1.3, 1.3]$	$[-0.95, 0.95]$	$[-0.12, 0.10]$	$[-0.16, 0.15]$
f_{T1}/Λ^4	$[-0.11, 0.12]$	$[-0.17, 0.17]$	$[-1.4, 1.4]$	$[-0.98, 0.99]$	$[-0.11, 0.12]$	$[-0.17, 0.17]$
f_{T2}/Λ^4	$[-0.27, 0.27]$	$[-0.38, 0.38]$	$[-3.1, 3.2]$	$[-2.3, 2.3]$	$[-0.27, 0.27]$	$[-0.38, 0.38]$

Summary & Results - II

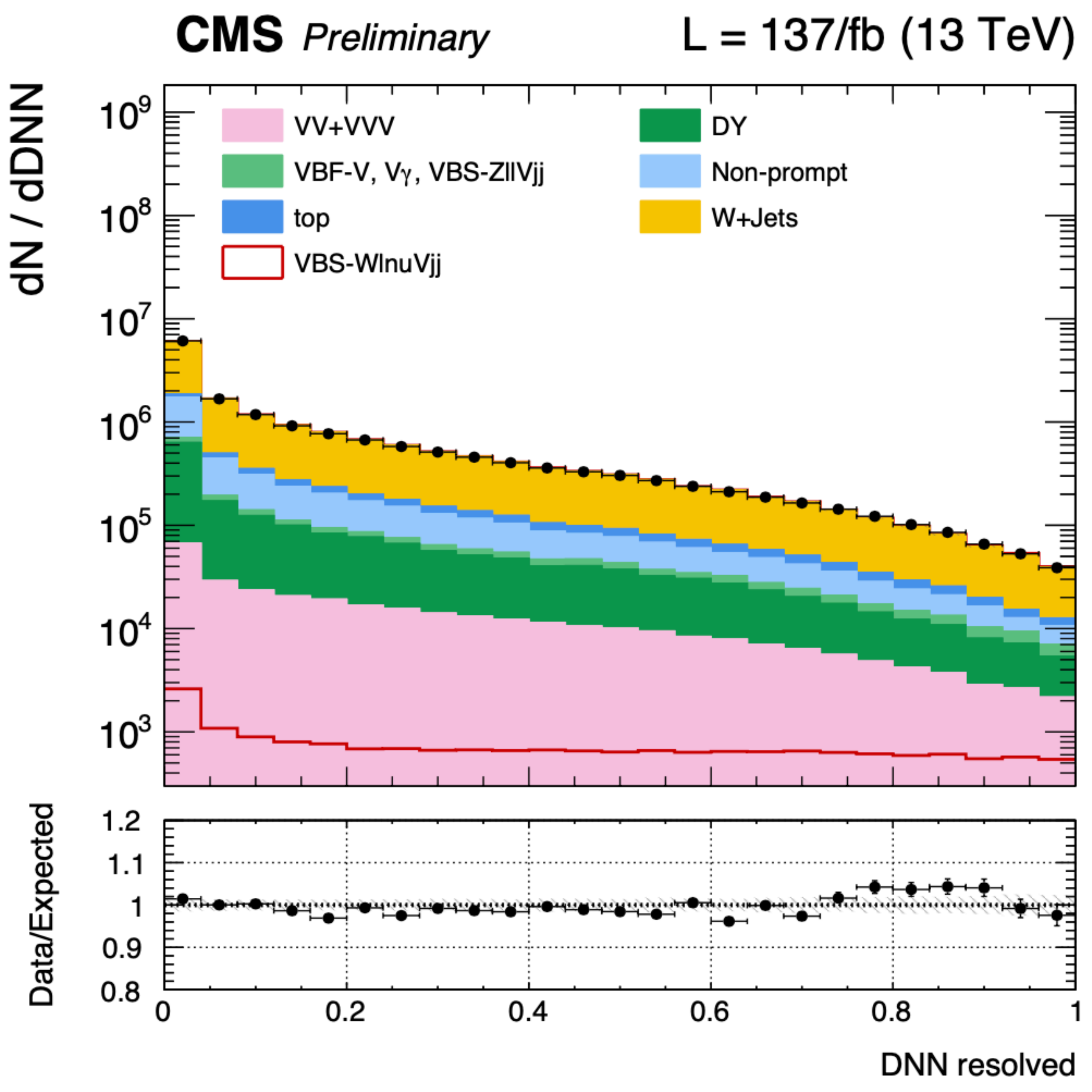


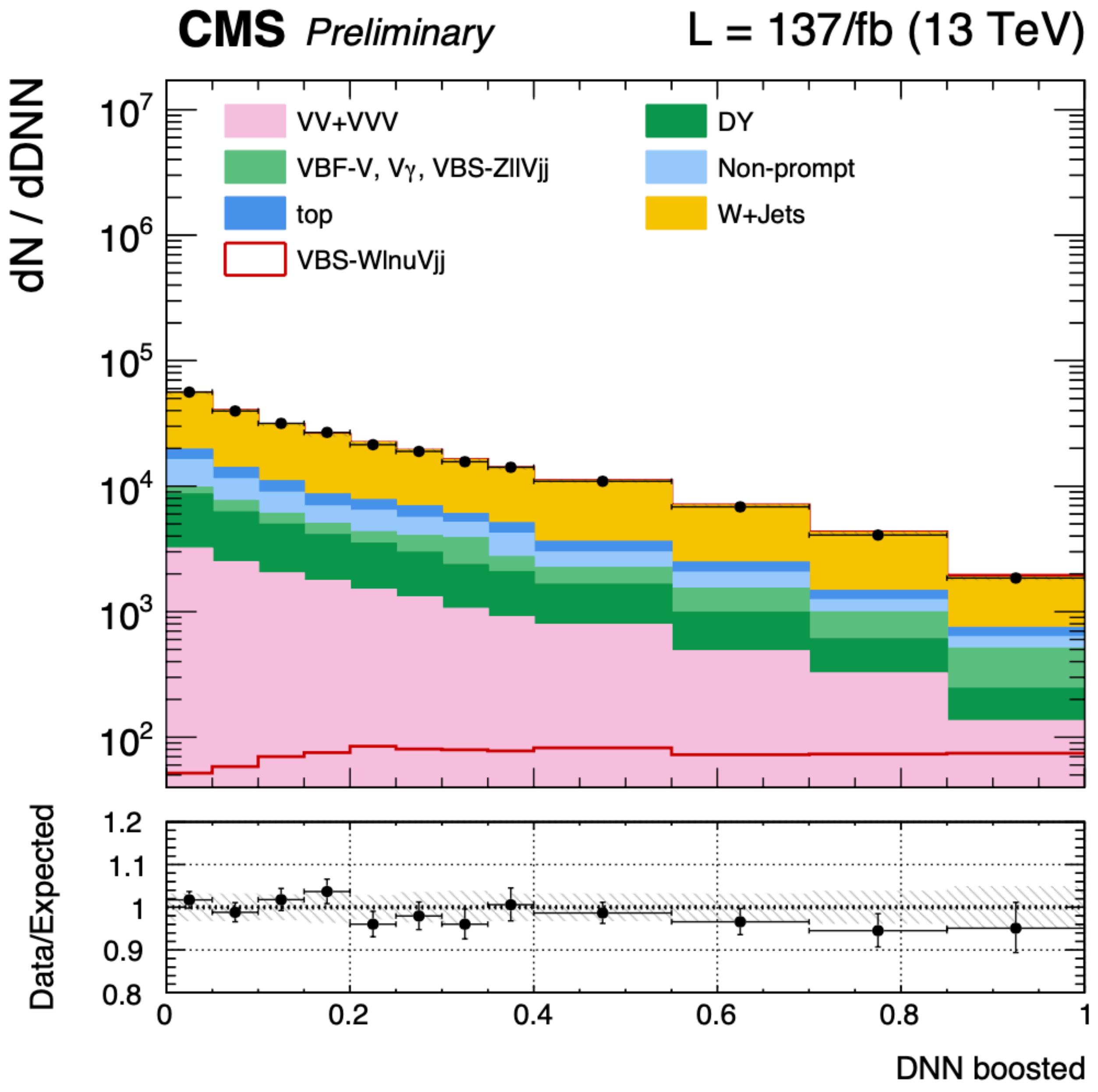
Thank you for your time!

- Backup

Control Regions

WJets CR





Top CR